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THE NEW ZEALAND GREYWACKES

A study of associated geological concepts

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Geology

The University of Auckland, 2003

Heather Halcrow Nicholson
Consent form
This thesis traces changes in geological concepts associated with the New Zealand greywackes. Since mineralogists adopted the German mining term ‘grauwacke’ in the 1780s to refer to a type of old, hard, grey, muddy sandstone, both the name and the rock have caused confusion and controversy. English geologists in the 1830s used the term ‘grauwacke’ as a rock name and a formation name for their most ancient rocks. The English abandoned the name, but ‘greywacke’ remained useful in Scotland and began to be used in New Zealand in the 1890s. New Zealanders still refer to the association of semi-metamorphosed greywacke sandstones, argillites, minor lavas, cherts and limestone constituting the North Island ranges and the Southern Alps as ‘the greywackes’. With the South Island schists, the greywackes make up 27% of the surface of the New Zealand landmass. They supply much of our road metal, but otherwise have little economic importance. Work on these basement rocks has rarely exceeded 10% of geological research in New Zealand.

Leading geologists of the nineteenth and early twentieth centuries competed to construct stratigraphical models for New Zealand where the greywackes were usually classified as of Paleozoic age. Controversy was generated by insufficient data, field mistakes, wrong fossil identifications, attachment to ruling theories and the inability of European-based conventional stratigraphical methodologies to deal with these Carboniferous to Jurassic rocks formed in a very different and unsuspected geological environment.

After 1945, growth of the universities, increased Geological Survey activity, and the acquisition of more reliable data led to fresh explanatory ideas about geosynclines, turbidity currents, depositional facies, low-grade metamorphism, and structural geology. New interest in the greywackes resulted in the accumulation of additional knowledge about their paleontology, petrography, sedimentology and structure. Much of this geological data is stored in visual materials including maps, photographs, and diagrams and these are essential today for the interpretation and transfer of information.

The development of plate tectonic theory and the accompanying terrane concept in the seventies and eighties permitted real progress in understanding the oceanic origin of greywackes within submarine accretionary prisms and their transport to the New Zealand region. In the last half century comparatively little geological controversy about the greywackes has taken place because of the acquisition of quantities of data, technological improvements, and the use of a dependable theory of the Earth’s crust. Scientific controversy takes place when data and/or background theory is inadequate.
DEDICATION

Dedicated to the geologists’ wives
who took care of everything else
ACKNOWLEDGEMENTS

The subject of ‘greywackes’ has been a rewarding vehicle for exploring the history of geology in New Zealand. Naturally, the project turned out to be a great deal larger and more sprawling than I expected, but now it is done. The exercise has changed and sustained me. It introduced me to many fine scientists and it taught me to open my mind to a great deal more than geological matters. My heartfelt thanks go to members of the Department of Geology at the University of Auckland who took me in as a very mature student. I am grateful for their kindness, patience, guidance, explanations, reminiscences, good humour and company. Thanks to Bernhard Spörli for his fortitude in the face of my persistent story-telling and to Peter Ballance and Philippa Black, for encouragement, interest, for reading chapters, and thanks to Peter for the use of Figure 0.4. Thanks also to Jack Grant-Mackie and Murray Gregory for conversations, books and good advice. Elva Leaming’s expertise as geology librarian, her unstinting help and her friendship is very much appreciated, as is Louise Cotterall’s and Bothwell Wong’s expert advice, and Richie Sim’s perceptiveness. Thanks are also due to Richard Le Heron who showed me how to plot my course, and to Ruth Barton for her companionship and good advice. I am especially grateful to the examiners Robert H. Dott Jr and Mike Johnston for their careful reading and valuable suggestions for improving this work.

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The library of the Institute of Geological and Nuclear Sciences and the Royal Society of New Zealand, the Alexander Turnbull Library, the Hocken Library of Dunedin generously granted permission to use images from their publications, and these are acknowledged in the captions. I am also grateful for the practical help given by Eamonn Bolger, archivist of Te Papa and to Brian Addley of GNS. Librarians of the University of Auckland provided several valuable scans of historical maps. I am grateful to the University of Auckland and the Department of Geology for a Graduate Research Grant and for assistance to travel to a conference of the Australasian Association for the History, Philosophy and Social Studies of Science held at the University of the Sunshine Coast in Queensland in 1999, and for assistance to attend the annual Geological Society of New Zealand conferences.

And very special thanks to my daughters, Ruth and Jessica, and to my sister Dawn, for their loving support and patience through these years.
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INTRODUCTION

Theories ... should be mutually compatible with one another and cohere. The theories of palaeontology, sedimentary petrology, tectonics, geomorphology, etc., all have to lock into one another — and ideally with any grander metaphysical beliefs that one might have.
(Oldroyd, 1990: 370)

The field geologist has a magnificent array of problems to tackle in New Zealand.
(Suggate, 1965)

The purpose of this study is trace the way in which geologists observed and interpreted the greywackes, one of the most common and enigmatic rock types in New Zealand, from the early nineteenth century through to the late twentieth century (1985) and to relate their observations to developments in geological concepts in New Zealand.

This work will help fill a gap in our knowledge of the development of geological science in New Zealand. The few substantial studies on the history of geology in New Zealand were produced over thirty years ago (Waterhouse, 1965; Waterhouse, 1966; Burton, 1965; Oldroyd, 1967; Fleming, 1969). Since then, geological science has undergone a major paradigmatic revolution.

When I began this project after many years away from geology, having written a thesis on greywackes in 1953, I was greatly surprised to find that the very name ‘greywacke’ had been the subject of intense debate among sedimentologists. It had never occurred to me that this ‘venerable and battle-scarred rock name’ (Dott, 1964) could be a troublemaker. In those earlier days everyone called the varied mass of rocks making up New Zealand’s mountain ranges ‘greywackes’ and that was that. It was even understood by non-geologists. We identified greywackes on field appearance as a dark grey, hard, sandstone consisting of mineral and rock particles set in a fine matrix. Quite simple, quite eighteenth century, and quite uncontroversial.

Defining the New Zealand Greywackes

The common New Zealand ‘greywackes’ constitute those rock sequences equivalent to the old ‘Undifferentiated Permian-Triassic-Jurassic’ greywackes of the 1940s and 1950s (Figures 0.1, 5.20, 5.21). These rocks, together with their metamorphosed equivalents, the South Island schists, occupy about 27% of the surface of the New Zealand landmass (Lauder, 1962). On their own, the greywackes occupy 16% of
Figure 0.1: Map showing distribution of rocks that have at some time or other been known as 'the greywackes'. In 1948 the greywackes (shown in blue) were classed as 'Undifferentiated Jurassic-Triassic-Permian' by the Geological Survey. These were later named as the Torlesse Group (Suggate, 1961), then Torlesse Supergroup (Bishop, 1971), and now, Torlesse Terrane (Landis, 1969). The greywackes of the Te Anau and Maitai Series, now known as the Caples and Maitai Terranes (light blue) lie to the south of the Haast Schists. The schists (pink) are derived from the greywackes of the Torlesse and Caples Terranes. The Hokonui rocks (green-blue), now known as the Murihiku Terrane, are of the same age as most of the greywackes, have been confused with them, but have a different origin. Maps adapted from figures 4.93, 4.94, The Geology of New Zealand (Suggate, 1978).
Figure 0.1: Map showing distribution of rocks that have at some time or other been known as 'the greywackes'. In 1948 the greywackes (shown in blue) were classed as 'Undifferentiated Jurassic-Triassic-Permian' by the Geological Survey. These were later named as the Torlesse Group (Suggate, 1961), then Torlesse Supergroup (Bishop, 1971), and now Torlesse Terrane (Lancel, 1969). The greywackes of the Te Anau and Matral Series, now known as the Caples and Matral Terranes (light blue) lie to the south of the Haast Schists. The schists (pink) are derived from the greywackes of the Torlesse and Caples Terranes. The Hokonui rocks (green-blue), now known as the Murihiku Terrane, are of the same age as most of the greywackes, have been confused with them, but have a different origin. Maps adapted from figures 4.93, 4.94, The Geology of New Zealand (Suggate, 1978).
the land surface (Figure 0.1). Greywackes and schists comprise most of New Zealand’s unseen basement rock and determine the country’s shape and structure. New Zealand owes its existence above sea level to these rocks being pushed up above the ocean by compression between two tectonic plates. Historically, the greywackes have long been typified by the ‘amount of mystification they have imparted to geologists’ (Waterhouse, 1965).

Exclusions

This study is not biographical except where biographical details affect it, and it has little to say about the role of government and business in determining what geological research is to be done. References to general and overseas geology are limited to explanations related to this study. It does not include the geology of the Upper Cretaceous and Tertiary rock sequences, or the histories of sedimentology, of stratigraphy or principles of stratigraphy, of economic geology, or of technical advances, nor is it an analysis of philosophical or historical models of science. The study touches on low-grade metamorphism as it affected the greywackes. The following rock groups are included only where they were correlated with, confused with, or otherwise affected interpretations of the greywackes or the schists:

♦ The Mesozoic Murihiku Terrane, previously known as the Hokonui System or Hokonui facies.
♦ The Maitai Terrane including the ophiolites of Dun Mountain. The name ‘Maitai’ plays an important role in this thesis because the greywackes were long correlated with the Maitai rocks.
♦ The Caples Terrane, which includes greywackes of the old Te Anau rocks south of the Otago schists.
♦ The old Paleozoic sedimentary rocks and schists of north-west Nelson, Westland and Fiordland, except where they were thought to be related to the greywackes of Canterbury and the North Island ranges.
♦ The period after 1985 except where publications shed light on pre-1985 problems.

What is this thesis about?

The thesis has never been simply about the rock name ‘greywacke’, or even just the petrography of these voluminous, difficult, and generally uninformative rocks. It is about numerous discourses relating to greywacke and to the concepts and theories that support it as a geological category. The New Zealand greywackes are said to have a history of controversy, and therefore constitute a useful vehicle for investigating some of the politics of geological knowledge in this country.

The thesis is written from inside geology, and is largely about how geologists observe and interpret the greywackes. It is not an historian’s or a philosopher’s or a sociologist’s view from outside geology. The
geological reports and debates recounted here are historically and geographically specific, being centred mostly in New Zealand from the mid 1860s onward and have usually taken place in an academic or Geological Survey setting. Several terms such as ‘paradigm’ and ‘puzzle-solving’ are used in the sense of Thomas Kuhn (1970), because of their usefulness, and because Kuhn’s 40-year old model of how science is supposed to work is familiar to many scientists. However, Kuhn’s model is based on physics, not geology.

This study reflects the dual nature of geology (Laudan, 1987): on one side the discipline is causal and process-oriented, and on the other it is historical, tracing unique episodes in the Earth’s history. Here, causal problems have to do with the origins of greywackes as a universal entity, and include sedimentological and tectonic processes common to New Zealand’s and all other greywackes. In contrast, the historical problems are focussed on reconstructing the singular geological histories of different parts of the New Zealand landmass.

Geological knowledge is multidimensional, contested and open to reinterpretation. The problems to do with the greywackes were repeatedly redefined as new evidence and theory strained existing views and explanations. These have to do largely with stratigraphic and paleontological questions, but also with specific geological episodes of sedimentation and tectonic activity.

**Major topics**

- How and why did the word ‘greywacke’ come into geological language? What were the intellectual currents at the time? Where did geology begin as a science? How did the term migrate from late eighteenth century Germany to late nineteenth century New Zealand?
- What changes to the meaning and usage of the term ‘greywacke’ occurred over the years? Why is it ‘battle-scarred’? What vicissitudes has it endured? What led to the term’s repeated banishment? What other terms replaced it?
- Why do ordinary, common greywackes constitute such a formidable scientific problem? Why has this rock type been subjected to scrutiny, to what purpose, and with what consequences?
- How were the greywacke sandstones and argillites (Figures 0.2, 0.3) named and described? How does petrological classification operate? How could the puzzling association of seemingly shallow-water sandy greywackes and abyssal sequences like cherts be explained? What problems faced geologists regarding the structure, petrology, origin and history of the different elements of the greywacke association?

---

1 Introduced in 1962.
How could several different stratigraphic schemes co-exist in New Zealand? How did the proponents and antagonists of each scheme support their views?

How were the boundaries of the New Zealand greywackes defined? Why were the greywackes problematical for stratigraphers? What difficulties were encountered in building a New Zealand stratigraphic column? Why were there so many problems to do with the Maitai beds, the schists and the Hokonui rocks?

Some questions to answer

What part does the recognition and collection of data play in New Zealand geology?

What is the role of visual language and intelligence in geology as a means of recording and interpreting data, and as communication between geologists?

What connections and exchanges operate between New Zealand geologists and those in other parts of the world?

How have global theories of geology affected understanding of the greywackes? How did the great paradigmatic change of the 1960s and 1970s affect the interpretations of these rocks? While the greywackes themselves remained greywackes, did the revolution cancel out previous geological knowledge about them?

Is controversy a normal part of a geologist’s work? How have the opposing aspects of co-operation and conflict affected geologists’ work in New Zealand? Is controversy necessary for the accumulation of knowledge? What counts as controversy?

What has this study revealed about how geological knowledge is accumulated in New Zealand?

Previous work on the history of pre-Cretaceous geology in New Zealand

Most publications on the history of geology in New Zealand were produced to mark an anniversary. New Zealand’s centennial year was celebrated with a collection of biographies of New Zealand scientists (Jenkinson, 1940). The centenary of Hochstetter’s visit to New Zealand was observed with several journal articles by C.A.Fleming (1959a) and A.R.Lillie (1959). Fleming’s translation of Hochstetter’s Geology of New Zealand (1959b) brought this remarkable work within reach of monolingual New Zealanders. Next, the centenary of the New Zealand Geological Survey was marked by a useful, concise history (Burton, 1965). The same year, a number of celebratory articles focussing on the work of the Survey appeared in the New Zealand Journal of Geology and Geophysics, in particular J.B.Waterhouse’s historical survey of the pre-Cretaceous rocks of New Zealand (1965, 1967), and J.J.Reed’s history of mineralogy and petrology in New Zealand (1965).

Many valuable reminiscences, memoirs, biographies and obituaries of individual geologists have been published in the Newsletter of the Geological Society of New Zealand, and the Society’s Historical Studies Group Newsletter. Besides geologists’ contributions to the history of geology in New Zealand, historians have recorded important episodes (Dick, 1951; Hoare, 1977; Barton, 2000). Besides all these, most formal academic works, including theses, include brief but very useful reviews of previous work with useful signposts towards sources in their bibliographies.

**Locating and collecting greywackes**

The greywackes and related schists form the axial mountain ranges in both North and South Islands and underlie much of our hill country. Greywacke landscapes are characteristically mountainous or hilly with steep slopes and triangular spurs (Whitehouse and Pearce, 1992). In Northland, coastlines are often indented with alternating rocky headlands and Christmas card beaches. The physical difficulties of access caused by rugged terrain, bush cover and poor roads have retarded research into the greywackes. Moreover, greywacke weathers readily into deep, poor, clay soils, so that it is not easy to find fresh outcrops away from alpine cliffs, steep stream valleys and open coasts.

New Zealand geologists can rarely make truly representative petrological (or fossil) collections of greywackes within a region (K.B.Spörli, pers.comm.) because samples can be collected only from accessible outcrops such as alpine or coastal sections or river and stream systems (Spörli and Barter, 1973: 376). Since shear planes of faults often control the latter, the collected rocks may therefore be quite unrepresentative of the surrounding rocks. Even roadside exposures can be misleading as many roads follow fault lines where the strata are highly sheared (Lillie, 1980: 191).

**Economic significance of greywackes**

During the nineteenth century the presence of small deposits of copper and manganese and the promise of gold encouraged some exploration of the greywackes especially in the Wellington district, but the lodes soon ran out (Kear, 1965). Gold-bearing veins occur throughout the South Island schists but most gold has been mined from alluvial concentrations (Craw, 1996). A modern bulk-rock, open cast gold mine is located at Macraes in East Otago. Because greywackes are heavily jointed and fractured they are
useless as building stone (Marshall, 1912). However, good quality greywacke sandstone is an important source of road metal and building aggregates. In 1965 aggregates displaced coal as the most important ‘mineral’ mined in New Zealand (Kear, 1965; Reed, 1965). Today, rock, sand and gravel for building and roads constitutes 73% of non-metal mineral production with a value close to that of coal and more than that of gold (Anon., 2001; Christie et al., 2001).

Maori used both greywacke sandstone and fine, hard argillites for tool-making and for hangi stones. A few contemporary artists like John Edgar produce beautiful small sculptures, medallions and jewellery using fine greywacke and argillite (Edgar, 2002), while others use beach pebbles of greywacke and chert to create personal jewellery (Anon, 2004).

De-forested greywacke regions are used for extensive pastoral farming, mostly for wool and for exotic forestry. Perhaps the most remarkable land use is as a foundation for the city of Wellington where suburban dwellings cling perilously to the sides of steep ridges and valleys. The major economic problem connected with the greywackes is that steep, weathered greywacke slopes are erosion prone. The removal of bush cover has resulted in soil loss, mass movement, increased run-off, flooding, the accumulation of rubble downstream on previously productive flats, and damage to bridges and roads. Land communications have always been expensive and difficult in sparsely settled greywacke and schist terrains, and still provide a challenge to road and rail engineers. Recent examples include the construction of the spectacular Otira Viaduct in Arthur’s Pass National Park designed to avoid a major rock avalanche and scree slope (Anon., 1999), and the present difficulties (March 2004) in reopening the Manawatu Gorge road because of multiple slips brought down by heavy rains.

Means of work

Unlike my student colleagues, my fieldwork has taken place in comfort and under cover in libraries and museums, mainly the Geology library of the University of Auckland, and Alan Mason’s fine private library specialising in the history of geology. The published New Zealand geological information is readily accessible in well-known geological journals. A great deal of use was made of interloan services especially for the chapters on Germany and Britain. Occasional use was made of the Internet to locate sources, but I was unable to find anyone interested in greywackes on geology related subscription lists. Email contacts were made with several Californian geologists who were concerned with developments in New Zealand during the 1970s. GeorefTM was used to find likely references, but the database turned out to be much more useful for measuring the growth of geology in New Zealand by using the system to count the numbers of relevant publications in succeeding years (Figure 7.1).

Travel to libraries in other centres was limited by cost. However, advantage was taken of attendance at annual conferences of the Geological Society of New Zealand to observe my subjects, the geologists, and
to visit local libraries and museums. Interviews and conversations with senior geologists were recorded by tape or written notes. A questionnaire was sent to a number of senior geologists with a very good response. Informal tearoom discussions and reminiscences provided insights into styles and ways of thinking, as well as pointers to useful references. Attendance at a conference held in Queensland by the Australasian Association of the History, Philosophy and Sociology of Science showed very interesting similarities and differences in the way in which geologists and non-scientists tackle their subjects.

The great bulk of this work has had to be based on published papers. Resources included books, textbooks, bulletins, memoirs and theses as well as journal articles. Visual materials are especially important to geologists and include maps, photographs, drawings, diagrams, through to highly abstracted analytical charts and graphs. In New Zealand there is a general lack of private documents in the form of correspondence, notebooks, field books and field sketches. A sense of history is yet to be developed among New Zealand geologists and their families (Alan Mason, pers.comm.), perhaps because New Zealand houses lack attics and the mobile lifestyle discourages most families from saving quantities of personal papers. However, some material belonging to a few geologists including Patrick Marshall, James Hector and Julius Von Haast survives in major libraries and archives.

It is not easy to access contemporary literature on eighteenth century geology. What little exists consists mainly of articles, private papers and monographs held in European museums (Rappaport, 1964). Few pre-1840 scientific publications of any sort exist in New Zealand, and I relied on Alan Mason’s library, on secondary sources, modern translations, interloan, and some correspondence with senior geologists overseas. Some relevant literature to do with English geology during the earlier decades of the nineteenth century was published in journals that are accessible in New Zealand, even if primary materials are unobtainable.

All references were recorded on a bibliographic database. Initially, Papyrus™ was used and found perfectly satisfactory, but data was moved to EndNote™ because it had become the university’s standard bibliographic database. Software of this kind is a very desirable aid when dealing with such a broad-ranging topic. The database contains nearly 2400 entries. Visual materials were scanned and edited with Photopaint™ and CorelDraw7™. Several historical maps were scanned in four sections, edited, ‘restored’ and assembled on screen before reduction to A4 size. The author made drawings to illustrate some ideas and processes.

As for most students, the major work problems were to do with time and the volume of material to be handled. Much time was diverted by health and family matters. Since graduating in 1954 I had not worked as a professional geologist, so there was rather a lot to catch up and it took several years before I began to feel familiar and confident with the subject. To obtain some overview of contemporary geology
I attended Stage 3 lectures on the Geology of the South-west Pacific Region and in Sedimentology. At the same time I began to learn about the changing geological paradigms and language of earlier periods since 1780. Effort was also made to obtain some understanding of the methods and views of historians, sociologists and philosophers. I sat a paper in Philosophy of Science and was gratified to achieve a B pass.

**Geological code words**

Geological names are code words (Bucher, 1936) for properties and concepts. Because this study covers a period of around 200 years in which many geological name changes took place, the New Zealand greywackes will be referred to as ‘the greywackes’ throughout this study, without the quote marks and irrespective of any anachronisms. Similarly, the related South Island schists, also known as the Otago schists, Alpine schists and Marlborough schists and collectively as the Haast Schists (Suggate, 1961), will be referred to as ‘the schists’. New Zealand and British geologists use the form ‘greywacke’ while North Americans use ‘graywacke’.

The name changes associated with the greywackes will be traced from the 1860s. They have been correlated with Hector’s Maitai series, with Park’s Hokonui System, mapped as ‘undifferentiated greywackes’ and renamed ‘Alpine facies’ by Wellman. Today the greywackes constitute the Waipapa Terrane (divided by some into separate terranes), the Torlesse Terrane (Pahau and Rakaia sub-Terranes), and the Caples Terrane.

The traditional name ‘Hokonui’ will be used as code for the neighbouring Triassic and Jurassic fossiliferous rocks of Southland, Nelson and the south-west Auckland coast, all of which are now known as the Murihiku Terrane. The name Murihiku Supergroup was first applied in 1966 (Campbell and Coombs, 1966). Although superficially similar to the greywackes (abundant, old, hard, grey, bedded sandstones), and of much the same age, they are different in general structural style, lithology and petrography from the greywackes.

Rocks belonging to today’s Maitai Terrane are important to this account because the greywackes were long thought to belong to the same group. These will be called ‘Maitai beds’ or ‘Maitai Series’ according to usage of the time. In the nineteenth century there was little consistency in nomenclatural styles or in the capitalisation of words like ‘series’ and ‘formation’ (Fleming, 1957).
Introduction

Figure 0.2: These greywackes at Waiheke Island belong to the Waipapa Terrane (Spörli 1978). The rocks are hard, dark grey and 'muddy'. Each sandstone-argillite pair is the product of a single depositional event. In this view the rocks are deformed by folding, an incipient thrust fault, and many small joints. Greywackes are hard as a result of very low grade metamorphism. Modified after Halcrow 1956, Transactions of the Royal Society of New Zealand.

Figure 0.3: Two graded beds in the alternating light-coloured greywacke and argillite strata of the Torlesse Terrane in the Porirua District. The sandstone grades upward into its argillite partner. Modified after Webby (1959). New Zealand Journal of Geology and Geophysics.
Basic background geology

A glossary is provided on pages 403-408 explaining many of the geological terms used in this work.

Greywacke sandstone and argillite

From the time that ‘classic’ greywacke sandstone was first described, four lithological features have remained constant whatever the reforming zeal of various writers on sedimentary petrography:

♦ It is a hard, grey, layered, muddy sandstone.
♦ It consists of mineral and rock fragments cemented together with what has been described as fine clay, as a matrix, or as a paste, or as diagenetic in origin.
♦ The fragments are usually sandy, but range in size from very fine silt through to pebbles.
♦ Particle size within beds may grade upwards from coarse below to very fine above.

Because of their considerable hardness, greywackes were often described as ‘indurated’ (p.269). This so-called induration is a result of low-grade metamorphism and greywacke is sometimes called ‘metagreywacke’ (p.239). The graded beds give the impression that the rock sequences consist of more or less regularly alternating greywacke sandstones and darker grey argillites (Figures 0.2, 0.3), but the proportions of sandstone and argillite can vary widely.

Argillite is hardened and usually, uncleaved mudstone (but cf. Figure 0.3), and it forms the topmost layer of a single graded greywacke bed. It consists of graded silty to clayey particles arranged in graded laminae (Halcrow, 1956: 53; Webby, 1959, and Figure 7.12). Each sandstone-argillite pair represents a single episode in which each layer was deposited by a catastrophic turbidity current (p.13, 232). The argillite layers represent the finest particles that settled out last when the turbidity currents ceased flowing. The contact between the top of an argillite layer and the base of the next sandstone layer is quite sharp, except where fragments of argillite or ‘rip-up clasts’ are caught up in the sandstone layer above (Figure 7.12). Argillites characteristically respond to stress faster than the sandstone layers and show increased jointing (Lensen, 1963), more fracturing (Figure 0.3) and a higher grade of metamorphism than the sandstone layers above and below (Reed, 1962). The Miocene Waitemata sandstone beds in the Auckland region were deposited in a similar way (Ballance, 1964) and can be thought of as non-indurated, unmetamorphosed proto-greywackes. Potential greywackes are being formed today on the seabed of the Hikurangi Trough offshore to the east of New Zealand (Lewis, 1980: 180-186).
ORIGIN OF NEW ZEALAND GREYWACKE ROCKS

1. THE COMPONENTS

Time: c. 250 - 100 million years ago.
Scale: more than 1000 km across, 20 - 30 km vertical.

<table>
<thead>
<tr>
<th>Forearc basin</th>
<th>Accretionary prism</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trench</td>
<td>Middle ocean spreading ridge, forming new ocean crust</td>
</tr>
<tr>
<td>Subduction Zone</td>
<td>Ocean floor ooze</td>
</tr>
</tbody>
</table>

This is where the greywacke rocks accumulated

This is the standard Plate Tectonics model

2. THE ACCRETIONARY PRISM.

Sediment from Gondwana, transported by turbidity currents fills the trench-slope basins & the trench

Scale: 10's to 100's of km.

Ocean crust bending into subduction zone arches up & breaks into blocks & rifts

Continual subduction of ocean crust forces trench sediment underneath the trench slope, and stacks up thrust-bounded packets of off-scraped & deformed sediment. The newest packet is at the bottom of the stack. This process builds an accretionary prism. As a consequence of the continual stuffing, packing and offscraping processes, the trench sediments become the hard, complexly folded, faulted, shattered and sheared greywacke rocks.

Figure 0.4: Origin of New Zealand greywacke rocks. How sediments accumulated to form an accretionary prism offshore of the continent of Gondwana. Slightly modified from original. P.F. Ballance (2001). The Geology of New Zealand - a Traveller's Guide (In prep).
The greywacke association

The whole association of sandstones, argillites and a variety of other rocks has come to be known colloquially as ‘the greywackes’ (p.167, 279). Included in the greywackes are lenses of distinctive, thinly bedded red, radiolarian cherts and volcanic rocks such as tuffs and fine pillow lavas, as well as small amounts of marble-like fossiliferous limestone. These seemingly minor but conceptually important components appear to be ‘interbedded’ with the sandstones and argillites (p.281-300, Figure 12.6 p.349). However, the cherts and lavas originated on abyssal ocean floors far away from the depositional sites of the greywackes, and the mystery of their true relationship with the rest of the greywackes has been solved only in the last twenty-five years.

Turbidity Currents

Turbidity currents transport sediment dislodged from the continental slope to be redeposited in deeper water in offshore basins (Figure 0.4). Turbidity currents consist of a very large mass of turbid water carrying a mixture of sand or even pebbles, silt and mud particles, held up by turbulent suspension. The fast-flowing mixture is denser than the surrounding water, sinks beneath it, and moves rapidly downslope. When it reaches the flat floor of a basin, the velocity of the current gradually decreases. The coarser sediment is deposited first, followed by successively smaller particles (Hamblin, 1992: 119). Each current deposits a single layer of sediment grading from coarse at the base (e.g. greywacke sandstone) to fine material at the top (e.g. argillites). Each graded bed, sometimes called a ‘turbidite’ or described as ‘redeposited’ represents a single cataclysmic event in which an earthquake or a violent storm set off slumping. Turbidity currents explain how coarse sediments are carried into deep-water environments, and in the 1950s, went some way toward explaining the close association of seemingly shallow-water sandstones and abyssal cherts (see p.233).

Subduction, accretion and the greywacke association

The special characteristics of the greywacke association, which include:

- Coarse clastic sediments together with abyssal red cherts and pillow lavas
- Greatly deformed rocks
- Metamorphism

are satisfyingly explained by plate tectonic theory (Figure 0.4, and Chapter 11). According to the theory, the upper layer of the Earth is divided into continental crust and oceanic crust riding on a mosaic of lithospheric tectonic plates that move relative to each other. The movement of an oceanic tectonic plate, sometimes likened to a conveyor belt, is driven by the formation of new oceanic crust by basaltic lava
Introduction

Figure 0.5: Time scale showing the position of the New Zealand greywacke rock association

<table>
<thead>
<tr>
<th>Era</th>
<th>Period</th>
<th>Duration m.y.</th>
<th>Millions of years ago</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cenozoic</td>
<td>Tertiary</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cretaceous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>78</td>
<td>66.5</td>
</tr>
<tr>
<td></td>
<td>100my</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mesozoic</td>
<td>Jurassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>26</td>
<td>208</td>
</tr>
<tr>
<td></td>
<td>Triassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>37</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td>Permian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>41</td>
<td>286</td>
</tr>
<tr>
<td></td>
<td>Carboniferous</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>74</td>
<td>360</td>
</tr>
<tr>
<td></td>
<td>Devonian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>408</td>
</tr>
<tr>
<td></td>
<td>Silurian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>438</td>
</tr>
<tr>
<td></td>
<td>Ordovician</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>67</td>
<td>505</td>
</tr>
<tr>
<td></td>
<td>Cambrian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>66</td>
<td>570</td>
</tr>
<tr>
<td></td>
<td>Precambrian</td>
<td>4030</td>
<td>Not present in New Zealand</td>
</tr>
</tbody>
</table>

Some old and obsolete group terms used in New Zealand

Cretaceous-tertiary
Notocone Covering strata

Basement or Undermass

Members of the greywacke rock association in New Zealand range in age from Carboniferous (in South Canterbury) to lower Cretaceous (in easternmost districts on both main islands). Different members may have different origins and different histories.

All representatives of these older rocks occur only in the western basement, that is, west of the Median Batholith Terrane

Not present in New Zealand

Figure 0.5: Time-scale showing the position of the New Zealand greywackes in time. Deposition of the oldest greywackes (not including the very old rocks of Westland) began around 250 million years ago in the Permian period, although late Carboniferous fossils have been found in a marble inter in South Canterbury. Deposition continued into the Lower Cretaceous, with the youngest greywackes found in the Raikumara Peninsula. By far the greatest volumes of these rocks were formed in the Triassic and Jurassic periods.
Introduction

upwelling from below at a mid-ocean spreading ridge. Old oceanic crust is consumed elsewhere by subduction, in which the crust sinks into the Earth’s mantle (about which little is known).

Subduction zones are often located adjacent to a continent and we see them as deep oceanic trenches, such as the Kermadec Trench. The surface of the oceanic plates forms the ocean floor and typically consists of pillow lavas. Over millions of years, the moving oceanic plates become covered with layers of siliceous ocean ooze made of the skeletons of microscopic radiolarians and diatoms. Eventually, if caught up in an accretionary prism, the ooze turns into layers of red chert, coloured by iron oxide. Very occasionally, small amounts of oceanic limestone are formed, often on the surfaces of guyots, and these may contain valuable diagnostic fossils like those of Marble Bay in Northland.

At a subduction zone at the margin of a continent like ancient Gondwana, clastic sediments brought down from the land are first deposited on the continental slope, and then redeposited in the deep trench by turbidity currents (Figure 0.4). The front of the continent acts like a great bulldozer blade and heaps up the sediments in an accretionary prism consisting of packets of folded, faulted and sheared sediments. If carried deeply enough in the subduction zone, the sediments are metamorphosed and turned into greywackes and schist. At the same time, slices of the surface of the ocean floor consisting of pillow lavas and cherts are incorporated with the clastic sediments, giving the false impression of having been deposited with them. However, these oceanic rocks are usually much older than the enclosing land-derived sediments.

Fossils and age

Fossils are needed to tell the relative ages of sedimentary rocks. Geochronological methods can now establish absolute ages without the aid of fossils, but while a geochronological evaluation may take months to complete, paleontologists may immediately assess the age of a rock in the field (B.W.Hayward, pers.comm.). The New Zealand greywackes are very sparsely fossiliferous and lack reliable marker horizons. In the nineteenth century many relative age determinations were made on long distance correlations, educated guesses, and occasionally, on rare fossil finds. Sometimes, incorrect identifications led geologists to become involved in stratigraphical disputes (Chapters 4, 5). Fossils and contemporary geochronological methods tell us that ages within the New Zealand greywacke association range in age from Upper Carboniferous for a rare oceanic marble inlier in South Canterbury (Jenkins and Jenkins, 1971), through Permian to the Triassic and Jurassic with some Cretaceous rocks (Figures 0.4, 9.2, 9.4). In nineteenth century Britain, greywackes were seen as age-specific, and confined to the Lower Paleozoic era (Chapters 1 and 2). In New Zealand they were eventually moved up the stratigraphic column (Chapter 5) and are now associated mainly with the Mesozoic period.
The New Zealand Paleozoic and Mesozoic stratigraphic column
as a collection of several stratigraphic columns

Since 1865 all of the sequences contained in the seven units shown above have been correlated together in a variety of configurations at different times, such as Hector's Maitai series (Chapter 4), as Marshall's Maitai System, as Park's Hokiupu System (Chapter 5) and as the Undifferentiated Jurassic-Triassic-Permian (Chapter 6). In this scheme, the units are seen as representing seven different terranes with seven different geological histories and seven different unknown sources of sediments.

Before 1950 the Otago Schists (represented by the vertical ruling between the Caples and Rakai Terranes) were seen as stratigraphically separate and of Paleozoic age. Before 1970, geologists were faced with the task of arranging the sequences in a traditional single stratigraphic column like that on the left.

This is just one of a number of tectonostratigraphic configurations that have been offered over the last two decades. As yet, none have satisfied all geologists.
Metamorphism and the schists

Metamorphic rocks are said to be by far the most abundant rocks accessible to direct observation at the Earth's surface (Touret and Jijland, 2002: 113). When rocks are buried deeply to depths of 15 to 20 kilometres or more in an accretionary prism, increased pressure and temperature cause the progressive formation of new minerals by fluid-assisted recrystallisation, leading to the formation of metagreywackes, semischists and schists. Similar rocks of much the same age that remain near the surface of the accretionary prism are only slightly changed and they grade downwards into the more metamorphosed rocks. Convergence of the Pacific plate and the Australian plate along the Alpine Fault, compressed and uplifted the greywackes. These were eroded away to expose the semischists and schists and form the Southern Alps (Cox, 1995), which are still growing. The large expanse of low temperature-high pressure Otago schists which grade laterally into the greywackes on each side without any apparent break (Figure 0.1) was caused by the collision between Torlesse and Caples terranes (Wood, 1978).

Structure of the greywackes

Structurally, the New Zealand greywackes are extremely complex. They are disturbed, deformed, folded, faulted and jointed (Chapter 10) largely because of deformation in the Mesozoic accretionary prism. These include narrow zones of very intense deformation called mélanges, some of which seem to mark the boundaries between terranes (Chapter 12). However, plate tectonic theory tells us very little about the tectonic processes aboard the rigid continents (Molnar, 1988). Since accretion ceased on the south-west Gondwana margin, all of these greywacke additions to the old continent have endured another 100 million years of complicated Earth movements.

Terranes

A necessary but surprising consequence of sea-floor spreading and subduction is that portions of continents, island arcs and other lithospheric flotsam are evidently conveyed hundreds of kilometres across the earth's surface floating aboard the oceanic crust. From time to time, stray pieces of continental flotsam collide with each other or with a continent and become accreted to it. These foreign fragments from unknown sources, and with different histories are called ‘terranes’ (p.359). Good, reliable evidence indicates that New Zealand is made up of a collection of nearly a dozen sub-parallel terranes (Figure 0.6). It so happens that several different terranes recognised today contain sediments of greywacke type, ranging in age from Upper Carboniferous to Lower Cretaceous. Recent work suggests that rocks of the Torlesse terrane may have originated near Queensland (Campbell, 1998). These terranes were rafted by the conveyor belt action of oceanic plates towards the south-west margin of Gondwana,
and welded to the great continent. Beginning in late Tertiary times, lateral movement along the Alpine Fault has complicated the parallel pattern and structure of the strip-like terranes (Figures 12.18, 12.21).

**Stratigraphical problems**

The principle of superposition, which was first recognised three hundred years’ ago by Steno — who also recognised graded bedding — simply means that layers of rock are arranged in order of age with the older rocks below, and the younger rocks above (Steno, 1667). Geologists seek to determine the ages and the order of superposition of the different formations in a region and to express the arrangement as a stratigraphic column (Figure 0.5). This information is needed to make geological maps and to reconstruct the geological history of a region, and the legends for geological maps are, in effect, stratigraphic columns (Figures 4.15, 5.9, 5.11, 5.13, 5.14, 5.15 a, b).

Throughout the nineteenth century and well into the twentieth century, any controversies to do with the New Zealand greywackes were usually about their age, stratigraphical position, and relationship with the schists and the Hokonui rocks. Geologists struggled to explain the origin and geological history of the greywackes in orthodox stratigraphic terms based on the comparatively straightforward geology of southern England and western Europe. However, their problem had to do with a very different history involving processes that took place in a rather more dynamic tectonic environment than could ever have been imagined before 1965.

The greywackes have always been seen as enigmatic, peculiar, mysterious, monotonous, difficult, complex and challenging, yielding little information about their origins and history until the great paradigm change of less than forty years’ ago began opening up pathways to new knowledge. In New Zealand, tracts of greywacke have attracted debate and curiosity, they have been ignored as economically useless or too difficult to decipher, they have been seen as stratigraphically controversial, as structurally fascinating, as a geo-historical record, and as repositories of unending surprises.
Chapter One

Before 1880: ‘Grauwacke’ in Europe

Geognosy is that part of mineralogy which acquaints us systematically and thoroughly with the solid earth, that is, with its relationship to those natural bodies that surround it and which are familiar to us, and also, especially, with the circumstances of its external and internal formation and the minerals of which it consists according to their differences and mode of formation.’

(Werner, transl. Ospovat, 1971a: 102)

The earliest published record of the geological term ‘greywacke’, perhaps the most controversial of rock names, appeared over 220 years ago in provincial Germany, and it is intimately linked with the establishment of the independent science of geology in that country between 1780 and 1810. The long international history of this notorious vernacular name for an old, hard, grey country rock is reflected in the remarkable (mainly) nineteenth century assortment of different spellings of ‘greywacke’ include Grauenwacke, Grauwacke, Grauwacke, Grau-wakke, grauwacke, grauwacke, greywacké, grey-wacké, grey wakke, grey-wacce, and graywacke. Nineteenth century English gentlemanly geologists unkindly described ‘graywacke’ as ‘uncouth’, ‘barbarous’, or ‘dissonant’ (p.43). Others used quite different terms to refer to the same rock type. James Hutton (1726-1797) of Edinburgh referred to the same rock as ‘schistus’ (fts p.6, 38, Hutton, 1899), Cornish miners talked about ‘killas’ (Playfair, 1811) and the French exchanged ‘grauwacke’ for the ‘not more harmonious’ term, ‘tramate’ (Bakewell, 1838). ‘Wacke’ on its own refers to partly decomposed basalt.

Artisans and scholars

The special feature of the sixteenth- and seventeenth-century western European scientific revolution, which had been gathering momentum since Mediaeval times, was the unique way in which the practical knowledge and skills of artisans such as miners, merchants and engineers began to be combined with the literary, philosophical and mathematical skills of scholars (Figure 1.1). Leonardo da Vinci’s engineering drawings and the brilliant record of miners’ lives and technology in the Erzgebirge by the scholar and physician, Georgius Agricola (1494-1555) characterise the new combination of craft and philosophy (for example Agricola, (transl. 1912).

The application of logical skills to the organisation and use of empirical data grew into a powerful method for obtaining yet more knowledge and control of the natural world (Bronowski, 1960). For the first time, philosophers got their hands dirty as they learned how to manipulate objects and experiment
The Roots of Modern Geology in Europe

Mediaeval Europe

Ancient Greece, Arabia, Persia and India
- Monastic scholars Universities, pastors, physicians, merchants, leisured
- Empirical data
- Philosophical mathematical literary skills. Applied to manipulation of empirical data

1450
- Gutenberg printing press c.1450 and increasing literacy
- Cosmogony: theory of the origin of the universe
- Genesis 1:2. Earth once an aqueous sphere

1500
- Minerals & ores recognised, named, classified. E.g. Georgius Agricola (1495-1555), scholar, physician, collector, mineralogist, observer, author

1550
- Ideas tested by experiment

1600
- Nicolaus Steno (1638-1686)
- Mining: Empirical data
- Cosmogony: theory of the origin of the universe

1650
- Nicolaus Steno (1638-1686)
- Superposition Succession
- 18C chemical cosmogony

1700
- Rocks recognised, given names, described
- 18C chemical cosmogony
- Field exploration e.g. de Saussure (1740-1799)
- Neptunism ‘organised fossils’

1750
- State mines
- Professional mineralogists
- Mining schools e.g. Freiberg 1765
- Primary, secondary, tertiary systems or groups of rocks recognised

1780
- Nicolaus Steno (1638-1686)
- Superposition Succession
- 18C chemical cosmogony
- Field exploration e.g. de Saussure (1740-1799)
- Neptunism ‘organised fossils’

1800
- Werner’s formations

Figure 1.1: Flow chart outlining the roots and early history of modern geology.
with materials, so that ‘the technician was at last welcomed into the circle of intellectuals’ (Ellenberger, 1996). Ideas of scientific method developed in a ‘new empirical philosophical climate where the idea of putting theoretical questions to an experimental test was ... taking root’ (Logan, 1986: 174). The invention of the Gutenberg printing press around 1450 and increasing literacy accelerated dissemination of practical knowledge around Europe and Britain. By the mid eighteenth century, inquirers into the nature of the Earth were in the field and exploring mountains.

**Mining, mineralogy and the invention of rocks**

From the fourteenth century, industrial developments resulted in increasing demands for raw materials such as metal ores, clays, sands and building stone. Europe’s most advanced mining technology had developed from Bohemia north through Saxony and Thuringia to the Harz, where mining had gone on for over 500 years (Adams, 1938; Laudan, 1987). Through these years, chemists had been building up skills and experience in the analysis of natural substances such as metals, earths, stones, crystals and ‘figured stones’ or fossils (Laudan, 1987: 20-69). Theories about changes of state were important because they related to ideas about the origin of the Earth. Chemical mineralogists now inferred the mode of origin of various rocky substances by their texture. Stony substances and crystalline substances such as granite were considered to have been deposited from water, whereas only the rare glassy substances had cooled from a melt. By the 1780s, chemistry had become quite accurate and it was possible to determine the percentage proportions by weight of various ‘Earths’ in a rock (Table 1.1).

Until the seventeenth century, there was little recognition of rocks as entities except as containers for mineralised veins, and this view of rocks is reflected in art of the time (Montgomery, 1996). However, it was realised that some rocks were more likely than others to contain valuable minerals, or were better sources of raw materials like sand and lime. From then on, rocks began to be distinguished from minerals and recognised as natural kinds in their own right rather than as simple aggregates of minerals. The increasing demands of mining exploration meant that mineralogists were now required to distinguish different rocks, correlate them with those in other areas, and predict the distribution of ores and other important materials (Laudan, 1987: 27).

The need for new sources of raw materials, with the development of field work, the growing curiosity about the construction of mountains and the drive to classify (Foucalt, 1970), led naturalists to be aware that the Earth’s rocks were not randomly distributed but occurred in more or less predictable groups found in certain locations. Field workers now dealt with expanses of rocks as well as minerals and found ways to describe such things as ‘location, elevation, slope, fossils, age, and mode of origin’ (Rudwick, 1976). Maps became necessary and traverse sections were invented to describe the likely disposition of rock layers below the surface.
An eighteenth century knowledge economy

In contrast to Britain, many eighteenth century industrial enterprises in continental Europe were owned and operated by the state, and mining directors played a large part in the growth of knowledge about the Earth. Industrial demands encouraged the study of mineralogy, and besides metals, there was interest in kaolin, rock salt, limestone, stone, clay, sand and road metal. The silver mines of the Erzgebirge in southern Germany attracted many mineralists, and from the 1730s, calls were made for formal training in mineralogy, engineering and mining administration (Laudan, 1987: 50).

Eventually, specialised mining institutes were established, such as the Bergakademie in Freiberg in 1765, followed by the mining schools at Clausthal-Zellerfeld and Berlin in 1770, and Chemnitz in 1775. Similar institutions were set up in Sweden and France. Industrial development professionalised European geological science, provided jobs in mining schools and other mining services, and encouraged the development of theoretical knowledge as well as fostering practical know-how. Great interest was now taken in the study of minerals and rocks by mining professionals, merchants and by leisured gentlefolk. A great deal of geological literature was produced, but there was no geological synthesis, and no agreement on nomenclature, classification and description (Ospovat, 1971b).

Grauwacke: a new rock name

Eighteenth century miners of the Harz district in western Germany applied the vernacular term ‘grauwacke’ to the common, dark grey country rock that contained many rich, metal-bearing veins (Bates and Jackson, 1987). The term appears to have been in more general use at least by 1780 (W. Langer, pers.comm.) and was introduced into the scientific literature as ‘Grauenwacke’ in 1785 by Friedrich Wilhelm Heinrich von Trebra (1740-1819), a mine director (Figure 1.2). Von Trebra’s illustrated folio essay is very rare (and not available in New Zealand), but his report of the discovery of fossil plants, shells and ammonites in Grauenwacke and related shales is quoted by Lasius (1789 p.12) who is often given the credit for introducing the term.

In his own detailed study of the rocks of the Harz Mountains, Georg Sigismund Otto Lasius (1752-1833), Director of the Survey Department in Oldenburg, also suggested the use of the local provincial name ‘Grauwacke’ to refer to those rocks consisting of grey quartz-breccia cemented by clay. Lasius pointed out how ‘Grauwacke’ was related to, but distinguished from, sandstone because of its clay cement, and that it alternated with slates\(^1\), it contained fragments of slate, and it became finer grained near slate. Lasius’s volumes were published several years after Werner’s Kurze Klassification appeared (Werner, 1787), but the two appear not to have been acquainted with each other’s work (W. Langer, pers.comm.).

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\(^1\) Similar to alternating greywackes and argillites in New Zealand.

24
However, their descriptions of ‘Grauwacke’ agree closely, indicating that the miners from whom they borrowed the name were well aware of the textural differences between ‘Grauwacke’ and other sandstones.

Lasius discussed the ‘Petrographie’ of his rocks and published the most up-to-date chemical analyses available (Table 1.1) showing that ‘siliceous Earth’ was predominant in the ‘Grauwacke’. In his view, the grains of ‘Grauwacke’ sandstone were derived from the weathering of granite; and the finer particles in the shales were the result of weathering (Zittel, 1901: 81-82). Such an inference of a
provenance for the ‘Grauwackes’ of the Harz indicates Lasius’s awareness of a long, complex history of the Earth, but does not necessarily indicate a world-view much different from that of Werner.

<table>
<thead>
<tr>
<th>Grauwacke 1789</th>
<th>Of 100 parts</th>
<th>English terms</th>
<th>Wellington greywacke 1957</th>
<th>Per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kieselerde</td>
<td>73</td>
<td>siliceous earth</td>
<td>SiO₂</td>
<td>71.1</td>
</tr>
<tr>
<td>Ulaunerde</td>
<td>11.25</td>
<td>alum earth</td>
<td>Al₂O₃</td>
<td>13.9</td>
</tr>
<tr>
<td>Eisen</td>
<td>8.37</td>
<td>Iron</td>
<td>Fe₂O₃</td>
<td>tr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FeO</td>
<td>2.7</td>
</tr>
<tr>
<td>Kalcherde</td>
<td>2</td>
<td>calcareous earth</td>
<td>CaO</td>
<td>1.8</td>
</tr>
<tr>
<td>Bittersalzerde</td>
<td>0.75</td>
<td>magnesian earth</td>
<td>MgO</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Na₂O</td>
<td>3.7</td>
</tr>
<tr>
<td>Wasser u. Luft</td>
<td>95.37</td>
<td>Water and air</td>
<td>H₂O⁺ , H₂O⁻</td>
<td>1.9 , 0.26</td>
</tr>
<tr>
<td></td>
<td>98.37</td>
<td></td>
<td>[other]</td>
<td>0.86</td>
</tr>
<tr>
<td>Berluf</td>
<td>1.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100 Theile</td>
<td></td>
<td></td>
<td>99.8</td>
</tr>
</tbody>
</table>

Abraham Gottlob Werner of Freiberg

Little genuine progress had been achieved in improving the identification and classification of minerals since Agricola’s time (Adams, 1938: 200). This was largely because, unlike plants and animals, which can be clearly differentiated on external form, it is difficult to separate members of a continuous series of minerals (Laudan, 1987: 70-89). Moreover, while practical knowledge about the occurrence of ores, minerals and other raw materials and ways to extract them had increased, more knowledge was needed to prospect for and find new sources of minerals.

As a young man, Abraham Gottlob Werner (1749-1817, Figure 1.3), published a little handbook on the identification of ‘fossils’ (minerals) based on simple external characters such as colour, lustre, hardness, fracture and shape (Carozzi, 1962). The handbook was meant only as a much-needed field manual for miners and prospectors and was not intended as a formal system of classification (Ospovat, 1967). Because the approach was practical, straightforward, orderly, logical and consistent, with the application of mineral names commonly used by miners of the Erzgebirge, Werner’s method became enormously popular. The great success of his practical book helped Werner earn his appointment in 1775 as Professor
of Mineralogy at the Bergakademie (Mining Academy) at Freiberg, where he taught mineralogy and geognosy (his name for geology) for the rest of his life. Werner did not re-publish his manual but his lecture notes on mineralogy were constantly revised and updated. Much of what is known of his teachings has been obtained from students’ lecture notes and his students’ publications, for example, Robert Jameson’s books of 1804 and 1808 (Chapter 2).

‘Grauwacke’, sandstone and Kurze Klassifikation

As more and more rock types were recognised and named by different mineralogists during the eighteenth century, much confusion had arisen regarding their identification and nomenclature, and now, Werner wanted clear definitions of both minerals and rocks in order to correlate them (Laudan, 1987: 97). In 1786 and in 1787 he published Kurze Klassifikation, based on part of his course in geognosy (Werner, 1787). The book contains the two main features of Werner’s geognosy:

- Concise descriptions of Werner’s four original rock formations:
  Primitive, flöz, volcanic and alluvial.
- Categorisation and descriptions of all the rock types characteristic of each formation.
The ‘primitive’ rocks consisted of all the crystalline, unfossiliferous rocks and the ‘flötz’ rocks included all the stratified, fossiliferous rocks (flötz means layer or stratum). At first, Werner included ‘Grauwacke’ in his ‘flötz’ formation along with limestones and sandstones and it was not until later that they were moved to his later ‘Transition’ series. Initially, Werner classified ‘Grauwacke’ with common sandstone and puddingstone (conglomerate). By categorising ‘Grauwacke’ as a ‘flötz’ rock Werner implied a relative time of formation, that is, younger than all the crystalline rocks, but unlike Lasius, he gave no opinion as to the likely source of such rocks. His description of sandstones (with a clear reference to graded bedding) is as follows (Ospovat, 1971a: 70-72).

The sandstones can handily be divided into common sandstone, graywacke, and puddingstone.

A) **Common sandstone** has as the main part of its aggregate quartz grains of various sizes, among which are sometimes grains of feldspar, hornslate, and flint. These grains are evenly held together by a cement which is usually mere clay, but is sometimes iron ochre, marl Earth, or quartz. Common sandstone is rarely metalliferous.

B) **Graywacke** consists of quartz and much hornslate, sometimes even grains of clay-slate, which are generally of different sizes, but in one and the same bed usually of the same size, and are joined to each other very firmly with clay, or sometimes with clay-slate pastes. This rock grades into clay-slate, and one often finds in the graywacke formations a true and uninterrupted transition from large and coarse grained graywacke through small and fine grained into the most distinct clayslate. In this rock formation clay-slate and graywacke often alternate with each other, which, too is very characteristic of graywacke formations. Graywacke contains fossils here and there, and in the Harz it has very considerable and rich metallic veins. For a long time the Upper Harz was the only region where this kind of sandstone was known to occur, but I have now discovered some at Braunsdorf near Freiberg. The rock at Abrudbanja also seems to me to be graywacke.

C) **Puddingstone** consists of small, rounded pebbles some of which are quartz, some hornslate, some flint, joined or cemented together sometimes by a paste of clay, sometimes by jasper, sometimes by a paste of quartz, yes, sometimes even by sandstone. To it belongs the Swiss Nagelfluhe. Puddingstone contains no metals.
Werner’s geognostical paradigm:

Werner has been unfairly characterised as the arch-fiend of geology who imposed nonsensical ideas on his pupils and held up the progress of geology (especially Geikie, 1905). However, Werner believed that the distribution of rocks in the Earth’s crust could be learned by geognostical methods rather than by speculative hypothesising. He insisted that his geognosy was the study of what was known about rocks, minerals and formations; that it was totally empirical and did not deal with theoretical speculations about the origin of the earth. Werner’s Neptunist views regarding the origin of rocks were based firmly on the currently orthodox, mainstream, cosmogonical interpretation of Genesis 1.2, in which the primeval Earth was believed to have originated as a water-covered sphere (Laudan, 1987: 89). This original ocean contained all the substances necessary to form the rocks of the Earth’s crust and all rocks were thought to have been deposited from this ocean, either as chemical crystalline precipitates or as sedimentary deposits from suspensions. This world view was later called ‘Neptunism’.

Because the primeval ocean had covered the whole Earth, Werner assumed that his formations were universal and that the rock layers occurred in the same order everywhere. These could be discovered by careful examination of the rocks themselves. The major rock masses or formations were identified and differentiated on three criteria:

- Lithology, especially mineral content.
- Mode of deposition, as inferred from stratification, and signs of turbulence and water depth.
- Relative time of deposition, determined by the application of the law of superposition.

Werner’s formations, stratigraphy, and Earth history

Werner may have been influenced by von Trebra (W.Langer, pers.comm.), and was almost certainly strongly influenced by such well-regarded mineralogists as Johann Gottlob Lehmann (1719-67), Georg Christian Füchsel (1722-1773), and Torbern Olaf Bergman (1735-1784) (Oldroyd, 1996: Ch.3), who all recognised a tripartite rock system (Table 1.3). Masses of primary or primitive rocks, which occupied mountain cores, were considered to be surrounded and overlaid by layers of secondary and tertiary rocks. Ideas of geological succession and relative age became established, irrespective of whether the naturalists accepted a short Biblical history of the Earth, or if they suspected that it was very much older.

These interpretations of field evidence tied in very satisfactorily with the current cosmogetic theory of the aqueous origin of the Earth (Laudan, 1987: 87ff). Werner was aware of recent work on the way in which crystals are precipitated from solutions, and ideas of deposition by crystallisation from a primitive ocean explained both mode of origin and the relative age of the resulting rocks (Figure 1.4). Steno’s
Table 1.3: Selected examples of eighteenth century rock and formation classifications. Most observers settled on a tripartite system with presumably ancient crystalline rocks at the base, sedimentary layers above and topped with recent alluvium and volcanic deposits.

<table>
<thead>
<tr>
<th>Johann Lehmann 1756</th>
<th>Giovanni Arduino 1760 (letters)</th>
<th>Georg Füchsel 1761, 1773</th>
<th>Torbern Bergman 1766</th>
<th>Peter Simon Pallas 1777-1778</th>
<th>A.G. Werner 1787</th>
<th>A.G. Werner 1796</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volcanos</td>
<td>Gravel, earth, soil</td>
<td>Hufvud: vulcaner, alluvial sediments e.g. streams, lakes</td>
<td>Tertiary; lowlands, sandstones, marls, clays, with fossils</td>
<td>Aufgeschwemmte Gebirge: gravels, alluvium</td>
<td>Vulcanische Gebirge</td>
<td>Vulcanische Gebirge</td>
</tr>
<tr>
<td>Flözgebirge:</td>
<td>Tertiary</td>
<td>Fiölgrige: sediments e.g. limestones, clays, coals, sandstone</td>
<td>Secondary: argillaceous schists, shales, fossiliferous limestones. Less tilted than primitive rocks</td>
<td>Flözgebirge: stratified rocks</td>
<td>Flözgebirge: stratified rocks</td>
<td></td>
</tr>
<tr>
<td>Deposited by huge Noachian flood</td>
<td>Secondary</td>
<td>Nine ‘formations’ or ‘series montana’</td>
<td></td>
<td>Flözgebirge: stratified rocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gange-Gebüren:</td>
<td>Primitive</td>
<td>Uråldrige: primitive crystalline rocks e.g. granites, quartzites, no fossils</td>
<td>Primitive: granite at core of mountains surrounded by unfossiliferous schists, serpentines, porphyries. Highly tilted</td>
<td>Uranfähliche Gebirge: primordial, primitive. Often crystalline, unfossiliferous</td>
<td>Uranfähliche Gebirge: primordial, primitive. Often crystalline, unfossiliferous</td>
<td></td>
</tr>
</tbody>
</table>
law of superposition (Steno, 1667) backed up the laboratory evidence that the poorly soluble siliceous crystalline rocks were deposited first. The more soluble Earths, such as limestone, which formed the secondary, stratified rocks, were deposited later and were superposed on the crystalline rocks. However, Steno’s view that all stratified rocks were originally horizontal was ignored because laboratory evidence showed that substances could crystallise on the sides of containers. This explained why the secondary (or flötz) strata appeared to be tilted at high angles against the older crystalline rocks (Figure 1.4).

The use of these criteria allowed Werner to group all the known rock types of Saxony into his redefined formations (the modern formation is defined purely lithologically). Werner derived the idea of formations from the German miners’ use of the word Gebürg or Gebirge (mountain) to refer to the major rock masses they encountered underground, and used the terms ‘Gebirgsmasse’ and ‘Gebirgsformation’. These masses were distinguished by their appearance, the methods needed to work the rocks, and their location (Ospovat, 1971b: 98).

Because Werner’s concept of ‘formation’ included the three elements of time, origin and content, the various rocks including grauwacke were locked into particular periods in the earth’s history. Werner believed that the Primitive, Flötz and alluvial rocks graded into one another so that closely related kinds could not be easily separated. Such gradations reflected how, under the Neptunist theory, each mode of deposition slowly gave way to the next over the vast period of time since the beginning of the Earth (Ospovat, 1971a: 44). While Werner noticed the kind of unconformity that had been predicted and found by James Hutton he was not aware of their significance (Tomkeieff, 1962) in terms of ‘deep time’ (McPhee, 1981).

**Transition formation: between Primitive and Flötz**

Based on his own research and on reports from his students and colleagues in other parts of Europe Werner kept updating and refining his system of classification. He and his colleagues identified rocks with no better aid than hand lenses. Because individual minerals could not be discerned in clay slates (shales) Werner understood them as monomineralic substances and typical of the primitive formation, that is, they had precipitated out of solution. Greywacke rocks then posed a lithological problem because they consisted of a mixture of mineral and flötz-like rock fragments set in a slaty cement typical of the primitive formation. This made it necessary for Werner to introduce another group, the transition formation, between the primitive and flötz formations to accommodate such rocks (Figure 1.4, Table 1.4).

All crystalline rocks were classified as ancient and primitive while all stratified or flötz rocks were seen as younger than all crystalline rocks. Grauwacke now had its own transition formation between the primitive and flötz rocks. In spite of its limitations, the idea of successive, predictable formations was of basic importance in creating a rational research framework for Werner’s pupils.
Table 1.4: Table showing Werner’s transition formation between the Flötz rocks above and the Primitive rocks below. ‘Trap’ is an obsolete name for basalt. It was thought to be a precipitate from the primeval ocean. Werner’s Grauwacke formation contains the familiar elements of greywacke, slate, basalt, limestone and chert, also typical of New Zealand greywackes. Table based on (Adams, 1938: 219, Ospovat, 1971a: 129).

<table>
<thead>
<tr>
<th></th>
<th>Flötz rock above</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Grauwacke formation</strong></td>
<td>Alternates with graywacke slate, but in ‘no particular order’, and with trap rocks, limestone and chert much thicker than the limestone and trap, and is the first well-marked mechanical deposit from the primitive ocean, e.g. in the Harz where it contains ores.</td>
</tr>
<tr>
<td><strong>Upper transition</strong></td>
<td></td>
</tr>
<tr>
<td>Transition trap</td>
<td>Greenstone and amygdaloids, the latter having a wacke groundmass, e.g., the diabase and diabase amygdaloid in Vogtland.</td>
</tr>
<tr>
<td>Transition limestone</td>
<td>With beds of trap. Examples the Devonian of Planitz near Zwickau, Carboniferous Limestone of Derbyshire</td>
</tr>
<tr>
<td><strong>Lower transition</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Primitive rocks below</strong></td>
<td></td>
</tr>
</tbody>
</table>

**Werner’s significance**

Werner made no grand scientific discoveries but he was a major contributor to the establishment of geology as an independent academic discipline (Ospovat, 1971b: 29; Laudan, 1987). His outstanding achievement was the creation of a paradigm or a true research tradition in geology (Laudan, 1977) that provided a framework for further research by others. ‘He was the first who taught the art of observing and distinguishing the formations; [so that] geognosy has become a positive science.... His real glory was ... founded on the discovery of the principles of the science, and on the means of research.’ (Humboldt, 1823: 82).

The eighteenth century was the age of classifiers (Foucault, 1970) like Linnaeus and Werner himself. Werner was a superb compiler and classifier who contributed enormously towards the refinement and precise definitions of pre-scientific vernacular terms such as granite, basalt and greywacke (Engelhardt and Zimmermann, 1988). He made the first attempt at ‘putting some order into the stratigraphic record’ (Carozzi, 1988). This special talent for defining, classifying, compiling, organising and categorising descriptions of rocks, minerals and formations made it possible for his followers to think rationally about geological information.

The problems with Werner’s system, which led to its demise in the 1820s, have been well explored by historians of science. The notion of a set order of universal formations was soon questioned and discarded by his own pupils. Nevertheless, his Neptunist views gave the new science an initial premise in which to begin serious research beyond simple collecting. Critics say that the passion for order and
Werner's Neptunian theory of the origin of rock formations by deposition from a primeval ocean

1. Primitive formation
   - Calm still ocean laden with chemicals. Primitive crystalline granites and gneisses are precipitated.

2. Transition formation
   - Sea level drops, the sea becomes stormy. Waves attack the primitive rocks. Mixed crystalline and mechanical deposits result in the deposition of slates and greywackes.

3. Flötz formation
   - The ocean becomes calm. Limestones and gypsum are precipitated. Then, periods of alternating storm and calm take place. Sea level rises and falls several times, causing alternating limestones and sandstones.

4. Alluvium

5. Volcanoes
   - Transition greywackes and slates
   - Flöz sandstones and limestones
   - Alluvium
   - Primitive granite and gneiss

Figure 1.4: Interpretation of Werner's Neptunian theory of the origin of formations by the deposition of Primitive (primary), Transition (Grauwacke) and Flöz (secondary) rock formations from the primeval ocean. Drawings based on published translations of Werner's ideas. The lower drawing is based on Bakewell's section of the Brocken Mountain (1813).
classification led towards a tendency towards rigidity of thought (Zittel, 1901; Geikie, 1905), on the other hand, his role as an inspirational, innovative, authoritative teacher with an international reputation made him enormously effective in communicating ideas (Ospovat, 1971b; Laudan, 1987).

Werner kept faith with his ruling theory until his death in 1817. However, other geologists, including his own pupils, were already radically modifying his geognostical paradigm while Neptunism faded away in the 1820s. Werner’s geognosy was transformed and combined with elements of plutonism and vulcanism to form a new and quickly evolving geological paradigm. Plutonism had to do with James Hutton’s theory of the earth, and vulcanism was associated with geologists who insisted that basalts were volcanic rocks.

Werner’s reputation as a mineralogist, as an inspirational and popular teacher, his course of geognosy, and his well co-ordinated field work attracted students to Freiberg from all over Europe. This led to a ‘Wernerian radiation’ (Laudan, 1987) in which his theories and methods were disseminated throughout Europe, including the British Isles. These included:

- A system or paradigm that could guide future work.
- The idea that formations are unique historical entities.
- The idea that formations are universal, having been deposited in a set chronological order.
- The idea that ‘grauwacke’ was characteristic of the ‘Transition’ group of formations.
Chapter Two

‘Grauwacke’ in Nineteenth Century Britain

[T]he Mendip and Quantock Hills... Afford fine specimens of the contorsions exhibited by that rock to which geologists have given the name of greywacke. What a delightfully sounding word! It must needs make you in love with my subject.

(Sedgwick qtd by Clark and Hughes, 1890: 211).

Grauwacke goes to Britain

Richard Kirwan of Dublin (1733-1812), chemical mineralogist and President of the Royal Irish Academy, introduced the term ‘grauwacke’ into the English language at least as early as 1794 (Kirwan, 1794).

<table>
<thead>
<tr>
<th>Rubble Stone.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grauwacke of Werner. Gres Gris of the French.</td>
</tr>
<tr>
<td>This is a particular kind of sandstone, containing not only grains of quartz, siliceous shifus, or hornstone, but also scaps of bluish argillite in a clayey cement, and of this there is often no more than is barely sufficient to hold the grains together, sometimes with, and sometimes without mica; commonly compact, sometimes flaty in the gros.</td>
</tr>
<tr>
<td>Its colour is yellowish, or bluish grey, or dark reddish brown mixed with grey.</td>
</tr>
<tr>
<td>Fracture, in the small, fine splinterly or earthy.</td>
</tr>
<tr>
<td>Hardness, from 7 to 9, rarely 10. Sp. gr. from 2.64 to 2.685, but when withered, only 2.68 *. See Leske O. 1278, and S. 474, 607.</td>
</tr>
</tbody>
</table>

Figure 2.1: Robert Kirwan’s description of ‘Rubble Stone’ or ‘Grauwacke of Werner’. The wording is different enough from Werner’s descriptions to suggest that it was taken from a student’s lecture notes, or even from notes made when he visited Werner. Kirwan (1794) Elements of Mineralogy, p.366.

Although he did not study at Freiberg, Kirwan visited Werner (Sweet, 1967) and was a devoted disciple. Kirwan was one who hotly disputed James Hutton’s theory of the Earth because of its implications of ‘atheism’ and ‘impiety’ (Playfair, 1802: 120). In his description of ‘grauwacke’ (Figure 2.1) Kirwan’s
reference to rock fragments and a matrix as well as mineral content is quite consistent with Werner’s description.

Kirwan instigated the purchase by the Royal Dublin Society in 1792 of the Leskean Mineral Collection (Sweet, 1967), which was modelled on Werner’s own teaching collection at Freiberg and assembled by one of Werner’s pupils, Nathaniel Gottfried Leske (1751-1786). It included a dozen or so specimens of ‘Grey Wacke’ from the Harz, one of which was a ‘very coarse grained Grey Wacke, consisting of Siliceous Schistus, Quartz, and common sandstone as a cement from Clausthal in the Hartz’ (Karsten, 1798).

Although there was no state funded training in mining operation and management in Britain (Porter, 1977: 170), the universities at Edinburgh, Dublin, Oxford and Cambridge had begun to provide lectures in mineralogy and geology by the 1780s. These sometimes included an introduction to Wernerian geognosy by men who had studied at Freiberg such as John Hailstone (1759-1847), the sixth Woodwardian professor at Cambridge (Porter, 1977: 144), and Robert Jameson of Edinburgh (Figure 2.3).

**Robert Jameson of Edinburgh**

After training at Freiberg, Robert Jameson (1774-1854) was appointed in 1804 to the Chair of Natural History at the University of Edinburgh on the recommendation of Kirwan (Sweet, 1967: 113). Jameson published his own translations of Werner’s lectures in which he introduced Werner’s geognostical system, his terminology, and the concept of formations into Scotland¹ (Jameson, 1804 - 1808; 1808; Fitton, 1832: 273; Geikie, 1905: 327-30 Greene, 1982: 37). Being a faithful disciple of Werner, Jameson founded the Wernerian Natural History Society in 1808 and its memoirs were published in Edinburgh from 1811 to 1839.

Jameson (Figure 2.2) described ‘gray wacce’ as an ‘aggregate rock, composed of fragments of flinty slate, clay slate, and quartz, connected by a basis of clay slate’, and warned against confounding it with ‘wacce’, a decompositional product of basalt (Jameson, 1804: 379). In his second book, Jameson began to use ‘grey-wacke’ and faithfully copied Werner’s major classes of primitive, transition, flötz, alluvial and volcanic rocks and their deposition in set order from a primeval ocean. The formations showed that ‘the ocean must have formerly covered the whole earth at the same time’, that each rock type signified a particular age (Bailey, 1930) and that the earth’s strata occurred in a set ‘order of succession’ (Fitton, 1832). As with Werner’s scheme, Jameson’s ‘Transition class’ followed deposition of the crystalline ‘Primitive class’.

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¹ Jameson may have introduced ‘greywacke’ in 1800, in his *Mineralogy of the Scottish Isles*, vol. 2: 226. Reported by R.W. Willet in a talk on greywackes given in 1937 to the Geology Section of the Wellington Branch of the Royal Society of New Zealand, Wellington, (Cotton, 1937).
Jameson’s Transition class:

♦ ‘Grey-wacke’ was the most important rock in the class, marking the beginning of a ‘new geognostic period, ... the appearance of mechanical depositions’.

♦ The transition class recorded the rocks ‘deposited during the passage or transition of the earth from its chaotic to its habitable state’.

♦ The transition class contained the first traces of organic remains.

♦ The transition rocks connected the ‘Primitive with the Floetz rocks ... preserving the beautiful series of transitions ... from the oldest primitive to the newest alluvial formation’ (Jameson, 1808).

When describing the distribution of Grey-wacke, Jameson noted that nearly all the mountains to the north of the Frith of Forth were composed of Grey-wacke, but it is likely that he really meant the Uplands south of the Frith (Bailey, 1930). In any case, the term ‘greywacke’ became well established among Scottish geologists.

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2 Var. of ‘Firth’
James Hutton (1726-97) of Edinburgh, Predicted unconformities and that granite intruded from below. Postulated a cycle of decay and renovation (Laudan, 1987).

Robert Jameson to Chair of Natural History, Edinburgh 1804, 1808

Hartz Mountains

Berlin

Thuringia Wald

Erzgebirge

Leskean Mineral Collection 1798

John Hailstone, Cambridge

John Hailstone (1759-1847), sixth Woodwardian Professor at Cambridge.

Richard Kirwan (1733-1812) returned to Dublin university, first known use of term 'grauwacke' in English language (1794).

Leskean Mineral Collection of rocks arranged according to Werner's system and containing samples of 'grauwacke' brought to Dublin in 1798 under the instigation of Kirwan.

Robert Jameson (1774-1854) appointed to Chair of Natural History at Edinburgh in 1804. Books on Werner's system 1804, 1808.


J.F. Berger described the geology of Cornwall, called the old rocks surrounding the granite core 'grauwacke' (1811). These were known to Cornish miners as 'killas' (Playfair, 1811).

Fig 2.3 : Werner's British pupils bring Werner's stratigraphic and mineralogical scheme to Britain.
Geology in England

By the beginning of the 19th century amateur naturalists in England, including local parsons, doctors and gentry had accumulated much local geological knowledge, along with good mineralogical and ‘organised fossil’ collections (Fuller, 1969). Even more important, skilled artisans including surveyors, quarriers, mining engineers, canal builders, and drainage engineers like William Smith (1769-1839, ‘the father of English geology’) now knew a great deal about local strata (Figure 2.4). These very pragmatic surveyors and engineers did not bother with theoretical speculation or make collections of fossils and minerals for their own sake (Fitton, 1832, 1833). For them, stratigraphical knowledge was the key to understanding the arrangement of the rocks, and only meticulous personal observation in the field achieved that aim (Fuller, 1969).

When the Geological Society of London was formed in 1807 under the presidency of George Bellas Greenough (1778-1855), the members absorbed the practical values of the practical men, if not their social company. The formation of the society coincided with the fashion for travel, the romance of nature, and the cult of outdoor fieldwork (Rudwick, 1985: Ch.2). The minority of members who had any kind of formal geological education brought Wernerian methods and theories into the society. Hypothesising had become philosophically unfashionable and the members deliberately attempted to reject theory and to concentrate on Baconian empiricism. Their aim was to be sociable and collect geological data with a long-term view of creating theories when enough information was available to safely do so (Woodward, 1911; Rudwick, 1963; Porter, 1977: 202-206; Greene, 1982: 56; compare Laudan, 1977). Although the avoidance of theory was rarely achieved, the attempts meant that members saw themselves as unconstrained by theory and were free to report their results as they saw them. For the rest of the nineteenth century, English geology was characterised by:

- An emphasis on fieldwork, with accumulation of empirical data.
- The naming and mapping of strata.
- The classification of strata and the development of stratigraphy using lithology and paleontology.
- The neglect of mineralogy, petrology, experimental geology and geomorphology. This was in contrast to Europe where professionally trained geologists continued to develop their petrological and mineralogical researches (Geikie, 1875: 105).

Nomenclature and Classification

Leading members of the Geological Society soon realised that a precise, unambiguous, non-theoretical geological language needed to be developed (Playfair, 1811) because even terms such as ‘class’, ‘group’, ‘series’, ‘formation’ and ‘system’ were yet to be settled. The problem of unambiguous language became
an issue with rock names such as Werner’s ‘grauwacke’, and uncertainty meant that ‘Geologists differ[ed] much respecting what is, and what is not, Grey Wacce’ (Mawe, 1818). While the better-educated members of the Society used Wernerian terms, others ‘stood by time-honoured names’ (Porter, 1977 p.209). When rocks in Devonshire and Cornwall were identified as ‘grauwacke’ by a Swiss Wernerian geologist (Berger, 1811), John Playfair (1748-1819) commented that Cornish miners called this rock ‘Killas; which, on account of its better sound, we should very much wish to see substituted for the uncouth German name of Grauwacke’ (Playfair, 1811). (A selection of nineteenth century definitions of ‘greywacke’ is given in Appendix 1).

Werner’s division of rocks into several major classes or formations based on their materials, position and fossils provided what seemed a workable framework for study. However, as geologists found that their own field observations conflicted with the Wernerian scheme, it was not always possible to slot rocks into epochs on lithological formulae, and Werner’s system was adjusted and modified. Increasing reliance was placed on the use of fossils rather than lithological means to distinguish various strata and to arrange them into chronological order (Geikie, 1905 p.406). As progress was made in marking out the stratigraphical column, Wernerism began to quietly die away, but this did not prevent geological controversy. In England the fiercest and most acrimonious battles were not about paradigms and theories. Instead, the disputes raged over order and territory within the stratigraphical column, among them the famous Devonian controversy (Rudwick, 1985) and the terrible Silurian dispute (Secord, 1986).

Classifications and more classifications

One of the earliest published geological maps of England and Wales is a simple, awkward-looking map that appeared in a popular textbook first published in 1813 (Bakewell, 1838). It shows the ‘the grand geological divisions ... without delineating the different strata’ with the rocks subdivided ‘according to the Wernerian system’ (Figure 2.4). The map owes little to William Smith’s work, but at least shows an awareness of the presence of older Transition (which included rocks of grauwacke type) and Primary rocks. The more detailed textbook map published by the Rev. W.D.Conybeare (1787-1857) and William Phillips (1725-1828) (Conybeare and Phillips, 1822) was based largely on the map made by George Bellas Greenough and members of the Geological Society in 1819, which itself was based on Smith’s map (Winchester, 2001). The 1822 map shows large expanses of featureless yellow space representing ‘Grauwacke’ and ‘Clay Slate’ in southern Scotland, Wales and Cornwall. Alas, Conybeare and Phillips never published the intended second volume on the older Transition and Primitive classes. While considerable progress was made in mapping the comparatively undisturbed secondary rocks including all the strata above the Old Red Sandstone, the ‘hardened, squeezed and broken [and] heterogeneous’ strata of the Transition system (with grauwacke) defied attempts to classify them (Geikie, 1875: 173).
Figure 2.4: An Outline Map of the Geology of England by R. Bakewell, first published in 1813. The pink areas to the west marked with the number ‘5’ consist of ‘Transition & Primary’ rocks (with grauwacke). Brown areas represent Tertiary rocks, yellow represents ‘Upper Secondary’ and green areas represent ‘Lower with Upper Secondary’. Original size 202mm x 258 mm. Robert Bakewell (1838), An Introduction to Geology.
Over the next twenty years, much effort was put into improving Werner’s classification of the stratified rocks and the American geologist Edward Hitchcock (1793-1864) tabulated eleven of 25 or so assorted proposed stratigraphic tables based mainly on English and French geology (1844). While these offerings apparently lacked any agreement, they were all based on natural divisions between stratified and non-stratified, fossiliferous and non-fossiliferous rocks, and the differences were largely to do with nomenclature. At any rate, Hitchcock reminded his readers that superposition and organic remains are the only safe criteria of relative age. Most schemes clearly showed an equivalent of Werner’s Transition group placed below a ‘Carboniferous’ Old Red Sandstone and above the Primitive or metamorphic rocks. In the version put forward by Henry De la Beche (1796-1855) in 1833 all the fossiliferous rocks below the Old Red Sandstone were ‘thrown’ into the ‘Grauwacke group’, consisting of a ‘large stratified mass of arenaceous and slaty rocks, intermingled with patches of limestone’. In this way, ‘grauwacke’ became formalised as not only the name of a kind of rock, but also the name of a stratigraphic system and at the same time referred to a particular division of geological time. The rock name now implied:

♦ A particular age of deposition, and
♦ That all ‘grauwacke’ rocks belonged to the same period.

This was an extraordinary use of a recognised rock name. Thirty years before, Werner’s system had required particular formations made up of particular rock types that were limited to particular periods in the Earth’s history. The neptunist-volcanist-plutonist controversies, and the fading of Wernerian geognosy, had liberated other rock kinds from being locked into particular epochs. Names such as gneiss, schist and alluvium were no longer used to denote groups, epochs or systems. In effect, rocks were removed from Werner’s temporal limits and became causal entities (p.42). Contrarily, De la Beche’s classification meant that ‘grauwacke’ represented both historical and causal objects, and such fundamental ambiguity caused inevitable confusion.

Why was ‘grauwacke’ such a problem in England?

♦ Gentlemen of the Geological Society thought the name ‘grauwacke’ was barbarous and being a foreign vernacular term, it was uncouth. But then English provincial rock names like ‘Clunch Clay’ were also considered uncouth and barbarous (Whewell, 1857: 432-435, Lyell, 1875: 83, Winchester, 2001).
♦ So little was known about the ‘chaos of Greywacke’ (Geikie, 1905: 417) that in 1833, Charles Lyell (1797-1875) devoted 300 pages to Tertiary deposits but only twelve lines to those below the Carboniferous coal measures.

3 The European Old Red Sandstone is Devonian in age, but before Murchison’s Devonian System was generally accepted (pp. 43-45) it was placed in the Carboniferous system.
4 ‘Fossiliferous’ referred to sedimentary rocks compared with unfossiliferous crystalline rocks.
The ‘Grauwacke’ formation was difficult to map because ‘everything betokened disorder [and it was] hopeless to expect that rocks so broken and indurated, generally so poor in fossils’ could yield any information about themselves (Geikie, 1905).

The Wernerian terms ‘Transition’ and ‘Grauwacke’ formed a convenient limbo in which to throw any group of rocks ‘which obstinately refused to reveal its relations with the rest of the terrestrial crust’ (Geikie, 1905: 410).

The confusion between ‘Grauwacke formation’, a historical term, and the rock name ‘grauwacke’, a causal term.

The dual nature of geology:

Geology is peculiarly dual in its aims because geological problems are either causal or historical (Laudan, 1987: 2-7), although geologists constantly move between the two modes of thought (Table 2.1).

Table 2.1: The dual nature of geology

<table>
<thead>
<tr>
<th>Causal geology</th>
<th>Historical geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Causes that shape the earth and produce its objects</td>
<td>Development of the earth from its beginnings to its present form - to reconstruct the past</td>
</tr>
<tr>
<td>Universal entities e.g. granite, greywacke, lithospheric plates</td>
<td>Unique entities e.g. Waipapa terrane, Grauwacke formation</td>
</tr>
<tr>
<td>Time sequence not important</td>
<td>What happened once at a particular place. Time sequence is paramount</td>
</tr>
<tr>
<td>To establish general laws of cause and effect, (Bucher, 1936, Laudan, 1987)</td>
<td>To establish a chronicle of particular events. No laws can be derived from individual entities</td>
</tr>
</tbody>
</table>

Invasion of the Grauwacke

In his student days Adam Sedgwick (1785-1873), later Professor of Geology at Cambridge University, became a staunch Wernerian, and later confessed to having been ‘eaten up with the Wernerian notions—ready to sacrifice my senses to that creed—a Wernerian slave’ (Clark and Hughes, 1890: 251). After recovering from this ‘water on the brain’ Sedgwick held firmly to inductive observation and carefully avoided the ‘dangerous position of those who “view all things through the distorting medium of an hypothesis”’ (Clarke and Hughes, 1890: 285). Both Sedgwick and his friend Roderick Impey Murchison (1792-1871), later Sir Roderick, had learned much of their field craft and interpretation from colleagues in the Geological Society of London. This was when the state of geological science meant that ‘a great work could be done by a man with a quick eye, a good judgement, a clear notion of what already been
accomplished, and a stout pair of legs’ (Geikie, 1875: 96). Both men were archetypes of the elite
gentlemanly members of the Geological Society (Rudwick, 1985). One was an eccentric clerical don, the
other a wealthy gentlemanly amateur very conscious of his social position.

Murchison firmly intended to determine the order of strata in those difficult old rocks, and early in the
1830s, he commenced his ‘invasion of the Grauwacke’ in South Wales (Geikie, 1875: 172). Sedgwick had
already begun to unravel the old, deformed rocks of the transition series in Cumbria that contained much
greywacke and greywacke-slate (Sedgwick, 1834) but now switched his attention to the Grauwacke of
North Wales.

At first, Murchison tried to use Wernerian mineralogy and lithology to identify various strata, but these
methods could not indicate geological age or the position of strata in the stratigraphic record. Fortunately
for his ambitions, his rocks contained identifiable, reliable fossils making it possible for him to
triumphantly divide De la Beche’s ‘Upper Grauwacke series’ into four separate formations (Murchison,
1834). This new group was named the ‘Silurian System’ after an ancient Celtic tribe, the Silures
(Murchison, 1835; Geikie, 1875: 356). In a paraphrase of Murchison’s work, the patriotic dictionary writer
William Humble (1860) proclaimed that ‘the Silurian loved to dwell amid … the old greywacke of the
Scottish region, as well as along the Welsh border; and thus I rejoice in having substituted a pleasing
name, full of glorious British recollections, for the foreign term, Grauwacke’. In the same year, Sedgwick
introduced his Cambrian system in North Wales, leading to the dreadful territorial dispute between the
two former friends (Secord, 1986).

What did Murchison have against ‘grauwacke’?:

♦ His complaints were in part an oblique criticism of Henry De la Beche’s interpretation of the older
rocks of Devonshire (Rudwick, 1985: 287).
♦ ‘Grauwacke’ was a barbarous foreign word.
♦ The word was nomenclaturally confusing; it referred to both a rock type and to a time of formation.

Murchison mounted and maintained a vigorously relentless campaign against the use of ‘Grauwacke’ as
either a lithological or as a formation name:

[As] this one county [Pembrokeshire] is shown to contain rocks in the true coal measures
and in the old red sandstone, as well as in the Silurian and Cambrian systems, which
from their lithological characters have been mistaken for “greywacke”, the use of that
word as expressing the age of the rocks is no longer consistent with the advanced state of
geological science, and that if used, the name should either be rigidly restricted to some of
the very oldest sedimentary deposits, or simply employed as a mineralogical definition of
peculiar grits which actually reoccur in strata formed in many successive epochs.

3 I. Ludlow Rocks, II. Wenlock and Dudley rocks, III. Horderley and May Hill rocks, IV. Builth and Llandelio flags.
Later, in a joint paper with Sedgwick, Murchison protested that:

>[A]s the term has done much disservice to geology, by inducing observers to merge, under an unmeaning name, deposits belonging to distinct periods in the history of the earth, we hope that the term may be henceforth discarded as a term of classification.

(Sedgwick and Murchison, 1837).

In another joint paper on the ‘Older Stratified Rocks’ of Devonshire and Cornwall, the term ‘Devonian System’ was proposed for the ‘great intermediate deposits between the Silurian and Carboniferous systems’. The authors warned against the error of trusting too much to mineral characters and the way in which they and others had been deceived in attributing too high antiquity to strata having an antique lithological aspect and a slaty cleavage: but the day is now passed, when such features, still less the mere colour or composition of rocks, can be allowed to lead to any true estimate of their age.

(Sedgwick and Murchison, 1839)

The authors again angrily objected to the use of the ‘minerallogically worthless’ term ‘grauwacke’ in any form and demanded that it should be dropped.

We proposed the use of the terms Silurian and Cambrian because we believed that their adoption ... when applied to well-defined mineral masses, might tend to clear away the obscurity which we were persuaded would hang over the older rocks as long as they were all considered to belong to the dark and undefined area of “Grauwacke”; and we trust that we have, in this memoir, shown strong additional grounds why this mineralogical term should be disused by geologists, as a term of classification, applied as it has been to rocks of such very different ages; thus serving as a shelter for ignorance, and paralyzing every effort for determining the succession of strata upon true principles. If its lovers wish still to cling to it, let them use it as an adjective and tell us of Carboniferous, Devonian, Silurian, and Cambrian “Grauwacke”, and then, at least, the term will do no mischief. The continuance of the use of this term to represent different epochs in the history of the earth would be as absurd as to retain the old “flötz” formations of Werner, after it has been shown that such rocks are often as highly inclined as the most ancient strata; but we trust that any wrangling about this barbarous word is nearly at an end; for already some of the best foreign geologists have discarded its application to the upper systems of transition rocks, and now restrict its use as a term of classification to the lowest slaty or Cambrian rocks.

Most opinions appear to have been Murchison’s alone (Rudwick, 1985). However, his formidable status in the Geological Society convinced other English geologists to give up using ‘greywacke’ as either a rock or formation name. The controversy regarding the age of very old-looking rocks in Devon was settled only when a new Devonian system incorporating rocks older than the Carboniferous system, younger than the Silurian rocks and including the Old Red Sandstone was accepted by the geological community (Sedgwick and Murchison, 1839; Rudwick, 1985). The troublesome link between rock type and age could
be broken, and it was necessary to recognise that what appeared to be very old-looking greywacke could be much younger than previously thought. ‘The practise of stratigraphical geology would have to abandon... one of its most heuristic* rules of thumb: rock type could no longer be regarded as a rough guide to relative age’ (Rudwick, 1985 p.449).

After 1840, ‘greywacke’ dropped out of common use in England and the term was sometimes described as archaic or old-fashioned. For the next forty years, it was ‘seldom employed, or employed only to designate a peculiar slaty siliceous grit, and the precision of fossil inquiry has all but exploded the idea of a transition period’ (Page, 1859; 1872).

Meantime, in Scotland

Scottish geologists ignored Murchison’s fulminations, continued on their own way and retained Jameson’s ‘greywacke’ to refer to the ‘particular kind of muddy sandstone’ characteristic of the ‘Ordovician and Silurian sandstones of the Southern Uplands’ (Bailey, 1930). Towards the end of the nineteenth century, the Scottish geologist brothers, Archibald Geikie (1835-1924) and James Geikie (1839-1915) reinstated ‘greywacke’ as an acceptable geological term in their textbooks. While James Geikie was Murchison Professor at Edinburgh University, he re-introduced greywacke into geological respectability without tying it to any geological epoch and gave it a standard description as a hard aggregate of rounded sub-angular and angular grains and splinters of quartz, felspar, and slate, sometimes with mica and grains of other minerals and rocks, embedded in a hard paste or matrix

\[(\text{Geikie, 1886})\]

Archibald Geikie published a number of successful and influential textbooks and popular writings (Oldroyd, 1990), many of which were exported to New Zealand. Geikie’s 1903 edition of his Text-book of Geology was among the first of the modern, comprehensive geology textbooks and one of the earliest to treat sedimentary rocks in any detail, inclusive of microscopic and sedimentary structures (Figure 2.7, p.42). The rock is characterised as a major sedimentary rock type alongside sandstone, consisting of:

\[
\text{a compact aggregate of rounded or subangular grains of quartz, felspar, slate, or other minerals or rocks, cemented by a paste}....\text{The rock is distinguished from ordinary sandstone by}...\text{its hardness, the variety of its component grains and, above all, by the compact cement in which the grains are imbedded.} \\
\text{(Geikie, 1903: 166-167)}
\]

Curiously, in spite of Murchison’s railings of sixty years’ before, Geikie restored an age association for his greywacke, which was perhaps related to their association with the Scottish southern uplands. Greywacke was limited to Lower Paleozoic sequences and never allowed to appear above the Silurian.

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* Heuristic = problem-solving process
Geikie was a strong proponent of thin-section petrography (Bailey, 1952), but like most other petrographers, he concentrated mostly on igneous and metamorphic rocks. Apart from Sorby’s sketches (1880) this is one of the earliest microscopic views of a sedimentary rock. Alexander McKay published his excellent photomicrographs of the rocks of Cape Colville Peninsula in 1905 (Sollas and McKay, 1905).
Chapter Three

NEW ZEALAND

Visitors and Settlers 1769-1865

To examine if not at too great a distance within the Country the places where such [Minerals and Fossils] are found.

It has been allledged by some Naturalists that Gold is not found in Veins, as other metals.

If that, or any other Metal should be met with, it would be curious and Instructive, to examine minutely how they lye in the Earth in their Brute State, and how the veins Had, as well with respect to the angle of their declivity, as their bearing to the Mariners Compass....

Gravel and Sand found at the mouths of Rivers, help to give a notion of the Minerals and Fossils of the Countrys thro’ which those Rivers take their course....

(Hints offered to Captain Cook ...
James Douglas, 14th Earl of Morton)

An assortment of naturalists, surgeons, surveyors, and tourists were responsible for the score or so of geological observations made by Europeans in this country before 1865 (Oldroyd, 1967). Most visitors were limited by time and all were faced with the difficulty of penetrating the New Zealand bush and the country’s mountainous terrain. Consequently, most early geological reports were made on coastal sections near anchorages such as Queen Charlotte Sound, the Bay of Islands and Port Nicholson (Figure 3.1). The scattered reports on greywackes range from sober accounts by members of scientific expeditions to a few, scrappy remarks by tourists like John Liddiard Nicholas (Nicholas, 1817: 426) who noticed that near Bream Head, the ‘stratum of the shore, and that of the rocks was of clay-stone, similar to those in the Bay of Islands.’

Note: Because it is not always easy to obtain copies of pre-1860 New Zealand geological records, text extracts from a selection of reports having to do with the New Zealand greywackes are provided in Appendix II.

Cook’s voyages: probing the southern ocean

When Lord Morton (1702-1768), President of the Royal Society, prepared his hints to ‘Captain Cooke, Mr Banks, Doctor Solander, and the other Gentlemen who go upon the expedition on Board the Endeavour’ (Beaglehole, 1955: 514-519), geology was only then developing out of mineralogy as an independent science. Although the voyagers were instructed to look for minerals and fossils, Sir Joseph Banks (1743-
and Doctor Daniel Carl Solander (1733-1782) were much more interested in botany and ethnography and paid comparatively little attention to geological features. A few brief references were made by them and by Cook to such minerals as floating pumice, iron sands, stones, and to veins which might contain mineral ores.

Although mineralogists had begun to recognise rocks as entities by the mid eighteenth century (Laudan, 1987: 56), their lithological vocabulary was limited. The English naturalists who sailed with Captain Cook on his first voyage (1768-1771) concentrated on biological subjects, but perhaps they said little about the geology of New Zealand because they lacked a terminology to describe rocks. Precious stones, building stone, and fragments and layers of rock were all referred to as ‘stone’ or ‘stones’, but terms like ‘rock’, ‘rocky’ and ‘strata’ were only beginning to come into common use.

During Cook’s second voyage (1772-1775), the German naturalist Johann Reinhold Forster (1729-98) used Linnaeus’s new binomial terminology and referred to quartz, pumice and nephrite as *quartzeum lacteum, pumex vulcani* and *talcum nephriticum* and described the ‘indurated stone’ on the shore of Endeavour Inlet in Queen Charlotte Sound (Figure 3.1) in terms of strata and dip (Appendix II). His son, Johann Georg Adam Forster (1754-1794) described the coastal rocks as ‘argillaceous stone’ running in ‘oblique strata’ (Appendix II). Miners’ and quarriers’ vernacular terms were being rapidly incorporated into technical language and the Forsters noticed how the English seamen used the word ‘shingle’ (Arkell and Tomkeieff, 1953) for the fragments of slate scattered on the beach. Cook would take no scientists on his
third voyage (1776-1779) having cursed them ‘and all science into the bargain’ (Beaglehole, 1969: xlvi) and the ship’s officers made all the scientific observations. On this voyage, Cook called only at Queen Charlotte Sound in New Zealand where William Anderson, the ship’s surgeon, briefly recorded observations of the shoreline rocks (Appendix II) before the ship departed for the North Pacific.

**The travelling naturalists**

Shortly after Cook’s first visit to New Zealand, Julien Marie Crozet, a member of a French expedition (1771-72) to the South Seas under Marion du Fresne (Roth, 1891: 72), reported blocks of white marble and red jasper on land surrounding the Bay of Islands (Appendix II). The Bay of Islands was a popular port of call for whalers and other visitors until the late 1840s. It was sheltered, it had several active mission stations as well as the whaling port of Kororareka and it provided supplies of fresh water, pork and potatoes. The missionary brothers Henry and William Williams were interested in natural history and told visiting naturalists about unusual landscape features, such as volcanoes, geysers and river terraces. Whatever written records the Williams brothers made of their observations may be buried in their voluminous correspondence with the Church Missionary Society.

The visiting naturalist, Samuel Stutchbury (1798-1859), sketched the earliest known geological section drawn in New Zealand during a busy two-day visit to the Bay of Islands in April 1826 (Stutchbury, 1826; Branagan, 1984). This intriguing little drawing (Figure 3.2) depicts a short length of the shore (300-400m) on the north coast of the bay with ‘Rangahu’ (Rangihoua), a steep, conical pa-site, and alongside, at ‘Tipoona’, the site of the first tiny mission station (now site of the Marsden Cross). Stutchbury uses the old term ‘schistus’ to refer to the main body of greywacke and records the presence of chert, basalt and manganese. During his brief stay, Stutchbury had time to travel 20 miles up the ‘River Kedi kedi’ to view

![Figure 3.2: Samuel Stutchbury's 1826 geological drawing of the section at Oihi on the north coast of the Bay of Islands. This copy was traced from a photocopy of a microfilm copy of Stutchbury's notebook. Alexander Turnbull Library, National Library of New Zealand, Te](image-url)
a 30 ft waterfall passing over a mass of basalt, and as he left New Zealand for Pacific islands to the north, sketched the outline of Piercy Island.

R.G. Jameson, ‘late Surgeon Superintendent of Emigrants to South Australia’, and more a travel writer (1841) than a naturalist, cheerfully dropped numerous rock names and was a great deal less hesitant than Darwin and Dana (below) about allocating rocks to Werner’s primary, secondary, carboniferous or transition systems (Appendix II). He confidently asserted that New Zealand was ‘obviously’ formed by the ‘simultaneous upheaving by volcanic force of argillaceous and basaltic rocks and mountains’. Jameson visited the island of ‘Wyheke’, and remarked on the ‘common argillaceous rock of New Zealand’, and the island’s manganese mine. Jameson’s major claim to geological fame is his early (but not quite the first) mention of ‘greywacke’ in New Zealand.

**Scientific Expeditions 1835-1841**

Charles Robert Darwin (1809-1882) stayed at the Bay of Islands for ten days in 1835 (Darwin, 1851: 142). He disliked the place intensely and in his geological report found space for just one paragraph and a footnote about New Zealand (Appendix II). Among the rocks of the Bay of Islands shore Darwin noticed chert, ‘clay iron-stone’ and clay-slate, but without fossils to guide him he was ‘unable to form any decided opinion on this formation’. He was more interested in the Reverend William Williams’ drawings of terraces in the valley of the Thames River, which he believed indicated slow elevation of the land.

Between August 1839 and November 1841, the young German naturalist, Johann Karl Ernst Dieffenbach (1811-1855), formed a notable one-man scientific expedition as he made the first comprehensive survey of New Zealand’s natural history on behalf of the colonising New Zealand Company (Dieffenbach, 1843, Bell, 1976). Dieffenbach takes the honour of being the first to publish the term ‘greywacke’ in reference to New Zealand rocks (Dieffenbach, 1840, Dieffenbach, 1841). He referred to the rocks of Queen Charlotte Sound and the Wellington district as yellow clay slate and greywacke (1840), and as slate, siliceous slate, argillaceous slate, argillaceous schist and clay slate, often with Lydian stone (chert), basalt and greenstone (1843, Appendix II). The rocks of Waiheke were described only as yellow argillaceous rock and basalt. Dieffenbach was reluctant to theorise but thought that the transition of one rock to another at Cloudy Bay and the structure and metamorphism of the slate rocks was caused by the ‘infusion of trappean rocks from below’. Because these and the rocks of Queen Charlotte Sound contained no fossils, he believed that they belonged to the transition series of Werner along with the rocks of Kapiti Island, where ‘clay slate rocks and greywacke are the most common’.

When commenting on the difficulty of doing geology in New Zealand because of the forests and ‘impenetrable thickets of esculent fern’, Dieffenbach (1845) identified ‘clay slate’ as the ‘fundamental’ rock everywhere. Although he did not visit the Southern Alps, Dieffenbach reported them as ‘supposed
to consist of primary rocks; quartzose sandstone and graywacke’. No clue was given as to his informant, or if the statement was merely a guess, but he was inclined not to acknowledge sources (Bell, 1976: 98). Dieffenbach used the word ‘greywacke’ only once in his book (1843: 108). Perhaps he was aware of Murchison’s and Sedgwick’s condemnation of ‘grauwacke’ (whatever its spelling), yet he did not attempt to please Murchison by using the latter’s Silurian system instead of Werner’s transition series.

While the ships of the great United States Exploring Expedition (1838-1842), visited the Antarctic from February to April 1840, the squadron’s commander, Charles Wilkes (1798-1877), remained for six weeks at the Bay of Islands in company with the distinguished American geologist James Dwight Dana (1812-1895) (Wilkes, 1845). During those summer weeks the explorers thoroughly examined the geology and geography of the district (while some colleagues who arrived earlier witnessed the signing of the Treaty of Waitangi). Dana (1849) noticed that the northwest trend of part of the New Zealand islands was parallel with ‘the grand ranges of the Pacific’ while the other part had a transverse north-north-east trend ‘being part of the same chain as Tonga and the Kermadec islands’.

Figure 3.3: ‘The Old Hat’, Bay of Islands. Geology : The United States Exploring Expedition during the years 1838, 1839, 1840, 1841, 1842. Dana 1849 (109, 442)

Among the few illustrations in Dana’s account of his New Zealand visit is his famous drawing of ‘The Old Hat’, a small island in the Bay of Islands (Figure 3.3), showing the characteristic horizontal shore platform cut into the ‘argillaceous sandstone’ in sheltered waters at just below high water level. The same drawing was used by Hochstetter in 1864 (Fleming, 1959b: 37), but C.A.Cotton used a photograph of the island taken from the mainland side to illustrate the same feature (Cotton, 1945: 415). Dana described the greywackes of the Bay of Islands as ‘singularly compact arenaceous argillaceous rocks’ (Appendix II) with chert and quartz nodules near Tipuna (where Stutchbury drew his section) as well as ‘chloritic slate’. Although Dana found it difficult to distinguish lines of strata, he measured dips ‘in all directions’ between 90° and 30°. Like Darwin, Dana was cautious about coming to any conclusions regarding any of these rocks. The lack of fossils caused him to believe that they were of great antiquity, earlier than the ‘coal series’, and he noted that ‘Dr Dieffenbach places the formation in the Silurian period’.
Unfortunately, the massive multi-volume report issued by the Wilkes expedition was of little use to the rest of the scientific world because, inexplicably, the United States Congress insisted that only a limited edition of 100 copies should be printed (Faul and Faul, 1975).

**Exploration science and its spread to a new land**

Ships like Cook’s *Endeavour*, Fitzroy’s *Beagle* and those of Wilkes’s fleet were themselves in the nature of scientific instruments as they probed the world (Sorrenson, 1996). With each voyage, more and more information was brought back to metropolitan ‘centres of calculation’ in Britain, Europe, and the United States in the form of maps, charts, drawings, samples, specimens and written accounts (Latour, 1987: 215). This ‘global harvesting’ (Livingstone, 1992: 130) meant that expeditions returned with ever more data to be accumulated, ordered, analysed and distributed (except for the thwarted scientists of the Wilkes expedition). Reports by independent travellers, merchants and missionaries, who were themselves products of a scientific culture (Basalla, 1967), added to the stock of knowledge. This rapid gathering of knowledge about the world by exploratory expeditions (Figure 3.4) quickly declined when

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1 A ‘condensed and abridged’ version of Wilkes’s narrative was published in London in 1845. More recently, a replica edition was published in New Zealand by R.McMillan, ISBN 0-908712-15-4
western colonies were established and settlers began setting up their own institutions or ‘centres of calculation’.

A simple three-phase model of the spread of Western European science (Basalla, 1967) very broadly approximates the establishment and growth of geology in nineteenth century New Zealand (Figure 3.5). Phase 1 is represented by the scientific expeditions in which the periphery (for example, New Zealand) ‘serves as a data base for the further development of European-based scientific theory’ (Inkster, 1985). Phase 2 is characterised by dependant ‘colonial science’ (Basalla, 1967) in which trained scientists were educated in Europe, studied the works of European scientists, and published in European journals. Phase 3 is marked by the effort to create an independent scientific tradition, with the establishment of home-based scientific organisations, journals and training.

Basalla’s simple model has come in for considerable criticism (Inkster, 1985, MacLeod, 1996). However, it more or less describes the establishment of Western European science in New Zealand but with much overlap of the phases, and it does not take into account the twentieth century internationalisation of science. In New Zealand, Basalla’s exploratory phase 1 was quickly followed by the introduction of ‘colonial science’ of phase 2 during the 1850s (see below). This soon began to merge into phase 3, the creation of an independent but internationalised scientific tradition in New Zealand that was completed probably by 1900 (Chapter 4).

**Mid-century settlers**

Among the mid-century settlers, Walter Baldock Durrant Mantell (1820-1895), son of Gideon Mantell, the discoverer of *Iguanodon* (Griggs, 2003), was best acquainted with geology. Walter Mantell travelled extensively through New Zealand, gathering a great deal of geological information along with numerous fossils, especially those of *Dinornis*, which he sent to his father in England (Sorrenson, 1990; Kidd, 1996). Mantell (1850) reported that the main ranges of the Southern Alps, and the Tararuua and Ruahine mountains consisted of slates, while Gideon Mantell (1848, 1850) deemed that the fundamental rocks of
New Zealand are metamorphic schists and clay-slate with the mountain ranges consisting of schistose metamorphic rocks.

Figure 3.6: Heaphy’s sketch map of the North Island, New Zealand. ‘Clay-slate and Wacke’ (marked by wavy lines) are shown at Waiheke, Hunua and Wellington. Heaphy (1860) Quarterly Journal of the Geological Society, London

As European settlement in New Zealand increased in the late 1840s and through the 1850s, yet more visitors and settlers sent data and specimens back to ‘centres of calculation’, usually in Britain. Although
expeditions continued to be sent out from European centres (Figure 3.4) scientific activity in New Zealand began its second phase (Basalla, 1967). Settlers like Walter Mantell who were trained in Europe and with a European scientific tradition gathered scientific tribute to be remitted ‘Home’ (to G.W.Mantell, 1848,1850) and prepared articles for publication in European learned journals (Heaphy, 1860, 1864). Charles Heaphy (1820-1881) artist, surveyor, explorer, and soldier (Fitzgerald, 1990: 181-83) developed an interest in geology during the 1850s. His 1860 paper ‘On the Volcanic Country of Auckland, New Zealand’ contains two notable maps: a map of the Auckland volcanic field, the subject of a dispute over plagiarism between Heaphy and Hochstetter (Mason, 2002b), and a ‘crude sketch map’ of the North Island (Figure 3.6). This map not only shows various volcanic regions but also shows greywacke regions around Auckland and Wellington, labelled ‘Clay-slate and Wacke’.

Although Transactions of the New Zealand Institute did not begin publication until 1869 (Fleming 1969c), local reports of scientific lectures and observations began to be published at length in provincial government gazettes (Hochstetter, 1859a, 1859b) and by newspapers (Mason, 2002b), to initiate a new, if small, ‘centre of calculation’ in this country.

**Hochstetter and the Provincial Surveys**

In nine brief months Hochstetter had laid the foundations of the geological history of the North Island and of those parts of the South Island outside Otago and Canterbury.

(Jenkinson, 1940: 31)

New Zealand geologists revere two very different nineteenth century cultural heroes both for their feats of pioneering exploration and their perceptive interpretations of New Zealand geology. The first is Christian Gottlieb Ferdinand von Hochstetter (1829-1884) son of a clergyman, born in Germany, highly educated, member of the Imperial Royal Geological Survey of Austro-Hungary, and later Professor of Mineralogy and Geology at the Imperial Royal Polytechnic Institute (Fleming et al., 1988). The other is Alexander McKay (1841-1917), a self-educated Scottish prospector, gold miner, fossil collector and New Zealand Geological Survey geologist (Chapter 4).

Hochstetter, a member of Austria’s Novara scientific voyaging expedition, visited New Zealand for nine months from 22 December 1858 to October 1859, in order to explore, observe, map and lecture on behalf of the Provincial Councils of Auckland and Nelson (Jenkinson, 1940; Fleming et al., 1988; Fleming, 1990; Kermode, 1992). His visit marked the end of fragmented geological traveller’s tales about the colony and provided a ‘firm foundation for later stratigraphical work’ (Oldroyd, 1967: 8). Hochstetter and Johann Franz Julius Haast (1822-1887) serendipitously met in Auckland on the day of Hochstetter’s arrival. Haast became Hochstetter’s pupil and assistant, they travelled together through the Auckland and Nelson districts, and remained life-long friends (Haast, 1948).
Hochstetter’s compilation of geological reports

Figure 3.7: Map of New Zealand indicating the sources from which Hochstetter compiled geological reports to support his own and Haast’s observations. These observations were supplied by other visitors, explorer surveyors, and from settler geologists such as James Hector.
Hochstetter is admired for his geological expertise and for establishing a tradition of systematic geological mapping in New Zealand (Willett, 1964; Fleming, 1990). His extensive report of 1864 (Fleming, 1959b) with its accompanying maps, lists, tables, drawings and traverse sections was a compilation of his own observations and conclusions neatly combined with reports from Julius Haast and other settlers and visitors (Figure 3.7). The provincial surveyors were especially important because they were usually the first European explorers to penetrate many areas and often had good geological knowledge. Consequently, exploring geologists like Haast frequently relied on the guidance of experienced surveyors (Easdale, 1988: 133).

The lack of fossils in the older rocks meant that the New Zealand formations and rocks could not be matched with the European stratigraphic column, and Hochstetter had to rely on their apparent stratigraphic relationships in the field to arrange them in chronological order. However, ‘representatives of stratified rocks from the oldest metamorphic rocks to the youngest sedimentary rocks and of igneous formations from the oldest plutonic rocks to the youngest volcanic lavas’ were identified (Hochstetter, 1868; Hochstetter and Haast, 1868; Fleming, 1959b). All of the rocks that came to be known as ‘the greywackes’, including those of the Southern Alps, were placed in the Paleozoic period together with the fossiliferous slates of Mt Arthur in north-west Nelson. As Hochstetter wisely observed their ‘petrographic habit... gives only weak grounds for an age determination; the evidence from stratigraphic relationships is hardly more conclusive; only the occurrence of gold-bearing quartz veins speaks ... for an early Paleozoic date, and indeed for a Silurian age’ (Fleming, 1959b: 55).

The report of Hochstetter’s public lecture in Nelson includes the first known mention of ‘greywacke’ published in New Zealand (Hochstetter, 1859). Hochstetter always meticulously used the term ‘greywacke’ as a lithological term to refer only to greywacke-type sandstones of Paleozoic age. It was never applied as a group term to the whole assemblage of sandstones, argillites, clays and lavas, and no rocks of presumed Mesozoic age were described as ‘greywacke’.

The mountain ranges of the North Island’s East Coast were described by Hochstetter as the ‘terra incognita’ of New Zealand, and the steeply dipping beds of the mountain ranges near Wellington were thought to ‘undoubtedly belong to the Paleozoic period’. Hochstetter visited much of the Hauraki Gulf where he found good sections of steeply dipping Paleozoic formations at ‘Waiheki’ where he noted the beds of red jasper and veins of manganese ore on the southern shore, on ‘Panui’ and the shore of Tamaki Strait. These were all seen as continuous with the old rocks of Kawau Island, Great Barrier Island, the Bay of Islands, and with the mainland from ‘Maraitai’ to the Hunua and Maungaroa Ranges where Hochstetter found that in forested areas, the rock was quite decomposed at the surface and ‘coated deeply with a loamy weathering crust.... There all geology ceases’ (Fleming, 1959b: 57).
Hochstetter saw little of the South Island for himself apart from parts of Nelson Province. Of particular significance to this study is his analysis of the ‘more or less vertical’ beds of sedimentary formations at Richmond, near Nelson (Fleming, 1959b: 231). A single fossiliferous locality with Monotis (1959: 244) indicated a Triassic age, but Hochstetter suspected that associated greywacke and argillite zones were members of Paleozoic formations. The conclusion was that if the fossils of his Richmond Sandstone are of Triassic age, then the Maitai Slates and Wooded Peak sandstone must also be considered as Trias, and ‘Triassic beds then ... play a very great part in the high mountains of the South Island of New Zealand’.

Table 3.1: Hochstetter's stratigraphy of Nelson (with oldest rocks listed first). The red and green Maitai slates appear to overlie the obviously Triassic Richmond sandstone (shaded). Hochstetter did not correlate the large tracts of greywackes to the east of Nelson with either of these formations.

The relationships between all the groups numbered 1 to 5 later caused unending problems, with special difficulties to do with the contact between the Richmond Sandstone (Hector’s Wairoa Series) and the Maitai slates (Hector’s Maitai Series).

<table>
<thead>
<tr>
<th>Formations</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A. Paleozoic Group</td>
<td></td>
</tr>
<tr>
<td>Greywacke sandstone and slates of Wairau district</td>
<td></td>
</tr>
<tr>
<td>B. Mesozoic group</td>
<td></td>
</tr>
<tr>
<td>1. The Serpentine Intrusion of Dun Mountain</td>
<td>Described and named ‘dunite’. Copper and chrome deposits</td>
</tr>
<tr>
<td>2. Limestone of Wooded Peak</td>
<td></td>
</tr>
<tr>
<td>5. The augite porphyry of Brook Street Valley near Nelson and the syenite of Wakapuaka</td>
<td></td>
</tr>
</tbody>
</table>

The Auckland and Nelson Provincial Governments paid Hochstetter for his surveys in New Zealand, but the Austrian government organised and paid for the Novara expedition and supported all the follow-up research. Hochstetter did much more than take scientific trophies back to Vienna. He arranged for them to be examined and described by such eminent geologists and paleontologists as Professor Doctor F. Unger, Professor Doctor Karl Zittel, Professor Eduard Suess, Felix Karrer, Doctor Ferdinand Stoliczka, Doctor Guido Stache, Doctor Gustav Jaeger and Professor Ferdinand Zirkel. Their findings were returned to this country. A great many contributions to the geological knowledge of New Zealand continued to be made by Austrian and German geologists until the First World War as shown by even the briefest inspection of pre-1950 bibliographies of New Zealand geology (Park, 1910, Hamilton, 1902, Adkin and Collins, 1967).
The Provincial Surveys

The discerning and educated type of colonist, which characterises New Zealand in contrast to many other colonies, well knew the importance of investigations of physical geography and geology by experts to provide a scientific foundation for various public enterprises. The provincial governments have spared no expense to obtain such services, whereby the geological and mineralogical investigation of the country could be carried out.

(Hochstetter qtd in Fleming, 1959b: 4)

Geological surveys are all the fashion in New Zealand. I have already sent out Dr. Hector to Otago on a three years’ survey, with a good assistant, and I have no doubt he will do capital work.

(Murchison, qtd in Geikie, 1875 V.II, 255).

Payable gold was discovered in New Zealand in the 1850s, but as the easily found gold in Otago and Coromandel began to run out, the Provincial governments of Wellington, Canterbury and Otago all looked to setting up their own geological surveys with the aim of searching for and developing their mineral resources. The members of the Auckland Provincial Council seemed satisfied with Hochstetter’s survey and ignored suggestions by Heaphy and others that a Provincial Geologist should be appointed (Mason, 2002a). Nonetheless, ‘the decade succeeding 1861 was one of intense geological activity in New Zealand. The rivalry of the provinces communicated itself to the State geologists. Expedition followed expedition ‘in rapid succession’ (Park, 1910).

Julius Haast in Nelson Province

After Hochstetter’s departure for Vienna in 1859, Julius Haast (later Sir Julius von Haast) in the company of the surveyor, James Burnett, and several other Europeans and Maori, made an astonishing eight months’ exploratory journey through west Nelson on behalf of the Nelson Provincial Government. (Haast, 1861; Haast, 1948: 69-104). Haast’s party travelled from Nelson to Lake Rotoiti, and thence followed surveyor’s trails blazed along river valleys to the south and west until they arrived the west coast at the mouth of the Grey River. From there, the exploring party returned to Nelson along the coast to Collingwood. During this journey Haast made geological maps and many landscape drawings, mapped the Grey coalfield, previously discovered by the explorer Thomas Brunner (1821-1874), and discovered the Westport coalfield. A copy of his handsome topographical map of central and western Nelson showing the party’s route (1860) is included in his biography (Haast, 1948).

Following his success in resurveying the line for a rail tunnel from Lyttelton to Christchurch, the Canterbury Provincial Council employed Haast in 1861 as Provincial Geologist (Jenkinson, 1940: 34-47).
During his numerous and important explorations of Canterbury and Westland, (then part of the Canterbury Province), Haast became very familiar with the ‘huge assemblage of beds’ (Haast, 1879: 279) that comprised the greywackes of the region (see Chapter 4).

James Coutts Crawford of Wellington Province

James Coutts Crawford (1817-1889), cattle farmer of Miramar, businessman and politician was greatly interested in the geology of the Wellington Province (Wilson, 1991) and made careful descriptions of the ‘steeply tilted slates of greywacke type [which] form the mountain ranges’ of the Port Nicholson district (Crawford, 1855). In an undated manuscript Crawford depicted the formation bounding the harbour of Port Nicholson as ‘metamorphic, and is called greywacke, by my cousin Dr Monro of Nelson who is the most important judge I have met with in the Colony’. The strata in the ‘abrupt mountain ranges’ and ‘precipitous and narrow gorges’ were so ‘broken, contorted and at all angles ... [and] so altered that it is difficult to decide if it be stratification at all. This formation is intersected by numerous veins of igneous rock and is destitute of fossils’. It was a small social world in the colony. Dr Monro (1813-1877), later Sir David Monro, wealthy sheep farmer of Nelson, and Speaker of the House, hosted Ferdinand von Hochstetter in 1859 (Fleming, 1959a). His eldest daughter Maria Georgiana married James Hector in December 1868 (Oldroyd, 1972; Wright-St Clair, 1990).

The Wellington Provincial Council employed Crawford as Provincial Geologist in 1861, following which he made a number of horseback journeys through the province, mainly to find coal or gold. Crawford (1861) produced a stratigraphic table in which he divided the region’s rocks into Recent, Tertiary, ‘possibly secondary or palaeozoic’, and ‘probably silurian’ and ‘plutonic’. Crawford was uncertain of the age of the older rocks but distinguished plainly between the stratified Cretaceous rocks of the East Coast and the ‘metamorphic or altered rocks’ of the Rimutaka and Tararua ranges. He was particularly concerned with the ‘Terawiti’ gold diggings in the Karori and Waireka valleys, and hypothesised that the ‘lower the bed of rock and the nearer to the central fires, the more the rocks seem to be rendered crystalline, traversed by veins and possibly transfused with gold’. Crawford understood ‘grauwacke’ in the old Wernerian sense of an age-related system and believed that we must be ‘content’ to call the ‘semi-metamorphic’ rocks in the main range of the Island ‘grauwacke ... until the discovery of fossils shall enable us to assign ... a definite geological age’. In later years, Crawford enjoyed a little geological speculation and hypothesised on the lack of fossils in the ‘Upper Palaeozoic’ greywacke rocks (1876), and on the possibility of past connections between New Zealand and South America (1872).

Lauder Lindsay and James Hector in Otago

The Otago Provincial Council had long tried to find a geologist (Dick, undated). Their first choice, a Dr Schmit, disappeared in the hinterland of Otago in 1855, and the Council did not succeed in obtaining
Hochstetter’s services. However, during the summer of 1861-1862, Dr W. Lauder Lindsay (1829-1880) botanist and amateur geologist, surveyed the goldfields of Tuapeka and then of Coromandel (Lindsay, 1862a, 1862b). Lindsay thought that the metamorphic slates of Tuapeka resembled those of central and southern Scotland, were probably of Silurian age, and were the source of the gold, as were the auriferous rocks of Coromandel. He believed these northern slates, which stood more or less vertically with ‘irregular upturned edges’ resembled Lydian stone or the slaty varieties of basalt, such as clinkstone. Like others, Lindsay commented how the mountains are ‘densely wooded’, and so difficult of access that sections of these slates may be examined ‘only here and there in the gorges’.

Towards the end of 1861 James Hector (1834-1907), later Sir James Hector, was appointed as Provincial Geologist by the Otago Provincial Council on the recommendation of Murchison, who was now Director of the Geological Survey of Great Britain (Chapter 2). Soon after his arrival in New Zealand in April 1862 (Jenkinson, 1940) Hector busied himself with establishing his new Survey and energetically set out on a number of expeditions throughout Otago including the fiords on its southwest coast (Jenkinson, 1940; Adkin and Collins, 1967; Byrnes, 1995). His reports to the Otago Provincial Council culminated in a ‘Synopsis of the Geological Formations in Otago Province’ (Hector, 1865) accompanied by a description and an inventive ‘Section across the Province of Otago’ representing a bold interpretation of field observations made along an unlikely traverse (Figures 3.7, 3.8).
Unlike Hochstetter, who did not hesitate to assign New Zealand rocks to the major systems, Hector (1865) was cautious about attributing particular ages to Otago rocks older than the Miocene period. However, he did attempt to correlate the metamorphic rocks of south-western Otago with Humboldt’s ‘gneiss-granite’ of South America and introduced two new series, the Te Anau Series (Lower Mesozoic) and the ‘Kahiku’ series. Hector’s Upper Mesozoic ‘Carbonaceous series’, which included fine quality brown coals, was placed above the Te Anau series. Much attention was paid to the ‘auriferous schistose formations’, which Hector divided into three parts based on regional variations within the schists.

By 1864, science in New Zealand was already moving into Basalla’s phase 3 (p.55) in which the elements of a new ‘centre of calculation’ can be discerned. New Zealand authorities sent explorers, surveyors, geologists, botanists, zoologists, and engineers out on their own data-gathering expeditions, and collections began to be set up in new, colonial institutions. Although many scientific reports were still published overseas (and remain so), at least the Provincial geologists’ reports were published in New Zealand, so that scientific information began to be accumulated here. However, no formal scientific training took place in New Zealand until the 1870s with the establishment of the University of Otago and the University of New Zealand, amid the usual provincial rivalry and dissension (L.J.W., 1966), so that quantities of data, samples and specimens were still sent back to European centres. As the time approached for the establishment of an enlarged central government in Wellington, New Zealand science remained somewhat dependent and colonial in nature. However, the relationship with the metropolitan centres in Britain and Europe was becoming less as a tributary and more as a trading association.
Chapter Four

The Settler Geologists and ‘The Greywackes’

The economic, much less cultural, benefits of science were less well understood by most colonial legislators. De la Beche, Murchison, and their appointees were constantly forced to emphasise geology’s utility in order to secure appointments and maintain funding.

(Stafford, 1989)

Any geological survey which makes the discovery of economic minerals its primary object is sure to be a failure.... The primary and fundamental object of a geological survey is to make a systematic investigation into the structure and palaeontology of the whole country in sufficient detail for its geological history to be ascertained with considerable accuracy.... It is the duty of the Government to take in hand an important work which cannot be done by private enterprise, and this is what most Governments of civilised countries have actually done.

(Hutton, 1899).

This review of how New Zealand’s nineteenth century settler geologists interpreted the rocks that later became known as ‘the greywackes’ includes discussions of:

- The way in which the rocks of the axial ranges (the greywackes) were correlated, or not, with a small tract of poorly fossiliferous rocks in Nelson, including paleontological problems affecting correlation.
- Competing stratigraphic schemes devised by Julius von Haast, James Hector, and Frederick Wollaston Hutton (1836-1905).
- How the geologists viewed the metamorphic rocks of the South Island and their relationship with the greywackes.
- Theories of New Zealand’s paleogeography in Paleozoic time, the structure of the New Zealand continent, and how subsurface geology was visualised.

By the time the central government was moved to Wellington in 1865, James Hector had successfully negotiated the establishment of a permanent New Zealand Geological Survey with himself as Director (Oldroyd, 1967; Hornibrook, 1990; Mason, 2002). Besides bringing most of his Otago staff to Wellington, Hector employed a series of assistant geologists either as permanent staff or on contract (Figure 4.3, Table 4.1). He was well equipped with his preliminary outline of the geology of New Zealand, experience in organising surveys, a loyal staff and entrée to Wellington’s highest political circles through Mantell, Crawford (Hornibrook, 1990), and his wife Georgiana Monro of Nelson (p.62). One of Hector’s earliest detailed surveys of the ‘Paleozoic slates’ (greywackes) was made at Kawau, Governor George Grey’s holiday island to the north of Auckland (Hector, 1869a).
The Four Leading Settler Geologists

4.1a: James Hector (later Sir James) (1834-1907) at about 30 years of age. Hocken Library, University of Otago.

4.1b: Julius Haast (later Sir Julius Von Haast) (1822-1887) at about 40 years of age.

4.1c: Frederick Wollaston Hutton (1836-1905).

4.1d: Alexander McKay (1841-1917)

Figure 4.1: Portraits of New Zealand's four leading settler geologists: Hector, Haast, Hutton and McKay. Figures 4.1b, 4.1c, 4.1d courtesy Alexander Turnbull Library, National Library of New Zealand Te Puna Matarangi o Aotearoa.
The settler geologists were young, fit, enthusiastic and ambitious, although sometimes only half-trained and with little experience (Table 4.1). Because of very poor career options in Britain, many young scientists were forced to emigrate and the ‘empire constituted an employment frontier’ (Stafford, 1989: 200). In addition, scientific talent flowed into the ‘gigantic laboratory of the colonies’ from other European countries with oppressive political climates (Stafford, 1989: 55-63). Emigration also promised the chance for adventure, exploration, fame, and perhaps the reward of being the very first to interpret the geological succession in a new land.

Table 4.1: Table showing the names, vital dates and qualifications of the settler geologists.

<table>
<thead>
<tr>
<th>Geologist</th>
<th>Vital Dates</th>
<th>Educated</th>
<th>Qualifications and experience</th>
<th>Arrived</th>
<th>Departed</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>James Coutts Crawford</td>
<td>1817-1889</td>
<td>Royal Naval College</td>
<td>Amateur</td>
<td>1839</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Julius Haast (later Sir Julius von Haast)</td>
<td>1822-87</td>
<td>Bonn</td>
<td>Obscure, Did not graduate</td>
<td>1858</td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>James Hector (later Sir James)</td>
<td>1834-1907</td>
<td>Edinburgh Canada</td>
<td>MD; Exploration and organisation experience</td>
<td>1862</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Edward Heydelbach Davis</td>
<td>1845-1871 Drowned</td>
<td>School of Mines Jermyn Street</td>
<td>Mineralogist Portugal Central America</td>
<td>1870</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Frederick Wollaston Hutton</td>
<td>1836-1905</td>
<td>Royal Navy Academy, Gosport; King’s College, London; Sandhurst</td>
<td>Active service, Army engineer, and geologist</td>
<td>1866</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Samuel Herbert Cox</td>
<td>1852-1920</td>
<td>Royal School of Mines</td>
<td>Associateship 1874</td>
<td>1874-84</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>Alexander McKay</td>
<td>1841-1917</td>
<td>Primary school in Scotland</td>
<td>On the job training and self-education</td>
<td>1863</td>
<td>22</td>
<td></td>
</tr>
<tr>
<td>James Park</td>
<td>1857-1946</td>
<td>Royal School of Mines</td>
<td>1873-74, Did not graduate.</td>
<td>1875</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Patrick Marshall</td>
<td>1869-1950</td>
<td>NZ. Canterbury, Otage, Auckland</td>
<td>BA, BSc Senior Scholar, MA, DSc 1900</td>
<td>1876-79, 1882</td>
<td>6, 12</td>
<td></td>
</tr>
</tbody>
</table>

There were never more than six or seven professional geologists working in New Zealand at any one time (Figure 4.2, 4.3). Of these, Hector, Hutton and Haast formed a contentious little geological trio at the heart of the wider community of scientists. The careers and the contrasting characters and styles of these three major protagonists have been examined by a number of writers (Jenkinson, 1940; Haast, 1948; Waterhouse, 1965; Burton, 1965; Oldroyd, 1967, 1972; Hornibrook, 1990, 1991; Barton, 1999; Dick, undated). In addition, numerous articles to do with our nineteenth and twentieth century geologists have been contributed to the Historical Studies Group Newsletter of the Geological Society of New Zealand, and the Newsletter of the Geological Society of New Zealand.
For over twenty years from 1865, Hector was at the centre of, and controlled much of, the public scientific activity in New Zealand (Stafford, 1989: 61). He may have modelled himself on his redoubtable old patron, Sir Roderick Murchison, who controlled the geological community in Britain, manipulated appointments to geological surveys abroad, and even had a hand in planning the Austrian Novara expedition (Stafford, 1989: 57). Haast and Hutton could operate independently of Hector by virtue of their positions as Provincial Geologists of Canterbury and Otago, as directors of their own provincial museums, and as academics at the two southern university colleges (Figure 4.3). Auckland and Wellington University Colleges were not established until 1883 and 1899. Haast and Hutton kept up a long friendship that was punctuated by only occasional quarrels, said by Haast’s biographer to have usually been set off by Hutton’s outspoken and pungent criticisms (Haast, 1948:665-673).

All three leading geologists are remembered as kind and courteous (Evans, 1949), and indeed, Hector earned great loyalty from his permanent staff (Park, 1934). However they were also strong, assertive characters who fiercely guarded their status as ‘elite’ scientists, and each man firmly believed he was
The Settler Geologists and the New Zealand Geological Survey

Figure 4.3: Timelines tracing the careers of settler geologists and their connections with the New Zealand Geological Survey from its formation in 1865 until it was disestablished in 1894. The wide red band represents the Geological Survey as well as the progress of Hector’s own career. HM/N

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right. Both Hector and Haast were guided by ruling theories (Chamberlin, 1890) that had to be defended, whereas Hutton was prepared to modify and change his ideas in the face of new data.

| Elite geologists | Rudwick, 1985: 420: The small number of geologists involved in the Devonian controversy of the 1830s with a ‘strong, indeed primary, commitment to geology rather than any other branch of science’, highly active in its institutions, in fieldwork, and highly productive in publication. Elite geologists interacted intensively with each other, and were regarded by themselves and by others as arbiters of matters of fact and theory in geology. |
| Ruling theory | Chamberlin, 1890) More typical of nineteenth century geology in which a scientist develops a single favoured theory rather than several working hypotheses to account for geological phenomena. Chamberlin maintained that the danger of excessive ‘parental affection’ for such a ruling theory will develop, facts are found to fit the theory, and the theory rules the scientist. |

Hutton worked for Hector as Assistant Geologist from 1871 to 1873 and he and Haast both worked for the Survey on contract in the late 1860s and early 1870s. Both upset Hector by proposing contrary stratigraphical opinions in their geological reports. In contrast, the closely knit members of Hector’s permanent staff, including Cox, McKay and Park (figure 4.3), were faithful supporters of Hector and rarely challenged his views, especially his concept of a Cretaceous-Tertiary system in New Zealand (Oldroyd, 1972). However, as McKay (Figure 4.1d) gained experience he became ever more confident in developing his own explanations (Burton, 1965).

**The theoretical background**

In Britain, geology was fast becoming professionalised through the 1860s with the growth of the Geological Survey (Secord, 1986) and the development of specific training courses, notably that at the Royal School of Mines established in 1851 (Anon, 2002). Traditionally, stratigraphy, paleontology and mapping were paramount, but petrology was neglected. Darwin had recently published *The Origin of Species*. Catastrophism was quickly dying out in the face of Lyellian uniformitarianism or various forms of gradualist progressivism, and the theory of a past ice age was generally accepted. Metamorphism of pre-existing rocks was recognised (Lyell, 1835: 290). Diluvialism and Wernerism were long gone although some important elements of Neptunism remained in mineralogy and petrography with assumptions about the great age of crystalline rocks, and in the supposition of an orderly stratigraphic column. European geologists were developing thin-section petrography based on Henry Clifton Sorby’s (1826-1908) pioneering techniques, and were deeply involved in the burgeoning arguments about mountain building and continents. Americans were puzzled about the very thick layers of rocks in their mountain ranges compared with the relatively thin layers of rocks of similar age elsewhere.
Most of the settler geologists arrived in New Zealand equipped with guiding theories based on learning and experience in lands half the world away. They assumed that the earth is extremely old, and that geological processes take place gradually. They believed, with Charles Lyell (1797-1875), that continents and ocean basins rise and sink in turn, and that rivers carry debris from the continents into the oceans where it is deposited in layers of sediment. These were later uplifted to form new continents. The geologists were therefore mindful that:

- Layered rocks come in definable, discoverable packages.
- Rocks are arranged vertically in chronological order with younger beds above older beds.
- Relative age is associated with variation in fossil content.
- Lithology may be used for correlations if fossils are not present.
- A well-defined break exists between Cretaceous and Tertiary rocks, and between Permian and Triassic rocks.
- Coal is Carboniferous in age.
- Hard, grey, highly disturbed rocks that look old ARE old, and are probably Silurian in age or older.

![Figure 4.4: Chart indicating the considerable importance given by Hector's Survey to economic geology, compared with 'Cretaceo-Tertiary' geology, and pre-Cretaceous geology (including the greywackes). The geologists had to please 'practical' politicians who often saw them as unnecessary and expensive luxuries. Figures are based on page counts in the Geological Survey's Reports of Geological Explorations.](image)

High-level theories on the origin of mountains or the sources of sediments scarcely touched the everyday field observations made by the geologists of the New Zealand Geological Survey whose primary tasks were to find coal, gold and other materials of economic importance, compile maps, construct a stratigraphic column, and to inspect mines (Oldroyd, 1972) (Figures 4.4, 4.5). Indeed, the British tradition of empirical natural history was supposed to discourage speculation. Hector’s first assistant geologist,
Edward Heydelbach Davis (1845-1871), emphasised that he ‘confined [him]self to bare facts, and abstained from all generalisations: the system worked on is that adopted by the officers of the Geological Survey of Great Britain which I believe is calculated to give the most reliable results’ (Davis, 1871a). This talented but unfortunate young man was killed that year by the New Zealand disease (drowning) after surveying the Greymouth coalfield (Anon., 1871; Johnston, 1987, 2003).

Figure 4.5: Flow chart showing the processes involved in the construction of a Geological Survey report for Hector.
The geologists had theoretical difficulties in adjusting to the new land. There were differences of opinion on how to interpret the positions of the major stratigraphic boundaries, which differ from those of Europe (Fleming, 1969: 126). Hector (1869b) early recognised a major break separating the basement Paleozoic and lower Mesozoic rocks from the younger beds, and for that reason introduced his ‘Cretaceo-Tertiary system’ (1869d). This led to a long dispute with Frederick Wollaston Hutton (1836-1905) who frequently sniped at Hector’s ‘omnivorous cretaceo-tertiary formation’ (Hutton and Ulrich, 1875) and insisted on an unconformity between the New Zealand Cretaceous and Tertiary strata in North Canterbury (Oldroyd, 1972).

Hector (1866) was soon occupied looking for Paleozoic coal in south Otago (Southland) but failed to find either Carboniferous coal (Burton, 1965: 26; Stafford, 1989:62) or even Mesozoic coal similar to the ‘carbonaceous series’ in New South Wales (Fleming, 1987: 264). Further north in Canterbury, Haast (1862) decided on a Carboniferous age for the inland Canterbury rocks because of the presence of small
seams of coal in the Malvern Hills district (Figure 4.6). Haast also found fossil plant beds at Clent Hills and Mt Potts, and a nearby deposit of fossil brachiopod shells (map and check list Campbell and Warren, 1965). Professor Frederick McCoy of Melbourne dated the plants as Jurassic, but erroneously dated the shells as of Upper Devonian or Lower Carboniferous age (Fleming, 1987: 2650-6), leading to much friction (for example McKay, 1878b: 105). Haast’s attachment to a Carboniferous age for his rocks complicated an uncertain relationship with the Geological Survey because of his controversial falling out with McKay and Hector in 1874 (Haast, 1948: 722-747). From then on, to the end of the century and much later, the age and stratigraphic relationships of the greywackes were subject to contention.

**Three pioneering stratigraphic schemes: resources and puzzles**

Hector, Haast, and Hutton soon began to differ on many points of interpretation, and New Zealand geological literature became involved in polemics which must be very confusing to foreign readers, since they can only with difficulty be followed by residents in the country.

(Thomson, 1913).

The geological polemics of the nineteenth century are even more confusing today than they were for residents of the time (Thomson, 1913: 11). New Zealand geology was marked by the ‘inherent obscurity and diversity of interpretation of the record’ (Benson, 1921: 48) with bewilderingly frequent changes in age determinations. Confusion for today’s readers is increased by the way in which brief but critical statements are hidden deeply in verbose reports, that sources were not always cited, and with confusion between the European time scale and New Zealand series and formation names.

**Stratigraphic terminology.** Through most of the nineteenth century stratigraphic terminology was not standardised, and terms like ‘series’, ‘formation’, and ‘group’ were used quite loosely and interchangeably (Page, 1872). Sometimes the names of rock units were capitalised, and sometimes not. At the first International Geological Congress in Paris in 1878, efforts were made to begin standardisation of geological stratigraphy and terminology. Hector learned about this from the Director of the Geological Survey of Canada and produced a somewhat muddled explanation of how the terms age, system, formation, series and beds should be used (Hector, 1884a).

F.W.Hutton remarked on the many stratigraphic ‘ups and downs’ experienced by the Maitai Formation of Nelson and tartly observed that the classification of the New Zealand rocks was ‘in a very unsatisfactory state’ (Hutton and Ulrich, 1875). For over twenty years, Hector and Hutton seemed to take turns at re-arranging each other’s stratigraphic columns, while Haast steadily insisted on a Carboniferous age for his inland Canterbury rocks. Why were so many changes made in the pre-Cretaceous basement portion of the New Zealand stratigraphic column? Why the ‘ups and downs’ for the Maitai Formation?
For this thesis a timeline was constructed (not shown here) to trace the various age allocations given to the pre-Cretaceous rocks between 1865 and 1900. There was an expectation of seeing how the stratigraphical column of New Zealand was constructed, developed and modified by the combined efforts of Hector, Hutton, and Haast. Instead, the result was a jumbled confusion of intersections and blind alleys, reflecting the many changes in the classifications of the various rocks. No satisfactory pattern of progress in the stratigraphic knowledge of New Zealand could be made out. In an attempt to simplify the problem, three separate timelines were then drawn to trace the stratigraphic interpretations made separately by Hector, Hutton and Haast (Figures 4.7, 4.8, 4.9).

The separate timelines show quite plainly that each geologist’s scheme was clear, coherent, consistent, rational and individual. The geologists themselves were not at all confused because each man was focussed on his own version of the New Zealand stratigraphic column. Although the three rivals used each other’s data and conclusions when it suited, they did not go out of their way to assist each other. Hector’s position as Director of the Geological Survey meant that until the end of the century, his scheme dominated in which the Canterbury and Wellington greywackes were correlated with and named for his Maitai series of Nelson.

**What caused the seeming ‘ups and downs?’**

The geologists had immense problems, and still do, trying to fit the assortment of ‘axial rocks’ or ‘greywackes’, into a rational tidy arrangement, with one rock layer neatly ordered on top of the one before (McKay, 1878a: 158). There was continuing difficulty in establishing relative ages by fossil control (Waterhouse, 1965). The restricted means of the tiny colony meant that no specialist paleontologist was resident in New Zealand until 1911 (Thomson, 1913: 14) and, in any case, few useful diagnostic fossils were found in the greywackes. Although Hector was a competent paleontologist he was responsible for a number of wrong identifications (Oldroyd, 1967), but at least he made them consistently and could make correlations within New Zealand (Waterhouse, 1965: 936). Hutton and Alexander McKay (1841-1917) also acquired useful paleontological skills, because otherwise they had to wait for months and years while fossil material was sent overseas for reliable identifications.

Of particular concern were two problematical fossilised troublemakers, the puzzling ‘Mount Torlesse Annelid’, and the deceptive ‘Dun Mountain *Inoceramus*’ (Figures 4.11, 4.12, 4.13, 4.14). These fossils caused several controversies. The Mount Torlesse Annelid played a major part in the stratigraphic battle between Haast and Hector, which did not end until Haast’s death in 1887, while misidentifications of the ‘Dun Mountain *Inoceramus*’ caused embarrassment to Hutton, James Park, and later, to Patrick Marshall. (To page 77)
Figure 4.7: Timeline showing the development of Hector's New Zealand Geological Survey pre-Cretaceous stratigraphic scheme. The heavy black lines, plain or broken, represent the way in which ‘the greywacks’ were classified. The single plain black lines represent fossiliferous Mesozoic series, and dashed lines represent the schists (see later). Ha = Haast, He = Hector, Ho = Hochstetter, Hu = Hutton.
The Maial: Hutton’s Pre-Cretaceous Stratigraphic Scheme

<table>
<thead>
<tr>
<th>CRETACEOUS</th>
<th>1860</th>
<th>1865</th>
<th>1870</th>
<th>1875</th>
<th>1880</th>
<th>1885</th>
<th>1890</th>
<th>1895</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kawhia (Ho) 1864</td>
<td>Cretaceous-Tertiary</td>
<td>Putataka Fm (Hu)</td>
<td>Mautara Ser (He)</td>
<td>Mautara Ser (He)</td>
<td>Mautara Ser (He)</td>
<td>Hokonui</td>
<td>Hokonui</td>
<td>Hokonui</td>
</tr>
<tr>
<td>JURASSIC</td>
<td>Mataura Fm (He)</td>
<td>triassic</td>
<td>triassic</td>
<td>triassic</td>
<td>triassic</td>
<td>triassic</td>
<td>triassic</td>
<td>triassic</td>
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<tr>
<td>TRIASSIC</td>
<td>Richmond Sndst (Ho)</td>
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<tr>
<td></td>
<td>Maial Beds (Ho)</td>
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<tr>
<td>PERMIAN</td>
<td>Kahlkhu Series (He)</td>
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<tr>
<td>CARBONIF's</td>
<td>Canterbury coal (He)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEVONIAN</td>
<td>Grauwacke, Wellington (Cr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SULURIAN</td>
<td>Grauwacke, Wellington (Cr)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>'PALEOZOIC'</td>
<td>greywacke sandstones and argillites (Ho)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Kakanui ser (He)</td>
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<td></td>
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<tr>
<td>METAMORPHIC</td>
<td>Crystalline schist (Ho)</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Contorted foldsphatic schists (He)</td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 4.8: Timeline showing the development of Hutton's pre-Cretaceous stratigraphic scheme. Hutton repeatedly reviewed his stratigraphical schemes and designed a sequence of up-to-date sophisticated nested classifications, incorporating a New Zealand version of the tripartite European stratigraphic system. Also indicated are Hutton's evolving views on the South Island metamorphic rocks. Mid-grey = greywackes, dark grey = Otago schists, light dotted pattern = Mesozoic Hokonui System (now Murhiku Terrane).
Figure 4.9: Timeline showing development of Haast's Canterbury pre-Cretaceous stratigraphic scheme. This scheme refers only to the inland Canterbury and Southern Alps greywackes and schists. Mid-grey = greywackes, purple = all schists.
Lithology as an aid

A great deal of reliance was placed on lithology to make what were often, tenuous long-distance correlations between the red and green slates of the Nelson Maitai beds and those of Canterbury and Wellington. In addition, the great mass and variety of rocks within the assemblages, their highly disturbed structure and the lack of well-defined horizons made the task enormously difficult because the geologists could not even depend on the principle of superposition. Nevertheless, in their efforts to identify and follow horizons both Haast and McKay made a number of outstanding lithological studies of the ‘endless succession of sandstones and shales, slates, conglomerates, and brecciated’ rocks forming the ‘stupendous chains’ of mountain-building rocks in Canterbury and Wellington, (for example Haast, 1871: 21; 1879; McKay, 1878b).

McKay (1877, 1881, 1886) noted the frequent field association of diabases (basalt lavas) and red and green slates with Triassic fossils in the Okuku district of North Canterbury (see p.90). This indicated to McKay that the lavas and slates were also of Triassic age, and represented the highest beds of the Wairoa series (Figure 4.7) and not of Carboniferous age, so disproving Haast’s contention that the Canterbury rocks could not yet be subdivided. From then on, McKay regarded all similar associations of coloured slates and diabases as of Triassic age, including the red and green slates and ‘chertose’ rocks running along the Rimutaka Range, and the coloured slates at ‘Red Point’ (Red Rocks) on Cook Strait (McKay, 1888b). McKay also distinguished ‘agglomerated blocks of calcareous diabasic ash’ and ‘frequent masses’ of limestone at Okuku but in his report they were conventionally figured as coherent, continuous beds dipping into hillsides (Figure 4.10) with no indication of any significant discontinuities within the limestone masses.

The Mount Torlesse annelids, Carboniferous shell beds and lithologies

In spite of diligent searches by the settler geologists, the only reasonably common fossil found in the rocks of Canterbury and Wellington, were mysterious little white tubes around 5cm long and either straight or curved (Figures 4.11, 4.12, 4.14). They were described as the ‘exuviae of serpulids’

1 Exuviae : cast skins or shells.

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Figure 4.11: Annelid Collection. Images of the 'Mount Tottes anneal' by Hector (1886), Bather (1905), and Morgan (1908)
Paleontological Troublemakers of the Nineteenth Century
The 'Mount Torlesse Annelids'

Maitai section in Nelson, worm tracks in grey slates seen by Hochstetter (1864) and E.H.Davis (1871)

Julius Haast, Canterbury (1862, 1871, 1872, 1879) markings and obscure 'exuviae' of an Annelid

J.C.Crawford: 'vermiform casts' etc north of Wellington 1868

Haast (1872): fossil shells show Canterbury rocks are Lower Carboniferous age (Prof. McCoy, Melbourne)

Hector (1877): Maitai series of Nelson are 'Permio-Carboniferous' (sic)

Hector (1878): divides Carboniferous fossil localities into two series
(a) Maitai series
(b) Rimutaka series:
   Annelid slates, Westland
   Annelid sandstones, Mount Torlesse
   Karori sandstones, Wellington

Hector (1879): Divides Nelson Maitai strata -
(a) Upper Maitai with annelid beds
(b) Lower Maitai from limestone at base of Maitai slates downwards.

Hector (1879): Wellington rocks correlated with Nelson's Carboniferous Maitai series on lithology and the 'peculiar fossil known as the Mount Torlesse annelid'.

McKay (1879): Wellington rocks with diabase lavas and red and green slates in North Canterbury, and now considers all similar lavas elsewhere in New Zealand as Triassic

McKay (1881, 1886): Describes Canterbury annelids as incapable of locomotion, could not make tracks as seen in Nelson strata. Criticises Haast.

Haast (1884): complains that Hector used the 'peculiar annelid' to classify Canterbury rocks as Carboniferous, but marked annelid localities as Mesozoic

McKay 1888: Tararua Range
1. Red and green rocks similar in Canterbury, Nelson, Wellington
   The 'calcareous' fossil is similar in Canterbury, Wellington
   But the Nelson annelid trails wholly unlike the others. However keeps Carboniferous age.

2. Correlates red and green slates, chertose bodies and diabase lavas e.g. Red Rocks, with similar Triassic rocks of Canterbury e.g. Upper Okuku

Go to Twentieth Century, Figure 9.3, page 266

Figure 4.12: Flow chart summarising the history of knowledge about the 'Mount Torlesse annelid' and the attempts to make age determinations based on its presence.
(Haast, 1862), and as ‘vermiform casts, *Theca, Dentalium, [and] probably Tentaculite’” (Crawford, 1868). McKay described them as calcareous tubes (McKay, 1881: 90), and Hutton thought they represented pelagic cephalopods (Hutton, 1899: 164). More recently, the animals have been thought to be sponges or giant foraminiferids (Gregory, 1977; Moore, 1987; Miller, 1995). These uninformative tubes became known as the ‘Mount Torlesse annelid’ (Hector, 1879: 30) and McKay mentioned the ‘peculiar fossil known as the Mount Torlesse annelid at Sinclair’s Head’ near Wellington (McKay, 1879b). The name does not seem to have been used before 1879, except that Haast (1872a) mentioned the ‘annelid of Mount Torlesse’ (McKay, 1881). Perhaps Hector and McKay themselves invented the name ‘Mount Torlesse annelid’ and then ascribed it to long-held custom.

Although the existence of these fossils had been known since 1862, no formal description was made until 1905, when F.A. Bather of the British Museum (1905, 1906), decided that the tubes consisted of chalcedony rather than calcareous material (Figures 4.11, 4.12). He named the straight form *Torlessia mackayi* and the curved form, which he considered to be a scaphopod, *Dentalium huttoni*, and considered them both as probably of Triassic age. The name *Torlessia* was later synonymised with the genus *Terebellina* (Jaworski, 1915; Campbell and Warren, 1965) and the tubes were shown to consist of agglutinated particles of quartz.

The strong emphasis on economic geology had earlier led to a new examination of Hochstetter’s Nelson section by Hector in 1866 and Davis in 1871 because of its proximity to the Dun Mountain mineral belt. This is the famous section containing the red and green Maitai Slates and worm-like markings in nearby grey slates (Fleming, 1959). Davis noted that the Maitai slates were very much disturbed and formed a large ‘synclinal curve’ with a north-east axis (Figure 5.13A, p.146). Associated with the slates was a bed containing some fossils discovered by the builders of the Dun Mountain Railway (M.R. Johnston, pers. comm.). These were recorded by Davis as having been ‘first discovered by Dr. Hector... chiefly *Inoceramus* and immediately above this is a bed full of Annellid (sic) tracks’ (Hector, 1869c: x; Davis, 1871a: 113), and were seen as similar to those observed by Haast in Canterbury (Haast, 1862).

Hector (1877b: v) considered that other fossil shells found near the Maitai slates were of ‘Permio-Carboniferous’ age and then of Carboniferous age (1878a: 198). The shells appeared to match Haast’s Lower Carboniferous shell bed at Mount Potts in Canterbury and supported the correlation of the Canterbury rocks with the Nelson Maitai slates. The assumption that the same creatures that lived in the annelid tubes of Canterbury had made the ‘annelid tracks’ in Nelson appears to have been tacitly accepted as backing up a Carboniferous connection between these districts.

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2 This may have been the similar but separate organism *Titahia corrugata*, Webby, B. D. (1958), found at Titahi Bay to the north of Wellington. *Torlessia mackayi* occurs in areas nearer the city.
Although Hector had long suspected that some of the Maitai rocks of Wellington would have to be ‘transferred to the Mesozoic’ (Crawford, 1868), he also correlated them (1879) with the supposed Carboniferous Maitai rocks in Nelson partly on lithology, and partly on the presence of annelid tubes. At the same time, Hector subdivided the Maitai series into an Upper Maitai with the annelids, and a Lower Maitai incorporating all rocks ‘from the fossiliferous limestones at the base of the Maitai slates downwards’ (Figures 4.7, 4.12).

The Canterbury and Wellington greywackes and the Carboniferous red and green Maitai slates at Nelson were now stratigraphically linked, and remained this way until 1888 (McKay, 1888b) The red and green slates at all localities seemed similar, but there was no proof of a Carboniferous age in either Canterbury or Wellington. Repeated investigations of the Mount Potts shell beds by McKay (for example McKay, 1878b) showed them to be as young as Permian in age (Hector, 1886a) if not Triassic. McKay now realised (1881: 90) that the ‘annelid trails’ in the Nelson slates were ‘wholly unlike’ the ‘calcareous’ fossils of Canterbury and Wellington. How could creatures fixed in one place and ‘incapable of locomotion’ move about and make trails? Strangely, although he doubted a correlation with the Maitai rocks, McKay continued to map the ‘lower division’ of the Wellington rocks with annelids as Carboniferous in age.

After Haast’s death in 1887 and the demise of the first New Zealand Geological Survey in 1893 (Burton, 1965: 37), concern about the annelids faded away except that McKay continued to hold that the Mount Torlesse annelid denoted a Carboniferous age. Thus, the presence of the annelids at Cape Terawhiti in Wellington indicated to him (1901) that the central mass of the Kaimanawa Mountains further north was also of Carboniferous age. Soon after, Park (1903: 392) set aside the annelids as being of no use in fixing stratigraphic position because they were never associated with shell beds that would indicate their true age. Spasmodic interest in the mysterious Mount Torlesse annelid continued through the twentieth century. A summary of views on the status and nomenclature of Torlessia and similar organisms is shown on Figure 9.3, pp. 286-287.

The Dun Mountain *Inoceramus*

Fossil shells discovered in Nelson during the construction of the Dun Mountain railway in 1861 (M.R.Johnston, pers.comm.) were probably the same as those found by Hector in 1864 close to the bed with ‘worm-like markings’ (Fleming, 1959: 243) and identified as *Inoceramus*, belonging to the ‘later Mesozoic period’ (Hector, 1869c Davis, 1871a). Altogether, Hector identified three species of *Inoceramus* from the Wairoa Valley and the Dun Mountain railway cutting (1870: 195, 196) and therefore dated the Dun Mountain eruptive rocks as ‘upper Mesozoic’ (Hector, 1869c). Soon after, he (1870: 196) introduced his Triassic Maitai series, containing the bed with annelid tracks (Figure 4.7). This Triassic Maitai series
lasted until 1873 when Hector began moving the series steadily down the stratigraphic column towards the Lower Carboniferous.

*Inoceramus* belongs to a group of mussel-like bivalves that have a shell structure in which the prismatic layer is much more highly developed than is usual in bivalves and may be several millimetres thick. Following death, *Inoceramus* shells may break into prismatic crystalline fragments. After the prisms have been fossilised, incorporated into a rock, and become a part of the land, weathering may cause the calcite prisms to appear as characteristically rectangular marks or gashes on the rock surface, sometimes containing fibrous crystals. The settler geologists were aware of this feature, but not that another, much older, Permian mussel, had a similar kind of shell (Figure 4.13, 4.14).

Hector’s identification of *Inoceramus, Mytilus and Spirifera* specimens from Nelson had led Hutton in 1873 to classify his Maitai formation in the Kaikoura district as of Lower Jurassic age and above the Upper Triassic Wairoa formation (Figure 4.8), causing one of ‘ups’ for the Maitai formation (Hutton, 1877: 33). Hector (1877a: ix) immediately demanded that the positions be reversed because new field evidence gathered by Samuel Herbert Cox (Figure 4.2, Table 4.1) early in 1877 showed that the Wairoa formation rested unconformably on the Maitai formation (McKay, 1878a: 159). Hector’s 1873 map showed the Maitai series as Paleozoic, below the Te Anau series, and he did not mention his Nelson *Inoceramus* again.

**McKay’s shrewd analysis of the Maitai section**

In 1878 Hector sent McKay to Nelson specifically to investigate the relations between the Maitai and Wairoa series and collect from the *‘Inoceramus’ beds* (McKay, 1878a, 1879a). McKay made a thorough examination of the Eighty-eight Valley, the Wairoa Valley and the slopes of Dun Mountain, paying unusually special attention to strike and dip, and in his usual rambling, conversational way, solved the ‘Maitai Problem’ long before it became problematic to others (Figure 5.13B p.146, 5.14). Among McKay’s observations and conclusions:

- Tertiary beds to the west are slightly overturned and appear to dip eastwards under the Triassic Wairoa beds (=Hokonui or Murihiku Terrane), although the actual contact is not visible.
- The Maitai formation forms an ‘overturned’ syncline (i.e. inclined or tilted to the west) running north-east and south-west with most beds dipping to the east (Figure 5.14, p.151).
- Crushed, indurated, brecciated, contorted and otherwise disturbed beds occur in the Eighty-eight Valley near the contact between the Wairoa and Maitai formations (also see Johnston, 1979: 1982).
- A set of ‘Permian’ fossiliferous Kaihikuan beds appears to ‘pass under the older beds’ to the eastward. Fossils showed that these older beds (Carboniferous Maitai) ‘are now in an overturned position, the overlying Triassic strata being also in a very complicated condition’.
Paleontological Troublemakers of the Nineteenth Century

The 'Dun Mountain Inoceramus'

- Fossils shells discovered 1861 during the construction of the Dun Mountain Railway

Hector (1864): Nelson. Specimens of 'Inoceramus' found near bed with annelid tracks. Strata identified as 'later Mesozoic'. Davis (1871) Nelson

- F.W.Hutton (1877) Kaikoura 1873
  (a) Rocks with annelid markings like those in Canterbury placed in his Paleozoic Kaikoura formation.
  (b) Rocks with 'Inoceramus', Mytilus, Spirifera placed in a Jurassic Maitai formation.
  Reversed by Hector

- McKay (1879). In Maitai series of Wairau and Motueka (Nelson) finds fragments of a form of Inoceramus', but with a different shape, and which may be a new genus. He uses other fossils to give a Lower Carboniferous age.

Both McKay and Hector avoided using this 'Dun Mountain Inoceramus' to establish geological age

- McKay (1881, 1886): North Canterbury finds 'Dun Mountain Inoceramus' with fibrous shell. However, gives Triassic age to many rocks in district on presence of Monotis and Mytilus in limestone

Go to Twentieth Century Figure 5.8, page 134

Figure 4.13 : Flow chart tracing the history of understanding of the 'Dun Mountain Inoceramus' in the nineteenth century.
Within the Wairoa River valley, the strike and dip of Triassic Wairoa beds (N30E, dip NW) containing fossils of *Monotis* differs from that of nearby Maitai slates (N55E, dip SSE 70). This indicated the existence of either an unconformity between the two formations, or that the Wairoa beds were ‘faulted into their present position’ so that the older Maitai beds appeared to overlie them.

There is an ‘inversion’ of the Wairoa and Maitai strata. That is, the older, Carboniferous, Maitai beds appear to overlie the younger, Triassic, Wairoa beds (McKay, 1879a: 118).

Two important sets of fossils occur within the Maitai formation. One set indicated a Carboniferous age to Hector, and another set that seemed to indicate a Mesozoic age.

### The Hector-McKay stratigraphic scheme

McKay (1878a: 124) found the Carboniferous fossils in a gully near the junction between the Triassic Wairoa formation and the older Maitai formation including ‘Spirifers, Productus, and a species of cup-shaped coral’. These finds caused Hector to place all of the Maitai series in the Carboniferous period, and this carried all of the correlated greywackes of Canterbury and Wellington with it into the Carboniferous age (Figures 4.7, 4.25).

Further up the section on the Dun Mountain tramway line McKay (1878a) found what he was looking for: specimens of the fibrous fossil resembling *Inoceramus* (Figure 4.14). These, he saw, were different from *Inoceramus* and thought they ‘may warrant ... being considered the type of a new genus’. McKay later mentioned (1879a: 116) ‘a form of *Inoceramus* at many points’ in Nelson but relied on the other fossils to give a Lower Carboniferous date to the rocks. He found a similar fossil with the characteristic fibrous shell structure between the Cass and the Bealey in Canterbury (about 30km north of Mt Torlesse) that he regarded as the same as the lower Maitai ‘Dun Mountain *Inoceramus*’ (McKay, 1881: 88). Both Hector and McKay wisely made little, if any, use of this curious fossil as a stratigraphic marker, and it was not until 1911 that its presence again caused enormous stratigraphic trouble when Marshall also mistook it for a Jurassic form (Chapter 5).

The stratigraphic rearrangements were made partly on lithological similarity with the rocks of Nugget Point in Otago and at Mount Potts in Canterbury, and partly on paleontology (Hector, 1877b; 1878b). Although Hector (1885a) suspected that many of the greywackes were of Mesozoic age (Crawford, 1868), he incorporated Haast’s Canterbury Mount Torlesse Formation, and Rimutaka Series of Wellington into this Paleozoic Maitai series which took a large ‘share ... of the great mountain ranges’ (Hector, 1873, 1877b). No further major changes were made to Hector’s scheme after 1877 (Figures 4.7, 4.15) so that he and his men remained with a simple classificatory system in which beds were divided into an imaginary vertical stack of series that were grouped into European time periods (Hector, 1884a: xii-xv).
Figure 4.14: Photographs of the fossil genera that have caused so many paleontological difficulties in dating the greywackes. Tortessia, the Mount Torlesse Annelid, and Titahia, appear to be confined to Triassic rocks - but may not be. The confusion between Atornodesma and Inoceramus was caused mainly because the prismatic fragments of their shells looked so similar. Speeden and Keyes (1981) Illustrations of New Zealand Fossils; a New Zealand Geological Survey Handbook.
Hutton's stratigraphic scheme

After Hutton (Figure 4.1c) left the Survey he continued to develop his own stratigraphic column by grouping rock series into several large formations (Hutton and Ulrich, 1875). His new Triassic Maitai Formation included Hector’s Kaihiku Series, Wairoa Series and Otapiri Series, while the vast sequences of axial rocks (‘the greywackes’) along with Hector’s Te Anau Series were placed in his Carboniferous-Devonian Kaikoura Formation (Figure 4.8). Ten years later, Hutton boldly erected a comprehensive tripartite set of major New Zealand systems quite different from those of Europe (Figure 4.8) with the most important breaks above the Silurian and the Jurassic periods (Hutton, 1885). Hutton removed the name ‘Maitai’ from his Mesozoic rocks and used it for his new Upper Paleozoic Maitai System, which incorporated all of the axial ‘greywackes’. The scheme was adjusted in 1899 with the Maitai System placed squarely in the Permo-Carboniferous, and with an important revision of the schists (p.99).

Hokinui, Hakanui, Hokanui, Hawkanui, and Hokonui. Hutton applied the name ‘Hokanui’ to his Triassic-Jurassic System in 1885, and changed it to ‘Hokonui’ in 1899. Hector referred to the Hokinui Mountains in the 1860s, while McKay discussed the Hokanui Hills in 1878. The Nomenclature Committee (a forerunner of the Geographic Board) recommended Hokanui in 1908, and Hokonui is said to be incorrect. (Information collated from files in the Turnbull Library by Dr W.A. Watters).

Haast’s stratigraphic scheme and its fate

While Haast (Figure 4.1b) did not attempt to develop a New Zealand-wide stratigraphical column, or to use the name ‘Maitai’ he clashed with Hector on how the Canterbury greywackes should be classified. Moreover, hard feelings from a previous controversy lingered on between Haast and McKay who ‘remained at daggers drawn’ (Haast, 1948: 747) and Hector repeatedly sent Cox and McKay to Canterbury to check on Haast’s reports. McKay (1878b) reviewed the Mount Potts Spirifer beds and pronounced them of Permian (Kaihiku) age rather than Carboniferous (Waterhouse, 1965), so that Haast’s interpretations of a lower and mid Paleozoic age for his Canterbury rocks were now under sustained attack.

Publication of Haast’s book (1879) on the geology of Canterbury and Westland with his daring proposal of an all-inclusive Mount Torlesse Formation taking in all of Hector’s Kaihiku, Te Anau, Maitai and Rimutaka Series as well as Hutton’s Putataka, Maitai, and Kaikoura Formations (Figure 4.9) caused more conflict. McKay made several more surveys in Canterbury where in ‘each district a common object was kept constantly in view — viz., the determination of the age, and relative position to the other rocks of the same district, of that group of strata hitherto known as the “Mount Torlesse annelid beds” ’ (McKay,
1881). In several brilliant surveys of North Canterbury McKay described the annelids, mapped their
distribution, and discussed the problem they posed at great length. He also looked for and found Triassic
fossils in limestones near Okuku including *Monotis salinaria* and *Mytilus problematicus* (as well as the
‘Dun Mountain *Inoceramus*’). At the same time, McKay repeatedly criticised Haast’s work (McKay, 1877,
1878b, 1881, 1886; Hector, 1881; 1886b).

| Haast first used the name ‘Mount Torlesse series’ without explanation in 1865 for the
| ‘Palaeozoic rocks of sedimentary nature ... of the Mount Torlesse series’ that continued
| without interruption ‘in huge foldings’ from Waitohi Gorge to Lake Sumner (Haast,
| 1865a, Haast, 1865b). Mount Torlesse is the main peak of the Torlesse Range, overlooking
| the road approach to Arthur’s Pass. The peak was named by a Captain Thomas for
| Charles Obin Torlesse, surveyor for the association for the founding of the settlement of

When the Canterbury plant fossils were reviewed and declared to be of Triassic age by Baron von
Ettingshausen Haast (1886) had to accept that they were indeed of Mesozoic age. He had always
convinced himself that the Canterbury fossil plant beds were not Mesozoic but were interstratified with,
and the same age, as the Carboniferous Mount Potts shell beds (Haast, 1879). However, he had long
understood that large tracts of Canterbury’s axial rocks belonged to several different periods from the
Carboniferous through to the Jurassic but, from experience, believed that it was not yet possible to divide
them ‘for want of fossils’ (Haast, 1871, 1872b, 1877; Waterhouse, 1965).

When Hector published his next sketch map of the geology of New Zealand (Figure 4.15), Haast was
greatly upset because Hector ignored his Mount Torlesse Formation and showed a division between
what Hector thought were the Mesozoic and Paleozoic rocks in Canterbury (Hector, 1884b). Haast’s
anguished protest against a ‘premature’ division of the rocks and Hector’s irritated response appeared in
the same issue of *Transactions of the New Zealand Institute* and in the *New Zealand Journal of Science* (Haast
and Hutton, 1884; Haast, 1885; Hector, 1885a).

Because Haast had to travel to London to take charge of the New Zealand Court at the 1886 Colonial and
Indian exhibition, he had no opportunity to further defend his Mount Torlesse Formation before his
death in 1887. Hector listed the ‘Mount Torlesse Annelid beds’ in 1883 (Hector, 1884a) and in his last
effective days as Director of the New Zealand Geological Survey, he instructed McKay (1893) to examine
the ‘Mount Torlesse formation in its typical locality’. However, Hutton (1885) was already splitting the
Mount Torlesse formation into his Hokanui and Maitai Systems. It was rarely heard of again until R. P.
Suggate (1961) resurrected Haast’s Mount Torlesse Formation to form what became an even larger
Torlesse Group and gave the greywackes of the North Island axial ranges and the Southern Alps a name
of their own.
Figure 4.15: Sketch Map of the Geology of New Zealand published in 1884 in Hector's Progress Report for 1883. Hector subdivided Haast's Mount Torlesse Formation into a Permian-Triassic-Jurassic series (blue) and an older, parallel, inland Silurian-Devonian-Carboniferous series (brown). Similar subdivisions were inferred in the North Island axial ranges. The Permian-Triassic-Jurassic rocks were age-correlated with the Southland Mesozoic rocks. The Auckland and Northland greywackes were inferred to belong to the older Paleozoic series as were all the semi-schists of south Otago and all the old sedimentary and schistose rocks of north-west Nelson and Westland.

Maori names were usually used for New Zealand series, formations and systems, but European time-stratigraphic names were used on these synoptic sketch maps, leading to more confusion for New Zealand readers. Original size 363mm x 518mm.

Table 4.2: Summary of names given to Hochstetter’s ‘Paleozoic slates’ ('the greywackes') in the nineteenth century.

<table>
<thead>
<tr>
<th>Geologist</th>
<th>The name ‘Maitai’</th>
<th>Classification of ‘the Greywackes’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochstetter 1864</td>
<td>Maitai beds</td>
<td>Red and green slates near Nelson. Triassic Paleozoic slates</td>
</tr>
<tr>
<td>Hector 1870</td>
<td>Maitai series</td>
<td>Triassic, then Permian, then Carboniferous Maitai series</td>
</tr>
<tr>
<td>Hutton 1875</td>
<td>Maitai formation</td>
<td>Upper Permian and Triassic Carboniferous-Devonian Kaikoura formation</td>
</tr>
<tr>
<td>Hutton 1885</td>
<td>Maitai System</td>
<td>Devonian-Carboniferous-Permian Maitai System</td>
</tr>
</tbody>
</table>

The name ‘Maitai’ has indeed had its ‘ups and downs’. Between 1875 and 1899 three different Maitais were offered: Hector’s Carboniferous Maitai Series and Hutton’s Permo-Triassic Maitai Formation, followed by his Upper Paleozoic Maitai System (Table 4.2). At the same time the greywackes experienced even more stratigraphically nomenclatural ups and downs as they were classified and re-classified into at least five different rock groups including Hector’s Maitai Series and Hutton’s Kaikoura Formation and his Maitai System.

The Settler Geologists and the Schists

[I]t appears that in the Middle Island of New Zealand, as in the North Island, the fundamental rocks are metamorphic schists and clay-slate, with dikes of greenstone and compact and amygdaloidal basalt, and intruded masses of obsidian, vesicular and trachytic lavas, and other igneous products. Hornblende and porphyritic rocks, gneiss and serpentine occur, but granite has not been observed…. lofty mountain ranges of schistose metamorphic rocks that extend through the country ... were called by Captain Cook "The Southern Alps".

(Mantell, 1850)

When the settler geologists arrived in New Zealand, they were already familiar with ideas about metamorphic rocks. Lyell had proposed the term ‘metamorphic’ in 1833, explaining how sedimentary rocks could be changed by subterranean heat and steam from granite intrusions, and that changes across country from unaltered rocks to completely changed rocks could be traced.
Lyell knew that unaltered rocks of Tertiary age could grade into metamorphic rocks, but believed that the ‘metamorphic rocks must ... be the oldest [and] must lie at the bottom of each series of superimposed strata’ (1835: 295; 1874: 9; 1875: 293-7). He reasoned that transmutation took place at great depth under the influence of subterranean heat, aided by thermal water, steam, and other gases. Because of the amount of geological time needed for uplift and denudation, metamorphic rocks must be very ancient. Later, geologists developed a rule of thumb in which ‘the greater the metamorphosis, the older the formation’ (Knopf, 1941).

Metamorphic ‘Stratigraphy’ 1865-1900

The schists discussed in this thesis include mostly those shown as the Haast Schists in Figure 0.1, p.2, Figure 0.6, p.18, and Figure 4.15 as ‘Foliated Schists’. The Haast Schists are the metamorphic equivalents of the juxtaposed Canterbury (Torlesse) and Otago (Caples and Maitai) greywackes. The settler geologists usually, but not always, saw the older metamorphic rocks of the western basement in north-west Nelson, Westland and Fiordland as the lowest members of their stratigraphic columns (Figures 4.7, 4.8, 4.9).

Over two dozen geological observations of the metamorphic rocks of Otago were published before 1875 (Hutton and Ulrich, 1875). Otherwise, in spite of their importance as gold-bearers, comparatively little detailed attention was given to them by the settler geologists other than to collect field data and make chemical analyses (Waterhouse, 1967: 923). The geologists did not possess the skills, techniques, and equipment for making detailed petrological and structural studies, and their theoretical background was limited. Accordingly, they saw their major problem as stratigraphic rather than tectonic and put their efforts into attempting to determine stratigraphic relationships.

Figure 4.16: Hector’s sections of the Southern Alps beautifully drawn by Koch of Wellington with dignified rounded folds representing the Maitai series (the greywackes). An inferred but imaginary unconformity (which looks like a thrust fault) has been drawn between the Maitai series and the schists below. Modified from Hector (1873). New Zealand Geological Survey.

The geologists repeatedly observed that the South Island schists graded ‘insensibly’ or passed upwards into unaltered rocks (i.e. the greywackes) (Hutton and Ulrich, 1875: 33; McKay, 1879a: 105; Haast, 1879: 260). Although Lyell himself (1835) had described how rocks may ‘pass insensibly’ from unaltered rocks
into hypogene\(^3\) rocks, the geologists were often puzzled by their inability to find an unconformity between the schists and the unaltered rocks (for example Haast, 1871: 22) but drew boundaries between them on maps and sections anyway (Figure 4.16). Haast (1879: 280) searched carefully for an unconformity between his Mount Torlesse formation and his schistose Waihao formation without success, but was in no doubt that one existed somewhere. Mapping was complicated because one geologist’s metamorphic boundaries between schist, sub-schist and unaltered rocks rarely coincided with another’s, for example between Otago (Hutton and Ulrich, 1875) and Canterbury (Haast, 1879).

The law of superposition and the concept of a single vertical stratigraphic sequence led to the idea among geologists that any kind of break or change in the sequence of rocks meant that the set of rocks above or below should be classified as belonging to the next geological period above or below (Thomson, 1913: 14). The geological periods were seen as a vertical stack of pigeonholes, each of which had to be filled whenever possible (for example Park, 1903).

Because the geologists could not distinguish between the schists of north-west Nelson (western basement) and those of Marlborough, the Southern Alps and Otago (eastern basement Haast Schists) they were seen as continuous with each other and classified together. These schists were always seen as older than any neighbouring upper Paleozoic sedimentary rocks (Waterhouse, 1967). Finds of trilobites, graptolites and other old Paleozoic fossils in north-west Nelson pointing to a Silurian age indicated that the nearby Nelson schists were even older, and probably the oldest rocks of New Zealand (Hector, 1870; 1878a). Their lithological resemblance to the Canterbury schists naturally suggested the same age to Haast for his southern rocks (1879).

The presumed depositional age of the sedimentary rocks making up the schists (figure 4.17, p.96) also depended on the age given to the apparently overlying sedimentary rocks (greywackes). Therefore the original rocks had to be older than Hector’s Carboniferous and Upper Devonian Maitai and Te Anau series (or older than Hutton’s Carboniferous Kaikoura formation, and Haast’s Mount Torlesse formation), and they were usually assessed to be of Silurian age (Lindsay, 1862). Few guesses were made about the age of metamorphism (Waterhouse, 1967), although Hutton believed that the rocks of his Wanaka and Kakanui formations were metamorphosed during the Carboniferous period during which they were deeply buried beneath the accumulating sediments of his Carboniferous Kaikoura formation (Hutton and Ulrich, 1875) (Figures 4.8, Table 4.3).

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\(^3\) Lyell’s ‘nether formed’ granites, gneisses and schists.
Hector’s and Haast’s interpretations

Hector (1865) said little about the probable age of his crystalline ‘gneiss-granite’ in south-western Otago (Fiordland) or the various metamorphic rocks of ‘not very ancient date’ wrapped around them (Figure 4.7). All the gold-bearing schistose rocks in Otago which ‘apparently lie very flat’, were incorporated into the ‘Foliated Schists’ of possibly Silurian age (Table 4.3, p.99, Figure 4.18). Hector evidently found this subdivision of the metamorphic rocks satisfactory enough and made few changes. Later, McKay and Cox began using Hutton’s scheme when mapping schists in Otago, thought to be of Devonian and Lower Carboniferous age (Hector, 1880b, 1886a; Waterhouse, 1967).

Hector did go so far as to speculate that the gneiss-granites of south-west Otago (Fiordland) were the most ancient part of New Zealand having been formed deep in the earth’s crust and ‘gradually upheaved’ (Bowden and Hector, 1869). These rocks were seen as much older than those in the North Island and had been ‘subjected to chemical changes at a greater depth in the earth’s crust’ (Hector, 1869b). The southern mountains had then been elevated and denuded more than those of the North Island, but Hector explained that even now, similar ancient crystalline rocks existed at great depths under the North Island, and were still undergoing the chemical changes that had ceased to operate on the southern schists. Haast related his Westland Palaeozoic (Azoic) Gneiss-granite to Hutton’s Manipori...
Nineteenth century interpretations of the South Island schists

Haast's scheme, 1879
Mount Torlesse fmnn
Waihao fmnn
Westland fmnn
Gneiss-granite
Kakanui fmnn (Hutton, 1875)
('Tuamarnina fmnn
Gneiss-granite (Hector, 1864)
Manipori fmnn (Hutton, 1875)
Manipouri fmnn (Hutton, 1885)

'Pyte's Line' (1940s)
Median Tectonic Line (1967)

Hector's stratigraphic classification
4 (olive green) Lower Greensand & Coal area
5 (orange) Permian-Triasassic-Jurassic
6 (brown) Lower Silurian-Upper Devonian
7 (pink) Foliated schists
8 (red with V pattern) Granite crystalline rocks

Hector's Waihao fmnn and Hutton's Kakanui fmnn are on the boundaries between
(7) Foliated schists and (6) Lower Silurian-Upper Devonian

Figure 4.18: Nineteenth century interpretations of the South Island schists. These were seen entirely in stratigraphical terms and with the assumption that each tract of schist must be older than neighbouring unaltered sedimentary strata. Modified from Hector (1879) 'Sketch Map of New Zealand showing Geological Formations' in Handbook of New Zealand. New Zealand Geological Survey.
formation (Fiordland) (Table 4.3), and both he and Hutton agreed that this Gneiss-granite was the ‘structural core’ of a huge anticline that had once formed an immense mountain range in Mesozoic times (Haast, 1885; McKay, 1894b) (Figure 4.5).

Table 4.3: Stratigraphic interpretations of the metamorphic rocks of the South Island; the broken lines indicate where the geologists found that one formation ‘graded insensibly’ from one to the other. Their boundaries were all arbitrary and all different, so that the different geologists’ stratigraphical versions are not comparable with each other.

<table>
<thead>
<tr>
<th>Hector 1865: Otago</th>
<th>Hutton: 1872, 1873 NE Canterbury, Southland</th>
<th>Hutton 1875: Otago</th>
<th>Haast 1878: Canterbury and Westland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Te Anau series (upper Palaeozoic)</td>
<td>Putataka and Maitai formations (Mesozoic, later = Hokonui) (≈Hokonui, Murihiku)</td>
<td>Kaikoura formation (Carboniferous: when Kakanui and Wanaka fmns metamorphosed. (=greywackes))</td>
<td>Mt Torlesse formation (Carboniferous to lower Mesozoic) (≈greywackes)</td>
</tr>
<tr>
<td>Foliated schists:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Grey argillaceous. Kakanui series</td>
<td>Kaikoura formation Not aged, as no fossils</td>
<td>Kakanui formation (upper Silurian) (=semi-schists)</td>
<td></td>
</tr>
<tr>
<td>2. Blue clay-slate. Micaceous or chloritic.</td>
<td>Waihao formation resembles fossiliferous Silurian rocks of Nelson</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Contorted felspathic schist</td>
<td>Mica-schists of Lake Wakatipu</td>
<td>Wanaka formation: mica schists (Lower Silurian?) (=Haast Schists)</td>
<td></td>
</tr>
<tr>
<td>Gneiss-granite (of Southwest Otago) (Fiordland)</td>
<td>Gneiss-granite (lower Palaeozoic)</td>
<td>Manipori formation: syenitic gneiss (Eozoic - Laurentian) highly metamorphosed much older than the above rocks. (Fiordland)</td>
<td>Gneiss-granite (Azoic)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Westland formation (Azoic)</td>
</tr>
</tbody>
</table>

**Hutton’s interpretations of the South Island schists**

Unlike Hector and Haast, Hutton repeatedly modified his stratigraphic schemes (Figure 4.8, Table 4.3). Beginning with his early reconnaissance surveys for the Geological Survey he arranged his schistose rocks in order of supposed increasing age based on increasing metamorphic grade (Hutton, 1872b, 1877). Hutton therefore supposed that his highly metamorphosed Manipori formation (=Hector’s Gneiss-granite) in south-west Otago (Fiordland), belonged to either the ‘Laurentian or Cambrian period’. The remarkably flat, ‘low, broad anticlinal curve ... running through’ Otago with its gold-bearing mica-schists constituted the Lower Silurian Wanaka formation (=Otago section of Haast schists). Hutton drew an

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4 ‘Manipori’ became ‘Manipouri’ in 1885.
Chapter Four

arbitrary boundary between the conformable Kakanui and Wanaka formations, which, as always, passed 'insensibly' into each other, and performed several intrepid inferential jumps in order to arrive at an upper and lower Silurian age for these formations (Hutton and Ulrich, 1875):

- Fossil evidence indicated a Triassic age for the Maitai formation in Southland (Hokonui).
- The Kaikoura formation (=greywackes) was unconformable below the Maitai formation and therefore of Carboniferous age.
- ‘[I]nspection of the map’ indicated an unconformity between the Kaikoura formation and the underlying Kakanui formation (= semischist) although it was ‘not so easy to prove this in actual sections’.
- The assumed break made it possible to infer a Silurian age for the Kakanui and Wanaka (= Haast) schists.

Hutton’s 1885 revision of his stratigraphic divisions produced a more sophisticated sequence of nested systems and series that reflected his advanced ideas of New Zealand’s geological history (Figure 4.8). Like Haast, Hutton visualised the South Island as the eastern half of a major ‘ge-anticlinal’ curving from Tasman Bay in Nelson south through the Southern Alps to Otago where it widened and turned east towards Dunedin (Figure 4.20). This accounted for the seeming continuity between the schists of Otago and the fossiliferous schists of north-west Nelson (Figure 4.18), where the ‘indefatigable Mr A.McKay’ and other Survey geologists had ‘provided’ Ordovician and Silurian dates. Hutton replaced his old Kakanui and Wanaka formations with a new Nelson-based Takaka System containing the Baton-River, Aorere and Mt Arthur Series. At the same time, the Kaikoura formation (=greywackes) disappeared into a new Carboniferous Maitai System (Figure 4.8).

The last major change to Hutton’s scheme followed a visit to the Lyell district on the Buller River in 1887. Here, Hutton was surprised to find only slates and granites and no schists. This indicated to him quite plainly that the schistose rocks of the Wanaka series (= Haast schist of Otago) were not continuous with the Takaka System of north-west Nelson after all (Hutton, 1889). Therefore, the Wanaka schists did not have to be of the same Ordovician and Silurian age as the Nelson schists (1891). This, along with the absence of folds and other characteristics of the Wanaka schists indicated that:

- The Wanaka schists had not been altered by crushing or ‘dynamic metamorphism’.
- There was no contact metamorphism.
- Metamorphism was caused by the ‘internal heat of the earth at a very early period in its history, when the temperature gradient was much steeper than now’.
- The Wanaka schists must have been buried very deeply and must be very old because the internal heat of the earth caused their schistose structure.
Hutton (1899) believed that the ‘Pre-Cambrian’ Wanaka schists were enormously thick, not less than
100,000 ft, or about nineteen miles. He regarded them as the oldest rocks in New Zealand, and as having
no relationship at all with the rocks of the neighbouring Maitai System (= greywackes) even if they
graded ‘insensibly’ into one another, and with no identifiable unconformity between them.

By the end of the nineteenth century, the geologists had gathered a great deal of data to do with New
Zealand’s metamorphic rocks, but no-one was any the wiser as to the causes of metamorphism, or about
any regional relationships between schists and neighbouring sediments. New Zealand geologists were
grounded in a fruitless struggle to understand metamorphism and metamorphic rocks by using
stratigraphic rules.

Petrographical Studies
of the greywackes and schists

Hutton (1891) pioneered microscopic studies of schists at Canterbury College, but rocks from New
Zealand were subjected to microscopical analysis as early as 1864. The pioneer microscopist Henry
Clifton Sorby, met the young Ferdinand Zirikel of Bonn in 1862 and taught him his methods (Zittel, 1901:
329, Hamilton, 1982). Zirikel then enthusiastically set out to acquire and describe as many examples as
possible of crystalline rocks from all parts of the world. Amongst them were thirteen samples of volcanic
rock brought by Hochstetter from the central North Island (Zirikel, 1864). Otherwise, the earliest record of
the use of a microscope to examine rocks in New Zealand is by Crawford who in 1861 noted that ‘Mr
Haast has discovered a speck of gold with the microscope’ in iron sand.

The few pre-1900 petrographic studies in New Zealand were made of crystalline igneous and
metamorphic rocks (Daintree, 1875; Cox, 1880, 1884; Park, 1934). Little, if any, work was done on the
petrography and taxonomies of sedimentary rocks until the First World War. In effect, sedimentary rocks
were still seen merely as stratigraphical units and repositories of fossils. However, a sample of New
Zealand greywacke was examined in some detail as an exotic Alpine curiosity in 1888 by a leading
English petrologist, Professor T.G. Bonney of Cambridge, when he was given a fragment of greywacke collected from near the summit of Mt Cook by the Rev. W.S. Green. In due course, the Professor reported the presence in the greywacke of fragments of quartz, felspar, biotite, and of rock fragments crowded with microliths, and fragments of argillites (Bonney, 1888). Bonney decided the rock could be ‘named an indurated, rather felspathic grit’. He did not think it to be Archean, but that its materials had probably been derived from rocks of that age, ‘being itself very possibly Palaeozoic’. Bonney (1896) performed the same favour for another visiting climber when he examined rock samples from Mounts Sealey and Sefton. These and the Mount Cook sample he thought were derived mainly from granitoid rocks and belong to the lower half of the Palaeozoic series. Since they were not schists it was ‘very likely beds containing fossils will be found ... among them, and for these an explorer should keep a careful look-out’.

Figure 4.19: Photomicrograph of greywacke from the Kawarau gravels magnified 30 times. Park (1908), Plate XX, in The Geology of the Cromwell Subdivision. New Zealand geological Survey

For his last major publication, McKay commissioned an ‘Oversea Expert’, Professor W.J. Sollas of Oxford University, to make a petrological study of 500 rock samples from Cape Colville (Sollas and McKay, 1905). Among the mainly igneous rocks, Sollas described a fine ‘Quartz Felspar Grit, or Grauwacke’ from the Tokatea Mine as having a microcrystalline matrix but with fragments of quartz, sericite pseudomorphs after felspar and rock fragments. McKay’s work reflects elements of both the nineteenth and twentieth centuries. He remained faithful to Hector’s old stratigraphic scheme and divided the old sedimentary rocks of Coromandel (greywackes) between Hector’s Te Anau series, Maitai series, and Wairoa series. At the same time he demonstrated his new skills in a major technical advance, the
photomicrography of thin sections\(^5\). Unfortunately, no photomicrographs of a ‘grauwacke’ are included nor is an account of how the photomicrographs were made. Park (1908) prepared the first known photomicrograph of greywacke published in New Zealand (Figure 4.19, p.102).

**Geological Theories and Structural Geology**

I am very averse to premature conclusions only partially unfolded.... In a science like geology, the principles of which are quite unsettled, we cannot be too cautious.  
(Hector quoted by Haast, 1948 p.458)

Even if all the facts were as accurately known as possible, the interpretation of them would not be so easy as might be supposed, for sometimes the facts admit of more than one explanation.... Consequently it is of no use saying that we ought to wait until our knowledge is more complete before attempting to theorise, for if we did so we might wait forever.  
(Hutton and Ulrich, 1875).

Accounts published by Survey geologists were mostly devoted to straightforward descriptive stratigraphy and mining reports (for example Davis, 1871b). This does not mean that the geologists were uninterested in theory, only that we have little or no record of what went on during, for example, the sociable weekly meetings held through the winter months by the Survey staff in the Colonial Museum (Park, 1934: 20-1). In earlier years, these discussions on ‘points of geological interest’ and ‘abstract problems’ often included William Mantell and Sir George Grey.

Apart from conjectures (all revealed in the one lecture) about the South Island schist, a Cretaceo-tertiary system and the seeming co-incidence of the geographical layout of Australian and New Zealand gold fields, Hector himself (1869b) was disinclined towards theoretical speculations, at least in public. He generally held to his early belief that the science of geology had not yet attained to ‘generalizations that warrant prediction’. Hector's nearest approach to a historical interpretation of New Zealand’s stratigraphy were restricted to several long, didactic articles in which was displayed little sense of geological time, continuity, or of progressive organic change (for example 1886a). The development of such ideas must have been inhibited by his method of recounting geological history backwards, beginning with descriptions of the youngest rocks and ending with the oldest. However, Hector evidently did not attempt to restrict others’ ideas and his staff members had access to many overseas...

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\(^5\) How much did McKay contribute to specialised photography in New Zealand? A drawing by McKay to guide the construction of a telephoto lens is in existence. Is the story that McKay ground his own camera lenses from bottle bottoms true?
books and journals that Hector had obtained in exchange for issues of Transactions of the New Zealand Institute and museum specimens (Nicholson, 1998).

In contrast, Hutton was deeply interested in discussing scientific theory, ranging from evolution (1902), through the causes of earthquakes (1882), to the relationship between land and deep sea (1883). He published in British journals and was probably aware of North American ideas about geosynclines when he asserted that ‘most geologists agree that thick formations of sandstones and clays have been deposited in a sinking area, about equal in rapidity with deposition’ (1872a: xxxi). He thought such strata would first be compressed and then expanded by heat to make folds or contortions. Haast (1879: 254) later agreed that this theory might explain the ripple-like contortions of mica schists he had seen enclosed between quartzose beds.

At this time, European geologists were much concerned with questions about the macrostructure and origin of mountains (Greene, 1982; Gohau, 1990; Oldroyd, 1996). Apart from Hutton’s contributions, (for example 1872, 1873) New Zealand geologists took little part in international discussions on tectonic theory. Like many American geologists (Greene, 1982: 258), the Survey geologists were still largely occupied with stratigraphy and mapping, and the structural aspects of their work was ‘mostly on a macroscopic scale founded on a stratigraphic approach’ (Lillie, 1961: 57). The New Zealanders had access to British and North American journals but were somewhat isolated from ideas about European Alpine geology until the English version of Suess’s Das Antlitz der Erde became available between 1904 and 1909 (Chapter 6). Nevertheless, the settler geologists were very interested in theoretical problems to do with New Zealand’s geological past (for example Crawford, 1872, 1876).

**Julius Haast’s Paleozoic World**

Through the 1860s, Haast reported to his political masters at great length and in enormous detail, but with ‘an eye on the savant overseas’ (Haast, 1948: 459). Members of the Canterbury Provincial Council were presented with Haast’s conjectures on the province’s Paleozoic past, its glaciated mountain ranges, along with lovingly meticulous descriptions of the ‘endless succession’ of its various rocks (1862, 1871: 20). He believed, that now, the geologist could ‘account for facts’, which in earlier days ... ‘could only hypothetically be explained’ (1872b). Unfortunately, he could not give the politicians their desired goldmines (Haast, 1948: 456).

Haast (1862: 124, 126) imagined a Lyellian world of slowly interchanging continents and seas. The distribution of conglomerates in the Canterbury sequences led him to create an ancient continent to the east of New Zealand (1864, 1872b), of which the old sedimentary and semi-metamorphic rocks of the
Chatham Islands were ‘probably’ a remnant. The ancient land was slowly worn down until it disappeared beneath the sea while its Carboniferous sediments were deposited in shallow water deltas. The conglomerates were deposited by ‘huge torrents’ in the littoral zone near the river mouths (1872b: 7), but the clay slates and shales represented deposition at the ‘bottom of the palaeozoic sea’ (1879: 275). Altogether, the beds reached a thickness of at least 25,000 feet, and were ‘formed during a gradual depression of the sea bottom’ during which a number of submarine eruptions caused ‘diabasic ashes’ (basalt tuffs and flows) to be ‘interstratified with them’ (1879: 243, 245).

Further ‘inter-stratified’ diabasic beds were found in the Malvern Hills district (1872b: 10-11) with an ‘intimate’ association between ‘kernels and strings of chert and enclosing diabasic layers’. Haast believed that the diabases resembled those of the Hartz Mountains in Germany, showing that the ‘same abyssodynamic causes’ worked everywhere to build up the ‘solid crust of the earth’. The associated compact marble did not form continuous beds, but occurred only in ‘lenticular’ shapes, ‘thinning out and disappearing, to appear after a few miles’.

Haast puzzled over the scarcity of animal and plant fossils in the rocks. He saw no reason to believe that the Paleozoic sea was devoid of life since many shales contained traces of an annelid and the ‘markings of fucoid plants’, so why did they not contain other fossils? What had so effectively destroyed all traces of the other inhabitants of the Paleozoic seas? Had the ‘turbidity of the bottom water’ (Haast’s italics, p.5) as suggested by the ‘latest deep sea researches [in] the Mediterranean’ sea’ prejudiced the existence of animal life? (1872b: 6). Soon after the deposition and consolidation of the Mount Torlesse formation (1879: 244), the strata were raised by ‘plutonic and volcanic action’ when the Southern Alps were ‘upheaved’ by crystalline ‘hypogene’ rocks, and the rocks were ‘folded, crushed and denuded’ (1872b: 12).

The Haast-Hutton ‘Geanticlinal’ of New Zealand

Theories of the macrostructure of New Zealand began with Hochstetter who believed that until the ‘latest period’ New Zealand was a ‘scene of the grandest revolutions and convulsive struggles of the earth’ (quoted by McKay, 1894b). In recent times the west coast of both main islands had gradually sunk, while the east coast was raised, about an axis on an imaginary line to the west of the west coast of the South Island, and extending through the North Island.

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6 Understood today as an association of deep-sea cherts, lavas and limestones enclosed within terrigenous greywackes during accretion within a subduction zone.
8 e.g. granites, porphyry, syenites, gneiss.
Haast (1871) developed a model of the Southern Alps that consisted of the ‘eastern wing of a huge anticlinal arrangement’, the western portion having been ‘either destroyed or submerged below the Pacific Ocean’ (1879: 242). Such one-sided arrangements were ‘conspicuous in every alpine chain’.

Hutton also referred to ‘the geanticlinal of New Zealand’ and ‘the eastern half of a huge geanticlinal arrangement of contorted rocks’ (Figure 4.20). The removal by denudation of much of the west side by heavy rains (Hutton, 1885: 195, 1899: 161) was ‘proof’ that moisture-laden westerly winds had predominated there for a very long time (Figure 4.21).

**Structural patterns in the Southern Alps.** Besides the huge ‘anticlinal arrangement’ Haast (1879: 240-248) also noted:

That the Southern Alps are highest where the mountain ranges and the South Island itself are at their narrowest, so that ‘abyssological forces’ produced the highest folds at the expense of breadth.

That the east coast of Australia and west coast of New Zealand form almost parallel lines.

Dobson’s observation that all the principal valleys in the Southern Alps ‘radiate as it were from a common centre’ about 40 miles west of Hokitika.

The belt of gneiss-granites running the length of the Southern Alps on the western side (Figures 4.18, 4.21) was considered by both Haast and Hutton to form the core of their ‘geanticlinal’, overlain by ‘schists, clay-slates, sandstones, felstones’ and the ‘Mount Torlesse formation’ (Haast, 1885 333). Hutton (1899) regarded the line of granites as the ‘tectonic, or structural axis of the Island’ that had been
intruded during a period of elevation and folding in the Permian. This structural axis continued into the North Island from Wanganui to the Bay of Plenty so that the ‘chief mountain-range lies to the west [sic] of it’.

**Alexander McKay’s hypotheses**

During the 1890s, McKay wrote at length on his observations and interpretations of the geology of the northern South Island (1890, 1893, 1894a, 1894b). When explaining the origin of gold-bearing gravels in Westland to the Minister of Mines, McKay (1893, 1894b) compiled all hypotheses advanced to date on the structure and geological history of New Zealand, and explored them in great detail. McKay’s helpfully lengthy explanations to politicians included a review of the method of formulating and testing a hypothesis and many other relevant statements. McKay (1894a) supported the current theory that the Southern Alps consisted of ‘only the eastern side of a huge anticlinal’ and provided a diagram to illustrate it (Figure 4.21). However, he added something new by considering that the steep slope of the western side of the mountains was only partly due to denudation and was ‘largely due to the existence of a line of fault running along the base of the mountains’. However, such a fault was not indicated on his innovative map showing ‘Principal Faults and Earthquake Rents’ (1892). McKay’s papers mark the ‘first great advance in structural geology in New Zealand’ (Lillie, 1961) in which McKay recognised:

♦ That the Kaikoura Mountains and the Southern Alps did not exist before the Miocene period.
♦ That great dislocations have taken place in late Tertiary and Quaternary times.
♦ That fault movement can be transcurrent as shown by such movement at Glen Wye in the Hope Valley in North Canterbury (1892: 17).

![Figure 4.21: McKay's 'ideal section' from the Canterbury Plains to the west coast illustrating the 'huge anticlinal' earlier hypothesised by Haast and Hutton. Granite (1) occupies the core of the geanticline, and is followed by schists (2) and then Carboniferous (3) and possibly Devonian rocks that appear 'on both flanks of the range'. Carboniferous (3) represents the greywackes, while Liassic (5) represents fossiliferous pockets like the Mt Potts shell beds. McKay (1892) New Zealand Geological Survey Reports of Geological Explorations.](image-url)
McKay’s novel ideas on transcurrent faulting and the age of the Southern Alps remained hidden from international notice in *Reports of Geological Explorations* and *Appendices to the Journal of the House of Representatives*. His work was not even published in *Transactions of the New Zealand Institute* let alone international journals. Therefore, although New Zealand geologists have long seen McKay as a hero, he has never achieved international recognition.

Although the name of the New Zealand geologist is unknown to many, it is highly honoured by those who can estimate the importance of his original contributions to science. Beginning as a fossil-collector, he subsequently became attached to the Geological Survey of the Colony under Sir James Hector, and spent twenty years in the field. A self-taught man, and owing little to books, he was led to study the structural geology of the country, and to form for himself opinions far in advance of the times. His views concerning the part played by block-faulting in the evolution of the mountain-system of New Zealand received scant regard, and have only been brought into prominence by others in later years. Had McKay possessed the power of presenting his conclusions more clearly and enforcing them more cogently, his merits as an original thinker would have been generally recognised.

(Harker, 1918).

**The Mesozoic elevation of New Zealand**

The conjectures regarding the macrostructure of New Zealand and speculations as to the country’s geological history based on field observations began leading to alternative views of stratigraphy. As early as 1869 Hector believed that two major breaks in sedimentation had occurred; one during the Jurassic period and the other before the Permian period (1869b). Such breaks in the stratigraphic record had long been understood by geologists as periods of folding and uplift of the rocks to form new lands, and were used by them to define the major rock units. In 1875, Hutton made a detailed analysis of the geological history of Otago (Hutton and Ulrich, 1875: 84) in which he traced a series of ‘oscillations’ (Figure 4.22, p.109). Each oscillation recorded a geological ‘upheaval’ indicated by a break in the sedimentary record, and the largest upheaval took place in the middle of the Jurassic period when ‘the chain of the New Zealand Alps was formed’. Although Hutton had identified a series of upheavals, he, Haast and others still believed that New Zealand was formed by a single cycle of deposition, Jurassic uplift and folding followed by denudation.

Hutton was primarily interested in tracing past glaciations, which he believed took place because of elevation. Thus, the postulated upheavals were seen more as causes of glaciation by elevation, than as mountain-building episodes. However, Hutton did relate sedimentary formations to periods of subsidence. In this scheme the sediments (greywackes) of the Kaikoura formation were deposited during the long Carboniferous subsidence.
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Figure 4.22: F.W. Hutton’s chart tracing oscillations in the ‘elevation’ of the Province of Otago. The chart records a major upheaval that took place in the late Jurassic period, followed by several smaller upheavals in Tertiary time. Hutton (1875). Report on the Geology and Goldfields of Otago

Hutton again traced New Zealand’s geological history in 1899 (180-3) with its episodes of subsidence and upheaval, but completely ignored McKay’s discovery that the Southern Alps did not exist before the Miocene. Hutton added little to his earlier conjectures but suggested that during the Triassic and Jurassic periods, New Zealand was ‘probably ... near the coast-line of a large continent stretching away to the north and west’. In the middle of the Jurassic period a ‘violent upheaval’ with major folding took place; ‘the Alps were formed, and the present land of New Zealand ... born’, and never ‘since entirely covered by the sea’, but land between New Zealand and Australia sank to form the Tasman Sea. Following the great upheaval, the north-western side of New Zealand was greatly denuded. Hutton did not use the expressions ‘orogeny’ or ‘mountain-building’.

Perceiving and visualising structures

While the settler geologists considered theories about the great folds forming the Southern Alps, they remarked only occasionally on the details of smaller, complex structures within the greywackes. Geologists’ visual language tells us something of how they perceive the world (Rudwick, 1976; Montgomery, 1996; Howarth, 1999). While field books belonging to Hector and other Survey men (Hocken Library, Museum of New Zealand) contain numerous little descriptive sketches showing the disposition of strata, comparatively few visual records of structures seen in hand specimens, outcrops and cliff faces were published. The geologists’ landscape drawings are realistic, recognisable and attractive with a clear appreciation of space, proportion and perspective (for example Haast, 1948: 97;
Gregg, 1964), but the conventionalised illustrations in journals and textbooks support the notion that most nineteenth century geologists did not often recognise structural detail within their rock sequences. The English geologist, Henry De la Beche, is an outstanding exception. His textbook drawings show a clear recognition of structural details (for example De la Beche, 1851).

Common experience tells us that we often do not perceive something in the field until we are aware it exists and ‘we tend to see what we are trained to see’ (Schumm, 1991: 27), just as neither Darwin nor Sedgwick, when geologising together in 1831, recognised the evidence of glaciations in the surrounding Welsh landscape (Clark and Hughes, 1890: 381). Pillow lavas were not ‘seen’ in New Zealand until those at Oamaru were recognised by James Park in 1905. Few geologists could distinguish tops and bottoms to strata until the 1920s (Bailey, 1930; Pettijohn, 1984; Dott, 2001), and New Zealand geologists rarely noticed graded bedding in greywackes until publication of the famous paper by Kuenen and Migliorini (1950).

Although Hector avoided theorizing, he was a perceptive field geologist. For example, he sketched ‘contorted’ structures in ‘hornstone slates’ (cherts) of Stephenson Island, near Whangaroa (Figure 4.23) in 1866. The images were not published until 1892, but Hector interpreted them solely in terms of the possible presence of economic mineral lodes and demonstrated absolutely no interest in the significance of the structures.

From time to time, structures within the basement rocks were observed, and in 1871, Davis remarked on the ‘inextricable confusion’ of crystalline and serpentinous rocks of the mineral belt in Nelson (quoted by McKay, 1878a: 133. These rocks are now mapped as Patuki Mélange, p.357). Hutton (1877: 32) noted much variation in the general north-east strike of the rocks of his Kaikoura formation, where the rocks did ‘not appear ... to be thrown into parallel folds but into huge domes and cup-shaped depressions’. The more thinly-bedded rocks displayed ‘great contortions and crumplings’ and at Porter’s Pass the beds

Figure 4.23: Hector’s observant sketch of Stephenson Island, drawn in 1866 but not published until 1892. Today, this island attracts considerable interest from geologists investigating the structural geology of the greywackes and associated cherts, and the Permian-Triassic boundary. Hector, (1892) New Zealand Geological Survey Reports of Geological Explorations
were ‘gnarled and twisted in an extraordinary manner’. McKay also reported (1881: 85) that although ‘contorted and much disturbed’ and often of an ‘uncertain dip’, the strike of the rocks of the Ashley district of Canterbury was ‘in the main... parallel to the main axis of the island’. He recorded a large syncline divided by a non-central anticline, and within it the ‘younger Oolitic rocks’ made ‘transverse superficial anticlines and depressions’ and the ‘general structure appears to be as described by Professor Hutton’.

Figure 4.24: Compared with Hector’s 1873 section (Figure 4.16), Haast’s sections through the Southern Alps dramatically symbolise disturbed beds and steeply dipping folds. Sectional diagrams in reports and textbooks usually showed an opposing relationship between strata and topography because it was believed that ‘synclinals generally form the summits of the mountains, while the deep broad valleys often run along their anticlinals’ (Haast, 1885). Also see p.113. Haast (1879) Geology of the Provinces of Canterbury and Westland, a Report Comprising the Results of Official Explorations. Lithography by F. Köke of Vienna.

Large structures such as ‘steeply dipping anticlines and synclines’ were readily identified by Haast in his semi-schistose Waihao formation (1879: 273-4), while the vast assemblage of rocks in his Mount Torlesse Formation formed a succession of huge folds dipping throughout at high angles. These folds were destroyed ‘during numberless ages’ so that now, ‘Mount Cook occupies a synclinal trough’ while the Godley river ‘runs along an anticlinal arch’ reaching ‘from the East Coast to within 20 miles of the West Coast’ (Figure 4.24).

**Figures and maps**

The history of the development and limitation of geological and other scientific illustration in New Zealand through the nineteenth century has been little explored. Generally, no diagrams were included in the geological reports to the provincial governments during the 1860s. The books by Hutton and Ulrich (1875) and by Haast (1879), and Reports of Geological Explorations were illustrated with woodcuts within the text, and lithographed plates for the black and white maps (for example Hector, 1869a). Early issues of Transactions of the New Zealand Institute contained few articles on geology, but did contain many beautiful botanical and ornithological lithographs. John Buchanan, artist-explorer-draughtsman-naturalist, prepared many of the maps and sections that appeared in Hector’s Reports and
In a lecture 'On the Geological Formations of New Zealand compared with those of Australia' given to the Royal Society of New South Wales, Hector presented an unusual idealised and illustrated Table of Fossiliferous Formations' with visual impressions of each formation stacked one upon the other and capped with a tiny volcano and 'Moa beds' (Hector, 1879, 1881).

The imaginative presentation represents a style of 'scenographical geology' (Rupke, 1998) rarely seen in New Zealand. Several years later, segments of the illustrated table were used together with drawings of characteristic fossils belonging to each series in the catalogue for the 1886 Indian and Colonial Exhibition in London. Copies of pages 37-101 were rebound separately to make a handbook, Outline of New Zealand Geology (Hector, 1886).

This was Hector's only book dedicated to geology, and the first book since Hochstetter's time to review the geology of the whole of New Zealand. It was published when Hector was experiencing increasing political criticism (Homibrook, 1991). It was Haast, and not Hector, who was invited to take charge of the 1886 exhibition. Hector published several other handbooks related to exhibitions.

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**Figure 4.25:** Illustrated or 'scenographical Table of Fossiliferous Formations, Modified after Hector, (1880), Progress Report, New Zealand Geological Survey Reports Geological Explorations 1879-80.
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these were based on the geologists’ field sketches (Burton, 1965). On his retirement in 1885 Buchanan was succeeded by C.H.Pierard.

Hector never managed to produce a standard set of coloured inch to the mile geological maps in spite of good intentions (Hector, 1884a). No standard scale was used for the maps published in Reports, and very often no scale of miles was shown at all. Each map was given a legend listing the series and formations according to stratigraphic age and these were marked on maps with conventional black and white patterns. True and magnetic north were indicated with arrows, but strikes or dips were rarely shown although strikes were marked along the lower border of a few earlier sections drawn by Hector (1871) and Haast (1871). With few exceptions, strike and dip were described only in qualitative terms within the text. River courses were shown, but other topographic details were rarely included. Eventually, professional-looking coloured and lithographed maps complete with a scale of miles, compass arrows, and a detailed legend were published in the 1890s (See Figure 5.5, p.129).

Structure was suggested by one or more accompanying traverse sections, although their main function was to illustrate stratigraphical relations, and in some cases substituted for a map (for example Hector, 1865). In contrast to the geologists’ pleasing landscape sketches, the diagrammatic traverse sections showing inferred sub-surface structures were highly conventionalised, giving the impression that geological strata were composed largely of neatly parallel bedding planes plunging towards the centre of the Earth (Figure 4.10, 4.21). Conventionally, mountains always occupied synclines and valleys occupied anticlines (Figure 4.24) on the theory that tension of rocks in anticlines allowed them to be eroded more quickly than those forming synclines. Most sections lacked both vertical and horizontal scales and all displayed a strong vertical exaggeration (cf. De la Beche 1830 quoted by Howarth, 1999). Little attention was paid to the real attitude of sedimentary beds, or to structures within them such as cleavage and joint planes.

For his 1879 lecture to the members of the Royal Society of New South Wales ‘On the Geological Formations of New Zealand compared with those of Australia’, Hector (1880) had prepared a most unusually elaborate scenographical ‘Table of Fossiliferous Formations’ (Figure 4.25). The diagram was recycled in his 1881 Progress Report for 1879-80 and later, segments were used to illustrate the catalogue for the 1886 Indian and Colonial Exhibition in London. These were accompanied by sketches of typical fossils including an unlikely depiction of a ‘Tubicolor annelide’ as a representative fossil of the Carboniferous ‘Maitai slates’ (Figure 4.11).
Some issues for New Zealand geologists in the 1890s

The New Zealand Geological Survey was to all intents and purposes closed down in 1894 (Oldroyd, 1967; Hoare, 1977). Later, Hutton (1899) angrily complained that no systematic geological survey had actually taken place in New Zealand since 1865 as too much effort had gone into examining mines and mining districts, and he deplored the emphasis on economic geology (see chart Figure 4.4, p.72). He pointed out that only three geological maps of the whole country had been published, in 1869, 1873, and 1883, while no regional maps and no inch to the mile maps had been produced at all. At the same time, thousands of fossils had still to be unpacked and identified, and that most identification that had actually been made was funded by the Austrian government.

Nevertheless, mining geology remained of major importance to politicians, and McKay was retained (with his son) as the only active government geologist and attached to the Mines Department. University geologists such as Hutton, Park, Speight, Marshall, and Thomas carried out all other geological research. This included thin section petrology, which by now had opened up new fields in igneous and metamorphic studies. Construction and nomenclature of the stratigraphic column remained an issue with both Hector’s and Hutton’s schemes in use.

Looking back

The nineteenth century geologists were men-of-all-work. Hector and the university men were involved with all aspects of natural history as well as geology, with teaching, the care of museum collections, a great deal of administration, and with the usual minimum of financial support from government (Dick, 1951; Hoare, 1977). Although they often travelled with companions and relied on surveyors and runholders for information (for example, Haast, 1948, Ch.110, 17) access to the field was often difficult and the geologists travelled to and covered their fields by back packing, canoe, horseback, carriage, coastal steamship and train, and often had to construct their own base maps (Figure 4.5). Moreover, the geologists were trying to map and understand a highly complex geological situation, brought about by tectonic factors that would not be understood for nearly a century hence.

Except for occasional sabbaticals to Britain and rare visits to Australia, the settler geologists had little direct contact with overseas geologists. However, they were a great deal less professionally isolated than might be expected. An enormous amount of correspondence and exchange of journals and specimens was carried on with geologists in Australia, Britain, Europe and the United States (Hector, 1880a; Fleming, 1987; Barton, 2000) as shown by collections in the major libraries. The establishment of the Australasian Association for the Advancement of Science in 1888 made it possible for New Zealand scientists to take less than a month to travel to Australia, attend conferences, and return.
Once the settlers learned that the greywackes contained few minerals of much worth, except for a few occurrences of copper, manganese, and a very little gold, there was little need to continue mapping such difficult rocks. Investigations of the Mount Torlesse formation/Maitai series after 1875 were not provoked by any kind of economic need, but were set off most often by:

- Hector’s use of McKay and Cox to review Haast’s Mount Torlesse formation.
- McKay’s dutiful inspections of various unpromising gold and copper mine sites in the Wellington district, in which he took the opportunity to make detailed descriptions of the rock sequences (1879b, 1888a).
- Haast’s defence of his Mount Torlesse formation.

The retirement and deaths of the nineteenth century settler geologists did not end stratigraphic wrangling over the position of various pre-Cretaceous rocks in the New Zealand stratigraphic column. Even as membership of the country’s geological community changed, problems with paleontological determinations remained, as did tension between the immediate pragmatic needs of economic geology and the seemingly more remote and academic problems of structure and stratigraphy.

Regardless of Hutton’s complaints, and of the limitations imposed on the settler geologists, Hector’s Reports of Geological Explorations, especially those by McKay, and including Hector’s own ‘Progress Reports’, maintained their place in every New Zealand field geologist’s reading list at least into the 1960s (A.Mason, pers.comm., pers.exper.). Even today, the written reports made by those fine, conscientious geologists should be revisited occasionally to see the Earth through their eyes and keep in touch with geological tradition.
Chapter Five

Maps and Stratigraphy

1900 -1950

There is not as yet any general accord amongst New Zealand geologists as to the number of formations represented amongst the rocks, nor as to the relationship and absolute age of the formations that are well recognised .... This is due to the absence of fossils over large extents of country, the lack of critical study of the fossil faunas known to exist, and the lack of detailed studies in critical localities, and, as pointed out by Marshall, to the prevailing philosophical creed of the earlier geologists that all formations recognizable in Europe should be found represented in New Zealand. McKay, Park and Marshall hold opinions today as much at variance as those formerly held by Haast, Hector, and Hutton.

(Thomson, 1913: 14).

The question of the age of the Maitai Series is one of the most important which concerns New Zealand geology, and one which has aroused the greatest controversy and uncertainty.... The Maitai beds are a series of great structural importance since they ... enter largely into the composition of the Alpine ranges of the South Island.

(Trechmann, 1917)

The years 1900 and 1950 were chosen as boundaries to this period because both marked rapid changes in New Zealand geology. Around 1900, the retirement and deaths of pioneer geologists had led to an almost complete change in the leading geological personnel. The New Zealand Geological Survey was in recess until 1905, and the university geologists dominated geological research (Waterhouse, 1965).

1950 is a convenient mid-century date marking further changes in geological thought concerning pre-Cretaceous rocks in New Zealand. Kuenen and Migliorini (1950) published their famous benchmark turbidity current paper, the revived New Zealand Geological Survey had recently produced a new coloured geological map of New Zealand (Marwick, 1948), and interest was turning towards the pre-Cretaceous ‘Hokonui’ rocks or ‘undermass’. Much data was accumulated by the field men ‘sweating away in Nelson or the Kaikouras’ (Lillie, 1985), and, in spite of ongoing uncertainties, the framework of a reasonably satisfactory, more or less generally accepted New Zealand stratigraphic column was developed by 1950. Several streams of geological research were evident:

♦ One stream consisted of data collection by the resurrected New Zealand Geological Survey as it focussed on gold, coal, and on the stratigraphy and structure of the younger Cretaceous and Tertiary ‘covering strata’ in its search for oil.
† The university geologists investigated the petrology of igneous and metamorphic rocks, while their 
students were usually occupied with local areal studies, contributing to the general geological 
knowledge of the university districts (for example Lillie, 1959).

‡ A third stream involved attempts to develop effective theories to explain the configuration of land 
and ocean in the south-west Pacific and the processes of orogeny (Chapter 6).

**Internationalisation**

Some contributions of international importance by 
resident New Zealand geologists 1900-1950

**Patrick Marshall.** *New Zealand and Adjacent Islands* is a synthesis of New Zealand geology 
and one of a series of eight subscription volumes constituting the *Handbuch der Regionalen 
Geologie* published in Heidelberg (1911). Marshall’s contributions include his ‘andesite line’ 
(1912b), and his method of modelling the abrasion of beach gravels (1929). (Also see Adkin 

**C.A.Cotton** (Chapter 6). Cotton’s ‘long standing and increasingly refined analyses of the 
New Zealand landscape’ from 1913 onwards were of international significance (Gage et al., 
1985), as he developed ideas on the relationship between tectonic structure and 
physiography. Cotton (1918) played an important part in the identification of multi-cycle 
mountains, and the realisation that some mountains were built by block faulting in a late 
Tertiary-Recent Kaikoura orogeny. He reared a whole population of geologists who could 
read a landscape in structural terms (Harrington, 1985) and created a foundation for 
neotectonics.

**W.N.Benson** (p.161). Benson’s work on the geology and petrology of the Great Serpentine 
Belt of New South Wales led to his analyses of the conditions of the formation and 
emplacement of basic and ultra-basic igneous rocks, that is, the Dun Mountain belt of New 
Zealand (Benson, 1919, 1921, 1922, 1927; Coombs, 1957). Much important work remains, 
unpublished in the Hocken Library of Dunedin.

**F.J.Turner** and **C.O.Hutton** (Chapter 6) probed the Otago schists and established the 
progressive nature of regional metamorphism in the area (Coombs, 1974, 1986). Their work 
on low-grade metamorphism showed how the schists were undoubtedly related to the 
neighbouring greywackes.

**Harold Wellman.** Wellman’s low-key announcement of 200 miles of transcurent movement 
on the recently identified Alpine Fault at the Pan Pacific Science Congress in Auckland, was 
briefly reported by Benson the following year (Benson, 1950, Rhodes, 1996, Kear, 2001).

Space does not allow acknowledgement of the fine work of those geologists trained in New 
Zealand but who made their careers overseas, such as J.Malcolm Maclaren, world expert on 
the geology of gold (Mason, 1994)

New Zealand geology became increasingly internationalised. Expert traders like Haast and Hector had 
exchanged moa relics for quantities of books, journals and museum specimens (Barton, 2000), and some 
geologists had occasional visits ‘Home’, but geological practice was always constrained by distance from 
Britain, Europe and North America. Meetings of the International Geological Congress were initiated in
1878 in Paris, but travel to the Northern Hemisphere was a rare luxury for most New Zealanders. It was expensive and required at least six months’ away from duties here. Next best, the Australasian Association for the Advancement of Science held its first conference in Sydney in 1888\(^1\). Considerable correspondence had always taken place between New Zealand and Australian geologists (Fleming, 1987), but New Zealanders were now only a week’s voyage from regular international contact. James Park (1857-1946; Figure 5.1a) presented a paper at the next A.A.A.S. meeting in Melbourne (1890a) and Christchurch provided the venue for the third meeting in 1891. From then on New Zealand geologists took an active part in the Association’s affairs; there were more frequent exchanges with overseas scientists, and it provided an international platform from which to announce their ideas. Thus, Patrick Marshall (1869-1950; Figure 5.1b) published frequently in New Zealand journals, but his most important generalisations were usually presented at A.A.A.S. and Pan-Pacific Science Congresses. Increasingly, the geologists submitted papers to overseas journals as well as to *Transactions of the New Zealand Institute*. The export of well-trained young New Zealand graduates to take up work with oil and mining companies and in overseas universities was well under way by the early 1900s (Mason, 1991, 1998a). A number of the later expatriates, such as F.J. Turner (Chapter 6) and B.H.Mason, (Mason and Nathan, 2001) retained contact with their homeland and encouraged exchanges of personnel and information.

In 1900, the Government employed only two geologists, Alexander McKay and his son William. Following a change in state policy, the New Zealand Geological Survey was re-established in 1905 as a division of the Mines Department, and it was made a branch of the newly founded Department of Scientific and Industrial Research in 1926 (Hoare, 1976). The Survey employed increasing numbers of graduates trained in New Zealand, and university geologists themselves e.g. Park, benefited by doing contract work for the Survey (Burton, 1965: 41). In later years, relationships between the survey and university geologists seem, at least on the surface, to have remained generally amicable, with considerable exchange of information and personnel (but see Gage, 1974: 97).

Besides their teaching duties, the university geologists worked on a range of practical and theoretical investigations (bibliography Adkin and Collins, 1967). They were no longer expected to teach several natural history topics, and could focus entirely on the subject of geology. Few petrographic investigations were yet made of sedimentary rocks other than to arrange them in stratigraphical order. In terms of mapping and stratigraphy, most attention was given to the younger rocks (Figure 5.2), and little time was given to the problems of the pre-Cretaceous rocks of New Zealand including ‘the greywackes’ (Waterhouse, 1965: 938)

\(^1\) The same year in which the Geological Society of America was established.
Figure 5.1a. James Park F.G.S., Professor of Mining, 1901-1931, University of Otago. Hocken Library, University of Otago

Figure 5.1b. Patrick Marshall, D.Sc., Professor and Lecturer in Geology 1902-1917. Hocken Library 1906, University of Otago

Figure 5.1c. William Noel Benson, F.R.S., Professor of Geology, University of Otago 1917-1957. Hocken Library 1924, University of Otago

Figure 5.1d. Percy Gates Morgan. Director: New Zealand Geological Survey 1911-1927. New Zealand Journal of Science and Technology

Figure 5.1: Portraits of four major participants in the development of New Zealand’s stratigraphic column 1900-1950.
‘Greywacke’ returns to New Zealand

James Park firmly established the term ‘greywacke’ in New Zealand. When preparing to publish his report on the geology of Collingwood County in Nelson (1890b), Park crossed out ‘indurated green sandstone’ and substituted ‘indurated greywacke’ (figure 5.2). How did Park learn about ‘greywacke’?

While he was Director of the Thames School of Mines (1889-1900), Park continued to use this new term for sandstone strata within the ‘great series of Palaeozoic slaty shales and greywacke, which form the basement rocks’ of the Hauraki Goldfields (1897: 13-5). In the hand specimen, fresh, undecomposed greywacke consisted of a ‘highly indurated aggregate of rounded or subangular fragments cemented in a siliceous matrix’, and it was difficult to distinguish fine-grained varieties from compact andesites. The alternating greywacke and thin-bedded slaty shales suggested to Park that frequent oscillations of the land took place during Palaeozoic times. Park’s strange new term earned him a scolding at the next meeting of the New Zealand Institute of Mining Engineers, when a member grudgingly supposed that Park’s paper was a ‘decided improvement upon his former efforts’ but that he was ‘unable to arrive at an accurate idea of what the author means by the term greywacke’.

‘Greywacke’ became far too useful for Park to give up and he continued to employ it when he was appointed as Director of the School of Mines and Professor of Mining at the University of Otago in 1901. ‘Greywacke’ was used to name sandstone strata in his three 1903 reviews of the upper Palaeozoic and
Mesozoic ‘mountain-builders’ of New Zealand (1903a, 1903b: 1903c). Other geologists now took up ‘greywacke’ including McKay (1897: 11, 28) and Marshall (1911: 4), while the geologists of the reconstituted New Zealand Geological Survey referred to various Paleozoic sandstones as ‘grauwacke’ (Bell and Fraser, 1906; Fraser and Adams, 1907; Bell and Clarke; 1909, Bell et al., 1911: 16). After Morgan used the form ‘greywacke’ in 1919 it became standard in New Zealand Geological Survey literature. ‘Greywacke’ was further embedded in New Zealand geological language by the publication of Park’s successful textbooks (1910: 60-65; 1914: 205-206; 1925: 191-192) and by Marshall’s textbook (1912a: 83, 137). Park (1910: 60-65) re-defined the petrology of greywacke in terms of the more ‘arkosic’ rocks of the Southern Alps, instead of Geikie’s classical description (p.47, also see p.24, 28, 35, 36).

Although ‘hardness’ was stressed, Park made no mention of a matrix or ‘paste’, and colour was described as ‘light greenish-grey’. Park emphasised the shattered nature of the rocks, and the inclusion of pebbles of slaty shale, flakes ‘resembling chips of Lydian stone’, thin layers of bedded-quartz, and a band of red jasperoid slaty shale in the Malte Brun Range. In thin section the greywacke consisted of a mosaic of quartz grains, a little feldspar, sericitic mica and chloritic matter.

Marshall (1912: 83-84, 137) simply defined greywacke only as a hard, compact sandstone with much feldspar, in contrast to arkose, ‘which was rich in mica’. He noted how greywackes passed into schists in the Southern Alps and outlined the chemistry of such a change (163-164).

**Bell’s New New Zealand Geological Survey 1905-1911**

The appointment of the young Canadian, James Macintosh Bell (1877-1934) in 1904 as Geologist to the Department of Mines, in succession to McKay, and then as Director of the Geological Survey of New Zealand in 1905 (Mason, 1993a, 1998b), had a mixed reception (McKay, 1905). Bell provided a North American geological viewpoint, but he knew nothing of palaeontology and made it quite plain that the primary task of the Survey was to investigate and map economic resources including coal, oil, limestone, gold and iron (Bell, 1907: 1-3; Burton, 1965: 41-49; Waterhouse, 1965, 1967; Reed, 1965; Mason, 1990, 1993a).

While Park and Marshall, both of the University of Otago, were developing their stratigraphical schemes, the new Survey commenced mapping and publishing its ‘new series’ of Bulletins (Figure 5.4). Over the next two decades, thirty-one bulletins were issued by Bell and his successor, Percy Gates Morgan (1867-1927) (Burton, 1965: 67). In spite of Bell’s emphasis on economic geology, several geologists including Park and Marshall (who worked on contract) and Morgan unashamedly used the bulletins as an opportunity to expound their diverse theories on glaciation, block mountains, the causes of metamorphism and the origin of the Southern Alps. While most attention was paid to the Upper
Cretaceous and Tertiary sequences (Figures 5.2, 5.4) many New Zealand geologists were increasingly aware of several inter-connected theoretical domains:

- Continuing problems to do with the elucidation of New Zealand’s upper Paleozoic-and Mesozoic stratigraphy including problems associated with paleontology.
- Interpretations of late Paleozoic and Mesozoic geological histories of New Zealand with the inclusion of an inferred geological history of each subdivision in each bulletin, taking the Survey geologists well beyond simple empirical data-collection.
- A growing interest in, and conflicting views of, problems to do with the origin, relationships, age and structure of the South Island schists.
- The concepts of diastrophism and orogeny, including the acceptance of a Jurassic-Cretaceous ‘Post-Hokonui’ orogeny and later, a Pliocene ‘Kaikoura orogeny’, as explanations for the origin of mountains, and for the disposition of rock formations.

Figure 5.3: Chart showing numbers of pages published in New Zealand Geological Survey bulletins 1905-1950 on Cretaceous and Tertiary geology or ‘covering strata’ and on pre-Cretaceous geology or ‘undermass’. Most work on pre-Cretaceous geology had to do with the older Paleozoic rocks of north-west Nelson and Westland.

The rapid publication rate of Bell’s time did not last, and output became intermittent until after 1950. This is said to be a result of Morgan’s emphasis on thoroughness (Burton, 1965: 59, 73-74), and that increasing specialist knowledge caused increased complexity of writing and editing. However, the chart shows that the Great Depression of the 1930s and the two World Wars, 1914-1918 and 1939-45, had the most inimical effect on systematic regional surveys.
Bell’s new Survey was focussed and methodical and data was attractively presented in its ‘new series’ of bulletins. In contrast to the cramped annual volumes published by the old Survey, each bulletin consisted of a separate, large format volume for each subdivision. The volumes were spaciously laid out with the text clearly divided into topic-based chapters, with an index, and a careful list of appropriate literature related to the district.

The text was well illustrated with landscape photographs, microphotographs, diagrams, and neatly tabulated stratigraphical columns. All previous classifications and age allocations of the various rocks were tidily shown on easily read comparative tables. Of major importance was the inclusion of a set of standardised, coloured, inch to the mile maps, sometimes interleaved, but usually in a map pocket at the back of each volume. There was no equivalent of James Hector’s commentary on the content of each issue, and routine reports on staffing and expenditure and the day-to-day accounts of exploration were published separately in Bell’s annual reports to the Minister of Mines. His well-designed model of geological reporting remained an example for all later Survey bulletins and for student theses.

Because of the emphasis on economic geology, there was little reason for Bell and his geologists to work on the greywackes as they lacked minerals of much worth (Introduction, p.7). Some of the subdivisions selected by Bell for detailed study included greywackes (Figure 5.4), and initially, they were as carefully described as neighbouring sequences containing coal or gold. However, from around 1910, much less space was given to pre-Cretaceous formations (Waterhouse, 1965: 937-938), although gold-bearing schists continued to be described in detail. The Survey now concentrated increasingly on Upper Cretaceous and Tertiary rocks because of their coal and oil-bearing potential while the greywackes and argillites were ignored as ‘basement’ and treated as a more or less homogeneous unit (for example, compare Ferrar, 1925 and 1934).

**Petrology of the greywackes**

During Bell’s time, ‘the greywackes’ were usually described as dark grey or dull-green ‘grauwackes and argillites’, or even as ‘arkositic grauwackes’ (for example Bell and Fraser, 1906: 19). Shales, tuffs, grits, conglomerates, cherts and quartzites were also recognised. ‘Curious breccias’ consisting of coarse grauwacke with inclusions of fine-grained indurated argillite were noted in parts of Westland as well as ‘schistose grauwackes’ (Bell and Fraser, 1906: 45; Morgan, 1908: 85). Sometimes the rocks were described as silicified (Bell and Clarke, 1909: 43), indurated, jointed or faulted. Graded bedding was noticed in greywackes of the Paleozoic Aorere Series rocks near Te Aroha in the North Island (Henderson and Bartrum, 1913: 57) and Reefton (Henderson, 1917: 70) but its significance and use in the identification of ‘way-up’ in folded rocks (Dott, 2001) was not understood until much later.
Fig. 4 Areas described and geologically mapped at a scale of 1 mile to an inch in bulletins, memoirs, and maps of the Geological Survey since 1905. The patterns indicate the Director under whose name the map was published, and the colour indicates the relevance to pre-Cretaceous geology, those in yellow being most important, and those in blue having some small extent on the subject. Papers, small maps, and lengthy reports deal with more other parts of the country, but some of the neglected areas, east of Taupo and South Canterbury, are the same as those not covered by Hector (see Fig 1).

Fig 5.4: Areas described and mapped in bulletins, memoirs and maps by the New Zealand Geological Survey 1905-1965. Colours (slightly modified) indicate relevance to pre-Cretaceous geology, those in yellow are most important, those in blue have some importance. Large labels point to subdivisions mentioned in this thesis.
By the beginning of the twentieth century, the pioneering phase of microscopic petrology was long over and polarising microscopes were no longer a novelty. Microscopic analysis permitted the investigation of processes of rock formation and rock change (Hamilton, 1982) and is among the most important of the investigative techniques used in geology. In New Zealand, the examination of metamorphic and igneous rocks in thin-section had become routine. Indeed, Survey geologists frequently made their own thin sections by hand in the field (Reed, 1965: 1005), and bulletins were illustrated with large, beautiful photomicrographs made by McKay (In Bell and Fraser, 1906; Fraser and Adams, 1907), Park (1908), and by Marshall (In Bell and Clarke, 1909). McKay’s Colville photomicrographs were so good that the Director of the British Geological Survey doubted that they could have been done as well in Britain (Mason, 1995). Fraser and Adams (Coromandel, 1907) made detailed petrological descriptions and explained how ‘angular grains, splinters and ... rounded granules of quartz’ were scattered through a ‘dusty granular or minutely crystalline matrix’. As in most bulletins, petrological descriptions were accompanied by chemical analyses.

The igneous rocks within the greywackes were rarely discussed. Exceptions included those associated with an ‘interesting white, compact crystalline limestone near Whangaroa’ (Bell and Clarke, 1909: 45-46). These rocks were described as having been ‘brecciated’ and mixed with associated volcanic and sedimentary rocks by ‘movement’ following the deposition of the Waipapa rocks.

In an unusual petrographical and chemical analysis of the ‘Maitai or Carboniferous’ sedimentary and diabasic tuff association at Red Rocks at Wellington (Broadgate, 1916, also see p.207), chemical analyses revealed that different proportions of ferrous and ferric iron caused the variations in colour of the red and green argillites. Surprisingly, the analysis indicated that associated grey cherts were chemically very similar to the greywackes and were therefore thought to be really greywackes altered by secondary silification.

**Age and stratigraphic classification**

Survey geologists had much difficulty in stratigraphically classifying the greywackes, and many authors have traced the various opinions regarding their age (Park, 1903a; Marshall, 1911: 6-9; Trechmann, 1917; Benson, 1921; Waterhouse, 1965:990-998). Where few or no fossils were found, the rocks were subdivided on lithology, and sometimes on the presence of ‘annelid’ traces (Chapter 4). Although the few fossils that were found pointed to a Mesozoic age, the idea that the bulk of the greywackes including the Southern Alps belonged to Hector’s Carboniferous Maitai series (Hector, 1886) remained fixed among Survey geologists, and continued to be a serious stratigraphic problem until the 1940s (Harrington, 1999: 14). The greywackes were usually said to be of Devonian, Carboniferous or Permo-Carboniferous age, while the
schists were assumed to underlie the greywackes and were sometimes considered as old as the Cambrian period (Park, 1909a).

Fraser and Adams (1907) followed McKay’s example in dividing the Coromandel greywacke basement rocks into three series, but gave them new names and allocated younger ages. Their ‘Manaia Hill Series’ was dated as Jurassic because of the presence of belemnites and a portion of an Inoceramus shell. The ‘Tokatea Hill Series’ and the ‘Moehau Series’ were seen as older, ‘pre-Jurassic’ rocks on appearance and their apparent stratigraphical position. Other new stratigraphic series defined within the greywackes included the ‘Waipapa Series’ of Northland (Bell and Clarke, 1909) and what was thought to be the early Mesozoic or Carboniferous ‘Arahura Series’ on the western slopes of the Southern Alps of Westland (Bell and Fraser, 1906). Bell and Clarke were not prepared to be any more precise when they suggested that the presence of basaltic lavas and limestone indicated that their Northland Waipapa Series was of Late Paleozoic or Early Mesozoic or perhaps even Middle Mesozoic age. They were aware that McKay had long since decided that diabasic lavas (basalt) associated with limestones within the greywackes in Canterbury were of Triassic age (p.80), and the presence of basic lavas at Whangaroa also suggested a Triassic or Jurassic age to McKay (1894a).

The Westland greywackes

Haast (1879: 256) had described an ‘Azoic’ Westland formation consisting of ‘older sedimentary and metamorphic rocks’ lying to the west of the Gneiss-granite formation of the Southern Alps and to the west of the ‘Crystalline’ rocks figured on cross-sections accompanying Hector’s 1873 geological map (Figure 4.16, p.94). McKay (1894a) believed that this Westland formation passed ‘insensibly’ westwards into the Maitai of the Southern Alps and formed part of the denuded western anticlinal limb (Figure 4.21, p.107). Consequently, McKay (1894b) correlated this Westland formation with the greywackes on the western slopes of the Southern Alps and the Carboniferous Maitai Series (Figure 5.5).

Bell and Fraser (1906) divided McKay’s Maitai rocks in the Hokitika subdivision (Figure 5.4) into two series: the Arahura Series (greywackes and schists lying parallel to and part of the Southern Alps and with a general north-easterly strike), and the Kanieri Series, occurring in small areas to the westward of the granitic belt (Table 5.1, Figures 5.5, 5.6). Both series were considered to be of Mesozoic age or older, and Morgan (1908: 31) correlated his Greenland Series in the Mikonui subdivision with Bell’s Kanieri Series. Although the ‘grauwackes and argillites’ of the Greenland rocks looked similar to those of the Arahura Series, they were less strongly folded and had a general direction of strike of north-west and south-east, almost at right angles to that of the Arahura rocks. According to Morgan, the two sets of rocks were separated by a ‘great reversed fault’.
Table 5.1: Classification of the Westland greywackes 1894 to 1908

<table>
<thead>
<tr>
<th>McKay 1894</th>
<th>Bell &amp; Fraser 1906</th>
<th>Morgan 1908</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maitai series (Carboniferous)</td>
<td>Kanieri Series (Early Mesozoic (?) or Carboniferous)</td>
<td>Greenland Series NW strike. Look less disturbed and younger than the Arahura series.</td>
<td>'Undifferentiated and Doubtful Palaeozoic' and Ordovician Aorere Series (Morgan, 1922). Much older than the greywackes</td>
</tr>
<tr>
<td>Maitai series (Carboniferous)</td>
<td>Arahura Series (early Mesozoic (?) and earlier)</td>
<td>Arahura Series. Probably Carboniferous and earlier. (a) Less altered 'greywackes' and argillites (b) Microschists; (c) Lower gneisses and schists;</td>
<td>Western margin of the Southern Alps, e.g. Lillie (1951) Plate 28. Part of the greywackes</td>
</tr>
</tbody>
</table>

Fig 5.5: McKay's geological sketch map of Westland, 1894 in which he correlated the Carboniferous and Devonian Maitai greywackes of the Southern Alps (blue) with what seemed to be similar rocks to the west. The two sets were separated by Bell and Fraser (1906) and Morgan (1908). This is one of the lithographed and coloured maps published by Hector's Survey in the late 1880s and 1890s. Improvements included a scale of miles, north arrow, increased topographic detail, and colour. 50% original size. Modified after McKay, 1894, New Zealand Geological Survey Reports Geological Explorations.
The Westland greywackes: Successive name changes and age determinations for these ancient Westland greywackes, with even more ‘ups and downs’ than the Maitai Series, are traced in detail by Waterhouse (1965: 944-946). After the discovery of the Alpine Fault in 1941 these ancient but comparatively young-looking Westland greywackes were confirmed as quite separate from the ‘Undifferentiated Jurassic-Triassic-Permian’ greywackes of Willett (Marwick, 1948). Later, Reed’s pioneering petrographic review of all greywackes in New Zealand (1957: 20) revealed that the ‘Waiuta and Greenland Group’ greywackes are mineralogically different from those of Wellington, consisting of ‘plentiful, large … sub-angular to sub-rounded crystals of quartz set in a finer-grained … partly recrystallised matrix’. These are described today as ‘quartzose flysch’ (P.F. Ballance, pers. comm.) A comparatively modern description of the Greenland and Waiuta Groups, once thought to be pre-Cambrian, is available in The Geology of New Zealand (Nathan, 1978), and is being updated in the new QMAP 1:250 000 sheets.

The recognition of terranes in the 1980s confirmed that the Westland greywackes, now thought to be a part of the Buller terrane (Mortimer, 2003: and references therein), have quite different origins from and separate, and much longer geological histories than, the cluster of greywacke-dominated terranes of eastern New Zealand.

The Maitai Problem and rivalry between Park and Marshall

In 1900, geologists had the choice of using Hector’s simple stratigraphic scheme (1886), or Hutton’s more sophisticated arrangement of nested series and systems (1899). Following the dissolution of the first New Zealand Geological Survey, further development in building the New Zealand stratigraphical column lay with the two University of Otago rivals, James Park (1857-1946), Professor of Mining (1902-1931), and Patrick Marshall (1869-1950), lecturer and then Professor of Geology (1901-1917). The intense personal antagonism between these two elite geologists resulted in acrimonious and painful clashes (Greene, 1982: 190; McLean, 1996). Their most famous confrontation occupied two protracted, exhausting public meetings on the subject of glaciation in New Zealand that went on long into the night (Anon., 1909; Watters, 1997; Hocken, 2002). The two men competed in the publication of their textbooks on the geology of New Zealand (Park, 1934), and geologists’ oral history recounts how the hostility between Park and Marshall was so great that they looked away from each other as they passed in the corridor (A.P. Mason, pers. comm.) Park may even have had a hand in Marshall’s resignation as Professor of Geology in 1917 (Hocken, 2002).

The rivalry between these two fine geologists reflects the state of uncertainty regarding the New Zealand stratigraphic column. The credit for establishing a reliable column representing the sequence of sedimentary deposition in New Zealand could still be snatched by either man and was thus fair game. In contrast to Hector and his team who aimed to subdivide sets of rocks into smaller and smaller packets, both Park and Marshall followed Hutton’s method of grouping series and formations into large systems.
Chapter Five

Figure 5.6: Map of the South Island showing most localities mentioned in the text. Most work on the older rocks in the period 1900-1950 was carried out in the South Island, but also see Figure 5.4 showing areas covered by New Zealand Geological Survey Bulletins 1905-1965.

Figure 5.7: Locality map of Nelson region. Most cross-sections that were made to illustrate the configuration of the rock groups (Figure 5.13) were based to the south-west of the city between B and C, and between the Dun Mountain mineral belt, marked D and across M, the Malaita Group, and towards R. Recent sediments. 70% original size. Cf Figures 12.11, 12.12. Modified after Bruce (1962) Transactions of the Royal Society of New Zealand.

Key to Symbols: B = Volcanic Group; C = Otago Intrusives; D = Mineral Belt; V = Te Anau Volcanics (from "The Geological Map of New Zealand 1: 2,000,000", 1958).
In addition, Marshall was extremely cautious about subdividing formations at all without good evidence for breaks or unconformities of any kind (for example Marshall, 1911: 20). He described New Zealand as a ‘land of fierce geological controversy’ (1912b), and because of the importance accorded to controversy in geology by historians (for example Greene, 1982), an account of how Park and Marshall arrived at their very different interpretations of the pre-Cretaceous geology of New Zealand is given here.

The state of paleontology

Little expert work had been done on Mesozoic fossils since Zittel worked on Hochstetter’s collection in the 1860s, and there was further difficulty when geologists were not always specific about the exact locations of their collections (Marshall, 1911: 7). Of particular importance was the repeated mistaken identification of the numerous prismatic or fibrous shell fragments in the Maitai beds as the Mesozoic genus, *Inoceramus* (Figure 5.8). Because of the correlations made by Hector and McKay (Chapter 4), the stratigraphical classification of all rocks of the Southern Alps and of the North Island ranges rested entirely on the geological interpretation of the succession of basement rocks within this small tract in Nelson (Figures 5.7, 5.9) and its poorly preserved fossils (Marshall, 1911: 17; Harrington, 1989). Equally important was the ability to make adequate field interpretations of what outcrops could be seen.

James Park’s Hokonui system

Park, appointed Professor of Mining at the University of Otago in 1901, carried out a busy programme revisiting, redefining and reorganising the classification of the South Island Paleozoic and Mesozoic rocks (1903a, 1903b, 1903c). He took into account that Hector’s Carboniferous Maitai formation, including the greywackes, was a ‘principal mountain-builder’. Like Haast, Park described the rock sequences in enthusiastic terms: an ‘extraordinary pile of Paleozoic and Mesozoic rocks’, ‘shales and sandstones in endless variety’, ‘great assemblage of beds’, ‘colossal pile’, ‘magnificent pile of clastic rocks’.

Following a visit to Nelson, Park (1903a: 82-83) was wapishly critical of McKay’s interpretation of the Maitai sequence. Like Hutton in 1873, Park assumed the Maitai rocks were of Jurassic age because of the presence of prismatic shell fragments that he too, thought to be *Inoceramus*, the ‘characteristic fossil of the Maitai formation in Nelson’ (1903a, and Figure 5.8). This convinced him that the Maitai beds were not overturned, as McKay believed, and that the fossiliferous Triassic Wairoa series was conformable below the Maitai formation.

Park noted the remarkable ‘harmony’ between the fossiliferous Triassic beds of Nelson and those of Nugget Point in Otago (Figure 5.6), leading to the idea that the ‘clearly’ Jurassic Maitai series of Nelson was correlated with the Jurassic Mataura series in Otago (part of the Hokonui). Because the name ‘Maitai’ had become ‘almost synonymous’ with ‘Carboniferous’, Park (1903b) dropped ‘Maitai’ in
Chapter Five

Paleontological Troublemakers of the Twentieth Century

The 'Dun Mountain inoceramus'

Continued from Chapter 4

Park (1903) believes that the prismatic fragments at Nelson are inoceramus. Attacks McKay's stratigraphic analysis and moves all Maitai series to a Jurassic Mataura series

Park (1909) now believes the 'inoceramus' fragments are inorganic. Returns the Maitai series to the Carboniferous, similar to McKay's scheme

Marshall (1911) also identifies the 'Dun Mountain Inoceramus' as a Jurassic form. Other fossils found of poor quality and unidentifiable. Sets up his encompassing Trias-Jura Maitai System

Trechmann (1917): identifies the Jurassic 'Dun Mountain inoceramus' as Aphanala, rediscovers McKay's fossil locality, correlates Maitai strata with Permian-Carboniferous of New South Wales. Destroys Marshall's great Maitai System

Marwick recognises need for a new generic name for a similar fossil from Clinton (1925), see Figure 6.13

Marwick (1935): erects new Permian genus Maitai and species trechmanni to replace the name Aphanala

Benson notes that the prismatic fossils are different from Aphanala (1921, first p.62)

Waterhouse (1958): Moves Maitai to Atomodesmo, with A. trechmanni and A. marwicki, Permian

Campbell and Warren (1965) identify a Permian Atomodesmo zone in South Island Torlesse

Figure 5.8: The 'Dun Mountain inoceramus' continued to create problems into the twentieth century when it was conclusively shown to be of Permian age and much older than the real Jurassic and Cretaceous inoceramus. Since Trechmann's time, the genus has undergone further name changes, and is now seen as the genus Atomodesmo, a reliable indicator of Permian deposition.
favour of ‘Mataura’, and at the same time renamed the Triassic Wairoa Series ‘Shaw’s Bay Series’. The two renamed series now formed a great ‘Juro-triassic’ (sic) or ‘Juro-Permian Hokonui system’ (Figure 5.9) in which the Mataura series (with the greywackes) became the ‘principal mountain-builder in New Zealand’ (Park, 1903a: 443). Park (1903a) concluded this phase of his stratigraphic reorganisation with the claim that a Carboniferous Maitai had ‘imposed many insoluble problems on the geology of New Zealand’. In moving the Maitai to its ‘natural’ position in the Jurassic (as the Mataura series) the way was paved for his new systematic subdivision of the Lower Mesozoic rocks. The name ‘Maitai’ had now disappeared — but only temporarily.

**Hokonui or Hokanui**: In this chapter ‘Hokonui’ or ‘Hokonui System’ usually refers the fossiliferous Triassic and Jurassic beds of Southland, Nelson and Kawhia-Port Waikato, equivalent to today’s Murihiku Terrane. In 1911, Park included the very different greywackes in his Hokonui System (see below).

**The Gondwanan system and Gondwanaland**: The name ‘Gondwána system’ was given to a very thick, widespread Carboniferous to Jurassic stratigraphic sequence in India that included coal beds with the characteristic Permian fossil plant *Glossopteris* (Geikie, 1903: 1058, 1079). Edouard Suess (see Chapter 6) borrowed the name ‘Gondwana’ for his large Paleozoic southern continent, composed of an amalgamation of Africa, India and Australia (1906, Vol.2: 254; Oldroyd, 1996: 334). Gondwanaland was supposed to have been separated into the modern continents by subsidence of the lands between them. The presence of glacial tillites in the lower Permian and the remains of *Glossopteris*, and a reptile, *Mesosaurus*, in the higher formations characterised typical Gondwana sediments. Hector (1886: 75) compared the Permian Oreti series of Southland with the ‘base of the Gondwinda series in India’, and Park (1903b) likened his ‘mountain-building’ greywackes to the ‘celebrated Gondwana system’ of India because of their age, vastness, sediments and tectonic importance. Park constantly looked for a connection with Suess’s Gondwanaland and believed he saw a resemblance between rocks of the Hokonui System and the Gondwana system of India, the Karroo of South Africa, and systems in New Guinea and New South Wales (1909). He searched for evidence of Permian glaciation and hopefully compared a ‘great conglomerate’ at the base of the Wairoa series (Triassic of Hokonui System) with that at the base of the Gondwana System, even though it contained no polished or striated blocks. Because of the lack of *Glossopteris, Mesosaurus* and the tillites, he had to settle for locating New Zealand on the offshore shelf of such a continent. (Park, 1920)

Park then explored the Kurow schists of Mount Mary in North Otago2 where McKay had found fossils in 1880. These schists had previously been included in Hector’s Devonian Kakanui series (1865), Hutton’s Kakanui formation (1875), and Haast’s Waihao formation (1879). The deformed fossils were thought by Hutton to be similar to the ‘Permo-Carboniferous’ of New South Wales, and samples were sent to Germany for identification. Although the Kurow schists passed ‘insensibly’ into the indurated greywackes nearer the summit of Mount Mary, Park still believed they were part of a separate, older system and separated the rocks into two series.

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2 Shown as Mt St Mary on the Geological Map of New Zealand 1:250 000, sheet 23, Oamaru, 1965
James Park's Hokonui System

| JURASSIC | Hector 1885 | Mataura series Putataka series Flag Hill series |
| TRIASSIC | Catlin's River series Bastion series Otapiri series Walroa series |
| PERMIAN | Oreti series Kaihiku series |
| CARBONIFEROUS | Maitai series |
| DEVONIAN | Te Anau, Reefton series Kakanui series |
| SILURIAN | Baton River ser. Aorere series |
| ORDOVICIAN | Undated foliated schists |
| CAMBRIAN | Manapouri system |

**Trans.NZ Institute 1903a, b, c**

**Park, 1909, Outline of New Zealand Geology**

**Park, 1910, The Geology of New Zealand**

**Park, 1921, Western Southland, NZGS Bull.23 n.s.**

**Hokonui System**

**Aorangi Series at base of Hokonui System**

**Aorangi Series 'Mountain-builders'**

**Kaihiku Series (Perm-Trias)**

**Kaihiku Series**

**Mount Marv Series (Permo-carb.)**

**Mataura Series - temp**

**Mataura Series Putataka Series**

**Otaperi Series**

**Walroa Series**

**Park's 'mountain-builders'**

**Kakanui Series (Perm-Trias)**

**Kakanui Series**

**Aorangi Series 'Mountain-builders'**

**Te Anau Series**

**Te Anau System**

**Maitaian System (Permo-Carboniferous) Nelson**

**Wangapeka Series: nw Nelson**

**Wangapeka Series (Baton R., Mt Arthur, Reefton)**

**Kakanui Series (Otao)**

**Maniototo Series**

**Maniototo Series: Otao, Westland**

**Canterbury to**

**Batonian System**

**Manapouri System**

**Manapouri System**

**System: Permian to**

**Hokonui System**

**Includes 'principly 'mountain-builders'**

**Hokonui Range (Perm-Jurassic)**

**Figure 5.9: Timeline tracing the development of Park's pre-Cretaceous stratigraphical schemes from 1903 to 1921. Park was the first to separate the greywackes from Hector's Maitai Series (1909), and attached them to a (mainly) Mesozoic Hokonui System. The greywackes were incorporated in his Aorangi Series (1910) and relegated to the Permian at the base of the Hokonui System. All of the schists were considered to be much older than the greywackes, and the Otao (Haast) schists were classified with his Cambrian-Ordovician Manapouri System.**

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Figure 5.10: Sketch Map of the Geology of New Zealand, 1: 3,000,000. Like Hector, Park used European time divisions rather than his own New Zealand system and formation names. Park's Perm-Jurassic (Hokonui System, blue) includes both the greywackes and the fossiliferous Hokonui sequences. The very large Ordovician to Carboniferous (Manapouri and Te Anau Systems, brown) included all the semi-schists and the Westland greywackes. Park's orthodox belief that the greater the metamorphism the older the schists (Maniototo Series, pink, Cambrian age) led to the interesting concentric pattern given to the Otago schists. Original size 48.1 x 32.6 cm. Park (1910). The Geology of New Zealand: an Introduction to the Historical, Structural, and Economical Geology.
Because the ‘prevailing philosophical creed’ meant that ‘all formations recognizable in Europe should be found represented in New Zealand’ (Thomson, 1913: 14), Park reactivated Hector’s old Devonian Kakanui series to contain the lower schistose rocks, moved it to the Carboniferous, and erected a new Permo-Carboniferous ‘Mount Mary series’ for the overlying, less metamorphosed rocks (Figure 5.9). Park was now satisfied that this new series filled the Permo-Carboniferous gap in the New Zealand geological record (left by removing the Maitai series). His stratigraphic subdivision of the southern greywackes and schists (Figure 5.9) was concluded with the introduction of a Palaeozoic ‘Maniototo Series’ (Otago schists) below the Kakanui and Mount Mary Series to replace Hutton’s Wanaka series and Hector’s Foliated Schists (Park, 1906).

After several years’ reflection and the production of several Survey Bulletins, Park (1909b) revised his views regarding the age of the Maitai sequence. The characteristic small, gash-like rents made on rock surfaces when fragments of prismatic shells like that of Inoceramus are weathered were now re-interpreted by Park as ‘contraction rents’ caused by the leaching away of some fibrous mineral (1910: 50-52). This meant the Maitai rocks were not necessarily of Jurassic age. Park was also aware of an inversion of Tertiary rocks against Triassic rocks to the west. He recanted and gracefully conceded that McKay was right, after all, about the inversion of the Maitai and Wairoa Series by an ‘overthrust fold’, and declared himself to be in ‘complete agreement’ as to the Carboniferous age of the Maitai series. Park thereupon removed the Maitai sequence from the Jurassic Mataura Series, and reinstated it as a Carboniferous Maitai Series, but very different from Hector’s Maitai.

The Maitai Series and Hector’s Te Anau Series were now seen as similar. Hutton and Park (1909b: 434-5) both regarded the two series as identical and Park used the name Te Anau Series for the lower portion and the name Maitai Series for the upper portion of a single great succession of slates and greywacke that constituted his new Maitai System (called Te Anau System in the 1910 textbook). Because it had not ‘been identified in any other part of New Zealand’, Park restricted his reinstated Maitai Series to the foothills of the Dun Mountain ‘olivine mineral belt’. At last, the mountain-building basement greywackes of Canterbury, the Southern Alps and the North Island ranges were separated from the ‘ups and downs’ of the Nelson Maitai (Figure 5.9). Any new determination of the age of these Maitai beds would no longer affect ideas on the age of the greywackes.

Park completed his revision of Hutton’s Hokonui system (1909b) by using several of the old Survey’s Mesozoic series names to create five ‘Permo-Jurassic’ divisions based on the fossiliferous strata of Southland, Otago and Port Waikato. Park included the greywackes in this reformed Hokonui System, regarding it as ‘the greatest continuous succession of sediments in New Zealand’ ranging in age from Permian to the close of the Jurassic (Figures 5.9, 5.10). In this scheme the greywackes were not placed in
Figure 5.11: Marshall amalgamated all pre-Cretaceous rocks except for the very old north-west Nelson and Fiordland rocks into his Trias-Jura Maitai System. Marshall had no need to find a representative of every geological period in the standard European stratigraphic column.
any of the five named series, and presumably, their age could be taken as ranging anywhere from the Permian through to the Jurassic, as already suspected by Hector, McKay and Haast. However, Park then (1910: 66) tidily slotted all the greywackes of the Southern Alps and the other great ranges into a new ‘Aorangi Series’ at the base of the Hokonui system (Figure 5.9). Although Mesozoic fossils had been found in the greywackes (Waterhouse, 1965: 976), Park assigned a Permian age to this Aorangi Series because they were ‘conformably’ overlain by the supposedly younger ‘Permo-triassic’ Mount Potts and Mount St Mary beds, and above the ‘Carboniferous’ Maitai Series.

**Patrick Marshall’s Maitai system**

Marshall (1911; 1912: 178-88) combined all of Hector’s pre-Cretaceous series (from the Carboniferous Maitai series to the Jurassic Mataura series), all the Foliated Schists, and all of the Paleozoic greywackes of Westland to form his huge Maitai System (Figures 5.12, 5.13). Marshall avoided subdividing a sequence of sedimentary rocks until some kind of break could be clearly demonstrated, claiming this was because of the way in which the stratigraphical relations of the younger rocks (Upper Cretaceous and Tertiary) of New Zealand had been previously dealt with (Marshall, Speight and Cotton, 1911). He complained that other geologists had each interpreted the same rocks differently, had described unconformities and placed them in different positions in the rock series, and in ‘almost every case the breaks recognised by one have not been admitted by others’. However, in a country riddled with hidden faults and stratigraphic breaks Marshall’s unconventional reluctance to recognise faulting, and then only as a ‘last resort’ (A.P.Mason, pers.comm.), was sure to lead to trouble.

Like Park, Marshall sometimes worked on contract for the New Zealand Geological Survey. With Bell and Edward de Courcy Clarke (1880-1956) he took part in a survey of the Dun Mountain subdivision in Nelson (Bell et al., 1911), including the Maitai sections in the Wairoa Gorge and Eighty-eight Valley (Figure 5.7). Bell’s survey team searched for fossils but did not relocate McKay’s 1878 localities and found only ‘unsatisfactory’ specimens including ‘worm-tracks and the obscure remains ... called *Inoceramus*’ consisting of numerous prismatic fragments, but no complete shells. Only casts and impressions of difficult-to-identify brachiopods were discovered, with no recognisably Carboniferous specimens. The steeply dipping Maitai rocks were seen as sharply folded, but Marshall was doggedly certain that ‘with the striking exception of the Richmond fault’ (Waimea Fault, Figure 5.7) the region had ‘not been affected by fault movements of any importance’. No faults were seen in the ‘excellent sections’ in the river-valleys, and there were ‘no important planes of rock movement inclined to the direction of strike’. Any repetition or suppression of strata in cross section could be explained by the observed folding (Figure 5.13D), and therefore, there were ‘few strike faults of any importance’. Marshall noted fault escarpments on the western slopes of the Richmond Hills, but because they had only a small throw, they were thought to be of little structural importance. Marshall concluded that there was no inversion of the Maitai and
Triassic Wairoa beds and the Maitai rocks were of Trias-Jura age and younger than the Wairoa beds (Bell et al., 1911: 14-15). The ‘deceptive appearance of conformity between the Trias and the Maitai’ (Trechmann, 1917) led Marshall to see no reason for subdividing the rocks into a number of separate formations. He therefore replaced the five members of McKay’s Upper Devonian to Upper Triassic series of 1878-79 and Park’s Hokonui and Maitai systems of 1909 with a single Trias-Jura Maitai System (Figure 5.11).

Marshall (1911: 17) regarded this small tract of land in Nelson as geologically the most important in New Zealand, because the ‘Maitai shales and greywackes are the same rocks which form such important mountain masses’. He believed that a ‘continuous outcrop’ of these Maitai rocks existed from Nelson southwards almost to Kakanui in north Otago where they become metamorphic. They could therefore all be included in his Trias-Jura Maitai System (Figures 5.11, 5.12), with the neighbouring ‘greywackes and shales’ of the Southern Alps. All the paleontological evidence based on fossils from Mt Potts, Nugget Point, the Hokonui Hills, Clent Hills, Ashley Gorge and the Okuku Range indicated a Mesozoic age. All of the similar-looking North Island basement ‘grauwackes’ were also included in this huge new Maitai System. Marshall was ‘compelled’ to group all these basement rocks as Trias-Jura until unconformities were established, or until there was sufficient fossil evidence to divide them into two or more series. Unlike Park, he did not need or expect to find a representative of every formation recognised in Europe, and was unconcerned about the very large time gap in his scheme between the end of the Silurian and the beginning of the Mesozoic period.

A second radical aspect of Marshall’s system was his inclusion of all of Hector’s Kakanui Series and Foliated Schists (=Hutton’s pre-Cambrian Wanaka System of Otago) in his all-inclusive Maitai System, because he believed that the schists were metamorphosed versions of the neighbouring greywackes and shales (Chapter 6). Marshall’s reasons for this revolutionary classification of the South Island schists were:

- That no unconformity had been shown to exist between the Trias-Jura of Southland (Hokonui) and the neighbouring schist.
- The Maitai rocks of Canterbury pass by ‘insensible gradations into schists’ (Marshall, 1912a: 181). The gradual transition from greywackes through phyllite and mica schist to highly crystalline schists had been observed in several places on the western slopes of the Southern Alps (Morgan, 1908).
- The fossiliferous Triassic beds of Canterbury (Mt Potts, Clent Hills, see Figure 9.4, p.288) are apparently conformable with the greywackes and shales.
- That altogether, no unconformities of any kind were known between the Trias-Jura and the schists of Otago although they extended ‘side by side for 200 miles’ (Marshall, 1911: 18).
Figure 5.12: Map of New Zealand, Geologically Coloured. 1: 2,900,000. This map accompanied Marshall’s textbook on the geology of New Zealand. Marshall’s Trias-Jura Maitai System (red-brown colour modified by computer) included the Westland greywackes and the old Maitai and Te Anau Series (Maitai and Caples Terrane) but was differentiated from the fossiliferous Hokonui System (deep pink). Marshall used New Zealand system names as well as the European time divisions, but he attached no presumed age to the “Metamorphic Schists” (green). The Dun Mountain belt is shown in Nelson and South Westland. Original size 340 mm X 500 mm. Modified after Marshall (1912) The Geology of New Zealand.
That if the schists were older than the Trias-Jura then pebbles of schist should appear in the latter, but Marshall knew of none.

That thin-section studies indicate gradual changes in the mineralogy as the greywackes pass into schists (Marshall, 1911: 21).

The connection that Marshall made between the schists and the greywackes was not an entirely novel idea in New Zealand. Bell and Fraser3 (1906: 43) introduced the possibility of a gradual transition between greywacke and schist in the Hokitika subdivision. Similarly, Park (1908: 28) traced a gradual transition from schist upwards into greywacke containing Permian or Permo-Carboniferous fossils near Mount St Mary. Park claimed this to be the first positive evidence that the Otago schists were of less antiquity than hitherto supposed.

Marshall’s scheme destroyed

Although Marshall introduced some important new ideas, many geologists saw his Maitai System as being so all-inclusive that it was meaningless. Marshall’s scheme was never generally accepted and was soon destroyed by new fossil finds. In 1915, Charles Taylor Trechmann (1885-1964), a cheerfully eccentric English geologist of independent means (Fleming, 1965; Mason, 1993b) visited New Zealand being interested in the marine Triassic of the ‘Alpine facies’ (Park, 1925). Besides collecting and borrowing numerous Hokonui fossils, including some from Marshall’s collection, he set out to find the Maitai Limestone fossils in the Wairoa Gorge and other localities (Trechmann, 1917; Fleming, 1965). Trechmann and his companion, Dr J.A.Thomson, carefully followed McKay’s 1878 instructions and duly found a number of Paleozoic fossils in the Wairoa Gorge, at the Dun Mountain tramway line and at Wooded Peak (Fleming, 1965).

After returning home to England, Trechmann wrote to Marshall, chatted about zeppelin raids, and blithely told Marshall that the large bivalves with the Inoceramus-like prismatic structure he found in Nelson were like Aphanaia of the Australian ‘Permo-Carb’, which would ‘lift a weight off your minds’ (Marshall, 1906-1949: 1916). The fossils from the Maitai Limestone also included Paleozoic brachiopods and the coral, Zaphrentis. These identifications, overwhelmingly favoured a ‘correlation of these beds with the marine Permo-Carboniferous of New South Wales and Tasmania’ (Trechmann, 1917). Trechmann kind-heartedly hoped that Marshall would not ‘mind my difference of opinion’ (Marshall, 1906-1949: 1917), but his conclusion meant that the Maitai sequence was of Paleozoic age after all, just as McKay and Hector had said. Marshall’s huge all-inclusive Triassic-Jurassic Maitai System was devastated and now ‘lay in ruins’ (Waterhouse, 1965: 962).

3 Colin Fraser (1875-1944)
Five Maitai Sections: 1871-1921

Davis (1871) Part of one of several posthumously published sections based on Davis's field notes. Davis recognised that the Maitai rocks formed a syncline but was unable to analyse his field data before his tragic death. Scale about 6000 ft to the inch.

McKay (1879) indicated synclinal structures in both the Maitai and Wairoa Series. Faults separate a lens of (Permian) Kahiuku rocks from the Triassic Wairoa sequences to the west and the Maitai beds to the east. Faults have been emphasised. The original diagram has been reversed east-west. No scale supplied.

Park (1909) placed a boldly marked reverse fault (emphasised) between the Wairoa Series (4) and the Maitai Series (3), with the Te Anau Series (2) to the east of the Dun Mountain serpentinite belt (5).

Marshall's fault-free section (1911) indicates his reluctance to accept unconformities or faults without good evidence. His structural interpretation involves a sequence of closely folded but conformable beds, justifying the inclusion of all these rocks within a single Trias-Jura Maitai System.

Benson (1921) emphasised the peridotite units of Dun Mountain (4) and clearly separated the Permian (Maitai) greywacke (1) from the Triassic beds (2, 3) with a thrust fault.

Figure 5.13: A selection of five cross-sections representing interpretations of the geology of the Dun Mountain-Maitai sequence and the relationship between the problematical Maitai sequences and the Triassic Wairoa rocks. No two traverses were drawn through exactly the same location (Figure 5.7). While the sections display an assortment of artistic styles, they also indicate an accumulation of data over the years. Regardless of the differences in presentation, the data was interpreted in one or other of two alternatives. Either there was a fault between the Triassic and the Maitai, or there was not. Sections A, B, D: New Zealand Geological Survey; Section C: New Zealand Mines Record; Section E: Australasian Association for the Advancement of Science.
Trechmann revisited New Zealand several times and examined many fossil localities, often in Marshall’s company. He produced a long-overdue paleontological review of the New Zealand Triassic and Jurassic sequences accompanied by a commentary on the general state of Mesozoic stratigraphy (Trechmann, 1918, 1923). The fossils of Mt Potts, Mount St Mary, Kaihiku Gorge, and Nugget Point were confirmed to be of Triassic age, and not Permian or Carboniferous or Permo-Carboniferous as had been believed for so long. Definite Permo-Carboniferous fossils were found only at Wairoa Gorge in Nelson (Marshall, 1917) leading Marshall to admit that some sort of discontinuity must be present between the Maitai rocks and the Mesozoic rocks, perhaps the thrust plane described by McKay. This new distribution of ages also supported Park’s limitation of the Maitai Series to Nelson and their separation from the greywackes, so that the greywackes were now set apart as a Mesozoic series.

Marshall’s stratigraphical downfall was followed by a long-standing antagonism between him and at least some Survey officers (Marshall et al., 1934). Eighty years later I was warned that Marshall’s book was singularly misleading and could not be relied upon. However, neither Marshall nor Park were incompetent and both maintained a huge, mutually respectful correspondence with well-known overseas geologists among whom they were esteemed for their own contributions towards the solution of many geological problems (Watters, 1997).

Marshall’s work in the Maitai affair was important because:

- It reinforced the idea that the greywackes that formed New Zealand’s main ranges were of Mesozoic rather than of Paleozoic age (to page 135).
- It introduced the hypothesis that the greywackes passed into the schists by increasing metamorphism and that both sets of rocks were of the same age.

Many geologists disbelieved Marshall’s surmise that the vast areas of Otago schist were altered versions of these Mesozoic greywackes (Chapter 6). Indeed, as late as 1948, the Survey mapped them as of Paleozoic age and separated them from the Undifferentiated Jurassic-Triassic-Permian greywackes and argillites of the eastern basement rocks (Marwick, 1948).
# The Maitai Problem: ‘what we now know’


<table>
<thead>
<tr>
<th>Geologist</th>
<th>Year</th>
<th>Inverted?</th>
<th>Conformable?</th>
<th>ID ‘Inoceramus’?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hochstetter</td>
<td>1859</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Richmond sandstone with Monotis. Triassic. Red and green Maitai slates. Triassic. But Hochstetter’s Nelson map shows this area as Paleozoic, so was he sure? (Harrington)</td>
</tr>
<tr>
<td>Hector</td>
<td>1870</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>‘Inoceramus’ with Maitai slates, placed at base of Mesozoic between Triassic Wairoa series (Richmond sandstone) and ‘Permian’ Kaihiku series.</td>
</tr>
<tr>
<td>Davis</td>
<td>1871</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Maitai series forms a syncline with NE strike. Triassic because of Inoceramus and annelid trails.</td>
</tr>
<tr>
<td>Hutton</td>
<td>1873</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Correlated with Kaikoura district. Jurassic Maitai overlies Triassic Wairoa series. Made to reverse this by Hector.</td>
</tr>
<tr>
<td>Hector</td>
<td>1873</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Maitai series is upper Paleozoic, below Te Anau series.</td>
</tr>
<tr>
<td>McKay/Hector</td>
<td>1878</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Fossils show Maitai Series is Carboniferous. The ‘Inoceramus’ represents a new genus. Wairoa series with Monotis is Triassic. Infers Triassic Wairoa beds faulted into position.</td>
</tr>
<tr>
<td>McKay/Hector</td>
<td>1879</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>As above. Quotes Davis that ‘rocks in inextricable confusion’ in the Dun Mountain mineral belt.</td>
</tr>
<tr>
<td>Park</td>
<td>1903</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Triassic Wairoa series conformable below Jurassic Maitai formation. Based on presence of ‘Inoceramus’</td>
</tr>
<tr>
<td>Park</td>
<td>1909</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>The ‘Inoceramus’ an inorganic artefact. Maitai formation Carboniferous.</td>
</tr>
<tr>
<td>Bell, Clarke</td>
<td>1911</td>
<td>No</td>
<td>Yes ?</td>
<td>Yes</td>
<td>Maitai formation Trias-Jura on presence of ‘Inoceramus’.</td>
</tr>
<tr>
<td>&amp; Marshall</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trechmann</td>
<td>1917</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Maitai formation Permo Carboniferous. Trias beds form a long, faulted synclinal strip. Both synclines faulted and thrust over towards the west or north-west.</td>
</tr>
<tr>
<td>Wellman</td>
<td>1946</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Maps Eighty-eight fault, notes scarp (at 1948 Survey Conference).</td>
</tr>
</tbody>
</table>

What exactly was it about the Maitai beds at Nelson that caused so much trouble for so long (Table 5.2)? Problems to do with Permian paleontology and stratigraphy are discussed in detail by Waterhouse (Waterhouse, 1965: 955-970). Park, Marshall and other geologists had examined the same region and saw much the same rocks, but developed very different ideas as to their meanings (Figure 5.13). Park’s and Marshall’s interpretations of similar field data filtered through their dissimilar stratigraphical theories led to the creation of two very different geological maps of New Zealand (Figures 5.10, 5.12).

No consensus was reached as to which stratigraphic scheme was unreservedly acceptable, and nothing was properly resolved, and as time passed, protagonists came and went, retired and died. Even the
collapse of Marshall’s scheme in 1917 did not result in agreement among geologists that Park’s rival scheme was therefore ‘correct’. Stratigraphical uncertainty regarding the relationship between these Upper Paleozoic and Mesozoic rocks remained, in spite of Benson’s syntheses, until at least the 1950s.

For non-geologists and those not familiar with the area, it is difficult to understand why perfectly competent geologists produced such conflicting interpretations of the stratigraphy (Table 5.2). Few drawings or photographs of the hilly landscape and deep, steep river beds in and around the key Maitai and Wairoa valleys are readily available that can tell us of difficulties to do with access to outcrops. Several photographs in the Dun Mountain bulletin (Bell et al., 1911), Campbell’s drawings of the Wairoa River-Mt Heslington area (Campbell, 1974), and Johnston’s recent photographs of the scarp associated with the Eighty-eight Fault (Johnston, 1979, 1982) give some indication of the terrain.

The difficulties to do with the ‘Maitai Problem’ rested mainly on two questions:

♦ The nature of the contact between Hector’s Wairoa Series (Hochstetter’s Richmond sandstone) and the Maitai Series (Hochstetter’s Maitai slates) and the disposition and attitude of the beds.

♦ The real identity of the ‘Dun Mountain Inoceramus’ (Waterhouse, 1958) and therefore the relative ages of the two sets of rocks (Figures 4.14, 5.8).

McKay addressed the major stratigraphic and paleontological problems of the Maitai and effectively solved them in 1878 and 1879 (Chapter 4), but later geologists somehow failed to appreciate his insight, leading to Park’s 1903 redefinition of the Mesozoic rocks and then to Marshall’s difficulties. Perhaps neither man had read or understood McKay’s remarks that the ‘Dun Mountain Inoceramus’ was perhaps a new genus. It would have saved them both much mortification had they done so. When Park’s attention was drawn (1909b) to the possibility that the apparent fragments of ‘Inoceramus’ could actually be mineralogical artefacts, he could honourably change his conclusions about the age of the Maitai rocks and agree that McKay was right. At around this time McKay was working with several assistants on unpacking, sorting and cataloguing fossils collected by the old Geological Survey (Thomson, 1913:13; Mason, 1995). Perhaps McKay allowed Park to see the Maitai brachiopods, but we have no record of this, and neither Marshall nor Bell could have seen those fossils as the collection was then packed away and inaccessible (Thomson, 1913: 19).

Marshall was very sceptical of the use of inferred faults and unconformities to solve stratigraphic problems (see before p.141), although he referred to ‘two remarkable faults’ shown in one of McKay’s cross-sections (Bell et al., 1911: 13), and, if a little doubtfully, to McKay’s views about the formation of the Kaikouras by thrust faulting (Marshall, 1911: 58). He interpreted the complex structures of the greywackes in the Dun Mountain-Maitai regions as ‘sharp folds’ (Bell et al., 1911: 14-15) and opined that any repetition or suppression of strata could be explained by folding (Figure 5.13D). Marshall (1911: 20)
insisted that a ‘very definite unconformity must be recorded’ before the Trias-Jura (greywackes) could be subdivided. Large strike faults exist in the Nelson district but are not readily detected on the ground (P.F. Ballance, pers.comm.), and perhaps Marshall’s hyper-scepticism regarding faults prevented him, unlike McKay, from being alert to field clues pointing to the existence of such faults.

What ‘we now know’ (Rudwick, 1985: 12) is that after Marshall’s scheme collapsed, the Maitai problem lingered on among the Survey geologists (Harrington, 1999). Final resolution of the problem was achieved when Harold William Wellman (1909-1999), an especially skilled geologist, made out the configuration of the various rock sequences. By the mid 1940s he had accumulated enough field experience (his own plus that of previous geologists) of the regional geological structural patterns (Harrington, 1999), so that he could perceive and verify the hidden structures that caused the inversion of the two rock sequences.

Having completed a survey of the serpentines at D’Urville Island early in the Second World War, Wellman, with Hilary James (Larry) Harrington (b.1924) as assistant, was given the task of solving the Maitai problem. They found that the Nelson structure was partly the continuation of a syncline at D’Urville Island, but far more complex. Wellman showed that the west limb of the Maitai syncline was faulted out by a large strike fault (Figure 5.7) with a 10 ft (3m) fault trace that he called the ‘Eighty-eight Fault’ (perhaps the escarpments seen by Marshall, p.141). Further, the rest of the Maitai sequence was broken into long lenses by strike faults with a strike-slip component (Wellman, 1948b: 13). Without the experience gained from working on the simpler structure at D’Urville Island, the faults could have been easily overlooked (Harrington, 1999).

Wellman’s work was not published, except for a summary accompanying the great 1947 map, which quite firmly separated the ‘undifferentiated’ greywackes from the Maitai and Te Anau sequences (Marwick, 1948: 5-6). Some of Wellman’s material was circulated among Survey geologists, and in 1964 some was incorporated into the Marlborough Sheet of the first 1: 250 000 series of the Geological Map of New Zealand (Beck, 1964), and in the current Nelson QMAP (Rattenbury et al., 1998). Both sheets show excellent sections showing the same small region as in Figure 5.13 (cf Figures 5.7, 5.15, 12.11, 1218). With the confirmation that no rocks related to those of the Maitai Group existed east of the Dun Mountain ultramafic belt, any connection between the Maitai rocks and the greywackes of the axial ranges and the stratigraphical ‘Maitai Problem’ finally disappeared (Harrington, 1999).

The major problems of interpretation were related to structure (Figure 5.14). The Eighty-eight Fault is not well exposed as it runs across country through valleys and hills, along riverbeds, and is hidden under soil, pasture, alluvium and bush. Along part of its length it does have an active trace that is visible in aerial photographs (M.J. Johnston, pers.comm). The fault has little resemblance to a cleanly defined
textbook structure, being a ‘gouge fault’ in which the rocks are finely pulverised (Lahee, 1941: 205) forming a pug and crush zone (Johnston, 1980: 27). Wellman (1948b: 13) reported that a ‘wide band of crushed rocks ... hide the contact of the Maitai and Triassic’. Similar strike faults in the region evidently present the same difficulties. In 1871 Davis walked a crush zone along the Whangamoa River without realising its significance (M.J.Johnston, pers.comm).

The geological situation is made even more complicated than thought in 1948 because the contact between the Triassic Wairoa sandstones, now classified with the Richmond Group, and the red and green Maitai slates, part of the Maitai group, has been recognised as much more than a large fault. It is now viewed as a suture between a narrow 2 km wide sliver of the Triassic Murihiku terrane and the Permian-Triassic Dun Mountain-Maitai terranes (Rattenbury et al., 1998). Thus rocks on both sides of the fault are actually of similar age, but belong to the two different, unrelated, terranes (P.F.Ballance, pers.comm.). Far from being an extension of Hector’s Maitai Series, the Canterbury and Wellington greywackes (Torlesse-Pahau Terrane) are separated from the former by two terrane boundaries and possess quite different origins and histories (Figure 5.15 and Chapter 12).
Figure 5.15: A recent terrane map of part of the Nelson region shows six distinct terranes and three mélanges belonging to the eastern province and lying to the east of the Median tectonic Line or Median Batholith (Figures 0.1, 0.6). All the rocks to the east of the Brook Street Terrane were placed in Marshall's Maitai System, and all those east of the Murihi Terrane were included in Hector's Maitai Series. The mélanges include the complex Esk Head Mélange as a suture between the Rakaia and Pahau (Torlesse) terranes. The other two mélanges are associated with the Maitai and Caples terranes. The Drumduan Terrane belongs to the ancient western province and lies west of the Median Tectonic Line. Terranes west of the Drumduan and the Brook Street Terranes are obscured by Quaternary gravels. Cf. Figures 5.7, 12.11, 12.18.

Adapted from Johnston (1990). Geological Map of New Zealand 1: 50 000, Sheet N29 St Arnaud.
Resolution, scientific conflict and personality clash

The ‘Maitai problem’ has been largely forgotten (Harrington, 1999). The matter is settled and today’s geologists get on with their tasks and take the separate origins of the rocks on either side of the Eighty-eight Fault for granted, just as on a larger, global, scale, geologists take the Devonian system for granted (Rudwick, 1985: xxi). Like the Devonian controversy, the partial resolution of the Maitai problem by Wellman in the 1940s set in place a piece of reliable geological knowledge.

Both the Devonian and the Maitai episodes were about a stratigraphical problem concerning the differentiation of particular sets of rocks and were therefore also about competency in fieldwork, the identification of fossils, structural analysis, and in the case of the Maitai problem, the part played by pre-set opinions about how unconformities appear in the field. The lack of palaeontological expertise (Burton, 1965: 31-34), in spite of McKay’s gift for fossil recognition, was always a major cause of uncertainty. It repeatedly led to misidentification of the deceptive ‘Dun Mountain Inoceramus’ and to the Survey’s habitual over-estimation of the age of pre-Cretaceous rocks (Waterhouse, 1965).

This history of the Maitai problem incorporates not one but several successive geological debates, reflecting the very complex and problematical nature of New Zealand geology, including the problem of access to broken and bush-covered country. Most of all, it was a consequence of having to use orthodox methods and theories based on the comparatively stable northern European geological environment. It involves the struggle to make sense of especially difficult geological conditions with inadequate explanatory theoretical backgrounds until after 1950, first with the introduction of geosynclinal theory, and then plate tectonics and terrane theory. Recent work has revealed that the tectonic processes have not ceased, and that westward overthrusting of the east Nelson and Marlborough region has caused reactivation of the Eighty-eight and other faults (Walcott, 1998).

Controversy often involves a network of personal relationships complete with friendships, loyalties, commitments, argument and conflict between the protagonists. Fewer geologists took part in the Maitai controversy than in Rudwick’s Devonian debate, none of them were ‘gentlemanly’, being paid professionals, and the process of partial resolution took over 80 years in New Zealand. Resolution of the Maitai depended much less on scientific rhetoric and persuasion, than on good fieldwork, with the discovery of new data, reinterpretation of old, as well as the development of, and changes within, the theoretical background. Rhetoric played a part at the Survey’s annual conference when Wellman discussed the distribution of Triassic rocks (Wellman, 1948a) and social dominance (as distinct from geological expertise) was of no importance. Survey geologists were aware of Wellman’s results, which appeared in routine geological reports. Apart from the brief description in the 1948 Outline (Wellman,
1948a: 5) there was no public announcement and the topic appeared rarely, if at all, in A.A.A.S. conferences except for Benson’s remarks (Benson, 1921).

Solution of the Maitai problem depended on the accumulation of geological data and experience leading to increased understanding of the structural complexities of the region. The Marshall-Bell reluctance to recognise unconformities raises the question of how far theoretical belief determines how or if field data will be observed and interpreted, and it appears that Marshall and his colleagues could not recognise clues pointing to an unconformity or fault. Is Marshall’s theoretical prejudice typical of geologists? How can supposedly expert scientific observation be trusted when it is so ‘theory-laden’? As in other sciences, all geological interpretations are subject to peer review and the rest of the geological community, mainly Survey, soon rejected the Marshall-Bell interpretation of the Maitai sequence, especially after reliable fossil identifications were made. However, the same geological community also could not accept Marshall’s radical but reliable views on the comparative youth of the Otago schists, regardless of his careful petrographic work, until the 1950s (Chapter 6).

It is not at all clear how far geological differences between Marshall and Park arose out of mutual personal antagonism, or if it they were entirely to do with their geological views. Both men were characteristic of nineteenth century scholars who cherished their personal ruling theories (Chamberlin, 1890; Gilbert, 1896), rather than more tentative working hypotheses, and they represent the last of the nineteenth century geological controversialists in New Zealand.

The Maitai controversy was a unique episode in New Zealand geology, and demonstrates how the lack of data, experience, field access, technology, and firmly held orthodox stratigraphical theory could lead so readily to disagreement. Controversies like those associated with the Maitai sequences are intensely interesting but exceptional, and like all noisy, public disagreements, they draw the attention of fascinated onlookers away from quiet, everyday work. For the most part, reliable geological knowledge is accumulated by routine field, office and laboratory work, with perhaps some robust discussion in offices and tearooms, followed by concerns to do with getting work published or presenting it at a conference. Today’s geologists probably face more emotional upsets dealing with administrative tasks and funding than from challenges to their best, but disposable, hypotheses. From time to time, there may be some brisk exchanges via letters to the editor of some journal and the rare diverting confrontation at a conference, but usually, today’s geologists must go without all the drama of the practical, theoretical and emotional difficulties encountered by the protagonists working on the Maitai problem.
Geological Map of New Zealand

Chapter Five

Figure 5.16: The New Zealand Official Year Books for 1914 and 1916 included this simple geological map of New Zealand, 1:5,000,000. Europeanarium period sequences including all of the South Island schists and Wairarapa greyswacks (green). The blue colour representing the Tertiary-Jurassic greyswacks has been brightened by computer.
Mapping New Zealand in the 1920s

On top of the practical difficulties in mapping and interpreting the pre-Cretaceous rocks, the publication of Park’s and Marshall’s very different stratigraphical schemes caused a quandary. Geologists could now choose between four different stratigraphical schemes:

- The simple Hector-McKay scheme with the greywackes tied to a Carboniferous Maitai series (Figure 4.7, p.77).
- Hutton’s nested scheme of 1899 with all the greywackes placed in his late Paleozoic Maitai System (Figure 4.8, p.78).
- Park’s 1910 scheme, with the greywackes included with the fossiliferous Mesozoic or Hokonui-Murihiku rocks of Southland, Nelson and south-west Auckland, placed in his Mesozoic Hokonui System (Figure 5.9, p.136).
- Marshall’s unorthodox 1912 scheme with all pre-Cretaceous rocks except those of north-west Nelson and Westland placed in his Triassic-Jurassic Maitai System (Figure 5.11, p.140).

New Zealand geologists now had too many stratigraphic schemes to choose from, but were without a generally agreed-upon reliable scheme, and no means whereby one could be agreed upon between them. The geological community consisted of less than a score of practising scientists, who were probably all acquainted with each other, and, with both Park and Marshall. How were these geologists to decide which of the four schemes to use?

Most geologists avoided using either Marshall’s Maitai System or Park’s Hokonui System for the basement greywackes. The Survey geologists loyally continued to use the Hector-McKay classification and allocate a ‘Permo-Carboniferous’ age to the greywackes. However, as more Mesozoic fossils turned up in them, it was acknowledged that the rock sequences were indeed younger than previously thought. Now, instead of using ‘Maitai’ or ‘Hokonui’, the geologists began cautiously classifying the Mesozoic rocks with safely neutral European names such as ‘Jura-triassic’ (Henderson and Bartrum, 1913), ‘Trias-Jura’ (Marshall, 1918), ‘Jura-Trias system’ (Henderson and Ongley, 1923), and even ‘Trio-Jurassic’ by Park himself (1921). Naturally, Park used his own classification of New Zealand formations in his textbooks (1910, 1914, 1925), and in his Western Southland Bulletin (1921) where he returned to the ‘Maitai System’ to replace his 1910 ‘Te Anau System’. This new Maitai System incorporated Hector’s Te Anau Series and the Nelson Maitai Series to represent the Permo-Carboniferous rocks of Otago, Southland and Nelson (now Caples and Maitai Terranes). The greywackes remained in the ‘Hokonui System’. Trechmann’s successful demolition of Marshall’s Maitai System in 1917 removed Marshall’s stratigraphic scheme from competition. However Marshall was not finished and in his Tuapeka Bulletin
Figure 5.17: Geological Sketch Map of the North Island of New Zealand, 1: 2,500,000. These black and white maps of the North and South Islands were issued by Morgan, Director of the New Zealand Geological Survey, for the 1921 meeting of the Australasian Association for the Advancement of Science in Sydney. The North Island greywackes and the Hokonui rocks of the Kawhia-Port Waikato region are classed together as 'Trias-Jura, Hokonui System &c' and marked in closely ruled horizontal lines. Original size 250 x 345 mm. Morgan (1922) New Zealand Journal of Science and Technology.
Figure 5.18: Geological Sketch Map of the South Island of New Zealand, 1: 2,500,000, issued by Morgan for the 1921 meeting of the Australasian Association for the Advancement of Science. The South Island greywackes and the Hokonui rocks (Southland) are classed together as "Trin-Jura, Hokonui System &c" and marked in closely ruled horizontal lines. The Otago schists and semi-schists and the Westland "greywackes" are included in the "Undifferentiated and Doubtful Paleozoic, Manitoto Series &c," marked in closely ruled diagonal lines. The Silurian and Ordovician series of north-west Nelson and Westland are shown separately. Original size 270 x 325 mm. Morgan (1922), New Zealand Journal of Science and Technology.
(1918) he used petrography to demonstrate how the ‘Trias-Jura’ greywackes of Otago evidently graded into, and were continuous with, the Otago schists (Chapter 6).

**Morgan and the black and white maps**

After taking over as Director of the Geological Survey in 1911, Morgan published several summaries of New Zealand stratigraphy. Two small, coloured geological maps appeared in the 1914 and 1916 New Zealand Official Year Books (Figure 5.16). In the accompanying text Morgan carefully explained how large areas (Maitai Series) had been assigned a Devonian or Carboniferous age but that the lack of fossils meant there was no definite proof of age. Similarly, the early and middle Mesozoic rocks of the extensive Trias-Jura system had yet to be clearly subdivided by unconformities or fossil evidence.

Morgan (1921) was well aware of the uneven knowledge of the geology of New Zealand. Nearly 40,000 square km had been mapped by the Geological Survey since 1905, over one-seventh of the Dominion’s total land area of 268,000 square km. Although he was optimistic about future progress, he warned that any slowing of his mapping programme meant that ‘progress of geological science will render the work already accomplished partly obsolete before the detailed survey’ is completed. At the request of Dr Benson of Otago (see below), Morgan (1922) reluctantly prepared a new geological map of New Zealand for the 1921 meeting of the A.A.A.S. in Sydney. He would have much preferred to wait for more data but accepted that new maps and explanations of New Zealand geology were ‘clearly called for’. Major difficulties included not only the complexity of New Zealand geology, but also that ‘New Zealand geologists have differed greatly on vital points, [and] accounts of one and the same area are often fundamentally irreconcilable’.

Morgan’s black and white sketch maps of 1922 (Figures 5.17, 5.18) were more detailed versions of the Year Book maps (Figure 5.16), but unlike most earlier maps included New Zealand series names as well as the European time scale. Morgan endorsed Park’s ‘great Trias-Jura Hokonui System’, which could not, ‘as yet’, be subdivided on lithology or on unconformities. This system contained the greywackes of North Island plus the Hokonui rocks and occupied east Nelson, Marlborough, Canterbury and Southland. The Maitai Series of Nelson were seen as separate and of Permian or Permo-Carboniferous age, and, following Park’s scheme of 1910, was reduced to a narrow sliver between the Nelson district and D’Urville Island. The Otago equivalents (Te Anau Series) were incorporated into the ‘Undifferentiated and Doubtful Paleozoic Maniototo Series’ together with the Otago schists. The origin and age of the Otago schists remained controversial, and Marshall’s demonstration (1918) that the Otago schists were

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4 Australasian Association for the Advancement of Science
continuous with the neighbouring greywackes was ignored. Because much stratigraphical and palaeontological research was then going on in New Zealand, Morgan expected that his sketch maps and tables would soon be modified. However, no attempt was made by the Survey to update Morgan’s map until 1947 when the Survey issued its large, new, brightly coloured maps and handbook (Marwick, 1948).

**Benson of Otago**

The matter of names for the late Palaeozoic and Mesozoic rock sequences was settled for a time by the young Australian, William Noel Benson (1885-1957), who followed Marshall as Professor of Geology at the University of Otago in 1917. Benson was unencumbered with the personal and professional networks that surrounded both Park and Marshall, and was quite even-handed towards the views of all the geologists working in New Zealand. In a comprehensive review of the state of New Zealand geology, Benson (1921) paid particular attention to the advances made in the ‘fundamental knowledge of New Zealand geology’ in the past decade. He generously excused the ‘inherent obscurity and diversity of interpretation of the record in New Zealand’ but commented that the ‘diversity of statements and frequent changes of nomenclature’ created great difficulty to anyone attempting to ‘find a path through the older records’.

Benson’s review of advances in New Zealand geology made since Hochstetter’s time included: eight stratigraphical views of the pre-Mesozoic formations, eight classifications of the Permian, Triassic and Jurassic rocks of New Zealand, eleven schemes of subdivision of the Cretaceous and Tertiary rocks as well as his own comparison of Permian and Mesozoic stratigraphy in New Zealand and New Caledonia. Benson noted the confusion in interpretation of stratigraphical and paleontological data including the ‘1ong, ... debated point’, on what rocks should be included in ‘The Permian (?) “Maitai” and Trias-Jura "Hokonui” Systems’, and outlined the two opposing views on interpretation of the fossil evidence in these rocks:

- The rocks should be subdivided ‘on the old lines’ (the Hector-McKay scheme), and tentative determinations of their fossils were sufficient for this task. Most Survey geologists took this view.
- That because of isolation from the Northern Hemisphere, ‘premature and belated forms’ could be expected in New Zealand (Bell et al., 1911: 22). Consequently, the sediments could not be divided into sub-series exactly like those of the contemporaneous formations of the Northern Hemisphere. However, the unity and apparent conformity of the whole Maitai sedimentary system was stressed.

Benson believed that most of the stratigraphical difficulties were no doubt caused by a poor supply of fossils from some these rocks as well as misidentifications. The lack of a resident specialist
Figure 5.19: Geological Sketch Map of New Zealand. This little map is ingeniously fitted into a tiny space but provides a very large amount of information. The greywackes are classified with the Hokonui System, based on the Southland sequences. Benson was uncertain about the existence of any unconformity between them and older Lower Triassic and Permian Maitai Greywacke. Original size. Benson (1922) Journal of Geology
palaeontologist in New Zealand was eventually remedied by the appointment of James Allan Thomson (1881-1928) by Morgan in 1911 (Galbreath, 2002: 182, 222), but Thomson left to become Director of the Dominion Museum in 1914. He was succeeded by John Marwick (1891-1978) who was appointed Assistant Geologist in 1920 and then Palaeontologist to the Geological Survey in 1923 (Fleming, 1979). Benson praised the palaeontological fieldwork and correlations ‘accomplished so rapidly and accurately’ over forty years earlier by Cox and McKay, as it ‘still held good’, but now, ‘precise ages’ could be established. He believed that the Mesozoic fauna was of ‘Tethyan circumpacific character’, and like Trechmann (1917), disagreed with the idea that various New Zealand forms were either local isolated survivals from Palaeozoic times, or were premature Jurassic forms.

**Tethyan character:** Eduard Suess proposed that a ‘Mediterranean’ sea which he called the ‘Tethys Sea’ had existed in late Palaeozoic to Mesozoic times between his two hypothetical continents, Atlantis (later Laurasia) and Gondwanaland. This Tethyan Sea was considered to be characterised by warm water flora and fauna (Suess, 1904-24: Vol.2, 334, Holmes, 1944, Swinnerton, 1946).

Uncertainty about the relationship between Morgan’s Permian Maitai and the younger Hokonui rocks remained, with much disagreement on whether or not a break existed between the Permian Maitai rocks (of Nelson) and the lower part of the Hokonui System. The absence of Lower and Middle Triassic fossils in the greywackes appeared to indicate some kind of break, but it was almost impossible to lithologically differentiate between them.

A simple little black and white map drawn by Benson himself (1922) accompanied the condensed version of Benson’s 1921 article that appeared in *The Journal of Geology* (Figure 5.19). This naïve-looking map clearly summarises Benson’s stratigraphy of New Zealand. The legend was more than a list of formations. It indicated stratigraphic breaks, and identified major geological episodes of marine transgressions or orogenies. The similarly patterned Permian Maitai and Mesozoic Hokonui systems express Benson’s doubt that any important break existed between them. Benson gave the unfossiliferous greywackes a Triassic age and placed them at the base of the Hokonui System. The schists of north-west Nelson and Fiordland were firmly separated from those of Otago and Marlborough. Benson departed from the Survey’s view of the Otago schists (that they were of Palaeozoic age), and like Marshall, regarded them as an ‘altered form’ of the rocks of the Maitai and Hokonui Systems. However, he changed his mind several years’ later (1929: 58), doubting that they could be as young as the Early Mesozoic. In a discussion of the Lower Mesozoic rocks (1928), Benson still could not clearly decide on the relationship between the Permo-Carboniferous Maitai, the fossiliferous Triassic and Jurassic Hokonui rocks of Southland, Nelson and Kawhia, and the supposedly underlying Triassic greywackes with *Terebellina* (*Torlessia*).
THE PETROGRAPHY OF THE GREYWACKES.

(This journal is one recently received by the N.Z. Geological Survey.)

As the classification of the greywackes in New Zealand constitutes probably a far greater problem than in any other country, the new scheme given in the above-named journal deserves some attention from New Zealand petrologists.

The term "greywacke" or "wacke" is one of the most loosely defined in geology, as was pointed out some thirty years ago by Sir Archibald Geikie when he pronounced it "a convenient limbo or No-man's Land, into which any group of rocks might be thrown which obstinately refused to reveal its relations with the rest of the terrestrial crust." (Founders of Geology, p. 410)

Fischer builds some order out of chaos by defining "wacke" as sedimentary rocks, the elastic grains of which are distributed in fairly even proportion over different grain sizes, and are formed during rapid deposition without suspension of the sedimentary particles. This definition does away with the derivation from particular rock types—a factor which has proved a stumbling-block in the previous understanding of the term.

The determination of the nature of the components of the wacke has led Fischer to divide the elastic minerals into two groups: first, the labile-components, and second, the stable-components.

The stable-components are those minerals distinguished by chemical and mechanical resistivity, and are usually the only ones found in detritus—namely, quartz, quartzites deficient in mica, and chert. Also included in this group are the heavy accessory minerals such as zircon, rutile, tourmaline, garnet, &c.

The second division (labile-components) includes rock fragments, and also the easily weatherable mineral grains such as biotite and the feldspars.

Muscovite and chlorite are separated from both groups. Although chemically stable, they are not mechanically so, and, on account of their form, remain very long in suspension, thus displaying a different kind of behaviour from the other components.

Using these data, Fischer divides the wackes into quartzwackes (those with less than 33 per cent. labile components) and mengwackes (those with more than 33 per cent. labile components).

Fischer has made an extensive microscopic study of the greywackes in the Hars mountains, and has evolved a method which has proved of value in stratigraphic correlation. In the thin sections, he selects the quartz grains of approximately 0.6 mm. diameter and measures in each grain the sum of the angles subtended at the centre of the grain by its angular edges, rounded portions being neglected. The average value of several grains is then expressed as a percentage of 360°, and the result is called the angularity or degree of rounding. Fischer has discovered that the Devonian and Lower Carboniferous mengwackes have an angularity of 60°, whereas the Silurian quartz-wackes scarcely retain 83°. Even the "personal-error" factor, which must be admitted may be considerable, could scarcely confuse such striking results.

Such valuable papers as this, written in a foreign language and published in a little-known Journal, are only too scarce, and this review is written to draw attention to the new methods of investigation into the nature of the rocks that constitute such a major portion of New Zealand's geological problems.

D. A. H.

Figure 5.20: Review of Georg Fischer's influential 1934 article on the petrography of the greywackes. Fischer provided methods for the analysis of greywackes and was used by such sedimentological luminaries as F.J. Pettijohn. The copy of Fischer's article reviewed by D.A.B. was used 20 years later by J.J. Reed when working on the Wellington greywackes. The article's reviewer, David Alexander Brown, graduated M.Sc. from Auckland University College (University of New Zealand) in 1937, and was working for the New Zealand Geological Survey when the review was written and continued his career overseas. Original size, D.A.B., Book review, New Zealand Journal of Science and Technology.
Although a more or less workable stratigraphic framework for the Cretaceous and Tertiary ‘covering strata’ was developed by 1930, little progress had been made with the greywackes. Marshall’s scheme was effectively banished, but some writers continued to use the name ‘Trias-Jura’ for rocks that yielded little evidence of their age (Ongley, 1940). Benson’s version of Park’s Mesozoic Hokonui System (Figure 5.19) was increasingly used to contain all rocks that appeared to belong whether fossiliferous or not. These included all of the greywackes, including the TeAnau series, (seen today as belonging to the Caples terrane), together with the fossiliferous Hokonui tracts in Southland, Nelson and south-west Auckland (Figures 5.17, 5.18, 5.19). The geologists could not reliably distinguish between any of the greywacke look-alikes until serious petrographic work was begun in the 1950s, although Henderson suggested that chemical analysis might be used to separate the greywackes into groups (Cotton, 1937).

**Greywacke: the name**

Very little more was done with any of these rocks except that the ‘meaning and significance’ of greywackes in New Zealand was closely discussed at a meeting in 1937 of the Geology Section of the Wellington branch of the Royal Society of New Zealand (Cotton, 1937). Richard Wright Willett (1912-1974) discussed the history of the term ‘greywacke’, its usage in Britain and the United States, the difficulties in subdividing the large areas lumped together as ‘greywacke’ in New Zealand., and referred to a promising new classification of greywackes by Georg Fischer (Figure 5.20). However, no new stratigraphic ideas were developed and the complexities of the ‘Maitai Problem’ concerning the relationships between the Nelson and Otago Maitai, the Te Anau Series and the basement greywackes remained unsolved for the time being (Harrington, 1989). If greywackes happened to form part of a Survey subdivision they were dealt with more and more briskly before the geologist got on with more rewarding rocks. Thus Hartley Travers Ferrar (1879-1932) dealt with his greywackes in some detail in 1925, but gave them only a page and a half in 1934, while in 1946, Marwick gave the greywackes of the Te Kuiti area four lines of description.

After some years working on the Kaitangata subdivision (Chapter 6) Montague Ongley (1888-1976) became concerned about how the ‘the unfossiliferous greywacke formations’ should be named and complained about the current practice in which geologists referred to these rocks by the ‘erroneous’ name of ‘Trias-Jura’ (1940). He preferred the working hypothesis that all these widespread formations were Palaeozoic, rather than Mesozoic, but thought it unwarranted to assign an age name without evidence. Ongley then recommended the use of an age-neutral binomial system for naming a formation, the first name being geographic and the other lithologic, so that in the Kaitangata subdivision, a name such as ‘Balclutha Greywacke’ should be used.
Soon after the Second World War, Ongley, now Director of the New Zealand Geological Survey, oversaw the publication of the first coloured geological map of New Zealand since Morgan’s little Year Book maps (Burton, 1965: 83). This important new map consisted of two generously large sheets, one for each island at a scale of 1:1,013,760, (Figures 5.21, 5.22), and it was accompanied by a small handbook (Marwick, 1948). It was the first major map:

- To show the Alpine Fault,
- To clearly separate the old Paleozoic Greenland Group ‘greywackes’ of Westland from the (mainly) Mesozoic greywackes of Canterbury,
- And to separate the other Paleozoic rocks, including the schists, of Fiordland, Westland, and northwest Nelson (today’s Western Province) from those east of the Alpine Fault (today’s Eastern Province).

The fossiliferous Triassic and Jurassic Hokonui System (Murihiku Terrane) was distinguished from the main body of greywackes (medium dark blue on the map), and the Carboniferous-Permian Te Anau and Maitai rocks of Nelson and Southland (Maitai Terrane) were differentiated mainly on style, lithology and a few fossils (grey on the map). The major part of the greywackes (Rakaia, Pahau, and Hunua-Bay of Islands Terranes and Waipa Supergroup) as well as greywackes of Otago (Caples Terrane), and portions of west Southland (Brook Street Terrane) was represented by the very large blue areas of the map and boldly called ‘Undifferentiated Jurassic-Triassic-Permian’ (9A). All the old series names including Aorangi Series, Waipapa Series and Arahura Series were set aside, and no attempt was made to assign an age or a stratigraphical name to these uninformative rocks. The Otago schists were shown as separate and of indeterminate Paleozoic age (purple on the map). After all the field work and map-making and controversies since 1865, so little was known about these undifferentiated greywackes that in a 47-page booklet, their description took up less than single page.

Ten years’ later, in the next geological map of New Zealand, the greywackes remained ‘undifferentiated’ but were restricted to Canterbury, Auckland and the North Island Main Ranges (Grindley et al., 1958). Those south of the schists were divided between ‘Undifferentiated’ greywackes of Southland, Otago and Marlborough (Permian-Carboniferous) and the Te Anau System (Carboniferous). These now belong to the Caples Terrane. The schists grew younger (Lower Mesozoic and Upper Paleozoic) and were subdivided into Turner’s Chlorite zones (Chapter 6) while the mysterious greywackes of west Otago re-emerged as the Eglinton Volcanics. (Lower Permian and Upper Carboniferous)

By 1948, the way in which the term ‘greywacke’ was used had changed again, indicating the ‘malleability’ of some technical terms (Rudwick, 1985: 447). The ‘undifferentiated greywackes’ were described as consisting of ‘conglomerates, grits, greywackes and argillites’ and frequently referred to by
the phrase ‘greywackes and argillites’. The term ‘greywacke’ was now used more or less colloquially to refer to any old-looking, hard, grey sandstones and fine argillites (Cotton, 1937). Ongley (1939) reflected common usage by geologists when he used ‘greywacke’ as a general inclusive term for all the rock types in his pre-Cretaceous series. We often attach the definite article to the names of geographical features and talk about ‘the Waikato’, and ‘the Coromandel’. If geologists referred to ‘the greywacke formations’ it would not have been long before they talked about ‘the greywackes’, and the term thus settled down as a general ‘carpet bag’ name that is still used for all the rocks making up the hills out there.
Figure 5.21: Geological Map of New Zealand, North Island, 1:1,013,760. The large tracts of 'Undifferentiated Jurassic-Triassic-Permian' greywackes (light blue, 9A) of the North Island Main Range, Waikato region, Auckland and North Auckland are clearly separated from the Triassic-Jurassic Hokonui System (mid-blue) on the west coast. The Lower Cretaceous greywacke-like sequences (green) were thought to have been formed in a geosyncline extending from East Cape to Marlborough. The large blank areas representing pre-Cretaceous rocks in both North Island and South Island maps reflect the limited knowledge of these basement rocks compared with the upper Cretaceous and Tertiary rocks. Digital photograph courtesy Library, University of Auckland. Original size 640 x 870 mm. 1947. New Zealand Geological Survey.
Figure 5.22: Geological Map of New Zealand, South Island, 1:1,013,760. The Otago, Alpine and Marlborough schists are coloured purple, and the large tracts of undifferentiated greywackes (light blue, 9A) of Canterbury and Marlborough are clearly separated from the Triassic-Jurassic Hokonui System (mid-blue) of Southland. The greywacke-like sequences south of the schists (now Caples Terrane) were not differentiated. The Maitai sequences (grey) with associated basic to ultrabasic rocks are shown as a thin silver north of the Southland Hokonui System, and as a broader tract in east Nelson. The Lower Cretaceous greywacke-like sequences (green) of Marlborough are not easily seen on this scale. Digital photograph courtesy Library, University of Auckland. Original size 670 x 810 mm. 1947 New Zealand Geological Survey.
Chapter Six

Diastrophism, Schist and Geological Histories

1900-1950

In New Zealand about the early Cretaceous there was a great diastrophic deformation, with wrinkling of the earlier Hokonui and so-called Maitai rocks and the formation of an extended land surface. Base-leveling and sea advance followed, and it was not until a comparatively late Tertiary period that a new cycle of major diastrophism commenced with the Kaikoura orogenic movements. (Thomson, 1917)

From the beginning of geological exploration in New Zealand, geologists were aware of a major unconformity between the strongly deformed basement rocks below, and the younger ‘Cretaceous-Tertiary’ series above (Hector, 1869). At first, this gap was seen as a stratigraphic matter, rather than as evidence of major tectonic and geomorphological processes. However, around 1890, New Zealand geologists began to see their geology in the context of the south-west Pacific region and to apply global mountain-building theories to New Zealand situations. Two theoretical systems became major influences in New Zealand:

♦ The theory of mountain-building by lateral forces caused by contraction of the Earth, as proposed by the Austrian geologist, Eduard Suess (1831-1914).
♦ The development of ideas about diastrophic cycles by Thomas Chrowder Chamberlin (1843-1928) of the United States.

Suess’s comprehensive theory on the origin of mountains had gained an international following. The English edition (1904-24) of Eduard Suess’s massive synthesis of world geology, Das Antlitz der Erde (1883-1904) brought European tectonic thinking to New Zealand geologists who had long pondered on the origin of the Southern Alps (p.105-109). Of particular interest were Suess’s ideas about the way in which lateral thrusting caused folded layers of strata to override a stable foreland, and how the trend lines of mountain ranges indicated the direction of thrust into the mountainous arc (Figure 6.1).

J.D.Dana began to develop his important tectonic concepts as early as the 1840s. These involved the formation of extensive ‘geosynclinal’ downfolds in which sediments accumulated (Ch.7) followed by ‘mountain-making’ upheavals of the sediments as a result of lateral pressure caused by the radial contraction of the Earth by cooling (Dana, 1873; Greene, 1982: 132-143 and references therein).
Suess’s volumes included a short description of New Zealand geology (Vol.2: 143-148) compiled from Hochstetter’s writings and contributions by Hector, von Haast and Hutton. Suess revealed that ‘in the southern half of the South Island two directions of strike and folding encounter one another almost at right angles [where] two independent unilateral chains meet in syntaxis’ (Suess’s italics). The north-east trending chain consisting of an ‘extremely thick zone of [Palaeozoic] slates’ forms the New Zealand Alps, while the second chain runs to the south-east (towards the Otago coast). Its oldest rocks including those of Stewart Island are to the south-west side.

New Zealand geologists increasingly saw their country in mobilistic terms. Suess’s theories generated a series of hypotheses regarding the structure of New Zealand’s folded mountain ranges and provided a mechanism to account for the observed complex structures in the greywackes (for example Bell and Fraser, 1906: 22). Morgan (1908, 1910) began by challenging the prevailing Hochstetter-Haast-Hutton model (Chapter 4, Figure 4.21) consisting of a primary fold or geanticlinal. The north-west folds of the greywackes belonging to the Greenland Series in Westland did not agree with the concept of a single primary north-east and south-west folding episode. Morgan believed that the Southern Alps corresponded to Suess’s alpine type folded mountain chains and had been formed by strata being pushed by a force acting towards the north-west against the immovable buttresses of older rocks to the west. He also postulated a ‘great overthrust fault [or faults] ... on the western side of the Alps’ and
supported McKay’s view that the present Alps did not exist as an uplifted mountain-chain before the Miocene (Figure 6.6).

**Some concepts advanced by Eduard Suess**

**Trend lines:** Following the European tradition, Suess advocated the analysis of maps in order to trace the positions and directional trends of folded mountain ranges. The arcuate trend lines of folded mountains were believed to reveal the patterns of mountain building caused by the secular (slow) contraction of the earth as it cooled. The resulting lateral or tangential thrusts pushed strata against an immovable ancient foreland to form a mountain arc with the direction of thrust against the concave side.

**Syntaxis:** Two mountain ranges meet at an angle (Greene, 1982: 188). This is also described as a sharp bend in an orogenic belt (Figure 6.3). Antonym of ‘virgation’.

**Virgation:** A mountain range diverges into two ranges as indicated by trend lines. Antonym of syntaxis.

**Eustatic movements:** Simultaneous worldwide changes in sea levels caused by periodic founderings of the ocean bottoms (Greene, 1982: 186; Hallam, 1992). This meant that long distance correlations were possible because sediments were thought to be deposited at the same time around the world.

Figure 6.2: Suess’s tiny map of New Zealand based on Hector’s maps. Original size. Suess (1906) The Face of the Earth, Vol II, p. 145.
Chapter Six

Suessian trend line analysis in New Zealand

J.W. Gregory, Scottish Australian geologist (quoted by Marshall 1910)

Ancient NW-SE folds

Younger NE-SW folds

Two mountain systems of different ages

Suess's syntaxis 1906

Fragments of sunken range

Submerged Paleozoic chain

Oldest rocks of NE-SW chain

Paleozoic anticline

North-west folds of Greenland Series Morgan (1908)

North-west folds of Greenland Series Morgan (1908)

Tonga-Kermadec fold Earthquakes evidence of continuing folding

North-west folds of Greenland Series Morgan (1908)

Syntaxis

Folding forces

Ancient foreland

Benson's virgation (1924)

Northwest folds of Greenland Series Morgan (1908)

Virgation

Trend line of Kaikouras did not support Suess's theory, Cotton (1916)

Immovable buried foreland

Figure 6.3: Suessian trend-line analysis in New Zealand. Diagrams illustrating four interpretations of New Zealand mountain structures, all based on the examination of maps 1906-1924.

'Anticline' and 'syncline' are obsolete terms used to refer to mountain-sized folds. These were thought to contain second order folds superimposed on the main fold. The terms 'anticlinorium', 'geanticline', 'synclinorium' and 'geosyncline' are used for very large structures.
Problems with trend-lines: Marshall and Cotton

For a while, trend line analysis yielded good results and it was pursued by eminent Australian and North American authorities interested in the structure of the south-west Pacific (Figure 6.3). Suess regarded the floor of the Pacific Ocean as a resistant ‘subsident foreland’, against which the arcuate mountain ranges and island chains bordering the Pacific Ocean were formed by the lateral thrusting of sediments (Greene, 1982: 180). However, Marshall (1910), who knew something of the nature of the Pacific Ocean floor criticised trend line analysis of linear groups of Pacific islands (Figure 6.4) in which it was assumed that they represented the emerged summits of folded mountain ranges (Marshall, 1912). A dozen or so postulated island chains, festoons, and arcs that ‘whirled’ to the north of New Zealand had been identified by the study of maps but without consideration of the soundings taken in the surrounding ocean. Marshall pointed out that in fact, some lines of ‘elevation’ actually passed through deep water. Instead, Marshall proposed the ‘true boundary’ of the Pacific basin separating the regions where andesites are erupted from those where only basic or alkaline rocks are erupted. This significant boundary became known as the ‘andesite line’ or the ‘Marshall Line’.

Confidence in Suess’s trend line analysis diminished further in New Zealand when Charles Andrew Cotton (1885-1970) opposed the idea that any consistently significant relationship existed between the general north-east and south-west trend line of the New Zealand mountain ranges and coastline, and the strikes of the Mesozoic folds (Cotton, 1916: 245). In the Wellington district, the ridges followed the general strike of the Mesozoic folds of 10-15 degrees west of north, but the coastline and the extended mountainous axis trended to the north-east. In the South Island there was even less agreement between the strike of the folds in the older rocks and major physiographic features such as the Kaikouras.

Cotton now challenged the view that the present day mountain ranges were formed during a single Mesozoic orogeny. He developed ideas on Pliocene block faulting initiated by McKay in the 1890s, and by Park (Figure 6.8) who suggested ‘differential uplift’ of mid Tertiary rocks (1905), and the formation of block mountains in Central Otago (1906, 1908). Cotton (1916, 1925) also introduced the concept of two-cycle and multi-cycle mountains by identifying how Mesozoic orogenic movements1 had folded and elevated the greywackes, which had then undergone a long period of peneplanation (Figure 6.6). The resulting sediment was turned into the upper Cretaceous and Tertiary ‘covering strata’ resting on the old ‘undermass’ (p.189). The diastrophic cycle was completed by another mountain building episode with differential uplift of faulted blocks during the Pliocene. Cotton named this second orogeny the ‘Kaikoura

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1 ‘Movement’ : a strangely delicate term when referring to massive folding, faulting, uplift and what were thought to be violent mountain-building episodes.
Figure 6.4: Marshall's map of the Pacific Ocean showing trend-line analyses by E.S. Dana (son of J.D. Dana), J.W. Gregory and E. Suess tracing supposed submerged arcuate mountain ranges. Marshall's andesite line marks the "true boundary" between the ocean and the continents, and closely delineated what was much later recognised as the junction between the Pacific plate and the Australian plate. Heavy dashed line added to mark the "andesite line". Map 88% original size. Modified from Marshall (1942) Proceedings Australasian Association for the Advancement of Science.
orogenic period’ in which the major relief features of present day New Zealand were blocked out, forming ‘a concourse of earth-blocks of varying size and shape’ (Figures 6.6, 6.7)

Suess’s great synthesis was now failing. Geophysicists successfully opposed the theory of contraction of the earth by slow cooling, because it could not explain the observed amount of deformation of the earth’s crust (Greene, 1982: 235-237). By 1910, the theory of contraction as a cause of tectonic movement was no longer tenable. However, Suess’s integrated global paradigm was enormously influential as it provided the first workable framework for understanding the tectonic history of New Zealand, and it remained influential into the 1950s (Figure 10.1, p.302). Elements of Suess’s work, like the postulated continent of Gondwanaland, remain to this day.

**Diastrophism, a concept from North America**

There are many and diverse views relative to the nature and causes of diastrophic movements.

(Chamberlin, 1909: 685)

North American geologists developed their own hypotheses on the relationships between continents and oceans, including concepts of isostasy (Greene, 1982: 245-257) and diastrophism (Greene, 1982: 258-275; Oldroyd, 1996: 182-191). ‘Diastrophism’ was introduced as a general term referring to all processes involved in the deformation of the earth’s crust including isostasy (Gilbert, 1890; Geikie, 1903a: 392-397; Chamberlin and Salisbury, 1905-1909: 502-522; Chamberlin, 1909). Grove Karl Gilbert (1843-1918) divided diastrophism into two kinds of major deforming movements (1890: 3, 340):

- **Orogeny**, the process of mountain formation, in which great thicknesses of sediments near the borders of continents are folded into gigantic wrinkles.
- **Epeirogeny**, the process of continent formation, where the land slowly rises and sinks or is warped relative to sea level.

Chamberlin, who in 1890 advocated the use of multiple working hypotheses in geology, developed the concept of diastrophism into an all-inclusive model (Dott, 1992) based on his concept that the Earth and other planets had been formed by the gravitational accretion of cold ‘planetismals’. He considered that diastrophic movements were ‘probably’ caused by continuing gravitational shrinkage of the earth, but adroitly avoided concern about the problem of mechanism by insisting that for the time being, there was no need to agree as to the causes of diastrophism whether the deforming movements were ‘shrinkages or expansions, or lateral shifts’ (Chamberlin, 1909: 685). Therefore, the first task of geologists was simply to investigate diastrophism’s effects working on the surface of the lithosphere. Chamberlin’s model incorporated the theory of cyclicity of orogeny, and emphasised its intimate relationships with geomorphological processes and biogeographical changes. Diastrophism had a fundamental role in
determining the limits of rock formations because geological formations constitute the basic unit of lithostratigraphy and are based on lithology, or the nature of the bedded rock. While Chamberlin’s fellow countryman, Bailey Willis (1857-1949), proposed the existence of independent dynamic districts (as used by Thomson, 1917), Chamberlin (1909) maintained that cyclic diastrophism was world-wide and because sea levels were affected it was the ‘ultimate basis of [world-wide] correlation’. In this scheme, prime importance was laid on the periodicity of orogeny, its recurrence in the same areas along continental margins and its close relationship to the ‘doctrine of base-levelling [and this was] specifically inconsistent with the doctrine of perpetual deformation’. Four stages in a diastrophic cycle were identified (Figure 6.5):

![Chamberlin's diastrophic cycle in New Zealand](image)

Figure 6.5 : Chamberlin's diastrophic cycle as applied in New Zealand.

In New Zealand, Chamberlin’s ideas about periodic global diastrophism were quickly taken up. He had suggested that if a longitudinal swell and sag developed parallel to a continent, then a great depth of sediment would accumulate in the sag (Chamberlin did not use the term ‘geosyncline’). The earlier deposition of the basement Mesozoic greywackes was considered to have taken place in such a ‘sag’ during a very long period of ‘quiescence’ (Figure 6.5. 1). Such a tract was the precursor of mountain formation and destined to eventually be folded into gigantic mountainous wrinkles by great diastrophic movements. In this way, continents were periodically rejuvenated by renewed relative elevation, and these events, in association with fossil evidence, could be used to correlate strata over long distances (Ulrich, 1911). Mesozoic quiescence and deposition were thought to have been terminated in New Zealand by an immensely energetic diastrophic episode during early and mid Cretaceous times (Figure 6.5 2-3), which became generally known as the ‘post-Hohonui Orogeny’ (Benson, 1921).
Figure 6.6: Interpretations of periodic or cyclic orogenic patterns in New Zealand, based on writings of the named geologists. The interval corresponding to deposition of the greywackes shaded in grey. The major Mesozoic Hekoulian or post-Hekoulian orogeny, later known as the Rangitata orogeny is shown with a heavy black line above the grey region.
After the great orogeny, the greywacke landscape was believed to have been peneplaned by erosion in Cretaceous times (Figure 6.5.4). The resulting peneplain (peneplane) marks the conspicuous break between ‘undermass’ and ‘covering strata’. No upper boundary to the ‘Hokonui’ greywackes (i.e., Park’s Hokonui strata plus the greywackes) was recognised because post-orogenic erosion had destroyed the original Mesozoic mountains and removed much of the stratigraphic evidence. According to Marshall, continuous deposition had occurred throughout the Cretaceous and Tertiary periods, because no substantial unconformity seemed to exist among the younger rocks (Marshall et al., 1911).

**The Notocene:** The idea of diastrophism and its relationship with the principles of stratigraphic correlation among the younger rocks was extended by Thomson (1917). He believed that geological classification was ‘no longer governed by ... conformity or unconformity’ but by a succession of faunas, and that diastrophism was a prime cause of the changes of fauna. Thomson suggested the term ‘Notocene’ to refer to all the sedimentary rocks of Upper Cretaceous, Tertiary and Pleistocene ages deposited between two ‘epochs of major diastrophism’; the Mesozoic ‘post-Hokonui’ and Cotton’s late Tertiary Kaikoura deformations. Benson accepted and used ‘Notocene’, but both Marshall and Park (1921b) attacked the term as ‘unscientific’, and Park suggested the name ‘Awatean’ for his ‘marginal’ Cretaceo-Pliocene strata. Bartram (1939) observed that it was not clear as to what beds were to be included in the Notocene and that the ‘younger beds’ did not constitute a single series. The term ‘Notocene’ was used only in New Zealand, with limited success, and has been abandoned. Thomson’s ‘Notocene’ is more or less equivalent to Hector’s ‘Cretaceo-tertiary’ and Cotton’s ‘covering strata’.

**Park’s developing ideas about mountain-building.**

![The block mountains of Central Otago. Modified after Park (1906), New Zealand Geological Survey](image)

The block mountains of Central Otago. Park (1906) recognised ‘upland plateau-like mountains’ with no spurs and no foothills as faulted blocks. The hills are uplifted and subsidence of the grabens is indicated by the associated lake deposits. The relationship between the ‘undermass’ blocks and landscape was later developed by Cotton (1917).
At first, Park (1910: 15-18) followed Hutton’s view that the South Island alpine chain consisted of the eastern half of a ‘great anticlinal’, with a ‘remarkably uniform’ structure throughout, of ‘great simplicity, mainly consisting of a series of overturned folds’. However, Park (1909a) combined ideas on the growth of mountain chains by close folding of rock-formations with mechanisms of ‘differential’ Pliocene uplift (Figure 6.6). Park’s five ‘schist’ bulletins indicate the development of his ideas about mountain building (1906, 1908, 1909a, 1918, 1921c), and he was deservedly proud of his early recognition of the Otago block mountains (Figure 6.7), which earned favourable comment from the famous American geomorphologist, William Morris Davis (1830-1954).

Park had also become very interested in the deformational structures to be seen in cliff faces and published a number of naturalistic drawings of folded and faulted strata in the greywackes and schists of the Mt Cook region (Figure 6.8). He also suggested (1909a: 58) that the apparently greater thickness of schists in west Otago was due in great part to overthrust faulting. However, Park’s increasing awareness of folded and other rock structures was not followed up in any detail by others until the late 1940s.

Figure 6.8: Structural drawings made in the Mount Cook region by Park (1910). These drawings of Mount Haast and Mount Haidering and of Malte Brun Range are among the earliest visual records of folds and faults seen in the greywackes and ‘slaty shales’ of the region.

Figure 6.8: Structural drawings made in the Mount Cook region by Park (1910). The Geology of New Zealand
Although Park’s Oamaru subdivision (1918: 10-20) contained only a small area of schistose rocks, he dwelt on their characteristics in some detail in a long, somewhat speculative and philosophical discussion on the difficulties of constructing geological histories, the dynamics of earth-movements, isostatic balance, and causes of rock-folding. Here, he further developed his ideas about long-term subsidence and deposition, crustal movements and regional folding.

In 1921, Park presented his fully developed theory of the geological history of New Zealand in which elements of Suess’s tectonics and Chamberlin’s diastrophism were combined to explain the country’s stratigraphy and structure (Park, 1921a, 1921b, 1921c). Park’s last bulletin (1921c: 22-32) was pushed to its limits as an empirical report as he ruminated at great length on New Zealand’s geographical role as a miniature continent, its geological history, and various theories of orogeny advanced by Suess, Dana and others. Park’s own evolution of theories regarding diastrophic cyclicity and mountain-building in New Zealand now culminated in the proposal of five major diastrophic movements or orogenies (Table 6.1).

Table 6.1: Table summarising James Park’s proposed orogenies.

<table>
<thead>
<tr>
<th>Diastrophic movements</th>
<th>Age and direction</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruahine</td>
<td>Pliocene. Differential uplift along the axis of the islands with profound faulting</td>
<td>Epeirogenic. Elevated New Zealand after the Oamaruian submergence</td>
</tr>
<tr>
<td>Rangitatan</td>
<td>Early Cretaceous NE-SW alpine folding, parallel with Tuhuan Southern Alps, N.I.main ranges</td>
<td>With ultra-basic intrusions. Thrust probably from east. Chains of folded greywackes. Also called ‘post-Hokonui Orogeny’</td>
</tr>
<tr>
<td>Hokonuian</td>
<td>Early Cretaceous, NW-SE folding Southland, Otago, Westland</td>
<td>Coeval with Rangitatan, but less intense</td>
</tr>
<tr>
<td>Atawhenuan</td>
<td>Late Permian, N-S folding</td>
<td>With dioritic intrusions</td>
</tr>
<tr>
<td>Tuhuan</td>
<td>Devonian, NE-SW folding</td>
<td>With granite intrusions</td>
</tr>
</tbody>
</table>

According to Park’s tectonic scheme (1921a), uninterrupted deltaic sedimentation took place following the Permian Atawhenuan diastrophic movement and continued through the Triassic and Jurassic epochs. Beginning in the early Cretaceous, sedimentation was closed by two crustal movements, the ‘Rangitatan movement’ and the ‘Hokonuian movement’ which took place ‘in syntaxis’.

The stronger north-east and south-west Rangitatan movement folded and elevated the ‘Juro-Triassic’ of the main alpine chains (Park, 1921b), and laid the framework and ‘determined the structure and direction of the axial chains of both islands’. The syntaxial north-west and south-east Hokonuian movement
produced the north-west and south-east transverse chains, by folding and elevating the ‘Trio-Jurassic Hokonuis’ of Southland, the mica-schists of Otago, and the Paleozoic rocks of Westland and north-west Nelson.

These energetic early Cretaceous movements were accompanied by rock-shattering, faulting and the extrusion of basic and ultra-basic magmas, followed by denudation and peneplanation during which the ‘marginal’ Upper Cretaceous and Tertiary sediments were deposited on the surface of the peneplain. The Pliocene uplift, or ‘Ruahine movement’, gave the ‘finishing touches’ to the structure of New Zealand (Park, 1921a). Cotton (1916) had earlier given the name ‘Kaikoura movements’ to the Pliocene uplift, but Park (1921b) insisted that he was the first to recognise the differential character of the uplift in 1905 (i.e., more uplift in some places than others) and preferred the name ‘Ruahine movement’. This was in deference to Suess’s earlier use of the term ‘Ruahine’ representing uplift and volcanicity of the region. Regardless of Park’s wish for his names to be recognised, the great Mesozoic orogeny became known as the ‘post-Hokonui’ Orogeny (for example Thomson, 1917), and the Pliocene orogeny was known as the ‘Kaikoura orogeny’ until Park’s term, ‘Rangitatan Orogeny’, was reinstated by Kingma in 1959.

Macpherson’s ‘recurved arc’

The last of the Suessian trend-line analyses was made by Eric Ogilvy Macpherson (1891-1948) in his unusually speculative Survey memoir (1946) in which he described the major tectonic plan of this country as a ‘recurved arc’ (Table 6.2, Figure 6.9). Macpherson was particularly concerned with explaining the patterns of Cretaceous and Tertiary diastrophism in New Zealand by the theory of recurrent orogenies alternating with geosynclinal phases.

A gravity-meter survey of regions where covering strata obscured the basement surprised senior geologists because it showed that instead of the expected flattish indurated basement, high basement ridges existed below the younger surface rocks. These were interpreted as constituting a multiple arc of late Cretaceous and Tertiary folds or ridges in the greywacke basement of the North Island, which had developed on a ‘subdued mature-land’. The main north-east trending Rimutaka-Ruahine-Kaimanawa range, which Macpherson believed to constitute a primary fold, was thought to curve to the north-west through the Bay of Plenty, rather than connect with the Kermadec ridge as Marshall believed (1911).

The South Island basement arc, which included all pre-Cretaceous rocks (Table 6.2, Figure 6.9) was interpreted as a major tectonic feature including a remarkable ‘tectonic contact’ where the Otago schist had been driven south, south-west and west over late Paleozoic and perhaps Triassic and Jurassic rocks. This long-lived thrust, later referred to as the ‘Macpherson Thrust’ (Wood, 1956: 97) was thought by Macpherson to curve north from Lake Te Anau and merge with the Alpine Fault. Macpherson took
into account the known structural trends of the south-west Pacific Ocean floor and incorporated seismic records made in New Zealand by the Dominion Observatory (Hayes, 1943). These indicated underthrusting of New Zealand from the Pacific Ocean and a subsurface discontinuity dipping to the north-west below the North Island.

Table 6.2: Key to Macpherson’s Generalised Tectonic Map, Figure 6.9. Macpherson focused on the structure of the Upper Cretaceous and Tertiary covering strata, and combined all the older rocks into a pre-Cretaceous basement.

<table>
<thead>
<tr>
<th>Series name</th>
<th>Age</th>
<th>Label on map</th>
<th>Today’s names</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hokonui Series</td>
<td>Triassic, Jurassic</td>
<td>II</td>
<td>Waipapa Terrane, Torlesse Terrane (Rakaia + Pahau), Murihiku Terrane</td>
</tr>
<tr>
<td>Maitai Series</td>
<td>Late Paleozoic, Upper Carboniferous</td>
<td>III</td>
<td>Maitai Terrane (with ultrabasics)</td>
</tr>
<tr>
<td>Kakanui Series</td>
<td>Late Paleozoic?</td>
<td>IV</td>
<td>Southern Rakaia Terrane</td>
</tr>
<tr>
<td>Wangapeka Series</td>
<td>Upper Silurian to Lower Devonian</td>
<td>V</td>
<td>Terranes and batholiths of the Western Province</td>
</tr>
<tr>
<td>Aorere Series</td>
<td>Lower Ordovician</td>
<td>VI</td>
<td></td>
</tr>
<tr>
<td>Dusky Sound Series</td>
<td>Lower Ordovician (in part)</td>
<td>VII</td>
<td></td>
</tr>
<tr>
<td>Wanaka Series (Otago schist)</td>
<td>Paleozoic</td>
<td>VIII</td>
<td>Rakaia Terrane + Caples Terrane</td>
</tr>
</tbody>
</table>

At the same time as he was preparing his memoir, Macpherson’s Survey colleagues, Wellman and Willett (1942), completed an intrepid wartime journey through South Westland to Fiordland (p.213) during which they discovered a ‘major fault that extends along the west of the Southern Alps’. Ever since McKay’s time (1894) there had been repeated conjecture on the existence of a great fault on the western margin of the Southern Alps, especially by Morgan (1908, 1910) and by John Henderson (1880-1959) (1929, 1937, Figure 6.10). Several engrossing accounts of how the Alpine Fault was revealed are available (Rhodes, 1996; Galbreath, 1998: Ch.9; Harrington, 1999). The very large strike-slip component on the Alpine Fault was later understood and measured only by matching the ultramafic and associated rock sequences at Nelson and north of Lake Te Anau (Marwick, 1948: 5-7, Lillie, 1951, Kear, 2001).

The amazing news of a horizontal movement of over 200 miles (322 km) slipped into the international scientific press in Benson’s routine report (1950) of the meeting of the Geological Division of the 1949 Pacific Science Congress. Two other large transcurrent faults were discovered at about the same time: the special nature of the Great Glen Fault in Scotland was reported in 1947 (Kennedy, 1947) and of the San Andreas Fault in 1953 (Hill and Dibblee, 1953). In New Zealand, the discovery of the Alpine Fault
Figure 6.9: Generalised Tectonic Map showing the New Zealand 'recurved arc'. See Table 6.2, p.186 for key to map. The blue areas represent anticlinal folds in the pre-Cretaceous basement (of all ages). The Roman numerals mark major stratigraphic series in the basement rocks (Table 6.2), and also indicate the inferred basement folds in the North Island. The North Island main ranges are outlined with marks representing 'Late Cretaceous and Tertiary geosynclinal margins'. Enlarged Roman numerals are added, as is an arrow to mark the 'South tectonic contact' between Otago schist-Mesozoic (Livingstone Fault). Modified after Macpherson (1946) New Zealand Geological Survey.
made plain, once and for all, that there was no relationship between the Westland greywackes and those of Canterbury. Moreover, that the Otago schists and those of north-west Nelson were quite distinct, that the Maitai rocks of Nelson and Otago were not only similar, they were identical, and that the Earth’s crust could move laterally.

Figure 6.10: Henderson’s map showing the faults and geological structure of New Zealand. Henderson, (1929) The N.Z. Journal of Science and Technology

Undermass, Covering Strata and Orogeny

Because of the focus on Cretaceous and Tertiary geology, the older greywackes and argillites were often referred to simply as the ‘basement’ or as an undifferentiated ‘oldermass’ or ‘undermass’. Cotton (1916, 1917) borrowed the latter terms from the great American geomorphologist, W.M.Davis. The terms had been invented for physical geographers who needed some simple words that indicated the general result of a succession of geological events, but without fear of ‘metamorphosing themselves into geologists’ (Davis, 1911). ‘Undermass’ or ‘older mass’ was used by Davis to refer to older, disordered resistant crystalline rocks that had been planed down by erosion, and ‘covering strata’ or ‘overmass’ to the less resistant and younger, stratified rocks resting on the undermass. Other New Zealand geologists, notably
Wellman, also found ‘undermass’ a useful term when referring to the basement greywackes and the Paleozoic rocks of the western South Island. It was generally held that the single large ‘post-Hokonui’ orogeny (Figure 6.6) that had taken place in Cretaceous times was followed by a long period of erosion and planation. The resulting erosion surface thus separated two entities, the undermass and the covering strata.

This custom eventually led to a debate between Cotton and Wellman (1950a, 1950b). Both men were aware that although ‘undermass’ and ‘covering strata’ were useful terms for indicating a large age difference between two sets of beds, there was potential confusion between the geomorphic and stratigraphic meanings of the terms. The stratigraphic usefulness of the terms depended on ‘all the covering beds being younger than all parts of the undermass’ (Wellman, 1950: 33). This, in turn, depended on a single postulated post-Hokonui orogeny having affected all parts of New Zealand at the same time. All of the older rocks had to be folded, uplifted and eroded simultaneously, followed by the deposition of the covering strata. Wellman questioned the assumption that any single New Zealand-wide post-Hokonui orogenic movement had taken place or that diastrophism was necessarily periodic. He argued that major unconformities, presumably recording orogenies, ranged in age from Triassic through to early Tertiary and suggested that even earlier or later orogenic movements might have taken place, so that a third group of beds would occur between the undermass and covering strata. Thomson (1917) had already suggested the existence of individual diastrophic districts in the New Zealand area during Tertiary times, in which sea-retreat and sea-advance took place at different times, with no single unconformity common to all districts.

In the light of the complications brought about by Wellman’s contention that formations of doubtful age could be placed between the undermass and the covering strata, Cotton (1951) withdrew from using ‘undermass’ in a stratigraphic sense, seeing it as ‘a regrettable betrayal of true Davisian principles’. He recommended that the younger rocks be referred to by ‘Thomson’s (1917) grouping of the late Cretaceous and Tertiary formations’ as Notocene, and the older basement rocks as pre-Notocene. Cotton then used ‘floor’ rather than ‘undermass’ when discussing the basement rocks (Cotton, 1954). Today, the once useful term ‘undermass’ has almost dropped out of common use by geologists.

**Diastrophism as a model**

Ideas about periodic diastrophism guided geological thought in New Zealand for over 50 years until they were displaced by plate tectonic theory. Diastrophism accounted for the seemingly periodic nature of orogeny in this country, so that some geologists still talked of ‘orogeny’ in the sense of a periodic upheaval of accumulated sediments into the 1980s. The model in which a mountainous region could be denuded to base level and the sediments deposited in a bordering ‘sag’ that was later folded and uplifted
explained the parallelism of ancient mountain ranges in New Zealand and the apparent younging of sedimentary sequences towards the east and away from the mysterious western continent. However, the cyclic diastrophism model could not account for the disappearance of the Paleozoic continent or identify it as Gondwanaland. There was still no mechanism to account for the origin of the huge compressive forces necessary to heave mountain-loads of rock some thousands of metres above sea level. Nor could it explain what caused the formation of the large faults that were steadily being discovered. However, in 1950, few doubts were expressed as to the reality of past brief episodes of violent orogeny separated by long periods of quiet erosion and deposition.

**From Greywacke to Schist: 1900 -1950**

We may here describe one of the most puzzling formations in New Zealand, a broad zone of mica-schists running to the southeast ... through the Otago province of the South Island (Benson, 1922).

Late 19th century European geologists had developed considerable understanding of the field occurrence and petrology of metamorphic rocks (Touret and Jijland, 2002). Investigations were made into metamorphic regions of Scotland and their petrology as early as the 1860s (Geikie, 1866, Forbes, 1867). Many attempts were made to develop hypotheses regarding the origin of metamorphic rocks, and to find workable methods of classification based on chemical composition or on depth zones in which they were thought to be formed (Zittel, 1901; Geikie, 1903a: 764-807; Turner, 1981: 49-50). Some geologists made a distinction between thermal metamorphism due to heat, and dynamic metamorphism due to pressure (Harker, 1902: 287). Heat was supplied by intrusive igneous magmas, by ‘mechanical generation’, and by the internal heat of the earth during subsidence (Harker, 1902: 290; Geikie, 1903a: 399). Rosenbusch introduced the term ‘dynamometamorphism’ in 1886 and described how shearing stress under great pressure could transform minerals by recrystallisation (Knopf, 1941) and produce foliated structures (Geikie, 1903b: 788). Geologists appreciated that, under enormous pressure at depth, rocks are subjected to shattering, fracturing, plastic flow, and recrystallisation (Geikie, 1903a: 398). This dynamic metamorphism could also crush rocks and generate cataclastic structures like ‘friction-breccias’ and mylonites (Harker, 1902: 318).

The progressive nature of regional metamorphism was first demonstrated in the Scottish Highlands by George Barrow (1853-1932) who mapped his ‘Barrovian’ zones of increasing metamorphism each of which was characterised by a specific set of minerals (Barrow, 1893, 1912, Benson, 1921: 52; Touret and Jijland, 2002: 118). Barrow showed that the metamorphic rocks were of sedimentary origin and that the processes of regional or progressive metamorphism and contact metamorphism were analogous, but that
the degree of alteration was different. Barrow’s ideas were ignored for some years until revived in 1924 by Cecil Edgar Tilley (1884-1973). Here in New Zealand, geologists like Alexander Moncrieff Finlayson (1884-1917) a student of both Park and Marshall (Finlayson, 1907, Watters, 2002), were familiar with the intensive studies of metamorphic regions and processes by Charles Richard Van Hise (1857-1918) and Charles Kenneth Leith (1875-1956) of the United States Geological Survey (Dott, 2001).

How did New Zealand geologists perceive the relationships between the greywackes and the neighbouring schists? The geologists recognised that the Otago schists were probably metamorphosed greywackes, but of what age? (Figures 4.7, 4.8, 4.9, 5.9, 5.11). As usual, they described how the one graded ‘insensibly’ into the other, searched uselessly for the elusive unconformities, and arbitrarily drew boundaries between unaltered and schistose rocks. In order to find a stratigraphic solution to the problem of the schists, the geologists had to infer two distinct ages: the age of deposition of the original sediments, and the age of metamorphism. (Figure 4.17, p.96). The ruling theory was maintained; the greater the metamorphism, the older the rocks.

While batholiths and other large igneous bodies were understood to cause contact metamorphism, little was known about the cause of regional or progressive metamorphism (Van Hise, 1904: 883). The best that the geologists could do was describe the mineralogical changes caused by the application of heat and pressure by contact with plutonic intrusions like those of Westland (Park, 1925: 242ff), but the cause remained a ‘difficult problem’. Park (1925: 246) proposed that regional metamorphism was caused ‘partly by folding and partly by the subsidence of crustal blocks till they come within the zone of considerable subterranean heat’, and was usually ascribed to the same mysterious forces that caused the folding and elevation of the whole Otago region.

**James Park’s stratigraphic interpretations**

Throughout his long teaching career as Professor of Mining at Otago, Park maintained his old connections with the New Zealand Geological Survey by carrying out a number of surveys on contract. In spite of new ideas from Scotland and the United States about progressive metamorphism, and his own field observations of the ‘insensible’ passage of underlying schists into indurated sandstones above them, Park (1903) maintained the traditional method of subjectively separating progressively metamorphosed rocks into unaltered, part altered, and fully altered age-related series. The last he considered to be of great age (Figure 5.9) and this is reflected in the curious concentric distribution of ‘Cambrian’ and ‘Ordovician to Carboniferous’ rocks of Otago in his 1910 map of New Zealand (Figure 5.10, p.137). Park (1921c: 33-38) upheld his conservative stratigraphic view of the metamorphic rocks, subscribing to Haast’s model in which the crystalline metamorphic schists of Westland formed the
exposed core of the Southern Alps. These displayed ‘progressive and increasing downwards (my emphasis) from unaltered argillites to the gneisses and schists of the lowest (and oldest) division where the high temperature of plutonic magma caused ‘deep-seated’ metamorphism.

**New interpretations: Bell and Marshall**

In regionally metamorphosed areas, where unaltered rocks graded ‘insensibly’ into schists, both Bell and Marshall moved away from the traditional model. Bell placed all of the metamorphosed ‘grauwackes’ and schists of the Hokitika subdivision (Table 5.1, p127) in a single lower Mesozoic ‘Arahura Series’ (Bell and Fraser, 1906: 40-45; Reed, 1965; Waterhouse, 1967), indicating that the schists were not necessarily older than the ‘grauwackes’. Morgan (1908: 33) correlated similar rocks in the neighbouring Mikonui subdivision with the Arahura Series, but subdivided them into grauwackes and schists (Table 5.1) and returned to the traditional assumption of a Palaeozoic age for the ‘grauwackes’ based on lithological characters. True to Survey tradition, Morgan believed that the huge thickness of rocks should be subdivided, because to ‘many geologists this grouping together of the whole of the rocks composing the alpine chain will appear a retrograde step’. Although Morgan gave careful petrographical descriptions of representative schistose rocks, the possibility that the samples might represent identifiable zones of metamorphism was not recognised. Apparent repetition of beds was explained by intense plication of the schists, while ‘great dynamic agencies’ were thought to have been the cause of metamorphism, but with some contact metamorphism by granite intrusions.

Like Bell, Marshall (1910: 435) described a ‘gradual transition from unchanged sediments to completely metamorphic rocks’ that took place over three to five miles of country in Otago. He believed it ‘reasonable’ to refer such schists to the neighbouring sedimentary rocks ‘into which they graduate’, some of which contained fossils of Triassic age, and he refrained from creating several separate series of younger greywackes and older schists. Marshall (1918) further developed the idea of progressive metamorphism of greywackes in his Tuapeka Bulletin, in which he carefully used petrography to demonstrate how the schists of his Tuapeka series (Otago schists, today’s Caples Terrane, Figure 6.11) were ‘almost certainly derived from greywackes of similar composition’ (1918 33-34) belonging to his Trias-Jura Maitai System. There were no ‘lithological or stratigraphic reasons’ to separate any of the greywackes and schists into different series, and Marshall supposed that the recrystallisation of the minerals during metamorphism was probably caused by ‘mechanical pressure’ but could not provide a cause of such pressure.

In spite of Marshall’s painstaking petrographical proof, and the overwhelming number of field observations by other geologists regarding the apparent continuity between the greywackes and the schists, many geologists still viewed a Mesozoic age for the Otago schists with great scepticism (for
Two alternative interpretations of the relationship between greywackes and schist in Otago, 1918 and 1939

Map outlines are based on Geological Map of New Zealand, 1:250 000, Sheet 25, Dunedin, 1966.
example Morgan, 1919; Park, 1921c; Ongley, 1939; Marwick, 1948). However Benson (1921: 71; 1924: 129), who continued to referee geological disputes, examined Marshall’s thin-sections for himself, and concluded that Marshall’s explanation of the gradual change from unmetamorphosed rocks to schist ‘though at first sight opposed to our general experience ... seemed to be very strong’ and his view involved fewer difficulties than any other hypotheses put forward. While Benson accepted that the Otago schists were the metamorphic equivalents of Middle and Lower Triassic and Permian formations, Marshall’s apparently successful demonstration of progressive metamorphism in Otago and the revolutionary inference that increasing degrees of metamorphism had little to do with stratigraphic age was not accepted by Survey geologists.

Unluckily for Marshall, the petrographical samples that were meant to show progressive metamorphism from Triassic greywackes into similarly aged schist had been collected in a series across two different terranes, the Maitai Terrane and the Caples Terrane (Figure 6.11). Worse, he supported his claim of a Trias-Jura age for the schists by an over-bold long-distance correlation between the greywackes at Balclutha and the Triassic Kaihiku beds at Nugget Point 25 km to the south.

**Ongley and the Kaitangata-Green Island subdivision**

While the issue of Marshall’s interpretation of the close relationship between his schistose Tuapeka Series (Otago schist) and the neighbouring ‘Trias-Jura’ greywackes (Maitai Terrane) remained unresolved, Ongley (1924) began a survey of the important coalfield in the Kaitangata subdivision (Figures 5.4, 6.11) adjacent to Marshall’s Tuapeka subdivision. However, the coalfields report was delayed because ‘examination of the older rocks ... brought the geologist into contact with the unsolved problem of the age of the Otago schists’ (Morgan, 1924).

Ongley had found fragments of a fibrous shell and other fossils (Figure 6.12) consisting of the remains of corals, echinoderms, brachiopods, pelecypods, and a gastropod near Clinton, between the Otago schists to the north and the Triassic Kaihiku beds to the south (Figure 6.11). ‘[T]o the glee of those who found Marshall over-willing to generalise’ (Waterhouse, 1965: 966) Marwick (1925) identified several undoubted Permian forms including the coral *Zaphrentis*, the brachiopod *Chonetes*, and a shell ‘very like *Inoceramus*’, perhaps related to Trechmann’s *Aphanaias*. This fossil find allowed Ongley to introduce a new Permian ‘Clinton Series’ (Maitai Terrane) between Marshall’s schistose Tuapeka Series to the north, and the Triassic Kaihiku Series (Murihiku Terrane) to the south (Ongley, 1933, 1939: 32-34). Ongley’s fossils confirmed traditional Survey opinion that, contrary to Marshall’s view, the greywackes and schists were Paleozoic in age, and the schists were older than the greywackes (e.g. Figures 4.18, 5.9).

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2 Today’s *Atomodesma*
Ongley found no angular unconformity between the schists and the Permian Clinton beds, and because metamorphism must have taken place at depth, below the Clinton beds, the schists ‘should be considered as at least pre-Permian’. Ongley (1939: 32) regarded all the greywackes as ‘nondescript’ although he could recognise lithological differences between the Tuapeka and Clinton greywackes. He had great difficulty in finding a contact between the two series, and proposed the existence of near-vertical faults between the Tuapeka schist, the Clinton beds, and the Triassic Kaihiku greywacke. Because the schist and greywacke of the Tuapeka Series appeared to underlie the ‘Permian or Carboniferous’ Clinton beds, Ongley (1933, 1939) decided that the schist had to be pre-Carboniferous in age. Since none of the nearby pre-Cretaceous rocks appeared to contain pebbles of schist, Ongley inferred that metamorphism did not take place until the ‘Hokonui movements’ at the end of the Jurassic.

Figure 6.12: Permian fossils found by Ongley at Clinton (1924) and identified by Marwick (1925). Figs 6 and 7 are casts of the pelecypod similar to that identified by Trechmann as *Aphanoia* and referred to by McKay as the ‘Dun Mountain Inoceramus’. Marwick (1925) New Zealand Journal of Science and Technology

Ongley and Marshall

Marshall’s objectives in 1918 had been to demonstrate that the apparently ‘insensible’ gradation from unaltered greywackes to schists was real, that all the rocks were of the same age, and that strong metamorphism was not necessarily an indication of great age. He also wanted to show that all the schists belonged to his Trias-Jura Maitai System (figure 5.11, p.140). However, his unfortunate choice of field
area ruined any chance of changing sceptical minds about the gradational nature of regional metamorphism. Even Benson, originally a hesitant supporter (1921), changed his mind against a Mesozoic age for the schists (1928) after the discovery of the Paleozoic Clinton fossils announcing that ‘the suggestion that they might be of Early Mesozoic age seems to have now lost its force’ (Benson, 1929: 58). Marshall’s conclusions regarding the supposed Mesozoic age of the schists were very strongly criticised by Ongley (1939:27) who went so far as to publicly accuse Marshall of making ‘palpably inaccurate’ statements regarding the distances between Balclutha and the Kaihiku Gorge and Nugget Point. Ongley also attacked Marshall’s lithological correlation between the greywackes at Balclutha and the fossiliferous Triassic rocks some 25 kilometres away at Kaihiku Gorge and Nugget Point (see also Ongley, 1940). These criticisms of Marshall’s work only added to the extreme enmity between him and Ongley (Marshall et al., 1934) and raises important questions as to how such personal clashes affect the way in which some scientific problems are tackled in New Zealand.

In any case, the Survey maintained its view that the Otago schists were somewhat older than the Trias-Jura Hokonui rocks and an unconformity was assumed to exist somewhere between them. Marshall’s interpretation that the Mesozoic greywackes graded into the Otago schists was seen to be wrong — regardless of the petrographic work by F.J.Turner and C.O.Hutton currently going on at the University of Otago (p.200). Geologists continued to compare the southern greywackes of Otago and Canterbury with the Ordovician Aorere greywackes of Nelson (Benson, 1921: 71) while stratigraphic confusion concerning the classification of New Zealand’s pre-Cretaceous rocks continued to prevail.

**Structure of the schists**

The peculiar structure of the Otago schists, with their low dips in the centre of the schistose areas compared with the steep dips on the margins, the seeming simplicity of structure, but with hidden complications (Park, 1909a: 56) and apparent lack of large scale tectonic folding was of continuing interest. Park (1908: 25-27) briefly considered that the schists consisted of the ‘ruins of great recumbent folds’ formed by tangential stresses but discarded the idea because of their apparent stratigraphic relationship with the overlying, conformable semi-schistose Kakanuian rocks (Figure 5.9 p.136). He pondered on the origin of the forces that had produced a ‘great belt [of] perfectly undisturbed (emphasis added) [and] highly metamorphosed schists’. His conclusion was that the cause of ‘dynamical’ metamorphism of ‘wonderful uniformity’ was intense lateral compression by horizontal forces and vertical tensional forces produced by the Earth’s contraction similar to the mechanism advocated by Eduard Suess. Park himself (1909a: 58) was inclined to the idea of ‘abyssal collapse’ producing compressive stresses that caused the metamorphism, and accounted for the great thickness of the schists by repeated overthrust folding.
Chapter Six

Benson (1921: 72) also suggested that the Otago schists consisted of a ‘great series of recumbent folds, broken by subsequent block-faulting’ (Figure 6.13). Next (1922: 7), he wondered if the flat arch of the metamorphic rocks was the ‘base of a great series of recumbent folds of late Paleozoic and Lower Mesozoic rocks ... pressed against a resistant or continental mass now concealed beneath the southern portion of the island’. The ‘microscopical structure’ of the picturesquely described ‘packet of recumbent folds’ indicated to Benson (1924: 129) that the folds were formed by strong lateral thrust rather than static metamorphism ‘by means of heating from below’ by ‘intrusive magmas’.

This hypothetical north-south section through the Otago schists, illustrates Benson’s view that the schists consist of a number of recumbent folds, similar to that inferred above Lawrence. In this scheme, Benson indicates a gradation or zone of passage between the greywackes and the schists near Balclutha on the diagram. Fine wavy lines = schist; fine smooth lines = greywacke; dashed lines = Jurassic sediments. Diagram slightly reduced in size.

Figure 6.13: Benson’s hypothetical diagrammatic north-south section across Otago. Benson (1921)
Australasian Association for the Advancement of Science

By the end of 1925, little more was known about the origin of metamorphic rocks than in 1900 and its cause was ‘still an open question’ (Benson, 1929). Microscopic evidence showed that ‘great shearing and crushing had taken place in these rocks’ (Benson, 1921: 74) but little else was known. Marshall (1918) had vaguely observed that the evidence for purely ‘dynamical alteration’ was rare, and hopefully suggested that metamorphic change was a result of ‘chemical recrystallisation under a controlling pressure’. Park (1914, 1925) was little more informative when he admitted that ‘dynamic metamorphism involving shearing and folding stress could not cover all the implications of regional metamorphism’. No progress was made as to age. All the stratigraphical classifications and correlations were unhelpful and solved nothing, while none of the current theories on the cause of regional metamorphism were of much use, including suggestions such as:

♦ Large-scale contact metamorphism may be caused by the upring of floods of plutonic magma,
♦ The subsidence of crustal blocks into zones of subterranean heat,
♦ Intense folding and plication of rocks subjected to the load of a pile of superincumbent strata caused metamorphism.
Chapter Six

Turner of Otago and metamorphic zonation

Francis John Turner (1904-1985), who had obtained his MSc at Auckland under John Arthur Bartrum (1885-1949), became lecturer and assistant in Geology to Benson at Otago in 1926 (Coombs, 1986). As Turner’s mentor, Benson pushed him into serious petrological research at a time when independent research by lecturers was seen as an eccentricity. At the same time, Park encouraged him into exploring the mountains. During his first expedition through the Haast Pass to Westland, Turner noticed the changes in metamorphic grade, just as Haast had done before him, and Benson drew his attention to the petrological investigations on progressive metamorphism by Barrow (1893, 1912) and Tilley (1924a, 1924b) in the Scottish Highlands.

Most of Turner’s fieldwork and collecting was done by him in the remote valleys and fiords of Otago and Westland, although some rock specimens were collected for him by members of climbing parties. In his first report on the Westland rocks Turner (1930) postulated that the metamorphic rocks and peridotites of the Cascade Valley near the coast of South Westland belonged to an ‘Older Metamorphic Series’, quite separate from the eastern rocks of lower metamorphic grade such as the Maniototo Series (Otago schists) of Central Otago.

Turner’s schists and gneisses were derived from ‘quartzo-feldspathic sandstones and grits of greywacke composition’. As he traced the mineralogical and textural changes from zone to zone through south Westland he identified Barrow’s chlorite, biotite, and oligoclase metamorphic zones (Turner, 1933: 237-38). This meant that the old subjective method of subdividing tracts of metamorphic rock on their appearance in the field could be replaced by an objective method based on index minerals.

Because the Cascade Valley rocks appeared to be a more intensely metamorphosed equivalent of the Otago schists, Turner abandoned the idea that they belonged to a separate series. All the metamorphic rocks of New Zealand (including those of north-west Nelson, Westland and Fiordland) were then grouped in ‘a single metamorphic series, which exhibits … the phenomena of progressive metamorphism on a regional scale’. Turner made the point that ‘[s]tratigraphic subdivision of the metamorphic rocks is … no longer advisable’. He dropped the term ‘Older Metamorphic Series’ and from then on moved away from using the term ‘series’ when discussing metamorphic rocks, except when referring to previously mapped and named stratigraphic units (for example Turner, 1935). Turner (1933: 235) also realised that Barrow’s metamorphic zones in the Scottish Highlands were based on pelitic (fine-grained) sediments, while his own petrologic investigations of progressive (regional) metamorphism in Southern Westland were based on the progressive metamorphism of the quartzo-
Chapter Six

METAMORPHIC ZONES IN N.W. OTAGO.

Chapter Six

METAMORPHIC ZONES IN N.W. OTAGO.

LEGEND.

Sub-Zones of Chlorite Zone
Chl. 1
Chl. 2
Chl. 3
Chl. 4
Marine Tertiary Rocks...
Seepetines, Gabbro etc...
Granites, Horites etc...
Faults...

SCALE

Figure 6.14: Turner's and Hutton's use of Chlorite zones to subdivide the Otago schists. The western (left) quarter of this map is the same as Turner's 1936 map in which he located his first three Chlorite subzones. Schists of Subzone Chl.4 occupy the whole eastern half of the map. Large labels referring to Chlorite zones added to map. Modified after Hutton and Turner (1936). Transactions of the Royal Society of New Zealand Vol. 65

Figure 6.15: C.O. Hutton's description of stages in the changes from Chl.1 greywacke to Chl.4 schist. A: Subzone Chl. 1. Consists of rock fragments and mineral grains in a finely crystalloblastic (see glossary) interstitial matrix.
B: Subzone Chl. 2. A few sheared and fractured clastic fragments remain, but amount of crystalloblastic materials has greatly increased.
C: Subzone Chl. 3. Rock is now completely crystalloblastic, although fine-grained.

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feldspathic sandstones and grits in New Zealand. It was therefore necessary to develop a suitably modified set of metamorphic zones.

**The chlorite sub-zones**

Investigations of the Te Anau Series north-west of Lake Wakatipu (Figure 6.14), showed that none of the rocks was entirely unaltered (Turner, 1935: 332). All of the greywackes always showed some effects of metamorphism even if they lacked schistosity and retained their clastic microstructure. Metamorphic grade varied from slightly altered greywackes through semischists to crystalline schists. However, the whole of the mapped area lay within the Chlorite zone so that all the rocks contained the same assemblage of reconstituted index minerals, making it impossible to use the index minerals to draw isograds and zone the area.

Turner devised a way of subdividing the rocks of the Chlorite zone into three subzones based not on index minerals, but on a slightly more subjective field technique in which texture was used to reflect metamorphic intensity as greywacke was converted through semischist to greenschist. Turner also suggested the likely existence of a fourth subzone where the schists are coarsely grained and thoroughly foliated. The three new subzones were:

- **Subzone Chl.1:** slightly altered greywackes with only incipient reconstitution.
- **Subzone Chl.2:** semischists, an 'ill-defined group of partially reconstituted rocks' intermediate between the greywackes and schists.
- **Subzone Chl.3:** the zone of fine-grained rather poorly foliated green schists.

Turner’s postulated fourth Chlorite subzone, Chl.4, was soon identified and described in a brief two-page paper (Figure 6.14) where Turner’s younger colleague, C.O. Hutton, catalogued six mineralogical equilibrium assemblages (Hutton and Turner, 1936). The new Chl.4 subzone contained all the typical Central Otago schists mapped as Foliated Schists by McKay (1881), the Wanaka Series by F.W. Hutton, and as the Maniototo Series by Park. All of Turner’s and Hutton’s work was brought together when Turner (1938) drew attention to mineralogical and structural differences between the Otago schists and those belonging to classic areas of regional metamorphism, such as the Scottish Highlands and the Caledonian chain of Norway. The mineralogical differences were caused by 'chemical peculiarities in the parent rock' because the mineral assemblages in the New Zealand metamorphic zones were based on their derivation from greywackes rather than from shales. Moreover, high shearing stress and relatively low temperatures governed the crystallisation of the low-grade mineral assemblages characteristic of the Otago schists. The transformations during early metamorphism could be traced by changes in clastic...
structure, and in cataclasis, grain-size, schistosity, chemical reconstitution and foliation. These textural features made it possible to subdivide Otago’s very large Chlorite Zone.

**C.O. Hutton and Pumpellyite**

Turner’s colleague, Colin Osborne Hutton (1910-1971), was born in Dunedin. He is unrelated to Frederick Wollaston Hutton (1836-1905) and there is no connection between either of these men and James Hutton of Edinburgh (1726-1797). Hutton was a student of Benson and Park, and of Turner himself (Coombs, 1974). In 1937, Hutton (1937) found large amounts of the mineral pumpellyite in schists derived from greywacke, although previously, few previous records of the mineral existed anywhere. Pumpellyite was shown to be a constituent of schists belonging to the Chlorite subzones Chl.1, Chl.2, and Chl.3, but not in the more metamorphosed rocks of the Chl.4 subzone, and provided a reliable means of separating these subzones. In a meticulously detailed memoir on the mineralogy and structure of the Otago schists, Hutton (1940) used pumpellyite to identify the semi-schists of the lower grade subzones, with a detailed explanation of how greywacke rocks progressively responded to increasing stress.

**Turner, Hutton and metamorphic processes**

The various regional stratigraphic names previously given to the greywacke-derived Otago, Alpine and Marlborough schists (Figures 4.7, 4.8, 4.9, 5.8, 5.10, timelines) could never assist geologists to understand relationships and metamorphic processes. All of the earlier attempts at stratigraphic subdivision had to rely on each person’s subjective choice as to where one grade of schist turned into another, and on the assumption that the assumed subdivisions were really all separated by hidden unconformities. Turner’s and Hutton’s investigations meant that the subdivision of the schists was now entirely a mineralogical and not a stratigraphic matter, and was concerned with metamorphic processes rather than with geological time and history. Being based on index minerals, subdivision was now comparatively objective and reliable, even though the separation of the Chlorite subzones did involve some subjectivity. By 1950, geologists were little further ahead in understanding the causes of metamorphism, but metamorphic zones could be dependably traced in the field. Later, they were put to use in mapping the schists for the 1:250,000 geological map series of the 1960s (Gage, 1985).

Turner (1936) also pioneered the study of structural petrology in New Zealand in which elements of the tectonic history of the Otago region were traced by the petrological analysis of crystal orientations. Turner’s later writings (1948, 1981) made Otago a classical geological area in world terms, which, like the Scottish Highlands, clearly demonstrate progressive regional metamorphism.

Turner’s and Hutton’s New Zealand publications are densely packed with petrographical descriptions and interpretations but neither man was ready to discuss either the age or the causes of metamorphism.
When dutifully, but briefly, addressing these problems, Turner usually suggested (for example 1933) that regional metamorphism was ‘dynamo-thermal’ being caused by Paleozoic or Lower Mesozoic folding and deep burial accompanied by contemporaneous invasion from below by extensive subjacent batholiths of granite. Hutton’s view (1940: 73-75) was that intense folding with intrusion at depth of an acid batholith caused dynamothermal metamorphism, and that this was completed before the ‘initiation of the Trias-Jura period of widespread sedimentation’.

Both men were always concerned more with tracing metamorphic processes than with the stratigraphic significance of the various sets of rocks, and both remained strictly distant from any stratigraphic controversies. Their scrupulously detailed petrographic work traced the mineralogical and structural sequences by which greywacke was converted into schist and validated Marshall’s and Bell’s claims of nearly 30 years’ earlier (Chapter 5) that the one graded into the other. Notwithstanding all this, the Survey geologists retained their traditional view that the Otago schists were of Paleozoic age, and were divisible into several recognisable stratigraphic units (Williamson, 1939; Ongley, 1939). When the Survey published the great 1947 geological map of New Zealand (Figures 5.21, 5.22), the Otago and Marlborough schists (Haast schists) were, for the first time, distinguished from the Westland rocks because of the discovery of the Alpine Fault (Marwick, 1948). An upper Paleozoic age for all of the Otago, Alpine and Marlborough schists was indicated on the map, but all of this was completely changed in 1958 when the Otago, Alpine and Marlborough schists were mapped as high stress low temperature schists of Lower Mesozoic and Upper Paleozoic age (Grindley et al., 1958).

**Geological Histories of Pre-Cretaceous New Zealand Interpretations and Origins 1900-1950**

‘By “geological history” is meant the attempt to depict the distribution of the land and water at the different epochs of geological time, to reconstruct the outline and physical features of the dry land, to clothe the land with vegetation, and people the seas with life, and lastly, from a study of the character of the contemporary vegetation and marine life, to indicate the probable climatic conditions prevailing at the time.’

(Park, 1918: 10-20)

A major innovation brought to the New Zealand Geological Survey in Bell’s time (Chapter 5) was the regular inclusion of geological histories in each of the new series of Survey bulletins. Instead of focussing simply on data collection and reporting, field geologists were now expected to evolve ideas about the
past, to develop hypotheses that accounted for what they observed in the field, and provide some kind of rationale for the way in which they constructed their maps and sections.

How do you write a geological history? Naïve students in the 1950s first read what other students had written about their neighbouring areas, then followed Lahee's advice (1941: 707) to place all their rocks in inferred stratigraphic order from bottom to top and then describe what they thought were 'the events in the natural sequence of their occurrence'. To make a credible reconstruction of, for example, the geological history of the New Zealand greywackes, students needed a good understanding of how rocks originated, of their stratigraphy, of their paleontology, and of tectonic change. Obviously, the presence of marine sedimentary rocks meant that the region was once below sea level, folding of strata indicated compressive forces had been at work and a break or unconformity in the sequence meant the land had been lifted above sea level and subsequently eroded. However, students were not always conscious that a stratigraphic break could represent the passage of far more time than any of the rock sequences (Ager, 1981).

**Hutton’s historical template**

Following his days as Hector’s assistant geologist, F.W.Hutton quickly moved far beyond simple empirical reporting of geological observations, and on to the analysis of New Zealand’s accumulating stratigraphical data. Hutton’s earlier ideas (Hutton and Ulrich, 1875: 84) of a relationship between large unconformities, elevation of the land, and glaciation (p.109) eventually led to his concepts of the relationship between stratigraphy and mountain building. Hutton (1885, 1899) arranged, rearranged, organised and grouped the Survey’s stratigraphical stack of rock series into a systematised stratigraphical column in which several rock formations were grouped into systems separated by inferred mountain-building episodes. Thus, a stratigraphic column not only acted as a legend for a geological map, it summarised the region’s geological history (Figure 4.8). Hutton developed the first coherent geological history of New Zealand, which became a historical template or model. This model featured a major episode towards the ‘middle of the Jurassic period [in which] folding of the rocks again occurred.... The Alps were formed, and the present land ... born, for since then it has never been submerged’ (1899).

The greywackes and argillites of Hutton’s Permo-Carboniferous Maitai System (Figures 0.6, 4.8, Table 6.3) were regarded as separate from, and older than, the fossiliferous Mesozoic Hokonui rocks, which he supposed to have been deposited in shallow water near to a large continent to the west. Hutton accepted that the Permo-Carboniferous Maitai sediments (greywackes) were of shallow water origin, but he also suspected that associated red jasperoid ‘slates’ with manganese oxide were of abyssal, oceanic
Table 6.3: Hutton’s template of a geological history of New Zealand. Shaded cells represent events to do with the greywackes.

<table>
<thead>
<tr>
<th>Stratigraphic systems</th>
<th>Geological History of New Zealand</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Late Tertiary</td>
<td>Tertiary sediments</td>
<td>McKay’s hypothesis (1881) of faulting and post-Miocene uplift of the Kaikoura Mountains and the Southern Alps ignored by F.W.Hutton and others</td>
</tr>
<tr>
<td>Early Tertiary</td>
<td>Subsidence to form a narrow chain. A less violent elevation at beginning of Tertiary era Upper Cretaceous sediments</td>
<td>BUT</td>
</tr>
<tr>
<td>Middle Jurassic</td>
<td>Major folding episode, New Zealand Alps formed</td>
<td>The ‘land of New Zealand born’</td>
</tr>
<tr>
<td>Hokonui System (Southland, Nelson, Kawhia-Port Waikato). (Today’s Murihiku Terrane)</td>
<td>Mesozoic and young Palaeozoic sediments - from a large continent somewhere to the north and west.</td>
<td>Hutton’s ‘proof’ of an important mid Jurassic elevation: 1. Absence of Upper Jurassic and Lower Cretaceous rocks. 2. Unconformity between Putataka and Upper Cretaceous Waipara formations. 3. All pre-Cretaceous rocks ‘partake’ in the folding of strata</td>
</tr>
<tr>
<td>Maitai System (Today’s six other ‘fold-out’ greywacke terranes, see Introduction Fig.0.5)</td>
<td>Permian elevation Thick Permo-Carboniferous sediments. Shallow and deepwater sediments</td>
<td></td>
</tr>
<tr>
<td>Takaka System (Today’s north-west Nelson, Westland and Fiordland rocks PLUS Otago, Alpine, Marlborough schists)</td>
<td>?Folding episode? Ancient Palaeozoic basement, mainly crystalline gneisses, granites, schists, slates</td>
<td></td>
</tr>
</tbody>
</table>

origin (Hutton, 1899). The nearest he came to explaining the association of shallow and deep water sediments was to suggest that the red slates formed in the deepest sea while debris from a Permo-Carboniferous Australian continent accumulated to the west. Many later interpretations of New Zealand’s pre-Cretaceous geological history were based on Hutton’s model, and Marshall (1910: 437) agreed with him that ‘The late Jurassic was the critical period in New Zealand and since that period New Zealand has been essentially the same in outline and configuration’.

The Survey geologists’ histories

Because of the common presence of large quantities of coarse sandstones, along with some grits and conglomerates, the general belief was that the ‘grauwackes’ and argillites (of whatever age) were entirely shallow water sediments deposited near the slowly sinking shore of a large continent. The shore had to sink to accommodate the large amounts of sediment. Hutton’s suggestion that the occasional red rocks were abyssal was simply ignored. There was continuing doubt about the exact location of the mysterious Palaeozoic continental source of the sediments although the majority choice was for a western landmass (for example Bell and Fraser, 1906; Park, 1909b; Marshall, 1911). On the other hand, the distribution of conglomerates was sometimes interpreted as indicating an eastern landmass (Fraser and Adams, 1907 23) or another to the north and east (Bell and Clarke, 1909).
Park (1909a: 58) opted for a Palaeozoic continent to the east of Otago because the sediments became more argillaceous to the westward. Morgan's continent, which supplied so much debris to the Mikonui (1908) and Greymouth (1911) regions in Westland lay to the west, and Morgan considered that the ‘buttress of gneissic rocks’ forming Western Otago (Fiordland) might be a remnant of the ancient land. Morgan also remarked (1908: 34) that ‘some writers have regarded New Zealand as having in Palaeozoic periods formed part of the lost Gondwana continent, and in Mesozoic times as being connected with an Australo-Indo-Malay land-mass’. However, by 1910, it was ‘generally accepted theory’ among the Survey geologists that their hypothetical Paleozoic granitic continent lay somewhere to the west of the present day land (Webb, 1910: 9).

While all the geologists agreed with the idea that folding of the sediments terminated a very long period of deposition, different opinions were expressed regarding just when such folding took place. Bell and Fraser (1906: 20-22) pondered on an early Mesozoic (or older) orogeny which elevated the sediments forming the rocks of the Hokitika subdivision (Figure 5.4) above the sea, resulting both in the folding of strata and regional metamorphism of part of the Arahura Series. In the Coromandel region Fraser and Adams (1907) saw that the sediments were folded in a more or less north-south direction and were perhaps elevated in the Jurassic period to form an anticlinorium by great ‘orogenic movements’ forming ‘one of the most pronounced breaks in the whole geological history of New Zealand’. At Whangaroa in the far north of the North Island, the igneous rocks that Bell and Clarke (1909: 22) considered to be contemporaneous with the sedimentary rocks of the coastal belt indicated that volcanic activity was common along the ancient sea-coast. However, no age could be given to the elevation and folding that followed the deposition of the Devonian to Triassic Waipapa Series.

In Westland, Morgan had great difficulty in reconciling the north-east to south-west folding directions of the ‘grauwackes’ of the Arahura Series on the western margin of the Southern Alps, and the north-west to south-east folding of the allegedly younger Greenland Series ‘grauwackes’ (Table 5.1 and Figure 5.5). He hesitantly accepted that both series shared in the Jurassic folding but also identified a later period of elevation and mountain-building at the beginning of the Tertiary. This was when a high mountain range ‘came into existence’, but Morgan was not at all certain if it represented today’s Southern Alps, or if it was another, older, mountain system that extended to the west of the present coast-line. To him, this Mesozoic-early Tertiary event was, perhaps, part of the great world-wide earth-movement postulated by Marcel Bertrand as one of a series of major movements that built the European Alps (Gohau, 1990: 178).
Marshall's account

In 1911 Marshall presented his own detailed stratigraphic scheme along with comparative tables summarising other geologist’s schemes. Because of the coarseness of the sediments in the greywackes and the occurrence of plant fragments, he believed that the whole series of sediments constituting his own Trias-Jura Maitai system (Figures 5.11, 5.12, p.140, 143) was deposited near the shore of a continent. What is more, some sediments in the Southland area were actually above sea level for a time and supported a ‘luxuriant forest’. The plant fossils seemed to be related to the flora of the later Gondwana period in Australia and India, and Marshall concluded that an ancient continent probably did indeed stretch far to the westward, united New Zealand with Australia, and was perhaps a part of Gondwanaland.

Marshall assumed that, in spite of the lack of animal remains, the sandy greywacke sandstone beds showed that the depositional environment was an ordinary shoreline with sandy beaches. At the same time, he interpreted the presence of conglomerates as indicating fluviatile conditions, while the alternating fine shales indicated deposition some distance from the shore. At the close of the Trias-Jura period, earth pressure was thought to have caused all the Mesozoic sediments to be folded and elevated to determine the present outline of New Zealand.

Sedimentary environments

Before 1940, New Zealand geologists paid very little attention to the details of sedimentology. In his geochemical investigation of the Red Rocks of Wellington (p.127), F.K.Broadgate (1916) concluded that, contrary to Hutton’s belief, the seeming absence of radiolarian cherts and glauconitic sands from among these rocks meant that the red rocks were not of deep-sea origin. Broadgate suggested that the rapid alternation of sandstones and argillites indicated deposition in an estuarine environment, but also referred to Joseph Barrell’s opinion (1912: 428) that periodic storms might churn the sediments which are then carried into deeper water where the sand settles first, then the silt, causing the alternation of sandstones and argillites.

John Henderson (1880-1959) noticed that fine greywacke commonly graded into the thinly bedded argillites that separated the massive layers of coarser sandstone. The coarser rocks contained argillaceous matter and Henderson (1917: 70) explained this by assuming that the beds were deposited near the shore and the loose material had not travelled far enough along the coast to be well-sorted. The absence of fossils, the alternation of coarse and fine beds and the occurrence of ripple marks in the greywacke

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3 Radiolarian cherts are present at this locality (Grapes et al, 1990).
sandstone, were seen as supportive of the view that sequences of greywackes and argillites indicated shallow-water deposition. Wave-action was supposed to sort the masses of silt into coarse (greywacke) and fine (argillite) beds (Henderson, 1917; Henderson and Ongley, 1923: 21).

**Park’s greywackes**

Park (1909b: 437) noted that fossiliferous beds are uncommon among the greywackes and in ‘thousands of feet of strata there is no trace of organic life except for some obscure plant remains. During sedimentation ‘mud and sands followed each other with monotonous\(^4\) regularity’ to form a ‘great pile’ of sediments of fluvialile and estuarine origin. These Park believed had been laid down on the sinking littoral of a great Indo-African continent. Moreover, the coarse, sandy nature of the greywackes indicated quite clearly that they were shallow water deposits (Park, 1914: 205-206; 1925: 191-192). In Park’s view, remnants of the fringe of the great continent are left in the Paleozoic areas of Nelson, Westland and Otago. Park (1914: 402; 1925: 352) divided the New Zealand Jurassic rocks into a ‘Coastal type’ and an ‘Alpine type’. The former contained plant and animal fossils (perhaps he meant locations such as Mount Potts and Clent Hills), while the Alpine type made up the Alpine Chain. It lacked fossils and consisted of a ‘vast pile of alternating greywackes and shales of the *Flysch*\(^5\) facies’ (Park’s italics) probably formed in the delta of a river that drained ‘Gondwana Land’.

Like McKay, Park usually had some idea that needed to be exercised over several pages of instructive discourse. While in a philosophic mood Park (1918) reflected on the considerable difficulties faced by New Zealand geologists in reconstructing the earth’s history. Because of their ‘profound ignorance’ of the earth’s subcrustal condition, there were many difficulties in the investigation of the causes and directions of crustal movements. The dynamics of earth-movements puzzled Park, who pondered on whether or not they were governed partly by the disturbance of isostatic balance. If denudation of mountain-folds shifted the load to the ocean floor fringing the land, then the now overloaded segment should gradually sink. This subsidence would be compensated by uplift of the neighbouring dry land. Only a continental land mass could provide enough detrital material to form ‘the pile of [marine, estuarine and deltaic] strata composing the great axial chain of folded mountains’. Today’s mountain chains stand where once a ‘sea-floor ... ran along the shore of some pre-existing land-mass’. Eventually, Park gloomily decided that the problems involved in investigating the geological history of New Zealand were ‘almost insoluble’. New Zealand was ‘merely’ a residual block of a much larger but submerged land, and therefore the conditions of Palaeozoic and Mesozoic times were forever ‘veiled in obscurity’.

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\(^4\) Perhaps the first time this unfortunate word was used to describe New Zealand greywackes.

\(^5\) Park did not indicate his source for the term ‘flysch’.
Chapter Six

Palaeozoic and Mesozoic Seas in Australasia

Benson (1923) made a bold attempt to reconstruct a detailed Paleozoic and Mesozoic geological history of the south-west Pacific incorporating the New Zealand, Australian and Indonesian regions. His major aim was to work towards making detailed stratigraphic correlations between Australia and New Zealand, and to do this Benson focussed on two main problems:

- The stratigraphic and structural relationships of east Australia and New Zealand, along with the tectonic relationships between these two countries and Antarctica.
- The broader features of Australian and New Zealand paleogeography from pre-Cambrian times to the close of the Cretaceous period.

Benson compiled the views of over 280 Australian, New Zealand, American and European geologists, including those of 19 authors of paleogeographic maps of Australasia published between 1893 and 1921. Although much of the region consisted of poorly explored territories and virtually inaccessible ocean, Benson brought together a wide range of information, conjecture and opinions regarding regional structural, stratigraphic and paleontological patterns. Much attention was paid to what appeared to be geological and biological connections within the Southwest Pacific region, with Antarctica, with South America, and north into the Himalayan regions.

Benson’s history reflects the considerable theoretical difficulties under which geologists worked. He noted the many speculations, conjectures and theories put forward by palaeontologists based on the affinities and assumed dispersal of various organisms in the past. Various ad hoc hypothetical land bridges and their presumed emergences, subsidences and founderings were generally used to account for the distribution of organisms. However, the fixist belief in the permanence of continents and oceans proved to be especially unhelpful to paleontologists working in the Pacific region. Such necessarily large land bridges were incompatible with isostasy and neither the paleontologists nor the structuralists could find mechanisms for the various postulated subsidences and upthrusts. Benson himself (1924) indicated sympathy towards the theory of continental drift proposed by Wegener in 1912 when discussing the tectonic relationships in the Australasian region but he did not discuss theoretical mechanisms.

To illustrate his paleogeographic reconstructions, Benson prepared eleven small black and white maps (Figure 6.17). These are the first known paleogeographic maps to be drawn in New Zealand, although the country had previously appeared in world maps drawn by global theorists like Haug (Aubouin, 1965) and Schuchert (1916) (see Figures 7.3, 7.5). As was customary, Benson’s maps were superimposed on a present-day outline map of the area and were intended to cover its long history from pre-Cambrian times through to the end of the Cretaceous period.
Paleogeographic maps as chronicles

Benson’s maps were not intended to add new knowledge, but to reconstruct the region’s history by synthesising knowledge about the stratigraphy and structure of the region’s rocks, their tectonic history and to make sense of the various inferences and theories concerning their origin. ‘Paleogeographic maps are both a product and a tool of stratigraphic research’ (Moore, 1941), but few geologists explain how they go about making their visual reconstructions of the earth’s history. The geologist must collect, inspect and analyse a great deal of stratigraphic information as well as contemplate other authors’ inferences and conclusions. The geological artist then tries to represent the state of the earth during selected past eras, show the inferred distribution of sea and land, indicate changes that took place through long periods of time, and somehow explain the way in which the present state of the earth was attained. In a fixist, pre-plate tectonic world, well-designed paleogeographic maps assisted in the understanding of the makeup and distribution of fossil assemblages, the sources and depositional environments of sediments, past physiographic features, past climates and in the concepts of change (Moore, 1941).

Benson’s first six maps (Figure 6.16) are confusing because each map includes the inferred seas of both the upper and lower parts of the period, presumably to save space. Thus in Map 2, the Lower Cambrian sea is indicated by vertical stripes, and the Upper Cambrian sea is marked by horizontal stripes, while the locations of present day exposures of rocks are marked in black. Land areas (dots) in these maps were identified partly by the absence of marine sediments, but this cannot account for areas where whole formations have been eroded away. Benson was unable to indicate the presence of past mountains, plains, volcanoes and other geographic features except for Pre-Cambrian sand dunes and the Permian ice sheets of Australia.

Benson’s brave effort was generally well received even though a ‘reasonable attainment of palaeogeographic objectives cannot be expected... in the early or intermediate stages of general stratigraphic knowledge’ (Moore, 1941). No other attempt was made on such a scale to clarify New Zealand’s geological history, and for many years, students learned simplified versions of Benson’s paleogeography showing sequences of puzzlingly changing shorelines of the New Zealand region (for example Cotton, 1945: 81).

Paleogeographic maps could never be more than one speculative interpretation of how the stratigraphic and fossil record suggested past connections throughout the region. Benson’s discussion of paleogeography was simply a collation of material with no general conclusion, and his conclusions had to ‘rest on a balance of probabilities’ (Geikie, 1905: 2). He could not draw any generalisations regarding the stratigraphic or structural relationships between New Zealand and Australia and the theoretical
background was insufficient to explain the distribution of fossils in the region. At first sight, Benson’s drawings seem incompatible with the ruling global theory of permanentism (fixism). Simply to flick quickly through the maps gives a strange impression of very impermanent continents wallowing in inexplicably transgressing and regressing seas flowing back and forth across the region. However, a land mass (such as the New Zealand microcontinent) would retain its continental identity by virtue of its constituent rocks rather than whether or not the surface is above sea level.

The paleogeographic map has since been partly supplanted by palinspastic maps in which folded or faulted strata are shown ‘restored as closely as possible to their original geographical positions prior to folding or faulting’ (Allaby and Allaby, 1991). Palinspastic reconstructions must account for the entire volume of the materials represented and allow for crustal movement. Thus, all those who have attempted to reconstruct the history of the same south-west Pacific region since the Cretaceous break up of Gondwanaland, have had also to account for all stray pieces of lithosphere as best they can.

After 1925 the little work that was done on the pre-Cretaceous rocks was limited mainly to igneous and metamorphic rocks, while the greywackes were largely abandoned and few further attempts were made to construct geological histories of New Zealand until the 1940s (Allan, 1940; Cotton, 1945; Fleming 1949). The geological history of New Zealand that students learned until the 1960s was a direct descendant of the simple two-part model set out by Hutton in 1899 in which a single major unconformity was identified. It was refined by Marshall in 1911, visualised by Benson in 1923 and modified by Cotton (1945: 64-95) when he added a Mesozoic geosyncline to the eastern coastline of the western continent, and by Fleming in 1949 (Chapter 7).

How do geologists see this period?

When a number of senior geologists were asked to nominate the most important ideas developed in New Zealand (Cooper, 1984), the years from 1900 to 1959 were characterised as a time when no new ideas were generated here, when much data was accumulated, but little was done to connect the detailed collection of facts (Cooper, 1984; Lillie, 1985). Most geologists agreed that the most important geological discovery of the time was that of the Alpine Fault (for example Gage, 1985) when wartime mineralogical needs gave Wellman and Willet (1942) the opportunity to explore South Westland and establish the fault’s existence (p.188). The lack of a sound basis for correlating sedimentary strata and the absence of clear principles regarding time and rock subdivisions hindered progress (Gage, 1985). There was continuing uncertainty about the use of European or New Zealand time divisions and the lack of an experienced resident palaeontologist for so long was unhelpful. Little wonder that Park and Marshall maintained the nineteenth century style of bitter fighting over priority of conception and discovery (Greene, 1982: 190-191).
Continued from page 192.

Chapter Six

Benson's Palaeogeographical Maps 1923, (frames 6-11)
Money for science was always in short supply so that the Survey and the universities constantly operated in a climate of austerity (Hutton, 1899; Dick, 1951; Lillie, 1959, 1983; Brothers, 1983). The Survey was dominated by economic needs and some Survey publications even owed their existence to voluntary work by overseas specialists (for example, Arber, 1917). Libraries were small and underfunded, and Professor Bartrum built the geology library at Auckland University College out of his own income (Lillie, 1983). Perhaps those geologists working from outstations like Greymouth experienced the greatest professional isolation, as they had no ready access at all to professional journals (Harrington, 1999).

The collapse of Suess’s theory of global cooling as a mechanism driving geological processes meant that by 1950, geology was fragmented into a number of semi-independent specialties including the related fields of geophysics and geochemistry (Hagner, 1963; Greene, 1982). Petrologists, paleontologists and structural geologists all inhabited their own specialised compartments and had little to say to each other. Pacific Rim geologists were aware that some kind of relationship existed between oceanic deeps, island arcs, deep earthquakes and andesitic volcanoes, but there was no over-arching theory that could account for and link such geological objects or processes (Galbreath, 1998: 225-244). However, the failed attempts to explain orogenies and the distribution of fossils did little to affect the normal day-to-day work of geologists here who were well occupied with the practicalities of mapping and interpreting field observations. In spite of the everlasting shortage of funds, a long depression and two World Wars, geology in pre-1950 New Zealand managed to ‘advance vigorously in the face of general and even cheerful agreement that no adequate comprehensive theory exists’ (Greene, 1982: 294).
Chapter Seven

The New Zealand Geosyncline and the Greywackes

It is rather unfortunate ... that most of the prevailing rocks of New Zealand seem to be
rather a dull lot, with too much schist, and unexciting schist at that, and still less
interesting greywackes (Book review of Cotton, 1945, Earth Beneath.)
(R.H.R., 1946)

Greywacke is the problem rock of New Zealand
(Korsch and Wellman, 1988)

Around 1950, some new interest began to be taken in the ‘Undifferentiated-Jurassic-Triassic-Permian
greywackes and argillites’. Before the great 1947 geological map was issued these nameless rocks had
been grouped with the fossiliferous Hokonui rocks of Southland and Kawhia (now Murihiku terrane),
and all were referred to as ‘the Hokonuis’, a relic of the stratigraphical schemes of F.W. Hutton (1899)
and Park (1910). Now, those ‘unfossiliferous indurated rocks lying stratigraphically below the
fossiliferous Triassic and above the fossiliferous Maitai-Te Anau’ were clearly distinguished from the
Hokonui System (Figures 0.1, 0.6, 5.20, 5.21), and we called them simply, ‘the greywackes’ (Gage and

Because of the demise of the first New Zealand Geological Survey, much understanding of the
greywackes had been lost (Waterhouse, 1965: 994). The meagre knowledge of the greywackes¹ was
contemplated by A.R. Lillie (1951) who discussed the difficulty of subdividing the Upper Palaeozoic and
Mesozoic strata including ‘thousands of feet of argillites and especially arkoses, commonly of the
greywacke facies’. He noted that while no Carboniferous and Permian strata had then separated from
the Trias, some rocks of Aptian age (Lower Cretaceous) appeared to belong to the same basement.

Lillie’s paper marked a striking increase in geological activity in the 1950s (Figure 7.1). Some of that
revival is attributable to post-war reconstruction, including an increase in student numbers, and some to
Ongley, who became Director of the Geological Survey in 1945, and brought ‘a new feeling of optimism

¹ Lillie used ‘the greywackes’ as an all-inclusive term for the Hokonui (Murihiku) rocks and the ‘Undifferentiated’
greywackes.
Chapter Seven

Figure 7.1: Growth of geology in New Zealand as indicated by numbers of publications 1933-1995 listed in GeoRef™. Numbers of publications of Upper Paleozoic and Lower Mesozoic geology are shown separately for comparison. The exponential growth curve was generated by Excel™. The counts were made in 1998 and the apparent reduction in publication rates from 1989 was partly caused by a time lag in logging publications, but must also reflect the breakup of D.S.I.R. and changes in funding to science (e.g. Cartner and Bollinger (1997)).

Figure 7.2: Growth of New Zealand geology 1949-1959 as indicated by abstracts of New Zealand geology compiled by G.L. Adkin and by B.W. Collins. The numbers of publications to do with the greywackes of the 'Alpine facies' and the 'Hokonui facies' are compared with those to do with other geological topics. The numbers of papers on the greywackes and schists rarely exceeded 10% of the total number. Of over 2800 Geological Survey bulletin pages issued between 1950 and 1969, only 7% dealt with Mesozoic rocks and five of the 30 bulletins focussed on Lower Mesozoic rocks.
and vigour’ to the whole organisation (Burton, 1965: 81). The economic value of the greywackes was no better than before, so why did they deserve attention?

The large, plain blue areas on the 1947 map posed an irresistible challenge to some geologists (D.S.Coombs, pers.comm), but just as important, a series of 1:250,000 geological maps planned in the 1950s (Burton, 1965: 90) began to be produced in 1956, with the first map (Wanganui) being published in 1959 (Webb, 1965). The mapping programme meant that greywacke areas as well as the younger covering strata had to be examined in detail, and this raised interest (Campbell & Warren, 1965: 99-100). Besides, a set of theoretical tools that could help to explain the origin and geological history of the greywackes was becoming available. They included:

- The development of geosynclinal models to explain New Zealand’s geological history and the distribution of basement and covering strata (Cotton, 1945; Macpherson, 1946; Fleming, 1949; Gage, 1949; Wellman, 1952b, 1956).
- The concept of transport and deposition of sandy sediments into deep water by turbidity currents (Kuenen and Migliorini, 1950).
- Increased understanding of progressive low-grade regional metamorphism in New Zealand through the work of Hutton and Turner (p.180-184) and D.S. Coombs (p.218).
- The revision of the divisions and faunas of the Triassic and Jurassic Hokonui System by J.Marwick (Marwick, 1950, 1953).

**The Geosynclinal Model of Mountain Building**

E.Argand … has pictured geosynclines as determined by stretching, by continental drift-apart, which attenuates the sial layer and … allows sima to reach the bottom of the sea at bathyl or abyssal depths. If such drift separation continues, a new ocean bed may be developed…. If, as thrice happened in the post-Cambrian history of Europe, a drift of separation gives place to a drift of approach, then a folded mountain chain comes into being.

(Bailey, 1936: 1719)

The geosyncline’s genealogy must be characterized as a semantical jungle, [but] it has provided a very important rallying theme for sedimentation and tectonics for over half a century.

(Dott, 1978: 29).

From its birth in 1859 until it began to die around 1965, the concept of the geosyncline provided geologists with a useful, if sometimes controversial, model. It was directed towards explaining how belts of thick sequences of sediments were created and then folded, metamorphosed and elevated to form
mountain chains such as the Appalachian Mountains and the European Alps (Glaessner and Teichert, 1947; Kay, 1951; Aubouin, 1965; McBride, 1973; Dott, 1974, 1978, 1979; Greene, 1982).

Based on his observations in the Appalachian Mountains, John Hall in 1859 initiated the concept that a portion of the sea floor marginal to a continent may subside deeply while being filled with sediments. The concept of a long-continued subsidence or ‘geosynclinal’, including the concept of continental accretion, was refined by J.D. Dana (1873: 430-431) (see also Dott, 1979: 253). Thus, a ‘geosynclinal accompanied by sedimentary depositions, and ending in a catastrophe of plications and solidification’ are characteristic of many mountain masses. European geologists like Emil Haug took up the idea of geosyncline but developed a different model based on the European Alps (Aubouin, 1965: 7-17).

Figure 7.2: Haug’s cross-section of a subsiding geosyncline to explaining the accumulation of layers of sediments, metamorphism at depth, and the transformation of schists into granite. Modified after Ouret and Nijland (2002), after Haug (1907-1910).
Haug believed that geosynclines were deep, elongated, sedimentary troughs formed between two continents or ‘cratons’. In Haug’s 1907 view of the Mesozoic world, the New Zealand area was part of a continuous geosyncline that encircled the Pacific Ocean (Figure 7.3). To accord with his own world theory it was necessary for him to hypothesise the previous existence of a large continent that occupied the present Pacific Ocean (Aubouin, 1965: 12-16). A great thickness of sediments could accumulate in Haug’s subsiding trough-like geosyncline because of continuous deposition over a long period. The downwarping caused an increase in temperature and pressure (Aubouin, 1965) with the oldest and deepest layers brought closest to the granitic basement where metamorphism took place (Figure 7.4) (Touret and Jijland, 2002: 120-121).

The American geologist, Charles Schuchert (1858-1942), postulated in 1916 that in Paleozoic times, two north-easterly trending sedimentary troughs existed in the Australasian area (Fleming, 1985). The western ‘Tasman geosyncline’ covered the area now occupied by the mountains and plains of eastern Australia and the western Tasman Sea (Figure 7.5, p.220). The eastern ‘New Zealand geosyncline’ was longer and narrower than its western neighbour and also appeared in the Paleozoic, but continued its existence into the Mesozoic and Cainozoic. The southern portion was elevated to form the mountains of New Zealand, while the rest subsided to form a submerged plateau on ‘which stand the volcanic islands of the Kermadecs and the Tongas’. No mechanism was supplied for either subsidence or elevation.

Since the Challenger expedition of 1872-1876, much oceanographic research had been carried out in the Pacific Ocean (Hobbs, 1944; Cotton, 1948). Based on this research, global theorists including Alexander Du Toit (1937), Arthur Holmes (1944), William Hobbs (1923, 1944), Hans Stille (1945), J.F.H. Umbgrove (1947) and Harry H. Hess (1939), Hess and Maxwell, 1953) attempted to account for the mysterious association between fold mountains bordering the Pacific coast, volcanic island arcs, earthquakes, gravity anomalies, peridotites, and ocean deeps. The idea of the geosyncline was often used to help account for the relationship between these mobile belts and the thick layers of sediments folded into mountain ranges like those of New Zealand.

In his reconstruction of Gondwana, Alexander du Toit (1878-1948), a leading proponent of continental drift (Du Toit, 1937), extended his huge late Paleozoic Samfrau Geosyncline from southern South America, the Cape of Good Hope, and Antarctica to eastern Australia (Figure 7.6). Sediments formed within du Toit’s great geosyncline were subjected to late Cretaceous and Tertiary compression giving rise to the mountains of New Zealand and New Guinea. New Zealand also appeared in a global synthesis by Arthur Holmes (1890-1965) where this country and New Guinea formed a mountainous arc within the orogenic belt on the periphery of the continental masses of Gondwanaland (Holmes, 1944: 397-406). Such orogenic belts (Figure 7.7) were supposed by Holmes to have originated as geosynclinal
downwarps of the crust driven by 'sub-crustal convection currents' in which exceptionally thick deposits of sedimentary rocks accumulated.
The geosyncline elaborated, Stille and Kay

In spite of ‘uncertainty and confusion regarding the concept of the geosyncline’ (Glaessner and Teichert, 1947), and the difficulty of deciding ‘what was a geosyncline and what was not’, the usefulness of the concept increased. The idea of the geosyncline as a depositional site and precursor of mountains was rapidly developed and elaborated by the German tectonicist Hans Stille (1876-1966) (Aubouin, 1965: 20-26) and the younger United States geologist, Marshall Kay (1904-1975). Stille postulated that ‘true’ or orthogeosynclines were located in mobile zones either between two stable continents or ‘cratons’, or marginal to a craton. An orthogeosyncline contained two longitudinal and parallel belts, the eugeosyncline and the miogeosyncline. The miogeosynclinal belt lay close to and parallel to the craton and lacked volcanic rocks. The mobile eugeosynclinal belt was located on the side away from the craton. It was characterised by ophiolitic to basaltic vulcanism and thought to be the necessary precursor to mountain chains. Igneous activity was supposed to follow a set sequence throughout the life cycle of a eugeosyncline in which initial basic magmatism was followed at the onset of orogenesis (mountain building) by andesitic to rhyolitic types of eruption. In due course, such geosynclinal zones were accreted to the continent or ‘cratonised’ by orogenesis, resulting in the growth of the continent (Dott, 1972: 253).

Kay (1951) extended Stille’s concepts, devising a ‘baroque taxonomy’ (Oldroyd, 2002: 4) for his numerous North American geosynclines. Somehow, Kay’s interpretation of the lower Paleozoic assemblage of rocks from New York to Maine (Figure 7.8) became the standard textbook model of a miogeosyncline-eugeosyncline couplet, although this was not his intention (reported by Dietz and Holden, 1974). Even
though it was already known that no example of an orthogeosyncline exists today (Dietz, 1963)\(^2\) Kay’s miogeosyncline-eugeosyncline couplet became a basic component in geological thought. It effectively determined the structural, tectonic and sedimentary model followed by many geologists for the next 15 years and a similar model came to dominate geological thinking in New Zealand.

![Figure 7.6: Marshall Kay’s classic New York to Maine orthogeosynclinal pair incorporating a miogeosyncline and a parallel eugeosyncline. The ‘zone of juncture’ between such belts is ‘almost invariably one of great deformation’ with thrust faults (66). Labels added. Modified after Kay (1951) North American Geosynclines.](image)

**Geosynclines in New Zealand**

Although New Zealand had been included by European and American geologists in their global syntheses, New Zealand geologists seemed to be in no hurry to take up the idea, to develop their own generalisations, or to make use of the structural models developed elsewhere. Park (1914, 1925) referred briefly to Dana’s geosynclinals but did not apply the idea to New Zealand. Marwick (1929) saw mountain chains as consisting mainly of marine beds that had been laid down on the floor of geosynclinal troughs which filled with shallow-water sediments as they subsided. Thus, the idea of a geosyncline in the New Zealand region drifted around the universities and the Survey (Bartrum, 1939; D.S.Coombs pers.comm.; J.B.Waterhouse, pers.comm.) but was little developed.

As the general concept of the geosyncline became more secure in the 1940s, New Zealand geologists used it to explain features of the geology of this country. In a pictorial centennial volume (1940), Robin Sutcliffe Allan (1900-1966) described how spoil from Gondwanaland was deposited on the site of New Zealand, causing the Earth’s crust to sag. Lateral pressure ‘led to folding on a large scale and the uplift of an extensive mountain system’. Then, in a little book for the ‘average reader’, Cotton (1945: 39, 76) developed the idea that thick layers of predominantly shallow-water sediments had accumulated in a vast Permian-Jurassic geosyncline at least as large as present-day New Zealand. This geosyncline was supposed by Cotton to form a mobile belt adjacent to and parallel to mountain ranges, but the ‘exact

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situation of the mountainous land that supplied sediment ... is not known’. The resulting thicknesses of unfossiliferous ‘greywacke-making sediments’ were afterwards intensely folded to form the bulk of the South Island mountain masses and the axial ranges of the North Island. Cotton distinguished contemporaneous beds ‘of a different, fossiliferous facies’ and noted that the Permian beds in these sequences are ‘sometimes known as the Maitai series and the Triassic and Jurassic as the Hokonui’.

To explain the sources and distribution of the modern biota of New Zealand, Charles Alexander Fleming (1916-1987) described a deep, wide, linear geosyncline that occupied the position of New Zealand during Triassic and Jurassic times (Fleming, 1949). It extended from Nugget Point in Otago in a ‘sinuous line’ across Canterbury and Marlborough, up the North Island to Kawhia and North Auckland. The structure was explained as a gradually sinking basin, a down-fold, and ‘almost certainly parallel to a welt, a rising mass of land ... believed to have been west of the geosyncline’. Fleming suggested that the structure probably stretched north-west and south, perhaps forming ‘land connections, or island arcs towards New Guinea’. During the Cretaceous period, sedimentation in the geosyncline closed with orogeny and uplift, which ‘must have amounted to many thousands of feet [with] erosion taking it off as it came up’.

That same year Maxwell Gage (1913-2000) proposed that the coal-bearing Upper Cretaceous strata in Westland had been deposited within several ‘miniature’ geosynclines (Gage, 1949).

**Meanwhile, in Australia**

A second, mid-Paleozoic ‘New Zealand Geosyncline’ was offered in 1952 to account for similarities between Devonian fauna in the South Island and those of eastern Australia and Tasmania (Gill, 1952; Fleming, 1985). Gill based his scheme on Schuchert’s 1916 south Pacific geosynclines with a Devonian
Tasman Geosyncline and a New Zealand Geosyncline separated by a Tasmanitis Massif occupying the present Tasman Sea (Figure 7.9). However, this geosyncline had no role in the formation of the Mesozoic greywackes.

**Another paradigmatic geological revolution in New Zealand**

On reviewing the Permian-Jurassic stratified rocks of New Zealand, Wellman (1952b) further developed the concept of a large upper Paleozoic to lower Mesozoic geosyncline in this region (Figure 7.10), and made the first real advances towards understanding the greywackes and argillites and their relationship with the schists and with the Hokonui (Murihiku) rocks. These included:

- The introduction of the idea that the greywackes and the Hokonui (Murihiku) rocks represented two parallel, coeval, but contrasting depositional facies. The sediments of both facies were supposed to have been deposited in different parts of the same geosyncline.
- The acceptance of the concept that the schists were of very similar age to the associated greywackes on both sides of the schist axis (Wellman et al., 1952).
- Promotion of the concept that the degree of metamorphism depended on depth of burial.
- The measurement of metamorphic rank of the greywackes by using coal rank (Wellman, 1952a).

A curving ‘schist axis’ was introduced as a major structural feature of the South Island (Figure 7.10) and although no schist was known in the North Island, the axis was thought to extend northwards under younger and less metamorphosed sediments. The South Island schist graded into less metamorphosed rocks on both sides of the axis (Figure 7.10). No abrupt change in lithology existed between the schist and the neighbouring slates and sandstones (greywacke), and there was no reason to suspect an unconformity between them. This meant that the whole of the extensive schist belt could be considered Carboniferous to middle Triassic in age (Table 7.1). Wellman believed that the degree of alteration of rocks showed a progressively decreasing depth of burial for rocks away from the schist belt.

Two closely parallel, depositional facies environments were identified, a ‘marginal syncline’ and a ‘major geosyncline’. The western margin of the major geosyncline was supposed to have been formed by lower Paleozoic rocks like those of western South Island, but nothing was known about the eastern margin (somewhere in the Pacific Ocean). The rate of deposition and sediment type within each facies was affected by distance from the shore, so that parallel bands of sediment were formed along the length of the geosyncline. Rocks of the fossiliferous ‘Hokonui facies’ were deposited in the marginal syncline nearest the shore on the western margin of this geosyncline, and these bordered the schist belt on the south-west and west side (marked on Figure 7.10 by cross-hatching). This Hokonui facies corresponded with the Triassic and Jurassic Hokonui System of the great 1947 map (Figures 5.20, 5.21, pp.168, 170).
The compacted sandstone, siltstone and mudstone of the ‘Alpine facies’ on the eastern, or Pacific side of the schist axis were reported as having complex structure, conspicuous graded bedding, rare fossils, and are ‘commonly known in New Zealand as “greywacke and argillite”’. These rocks were considered to have formed nearer the centre of the trough where ‘deposition was more rapid’. Wellman saw no evidence for deep water beds and believed the ‘sediment supply was sufficient to keep the geosyncline filled almost to sea level at all times’. These rocks were recognised as being more altered than the Hokonui facies, and Wellman used his own coal rank system to indicate the degree of metamorphism. This varied from ‘high volatile bituminous rank’ for Upper Triassic rocks of the Hokonui facies, to ‘anthracite rank’ for Upper Triassic beds of the Alpine facies at Clent Hills, and to ‘graphite rank’ nearer the schist. Little was known of the stratigraphy of the Alpine Facies, but the recently found Permian fusulinids and corals near Whangaroa in Northland (Hornibrook, 1951) meant that the facies could be divided into an upper Paleozoic Waipapa series and the Mesozoic rocks.

Wellman’s paired facies scheme meant that New Zealand geologists no longer had to slot all the different rock formations into a single, layer-cake, stratigraphical stack according to age. It was no longer necessary to make the greywackes older than the Hokonui, or to make the schists very much older than the greywackes. Rocks of the Hokonui Facies and the Alpine greywackes could form at the same time but in two different, parallel environments.

Table 7.1: ‘A Major Geosyncline’. Table based on the legend to Wellman’s 1952 map.

<table>
<thead>
<tr>
<th>‘A MAJOR GEOSYNCLINE’, 1952</th>
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<tbody>
<tr>
<td>HOKONUI FACIES</td>
</tr>
<tr>
<td>Marginal syncline</td>
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<tr>
<td>Fossiliferous</td>
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<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td>Jurassica &amp; Triassic</td>
</tr>
<tr>
<td>Southland, Nelson, south-west Auckland</td>
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<td></td>
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<tr>
<td>Upper Paleozoic</td>
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<tr>
<td>Te Anau, Maitai &amp; Clinton formations</td>
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<tr>
<td>Brook St volcanics</td>
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</tbody>
</table>

3 Reminiscent of Park’s ‘Alpine type of the flysch facies,’ 1925.
Chapter Seven

Figure 7.10: Wellman’s 1952 map showing the main features of upper Palaeozoic and lower Mesozoic structure of New Zealand. The map is in part based on Macpherson’s 1946 map (Figure 6.9). In this map the greywackes and schists of the Alpine Facies are clearly separated from the Hokonui Facies to the south and west (see Table 7.1). The ‘schist axis’ curves north towards the Alpine Fault from near Dunedin. The relationship between the two parallel facets appears to resemble the Stille-Kay miosyncline-eugeosyncline couplet. Wellman (1952) Symposium sur les Séries de Gondwana.

NEW ZEALAND

Showing main features of upper Palaeozoic & lower Mesozoic structure.

Legend

Hokonui Facies Alpine Facies

Jurassic & Triassic
Maipapa Formation

Te Anau, Maitai a Clinton formations

Brook St. volcanics

Alpine, Otago & Marlborough Schist

Figure 7.10: Wellman’s 1952 map showing the main features of the upper Palaeozoic and lower Mesozoic structure of New Zealand. The map is in part based on Macpherson’s 1946 map (Figure 6.9). In this map the greywackes and schists of the Alpine Facies are clearly separated from the Hokonui Facies to the south and west (see Table 7.1). The ‘schist axis’ curves north towards the Alpine Fault from near Dunedin. The relationship between the two parallel facets appears to resemble the Stille-Kay miosyncline-eugeosyncline couplet. Wellman (1952) Symposium sur les Séries de Gondwana.
Figure 7.11: Wellman's New Zealand Geosyncline of 1956 with the upper Paleozoic and lower Mesozoic rocks divided into two parallel, coeval facies. Original legend shown, but see explanatory Table 7.2. The schist axis continues into the North Island. P = pre-Triassic rocks. Ts, Js = Triassic and Jurassic shelf sediments, i.e., Hokonui Facies. Tg, Jg = Triassic and Jurassic geosynclinal sediments. Upper Mesozoic Geosyncline = Lower Cretaceous. 54% original size. Large labels added, colour modified after Wellman (1956). New Zealand Department of Scientific and Industrial Research Bulletin 121
The third (and last) New Zealand Geosyncline

Several years’ later, and after much discussion with colleagues of the Geological Survey, Wellman (1956) updated and refined his geosynclinal model in a wider review of the structure of New Zealand. In this more sophisticated and much more influential version, the upper Paleozoic and lower Mesozoic rocks were again divided into the Hokonui Facies and the Alpine Facies, but were now subdivided into periods (Table 7.2, Figure 7.11). Strata were rearranged with the older Maitai, lower Clinton, upper Tuapeka and Te Anau rocks of south Otago being moved from the Hokonui Facies to the Alpine Facies. The greywackes were characterised as ‘mostly thick, dark, feldspathic sandstones … that imply mountains with volcanoes, fast rivers and quick transport to rapidly subsiding marine trenches’, deposited in a large geosyncline that extended northwards towards New Caledonia. Now, it was given a name, the ‘New Zealand Geosyncline’, suggested by Wellman’s colleague, Alexander Russell Mutch (1925-2000) who used it in his analysis of the facies and thickness of the Hokonui rocks of Southland (Mutch, 1957: 509).

1: Wellman’s 1956 division of upper Paleozoic and lower Mesozoic rocks into two parallel, coeval facies. Table based on legend to Figure 7.11, New Zealand Geosyncline.

<table>
<thead>
<tr>
<th>THE NEW ZEALAND GEOSYNCLINE, 1956</th>
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<tr>
<td><strong>HOKONUI FACIES</strong></td>
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<tr>
<td>Shelf and transitional beds of</td>
</tr>
<tr>
<td>the Marginal Syncline.</td>
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<tr>
<td>Fossils not uncommon</td>
</tr>
<tr>
<td><strong>Jurassic</strong></td>
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<tr>
<td>Freshwater beds with plant</td>
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<tr>
<td>impressions and marine beds</td>
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<tr>
<td></td>
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<tr>
<td></td>
</tr>
<tr>
<td><strong>Triassic</strong></td>
</tr>
<tr>
<td>Marine beds</td>
</tr>
<tr>
<td>**Permian Marine beds: Maitai,</td>
</tr>
<tr>
<td>upper Clinton, and</td>
</tr>
<tr>
<td>Productus Creek</td>
</tr>
<tr>
<td><strong>Permian, Carboniferous?</strong></td>
</tr>
<tr>
<td>Mostly igneous with thin</td>
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<tr>
<td>sediments.</td>
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<tr>
<td><strong>Resembles Kay’s miogeosyncline</strong></td>
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<td><strong>Resembles Kay’s eugeosyncline</strong></td>
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</table>
The greywackes of the Alpine Facies represented the farthest off-shore deposits to the east of the New Zealand Geosyncline, and were now interpreted as mostly redeposited sediments with few fossils and with thin ‘interbedded’ layers of spilitic basalt. Although the North Island axial ranges constituted the least known area of New Zealand greywacke, it was believed that the metamorphic grade of these greywackes increased to the north-west reaching sub-schist rank in the Kaimanawa Range (p.321). The schists were now accepted as having been formed from geosynclinal greywacke and argillite ‘into which it grades up’ and they were now ‘considered to represent the sediments most deeply buried in the axial part of the New Zealand Geosyncline’.

Wellman believed uplift and sedimentation to be complementary so that as some parts rose, other parts sank, and over time, new geosynclines formed on the Pacific side of the old ones, that is, the geosynclinal axis migrated eastwards. Accordingly, an earlier lower Paleozoic geosyncline had been situated to the west of present day New Zealand, while the great upper Paleozoic-lower Mesozoic New Zealand Geosyncline more or less corresponded to present-day New Zealand. Then, while it was being ‘everted’ and its sedimentary contents folded and uplifted, the lower Cretaceous greywacke sequences of eastern Marlborough, and eastern North Island were deposited in new geosynclines formed to the east (figured in sequential cartoons of Grindley, 1957). The process was thought to continue so that today’s geosyncline is the oceanic trench situated to the east of the New Zealand landmass.

The invention and formalisation of the New Zealand Geosyncline ‘constitutes a milestone in New Zealand geology’ (Landis, 1969: 54). Kay’s ‘luxuriant terminology’ to do with his assortment of geosynclines (Oldroyd, 1996: 175) may well have indicated a science in the doldrums (Menard, 1971: 136), but in New Zealand, Wellman’s version came when geology was beginning to expand rapidly (Figure 7.1). A very large proportion of New Zealand’s sedimentary rocks of all ages were characterised as being geosynclinal, and the New Zealand Geosyncline, along with the turbidity current theory provided a plausible model to account for their origin, stratigraphy and structural style. Wellman’s model meant that the two coeval, contrasting, but neighbouring sets of rocks of similar age could each be given names, a place, a time, and their origin and relationships explained. It constituted a successful, understandable, and workable paradigm that was readily accepted by members of the geological community, and which lasted for nearly twenty years. It was welcomed so willingly by geologists who had no other adequate global theory to guide their ideas, and who were already familiar with the idea of an ancient geosyncline in this region.

**Was the New Zealand Geosyncline made in New Zealand?**

Although the New Zealand Geosyncline seems very like the Stille-Kay miogeosyncline-eugeosyncline model, Wellman did not refer to Stille or Kay, or use the terms ‘orthogeosyncline’, ‘miogeosyncline’ or
'eugeosyncline’. Earlier Survey writers habitually cited only New Zealand works related to their subdivision and Wellman appears to have followed this custom. In any case, he had little interest in the scientific literature and always maintained that you ‘could not develop your own ideas if you filled your head with other people’s thoughts’ (S.Nathan, pers.comm.). In this he was like many other ‘fruitful and imaginative scientists’ who were quite ‘casual’ about reading the literature (Menard, 1986: 4-6). We do not know if Wellman devised his Alpine-Hokonui model without knowledge of the Stille-Kay model, and independently invented the model here, based on the clearly contrasting styles of the two facies.

By 1948 Wellman was experimenting with several ideas about New Zealand’s regional geology by 1948, and these were introduced during the New Zealand Geological Survey staff conference at Rotorua. He described a major Carboniferous to Triassic geosyncline complete with a synclinal ‘marginal belt’ (similar to his 1956 ‘Marginal Syncline’, Figure 7.11). The regional distribution of fossiliferous Triassic rocks was described, in which Wellman recognised ‘two distinct Triassic facies’, with a near shore fossiliferous facies and the deeper water, less fossiliferous, beds to which belonged the ‘apparently isolated Mt St Mary, Mt Potts, Okuku and other areas in Canterbury’. The Triassic rocks thicken towards the Marlborough-Alpine-Otago schist belt, while the depth of burial is indicated by the coal rank of the Jurassic beds. These ideas about geosynclines appear to have been at least partly triggered by Wellman’s recent work in the Nelson district as well as the implications of the ‘300 mile horizontal shift’ along the Alpine Fault, which he introduced at the same 1948 Survey conference (Kear, 2001). The ensuing discussion indicates that other participants (including Professor Bartrum, Mr Fleming and Drs Marwick, Cotton, and Lillie) were intrigued and interested. No reference was made to overseas authorities.

Wellman’s geosynclinal model (1956) was further developed during discussions with colleagues, when a number of geologists would have been drawn into the debates and contributed ideas. Wellman was famous for provoking energetic discussions that grew into noisy geological free-for-alls in which ‘arguments developed, matured and recycled’ (Walcott, 1999). Any ideas brought into such sociable but intellectually intense sessions would be tossed about, criticised, remodelled and revised, and at the end, no one would have any recollection of their origin. The design details of the New Zealand Geosyncline were probably largely indigenous. Alan Patrick Mason (b.1923) made a rare New Zealand reference to Stille’s orthogeosyncline and its division into a eugeosyncline and miogeosyncline (Mason, 1953: 369) and greywackes were described as ‘typical eugeosynclinal deposits’ (Hopgood, 1960), but otherwise, the terms ‘eugeosynclinal’ and ‘miogeosynclinal’ were not commonly used in New Zealand (Hatherton, 1969: 214; Fleming, 1969: 130). These had to wait until comparisons began to be made in the 1960s between what seemed to be sedimentary pairs in New Zealand (Alpine facies and Hokonui Facies), California (Franciscan formation and Great Valley facies), and elsewhere round the Pacific perimeter.
Regardless of early criticism that Wellman’s unified scheme was ‘over-simplified’ because it ‘equates and coordinates two contrasted tectonic settings and two entirely different metamorphic environments’ (Brothers, 1956: 480), the New Zealand Geosyncline became the ruling paradigm in New Zealand throughout the 1960s and into the 1970s. Geologists soon referred to it as a matter of course as a sedimentary environment for the greywackes (Fleming, 1962) and constructed a number of stratigraphic nomenclatures based on it (Chapter 8). The New Zealand Geosyncline governed much geological thinking because of its ability to provide explanations for a number of puzzles. It explained why our mountains are where they are, and it provided a deep-water site for the reception and accumulation of graded sediments by turbidity currents (Kuenen and Migliorini, 1950), as well as the depth needed for burial metamorphism. The deep, subsiding geosyncline even provided a likely site for the occurrence of ‘interbedded’ basic lavas and deep-water cherts.

**Problems in the paradigm**

Not long after the naming of the New Zealand Geosyncline in 1956, it was revealed that the mineralogies of the clastic rocks in the two facies were different from each other (Reed, 1957: 19). The greywackes of the Alpine Facies were shown to be rich in quartz and feldspar and lacked volcanic (volcaniclastic) sequences (p.272-3), at least in the South Island. In contrast, the Hokonui rocks of Southland contained large amounts of lithic volcanic greywackes and vitric tuffs (Coombs, 1950, 1954). Although both sets of rocks were supposed to be derived from the same continental source to the west, these anomalies did not cause immediate trouble (Chapter 8). While the petrography of the New Zealand greywackes seemed to agree broadly with those of the Franciscan greywackes of California (Reed, 1957), the rocks of the Alpine and Hokonui facies did not agree with Kay’s Appalachian model in which the eugeosynclinal belts contained … ‘thick volcanic sequences … whereas miogeosynclines do not’ (Kay, 1951: 66-67).

In spite of its long-lived usefulness in explaining the differences in sedimentary style, lithology, and metamorphism between the Hokonui and the Alpine Facies, the explanatory power of the New Zealand Geosyncline was limited. It could not explain the fate of the old Paleozoic continent to the west, nor could it explain the causes of volcanism or the formation of island arcs, and the distributions of living and fossil plant and animal species around the Pacific basin remained a mystery. No truly credible explanation was ever given for the geosyncline’s initial subsidence or its later mobilisation with the deformation of sediments and uplift to form the Southern Alps and the North Island ranges. The New Zealand Geosyncline was of little help in explaining structural patterns or in differences of structural style between the two facies. Wellman described the Hikurangi trench as a present-day geosyncline, but as a rule, today’s deep-sea trenches are sediment-poor. Further, the geosynclinal model did not fully unify the various geological specialties. For the time being, however, it provided an effective foundation for later work and many geologists became deeply attached to the New Zealand model. So much so that
as late as 1985, J.D. Bradshaw of Canterbury was driven to making an exasperated appeal for the non-
actualistic New Zealand Geosyncline to be set aside and forgotten (Bradshaw, 1985).

Turbidity Currents in New Zealand

Until 1950, most geologists took it for granted that coarse, sandy, marine sediments were deposited in
shallow-water environments close to the seashore (Fraser and Adams, 1907: 23; Marshall, 1911: 35;
Marwick, 1929; Holmes, 1944: 24; but also see Cotton, 1945: 32-39). Greywackes were therefore generally
thought to be shallow-water deposits formed within a large subsiding geosyncline that was kept topped
up by incoming coarse sediments (Cotton, 1945: 39-40; Wellman, 1952b; Brodie, 1953). Regardless of the
suggestion years before by F.W.Hutton (1885, 1899) that the presence of manganese and red jasperoid
slates among greywackes suggested a deep water environment, no-one had an explanation for their
relationship with the coarser sandstones.

Graded bedding

Geologists often remarked on the ‘monotonous’ sequences of alternating greywackes and argillites (for
example Coombs et al., 1959: 58; Fleming, 1969: 143) but none could provide a good explanation for the
phenomenon. The puzzling alternations between coarser and finer layers of sediment were ascribed to
seasonal changes (Park, 1909: 436), to deposition in an estuarine environment (Broadgate, 1916), by
‘winnowing of sediments’ during exceptionally heavy storms (Cotton, 1945: 38) and, doubtfully, to
‘rapid changes in the depth of deposition’ (Wellman, 1952b: 23). In reality, each sandstone-argillite pair
usually forms a single unit in which the size of the particles grades upwards from large to small (Figures
0.2, 0.3, 7.12c) with a lower, muddy sandstone component and an upper mudstone component, creating
an illusion of alternating coarse and fine beds.

Graded bedding was put to geological use in the 1920s when Canadian geologists used ‘texture
gradations’ along with cross-bedding and other structures to distinguish the tops and bottoms of ancient
strata and their younging direction (Dott, 2001). In 1927 the technique was passed on to Frances John
Pettijohn (1904-1999) of the United States (1984: 116-117) and Edward Battersby Bailey of Scotland (1881-
1965). Bailey (1930, 1936, 2001) searched Scotland for strata with graded bedding, and realised that
generally, graded bedding and current bedding were characteristic of ‘two different sandstone facies’
(Bailey’s emphasis, 1930: 85). He recognised the muddy character of graded sandstones and suggested
that graded sandstone and mudstone marked the sporadic delivery of a mixture of grit, sand and mud
onto the sea floor beyond the reach of ‘ordinary sand-pushing bottom currents’ and perhaps caused by
seawakes. Graded beds were known to, but not widely recognised by, geologists before 1950 (Pettijohn,
1984: 185), and these and other structures within the greywackes appear to have been generally overlooked and unrecorded in New Zealand except by Henderson (Henderson and Bartrum, 1913: 57; Henderson, 1917: 70). Graded bedding was later noted by Cotton (1945: 35), and used in Otago some time in the 1940s to determine way-up (D.S.Coombs, pers.comm.).

**Turbidity current theory - a paradigmatic revolution**

Geologists’ fascination with turbidity currents (Introduction, p.15, Figure 0.4) has been ascribed to their ‘size, power, velocity, mystery, and elegance’ (Walker, 1973: 1). Following the publication of the classic paper on turbidity currents as a cause of graded bedding by P.H.Kuenen and C.I.Migliorini in 1950, ‘graded beds … appeared everywhere’ (Pettijohn, 1984: 181-184). Turbidity currents had never been observed in the ocean but laboratory evidence (Kuenen, 1948) together with field data produced ‘the only true revolution in thought in this [20th] century about clastic rocks’ and the paradigm ‘succeeded because of its simplicity, flexibility and its predictive power’ (Walker, 1973: 30).

In New Zealand, Cotton promptly suggested (1951) that the alternating sandstones and mudstones of the thick east coast Miocene Tutamoe Formation⁴ were a result of ‘redeposition’ by turbidity currents, and that a study of the formation might reveal graded bedding. For some years’ afterwards, these sediments as well as the greywackes were often described as ‘redeposited sediments’. Students working on the greywackes (Halcrow, 1953, 1956; Webby, 1959) found that the new hypothesis could explain many of their sedimentological puzzles including graded bedding and other sedimentary structures (Figure 7.12). The hypothesis, which accounted for the deposition of coarse sediments in deep water, went some way towards answering old questions, such as the puzzling association of coarse sandstones and abyssal cherts and manganese.

**A contrary opinion in New Zealand**

The turbidity current hypothesis was not wholeheartedly accepted in this country. Jacobus Theodorus Kingma (1916-1974), with his unorthodox approach to geological problems (van der Lingen, 1975) described a set of Tertiary turbidites complete with graded beds in the Hawke’s Bay district (Kingma, 1958) and challenged the view that they were laid down by turbidity currents. He developed a scenario in which the alternating sandstones and mudstones were deposited in a ‘geosynclinet’, the Makara Basin, situated between a structural high to the west and a ‘geosynclinal ocean’ to the east. A bar between the basin and the open ocean was supposed to control the pattern of deposition of the graded beds. The bar and basin subsided intermittently, permitting periodic currents to flow in from the ocean and deposit the graded beds within the basin. Kingma also claimed that the same, somewhat

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⁴ Obsolete name for Miocene rocks in the Dannevirke area.
complicated, repeating pattern of deposition could explain the formation of other, similar ‘flysch-type’ (glossary) Tertiary deposits as well as the Mesozoic and Paleozoic greywackes.

Kingma’s resolute opposition to the turbidity current theory led to disagreements with Kuenen (Kingma, 1958, 1960; Kuenen, 1960) including a confrontation at the International Geological Congress in Copenhagen, and between Kingma’s colleague, Gerrit van der Lingen, and Kuenen (van der Lingen, 1969, 1970; Kuenen, 1970). Although a ‘refreshing challenge’ (Dott, 1963), Kingma’s objections to the turbidity current hypothesis were also described as ‘insubstantial’ (Walker, 1973: 24). Throughout the quarrel, Kingma’s theory gained little support in New Zealand. The basin and bar concept could not account for the extensive volumes of alternating strata of the New Zealand geosyncline because it depended on special conditions with a fine adjustment between water depth and the state of the bar (Webby, 1959: 479). The controversy added no new knowledge to New Zealand geology, and although interesting, it had no effect on the main stream of sedimentological research here.

The student contribution

Because I was a student in the early 1950s, the rest of this section will be written in a more personal style. Besides demonstrating proof of their ability to carry out a unit of research, geology students have always made positive contributions to their science (and still do) and their theses were and are an important source of data especially for the compilation of local and regional geological maps like those of the first 1:250,000 series and its successor, the QMAP series. Students continued the tradition of contributing to their university college’s own mapping programme with their areal and physiographic studies, and following through the current interests and concerns of their supervisors. Some theses were later expanded as Survey Bulletins (Grindley, 1958; Purser, 1961) while other projects resulted in the discovery of new fossil organisms, such as the annelid-like, Titahia corrugata, (Webby, 1958). A student’s special knowledge sometimes led to important discoveries, like that of George William Grindley (b.1925) whose knowledge of the remote Eglinton and Hollyford Valleys contributed to the recognition of large transcurrent movement along the Alpine Fault (Galbreath, 1998: 233-234; Harrington, 1999: 18, 22; Suggate, 1999)

Students as pioneers

The few unsuspecting students who were set to work on making something of the greywackes (Table 7.1) became pioneers in reading these difficult, enigmatic, rocks. Compared with our colleagues working on the seemingly similar, but far more comprehensible fossiliferous rocks of the Hokonui System, we were limited in what we could do with stratigraphy. We were thus forced to pay attention to petrography, structure, and various sedimentary features. Fieldwork was very different from that described in British
student texts. There were no handy quarries exposing tidily arranged layers of rocks filled with nicely shaped fossils. There were few, if any, identifiable and no continuous horizons, with little opportunity to make use of our undergraduate mapping exercises. Equipment consisted of a departmental hammer, a Brunton compass, a notebook and camera, and topographical maps if we were lucky, but with no hard hats or cell phones. Otherwise, we were outfitted with very little idea of what to do with those puzzling sequences of greywacke and associated rocks. Our most important references consisted of Hector’s Reports of Geological Explorations (Chapter 4), the brief description in the handbook accompanying the 1947 map (Marwick, 1948: 11) and the classic paper on turbidity currents (Kuenen and Migliorini, 1950).

Before any routine mapping could be done, we had to find methods of making sense of our inscrutable rocks. The best progress was made on open shorelines where fresh rock surfaces were exposed, and where bedding planes, joints, folds and faults in the long succession of greywacke sandstones and argillites could be made out (Figures 0.2, 0.3). We developed new ‘search images’ (see p.305) in order to

<table>
<thead>
<tr>
<th>Student’s Name</th>
<th>University College</th>
<th>Thesis year</th>
<th>Thesis Title</th>
<th>Today’s Terrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>G.W.Grindley</td>
<td>University of Otago</td>
<td>1948</td>
<td>Reconnaissance geology of the Eglinton and East Branch Valleys, Western Southland</td>
<td>Caples Terrane</td>
</tr>
<tr>
<td>J.W.Brodie</td>
<td>Victoria Wellington</td>
<td>1949</td>
<td>Geology of the southern portion of the Wellington peninsula</td>
<td>Pahau Terrane (younger Torlesse)</td>
</tr>
<tr>
<td>B.L.Wood</td>
<td>University of Otago</td>
<td>1949</td>
<td>Geology of the Waipahi Group</td>
<td>Caples Terrane</td>
</tr>
<tr>
<td>A.L.Bloom</td>
<td>Victoria Wellington</td>
<td>1951</td>
<td>The geology along the south-east flank of the Rimutaka Mountains,</td>
<td>Pahau Terrane (younger Torlesse)</td>
</tr>
<tr>
<td>H.M.Halcrow aka Nicholson</td>
<td>Auckland</td>
<td>1953</td>
<td>Geology of Waiheke Island</td>
<td>Waipapa Terrane</td>
</tr>
<tr>
<td>G.Warren</td>
<td>Canterbury</td>
<td>1955</td>
<td>The geology of part of the Okuku Survey District, North Canterbury,</td>
<td>Torlesse Terrane, Esk Head Mélange</td>
</tr>
<tr>
<td>A.M.Hopgood</td>
<td>Auckland</td>
<td>1956</td>
<td>The stratigraphy and structure of the basement and tertiary rocks in the</td>
<td>Waipapa Terrane</td>
</tr>
<tr>
<td>B.M.Gunn</td>
<td>University of Otago</td>
<td>1956</td>
<td>The geology of the Franz-Josef-Fox Glacier region, South Westland</td>
<td>Rakaia Terrane (older Torlesse)</td>
</tr>
<tr>
<td>P.Robinson</td>
<td>University of Otago</td>
<td>1958</td>
<td>The structural and metamorphic geology of the Brighton-Taieri Mouth area,</td>
<td>Caples Terrane</td>
</tr>
<tr>
<td>I.M.Paltridge</td>
<td>Auckland</td>
<td>1958</td>
<td>The geology of the north-east part of Whakatane County</td>
<td>Pahau Terrane (younger Torlesse)</td>
</tr>
<tr>
<td>B.D.Webby</td>
<td>Victoria Wellington</td>
<td>1958</td>
<td>The geology of the Porirua district</td>
<td>Pahau Terrane (younger Torlesse)</td>
</tr>
</tbody>
</table>
see and record previously overlooked internal features in these rocks including graded bedding and intra-formational conglomerates ('chipwackes', or 'rip-up clasts'. Figure 7.12). Fine sedimentary structures such as ripple marks, lamination and current markings, were identified, described and explained as having been deposited by turbidity currents (Brodie, 1953; Webby, 1959). We noted changes from mainly sandstone to mainly argillite sequences, and pondered on the slickensiding, boudinage and sets of veins (Chapter 10) found in the more disturbed sequences. Sometimes we found pillow lavas or layers of green or red rocks that turned out to be tuffs or lavas, or tightly folded beds of ribbon chert that were nearly always associated with lavas.

Our standard, unremarkable petrographical descriptions of greywackes differed very little from those of Geikie (1903: 166-167) or Pettijohn (1949: 243-255). Auckland students of greywackes reported on the rough, angular fragments of minerals and rocks set in a finer matrix, its dark colour, hardness, and general state of induration (Halcrow, 1953; Hopgood, 1956). In contrast, the Wellington sandstones were
described as arkosic and light grey in colour (Brodie, 1949, 1953). We described the state of the mineral fragments, the various alteration products, the mineralogy of the lithic fragments and developed some idea of the provenance of the greywackes. We were concerned about the degree of metamorphism exhibited by our Auckland greywackes. Could any resemblance with the greywackes belonging to Turner’s Chlorite 1 zone (p.201) be detected? We eventually plumped for low-grade metamorphism based largely on the presence of the alteration mineral, prehnite (Brothers, 1956; Halcrow, 1956; Hopgood, 1960). The problems of the origin of the apparently huge thicknesses of greywacke sediments seemed to be solved by the notion of a subsiding geosyncline into which turbidity currents could dump graded beds. It was now possible to begin making sense of those long sequences of greywacke sandstones and argillites and the associated deep-water cherts. We abandoned the traditional view of a shallow-water origin for the coarser rocks and claimed deep-water deposition for our graded sandstones. But the question of how a sediment-filled geosyncline could heave itself up and turn its contents into mountains was never answered. Students had played a worthy role in helping to demonstrate that with careful work, the greywackes were anything but ‘monotonous’. They could be mapped with a view to eventual structural analysis, and they were susceptible to various kinds of field and laboratory analysis. These old rocks were now a little less enigmatic than before.

**Student petrology in Southland**

When Douglas Saxon Coombs (b.1924) of Otago began a study of the Taringatura area to the north of the Hokonui hills (Figure 7.14) for his M.Sc. in 1946, he was advised by F.J.Turner to investigate any early metamorphic changes to greywackes located on the southern flank of the Otago schist (D.S.Coombs, pers.comm.). Coombs soon found some strange vitroclastic rocks and volcanic greywackes interbedded with Triassic greywackes and siltstones. Their ‘bizarre’ mineralogy included laumontite, a zeolite, which was shown to be a replacement mineral for glass shards (Coombs, 1950).
Coombs (pers.comm.) continued to work on the Taringatura rocks for his Ph.D. at Cambridge. Little, if anything, was known about the extreme low-grade end of the metamorphic spectrum, and Coombs used the analytical facilities at Cambridge to do new work on alteration phenomena. This led to important advances in the understanding of very low-grade metamorphism, the stability of zeolites (Figure 7.13), and to the way in which rocks such as greywackes were formed.

On his return to New Zealand, Coombs (1954) worked with chemists who synthesised zeolites in the laboratory. Their work showed that increasing pressure under increasing load caused volcanic glass to be replaced by the zeolites heulandite and laumontite with the release of large amounts of water. Similar low-grade alteration processes were thought to be caused by deep burial of the Taringatura rocks and were compared with the rather different course of dynamo-thermal metamorphism of the Otago schists. A new zeolite facies was proposed to bridge the ‘wide gap between the initial sedimentary processes and the ... metamorphic facies’ (Coombs et al., 1959: 53).

![Sketch map showing distribution of mineral facies of the New Zealand Geosyndcline, Coombs (1960: 344). Transactions of the Royal Society of New Zealand](image-url)
Because Coombs (1954) was sceptical that progressive metamorphism (as distinct from hydrothermal alteration) was caused simply by increasing depth of burial in the New Zealand Geosyncline, he believed it unjustifiable to extrapolate stratigraphically downward from the slightly altered Taringatura rocks through greywacke to schist. However, even though an ‘unchallengeable transition’ between the zeolite facies and the greenschist (Chlorite zone 1) could not yet be demonstrated (Coombs et al., 1959: 58), a ‘metamorphic sequence from the zeolite facies through a very broad zone characterised by prehnite and pumpellyite, to the greenschist and hence to higher facies’ appeared to be present. Coombs (1960) proposed a new metamorphic facies, the ‘prehnite-pumpellyite metagreywacke facies’, and tentatively divided the rocks of the New Zealand Geosyncline into several petrographic provinces. In these, most of the undifferentiated greywackes of Wellman’s Alpine Facies were classified as belonging to this new prehnite-pumpellyite facies (Figure 7.14) rather than in Chlorite 1. The term ‘metagreywacke’ was introduced to indicate that the greywackes had undergone some degree of alteration.

Coombs’ line of research that began as a student thesis resulted in fundamental discoveries in low grade metamorphism (Lillie, 1980: 222). A major, and much cited, contribution (Coombs, 1960) documented the huge thickness of volcanogenic sediments in Southland, and its perceptible pattern of secondary zeolitic mineralisation, especially in glass-rich beds (P.F. Ballance, pers.comm.) In spite of the later disappearance of the geosynclinal model and the different initial mineralogies of the different regions, Coombs’ basic model of low-grade alteration remains in place.
Chapter Eight

Naming the Greywackes 1950-69

One seems to spend more time worrying about names for rock units than actually studying the rocks themselves.

(Turnbull, 1977).

The differences in sandstone petrology between the two great coeval terranes of the Hokonui and Alpine assemblages have long plagued interpretations of New Zealand tectonics.

(Dickinson, 1982: 131)

Wellman’s (1956) well-developed regional model with its two parallel but contrasting ‘Hokonui facies’ and ‘Alpine facies’ consolidated the previously vaguely defined ideas about some kind of geosyncline in the New Zealand region. Geologists concerned with the basement greywackes took to the New Zealand Geosyncline very quickly and for the next decade or so, were engaged in ‘mop-up work’ (Kuhn, 1970: 24). Most contributions appeared to support the concept of the New Zealand Geosyncline although a rash of alternative names for the two facies was set off (as noted by Kear, 1971, and Tables 8.1-8.4, 232-238).

Stratigraphical solutions 1950-1969

The greywackes have never readily submitted to stratigraphic analysis, having constantly ‘defied attempts’ to understand them (Fleming, 1969: 130). Stratigraphy is concerned with the way in which stratified rocks are arranged in terms of time and space. A stratigrapher correlates or matches beds or strata between different localities with the use of fossils (biostratigraphy), rock units (lithostratigraphy) or geologic time units (chronostratigraphy). The aim is to draw geological maps and build up a stratigraphic column expressing the temporal order in which the rocks were formed, thus reconstructing the geological history of a region. Stratigraphical research constituted the primary tasks carried out by our nineteenth century geologists. By 1880, Hector and his men had developed
Figure 8.1: Map showing the distribution of Jurassic rocks in the Kowhia region, south-west Auckland, and a geological cross-section along the line X-X'. Keir (1978). The Geology of New Zealand

Conventional lithostratigraphic methods are effective in mapping the Jurassic rocks of the Kowhia Regional Syncline. These rocks had been included with Wellman's Hokonui facies (1956), then with the Murihiku Supergroup (1966), and later still, Murihiku terrane. These coherent sequences are in contrast to the more or less coeval greywackes to the east of the Waipa Fault, most of which on this map belong to the Mauaia Hill Group, and are continuous with the greywackes of the Hauraki Gulf. They are here classed with the Torlesse Supergroup, but were later included in the Waipapa terrane (Spörli, 1976). See Figures 8.2, 12.14.
a good understanding of the Triassic and Jurassic stratigraphic sequences of Southland and Kawhia (Waterhouse, 1965: 970-982). These strata are folded and tilted, but unlike the greywackes, their stratigraphical succession or order of deposition are readily determined and correlated by tracing recognisable beds or ‘horizons’ (Figure 8.1) across country (Kear, 1978).

Because conventional stratigraphic methods do not work readily with greywackes, work on them became confined to those localities with economic mineral deposits (Lillie, 1980: 188). Attempts have been made to stratigraphically map greywackes, using red chert beds as marker horizons. Several formations were later distinguished in the Hauraki Gulf region to make up the Waiheke Group and the Manaia Hill Group (Schofield, 1971, 1974). Greywackes are indeed stratified like other rocks; but their coherence has been destroyed by tectonic activity soon after deposition (Figure 0.4, p.14, 12.3, p.344). As a result, recognisable horizons can be traced for no more than a few kilometres before they taper out and disappear. Worse, on a regional scale, true correlations are impossible because, unlikely as it seems, adjacent regions may well have quite different geological histories (p.359).

Tabulating names

Tables 8.1, 8.2, 8.3, 8.4 summarise efforts to solve the stratigraphic puzzles presented by the basement greywackes, first in terms of the New Zealand Geosyncline, and then in the developing plate tectonic model of the 1970s. Tables 8.1 to 8.3 contain seven columns, three of which indicate author, topic and notes. The central four columns represent Wellman’s Hokonui and Alpine facies, the schists, and the upper Paleozoic Maitai and Te Anau greywackes, and are arranged in geographic order from Hokonui facies to the left (west) through to Alpine facies to the right (east, also see Figure 0.1, 7.11). Present day terrane names are included in column headings to assist in matching the older names for different sets of rocks with present day terms as shown in Figure 0.6. Five central columns are shown in Table 8.4 to represent terranes recognised in the late 1970s.

The double vertical line near the left side of the tables represents an important structural boundary (Figure 0.1). During the 1940s this boundary was informally known among Survey geologists as ‘Fyfe’s line’, (Fleming, 1969: 127; Waterhouse and Norris, 1972; Harrington and Korsch, 1985; Harrington, 1999) and was supposed to represent the western margin of the New Zealand Geosyncline (Wellman, 1959: fig.1) but it was more or less forgotten for some years. The fundamental contrasts in age, style and metamorphism between rocks to the east and west of this line were recognised by Landis and Coombs (1967) who named it the ‘Median Tectonic Line’. This idea of a median tectonic line was based on a concept of parallel metamorphic belts advanced in Japan (Miyashiro, 1961, 1973). In New Zealand, the ‘Western Province’ to the west of the line is thought to be part of old Gondwanaland, while the ‘Eastern Province’ to the east incorporates all of the rocks of
Wellman’s New Zealand Geosyncline including the ‘undifferentiated’ greywackes (Marwick, 1948). The Median Tectonic Line has since been redefined as the Median Tectonic Zone (Bradshaw, 1993) and as an extremely complex Median Batholith (Mortimer et al., 1999, 2003). The double line on the right of the table represents the eastern, still unknown, margin of the New Zealand Geosyncline, somewhere in the Pacific Ocean.

The various schemes based on Wellman’s two facies (Alpine and Hokonui) worked very satisfactorily through the 1950s and 1960s (Table 8.1). Geologists found that overall, their subdivisions of the basement rocks fitted in with the familiar map pattern of curving, parallel, and more or less coeval rock belts that were supposed to have been deposited in different parts of the New Zealand Geosyncline. As expected, the layers even increased in thickness towards the axis of the geosyncline (Mutch, 1957). The source of all of these sediments was that mysterious continent to the west. Differences in lithology between the facies were explained as due to the mountains and volcanoes of the source land being reduced from superficial sediments and through metamorphic rocks to its old granite foundations (Wellman, 1956: 7), similar to the changes later traced in Coromandel Mesozoic rocks (Skinner, 1972: 220-2, Fig. 7).

**Emerging anomalies**

Although the New Zealand Geosyncline provided such a useful working scheme, unexpected curiosities soon showed up (see p.231). John James Reed (b.1922) revealed two mineralogical problems:

- The clastic rocks in the Alpine and Hokonui facies have different mineralogies (Reed, 1957: 19). The greywackes of the Alpine Facies are rich in quartz and feldspar and lack volcanic detritus, at least in the South Island and Wellington, while the Hokonui rocks of Southland contain large amounts of lithic volcanic greywackes and vitric tuffs (Coombs, 1950, 1954). These perplexing and intractable differences led to several ingenious attempts (for example, Landis and Bishop, 1972) to explain how they could be derived from a single source (Tables 8.1 to 8.4, chapter 10).

- A clear transition was traced between the Alpine greywackes of Canterbury and Alpine schist (Wellman et al., 1952), but Reed (1958: 13, 48-49) showed that in Otago, the schists contained metamorphic derivatives of both the Alpine quartzo-feldspathic facies of Canterbury (Torlesse) and his ‘Alpine volcanic facies’ of Otago. This Alpine volcanic facies contained ‘undifferentiated greywackes’ of the Upper Permian Te Anau, Maitai and Clinton formations (Grindley, 1958), and much later was recognised as the Caples terrane. However, the problem of two kinds of greywacke making up the schists was not revisited for some years (Chapter 10).
New names for old rocks: Torlesse and Murihiku

The implementation of plans to produce a series of 1:250,000 geological maps (Webb, 1965) meant that the South Island schists and undifferentiated greywackes and schists needed suitable rock-stratigraphic names (Suggate, 1961). On the earliest published sheets the greywackes were shown either as ‘undifferentiated’ or with local stratigraphic names (for example Grindley, 1960). Richard Patrick Suggate (b.1922) took up a suggestion by B.H.Mason (Gage, 1980: 111) and imaginatively memorialised Haast’s contributions to Canterbury geology by naming the greywackes ‘Torlesse Group’, while the schists became ‘Haast Schist Group’, replacing the separate names, Otago, Alpine and Marlborough schists. The boundary between the two groups was set arbitrarily at the Chl.1 and Chl.2 isograd (p.201). The Torlesse group was extended to the North Island greywackes in 1963 (Stevens, 1963), and for a while, all of the greywackes (except for the Upper Paleozoic Maitai and Te Anau greywackes south of the Haast Schists) became known as ‘the Torlesse’ (Figure 0.1).

Names for everything

Stratigraphic terminology in New Zealand is governed by rules hammered out by the International Subcommission on Stratigraphic Terminology, a section of the International Geological Congress, and introduced here only after much discussion (Hornibrook, 1965, 1967). Lithostratigraphic or rock-stratigraphic terms are based on the general characters of rocks, and are not necessarily linked with geological time.

| Supergroup: Used when a larger unit than a group is needed, e.g. Murihiku Supergroup. |
| Group: An assemblage of two or more association formations with significant features in common. |
| Formation: Fundamental lithostratigraphic unit, based on specifically described and defined type section, with the base and top defined as well as lithological diagnostics. |
| Member: Lithological subdivision of a formation. |
| Bed: Ultimate subdivision of a formation. Lithologically similar beds constitute a formation. |
| Zone: In informal usage, zone is a general working term for a stratigraphic unit of any kind. Zone is used as a formal stratigraphic unit … where other stratigraphic terms are not available (Hornibrook, 1967: 18-19) |

Suggate’s Torlesse Group embraced Haast’s original Mount Torlesse Series, along with numerous local formations e.g. Tararua, Waiheke and Moehau formations, and some local groups e.g. Rimutaka Group. This use of ‘group’ by Suggate and the proposed elevation of the Torlesse Group to Torlesse Supergroup (Bishop, 1971) was later strongly criticised by Robert Merlin Carter (1971). Carter argued
Figure 8.2: Petrographic investigations of 'wacke' type rocks in South Auckland quarries showed that the greywackes could be divided into three main tracts based on their mineralogy. The Kawhia Syncline to the west incorporates Wellman's Hokonui Facies (Murihiku Supergroup). It is separated from the prehnite-bearing Manaia Hill Group (Waipapa Group) in the centre by the Waipa Fault. Further to the east is a separate tract of greywacke including the Kaimanawa greywacke and schist (Toriesse Group, Speden, 1963).

Theses rocks belong to Coombs' zeolite facies. The zeolite laumontite changes reversibly into leonhardite during wetting and drying. Not suitable for heavy duty aggregate.

These rocks of the Manaia Hill Group belong to the prehnite-pumpellyite metagreywacke facies. They are albised and contain the hard minerals albite, prehnite and quartz. Sandstone very suitable for heavy duty aggregate. Argillite unsuitable.
that the use of ‘Supergroup’ had connotations of exact lithostratigraphic meaning, but no true stratigraphic boundary existed between the Torlesse Group and Haast Schist Group, and only a textural boundary separated ‘unmetamorphosed greywacke from metamorphosed greywacke’. Carter suggested that the class-name be changed to the technically legitimate term ‘zone’, to give Torlesse Zone and Haast Schist Zone (Hornibrook, 1967: vii). However, Suggate’s terms already appeared on the 1:250,000 maps and the term ‘group’ became a part of the nomenclature of the greywackes. As Carter feared (1971: 5), usage indeed triumphed over logic, but only for a time.

Compared with the name ‘Torlesse’, the replacement of Hutton’s time-stratigraphic Triassic and Jurassic Hokonui System (1885) of Southland with ‘Murihiku Supergroup’, based on the Maori name for Southland, (Campbell and Coombs, 1966) roused no protests since these rocks possessed a good stratigraphic framework, based on well-defined units.

As more data came to hand, other stratigraphical problems that had been waiting for attention for many years now became more important (Table 8.2). Intensive petrographical investigations of South Auckland-Waikato-Bay of Plenty greywackes related to problems with road metal (Figure 8.2, and p.275) resulted in their being clearly subdivided into the zeolite facies of the Kawhia Syncline to the west (Murihiku terrane) and the prehnite-pumpellyite facies to the east (Kear, 1965). The latter were separated into the central prehnite-bearing Manaia Hill Group (Waipapa terrane) and the Kaimanawa, Kaiweka and Urewera greywackes further to the east (Torlesse terrane). Kear’s division of the South Auckland greywackes was soon supported by Wolfgang Mayer (1969) who distinguished clearly between the petrography of Waipapa Group greywackes from near Auckland and those of the Hokonui facies near Port Waikato (Figure 8.1).

**Magnetic anomalies and stratigraphy**

A series of investigations into the geological significance of magnetic anomalies (Wellman, 1959; 1973; Hatherton, 1969; Hatherton and Sibson, 1970; Hatherton, 1975; Hunt, 1978) led to the important inference that the junction between Hokonui (Murihiku) and Alpine (Torlesse) facies was marked by large, longitudinal faults (Figures 8.1, 8.3) (Kear, 1963, 1967; Fleming, 1969: 130, 141). The line of magnetic anomalies, called the Stokes Magnetic Anomaly by Wellman (1973) and now known as the Junction Magnetic Anomaly (Hatherton and Sibson, 1970) is associated with the upper Paleozoic ultramafic belts represented by the Dun Mountain ophiolites (Figure 8.12). Obviously, Wellman’s two facies were separated by more than a geographic difference in sedimentary environments and perhaps the junction marked a ‘persistent structural feature ’ at the Pacific edge of sial (Fleming, 1969: 142). The bipartite geosynclinal model remained useful until the late 1960s, but came under increasing pressure as more data was accumulated, and as fundamental concepts about the behaviour of
Figure 8.3: Relationship between the two major geosynclinal facies in the Waikato region. Modified after Kear (1971).

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The Oparau facies to the west is equivalent to Wellman's Hokonui facies. The Alpine facies (greywackes) is represented by the Morrinsville and Hunua facies to the east of the Waipa Fault. The Manaia Hill Group greywackes are typical of Waikato and Coromandel greywackes while the Hunua Facies are found further north in the Hauraki Gulf and North Auckland.

This model was developed by Kear over many years. The 1963 version provided one of the first explanations for the differences in petrography between the two geosynclinal facies with its wind-blown showers of tuff arriving from the west.

The two facies are separated by a major fault, the Waipa Fault (Figure 8.1). Vertical movement along the Waipa Fault could account for the apparently different thickness of the sediments to east and west of it. Transcurrent movement may have accommodated some of the postulated 300 mile shift on the Alpine Fault (Kear, 1963: 203-5).

The Waipa Fault is accompanied by a serpentine intrusion, likely to be continuous with the ultramafic rocks of Nelson (Kear, 1963).
the earth’s crust began to change. How could the compositional and structural differences between the Torlesse Supergroup (previously Alpine facies), and the Murihiku Supergroup (previously Hokonui facies) be resolved? How could the same source area yield two different petrographic facies? Stratigraphical difficulties continued to be encountered by those using classical stratigraphical methods to classify, subdivide and correlate basement rocks. Whole teams of authors designed increasingly elaborate nomenclatural experiments (Tables 8.3, 8.4) while trying to reconcile their data with the concept of a single integrated New Zealand Geosyncline. All of these offerings reflected the increasing difficulty in maintaining a coherent stratigraphical system that could correspond to all the entities supposed to belong to the geosyncline.

**Last days of the geosyncline**

The two major but dissimilar geosynclinal facies were inventively explained as having been deposited during two alternately operating sedimentary regimes in the geosyncline (Landis and Bishop, 1972). In this model, vulcanism on the western margin together with contemporaneous subsidence of the western shelf led to the deposition of volcanic debris in the Hokonui belt. Meantime, the Torlesse basin was starved of sediment. Then, uplift of the western province and reduced volcanism permitted voluminous quartzo-feldspathic debris to be transported, possibly by submarine canyons, by-passing the temporarily stable and filled Hokonui basin to the geosynclinal Torlesse basin.

As the stratigraphic interpretations of the basement rocks became more complex, so did the proposed nomenclatures. The geologists laboured on through the 1970s to construct ever better integrated stratigraphic systems to replace Wellman’s Hokonui and Alpine facies, all in the face of an accelerating paradigm change. The Otago team looked for a very high-level term above that of ‘supergroup’ to cover the concept “all rocks of the Eastern Facies of the New Zealand Geosyncline” (Carter, 1971; Carter et al., 1974: 8). The team settled on ‘sequence’ and subdivided the South Island rocks (North Island basement rocks went unconsidered) according to their orogenic history and delimited all the rocks of their Rangitata Sequence (≈New Zealand Geosyncline) with a Permian Tuhua Orogeny below, and the mid Mesozoic Rangitata Orogeny above. This very large set of rocks was divided into three coeval assemblages — similar to Wellman’s facies except that now, the greywackes and schists were combined to form an ‘Alpine Assemblage’ that included the Torlesse Zone, much of the Haast Schist Zone and a Cretaceous ‘Taitai-Raukumara’ Assemblage. Their ‘Transitional Assemblage’ harked back to Wellman’s idea of a transitional zone between the Hokonui shelf facies and the geosynclinal Alpine facies (Table 8.4).

Canterbury geologists offered their alternative dual lithostratigraphic and tectonostratigraphic system (Andrews et al., 1976) based on their Carboniferous-Jurassic ‘Canterbury Suite’ incorporating eleven
lithotypes and 15 faunal zones. Because the name ‘Torlesse’ had been used so many different ways (Group, Supergroup, Facies, Zone, Terrane, and rocks), the members proposed a name change to ‘Canterbury Suite’ for the quartzo-feldspathic greywackes. All rocks of the Mesozoic Murihiku Terrane, the Permian Caples Terrane and part of the Haast Schist Terrane were included in a contrasting volcaniclastic ‘Wakatipu Suite’. At the same time, a parallel tectonostratigraphic scheme incorporating the informal terranes (p.359) earlier named by Landis (Landis, 1969; Blake et al., 1974; Coombs et al., 1976) was included. However, the lithostratigraphic boundaries did not correspond with the tectonostratigraphic boundaries (Table 8.3 and p.359). Because the authors had to rely on stratigraphic nomenclatural rules to help solve sedimentological and tectonic puzzles, the classifications had to become ever more intricate and less easy to use.

Nomenclatural controversy and mutual criticism briefly flared (Landis and Coombs, 1978, Andrews et al., 1978, Bishop et al., 1978) as geologists argued about stratigraphic terms for what were essentially tectonic or tectonostratigraphic units (Chapter 12). The Otago team (Landis and Coombs, 1978) expressed concern and perturbation ‘at the increasing proliferation of suggested systems of formal nomenclature for the broader grouping of rocks of the Rangitata Orogen’ and preferred their own use of ‘relatively non-controversial “terranes”’. Their major ‘tectonostratigraphic’ units were ‘intentionally’ based on multiple criteria (Bishop et al., 1978) rather than introducing subdivisions based on a single criterion such as petrographic suites or structural domains.

In defence, the Canterbury team (Andrews et al., 1978) criticised the ‘clumsy’ multi-word groupings of their Otago rivals and pointed out how different writers had placed the boundary between the Transitional (Caples) and Alpine (Torlesse) Assemblages at several different locations. These included the south-west margin of the Haast Schist (Carter et al., 1974), the Livingstone fault1 (Blake et al., 1974), and somewhere in the Haast Schist (Bishop et al., 1976). In contrast, the Canterbury team’s division of sedimentary regions into quartzofeldspathic and volcaniclastic suites was considered by them to be observable and measurable, not notional or conceptual. At the same time, they worried about the worth of tectonostratigraphic units, believing it necessary to distinguish tectonic and stratigraphic units as well as petrographic and faunal provinces.

The last major scheme shown on Table 8.4 incorporates several different zones and supergroups in the Rangitata Orogen, equivalent to the old New Zealand Geosyncline (Carter et al., 1978). By now, many geologists had turned away from experimenting with stratigraphic nomenclature and were more focussed on sedimentation patterns in a Mesozoic trench-cum-geosyncline fitted with an active

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1 The Livingstone Fault, or the Macpherson Thrust Fault (Wood, B. L., 1956), or the ‘south tectonic contact’ (Macpherson, E. O., 1946), separates the Dun Mountain belt from the Caples terrane, see Macpherson’s map, Figure 6.9, p.168.

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subduction zone (Figure 8.4). The sedimentary differences between the members of different assemblages were explained by the Otago team in terms of their position within the geosyncline, whether on the shelf, the trench slope, or within the trench. Now, the belts of volcaniclastic greywackes from Hokonui through to the Te Anau (now Caples) were shown to be a part of the ‘subduction wedge’ while the quartzofeldspathic Torlesse rocks occupied the outboard plate beyond the trench, and presumably, with a very different provenance from all the rest.

These complex, integrated schemes became redundant once geologists found that plate tectonic theory meant that the belts of rocks did not have to share the same geological history. The belts of rocks began to be considered as separate entities or ‘terranes’ (chapter 12), each with its own unique history and stratigraphy, independent of its neighbours (Coombs et al., 1976; Bishop et al., 1976). This liberated geologists from having to find a near-by source for the sedimentary piles (Coombs, 1997), and allowed them to focus on mapping and understanding the stratigraphy of each terrane as a distinct unit within a collage of terranes.

(to page 259).
Table 8.1: The New Zealand Geosyncline 1950-1959, stratigraphical solutions. All stratigraphic schemes before 1970 to do with the greywackes were variations on the two-facies theme like that outlined by Wellman (1952, 1956). Key stratigraphical terms are marked in bold and underlined.

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Topic</th>
<th>Mesozoic miogeosyncline Murikhu Terrane</th>
<th>Paleozoic miogeosyncline Caples Terrane</th>
<th>Haast Schist Axial schists</th>
<th>Eugeosynclinal greywackes Torlesse Terrane</th>
<th>Notes</th>
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<td>J.Marwick (ed) and Officers of the Geological Survey (1947, 1948)</td>
<td>Geological Map of New Zealand (16 miles to 1 inch) and handbook</td>
<td>Hokonui: Triassic, Jurassic</td>
<td>Maitai and Te Anau Groups: Carboniferous-Permin</td>
<td>Schist Paleozoic</td>
<td>Undifferentiated Jurassic-Triassic-Permian (9A)</td>
<td>First coloured map by NZGS since Hector 1881</td>
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<td>J.J. Reed (1957)</td>
<td>Petrology of the Lower Mesozoic Rocks of the Wellington District</td>
<td>Hokonui Facies Lithic volcanic greywackes</td>
<td>South Auckland, Waikato, Clinton districts: lithic volcanic greywackes = Hokonui facies</td>
<td>Alpine Facies: detailed petrographic study quartzofeldspathic greywackes</td>
<td>Identified differences in petrography between Wellington, Reefton and Hokonui greywackes</td>
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<td>A.R. Mutch (1957)</td>
<td>Facies and thickness ... Upper Paleozoic and Triassic sediments of Southland</td>
<td>Hokonui Facies</td>
<td>Maitai and Te Anau</td>
<td>Increasing thickness, increasing metamorphism, deformation towards schist axis.</td>
<td>New Zealand Geosyncline</td>
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<td>J.J. Reed (1958)</td>
<td>Regional metamorphism in south-east Nelson</td>
<td>Hokonui facies: No apparent unconformity, Alpine volcanic facies: Upper Paleozoic Te Anau, Lower Clinton, Upper Tuapeka rocks, Quartzofeldspathic schist + schist derived from volcanic facies, Alpine feldspathic facies: Jurassic to Permian, greywacke &amp; argillite, Otago schist contains derivatives of both Alpine facies</td>
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<td>J.T. Kingma (1959)</td>
<td>The Tectonic History of New Zealand</td>
<td>Hokonui Sedimentary System, Alpine Schist Arc, Aotearoa Geosynclinal Sequence, Used ‘New Zealand Geosyncline’ but in context of a very different tectonic paradigm</td>
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<td>H.W. Wellman (1959)</td>
<td>Geological interpretations of... airborne magnetic observations</td>
<td>Magnetic anomaly between Hokonui and Alpine facies belts, Relates magnetic anomalies to basic lavas and ultra-basic rocks associated with Upper Paleozoic sediments</td>
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<td>H.W. Wellman (1959)</td>
<td>Divisions of the New Zealand Cretaceous</td>
<td>Lowest stages deposited in eastern geosyncline, Straiographical subdivision based largely on the fossil, <em>Inoceramus</em></td>
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Table 8.2 The New Zealand Geosyncline 1960-69. The geosyncline paradigm is still functional, but tectonic complications like the Waipa Fault and the Magnetic Junction Anomaly raise interesting questions.

Rocks of the New Zealand Geosyncline

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<thead>
<tr>
<th>Author, Year</th>
<th>Topic</th>
<th>Murhiku Terrane, Mesozoic miogeosyncline</th>
<th>Caples Terrane, Paleozoic miogeosyncline</th>
<th>Haast Schist</th>
<th>Torlesse Terrane, eugeosynclinal greywackes</th>
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<td>C.A.Fleming (1962)</td>
<td>New Zealand Biogeography</td>
<td>Marginal Gore, Baitour, Herangi, Kawhia, Oteke Series</td>
<td>Marginal facies: Maitai &amp; Te Anau groups - Permian</td>
<td>Haast Schists - Carboniferous, i.e. oldest rocks of NZG</td>
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<td>G.R.Stevens (1963)</td>
<td>Jurassic belemnites in the Torlesse Group of the North Island</td>
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<td>Torlesse extended to North Island main ranges</td>
<td>Waipapa group later included with Torlesse (Speden 1976)</td>
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<td>D.Kear (1965)</td>
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<td>West (Kawhia Syncline) - Hakarimata Formation + younger Mesozoic rocks with zeolites</td>
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<td>Subdivided North Island undifferentiated greywackes on petrography, using North Island names</td>
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<td>C.A. Landis, D.S. Coombs (1967)</td>
<td>Metamorphic belts and orogenesis in southern New Zealand Intrusives and High T-P Metamorphics of the Tasman Metamorphic Belt of Western Province</td>
<td>Median Tectonic Line of dislocation</td>
<td>Wakatipu Metamorphic Belt (east of MTL) High pressure, low temperature. To do with a distinctive metamorphic history, not sedimentological or stratigraphic</td>
<td>Eastern Province</td>
<td>Paired metamorphic belts Editor sees problems with tectonic nomenclature (but stratigraphic nomenclatures becoming strained.)</td>
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<td>D. Kear (1967)</td>
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<td>T. Hatherton (1969)</td>
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<td>C.A. Fleming (1969)</td>
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<td>Comprehensive review of work to date</td>
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</table>
Table 8.3: The New Zealand Geosyncline 1970-1976 begins to change shape and disappear as it gains a convergent margin and an accretionary prism. Stratigraphic interpretations grow more complicated as writers try to stay within the geosyncline’s boundaries. The Dun Mountain ophiolite belt becomes significant (Chapter 12). The terms ‘terrane’ and ‘tectonostratigraphic’ come into regular use. Separate suspect terranes are recognised. Upper Paleozoic sequences of Otago are divided into the Caples terrane and the Maitai (and Brook Street) terranes.

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Topic</th>
<th>Murihiku Terrane</th>
<th>Caples, Te Anau, Upper Paleozoic</th>
<th>Haast Schist</th>
<th>Torlesse Terrane</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. Kear, (1971)</td>
<td>Basement rock facies - northern North Island</td>
<td>Oparau Facies (synonyms - Hokonui; Shelf; Western; marginal)</td>
<td>Hunua Facies</td>
<td>Morrinville Facies</td>
<td></td>
<td>Criticises various facies names to date as genetic and confusing. Offers Hunua and Morrinville facies as substitute names for Wellman’s Alpine Facies</td>
</tr>
<tr>
<td>W. Dickinson (1971)</td>
<td>Detrital modes of New Zealand Graywackes</td>
<td>Western marginal facies</td>
<td>Appear to differ from the other facies</td>
<td></td>
<td>Eastern axial facies</td>
<td>Fault juncture between the two facies (Hatherton 1966)</td>
</tr>
<tr>
<td>D.G. Bishop (1971)</td>
<td>Stratigraphic and metamorphic content of the Torlesse Supergroup in the South Island</td>
<td>Included in Torlesse Supergroup</td>
<td>Included in Torlesse Supergroup</td>
<td></td>
<td></td>
<td>Torlesse Symposium run by Royal Society of New Zealand</td>
</tr>
<tr>
<td>C.A.Landis &amp; D.G.Bishop (1972)</td>
<td>Plate tectonics - regional stratigraphic relationships ... southern part ... New Zealand Geosyncline</td>
<td>Hokonui Facies</td>
<td>Torlesse Facies - Schistose &amp; non-schistose</td>
<td>Torlesse Facies - Schistose</td>
<td>Torlesse Facies - Non-schistose</td>
<td>‘By-pass’ model to explain differences between Hokonui and Alpine Facies. Fundamental questions about relationship.</td>
</tr>
<tr>
<td>D.N.B.Skinner (1972)</td>
<td>Subdivision and petrology of the Mesozoic rocks of Coromandel</td>
<td>Manaia Hill Group:</td>
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<td></td>
<td></td>
<td>Tokatea Hill formation</td>
<td>Moehau formation</td>
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<tr>
<td>E.R.Force (1973)</td>
<td>Comparison of ...Triassic rocks ... Hokonui and Alpine belts of South Island</td>
<td>Hokonui belt</td>
<td>Kaitikuan (upper Middle Triassic) clastics</td>
<td>Dissimilar belts juxtaposed by strike-slip faulting</td>
<td>Alpine belt</td>
<td>Compares samples of Kaitikuan stage in both belts. Torlesse cannot be distal facies of Hokonui basin</td>
</tr>
<tr>
<td>J.D. Bradshaw &amp; P.B. Andrews (1973)</td>
<td>Geotectonics and the New Zealand geosyncline</td>
<td>Hokonui realm</td>
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<td>Torlesse realm</td>
<td>Provenance problems if NZ Geosyncline... Eastern source for Torlesse rocks</td>
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<tr>
<td>Uses stage and series names</td>
<td>Caples, Maitai, Tuapeka groups</td>
<td>Otago Schist Belt</td>
<td>Alpine Flysch Facies Torlesse Group</td>
<td></td>
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<tr>
<td>J.D. Campbell (1974)</td>
<td>Torlesse Supergroup - a Review</td>
<td>Torlesse Supergroup</td>
<td>Name, lithology, fossils, structure, age and provenance</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>J.B. Waterhouse (1975)</td>
<td>The Rangitata Orogen</td>
<td>RANGITATA SEQUENCE = Rangitata Geosyncline = New Zealand Geosyncline</td>
<td>New Zealand geosyncline with plate tectonics</td>
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<tr>
<td>I.G. Speden (1976)</td>
<td>Fossil localities in Torlesse Rocks of the North Island</td>
<td>Murihiku Supergroup Mokorea trough</td>
<td>North Island Torlesse faunal zones outlined</td>
<td></td>
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<tr>
<td>Uses, groups, supergroups e.g. Murihiku Supergroup</td>
<td>Caples/Pelorus Terrane Haast Schist Terrane</td>
<td>Formations, groups, e.g. Mts Potts group</td>
<td>Formations, groups, e.g. Mts Potts group</td>
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<td></td>
<td>Brook St, Maitai, Dun Mt, and Murihiku Terranes</td>
<td>Haast Schist Terrane</td>
<td>Torlesse Terrane</td>
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<td></td>
<td>RANGITATA SEQUENCE</td>
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</table>
Table 8.4: The New Zealand Geosyncline has disappeared and is replaced by a set of tectonostratigraphic terranes, 1976-1979. The five central columns represent terranes recognised in the late 1970s and 1980s. The history of each terrane is recognised as entirely separate, until two terranes collide and are welded together.

<table>
<thead>
<tr>
<th>Author(s) and Date</th>
<th>Lithostratigraphy and structure of the Caples Terrane of the Humboldt Mountains, New Zealand</th>
<th>Murihiku terrane</th>
<th>Maitai and Brook Street terranes. Dun Mt ophiolite belt. Livingstone Fault</th>
<th>CAPLES TERRANE</th>
<th>Haast Schist terrane: metamorphosed amalgam of Torlesse and Caples</th>
<th>Torlesse terrane</th>
<th>Caples terrane defined 'Terrane' an informal term. Caples and Torlesse rocks petrographically and lithologically distinct</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.P. Suggate (1976)</td>
<td>Lithostratigraphic and Tectonostratigraphic units-comment. Questions need for 'non-Hedbergian' nomenclature</td>
<td></td>
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<tr>
<td>J.D.Bradshaw (1978)</td>
<td>Non Hedbergian terms for Non-Hedbergian geology - a reply</td>
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<tr>
<td>K.B.Spörrli (1978)</td>
<td>Mesozoic tectonics, North Island</td>
<td>Kawhia synclinorium Murihiku terrane</td>
<td></td>
<td></td>
<td>schists</td>
<td>Torlesse terrane, eastern North Island</td>
<td>Introduces Waipapa terrane to west of Torlesse.</td>
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</table>
All of the different contributions to the long debate about the constituents of the New Zealand Geosyncline reflect the difficulties encountered when data and working hypotheses outgrow a once useful paradigm. Quite unlike the difficulties in classifying sandstones, the various name changes that were made as one global model evolved into another had little to do with time-wasting obsessions with terminology and were never a sign of a science in the doldrums (Menard, 1971). On the contrary, they took place during a scientifically exciting period in which each new round of rapid conceptual developments meant that geologists had constantly to adjust to new data, new interpretations of old data, and a new, progressive paradigm. My simple tables (Tables 8.1 to 8.4) became less and less useful for representing the changes that took place after 1980 and much less able to portray newly developed models. The paradigm had changed, the geosyncline had gone, and now, geologists began to re-interpret the major tectonostratigraphic divisions of the New Zealand microcontinent, all with separate geological histories.

**Sedimentology and Petrographic Solutions**

Near the end of the dormant period in geology, from 1940 to 1960, some seventeen different field and laboratory classifications of sandstones were proposed in the North American geological literature. Thus, approximately once a year, somebody developed a classification, somebody wrote, somebody edited, somebodies reviewed, and many people read and tried to apply these classifications.

[[Menard, 1971: 148]

Sedimentary geology has grown hand-in-hand with the petroleum industry in a classical symbiotic relationship

(Dott, 1988: 364)

Sedimentology is the study of sedimentary processes and sedimentary rocks including their field occurrence, mineral content, structure, and history. No definitive history of sedimentology yet exists, although many short accounts are available as articles and textbook chapters (including Trask, 1941; Milner, 1962: 19-53; Pettijohn et al., 1972, 1987; Friedman and Sanders, 1978: 4-13). As geologists reorganised their thinking after the plate tectonic revolution, several valedictories to the dying geosyncline and its role as a sedimentary basin appeared (including Hsü, 1973; Dott, 1978), while a collection of nineteen Benchmark Papers on sedimentology, including the classic Kuenen and Migliorini paper on turbidity current theory, was published (Carozzi, 1975).
In 1984, Francis John Pettijohn (1904-1999) reminisced on the development of ideas about sediments and sedimentary processes, and discussed the benefits of increasingly sophisticated laboratory tools while stressing his faith in fieldwork and mapping. Robert H. Dott Jnr is currently providing many lucid, thoughtful contributions to the history, and conjecture on the future, of sedimentology (for example Dott, 1988, 1995), while Gerald M. Friedman has highlighted the role of petroleum geology in the rapid post-1950 advancement of sedimentology (Friedman, 1998). In a recent pithy review of twentieth century sedimentology, Eugen and Ilse Seibold outlined the major phases of research with a valuable list of important references (Seibold, 2002).

Between 1950 and 1970, sedimentologists became strangely infatuated with the construction of sandstone classifications involving much ‘feverish activity’ (Dott, 1978: 20). Concern about classifications may be only about semantics, but the long fixation on names for sandstones is relevant to the way in which the New Zealand greywackes have been studied, why greywackes were seen as a sedimentological problem, and why they were banished yet again.

**How to identify a sandstone**

The construction of systems of sandstone nomenclature and classification became a major preoccupation as sedimentology became a separate specialty around 1950 (Dott, 1978: 20). The challenge to petrological systematists is that the composition of rocks varies continuously (Williams et al, 1954: 269) and there are no truly discrete rock types comparable with biological species. Perhaps the most rational, logical, and quantitative solution is to both describe and classify rocks by continuously variable numbers based on measured amounts of diagnostic minerals (Rodgers, 1950; Dickinson, 1970, 1982). However rational, such systems are hardly rememberable, not easy to use in conversation, and did not achieve popularity among geologists.

Most geologists prefer to use discrete names for rocks, and this needs agreement on where to place the necessarily arbitrary boundaries between each named kind (Pettijohn, 1957: 229-232; Engelhardt and Zimmermann, 1988: 108-118). Consensus was needed on what information was required to separate one kind of sandstone from the next (Pettijohn, 1948; Blatt et al., 1980: 10-12), and attempts to classify by the simplest objective descriptions even resulted in disagreement as to what was really objective. Sedimentological systematists were repeatedly dissatisfied with other systematists’ definitions of terms. More confusion and uncertainty was caused when sedimentologists used various subjective inferences about provenance, diastrophic history, transport of materials and conditions of deposition to classify their rocks (Klein, 1963; Dott, 1964).
During a dormant period in geology from 1940 to 1960 (Menard, 1971: 145) North American petrologists proposed seventeen assorted field and laboratory classifications for the sandstones (Klein, 1963). The flow of new classifications continued and by 1971, nearly 50 schemes in seven languages from more than 10 countries were developed, all claiming to be reliable and workable (Okada, 1971). Okada did not stop there as he then proffered his own system, declaring it workable in both field and laboratory. The issue of classification and nomenclature, the question of parameters, and the major trends in sandstone classification over the years was again reviewed in 1987 (Pettijohn et al., 1987: 139-144) in which the authors provided a tabulated summary of 23 schemes, including several by Russian writers.

These concerns had little effect on New Zealand geologists until around 1960, although some geologists remember experiencing much bewilderment, frustration and increasing ennui with ever more classifications. However, work on the 1:250,000 mapping project and new problems to do with the strength of greywacke road metal (p.275) drew attention to the rocks of the Torlesse Group (Suggate, 1961), so that the classification of sandstone, and especially greywacke classification, became significant.

**Greywacke and Arkose**

Much argument in North America and Europe centred on the status of greywacke and arkose as type representatives of contrasting major suites of sandstones.

*Arkose*: The term ‘arkose’ was introduced by the French mineralogist Alexandre Brongniart in 1823. It was defined as a granular rock ‘composed essentially of large grains of feldspar and glassy quartz’ with some mica and clay (Bates and Jackson, 1987). It was sometimes described as ‘clean’ sandstone as distinct from ‘muddy’ greywacke.

The name ‘graywacke’ was little used in the United States or Canada before 1950 and it was mainly applied to the Archean graywackes\(^2\) of the Lake Superior region (Pettijohn, 1984: 124). During the 1940s the graywackes of the Franciscan assemblage in California were called ‘arkosic sandstones’ (Taliaferro, 1943), and Pettijohn (1984: 107) recollected how Californian students were baffled by these Franciscan rocks with their ‘igneous’ look. On the other hand, students mapping the Canadian Shield called ‘any dark rock that is not positively known to be igneous a greywacke’ (Adolph Knopf, quoted by Sanders, 1978). Although greywacke had been exiled from England by Murchison (Chapter 2) it was vaguely remembered as an ‘old field term’ (Milner, 1962: 332) and was sometimes regarded with considerable disfavour (Boswell, 1960). However, it had been in constant use in Scotland since

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\(^2\) Both ‘greywacke’ and ‘graywacke’ are used in this chapter according to different authors’ usage.
Jameson introduced it in 1804 (Jameson, 1804 - 1808, 1808) for a ‘particular kind of muddy sandstone’ (Bailey, 1930) characteristic of early Palaeozoic rocks found in Southern Scotland and Wales (p.47). From the time of its reintroduction to New Zealand in the 1890s by Park (p.121), greywacke was increasingly employed to refer to the rocks of the Southern Alps and the North Island main ranges.

Over time, both ‘arkose’ and ‘greywacke’ gathered new meanings as petrologists went beyond the original hand specimen ‘as-is-where-is’ mineralogical and textural descriptions. William Henry Twenhofel (1875-1957) imposed a new, unhistorical meaning to the term when he claimed that greywacke was derived from basic igneous rocks and was the ferromagnesian equivalent of arkose (Twenhofel, 1926: 175-176). Twenhofel devoted several pages of detailed description to arkose, but only a brief paragraph to ‘greywacke’, and referred to a glossary published by the U.S. Bureau of Mines. Twenhofel’s definition greatly displeased Bailey (1930) who tartly observed, ‘if this definition be true, then Scottish geologists have been sadly deceived by Jameson’. The same heresy, that greywacke was formed by the break up of basic igneous rocks, was repeated by the British petrologist, George Walter Tyrell (1894-1973). The petrologists were perhaps misled by the old definition of ‘wacke’ as a decomposition product of basalt (Jameson, 1804 - 1808: 376-379). The New Zealand greywackes are not greywackes in Twenhofel’s sense (Reed, 1957: 23). By the 1960s, some writers believed that regardless of its ‘evils’ the term ‘graywacke’ was too firmly entrenched in the literature to be dropped (McBride, 1962), but others thought that because of confusion regarding its use, the term was ‘an example of bad practice’ and should be abandoned (Boswell, 1960).

**Pettijohn and Krynine**

Existing classificatory systems for sedimentary rocks were based on bulk composition, or on texture and grain size, or on more interpretative features such as mode of origin, or on the presumed transport medium. Paul Dimitri Krynine (1901-1964) denounced all these systems in 1948 and presented his stylish new scheme using observable mineral composition and texture as major criteria. Krynine modelled his nomenclatural system on that used for naming igneous rocks and used ternary diagrams (Figure 8.5) to quantitatively illustrate the composition of sedimentary rocks (Carozzi, 1975: 13). Ternary diagrams had been used in mineralogy since the 1890s (Howarth, 2002:68) and previously used in sedimentology to show the proportions of sand, silt and clay in rocks (for example Holmes, 1921: 226-230).

Krynine chose quartz and chert, micas and chlorite, feldspar and kaolin, as the end members of his compositional triangle and the detrital rocks were divided into three major series, the quartzite series, the graywacke series, and the arkose series. The role of clay matrix as a textural feature was unimportant to Krynine and he emphasised mineralogical content by counting all matrix as fine
particles of mica and chlorite (Figure 8.5). He was especially insistent on a well-defined relationship between diastrophism (tectonism, Chapter 6) and sedimentation (Table 8.5) and linked his three major rock families with the three major stages in his diastrophic or tectonic cycle (Klein, 1963; Hsü, 1973; Dott, 1978; Pettijohn, 1984: 124).

Table 8.5: Krynine related his three major rock series with the supposed diastrophic or tectonic stages. Greywackes were linked with geosynclines, and arkoses with mountain formation. Orthoquartzites and carbonate rocks were linked with the period of tectonic quiescence when a continent was peneplained.

<table>
<thead>
<tr>
<th>Diastrophic stage</th>
<th>Characteristic sediments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peneplanation or quiescence</td>
<td>orthoquartzites and carbonate rocks of stable continental platforms</td>
</tr>
<tr>
<td>Geosynclinal or pre-orogenic stage</td>
<td>Greywackes formed during subsidence, filling and very early deformation of geosynclines.</td>
</tr>
<tr>
<td>Orogenic stage i.e. folding, uplift, block faulting</td>
<td>Arkoses formed after the closing of a geosyncline. Contemporaneous with large-scale block faulting, often of continental origin.</td>
</tr>
</tbody>
</table>

Krynine described greywackes as ‘dark, dirty sandstone’ and considered them the single most abundant rock type in the geologic column, constituting up to 45% of all sandstones (Pettijohn, 1949:229-230; Carozzi, 1975: 13). Because descriptive sedimentary petrography was in its infancy, Krynine refrained from ‘coining new and fancy rock names’, used well-known common rock names, such as ‘graywacke’ and ‘arkose’ and left the ‘agreeable ... occupation’ of inventing new names to future students.

Krynine’s 1948 scheme in which sedimentary rocks are defined entirely on their mineral content. Matrix was counted with mica and chlorite.

Pettijohn’s 1949 scheme in which clay (matrix) is one of the end members together with feldspar and quartz.

Figure 8.5: These triangle or ternary diagrams illustrate the contrasting petrographical schemes offered by Krynine (1948) and Pettijohn (1949)
Unlike Krynine, Pettijohn (1943, 1948, 1984: 240-242) had an extensive field experience with pre-Cambrian greywackes of the Lake Superior region, and understood them well. He, too, saw no need for the invention of new rock names. Pettijohn always regarded the greywacke matrix as a diagnostic feature separating greywackes from arkoses and orthoquartzites, and included clay as a classification parameter (Figure 8.5). Later, he combined composition and texture and elaborated his system by using a tetrahedron to represent a four-way mix of detrital matrix, quartz and chert, feldspar, and rock fragments (Pettijohn, 1949: 245-251, 1954, 1957: 291-293).

Pettijohn regarded genesis, or the discovery of geological history, as the fundamental aim of any rock study and also believed that diastrophism was the ‘ultimate cause of sedimentary deposits’ (Pettijohn, 1949: 436). He called attention to Fischer’s description (1934) of greywacke as a ‘poured in’ kind of sandstone (Fig 5.19, p.164), and how the association of greywackes with deep-water spilitic greenstones and radiolarian chert indicated their geosynclinal origin.

All later attempts to construct ever better schemes of sandstone classification were based on either Krynine’s or Pettijohn’s systems (Klein, 1963; Carozzi, 1975: 14). However, there was very little agreement between the sedimentologists as to classification criteria. What and how many substances making up a rock are diagnostic? How should the mineralogical end-members be chosen, and should chert fragments be counted with quartz or with rock-fragments? How is mineralogical maturity determined, and how much matrix makes a greywacke? Few of the writers, except perhaps for Pettijohn, Fischer and Krynine, appear to have taken into account that greywacke sandstones do not appear on their own. They are always in an association with alternating argillites (the upper section of each greywacke bed) and with lenses of abyssal chert and pillow lavas (for example Pettijohn, 1949: 254, 1950; Pettijohn et al., 1987: 164, 167).

**The greywacke problem and that matrix**

Early definitions of greywacke clearly refer to a kind of sandstone composed of mineral and rock fragments ‘joined to each other very firmly with clay’ (Ospovat, 1971: 72). The distinctive, dark, fine-grained compact matrix is seen as characteristic of the ‘impure sandstones or wackes’ (Gilbert, in Williams et al, 1954: 291) and the ‘essence of the greywacke problem’ (Cummins, 1962: 52). This distinctive greywacke matrix became very important to the systematists (Figure 8.6) and a number of classifications used clay or matrix as a compositional end-member (Klein, 1963).

No modern, muddy sandstones of greywacke type have been found. Not all greywackes are turbidites (Figure 8.6), although most New Zealand greywackes are. Not all turbidites are greywackes, and Kuenen’s experimental turbidites are not greywackes (Cummins, 1962: 58).
Greywackes are more abundant in ancient geological formations, and although younger ‘flysch sandstones’ (similar to Waitemata Group sandstones, p.13, 270), may have a similar origin to the older greywackes, their texture and degree of compaction are different. Greywackes are mineralogically immature, that is, they contain unstable minerals that are readily altered, and these can be converted into matrix by deep burial, by low-grade regional metamorphism, or even by prolonged exposure to surface weathering. Cummins concluded that several lines of evidence supported his contention that the peculiar texture of greywackes was derived from post-depositional alteration and had little to do with what went on during sedimentation.

Now, petrographers were surprised to be told that samples of greywacke and arkose taken from their type areas, the Auvergne in France (arkose) and the Harz Mountains in Germany (greywacke) were similar (Huckenholz, 1963). Far from being distinct representative types of ‘muddy’ and ‘clean’ sandstones, the mineralogical and textural features of the samples overlapped, the arkose sample contained matrix, whereas the Harz greywackes did not, and there was otherwise no clear distinction between them. Therefore, the use of greywacke and arkose as contrasting rock types representative of different stages in the diastrophic cycle was quite misleading.
Figure 8.7: An outline of the changing views regarding the greywacke matrix. Whether the matrix is depositional or diagenetic does not change the reality that the matrix gives greywackes their special character and records events in their history.
The overlap of the ‘type’ arkose and the ‘type’ greywacke, meant that sedimentologists had now reached ‘near absurdity’ in their classifications of immature sandstones (Dott, 1964). R. H. Dott Jnr argued eloquently that the rigid zoological ‘type’ approach for the definition of rocks was archaic. It emphasised microscopic petrographic and chemical analyses, but the megascopic qualities of greywacke had been used to characterise it 100 years before the use of thin sections (and ignored the way in which rocks exist in a continuum). Dott reminded readers that arkose is traditionally linked to a specific source rock (granite), while ‘greywacke’ was essentially a field textural term representing a rock clan of many compositions, and regardless of how and when greywacke matrix is formed, it constitutes a valid descriptive and classificatory criterion.

While geologists now accepted that the matrix of ‘dirty’ sandstones was of more than one origin (Figure 8.6), the main cause of schism between the Pettijohn and Krynine schools of thought was about whether or not the matrix was useful in sandstone classification (Pettijohn et al., 1987: 144). Pettijohn and his co-authors always maintained that matrix is the essential characteristic of greywacke and faithfully retained greywacke as a legitimate petrological name (Pettijohn et al., 1987: 172-174). They felt that abandonment of the term would not solve the problem of defining and naming the rock (Pettijohn, 1987: 140). However, matrix was removed from the compositional triangles and used to define two major sandstone clans, the arenites (with little or no matrix) and the wackes (with quantities of matrix).

**R.L.Folk and his version of ‘graywacke’**

Krynine’s scheme was developed and modified by Robert L. Folk, a student of Krynine, and who had considerable influence on sedimentary petrography in New Zealand (p.277). Folk, (1968:120-125), continued to acknowledge the importance of tectonic control on sedimentation, to use ternary diagrams, and maintained Krynine’s strange belief that greywacke was first described in 1850 by Carl Friedrich Naumann (1858). Like Krynine, Folk modelled his nomenclature on that used for igneous rocks. He was especially critical of the confusion of grain size with mineral composition, and complained about the way in which some geologists applied the term ‘graywacke’ to all clayey sandstones, irrespective of the mineralogy (suggesting that none of them considered hardness or compaction).

Folk worried about the difficulty of devising a nomenclature that could also indicate the essential properties of a specimen, that is, a name and comprehensive description all in one expression. Krynine (1948: 92) had devised a nomenclatural system in which the main name of a rock is accompanied by qualifying phrases. Folk (1954) took up this system in which the descriptive terms for texture and minerals were separate statements indicating that they could vary independently of each
Chapter Eight

Volcanic rock fragment

Matrix

Figure 8.8: Photomicrograph (X12) of greywacke sandstone from Waheke taken by E.J. Searie in 1953. It shows angular fragments of quartz (white), saussuritised feldspar (grey), and argillite fragments set in a fine clay matrix (Halcrow, 1956). It was never possible to distinguish individual mineral grains in the matrix, and sometimes, decomposed minerals were mistaken for matrix (K.B. Spörli, pers. comm.).

Figure 8.9: An electron microprobe image of similar greywacke sandstone from Hunua taken in 2003. The quartz particles show up clearly in contrast to the flaky, honeycomb-like structure of the matrix in which the clay minerals illite and chlorite are identified. P.M. Black (2003).
other, while textural maturity was made into an associated property. Thus a Cambrian sandstone could be named as ‘well sorted fine sandstone: siliceous supermature orthoquartzite’. The major rock clans were defined entirely on mineralogy, and to begin with, Folk retained the terms ‘arkose’ and ‘graywacke’. Strangely, ‘graywacke’ was redefined according to composition as the ‘archetype of a sediment derived wholly from a metamorphic source’ (Folk, 1954: 354), and even more strangely, the presence or absence of clay was not considered to be a diagnostic feature.

In the end, ‘graywacke’ was abandoned by Folk (1968: 125). He granted that the term originally referred to a ‘hard, dark, semi-metamorphosed sandstone that was rich in rock fragments and chloritic clay matrix’. However, other modern writers had ‘seized’ on one or other feature of the type “graywacke” and used it ‘to define their particular kind of “graywacke” (Folk’s emphases). Folk decided that the term could not have any place in a ‘quantitative, minerallogically oriented classification of sandstones’. It should revert to being a very loose field term for a ‘very hard, dirty, dark rock that you can’t tell much about in the field’ (Folk, 1968:120-125).

Eventually, the stream of sandstone classifications slowed to a trickle and stopped. Presumably the plate tectonic revolution caused the sedimentologists to hurry off to consider the exciting new implications about the relationships between sediments and moving tectonic plates. Intricate nomenclatural systems lost their allure as wonderful new tools and new techniques and new concepts were developed encouraging the systematists to turn away from constructing classifications and towards the reconstruction of paleoenvironments. Menard was highly critical of the flood of sandstone classifications even though they were offered ‘in good faith and with the best motives’ (Menard, 1971: 129-147), and others regarded the debates about terminology as an ‘unnecessary distraction from the major problems in the science’ (Blatt et al., 1980: 12). In a sense, sedimentologists were trying to construct the rules of their new craft, but enough was enough, and the price of time spent by geologists on organising nomenclatural systems was time not spent on doing geology (Menard, 1971: 141).

**Two more terms: induration and flysch**

Since at least 1868 (Hutton, 1868; Haast, 1871) the hard, old rocks of the prehnite-pumpellyite metagreywacke facies have been commonly described as ‘indurated’. It was largely because of their indurated condition (also described by F.W.Hutton as ‘sub-metamorphosed’) that the settler geologists referred the greywackes to the older Paleozoic (Waterhouse, 1965: 991).

The adjective ‘indurated’ has been criticised as worthless (K.B.Spörli, pers.comm.) but it usually means that a rock is hard or tough or compact, in contrast to the softer, less consolidated, and very different-looking, Tertiary rocks (for example Willet, 1948). Even the Geological Society of New
Zealand’s subcommittee on greywacke terminology described greywacke as ‘a well indurated, poorly sorted sandstone’ (Reed, 1967). The hardening process is assumed to be due to compaction, with chemical reactions affecting the clay minerals and cementation (Lillie, 1980:29-30) and is thus a version of diagenesis, the process in which loose, unconsolidated sediment is turned into a sedimentary rock (Coombs, 1960). Glossaries define ‘induration’ as to do with rock or soil ‘hardened or consolidated by pressure, cementation or heat’ (Jackson, 1997), or hardened ‘by impregnating solutions or by the normal sedimentary process of compaction and removal of pore water’ (Tomkeieff, 1983). As more precise ideas of diagenesis and low-grade metamorphism developed in the 1950s and 1960s, induration became a synonym for such processes and their products, but it has since been dropping out of use. Perhaps it has indeed become a meaningless archaism although it still has use as a non-specialist descriptive term.

The Swiss noun ‘flysch’ refers to a crumbly or fissile rock material that slides or flows (Bailey, 1935: 37). Flysch has a history similar to that of greywacke, having been borrowed from a rural vernacular. B.Studer (1794-1887) brought it into geological language in 1827 as a stratigraphic term for the succession of sandstones and shales in the Simmenthal region of Switzerland (Tomkeieff, 1983), and later regretted it (Trümpy, 2003: 36). Since then, its meaning has been modified several times (Hsü, 1970) and extended to ‘a marine sedimentary facies characterised by a ‘thick sequence of poorly fossiliferous, thinly bedded, graded deposits composed chiefly of marls and sandy and calcareous ... muds’. It has also been loosely applied to any sediment with nearly all of the lithologic and stratigraphic characteristics of a flysch, such as ‘almost any turbidite’ (Jackson, 1997).

Some Swiss geologists assert that ‘Flysch is not for export’ (Hsü, 1970) and in New Zealand the use of ‘flysch’ as a geological term has been condemned because its nomenclatural status is much the same as the colloquial New Zealand term ‘papa’ used for soft rocks in Taranaki (K.B.Spörli, pers.comm.). Nevertheless, New Zealand turbidites have been described as ‘flysch’ (Ballance, 1974), as ‘flysch-like’ (Kingma, 1967; van der Lingen, 1968), and as ‘flysch-type’ (Van der Lingen, 1969), sometimes to avoid the genetic connotation of ‘turbidite’. The turbiditic flysch of the Waitemata Group (Ballance, 1974) has also been described as ‘lithic subgreywackes’ (Ballance, 1964). The terms ‘flysch’ and ‘greywacke’ are not synonymous (Dzulynski and Walton, 1965) although ‘graywacke, turbidite and flysch became more or less interchangeable with one another’ (Dott, 1978: 20). Flysch has a connotation of facies while greywacke implies a certain type of sandstone, and in New Zealand, it also refers to an association of greywacke sandstones, argillites, pillow lavas and cherts.
Greywacke Petrography in New Zealand

The word ‘graywacke’ is encumbered by so many radically differing definitions that it has been rendered almost useless.

(Folk, 1968: 123)

The business of terminology can create considerable confusion, especially where legal issues are involved’.

(Milner, 1962: 583, on road metal and aggregates)

In the first half of the twentieth century petrographic studies of sedimentary rocks in New Zealand were unusual, except for brief studies by Park and Marshall (p.122) and those to do with schists by Bell’s Survey geologists (p.124), by Marshall in his 1918 Tuapeka study (p.194), and by Turner and Hutton (p.201).

Heavy mineral studies of rocks in the Southland area were made in 1936 by C.O.Hutton and F.J. Turner (1936), and by Raymond Nicholas Brothers (1924-1988) during the 1950s (1959a, 1959b). Heavy minerals, sometimes called accessory minerals, include ilmenite, magnetite, zircon, rutile, tourmaline, and garnet. Because these minerals are stable, resist chemical breakdown and may survive several cycles of erosion and deposition, they are used to assist in stratigraphic correlation and provide a guide to provenance (Milner, 1940; Pettijohn, 1984: 241).

From 1950 onwards sedimentology in New Zealand grew in much the same way as in North America and Europe, and was largely pushed along by what was happening in the petroleum industry (Pettijohn, 1984: 240-250; Friedman, 1998; Seibold, 2002). This was encouraged by improvements in libraries, better funding for education and research, better communications, and especially the advent of cheaper air travel in the 1960s. More New Zealand trained geologists travelled overseas for study and employment, and more overseas geologists came here for the same purposes. Californian geologists were especially interested in the Alpine-Hohonui couplet, which appeared to be so similar to the Franciscan and Great Valley pair of California (p.363) in their stratigraphy, sedimentology and because of the presence of the Alpine and San Andreas Faults.

Reed and the Wellington greywackes

An interest in the role of the Wellington greywackes as parent rock to the local soils led J.J. Reed (1957) into making a meticulously detailed investigation of the petrography of Mesozoic greywackes and associated rocks of the Wellington district. Reed’s interest in greywackes as research material was increased by their economic importance as aggregate, and when the construction of the Rimutaka rail tunnel made over eight kilometres of clean, fresh rock available for inspection (J.J.Reed, pers.comm.).
Reed advanced the role of thin section petrography in New Zealand by using the petrographical microscope to reveal clues as to the regional distribution of various rock masses, making it possible to distinguish and correlate rock units in different and widely separated parts of the country. Reed also used two important analytical tools:

- An integrating microscope stage, which permitted him to readily measure the proportions of the mineral and lithic components in his rocks.
- Graphical representation and interpretation of quantitative chemical data with ternary diagrams (Figure 8.10).

![Figure 8.10: Reed's pioneering von Wolff diagrams clearly differentiated between the Wellington greywackes, the old Paleozoic Westland Waipara and Greenland Group greywackes near Reefton, and the Hokonui facies greywackes, represented by samples from Clinton and Taringatura. At the same time the similarity between the Wellington and Alpine greywackes was confirmed. Labels added. Modified after Reed (1957) New Zealand Geological Survey]

Since the earliest days of Hector’s New Zealand Geological Survey, standard chemical analyses of rocks were expressed as tabulated percentages of each oxide (Table 1.1, p.26). Reed (1957: 50) demonstrated the possibilities of geochemical analytical techniques by assembling the ‘meagre ... data’ relating to greywacke rocks in New Zealand, consisting of all thirty chemical analyses of New Zealand greywackes and argillites (and a granite and a granodiorite for comparison) that had been made as far back as Morgan (1908). The analyses were recalculated to show percentages of quartz, leucocratic minerals (e.g. feldspars) and melanocratic minerals (e.g. ferromagnesians and ores), checked against measurements of modal minerals in thin sections, and the results displayed using ternary diagrams. These clearly showed that while the Wellington greywackes were like those of
Wellman’s lower Mesozoic Alpine Facies (1952), the early Paleozoic Westland greywackes (Figure 5.5 p.129) were quite distinct from the Mesozoic rocks (Figure 8.10).

Reed’s geochemical findings plainly supported the initial stratigraphic division of the Upper Paleozoic and Mesozoic rocks into the Hokonui Facies and the Alpine Facies (Marwick, 1948; Wellman, 1952) and confirmed the petrographic differences between them as earlier reported by Coombs in Southland (1950, 1954). The Alpine Facies included all other North and South Island ‘undifferentiated’ greywackes except for the greywackes of the upper Paleozoic ‘Alpine Volcanic Facies’ south of the Otago schists (Figure 8.12). Brodie (1953) had previously described the Wellington members of the Alpine facies as ‘arkosic’; Reed himself (1957: 25) described them as ‘well-indurated, feldspatic (arkosic), meng and quartz-meng sand-wackes’, similar to those of the axial ranges (‘meng’ refers to rocks with a high proportion of labile or unstable constituents). Lillie had also noticed that the Alpine greywackes were paler in colour, ‘cleaner’, and more ‘arkosic’ than the Auckland greywackes (Lillie et al., 1957, Lillie, 1962, 1972).

Reed (1957: 20) also observed a difference between the Alpine facies and south Auckland greywackes and subdivided the ‘undifferentiated’ greywackes based on several samples of lithic greywackes from the Waikato, and from the Clinton district in Otago. Because they contained volcanic materials, Reed classified them in Wellman’s Hokonui Facies (Table 8.1, Figures 8.11, 8.12). While a clear transition existed between Triassic Alpine greywacke and Alpine schist in Canterbury (Wellman et al., 1952), the relationship between greywacke and schist was not simple (Reed, 1958: 13, 48-49). Reed’s ‘Alpine volcanic facies’ consisting of upper Paleozoic Te Anau-Clinton-Tuapeka rocks (Grindley et al., 1959) also passed into the schists (Figure 8.11, 8.12). This meant that the Otago schists contained metamorphic derivatives of both these volcanlastic rocks and the Alpine quartzo-feldspatic facies of Canterbury. Reed’s conclusions thus supported Marshall’s 1918 contention (and for which he had been so severely criticised, p.195-197) that the Otago schists were derived from the neighbouring greywackes (but which Marshall thought to be of Mesozoic age).

These distinctly dissimilar rocks were all supposed to be derived from the same mysterious continental source to the west, so how could their mineralogy be so different? Reed (1957: 19) suggested that his Wellington greywackes were derived from a plutonic terrain of granite, gneiss and slate, but he could not adequately explain why the Hokonui rocks were different. The compositional differences between the Alpine and Hokonui facies as well as the mixed constitution of the schists raised serious paleogeographic problems, but they were not tackled for nearly a decade, following which, the search for a solution to the problem dominated basement geology until well into the 1970s (Tables 8.1 to 8.4).
Figure 8.11: Map of New Zealand showing distribution of pre-Cretaceous rocks. The greywackes of Northland, the North Island main ranges and Canterbury are classed as 'Alpine facies'. Auckland and Waikato greywackes are included in the Hokonui Facies because of the presence of volcanic fragments. Reed (1957).

Figure 8.12: Map of South Island showing the schist belt and pre-Cretaceous rocks. Reed's petrographic skills showed that two different rock facies were involved in the schists. Reed (1958).

Chapter Eight

‘Wacke’ in New Zealand

Reed’s views regarding greywacke petrography became very influential among Survey and academic geologists for many years. His ideas about greywacke terminology were based on those of the German writer, Georg Fischer (Fischer, 1934; D.A.B., 1937-38 and Figure 5.20 p.164; Pettijohn, 1949: 253), and of Charles M. Gilbert (Williams et al, 1954: 290-304). Gilbert divided sandstones into two major divisions, the pure sandstones or arenites, and impure sandstone or wacke. greywacke was regarded as a class of wacke characterised by poor sorting, dark colour and firm induration. Like Gilbert, Reed (1957: 24) favoured Fischer’s use of the textural term ‘wacke’ for all those sediments characterised by little or no sorting, ignoring the much older use of ‘wacke’ to refer to clay-like decomposed basalt (Ospovat, 1971: 157). Reed added graded bedding as a criterion, and introduced the following terms to distinguish different members of this wacke class in New Zealand:

- gravel-wacke
- sand-wacke (true greywacke)
- silt-wacke (argillite)
- clay-wacke (argillite)

Soon after, D. Kear and J. Healy invented ‘chipwacke’ as a name for intraformational conglomerates consisting of ‘rip-up clasts’, or ripped up pieces of argillite set in sandstone (Figure 7.3a, 7.3b, 7.3c) (D. Kear, pers.comm.).

Greywackes and the aggregate problem

Besides contributing to theories regarding the structural and stratigraphic arrangements of the New Zealand land mass, petrographic studies of the greywackes played an indispensable part in the much more pragmatic matter of road construction (Introduction p.8). During the 1960s, the nature of the greywackes and their nomenclature became a serious economic issue. Post-war recovery and economic growth had led to a huge increase in road and motorway construction. Several years after the new southern motorway from Auckland came into use in 1955, portions of the motorway surface began to fail.

Engineers and quarrymen frequently used the term ‘greywacke’ for all hard, grey Mesozoic sediments (Sameshima et al., 1978: ftn 23). Contractors knew that sandy greywacke was hard and strong enough for road metal, whereas the finer argillite layers were weaker and broke down under heavy-duty use (Reed and Grant-Taylor, 1966). However, during motorway construction, sandy greywacke was in short supply and a particularly hard, stron g, albitised variety of silty argillite from South Auckland was used for aggregate. After making numerous tests, Reed (‘1965: 12) concluded
that, although hardened, this albitised siltwacke (argillite) was suspect as a source of high-grade heavy-duty motorway aggregate, and it had evidently broken down by fatigue degradation.

Several years’ later, improved techniques employed by Teruhiko Sameshima (1924-1992) showed that the problems in aggregate from the failed sections were caused by the presence of the clay minerals montmorillonite and kaolinite (Sameshima, 1977). Even before aggregate went into service as motorway basecourse the minerals albite and chlorite could decompose to form these clay minerals during the crushing processes. Sameshima also showed that powdered greywacke and argillite rapidly altered to clay when in contact with water (Sameshima et al., 1978).

Terminology was now an issue. Besides contractors’ confusion between greywacke and argillite, two compositionally different kinds of greywackes existed in the South Auckland-Waikato area (Figure 8.2, p.246). Those belonging to the prehnite-pumpellyite metagreywacke facies (Coombs, 1960) yielded first grade road metal, but those belonging to the zeolite facies did not, although it was suitable for light use (Table 8.2).

Blaming greywackes: the greywacke subcommittee 1967

Get rid of “Greywacke” as a specific term, since it is the one that has caused all the trouble... leave, however, the NZ Geologists with their term “the Greywackes” as a loose term, never to be thought of as having a specific rock-type meaning.

(Kingma in Appendix 7 to Reed, 1967).

The aggregate problem at last drove some New Zealand petrologists and stratigraphers into importing the North American debate on sandstone classification, and in particular, to question the status of ‘greywacke’ as a petrological and stratigraphical term. Both Reed and T. Sameshima blamed the loose use of ‘greywacke’ as a group term for greywacke, argillite and associated rocks for causing such expensive problems. However, instead of filling the pages of The New Zealand Journal of Geology and Geophysics with rival classifications, the geologists sensibly formed a subcommittee of the Geological Society of New Zealand in 1967 (Jenkins, 1967; Reed, 1967; Reed et al., 1968). Its task was to consider how the term greywacke was used and to see if unanimity about its use in New Zealand could be reached. A questionnaire was duly prepared and circulated among the various institutes. The main issue was that in New Zealand, as in other parts of the world, ‘greywacke’ was used in two very different ways:

♦ As a strict scientific term applied to a special type of sandstone.
♦ As a loose group term used colloquially as a convenient way of referring to the large tracts of harder, older sedimentary formations (greywacke, argillite, cherts, and volcanics). It was said that this group use caused confusion, ‘particularly in the aggregate industry’.
The circular attracted 17 responses (Reed, 1967) with 17 different options expressed on the subject of ‘greywacke’ along with several offers of alternative pet sandstone classifications. Most respondents wanted to retain ‘greywacke’ as the sandstone name. Reed’s suggestion that ‘wacke’ should be used as a class name was rejected, partly because it was no better than ‘greywacke’, its original meaning was different, and it was not a very ‘euphonious’ word. ‘Greywacke class’ was chosen as a class name, and ‘greywacke suite’ was selected to refer to a field association of related rocks in which greywacke is a major constituent. Thus, little had changed. Because most respondents wanted to continue using ‘greywacke’, the subcommittee could not advocate abandoning the term. No firm nomenclatural direction was set (C.A. Landis, pers.comm.), and no new classification system was devised to suit all users, whether highway engineers, quarry managers or sedimentologists.

Our own New Zealand sandstone classification

Meanwhile, a group of Canterbury geologists3 reported that they were much concerned about the proliferation of competing sandstone classifications. Because of the increasing numbers of petrographic studies, the matter of greywacke nomenclature had become important (D.W. Lewis, pers.comm.), and a ‘multinomial nomenclature for scientific purposes’ was advocated (Reed, 1967: Appendix 6). It just so happened, members explained, that a group of eminent sedimentary petrologists, including the brilliant sedimentologist, R.L.Folk himself, was engaged in devising a system of classifying detrital sedimentary rocks. They aimed to develop a reliable international system suitable for the field and the laboratory, rather than one that was particular to New Zealand, or for non-geologists (P.B. Andrews, pers.comm.).

The collaboration between Peter Bruce Andrews (b.1935) and Douglas Windsor Lewis (b.1937) resulted in the publication of a clear, comprehensive method for classifying detrital rocks, complete with grain size scales, ternary diagrams, a comparison chart to aid visual estimates of components, and detailed guidance on the determination of texture and composition (Folk et al., 1970).

Sedimentologists were given all the advice they needed to describe and identify detrital sedimentary rocks. Andrews had earlier studied in Texas under Folk, and because the new classification was firmly based on Folk’s own work, he was invited to be named as prime author (P.B. Andrews, pers.comm.).

Following Folk’s views, single names were rejected because they were thought to have hindered progress both in the description of sedimentary rocks and the interpretation of their geological history. ‘Greywacke’ itself received yet more battle-scars, being accused of imprecision and of causing

3 Prof.M.Gage, Drs D.W.Lewis, J.D.Bradshaw, and D.Shelley, of the University of Canterbury, and Dr. P.B. Andrews of the New Zealand Geological Survey Sedimentation Laboratory.
confusion. It was claimed that all its connotations of texture, composition and induration, along with repeated redefinitions of the term by numerous authors had made it impossible to restrict its meaning. Plainly, greywacke could no longer be used as a precise, unambiguous petrographic term in New Zealand, and had lost all value as a specific petrographic name forever.

The Folksian polynomial descriptive nomenclatural system does indeed reflect the way in which sedimentary rocks exist in a continuum and at the same time makes no assumptions regarding origin and history. By using a combination of descriptive texture terms and composition terms, each individual and unique kind of rock is given its own descriptive name. The textural terms include brief statements to describe grain sorting and size, while the compositional terms are based on the proportions of quartz, feldspar and rock fragments (Figures 8.14, 8.15, 8.16) (to page 260).

Several examples are provided to show how different greywackes from different parts of New Zealand may be both named and described. One sample from the Torlesse Group is called a ‘moderately sorted medium sandstone: feldsarenite’, while another from the Waipapa Group is named as a ‘moderately sorted coarse sandstone: lithic feldsarenite’. Comparatively soft sandstone from the Waitemata Group was named as a ‘poorly sorted muddy medium sandstone: litharenite’. No distinction was made between the very different look and feel of the Tertiary and Mesozoic rocks, and no terms appeared available to describe the special ‘indurated’ character of greywackes.

Nevertheless, New Zealand geologists were ready to accept the principles of this new rock classification. The system makes it comparatively easy to accurately describe and name any detrital rock, especially arenites (sandstones). It uses very little scientific jargon, much of it can be applied in the field, genetic and environmental connotations are avoided, and it continues to be successfully used today (P.F. Ballance, pers.comm.).

**Greywacke abolished yet again (but returns yet again)**

In Folk’s nomenclatural system the ‘name’ is not just a name. It incorporates a detailed description so that a Jurassic greywacke from Waiheke Island could well be precisely named as a ‘dark grey, well indurated, graded bedded, poorly sorted, muddy, fine sandstone: lithic feldsarenite, prehnite-pumpellyite metagreywacke facies’ (P.F. Ballance, pers.comm.). Such a name is scarcely conversational, and is not likely to be written out by a geologist making field notes. As a name for a kind of sandstone, greywacke is replaceable by terms like litharenite or meta-arenite or metagreywacke. They are accurate and easy to say — but they can refer only to the sandstone elements in those ‘magnificent piles’.
Precise definitions are, of course, necessary for the correct transmission of information between scientists. Scientific terms should have only one meaning (Engelhardt and Zimmermann, 1988: 42), but ‘greywacke’ had acquired two main meanings, that is, to a kind of sandstone, and to the assemblage of rocks in the Southern Alps and North Island ranges (see before). Words, even scientific words, may shift meaning over the years. As a name for the sandstone element, ‘greywacke’ was used differently in New Zealand from the old pre-scientific German term ‘grauwacke’, which referred to similar sandstones and fine-grained conglomerates specifically of a Precambrian to Lower Carboniferous age (Wagenbreth, 1967).

Because of its troublesome reputation, the use of ‘greywacke’ as a group term was frowned upon for some years and its inclusion in publications was strongly discouraged. This left us without a generally understood group term for the complex assemblage of Mesozoic basement rocks. If the old name did appear, it was kept safely confined between a large pair of custodial quotation marks. Nevertheless, scientists need their own common vernacular with a few loosely defined, everyday field terms (Wagenbreth, 1967; Menard, 1971: 141; Pettijohn et al., 1987: 144). A name was needed for the association of basement rocks. It had to be familiar, easily understood, scientific enough for the literature and imprecise enough to be inclusive (Nicholson, 2002). Common usage prevailed and geologists have re-employed ‘greywacke’ as a group term quite safely without using the enclosing quotation marks. Its loose colloquial usage means that ‘greywacke’ has ‘survived all attempts to control it by rigorous application of petrographic criteria’ (Dickinson, 1970: 697), although its meaning has evolved and changed since the days of Lasius. In its traditional New Zealand usage, professional geologists, geographers, engineers, and the public understand ‘greywacke’, even if the connection that goes back over 220 years to the pre-scientific mining artisans of the Harz Mountains is not always understood.
Chapter Nine

Fossils and an Exotic Facies, 1950-1969

In part this apparent scarcity of fossils ... is due to lack of detailed examination ... [But in the alps] shell beds are either rare or absent

(Wellman et al., 1952)

Fossils are so seldom found in the Torlesse facies that few geologists have dared to generalize from the sparse occurrences.

(Fleming, 1969b: 145)

A formal biostratigraphic zone is a body of strata characterised by the occurrence of a taxonomic form or forms from one of which it receives its name.

(Hornibrook, 1967)

When the great 16 mile to 1 inch Geological Map was published (Marwick, 1948), the most up-to-date reference on Triassic and Jurassic faunas was over 20 years old (Wilckens, 1927), and much reliance was placed on Trechmann’s studies (1917, 1918, 1923) for fossil identification and stratigraphical guidance.

After a long period devoted to working out New Zealand’s Cretaceous and Tertiary stratigraphy Marwick’s interest turned towards the fossiliferous Hokonui facies rocks (now Murihiku terrane) in Southland and Kawhia where he recognised new series and stage divisions for the Triassic and Jurassic rocks (Marwick, 1950). This was soon followed by his Paleontological Bulletin (1953) on the divisions of the Hokonui System based on these Triassic and Jurassic strata. Marwick’s revision encouraged new work on these rocks, some of which spilled over to the greywackes and argillites of the Alpine facies (now Torlesse terrane). It was followed by two other key publications that provided a wider framework upon which geologists could develop ideas about Upper Paleozoic and Mesozoic paleoenvironments and geological histories. These were Wellman’s 1959 subdivision of the Cretaceous sequences into stages based largely on forms of the fossil bivalve Inoceramus (Figure 4.14d, p.88). The other, a bulletin by Permian expert J. Bruce Waterhouse (1964), defined Permian sequences and fossils in Nelson and Otago.

Although the undifferentiated greywackes were always obstinate about giving up any information about their geological age and affinities, a few fossils similar to those found in the Hokonui (Murihiku) strata turned up from time to time, (for example Milligan, 1959; Fleming, 1961; Grant-Taylor and Waterhouse,

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1 Geologists continued to use ‘Hokonui’ until well into the 1970s, see column under Murihiku Terrane’, Table 8.1 pp.241-247.
1963). These finds could be matched against Marwick’s stages to make tentative age determinations of parts of the Alpine facies greywackes. The sporadic discoveries of fossils in the greywackes, mostly close to roads and accessible river valleys, slowly mounted up, with many more finds made between 1956 and 1965, during the 1:250,000 mapping project. Eventually, John Douglas Campbell (1927-2001) and Guyon Warren (1933-2003) could compile a detailed checklist and map of the 350 known South Island fossil localities within the Torlesse Group (Campbell and Warren, 1965). The fossils, ranging in age from Permian to Lower Cretaceous, were found as:

- Isolated shell fragments transported, presumably from a shelf environment, as dead shells and re-deposited e.g. worn specimens of *Inoceramus, Monotis*, fragments of *Atomodesma*, and leaf and stem fragments.
- Assemblages preserved at or near the life sites including the Kahi Kuan (Upper Triassic) faunas of Mt St Mary and Mt Potts (p.289 and Figure 9.4).
- Benthic or bottom-living forms such as *Terebellina* (*Torlessia*).
- Shell-beds e.g. *Monotis* limestones at Okuku Gorge, a part of ‘vast chaotic breccia bodies’ (Bradshaw, 1971).
- Microfossils in limestone faunas associated with spilitic pillow lavas e.g. Marble Bay at Whangaroa.

Most fossils belonged to familiar species that also occurred in the Hokonui (Murihiku) facies of Southland, Nelson and South Auckland, thus reinforcing the idea of a single bipartite geosyncline, although Campbell and Warren were sceptical about the subdivision into two simple facies. Only a few types such as the tube-fossil *Terebellina* were restricted to the Torlesse Group (but see Begg et al., 1983). Nine faunal zones were identified (Figure 9.1, 9.4), supporting the long-held view that the Canterbury rocks belonged to several different periods (Crawford, 1868; Haast, 1885; Hector, 1885; Wellman, 1956; Waterhouse, 1965). More importantly, the faunal zones indicated an age span from the oldest rocks characterised by the Permian bivalve *Atomodesma* (the ‘Dun Mountain *Inoceramus*’, Figures 4.14c, 5.8) in parts of South Canterbury and Otago through Middle and Upper Triassic, and Upper Jurassic zones in Canterbury to Lower Cretaceous rocks in Marlborough.

No Lower Triassic or Lower and Middle Jurassic fossils were recorded, so that out of a 135 million year Permian to Jurassic time span, only 35 million years (25%) appeared to be present. Strangely, no obvious unconformity complete with erosion surfaces has been found in the Torlesse greywackes\(^2\) corresponding to this enormous time gap. The somewhat patchy geographical distribution of fossils led to Fleming’s suggestion (1969a) that ‘small basins of rapid subsidence migrated up and down its axis’, creating a curious mental image of a heaving, billowing, geosynclinal basin. At any rate, the nine faunal zones at last

\(^2\) Alpine facies renamed Torlesse Group 1961, now the Torlesse terrane. Tables 8.3, 8.4.
provided some pattern and chronological order to the mass of greywackes giving hope that they could be subdivided into smaller units, and that their geological history might be discerned.

The Torlesse Group was extended to the North Island in 1963 by Graeme Roy Stevens (b.1932), based on fragments of Jurassic belemnites within the younger greywackes in the Urewera ranges south of the Bay of Plenty. No North Island name was applied to these rocks (Kear, 2001: 5) but a checklist of Torlesse fossil localities in the North Island was made in 1976 by Ian G. Speden. Fewer and less readily defined faunal zones than in the South Island could be distinguished by Speden (Figure 9.2), but the general pattern of northward and eastward younging of the Torlesse rocks was maintained. Much uncertainty remained regarding the age of Waipapa Group rocks south of the Bay of Islands, and the Torlesse rocks west and northwest of Lake Taupo. Speden warned of the possibility that some fossils may be ‘derived’ in origin, i.e., ‘redeposited’ indicating tectonic mobility, and suggested that perhaps part of the sequence is allochthonous. By 1976, about 500 fossil localities were known in the Torlesse rocks and in Canterbury,
Figure 9.2: Map of Torlesse rocks in the North Island and the northern part of the South Island, showing the distribution of major fossil zones and their relation to elements of the New Zealand Geosyncline. 47% original size. Large labels added. Modified after Speden (1976) Journal of the Royal Society of New Zealand.
15 biostratigraphic zones, excluding the Cretaceous rocks of Marlborough, were recognised (Canterbury Suite of Andrews et al., 1976). The significant gaps seen earlier remained, with no early Triassic, or very late Triassic to middle Jurassic finds.

Speden’s map and checklist was compiled as a voluntary spare-time project (I.Speden, pers.comm.). We do not know how much ‘spare time’ science is freely contributed to the body of geological knowledge by scientists throughout their working lives and during retirement. This is very difficult to assess because normal research projects often overflow into private time and a ‘true research scientist does not even know there is a holiday’ (Menard, 1976: 12).

**Environmental indicators: shallow or deep?**

Before 1950, fossils were used mostly as stratigraphical time-keepers (Weller, 1960) and speculations on past geography focussed mainly on broad outlines of the transgression and regression of seas, land connections and ideas of past climates (for example Benson, 1923; Bartrum, 1938: 21). Through the 1950s and 1960s, the use of fossils as environmental indicators grew together with the increasing interest and expertise in determining sedimentary environments (Friedman, 1998).

By now, most New Zealand geologists accepted that the sandy greywackes had been deposited in deep water by turbidity currents (p.232, and this was supported by the reasonably frequent presence of radiolarian cherts and red abyssal clays among greywacke sequences. However, during the 1970s, doubts were raised by Canterbury geologists regarding the depositional depth of the Torlesse greywackes, and whether the sediments were deposited in a deep sea or a coastal deltaic and shallow marine environment (Andrews, 1974; Andrews et al., 1976).

All of the fossil forms found in the greywackes are extinct, so any discussion about their life environments must be speculative and sometimes controversial. The only organisms known to have actually lived within Torlesse sediments at the time of deposition are the enigmatic tube fossils *Terebellina* (*Torlessia*) and *Titahia* (Figure 9.4) and unknown creatures that left several trace fossils (Stevens, 1972, 1978). None of these organisms have been very helpful as indicators of either age or depositional environment. Later discussion centred on whether the occasional association of shells of bivalves and brachiopods with worm-like trace fossils indicated shallow water deposition (Spörli and Grant-Mackie, 1976), or if the trace fossil was of any significance at all because sedimentological evidence indicated deep-water deposition (Ballance, 1976). Although heavy-shelled bivalves like *Atomodesma* and *Inoceramus* appear similar to today’s shallow water benthic animals, dead shells could have been carried into deep water by turbidity currents. Recently, heavy-shelled mussel-like bivalves have been found associated with deep submarine seeps (MacDonald et al., 1990; Campbell et al., 1993) Thin-shelled pterioid (scallop-like) molluscs
Paleontological Troublemakers of the Twentieth Century

The 'Mount Torlesse Annelids'

Continued from Chapter 4

McKay (1901): Kaimanawa Range. Annelids indicate Carboniferous age. McKay certain that the rocks are older than Trias

Park (1903): cannot fix age of annelid beds in the absence of shell beds. Discards annelids as they are of no stratigraphic use

Bather (1905): names the annelid Torlessia Mackayi, describes calcareous walls, possibly siliceous, names curved form Dentalium huttoni

Jaworski (1915): synonymises Torlessia with the Triassic Terebellina. Shell agglutinated cherty fragments

Webby (1958) describes a new agglutinating annelid from the Wellington greywackes, Titahia corrugata

Campbell and Warren (1965): Identify an Upper Triassic Terebellina zone in South Island Torlesse

Webby (1967) argues separation of Torlessia mackayi from Jaworski's Terebellina. Discusses Terebellina in Whangai Shale (Upper Cretaceous-Eocene) in Wairarapa. Probable bentonic habit. The 'annelids' may be polychaete worms, or belong to the Pogonophorae, or giant foraminifera e.g. Bathysiphon.


Figure 9.3 (page 1). Although 'The 'Mount Torlesse Annelids' were of doubtful use as indicators of age or of depositional environment, they have continued to fascinate geologists. Much of the attraction is because they represent the only animals known to have lived where the greywackes were deposited. Another is that much doubt exists as to whether the 'annelids' are worms or if they belong to some other animal phylum.
Continued from page 286

Campbell and Campbell (1970): Titahia corrugata and Torlessia in Tuapeka group, South Otago. Precludes simple age progression between Murihiku Supergroup and Haast Schist

Stevens (1972) sees Titahia and Torlessia simply as indicators of a soft bottom environment, but they are unable to signify whether they grew in either a shallow or deep water depositional environment.

Gregory and Wakefield (1974): describe non-calcareous tubes in the Miocene of Northland and Hawkes Bay

Speden (1976) defines North Island Late Triassic Torlessia zone in Wellington district to the south of the Monotis zone

Gregory (1977) doubts Torlessia agglutinated or limited to late Triassic. Perhaps distribution is facies dependent, not temporal or spatial. Little reason to consider Torlessia a late Triassic marker.

Force and Force (1978) report a Torlessia tube in the same horizon as Triassic shells in Canterbury Torlesse

Cave (1982): reviews NZ literature. Terebellina and Torlessia are synonymous. They lived in sediment with tube open to sea water. Suggests slightly different habitats for Terebellina and Titahia.

Campbell & Pringle (1982) find Torlessia with late Middle and early Upper Triassic shelly fossils in Central Canterbury

Begg, Cave, Campbell (1983) Terebellina mackayi found in Oretian Murihiku rocks in Southland. First 'annelid' occurrence outside Torlesse

Moore (1987): Terebellina from NZ Paleocene virtually identical to Makiyama, a sponge, from Miocene of Japan

Miller (1995) Reviews history. Fossil annelids may be large bathysiphonid foraminifers. Terebellina reinterpreted as a large species of Bathysiphon

Figure 9.3 (page 2): Terebellina-Torlessia may be a very large one-celled animal or foraminiferid similar to a living type called Bathysiphon. Since tube fossils were found together with known Triassic fossils in 1982, they can be counted as Upper Triassic markers.
Table 9.1: Middle Triassic shallow-marine and Upper-Jurassic-Lower Cretaceous land plant fossil localities in Canterbury.

<table>
<thead>
<tr>
<th>Location</th>
<th>Fossil type</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clent Hills</td>
<td>terrestrial plant fossils</td>
<td>Lower Cretaceous-Upper Jurassic</td>
</tr>
<tr>
<td>Wakaepa</td>
<td>terrestrial plant fossils</td>
<td>Lower Cretaceous-Upper Jurassic</td>
</tr>
<tr>
<td>Carney’s Creek</td>
<td>marine fossils</td>
<td>Middle Triassic (Kaihikuan)</td>
</tr>
<tr>
<td>Mt St. Mary</td>
<td>marine fossils</td>
<td>Middle Triassic (Kaihikuan)</td>
</tr>
<tr>
<td>Corbies Creek</td>
<td>marine fossils</td>
<td>Middle Triassic (Kaihikuan)</td>
</tr>
<tr>
<td>Mt Potts</td>
<td>marine fossils</td>
<td>Middle Triassic (Kaihikuan)</td>
</tr>
<tr>
<td>Benmore Dam</td>
<td>terrestrial plant fossils</td>
<td>Middle Triassic</td>
</tr>
</tbody>
</table>

Figure 9.4: Map of the South Island compiled to show fossil localities, faunal zones and the five shallow-marine and two terrestrial fossil enclaves. The Esk Head Mélange includes McKay’s Okuku site and it contains Upper Triassic Monotis shells and Upper Jurassic fossils. Labels added and enlarged. 70% original size. Modified after MacKinnon (1983), Geological Society of America Bulletin.

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such as *Halobia* and *Monotis* could float about attached to floating seaweed and wood (Stevens, 1972) and sink to the bottom when they died. Either way, the question of depositional environment helped to set off a series of significant examinations of the Canterbury greywackes in the 1970s (Bradshaw, 1972; Andrews, 1974; Andrews et al., 1974). Later, sedimentologists were inclined to agree that the Torlesse sediments represented deposition in deep water submarine fans (for example Howell, 1981), but this left the problem of seven isolated sets of shell and plant beds in the Torlesse.

**Shell beds and plant fossils**

Seven abundantly fossiliferous Kaihikuan-age (Triassic) shell beds and Jurassic plant beds (Table 9.1, Figure 9.4) among the Canterbury Torlesse rocks are like little stratigraphical enclaves, seemingly akin to micro-terranes, being in faulted contact with the surrounding highly deformed greywackes and argillites typical of the Torlesse Supergroup (MacKinnon, 1983). Unlike the greywackes:

- The sequences are unusually fossiliferous and this is their distinctive common characteristic (Andrews et al, 1976). Plant fragments and coal layers interbedded with conglomerates support the hypothesis of an eastern source for Torlesse rocks.
- The rocks are of shallow water origin, either estuarine or terrestrial (Force, 1974).
- The rocks are lithologically and petrologically dissimilar to the greywackes and thus have a different provenance or origin (Force, 1974; MacKinnon, 1983: 973). Their lithology cannot be matched with any of the eleven lithotypes distinguished in the surrounding Torlesse rocks (Canterbury Suite of Andrews et al, 1976, and Table 8.3)
- The enclaves can be mapped by conventional stratigraphic methods (Figure 9.5). Formations can be identified, named, and shown on a stratigraphic column (Campbell and Force, 1972).
- However, the sequences have undergone low-grade metamorphism like the surrounding prehnite-pumpellyte metagreywackes.

**Origin of these shell and plant beds**

When sandy geosynclinal greywacke beds were regarded as of shallow-water origin e.g. (Cotton, 1945: 39; Wellman, 1952) the presence of these fossil beds was not seen as a problem and they merely confirmed the Mesozoic age of the Canterbury rocks. In Wellman’s 1956 model of the New Zealand Geosyncline, the unconformable Jurassic fresh-water beds were considered to foreshadow the end of the geosyncline as a basin of deposition. Later, the concept of deposition by turbidity currents into a deep geosyncline led to the usual suggestion that parts of the geosyncline occasionally became shallower, permitting the deposition of shallow-water and terrestrial beds (for example Force, 1974: 46; Stevens, 1978:262).
Figure 9.5 (left). This map shows the Middle Triassic Corbies Creek Group which occupies a 2 km wide fault-bounded strip in Long Gully, near Otematata, North Otago (Figure 9.4). The comparatively orderly layers (compared with greywackes) of shallow marine and terrestrial rocks were mapped and interpreted by Retallack as the remains of a large marine delta.

Figure 9.6 (above). Reconstructed Middle Triassic estuarine environment near Benmore Dam, South Canterbury (Figure 9.4). The sediments were seen as evidence of a Middle Triassic shoreline in the predominantly deep-marine Torlesse rocks. 80% original size. Modified after Retallack, 1983. Journal of the Royal Society of New Zealand
As a result of making detailed studies of the shell and plants beds, the Australian geologist Gregory J. Retallack (1980, 1981, 1983a, 1983b, Retallack and Ryburn, 1982) reconstructed a number of past environments illustrated with excellent drawings of ancient landscapes, vegetation and fauna (Figures 9.5, 9.6). Retallack (1983a: 107) saw these enclaves as ‘evidence of a Middle Triassic shoreline in the predominantly deep-marine Torlesse rocks’, which had a similar history of deformation to other Torlesse rocks. However, he did not explain how rocks from such contrasting environments became so closely associated.

The replacement of the geosynclinal model with a Mesozoic trench, subduction zone and accretionary prism (Chapter 11) began to provide some explanations for these local fossil associations. Their appearance of ‘floating’ in the midst of highly deformed Torlesse rocks was taken as significant (Carter et al, 1978). One explanation was that they were rare and atypical of the redeposited (greywacke) facies, and that they might be explained as olistoliths (glossary). Another explanation (and not altogether different from the shallowing geosyncline idea) is that the shallow-marine and non-marine strata were seated on the upper surface of a ‘tectonically kneaded’ Middle Jurassic accretionary prism, and that portions of the prism were raised above sea level from time to time (Howell, 1981). At the same time, the normal greywackes were deposited in submarine fans. Thomas C. McKinnon (a Ph.D. student from the United States) provided a useful summary and maps (Figure 9.4) of the locations and geology of the seven fossiliferous, fault bounded localities (MacKinnon, 1983). He, too, suggested that the fossil sequences may represent subaerially exposed trench-slope-break highs or uplifted borderlands. Perhaps the nearest modern analogues of these strangers in the greywackes are the Andaman and Nicobar Islands perched on the highest parts of a vast accretionary prism in the Bay of Bengal.
Figure 9.7a: Lava pillow with a calcite centre, Walheke Island. Photograph HMHN (1952).

Figure 9.7b: Section through coastal rock platform near Surfside, Walheke Island, showing relationships between various 'exotic' rocks. Modified after Halorow (1956). Transactions of the Royal Society of New Zealand.

Figure 9.7c: Pillow lavas at Walheke Island 2002. The pillows are right way up, as indicated in this photograph. Photograph HMHN (2002).

Figure 9.7: Pillow lavas near Surfside at Walheke Island, located on an in-shore rock platform and easily accessible at mid and low tide. The red argillites are greatly deformed and mixed with fragments of lava.
An Exotic Facies: Pillow Lavas and Cherts

Now let us … consider the association of ophiolites and radiolarian chert, which is far too widespread in time and place to be accidental….

(Bailey, 1936: 1719)

A strong New Zealand tradition is to consider ultrabasic intrusions as genetically related to pillow lavas with which they are often associated.

(Fleming, 1969b: 142)

In early 1951, some rock samples from near Blackpool at Waiheke Island were given to Maurice Hugh Battey (1922-1996), geologist at Auckland War Memorial Museum (A.P.Mason, pers.comm.). At first, all the fragments looked like the expected weathered greywacke, but a closer look showed that some were of igneous origin. When Battey and his volunteer assistant, A.P. Mason, visited the site (518670, 1/25,000 series, Oneroa) both men were greatly pleased to see genuine pillow lavas in the rock platform (Fig 9.7). Entries in the Museum’s accession book show that samples of green and red lavas, pillow margins, dark red interstitial material, red shale and pieces of marble were collected. Later, several students accompanied Professor A.R.Lillie and the two discoverers on an expedition to view the site, and happily discussed whether these were indeed true pillow lavas. Unfortunately, neither Battey nor Mason published anything on their discovery, and regrettably, the discoverers of these pillow lavas have not been acknowledged until now. Pillow lavas were first recognised in the New Zealand greywackes only about two years before Battey’s and Mason’s discovery, when Wellman (1949) identified the ‘diabasic tuff’ at Red Rock Point on the Wellington coast as a variolitic pillow lava. Like other pillow lavas in New Zealand greywackes, it is associated with red argillites and radiolarian cherts.

The first pillow lavas

Towards the end of the nineteenth century, ‘spherooidal’ and ‘ellipsoidal’ basalts, and variolitic diabases began to be reported and described in detail from Britain, Europe, Canada and the United States. In 1883, the British geologists Howard Fox and J.J.H.Teall described ‘rude rolls’ of igneous rock found in association with radiolarian cherts, shales and limestones on Mullion Island on the Cornish coast. The geologists were reminded of pahoehoe lava, and suggested that the rolls were probably formed by contemporaneous submarine flows insinuated between layers of sedimentary deposits (Fox and Teall, 1893). Several other hypotheses were advanced as to the origin of such rounded blocks of lava, as detailed by J.M.Clements and H.L.Smyth in the United States who preferred the explanation that the ‘ellipsoids’ originated as blocks of aa lava that had been rounded by rolling in the lava stream (Clements and Smyth, 1899: 112-124). Geikie described ‘pillow’ or ‘ellipsoidal’ structures in his textbook and somewhat tentatively suggested a submarine origin (Geikie, 1903: 136,306). The question of the origin of pillow lavas
was soon settled when Tempest Anderson (1910) saw pillows budding into the sea during the Matavanu eruption of 1905 in Savaii (Samoa).

**Diabase tuffs and pillow lavas**

The settler geologists often reported ‘aphanites’ and ‘diabase tuffs’ in the greywackes. Today, the term ‘tuff’ refers to a compacted layer of fine volcanic ash, often with comminuted country rock, but in the nineteenth century, tuffs were often defined as being composed of fragments of volcanic rocks, ‘like a breccia conglomerate’ (Van Hise, 1904). A jointed, fractured and altered accumulation of Mesozoic pillow lavas (Figure 9.7c) does indeed look like a ‘breccia-conglomerate’.

In New Zealand, Haast frequently noticed ‘diabasic beds’ or ‘ashes’, interstratified with young Palaeozoic ‘cherts, sandstones and shales’ (for example Haast, 1872). On an expedition to the West Coast (1865) he observed ‘trappean rocks of a diabasic nature... interstratified’ within the sedimentary rocks and frequently mentioned the presence of compact diabases, diabasic tuffs and cherts (Haast, 1879: 277). McKay’s experience with the diabases, ash, and cherts associated with the Triassic *Monotis*-bearing limestones of the upper Okuku Valley in North Canterbury, (p.80 Figure 4.10), caused him to regard all rocks containing diabasic tuffs as of Triassic age (McKay, 1894: 88). McKay (1888a: 3) also reported several occurrences of brecciated diabasic tuffs associated with chertose quartzites and jasperoid rocks in the Wellington district. At Red Point on Cook Strait (Red Rocks), he distinguished a leek-green ‘finely crystalline volcanic rock’ with numerous cavities filled with carbonate of lime. McKay (1888b: 66) had first thought that similar rocks found in the Makara Valley (west of Wellington) were dyke-rocks, but changed his mind and considered that the Red Point lavas were contemporaneous with the surrounding sedimentary rocks.

Little more was reported of ‘diabases’ until F.K.Broadgate reviewed the Red Rocks of Wellington Peninsula (Broadgate, 1916) in which the lavas were regarded as ‘diabase tuff’ interbedded with the coloured argillites, chert and greywacke (p.127, 207). Benson (1921: 62) later noted the association of these and other diabase tuffs with ferruginous jaspilites and argillites which reminded him of ‘the features of Palaeozoic submarine flows (though not pillow-lavas)’ he had seen in Europe and Australia.

James Park (1905) first recognised pillow lavas in New Zealand when he realised that the Tertiary igneous rocks in sea cliffs near Oamaru, which had earlier been described as ‘basaltic agglomerate and ash’ (Hutton, 1886), were ‘pillow-form’ lavas that had originated as submarine flows. Some time later, Professor John Arthur Bartrum (1885-1949) identified Cretaceous pillow lavas in Tangihua Volcanics at

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3 The first known mention by Haast of his ‘Mount Torlesse series’ is in the introduction to this 1865 report
North Cape and Tertiary pillow lavas within the Waitemata group at Muriwai, near Auckland (Bartrum and Turner, 1928; Bartrum, 1930).

**An exotic facies: pillow lavas and cherts**

Again and again, these rocks [radiolarian chert and ophiolites] are together in the middle belts of geosynclines, ancient and modern.

(Bailey, 1936: 1718)

Basic pillow lavas and other basic and ultrabasic rocks including serpentines, peridotites and gabbros constitute a natural group that was given the name ‘ophiolite’ by Gustav Steinmann (1856-1926) in 1905 (Hsu, 1973; Trümpy, 2003). Such rocks were considered to occur only in association with folded ‘alpine-type’ mountains and to be commonly coupled with some kind of tectonic disturbance (Bailey, 1936; Hsu, 1973). Geologists conjectured on the relationships between eugeosynclines, ophiolites and orogeny, and pondered on the association of pillow lavas, serpentinites and radiolarian cherts in what Bailey called the ‘Steinmann trinity’ (Bailey and McCallien, 1950, 1960). Bailey (1936: 1718) regarded the association of radiolarian chert, brown-red clay and ophiolites (glossary) as an ‘exotic facies’ within contrasting geosynclinal sediments.

In New Zealand, Benson produced a series of thoughtful articles on the tectonic conditions necessary for the intrusion of serpentines along thrusts (for example Benson, 1918, 1919). Later, the pods or lenses of pillow lavas and cherts found throughout the greywackes were thought to be related to the much more voluminous ophiolite belts characteristic of ‘all alpine mountain systems and nowhere else’ (H.H.Hess quoted by Reed, 1950: 122, also see Moores and Vine, 1988), although Reed recognised differences in the chemistry between these igneous rocks.

In 1950s New Zealand, as elsewhere, pillow lavas and other basalt flows were regarded as interbedded with the surrounding greywackes and argillites and contemporaneous with them (for example Halcrow, 1956: 54) as indicated in Kay’s eugeosyncline (Figure 7.8, p.222). The fluid lavas were imagined as leaking upwards from the simatic ocean floor below, through the thick layers of geosynclinal sediments, and on reaching the submarine surface, pillows of lava budded off and spread over the surface and between layers of unconsolidated sediments. The frequent association of the submarine lavas with abyssal cherts and argillites and with what were seen as shallow water coarse greywacke sandstones and limestones made from the skeletons of shallow water molluscs and corals (Figure 9.9), was a continuing conundrum (Bailey, 1936). This was only partly solved when turbidity currents were shown to be capable of delivering coarse sediments into deep water (Kuenen and Migliorini, 1950).
New Zealand’s ‘exotic facies’ constitute only about 1% of the whole greywacke assemblage (Paltridge, 1958; Hopgood, 1960: 210-2; Meshesha and Black, 1989: 30), often accompanied by cherts. Spilites are basalts that contain a higher sodium content than usual, contained in the feldspar variety, albite. Their origin presented another puzzle (Hatch et al., 1949: 331) but many authors then regarded albitisation as a secondary process caused by ‘stewing’ of basaltic extrusions in a ‘sodic’ environment, that is, in seawater (Hopgood, 1960: 212).

Thinly bedded red cherts may constitute the whole lens, and be 150 m or more in thickness. Within Waipapa greywackes, large chert lenses often form the topographic highs (Ferrar, 1925; Halcrow, 1956). Vast numbers of radiolarian skeletons are seen in some cherts, and sometimes recrystallised ‘ghosts’ of their tests can be made out in thin sections (Mayer, 1968: 224). More often, recrystallisation has partly or wholly destroyed the radiolarian skeletons, leaving a somewhat homogenously microcrystalline mass.

Radiolarians are marine one-celled animals with sculptured siliceous shells (Figure 9.9b, 9.9c). Radiolarians in cherts were difficult to identify, as no technique was available for their extraction and identification until the 1970s (Feary and Hill, 1974; Le Grand and Glen, 1993). Chert beds represent ancient deep-sea radiolarian oozes and much of today’s deep-sea radiolarian ooze accumulates in tropical oceans below the carbonate-compensation depth (about 4500 m) where calcium carbonate skeletons dissolve. The origin of the bedded cherts, so different from the enclosing greywackes, was much disputed, perhaps because radiolarians were not always seen in them. Theories regarding the origin of cherts ranged from ideas of silicification of previously existing sandstones, deposition by flocculation in

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4 Neither benthic nor planktonic calcareous foraminifera existed until the Triassic.
shallow-water, through to their origin as deep-water radiolarian oozes (see discussions Halcrow, 1956; Hopgood, 1960).

Associated thinly bedded fine-grained red and green argillites were generally understood as ancient abyssal clays, as suggested much earlier by F.W.Hutton (1885, 1899), and were usually found in association with ‘interbedded’ volcanics or cherts (Halcrow, 1953: 12). All of these red rocks, cherts and clays, are often laced with nests and stringers of soft, black manganese ore similar to present-day sea-floor manganese nodules (Reed, 1960; Glasby, 1976). All of the manganese ore mined in New Zealand has been extracted from the cherts (Reed, 1960) within the Waipapa Group (later Waipapa Terrane) greywackes.

Adding to the puzzle is that small amounts of apparently shallow-water limestone may be present, often filling interstices between the lava pillows (Figure 9.7a). Large blocks of limestone associated with chert and spilites in South Canterbury may be up to 30 m in thickness (Hitching, 1979: 193), while others with an area of up to 100m² are found mixed with pillow lava, red chert and sandstone blocks in North Canterbury (Bradshaw, 1973). These exotic limestones sometimes contain recognisable fossils, but are often fragmented or converted into marble and any fossils destroyed.

The upper and lower contacts between rocks of the exotic facies and greywackes may be sharp, the layers may interfinger with each other, or the contact may appear to be faulted. Some kind of structural disturbance among these rocks, especially the cherts, is almost invariably present, usually expressed as crumpled and elaborately folded bedding, sometimes as the fragmentation and mixing of chert and lavas, and sometimes as faults. Similar, localised deformation of the neighbouring greywackes, as folds, faults, boudinage, slickensides and quartz veins, is common (Halcrow, 1956). At a more extreme level, the disturbances take the form of crush zones, broken formations and mélanges (p.357).

Apart from studies of the petrography of the spilitic pillow lavas and discussions on the origin of the cherts, these exotic pods received little attention in New Zealand until the 1970s. While the Dun Mountain ophiolite belt had long been recognised as intimately associated with tectonic activity, few connections were made between the small-scale folding and crumpling of the cherts and red argillites, the pillow lavas and tectonism. Strike faults, later described as ‘knife sharp’ (D.Howell, pers.comm.), may be virtually invisible, and if noticed, were perhaps seen as fortuitously coincidental, although strong deformation of neighbouring greywackes is nearly always restricted to zones that include the exotic facies. Away from these zones of deformation (Chapters 10, 12), bedded greywackes are tilted and folded but not so ‘inextricably’ deformed that they cannot be mapped at all (Figure 10.4). However, there was no reason to see tectonic significance in the presence or style of the exotic rocks so long as the lavas were thought to have seeped upwards through layers of sediments in a passively subsiding geosyncline (p.222).
Figure 9.9a. Sections of Permian fusulinid foraminifera found by R.F.Hay in marbles associated with pillow lavas near Whangaroa in Northland, and identified in thin sections by N.de B.Hornibrook. Although the animals were uncelular, their shells were subdivided into numerous tiny chambers. The large specimen is a little over 10mm in diameter. Image slightly reduced. Modified after Hornibrook (1951) Transactions of the Royal Society of New Zealand.

Figure 9.9b. Sketches of radiolarians drawn in 1963 from thin sections of cherts from Waipapa Group greywackes. Such images were of little use in making identifications. X200.

Figure 9.9c. An electron micrograph image of the radiolarian Glomeropyle grantmackiei Alta, found in phosphatic concretions in argillites of the Waipapa Terrane. 100 µ. Modified after Alta and Bragin (1999). Geodiversitas.

Figure 9.9d. Scanning electron micrograph of a conodont of Upper Carboniferous age from Kakahu Marble. Scale bar = 0.1mm. Modified after Hitching (1978). New Zealand Journal of Geology and Geophysics.

Figure 9.9: Microscopic fossils including fusulinids, radiolarians and conodonts. Fossils found in lenses of limestones and cherts of the exotic facies provided significant information about the ages of that facies alone. They could not inform geologists as to the ages of the enclosing greywackes. Technological improvements during the 1960s made the micropaleontologists' identification tasks much easier. All images reduced slightly.
Work on greywackes during the later 1950s and 1960s was focussed on mapping folds in the Torlesse greywackes that contain fewer exotic layers (Chapter 10) than the Waipapa greywackes.

**Limestones, marbles and microfossils**

In New Zealand, limestone is closely associated with volcanics in sequences of many different ages. The association is too direct to be accidental, but the controlling mechanism is uncertain.

(Wellman et al., 1952: 219).

In 1950, the remains of Permian fusuline foraminifera (Hornibrook, 1951), reef-building corals (Leed, 1951, 1956), ostracods, polyzoans and other foraminifera (Figure 9.9a) were found in fragments of marble mixed with the brecciated pillow lavas of Marble Bay near Whangaroa and several other localities in Northland (Speden, 1976). This significant discovery meant that the Northland greywackes north of Whangarei were also judged to be of Permian age. The fusulines, corals, and other reef-building fossils were believed by N. de B. Hornibrook (1951: 321) to indicate that in Late Paleozoic times, the warm, clear, shallow waters of the Orient and Tethyan seas (p.163) extended far southwards to the New Zealand area. This suggested a very different setting from the deep-water environment subject to periodic dumps of sediment that had recently been postulated for the greywackes (Kuenen and Migliorini, 1950)

Fusulines or fusulinids (Figure 9.9a) are marine one-celled animals and belong to the group of foraminifera that have calcareous or siliceous or chitinous tests (shells), or made of agglutinated sedimentary particles. Members of the group are important Upper Paleozoic index fossils. While most ‘forams’ are microscopic and less than 1mm in diameter, fusulinids may be up to 100 mm in diameter. The Whangaroa fusulinids have fusiform or disk-like shapes and look rather like miniature flying saucers.

Marble and limestone are uncommon in the greywackes, and when present are usually associated with pillow lavas (for example Haast, 1872: 11; McKay, 1881:99-100; Bradshaw, 1972: 74). The lavas of Marble Bay were the same basic flows, tuffs, and breccias of the ‘profoundly’ jointed, faulted, and ‘brecciated’ Waipapa Series seen by Bell and Clarke (1909: 21-22,44-45) and who described the associated marble blocks as ‘much brecciated, and mixed with the ... volcanic and sedimentary rocks’. These appear to have been part of a ‘friction breccia’ about five chains wide (100m.) on the coast, and consisting of intensely fractured igneous and sedimentary rocks. Similar Permian fusulines were later found in limestones near Benmore Dam (Figure 9.4) (Hornibrook and Shu, listed in Campbell and Warren, 1965).

The next remarkable microfossil discovery was that of conodonts in the Triassic Okuku limestone of North Canterbury (Jenkins, 1968, Jenkins and Jenkins, 1971a). Conodonts are microscopic tooth-like phosphatic fossils (Figure 9.9d), and are of great value in dating rocks of Cambrian.
to Triassic age. Conodonts are quite extinct and paleontologists had conjectured for many years as to the appearance and relationships of the living animal. A single fossil found in 1982 revealed that conodont animals were small, slender, soft-bodied, worm-like animals about 4 mm long, with the tooth-like conodont ‘apparatus’ in the head region. Conodont animals may be related to chordates (Briggs et al., 1983).

Upper Carboniferous conodonts (Figure 9.9d) that were discovered in a complexly folded marble inlier with ‘confused bedding’ (Wellman, 1953: 12) at Kakahu in South Canterbury (Figure 9.4) (Jenkins and Jenkins, 1971b; Hitching, 1979) extended the history of the Torlesse rocks further back into the past, and a new Carboniferous faunal zone was created. This was the first genuine record of Carboniferous fossils in New Zealand (and so far the only one), and seemed to prove the Carboniferous initiation of deposition of the greywackes. The conodonts certainly established the age of the Kakahu marble and showed that it was as old as, but no older than, Upper Carboniferous in age, and that no Lower Paleozoic rocks appeared to exist east of the median tectonic line. This more or less confirmed that there was no older granitic basement to the Torlesse greywackes, which had probably been deposited directly on oceanic crust (Landis and Coombs, 1967: 505).

Are well-known and correctly identified fossils always reliable indicators of their host rocks? Are worn, redeposited fossils found in the greywackes themselves perfectly dependable? What if they were derived from older, cannibalised rocks? Are the fossils enclosed in cherts and limestone belonging to exotic pods reliable guides to the relative ages of the surrounding greywackes? Northland greywackes had been regarded as of Permian age since 1951 (Figure 9.9a). However, fossils from similar greywackes of the Waipapa group near Auckland indicated an upper Jurassic age (Spörli, 1975). This age difference could be taken as ‘circumstantial evidence’ that an age gap existed between the igneous rocks that formed part of the Permian oceanic floor, and the host greywackes. Therefore, were the greywackes near Kakahu really of Carboniferous age, or were the Kakahu limestones associated with chert and pillow lavas rather older than surrounding greywackes? (p.348).
Chapter Ten

Structural Solutions 1950-1970

New Zealand geologists can advance quickly in structural work on schists only if we bear in mind the limitations of any particular line of field work and that in the long run we shall have to consider petrographic evidence, often quite detailed, particularly for stratigraphic correlations. We have a remarkable field in the New Zealand Alps and it will retard progress if either the geologist engaged in reconnaissance or the specialist imagines that the other’s work is irrelevant in the total picture.

(Read, 1949: 125).

No comprehensive history of structural geology is available, but several histories of various aspects of structural geology have been published in recent years (Oldroyd, 1990, 2002; Sengör, 1990; Howarth, 1999; Dott, 2001; Sengör and Sakınç, 2001). Structural geology is about the geometry and the mechanical behaviour of rocks (Wilson, 1982) once displaced from their original horizontal depositional position, while tectonics has to do with the ‘forces and movements that have operated in a region’ (Read, 1949: 125).

Greywacke assemblages began their existence as soft layers of sand, mud, siliceous oozes and as liquid basaltic lavas that accumulated on an ancient sea floor. What forces turned these soft materials into the familiar old, hard, grey rocks? In what directions did they operate and how did they affect different kinds of rocks? How were the igneous rocks incorporated into the greywackes? How did New Zealand geologists recognise and describe the effects of these forces on the greywackes as they were folded, faulted, and crushed. Could these rocks be unfolded, unfaulted and uncrushed in the imagination in order to reconstruct the past and decipher the history of the rocks since their deposition as sediments?

The skills required for recognising certain marks in rocks as clues to various structures have been acquired in comparatively recent times. Before the mid eighteenth century, artists and naturalists rarely depicted details of structures within rock masses in landscape illustrations (Montgomery, 1996: 16). When Sydney Parkinson drew parts of the New Zealand coastline during Cook’s first voyage, he treated coastal rock masses as sculptural forms (e.g. Mercury Bay 1769), but indicated little of the internal structures within cliffs and stacks such as bedding planes, joints or faults. Nineteenth century New Zealand geologists sometimes did not perceive and respond to structural details shown in their own field sketches (p.109-111). Like the Scottish and European geologists (Oldroyd, 1990; Bailey, 1935; Trümper, 2003: 19), the settler geologists tended to be preoccupied with large-scale tectonics along with stratigraphic matters.
Figure 10.1: Map of New Zealand by A.R. Little showing structural trend lines, indicating the state of knowledge in 1951 of the geological structure of New Zealand. Little was concerned about the paucity of knowledge about the basement rocks and summarised what little was known about the trend lines (in Suess's sense). No more than half-a-dozen lines were marked representing trends of fold axes formed during the Late Cretaceous-Jurassic (Post Hokonui Orogeny). 88% original size. Modified after Little (1951). Transactions of the The Royal Society of New Zealand.
Survey geologists were still largely involved with reconnaissance mapping and their work was ‘mostly on a macroscopic scale founded on a stratigraphic approach’ (Lillie, 1961: 57).

From around 1900, geologists began to move beyond pure stratigraphy and reported structures within the greywackes and schists including bedding, folds, faults, cleavage and foliation (Chapter 6). However, after 1914, geological attention was concentrated mainly on igneous petrology and Late Cretaceous and Tertiary stratigraphy resulting in a ‘consequent dearth of information concerning the undermass’ (Lillie, 1951) (Figure 10.1).

**Mesostructures as signs in the rocks**

Structural marks in rocks are the signs by which geologists may discern geological history and processes. Structural signs may be classed on their scale or size so that a microscope is needed to see microstructures, while macrostructures range in size from around 10 metres to many kilometres in size. Mesostructures range in size from the hand specimen to several metres across.

![Figure 10.2](image-url)  
*Figure 10.2: A collage of mesostructures based on sections within Paleozoic rocks of Scotland and Cornwall. The collage illustrates mainly schistose structures but some structures e.g. boudins, are found in greywackes. Modified after Wilson (1982), Introduction to Small-Scale Geological Structures.*
Structural analysts are especially interested in mesostructures because they are large enough to be seen without the aid of microscopes, but are not too large for the ‘windows’ into the Earth provided by outcrops and cliff faces. Mesostructures such as drag folds and boudins (Figure 10.2) provide clues to:

- The existence and shape of otherwise invisible macrostructures hidden below the surface.
- Stratigraphic succession.
- The direction and magnitude of stresses that cause deformation of the rocks.
- The tectonic history of the locality.

Mesoscopic structures were rarely mentioned in New Zealand until F.J. Turner (1936) began work on schistosity and the structural petrology of schists in eastern Otago. When on a scholarship to Yale University during 1938, Turner used standard universal-stage methods to analyse the microstructure of a set of schists from east Otago under the direction of structural petrologists Professor Adolph Knopf and Mrs E.B. Knopf, and the ‘legendary’ Professor Bruno Sander of Innsbruck University. Turner (1940) drew hand specimens showing small mesostructures in the schist (Figure 10.3) but the bulk of his work was expressed as a series of ‘fabric diagrams’ (stereonets) based on the analysis of thin sections. From these he identified two Mesozoic phases of metamorphism and a strong lineation in the plane of schistosity in east Otago.

Arnold Robert Lillie (1909-1999) saw a great gap between Turner’s studies and the sweeping attempts to map macroscopic structures (such as Suess’s trend-lines). It was difficult for him to see Turner’s detailed
petrofabric work in ‘proper focus in relation to regional structural geology’. Lillie (1961: 58) held there were no short cuts to visualising macroscopic structures within the basement rocks, but that the study of mesoscopic structures would bridge that gap between the microscopic and macroscopic structures, and become standard in mapping schists and deformed greywackes.

The use of microscopic structural analyses continued in New Zealand, but geologists began to place more emphasis on field observations of the small structures that, once recognised, are readily visible in outcrops (Howarth, 1999). They developed their mental ‘search images’ (Gee, 1999: 61) for a range of mesostructures in sedimentary and low-grade metamorphic rocks (Figure 10.2). From the mid twentieth century onwards, common mesostructures were used to reveal the patterns and tectonic history of macroscopic structures such as regional folds.

Search image. It is common experience that in order to search skilfully for specific objects we must develop some kind of ‘search image’ in our minds in order to perceive them. This is because we ‘tend to see what we are trained to see’ (Schumm, 1991: 27). Experienced scientists are especially effective at data-gathering because they have developed numerous search images in their intellectual toolkits.

Knocking on the basement door: the greywackes

The use of mesostructures in the basement schists and greywackes soon showed that it was indeed possible to extract information out of these enigmatic rocks. Although no regional marker beds could be distinguished, a number of folds or portions of folds and other structures were mapped (Figure 10.4) including the ‘Rimurapa Syncline’, an ‘overturned, closely-folded, inverted syncline’, involving Wellington’s Red Rocks (Brodie, 1953). Wood figured a drag fold in beds of the Tuapeka Group (Wood, 1956:98), and a large number of small, plunging, fold structures were described in the Porirua district by Webby (1959) who tentatively suggested that some of the smaller folds were caused by gravity slumping. Most cliff-face folds turned out to have a northerly strike and dip to the west (Brothers, 1956; Halcrow, 1956; Webby, 1959; Hopgood, 1960b). Stereographic projections (stereonets) were employed to detect the presence of folds and the direction, intensity and relative age of the folding forces (Brothers, 1956), and two contrasting phases and styles of folding were distinguished (Hopgood, 1960b). Several ‘disturbed’ zones associated with cherts and pillow lavas suggested the presence of strike faults which replaced the eastern limbs of overturned, asymmetric folds causing repetition of strata (Halcrow, 1953: 25, 1956: 52, 54, 57).
Figure 10.4a: South coast of Wellington Peninsula, with structures associated with the Red Rocks. Modified after Brodie (1953). New Zealand Journal of Science and Technology

Figure 10.4b: Webby detected a large plunging fold and numerous smaller folds and faults in the Parapara District north of Wellington. Modified after Webby (1959). New Zealand Journal of Geology and Geophysics

Figure 10.4c: Coastal sections at Waiheke Island with folds and faults. Modified after Hallorow (1956). Transactions of the Royal Society of New Zealand

Figure 10.4d: Waiheke Island, with postulated strike faults. Modified after Hallorow (1956). Transactions of the Royal Society of New Zealand

Figure 10.4: Students' drawings made in the 1950s are among the first modern depictions of folds and faults in the greywackes. All about 65% original size.
Lillie of the Southern Alps

The European geologist has his distinctive rocks, quite commonly good fossils, usually good tracks and always wonderful maps to help him. In the New Zealand Alps, alas, it is very much different. We have greywackes and greywackes all very much alike, fossils are extraordinarily rare, and gaining access is generally laborious. Our topographic maps ... are not detailed enough...

(Lillie, 1963: 8)

Lillie set out to correct the lack of information about the basement rocks by combining his experience of alpine geology in Switzerland, his great love of climbing, and his companionable nature. Lillie began with a reconnaissance of the central Southern Alps in the Mount Cook region with Brian Harold Mason (b.1917). Mason was interested in tracing Turner’s petrographic metamorphic zones north from Otago and successfully extended them northward through the Southern Alps to the Taramakau River in Westland (Lillie and Mason, 1955; Mason, 1962; Mason and Nathan, 2001: 45-49).

Lillie, with co-authors, turned out a series of ten papers based on reconnaissance expeditions in the Mount Cook region, which straddled the area where prehnite-pumpellyite metagreywackes graded through the chlorite and biotite zones into garnet and oligoclase schists. The work was almost entirely exploratory with the aim of gathering as much data as possible on the structures of the greywackes and schists. The expectation was that the geometric form of the folds would be revealed, and these would be representative of the structural patterns in similar rocks elsewhere in New Zealand and in the Pacific basin.

So little geological work had been done in the Southern Alps that Lillie’s most recent geological reference were Park’s 1910 drawings of folds in the Mt Cook region (Figure 6.8, p.183) and the Hokitika and Mikonui bulletins (Bell and Fraser, 1906; Morgan, 1908). The only other recent work was that by Wellman and colleagues at Harpers Pass (Wellman et al., 1952), nearly 200 kilometres to the north (p.318). From then on until approaching retirement in 1974, Lillie was deeply involved in mapping structures in the basement greywackes and schists. The bare rock faces in the mountains provided views of large fold structures that had rarely been seen in the past, like the spectacular syncline on the western face of Häckel Peak (to the south-west of Mt Cook, Figure 12.8, p.352) (Waterhouse, 1955, 1966).1

The reconnaissance surveys confirmed that in the Mount Cook region, greywackes and schists are folded more or less parallel with the main alpine chain, with strike between N30°E and 45°E (Lillie, 1961: 69,

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Chapter Ten

Figure 10.5a (left): Geological sections through the Dent du Midi. Diagram used by A.R. Lillie to explain the geology of the European Alps to climbers, and to explain some of the structural differences between them and the Central Alps of New Zealand where most of the beds dip steeply. 45% original size. Modified after Lillie (1963) The New Zealand Alpine Journal.

Figure 10.5b: Cliff face of Dent de Morcles showing contact of the Dent de Morcles Nappe, along slice of pre-Triassic crystalline rocks, with highly disturbed autochthon. After photo by R. Lugeon, in Collet, 1927. Fl., Flysch; Nu., Nummulitic; Cr., Cretaceous; Ju., Jurassic; Tr., Trias. Bailey50.tif

Figure 10.5c: Sections through the Sealy Range overlooking the Hermitage at Mt Cook, indicating the very large plunging folds, strike faults, and the pervasive steep dips characteristic of the Southern Alps. 76% original size. Modified after Lillie and Gunn (1964). New Zealand Journal of Geology and Geophysics.

Figure 10.5: A comparison between recumbent nappes of the European Alps and the steeply plunging folds of the Southern Alps. Swiss geologists follow the strata with field glasses from the valley side. New Zealand geologists must physically traverse the ridges. Lillie drew no more cross sections after the Sealy Range set because they could not adequately show the steep plunge of the folds. Instead, he turned to structural and form-line maps, Figures 10.7, 10.8, 10.9 (K.B. Spörli, pers. comm.).
1964: 173), and strata dipping steeply at rarely less than 60°, often to the west (Figure 10.5c, 10.7). The lack of distinctive marker beds meant that initially, no ‘coherent stratigraphic sequence could be constructed’ (Lillie et al., 1957), let alone determine sequence and structure over a large distance (Lillie, 1962: 256). Structural maps were constructed using:

- Data from lithological features such as graded bedding and micro-current bedding. These indicate tops and bottoms of the strata, or way-up, and thus the direction of younging.
- Mesostructures such as drag folds that indicate the direction and attitude of very much larger structures (for example Figure 10.6).
- Distant views of rock faces, being aware of the ‘tricks of the trade’ of how to read them because they may mislead if strata plunge or rise away from the rock face (Lillie, 1963: 12-13).
- Both ground and air photographs to support the mass of field observations.

![Diagram of major fold axes](image)

In a study of the Alpine schists in the Franz Joseph and Fox Glacier region, B.M. Gunn (1960) illustrated criteria by which the superposition of beds could be determined, and the presence of very large folds revealed. In each case the anticline axis is to the right, and the folds have not been overturned.

Lillie (1961: 59, 80) made two major structural discoveries: (1) the greywackes and schists have been compressed into very large, steeply plunging folds, and (2) wrench or transcurrent faulting is
Figure 10.7: Lillie's structural stereogram, a "very imaginative synthetic diagram of the inferred structures as they would appear on a horizontal plane surface 5,000 ft above sea level" (p. 404). The extremely steep plunge of the large folds is not easy to show on ordinary sections, but is readily expressed in this diagram, along with the numerous large faults, and explains why attempts to map greywackes by orthodox stratigraphic methods have been fraught with difficulties. Original size. After Lillie (1964). New Zealand Journal of Geology and Geophysics.
prevalent and folding with a wrench component appears to have been established early. The large folds plunge very steeply, sometimes as though the axes have been rotated more than 90 degrees from horizontal (Figure 10.7) (Lillie, 1964: 173). The folding is so complex that exploring scientists at times disagreed as to whether some of these large folds are anticlines or synclines. The very steep plunges meant that some antiformal folds looked like synclines, while synformal folds looked like anticlines, as discussed by J.B.Waterhouse (1966: 186, 1972). If the strata in the cores of these folds can be examined (with field glasses or by climbing up to them) and way-up determined, then their true attitude can be determined because older cores mean antiforms, and younger cores mean synforms (Lillie, 1963: 11).

These plunging folds are so large that Lillie traced one fold through 2,000 metres of strata and another that was followed for over 5 kilometres. Some years later a fold in the Ben Ohau Range with a wavelength of 10 km was traced on a form-line map over a distance of 36 km (Ward and Sporli, 1978). Lillie cited work done elsewhere in New Zealand that supported this view, including that of V.R.McGregor at the Godley Valley 40 km to the north-west of Mt Cook (McGregor, 1963), as well as Brodie (1953), Brothers (1960), Hopgood (1960) and Webby (1959). Lillie believed that large folds with horizontal axes were formed first, and the steep plunges were caused by ‘lateral dragging’ of structures along the fold belt (Lillie, 1963: 13) with more intense deformation and the later development of further folds with steep axes (Lillie, 1961: 73; 1964: 175).

Lillie’s second major discovery was the predominance of dextral wrench faulting throughout the region along faults striking nearly north-east, and with a strong strike-slip or transcurrent displacement to the right. Previously, most faulting had been described in terms of throw because it is readily measurable, although Lillie (1961: 59) thought that ‘hybrid faults’ with both horizontal and vertical displacement existed. Thus, the rock mass west of the Alpine Fault moved dextrally ((Lillie, 1963: 14) in relation to the schistose rocks east of the fault and was thrust under them, while the schists on the eastern edge were thrust over the western rocks.

It was generally accepted that deformation of the greywackes took place during the Lower Cretaceous Rangitata orogeny (Kingma, 1959), previously known as the ‘Post-Hokonui Orogeny’. However, Lillie (1964: 178-9) was sceptical of the common belief that the greywacke basement was generally passive during Tertiary movements and he raised the possibility that folding begun in the Rangitata orogeny may have continued to develop ‘quite intricately’ later on. He was aware that wrench faulting is prevalent in the Quaternary tectonic pattern, and continues to the present day (Wellman, 1955b), but believed that folding with a large wrench factor was established early during the evolution of the greywackes (Lillie, 1961: 80). Lillie was enormously successful at gathering a vast amount of data. His papers trace an increasing ability to recognise mesostructures in the field, a growing inventory of real knowledge
about the rocks, and increasing confidence and ability in the interpretation of the collected data. Inferences regarding local sub-surface structure were drawn, and tentatively, some views on tectonic history were advanced. Lillie was ever cautious about going too far into theoretical constructions without good reason but did venture to suggest that the schistose strata had been crumpled by compression perpendicular to the trend of the Alpine Range (Lillie, 1960).

Throughout his Southern Alps series, Lillie made generous use of visual material with numerous photographs showing lithologic characteristics, panoramic mountainscapes, large cliff-face folds, and various mesostructures. He was admired for his ability to visualise three dimensional subsurface structures and this skill was put to good use in drawing sets of longitudinal and cross sections of ranges in the Central Alpine Region (Figure 10.5c). These visual contributions culminated in 1964 with Lillie’s famous structural stereogram representing the interior of the Sealy Range, showing complex plunging folds sliced into blocks by numerous steeply dipping faults (Figure 10.7).

Form-line maps

![Form-line map](image)

Figure 10.9: Tectonic profile of southern part of Cook range. An early attempt to express structural patterns in the Southern Alps. After Lillie (1961). Proceedings of the Royal Society of New Zealand

Lillie began experimenting with form-line maps (Figure 10.9). These are similar to the ‘tectonic profiles’ drawn normal to the regional fold axes described by Weiss (1958: 135-137). Lillie (1961) began
Figure 10.10: Crushed and contorted green argillites marking a fault zone within greywackes and argillites at Waiheke Island. Drawing is based on a sketch made by the author in 1953. Also indicated on coastal section Figure 10.4c.

Figure 10.11: Slab of crushed and refolded green argillite from the fault zone shown above. This argillite surrounds numerous boudins and fragments of sandstone. The un-named radiolarians shown in Figure 9.9b were found in this rock. About 2X original size. Photograph: R.L.Bieleski 1952.
drawing his own tectonic profiles following Weiss’s geometrical method in which ‘no speculation is used in its construction’. Geological form-lines are not topographical or structural contours, and unlike traditional geological maps, form-line maps are not made to indicate the locations and boundaries of lithotypes or formations (Figures 10.8, 10.9). They indicate the outcrops of specific, identifiable marker beds only when suitable beds are present. The maps are expected to give geologists a virtual threedimensional impression of the general grain and texture of the geological structure of a region. Form-line maps are something like imaginary horizontal sections or a CAT scan cut through the mapped area, and in the Southern Alps, the plunge is so steep that the map view is nearly normal to the regional fold axes and little or no correction need be made for dip (Lillie, 1961: 82).

Lillie’s reconnaissances successfully confirmed that the greywackes were mappable even if they defied traditional stratigraphical methods. The major aim was always to work out the geometry of the structures, rather than be too concerned about the processes that created the great, plunging folds. Faced with the considerable complexity of the rocks and the sheer volumes to be mapped, growing questions about the not-so-monotonous petrography, together with an unhelpful geosynclinal paradigm, Lillie wisely refrained from making too many pronouncements about the structural geology of the greywackes before he was ready.

**Faults, breccias and schists: some mid-twentieth century reports**

Throughout the first half of the twentieth century, there was as little analysis of faulting as of folding in the greywackes. The emphasis was on stratigraphy (Lillie, 1951: 219) and the greywackes mapped as ‘undermass’ were often described simply as ‘much shattered and folded’ (Turner and Bartrum, 1928) with an ‘intricate structure’ (Ferrar, 1934: 25). Towards the middle of the twentieth century, geologists began to notice a range of structurally deformed zones within the greywackes. Ferrar mapped a narrow ‘schistose belt’ on the east coast of Kapiti Island (Ferrar, 1928), and this was revisited by Fleming and C.O.Hutton in 1949. The belt was then described as forming a linear zone of ‘phylionites’ about 30 chains wide (600m.), with a sharp, clean contact between it and the surrounding quartzo-feldspathic greywackes. The ‘schistose rocks’ were thought by Hutton to result from ‘intense cataclastic metamorphism’ of the greywackes, should be classified as ‘phyllite-mylonites or phyllonites’, and were not homologous with the schists of Marlborough and Otago.

Bands of cherts and lavas about 1.5 km to 4 km apart at Waiheke Island (Figure 10.4d) seemed to coincide with zones of deformation marked by close folding, boudinage, slickensides and many quartz veins, and suggested the presence of strike faults (p.297) causing much repetition of strata and over-estimation of the thickness of the greywackes (Halcrow, 1956: 54, 57). Such faults are often not readily detected, but are sometimes marked by crushed, closely crumpled and contorted green argillites with slickensiding.
including sandstone boudins (Figure 10.10). Similar ‘crush zones’ were described at Kawau Island and Tawharanui Peninsula north of Auckland, with ‘zones of parallel planes separated by layers of brecciated sandstone cemented by secondary quartz and chlorite’ (Hopgood, 1960a). The copper ores at the historical mine site at Kawau Island occur in a 2m to 5m wide crush zone adjacent to a parallel belt of banded jasperoid cherts. Similar lodes linked with cherts and jaspers are located in crush zones (Lillie, 1953) at the copper mine sites at Great Barrier Island and at Maharahara (east Rimutaka Range).

![Map showing structural interpretation of the Torlesse Supergroup near Hawarden, between the Hurunui River and the North Branch of the Waipara River, North Canterbury. Modified after Bradshaw (1972). New Zealand Journal of Geology and Geophysics.](image)

Figure 10.12: Map showing structural interpretation of the Torlesse Supergroup near Hawarden in North Canterbury. The fine dashed lines represent bedding plane trends. The tectonic slides lie on or close to the bedding planes and are about 5 km apart. Three major mappable hinges are shown marked Ha F, Hu F, THF. The area is about 10 km across.

Later studies of the structure of Torlesse Supergroup rocks led to the recognition of ‘tectonic slides’ (Bradshaw, 1972:79) in greywackes near Hawarden in North Canterbury. Such tectonic slides lay close to or on bedding planes (Figure 10.12) and Bradshaw believed they were developed at an early stage of deformation when the rocks are still plastic. The movement plane was not easy to see and often detected by stratigraphic rather than structural criteria. In places, these tectonic slides passed into autoclastic breccias. Soon after, a number of similar tectonic slides associated with recumbent tight-to-isoclinal folds...
were recorded in the Lord Range in the central Southern Alps (Andrews et al., 1974: 290). Here, the tectonic slides, which also seem to have had an early tectonic origin, appeared to have excised the lower limb of isoclinal folds (Figure 12.9).

**Autoclastic breccias**

In Wellington, Reed identified zones where a characteristic argillaceous matrix consisting of recrystallised fragments of greywacke, green lava, and chert ‘flowed’ around fragments of various rock types, as ‘autoclastic breccias’ (Reed, 1957b: 31-4, 1957a) because of their resemblance to those described by Greenly in Anglesey (Greenly, 1919: 65,193, 306). Reed did not use Greenly’s term, ‘melange’ and compared a second, rarer, type of disturbed rock consisting of coarse quartzose pebbles in an argillaceous matrix with Greenly’s ‘pseudo-conglomerates’. These Reed called ‘pseudo-tillites’ (Pettijohn, 1950) because of their texture, and he attributed them to submarine mudflows connected with turbidity currents. Later, Reed (1964) produced a well-illustrated comprehensive study of the volumes and variety of fault rocks along the Alpine fault.

While Reed (1957b: 32) saw the Wellington autoclastic breccias as having a tectonic origin’, John Bradley (1963) of Victoria University College, regarded all large scale breccias, or ‘megabreccias’, very differently, being caused by ‘gravitational sliding following uplift’ rather than ‘diastrophic cataclysm’. Bradley regarded all structures that had been described as ‘mélange’, ‘chaos’, and ‘olistostrome’ as megabreccias, and attempts at mapping them in ‘simple structural terms’ were ‘irresolvable’. After reviewing numerous descriptions of megabreccias, Bradley pronounced them all to be ‘collapse or sliding structures’ caused by plastic flow of material, often from the upthrow to the downthrow side of a large fault, to form a ‘chaos’. The whole idea was taken even further (1963: K4) with the suggestion that the structure of the Southern Alps is really a huge ‘chaos’ on a ‘mountainous scale’.

**Okuku and Esk Head ‘chaotic’ limestones**

In 1954, J.D.Campbell and G.Warren (1955) relocated McKay’s Triassic fossil site at Okuku in North Canterbury (McKay, 1877, 1881), which had been ‘mislaid’ for some years. Rather than the neatly bedded limestones indicated by McKay (Figure 4.10, p.80) the rediscoverers found several large limestone masses composed of *Monotis* shells with associated vesicular basalt interbedded in siltstone-sandstone boudinage beds. When Warren (1955) set out to stratigraphically map the Okuku district he found a ‘great many small-scale structural and lithological complexities’, and in places, ‘the chaotic nature [of the rocks] foiled all attempts to gain an indication of the strike’.

Some years’ later, the limestones at Okuku and Esk Head were described as part of ‘vast chaotic breccia bodies’ by Bradshaw (1971). Bradshaw described a northwest trending belt about 8 km wide and 40 km
long consisting of mudstone, sandstone, pillow lavas, bedded chert, limestones and roundstone conglomerates with fragments from 0.5 cm to 100 m in length (also see Bradshaw, 1972). Perhaps the belt was formed by olistostromal submarine sliding, but because of strong shearing the belt was more like a tectonic mélange. Bradshaw (1972: 81) compared similar structures further north, near Hawarden, with Reed’s autoclastic breccias and established that similar ‘chaotic terrains’ containing ‘allochthonous’ fossiliferous limestone blocks, form a broad belt through North Canterbury. Bradshaw (1973) proposed the name ‘Esk Head Melange’ for this belt, which he saw as geotectonically significant ‘in terms of the evolution of the New Zealand Geosyncline’.

There was no known mechanism that could account for these extensive deformed zones in the greywackes, except that somehow or other, the rocks had indeed been deformed, sheared, broken, and sometimes metamorphosed. It had to be assumed that some kind of mysterious force had been applied, probably when the eugeosynclinal sediments were folded and uplifted.

**Greywackes into Schists - how?**

[T]he Haast Schist Group of greenschist ... and amphibolite schist ... represent one of the world’s best examples of regional-low-temperature-high-pressure metamorphism. They are the field laboratory from which Turner (1938, 1948), Hutton (1940) and Coombs (1950, 1954) and others gained their experience and philosophies of metamorphic petrology.

(Fleming, 1969: 131).

Where do greywackes stop and schists begin? When they grade ‘insensibly’ into each other (for example Lillie and Mason, 1955: 1125)? The re-discovery of the Triassic fossil, *Monotis*, by three Geological Survey geologists in sub-schists near Harpers Pass in North Canterbury at last put a definite Triassic age to at least some of the Alpine schists (Wellman et al., 1952), and showed beyond doubt that the Alpine schists were continuous with the Canterbury greywackes. The geologists confirmed that metamorphism of these rocks increased progressively towards the Alpine Fault, and their metamorphic zones correlated with those of Turner and Hutton in north-west Otago (1936).

**The age and cause of metamorphism**

An earlier theory that the schists were Paleozoic sediments metamorphosed in a pre-Triassic orogeny was now discarded (Mason, 1962: 241). Before the use of radiometric analyses, the age of metamorphism had to be inferred indirectly (Figure 4.17 p.94-96, 191-196), usually by locating pebbles of schist in datable younger sedimentary rocks. Pebbles of schist found in an upper Jurassic formation in Otago (Williamson, 1939) and at Kawkia (MacDonald, 1954), turned out to be similar to the lower Paleozoic rocks of Westland, and unlike those of the Otago-Marlborough schist belt (Reed, 1958b: 54). No pebbles of true Alpine schist appeared until the beginning of the Pleistocene period in gravels in Westland (Morgan, 1908; Wellman, 1955a), long after any Mesozoic orogeny. Most geologists agreed that metamorphism
accompanied the supposed Upper Jurassic - Lower Cretaceous Rangitata orogeny (Reed, 1958b: 54; Kingma, 1959: 5,29), and this was supported by the radiometric analysis of uranothorite from a pebble of schist from South Westland which yielded an age of 119 m.y., corresponding to a Lower Cretaceous age (Hutton, 1950: 677).

Samples of biotite schist and gneiss collected from near the Alpine Fault were radiometrically dated in the United States by the potassium-argon or K-Ar method with startling results, yielding very young ages of metamorphism between four and eight million years (Mason, 1961a, 1961b). On the other hand, samples of low-grade Haast schist from the east Otago coast yielded the expected Lower Cretaceous ages of 133 and 141 m.y. (Harper and Landis, 1967: 122). Generally, the closer to the Alpine Fault, the higher the textural grade, and the lesser the K-Ar age. The very young K-Ar ages close to the Alpine Fault were deemed to be caused by the loss of radiogenic argon gas. So long as the rocks were deep enough to be held at a temperature of 300°C or more, the argon gas would diffuse away and be lost (Mason, 1962). The once deeply-buried high grade schists began to retain 40Ar only in Pliocene times as they were uplifted against the Alpine Fault and cooled. At the same time, the low-grade schists some distance away from the fault recorded a cooling age much closer to the age of an ‘Early Cretaceous metamorphic climax’ (Harper and Landis, 1967:422).

The cause of progressive metamorphism in which sediments were turned into greywackes and then schists remained a puzzle. The theory that progressive regional metamorphism was caused by a subjacent batholith was set aside (Reed, 1958b: 56; Mason, 1962: 244), but Wellman’s earlier experience with the use of coal rank to indicate depth of burial (Wellman, 1947, 1952a; Fleming, 1969: 136) made him a strong proponent of load metamorphism. In this case, metamorphism was supposed to be caused by very deep burial under thick geosynclinal sediments (as in Figure 7.4, p.219). Colleagues supported the idea of load or burial metamorphism in which high-stress, low-temperature metamorphism of the schists was governed by: load, horizontal stress at right angles to the geosyncline and the geothermal gradient (Grindley et al., 1959: 71). Very great thicknesses of geosynclinal sediments were estimated (Fleming 1969: 145), but little account had been taken of the possibility of repetition of strata (p.297, 305) by strike faulting (Halcrow, 1956; Grindley et al., 1959) or by isoclinal folding (Lillie et al., 1957).

Mason (1962: 244) thought metamorphism was caused by deep burial, but not by the simple accumulation of a great mass of sediments. He ascribed deep burial to ‘tectonic thickening’ that is, compression of the geosyncline and piling up of isoclinally folded beds, making estimates of stratigraphic thickness by measuring across planes of schistosity quite ‘illusory’. Lillie (1964: 175) also preferred that strong metamorphism should be ’attributed entirely to the effects of tectonics’ rather than a large overburden and suggested that the main schist mass had been uplifted, and thrust over rocks both west and
Chapter Ten

Figure 10.13: Disposition of the greywackes and schists in the South Island as interpreted prior to 1970. The greywackes are visualised as layered above increasingly metamorphosed schists down below. The implication is that simple passive burial metamorphism has taken place, although the word "climax" implies an active process. Suggate's diagram (above left) indicates how the schists were uplifted along the Alpine Fault to form the Southern Alps. Both diagrams 85% original size.
east of it. Reed (1958b: 55-57), calculated a minimum depth at which metamorphism would take place as 50,000 ft (15 km) but cautiously favoured Turner’s evidence (1938, 1940) for ‘directed pressure’ in which greywackes were ‘reduced to a phyllonitic condition’.

The concept of load metamorphism seems to have been tacitly accepted by many members of the geological community, but most writers continued to carefully skirt round the cause of metamorphism while describing its effects (Landis and Coombs, 1967). Diagrams by Suggate (1963) and Landis and Coombs (1967) show the greywackes layered over a foundation of schists, with the latter exposed by rapid faulted uplift during the late Tertiary Kaikoura Orogeny (Figure 6.6, p.181, Figure 10.13). Suggate’s concept of the way in which the Southern Alps evolved has since been generally accepted and developed by a number of writers (for example Wellman, 1979; Cox, 1995; Coates, 2002). If simple, vertical pressure caused metamorphism, then the planes of schistosity should be parallel to the bedding planes, but a consistently simple relationship between stratigraphic depth and metamorphic grade could not be shown (Lillie et al., 1957). Moreover, the apparent age and degree of metamorphism did not always match.

Perhaps the strongest arguments against stratigraphic load as a cause of metamorphism came from Ph.D. student Peter Robinson2 (1958: 140-142) because of a lack of parallelism between schistosity and metamorphic zones. In contrast to the depths of 50,000 to 250,000 ft (15 km-76 km) postulated by Wellman and Grindley, Robinson’s schists along the east Otago coast graded from Chlorite 1 to Biotite but were only 7,000 to 9,000 ft thick (2,150-2,700m), not deep enough for load metamorphism. According to Robinson, cataclasis and differential stress played a major role in regional metamorphism, and regional metamorphism in Otago was ‘clearly the result of orogeny and not merely deep burial in a sedimentary sequence’ (1958: 142). Obviously, the identification of the cause of metamorphism, whether by simple load or ‘directed pressure’ by some unknown force, still had numerous ‘problems … to be elucidated’ (Reed, 1958a).

**The North Island and the Kaimanawa schist mystery**

Does schist similar to that in Otago exist in the North Island? The catalogue of rock specimens issued by the Colonial Museum in 1870 lists ‘Paleozoic schist’ from Whangarei, and ‘Schist’ from the Kaimanawa Range without explanations (Hector, 1870: 145, 149). Perhaps Hector had these specimens in mind when he claimed that schist was currently being formed deep beneath the North Island (Hector, 1869). Little more was heard of these schists for sixty years and even McKay (1901) said nothing about them in his report on the Kaimanawa Range.

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2 From the U.S.A., studied for his Ph.D. under Professor D.S.Coombs at Otago.
In a review of the metamorphic rocks of New Zealand, Benson (1929: 65) only remarked cryptically that ‘a much smaller amount of rock-metamorphism’ has been noted in the North Island because of the absence of exposed areas of Palaeozoic sediments. The first firm report of schist in the North Island appears to be that by Leslie Isott Grange (1894-1980) (1937: 56). Grange briefly mentioned that in the Kaimanawa Range ‘there are bands of subschistose rocks in the greywacke which possibly indicates a Palaeozoic age for a part of the range’.

In their discussions of regional structures, neither Macpherson (1946) nor Fleming and Hutton (1949) refer to any North Island schist. Wellman’s first structural map of New Zealand (1952b) shows a ‘Schist Axis’ curving through Otago until cut off by the Alpine Fault (Figure 7.10, p.226), and, while the ‘schist axis is a major structural feature in the South Island ... schist is not known from the North Island’. Grindley rediscovered Grange’s ‘subschistose rocks’ in the Kaimanawas, and recorded a metamorphic anticline with a gently northward plunging axis (reported by Gregg, 1960: 28). Wellman’s second structural map (1956: 21), probably based on Grindley’s information, features the Schist Axis continuing north-east from Marlborough Sounds to the Kaimanawa Range with ‘the least known area of greywacke in New Zealand’ where sub-schist rank was reached in the north-west, indicating a ‘greater age’ for the greywackes in that region (Figure 7.11, p.228).

On the 1958 geological map of New Zealand (Grindley et al., 1958), a north-east striking sliver of chlorite zone schist is shown penetrating the Kaimanawa Range from opposite Rangipo Desert on the slopes of Ruapehu. This, and the Otago, Alpine and Marlborough schists, were described in the accompanying bulletin (Grindley et al., 1959: 71) as ‘high-stress, low temperature’ metamorphic rock formed at the time of deepest burial in the New Zealand Geosyncline. The Kaimanawa schist was later described on the Taupo sheet of the 1:250,000 series (Grindley, 1960) as a low-grade pelitic schist and schistose conglomerate of, perhaps, Permian or Triassic age, flanked by younger complexly folded sub-schistose greywackes and argillites with quartz veins (also shown Figure 8.2, p.246).

The concept of a schist axis was carried through in Grindley’s 1961 paleogeographic maps (Grindley, 1957), followed by a detailed description of lithology and structure in The Geology of New Zealand (Grindley, 1978: 306-7). Compared with South Island rocks, the Kaimanawa schist shows ‘greater small-scale deformation of cataclastic type’. Grindley now considered that the cataclastic deformation was younger than the regional metamorphism and that the Kaimanawa rocks were comparable with the phyllonites at Kapiti Island (p.315). Could they then be considered part of the schist axis and a northward extension of the southern schists?
**The old global tectonics and unsolved mysteries of the greywackes**

By the end of the 1960s, survey and university geologists and their students had accumulated a very great deal of data about the greywackes and schists. Quantities of information about the general configuration of the strata had been collected, plotted on stereonets and macrostructures inferred. Experienced geologists made conjectures as to how many orogenic phases their rocks had endured, in what direction and order deformational events had taken place, and traced in detail the structural and metamorphic changes that had occurred as sediments were turned into greywackes and then transformed into schists.

At the same time, a very great deal of knowledge about the chemistry and physics of the structural and metamorphic change had been acquired.

Only appeals to vaguely defined ‘compressive forces’ normal to the major strike axes could be made to account for these changes, and the cause of compression could not be imagined. Geologists simply stated that the New Zealand Geosyncline began to ‘evert’ in the middle Jurassic, and that the process culminated in the Early Cretaceous Rangitata Orogeny. Since the collapse of Suess’s global theories fifty years’ earlier, geologists were still without a credible theory to explain the causes of folding and uplift and the formation of mountains. The geologists continued to follow Chamberlin’s sensible advice of 1909 not to be too concerned about the causes of diastrophism, but continue to investigate its effects (p.179) and take it for granted that they could describe and infer, but explain very little in global terms (but help was at hand).
Chapter Eleven

Making Mountains out of Models

It is evident that the andesite line which is the structural Pacific margin is not merely one of steep slopes, and of active volcanoes, and pronounced rock folding, but also of [earthquake] disturbances originating deep within the crust of the earth.

(Marshall, 1946).

[F]ascinating corroborative detail is coming to hand, almost monthly, and there is now a widespread belief a new synthesizing theory for global tectonics has been established. The testing of its consequences will make an exciting start to the next hundred years.

(Coombs, 1969).

Since the collapse of Suess's contractionist global theory early in the twentieth century (p.177), New Zealand geologists, like others, had worked without an effective over-arching theory of the earth. In contrast, biologists were guided by the theory of evolution and chemists by atomic theory. By 1950, the branches of geological science had become so specialised they had grown into virtually separate sciences (Marshall, 1946: 1; Greene, 1982: 275). Although paleontologists and stratigraphers shared some common ground (as it were), they had little to do with igneous and metamorphic petrographers, and had nothing in common with the seismologists and other geophysicists. Mid-twentieth century students of geology did not see their various specialties as aspects of a single entity operating under a unifying theory. In effect, each specialty had created its own paradigm (Engelhardt and Zimmermann, 1988: ix-x), so that geology had become a multiparadigmatic science (Masterman, 1970). ‘[A]bout the only common element for such a hotchpotch of views [was] a belief in a ‘stabilist’ rather than a “‘mobilist’” earth, that the continents have remained fixed in position with respect to each other’ (Hallam, 1973: 107-8).

Most New Zealand geologists assumed that the continents and ocean basins were permanent (for example Marshall, 1946). Although there was sympathy (especially among biologists, and Benson, 1924: 111) towards continental drift as proposed by Wegener (1924), there was, regrettably, no generally accepted mechanism to drive it. The quite plausible mechanism advanced by D.Griggs (1939), and Arthur Holmes (1944) were ignored especially in North America. This no-mechanism argument was put forward despite the fact that, except for Holmes’s convection cycles (1944: 406-413), there was also no mechanism supplied for the recurring diastrophic cycles (Chapter 6) and the periodic, if mysterious, orogenic upheaving of geosynclinal sediments to form mountain ranges, Students learned how faults,
Chapter Eleven

Fig. 11.1a. Left: The subcrustal structure in the New Zealand region from seismic data. Hayes suggested that New Zealand lay near a region of crustal change between continental and oceanic crust. Modified after R.C. Hayes, 1943. *Bulletin Seismological Society of America*

Fig. 11.1b. Above: The structure of New Zealand from seismic evidence. A difference in crustal structure on each side of the "Sub-Crustal Rift" was detected, that on the north-east side being similar to continental crust. Modified after G.A. Elby, 1958. *Geologischen Rundschau*

Figure 11.1: Much geophysical data about the Earth's crust in the New Zealand region was collected by seismologists. Deep focus earthquakes were shown to be confined within a "Sub-Crustal Rift" (Elby, 1958), which extended to the Kermadec Trench. There was no evidence of an arcuate structure.
folds and uplifted coral reefs were evidence of earth movements having taken place (Holmes, 1944; Gilluly et al., 1957), but no explanations were made (or expected) except for discussions of isostasy. Thus, the idea of periodic orogenic uplift was widely accepted and rarely disputed, while the concept of lateral motion was rejected (even in New Zealand). It was as though the most important role for orogenic episodes was to stratigraphically delineate major geological eras (for example Holmes, 1944: 108-9).

In New Zealand, ‘the deformation that followed the long Trias-uppermost Jurassic period of deposition’ was said to be ‘one of the most critical episodes in the history of the New Zealand area’ (Bartram, 1939), but the lack of an explanation for such an episode was taken for granted and hardly ever scrutinised. New Zealand geologists also followed Chamberlin’s (1909: 685) counsel that it was immaterial to know what caused periodic mountain-building episodes ‘provided we agree as to the general nature of their effects on the agencies at work on the surface of the lithosphere’ (p.179, 323). Geologists were encouraged to get on with data collection in the meantime and geology ‘functioned without a universally accepted theoretical framework for decades thereafter’ (Greene, 1982: 290).

The elaboration of geosynclinal theory in the 1950s by Kay (1951; Dott, 1974) and the creation of the New Zealand Geosyncline (Wellman, 1952, 1956) provided workable and welcome explanations for the existence of the belts of different but coeval Upper Paleozoic and Mesozoic Hokonui and Alpine facies (Chapter 8). However, among other failings, the New Zealand Geosyncline could not explain or provide the forces needed to deform and lift the deep sediments to make mountains, and the ‘causes of horizontal compression were simply neglected’ (Stewart, 1990: 60). Whatever the shortcomings of geosynclinal theory, geologists had no better explanation for deformation in tracts of folded rocks.

The New Zealand Geosyncline was not fully developed and elaborated until the 1950s just when paleomagnetic studies on land were leading to new ideas about polar wandering and continental drift (Le Grand, 1988: 138ff). Post-war geophysical and oceanographic researchers using geomagnetic, gravimetric, seismic, and bathymetric methods made a number of unexpected and interesting discoveries about magnetic patterns and the topography of the ocean floor (Oldroyd, 1996:261ff.). Here in New Zealand, seismologists (Hayes, 1943; Eiby, 1958; Galbreath, 1998: 228ff) were already aware of a pattern of deep-focus earthquakes that dipped to the west beneath the North Island (Figure 11.1). This was interpreted by leading geologists (for example Macpherson, 1946) as underthrusting of New Zealand by the Pacific Ocean floor (p.185) but it did not suggest continental drift to the geologists (Galbreath, 1998: 229).
Figure 11.2: Nested theories. The theory of plate tectonics is a complex construction based on very large amounts of empirical data linked by a network of hypotheses of different levels. Geoscientific hypotheses and theories ‘encompass a wealth of empirical facts and are the most concentrated form of all forms of geoscientific knowledge’ (Engelhardt and Zimmermann, 1988: 233). Theories constitute ‘approximative’ models of reality. Modified after Engelhardt & Zimmermann (1988), Theory of Earth Science, p.242.
The new global tectonics

[1]n the 1950s .... We suddenly had available a flood of money, ships, facilities, equipment, and students. Nature provided the only other thing necessary for happy science, namely an abundance of unknown problems which we could solve with the new instruments and techniques.

(Menard, 1979)

The enthralling story of how ‘the new global tectonics’ (Isacks et al., 1968) developed since Alfred Wegener first published his theory of continental drift in 1912 has been recounted many times by historians, philosophers, sociologists and by the scientists themselves (for example Hallam, 1973, 1989; Menard, 1986; Le Grand, 1988; Stewart, 1990). In New Zealand, Graeme Stevens’ boldly illustrated *New Zealand Adrift* (1980) explains plate tectonic theory and the geological history of this country to the general reader.

The advent of plate tectonic theory provided a comprehensive and cohesive theoretical framework in which geologists could find many possibilities for novel solutions to old problems. Old data could be reinterpreted and new data discovered in the light of the completely new view of the behaviour of the Earth’s crust. Among other tasks, geologists could begin developing a more or less reasonable geological history of the New Zealand greywackes.

Plate tectonic theory may be characterised as a ‘system of propositions bringing together the two partial hypotheses of continental drift and sea-floor spreading’ (Engelhardt and Zimmermann, 1988: 247). It constitutes an over-arching general theory incorporating a strong, stable, complex network of nested theories, hypotheses and empirical data (Figure 11.2). Models of sea-floor spreading, transform faults, subduction, and the later addition of accretionary prisms, involve reliable knowledge (Ziman, 1978) solidly based on large amounts of empirical evidence and supporting interlinked hypotheses. Together, the theoretical system forms a complex construction consisting of numerous structural interconnections between different levels. The plate tectonic model is not a monolithic theory that can be proved or disproved by one or two crucial experiments or observations, like James Hutton’s unconformity at Siccar Point (Playfair, 1802). Each constituent hypothesis can be modified with little or no disturbance to the prime theory. New data has not (as yet) caused the collapse of the model. Indeed, apparent empirical discrepancies and anomalies may provide further research opportunities.

Unlike Suess’s grand synthesis (Chapter 6) and Carey’s inventive tectonic system (1958), plate tectonic theory was not created by a lone genius. The initial, tentative hypotheses grew out of straightforward exploratory data collection carried out in a period of post-war scientific expansion, with contributions from many scientists working in different specialties. The grand assembly into a global theory, made by
a few gifted scientists, was completed before 1970. As avant-garde geologists explored this exhilarating new ‘working hypothesis’ (Dickinson, 1970), they speculated on its implications for land geology. Many of their predictions and hypotheses were of special interest to land geologists concerned with the origin and structure of mountain belts and ‘eugeosynclinal’ assemblages like those of the New Zealand greywackes. Some of the explanatory possibilities of the new paradigm related to:

- The ‘eugeosyncline’, which no longer referred to an elongated trough, but to oceanic, crustal and sedimentary materials carried on moving plates (Hsü, 1971).
- The tectonic settings of eugeosynclinal sequences including greywackes, cherts, pillow lavas, and mélanges.
- The relationship between orogenic belts and the elongate junctions between converging plates of lithosphere, now referred to as ‘convergent margins’.
- The association between oceanic trenches, metamorphic belts, inclined seismic zones (Benioff-Wadati zones, subduction zones), and volcanic arcs.
- The processes leading to the formation of jumbled mélanges of turbidites, sea-floor pillow lavas and cherts (Hamilton, 1969).
- The processes by which ‘ophiolite’ complexes representing the surface skin of ancient sea-floor plates, were generated at the mid-ocean ridges, then transported laterally and incorporated into continental margins during orogeny (Dickinson, 1970).
- The cause of orogenic or mountain-building episodes in which sea-floor spreading and subduction resulted in collisions between continents, or between continents and island arcs (Dewey and Bird, 1970).
- The possibility that continental margins may contain fragments of other continents (Wilson, 1968b: 316)

**How was all this accepted in New Zealand?**

Before 1960, Wegener’s continental drift theory was strongly supported by several Southern Hemisphere geologists (Menard, 1979: 21; Stewart, 1990: 60) including Samuel Warren Carey (1912-2002) of Tasmania who was the most outspoken of the proponents of drift (Carey, 1955, 1958, 1988). Among those New Zealand geologists and biologists associated with New Zealand who rather hoped that the Wegener-Holmes-Du Toit model of continental drift (Wegener, 1924; Du Toit, 1937) was true, were several outright convinced believers, prepared to proselytise. These included Lester Charles King and John Bradley.
Lester King (1907-1989) was educated at Victoria University College where he lectured from 1930 to 1934. Because of the 1930s depression his contract was not renewed, and he eventually obtained a lectureship at Natal University in South Africa where he concentrated on geomorphology. At Natal, he was influenced by Alexander Logie du Toit (1878-1948), a committed advocate of continental drift (Du Toit, 1937). King (1939) regarded the apparent offset of the North and South Islands of New Zealand as caused by ‘prodigious faults’ around Cook Strait. During the 1950s King made several brave lecture tours, to the United States (Branagan, 1999) as the American Association of Petroleum Geologists Distinguished Lecturer (1951-52), and to Britain where he gave the William Smith Lecture to the Geological Society of London (King, 1958). He visited New Zealand in 1955, promoting the concept of continental drift, (King, 1950, 1953; Le Grand, 1988: 123; Mason, 1998; Ballance, 1999).

John Bradley (1910-1985) was born in England and educated at Durham University and the University of Tasmania where he was greatly influenced by the ideas of continental drift promoted by S.W. Carey. As Senior Lecturer in geology at Victoria University in Wellington, Bradley in turn influenced many of his own students towards the ideas of continental drift (Stevens, 1998). Bradley’s ideas were very advanced, but he published little about them except for a paper on ‘The meaning of paleogeographic pole’, in which he showed that polar wandering supported the concept of continental drift (Bradley, 1957).

Albert Mathieson Quennell (1906-1985) took his B.Sc. in physics at Otago University in 1935, and his M.Sc. at Victoria University College and later worked for surveys in Nigeria and the Sudan. Quennell was not so much an active proponent of continental drift as having very advanced three-dimensional tectonic ideas regarding the African Arabian Rift System and the role of strike-slip or transform faults in the origin of the Dead Sea and the Red Sea (Quennell, 1958, 1959). He used the ‘principles of plate tectonics in the 1940s and 1950s’ (Girdler, 1989) to describe the pole of rotation of the Arabian plate in relation to that of Sinai-Palestine. His pioneering work was long before its time and is usually overlooked in histories of plate tectonics (Lillie, 1985, 1991; Girdler, 1989).

New Zealand geologists live and work in a geologically mobile land dominated by a very large transcurrent fault, now known to be a transform boundary, demonstrating the reality of horizontal movement of continental crust (Benson, 1950; Wellman, 1952b, 1955a, 1955b; Cotton, 1956). By the 1960s, it was well known that land north-west of the Alpine Fault and other major north-east striking faults was slowly moving to the north-east in relation to land to the south-west of the faults at a rate of about 0.2 inches (0.5 cm) per year (Lillie, 1963: 14). As to be expected, the responses to the profoundly different new ideas about the behaviour of the earth’s crust in which ‘continents [are] carried ... along with the ocean floor like logs frozen in ice’ (Wilson, 1968a) were mixed. They tended to be similar to those in Britain where a gradual evolution of ideas took place as new information came to hand (Le Grand, 1988: 244). Many geologists were initially cautious about the ‘new global tectonics’ because for some, the notion of moving crustal plates seemed unacceptable. Others were warily reluctant to give up the still useful New Zealand Geosyncline and repeatedly tried to adapt it to the developing plate tectonic model.
In the United States, a 1978 survey of geologists on their attitudes to plate tectonic theory showed they could be divided into ‘Old Believers’, ‘Converts’ and ‘Sceptics’ (Nitecki et al., 1978). A similar but informal questionnaire given by the author to veteran New Zealand geologists in 1999 was at least a quarter century too late to be of any statistical use, but it indicated that their reactions were just as varied, and it did yield informative anecdotes.

The comparatively ready, if uneven, acceptance of the new theory in New Zealand appears to have been influenced more by education than by the geological nature of this country. Bradley’s students at Victoria University had little trouble in understanding and accepting plate tectonics (G.W.Gibson, pers.comm.). Similarly, Lillie’s students at Auckland University who learned about Carey’s radical tectonic ideas in the 1950s soon supported the new theory (M.R.Gregory, pers.comm.).

Admirers of the British geologist Arthur Holmes (1944) were already halfway to acceptance, while postgraduate training at some British universities often primed geologists to convert to plate tectonic theory. David Kear, then of the Geological Survey, who had learned about continental drift at Imperial College in 1941, used it to explain North Island structure (Kear, 1963: 268). For him, plate tectonic theory ‘flowed naturally’ from Wegener’s work. Coombs of Otago University had been aware of the work on polar wandering since his days at Cambridge and in the 1950s predicted that the ‘celebrated Wegener hypothesis of continental drift is about to be put to quantitative test’ (Coombs, 1957: 18). Others happened to be studying overseas in active research centres during the 1960s where they could hardly help but be aware of new discoveries (M.R.Gregory, J.B.Waterhouse, pers.comm.). Those geologists who had experience of the geology elsewhere in the Southern Hemisphere (Branagan, 1999) such as the Antarctic (M.R.Gregory, pers.comm.), or South Africa (P.R.L.Browne, pers.comm.) only needed a credible mechanism for quick conversion to plate tectonic theory. Learning about sea-floor spreading in the Tasman Sea (for example Griffiths and Varne, 1972) was enough to convince P.F.Ballance (pers.comm.).

Visitors from California, such as Clark Blake, who himself was influenced by Turner at Berkeley and worked under C.O.Hutton at Stanford, was an important influence in New Zealand. In 1970-1971 he taught a course on plate tectonics in Auckland and lectured at Christchurch, Victoria, and Otago (M.C.Blake Jr, pers.comm.). Other significant Californian visitors at this time included the sedimentologist William Dickinson (1971a) and later, the terrane proponent, David Howell (1979).

Some geologists were slow to ‘convert’ simply because they were unaware of developments in marine research until the early 1970s. Slow sea mail from overseas and limited library funds delayed communication of the good news. Moreover, the separation of geophysics and land geology into different departments meant that geologists often did not see reports in geophysical journals (P.F.Ballance, pers.comm.).
Not all geologists were easy converts to the new paradigm but although a few staunch ‘Sceptics’ remained firmly attached to the New Zealand Geosyncline into the 1980s any hot lunchroom discussions were not recorded, and much sceptical opposition was expressed simply as stoic indifference to the new global model. Elsewhere, the ‘lemming-like rush towards geological chaos’ was emphatically deplored (Schofield, 1975), and in the 1980s, the possibility that the Permian warm climate fossils of Whangaroa had arrived in the New Zealand region by sea-floor spreading was vigorously contested (Ramsay and Moore, 1985). The important two-volume publication of the New Zealand Geological Survey The Geology of New Zealand (Suggate et al., 1978) contains nothing of plate tectonic theory. It was prepared during the 1960s, but after very long printing delays through the 1970s (Carter, 1980), revision of the work would have caused further delay and the decision was made to print (M.R. Johnston, pers.comm.)

A very different and idiosyncratically ultra-conservative and entirely speculative model was proposed by Kingma in 1974 to account for the structure and geological history of New Zealand. It is based wholly on the concept of successive diastrophic cycles (Kingma, 1974) and owes much to the geochemical concepts of crustal evolution developed by the Dutch geologist Rein van Bemmelen (1954). In his beautifully illustrated 407-page book Kingma identified and named seven cycles of geosynclinal and orogenic episodes that he considered to have taken place since pre-Paleozoic times. Kingma died at the early age of 58 shortly after the publication of his book (van der Lingen, 1975). His carefully prepared work made no noticeable impact on geological thinking in this country. As a solo construction it was based on insufficient data, it employed an unfamiliar vocabulary and an outmoded paradigm that failed to appeal to other geologists. In any case, progressive geologists were now fully occupied in pursuing plate tectonics with its exciting explanatory possibilities.

**Applying the ‘new global tectonics’ in New Zealand**

The potential of the developing theory of plate tectonics set off a renewed series of attempts to reconstruct the geological history of New Zealand, and especially to explain the peculiar stratigraphic and tectonostratigraphic relations between the tracts of basement rocks. Among these were the everlastingly problematical relationships between the greywackes of the Torlesse facies, the Hokonui facies and the greywackes and ophiolites of the Te Anau and Maitai rocks (Chapter 8, Table 8.1, Chapter 12).

Speculation commenced with Fleming’s (1969) surmise that a Mesozoic ‘conveyor-belt mechanism of sea-floor spreading’ originated in a linear rise in the Pacific Ocean to generate foredeep trenches. Fleming’s map view diagrams (Figure 11.3) depict a fragmented New Zealand in a geosyncline or

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1 C.A. Fleming’s brilliant compilation and review of the Mesozoic of New Zealand constituted the 22nd William Smith lecture delivered to the Geological Society of London in 1968.
foredeep trench on the border of a Paleozoic foreland, now the underwater portion of the New Zealand microcontinent. This was not a part of Gondwana and Fleming saw little evidence for drift away from Australia. The diagrams suggest how transcurrent movement along the Alpine fault had assembled pieces of New Zealand since Mesozoic times, but Fleming was concerned that there was no explanation for the sharp oroclinal bend forming the Chatham rise.

![Figure 11.3: Speculative paleogeographic reconstruction of the New Zealand region from Triassic to Tertiary times. Modified after Fleming (1969b), Quarterly Journal of the Geological Society of London.](image)

Fleming’s Mesozoic scenario contrasts with that of J.R.Griffiths (1971, 1972) of the University of Tasmania, who depicted a Late Paleozoic and Mesozoic New Zealand Geosyncline as part of a submarine plateau that was tucked into the south-east flank of Gondwana (Figure 11.4), but later became separated from the continent by a sphenochasm. The mystery of the disappearing Paleozoic western land mass was solved by the hypothesis that the central Tasman Sea had opened up by a short period of sea-floor spreading between 60 and 80 million years ago (van der Linden, 1969; Griffiths and Varne, 1972; Hayes and Ringis, 1973). New Zealand was at last admitted to have been a part of the new, revitalised version of Suess’s Gondwana, and the hypothetical western land mass was indeed eastern Australia.

Griffiths extended Fleming’s 1969 concept of New Zealand’s geological history and visualised the New Zealand Geosyncline in a sequence of cross-sections on the margin of the mega-continent of
Gondwana (Figure 11.5). Sediments of the Te Anau System\(^2\) and the Hokonui facies\(^3\) are deposited on the continental shelf, with greywackes of the Torlesse facies deposited on the continental slope. In this scenario it is not until Upper Jurassic times that an active subduction zone was installed outboard of the Torlesse deposits. This results in the consumption of some of the Torlesse sediments, uplift, regional metamorphism, subsurface melting and the formation of granite batholiths, but no magmatic arc. In other words, long-term deposition in a geosyncline was still followed by a short-lived orogeny, but now with a causal mechanism, subduction.

\(^2\) Now Caples terrane  
\(^3\) Now Murihiku terrane
Both old and new paradigms were in use at a 1971 symposium devoted to the geology of the Torlesse rocks. Some papers were solidly based on the geosynclinal model (for example Schofield, 1971), others seemed non-committal, but several presentations at least touched on the new paradigm with ideas implying tectonic activity. The inclusion of fossiliferous limestone in allochthonous blocks apparently within an ‘extensive tectonic breccia’ (Grant-Mackie, 1971) and the expanse of ‘chaotic mega-breccias’ of Okuku and Esk head in North Canterbury (Bradshaw, 1971) resembled tectonic mélanges.

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4 Sponsored by the Royal Society of New Zealand (P.R.L.Browne, pers.comm)
Fleming’s (1971) combination geosyncline-plate tectonics model consisted of a Permian to Jurassic geosyncline between Gondwana and the Pacific Ocean, the sediments of which he considered a continuation of the geosynclinal rocks of West Antarctica. Fleming added a periodically active volcanic arc to the west of the Hokonui facies, with the latter lying over an ancient Benioff Zone representing the continental boundary between plates. This continental boundary became the ‘Facies Junction’ between the Hokonui facies zone and the ‘axial geosynclinal zone’. The sediments of the Torlesse Supergroup were supposed, with pillow lavas, to be deposited over a periodically down-buckled oceanic crust. Most radically of all, Blake and Landis (1971) identified the Dun Mountain Ultramafic Belt as a tectonic melange consisting of chaotically deformed oceanic crust and upper mantle components that once formed the base of the Upper Permian Maitai Group.

The following year, Landis and Bishop (1972) visualised a similar geosynclinal arrangement of geological belts in the South Island (Figure 11.6 and p.249). Like Fleming’s 1971 scheme, the Hokonui facies was thought to have developed above a westward dipping seismic or Benioff zone, but now, the Torlesse sediments were deposited on the oceanic plate as a mixture of trench, deep-sea fan, and abyssal plain deposits with oceanic volcanic elements. As before, a long sedimentary phase was followed by an orogenic phase, but the onset of the Rangitata orogeny in Late Jurassic time was ascribed to a change of plate motion so that the Torlesse rocks began to be consumed as they were drawn into the subduction zone.

Figure 11.6: Schematic cross-section through the New Zealand Geosyncline from Fiordland to Otago. Modified after Landis and Bishop (1972). Geological Society of America Bulletin

Several different paleogeographic solutions to the problem of the Hokonui-Torlesse couplet were explored by Landis and Bishop (1972: p.2277) from a semi-fixist viewpoint, including one in which the Torlesse sediments were supplied from an eastern sialic landmass, while the Hokonui basin developed
‘pencontemporaneously’ in an island arc environment offshore of Gondwana. This solution, however, required ‘an essentially fortuitous juxtapositioning’ of the two members of the geosynclinal complex and seemed unlikely. A more favoured solution involved an elaborate ‘by-pass mechanism’ involving alternating phases of deposition in which either volcaniclastic material was delivered to the Hokonui basin or quartzofeldspathic debris from the Gondwana hinterland by-passed the Hokonui basin en route to the outboard Torlesse basin (p.249).

Such far-reaching explorations of the rapidly developing plate tectonics model opened up a number of entries into new ways of dealing with the long-standing questions concerning the greywackes. These included the problem of the petrographic contrast between the Torlesse and Hokonui rocks (Chapter 8), the biostratigraphic zonation of the Torlesse rocks (Figures 9.2, 9.4) and metamorphic zonation in the Torlesse facies (Haast schists, p.201).

**Farewell to the New Zealand Geosyncline**

The use of two different paradigms during the Torlesse Symposium of 1971 was typical of the somewhat ambivalent nature of New Zealand geology over the next decade, where a hybrid geosynclinal and plate tectonic terminology were repeatedly employed. Inevitably, when geologists adhering to the rival paradigms considered the same field data they came to very different conclusions as to the history and causes of geological phenomena. As in the past, the use of different paradigms led to increasing controversy (e.g. p.249-259) and sometimes as far as public disputes via critical letters to the editors of journals (Spörli, 1975; Landis and Coombs, 1978). Regardless of controversy and disagreement, geologists continued to talk to each other through the 1970s using the terminology of both old and new paradigms, while juggling the geosynclinal and the plate tectonic models of New Zealand’s geological history. At the same time, the growth of geology in New Zealand kept increasing as indicated by publication rates (figure 7.1 p.215). Elements of both models were frequently used together until the early combination geosyncline-with-subduction zone model evolved fully into a convergent margin with continuous sedimentation, accretion and subduction.

The New Zealand Geosyncline had been born not long before elements of plate tectonic theory began to be articulated (for example Dietz, 1961). The concept provided an enormously useful working hypothesis for some years and many geologists were reluctant to abandon it, perhaps because for some, it seemed to represent the old tried and true verities of geology. Terms and concepts associated with the old paradigm, especially ‘eugeosyncline’ and ‘miogeosyncline’ remained in frequent use in New Zealand even though one of their originators, Marshall Kay (1969), had long accepted sea-floor spreading as a mechanism in plate tectonics and its role in the formation of the Atlantic Ocean. The term ‘New Zealand Geosyncline’
continued to be used into the 1980s, probably because there was no other familiar and accepted comprehensive term for the Carboniferous to lower Cretaceous basement sequences (Carter et al., 1974).

Admonitions from sedimentological authorities (Dickinson, 1971b; Dott, 1974) to abandon these old geosynclinal terms and concepts made little impression, and for a time, some New Zealand geologists took up the term ‘miogeoclone’ for continental terrace deposits (as used by Dietz and Holden, 1974). Eventually, Bradshaw of Canterbury (1985) sharply pointed out that the term ‘geosyncline’ had been dropped by those working in orogenic belts and exasperatedly insisted that the term geosyncline and all the geotectonic concepts associated with it be dropped.

The New Zealand Geosyncline quietly faded away only when the plate tectonic model consistently outperformed it in providing likely solutions to geological problems and in indicating further research pathways. In due course, older hard-line ‘sceptics’ retired, and as students learned about plate tectonics, the old New Zealand Geosyncline disappeared from view and 30 years later, many of today’s senior geologists have scarcely heard of it.

As geosynclines withered, the whole concept of a deterministic geotectonic cycle with the accumulation of thicknesses of geosynclinals elements, followed inevitably by episodic orogeny and the uplift of mountains, also disappeared, and the previously somewhat uncritical acceptance of this paradigm gave way to ‘an optimistic and enthusiastic pursuit of knowledge’ (Kitts, 1974). Orogeny eventually began to be seen as a continuous process closely associated with the process of subduction at a convergent plate margin like that believed to have once existed on the south-east margin of Gondwana (Introduction p.15, p.376).

The inadequacies of the geosyncline model did not cause geologists to go to sea in search of a better scheme and its shortcomings did not lead to any observable serious scientific crisis (Kuhn, 1970: 77) in New Zealand. While ‘the plate theory ... evolved with breathtaking rapidity from an attractive new hypothesis to a somewhat dogmatic new orthodoxy’ (Dott, 1978: 30) there was no sudden mass abandonment of one paradigm in favour of another in New Zealand, or any abrupt change in the way geologists viewed their world. Different individuals ‘saw the light’ at different times and for different reasons. A few geologists resisted change on principle but the majority did not, resulting in a rapid evolution in geological thought in New Zealand as new data appeared and new interpretations of old data were made in the light of the new model (Laudan, 1977). In geologist’s terms, most members of their community simply moved from using one working hypothesis concerning the Earth’s behaviour, through to another (Chamberlin, 1890; Laudan, 1980).
Plate tectonic theory unified geological and geophysical specialities and the multiple geological paradigms of the past merged so that different geological phenomena could begin to be explained in terms of the same over-arching paradigm. Most importantly, this led to co-operation and information sharing between experts so that sedimentologists, paleontologists, structural geologists and other specialists cooperated to solve geological problems.5

Now, geologists working on New Zealand’s Late Paleozoic and Mesozoic greywackes, could profitably explore the mechanisms and consequences of movement, compression and extension of rocks aboard crustal plates. The discovery of convergent margin processes opened up the possibility of making some sense out of the perplexingly complex deformational patterns in the greywackes and schists. The new theory provided a surprising explanation for the presence of pillow lavas, limestones and cherts among the clastic greywackes, for the patterns of regional metamorphism, and a drastic solution to the differences between the Torlesse and the Hokonui facies (p.359). Geologists could now get on with their work in anticipation of making real progress in solving what had been intractable theoretical problems. The only problem is that plate tectonics is about oceans and tells us very little about what goes on in continents.

5 One result is the growth of multi-author papers.
Chapter Twelve

Oceans, Continents and Terranes

The discovery of principles is always more exciting and more useful in science than the collection of data alone. It appears that a great new principle in Earth behaviour may have just been discovered. This should be quickly and vigorously explored and exploited. It seems that we know now what is going on in the earth. This could be as important to geology as Harvey’s discovery of the circulation of the blood was to physiology or as evolution was to biology. This is the most exciting event in geology for a century and every effort in research should be bent toward it.

(Wilson, 1968a: 16)

A remarkable coincidence has been demonstrated for South Island New Zealand between the pattern of regional tectonosedimentary events predicted by sea floor spreading data, and that inferred from regional stratigraphic evidence.... The geophysical data used in the plate tectonic predictions and the geologic data that confirm those predictions were collected ... by different teams of investigators. In the precision with which geophysical prediction and geologic observation coincide lies much of the beauty and power of the plate tectonic-sea floor spreading hypothesis.

(Carter and Norris, 1976).

As the plate tectonic revolution triumphed over fixism, ‘mopping-up operations’ (Kuhn, 1970: 24) were already underway and continue to the present time (Figure 12.1). With the paradigm change came the effects of increasingly powerful and ingenious technology that takes geologists far beyond reliance on boots, compass and hand lens.

As more information about the ocean floor became available in the 1970s, New Zealand geologists applied it to entities like the greywackes. They could now go beyond simply recording the geometry of structures and search for causal patterns with the expectation of finding comprehensive, cohesive and actualistic explanations with new, workable solutions to old problems, and to develop a more or less coherent tectonic history of the New Zealand greywackes.
Figure 12.1: Flow diagram showing a very simplified scheme of post-revolutionary interpretations of the greywackes. The processes and products of geological change are connected except that the ocean and the continents form two different geological environments. Plate tectonic theory informs us only about the oceanic phase of the greywackes.

Chapter Twelve

Geology in New Zealand: an integrated science

Greywackes: a product of oceans, a component of continents

TECHNOLOGICAL ADVANCES
Global politics: money, ships, equipment, scientists, petrology, geochemistry, provenance, age, diagenesis

OCEANOGRAPHY

SEA-FLOOR SPREADING
Exotic facies from the deep ocean Deep ocean cherts, clays.

OCEANS

SUBDUCTION
Oceanic trench

ACCRETIONARY
Clastic sediments Terrigenous
Isoclinal folds Strike Faults
Diagenesis 'burial' metamorphism

NEW ZEALAND GREYWACKES

TERRANES
Pieces of continent, island arcs, oceanic plateaux 'collision' metamorphism or mélanges.

NEW ZEALAND MICRO-CONTINENT Late faults

MÉLANGES
Sometimes mark strike or thrust faults between packets of sediments

Global politics: money, ships, equipment, scientists, petrology, geochemistry, provenance, age, diagenesis

Global politics: money, ships, equipment, scientists, petrology, geochemistry, provenance, age, diagenesis
Oceanic greywackes

Oceanographical surveys across Pacific and Indonesian trenches (Karig and Sharman, 1975) unexpectedly yielded explanations for many problems of land geology including isoclinal folds and strike faults in greywackes. Using techniques such as dredging, deep sea drilling and acoustic and seismic reflection methods the oceanographers found great masses of sediment over 100km across, 10 or 12 km deep, and up to 2,000 km² in area, lining the inner slopes of many trenches. Most of the sediments in these ‘accretionary wedges’ or ‘accretionary prisms’ (Karig and Sharman, 1975; Moore and Karig, 1976) are derived from a neighbouring continent or island arc (Figure 12.2). Some of the most recent sediment is ponded in basins on the slopes, while more is carried down towards the deep oceanic floor by turbidity currents.

A series of general models was developed (Figure 0.4, pp. 14), in which subduction takes place at the base of trenches. Layers of sediments are scraped off the down-going oceanic plate, transferred to the base of the lower trench slope on the upper plate and accreted in packets (Figure 12.3). The accreted material consists of imbricated packages of folded sediments together with deep ocean floor or pelagic materials including cherts, red argillites, and pillow lavas. Because packets of older sediments are thrust over younger sediments, they appear to be younger, but because fossil ages increase in the apparently overlying strata (for example Bradshaw, 1972: 79), they indicate the true sequence of accumulation. The accretionary prism eventually becomes welded to, and part of, the neighbouring continent.

Direct geological examination of recently emerged portions of a large accretionary prism along the Sunda arc near Sumatra helped to confirm the reality of what had been ‘seen’ by instruments at depth (Moore and Karig, 1976). Similar very large accumulations of sediment constitute the inner trench slope of the
Hikurangi trough (Figure 12.10) off the east coast of the North Island of New Zealand (Lewis, 1980; Cole and Lewis, 1981) and the structures within these accretionary sediments are inferred to be similar to those within the New Zealand greywackes.

The model also explains the frustrating impracticality of making an orthodox stratigraphic survey of greywackes, while the stacked slices account for their seeming extreme thickness of greywacke tracts, the presence of strike faults (p.297, 305) and the tectonic slides (Figure 10.12, p.316). Multiple chert horizons could be interpreted as a single surface broken up by imbrication (Spörli and Gregory, 1986), so that in a stratigraphic reconstruction, the units should be ‘reassembled side by side instead of being stacked vertically’ (Spörli, 1975: 759 and Figure 12.6). Four or five slabs of sediments 1500 to 4000 metres thick (equivalent to the distance between chert lenses, Figure 10.4d, p.304 or tectonic slides, p.316) are enough to make up the apparent 15,000 metres thickness (48,000ft) of greywackes at Waiheke Island.

Ever more complex and sophisticated models of accretion have since been developed (Lewis, 1980; Moore et al., 1985). For example, large faults may occur inside accretionary prisms as they adjust to ‘critical taper’ (Moore et al., 1985; Howell, 1995: 44-5), which may later become the locus for strike-slip motion and terrane displacement. More recently, the concept and theory of ‘critical wedges’, which focuses on tectonic processes within an accretionary prism complex has been advocated (Kamp, 2001: 199). This stresses the internal unity of the structural elements, the dynamics of the accretionary prism or wedge...
and of emergent fold-thrust belts such as the Torlesse Complex, whereas the classical terrane concept emphasises terrane boundaries and differences between adjacent blocks (p.359).

Submarine metamorphism

Regional metamorphism is indeed associated with depth of burial, but the relationship is not simple. While a sedimentary apron accumulates on the surface of an accretionary prism, newly accreted sediments are ‘underplated’ behind the leading edge of the prism to form a two- or three-storey structure or duplex. The mass is greatly thickened to 15 or more kilometres (Silver et al., 1985) and at the same time, deeper sediments are carried to even greater depths by subduction. If packages of ‘proto-greywacke’ turbiditic sediments are buried about 12 km deep they are ‘indurated’ and turned into metagreywacke, and at about 18km depth, the sediments become metamorphosed and ductile. Other metamorphic changes caused by movement take place higher up in the accretionary prism as the mass is pushed backwards by continuing subduction and offscraping. This means that much of the structural deformation in the New Zealand greywackes and schists, and a great deal of regional metamorphism, took place entirely in an accretionary prism on the margin of Gondwana (also see Andrews et al., 1974: 294-6)), long before the mass rose above the sea (Figure 0.4, p.14).

Sedimentary environments of the 1980s - the return of deep-water sedimentation

Around 1965, sedimentologists began turning to a more integrated approach (for example Ballance, 1964, 1974, 1976b) so that teams of specialist geologists, rather than individuals, worked together so that data from previously separate fields were more readily integrated. Detailed studies of greywacke sedimentology leading to improved understanding of processes and geological history owed more to new technologies than to plate tectonic theory. Petrography was combined with stratigraphy, statistical analyses and computer modelling, paleontology and other specialties to develop expanded concepts of the geological history of New Zealand through facies analysis, (Figure 12.4) basin analysis and process sedimentology, much of which had been developed by oil companies (Carozzi, 1975: 15; Pettijohn, 1984: 240-244; Friedman, 1998; Seibold, 2002).

The 1970s shallow-water, deltaic depositional model (p.285) faded away, largely because of the lack of any of the diagnostic features of a true deltaic environment (Hicks, 1981). In any case, a necessarily local deltaic model was not supported by the uniformity of greywacke facies associations throughout New Zealand (Ballance, 1976a), and the turbidites among the Torlesse greywackes represented bathyal, if not abyssal, deposits formed by sediment gravity flow. Meanwhile, sea-floor mapping had resulted in the discovery of large, deep-water, delta-like submarine fans at the mouths of submarine canyons (Figure 12.5). These submarine fans have much in common with shallow-water deltas (P.F.Ballance, pers.comm.)
Figure 12.4: Conventionalised diagrams representing sedimentary styles of composite facies associations in the Lake Ohau Ski-basin. These are not realistic drawings of cliff faces. They are representations of sediment style in different parts of the kind of fan complex shown in Figure 12.4. The wider the unit, the coarser the sediment grains (key at upper left of diagram). While dark-coloured units mean the beds thin upwards, light-coloured units mean the beds thicken upwards. This diagram conveys a great deal of information that would otherwise use many closely printed pages. Conventionalised diagrams like these are enhanced when supported by clear, descriptive photographs. Modified after Hicks (1981) New Zealand Journal of Geology and Geophysics.
Several new, detailed studies of the Torlesse rocks were carried out in Temple Basin near Arthur’s Pass (MacKinnon, 1980) and in the Ohau Ski-basin (Hicks, 1981). Because the original stratigraphic structures were sliced and broken up in their accretionary prism, they were much more difficult to understand than those deposited in other, less active, settings (MacKinnon and Howell, 1985: 223). However, both Hicks and MacKinnon concluded that deep-water sedimentation involving sediment gravity flows had indeed taken place in large, submarine fans (MacKinnon, 1980, 1983, MacKinnon and Howell, 1985) as in Figures 12.4, 12.5. The same Torlesse sediments were also interpreted by Howell (1981b) as characteristic of submarine fans of ensialic (continental) provenance deposited in a deep marine environment.

![Diagram of a deep-sea submarine fan at the base of a submarine canyon. The Indus submarine fan is among the largest of the present day fans being 1500km in length and 950km in width. Characteristic patterns of sedimentation exist in different parts of these fans, and similar patterns can be seen in the greywackes. The Mesozoic fans have been sliced across every few kilometres, he slices folded, distorted, tipped on edge and tucked into an accretionary prism. The greywacke geologist’s task is to disentangle the resulting steeply dipping, deformed layers from what can be seen on the surface of cliff-face outcrops.](image)

**Figure 12.5:** Diagram of a deep-sea submarine fan at the base of a submarine canyon. Modified after Hicks (1981) *New Zealand Journal of Geology and Geophysics.* A similar Cretaceous fan is described more recently by Axel Leverenz, (1999) Ph.D. student from Germany at Auckland.

### Provenance problems, again

The differences in sandstone petrology ‘between the two great coeval Hokonui and Alpine Assemblages [that had] long plagued interpretation of New Zealand tectonics’ (Dickinson, 1982) continued to trouble sedimentologists. Neither Hicks nor MacKinnon considered the Western Province as a source of sediment. Paleocurrent directions are difficult to read, but Hicks (1981: 227) traced probable depositional cycles and environments, and his paleodirection indicators suggested a source of sediments to the

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1 Ph.D. student at Otago
2 Ph.D. student at Otago
south-east. MacKinnon disagreed that the arkosic Torlesse sandstones had an eastern source. He was unwilling to make a firm claim to any particular source direction, but his petrological studies indicated a large, mountainous continental source. MacKinnon proposed an east-west alignment of the Gondwana coast, with a western island-arc-trench forming the volcanogenic terranes (Murihiku, Maitai, Caples), and an eastern trench-transform setting where the Torlesse sediments accumulated. The two sets were then re-arranged by major parallel strike-slip faulting which fortuitously placed the Torlesse directly outboard of the others.

Provenance of the Torlesse sediments and those of the Murihiku, Waipapa and other terranes remains unsolved. Heavy minerals, mainly zircons, are back in use by geochemists in attempts to trace both provenance and age. Zircon grains from Torlesse greywackes range in age from around 160 Ma to 1240 Ma, but most are about 260 Ma (Ireland, 1991). U/Pb (uranium-lead) data were determined using a sensitive high-resolution ion microprobe (SHRIMP) to date detrital zircons in Cretaceous sediments of North Island Torlesse and Waipapa terranes (Cawood et al., 1999: 1109), and these indicate a Lachlan (south-east Australia) and Antarctic source of sediments. Sm-Nd\(^3\) isotope analyses of argillites of the Torlesse terrane have provided crustal residence ages indicating ages of 1.0 to 1.4 Ga, \((Ga = 1000 \text{ Ma})\) that is, Middle Proterozoic time (Frost and Coombs, 1989). However, none of these impressive results can as yet tell us how often the minerals have been recycled through deposition and uplift, the location of the original continental source region or the depositional site of the Torlesse terrane sediments (Coombs and Cox, 1991: 5).

So far, the most popular choices of source rocks for the Torlesse greywackes include Marie Byrd Land, south-east Australia, the hypothetical ‘lost continent’ of Pácia (Pirajno, 1980; Kamp, 1980), and most recently, Queensland, based on \(^{40}\text{Ar/}^{39}\text{Ar}\) Argon dating of detrital micas in Torlesse greywackes (Adams et al., 1998; Adams and Kelley, 1998; Campbell, 1998).

**The meaning of the exotic facies: cherts, pillow lavas, limestones**

Cherts, pillow lavas, and limestones (Figure 9.8) were long believed to be minor accessory rocks interbedded with the terrigenous greywackes (Halcrow, 1956: 54), forming part of continuous stratigraphic sequences (p.293-299), and sometimes considered useful as marker horizons (Schofield, 1974). The Permian fusulinids and other Permian forms in limestones associated with the lavas at Whangaroa and elsewhere in Northland indicated that the warm, clear waters of the Tethyan Sea had once extended to New Zealand (Hornibrook, 1951) (Figure 9.9, p.298, Figure 12.7) and that the enclosing greywackes were also of Permian age. On the other hand, fossil evidence (Figure 9.2) showed that similar

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\(^3\)Samarium (Sm) and neodymium (Nd) are both rare earths.
clastic greywackes nearer Auckland region are of Upper Jurassic age (Milligan, 1959; Spörli and Grant-Mackie, 1976; Speden, 1976). This meant that the lack of feeder dikes for the basaltic lavas (as seen in Kay’s geosyncline Figure 7.8, p.222) raised questions about the origin of the pillow lavas (Spörli and Barter, 1973).

As ideas about sea-floor spreading became established the pillow lavas were inferred to represent the upper crust of the oceanic floor while the red radiolarian cherts were considered as analogous with pelagic ooze (Bailey et al., 1964; Hamilton, 1969). According to the plate tectonic model, the exotic cherts, limestones and lavas were carried aboard an oceanic lithospheric plate (Dewey and Bird, 1970; Hsü, 1971) from somewhere in the Paleozoic-Mesozoic Pacific Ocean (Fleming, 1969: 163) towards a subduction zone bordering south-east Gondwana (Griffiths and Varne, 1972). Here, they were clawed up and incorporated as lenses into the layers of clastic greywackes (Figures 0.4, 12.3, 12.6). This meant that there could be an age gap between the volcanics, limestones and cherts and the enclosing greywackes (Spörli, 1975: 758) and that the presence of Permian microfossils at Whangaroa to the north did not necessarily mean that the greywackes themselves had to be of Permian age (Spörli and Gregory, 1981, 1986). Further, paleomagnetic data and plate reconstructions indicated that in Permian times, New Zealand lay at very high latitudes (Spörli and Gregory, 1981: 227), far from any warm, Tethyan seas. Chemical analysis had
shown that the spilitic basalts at Whangaroa were derived from intraplate volcanic piles or guyots rather than a mid-ocean spreading ridge (Spörli, 1978: 422). This suggested that the shallow water limestones had accumulated on the upper surface of a guyot, and later, limestone, basalts and abyssal cherts were sheared together off the subducting plate, while the deeper true ophiolites were carried on down into the mantle (Figure 0.4).

Two independent studies of the pillow lava and limestone associations in Northland produced quite different interpretations of age and origins. One team (Spörli and Gregory, 1981), interpreted the fusulinid limestones of Whangaroa as of exotic origin, having been formed near the Permian equatorial belt and transported to the Gondwana margin by sea-floor spreading. The other team (Moore and Ramsay, 1979; Ramsay and Moore, 1985) believed that similar pillow lavas and the enclosing sedimentary rocks of the nearby Cavalli Islands were contemporaneous and that stratigraphic continuity existed between all elements including the lavas, cherts, limestones and clastic sediments. All of this ended in an increasingly disputatious exchange of letters to the editor in the New Zealand Journal of Geology and Geophysics in which each pair of authors exchanged point-by-point refutations of each others’ views and field interpretations (Spörli and Gregory, 1986; Ramsay and Moore, 1986). Minds were not changed, and one pair ended up believing that the pillow lavas and limestones were exotic, and the other did not.

Tethyan fusulinids similar to those found at Whangaroa and Benmore Dam occur in Japan, South China and in the Canadian Cordillera. Fusulinid distribution in Canada gave early backing to the idea of lateral movement of the Earth’s crust within the North American continent (Monger and Ross, 1971).

The overall distribution of the fusulinids (Figure 12.7) indicates the dispersal of equatorial terranes (see later) to high latitudes (Howell et al., 1985) and at the same time gave strong support to the idea that the exotic facies and the enclosing greywackes had very different origins.

The prediction on circumstantial evidence of an age gap between oceanic basement (pillow lavas, limestones and cherts) and the enclosing clastic greywackes (Spörli, 1975: 758) was soon confirmed when techniques became available for the extraction of radiolaria from chert using hydrofluoric acid (Feary and Hill, 1974, 1978; Le Grand and Glen, 1993). An examination of chert from Raukumara Peninsula revealed that the chert was around 80 million years older than the enclosing clastic strata (Feary and Pessagno, 1980). That oceanic cherts and limestones and accompanying terrigenous greywackes are of different origin and age was later repeatedly confirmed e.g. (Foley et al., 1986; Silberling et al., 1988; Spörli et al., 1989; Grapes et al., 1990; Aita and Sporli, 1992, 1994). A long-term collaboration between geologists at the University of Auckland and Japanese geologists has sought to clarify problems to do with the radiolarian cherts, and includes a search for strata that may record the great extinction at the end of Permian time (for example Spörli and Aita, 1988; Aita and Sporli, 1992).

Dinoflagellates are unicellular algae whose cysts preserve well, and are especially useful in greywacke biostratigraphy because the cysts or spores are found in the clastic greywackes themselves and give their ages (Wilson, 1978, 1984). Dinoflagellate assemblages from the Torlesse greywackes of the Urewera Ranges in the Raukumara district indicated that most of the greywackes east of the Whakatane Fault are of earliest Cretaceous age, and not Jurassic as previously thought (Wilson and Moore, 1988; Moore et al., 1989).

Multiphase folding in the greywackes

The greywackes are structurally complex partly because they have undergone ‘multiphase’ or ‘polyphase’ folding, with each phase folded in a different direction and in a different style (Lillie, 1961; Bradshaw, 1972; Bishop, 1974: 301). Each fold generation displays a characteristic appearance, and the folding sequence varies from place to place. A general sequence of folding events so far recognised is:

- Early isoclinal folds with associated ‘tectonic slides’ (see below).
- Open, horizontal folds (Schofield, 1974: 827)
- Steeply plunging folds p.353 (Spörli and McAlister, 1995).

Large isoclinal folds with steeply dipping limbs like that on Mt Häckel (figure 12.8) (Waterhouse, 1955, 1966) were generally thought to have been formed early in their history when the rocks were still plastic (Bradshaw, 1972: 79; Andrews et al, 1974: 287-290; Spörli and Barter, 1973: 374; Spörli and Bell, 1976: 430). Waterhouse referred to such folds as schuppen (imbricated structures) and suggested that ‘tectonic
Figure 12.8: A large synform exposed in the Malte Brun Range on the western face of Háckel. This classic photograph of an isoclinal fold on Mt Háckel in the Mt Cook region is among the first published clear images of such folds in the Southern Alps. Photograph by J.B. Waterhouse (1955) Transactions of the Royal Society of New Zealand.
thickening’ accounted for the apparently very large thickness of the Torlesse greywackes (Waterhouse, 1972: 423). These folds range in shape from open asymmetric flexures to tightly folded isoclinal folds, commonly with attenuated limbs, and sometimes with inverted limb sheared out by strike faults or tectonic slides (Bradshaw, 1972: 79; Andrews et al., 1974: 290, and Figures 10.12, 12.2). No satisfactory explanation could be offered to account for these isoclinal folds and strike faults, although Spörli and Barter (1973) toyed with the possibility that asymmetric folding in the Kaimanawa Ranges was caused by some kind of gravity sliding. More recently, analogies have been drawn between fold and thrust belts (like those constituting the New Zealand greywackes) and initial deformation in modern accretionary prisms (Moore et al., 1985). Apparently the great fold shown in Figure 12.8 and the tectonic slides were all formed in an ancient submarine accretionary prism similar to that in Figure 12.3.

Geologists have not yet accounted satisfactorily for the very large steeply plunging folds like those mapped by A.R.Lillie (Figure 10.7, p.310). Although such folds were linked with subduction ‘at the leading edge of the East Pacific plate’ (Ward and Sporli, 1978: 187), the 1975 model of an accretionary prism could not explain how these folds were formed. They may be related to strike-slip along the Torlesse margin as it was moved towards the New Zealand area (Spörli and Ballance, 1989:180), or a relatively late strike-slip faulting episode (Spörli and Bell, 1976: 435). Perhaps the open folds and the
steeply plunging folds were formed by oblique compression in the accretionary prism after décollement (Figure 12.10) and before uplift (Spörli and McAlister, 1995) and perhaps some of these folds were formed at least partly in Cenozoic time (Spörli, 1978: 422).

Figure 12.10: Schematic diagram showing the tectonic situation of the accretionary prism in which the greywackes of Tiritiri Matangi were deformed in the late Mesozoic. From Spörli and McAlister (1995), modified after Lewis (1980).

**Soft sediment slumping:** Closely spaced, mesoscopic intraformational folding in some fine greywacke argillites and red cherts have often been explained as a result of penecontemporaneous soft sediment slumping under gravity (for example Waterhouse, 1972; Lillie, 1980: 391), also see Waterhouse and Bradley (1957). This view was challenged by Klaus Bernhard Spörli (b.1936) who argued that the cherts, associated volcanics and red argillites are distorted because much larger sheets of greywacke-type rocks had moved over them. Thus the folds are related more to tectonic activity than a response by soft, unconsolidated sediments to gravity (Spörli, 1975).
Mélanges

The essential characters of an autoclastic mélange may be said to be the general destruction of original junctions, whether igneous or sedimentary, especially of bedding, and the shearing down of the more tractable material until it functions as a schistose matrix in which the more obdurate rocks float as isolated lenticles or phacoids...[C]ould we take in the whole region at a glance, it would present itself to us as a mélange of torn and sheared lenticular masses of all sizes from such as are two or three miles in length to the smallest that the eye can see, of spilitic lava, diabase, quartzite, limestone, jasper, and grit, floating in an undifferentiated schistose body.

(Greenly, 1919: 65, 193-195, 306)

The terminology of chaotic unbedded assemblages is as disorderly as the deposits themselves.

(Bradshaw, 1973)

The English geologist, Edward Greenly (1861-1951) introduced the term ‘mélange’, meaning ‘mixture’ into geological language in 1919 in his memoir on the geology of Anglesey. ‘Mélange’ was next used by the British geologist E.B.Bailey to describe very large tectonic mixtures in Turkey (Bailey and McCallien, 1950, Sengőr and Sakinç 2001), and then independently reintroduced and redefined in 1968 by Kenneth Jinhwa Hsü (b.1929) to describe the complex Franciscan rocks of California, which were often compared with the Torlesse rocks. Hsü’s definition is that mélanges are ‘mappable bodies of deformed rocks characterised by the inclusion of tectonically mixed fragments or blocks, which may range up to several miles long, in a pervasively sheared, fine-grained, and commonly pelitic matrix. Each mélange includes both exotic and native blocks and a matrix’ (Hsü, 1968: 1065). Olistostromes are also disordered mixtures but are supposed to be caused by submarine sliding of unconsolidated sediments.

As a general term, ‘mélange’ has been widened to include ‘rock mixtures caused by tectonic movements, sedimentary sliding, or any combination of such processes, with no mixing process excluded’ (Silver and Beutner, 1980), or more simply, ‘mélanges are bodies of mixed rocks’ (Raymond, 1984: 1). Where once, mélanges were seen as ‘hopelessly complex’ they may now be seen as holding the keys to ‘understanding the most fundamental tectonic environments on earth’ (Silver and Beutner, 1980). In New Zealand the term ‘mélange’ is usually used for localised zones of intense folding and shearing incorporating fragments of cherts, pillow lavas and terrigenous rocks. The significance of deformed and shear zones associated with exotic facies including pillow lavas and cherts and structural rocks, including broken formation and mélanges, ‘could be recognised [only] once the processes that created them were understood’ (Sengőr and Sakinç, 2001: 191) (Sengor’s italics). Sengör regards mélanges as indicators of past subduction and of great strike-slip faults like the Alpine Fault, while Pacific Rim geologists believe them to be caused by collisions between terranes.
Figure 12.11a: Mesostructures in the Pohangina Mélange, traced from photographs. Disruption and deformation of beds is characteristic of mélange structures. Black = sandstone, white = argillite, cross-hatching = volcanics. Scale bars shown. 80% original size. Modified after Spörli and Bell, 1976, New Zealand Journal of Geology and Geophysics.

Fossil zones
3: Late Triassic (Töressa?)
4: Late Triassic (Monotis)
5: Late Jurassic - Early Cretaceous

Figure 12.11b: Geology of the pre-Tertiary rocks of eastern and southern North Island. Mélanges marked in checked pattern. Kaimanawa schist marked by heavy cross-hatching in B. 64% original size. Modified after Spörli, 1978, Geological Society of America Bulletin.

Figure 12.11c: Central New Zealand showing position of the Esk Head Mélange in Canterbury and possible North Island correlatives. From Orr, Korsch & Foley, 1991. New Zealand Journal of Geology and Geophysics.

Figure 12.11: Mélanges in New Zealand. The Esk Head Mélange appears to continue northwards through Rimutaka and Pohangina towards the Bay of Plenty. Do they belong to the same system? The Kaimanawa schist-mélange lies about 50 km to the west of the great line of mélanges.
Mélanges in New Zealand

In New Zealand, several mélanges and mélange-like structures began to be recognised in the early 1970s (for example Grant-Mackie, 1971: 21). Dun Mountain was initially seen as a huge ‘knocker’, or tectonically shattered section of rock (M.C.Blake, pers.comm.) and the Dun Mountain Ultramafic Belt itself (D in Figure 5.7; and Figures 12.13, 12.18) was perceived as a tectonic mélange representing chaotically deformed oceanic crust and upper mantle (Blake and Landis, 1971: 29; 1973). It was later considered an ophiolite belt with some segments of tectonic mélange (Coombs et al., 1976).

A narrow band containing blocks of metasediments in a sheared serpentinite matrix immediately east of the Dun Mountain Ophiolite Belt, described in 1871 by the unfortunate E.H.Davis as inextricably confused (p.110), had been mapped as the Patuki Volcanics Complex in 1964 (Waterhouse). This band is now recognised as the Patuki Mélange (Johnston, 1990a, 1990b: 26) forming an impressive suture between the Dun Mountain-Maitai Terrane and the Caples Terrane (Figure 5.15, p.152), and perhaps was caused by collision between them. A little further to the east the Croisilles Mélange also consists of blocks of sedimentary and igneous rocks within a serpentinite matrix, but curiously, it lies entirely within the Caples Terrane, cutting obliquely across formations within it (M.R.Johnston, pers.comm.).

South of Dunedin, the Chrystall’s Beach Complex, a part of the Caples Terrane, features ‘classic’ mélange structures as well as broken formations (Nelson, 1982). This complex may be related to Nelson’s Croisilles Mélange, or may represent the tectonic suture between the Caples and Torlesse terranes (Howell, 1979). It may even represent a south-eastward continuation of the Aspiring lithologic association (Norris and Craw, 1985) between the Caples and Torlesse terranes in Otago (Figure 12.18, 12.23, p.374).

Unlike the ultramafic mélanges in Nelson, the ‘vast chaotic breccia bodies’ and ‘mega-breccias’ (p.317) of Okuku and Esk Head in Canterbury (Figures 12.11c, 12.17, 12.18), consist of blocks of limestone, sandstone blocks, pillow lava, red chert, and cherty mudstone (Bradshaw, 1971: 13), and form part of the very large Esk Head Mélange (Bradshaw, 1973, 1977). Some geologists regard this mélange as a sub-terrane (Silberling et al, 1988) with material derived from the two Torlesse sub-terranes, the older Rakaia sub-terrane to the south, and the younger Pahau subterrane to the north (Bradshaw et al., 1981), which is partly formed from debris reworked from the Rakaia subterrane (Figures 5.15, 12.17). The Esk Head Mélange is usually seen as a collision zone between the Rakaia and Pahau subterrane (MacKinnon, 1983) (Figure 12.18), but it may represent traces of thrust faults that took place early in the history of accretion involving seamount and sea-floor origin (Silberling et al., 1988). Its oceanic sediments range in age from Late Triassic through to Late Jurassic, and could therefore represent parts of a single large oceanic plate, although it is not a simple paleogeographic entity.
The Pohangina Mélange within the Torlesse basement of the Ruahine Range in the North Island (Spörli, 1974, Spörli and Bell, 1976) is up to 2 km wide. This mélange contains red and green sheared volcanic, red and green argillites and red bedded cherts with copper sulphides in a matrix of dark argillite and siltstone with a little crystalline limestone (Figure 12.11a, 12.11b). It seems related to Reed’s ‘autoclastic breccias’ and pseudotillites’ (p.317) found further south in the Wellington region (Reed, 1957a, 1957b; Lensen, 1957). Later investigations of similar mélanges in the Torlesse Complex (Korsch, 1984) of the eastern Tararua Range (Foley et al., 1986; Orr et al., 1991) revealed typical disrupted bedding, lenticular phacoids and rhombic-shaped lozenges of sandstone rock, thought to be related to activity in an accretionary wedge and to Holocene strike faulting (Orr et al., 1991: 71). This mélange is often considered a continuation of the Esk Head Mélange to the south and the Pohangina Mélange to the north (Figure 12.11c), and represents the contact between the Rakaia and Pahau Terranes (Begg and Johnston, 2000: 27).

Many puzzles remain, with a 50 Ma difference in age between the youngest fossils of the Permo-Triassic Rakaia subterrane and the oldest autochthonous fossils in the late Jurassic-Cretaceous Pahau subterrane (Bradshaw, 1989). The northern boundary of the Rakaia sub-tErrane is tectonically truncated, probably before the formation of the Pahau, and perhaps the nonclastic exotic elements of the intervening mélange including chert, limestone and pillow basalt are fragments of Late Triassic to Late Jurassic seamounts that ploughed into the lower slope of the Pahau accretionary prism.

**The Kaimanawa schist problem solved**

The mystery of the North Island’s Kaimanawa schist (p.321) increased when doubts were raised about its schist-like nature. It was suggested that sampling bias gave an impression of the presence of a regional belt of schists (Spörli and Barter, 1973). Because of steep, bushed terrain, rock samples were all taken from along river and stream courses. These appear to be controlled by shear planes and faults lined by thin bands of schistose rocks separating blocks of non-schistose greywacke, but no fresh samples from the divides between streams were available. However, construction of the hydroelectric project at Tokaanu at the south end of Lake Taupo provided an exceptional opportunity for underground access to fresh rocks of both the Torlesse and Waipapa terranes, and with rocks of the Kaimanawa schist (Beetham and Watters, 1985). The Kaimanawa schist was found to belong to the Torlesse terrane but showed ‘pervasive very low grade metamorphism’, with widespread shearing and a metamorphic grade slightly higher than the adjoining metagreywacke. Broken formations and mélanges from the tunnels consists of ‘fragments of exotic rock, particularly chert’. Since chert is considered a mélange marker, the authors concluded that the Kaimanawa subschist or semischist is really a mélange zone and not true schist.
The Terrane Concept in New Zealand

Continental geology stands on the threshold of a change that is likely to be as fundamental as plate-tectonic theory was for marine geology.

(Saleeby, 1983).

The word terrane is a lump term for a number of older and more informative non-genetic (block and sliver) and genetic (fragment, nappe, strike-slip duplex, microcontinent, island arc, suture, etc) terms…[and] is best avoided.

(Sengor and Dewey, 1990; 473).

A number of histories of the terrane concept in North America are available (Schermr et al., 1984; Le Grand, 1988: 248-50; Howell, 1995; Stewart, 1990: 111-2), but this account is about how geologists developed the terrane concept in New Zealand. The modern tectonostratigraphic terrane is a particularly Pacific rim concept (Figure 12.21). It has been subjected to considerable criticism, mainly from a European perspective (for example, Sengör and Dewey, 1990); nevertheless, it provides New Zealand geologists with a useful working framework for the investigation of the basement rocks..

The term ‘terrane’ originally had an imprecise, vaguely stratigraphical meaning as an ‘area over which a group of formations is prevalent’ (Howell, 1960). In western North America geologists often used ‘terrane’ when referring informally to a recognisable geological entity, a group of rocks related in some way. These were given general names such as ‘graywacke terrane’ or ‘metamorphic terrane’. ‘Terrain’ is used by military personnel, surveyors and engineering geologists to refer to the characteristics of a land surface. During the 1970s ‘terrane’ developed a new specific tectonic meaning. A tectonostratigraphic terrane is today defined as a ‘fault-bounded package of strata that is allochthonous to, and has a geologic history distinct from, the adjoining geologic units’ (Howell, 1995: 225), and it also relates to an assemblage of structures. The first known published use of ‘terrane’ in more or less the contemporary geological sense is by W.P. Irwin of the United States Geological Survey in 1972 (Irwin, 1972; Bates and Jackson, 1987).

The origin of the adjective ‘tectonostratigraphic’ is unknown. K.J. Hsü used a similar term in 1968 when referring to mélange (Hsü, 1968: 1065). D.G. Howell (pers. comm.) believes it was invented to denote tectonic terranes around 1980, but it was previously used in connection with the stratigraphy of tectonic units in New Zealand basement rocks by Otago geologists as early as 1974 (Carter et al., 1974), see Table 8.3, p.257-7.

The terrane concept is a ‘natural outgrowth of plate tectonic theories’ (Schermr et al., 1984:107), in which rifting, large-scale strike-slip faulting (Jones et al., 1977), sea-floor spreading (Blake et al., 1974: 865) and drift are believed to cause the creation and dispersal of terranes. These may be island arcs, oceanic plateaus or continental fragments like the New Zealand microcontinent (Ben-Avraham et al., 1981; Spörli, 1987). Displacement of a terrane may be as great as several thousand kilometres (Schermr et al., 1984: 118) before it collides with a continent and is accreted to it. Collision, such as that between the Torlesse
Chapter Twelve

Figure 12.12: Landis's 1974 map of New Zealand showing eight major geologic terranes and petrofacies. The South Island part of the map was modified after one produced by Coombs and his Otago team for a world conference on ophiolites held in the USSR in 1973. Unfortunately, the full conference proceedings and the map were never published (D.S. Coombs, pers. comm.). The Haast schist terrane was later removed as a separate terrane because of its mixed parentage. Map 80% original size. Large labels added. Modified after Blake, Jones and Landis (1974) in Burk and Drake, The Geology of Continental Margins.
sediments and Gondwana during the Mesozoic, results in deformation and metamorphism, uplift and the formation of mountains.

Some have seen the concept of the accretion of terranes as a reinterpretation of the old geosynclinal model (p.221) of continental accretion (Le Grand, 1988: 248). However, the idea introduced by J.Tuzo Wilson (1968b: 316) that continents consist of a collage of exotic or allochthonous fragments signifies a basic shift away from the concept of the geosyncline. The terrane concept changed the whole theoretical framework in which orthodox mapping and stratigraphy is done, and it had surprising paleogeographic implications for the reconstruction of regional geological histories. The terrane concept:

♦ Accounted for strange geological neighbours, and allowed geologists to make progress in the stratigraphic and structural analyses of the different regions
♦ Explained the puzzling dissimilarities between coeval rocks such as the Murihiku, Torlesse and Waipapa terranes,
♦ Explained pervasive regional metamorphism and the presence of large mélanges (Figure 12.11).
♦ Freed geologists from having to find a westerly source for the Torlesse sediments and abolished the need to transport quartzofeldspathic sediments from the west across an otherwise peaceful volcaniclastic Hokonui (Murihiku) continental shelf (for example Landis and Bishop, 1972).
♦ Liberated geologists from having to construct a comprehensive stratigraphic system that regarded all the basement rocks as members of a single geosynclinal environment (Chapter 8).
♦ The terrane concept put an end to the old bipartite New Zealand Geosyncline, which was no longer required as a sedimentary environment.

In his study of the Upper Permian Maitai rocks of Southland and Nelson, Charles Alexander Landis (b.1938), then a Ph.D. student from the USA at the University of Otago, found that stratigraphic nomenclature was often complicated by the use of different names for similar formations on opposite sides of the Alpine Fault, such as the Caples, Pelorus and Tuapeka Groups (Landis, 1969: 42). The many stratigraphic names used for similar rocks of similar ages were a deterrent to understanding broad stratigraphic and tectonic problems (C.A.Landis, pers.comm.). Landis adopted the informal term ‘terrane’ (Nathan, 2002) as used by Cordilleran geologists of western North America to combine apparently equivalent tectonic units (Landis and Coombs, 1967; Landis, 1969). This practice made it easier to clarify structural relations in geologically disturbed areas because each ‘terrane’ was considered as a separate entity, and thus opened up new possibilities in the analysis of their structure and history.

Besides delineating a Torlesse terrane and a Haast schist terrane, Landis correlated his Caples terrane with the Nelson Pelorus group and its North Island tectonic correlative, the Manaia Hill Group (Landis, 1969: 45), to create a continuous volcanogenic western belt (Figure 12.12). Landis was also concerned
A possible model for evolution of the Dun Mountain ophiolite belt and the eastern or Geosynclinal Province of New Zealand (see text for explanation). No vertical exaggeration.

**A. EARLY PERMIAN**

**B. LATER PERMIAN**

**C. TRIASSIC**

**D. EARLY CRETACEOUS**

**Figure 12.13**: This sequential diagram models the evolution of the Dun Mountain Ophiolite Belt and terranes of the eastern or 'Geosynclinal' province of New Zealand. It is a slightly more detailed version of Landis's 1974 version (Blake et al., 1974, Fig.8) in which Torlesse sediments are shown on the outboard side of the Mesozoic convergent margin, having originated in some distant location. The sediments are being rafted by sea-floor spreading towards the Mesozoic convergent margin on the south-east coast of Gondwana. 80% original size. Modified after Coombs, Landis, Norris, et al. (1976). American Journal of Science.
about the use of stratigraphic terminology to refer to units like the Tuapeka, Pelorus and Torlesse greywackes as ‘groups’ (Table 8.2, p.253). Although the Torlesse had tectonic integrity, it was not a single stratigraphic unit and it had no ‘original stratigraphic continuity’ (C.A.Landis, pers.comm.). The ‘Haast Schist Group’ was even more questionable as a stratigraphic entity being composed of Torlesse and Caples greywackes (Figure 8.12 p.274, Figures 12.13, 12.18, 12.22). Landis’s terranes were often bounded by faults, but this was before tectonostratigraphic terranes were formally defined as having faulted boundaries.

**New Zealand and California**

The seeming similarities between the Torlesse—Hokonui couplet of New Zealand, and the Californian Franciscan—Great Valley pair had interested both California and New Zealand geologists for some years (Hatherton, 1966; Dickinson and Hatherton, 1967; Hatheron, 1969; Landis and Bishop, 1972: 2269). Both regions consist of two parallel Mesozoic sedimentary belts adjacent to older crystalline terranes (Blake, 1974 #1150). California’s eastern Great Valley sequence and New Zealand’s western Hokonui assemblage were both considered to be continental shelf and slope ‘miogeosynclinal’ deposits, while the outboard Franciscan and Alpine assemblages were seen as ‘eugeosynclinal’.

How could two neighbouring, coeval, but dissimilar sets of rocks have evolved independently in California and New Zealand? When comparing the two regions, the Californian geologists placed a remnant volcano-plutonic arc between the two parallel basins containing the growing Franciscan assemblage and the Great Valley sequence, with an active trench located outboard of the Franciscan basin (Blake et al., 1974: fig.6). Subduction and underthrusting was believed to have caused the Franciscan sediments to be rammed against the Great Valley sequence, with the formation of mélanges. Thus, elements of the marginal geosynclinal model were retained with sediments deposited inside the trench boundary.

In the same paper, Landis dealt with the New Zealand situation from a terrane perspective, and produced New Zealand’s first terrane map (Figure 12.12). The old problem remained: how to account for the coeval but contrasting volcaniclastic Hokonui and quartzofeldspathic Alpine (Torlesse) sediments? The traditional western source for Torlesse sediments was given up, but the deep Pacific Ocean to the east still meant difficulty in finding a source for the necessary great volumes of sediment. This long-standing problem was frequently discussed by members of the Otago group, including D.S.Coombs, R.J.Norris, and C.A.Landis.

Based on the earlier proposal of an eastern source (Andrews, 1971; Bradshaw and Andrews, 1973), someone in the group suggested a radical solution for the origin of the Torlesse greywackes (Blake et al.,
1974: 865, 869). What if the Torlesse sediments constituted a terrane located on the outboard side of the convergent margin (Figure 12.13) having been ‘rafted into their present position by sea-floor spreading’? In the North American continent, the transport of terranes was sometimes thought to be by transcurrent (strike-slip) faulting or thrust faulting (for example Irwin, 1972). However, if the Torlesse terrane were to be conveyed by sea-floor spreading from some quite separate, distant region, then at a subduction rate of 1 to 10cm per year for 70 Ma, the rocks could have originated at least 700km to 7000km away (Coombs et al., 1976: 595). The source could be a continental block lying somewhere to the east in an area now occupied by deep oceans, or it could be the Marie Byrd Land-Jones Mountains area of West Antarctica. At the time, a rafted origin for the Torlesse could not be backed up with other data but since then, geochemical methods have suggested a source area in eastern Queensland (for example Adams and Kelley, 1998; Campbell, 1998)

**The North Island**

The Torlesse Group had been traced into the North Island (Stevens, 1963) in 1963 and in 1976, all northern greywackes were classified with the Torlesse Supergroup by Speden (Figure 9.2, p.284). However, the dark grey, ‘muddier’ volcanogenic Waipapa Group greywackes of the Auckland region are different from the ‘cleaner’ arkosic Torlesse greywackes to the south (A.R.Lillie, pers.comm.), and petrographically, are more like those of the Caples-Croisilles-Pelorus terrane4 (Blake et al., 1974 and Figure 12.12). However, unlike its southern analogue, most of the Waipapa greywackes are of Jurassic age with some recycling of Triassic rocks. Spörli (1978) distinguished the Waipapa Terrane (Figure 12.14, p.365 opposite) as a separate tectonostratigraphic terrane.

**Another Californian connection**

The terrane concept was already steadily developing in New Zealand when David G. Howell of the United States Geological Survey in California and an enthusiastic supporter of the terrane concept, visited in 1978. His long-term aim was to produce a world paleogeographic volume based on palinspastic reconstructions (Le Grand, 2002: 208). While in New Zealand, Howell published a preliminary sketch map of this country (Howell, 1979) featuring five Mesozoic microplates (Figure 12.15), and it was quickly followed by another showing four lithostratigraphically distinct tectonostratigraphic terranes (Howell, 1980, and Figure 12.16). This was the first comprehensive review, analysis, and tectonostratigraphic history of terranes outside the North American Cordillera (P.F.Ballance, pers.comm.). (to page 369).

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4 Then referred to as the Manaia Hill Group

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The Waipapa Terrane consists of the Morinsville facies and the Hunua facies (Kear, Figure 8.3, p.228). The Hunua facies is located in Auckland, the Hauraki Gulf and Northland. The Morinsville facies occupies Coromandel and the Waikato region and includes the Mania Hill Group (Skinner, 1972). Ages of the greywackes are indicated by letters. Ages of oceanic basalts (microfossils in cherts and limestones) marked by letters in parentheses. P = Permian, (P) = Permian oceanic basement, T = Triassic, LJ = Lower Jurassic.

Figure 12.14: See text p.364. The Waipapa terrane is a northern, younger, analogue of the Caples terrane, being situated between the Murphiku terrane and the Dun Mountain ophiolite belt to the west, and the schists and Torlesse terrane to the east. From Spörli (1978), Geological Society of America Bulletin.
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Rakalia sub-terrane, late Carboniferous to late Triassic, sediments from what is now Marie Byrd Land in the Antarctic.

Figure 12.17: Block diagrams of Gondwana margin. Top, Late Triassic showing the convergent margin suite, trench and encroaching quartzofeldspathic sediments derived from Marie Byrd Land. Below, after deformation of older Rakalia rocks in Rangitata I, Pahau sediments accumulate on Pacific facing slope to the SE of a new trench. The fore-arc basin continues to fill in the SW.

Figure 12.17: Block diagrams of the Gondwana margin with the inner terranes in place. The top diagram shows the formation of the quartzofeldspathic Rakalia wedge outboard of an active trench. Below: Following the collisional Rangatira event, Pahau sediments, much of which are reworked Rakalia sediments, are accumulated. Large labels added. Modified after Bradshaw, Andrews and Adams (1981). Fifth International Gondwana Symposium.

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Figure 1: Provisional tectonostratigraphic terranes of South Island, New Zealand. MTL = Median Tectonic Line; EHM = Esk Head Mélange.

Figure 12.18: Provisional tectonostratigraphic terranes of South Island, New Zealand. The older (Rakia) and younger (Pahau) Torlesse terranes are separated by the Esk Head Mélange. Also shown is an inferred suture between the Caples and Rakia terranes within the Haast schist. 70% original size. From Bishop, Bradshaw and Landis (1985) in Howell (Ed.), Tectonostratigraphic Terranes of the Circum-Pacific Region.

Figure 12.19: This time-space or tectonic assembly diagram illustrates how the terranes are seen as separate entities until accreted. The use of diagrams to compare stratigraphical histories of different regions is not new (for example Wellman, 1956). Modern time-space diagrams express the separate geological histories of terranes, accretion events, and provenance linking between neighbouring terranes. 60% original size. Modified after Bishop, Bradshaw and Landis (1985) in Howell (ed.) Tectonostratigraphic Terranes of the Circum-Pacific Region.
Figure 12.20. Cenozoic terranes from a North Island viewpoint. It represents the transition of the Alpine Fault transform zone into the North Island and its possible subdivision into Cenozoic terranes, as well as current tectonic processes. The Mata River terrane outboard of the Torlesse terrane records Albian-Aptian (early Cretaceous) accretion. After Spörli and Ballance (1989) The Evolution of the Pacific Ocean Margins.
Figure 12.21: New Zealand's geological foundations. A contemporary interpretation of New Zealand's basement terranes including their submarine extensions. Metamorphic rocks and tectonic overprints are shown superimposed on original tracts. In this scheme the Waipapa Terrane is divided into a Bay of Islands Terrane and the Waipa Supergroup, which has recently been proposed as a late Jurassic volcaniclastic assemblage overlapping and linking several Eastern Province terranes. After Kear and Mortimer (2003), and N. Mortimer (2003) (in press).
The Torlesse is described as structurally coherent on a regional scale, but disrupted and deformed in detail, consisting of a stacked sequence of nappes. The whole terrane was inferred to be exotic, having been rafted into the region in the Jurassic (Coombs et al, 1976).

In an alternative model (Bradshaw et al., 1981) terranes are arranged in order as components of an island arc and convergent margin system (Figure 12.17). The great volume of material making up the Torlesse terrane (including all the North Island greywackes) was identified as the main geotectonic problem. The terrane was understood as being composed of four sub-terrane, and the Rangitata orogeny was thought to occur in two phases. ‘Rangitata I’, recorded a Triassic collision event between the Rakaia sub-terrane and the Caples terrane, which formed the Haast schist (cf Wood, 1978, and p.373). A new trench was then established outboard of the Pahau sub-terrane with ‘Rangitata II’ occurring near the end of the early Cretaceous.

By the mid 1980s, the concept of exotic terranes representing a number of accretion and amalgamation events from Paleozoic to the late Mesozoic had become well established (Figures 12.18, 12.19, 12.24). The boundaries of the nine tectonostratigraphic terranes shown on the ‘Provisional Terrane Map of New Zealand’ (Bishop et al., 1985, Howell et al., 1985), have since been modified and re-modified (for example Mortimer, 2003), but the general pattern remains.

The 1985 time-space diagram (Figure 12.19) indicates the inferred separate geological histories of neighbouring terranes. The five terranes shown to the right of the vertical line marked MTL have at some time or other been thought of as ‘the greywackes’ (compare Figure 0.3), and the source of endless stratigraphical trouble ever since Hector’s time. Time-space diagrams came into common use in the early 1970s (for example Monger et al., 1972: 579) and successfully replaced the attempts to create single integrated stratigraphic systems based on the geosyncline (Table 8.3, 8.4). Time-space diagrams are, in effect, specialised stratigraphic columns that emphasise the different histories of juxtaposed terranes but also indicate links between belts, for example, provenance linkage. Sediments may be shed from one belt to another, as indicated by the arrows on Figure 12.19, or stratigraphic units may be shared between neighbouring belts, for example, the Upper Cretaceous and Tertiary covering strata link all the basement terranes. Adjacent belts, such as the Torlesse and Caples belts, may be metamorphically welded together.

A very different style of terrane map with a North Island viewpoint (Figure 12.20) combined ideas about currently active tectonic processes with a subdivision of New Zealand into Cretaceous and Cenozoic terranes (Spörli and Ballance, 1989). These include the Northland Allochthon, its extension to East Cape, and the Mata River terrane in the Raukumara Peninsula, outboard of the Torlesse, and the record of Aptian-Albian (early Cretaceous) accretion and subduction.
Are terranes real or imaginary?

The terrane concept quickly became acceptable to most New Zealand earth scientists although the ‘amount and direction of displacement remain[ed] contentious’ (Cooper, 1987: 51). Unlike North America and Europe (Le Grand and Glen, 1993; Le Grand, 2002) the introduction of the concept into New Zealand in the early 1970s set off little noticeable public controversy, even if some scepticism was privately expressed (A.R.Lillie, pers.comm.). The only words to be exchanged in print were those between J.D.Bradshaw and D.G.Howell when Bradshaw criticised Howell’s ‘novel interpretation’ (1980) of New Zealand’s geological history, but not on the soundness or otherwise of the terrane concept (Bradshaw, 1981; Howell, 1981a).

In New Zealand, the universities rather than the Geological Survey, carried out most of the early work on terranes (cf. USA, Le Grand and Glen, 1993: 26, ftn.). However, survey and university geologists frequently worked together while using the terrane concept (for example Bishop et al., 1976). Survey geologists have since worked in the context of the terrane model as a matter of course (for example Cox and Begg, 1999; Mortimer, 2003, see Figure 12.21).

Why has there been so little controversy here? Pragmatic New Zealand geologists use the terrane concept because it works. Whether or not terranes are real or imaginary (Cooper, 1987) and despite conceptual arguments about what really goes on at continental margins (Sengör and Dewey, 1990; Dewey, 1990: 644; Le Grand, 2002: 203), the model provides a valuable guide and an effective working methodology towards understanding the geological evolution of the New Zealand region. The whole of the New Zealand basement, including both Eastern and Western provinces, is thought to be an amalgamation of exotic terranes (Figure 0.5, and figures in this section) that became accreted to south-east Gondwana during Paleozoic and Mesozoic time. Terrane analysis methodology (Le Grand, 2002: ftn 31) proceeds from initial stratigraphic analysis through a series of data-gathering and analytical phases to paleogeographic reconstructions (Cooper, 1987: 47). Terranes are seen as second-order interpretive entities so that once the terrane boundaries have been adequately defined ‘terrane analysis and terrane mapping therefore should ... follow orthodox geological mapping’ (Cooper, 1987: 44).

Another metamorphism

Metamorphism of the greywackes to form the Haast schists (as described by Suggate et al., 1978: 281-316, and see Table 8.1) continued to present problems but plate tectonic theory began to provide several likely solutions to the problem of causes of metamorphism. Besides deep burial in an accretionary prism (Figure 12.3), and stresses caused by uplift, rifting, drifting, subsidence, and post-Miocene compression, metamorphism could be caused by collision between terranes (Figures 12.21, 12.22).
Figure 12.22: A dramatic visualisation of the ‘megaculmination’ that created the mass of Otago schists and accounted for their peculiar structural features. Modified after Wood, 1978, Tectonics

Whether the Torlesse terrane arrived at the south-east New Zealand margin of Gondwana by strike-dip faulting or by rifting and drifting (Spörli and Ballance, 1989: 180), a collision between it and an already accreted Caples terrane would have resulted in considerable high-pressure regional metamorphism to form the Haast schists (Figure 12.18). Potassium-argon (K-Ar) age determinations give consistent maximum ages at about 140 to 150 Ma, indicating that the Haast schists were metamorphosed in Late Jurassic-Early Cretaceous time (Sheppard et al., 1975), and this dates the presumed collision event.

This major collision event, also interpreted as the Rangitata Orogeny, was thought to have caused ‘widespread dynamothermal metamorphism’ and development of the metamorphic rocks of the Caples, Haast Schist and Torlesse Terranes (Wood, 1978: 364). Unlike the steeply dipping Alpine schists, those of Otago are flat-lying but with steep dips on the margins, stunningly visualised in Wood’s perspective diagram (Figure 12.22). The main regional structure is pictured as an irregular flat-crested antiform, while the schist’s internal structure is made up of an enormous complex of isoclinal folds and nappe-like structures facing northeast, passing into reclining isoclinal folds in the west, southwest and northeast.
In a more recent model, a new terrane, the Aspiring Terrane, was identified lying within the higher grade Haast Schists and between the Torlesse and Caples terranes (Roser and Cooper, 1990: and references therein).

In a startling set of sequential diagrams (Figure 12.23) a geological history is envisaged in which the unlucky Aspiring terrane was compressed between the Torlesse and Caples terranes and overwhelmed during the Jurassic collision event. The lowest diagram agrees very well with all the traditional descriptions of the flat-topped Otago schists (compare with Benson’s 1921 north-south section across Otago, Figure 6.13, p.198).
Growth of a sub-field

The terrane concept proved to be so useful that it became a geological sub-field and quickly spread, especially to other Pacific rim countries. Below is a 1999 analysis of the growth of the terrane sub-field made by counting the number of papers recorded in Georef™ between 1964 and 1996 containing the term ‘terrane’.

![Histogram tracing the growth of the terrane concept in Pacific rim countries, Europe and the United Kingdom. New Zealand geologists have made a noticeable contribution to the concept, reflecting its usefulness in this country.](image)

The contemporary tectonostratigraphic meaning of ‘terrane’ was accepted by Georef™ in 1983 and included in the Thesaurus. Abstracts were inspected to avoid including papers referring to ‘terrains’ and those using ‘terrane’ in the older sense of a region characterised by a rock type (see p.359). Figure 12.22 depicts the growth and maturation of a distinct sub-field within the plate tectonic model5. The rapid exponential growth from 1976 is typical of successful sub-fields, with a twenty-eight fold increase to 1990, or a doubling rate each two years6. The graph indicates the importance of the terrane concept in Pacific rim countries compared with Europe, and the reasonably significant contribution made by New Zealand Earth scientists on the subject.

Since 1990, worldwide output of papers on terranes has diminished. Some of this decrease may simply have been caused by the time lag in recording papers. Some could be disillusionment with the terrane

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5 Counts of permuterms ‘terrane’ and ‘terranes’ in the Science Citation Index 1965-1992 yield exactly the same pattern.

concept. Some might be the result of reductions in science funding (Cartner and Bollinger, 1997). Some may be because all the big discoveries had been made, and the terrane concept has had limited use in Europe. A very likely reason is that for a decade or so, the terrane concept constituted a fast-moving emergent sub-field, attractive to young, imaginative and ambitious geologists. Now that the concept is well-established, avant garde geologists have moved on to more fashionable fields.

**Continental greywackes and the obsolescence of orogeny**

The term ‘orogeny’ referring a mountain-building process (Figure 6.6 p.181) was introduced in 1890 (Gilbert, 1890: 3, 340) and by the mid twentieth century, two meanings of the term were in use. In the first, the processes of orogenic folding movements and uplift were considered together (Holmes, 1944: 377-378), in the second, the separate processes of folding and uplift caused by isostatic adjustment were carefully distinguished (Read, 1949: 148).

Plate tectonic theory brought fresh meaning to elongate orogenic belts, now seen as junctures between converging plates of lithosphere (Dickinson, 1970). The deterministic concept of a diastrophic or geotectonic cycle through a set sequence of tectonic and sedimentary events (Figure 6.6 and p.339) became obsolete (Coney, 1970). A new model was sought in which orogenic episodes were caused by sea-floor spreading and subduction resulting in the collisions of continents with continents, or continents and island arcs (Dewey and Bird, 1970), and by the accretion of trench (geosynclinal) materials onto a continent. Orogeny has since been defined as a ‘collective term for convergent margin processes’ (Sengör, 1990: 1) and it means that folding, metamorphism and other orogenic processes are continuous so long as plate convergence continues. Contrasting with the deterministic diastrophic model, each orogenic belt is thought to have its own unique history (Dickinson, 1970: 22). A limited number of possible orogenic events and tectonic elements can probably be recognised, but the sequence of events and the exact juxtaposition of the elements do not have to be pre-determined. The plate tectonic model is process oriented and within it, no two crustal configurations can be exactly the same (Helwig, 1974).

In contrast to the traditional, short, paroxysmal Rangitata orogeny, the folding phase probably occupied the whole 150 million year period throughout which the New Zealand greywackes were deposited and scraped up into accretionary heaps. Concurrently, the sediments that were folded and imbricated into the prism were lithified, partly metamorphosed, accreted to the margin of Gondwana and turned into continental crust. During early Cretaceous time, about 105 Ma, the convergent margin processes including subduction and accretion that manufactured greywackes on the south-west margin of Gondwana ceased (Bradshaw, 1989; Spörli and Ballance, 1989; Laird, 1993).

After the cessation of subduction and accretion the forces acting on the accretionary prism changed and the new section of continent (the greywackes) was uplifted by buoyancy because of isostatic adjustment.
to form new land (Molnar, 1986). It is this comparatively passive uplift phase that has been traditionally interpreted as the vigorous Cretaceous orogenic episode (K.B.Spörli, pers.comm.), and referred to as the Post-Hokonui Orogeny (Benson, 1921) or the Rangitata Orogeny (Kingma, 1959).

Although the ‘validity of the original concept of a single late Mesozoic orogeny affecting all New Zealand’ was sometimes questioned (Wellman, 1950; Coombs and Cox, 1991: 17), the concept of a comparatively brief Late Jurassic-Early Cretaceous Rangitata Orogeny was not easily abandoned. During the 1970s, the greywackes were still thought of as having been formed during a prolonged period of deposition in a hybrid, non-subducting geosyncline-trench. Orogenic folding and uplift was sometimes thought to be caused by the initiation of subduction in the late Mesozoic (for example Landis and Bishop, 1972), or by collision between terranes (for example Wood, 1978: 352).

When subduction and accretion were recognised as phases of a continuous ‘orogenic’ folding process, no usable alternative term for such long-term tectonic events existed. The terms ‘Rangitata Orogeny’ and ‘Kaikoura Orogeny’ (late Tertiary, Figure 6.7 p.182) survived for some years and were sometimes used interchangeably with ‘Rangitata phase’ and ‘Kaikoura phase’ (for example Adams, 1979). The term ‘Rangitata Orogeny’ was also turned into ‘Rangitata Orogen’ as a replacement synonym for the sedimentary belts supposed to occupy the (almost) defunct New Zealand Geosyncline (Carter et al., 1978), but otherwise, the terms are now obsolete.

Rifting between Gondwana and ‘proto’-New Zealand to form the Tasman Sea began about 100 Ma (Laird, 1981). The newly formed New Zealand microcontinent was stretched with extensional faulting, and many of the Cenozoic fault patterns have been inherited from Cretaceous fractures (Spörli, 1979). As the continental crust was thinned it subsided and by the late Oligocene about 30 Ma it was more than 90% submerged (Spörli and Ballance, 1989: 181). In effect the New Zealand microcontinent was now a large roaming terrane within which the basement greywackes had been subjected to various forces from uplift, rifting, subsidence, and drifting to wrenching.

**Did we need plate tectonics?**

Although plate tectonics explains the processes of off-shore sedimentation and accretion, it tells us little about what goes on in continents (for example Walcott and Cresswell, 1979; Walcott, 1984; Gohau, 1990: 212). Compared with the comparatively simple motion of the rigid oceanic plates, deformation in continental regions is ‘complex and diffuse’ because the continental crust and the mantle below may not move together as parts of the same, coherent, rigid plate (Molnar, 1988). The long and complex deformational history of the greywackes is in part recorded by post-subduction faulting, (for example Spörli, 1979, 1980, 1987a), and as further metamorphism (Findlay, 1979, 1987).
The ‘Alpine Assemblage sediments remain as outstanding problems in New Zealand geology’ (Hicks, 1981). A very great deal of research into the various greywackes of New Zealand remains to be done before their origin and history is well understood. Although these rocks constitute the bulk of the New Zealand landmass, the lack of valuable metals means that we can expect little funding for such work except for routine mapping such as that presently taking place to prepare QMAP, the second edition of the 1:250,000 Geological Map of New Zealand (QMAP), (Cox and Begg, 1999).

Nevertheless, plate tectonic theory has made possible a series of rational interpretations of much of the petrography and structures of the greywackes. Geologists could construct a coherent and believable account of the way in which sedimentation occurred, through to accretion and deformation in terms of current plate tectonic theory, and without any substantial anomalies. Apart from the results of seismic investigations, no one has seen inside a living accretionary prism, but geological investigation of fossil prisms such as the Torlesse and Waipapa greywackes tie in with plate tectonic theory. In contrast, the post-subduction structures produced within the New Zealand micro-continent (Spörli, 1987, 1987a) are a great deal less readily interpreted and only limited investigations are being made into greywacke structures.

The related terrane concept has proved to be extremely profitable. In contrast to the years of frustration and controversy caused by trying to fit different tracts of basement rocks into a fixist geosynclinal model, genuine progress has been made regarding the separate geological histories of the basement terranes in New Zealand (for example Frost and Coombs, 1989; Adams and Kelley, 1998). Questions remain, however. For example, how and why does a huge mass of sediment such as that making up the Torlesse Terrane become detached from its parent continent? Where was the Waipapa Terrane formed? What happened to the missing Lower and Middle Triassic strata in the Torlesse?

Plate tectonic theory has been accepted and used for 35 years. It is as settled in western scientific cultures as atomic theory and evolutionary theory. It is still useful, still strong and can be considered as the geological ruling theory (Chamberlin, 1890) of the behaviour of the earth’s crust, rather than as one of several working hypotheses, and now constitutes ‘scientific dogma’ (Dott, 1978). Dogma or not, much opportunity remains to develop further refinements of supporting theories and hypotheses. Plate tectonic theory remains a fruitful guide to further research and it is capable of absorbing a great many interesting anomalies.
Chapter Thirteen

CONCLUSIONS

I rejoice, on many accounts, to find myself arriving at the termination of the task which I have attempted... I have been compelled ... to speak as a judge respecting eminent philosophers whom I reverence as my Teachers in those very sciences on which I have had to pronounce a judgement.

(Whewell, 1857: 518)

I hold that scientific theories about the world and its geological history are socially constructed, but that the world and its history are not [but] some recent commentators ... seemingly would have it otherwise.

(Oldroyd, 1990: 371)

Ordinary, common greywackes are replete with examples of the kinds of practical and theoretical conundrums faced by geologists. The major part of this thesis deals with the formidable problematical issues outlined on pages 3-5. Everything about the greywackes was (and is) challenging and sometimes controversial. The problems were not only about the name ‘greywacke’. As shown in the previous pages the issues involve geological matters to do with their stratigraphical status, paleontology, sedimentology, petrography, structure, metamorphic status, and their origin and history.

Nothing about the great piles of ‘monotonous’ greywackes is easy. Even the name has caused difficulties because of the need for accurate terminology in science. Murchison’s chauvinistic complaints about the confusing use of the term in England of the 1830s (Chapter 2) was repeated in the 1950s and 1960s and compounded by the long series of attempts to fit greywackes into one or other sandstone classification (Chapter 8). While these efforts reflect the need for accurate terminology in science, it is difficult not to agree with Menard’s observation (1971) that much of that work was obsessively time wasting and a symptom of a science in the doldrums.

Stratigraphy of the New Zealand greywackes constituted a major problem. Geologists struggled for years to solve stratigraphical problems to do with the basement rocks using orthodox stratigraphical methods based on British and European examples modelled on more stable shelf environments (Chapters 4, 5). After a number of attempts by nineteenth and early twentieth century geologists to establish generally accepted stratigraphic columns, no further efforts were made after Benson’s compilation of 1921 and Morgan’s 1922 maps (Chapter 5). Stratigraphic matters were set aside until Wellman formalised the New Zealand Geosyncline in the 1950s (Chapter 7). This new and useful model led to a new series of
competing, and increasingly elaborate attempts in the 1960s and 1970s to create a New Zealand-wide integrated stratigraphic scheme for the basement rocks (Chapter 8). This sequence of classifications was eventually diverted by the introduction first of plate tectonics, and then the terrane concept. The latter has proved to be very useful in the New Zealand tectonic environment (Chapter 12) in which geologists may focus on intra-terrane stratigraphy and avoid confusion by no longer trying to correlate uncorrelatable rocks in neighbouring terranes. Even today, greywackes cannot be mapped using conventional stratigraphic methods in which recognisable units can be followed over long distances.

A lack of both data and a workable tectonic model meant that very little was known about the structural geology of greywackes until the 1950s. Many mesostructures were either not ‘seen’ at all, or if they were seen, their significance was not understood. For the next twenty years, geologists learned how to recognise and record mesostructures (Chapter 10). This led to the increasing use of mathematical procedures to analyse the positions in three-dimensional space of bedding planes, faults and schistosity. Once more, no adequate explanations of deformations could be advanced until the development of plate tectonic theory and the recognition of accretionary prisms (Chapters 11, 12). However, accretionary prisms tell geologists little about what happens to greywackes during the complex deformation processes that go on in continents.

In contrast to the above issues, advances in greywacke petrography, sedimentology and geochemistry have been much more dependent on technical improvements in analytical methods than in model making, except for the significance of Kuenen’s turbidity current theory. Laboratory techniques ranging from X-ray analysis to experiments in sedimentation, to geochemical methods for age and provenance determinations have become increasingly important. These included experimental flume studies leading to important insights into the transport of sand and the origins of such structures as ripples, dunes, and cross-bedding (R.H.Dott Jr, pers.comm.)

Throughout the whole history of geology, including that of the greywackes in New Zealand, the same two problems have dominated:

♦ How to extract and select enough usable data from field and laboratory, and
♦ Getting a workable hypothesis to guide and explain the data.

The rest of this section is focussed on issues of data collection, and the roles of visual language and controversy in New Zealand geology.
Data collection

Geologists … have attuned themselves to the sign language of the natural landscape, learning the grammar and logic of stone.

(Frodeman, 1996: 422)

Geology is a science of connection to our real environment, informed by the action of signs, a geosemiosis, that leads investigators on a fruitful course of hypothesis generation.

(Baker, 1999: 635)

Many problems encountered by New Zealand geologists were caused as much by a lack of observed field and laboratory data as by an inadequate paradigm. The Earth is very large and much data in the forms of written records, measurements, samples, photographs and drawings had to be collected before useful generalisations about rocks and formations could be made. Werner’s eighteenth century Neptunist model of geological history (Chapter 1) failed because he did not have enough data, and the emerging ‘geognostic’ community had yet to build up substantial reserves of knowledge. Eventually, we had to wait until the three-quarters of the Earth’s surface under the ocean could be explored before truly effective tectonic models could be developed, and geologists could move from collecting and organising data to predictive science.

Through the nineteenth century and half of the twentieth century, New Zealand geologists attempted many stratigraphic classifications and correlations on insufficient data largely because early reconnaissance mapping had not delivered enough detailed field information. When field geologists were directed to more economically promising areas even less data on the greywackes was collected. Limited accessibility also reduced the amount of collectible data and perhaps skewed results because samples collected along roadsides and streams may be petrologically atypical if the routes are determined by faults (p.8). Data supply is also limited so long as certain geological features remain unrecognised, such as graded bedding (p.233), until attention is drawn to them. On top of the lack of data, field mistakes and incorrect fossil identifications compound the difficulties (Chapter 5).

Geologists have increased the data supply by developing (and sometimes discarding) new collecting techniques and instruments. The petrographical microscope is certainly the most successful of all geological laboratory equipment (Hamilton, 1982). Other techniques were less successful. During the 1960s and 1970s grain size analyses involving much time and labour were popular among sedimentologists, but although the results yielded neat graphs, they said little about the origin and history of the rocks.
Considerable skill is needed to collect geological data. Craft skills are needed to decide what data is recorded, how much is enough, and what data is sound. Trust must be placed on personal experience and judgement as to both reliability and relevance of the data and the ‘hazardous’ nature of its transition to interpretation (Ravetz, 1971: 75-108). H.H.Read’s aphorism still seems to hold that ‘the best geologist is, other things being equal, he [she] who has seen most rocks, so that the experience of a geologist in fieldwork is of fundamental importance’ (Read, 1952). Geologists develop a type of ‘visual intelligence’ and during fieldwork use a set of mental templates that organise sets of marks into a body of significant signs (Frodeman, 1996: 418).

The hard-earned accumulation of shared experience, practical skills and personal knowledge within any geological community is extremely valuable and difficult to replace. Much of this kind of communal knowledge (Polanyi, 1958, 1962) was lost when the first Geological Survey was placed in recess in the 1890s (Waterhouse, 1965: 994). Similar losses may have occurred in more recent years with the substitution of the second New Zealand Geological Survey with the formation of a Crown Research Institute (Mason, 1990; Galbreath, 1998: 254; Cartner and Bollinger, 1997). The total amount of shared geological knowledge may be decreasing as students turn from standard geology to more fashionable environmental and biological sciences and away from geology altogether.

Regardless of the assertions of social constructivists (Latour, 1987: 99), in no case has a geological problem in New Zealand been solved to the satisfaction of all without the application of firm field or laboratory data supplied by Nature. The generalisation that Nature plays ‘no significant role in determining the scientific consensus’ (qtd by Cole, 1992: 109) is in part because of the conclusions reached about science by sociologists who have studied physicists and molecular biologists at work in laboratories (Knorr-Cetina, 1981). Because the objects studied by the scientists are ‘highly artificial’ and their visibility ‘depends on complex instruments’ (Lynch, 1985), the sociological observers concluded that the objects are artefacts and therefore, scientific facts are ‘constructs established by rhetorical means’ (Parsons, 2001: 85). Geologists are baffled by such claims because they are concerned with ‘concrete things like mountains and rivers rather than presumptive entities like electrons and protons’ (Kitts, 1977: xiv) and if they consider them at all, reject the constructivist conclusions as unjustifiable generalisations.

Nevertheless, geological models are constructions, but they are based on observable data and ordinarily, the observations can be repeated by independent observers. While models are essential to scientific reasoning, geologists are warned to be cautious. Computer models postulate an ideal world, in which the abstracted ‘model only applies to the closed system of design criteria’, whereas the real world is not a
closed system (Baker, 1996). No matter how much data is available, it is always possible that more than
one theory can explain the observations, and the primary value of models is to guide future study
(Oreskes, 1994).

**Data exchange and research networks**

From the earliest days of European exploration, quantities of data including maps, navigation details,
samples, images, specimens, and notebooks were carried back to ‘centres of calculation’ in Europe
(Latour, 1987: 232). However, New Zealand did not last long as an undemanding tributary to European
centres. Settlers began developing their own ‘centres of calculation’, and the Austrian geologist,
Ferdinand von Hochstetter, was invited to contribute data and his opinions to the new ‘centres’ in
Auckland and Nelson (Chapter 3). Unlike tributes of gold and silver, the collected data, inferences and
conclusions made by Hochstetter and others could be simultaneously sent away and retained. After
Hochstetter returned to Vienna, the results of laboratory studies based on material from New Zealand
were shared with scientists here.

Geological understanding in this country has always reflected what was going on in other parts of the
(mainly) English-speaking world. Ever since Hochstetter’s time, New Zealand geologists have belonged
to international ‘research networks’ (Menard, 1971) or ‘invisible colleges’ (Price, 1975: 105). To this end,
the settler geologists exchanged vast amounts of personal correspondence, as well as quantities of moa
bones and bird skins (Barton, 2000) with colleagues in Australia, Britain, North America, Germany and
Austria. Exchanges were slow as they depended on generally ungenerous library funding and the weeks
and months needed for sea mail to reach this country. The institution of the Australian and New Zealand
Association for the Advancement of Science (Chapter 5) initiated invaluable links with the rest of the
scientific world. Sea travel was expensive and slow, and the return fares for a family of four on a
sabbatical to Britain could take close to a year’s salary. International research networks were further
developed by the export of trained geologists beginning in the early 1900s (Mason, 1998), and by the
employment of overseas trained geologists in universities and the Geological Survey. The networks were
extended by post-graduate study overseas, and the importation of overseas post-graduate students for
study here. Geological ‘advances have often accompanied improvements in transportation, and freedom
to travel’ (Harrington, 1974: 401) and the advent of comparatively cheap, quick, air travel in the mid 1960s
meant that New Zealand at last became part of the international scientific travel circuit (Price, 1963, 1975).
Now, pre-prints, telephones, fax and emails permit rapid communication between scientists here and
overseas.
Visual language as an information carrier

[V]ery many if not most scientific writings are supplemented and embellished by plates, photographs, figures, graphs, tabulations, and similar aids to exposition and aids to proof.... as an inveterate reader ... a little of them goes a long way with me. My general view is that, if a writer cannot make himself clear by the aid of words, all the illustrations in the world will not retrieve the position.

(Smith, 1951).

Communication between scientists ... cannot do without non-verbal codes, as they help express something which can neither be directly expressed verbally, nor completely transcribed into verbal language.

(Engelhardt and Zimmermann, 1988: 52).

Thinking with pictures is an essential strand in the intellectual history of technological development.

(Ferguson, 1977).

Geologists and other scientists do not literally ‘read’ their conference papers (also see Gross and Levitt, 1994:240) and their talks and posters are supported by visual images that are often constructed, coloured and displayed using computer technology. Carefully designed illustrations are essential tools of communication for geologists, and no modern geological seminar or published paper is complete without its supporting Powerpoint™ presentation complete with photographs, drawings, graphs, diagrams, charts or maps (Nicholson, 2002). To obtain a quick appreciation of the content of a geological article, students are advised to read the abstract and the conclusion and be sure to study the illustrations with care. In contrast, historians and philosophers who write about geology and other sciences generally ignore the presence and role of visual representations (Rudwick, 1976).

The liberal use of illustrations suggests that geological thinking involves whole-brain activity incorporating left-brain verbal and symbolic activities with right-brain non-verbal visual, tactile, olfactory senses and intuition (Edwards, 1979). Geologists then, must think holistically as they gather data, visualise structures, processes and changes through time, and then convert their ‘visions’ into words. Because of geologists’ reliance on illustrations, this thesis contains a number of images notable for their historical value and their effectiveness in displaying data and ideas.

Educated nineteenth century men and women were usually trained in drawing and watercolours, and in New Zealand, settler geologists used this ability to make visual records of data in the field (Collins, 1965). Although Hector’s handwriting is famously indecipherable, his tiny thumb-nail sketches are neat and clear, while Haast produced a number of fine water colour sketches of the Southern Alps. One of James Hector’s first appointments to his Otago staff was the draughtsman Thomas Forrester, who drew Hector’s first geological map of New Zealand in 1865, and later designed Oamaru’s celebrated stone buildings
(Maling, 1996; Halcrow Nicholson, 1996). Ever since then, a draughtsman or woman has been an essential member of any geological institution’s staff, along with technicians, librarians and curators.

Communication with the public, as well as geologists, is enhanced by well-designed, clear, bold, visual images in publications such as G.R.Stevens’ *New Zealand Adrift* (1980), guide books published by the Geological Society of New Zealand and an information series published by the Institute of Geological and Nuclear Sciences.

Illustrations are meant to explain and clarify the text, and not simply to beautify it. Geologists’ visual language has to be learned (Rudwick, 1976). Like verbal language, it incorporates a ‘complex set of implicit rules and conventions and such communication ... [and is] broadly complementary to verbal communication’. Geological mapping is fundamental to geoscientific research (Betz, 1963; Engelhardt and Zimmermann, 1988: 131) and the construction of a detailed geological map is the most important long-term outcome of data collection in the field. Maps provide overviews and interpretations of geological information, and are a ‘highly complex, abstract and formalized kind of representation’ (Rudwick, 1976 159). The information in maps and other representations is expressed almost entirely non-verbally but it can be ‘read’ by those who understand the established coding and decoding rules (Engelhardt and Zimmermann, 1988: 51-71). Verbal texts are used to explain maps, but cannot replace them.

Geologists interrogate their rocks using both qualitative and quantitative methods. Field records may include written descriptions, sketches, maps, including form-line maps, photographs, and other ‘fuzzy’ non-numerical data (Frodeman, 1995, 1996). When sedimentologists make graphic logs in which the characteristics of a series of greywacke and argillite beds are visually coded, qualitative and quantitative recording techniques are clearly linked and related. The commonest structural information consists of numerical measurements of strikes and dips, which describe the attitudes of bedding planes, fault planes and other linear and planar features in three-dimensional space. This kind of information may be displayed as tables, charts, graphs and stereonets.

Visual language does more than explain text when it succeeds in showing up unexpected connections and interrelationships. The study of maps led Eduard Suess and Alfred Wegener to construct their global theories, and the post-war construction of physiographic maps of the seabed led to the discovery of the mid-Atlantic rift by Marie Tharp (Barton, 2002). Much of the scientific evidence leading to the plate tectonic revolution was presented in the key literature as explanatory visual models (Le Grand, 1988: 260). Without such a specialised mode of communication, we might well still be arguing about the reality of plate tectonics if the explanations had to be made entirely in words.

Personal visualisation of geological phenomena is a necessary skill to geologists, and if ‘you want to be a working geologist you will be useless until you can think clearly in three dimensions’ (Lillie, 1980: 31).
Based on their field observations, many New Zealand geologists can indeed visualise theoretical three-dimensional structures beneath the Earth's surface, and picture in their minds how rocks respond to an array of compressional and extensional forces over geological time (questionnaires, conversations). Over the past fifty years the use of visual language in New Zealand geological writing has increased enormously, and it is not just coincidence that some papers published by structural geologists consist of 60% or more of visual images.

**Role of controversy in New Zealand geology**

Though I don't care for geology, I do like to see the fellows fight.


[The] history of science echoes with as many venomous controversies as the history of literary criticism.

(Koestler, 1978: 153).

Geology has come in these modern days to be a relatively well-restrained and orderly science….How utterly extinct is rudely polemical dissension.

(Davis, 1926: 464)

A historian investigating late nineteenth century geology ‘found a science deep in controversy’ (Greene, 1982: 13). The history of geology is generally thought to be infused with theoretical controversy, giving the impression that various conclusions were arrived at only after a great deal of disagreement. What is meant by ‘controversy’ in science? Does it always mean a fight? Synonyms for ‘controversy’ include debate, argument, disagreement, storm and hullabaloo as well as quarrel, dispute and row. Has a controversy occurred when a published observation or conclusion is silently ignored and never cited? Does good-natured noisy argument over drinks qualify as controversy? What about question time during a seminar when the speaker’s conclusions are searchingly questioned? Over the last thirty years, the accumulation of a very great deal of geological knowledge appears to have proceeded quite uncontrovertially in New Zealand. Some observers believe that science is in the doldrums when review articles and bibliographies largely replace research papers and where ‘controversy and debate replace problem solving, and ... halt construction of the scientific edifice’ (Menard, 1971). More recently, controversy has been seen as a ‘motor’ driving researchers to keep correcting and refining their work (Segerstråle, 2000), and it certainly stimulates further investigation of data (R.H.Dott Jr, pers.comm.).

In nineteenth century New Zealand the shortage of firm empirical data, mistaken palaeontological identifications, lack of understanding of the tectonic setting, and the formulations of personal ruling
theories were perfect recipes for dissension and rivalry. For example, during the 1870s and 1880s three different geologists promoted three stratigraphic schemes, each hoping to have his own scheme and nomenclature accepted (Chapter 4). So long as stratigraphic opinions could differ, rivalry and competition lasted well into the twentieth century with the very different schemes promoted by Park and Marshall (Chapter 5).

Angry conflicts like those between Park and Marshall, and between Marshall and Ongley, are usually discussed by other geologists (if at all) only in terms of the reported geological issues, regardless of whether or not the personal dislike between the antagonists affected their methods and conclusions in some way. Could they separate their personal feelings about each other from their scientific considerations? The strong animosity between Marshall and Ongley is very clearly expressed in correspondence to do with a ‘heated controversy’ between them (Marshall et al., 1934). How did these quarrels influence their scientific work? Their clash did affect what papers were to be presented at a forthcoming conference. We cannot be sure if such intensely emotional episodes did not affect the antagonists’ scientific outlook, but they are sure to have upset their friends and fascinated bystanders. Was it possible to take scientific sides based on friendship?

Marshall described New Zealand as this ‘land of fierce geological controversy’ (Marshall, 1912), as he and Park played out the last of the 19th century style geological confrontations in New Zealand (p.131) (Watters, 1997; Hocken, 2002). Their disputes were as vituperative as any of the classic scientific controversies (for example Secord, 1986, Hallam, 1989). We do not know how far personal antipathies and competition for stratigraphical glory led each man to create his own stratigraphic system or how far their public theoretical differences (Watters, 1997) were driven as much by their contrasting personalities as by their different observations and interpretations of geological data.

Geological controversies have attracted much attention from historians (Oldroyd, 1996: 313) and several major accounts of the history of geology deal with important nineteenth century stratigraphical controversies (Rudwick, 1985; Secord, 1986; Oldroyd, 1990). All of these episodes happened to involve the formidable Sir Roderick Murchison, and all have been identified as eventually leading to some kind of resolution (sometimes after the deaths of the participants) with the establishment of a new piece of geological knowledge. Intense disputation lasted well into the mid twentieth century on such subjects as the age of the earth (Albritton, 1980; Gohau, 1990; Oldroyd, 1996), the origin of granites (Oldroyd 1996: 207-223), and the great twentieth century debate on continental drift (Ch. 11).

Scientific conflict is dramatic and far more interesting to recount than everyday routine work in the field and office, but is hot controversy necessary before scientific progress is made? Does acrimonious controversy characterise geology of today? The Park and Marshall disputes have attracted attention in
New Zealand because they were unusual. Rather than being a means of hammering out a reliable interpretation of field data, their quarrels may have set the understanding of New Zealand stratigraphy back for some years. Had the two been able to co-operate perhaps some of the problems in understanding the relationships between the greywackes, the Maitai beds, the Otago schists and the fossiliferous Hokonui may have been at least partly deciphered by the 1920s.

Activities of the geological community are likened to a ‘field of contest’ (Oldroyd, 1990: 344) but while this may be true of nineteenth century geology, it seems not to be so true of more recent geological activity — except to secure contestable funding. The geological milieu of the decades since 1970 represents a period of ‘normal science’ (Kuhn, 1970) during which research has proceeded comparatively smoothly without serious challenges and during which a very great deal of geological knowledge has accumulated.

The characterisation of geology as being highly ‘controversy laden’ (Rudwick, 1985: 431) is based entirely on nineteenth century examples, such as those do with the daunting status-driven Murchison (see above), as well as the classic Europe-wide disputes to do with Neptunism, Volcanism, Plutonism, catastrophism and uniformitarianism. These were followed by the classic twentieth century controversies to do with the age of the Earth, continental drift and the origin of granite. These have given a skewed view of modern geology. Controversy, competition, debate and discussion continue to take place, but are rarely as vindictive and acrimonious as in the famous confrontations of the past. That role has passed to others.

Evolutionary biologists and constructivist sociologists of science took over the function of abusive public controversialists in the 1980s and 1990s (Gross and Levitt, 1994, Segerstråle, 2000). Angry exchanges in daily newspapers on global warming are presently taking place among climate scientists, while neuroscientists emphatically disagree as to the biological basis of human nature (McKie and Thorpe, 2002). In every case, opinionated controversy has taken place in conjectural areas where there is either or both insufficient data and unsatisfactory hypotheses capable of explaining phenomena and to yield a unique solution (Müller et al., 1991: xii), or even to agree whether or not phenomena such as global warming actually exist.

What distinguishes a scientific controversy from an energetic, on-going, but otherwise civil debate? When does it turn into a hot controversy? Why was nineteenth century and early twentieth century geology notable for acrimonious controversy? Such controversies appear to be set off by a combination of causes:

♦ A lack of enough dependable data.
♦ The lack of reliable hypotheses about the Earth.
♦ The nineteenth century tendency by leading academics to create a ‘school of thought’ lasted in some European and American universities until the Second World War (Müller et al, 1991: x). These were determined by an elitist, status-driven social structure and professional reputations were invested in a single ruling theory that had to be vigorously defended.

♦ Few, if any, ruling theories of geology now see the light of day in a world of peer review.

While nineteenth and early twentieth century geology was ‘notable for the acrimony of its controversies’ (Greene, 1982: 192), a short-lived period of academic calm took place when Suess’s powerfully comprehensive theory of the Earth came ‘close to unifying geologists into a single community’ (Greene, 1982: 14). However, the theory collapsed early in the twentieth century. Even more importantly, a major change in methodology took place around 1890 when leading geologists began to abandon the creation of unique ruling theories and turned to the development of working hypotheses, in each of which somewhat less ‘parental affection’ (Chamberlin, 1890), emotional energy and personal status was invested than in a ruling theory. In New Zealand, McKay (1894) was the first to recognise the value of testable hypotheses when reviewing theories of the geological history of this country, but the method appears to have escaped both Park and Marshall.

Today’s geologists are no less red-blooded than their predecessors, but they possess a strong background global theory and a very great deal more reliable data, and thus any disputes appear to be far more manageable. The geologists are regularly engaged in formal and informal discussion, argument, debate, and exploration of ideas. In contrast, the hard feelings demonstrated in the past sometimes went far beyond ordinary professional questioning and argument about observations and conclusions and into obsessive disputatiousness. Today’s geological seminars and conferences are generally calm, orderly affairs, and at question time lack the kind of vituperative (if entertaining) verbal battles that W.M.Davis yearned for in 1926.

The team competitions during the 1960s and 1970s to achieve a workable stratigraphical scheme for the basement rocks of the New Zealand Geosyncline (Chapter 8) were hot but the style, even in letters to the editor of the New Zealand Journal of Geology and Geophysics, was civil and dignified. The competition took place during a period when the background paradigm was being replaced by a far more comprehensive multileveled model of the earth, and all participants seemed to be mindful of the precarious status of all of their hypotheses, all liable to modification or even total defeat.

Several individual post-1950 disagreements were set off during periods of paradigm change with most instances involving one or two very sceptical individuals concerned about the existence of turbidity currents (Kingma, 1958, and p.234), on the amount of transcurrent movement on the Alpine Fault (Schofield, 1960), and on the reality of plate tectonic motion (Schofield, 1975). The turbidity current
dispute became a personal quarrel between Kingma and Kuenen himself. Perhaps some holdouts against new hypotheses had begun by playing devil’s advocate and then found themselves trapped in a position where it was difficult to gracefully retreat, although other conflicts perhaps began as genuine scientific disputes. No new geological knowledge came of these sporadic disagreements, and none of these episodes, even when there were hurt feelings, can support the idea that today’s geology is controversy-laden.

After thirty years’ of Kuhnian puzzle-solving, plate tectonic theory is set comfortably in place as an orthodoxy (Dott, 1978), and operates as a true and fruitful model of the actual Earth. Perhaps geologists have become a little too complacent about their paradigm and it is true that ‘controversies are good for us’ (Müller et al., 1991: xiii). Perhaps it is time for conferences to be enlivened by a couple of ‘outrageous theories’ in which ‘violence must be done to accepted principles and accumulated convictions’ (Davis, 1926) in order for further progress to be made.
Appendix I

Selected 19th Century English Language Definitions of Greywacke

The following passages were extracted from several articles as well as popular and academic textbooks. However styled, there is general agreement among the writers as to what kind of rock constitutes a grauwacke or greywacke.


I give the name grauwacke to a rock composed of separate siliceous particles united by an argillaceous cement, with a little magnesia and iron. It might be called a sandstone, having a base so fine that the rock appears homogeneous but the name grauwacke, made us of by the school of Werner, has been generally adopted.


Dr Berger is the first mineralogist that has given a general name to the rocks that lye on the granite ridge of Cornwall, and has pronounced them to be Grauwacke; a rock, he says, composed of separate siliceous particles, united by an argillaceous cement with a little magnesia and iron. We believe that it is true, that the Cornish rock here meant is to be referred to the tribe of the Grauwacke; at the same time we must object to the definition above, if it is to be understood as general. The particles united by the argillaceous cement of grauwacke consist often of felspar, and have the appearance of proceeding from the disintegration of porphyry. The term applied by the Cornish miners to this rock is Killas; which, on account of its better sound, we should very much wish to see substituted for the uncouth German name of Grauwacke.


Grey Wacce. Is a mechanical deposit of Quartz, Clay-slate, and fragments of Primitive Rock, in coarse and fine particles; sometimes slaty. Geologists differ much respecting what is, and what is not, Grey Wacce. Varieties of it are nearly allied to Greenstone, and some contain organic remains.

Robert Bakewell (1838): An Introduction to Geology. 5th ed. (intended to convey a practical knowledge of the science, and comprising the most important recent discoveries, with explanations of the facts and phenomenæ which serve to confirm or invalidate various geological theories.) Longman, Orme, Brown, Green, & Longmans, London.

[Re primary, transition and secondary rocks pp 12-13] the prevailing rocks in the transition series are limestone, slate, called clayslate, and coarse slate, passing sometimes into sandstone, and conglomerate; this has been called by the Germans grauwacce, or grey wacce.

[p.134] Greywacke and Greywacke-Slate : German Grauwacke.- This dissonant term, which we have borrowed from the German, the French geologists have exchanged for a name not more harmonious, though more expressive, Tramate, from the Greek Thrausma, a fragment. Greywacke, in its most common form, may be described as a coarse slate containing particles or fragments of other rocks or
minerals, varying in size from two or more inches to the smallest grain that can be perceived by the eye. When the imbedded particles become extremely minute, greywacke passes into common clay-slate. When the particles and fragments are numerous, and the slate in which they are cemented can scarcely be perceived, greywacke becomes coarse sandstone or gritstones. When the fragments are larger and angular, greywacke might be described as a breccia with a paste of slate. When the fragments are rounded, it might not improperly be called an ancient conglomerate. When rocks of greywacke have a slaty texture, they form greywacke-slate.

Greywacke has, by some of the French geologists, been described as a transition sandstone, with a cement of siliceous earth or of slate. This definition agrees with the gritstones associated with the upper transition or mountain limestone. Where the paste is hard and siliceous, as I have observed in the greywacke of Savoy, that separates the primary from the secondary rocks, many of the siliceous particles may have been original concretions formed at the same time as the paste; and where these concretions are all composed of quartz, we may infer that such has been their mode of formation. In other instances, the fragments are evidently the debris of more ancient rocks, that have been broken down by some great catastrophe, and mixed with more recent beds at the period when they were forming. This mode of formation implies, that a considerable period elapsed, between the formation of the primary and secondary rocks. The fragments are always those of lower rocks, and never of the upper strata. In some situations immense beds of loose conglomerate, composed of large fragments and boulders of the lower rocks, separate the slate rocks from the calcareous formations: such conglomerates may be regarded as occupying the geological place of greywacke, and belonging to the greywacke formation.


The Transition Class, consisting of rocks formed of fragments of the rocks forming the ‘primitive mountains and plains’... becoming agglutinated by their own pulverulent cement, soon recomposed continuous strata... to form the ante-diluvian transition rocks. [They contain] some vestiges of animal existence [and are part of] the inscrutable pathway between nonentity and existence, which an Almighty Being alone could traverse [the transition between the upright primitive, and the horizontal secondary strata]. They consist of a single Order, viz, Greywacke rock which include conglomerate, clay-slate, flinty-slate, alum-slate, limestone, dolomite with Encrinites.

These rocks are called conglomerate or greywacke formation... refers to the puddingstones of Savoy as greywacke schists, containing rounded fragments of gneiss and mica-slate, 6 or 7 inches in diameter.

Class II. Transition or Submedial Rocks

Order I. Greywacke - conglomerate, clay-slate, flinty-slate, alum-slate, limestone, dolomite with Encrinites

Greywacke is commonly composed of grains or fragments of quartz, and Lydian stone, among which bits of clay-slate are disseminated. These parts are agglutinated by a cement of an argillaceous kind, usually imprgegnated with coarse siliceous matter. The size of the grains of quartz and Lydian stone, rarely exceeds a nut ; but the pieces of clay-slate are sometimes as large as the hand. Occasionally these fragments are so comminuted, as to be no longer discernable ; the rock takes then a schistose texture approaching to clay-slate.

The greywacke formation is the first of Scotland in geognostic importance. It constitutes alone almost all the mountain chains of the south of this country.... This chain of greywacke crosses the island extending from sea to sea. It abounds in metal veins [p147].

Greywacké; (Ger. grauwacke) - a German term originally employed to designate the grey-coloured argillo-arenaceous beds, or coarse slaty strata of the Transition rocks, and subsequently as a name for the entire transition series. It is now seldom employed in this sense - the "transition" rocks having been resolved mainly into the Silurian, and partly into the Cambrian and Hypozoic systems. It is still, however, used to designate the hard, gritty, brecciated, or breccia-conglomerate beds which occur in these formations; and, as a mere lithological term for these ancient grits and breccias, is by no means without its convenience.


[p.140] These so-called Cambrian strata, and those now regarded as unmistakably Silurian ... formerly known as the Greywacke or Transition formation; the former term being a German word applied to certain pebbly or gritty slates of a grey rusty colour which occur in the series.... The term greywacke is now seldom employed, or employed only to designate a peculiar slaty siliceous grit, and the precision of fossil inquiry has all but exploded the idea of a transition period.


These Laurentian and Cambrian strata, along with ... Silurian, constitute the [iGreywackeè] or [iTransition] formation of the earlier geologists; the former term being a German word applied to certain slaty grits of a grey rusty colour which occur in the series.... 'The term Greywacke is now seldom employed, or... only to designate a hard grey gritty rock of Cambrian or Silurian age...'

GREYWACKE (Ger.grauwacke. A German term originally employed to designate the grey-coloured argillo-arenaceous beds, or coarse slaty strata of the transition rocks, and subsequently as a name for the entire transition series. It is now seldom used in this sense; but is still employed to designate the hard, gritty, brecciated, or breccia-conglomerate beds which occur in these formations; and, as a mere lithological term for these ancient grits and breccias, is by no means without its convenience (p.461).


Greywackeè - This is an aggregate of rounded sub-angular and angular grains and splinters of quartz, felspar, and slate, sometimes with mica and grains of other minerals and rocks, embedded in a hard paste or matrix, which may consist of siliceous, calcareous, argillaceous, or felspathic matter. The rock is generally harder than most sandstones. Grey and pale blue are the most common colours, but green, brown, yellow, red, and purple greywackes are not uncommon, and black (anthracitic) varieties are known. All textures are met with from close-grained compact rocks to coarse grained varieties made up of small angular fragments like a breccia. The finer-grained rocks frequently contain fragments of hard shale and clay, like the corresponding clay-galls in sandstone. It is often impossible to distinguish the granular texture of the fine-grained varieties without the aid of a strong lens. Occasionally the rock takes on an incipient crystalline texture. This is especially the case with felspathic varieties, which are sometimes mistaken for igneous rocks. Frequently solution or fusion of the grains and minute angular fragments seems to have taken place, rendering the rock extremely hard and compact. At other times such peculiarly compact varieties probably owe their hardness to the infiltration of siliceous cement. The rock occurs in thick massive strata like liver-rock, and in thinner beds and layers like ordinary sandstone and flagstone.
Appendix II

Selected geological reports by visitors to New Zealand to 1855

These reports usually have some reference to the greywackes, even if not mentioned by name. Most references were found by Alan Mason and recorded in the Geological Society of New Zealand Historical Studies Group Newsletter. Large libraries usually have copies of Beaglehole’s volumes on the voyages of Captain Cook. Archives of the Alexander Turnbull Library and the National Archives constitute extremely important resources especially for newspaper and private papers, but require careful searching.

Journal kept by Sir Joseph Banks Esqr from August 25th 1768 to July 12th 1771, 2 vols. Autograph manuscript in Mitchell Library Sydney, transcript believed to have been made by daughter of Dawson Turner, botanist and antiquarian 1775-1858.

[March 30, 1770, D’Urville Island.] ‘I examined the Stones which lay on the Beach, they showed evident signs of mineral tendency being full of Veins, but I had not the fortune to discover any ore of metal (at least that I know to be so) in them as the place lay in had no bare Rocks in its neighbourhood; this was the only method I had of even conjecturing.’


[Saturday 31 March 1770:] ‘Iron ore is undoubtedly to be found here, particularly about Mercury Bay where we found great quantities of iron sand, however we met with no ore of any sort neither did we ever see any sort of metal with the natives. We met with some stones in Admiralty Bay that appeared to be Mineral in some degree but Dr Solander was of the opinion that they contained no sort of Metal: the white stone we saw near the South Cape and some other parts to the Southward which I took to be a kind of Marble such as I had seen on one of the hills I was upon in Mercury Bay. Mr Banks I afterward found was of the opinion that they were mineral to the highest degree, who is certainly a much better judge of these things than I am and therefore I might be mistaken in my opinion....however, I am no judge how far mineral can be distinguished as such - certain it is that in the southern parts of the country there are whole Mountains of nothing else but stone, some of which no doubt may be found to contain metal....’


Julien Marie Crozet: second in command of the French expedition under Marion du Fresne, which arrived in New Zealand in 1772:] ‘I first of all observed that the mass of the land of New Zealand looked like a great range of mountains, which might formerly have formed a portion of some great continent.... Might not the subterranean fire, which formerly burned and vitrified so much matter in New Zealand, have also by several shocks detached this island from New Holland or from the Austral lands or from some other continent?’ [p.71].

‘In my wanderings on the land which surrounds the Bay of Islands I found here and there blocks of white marble, or red jasper, ideous marble which suggests that there exists in this island some marine deposit around the nucleus of the ancient rock of granite, the base of which appears to be gabbro laminated and more or less black, containing a white substance which is pulverulent and dull in some, but brilliant and solid in others; crystallized quartz, firestone, flint, chalcedonic agates, pebbles crystallized in the interior, others translucent and similar to those which one finds in India on the Malabar Coast.’
Appendix II


[In Dusky Sound, Monday April 12 1773] ‘Huge heaps of stones lies at the foot of this Cascade which have been brought by the force of the stream from adjacent mountains the stones were of different sorts none however appeared to contain either Minerals or Metals nevertheless I brought away specimens of every sort as the whole country that is the rocky part of it seems to be made up of these sort of stones and no other.’

George Forster, 1777. *Voyage Round the World in His Britannic Majesty’s Sloop, Resolution, commanded by Captain James Cook*. 2 vols London. Vol 1

[The cascade in Dusky Sound, p.149.] ’The rocks and stones] about the cascade consisted of masses of granite, and moorstone (saxum) and of a kind of brown talcous clay-stone, in strata, which is common to all New Zealand.’

[Queen Charlotte Sound, p.203] ‘The argillaceous stone, of which most of the hills about Queen Charlotte’s Sound consisted, is sometimes sufficiently soft for that purpose [holes as nesting sites for shags]. It runs in oblique strata, commonly dipping a little towards the south, is of a greenish-grey, or bluish, or yellowish-brown colour, and sometimes contains veins of white quartz. A green talcous or nephritic stone, is also found in this kind of rock, and when very hard, capable of polish, and semi-transparent; it is used by the natives for chisels, hatchets, and sometimes for pattoo-pattoos: it is of the same species which jewellers call the jade. Several softer sorts of this stone, perfectly opaque, and of a pale green colour, are more numerous than the flinty semi-transparent kind; and several species of hornstone and argillaceous slate likewise are seen running in great strata through some of the mountains. The latter is commonly found in great quantity, and broken pieces, on the sea beeches, and is what our seamen call shingle, by which name it is distinguished in the account of Captain Cook’s former voyage. On these beaches, we also met with several sorts of flinty stones and pebbles, and some loose pieces of black, compact, and ponderous basaltes, of which the natives form some of their short clubs, called pattoo-pattoos. In many places we likewise saw strata of a blackish saxum Lin. Consisting of black and compact mica or glimmer, intermixed with minute particles of quartz. The argillaceous slate is sometimes found of a rusty colour, which seems evidently to rise from irony particles; and from this circumstance, and the variety of minerals just enumerated, there is great reason to suppose that this part of New Zealand contains iron ore, and perhaps several other metallic bodies. Before we left this place, we found some small pieces of a whitish pumice-stone on the sea-shore, which, together with the basaltine lava, strongly confirm the existence of volcanoes in New Zealand.’


‘[In Queen Charlotte Sound] under [the soil] we found an argillaceous substance nearly related to the class of talcous stones, which is turned into a kind of earth, by being exposed to the action of the sun, air, rain, and frost, and is of various thickness; still deeper the same is indurated into stone running in oblique strata dipping generally to the South; their hardness varies considerably, for some of the most indurated and compact will strike fire with steel. Their colour is generally a pale yellow, sometimes with a greenish hue. These strata are intersected perpendicularly or nearly so by veins of white quartz (quartzeum lacteum Linn.) and sometimes contain a green kind of stone of a lamellated structure, and nearly related to the talcous stones. On shingley beaches I have, though, seldom, found a few black smooth stones of the flinty order, and some large detached pieces of a solid, ponderous, speckled grey or blackish green lava employed by the natives to form the emitties, or, weapons for close engagement. A few pumice stones (pumex vulcani Linn.) were likewise collected on the shingley beaches of this isle: but whether they were thrown up by a volcano in the neighbourhood, or carried there from remote parts by the sea, I cannot determine. Among the fossil productions of the country we must likewise reckon a
green stone, which sometimes is opaque, and sometimes quite transparent, manufactured by the natives into hatchets, chisels, and ornaments, and seems to be of the nephritic kind (talcum nephriticum Linn.). This stone is commonly brought by the natives from the interior parts of Queen Charlotte’s Sound to the South West, in which direction they pointed.’

‘We asked for its native place, and they called it Poenamoo, from whence probably the above mentioned part of the country obtained the denomination of Tavai Poenamoo: but next to Motoo-aroo, on the little islet, where the natives formerly had one of their hippa’s or strong holds, this stone is found in perpendicular or somewhat oblique veins, of about two inches thickness, in the above mentioned strata of talcous greyish stone. The nephritic (sic) is seldom solid or in large pieces, for the greatest fragments we saw, never exceeded twelve or fifteen inches in breadth and about two inches in thickness. On the shores we commonly met with a blueish grey, argillaceous slate of a lamellated structure, easily crumbling to pieces, when exposed to the weather: sometimes this slate is more solid, ponderous, and of a darker colour probably on account of some metallic irony particles, which I suppose it to contain. The fragments of this slate scattered on the beach our seamen called shingle. We found in Norfolk Island almost the same strata as in New Zealand.’

**William Anderson** sailed as surgeon on Cook’s third voyage on which there were no scientists. Anderson carried reagents, a blowpipe, a microscope and spirits of wine. Beaglehole, J.C. (1967), The Voyage of the Resolution and Discovery 1776-1780, Cambridge University Press, 2 vols. P. lxxxiv.

[p.802, Queen Charlotte Sound] ‘The land everywhere about the sound is uncommonly mountainous.... The bases of these mountains, at least towards the sea, are constituted of a brittle yellowish sandstone which acquires a blueish cast where the sea washes it. It runs sometimes in horizontal and at other places in oblique strata, being frequently divided at small distances by thin veins of coarse quartz which commonly follow the direction of the other though they sometimes intersect it.’

[p.809] ‘Neither is there any mineral worth notice but a green jasper or serpent stone of which the natives make their tools and ornaments. This is not found in the sound and is esteem’d a precious article by these people who have some superstitious notions about the method of its generation which we could not perfectly understand. It is plain however that wherever it may be found, which they say is in the channel of a large river far to the southward, it is dispos’d in the earth in thin layers or perhaps in detach’d pieces like our Flints; the edges of those pieces which have not been cut are cover’d with a whitish crust like these.’

**Samuel Stutchbury** 1826 Visit to Bay of Islands. ATL MS-Copy-Micro-0189. Diary for April 3-4 1826. Following is transcript of diary notes as micro-film held at Alexander Turnbull Library.

[April 4th Tuesday] ‘On approaching from Sea, the Bay of Islands; you are surprised at the perpendicular appearance of two rocks, called the Sugar Loaves, on passing these rocks you observe to the South westward some exceeding Black rocks, which I afterwards found to be Basaltic, externally bearing the appearance of Scoria. [?]3/4 of a mile distant is an Island named Moturua, (ie Long Island). This Island between high and low water mark, is composed of Clay iron stone above white potters clay, the top sand and loam....’

‘At Tipoonah [Te Puna] which lies on the Western side of the Bay, the rocks are composed of bluish green Chert[?] Chert with manganese. Tipoonah is situated in a valley with a fresh water stream running through it. Rangahu is situated on a hill to the Southward and overhanging Tipoonah. This hill is composed of Argillaceous Schist resting upon the Rocks before mentioned’. [Sketch inserted]

‘At the River Kedi Kedi about 20 Miles from the Bay is a waterfall of about 30ft in height, the water [passing] over immense masses of Basalt [containing?] Chrysolite or Olivine - this fall is deep seated between 2 hills which were composed of stiff brown clay or brick earth with over-laying sand, in the clay strata the natives assured me they found the Red ochre with which they color themselves and canoes. The Bay and Rivers, generally, I should suppose to have been formed by Volcanic eruption, Accounting
for the jumbled incongruous state of the strata. The Rivers are formed in Bays, Bites, Depths, Sudden Flats, Rocks, Reefs, Short turns, etc. The principle rivers falling into the Bay are named the Cawa Cawa, Whyccadde, Whytangi, there is a waterfall up this river the word Whytangi means [??] river, Kedi kedi, and the [Mangoona].’

[5th Wednesday. Left for the Pacific. Sketched the natural arch at Cape Brett.]

R.G. Jameson, Esq. 1841. Late Surgeon Superintendent of Emigrants to South Australia. New Zealand, Australia and New South Wales. New Zealand, Australia and New South Wales (A Record of Recent Travels in these Colonies) Smith, Elder, and Co, London. Jameson’s account is a travel book for intending emigrants and includes observations on life, customs and dress in New Zealand, in which Maori exchanged pork and potatoes with seamen for jerseys and blankets.

‘Without hazarding a geological theory, I should say that the scenic character of New Zealand is such as might be supposed to have resulted from the simultaneous upheaving, by volcanic force, or argillaceous and basaltic rocks and mountains, which have been subsequently disintegrated and rounded off by the action of the elements. The influence of a warm, moist, and genial climate has then fostered a profuse vegetation, which passes through countless varieties, from the kaori (sic) tree to the creeping liane and epiphyte. Rocks of the primitive and secondary classes, including the carboniferous strata, are extensively found in some parts of New Zealand, and there is abundance of transition slate in the neighbourhood of Hokianga. Isolated masses of quartz and granite occur through the island, but the predominant structure and aspect of the rocks and mountains marks them as belonging to the igneous classes denominated trap, basalt, and greywacke.’

‘Besides the principal peaks, all of which are, or have been, volcanic, there occur in all parts of New Zealand, but particularly about Waimate and the Frith of Thames, numerous isolated eminences, each having its crater well defined; the monuments of a bygone age, of intense igneous action, which has extensively changed the relative position of the sea and land throughout the southern hemisphere, and probably given birth to New Zealand itself. In the fires of Tongarido and Wakari, we perceive the surviving energies of that volcanic agency whose visible effects are attributed by the New Zealanders to the great Mawe, a mythological personage .... by whom ... these islands to have been fished up from the bottom of the ocean .... The exuviae of ammonites and other marine shellfish have been found by some of the missionaries in the secondary calcareous strata, which are observed in the east coast, between Tauranga and East Cape; and elsewhere they will doubtless be found, when these islands are more minutely examined by geologists.... the New Zealanders, observing [fossils hills, mountains] . adopted the ...supposition that the land which contains in its rocky strata these instructive relics, had at some period been covered by the ocean’.

[p.291] ‘The island of Wyheke consists of the common argillaceous rock of New Zealand, and in some situations it assumes the appearance of an amygdaloidal trap, like that which is so abundant in Coromandel harbour.... The neighbouring islets are all of the eruptive or volcanic class; and some of them assume that remarkable sugar-loaf shape which has elsewhere been noticed as a very frequent characteristic of that formation. On the side of the island which faces the coast of Maraetai, a mine of manganese has been discovered by Mr Henry Taylor, a gentleman who has devoted himself to mineralogical observations in New Zealand’.

[p.311] Thames valley plain] ‘The composition of the soil throughout this extensive plain bears an affinity to the geological constitution of the elevated mountain ranges on either side, which consist of the unstratified classes of rocks that predominate throughout New Zealand - viz., greywacke, basalt, trap, and pumice. The decomposition of such rocks furnishes a clayey soil, extremely fertile.’

[p.320. Tavai-poenameo. South Island] ‘The coal is described by Dr Dieffenbach [sic] as being of excellent description, burning nearly without residuum’ at Blind Bay on the west coast. ‘Tavi-poenameo is traversed in its whole length by a range of mountains which are covered with perpetual snow.... Of the interior ... we know nothing but from the vague oral descriptions of the few natives who inhabit its
shores.... The romantic scenery of Wales and Scotland... will sink into tameness if compared with .... Tavai-poenamoo’.

Charles Darwin (1851): Geological Observations. (Geology of the voyage of the Beagle under the command of Captain Fitzroy R.N. during the years 1832 to 1836) Smith, Elder and Co, London.

[Darwin’s only mention of New Zealand geology in this book consisted of a footnote p.142, Part II, and a paragraph on river terraces p.141] ‘In the neighbourhood of the Bay of Islands in New Zealand, I observed that the shores were scattered to some height, as at Van Diemen’s land, with sea-shells, which the colonists attribute to the natives. Whatever may have been the origin of the shells, I cannot doubt, after having seen a section of the valley of the Thames river (37°S) drawn by the Rev. W.Williams, that the land has been elevated: on the opposite side of the great valley, these step-like terraces, composed of an enormous accumulation of rounded pebbles, exactly correspond with each other, the escarpment of each terrace is about fifty feet in height... formed during intervals of rest in the slow elevation of the land.... Dr Dieffenbach, in his description of the Chatham Islands ... states that it is manifest "that the sea has left many places bare, which were once covered by its waters.”

[Footnote] ‘I will here give a catalogue of the rocks which I met with near the Bay of Islands, in New Zealand:- 1st, Much basaltic lava, and scoriform rocks, forming distinct craters; 2nd, A castellated hill of horizontal strata of flesh coloured limestone, showing when fractured distinct crystalline facets; the rain has acted on this rock in a remarkable manner, corroding its surface into a miniature model of an Alpine country; I observed here layers of chert and clay iron-stone; and in the bed of a stream, pebbles of clay-slate; 3rd, The shores of Bay of Islands are formed of a feldspathic rock, of a blueish-grey colour, often much decomposed, with an angular fracture, and crossed by numerous ferruginous seams, but without any distinct stratification or cleavage. Some varieties are highly crystalline, and would at once be pronounced to be trap, others strikingly resembled clay and slate, slightly altered by heat; I was unable to form any decided opinion on this formation.’


In 1840 the scientific party led by Charles Wilkes, and including the geologist, James Dana, was left at Sydney while the squadron visited Antarctica. They sailed to the Bay of Islands on the British brig, the Victoria, arriving on 24 February 1840. The squadron dropped anchor in the Kawakawa River on 30 March (p.370). Wilkes wanted to shorten the stay in New Zealand and all departed on 6 April 1840.

[p.371] ‘The land ... barren hills without accompanying valleys ... so little level ground that terraces are cut in the hills to build the cottages. [as can be seen today at Oihi].... bare hills and extensive sheets of water.... resemblance to Tierra del Fuego. Black islets and rocks.... These rocks are of basaltic character. About the Bay of Islands the rock is compact and argillaceous, showing little or no stratification, and is for the most part covered with a layer of stiff clay, two or three feet thick, the result of its decomposition. The hills about the Bay of Islands are generally from three to five hundred feet high, but some of those at the head of the bay reach one thousand feet. The district about the Bay of Islands, and the northern part of the island, may be styled volcanic; for, in addition to rocks of undoubted volcanic origin, all the others had in a greater or lesser degree undergone the action of fire....’

[Wilkes mentions Henry Williams’ remarks on Port Nicholson, Tauranga and the volcanic district with geysers. Wilkes also describes the volcanic cones and hot springs near Bay of Islands and gives fascinating observations of New Zealand life and customs. Several of his gentlemen who arrived several weeks’ earlier witnessed the signing of the Treaty of Waitangi.]

Dana visited the Bay of Islands only and depended on Ernst Dieffenbach’s reports on the rest of the country. The drawing of the Old Hat Island is on p.442, with a discussion of the formation of the shore platform a result of wave action and breaker roll pp.109-110. Little is known of Dana’s New Zealand work because of the strange decision by the US Congress to limit the number of copies of the Expedition reports to 100.

Chapter VIII. Geological Observations on New Zealand.

[The Bay of Islands] ‘waters are studded with islands ... where the sea dashes wildly through narrow channels ... A dense growth or thicket of ferns has succeeded the former forests which have been burned’.

‘[T]he portion of the group trending northwest is parallel with the grand ranges of the Pacific, while the other portion has the transverse direction of the Tonga islands, ... with the Kermadec Islands, is part of one and the same north-northeast and south-southwest chain.’

‘The most prevalent [rock] in the northern island is a sub-argillaceous rock in general scarcely schistose, and apparently of ancient date. This is the rock of the Bay of Islands and the adjoining country’.

‘Owing to the prevalence of the argillaceous rock, the country ... about the Bay of Islands is covered with a poor soil of a hard clayey nature, producing but little without great labour.... informed by the Rev. Mr Williams that the same was the general character of the northern island ... [but] volcanic tracts, which, though small, afford a rich soil. There is no natural pasture land ... a great obstacle to the introduction of horses and cattle. Where the forests are cleared away, the fern springs up and covers thickly the land’.

‘The arenaceo-argillaceous rock of the Bay of Islands is singularly compact, seldom showing any appearance of lamination or stratification. It is fine in texture ... with no traces of pebbles or even coarse sand. The general colour is greyish-yellow, passing into greyish-brown. It is rather soft, but is intersected ... by veins which are more siliceous and hard, and more or less ferruginous ... veins are often so numerous as to cut up the rock into small irregular blocks. The blocks readily separate, and show that the veins are properly lines of fracture and that they owe appearance and character to a silico-ferruginous solution, which hardened the walls either side’.

‘This ... passes into an extremely hard, siliceous rock, apparently of the same constitution as the softer variety. These siliceous portions [are not in layers alternating with the soft, but] are local, arising seemingly from an alteration of the other rock, and graduating into it laterally, instead of vertically [and produce] the peculiarly rugged scenery of the coast. Seams or veins of pure quartz are numerous’.

‘The ... colour of the siliceous cliffs is a dirt-brown or greyish-black... [or] dirty white, greyish-blue or pale flesh-red colour. At [Tipuna], the rock contains layers of red and brown chert, and also nodules one to six inches in diameter, of white and coloured quartz.... At the same place, there are small seams of black or greenish shining shale, which cleaves readily, affording curved laminae. The rock in these parts has much resemblance to some chlorite beds and the slate, where green, is actually a variety of chloritic slate. A hand specimen would be taken without hesitation for a fragment from a true chloritic rock. The metamorphic changes here indicated are hence of great interest: and we regret that so little opportunity was offered us for following them out’.

‘The stratification [is] occasionally indicated by distant parallel lines along the cliffs of a coast, though seldom distinguishable, even when a cliff is forty or fifty feet high. These parallel lines, when apparent, vary from six inches to as many feet in width [and are] most distinct where the surface is water worn, and are thus brought out when not seen on a fresh fracture. The dip is in all directions between 90º to 30º, but generally ... 45º and 90º ... other lines or fissures crossing those just referred to ... throw doubts on any conclusions as to ... stratification’.
When Dana measured dips in a small area near the mouth of the Waikate river: he found a ‘diversity in direction’ but a general direction to the northward and eastward. ‘In many parts ... there is too great a confusion of lines to make out any general direction; and in many others no fissures whatever could be detected’.

‘No fossils were observed in this rock....although we suspect the rock to be one of the earlier deposits, belonging in the geological series below the coal, we have no decided evidence on this point from organic remains. Dr. Dieffenbach places the formation in the silurian period’.

Dana remarked on the rapid decomposition of the argillaceous rock, and went on to describe the local volcanic cones p.443, the hot springs of Waieri p.445 as well as sketchy descriptions of Egmont, Tongariro, Edgecombe, White Island, Taupo, and Terapaare pp 447-8.

On metamorphism, p.448 ‘the permeating waters which enable the rocks to conduct heat from its source have the same faculty of dissolving the silica of the rock when heated, and will deposit it again on cooling. We may believe that this cause in its different modes of operation has been the great agent in metamorphic modes of operations on the globe’.

‘New Zealand, through its coal beds and copper veins promises to be a better mining than agricultural region’. (p.448)


‘The formation of hills in all places, visited by me, in Ship Cove, Tory’s Channel, Queen Charlotte’s Sound, Cloudy Bay, and Port Nicholson, is either a stratified yellow clay slate, or an unstratified greywacke of the same colour. This rock is one of the most barren for the researches of the geologist.’

**Dr Dieffenbach’s Report … to the Directors of the New Zealand Company Respecting the Natural productions and Present State of New Zealand. The New Zealand Journal No 31, 27 March 1841.**

[On the island of Kapiti] ‘This island is about 25 miles in circumference. The rocks belongs to the transition formation, and consists of clayslate, with numerous veins of quartz, sometimes very soft, greywacke, and occasional beds of siliceous slate, of a black colour and firm texture.’


p.23 D’Urville’s Island: barren-looking yellow stratified rock. Long Island, a sharp ridge of hills with yellow argillaceous slate.

p.26 Queen Charlotte Sound: ‘the geological formation of these hills is very simple. The rock is a stratified yellow argillaceous slate, or a pepper-coloured soft wacke. In a few places this rock is interrupted by siliceous slate, or Lydian stone, of various colours. Little decay has taken place on the surface of this rock ... but it is covered with a moderate array of vegetable mould’.

p.30. The hill above Ship Cove: ‘the same rock, a metamorphic slate, formed its entire composition’.

p.108 ‘Kapiti is about twenty-five miles in circumference. It belongs to the transition formation, and contains much ancient trap-rock : clay-slate rocks and greywacke are the most common.’

p.282-283. Hauraki Gulf, copper-ore at Great Barrier. Waiheke - yellow argillaceous rock and basalt. Ch II p.57. Port Underwood to Cloudy Bay.... ‘A more accurate examination of the coast showed the argillaceous schist in stratifications from east to west, and dipping to the north [see NZGS 1:250,000]. Sometimes no stratifications could be observed, and the rock was of a more granular nature, but still
very soft, and with fissures in many directions, as if it had been acted upon by fire. I observed in the
Straits no indications of any other kind of rock, except the occasional appearance of Lydian stone, massy
basaltic rocks, and greenstone. It became very apparent to me, from the various transitions from one
rock to another, that they had assumed that structure in consequence of the infusion from below of the
trappean rocks, and the consequent metamorphosis of the slate-rocks. I could not discover any trace of
organic remains in the latter, and it is therefore most probably to the transition series that the hills in
Queen Charlotte’s Sounds belong. . . . Notwithstanding the barren quality of this substratum, and the want
of decomposition on the surface, a character common to all the hills of this formation, the vegetation is
by no means defective’

Ernst Dieffenbach, (1845): On the Geology of New Zealand. Reports of the British Association for the
Advancement of Science 1845, 50.

Abstract. New Zealand is a ‘group of mountainous islands nearly as large as England and Wales ...
geological structure is rendered difficult of discovery by the primitive forests that fringe the coast, or,. . .,
impenetrable thickets of the esculent fern. The fundamental rock is everywhere clay-slate, frequently
containing greenstone dykes, as at Port Nicholson, Queen Charlotte’s Sound and Cloudy Bay; in the
neighbourhood of the dykes the clay-slate sometimes assumes the character of a roofing-slate’

Copper pyrites from the Great Barrier Island, ‘where it forms veins in the clay-slate’.

‘The mountain chains of the Middle Island are supposed to consist of primary rocks; quartzose
sandstone and graywacke are met with at the height of 3000 feet; the lofty pyramidal summits are
covered with snow, and deep narrow valleys separate the various ridges, and radiate from the central
cones’.

Robert McCormick. Surgeon to H.M.S.Erebus, Bay of Islands 1841. In Ross, Captain Sir James Clark
Ross, R.N., A Voyage of Discovery and Research in the Southern and Antarctic Regions during the years 1839-

[p.408] ‘New Zealand has a volcanic substratum of basalt and greenstone, with a superincumbent
deposition of clay, [Bay of Islands greywacke?] through which beds of limestone and sandstone outcrop
in various places. The limestone cliffs of Waingaroa Bay contain fossil shells of the following genera:-
Ostrea, Pecten, Terebratula, and Turritella, with Asterias and Echinus; the neighbouring sandstone being
much interrupted by greenstone dykes. Layers of lignite are found in beds of loam. This carbonised
wood . . . is abundantly distributed, both on the east and west coast, especially in the valley of the
Thames, associated with horizontal sandstone formations near Auckland. Copper ore, in micaceous
slate, has also been found in this locality. Fossil shells occur in the vicinity of Poverty Bay.... Cape Maria
Van Diemen ... is composed of a volcanic conglomerate’.

Walter B D Mantell, (1850): On the Geological Structure of the Middle Island of New Zealand. New
Zealand Magazine. 1(1). [Mantell, 1850 #322]

‘In the Middle Island of New Zealand, as in the North Island, the fundamental rocks are metamorphic
schists and clay-slate, with dikes of greenstone and compact and amydaloidal basalt, and intruded
masses of obsidian, vesicular and trachytic lavas, and other igneous product. Hornblende and
porphyritic rocks, gneiss and serpentine occur, but granite has not been observed.’

‘The lofty mountain ranges of schistose metamorphic rocks ... are flanked by volcanic grits, and covered
at their base by alluvial deposits, which have evidently originated from the decay of trachytes ad earthy
lavas, and the detritus of the harder minerals which entered into their composition. No active volcanoes
are known in the Middle Island, nor have any extinct craters been discovered . . . Strata of limestone,
composed of organisms similar to those which prevail in certain cretaceous beds of Europe, crop out in a
few localities of the eastern coast, from near Morakura to Kakanui; but their relation to the adjacent
igneous and metamorphic rocks has not been ascertained’.
Frederick S. Peppcorne (1852), T D Triphook (Napier), William Swainson (1853); Charles Heaphy, were all settlers. All except Triphook published reports, but had little to say about the greywackes.


During a coastal survey by H.M.S. Acheron & H.M.S. Pandora, Forbes was assistant surgeon on Acheron. Forbes believed that New Zealand coal was Paleozoic: ‘In a country in most places so difficult of access, and so thickly wooded, as New Zealand ... little more can be done than simply to specify the series... the relative positions, of the various rocks along the sea-coast.... The water courses are either precipitous torrents, or gentle streams flowing through alluvial deposits; in no case showing a regular and well-defined series of sedimentary rocks.... Appear to be the fundamental rocks of the Middle Island, are granite, gneiss, mica-slate, clayslate, and other metamorphic schists, with rocks of igneous origin’
GLOSSARY


**Accretion**: process by which an inorganic body grows by the addition of particles to its exterior. The addition of material to the edge of a continent, once thought to be because of the conversion of marginal geosynclines into mountains, is now thought to be by the accretion of terranes.

**Accretionary prism, accretionary wedge**: a tectonically thickened mass of sediments within an oceanic trench with a subduction zone. It consists of sediments derived from the land as well as oceanic sediments scraped off the incoming subducting plate.

**Allochthonous**: refers to masses of rocks and or fossils removed from their original site of deposition and transported to another site by such processes as lateral thrusting, overfolding or gravity gliding.

**Aphanite**: In the 19th century referred to a dark coloured, very fine-grained igneous rock in which the mineral crystals are too small to be seen without a microscope. A variety of diabase or basalt. The term was commonly applied to pillow lavas.

**Arenite, lutite, rudite**: technical terms for sandstone, mudstone or argillite, and conglomerates.

**Argillite**: ‘indurated’ mudstone or siltstone. Argillite appears to alternate with beds of greywacke sandstone, but actually forms the fine, upper part of the greywacke layer.

**Archean**: The Precambrian era is divided into older and younger eons. The Archean eon is older than 2500 m.y. The younger Proterozoic eon lasted from 2500 million years to 570 m.y.

**Arkose**: Sandstone consisting of quartz and 25% or more of feldspar. By ‘arkosic’ both Brodie and Lillie meant that these rocks contained much more quartz and feldspar, and were much less ‘muddy’, than the Auckland greywackes

**Bedding**: The sedimentary layering of rock. Bedding planes separate the layers.

**Benthic**: refers to organisms in fresh-water or marine environments that rest on or are attached to the bottom or burrow into bottom sediments, e.g. Torlessia, Titahia.

**Chordate**: animals with a dorsal rod of cartilage-like tissue or notochord associated with a nerve cord. The phylum includes vertebrates in which the notochord is protected by vertebrae as well as seemingly unlikely members such as sea-squirts.

**Clastic**: made of clasts.

**Clasts**: rock particle. Clasts range in size from silt-like grains to boulders.

**Cleaved, uncleaved**: cleavage in rocks refers to the formation of sets of closely spaced, parallel fractures characteristic of low-grade metamorphic rocks e.g. in slates.

**Conodont**: tiny, tooth-like fossils found in Cambrian to Triassic rocks that have become important in dating greywackes. The now extinct conodont animals may have belonged to the chordates.

**Critical taper, critical wedge**: similar to angle of repose, in which a large pile such as an accretionary prism tends to maintain the same shape regardless of size.

**Crystalloblastic**: a metamorphic texture characterised by mutual interference between competing crystals during solid state crystal growth (Allaby, 1991).

**Detrital**: Refers to sedimentary rocks made up of mineral and rock particles. Similar to ‘clastic’.
Dextral: right-handed, clockwise, cf. sinistral.

Diabase, dolerite: medium grained, dark coloured igneous rock of the same composition as basalts and gabbros. Diabase obsolete. Also see anaphite.

Diagenesis: post-depositional chemical alterations in rocks, not classed as metamorphism.

Diatom: Diatoms are unicellular algae, and their cell walls are impregnated with silica. Diatom skeletons have become important in deep-sea deposits since the Cretaceous.

Dinoflagellate: unicellular with two thread-like flagellae. The cysts are useful in biostratigraphy.

Dip: the angle between a surface such as a bedding plane, a fault, joint, foliation or other planar feature and the horizontal plane.

Ensic: refers to an orogenic belt supposed to have developed on sialic continental crust.

Fabric diagrams: see stereonet

Facies: all the features reflecting the particular environmental conditions under which a rock was formed and includes composition, grain size and fossils. A metamorphic facies consists of rocks subject ed to the same conditions of metamorphism.

Fault: a plane surface along which rocks have been broken and displaced.


Friction breccia: includes fault breccias and ‘shatter zones’ caused by mechanical stresses acting through the earth ([Lahee, 1941 #1790: 260]). Obsolete. Today, friction breccias are known as ‘broken formations’ or even ‘mêlanges’.

Fusulinids: members of the foraminifera, marine one-celled animals that have shells made of a substance like chitin, or of agglutinated sedimentary particles, or are calcareous or siliceous. Most ‘forams’ are less than 1 mm in diameter. Fusulinids have fusiform or disk-like shapes and may be up to 100 mm in diameter. They are important Upper Paleozoic index fossils.

Geochronology: determination of geological time. Fossils are used to determine relative ages. Radioactive minerals are used to determine absolute age, see K-Ar method (below).

Gondwana or Gondwanaland: the former Paleozoic-Mesozoic Southern Hemisphere super-continent which broke up to form South America, Africa, Madagascar, India, Sri Lanka, Australia, Antarctica and New Zealand.

Group: a formal lithostratigraphic term referring to ‘an assemblage of two or more contiguous associated formations’. The formations must have some kind of unifying lithologic features in common.

Guyot: a flat-topped, volcanic sea mount.

Heavy minerals: include ilmenite, magnetite, zircon, rutile, tourmaline, garnet. Usually less than 1% of sedimentary rocks ([Tyrrell, 1929 #461: 193]). Often separated in a separating funnel using the heavy liquid bromoform in which quartz and feldspar floats ([Krumbein, 1938 #1746: 319-340]). A heavy mineral ‘crop’ may be diagnostic for a particular formation. Used for correlation by comparing heavy residues, requiring accurate counts and percentages, much skill and experience. The whole method being based on the degree of separation of mineral suites ([Milner, 1940 #1745: 450-458]). Went out of favour in the 1960s, heavy minerals are now used for - what?

Imbricate, imbrication: where pebbles, rock fragments, or tectonic units overlap each other like tiles.

Induration: see p.250. Greywackes are also described as ‘tough’, ‘compact’, ‘hard’.

Integrating microscope stage: A mechanical stage used with a petrographic microscope. The apparatus has six independent revolving measuring drums by which the proportional amounts of six different constituents may be measured in one operation ([Krumbein, 1938 #1746: 369, 467]).
Intrusion or intrusive: a body of rock, usually igneous, that has been intruded into other, older rocks.

Isogords are lines on a map indicating the first appearance of an index mineral and represent a line of constant metamorphic grade ([Allaby, 1991 #12])

Isostasy: a model of the Earth’s crust in which the mass of high-standing mountain chains is compensated by a root of low-density rocks below, rather like a yacht’s keel.

K-Ar method: potassium-argon method of determining the age of geological events, based on radioactive decay of $^{40}$K to $^{40}$Ar. This is a valuable dating method because the potassium isotope has a half-life of 1,300,000,000 years, with a minimum age limit of about 250,000 years. As radiogenic argon gas is formed it escapes from the biotite crystal unless the rock is cool enough to retain it.

Lithic: adjective referring to (usually) sandstones containing more than 25% of rock fragments, for example, greywackes of the Waipapa terrane.

Lithosphere: The rigid, brittle upper layers of the Earth, consisting of the crustal rocks and including all oceanic and continental plates.

Lydian stone: obsolete, refers to chert and chert-like rocks.

Mélange: probably first used in New Zealand by Blake and Landis (1971) referring to the Dun Mountain Mélange and by Bradshaw (1971) referring to the tectonic mélange at Okuku and Esk Head.

Meng: Georg Fischer’s term (p.150). It refers to rocks with a high proportion of labile or unstable constituents, such as rock particles and ferro-magnesian minerals which are easily destroyed e.g. Reed (1957): 24-25.

Metamorphism: the process by which rocks are changed by (usually) increased temperature and or pressure. Many changes are expressed by the crystallisation of new minerals and the development of various lineations (lines or planes) in the rocks.

Modal analysis: The ‘mode’ is the percentage by volume of the minerals making up a rock. Modal analysis is the determination of the mode and usually involves point counting minerals in a thin section using a point counter attached to a petrographical microscope.

Nektoplanktonic: Free-swimming marine organisms whose remains have fallen into the sediments,. These include belemnites and pteroid bivalves like Daonella.

Olistolith: huge clast forming part of an olistostrome.

Olistostrome: a chaotic mass of rock forming a sedimentary deposit. Olistostromes are formed by gravity sliding of material, sometimes into oceanic trenches. Very large portions of rock are called olistoliths.

Ophiolites: sequence of rock types that include deep-sea sediments e.g. cherts above basaltic pillow lavas, gabbro and ultramafic rocks. Most ophiolites are remnants of oceanic crust.

Orocline, oroclinal bend: term introduced by S.W.Carey (1955, 1958) for an orogenic system (a folded mountain range) flexed in plan ti a horse-shoe or elbow shape. The bend between the New Zealand mainland and the Chatham Rise to the Chatham Islands was sometimes seen as an orocline.

Orogeny: mountain-building process, usually by lateral compression of sediments to form a chain of fold mountains. Many geologists now consider orogeny to be an obsolete concept.

Paleontology, palaeontology: the study of fossil plants and animals (the former spelling is used in New Zealand).

Pelagic: Applied to (1) organisms that inhabit open water, (2) deep ocean sediments e.g. pelagic ooze consisting of calcareous tests of globigerina, or siliceous diatoms and radiolaria. Small amounts of volcanic, terrigenous and extraterrestrial dust are found in pelagic sediments.

Pegmatite: igneous rock consisting of very large crystals of granite composition, mainly quartz and feldspar.

Peneplain or peneplane: an area of low relief believed to be the end-product of a very long period of erosion in which the landscape has been worn down. Peneplanation refers to the long-term geomorphological
process of down-wearing of a land mass by rain, wind, streams and rivers to a very low relief until it becomes a peneplane. **Base-levelling** also refers to the erosion process.

**Phacoid, phacoidal:** describes the peculiar rhomboidal shape of fragments of rock strata pulled apart in a mélangé.

**Planktonic:** Minute aquatic organisms that float and drift with water movements such as radiolarians and conodonts. No planktonic foraminifera had been recorded in Torlesse rocks by 1972 (Stevens, 1972).

**Plate tectonics:** the over-arching concept that unifies ideas to do with sea-floor spreading, continental drift, crustal structures, volcanism, seismic activity, leading to a coherent model of how the outer part of the Earth behaves.

**Pluton:** a general term for a very large intrusive body of igneous rocks, e.g. granite.

**Potassium-argon:** see K-Ar.

**Point Counter:** a calibrated slide holder attached to a petrological microscope used for counting mineral populations in a thin-section. The counter can be moved incrementally to make point-by-point traverses across the slide.

**Protolith:** the original rocks of whatever kind, from which a set of metamorphic rocks was formed.

**Pseudo-tillite:** Disordered deposit perhaps caused by a submarine mudflow, consisting of sporadic boulders in a predominantly clay matrix. Used by Pettijohn (1950: 150).

**Radiolarian:** a large group of marine one-celled organisms with a siliceous, lattice-like skeleton. Deep-sea radiolarian ooze consists of 30% or more of radiolarian tests and is believed to form the lenses of red, radiolarian cherts found within the greywackes. Radiolarians are used to make biostratigraphic correlation.

**Redeposition, redeposited sediments:** Synonym for turbidites, referring to the view that near-shore sediments are dislodged, become turbidity currents and are redeposited at the base of the slope.

**Schistosity:** foliation or layered texture characteristic of schist caused by the parallel arrangement of platy minerals such as mica and chlorite.

**Siliciclastic:** refers to sediments formed from silicate minerals and rock fragments, e.g. sandstone, mudstone, greywacke sandstone.

**Sphenochasm:** A triangular gap in continental crust caused by the rotation of one crustal block against another. The gap is filled with oceanic crust. See S.W. Carey (1955).

**Stereonet:** a two-dimensional representation of a sphere. The lines of latitude and longitude form a grid or ‘net’ on which the positions of planes in three-dimensional space e.g. bedding planes, fault planes, can be plotted. Patterns of deformation may then be detected.

**Stratigraphy:** the study of stratified rocks in time and space, and the correlation of rock units from different areas. Correlation may be by means of fossils (biostratigraphy), the rock units (lithostratigraphy) or by geologic time-units (chronostratigraphy).

**Stratigraphic column:** Refers to a diagram representing the succession of stratigraphic units in geologic time. Also refers to the succession of rocks laid down during a specified period of time, or to the whole sequence of strata deposited through geologic time.

**Superposition:** law or principle of superposition first proposed by Nicolaus Steno in the 17th century. Strata are deposited in a sequence so that when undisturbed, each layer of rock is younger than the layer beneath it.

**Tectogene:** obsolete concept in which the gravity anomalies associated with oceanic troughs indicate the presence of a down-buckled part of the continental crust.
**Tectonostratigraphic**: Adj., of uncertain origin, refers to the stratigraphy of tectonically delineated regions e.g. terranes. See page 339.

**Terrane concept**: see p.339-353. A fault-bounded region that is stratigraphically or structurally distinct from neighbouring regions.

**Terrigenous**: refers to siliciclastic sediments derived from the land.

**Texture** in sedimentary rocks: expressed in terms of particle size and shape. Greywackes are described as ‘texturally immature’ because they consist of a range of angular and sub-angular particles including clay, indicating little sorting by stream, wave and current action. **Texturally mature** rocks like quartzite consist of well-worn particles of much the same size.

**Thin section**: a slice of rock is glued by a resin-like substance to a glass microscope slide and ground down until about 0.03mm in thickness, so that light can pass through the rock slice, permitting the examination of the constituent minerals with a petrological microscope.

**Tholeiite**: A type of basalt that is oversaturated with silica. Thoeliites are extruded on the ocean floor and also occur as plateau lavas on the continental crust.

**Thrust**: a low-angle reverse fault in which the hanging wall overlaps the foot wall.

**Trap, trappean**: obsolete term for basalt.

**Tuff**: Compacted rock consisting of fine fragments of volcanic origin. Ash beds are similar but loosely compacted. In the 19th century rocks consisting of large fragments were often called tuffs.

**Turbidite**: see p. 213-215. Sandstone and mudstone deposited by gravity processes.

**Ultramafic** or **ultrabasic** rocks are igneous rocks that consist almost entirely of ferromagnesian minerals. No free quartz is present. Rock types include dunite, peridotite, gabbro, rodingite, serpentine and greenstone or pounamu. They may contain metals such as chromium and copper. (see ophiolites).

**Unconformity**: the contact surface between two sets of unconformable, and often different, rocks representing a gap in the geologic record, such as that between the greywackes and the covering Upper Cretaceous and Tertiary strata in New Zealand.

**Universal stage**: attachment for a petrographic microscope. A microscope slide carrying a thin section is placed between two glass hemispheres. The slide may be tilted into any plane and rotated in that plane. Its orientation is read from graduated circles and arcs ([Krumbein, 1936 #1746: 368]).

**Von Wolff diagrams**: ternary or triangle diagrams. See Howarth.

**Variolitic**: refers to the spherulitic texture formed in chilled, glassy margins of rapidly cooled basalt lavas. The small spherules consist of fine, radiating, fibrous crystals of plagioclase or pyroxene.

**Wacke**: a friable, weathered, clayey basalt.

**Zone**: If used as an informal term ‘zone’ is a general working term for a stratigraphic unit of any kind ([Anon., 1967 #2320]). The more formal ‘Zone’ is used as a stratigraphic unit when other special terms are not available.
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