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Albite

Throughout all grades of metamorphism in the Diahot region the plagioclase is consistently albite with compositions having a range in An-content from 0-4 in lowest grade and lawsonite zone rocks and 2-6 in transitional and lowermost epidote zone rocks (data determined from 23 rocks by the Michel-Lévy method using an universal stage). Brothers (1974) records similar compositions in the New Caledonian metamorphic belt and described maximum values of An7 in highest grade rocks.

Fine-grained untwinned albite is sometimes difficult to identify especially in rocks of lower grade but tends towards a porphyroblastic habit and is more commonly twinned in higher metamorphic grades. Also at lower grades it is generally clear and free of inclusions but at higher grades it is invariably poikiloblastic, often with an alignment of rows of inclusions describing an internal foliation. In twinned albites the composition planes are always straight and unstrained, usually set at high angles to the foliation. Rotated albite poikiloblasts are extremely rare and have been observed in only one rock (23911) in Balade Mine Stream. In the latter case a few poikiloblasts exhibit rotational textures with s-shaped rows of inclusions indicating poikiloblastic growth contemporaneous with the development of foliation (Zwart, 1960; 1962); furthermore, the rows of
inclusions show a consistent degree of rotation i.e. all appear rotated by an equal amount and always with the same sense of rotation. However, as discussed in Chapter 3, porphyroblastic growth of albite has occurred at various points in time (with respect to the time of development of foliation) even in the same rock, some crystallizing prior to the development of foliation, most crystallizing contemporaneously with the foliation and others post-dating the foliation. Some albite porphyroblasts which have crystallized early and where the foliation and schistosity has been flattened later and wraps around the porphyroblasts, have pressure shadows or pressure tails of quartz.

Modally, albite is most common in pelitic schists constituting up to approximately 30 modal percent in some rocks, is less common in rhyolitic metatuffs and quartzose schists and is generally a minor phase, when present, in metabasaltic rocks. As mentioned above, in fine-grained phyllites untwinned albite is difficult to identify and its presence or absence was confirmed by routine whole rock x-ray data.

**Microcline**

Apart from albite and relict igneous plagioclase, microcline is the only other feldspar recorded in this area. It has only been found in rhyolitic metatuffs at Fern-Hill Mine but in some metatuff layers it is very abundant and may constitute as much as about 30 modal percent. This is
reflected in a whole rock chemical analysis (Table 2.1, analysis 4) of a rhyolitic metatuff at Fern-Hill which contains 7.6 weight percent \( K_2O \).

In these rocks microcline often forms large porphyroblasts up to 0.8 mm in diameter, some show the typical grid-iron twinning but a few crystals are patchily twinned and have a mottled wavy extinction, reminiscent of a perthite. K-feldspar has been confirmed from staining with sodium cobaltinitrite following the method of Chayes (1952).

**Lawsonite**

Lawsonite is a common mineral in most rock types in the lawsonite zone. Its form is very characteristic occurring in stubby rectangular euhedral crystals with perfect prismatic and basal cleavages or in euhedral rhombic sections. When lawsonite first appears it forms small prisms (as small as 0.015 mm) but often becomes porphyroblastic in the middle and lower parts of the lawsonite zone in metasediments. Lawsonite is generally much coarser in grain size in metaigneous rocks and reaches up to 0.6 mm long.

The lawsonite zone is defined by the first appearance of lawsonite in pelitic schists, extending to the last appearance of lawsonite which in the region of this study culminates before the first appearance of epidote. In basic metaigneous rocks lawsonite appears approximately at the same time as in pelitic schists, or a little later, but persists up to the lowermost epidote zone where it coexists with epidote as discrete crystals (e.g. 23965, 23962).
Lawsonite varies greatly in quantity in metasediments, ranging from one or two tiny crystals in a thin-section to as much as about 50% of the whole rock in 23748. It can also be an abundant phase in metabasalts but is comparatively rare in acidic metavolcanics and metatuffs.

A notable characteristic of lawsonite is the incidence of crystals standing with their longest prismatic direction at high angles to the foliation. This feature (discussed in Chapter 3, and illustrated in Figs. 3.96-8) can be summarised, viz. (1) Some lawsonites stand at high angles to the foliation which wraps around them, often with pressure shadows of quartz, due to later flattening of the foliation - such crystals are interpreted as pre-tectonic. (2) Most lawsonites lie parallel to the foliation and are considered syn-tectonic. (3) A third case exists where lawsonites stand at high angles to the foliation but which is not bowed around them. Lawsonites in this case are post-tectonic and crystallized after the development of foliation. All three cases may occur in the same thin-section and indicate an early crystallization of some lawsonite which continued to a later stage.

In rare occurrences (e.g. 23595, 23773) there appears to be two different sets of lawsonite crystals in the same rock, one set which is large and partly dirty-brownish that appears slightly altered, and a second typically smaller set consisting of very clear crystals. Such textures suggest that there are two generations of lawsonite, the former being the first partially altered generation and the latter being the second generation. However, these features occur in
rocks which are located in the hinge zones of large regional folds where there was probably multiple deformation and presumably fluctuations in the physical conditions of metamorphism. It is thought that rather than two quite separate generations in time of the crystallization of lawsonite with a period of no metamorphism between each generation, there was continuous metamorphism but which varied in PT conditions with time.

In most cases lawsonite is untwinned but twinning has been observed in some large crystals and fine polysynthetic twinning occurs in lawsonite in a rhyolitic metatuff (23762). This rock is also unusual in that many lawsonites exhibit hour-glass structures, some contain spindle-shaped cores of rather dirtyish, altered lawsonite and many are bent and fractured (especially along (001) basal cleavages) and recemented later with quartz. Bow-tie bundles of lawsonite occur in metasediments near Col de Crève Coeur rather similar in appearance to those in prehnite.

Partial analyses for calcium and aluminium were determined in lawsonites in three metabasalts using an electron microprobe:

<table>
<thead>
<tr>
<th></th>
<th>23751</th>
<th>23606</th>
<th>23965</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaO</td>
<td>16.7</td>
<td>16.6</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>weight %</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>-</td>
<td>-</td>
<td>29.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>weight %</td>
</tr>
</tbody>
</table>

$2V_\gamma$ measurements in about six crystals from each of 16 rocks showed a range of $2V_\gamma = 78^\circ-89^\circ$, averaging $84^\circ$. 
Epidote

The first appearance of epidote in paraschists defines the beginning of the epidote zone. In the region of this study epidote is never abundant in metasediments, constituting less than several percent in the mode. Epidote first appears as small crystals 0.02 mm in diameter and rarely achieves a large grain size. Epidote first occurs in metabasalts at an isolated locality along the Mérétice Road (11003) in the middle portion of the lawsonite zone but does not appear again in metabasalts in situ until just inside the epidote zone, approximately 150 m from the epidote iso-grad. However, no metaigneous rocks have been found in the transitional zone and in the metabasalts mentioned above in the epidote zone it occurs in some large euhedral porphyroblasts up to 2 mm long, suggesting that it would most likely occur at lower grades if favourable parent rocks were available. Nevertheless, many metabasaltic bodies in the region of the beginning of the Mérétice Road are bounded by faults and are probably out of place and the epidote-bearing metabasalts at locality 11003 may in fact represent such a tectonic block higher in metamorphic grade than the country rocks.

Epidote makes an anomalous very early appearance in a rhyolitic metatuff in lowest grade rocks in the Pilou area (23564). In this instance epidote ($2V_\alpha = 81^\circ$) is quite abundant and occurs as anhedral crystals disseminated throughout the rock forming a mosaic texture with quartz and carbon-
ates. The rock has the complex assemblage: quartz-albite-pyrophyllite-chlorite-epidote-calcite-magnesite-opaques (mainly pyrite). The presence of carbonates and large pyrite cubes strongly suggests that the rock is associated to some degree with mineralization.

Epidote is typically colourless but shows slight pleochroism in large porphyroblasts from $\alpha = \text{colourless}, \beta = \text{pale greenish-yellow}, \gamma = \text{pale yellowish-green}$. $2V_\alpha$ ranges from $74^\circ-88^\circ$, averages $81^\circ$, data from a number of crystals in 13 rocks. A partial chemical analysis from electron microprobe data gave the following in a metabasalt in situ from the epidote zone (23965): $\text{Al}_2\text{O}_3 = 26.8$ weight %, $\text{CaO} = 23.8$ weight %.

**Clinozoisite**

Clinozoisite has been identified in only two rocks in the epidote zone, occurring in derivatives of basic metaigneous rocks as discrete crystals coexisting with epidote. In both rocks (23980, 23982) epidote is highly birefringent, forms large euhedral porphyroblasts up to 2 mm long with perfect (001) cleavage, $2V_\infty = 80^\circ$, weakly pleochroic, while clinozoisite occurs in characteristically smaller colourless bladed crystals up to about 0.5 mm long with anomalous greyish-blue interference colours and $2V_\gamma$ ranges from $78^\circ-85^\circ$.

Zoisite has not been found but piemontite occurs in some manganese-rich paragneisses in the glaucophanite assemblage.
Pumpellyite

Pumpellyite is a common mineral in lower grade metabasalts, green veins cutting metabasalts, basic metatuffs and intermediate meta-igneous rocks. It has not been found in derivatives of acid volcanics or in pelitic assemblages.

Pumpellyite is generally the first metamorphic indicator of recrystallization in metabasaltic rocks and its first appearance is the lowest isograd that can be drawn in the progressive metamorphism of the sedimentary-igneous sequence in the Diahot region. On a regional scale pumpellyite generally crystallizes before Na-amphibole in metabasalts (the one exception being the locality in Tchalabel Creek) and in most areas it appears before first lawsonite crystallization in pelites. Pumpellyite remains a stable phase to approximately the middle portion of the lawsonite zone.

In thin-section pumpellyite shows variable optical properties and forms acicular crystals, radiating aggregates, rosettes, bladed prisms, and dense patches composed of very fine-grained crystals often with an overall mosaic pattern produced by an irregular high-relief fracture cleavage (e.g. 23759). Pumpellyite is always pleochroic, most crystals varying from colourless to bright apple green with anomalous interference colours, usually in shades of bluish-grey or browns to purples. Other varieties exhibit colourless or pale yellow to bright golden yellow pleochroism and these varieties characteristically show a higher birefringence with upper first to lower second order interference colours.
Varieties with higher birefringence have been suggested by Coombs (1953) to be more Fe-rich and correspondingly alumina-poor pumpellyites.

In some of the green veins cutting metabasalts pumpellyite constitutes as much as 80% in the mode occurring as dense aggregates and acicular needles. These veins also contain patches of recrystallized quartz (illustrated by sutured grain boundaries and triple-point junctions) with an overall subhedral outline, probably representing relict quartz phenocrysts, which are penetrated in many cases by fine acicular pumpellyite, radiating into the quartz patches from their margins. Sphene is a relatively abundant accessory in these green veins and in most instances pumpellyite has nucleated on the borders of sphene and form radiating rosettes around them. Interestingly, in such cases where this occurs, there appears to be a reaction where pumpellyite adjacent to sphene shows bright yellow pleochroism and upper first to lower second order interference colours, but further away from the sphene and even along the same individual pumpellyite needles, the pleochroism changes to the usual green variety showing anomalous interference colours. Thus, the overall reaction effect is a halo of bright yellow pumpellyite immediately adjacent to the edges of sphene crystals and which gradually changes to an outer border of bright green pumpellyite. Following Coombs (1953) this may suggest a decrease in Fe-content with increasing distance away from sphene and along the length of individual pumpellyite needles, the total length of which is about 0.2-0.3 mm.
Dr P.M. Black (pers. comm.) has analysed eight pumpellyites from the Ouégoa-Boat Pass district using an electron microprobe and has found a wide variation in Fe-content (ranging from 3.65-13.1 weight percent) and a corresponding variation in alumina (ranging from 27.0-20.3 weight percent). However, these analyses are those of the pleochroic green variety and although they are in general quite iron-rich, they may not be as iron-rich as the bright yellow variety described above.

Pumpellyite crystallizes mainly as a replacement of relict igneous calcic plagioclase. In lowest grade metabasalts where pumpellyite first appears it occurs as tiny needles set in relict calcic plagioclase laths but with progressive metamorphism all transitions can be seen until in many cases, especially in the coarser-grained metabasalts, pumpellyite replaces plagioclase completely. In fact in the latter case, sometimes the relict igneous ophitic or subophitic relationships are still preserved with relict augite being characteristically quite unaltered but with perfect pseudo-morphs of dense pumpellyite after calcic plagioclase (e.g. 23574, Fig. 5.1).
Fig. 5.1 Photomicrograph showing compact pumpellyite (p) which has completely replaced calcic plagioclase in a metabasalt. The rest of the rock is composed mainly of unaltered relict igneous augite (a). X20, plane polarized light.

Amphiboles

The sodic amphibole isograd in pelites generally lies at a consistently deeper level than the lawsonite isograd except in the region extending for about 4 km from Pouagone Creek to Forêt d'Ougne where Na-amphibole appears slightly before lawsonite in pelites. In this latter case Na-amphibole occurs in a narrow band of greyish-white siliceous schists which is apparently a particularly favourable lithology for early Na-amphibole crystallization. Moreover, the Na-amphibole in the white siliceous schists (23626-7) forms large acicular crystals reaching 2 mm in length; the presence of such large crystals especially considering that it is the first appearance of the mineral suggests that it could possibly occur even
earlier in the metamorphic sequence if suitable parent lithologies were available.

Na-amphibole always appears prior to lawsonite in metabasaltic rocks but in most cases after pumpellyite crystallization. Also, Na-amphibole appears in metabasalts prior to its first occurrence in pelitic assemblages and Black (1973) has already shown that the first appearance of Na-amphibole in the Ouégoa district is controlled by bulk-rock chemistry. This is supported by the data in the broader region of this study and the interesting case described above where sodic amphibole appears prior to lawsonite crystallization in pelites further proves the dependence and close control of sodic amphibole crystallization on subtle variations in the bulk-rock chemistry even within the range of pelitic composition.

Sodic amphibole continues to crystallize as an apparently stable phase throughout all rock types up to the highest grades of metamorphism and is an abundant constituent in the high grade glaucophanite assemblage.

In a comprehensive study of the composition of amphiboles from the Ouégoa district Black (1973) showed a number of important features enumerated below.

1. Sodic amphiboles show an increase in Mg/(Mg + Fe) ratio from equivalent rock types with increasing metamorphic grade.
2. The sodic amphiboles from metasedimentary and metabasaltic rocks show different compositions - those from metabasalts have relatively lower Na/(Na + Ca), higher Mg/(Mg + Fe), and are less aluminous than the amphiboles from metasediments.
Using Miyashiro's (1957) classification of sodic amphiboles, those from lowest grade metabasalts are iron-rich crossites but those from the lawsonite and epidote zones are more-magnesian crossites and glaucophanes. Sodic amphiboles in pelitic assemblages from the lawsonite zone are ferroglaucophanes while those from the epidote zone are mainly glaucophanes and crossites. Ferroglaucophane has also been identified in the epidote zone in metamorphosed acid volcanics at Bouehndep on the Pam peninsula (Black, 1970) and in a few metasediments rich in Al₂O₃, FeO, and Na₂O in the Ouedoa district (Black, 1973). A reaction involving change in Mg/Fe ratio from ferroglaucophane to glaucophane across the epidote isograd is given under garnet and incorporates the two iron-rich phases almandine garnet and epidote.

The variation in composition of sodic amphiboles from metasedimentary rocks and metabasalts is also illustrated in their 2Vₒ values (Fig. 5.2).

Metamorphic calcic amphiboles, in comparison with the sodic amphiboles, are relatively uncommon and have been found in only two metabasaltic rocks by the present author (23776, 23965). One of them, 23776, is a metabasalt on the Ouedoa-Koumac Road in the lawsonite zone and contains a colourless to pale green fibrous actinolite (composition determined from Ca-amphibole in the same metabasaltic body by Black, 1973). The other rock, 23965, occurs just inside the epidote isograd in the lowermost epidote zone and contains a prismatic green tremolitic amphibole. An electron microprobe
Metasedimentary rocks

Metabasalts

Fig. 5.2 Histograms illustrating variation in $2V_a$ of sodic amphiboles in metasedimentary and metabasaltic rocks in the Diahot region.
analysis of the tremolitic amphibole in the latter rock is given below (Table 5.1).

**TABLE 5.1** Electron microprobe analysis of calcic amphibole in a metabasalt (23965) from the lowermost epidote zone. (Analyst: R.M. Briggs)

<table>
<thead>
<tr>
<th></th>
<th>weight %</th>
<th>Ions per unit cell on basis of 23(O)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>55.1</td>
<td>7.75</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.6</td>
<td>0.06</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>2.8</td>
<td>0.47</td>
</tr>
<tr>
<td>Total Fe as FeO</td>
<td>9.9</td>
<td>1.17</td>
</tr>
<tr>
<td>MnO</td>
<td>0.3</td>
<td>0.04</td>
</tr>
<tr>
<td>MgO</td>
<td>16.0</td>
<td>3.35</td>
</tr>
<tr>
<td>CaO</td>
<td>12.6</td>
<td>1.90</td>
</tr>
<tr>
<td>Na₂O</td>
<td>1.5</td>
<td>0.41</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.13</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>98.9</td>
<td></td>
</tr>
</tbody>
</table>

**Pyroxenes**

A pale green metamorphic clinopyroxene first appears approximately half-way through the lawsonite zone as irregular rims on relict igneous augite in metabasalts. In rocks of the epidote zone it occurs as discrete subhedral prismatic crystals up to 0.5 mm long. In the region of this study pyroxene is absent in metasediments in situ but has been recorded elsewhere in the New Caledonian metamorphic belt in high grade metasediments of the upper epidote zone (Brothers, 1974; Black, 1974) and in acid metavolcanics
(leptynites) at Bouehndep also in the epidote zone (Black, 1970a).

A comprehensive study of the metamorphic pyroxenes in the Ouégoa district by Black (1974) found that their compositions in metabasalts in situ of the lawsonite zone are omphacites or chloromelanites whereas in the epidote zone they are omphacites (using the terminology for the sodic pyroxenes of Essene and Fyfe, 1967). Furthermore Black (1974) showed that with increasing metamorphic grade pyroxenes in metabasalts become more aluminous (jadeitic) and more calcic (diopsidic) at the expense of their acmite components ($\text{Fe}^{3+}$, $\text{Na}^+$). Omphacites from the Ouégoa district have all crystallized in the high pressure $\text{P}_2$ spacegroup.

Table 5.2 presents three partial electron microprobe analyses of pale green pyroxenes, 23576, 23756 from the lawsonite zone, and 23965 from the epidote zone, all from metabasic rocks.

<table>
<thead>
<tr>
<th>TABLE 5.2</th>
<th>$\text{Al}_2\text{O}_3$</th>
<th>$\text{CaO}$</th>
<th>$\text{Na}_2\text{O}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>23576</td>
<td>10.4</td>
<td>13.7</td>
<td>7.6</td>
</tr>
<tr>
<td>23756</td>
<td>n.d.</td>
<td>12.5</td>
<td>6.7</td>
</tr>
<tr>
<td>23965</td>
<td>11.0</td>
<td>12.0</td>
<td>8.1</td>
</tr>
</tbody>
</table>

From comparison with the data in Fig. 1 and Table 1 in Black (1974), the compositions of the pyroxenes given above plot in the omphacite field. The pyroxene is pale grass green, weakly pleochroic, medium birefringent, and in the metabasalts in the epidote zone (23965, 23966) $2V_\gamma$ ranges from $72^\circ$-$75^\circ$. 
The metabasalt 23576 is unusual within the whole metamorphic belt as it contains the assemblage pumpellyite-glaucophane-omphacite-stilpnomelane-chlorite; elsewhere in New Caledonia omphacite invariably is accompanied by lawsonite and/or epidote. However, metabasic igneous rocks in the vicinity of 23576 carry lawsonite but epidote is absent.

Metamorphic pyroxenes with compositions outside the omphacite and chloromelanite fields have been recorded in New Caledonia by Brothers (1970) and Black (1970; 1974) and pyroxene compositions were found to be strongly dependent on parent-rock chemistry (Black, 1974). Aegirine-augite occurs in siliceous metasediments (cherts) within the lawsonite and transitional zone rocks in the Ouégoa-Col d'Arama district (Black, 1974), aegirine has been found near Col d'Arama in metabasic igneous parent rocks (Brothers, 1970), (possibly from a tectonic block not in place), and omphacite with composition intermediate between jadeite and hedenbergite has been found in epidote zone acid metavolcanics at Bouehndep (Black, 1970).

Jadeite has not been found in the New Caledonian metamorphic belt (Brothers, 1974; Black, 1974a) and the ubiquitous occurrence of albite even in very high grade rocks suggests that the high pressure transition from albite to jadeite + quartz is not attained in New Caledonia.
Garnet

Garnet first appears in metasediments in the upper part of the lawsonite zone as rare tiny crystals (approximately 0.02 mm in diameter) but becomes abundant and porphyroblastic in metasediments of the transitional and epidote zones. In the region of this study garnet does not occur in any metabasaltic rocks in situ nor in any acidic metavolcanics or metatuffs, but is abundant in orthogneisses in the glaucophanite assemblage occurring in tectonic blocks in fault zones. However, elsewhere in New Caledonia in the transitional, epidote and Ca-amphibole zones garnet is present in metabasaltic parents in situ (Black, 1973; Brothers, 1974).

In metasedimentary rocks in the lawsonite zone, garnet occurs as clear colourless euhedra, often hexagonal in outline, and in many instances is not totally isotropic probably due to the fine grain size. In higher grade rocks of the transitional and epidote zones it is characteristicallypoikiloblastic with inclusions mainly of quartz, and is pinkish in hand-specimen and very pale pinkish-brown in thin-section.

Chloritization of garnets occurs in many rocks in the vicinity of Murat Mine but this is one of the rare localities where retrogressive metamorphic effects are observed in any in situ rocks over the whole of the metamorphic belt. In this instance, Murat Mine is situated close to a large fault where late movement occurred and also where there is late remobilization of sulphides and folding of the epidote
Black (1973) did detailed analyses of the compositions of garnets in the Ouégoa district and found wide variations in composition with metamorphic grade and bulk-rock chemistry—garnets from lawsonite zone metasediments including calcareous schists are spessartine-rich in composition whereas those from epidote zone metaigneous rocks and typical metasediments are almandine- and pyrope-rich. Furthermore, garnets in metabasaltic parents were found to be more pyropic compared with those in adjacent pelites and there was a general increase in pyrope content in all rock types and an increase in grossular content in pelitic rocks with increasing metamorphic grade.

Black (1973) also found that the garnets in the Ouégoa district are always zoned with cores enriched in Mn relative to Fe and the rims enriched in Fe, Mg and frequently in Ca, the latter especially in rocks not coexisting with omphacitic pyroxenes. The present author observed similar zoning patterns in spessartine-rich garnets from the lawsonite zone in siliceous pelitic parents; partial analyses from electron microprobe data are given below in Table 5.3 from scanning across two single crystals of garnets in one rock, 23595, from near Port Pilou.
### TABLE 5.3

<table>
<thead>
<tr>
<th>Composition</th>
<th>MnO wt %</th>
<th>Total Fe wt % (as FeO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>average rim composition</td>
<td>12.6</td>
<td>14.6</td>
</tr>
<tr>
<td>average core composition</td>
<td>19.7</td>
<td>11.3</td>
</tr>
<tr>
<td>average rim composition</td>
<td>10.6</td>
<td>11.8</td>
</tr>
<tr>
<td>average rim composition</td>
<td>13.5</td>
<td>15.8</td>
</tr>
<tr>
<td>average core composition</td>
<td>18.1</td>
<td>12.9</td>
</tr>
<tr>
<td>average rim composition</td>
<td>13.0</td>
<td>15.3</td>
</tr>
</tbody>
</table>

Interestingly, Black (1973) noted that there was a chemical reaction in the transition from the lawsonite to the epidote zone giving rise to almandine garnet associated with a sharp drop in the Mg/Fe ratio in chlorite and a sudden change from ferroglaucophane (Fe$^{2+}$, Al-rich type) to glaucophane (Mg-rich type), and wrote a simplified reaction: ferroglaucophane + Fe-rich chlorite + lawsonite + glaucophane + Mg-rich chlorite + epidote + almandine.

**White Micas**

White micas are generally widespread throughout all metamorphic grades forming a dominant constituent of metasedimentary rocks but only a minor accessory phase in metaigneous rocks. Two white micas have been identified in the Diahot region, phengitic muscovite and paragonite. The bright green chromian muscovite, fuchsite,
also occurs but only in high grade rocks of the glaucophanite assemblage and has not been found in rocks in place in this region.

Phengitic muscovite and paragonite cannot be distinguished confidently in most thin-sections and in all cases the presence or absence of paragonite has been confirmed by X-ray diffraction data. More than 150 whole-rock X-ray analyses have been made of all rock types ranging over all metamorphic grades, mainly as a confirmative check of the composition and presence or absence of the sheet silicate minerals.

The potassic muscovite is consistently phengitic in composition, pale green or colourless in thin-section and occurs throughout all metamorphic grades, present in many rocks as the single mica phase. Black (1969) showed that the amount of phengite component and the Fe/Mg ratio in K-micas depends on bulk-rock composition, those from derivatives of acid volcanics are most phengitic, meta-basalts are generally less phengitic than acid volcanics, and those from pelites are generally the least phengitic. Also Black suggested that for phengites of any individual mineral assemblage the amount of phengite component in muscovite shows a slight decrease with increasing metamorphic grade; a similar decrease in the phengitic component in muscovite with increasing metamorphic grade has been recorded in several other metamorphic terrains, e.g. in the Moine Schists of the Ardnamurchan area, Scotland, (Butler, 1967; in: Guidotti, 1969). Phengitic muscovite is the most dominant mineral in defining the foliation of
the metasedimentary schists and the sequence of photomicrographs in Fig. 2.1, p. 21 shows the gradual increase in grain size of phengitic muscovite with increase in metamorphic grade, i.e. from a fine-grained sericite to a coarse-grained muscovite.

Paragonite, unlike the K-mica, shows no phengite-type substitution (Black, 1969). It first appears prior to lawsonite and Na-amphibole in pelites although it does not occur in the very lowest grade rocks. Paragonite continues to crystallize right through to highest grade rocks mainly in pelites, occasionally in green rocks possibly derivatives of basic tuffs, but has not been noted by the present author in metabasalts, acidic metatuffs or metacherts. However, Black (1969) has recorded the presence of paragonite in a few high grade metabasalts. Paragonite always crystallizes in assemblages together with phengitic muscovite with only one exception, a green rock (23863) in the upper part of the lawsonite zone, where paragonite occurs in the following assemblage: quartz-albite-paragonite-chlorite-lawsonite-Na-amphibole-sphene-pyrite. As mentioned above paragonite appears identical to phengitic muscovite in thin-section but in some rare cases paragonite occurs as smaller crystals showing a lesser degree of alignment and foliation compared with the larger muscovite plates. Also, in many cases the two micas occur interlayered in parallel intergrowths on a fine scale, both micas having quite distinct compositions.

White micas generally crystallize syn-tectonically but in some cases, e.g. at locality 23592, white micas have crystallized post-tectonically and form unbent, polygonal
outlines in the hinge zones of folds (see Fig. 3.34, p. 75).
In other cases two or even three sets of micas, each set with a parallel alignment of micas, define two or even three different foliations (respectively) at wide angles to each other in the same rock (e.g. locality 23785 along the Ouégoa-Koumac Road near the Bondé Road intersection). Such cases strongly suggest two or possibly three generations of crystallization of muscovite although it is generally believed that no great time interval was involved between each generation and that it reflects fluctuating physical conditions of metamorphism over a single broad time span involving multiple deformation. In some metabasalts sericitization of relict igneous plagioclase is sometimes the first indication of the alteration of feldspar and incipient recrystallization of the rock, and in many cases the sericite flakes (often together with tiny lawsonite crystals) parallel crystallographic directions which can be a notable texture especially in coarse-grained twinned plagioclases where the crystallographic directions in adjacent twins are at high angles to each other.

Pyrophyllite

Pyrophyllite is a comparatively rare mineral in the Diahot region and has been identified only in rhyolitic metatuffs and some siliceous rocks closely associated with rhyolitic metatuffs. It occurs in two metatuffs in the Pilou district (23564, 23571) in lowest grade rocks fairly
close to the lawsonite isograd in pelites and in one siliceous schist at Fern-Hill Mine (22940) interbedded with potash-rich metatuffs.

The identification of pyrophyllite has been confirmed in all cases by X-ray diffraction data of whole rock samples. In thin-section it is fine-grained, colourless, occurs in rather ragged and felty aggregates, highly birefringent and appears similar to sericite or talc. Pyrophyllite constitutes only several percent in the mode and coexists with phengitic muscovite in two rocks (23571, 22940) but phengitic muscovite is absent from the assemblage in 23564 which contains: quartz-albite-pyrophyllite-chlorite-epidote-calcite-magnesite-opaques.

The presence of pyrophyllite, a hydrated aluminium silicate, at these lower grades of metamorphism would tend to suggest that kyanite could occur in similar parent rocks at higher pressures and temperatures. However, kyanite has not been noted in higher grade rocks in New Caledonia probably on account of an absence of suitable parent lithologies at higher grades.

Pyrophyllite often occurs in rocks subjected to low grade regional metamorphism e.g. the pyrophyllite deposits of North Carolina (Zen, 1961) but its occurrence as discontinuous felty layers often defining the foliation in the schists would seem to preclude its origin pertaining to the hydrothermal alteration of feldspars as has been described by some authors (Deer, et al., 1962). Zen (1961) postulated that pyrophyllite could have been derived from a
process starting with original saprolite bodies forming on the weathered surfaces of volcanic rocks which were later buried and subsequently metamorphosed. However, no such original weathering profiles have been observed in the Cretaceous sequence in the Diahot region - the metasedimentary sequence was probably one of more or less continuous sedimentation without any major stratigraphic break. In all cases, rocks carrying pyrophyllite have some association with mineralization and appears to be a primary low grade metamorphic mineral restricted to silica-rich rocks.

**Stilpnomelane**

Stilpnomelane has been found in an iron-rich metasedimentary zone, several metres wide, at Balade Mine, and in a few rare cases in low grade and lawsonite zone metabasaltic rocks.

At Balade Mine, stilpnomelane occurs in schists (porphyroblastic biotite sericite schists of Lacroix, 1941) as very large porphyroblastic flakes up to about 3 mm long, often in radiating splays cutting right across the plane of foliation at a variety of angles. Most of the flakes are straight and unbent but a few are slightly bent at their ends. Stilpnomelane is very strongly pleochroic: \( \alpha = \) brownish-yellow, \( \beta = \gamma = \) very dark brown, almost black; it occurs in schists with the following assemblage: quartz-phengitic muscovite-stilpnomelane-chlorite-garnet-ilmeneapatite=various sulphide phases (e.g. chalcopyrite, pyrite). Modal percentages of mineral phases at Balade Mine are given in Table 6.3,
p.310. The presence of abundant stilpnomelane at Balade Mine, 23922 (23 modal % in one rock) together with other iron-rich phases, e.g. ilmenite, almandine garnet, chlorite, indicates an original iron-rich sedimentary host rock and in fact some rocks, composed almost entirely of massive, extremely coarse-grained stilpnomelane (up to 2 cm long) have been sampled from the old mine waste at Balade. Such rocks have not been observed in situ and most probably are located on the same iron-rich metasedimentary horizon at deeper levels in the mine, now completely inundated.

Stilpnomelane with the same pleochroic scheme as that at Balade Mine, also occurs in three metabasaltic rocks, two of them (23724, 23726, in Tchalabel Creek) situated at the lawsonite isograd and the other (23576, north of Pilou Mine) situated in the lower part of the lawsonite zone. In all cases identification has been confirmed from X-ray diffraction data. Stilpnomelane appears very similar to vermiculite but the former is generally darker brown with a slight greenish tint compared with vermiculite and both can be distinguished on X-ray diffraction patterns. In the metabasalts stilpnomelane crystallizes in small closely interlaminated patches and radiating sheaf-like tufts and splays that vary from about 0.05 - 0.4 mm. In rocks 23724, 23726, it is associated with pumpellyite, Na-amphibole, plagioclase and amphibole. Specimen 23576 contains the assemblage: pumpellyite-Na-amphibole-stilpnomelane-chlorite-omphacite-sphene-relict igneous pyroxene and plagioclase.

An interesting textural feature of stilpnomelane, especially seen in the schists at Balade Mine, is its consistent
habit of crystallizing at any angle with respect to the foliation and schistosity (see Fig. 3.100, p.185); instances can be found where stilpnomelane stabs right across quartz, chlorite and muscovite (although it sometimes contains small inclusions of quartz). There appears to be little doubt that at least most of the stilpnomelane crystallized after the development of foliation and schistosity. A few stilpnomelane flakes are very slightly bent in 23922 but in 23925 they cut right across the foliation and schistosity which is strongly contorted and microfolded. Persistent post-tectonic crystallization of stilpnomelane has been noted in other metamorphic terrains including the blueschists in California (Hutton, 1956) and the Otago schists in New Zealand (Hutton, 1940; 1945; 1956).

Chlorite

Chlorite is a very common mineral, present in all rock types and throughout all metamorphic grades. It occurs in every metabasaltic rock thin-sectioned by the author, often in large amounts. In some fine-grained low grade metasedimentary rocks its presence was often confirmed by whole-rock X-ray diffractographs.

Chlorite is commonly partially or completely replaced by vermiculite but which can only be differentiated from chlorite by X-ray diffraction techniques involving ethylene glycol vapour treatment and heating. Thus in fine-grained rocks where the optical distinction between chlorite and vermiculite is unresolvable, chlorite or chlorite/vermiculite or vermiculite has been denoted in the mineral assemblage by
"chlorite".

In a study of the composition of chlorites in the Ouégoa district Dr P.M. Black (pers. comm.) noted a number of features enumerated below:

(1) Chlorites from metabasalts and pelitic rocks become more Mg-rich (at the expense of Fe) and slightly less aluminous with increasing grade.

(2) Chlorites from metabasalts are less aluminous than those in pelites. A reaction involving the Mg/Fe ratio of chlorite at the epidote isograd from an Fe-rich chlorite to a Mg-rich chlorite is given under garnet.

Typically, chlorite is pale green, green, pale yellowish-green, usually moderately pleochroic, exhibits a variety of anomalous interference colours, mainly blue-greys and golden browns (rarely brownish-mauve) and often occurs finely interlayered with phengitic muscovite in metasedimentary rocks.

Chlorite together with phengitic muscovite are the dominant minerals in defining the foliation in metasediments.

The time of crystallization of chlorite varies from syntectonic to post-tectonic and in some rocks, e.g. 23801, 23804, chlorite (partially or completely altered to vermiculite) crystallizes parallel to late strain-slip cleavages (S₂) which cut the foliation and S₁ schistosity at high angles. In a few rare rocks it crystallizes during retrogressive metamorphism shown especially by the chloritization of garnet at Balade and Murat Mines (e.g. 23921, 23949, 23946, 23947) and more rarely Na-amphibole (e.g. 23958).
Vermiculite

A yellow to brown, strongly pleochroic mica-like mineral occurs in many rocks in the Diahott region and is identified as Fe-vermiculite (Black, pers. comm., from several electron microprobe analyses and X-ray data). It has the following optical properties: strongly pleochroic, $\alpha =$ pale yellow or pale brown; $\beta = \gamma =$ bright golden yellow or brownish yellow and sometimes dark brown; $2V_\alpha =$ very low, $(-)$; birefringence extremely high, very similar to muscovite and has a mottled extinction similar to that of the micas. Optically it appears very similar to stilpnomelane although its colours are somewhat paler and more yellowish than stilpnomelane (e.g. at Balade Mine, where stilpnomelane has very strong absorption colours, almost black) but can be readily distinguished by X-ray diffraction methods.

Vermiculite appears to form from oxidation or weathering of chlorite and in many cases it appears rather limonitic.

Vermiculite most commonly occurs in pelites, crystallizing from lowest grade rocks up to the epidote zone but is only an itinerant minor phase in metaigneous assemblages. In some pelites, e.g. 22939, vermiculite may constitute approximately 10% in the mode.

Chloritoid

Chloritoid has been found in several metamorphosed iron-rich pelitic sediments in Balade Mine Stream. It occurs in four rocks in the vicinity of Balade Mine (23913, 23915, 23917) in the transitional zone and in one rock at Murat Mine (23946) in the lowest part of the epidote zone. Chloritoid
constitutes about 8 modal percent in one rock (23915) but some samples collected by previous workers contain as much as about 50 modal percent.

Chloritoid is characteristically restricted to particular folia in the pelitic schists, even on the scale of a single thin-section (e.g. 23913) where chloritoid-rich layers are finely intercalated with typical siliceous mica schists. Chloritoid has not been observed coexisting in the same rock with stilpnomelane or Na-amphibole and chloritoid-bearing assemblages are: quartz-phengitic muscovite-chlorite talmandine garnet-chloritoid-ilmenite; minor accessory phases are traces of albite and apatite in 23923, sphene in 23915, and minor opaques other than ilmenite, mainly carbonaceous matter and sulphides.

In Balade Mine Stream chloritoid occurs in rocks with a high content of iron and alumina, low total alkalis and lime, and with more iron than magnesium. A representative bulk-rock chemical analysis of a chloritoid-bearing schist at Murat Mine is given by Lacroix (1941) and is shown in Table 6. 4, analysis 31). Highly aluminous parent rocks have also been favoured for the crystallization of chloritoid by Halferdahl (1961) and Deer, et al. (1962) although whole-rock analyses of other chloritoid-bearing schists in Balade Mine Stream (Table 6. 4, p.311, analyses 14, 16, 17, 21, 27) depict variable alumina contents and in many cases are less aluminous than some rocks not carrying chloritoid. However, it should be borne in mind that chloritoid crystallizes in particular folia within the schists and these
other chemical analyses are of rocks which also incorporate folia not carrying chloritoid and are thus not strictly representative of chloritoid assemblages.

Chloritoid is strongly pleochroic: \( \alpha = \) greenish-blue; \( \beta = \) greyish-blue; \( \gamma = \) colourless to pale yellow, and exhibits anomalous interference colours ranging from green, bluish-grey and brownish-mauve. It occurs as large prismatic porphyroblastic crystals reaching 3 mm in length, often in radiating post-tectonic splays cutting across the foliation at all angles. Polysynthetic twinning is invariably present with the twin lamellae parallel to the (001) cleavage.

**Carbonates**

A variety of carbonates have been found throughout the Diahot region in many contrasted parent lithologies and include: calcite, dolomite, aragonite and magnesite. Other carbonates in association with the mineral deposits, and which are not further considered here, are malachite and azurite, ubiquitous at most of the mines, and cerussite and smithsonite at Mérétrice Mine. Identification has been confirmed in all cases by X-ray diffraction of powder samples. In some instances the identification, particularly of fine-grained aragonite, was confirmed by X-ray diffraction of a heavy separate (using heavy liquids) obtained by centrifuging a crushed sample with a grain size of -200 mesh.

Calcite is a persistent accessory mineral in all rock types, occurring as irregular aggregates, often in veins associated with quartz. In the intermediate metagneous rocks, calcite is sometimes quite abundant, forming large crystals up to 1 mm in diameter, patchily replacing relict
igneous plagioclase and in interstitial patches between plagioclase laths.

Dolomite may predominate over calcite in some rocks to the extent of a ratio about 10 to 1 (from comparison of the intensities of peaks on X-ray diffractographs) and in some cases it is the sole carbonate phase (e.g. 23583). Dolomite has not been observed in pelitic schists except in veins (e.g. 23545, which contain narrow quartz-calcite-dolomite veins) but occurs in metabasaltic, intermediate metaigneous and rhyolitic metatuff assemblages, and coexists with magnesite in some serpentinites (23940).

Aragonite has only been positively identified in two rocks (23681, 23685), both derivatives of intermediate metaigneous parents situated in the lowest grade zone. Sample 23681 comes from near Mérétrice Mine only approximately 100-200 m from the lawsonite isograd in pelites and the other, 23685, lies approximately 1 km from the lawsonite isograd about half-way between Mérétrice Mine and the Cretaceous-Tertiary boundary. However, both assemblages carry tiny prisms of lawsonite, in many cases aligned with its longest dimension parallel to crystallographic directions in relict igneous plagioclase. The assemblages are: 23681, quartz-phengitic muscovite-chlorite-lawsonite-calcite-aragonite-sphene-(relict igneous plagioclase); 23685, quartz-chlorite-lawsonite-aragonite-pumpellyite-sphene-(relict igneous plagioclase). Thus, aragonite has not been found coexisting with Na-amphibole and it is the sole carbonate phase in 23685, calcite being absent.
The rarity of aragonite plus its restricted crystallization to intermediate metaigneous lithologies (probably andesites or trachytes) which are themselves uncommon rock types, precludes the utilization of aragonite as a regional zonal marker for progressive metamorphism in the Diahot region. Aragonite has been identified only at the northern part of the New Caledonian metamorphic belt in the Boat Pass-Tiebaghi area in calcareous metasedimentary rocks of uppermost Cretaceous or Eocene age (Brothers, 1970). However, aragonite is apparently absent from the schists south of the Diahot region and consequently in a more recent paper, Brothers (1974) found it impossible to continue an aragonite isograd in the southern sector. Furthermore, Brothers (1974) cited evidence that the presence of aragonite in the north but its absence in the south indicated a deeper regime for metamorphism with higher maximum temperatures in the northern sector than were attained further south.

Magnesite is a rare carbonate in the Diahot region and has been noted only in rocks associated with mineralization, for instance in some rhyolitic metatuffs in the Pilou district and at Ao Mine; as already mentioned above it also occurs in some serpentinites. At Ao Mine the magnesite has been iron stained to a dark brown colour and was possibly recorded by Rossello (1962) as siderite; certainly its colour is very similar to that of typical siderite.
Accessory Minerals

Sphene  Sphene is a widespread accessory mineral in all rock types and throughout all metamorphic grades in the Diahot region. It occurs chiefly as small anhedral grains and only rarely shows the rhombic euhedral wedge-shaped cross-sections more typical of sphene. Rutile is absent from the higher grade in situ rocks studied in this region but has been recorded in orthogneisses, glaucophanites and a few paragneisses at the highest grades of metamorphism (Brothers, 1974).

Sphene forms an interesting sympathetic relationship with ilmenite in the iron-rich metasediments in Balade Mine Stream. In this case, sphene becomes gradually more abundant towards the iron-rich metasedimentary horizons but suddenly close to these horizons it diminishes in quantity when ilmenite becomes very prominent; within the iron-rich horizons sphene is totally absent and ilmenite constitutes nearly 3 modal percent. This aspect is discussed in more detail on p.316.

Iron oxides, where present, are often covered with a thin veneer of leucoxene. According to Heinrich (1965) and Ramdohr (1969), leucoxene is an alteration of ilmenite and actually refers very often to extremely fine-grained anatase or more rarely rutile or brookite, and only very rarely and only in Ca-rich rocks is thought to be sphene. However, especially in lawsonite zone metabasalts, iron oxides are generally rare or absent except for occasional grains of limonite, and large dark brown patches of sphene occur which appear to have replaced original iron oxides completely. This is particularly exemplified by the skeletal
outline of some of these patches where sphene has apparently replaced original skeletal iron oxides, a typical habit of such minerals in many basic igneous rocks. Some large sphene patches contain darker-brown, almost black, octahedrally arranged spindles set in lighter-brown material and may represent a textural preservation of original ilmenite lamellae in titanomagnetite.

**Apatite** Apatite occurs in minor amounts throughout all metamorphic zones and in most rock types. It is probably most abundant in the green veins cutting metabasalts where some needles occur up to 1.5 mm in length with characteristically good basal (0001) cleavages and hexagonal cross-sections.

**Zircon** Zircon is a rare phase forming tiny anhedral crystals and has been noted mainly in the siliceous pelitic schists and some rhyolitic metatuffs.

**Opal** Opal has been found in veins associated with quartz cutting rhyolitic metatuffs (e.g. 23661, 23829, 23831) occurring in the lowest grade and the lawsonite zone. Many of these veins also lie parallel to the foliation and schistosity in the metatuffs and opal often displays a tendency to line the margins of the veins. In thin-section opal is brownish, isotropic, high negative relief, and its identification has been confirmed using an electron microprobe.
Tourmaline has been identified in a coarse-grained metabasaltic rock (23964) in the lowermost epidote zone, situated very close to the epidote isograd in the Ouégoa district, and tentatively identified in a siliceous pelitic schist (23600) in the lawsonite zone near the mouth of the Diahot River.

In the former case tourmaline occurs as stubby needles 0.6 mm long with hexagonal cross-sections. It is strongly pleochroic, \( \varepsilon = \) very pale brownish to colourless, \( \omega = \) brownish-green, uniaxial negative, moderate to high birefringence, length-fast and occurs in a metabasalt carrying the following assemblage: epidote-sodic amphibole-omphacite-lawsonite-chlorite-albite-sphene-opaques-relict igneous augite.

In the siliceous schist (23600) tourmaline forms tiny green to greenish-brown pleochroic crystals (uniaxial negative) and is contained in the assemblage: quartz-phengitic muscovite-sodic amphibole-spessartine garnet-apatite-sphene-zircon.

Tourmaline has been previously noted in the New Caledonian metamorphic belt in the Boat Pass area (Brothers, 1970) where it occurs possibly in derivatives of acid tuffs in the lawsonite zone.

Jarosite (KFe\(_3\)(SO\(_4\))\(_2\)(OH)\(_6\)) is quite an abundant accessory mineral mainly in rhyolitic metatuffs and is particularly common in the metatuffs at Fern-Hill Mine. Jarosite occurs in layers in the schists, veins, and forms yellow coatings on schistosity and joint surfaces. In thin-section jarosite shows pale yellow to bright golden yellow
pleochroism, extremely high relief and birefringence, and identification has been confirmed from electron microprobe qualitative data. Jarosite is generally believed to be a decomposition product of pyrite in the oxidation zone.

**Unknown Fibrous Mineral** An unknown fibrous mineral occurs in the central portions of some thick metabasalt sills (e.g. 23678, 23666) in the Mérétrice area. The metabasalt bodies lie approximately on the lawsonite isograd.

In thin-section the unidentified mineral is fibrous, brownish and rather turbid, and under crossed nicols displays maximum interference colours of upper first order. It occurs as a replacement of relict igneous calcic plagioclase, individual fibres are length fast and reach lengths of approximately 0.2 mm and are generally aligned parallel to crystallographic directions in the original feldspar.

A partial electron microprobe analysis of the unknown mineral in 23678 is given below: (analyst: R.M. Briggs)

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>46.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>29.1</td>
</tr>
<tr>
<td>Total Fe as FeO</td>
<td>1.01</td>
</tr>
<tr>
<td>MgO</td>
<td>0.22</td>
</tr>
<tr>
<td>CaO</td>
<td>14.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.07</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.23</td>
</tr>
<tr>
<td>Total</td>
<td>91.73</td>
</tr>
</tbody>
</table>

The chemical analysis is fairly similar to that of scolecite although the Si:Al ratio is slightly greater than that recorded for scolecite which is generally relatively
constant at 3:2 (cf. scolecite analyses by McLintock (1915),
Gennaro (1929), Hey (1936), in: Deer, et al. (1962)).
Interestingly, X-ray diffractograph patterns of the unknown
mineral are possibly also similar to that of scolecite
although pure samples of the mineral could not be run due to
its fine-grained, fibrous nature and there was always a large
amount of interference by a variety of other phases in the
same rock. Scolecite is oriented length fast but its maximum
birefringence is much lower (0.007) compared with the unknown
mineral (approximately 0.02).

The unknown mineral occurs in rocks with the following
assemblages: (23678, 23666) chlorite-lawsonite-Na-amphibole-
pumpellyite-albite-sphene-opaques-(relict igneous augite,
Ca-amphiboles)±quartz; 23679 chlorite-lawsonite-phengitic
muscovite-albite-quartz-opaques-(relict igneous augite).

However, if the unknown mineral is in fact a zeolite its
apparent stability in assemblages carrying lawsonite-Na-
amphibole is puzzling; possibly, it may have crystallized
during retrogressive metamorphism in the central portion of
a thick metabasalt sill which is an extremely competent body,
the central portion of which might be subjected to relatively
higher temperatures but lower pressures with respect to the
margins of the body (which in places show a greater develop-
ment of schistosity than the core) and the less competent
country rock. Such a thick metaigneous body may well be
more susceptible to retrogressive metamorphic effects in
the hard competent core and more favourable to the crystalliza-
tion of relatively lower pressure phases, e.g. zeolites or prehnite.

**Opaque Minerals**

A variety of opaque minerals have been identified in metasedimentary and metaigneous rocks (outside the areas of mineralization) in the Diahot region, including carbonaceous matter, limonite, hematite, magnetite, ilmenite, rutile, pyrite, chalcopyrite, pyrrhotite, chalcocite, covellite and bornite.

Carbonaceous matter is common in many paraschists, especially in the fine-grained black phyllites; it occurs in all metamorphic zones from lowest grade to epidote zone rocks. An attempt was made to determine the classification of the carbonaceous material following the method of Landis (1971) but purification of the carbonaceous material could not be achieved even after digestion of rock powder with hot HF and HCl for several hours.

Limonite is the most common of the opaque minerals in the Diahot region occurring in both paraschists and orthoschists and in many rocks it constitutes the sole oxide phase.

Hematite was identified in only one rock (10912), a siliceous pelite, and occurs in a tiny aggregate of fine-grained needles.

Magnetite has not been observed but has been described in two rocks by Lacroix (1941), a grunerite quartzite (L.Ca.87) and a metachert (L.225.9), and in one rock by Black (1973a) in an epidote zone metasediment (9674). Assemblages containing
magnetite are: (from Black, 1973a, b) (L.225.9): spessartine-aegirine-Na-amphibole-quartz-magnetite; (L.Ca.87): grunerite-riebeckite-almandine-quartz-magnetite-deerite; (9674): almandine-epidote-Na-amphibole-Ca-amphibole-chlorite-quartz-rutile-magnetite.

Ilmenite is an abundant mineral in Balade Mine Stream where it occurs in iron-rich metasediments associated with the copper mineralization at Balade and Murat Mines. Ilmenite (also rutile) has already been described under sphene and is discussed in more detail in Chapter 6.

In the country rocks outside the areas of mineralization pyrite is by far the most common sulphide and is especially ubiquitous in the rhyolitic metatuffs. In the latter rocks it occurs as fine granular disseminations, sometimes in large cubic form, and is very often completely or partially pseudomorphed by limonite.

A variety of sulphides have been identified in some high grade gneisses (e.g. 9850, 10987, 10993) outside the area of this study; for instance in 10987 (from Balade River near the East Coast) the opaque mineral assemblage included: pyrite-chalcopyrite-chalcocite-covellite-pyrrhotite-ilmenite-limonite-rutile. 9850, a glaucophanite west of Col d'Amoss, contained: pyrite-chalcopyrite-pyrrhotite-covellite-chalcopyrite-bornite, and in 10993 near Col de Parari, limonite was seen replacing pyrrhotite along well-developed cleavage planes.
Relict Plagioclase  Relict igneous plagioclase is very common in derivatives of igneous rocks and tuffs in the lowest grade zone and persists up to about the middle of the lawsonite zone. In the metabasalts relict calcic plagioclase characteristically shows subophitic and ophitic intergrowth relationships with relict pyroxenes (see Fig. 2.2, p. 26) and in some blastoporphyritic rocks relict plagioclase forms large porphyroclasts up to 1 cm long.

Compositions of relict plagioclase have been determined in a number of rocks by the universal stage method of Turner (1947) using the revised determinative graphs of Slemmons (1962) and are given in Table 5.4. Many plagioclase compositions could not be determined by the universal stage method, most probably on account of their alteration by partial or complete metamorphic recrystallization, and in fact the compositions given in Table 5.4 are not considered to be particularly significant for this reason. Wide compositional variations were observed within the same rock and the compositions in the metabasaltic rocks which presumably would have lain originally in the labradorite compositional field now have irregular compositions ranging from sodic andesine to albite.

A variety of minerals have been observed replacing relict plagioclase. In metabasalts pumpellyite is the most common replacement of relict plagioclase, occurring as small radiating needles and patches, and in some instances, e.g. 23631, pumpellyite appears to preferentially replace the cores of
plagioclase. In other cases, e.g. 23574, pumpellyite replaces plagioclase laths completely (Fig. 5.1). Sodic amphibole partially replaces plagioclase in some metabasaltic rocks, e.g. 23640, 23724 (Fig. 5.3), and has been noted in long prismatic sections sometimes cutting across plagioclase but not cutting across adjacent relict pyroxene with the prisms ceasing abruptly at the plagioclase-pyroxene boundary. In other cases sodic amphibole may cut right across both relict plagio-
clase and pyroxene.

Fig. 5.3 Photomicrograph showing Na-amphibole (light grey, acicular) partially replacing relict igneous plagioclase (white) in a metabasalt (23724). X44, plane polarized light.

Radial splays of stilpnomelane have also been observed nucleated on the margins of relict plagioclase and splaying into the cores, e.g. 23724. Phengitic muscovite and lawsonite also occur as partial replacements and often occur strongly oriented with their longest dimensions parallel to crystallographic directions and composition planes of twinned plagioclase, (e.g. 23667, 23678, 23666). Grains of quartz and metamorphic albite may also be associated with the replacement of plagioclase, and a variety of carbonates (e.g. calcite, dolomite, aragonite) are particularly common replacements of relict plagioclase in the intermediate metaigneous rocks (e.g. 23681, 23584, 23685, 23567).
Relict Pyroxenes  Igneous pyroxene is abundant as relics in metabasalts and persistently occurs in these rock types even up to the lowermost epidote zone, e.g. in the metabasalt 23965. Thus, it remains as a stable phase to a much greater extent or deeper level in the metamorphic environment than plagioclase which as mentioned previously persists only into the lowest half of the lawsonite zone.

Relict igneous ophitic and subophitic textural relations with relict plagioclase are still preserved in lowest grade and lower lawsonite zone metabasalts and uralitization of pyroxene is seen in some metabasalts e.g. 23544, 23631. In the latter case clinopyroxene is replaced along margins, fractures and cleavages by a pale green calcic amphibole.

Compositions of relict igneous pyroxene in all cases appear to be augite although they are generally slightly titaniferous (pers. comm. Dr P.M. Black) and electron microprobe analyses are given in Table 5.5. In thin-section they are colourless or slightly brownish especially on the margins of some crystals, $2V_\gamma$ averages $51^\circ$ and ranges from $48^\circ$-57$^\circ$ (data from about six individual crystals in each of 16 thin-sections of metabasaltic rocks). Neither orthopyroxene nor olivine have been found as relict minerals in any of the metabasalts in the Diaphot region.

A bright dark green to greenish-brown pleochroic mineral with high second order interference colours occurs on the rims of a few relict augites in the metabasalt 23631, and is tentatively identified as aegirine-augite. The metabasalt lies in the lowest grade zone rocks and the aegirine-augite(?).
TABLE 5.5 Electron microprobe analyses of relict titaniferous augite in the Ouëgoa district (analyst: Dr P.M.Black) and one partial analysis of a pyroxene rimmed by metamorphic omphacite in the Pilou district (specimen number 23576, analyst: R.M. Briggs)

<table>
<thead>
<tr>
<th></th>
<th>10866</th>
<th>10946</th>
<th>9793</th>
<th>23576</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>50.9</td>
<td>51.6</td>
<td>52.0</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>1.2</td>
<td>1.0</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.2</td>
<td>2.8</td>
<td>2.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Total Fe as FeO</td>
<td>7.3</td>
<td>6.5</td>
<td>9.0</td>
<td></td>
</tr>
<tr>
<td>MnO</td>
<td>0.2</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>15.2</td>
<td>16.0</td>
<td>15.5</td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>21.2</td>
<td>20.9</td>
<td>20.1</td>
<td>19.7</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>100.7</td>
<td>99.5</td>
<td>100.7</td>
<td></td>
</tr>
</tbody>
</table>

Ions per unit cell

<table>
<thead>
<tr>
<th></th>
<th>10866</th>
<th>10946</th>
<th>9793</th>
<th>23576</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.87</td>
<td>1.91</td>
<td>1.92</td>
<td></td>
</tr>
<tr>
<td>Al⁴⁺</td>
<td>0.13</td>
<td>0.09</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>Al⁶⁺</td>
<td>0.05</td>
<td>0.03</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Fe²⁺</td>
<td>0.22</td>
<td>0.20</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.03</td>
<td>0.03</td>
<td>0.02</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>0.83</td>
<td>0.88</td>
<td>0.85</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>0.83</td>
<td>0.83</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>0.04</td>
<td>0.01</td>
<td>0.03</td>
<td></td>
</tr>
</tbody>
</table>
is considered to be an igneous relict and not of metamorphic origin. Also it introduces a slight alkaline element into the suite of basaltic igneous rocks which is dominantly tholeiitic in character.

**Relict Amphiboles** A variety of green, green-brown and dark brown calcic amphiboles occur as relicts in many of the lower grade metabasaltic rocks in the Diahot region. They persist in metabasaltic rocks, mainly in the medium to coarse-grained varieties, as far as the lower parts of the lawsonite zone and are thus approximately comparable in their persistence to relict igneous plagioclase.

In the lowest grade partially recrystallized metabasalts, e.g. 23631, 23544, green and green-brown relict amphiboles, probably actinolite and common hornblende respectively, are seen as alteration products on the margins and along fractures and cleavages of relict clinopyroxene; they do not occur as discrete phases and appear to be of relict igneous origin. With progressive metamorphism such relict amphiboles are themselves very often partially or completely rimmed and replaced by metamorphic blue sodic amphiboles (e.g. 23666, 23678). The sodic amphiboles (crossites or glaucophanes) occur in fibrous masses or fine prisms and where they form as a replacement of relict igneous amphibole, the fibres or prisms are generally strongly aligned parallel to each other.

In some cases relict green-brown amphibole is rimmed by a pale green amphibole which is rimmed in turn by metamorphic blue sodic amphibole. However, contacts between the three
amphiboles have only been observed as gradational, and only the blue sodic amphibole occurs as a discrete phase. Textural relations described by Brothers (1974) in metabasalts in the lawsonite zone where relict brown hornblende coated with metamorphic actinolite and in turn rimmed by sodic amphibole with sharp contacts at both interfaces and in which both actinolite and sodic amphibole also occur as discrete phases in the same assemblage have not been observed by the present writer. Brothers interpreted these textural relations as due to an earlier metamorphism of actinolite crystallization (of pumpellyite-actinolite grade) preceding the first crystallization of sodic amphibole.

Relict brown to dark brown pleochroic amphiboles have also been noted in many metabasalts and an electron microprobe analysis (Table 5.6) proved it was titaniferous and probably kaersutite (pers. comm. Dr P.M. Black).

In sample 23776 (sampled from the same metabasalt body as 7936 recorded above) relict kaersutite is strongly pleochroic from yellowish-brown to dark reddish-brown, shows upper second order interference colours and occurs both as a partial rim on relict augite and as a discrete phase. In some cases the dark brown amphibole is partially rimmed by a large well-developed prismatic brownish-green to bright bluish-green pleochroic calcic amphibole and which is sometimes separated from the dark brown amphibole by a narrow band of colourless amphibole. Furthermore, both the dark brown kaersutitic amphibole and the green variety are partially or completely rimmed by a fibrous or finely prismatic colourless calcic amphibole which on textural grounds appears most
TABLE 5.6 Electron microprobe analysis of relict dark-brown amphibole in a metabasalt (7936) 800 m northeast of Col de Crève Coeur. Analyst: Dr P.M.Black

<table>
<thead>
<tr>
<th>oxide</th>
<th>weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>45.8</td>
</tr>
<tr>
<td>TiO₂</td>
<td>3.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>11.4</td>
</tr>
<tr>
<td>Total Fe as FeO</td>
<td>7.8</td>
</tr>
<tr>
<td>MnO</td>
<td>0.1</td>
</tr>
<tr>
<td>MgO</td>
<td>13.7</td>
</tr>
<tr>
<td>CaO</td>
<td>12.2</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.6</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.5</td>
</tr>
<tr>
<td>Total</td>
<td>98.5</td>
</tr>
</tbody>
</table>

likely to be metamorphic in origin. Interestingly, blue sodic amphiboles, which are otherwise ubiquitous phases in lawsonite zone metabasalts, are absent from this section (23776).

While the kaersutitic amphibole is regarded as a relict of the igneous rock and the fibrous colourless calcic amphibole is metamorphic, the origin of the green amphibole and the colourless variety developed between the kaersutitic and green amphiboles is conjectural. However, the metamorphic amphiboles in the lowest grade and lower parts of the lawsonite zone are generally fibrous or finely prismatic whereas the green amphibole and the narrow band of colourless amphibole
are relatively coarsely prismatic and on these textural grounds the author favours a relict igneous origin for the latter varieties in this particular case.

Relict brown amphiboles have also been observed in several other metabasaltic rocks e.g. 23724, 23655, 23666, where rather similar but significantly different textural relations exist to that described above in section 23776. In 23724 relict pale brown amphibole is rimmed by metamorphic sodic amphibole and in many cases the two varieties are separated by an intermediate narrow zone of bluish-green amphibole, the contacts between the three amphiboles appearing quite optically gradational. Also, the sodic amphibole shows a strong tendency to preferentially rim and replace relict amphiboles before relict pyroxenes, the latter in most cases showing little if any replacement and have sharp grain boundaries whereas the relict amphiboles are always at least partially replaced.

However, the narrow rim of bluish-green amphibole in this case (in 23724) may have a different origin from the well-developed blades of green amphibole in 23776 in that it is possibly metamorphic. The contacts between the brown-green-blue amphiboles appear optically gradational but in contrast to the green amphibole in 23776, it forms a very narrow zone and appears to be a reaction product between relict kaersutite and metamorphic sodic amphibole. The textural relationships between the varieties of amphiboles are always consistent, i.e. the brown kaersutitic amphibole is always the core and the green calcic amphibole, when present, is always between kaersutite and sodic amphibole - sodic amphibole has never been observed rimmed by the green amphibole or kaersutite. Optically
and chemically sharp contacts between coexisting amphiboles, considered to be in equilibrium coexistence, as illustrated by Klein (1968), Himmelberg and Papile (1969), Black (1970; 1973) have not been observed by the present writer in the metabasalts of the Diahot region. However, coexisting pairs of metamorphic amphiboles with optically and chemically sharp contacts have been recorded previously in the Ouégoa district, namely grunerite with riebeckite in a metamorphosed ironstone (Lacroix, 1941), glaucophane with riebeckite-arfvedsonite in a low grade metabasalt (Black, 1970) and a number of sodic and calcic amphibole pairs (Black, 1973; Brothers, 1974).
CHAPTER 6
MINERAL DEPOSITS

1. Introduction

The mineral deposits in the Diahot region studied in this thesis occur at five relatively major sites, Pilou, Mérétlice, Fern-Hill, Balade and Murat mines and at numerous smaller localities throughout the field. Although the deposits vary considerably in size and show certain differences, but are in many aspects similar to one another in their mode of occurrence, form and shape, mineralogy, texture and genesis, they are considered to belong to a single metallogenetic province.

Of the five major mines, Pilou and Mérétlice occur very close to the lawsonite isograd in pelites, Fern-Hill is situated in about the middle of the lawsonite zone, Balade occurs in the transitional zone near the epidote isograd, and Murat occurs just inside the epidote isograd.

The mineral deposits in the Diahot region afford a very interesting study of successive mineralogical and textural changes due to progressive metamorphism and deformation, especially as the temperatures and pressures of metamorphism are comparatively well documented.

2. Previous Mining Activity and Research in the Diahot Region

Mining activity started in the Diahot region with the discovery of Fern-Hill Mine in 1870, followed by the discovery of Balade Mine in 1872, Murat in 1873, Pilou-Nemou in 1874, Mérétlice in 1884, and finally the discovery
of deposits at Ao in 1887. Mining work continued intermittently until about the end of the nineteenth century and all of them except Mérétrice were closed down by the beginning of World War I. Most of the old shafts and adits are now completely or partially collapsed at the present day.

Mérétrice and initially Fern-Hill were mined by open-cast methods and all the other mines in the Diahot region were exploited by underground operations. Mine labour was mainly done by French convicts and ruins of barricaded barracks are still in evidence at Pilou Mine and Port Pilou, and relict dungeons still exist beneath the old gendarmerie near Balade Mine.

In 1952 and 1962 the S.E.P.A.M.I.F.O.M. and the B.R.G.M. (Bureau de Recherches Géologiques et Minières) organized a drilling program, collected samples for geochemical analysis, and estimated possible reserves to determine whether any of the deposits could be economically exploited using modern mining techniques.

The present thesis is part of a continuing program of research and exploration in the Diahot region initiated by the B.R.G.M. and is a study more on a regional basis, mapping on a scale of 1/10,000, in conjunction with very detailed mapping on a scale of 1/2,000 in the immediate vicinity of the mines at Mérétrice, Pilou, Balade and Murat by M.B. Guéranget of the B.R.G.M. A regional geochemical survey has also been carried out by the B.R.G.M. (M. Bouleau) and some geophysical resistivity surveys have been done locally around the above three mining areas (Murat Mine lies approximately 700 m from Balade Mine and is regarded as a
single mining area).

Table 6.1 presents the data of previous mining work in the Diahot region and shows the years of operation at each mine, gross tonnages of ore extracted, ore grades, metal content and approximate values of metal contained based on the 1961 NF valuation. The data presented here are mainly that documented by Espirat and Millon (1965, 1967) and Rossello (1962). The mining records given by Espirat and Millon (in the notes on the Pam-ouégoa and Paagoumène 1/50,000 maps) and Rossello are those incorporated from old mining reports of Heurteau (1876 a, b), Pelatan (1891) and Glasser (1903-1904).

The following are additional notes on the history of mining operations in the Diahot region.

Balade Mine

Balade Mine was discovered in 1872 and was exploited by the Compagnie des Mines de Balade from 1874 to 1884. Tonnages of copper ore extracted during this time are given in Table 6.1. Relatively rich ore was untreated and less rich ore was crushed and washed on the mine site. From the mine it was carted by trucks to the banks of the Diahot River and was then barged to Pam from where the ore was shipped to Australia. Drilling by the S.E.P.A.M.I.F.O.M. and the B.R.G.M. in 1953 and 1962 proved the mineralized horizon to extend 300 m to the east and southeast from the site of old workings.
### TABLE 6.1 Statistics of Previous Mining Work in the Diahot Region

<table>
<thead>
<tr>
<th>Mine</th>
<th>Years of operation</th>
<th>Gross tonnages of ore</th>
<th>Grade %</th>
<th>Metal content in tons</th>
<th>Metal value (in NF, 1961 valuation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balade</td>
<td>1874-1884</td>
<td>40,000(^{(1)})</td>
<td>15% Cu</td>
<td>6,000 Cu</td>
<td>19.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>60,000(^{(2)})</td>
<td>18-20% Cu</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Murat</td>
<td>1874-1884</td>
<td>900(^{(3)})</td>
<td>13-24% Cu</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>325(^{(4)})</td>
<td>10% Cu</td>
<td>35 Cu</td>
<td>0.11</td>
</tr>
<tr>
<td>Delaveuve</td>
<td>?</td>
<td>85(^{(3)})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pilou-Nemou</td>
<td>1886-1891</td>
<td>14,500</td>
<td>6.6% Cu</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1891-1897</td>
<td>10,700(^{(5)})</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1886-1901</td>
<td>20,000(^{(4)})</td>
<td>10% Cu</td>
<td>2,000 Cu</td>
<td>9.52</td>
</tr>
<tr>
<td></td>
<td>1908-1914</td>
<td>19,400</td>
<td>4.75% Cu</td>
<td>920 Cu</td>
<td>-</td>
</tr>
<tr>
<td>Mérétrice</td>
<td>1886-1891</td>
<td>5,000</td>
<td>30%Pb, 5%Zn</td>
<td>1,500 Pb, 250 Zn</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1896-1898</td>
<td>2,200</td>
<td>15-20% Pb, 25-30% Zn</td>
<td>400 Pb, 550 Zn</td>
<td>6.93</td>
</tr>
<tr>
<td></td>
<td>1925-1930</td>
<td>8,000</td>
<td>13.5% Pb, 25% Zn</td>
<td>1,100 Pb, 2,200 Zn</td>
<td>-</td>
</tr>
<tr>
<td>La Folle</td>
<td>? 1900</td>
<td>100</td>
<td>25-30% Cu</td>
<td>25 Cu</td>
<td>0.08</td>
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Table 6.1 continued

<table>
<thead>
<tr>
<th>Mine</th>
<th>Years of operation</th>
<th>Gross tonnages of ore</th>
<th>Grade %</th>
<th>Metal content in tons</th>
<th>Metal value (in NF, 1961 valuation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fern-Hill</td>
<td>1872-1874</td>
<td>900</td>
<td>140g/t Au</td>
<td>128kg Au</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>1876-1878</td>
<td>?</td>
<td>?</td>
<td>85kg Au</td>
<td></td>
</tr>
</tbody>
</table>

Data from:  
1. Glasser, in: Espirat and Millon (1965)  
2. Pelantan, in: Espirat and Millon (1965)  
3. Espirat and Millon (1965)  
5. Charleton, in: Espirat and Millon (1965)
Murat Mine

The deposits at Murat were discovered in 1873 and were mined on a small scale during 1874 and were then abandoned. Some expansion occurred in 1883 by the Compagnie des Mines de Balade and a haulage rail was lain to connect Murat with Balade Mine. Mining continued until 1884 when the closing of Balade brought a closure of operations. Further mining was considered in 1912 by the Société Calédonienne des Mines and again in 1930 by the Société Minière du Diahot. The S.E.P.A.M.I.F.O.M. and the B.R.G.M. did some drilling and geochemical sampling in 1953 and 1962. According to Espirat and Millon (1965) estimated reserves are 16,000 tons at five per cent or 50,000 tons at 2.5 per cent copper and appreciable silver values.

Bruat Deposits

According to Espirat and Millon there is a 15 m wide zone of banded schists containing less than one per cent copper; also recorded are two levels containing two to six per cent copper. During mining in 1912 and in 1930, it was attempted, without success, to try and find a connecting level with Murat. Evaluation of reserves from exploration drilling by the S.E.P.A.M.I.F.O.M. and the B.R.G.M. in 1953 and in 1962 were 35,000 tons at 4.8 per cent copper with an estimation of more than 300,000 tons (and probably 650,000 tons) at less than one per cent copper.

Many other minor showings of mineralization are known in the vicinity of Balade Mine but only Delaveuve was exploited (85 tons taken).
Pilou-Nemou Mine

Nemou is the historical name given to the actual mine in this area and is part of a larger field of localized showings of mineralization named Pilou. However, in this thesis the major deposit in this area is referred to as Pilou Mine.

The deposit was discovered in 1874 and was mined from 1886 to 1891 by the Société des Mines du Nord. From 1891 to 1897 the mining records are conflicting - according to Glasser there was no mining during this period but Charleton reported 10,700 tons of ore were taken. Finally from 1907 to the beginning of World War I, the mine was worked by the Société Calédonienne des Mines. In total, 60,000 tons of ore at five per cent Cu were extracted.

Mining was done along eight levels, related to a 165 m deep shaft; levels four, five and six are the longest and extend for approximately 300 m (data from unpublished B.R.G.M. report, D 341, by R. Millon). Assay values vary: 3-20% Cu, 0-10% Zn, 0-6% Pb, 20-300g/ton Ag. Rich ore, containing at least 20% Cu, was put in sacks and exported directly. Less concentrated ore was smelted to a concentrate assaying approximately 25% Cu, 10% Pb and 400g/ton Ag. Poorer quality ore was crushed, washed and concentrated to 6-14% Cu and then smelted. From Pilou it was railed to Port Pilou at the mouth of the Diahot River, then barged to Pam and later to Dilah. Actual reserves remain beneath the lowermost 150 m level.
Tourris Deposits

Tourris is situated to the southeast of Pilou and copper assays are reported by Espirat and Millon to be five per cent in the oxidation zone and two per cent at depth.

Tchiengane Deposits

The copper showings at Tchiengane (northwest of Pilou) were assayed by the B.R.G.M. and one sample is recorded to contain 5.7% Cu.

Mérettrice Mine

The Pb-Zn deposits at Mérettrice were discovered in 1884 and occur as lenses in black carbonaceous phyllites; the largest lens is recorded by Espirat and Millon to have been 65 m in length and four metres in thickness. The companies involved in mining at Mérettrice before the turn of the century are not documented by Rossello or Espirat and Millon but during the period of operation from 1925 to 1930, Mérettrice was mined by the Société Minière du Diahot. This company left much of the ore stockpiled at the mine in 1930 when the company went bankrupt and this ore was not exported until 1949. Overall average assays of ore from Mérettrice are recorded to be 10-15% Pb, 20-30% Zn, 0-6% Cu, and 100-400g/t Ag by Espirat and Millon, who also estimated a further 9,000 tons exposed and probably considerably more at depth. However, the information from reconnaissance drill-hole data was not sufficient to estimate reserves.
Tchimbo Deposits

Two very small showings of mineralization occur near Tchimbo Creek and one of them, Moyen Tchimbo, is the site of a geochemical anomaly. Drilling was done on this anomaly by the B.R.G.M. and zinciferous mineralization (mainly sphalerite) was found in the proximity of metamorphosed rhyolites or rhyolitic tuffs. Rossello reports that the geochemical anomaly at Moyen Tchimbo has values with greater than 100 ppm Pb, extending in a long band for approximately one kilometre and is 100 to 150 m in width - background in the country rocks being less than 30 ppm Pb.

La Folle

La Folle is situated about two kilometres east of Mérétrice and is the site of minor copper mineralization. Tonnages extracted and copper assays are given in Table 6.1.

Fern-Hill Mine

Fern-Hill was discovered in 1870, worked mainly by open-cast methods from 1872 to 1874, and later by underground operations from 1876 to 1878. The former mining period involved exploitation of the oxidation zone and from a section 40 m in length, 25 m deep, and 1.5 m thick, 128 kg of Au was taken. During the latter mining period the ore was extracted from depth and was treated by crushing and amalgamating but a large portion of the gold could not be recuperated. At the 80 m and 110 m levels from Hill shaft (a deep vertical shaft still preserved at the present day), sphalerite, chalcopyrite and galena mineralization was traced and 13,000 tons at 50 g/t Au were taken. Espirat and Millon considered that further gold could be extracted
from Fern-Hill if modern flotation and chemical separation techniques were used.

From 1878 to 1900 the mine was prospected by a number of different companies and was finally abandoned. (The English name of the mine is derived from an early Australian miner, according to local knowledge in Ouégoa.)

**Euréka Deposits**

Euréka is a very small showing of mineralization and ore samples have been assayed at 22% Cu, 50g/t Au.

**Ao Mine**

Ao Mine was discovered in 1887 and was first worked by the Société des Mines du Nord - the same company that worked Pilou, and a rail track still partially exists at the present day connecting Ao and Pilou mines. In 1897 the Société "Les Mines de Cuivre de Pilou Ltd" made a shaft 80 m deep and a level at a depth of 40 m. Copper ore was found and the mine was equipped for extraction but was abandoned in 1901 when the company stopped work in the Pilou region. The B.R.G.M. did further research on the deposit in 1956 and estimated a certain quantity of Cu and Zn but not sufficient to be economic. The most significant ore assays are recorded by Espirat and Millon (1967) to average 2.5% Cu and 2.5% Zn.

Rossello (1962) has estimated the value of total metal production in the Diahot region at approximately 36.77 millions NF (on the 1961 NF valuation). Rossello also estimated that the reserves seemed to be of a similar order but with lesser ore grades, with the exception of
<table>
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<th>Sample No.</th>
<th>Locality</th>
<th>Rock type</th>
<th>Cu value (ppm)</th>
<th>Pb value (ppm)</th>
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<td>Rhyolite</td>
<td>110</td>
<td>90</td>
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<td>Rhyolitic Tuff</td>
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<tr>
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<td>Moyen Tchimbo</td>
<td>Pyritic sericitic quartzite</td>
<td>280</td>
<td>1400</td>
</tr>
<tr>
<td>RM/60/114</td>
<td>Mérétrice</td>
<td>Trachy-andesite</td>
<td>120</td>
<td>1000</td>
</tr>
<tr>
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<td>Dolerite</td>
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<td>5</td>
</tr>
<tr>
<td>GR/61/52</td>
<td>Pilou</td>
<td>Dolerite</td>
<td>240</td>
<td>5</td>
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<tr>
<td>RM/60/114</td>
<td>Ao</td>
<td>Dolerite</td>
<td>180</td>
<td>20</td>
</tr>
<tr>
<td>GR/59/25</td>
<td>Ao (drill-core)</td>
<td>Pyritic sericitic dolomitic sandstone</td>
<td>330</td>
<td>700</td>
</tr>
</tbody>
</table>
Mérétrice; overall reserve ore grades in the Diahot region generally vary between 2.5 to 5% Cu (Rossello, 1962).

Rossello reports several of the results of trace element geochemical analyses for Cu and Pb in some rocks of the Diahot region and these are given in Table 6.2 (only those localities in the region of the present study are shown).

Background in the country rocks; 10-40 ppm Cu, 5-20 ppm Pb. Zn was also analysed for in several rocks and the values were found to be generally comparable with those for Cu and Pb.

3. **Mode of Occurrence of Mineral Deposits**

For descriptive purposes the mode of occurrence, composition and texture will be given separately for each major deposit as these features differ somewhat from one another; general remarks concerning the numerous minor mineral showings will be grouped together under one heading.

(1) **Mérétrice Mine**

Mérétrice Mine is situated five kilometres west of the Ouégoa-Koumac Road, four kilometres south of the Diahot River and 1.6 km north of the Cretaceous-Tertiary boundary. Previous mining about 70 years ago was by open-cast methods and good exposures exist in the quarry today (see Figs. 6.1 to 6.4). It lies exactly on the lawsonite isograd defined in pelitic assemblages and several hundred metres inside the Na-amphibole and lawsonite isograds in basic orthoschist assemblages.

Pb-Zn mineralization, predominant at Mérétrice, consists
Fig. 6.1  Mérétrice Mine looking towards the northwest (July, 1971).

Fig. 6.2  Mérétrice Mine looking towards the southeast (July, 1971).
Fig. 6.3 Mérettrice Mine looking towards the southwest wall of the quarry (July, 1971).
of compact, fine-grained, massive and layered galena-sphalerite lenses which are restricted to black carbonaceous phyllites, intercalated between rhyolitic metatuffs. The planar structural element, i.e. layering in the sulphide lenses and concordant to it the foliation and schistosity of the phyllites, represents most likely relict bedding. Only one lens was seen in situ which measured 1.5 m by 0.3 m (third dimension unknown). The relationships of this lens to the surrounding wall rocks is shown in detail in Fig. 6.5. The broader relationships on the southwest wall of the quarry are sketched in Fig. 6.4. One other massive sulphide body, four metres by one metre, occurs on the floor of the quarry but the contact relationships are obscured and it is not certain whether it is in place.

Lithologies and Structure

(a) Carbonaceous Phyllites

The phyllites which enclose the ore lens seen on the southwest face of the mine are extremely fine-grained, soft, black carbonaceous phyllites. The strike of the foliation is 115-140°, and dips are to the southwest at 30-55°. In thin-section they contain quartz-muscovite-chlorite-carbonaceous matter and are notably barren of any sulphides, and particularly lack even pyrite. Thin quartz stringers, about one millimetre thick, cut across the foliation in many places but parallel the foliation in others. The contact between the phyllites and the compact ore lens is sharp and no alteration features in the wall-rock were seen.

In the vicinity of the ore lens the phyllites show no deformation except for local slumping as a result of their soft incompetent nature in a steep quarry face and an over-
Fig. 6.4 Sketch of the southwest wall of the quarry, Mérétrice Mine, May 1970.
p = fine-grained, black carbonaceous phyllites with thin quartz stringers.
r.t. = light brown to pink, weathered vuggy rhyolitic tuffs.
F-F = fault, unknown throw (probably of several metres displacement).
Fig. 6.5 Sketch of the relationships of a Pb-Zn ore lens and the surrounding wall rocks seen on the southwest face of the quarry at Mérétice Mine.
burden of mine waste. However, 40 m to the northwest on the same side of the mine, local zig-zag recumbent kink folds occur on a mesoscopic scale and appear to be tectonic rather than as a result of slumping. The folds are localized and are not thought to have any significance on a macroscopic scale. Fold axes, rodding and fine lineations generally trend about 110-120°, and plunge at 10-15°.

The thickness of the black phyllites varies but appears to be a maximum in the quarry itself where there is a minimum of six metres thickness. They extend laterally along the strike for approximately 200 m. To the northwest they are in fault contact with a thick metabasalt body and appear to thin out rapidly to the southeast where they are intercalated with bands of rhyolitic metatuff. A small trench 50 m east of the mine creek exposes only light grey sericitic metasiltstones indicating that the black phyllites must wedge out completely between the mine creek and the trench.

To the south and lying stratigraphically above the black phyllites, the lithologies become coarser-grained, i.e. grey to light grey sericitic metasiltstones weathering to light brown. Exposures in the mine creek upstream from the mine often show unreliable attitudes due to slumping and surficial creep but reliable ones strike 90-120° with southwesterly dips at 50-60°. In places many thin quartz veins occur, generally concordant with the foliation, and some schists are rather sandy in appearance and often hard and siliceous.

Stratigraphically below the black phyllites, exposed on the north face of the quarry and in the mine creek, the
schists are slightly coarser-grained dark grey sericitic metasiltstones. In thin-sections they have the assemblage quartz-phengitic muscovite-chlorite-sphene-carbonaceous matter - minor iron oxides. Sulphides have not been observed. In the mine creek the sericitic metasiltstones are approximately 15 m thick and are separated from the metabasalt body by coarse-grained, tuffaceous, feldspathic schists, approximately ten metres thick. The latter schists are whitish, sometimes greenish-white, thin out rapidly to the northwest and southeast, and they have a considerably different composition from the hard, highly siliceous rhyolitic metatuffs associated with the black phyllites further upstream at the mine.

The schists on the north face of the quarry generally strike about 140°, dip southwest at 40° but in one locality in the central portion of the face considerable deformation occurs with mesoscopic folding and jointing. The form of the folds could not be analysed in the field and the attitude of foliation could only be determined from study of oriented thin-sections. Similarly, the scale of folding is very difficult to determine but the folds are not presumed to have wavelengths and amplitudes in excess of one metre, i.e. they are of mesoscopic scale only. In one sample (see stereo-plot Fig. 6.6) the faltenspiegel of the folded folia strikes 100°, dips south at 60° and is cut by a well developed axial-plane cleavage (140°/40° southwest, i.e. generally parallel to the regional strike of the foliation). The line of intersection between the faltenspiegel and the axial-plane cleavage coincides with the fold axis and is seen as a faint lineation on the cleavage surface, trending
Fig. 6.6 Stereographic projection showing the relations of foliation ($s_1$), axial-plane cleavage ($s_2$), kinks and joints seen on the north face of the quarry at Mérétrice Mine.
254° and plunging at 37°. Jointing is strongly developed 035-055°/80-85° southeast), and two faint lineations can be seen on the joint planes, one being the joint plane/axial-plane cleavage intersection (217°/40°), the other being a joint plane/faltenspiegel intersection (205°/60°). Also, a well developed kinking occurs in many places, the plane of kinking striking 120°/dipping 55° northeast.

Thus, the folds seen here on the northeast face of the quarry have different styles and orientations from those kink folds seen in the black phyllites on the southwest face. The style and orientation of the former resemble those generally observed on a regional scale, and the latter are rather akin both in style and orientation to the late kink folds usually restricted to well-foliated, less competent phyllites and schists. (It should be noted that the intersection of the kink plane with the foliation plane in Fig. 6.6 trends 109°, plunges 15° - i.e. the same orientation as the fold axes in the zig-zag recumbent folds on the southwest face.)

(b) **Rhyolitic Metatuffs**

Rocks identified as metamorphosed rhyolitic tuffs or tuffaceous sediments vary considerably in general appearance and thin-section at Mérétrice. Two types have been recognized:

(1) Hard, siliceous, chert-like, non-foliated, grey, whitish grey, sometimes pinkish or pinkish-brown carrying minor disseminated pyrite and cut by numerous quartz veins. In thin-section (23693) they are comprised dominantly of quartz with minor phengitic
muscovite, pyrite, and limonite. This type outcrops on the east side of mine creek in two main bands one to three metres thick intercalated and concordant with dark grey phyllites and sericitic schists. The rock shows strong iron staining and leaching and is rusty, reddish-brown in outcrop and has been interpreted as a gossan by Rossello (unpublished Bureau Minière de la France d'Outre Mer, map of Mérétrice, scale 1/1,000). However, I consider that while an oxidation zone is certainly developed, the country rock is actually an acidic metatuff, most probably rhyolitic. Furthermore, this rock type is identical to those bands seen and mapped as rhyolitic metatuffs to the northwest of Mérétrice, 600 m along the strike, and to many similar bands in the vicinity of Pilou and elsewhere.

(2) The exact nature of the second rock type (but considered here as a rhyolitic metatuff or tuffaceous sediment) is conjectural. It is generally less siliceous than the first type, rather softer and in some places shows banding or layering, almost with the semblance of flow banding in one sample (23697). It is dark grey, occasionally greenish-grey, strongly spotted or porphyroblastic, the porphyroblasts being white or greenish-white when fresh, brown when weathered, many of which have been nearly completely leached out giving the rock a vughy appearance. Hard porphyroblasts of up to one centimetre diameter consist of quartz; others are soft and partly leached and consist of chlorite-kaolinite, while in one rock (23695) they are
smithsonite.

In thin-section, the following assemblages were observed: 23695, quartz-albite-chlorite-lawsonite-smithsonite-sphene-minor opaques; 23697, quartz-phengitic muscovite-chlorite-minor opaques. Quartz veins up to two centimetres wide are prevalent in some localities and one hand-specimen showed a two millimetre wide pyrite-quartz veinlet.

The strong replacement and leaching that this rock has undergone makes it very conjectural as to its original composition, but its nature is considered to be most likely a tuffaceous sediment. Its semblance of flow banding suggests it may have been originally a flow rock in part but this is uncertain. The localization of banding to particular layers in an apparently homogeneous rock body precludes the banding as being derived from a metamorphic feature but rather to a relict texture.

Further evidence of pyroclastic-derived material comes from small siliceous lenses, 20 cm by 4 cm, occurring in the black phyllites in the vicinity of the Pb-Zn lenses. The longest dimensions of the lenses lie parallel to the foliation in the host phyllites. The cores of the lenses are usually comprised of a box-like network of quartz veinlets, and the rims of compact hard siliceous rock. They possibly have similarities with the rhyolitic balls described by Kinkel (1962) at Rio Tinto Mine, Huelva District, Spain.
(c) **Metabasalts**

A metabasalt body lies to the north of Méretrice Mine approximately 30 m stratigraphically below the black phyllite band containing the Pb-Zn deposits. It is a coarse-grained greenish rock, massive, poorly foliated and relict igneous textures persist. A chemical analysis of this metabasalt body is given on p.28 (Table 2.1, analysis 11) from a sample taken in Balangahou Creek. The metabasalt has a poorly developed foliation but which parallels that of the metasedimentary rocks at the contacts; it is interpreted as a sill and therefore somewhat younger than the metasedimentary sequence which it intrudes. It is approximately 750 m long and reaches a maximum thickness of about 150 m.

In the mine creek the rock varies in texture near the contact from white tuffaceous feldspathic schists to a coarser-grained phase containing large white relict phenocrysts (23678, 23679, 23682). The phenocrysts, originally calcic plagioclase, are now composed of various assemblages, quartz-albite-pumpellyite-lawsonite. Further downstream and away from the stratigraphically upper contact, veins of an apple-green colour up to ten centimetres wide cut the metabasalt in several places. The veins (23680, 23691, 23681) are blastoporphyritic but finer grained than the metabasalt, discontinuous, and are sometimes cut off by small faults. The veins were only found cutting the metabasalt and were never observed cutting metasedimentary rocks.
Pilou Mine is situated 13 km northwest of Mérètrice and more or less on the same stratigraphic horizon within the Cretaceous strata. It also lies in a similar position with respect to the grade of metamorphism as Mérètrice, i.e. about 500 m outside the lawsonite isograd in pelitic assemblages and about 500 m inside the pumpellyite and Na-amphibole isograds in basic metaigneous assemblages.

The deposits at Pilou consist predominantly of chalcopyrite, galena, sphalerite and pyrite. Unfortunately no primary sulphides were found in situ and all samples were collected from mine dumps and waste - consequently the relationships between sulphide deposits and wall rocks have only been interpreted from hand-specimens and from features seen in the oxidation zone. Considerable underground mining activity about the turn of the century was carried out at Pilou but at the present day all shafts and adits are completely collapsed (see Fig. 6.7).

The deposits are considered to be stratiform in nature for the following reasons. Exposures on cuttings in the upper levels of the mine about 50 m below the summit of Pouape (Fig. 6.8) show that the overall fabric of the rocks, exemplified by layers of copper carbonates (malachite and azurite), iron oxides, and so on, generally parallel the foliation of highly oxidized and bleached schists. However it may be argued that planes of foliation and schistosity provide preferential paths for oxidizing fluids and that this is the reason for the apparent stratiform nature of the oxides, carbonates, etc. in the oxidation zone. Much
Fig. 6.7 Pilou Mine, view looking towards the east (July, 1971).

Fig. 6.8 Exposures on old cuttings near the upper levels of Pilou Mine.
better evidence is revealed from the sulphides themselves, presumably primary ores which show stratification, i.e. a moderately-developed foliation on a hand-specimen scale of gangue minerals, e.g. quartz, and sulphide layers where one particular mineral, e.g. sphalerite, predominates.

Lithologies and Structure

The lithologies at Pilou Mine are mainly bands of rhyolitic metatuffs intercalated with black, dark grey and greenish phyllites. Exposures are not very good in the vicinity of the mine itself but some excellent exposures occur in Pilou Creek. Fig. 1.12 is a detailed geological section of Pilou Creek and the major workings lie in perspective of this map about 300 m to the east along the strike, corresponding both structurally and stratigraphically to the region approximately where the stream forks at the southern end of the map section in black metaclaystone lithologies. It should be noted that the three bands of rhyolitic metatuffs exposed on the high ridge to the south-east of the mine (and considered greatly significant with respect to metallogenesis) do not extend as far west as Pilou Creek.

The structure is relatively simple with dips constantly to the southwest at angles varying from 40-80° (av. 65°) with strikes generally between 100-130° (av. 105°). There is no evidence for any large-scale folding, and the regional isoclinal folds with horizontal fold axes described by Millon (B.R.G.M. report of Pilou-Nemou, D341, date unknown) were not observed by the present author. In the close vicinity of the mine the largest folds observed occur about 80 m below the road crossing in Pilou Creek (see
Fig. 3.25). Here, a fold with amplitude of approximately 80 m and a wavelength of about 30 m occurs in metamorphosed tuffaceous strata containing small nodules, possibly relict pumice particles, and showing relict graded bedding (see p. 68). The only other folding observed occurs on a mesoscopic scale with amplitudes and wavelengths of several decimetres, never exceeding more than one metre.

The map symbol for bedding was only used where this was definitely seen on a small mesoscopic scale, e.g. graded bedding, finely interbedded layers of different lithologies. However, I regard the intercalated layers of rhyolitic metatuffs and pelitic schists or phyllites at the mine as most probably representing original bedding even though only the symbol for foliation is used on the maps. Furthermore, this foliation is also considered to be parallel to the foliation in the ore samples.

The following are descriptions of lithologies seen only in the vicinity of the mine. (For a description of lithologies in Pilou Creek see Fig. 1.12.)

(a) Phyllites

These are dark grey to black, sometimes greenish, weathering to brown and light brown, strongly foliated, sericitic, extremely fine-grained in some places and often rather hard and siliceous. Some layers have tiny nodules less than one millimetre in size and quartz veins are common. General assemblages are: quartz albite-phengitic muscovite-chlorite sphene-carbonaceous matter-tiny granular opaques. The nodules are comprised of granular quartz, sometimes quartz-albite, and in one sample (23545) there are nodules and fine narrow veins of quartz-calcite-dolomite.
Sulphides have not been observed but a black carbonaceous phyllite from Tourris (a showing to the southwest of Pilou Mine) contains small pyrite cubes.

Some phyllitic rocks are white to greenish-white and appear feldspathic and tuffaceous and represent a rock transitional between rhyolitic metatuffs and normal sericitic phyllites. Many outcrops of schists in the oxidation zone are white and greenish-white due to bleaching but in this case the original rock was probably a dark-grey or black carbonaceous phyllite.

Lithologies immediately south of the mine and stratigraphically higher in the succession become rather coarser grained than the overall fine phyllites seen in cuttings around the mine itself. Exposures along the side of the ridge to the south of the mine towards locality 23572 are generally brown or pinkish-brown sericitic schists and medium to fine in grain-size. Some rocks are quite siliceous and hard, and quartz veins and stringers are abundant, some cutting across the foliation at variable angles while others are parallel to the foliation. The assemblages in a nodular phyllite, probably a metasiltstone, from just above the mine in Pilou Creek (at locality 23541) is: quartz-albite-phengitic muscovite-chlorite-sphene-opaques (probably including carbonaceous matter).

Phyllites to the north of the mine are variable in grain-size although generally remain rather fine-grained but on the whole they are much more siliceous and hard and are interbedded with numerous metacherts. Quartz veins are ubiquitous and are particularly abundant cutting metacherts. Thin-sections from metacherts (23532-3) show simple
assemblages dominated by quartz and carrying very minor phengitic muscovite-chlorite-sphene-tiny opaques. The metacherts form discontinuous, narrow layers up to four metres thick and were mapped as rhyolitic bands by Millon (B.R.G.M. report).

(b) Rhyolitic Metatuffs

Three bands of rhyolitic metatuffs occur at the mine and as mentioned previously they are concordant and inter-stratified with metasedimentary phyllites. A further fourth band occurs about 500 m south of the mine. The two stratigraphically lower bands are a few metres thick and appear to cut out along the strike but the third band reaches about 20 m thick (measured in a small trench on the Pouape-Bouanat ridge) and seems to be continuous for approximately 500 m. However, the exposures are not actually continuous for that length and it is possible that while lying along one stratigraphic horizon, the band may be discontinuous and may pinch and swell. It is also cut by two small faults striking approximately normal to the foliation. A small complicated shear zone (120°/30° northeast) was also seen in the small trench on the ridge and is also probably only of several metres displacement.

The metatuffs are whitish-grey to grey when fresh and on weathering they change to pink and pinkish-brown; highly weathered surfaces vary from red to brown. They are hard, highly siliceous and often contain cavernous limonitic lensoid patches several centimetres in length and up to above five millimetres in width. In general they show a rather irregular, wavy, moderately developed foliation and
schistosity. Typical assemblages are: quartz-albite-phengitic muscovite-chlorite-pyrophyllite-opaques (commonly including pyrite). The fourth tuff band to the south at locality 23564 contains the complex assemblage: quartz-albite-phengitic muscovite-pyrophyllite-chlorite-epidote-calcite-magnesite-opaques (including limonite). The latter rock is hard, very siliceous, generally whitish and has patches of light brown calcite-magnesite. Some of the showings in the region around Pilou, e.g. Pilou West, are associated with dark greenish-grey and green rhyolitic metatuffs or tuffaceous metasediments which carry porphyroclasts of relict plagioclase, but such porphyroclasts have not been found in thin-sections of metatuffs around the mine.

(c) Metabasalts

Several, lensoid bodies of metabasalts occur in the region around the mine. One is situated about 60 m north of the mine and is approximately 20 m thick. Two other isolated bodies are exposed north of the Pouape-Bouanat ridge, and two narrow bands of metabasalt occur in the section mapped in Pilou Creek. Also, a large sheet more than 100 m thick occurs about 200 m north of the mine. They are similar to other such metabasalts elsewhere in the Diahot region and are generally considered to be sills. They are coarse-grained green rocks with relict igneous textures in thin-section. Typical assemblages are: relict augite-relict plagioclase-pumpellyite-Na-amphibole-chlorite-actinolitic amphibole (probably relict)-sphene-quartz-minor opaques. Sulphides are absent and relict augite and
plagioclase show ophitic and subophitic textures.

As at Mérétrice, the interpretation of these bodies as sills implies that they are somewhat younger than the country metasediments and are not thought to be genetically significant as far as the mineralization is concerned.

In some cases they show variation along the strike grading into greenish-brown finer-grained schists with a well-developed foliation containing brownish lenses, possibly relict igneous minerals, e.g. plagioclase.

(3) **Fern-Hill Mine**

Fern-Hill Mine (Fig. 6.9) is situated south of Ouégoa and the Diahot River and approximately 2 kilometres east of the Ouégoa-Koumac Road. The mine was exploited mainly for gold although considerable Cu-Pb-Zn mineralization is also present. As at Pilou, samples of primary mineralization were collected only from dumps and piles of waste. Some adits and shafts are still open although they are rather dangerous and partly collapsed at the present day; some have collapsed completely and others are vertical and were impossible to enter.

Native gold was found in two samples, one in a highly quartzose schist containing abundant pyrite (23841) and the other in a specimen of massive compact sulphide containing pyrite-sphalerite-chalcopyrite-galena-arsenopyrite (23859). In the former case, the gold is present as isolated grains set in quartz associated with pyrite. Espirat and Millon (1965) postulated that gold-quartz veins occurred along or in the vicinity of a series of northwest-southeast faults, dipping 50° southwest but no such faults or gold-quartz
Fig. 6.9 View overlooking Fern-Hill Mine, largely overgrown with scrub and niaouli trees at the present day. Ouégoa and the main divide between Vengaya and Col de Balade are seen in the far background (July, 1971).
veins have been observed by the writer - evidence for this may have come from underground data not presently available.

The sulphide mineralization shows moderately developed layering of sulphides in hand-specimens although this is not as well developed as that found at Mérétrice. Some polished sections, however, display allotriomorphic or granular textures with a mosaic of sulphides but with an overall foliated fabric on a small mesoscopic scale. Such textures are most probably produced by higher grades of metamorphism as Fern-Hill lies approximately half way between the lawsonite and epidote isograds, i.e. at a higher grade than Pilou and Mérétrice mines.

Structure

Structurally, Fern-Hill lies in the region where the foliation strikes northeast-southwest. Very significantly, it still lies approximately on the same stratigraphic horizon and the same structural form line as that of Pilou and Mérétrice in the Cretaceous rocks. The average strike of the country schists is regular at about 030° northeast (varying between 000°-070°) and dips are vertical or very steep to the northwest, averaging about 80° (varying from 45° northwest to vertical). Most schists are strongly lineated and some show well-developed rodding. The lineations are mainly small crenulations on the foliation plane and trend to the southwest (at varying angles between 190-280°) plunging about 50°, varying from 35°-85°. Large-scale folds were not observed and folding appears to be restricted to a mesoscopic scale only, with wavelengths and
amplitudes less than one metre. Near the trig at locality 23838 above the mine, the foliation and primary schistosity is strongly crenulated and transposed by a second more dominant schistosity or strain-slip cleavage ($130^\circ/80^\circ$ southwest). Further transposition of schistosity and small-scale parasitic folds were observed on the small ridge immediately east of the mine. Folds at both localities indicate a dextral vergence.

At locality 23838 a closely-spaced strain-slip axial-plane cleavage is developed in the hinge zones and strikes $145^\circ$, dipping $45^\circ$ southwest. Lineations produced by the intersection of the crenulated foliation and axial-plane cleavage trend approximately $235^\circ$ and plunge at $35^\circ$.

It should also be noted that further away from the mine (about 200 m to the east of the ridge between the mine and the Diahot River) the foliation sometimes flexes on a mesoscopic scale from a northeast-southwest strike to an east-west strike and then folds back again with a dextral vergence. In the hinge zones of these folds the faltenspiegel of the crenulated foliation planes strikes east-west, dipping nearly vertical (between $75^\circ$ north to $85^\circ$ south), and is transposed by a closely-spaced (two to four millimetre apart) axial-plane strain-slip cleavage striking between north and northeast, i.e. oriented similar to the regional strike of the foliation in this area. If further mining work goes ahead folds of this style could be encountered at depth.

Cross jointing is very prominent in some places and have an average northwest-southeast strike of $145^\circ$ (varying from $120-170^\circ$) and dips constantly to the northeast at $50-80^\circ$. Most joints have a thin veneer of quartz along them and
kinking along a joint was seen near locality 23838. Although quartz is the dominant mineral lining the joints, quartz-jarosite and quartz-jarosite-pyrite veins have also been observed. Some quartz veins follow the schistosity but also zig-zag across it in places (see Fig. 3.43b, p.89); small ptygmatitic veins up to three millimetres wide were observed at locality 23827.

Most reliable exposures and outcrops occur on ridge tops and strong surficial creep is prevalent especially on the flanks of ridges.

Lithologies

Lithologies at Fern-Hill consist of bands of rhyolitic metatuff intercalated with siliceous sericitic schists. Quartz veins are prevalent over the whole region.

(a) Rhyolitic Metatuffs

The rhyolitic metatuffs are very hard splintery fine-grained laminated sericitic schists but with a well developed foliation cut by numerous quartz veins. They are dark grey on fresh exposures and generally weather to brown rusty limonitic colours on the surfaces of joints and schistosity planes. As noted above, pronounced lineations occur on the foliation and schistosity planes. Some metatuffs vary in grain-size from fine pelitic layers to coarser-layered, psammitic intercalations with disseminated pyrite. Yellowish jarosite in veinlets, sometimes with quartz and pyrite, is often visible in hand-specimens.

Of particular importance, the rhyolitic metatuffs are notably potash-rich and a chemical analysis (Table 2.1, analysis 4) sampled from a profile of metatuffs on the west
ridge close to the vertical Scott shaft contained 7.6 weight per cent $K_2O$. In thin-sections the potash-rich nature is evidenced by abundant microcline occurring as porphyroblasts (up to 0.8 mm) generally restricted to particular layers. Quartz is the most abundant mineral and typical assemblages are quartz-phengitic muscovite-microcline-albite-jarosite-opaques (mainly pyrite). Sphene and zircon are accessories and opal was found in four thin-sections associated with quartz.

The microcline-bearing rhyolitic metatuffs have been mapped from detailed thin-section studies and extend for 950 m, i.e. twice the distance mapped by Espirat and Millon (1965) in the 1/50,000 sheet. They are finely intercalated with siliceous sericitic schists but the overall thickness of the tuffaceous horizons at their widest part is approximately 120 m.

(b) *Siliceous Schists*

These are usually slightly lighter grey than the metatuffs, highly siliceous but tend to part easily along schistosity planes. They consist of whitish medium grained quartz-rich layers intercalated with finer-grained dark-grey sericitic layers. Pyrite is disseminated throughout the schists and strong lineations, especially rodding of the quartz-rich layers, is prevalent. Assemblages are: quartz±albite-phengitic muscovite-opaques (mainly pyrite)±pyrophyllite.

In the wider region away from the mine, to the east and west normal to the strike, the schists become notably less siliceous and are softer, dark grey phyllites, probably metasiltstones. At some localities, e.g. 23939, the
phyllites have whitish-grey, quartz-rich layers finely laminated with darker-grey more carbonaceous layers. This probably represents relict bedding and lies exactly parallel to the foliation and schistosity. Typical assemblages are: quartz-talbite-phengitic muscovite-chlorite-Na-amphibole-sphene-opaques.

On the neighbouring ridge to the west, about 300 m from the mine, a band of relatively coarse-grained, orange-brown, highly siliceous schists or quartzites occurs which may be in part tuffaceous. This band is separated from the metatuffs at Fern-Hill by soft, medium to coarser-grained sericitic phyllites containing needles of Na-amphibole and are barren of any sulphides.

(4) Balade and Murat Mines

Balade Mine (Fig. 6.10) is situated in Balade Mine Stream two kilometres northwest of Ouëgoa, and Murat (Fig. 6.11) lies approximately 700 m further upstream. Both mines occur north of the Gendarmerie Fault, Balade is situated in the transitional zone and Murat lies just inside the epidote zone.

Previous mining activity was by underground means but all shafts and adits are partially or completely collapsed and cannot be entered at the present day except for a few metres. However, mineralization can be seen in place at the entrances of old workings but the best sulphide samples, especially at Murat, are found on waste dumps. Copper mineralization at Balade occurs in stratiform layers one to five centimetres thick finely interstratified with stilpnomelane-bearing quartzitic schists, green chloritic
Fig. 6.10 View looking down Balade Mine Stream towards Balade Mine. Note the rust-coloured schists of the oxidation zone (July, 1971).

Fig. 6.11 Waste dumps at Murat Mine (July, 1971)
mica schists and siliceous mica schists with abundant garnets. The country rocks at Murat are generally similar although stilpnomelane-bearing quartzitic schists are absent. Chloritoid is an additional phase in some rocks and long blades of ilmenite generally become increasingly abundant towards the zones of mineralization at both mines. Detailed mineral assemblages, chemical and modal analyses of selected rocks in the section of Balade Mine Stream from the Col d'Amoss Road up to the top of Murat are given later in this section, and a detailed geological section is shown in Fig. 1.13.

Lithologies and Structure

The structure in the region around Balade and Murat mines has already been discussed on pp.108 to 113 and only a brief résumé will be given here. Excellent exposures exist in Balade Mine Stream for about 400 m from the Col d'Amoss Road up to Balade Mine but thereafter, for about 500 m, very few exposures occur, and the stream here is largely choked with fallen glaucophanite boulders. Further upstream the exposures are reasonable for about 200 m up to Murat Mine. The foliation is generally very constant, remarkably so in the lower parts of the stream, but there are some local complex swings in the vicinity of Murat. The average strike of the foliation is 140°, with dips averaging approximately 35°, varying from 30-53°. Some broad swings in the foliation occur around Balade Mine but large scale folding is generally absent. Mesoscopic folds with transposition of schistosity were found at only two localities (23913 and 23938) but this is extremely localized.

At Balade Mine a band approximately 80 m thick of
generally hard rusty red-brown to purplish siliceous schists extends along the strike for considerable distances (at least 1,700 m). It is a unit very rich in iron with abundant limonite material and probably represents a zone of oxidation (see Figs. 6.12 and 6.13). In the vicinity of Balade Mine itself, it certainly does represent a zone of oxidation and contains (in place, on the east side of the stream) cuprite, tenorite, native copper and malachite. The iron-rich formation extends to the southeast following the strike of the foliation for 900 m where it is cut off by the Gendarmerie Fault. The Gendarmerie Fault in this region strikes approximately 115° and dips steeply to the southwest. From the mine to the Gendarmerie Fault the iron-rich formation retains a fairly constant thickness similar to that at the mine. It extends to the northwest for at least 800 m but thins out considerably to about 30 m on the ridge near locality 23989. Few exposures occur to the northwest of the mine on account of a covering of fallen glaucophanite boulders and its extension beyond locality 23989 could not be traced for the same reason. Certainly it does not extend as far as the Col d'Amoss Road or Gendarmerie Creek.

Jointing normal to the foliation is well-developed in this hard iron-rich siliceous unit. The joints strike northwest-southeast and dip steeply to the northeast and have aided the formation of a cuesta-like escarpment from just above Balade Mine up to the ridge to the east (Fig. 6.13). The escarpment was interpreted as demarcating a fault by Espirat and Millon (1965) and Millon (unpublished B.R.G.M. report), upthrown to the south, and resulting in the
Fig. 6.12 View overlooking Balade Mine Stream and the Diahot Valley, showing the iron-rich formation at Balade Mine in the centre of the photograph. The old gendarmerie and the Diahot River are seen in the middle background, and the ultramafic massif of Tiebaghi is seen on the right skyline (July, 1971).

Fig. 6.13 Photograph of the cuesta-like escarpment of the iron-rich formation at Balade Mine (July, 1971).
repetition of the mineralization at Balade up the direction of dip to Murat. However, no such fault was observed by the writer and the mineralization at Balade and Murat is considered to lie along distinct stratiform layers, most probably distinct relict bedding. Cubanite and mackinawite characterize the mineralization at Balade but their complete absence from Murat (evidence from at least nine polished sections from each deposit) supports the interpretation that they are stratigraphically separate deposits.

Furthermore, the mineralization at Bruat, separated from Murat by a large fault with a possible sinistral transcurrent displacement, is not considered an extension of the mineralization at Murat. Also, to the southwest of the Gendarmerie Fault, adjacent to the iron-rich unit, there are some exposures of rusty limonitic siliceous schists with pyrite, rather like those on the other side of the fault. However, the displacement on the Gendarmerie Fault is considered to be large and separates lawsonite zone rocks to the southwest from epidote zone rocks to the northeast. Consequently this rusty zone cannot be an extension of the Balade iron-rich unit on the other side of the fault.

The mineralization at Balade, although concentrated in particular layers, is actually disseminated throughout those layers, and compositional layering within massive chalcopyrite is poorly developed and even lacking in some cases. Furthermore, the mineralization is not concentrated within a particular lithology but is interlayered with a variety of lithologies, namely stilpnomelane quartzitic schists, green chloritic mica schists and siliceous mica schists. Fig. 6.14 is a sketch of the relationships of
Fig. 6.14 Sketch of the relationships of the mineralization to the country rocks exposed at Balade Mine.
the mineralization to the country rocks (including assemblages) at locality 23922 where primary sulphide mineralization is seen in place. In this instance, the mineralization is confined to layers in the stilpnomelane quartzitic schists but many samples collected from the mine dumps indicate that the mineralization is also interlayered with chloritic mica schists and siliceous mica schists. As mentioned above, stilpnomelane quartzitic schists have not been observed at Murat and the mineralization is associated and interlayered with siliceous chloritic mica schists.

Modal analyses are given in Table 6.3 from 23 thin-sections sampled from localities in Balade Mine Stream extending from close to the Col d'Amoss Road up to immediately above Murat Mine. Modal analyses were calculated by point-counting at angles of approximately 30° to the plane of foliation, following Chayes (1956). As illustrated in Fig. 6.14, it should be realized that localities 23921-5 are from a detailed continuous section about four metres in length, and at Murat localities 23946-9 are from a section approximately ten metres long. All localities are shown on Fig. 1.13.

Table 6.4 presents 18 bulk chemical analyses of selected rocks from Balade Mine Stream, both at Balade and Murat mines. All rocks analysed are pelites and metaigneous parents appear to be absent.

The most significant factor concerning the relationships of mineralization with respect to country wall rocks, is that the mineralization is localized within siliceous and iron-rich metasediments, indicated by the abundance of quartz and iron-rich silicate and oxide phases, e.g. stilpnomelane,
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TABLE 6.4  Bulk Rock Chemical Analyses of Rocks in Balade Mine Stream at Balade and Murat Mines. Analyses Numbered 12-29 by R.M. Briggs; Analyses 30-31 from Lacroix (1941), 30 = Stilpnomelane Schist at Balade Mine (Biotite Schist of Lacroix), 31 = Chloritoid Schist at Murat Mine; Analysis 32 = Siliceous Mica Schist at Balade Mine from Coleman (1967).

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<td>&lt;10</td>
<td>&lt;10</td>
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<td>99.9</td>
<td>99.3</td>
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ilmenite, chlorite, garnet and chloritoid. Lacroix (1941, p.71) also records hematite-magnetite-garnet schists from Balade Mine which he described as "itabirites" - I prefer the term ironstone following the nomenclature of James (1966) but I have not observed such extremely iron-rich rocks and it is possible that they were collected from a deeper level of the mine, now completely inundated. Lacroix also describes a grunerite quartzite which is likely to have been collected from Balade Mine although the exact location of this interesting rock type is not known. The iron-rich nature of the wall rocks is also confirmed by the corresponding chemical analyses, especially those analyses of Lacroix (1941). Analyses of specimen numbers 23924 from Balade and 23949 from Murat, are both very chlorite-rich and ilmenite-rich and contain 14.2 and 14.4 weight per cent total iron respectively. Similarly, 23922, rich in stilpnomelane, contains nearly 12 weight per cent total iron.

Part of the reason for chemically analysing the rocks was to determine whether the quartzitic schists had chemical compositions analogous to those rocks known to be rhyolitic metatuffs at lower grades, e.g. those around Mérétrice. At higher grades of metamorphism, as at Balade, it might be possible that metamorphosed tuffs would not be recognizable as such. However, when analyses of those rocks associated with the mineralization are plotted on AFM and ACF triangular diagrams (Fig. 6.15) which should demonstrate any such analogies, it was found that the rocks at Balade and Murat are very much more iron-rich and have distinctly different compositions from any of the rhyolitic metatuffs (analyses
Fig. 6.15  AFM and ACF (of Osann) triangular diagrams. Crosses numbered 1 - 6 refer to chemical analyses of rhylolithic metatuffs (Table 2.1) and circled dots numbered 12 - 29 refer to analyses of rocks in Balade Mine Stream (Table 6.4).
1-6) in the Diahot region. In fact, the rocks in Balade Mine Stream which resemble more closely the rhyolitic metatuffs are the normal dark grey mica schists (analyses 12, 13, 17, 24-26, 28), the ubiquitous lithology over the whole of the Ouégoa district, rather than the siliceous iron-rich schists associated with the mineralization (analyses 14-16, 18-23, 27, 29).

Thus it appears that while the mineralization at Fern-Hill, Mérétrice and Pilou are closely associated with rhyolitic metatuffs and black carbonaceous phyllites, at Balade and Murat there is quite a different association with siliceous and iron-rich metasediments, which were most probably originally chemical sediments perhaps having some analogies with ironstones.

Brief descriptions of country rock types in the vicinity of Balade and Murat are given below:

The quartzitic schists are light greenish-grey and whitish, with generally a poorly developed foliation and often veined with quartz. Stilpnomelane generally occurs in these highly siliceous schists and when present it gives the rock a black speckled semblance. Stilpnomelane is characteristically very coarse-grained forming radiating splays and large flakes up to five millimetres long and invariably with the longest dimension lying at all angles to the plane of foliation. Some specimens collected from dumps are comprised of massive, nearly pure stilpnomelane, extremely coarse-grained with some individual flakes up to one centimetre across. Garnets are abundant, always coexisting with stilpnomelane, and give most rocks a pink speckled and nodular appearance. Chloritoid is generally
confined to the quartzitic schists and also to particular folia within the schists and its presence suggests a derivation from an original iron- and alumina-rich parent. Chloritoid is visible in some hand-specimens (e.g. 23913) and like stilpnomelane it also occurs in bladed splays cutting across the plane of foliation at all angles.

The quartzitic schists grade into and are finely interbedded with greenish mica schists. The mica schists are dark greenish-grey to black, finer-grained, softer, and much better foliated than the quartzitic schists, usually nodular due to small pink garnet porphyroblasts and they often contain tiny stringers and lenses of quartz. One sample (23917 - analysis 17) is extremely fine-grained considering it occurs in a medium grade of metamorphism and should be described as a dark grey to black phyllite, rather than a mica schist. This sample also shows very fine pencil-line lineations or tiny crenulations on the plane of foliation.

Ilmenite is an ubiquitous accessory mineral in both quartzitic and mica schists and characteristically occurs in long blades (up to 0.5 mm) and stubby prisms, poikilitic and shows a good basal cleavage. However, the most striking feature about ilmenite is that it becomes increasingly abundant towards the zone of mineralization and has a sensitive sympathetic modal relationship with sphene. Ilmenite is typically absent from the normal country rocks and sphene is a common accessory. However, towards the zones of mineralization at both mines or rather particularly towards the iron-rich metasediments, sphene becomes increasingly abundant but is then "consumed" by metamorphic
reactions while ilmenite starts to crystallize and reaches a modal maximum in the wall rocks intercalated with the mineralization. Modal analyses of rocks just above Balade Mine (23926, 23938-9) show the reverse of this sympathetic sequence with increasing distance away from the mine. Thus, in this situation ilmenite can be used as an excellent marker for iron-rich metasediments and consequently, perhaps, for localization of mineralization in this region.

The general rock types around the mines show variations and gradations between quartzitic and mica schists, but at Balade a large, pale green pod of chlorite-talc schist occurs, several metres in length, set in siliceous chloritic mica schists. The chlorite-talc schist is strongly lineated, contains abundant lenses and veins of quartz, and sometimes hollow rhombohedral spaces where large porphyroblasts (possibly magnesite) have been weathered-out. In thin-section the chlorite is unusual in that it is nearly colourless suggesting it has a high Mg:Fe ratio, and in some hand-specimens long acicular dark green needles occur, probably actinolite. Similar rocks have been found elsewhere within fault zones but no trace of a fault could be found even though exposures are very good - huge quartz pods and boulders also occur in the vicinity but similarly do not appear to lie along fault zones.
(5) **Ao Mine**

Ao Mine lies outside the field of regional study of this thesis but it was visited briefly mainly to collect samples of sulphide mineralization. It is situated 3.5 km south of Pilou Mine in the upper part of the Aho River approximately half-way between the east and west coasts of the island in this region. According to the 1/50,000 Paagouméne B.R.G.M. map of Espirat and Millon (1967) it occurs in a large lens-shaped segment of the Cretaceous Pilou Formation lying within phanitic Tertiary strata. Structurally, this segment of Pilou Formation probably represents a detached slice of an overlapping Schuppen-type or imbricate structure - the local occurrence of lawsonite in pelitic rocks at Ao Mine would seem to confirm this, probably crystallizing under the sole of an over-riding small thrust sheet (cf. Brothers, 1974). Lawsonite is absent north of Ao and does not occur again until on a regional scale immediately north of Pilou Mine. Some folding occurs, seen by strong transposition of schistosity in some of the softer phyllitic rocks (e.g. 23505).

Ao was mined mainly for Cu, chalcopyrite being the dominant sulphide with lesser amounts of pyrite, sphalerite and galena. Other minerals found are malachite, azurite, chalcocite, covellite, two Bi-minerals, and limonite. Most samples of mineralization collected show dissemination of sulphides throughout a massive quartz gangue often with abundant carbonates (magnesite, dolomite, calcite).

The mine consists of several adits and shafts, mostly collapsed, but no mineralization was observed in place, all samples coming from dumps and piles of waste.
The country rocks are black and dark-grey nodular phyllites intercalated with dark grey, hard, massive non-foliated flinty rocks, very similar to the rhyolitic metatuffs in the Mérétrice region but rather more chert-like. A metabasalt body occurs in the vicinity of the mine but its relationships with the mineralization, if any, are unknown. Some curious lenses, 80 by 25 cm, with limonitic rims occur in hard massive dark grey schists exposed in the stream immediately along the strike from the mine. Some of them have a core of a box-like network of cross-cutting quartz veins very similar to those seen in such lenses in the black carbonaceous phyllites at Mérétrice, and like those, are thought to be some sort of acidic pyroclastic material. Others are constituted of a massive non-foliated chert-like rock as described above.

Assemblages in the hard cherty, possibly acidic tuffaceous rocks are: (23506, 23508-9) quartz-phengitic muscovite-chlorite+sphene+albite-opaques (including limonite, carbonaceous matter, pyrite); those in phyllites are (23505): quartz-phengitic muscovite-chlorite-lawsonite sphene-opaques (mainly limonite and carbonaceous matter). Jarosite is often present in veins associated with quartz.

(6) Mineral Showings in the Diahot Region

There are numerous small showings of Cu-Pb-Zn mineralization in the Diahot region and some of these are very small workings, mainly small shallow trenches, shafts or adits, partially or completely collapsed. Because
of their small size some of those recorded in the 1/50,000 Pam-Ouégoa and Paagoumène B.R.G.M. maps of Espirat and Millon (1965, 1967) could not be found and others were discovered which were not noted on these maps. Their locations are shown on the geological maps (Figs. 1.3, 1.4, 1.5, 1.6, 1.7).

(A) Showings in the Pilou Region

Tourris

This showing is situated about 500 m south of Pilou Mine and about 100 m south of the Pouape-Bouanat ridge. It consists of two small trenches and a cross-drive. Malachite, azurite, chalcopyrite, pyrite and dark red iron oxides were found in waste and the country rocks are dark grey carbonaceous, very fine-grained phyllites intercalated with greyish-green phyllites. One thin-section (23563) of the dark grey phyllites had the assemblage: quartz-phengitic muscovite-paragonite-chlorite-sphene-opaques (including pyrite cubes and carbonaceous matter). Some samples show wavy, irregular, deformed streaks and patches of green phyllites intercalated with black pyritic phyllites cut through by an anastomosing network of quartz veins. Considerable amounts of chalcopyrite are disseminated throughout the quartz veins and green phyllites but were not seen disseminated in the black rocks.

Pilou Creek

Copper mineralization occurs in Pilou Creek (see Fig. 1.12) in highly siliceous schists which are strongly deformed and probably occur along a shear zone. The schists
are fine to medium-grained metaclaystones and metasiltstones containing some greenish-grey siliceous lenses up to two metres long, 0.5 m wide. Crenulated and rodded quartz veins are abundant and malachite, azurite and chalcopyrite were found. This showing has not been worked.

One hundred and twenty metres to the west on the ridge are two small adits where further copper mineralization occurs as malachite and azurite. At the adits, medium to coarse grained light grey siliceous schists strike 125°, dip southwest at 60° and quartz veins are abundant, generally cutting across the foliation and schistosity.

Pilou West

Three hundred metres south of the above showing and approximately opposite Pilou Mine are another two small adits named Pilou West by the writer. Malachite, azurite, minor chalcopyrite, possibly chalcocite, and rusty-red iron oxides were found. Lithologies here are dark grey to black phyllites intercalated with a wide variety of green chloritic schists, some of which are softer nodular phyllites and others are hard, splintery and highly siliceous. The latter rock type (23540) contains quartz-phengitic muscovite-chlorite-relict plagioclase-sphene-opaques in thin-section and a chemical analysis is given in Table 2.1, analysis 6. Some green chloritic rocks also contain relict plagioclase porphyroclasts which gives some of the schists their nodular appearance and is thought to indicate an acid volcanic-derived source - i.e. they are probably rhyolitic metatuffs but their green colour distinguishes them from the pinkish-brown to grey type at Pilou and numerous other bands
mapped elsewhere in the Diahot region. One of the samples, 23539, is a particularly coarse-grained schist that is strongly nodular with a gritty semblance in hand-specimen and has the same assemblage as 23540. Quartz veins are plentiful and are notably conspicuous in mineralized rocks lying subparallel to the foliation.

Two hundred metres southwest on the ridge is a small adit not marked on the 1/50,000 sheet of Espirat and Millon (1965) where malachite, red and dark brown copper and iron oxides, and possibly chalcocite were found. The country schists strike 110°/dip 50° southwest and are whitish to light brown metasiltstones to metasandstones, siliceous in parts and veined by quartz.

**Tchiengane**

Four showings are marked on the 1/50,000 map of Paagoumène of Espirat and Millon (1967) near Tchiengane Creek but only one small hole in the ground was discovered by the author. The schists here are white metasiltstones and metasandstones, probably tuffaceous, intercalated with grey to light grey siliceous metasiltstones and metasandstones; a sample of the latter rock showed evidence of folding. Many rocks are rusty and strongly oxidized, and malachite, sometimes in radial splays, is also present.

**Lilas**

This showing is situated on the side of a small ridge between Balaguet and Tchiengane Creeks, localized along a narrow band of rhyolitic metatuffs. It consists of a tiny pit in the ground and schists found in the vicinity are light brown metasandstones intercalated with coarse-grained
pinkish rhyolitic metatuffs that strike 165°, dip 30° southwest. Malachite, dark red and brown Cu- and Fe-oxides and chalcopyrite were collected from waste.

(B) Showings in the Mérétrice Region

Moyen Tchimbo

This is situated about 500 m west of Tchimbo Creek and consists of a small pit in the ground. The country rocks are not especially rusty or conspicuously oxidized and no evidence of mineralization was noted by the author. The B.R.G.M. discovered a geochemical anomaly in this vicinity and found sphalerite at depth by drilling. Light brown sericitic schists and dark grey, siliceous nodular porphyroblastic schists occur in waste and are near to several bands of rhyolitic metatuffs. A thin-section of the light brown sericitic schists (23649) contained: quartz-phengitic muscovite-chlorite-minor opaques.

Bas Tchimbo

Situated between Pouagone and Tchimbo Creeks, this showing consists merely of a small digging in the ground where malachite, azurite and pyrite were found. The schists strike 140°, dip southwest at 20° and consist of a variety of dark grey, whitish green, greenish-grey, strongly laminated sericitic schists, the laminae most probably representing relict bedding. From study of thin-sections, the whitish-green schists (23644), interstratified with mineralized layers, contained the assemblage: quartz-albite-phengitic muscovite-chlorite-magnesite-malachite-pyrite (mainly pseudomorphed by limonite). Porphyroblasts of pyrite, occurring as cubes one millimetre across, and lenses
of quartz give some of the schists a strongly nodular appearance in certain layers. Assemblages in the dark grey and greyish green phyllites and schists (23645-6) carried: quartz-albite-phengitic muscovite-chlorite-opaques (mainly limonite and probably a little carbonaceous matter). Quartz occurs in some places either as veins or layers parallel to the schistosity.

Espoir

This showing occurs about 1,500 m east of Forêt d'Ougne, several metres away from the Forêt d'Ougne-Mérétrice Road. It consists of a vertical shaft but waste from the shaft is particularly difficult to find. The country rocks are light brown sericitic schists and one sample containing malachite was found.

La Folle

Two kilometres east of Mérétrice Mine and east of Djavel Creek are a number of showings of mineralization, i.e. three showings at La Folle, and three small trenches at Sommet 206. The showings at La Folle are all aligned along a thin rhyolitic metatuff band striking northwest-southeast (about 130°, dip 45-60° southwest) which then, a 100 m or so further to the southeast, folds very complexly through Sommet 206 and finally to a northeast-southwest strike towards the Ouégoa-Koumac Road. Three small adits occur at La Folle where malachite, azurite, chalcocite, chalcopyrite and Fe- and Cu-oxides were found. Mineralization is localized along contacts between the rhyolitic metatuffs and sericitic phyllites and schists. One sample of a greenish-pink siliceous schist (23733) from waste showed
strong folding deformation and abundant quartz veins, some of them ptygmatic, and contained quartz-chlorite-opaques (mainly limonite). Other rocks, also only seen in waste, were finely laminated whitish-grey schists carrying much pyrite. The sericitic schists are lineated in places, light brown, with a medium grain-size.

Sommet 206

As stated above, Sommet 206 occurs aligned along a complexly folded rhyolitic metatuff band. The rhyolitic metatuffs are whitish-grey weathering to pinky-brown, sometimes pyrite-bearing, hard and siliceous with an overall wavy foliation and schistosity sometimes exemplified by narrow discontinuous layers and elongated lenses of limonitic material. Schists at the contacts with the metatuffs are dark grey to black carbonaceous phyllites having the assemblage (in 23734): quartz-albite-phengitic muscovite-chlorite-lawsonite-opaques (probably mainly carbonaceous matter and limonite). Rocks around the trenches are extremely oxidized to red and purplish-black iron oxides and cerussite was suspected in some samples.

Djavel

This showing is situated about one kilometre to the northeast and roughly along the strike from La Folle. The rhyolitic metatuff seen at La Folle appears to thin out at La Folle and does not continue as far as Djavel. However, a greenish siliceous rock occurs here containing relict plagioclase with a composition more calcic than albite and which most probably indicates a partly tuffaceous derivation; the assemblage is: quartz-relict plagioclase-
phengitic muscovite-chlorite-sphene-opaques. Country rocks consist of greyish-green fine-grained siliceous phyllites, in some places rather contorted with a moderately developed strain-slip cleavage normal to the foliation and $S_1$ schistosity. A small adit is present and malachite and red-brown oxides are the only evidence of mineralization.

**Banianou**

Banianou is situated close to the south bank of the Diahot River about four kilometres west of the ferry crossing. Two small trenches occur there and although it is only a few metres away from a large metabasalt body, the rocks seen in the trenches and waste are white to pinkish-purple metatuffs, probably rhyolitic, associated with dark grey to black phyllites. White tuffaceous schists contain quartz-phengitic muscovite-chlorite-carbonate-sphene-opaques, and are rather massive with a poorly developed foliation and schistosity. The black phyllites are finely striated with the semblance of pencil markings and in a thin-section cut normal to the striations it was found that they are traces of a closely-spaced strain-slip cleavage; the assemblage is: quartz-phengitic muscovite-chlorite-sphene-opaques with thin quartz stringers parallel to the foliation. Malachite occurs particularly along joints of schists, and some highly oxidized black to dark brown limonitic rocks contain cerussite.

**Henri**

This showing occurs several hundred metres south of Banianou and consists of two trenches a few feet deep aligned along a band of rhyolitic metatuff. No mineralization
could be found but highly oxidized black to dark brown limonitic rocks form a possible gossan on the metatuffs. Light brown sericitic schists occur in contact with the metatuff which could be traced for approximately 200 m along the strike.

**Boualap**

A small adit occurs on the east side of the ridge leading to Boualap hill about one kilometre north of La Folle. No sign of mineralization was seen and the schists exposed here are dark grey siliceous schists, possibly tuffaceous. The rocks up on the ridge a few metres away are slightly rusty-coloured metatuffs, strongly jointed and show two sets of lineations. This showing is not marked on the 1/50,000 B.R.G.M. map.

**C** Showings in the Fern-Hill Region

**Euréka**

Euréka consists of a small trench situated about 500 m south of Fern-Hill Mine and about 100 m south of the 94 m peak. Malachite and possibly chalcocite were found. The country rocks consist of bands of rhyolitic metatuffs, similar to those described at Fern-Hill, intercalated with dark grey to greyish-green sericitic schists.

**Jack**

This showing lies a short distance to the west of Euréka along the prolongation to the south of the potassic rhyolitic metatuffs at Fern-Hill. A small trench occurs here and the author could find no evidence of mineralization. The schists consist of numerous finely-laminated, hard splintery metatuffs intercalated with hard siliceous schists.
Tirima

This showing is not marked on the 1/50,000 map and is situated directly west of Fern-Hill, a few hundred metres to the east of the Ouégoa-Koumac Road on a small hill named Tirima. Two adits have been cut into the side of the hill on a dip slope of rhyolitic metatuffs. The metatuffs vary in texture and mineralogy, some are pinkish-brown hard siliceous schists, with a moderate to poorly developed foliation, varying along the strike to brownish-green non-foliated massive rocks with pink porphyroclasts of relict plagioclase (23812). These are intercalated with dark grey to black softer phyllites and hard dark grey metacherts. This region is one of very complex structure and many rocks in the vicinity show strong folding, crenulations, lineations and transposition of schistosity. Average strike of the schists is 150°/dipping southwest at 20-40°. No evidence of mineralization was found.

(D) Showings in the Area Around Balade Mine

Only a few of the recorded showings on the 1/50,000 B.R.G.M. map were found; those not seen were: Raton, Zola, Patry, Coupeau, and Pamala.

Delaveuve

Delaveuve is situated about 600 m to the northwest of Balade Mine and consists of a deep vertical shaft and a small adit. Irregular layers of malachite, azurite and red-brown oxides generally parallel the foliation and schistosity. Minerals noted (including data from three polished sections, 23900-2) are: malachite, azurite, limonite (probably both goethite and lepidocrocite), ilmenite,
and small grains of pyrite and chalcopyrite, usually in a quartz gangue. The country rocks exposed in the adit and near the shaft are dark grey mica schists (115°/40° southwest) with garnet porphyroblasts, in places rather siliceous with quartz stringers and veins up to 15 cm thick. A set of joints, striking 145°, dipping 57° northeast, is fairly prominent in this region and are spaced 0.5-2 m apart.

Lacroix (1941, p.70) describes an aegirine-magnetite metachert from the hill at Delaveuve Mine - unfortunately it is not known whether the chert was actually collected from the mine or from a fault zone which passes very close to the mine and which is known to contain a variety of glaucophanites and metacherts.

Moonta

No workings occur at this showing and only a few patches of malachite were found. It occurs on the ridge about 300 m south of Balade Mine along a traced southeasterly extension of a quartzite band also exposed in Balade Mine Stream about 200 m downstream from the mine. Dark grey, rusty, siliceous schists are intercalated with greyish-green chloritic siliceous schists. Both rock types (23960-1) contain the same assemblages: quartz-chlorite-phengitic muscovite-opaques (mainly limonite and pyrite) although chlorite is much more abundant in the latter green rock (23961). Quartz veins and lenses are abundant, some parallel to the foliation, others cutting it at high angles.
26° Soldat

26° Soldat occurs about 200 m south of Moonta in a small stream along the strike of the same band of quartzites as the previous showing. The quartzites are hard dark grey, rather rusty, chloritic mica schists containing quartz-phengitic muscovite-chlorite-garnet-ilmenite and possibly chloritized stilpnomelane. Minerals identified from two polished sections include malachite, limonite, ilmenite, pyrite, chalcopyrite, covellite and chalcocite. Quartz is abundant, especially associated with mineralization, occurring as irregular fractured lenses and veins; generally, like the mineralization, the quartz veins follow the foliation and schistosity.

Podemba

Podemba is situated in the lower part of Podemba Creek about 200 m south of the Gendarmerie Fault. It consists of a steeply dipping shaft, following the angle of dip of the foliation (110°/70° southwest) and minor traces of copper mineralization were found (malachite, pyrite). The rocks are siliceous dark grey sandy schists (assemblage: quartz-albite-phengitic muscovite-glaucophane-garnet-chlorite-sphene-opaques (including pyrite)) intercalated with greenish chloritic schists, possibly tuffaceous. Malachite layers and patches generally lie parallel to the foliation and schistosity planes.

Bruat

Bruat occurs on a hill (Dôme de Bruat) about 200 m northeast of Murat Mine and separated from Murat by a large fault. No copper mineralization was found in several small
trenches but the rocks forming the dome are red-brown to purple, extremely rusty and limonitic, siliceous coarse mica schists, forming a possible zone of oxidation.

4. Composition and Texture of Mineral Deposits

The mineral deposits in the Diahot region show many differences in their composition and texture. Consequently these aspects at the major mineral deposits in the region will be described separately. A list of all sulphides, native metals, oxides and carbonates found by the author at each of the six major deposits (Pilou, Mérétrice, Fern-Hill, Ao, Balade, Murat) are shown in Table 6.5.

(1) Composition and Texture of the Mineral Deposits at Mérétrice Mine

The mineral deposits at Mérétrice occur as lenses of massive, compact, laminated and fine-grained sulphides. The laminae are due to mineral compositional differences, most commonly pyrite- or galena-rich layers set in a massive sphalerite matrix. Sphalerite is generally the most abundant sulphide present with pyrite, galena, arsenopyrite and chalcopyrite in approximately decreasing consecutive order of abundance. Tetrahedrite is relatively rare and has been identified in only two of the polished sections studied. In the massive lenses, sulphide minerals constitute approximately 80 to 90 per cent, the remaining 10 to 20 per cent usually consisting of quartz or carbonate gangue materials.

As mentioned previously, the compositional banding
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in the lenses is conformable with the foliation and schistosity of the country rocks, and in most samples is extremely well-developed, occurring as much finer, more delicate banding than any of the sulphide deposits elsewhere in the Diahot region except for some samples from Fern-Hill Mine. Typical compositional banding on a mesoscopic scale is illustrated in Fig. 6.16. Some of the banding is quite continuous for the whole length of the lenses but many bands are finely lenticular and discontinuous. In some cases, the bands show structures reminiscent of cross-bedding and sedimentary slumping on a small scale (Fig. 6.16b).

Hand-specimens of laminated massive sulphides collected from waste, probably dumped there for some forty years, show preferentially greater leaching of sphalerite-rich layers, leaving galena-rich layers with positive relief beautifully accentuating original bedding features (Fig. 6.16a).

The sulphide bands are not composed, in a general sense, of purely monomineralic layers but rather of alternating pyrite-rich, galena-rich, arsenopyrite-rich or chalcopyrite-rich layers associated with sphalerite or any one or more of these minerals (Fig. 6.17).

It is particularly interesting to note that in the section 23717, sampled from the stratigraphically lowest or very bottom surface of the sulphide lens seen in situ at Mérétrice, there is a tetrahedrite-rich layer, nearly monomineralic in composition. Tetrahedrite occurs again above this layer and is present in section 23716 sampled from the top surface of the same lens but only as isolated, anhedral grains, often associated with galena.

Zoning or any ordered sequence of compositional banding
Fig. 6.16a, b  Photographs of fine compositional banding and original sedimentary bedding features in massive Pb-Zn ore samples at Mérétrole Mine (23719, 23720).
has not been observed at Mérétrice, or indeed at any of the other mineral deposits studied in the Diabhot region.

The following are brief notes on some of the constituent minerals at Mérétrice Mine:

As mentioned above, sphalerite is the most abundant sulphide and forms the general matrix of the deposits. In many sections certain layers of sphalerite show brownish-yellow to dark brown internal reflections while in adjacent layers this is entirely lacking.

Pyrite usually occurs in well-developed cubic habit but in some cases it is subhedral to anhedral. The grain size of pyrite cubes varies from $<0.01$ mm to 0.6 mm, averaging 0.02 mm. Pyrite is often fractured, showing an island-like texture, and usually is cemented or replaced by chalcopyrite, more rarely by galena and gangue minerals, e.g. quartz, carbonates. The cementing chalcopyrite invariably occurs only up to the overall pyrite grain-boundary margin and does not enclose the pyrite grains entirely. Sphalerite, galena, chalcopyrite and arsenopyrite occur as inclusions in pyrite. The first three of these minerals always occur in rounded blebs but arsenopyrite invariably forms idiomorphic crystals in pyrite due to the greater interfacial free energy of arsenopyrite compared with pyrite (Stanton, 1964).

Many polished sections, e.g. 23713, 23717, 23703A, contain framboidal pyrite and pyrite atoll structures consisting of tightly-packed granular pyrite spheres often with cores of galena and black gangue minerals, possibly carbonaceous matter (Fig. 6.18).

Large euhedral pyrite crystals are often developed as overgrowths on the outermost margins of spherical framboids.
Fig. 6.17  Photomicrograph of fine compositional layering at Mérétrice Mine. Pyrite, arsenopyrite (both white, granular) and galena (greyish-white, irregular patches, wispy trails) occur as discontinuous layers in massive sphalerite (grey). X10, 23701

Fig. 6.18a, b  Photomicrographs of framboidal pyrite and pyrite atoll structures in massive sulphide ore at Mérétrice Mine. Pyrite (white), galena (light grey), sphalerite (grey), gangue (dark grey, black).
(a) X44, )both 23717.
(b) X224, (both 23717.
Fig. 6.18c, d, e  Photomicrographs of framboidal pyrite and pyrite atoll structures in massive sulphide ore at Meretrice Mine. Pyrite (white), galena (light grey), sphalerite (grey), gangue (dark grey, black).

(c) 23717
(d) and (e) 23703A, X224
and are illustrated in Fig. 6.18c, d, e. Such overgrowths on framboids have been observed in Recent sediments and sediments which have undergone diagenesis, and have been produced under laboratory experiments (e.g. Maucher and Saupé, 1967; Farrand, 1970; Sweeney and Kaplan, 1973). At Méretrice, euhedral overgrowths of pyrite only occur on a few of the framboids present, and if the overgrowth resulted from metamorphic recrystallization then it would be expected that they would be developed on all framboids; it seems more likely that the pyrite overgrowths occurred during sedimentation or diagenesis.

Galena is associated with many pyrite framboids and pyriteatolls at Méretrice, as irregular patches, as spherical cores surrounded by pyrite, sometimes as concentric layers around pyrite cores and occasionally surrounded again by another layer of pyrite (Fig. 6.18b, c, d). Schouten (1946a, b) described similar features from Rammelsberg and Mt Isa ores and argued in favour of a pseudomorphous origin of the various sulphides associated with pyrite in framboidal spheres (e.g. galena, chalcopyrite, sphalerite) in contrast to the ideas of Schneiderhöhn (1923; in: Schouten, 1946b) who postulated an origin from mixed gels and the existence of fossil sulphur bacteria.

Framboidal spheres of pyrite have been best documented from the Permian Kupferschiefer (Germany) (Schneiderhöhn, 1923; in: Sunagawa, et al. 1970; Love, 1962), the Rammelsberg Banderz (Germany) and the Devonian Chattanooga Shale (U.S.A.) (Amstutz, et al. 1967), and the Mt Isa shale of lower Proterozoic age of Queensland, Australia (Schouten, 1946a, b; Love and Zimmerman, 1961). Their formation is generally
thought to belong to the normal formation of the shale and its early diagenesis.

Three principal hypotheses have been suggested for the origin of frambooidal pyrites (reviewed in detail by Love and Amstutz, 1966; in: Sweeney and Kaplan, 1973). One was that a framboid represented the pyritized micro-fossil of a colony of sulphate-reducing bacteria (e.g. Love, 1957; Love and Zimmerman, 1961; Love, 1962). This has been convincingly illustrated by the preceding authors and undoubtedly at least some frambooids have been produced by this mechanism. However, the occurrence of frambooidal aggregates in andesites has cast doubt on their strictly biogenic origin (Steinike, 1963). A second hypothesis was that they were formed by crystallization of an inorganic gel of iron sulphides (e.g. Schouten, 1946 b). The third hypothesis, originally suggested by Schneiderhöhn (1923; in Sunagawa, 1971), considered that they were formed as a result of bacterial action due to the reaction between metal-bearing water and sulphur originating from sulphur bacteria.

Recently, successful attempts to synthesize pyrite frambooids under a variety of chemical conditions mainly by processes of pyritization of iron sulphides, in the laboratory, have conclusively demonstrated that biological control is unnecessary in framboid formation (e.g. Berner, 1969; Farrand, 1970; Sunagawa, et al. 1971; Sweeney and Kaplan, 1973). Whatever the origin of frambooids in the Mérétice sulphides, it is interesting to note the preservation of such relict microscopic structures especially at these medium grades of high pressure metamorphic recrystallization. Arsenopyrite generally has a smaller grain-size compared
with pyrite but probably shows a greater tendency to idiomorphism than pyrite, rarely occurring as anything other than sharply defined rhombic sections. This greater propensity to idiomorphism of arsenopyrite has been observed in many stratiform ores throughout the world by Stanton (1964) who convincingly proved that the decreasing order of degree of idiomorphism in sulphide minerals in stratiform ores, i.e. arsenopyrite, pyrite, pyrrhotite, sphalerite, chalcopyrite, galena (in consecutive order), are a function of the interfacial free energies of these minerals rather than to any paragenetic sequence of deposition. Tiny chalcopyrite and pyrite inclusions have been observed in arsenopyrite but inclusions in arsenopyrite are more rare than in pyrite. In some sections, e.g. 23706, arsenopyrite predominates modally over pyrite. In others, e.g. 23704, 23715, the average grain-size of arsenopyrite is very much smaller than in most sections (approximately 0.01 mm) occurring as extremely finely disseminated euhedral crystals in layers and patches in sphalerite.

Galena and chalcopyrite tend to anhedral form, usually occurring in elongated irregular lenses or wispy trails parallel to the banding. Chalcopyrite also occurs in tiny ovoid blebs in sphalerite grains (e.g. 23704), producing an emulsion-like texture.

Chalcocite occurs in compact masses replacing sphalerite, galena, chalcopyrite and pyrite along grain boundary margins, cleavage cracks and fissures. Covellite is often associated with chalcocite which it replaces in many cases and is often separated from sphalerite, galena, chalcopyrite and pyrite by a crust of chalcocite.
Native silver and two silver minerals, argentite and jalpaite, have been found in situ on the north face of the quarry at Mérétrice, associated with a quartz-limonite gangue. This is the only occurrence of these silver minerals and they are absent from the typical dark grey laminated massive pyrite-sphalerite-chalcopyrite-galena lenses. Native silver occurs as isolated irregular patches set in a quartz gangue, and is often partially replaced by argentite. Argentite also occurs in discrete crystals, forming irregular patches up to nine millimetres in length. However, the argentite associated with native silver exhibits different optical properties from that occurring as discrete crystals although both optical varieties have identical compositions, as determined by comparative electron microprobe analyses. Argentite associated with native silver is light grey with very low reflectivity rather similar to sphalerite, and in the second case, the argentite not associated with native silver is greyish white with moderate reflectivity more analogous to galena but has a distinct greenish tint especially against covellite and jalpaite. Covellite is a common replacement of argentite/and is especially better developed on the larger masses of argentite than the smaller grains which are possibly protected by a rim of quartz gangue. Covellite occurs particularly around the margins of argentite from which it invades the crystals in flame-like patches; some of these "flames" grade from the typical blue colours of covellite at the base into a light pink tint (in air) at the tips of the flames and with a much duller anisotropism than normal blue covellite. The composition of the light pink mineral could not be determined on account of
the extremely fine grain-size.

Jalpaite (Ag₃ Cu S₂) generally forms euhedral prismatic crystals or subhedral grains and is either isolated in quartz gangue or associated and intergrown with argentite; its identification has been confirmed by qualitative electron microprobe analysis. Compared with argentite its idiomorphic habit is quite striking. Jalpaite is harder and has a slightly higher reflectivity compared with argentite and is light whitish-grey with a pinkish tint beside argentite; it exhibits strong anisotropism with colour tints of green-golden brown and greenish-blue-grey. Jalpaite is often replaced around grain boundary margins and along irregular fractures by a very thin crust of chalcopyrite and some crystals of jalpaite contain rounded inclusions of chalcopyrite and argentite. Ramdohr (1969, p.482) records for jalpaite "fast light etching, but somewhat weaker than that of argentite", but light etching experiments under strong light conditions showed that while argentite etched very quickly with noticeable effects seen within one minute, no etching occurred in jalpaite under the same light conditions for at least one hour and strong light etching took two hours to develop.

Other sulphides present in those polished sections which contain native silver, argentite and jalpaite, are pyrite, sphalerite and chalcopyrite; associated non-sulphide minerals are quartz, limonite and malachite.

The question of the paragenetic position, i.e. whether supergene or hypogene deposition, of native silver and the two Ag-sulphosalts, argentite and jalpaite, in this situation is not certain. However, the author is inclined to the
Fig. 6.19a Photomicrograph of jalpaite (greyish-white, good polish) set in argentite (light grey, pitted). Argentite is partially replaced by flames of covellite (grey). X44, 23718A, Mérétrice Mine.

Fig. 6.19b Photomicrograph of jalpaite (white, good polish, prismatic) set in argentite (greyish-white, pitted). Argentite is partially replaced by covellite (light grey). X44, 23718A, Mérétrice Mine.

Fig. 6.20 Photomicrograph of compositional layering of chalcopyrite (white) and sphalerite (grey) at Pilou Mine. X44, 23559.
opinion that they were deposited in the zone of secondary enrichment or oxidation on the following grounds:

(a) These minerals have only been found in one location which was topographically higher than the massive pyrite-sphalerite-chalcopyrite-galena lenses which are certainly primary deposits.

(b) They have not been observed in the massive lenses.

(c) They are associated with abundant limonite, malachite, chalcocite and covellite.

Qualitative electron microprobe analyses of several galena crystals from the massive ore at Mérétroce, e.g. 23717, showed very small quantities of Ag in galena probably of the order of tens to several hundred ppm at the most (exact quantitative values could not be obtained). However, analyses of tetrahedrite proved a predominance of Sb, i.e. the tetrahedrite-type of the fahlore group, but significant quantities of Ag probably a few weight per cent. The tetrahedrite contains Sb, Cu, Zn, Fe, Ag in decreasing order of abundance of cations; Sn, Co, Ni, V, Ge, Bi, Hg, Te and As, if present, were below the level of detectability.

Previous assay reports from Mérétroce record significant quantities of silver (e.g. Rossello, 1962; Espirat and Millon, 1965, see p.272) but it is not known whether these figures represent total bulk sulphide ore, including such material as the silver-bearing mineralization, or merely the massive laminated sulphide ore.

Pyrrhotite is extremely rare at Mérétroce and was found in a few tiny grains in only one polished section (23712) associated with sphalerite, galena and chalcocite.

Cerussite is abundant in oxidized material occurring in
some large euhedra up to one centimetre long usually in limonitic box-works. **Smithsonite** was found in dark grey lawsonite-bearing schists *in situ* on the south side of the quarry, situated several tens of metres away along the strike from the sulphide lenses. Smithsonite occurring at greater distances away from primary mineralization than cerussite is consistent with the relative solubilities of these carbonates, smithsonite having the greater solubility and hence the tendency for it to be carried away in solution for considerable distances before precipitation.

**Malachite** is ubiquitous in oxidized material and predominates over **azurite**. Gangue minerals include quartz, limonite, calcite and dolomite.

Barite has been reported by both Rossello (1962) and Espirat and Millon (1965) but has not been found by the present author. Barite invariably occurs in similar types of deposits throughout the world, e.g. in the Japanese "kuroko" type of deposits, and its presence is certainly expected. Espirat and Millon also record anglesite and pyromorphite at Mérétrice.

(2) Composition and Texture of the Mineral Deposits at Pilou Mine

*In situ* sulphide deposits have not been examined by the author at Pilou due to the almost total collapse of old shafts and adits. Consequently polished sections described are those taken only from old mine dumps. Composition and textures of sulphide samples differ significantly from those at Mérétrice with chalcopyrite probably being the most abundant sulphide followed by lesser but still considerable
amounts of galena and sphalerite.

Compositional layering or banding of sulphides is not nearly as well-developed as that at Mérétrice and is exemplified by discontinuous layers of pyrite crystals or wispy irregular trails, lenses, and interdigitations of sphalerite and galena, generally set in massive compact chalcopyrite (Fig. 6.20).

The layering or banding is considered to be most probably relict bedding and sometimes shows gentle folding. Some specimens contain up to 95 per cent massive chalcopyrite with small quantities of pyrite, sphalerite or galena, some contain approximately equal proportions of chalcopyrite and sphalerite, or chalcopyrite and galena, and others carry massive compact galena up to 70 to 80 per cent in polished sections. The absence of in situ sulphide deposits unfortunately precludes any observations on possible spatial zonation patterns of relative abundances of chalcopyrite, sphalerite or galena.

Pyrite usually occurs in subhedral to anhedral grains, less commonly with perfect cubic habit, and grain sizes vary from 0.005 mm to 1.5 mm. The lack of idiomorphism and rounding and fracturing in pyrite crystals at Pilou is a noticeable feature especially in comparison to other deposits in the Diahot region. This fabric is thought to have been formed during deformation and to have resulted from kneading and fracturing of pyrite in a matrix of relatively plastic chalcopyrite. Chalcopyrite appears to have annealed and recemented the fractured pyrite and no evidence for replacement of pyrite by chalcopyrite has been observed. Larger pyrite porphyroblasts often contain a variety of tiny inclusions
including chalcopyrite, sphalerite, galena and pyrrhotite; in some sections, e.g. 23556, extremely small inclusions are concentrated in the cores while the rims are clear and appear optically homogeneous. In one section, 23559, there are structures reminiscent of pyrite frambooids.

Pyrrhotite is rare occurring usually as small rounded inclusions in pyrite porphyroblasts (e.g. 23548(a), 23559, 23558, 23548(b) but in section 23557 it is present in several small grains approximately 0.02 mm in diameter set in sphalerite, galena and chalcopyrite.

Sphalerite and galena are abundant, generally as solitary anhedral grains or in discontinuous subparallel irregular patches, bands and trails, interlayered and interdigitated with chalcopyrite. In 23550 galena forms an anastomosing and interdigitating network with chalcopyrite but still shows a rather vague foliation. Sphalerite and galena mutually replace one another along irregular cracks, grain boundaries and cleavages (23548) and both are replaced by covellite. Many sections, e.g. 23557, show bent and complexly folded cleavages in galena proving a mild degree of post-mineralization deformation. Emulsion textures with tiny spherical blebs of chalcopyrite in sphalerite occur in a few sections but the reverse relationship with sphalerite "emulsions" in chalcopyrite have not been observed.

Chalcopyrite is generally in massive compact form except where it cements and anneals pyrite along narrow fractures (23557). Chalcopyrite is replaced by a variety of minerals or a sequence of minerals, in some cases directly by limonite and in others (e.g. 23562) by chalcocite or covellite, and in many sections (e.g. 23558, 23548(a), 23557) by an idaite-
like phase. Replacement sequences observed are:
chalcopyrite $\rightarrow$ covellite $\rightarrow$ malachite
chalcopyrite $\rightarrow$ chalcocite $\rightarrow$ covellite $\rightarrow$ malachite
chalcopyrite $\rightarrow$ idaite $\rightarrow$ covellite $\rightarrow$ limonite

The idaite-like phase invariably occurs in tiny compact granular form (generally less than 0.01 mm) in irregular narrow cracks and fissures in chalcopyrite and rarely, in section 23557, in similar habit in galena. In most cases the idaite-like mineral is closely associated with covellite where it forms a very narrow rim separating chalcopyrite from covellite; in this situation it appears to be a supergene alteration product of chalcopyrite. Variation in the chemical composition and corresponding formulae of these idaite-like minerals are given in Table 6.11. This type of idaite shows very strong bireflectance from reddish-brown to greyish-brown and its anisotropism is enormous in colours of greenish-grey. By comparison, the idaite at Fern-Hill is a duller orange-brown and its bireflectance and anisotropism very much weaker. One exception to the typical idaite-like phase found at Pilou occurs in section 23558 where it occurs in a single grain or more likely in a compact granular aggregate approximately 0.09 mm wide but is not localized along a fissure in chalcopyrite; the optical properties in this case are more akin to the idaite from Fern-Hill.

Chalcocite and covellite are very abundant especially in samples most probably originating from the zones of cementation or oxidation, and commonly replace chalcopyrite, sphalerite and galena. In some typical sections, e.g. 23562, chalcocite and covellite replace chalcopyrite which
occurs as anhedral relics in an island-like texture.

Malachite is more abundant than azurite, the former often forming splays of crystals nucleated on chalcocite and/or covellite. Quartz, limonite, phengitic muscovite and calcite are ubiquitous gangue minerals.

(3) **Composition and Texture of the Mineral Deposits at Fern-Hill Mine**

In situ samples of massive sulphide mineralization at Fern-Hill have not been found and all specimens of massive sulphides are those collected from old dumps and waste. The mineralization is pyritic in character, pyrrhotite being absent, and massive sulphide samples are composed dominantly of sphalerite, chalcopyrite, galena and slightly lesser amounts of pyrite. Sphalerite is the most abundant mineral in the compact sulphide ore and idaite and tetrahedrite are additional minor phases.

The mineralization may be divided into three broad types based on compositional and textural criteria.

Type (1) samples are characterized by containing abundant disseminated pyrite and types (2) and (3) are both massive sulphide ores. Only the type (1) specimens are found in situ. It seems likely that type (2) ores occur at some stratigraphically and spatially different horizon from that of type (3) because each type was collected from separate mine dumps, although any considerations on the actual spatial relations between (2) and (3) would be conjectural.

**Type (1)** These are hard dark grey splintery quartzitic rocks with abundant disseminated pyrite usually showing a vague foliation or banding. Some polished sections of such
specimens (e.g. 23841) carry a few microscopic grains of native gold, up to 0.03 mm long. Chalcopyrite, galena and sphalerite are rare phases in this type and often occur as tiny inclusions in pyrite porphyroblasts.

Type (2) This type consists of massive sulphide ore which generally lacks any foliation or compositional layering and has an overall granoblastic fabric consisting of a compact mosaic of sulphide minerals and quartz gangue (Fig. 6.21). Sphalerite, galena and chalcopyrite occur in roughly equal proportions with slightly lesser amounts of pyrite. Idaite and more rarely tetrahedrite are additional but significant phases. Gangue minerals, e.g. quartz, phengitic muscovite, constitute only about 10 to 20 modal per cent.

Type (3) The third type shows excellent compositional layering developed on a very fine scale and is as delicately banded as that seen at Mérétrice (Fig. 6.22). The compositional layering or foliation is constituted of trails, lenses and sub-parallel bands of chalcopyrite-, galena- and pyrite-rich layers set in a matrix of compact sphalerite. Sphalerite is the most abundant phase, constituting up to 75 modal per cent in some sections, but this type (3) notably lacks idaite and tetrahedrite typical of type (2), and perhaps more significantly, contains tiny grains of native gold not found by the author in type (2).

Strong deformation is exemplified by gangue minerals, mainly micas, in some polished sections of type (2) ore. One sample, 23845, shows localized isoclinal folding of gangue micas on a microscopic scale with wavelengths of about 1.2 mm. However, the sulphides adjacent to the micas show no evidence
Fig. 6.21 Photomicrograph of mosaic texture at Fern-Hill Mine. Chalcopyrite (greyish-white, good polish), pyrite (white, high relief), sphalerite (grey), galena (greyish-white, poor polish, scratched), quartz gangue (black). X88, 23847.

Fig. 6.22 Photomicrograph of fine compositional layering in pyrite (pure white), sphalerite (grey), chalcopyrite (white), gangue (dark grey, black) at Fern-Hill Mine. X44, 23850.

Fig. 6.23a Photomicrograph showing segregation of small chalcopyrite and galena grains (both white, galena has higher relief) along grain boundary margins of large ovoid sphalerite crystals or aggregates (grey). X44, 23851. Fern-Hill Mine.
of folding and form a mosaic pattern of compact grains, probably indicating that considerable post-deformational recrystallization has occurred. Furthermore, the micas in the hinges of the folds form polygonal arcs which support this hypothesis (e.g. Zwart, 1962).

On the other hand, the ore of type (3) shows only gentle folding at most, with broad wavy layers of sulphides, seen mainly on a microscopic scale and which may represent an original sedimentary or diagenetic feature rather than be due to any tectonic deformation (Fig. 6.22). In some examples, e.g. 23851, there are long continuous sharp contacts between finely-bedded sphalerite-chalcopyrite-galena layers and pyrite-rich or pyrite-galena-sphalerite-chalcopyrite-rich lenses or pockets, i.e. features reminiscent of sedimentary scour and fill structures. It is thus unfortunate that such samples could not be located in situ but on regional structural grounds, stratigraphic tops should be directed towards the southeast at Fern-Hill where the regional strike of the foliation is northeast-southwest. Most of the pockets and lenses, interlayered between finely-laminated sulphides, are comprised of pyrite-rich aggregates which generally lack banding or show poorer-developed banding than the sulphides outside the lenses. Certain areas in some sections (e.g. 23851) show features reminiscent of cross-bedding and some layers consist of large ovoid grains or aggregates of sphalerite about 0.3 mm long, usually with their longest dimensions parallel to the banding and with their grain boundaries delineated by tiny grains of chalcopyrite (Fig. 6.23).

General notes on textures and compositions of all types of ores are given below.
Fig. 6.23b Photomicrograph showing segregation of small chalcopyrite and galena grains (both white, galena has higher relief) along grain boundary margins of large ovoid sphalerite crystals or aggregates (grey). X44, 23851. Fern-Hill Mine.

Fig. 6.24 Photomicrograph of typical mosaic texture at Fern-Hill Mine consisting of sphalerite (grey), pyrite (white), chalcopyrite (greyish-white, good polish), galena (greyish-white, poor polish, scratches, triangular pits), idaite (light grey), covellite (grey, mottled, partially replaces idaite around margins and along cracks in idaite), quartz (black). X88, 23843.

Fig. 6.25 Photomicrograph of idaite (greyish-white) set in quartz gangue (dark grey) at Fern-Hill Mine. Idaite is rimmed by a thin crust of chalcopyrite (white), and is partially replaced by covellite (grey) along tiny irregular cracks; small spindles or lamellae of chalcopyrite penetrate into idaite from the margins. X448, 23844.
Grain sizes of pyrite range from 0.006 mm to 0.8 mm, average approximately 0.08 mm, and vary in outline from euhedral to anhedral. Pyrite porphyroblasts contain a variety of inclusions including chalcopyrite, galena, sphalerite, idaite and native gold. Many pyrite crystals exhibit island-like textures set in a matrix of chalcopyrite, sphalerite or quartz and have probably been produced by cataclastic deformation during metamorphism with annealing and recementation by the minerals in the matrix.

Native gold is found as isolated grains in quartz and associated with pyrite in type (1) specimens. In type (3) ore, native gold has been observed set in pyrite, galena and chalcopyrite. One pyrite porphyroblast in section 23858 (type (3)) contains abundant inclusions of native gold with a grain size reaching 0.03 mm. Native gold is bright golden yellow, distinctly greenish under crossed nicols and probably contains very little Ag content.

Tetrahehrite has been found only in samples of type (2) and occurs in anhedral grains up to 0.1 mm, usually adjacent to galena. It is light greenish-grey with a definite greenish tint beside sphalerite and galena, and qualitative electron microprobe analyses of several crystals in 23843 showed it to contain Sb>As (i.e. of tetrahedrite-type in the fahlore group), significant quantities of Zn and trace amounts of Fe. Ag, Ni, Co, V, Hg, Bi, Sn, Ge, Te are absent or below the level of detectability.

Sphalerite in many sections, e.g. 23848, contains brown, reddish-brown or yellowish-brown internal reflections, and generally shows mutual grain boundaries against chalcopyrite. Galena, however, usually shows slightly cuspate margins against
sphalerite and chalcopyrite and is best seen in the mosaic fabric of type (2) ore. A qualitative electron microprobe analysis of galena in 23843 did not detect any Ag content, unlike that in the argentiferous galena at Mérétrice.

Idaite is a conspicuous phase in type (2) samples occurring in some large, anhedral grains and very often shows partial or even complete replacement by covellite. It is orange-brown to pink-brown, weakly bireflectant and moderately anisotropic. In contrast to its occurrence as a supergene alteration product of chalcopyrite at Pilou, idaite at Fern-Hill occurs as a constituent of the typical mosaic of sulphides and appears in this case to be a primary mineral (Fig. 6.24). This aspect is elaborated further on p. 390 and the variation in chemical composition and corresponding chemical formulae of idaite are given in Table 6.11.

In general, covellite replaces idaite in preference to any other sulphides and in many cases replaces idaite completely even though the surrounding mosaic of sulphides, e.g. chalcopyrite, sphalerite, galena, are unaltered.

An interesting relationship occurs on those patches of idaite or idaite-covellite juxtaposed against quartz gangue—in many cases where this occurs the idaite or idaite-covellite has a thin crust of a chalcopyrite-like phase which also penetrates inwards along cleavage directions of idaite in the shape of small spindles or lamellae (see Fig. 6.25). The paragenetical relations are discussed further on p. 393.

Covellite is also an abundant secondary mineral replacing galena, chalcopyrite and sphalerite along fissures and cleavage cracks and is associated with patches of malachite. Chalcocite has not been observed by the author in any of the
polished sections from Fern-Hill.

Arsenopyrite is rare, identified in one section (23858) occurring as several idiomorphic rhombohedra, and bornite has been observed only as a solitary tiny inclusion in a pyrite porphyroblast in 23848.

Malachite has been the only carbonate discovered at Fern-Hill; quartz is the dominant gangue mineral, followed by a variety of other silicates, e.g. micas, and limonite is an ubiquitous accessory.

(4) Composition and Texture of the Mineral Deposits at Balade Mine

Although all the old underground workings at Balade Mine are largely collapsed, primary sulphide mineralization is exposed in place on the west bank of Balade Mine Stream. Chalcopyrite is the dominant primary sulphide phase with generally much lesser amounts (approximately in decreasing order) of pyrite, pyrrhotite, cubanite, arsenopyrite, mackinawite, sphalerite, and galena. Bornite, native silver and native gold are very rare.

Of particular interest at Balade Mine is the well-developed oxidation zone, seen in situ on the east side of Balade Mine Stream, where samples containing native copper, cuprite, tenorite, chalcocite, covellite, malachite and limonite have been collected. The oxidation zone extends for considerable distances on either side of the stream but this is the only locality where such copper-rich material has been found.

At the locality where sulphide mineralization is exposed in place, the relationships between country schists and sulphides are well seen where chalcopyrite-rich layers are intercalated with quartzitic and chloritic mica schists.
carrying garnet, stilpnomelane, ilmenite, and chloritoid. Many layers contain large pyrite porphyroblasts up to three millimetres across generally disseminated in chalcopyrite. The bands of sulphides vary in width from a few millimetres of discontinuous chalcopyrite-rich or chalcopyrite-pyrite-rich layers to up to five centimetres of more massive chalcopyrite and are always parallel to the foliation in the country schists. Within these thicker bands of massive chalcopyrite, vague compositional layering can be seen on a mesoscopic scale but the degree of banding is never as well developed as the Pb-Zn ore at Mérétrice or Fern-Hill. The compositional layering consists of trails of pyrite grains or an alignment of flaky silicates (e.g. micas, chlorite) in compact chalcopyrite. Much of the mineralization, although more confined to particular layers in the schists, occurs merely as disseminations within those layers and many samples lack any compositional banding on a microscopic scale.

**Cubanite** is a notable mineral at Balade and occurs as an exsolved phase in chalcopyrite. A chemical analysis of cubanite is given in Table 6.7 and analyses of chalcopyrite at five of the major mines are given in Table 6.6. Cubanite forms long lamellae usually approximately 0.05 mm wide but sometimes as much as 0.1 mm wide and reaches lengths of up to approximately one millimetre. In many instances, several lamellae occur close together and parallel to each other, usually fairly uniform in thickness along their length, often pinching out at their ends or suddenly terminating. Some lamellae form at high angles to others and appear to follow (111) cleavage directions in chalcopyrite.

According to Ramdohr (1969) cubanite is apparently very
unstable and is easily replaced by other minerals - this is indeed the case at Balade Mine where it shows partial or complete replacement by a variety of minerals including covellite, pyrite, marcasite, chalcopyrite, pyrrhotite and mackinawite. Covellite is the most common replacement of cubanite and often replaces it completely, occasionally in association with limonite especially near weathering cracks. In more oxidized samples, e.g. 23937, chalcopyrite strongly replaces cubanite leaving minute relics of lamellae, but in less weathered samples it occurs in small rounded globules and blebs in certain parts of the lamellae. Pyrrhotite generally occurs only as a partial replacement of cubanite lamellae. Pyrite, occasionally containing tiny irregular patches of marcasite, has textures similar to that of pyrrhotite replacing cubanite. Ramdohr (1969) suggested that this pyrite and marcasite forms from the alteration of pyrrhotite. Mackinawite forms small globules and elongate patches partially replacing several lamellae of cubanite, in a similar fashion to that of chalcopyrite. However, no evidence of mackinawite replacing chalcopyrite or vice versa within cubanite lamellae has been observed, neither has pyrite nor marcasite been seen replacing pyrrhotite.

There seems little doubt that cubanite forms as an exsolution from chalcopyrite, parallel to (111), and has been previously recorded as such by very many authors (e.g. Ramdohr, 1969). Twinning has been observed on (111) in chalcopyrite in a few sections (e.g. 23928) and some sets of twin lamellae parallel cubanite lamellae. The twin lamellae are rather similar to cubanite lamellae and usually pinch out or terminate suddenly.
Mackinawite is a common accessory at Balade, in tiny thin irregular wormlets, often in platelets or thin lamellae bent at sharp angles or bent T-shapes which are parallel to crystallographic directions in chalcopyrite. In some instances, mackinawite lamellae lie parallel to each other on different crystallographic planes in chalcopyrite, and when oriented in this fashion, all the individual mackinawite lamellae appear to show identical crystallographic orientations indicated by their coincidence in the degree of anisotropism at the same angle. Single crystals are usually very small, never comparable in size to cubanite, usually less than 0.2 mm long and approximately 0.01 mm wide.

Pyrrhotite is much more abundant than mackinawite but never predominates over pyrite and occurs in small anhedral grains, as irregular wormlets and sometimes in thin lamellae. It appears to partially replace pyrite porphyroblasts in 23933 in a patchy fashion and is itself replaced by chalcopyrite in more oxidized samples (e.g. 23937).

Arsenopyrite forms numerous small rhombohedra in several sections and shows a notable lack of any alteration even in samples typical of the zone of cementation where covellite forms a ramifying network texture replacing chalcopyrite.

Sphalerite generally occurs either in disseminated solitary blebs or in discontinuous trails. Star-shaped sphalerite crystals characteristic of exsolution textures in chalcopyrite have not been observed.

Galena is a very minor accessory as tiny anhedral grains usually broadly aligned and concentrated along particular layers in chalcopyrite. Galena is closely associated with very fine-grained (0.01 mm) native silver in some sections.
Native gold reported previously by Rossello (1962), has also been identified in one section, where it occurs as a solitary grain within silicate folia.

Pyrite is very abundant varying in size from small anhedral grains (0.005 mm) to large subhedral to euhedral porphyroblasts up to three millimetres in diameter. Many porphyroblasts are poikilitic containing numerous inclusions of chalcopyrite, galena, pyrrhotite, bornite and silicate gangue minerals, often in lens-like bodies aligned parallel to crystallographic directions in the pyrite host. Bornite has only been found as inclusions in pyrite poikiloblasts, and never as disseminations in chalcopyrite. In one section (23933, Fig. 6.26) ovoid inclusions of chalcopyrite and bornite form radially arranged graphic intergrowths in poikiloblastic pyrite; these textures are thought to have formed from contemporaneous recrystallization of chalcopyrite, bornite and pyrite during prograde porphyroblastic growth of the pyrite. In many cases the foliation in the schists wraps around pyrite porphyroblasts in a similar fashion to that of garnets, indicating that some recrystallization of pyrite (and garnet) actually occurred prior to the development of foliation (e.g. Zwart, 1960, 1962). As at Murat and elsewhere in the Diahot region, pyrite is typically fractured and recemented by chalcopyrite.

Ilmenite is an ubiquitous accessory in the gangue and persists into the oxidation zone. It characteristically forms long blades up to 0.5 mm long and stubby prisms with a well-developed basal (0001) cleavage and is usually poikilitic with rounded inclusions of silicates, pyrite and
chalcopyrite.

In polished sections of the oxidation zone (14050), copper oxides are very abundant with tenorite predominating over cuprite, and are finely interlayered with ubiquitous limonite. Native copper occurs as brilliant reddish-brown anhedral insets in cuprite but which according to Ramdohr are generally not replacement remnants and have resulted from simultaneous crystallization with cuprite. Cuprite is often encrusted by a thin layer of limonite, even on euhedral crystals, other grains of cuprite have straight mutual boundaries against tenorite, but in many cases cuprite is embayed and altered by both limonite and tenorite.

Tenorite occurs in a variety of habits, usually interlayered with limonite or in colloform growths consisting of rhythmical concentric shells often alternating with limonite. Textural relations with cuprite indicate that, paragenetically, tenorite formed contemporaneously with cuprite but continued to form later than cuprite. Tenorite in turn shows embayments and alteration by limonite. Some of the rhythmical colloform masses alternating with limonite have an outermost layer of limonite from which there is a further radial growth of malachite. Malachite has also been noted embaying cuprite from which it also splays out in long radiating crystals.

Pyrite does not persist into the oxidation zone but small remnant patches of chalcopyrite occur surrounded by chalcocite and/or covellite. Chalcocite and covellite in turn generally show further oxidation to limonite.

Ilmenite shows very little effect of any replacement or oxidation but a few blades are embayed and veined with limonite, some of which contain a thin central core of
Fig. 6.26 Photomicrograph showing graphic intergrowths of chalcopyrite (light grey) and bornite in poikiloblastic pyrite (white) at Balade Mine. Bornite (grey) is rare and occurs in three tiny grains near the centre of the photograph associated with chalcopyrite. X88, 23953.

Fig. 6.27 Photomicrograph depicting a chalcopyrite (white)-quartz (grey) veinlet occurring along a strain-slip cleavage ($s_2$) which cuts obliquely across the foliation ($s_1$). Fine-grained granular pyrite occurs in the country rock outside the veinlet. Murat Mine, X20, 17256.
tenorite; the veins tend to parallel (0001) basal cleavages. Similar veins, some of them also with a central core infilled with tenorite, cut fractured poikilitic garnet porphyroblasts which also tend to be largely resistant to oxidizing solutions.

In summary, some sequences of oxidation observed at Balade in the zone of oxidation are the following:

?-native Cu+cuprite+tenorite+limonite+malachite

?-native Cu+cuprite+limonite+malachite

?-native Cu+cuprite+malachite

chalcopryrite+chalcocite+covellite+limonite

ilmeneite (+silicates, e.g. garnet)+limonite (+tenorite)

Bismuthinite and enargite are additional minerals recorded by Rossello (1962) from Balade Mine but they have not been identified (in more than 20 polished sections) by the present author. Calcite is an additional gangue mineral; it was collected from mine dumps and is strongly iron-stained which gives it the appearance more typical of siderite.

(5) **Composition and Texture of the Mineral Deposits at Murat Mine**

Mineralization at Murat Mine occurs as pyrite-chalcopyrite-rich bands generally parallel to the foliation and schistosity of the country mica-schists. Individual bands are of variable width and are estimated from the size of samples collected from the mine dumps to be at least eight centimetres thick. Compact massive chalcopyrite ore generally shows poorly developed foliation or compositional layering in the form of discontinuous trails of pyrite, sphalerite, micas and other gangue silicates.
### TABLE 6.6  Electron Microprobe Analyses of Chalcopyrite Compositions at Mérétice, Pilou, Fern-Hill, Balade and Murat Mines

<table>
<thead>
<tr>
<th></th>
<th>Mérétice</th>
<th>Pilou</th>
<th>Fern-Hill</th>
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<tbody>
<tr>
<td>Cu</td>
<td>33.6</td>
<td>34.4</td>
<td>33.6</td>
</tr>
<tr>
<td>Fe</td>
<td>29.4</td>
<td>30.0</td>
<td>30.0</td>
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<tr>
<td>S</td>
<td>34.1</td>
<td>34.1</td>
<td>34.9</td>
</tr>
<tr>
<td>Total</td>
<td>97.1</td>
<td>98.5</td>
<td>98.5</td>
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</tbody>
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<table>
<thead>
<tr>
<th></th>
<th>Balade</th>
<th>Murat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>34.2</td>
<td>34.6</td>
</tr>
<tr>
<td>Fe</td>
<td>29.9</td>
<td>29.8</td>
</tr>
<tr>
<td>S</td>
<td>35.6</td>
<td>34.6</td>
</tr>
<tr>
<td>Total</td>
<td>99.7</td>
<td>99.0</td>
</tr>
</tbody>
</table>

### TABLE 6.7  Electron Microprobe Analysis of Cubanite at Balade Mine

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Cu</td>
<td>23.3</td>
</tr>
<tr>
<td>Fe</td>
<td>38.8</td>
</tr>
<tr>
<td>S</td>
<td>37.3</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
</tr>
</tbody>
</table>

Formula: $\text{Cu Fe}_{1.89} \text{S}_{3.17}$
In the massive ore, chalcopyrite is the dominant sulphide followed by lesser amounts of pyrite and pyrrhotite, and rare sphalerite and galena. Pyrite is always modally dominant over pyrrhotite. Minerals notably absent from the mineralization at Murat, compared with those at Balade Mine, are cubanite and mackinawite.

Grain sizes of pyrite crystals vary from tiny anhedral grains 0.005 mm in diameter to large euhedral to subhedral porphyroblasts 2.5 mm across. Most porphyroblasts are poikilitic containing numerous inclusions of chalcopyrite, pyrrhotite, sphalerite, galena and rarely of bornite (e.g. 23951, 23952). Also in some pyrite porphyroblasts there are inclusions of smaller pyrite crystals with perfect cubic form, and in many cases there are compact masses and aggregates of granular pyrite juxtaposed against and surrounding the boundaries of the pyrite porphyroblasts. Marcasite sometimes occurs in these surrounding masses, typically as small patches probably formed from the decomposition of pyrite. Thus, it appears that there are probably at least two generations of recrystallized pyrite, an earlier generation forming porphyroblasts of pyrite and a later one forming finer-grained masses and aggregates. The inclusions of small cubes of pyrite in some porphyroblasts may represent either a further third episode preceding that generation which formed the porphyroblasts or a contemporaneous intergrowth with the larger host.

Further evidence for more than one episode of recrystallization is shown in several sections (17256) where there is a primary phase of recrystallization of fine-grained chalcopyrite- and pyrite-rich layers parallel to the
foliation and $S_1$ schistosity, and a second, characteristically coarser-grained phase of chalcopyrite, pyrite, pyrrhotite and quartz, occurring in veinlets and thin stringers infilling small mesoscopic shear zones and $S_2$ strain-slip cleavages (Fig. 6.27). Some of these veinlets are partially lined with quartz which is often euhedral, and carry interstitial chalcopyrite infilling the central portions of the veinlets together with occasional anhedral grains of pyrite and pyrrhotite.

Narrow pyrite-quartz veins in some sections of massive ore (23950) cutting massive chalcopyrite at high angles to the plane of layering or foliation may also be related to these late veinlets, but in these cases no deformation is visible in the massive chalcopyrite and it is not known whether these pyrite-quartz veins are infilling shear zones. Further details of the deformation of the ore deposits at Murat are discussed in the next section (p.396).

Island-like textures of pyrite porphyroblasts occur in many instances where the porphyroblasts have been cataclastically shattered and the fractures have been infilled and recemented by chalcopyrite, and more rarely by pyrrhotite.

Pyrrhotite characteristically occurs in small anhedral grains up to 0.3 mm in diameter, rarely exhibiting subhedral form, and very often forms tiny irregular wormlets possibly filling interstices between chalcopyrite grain boundaries. Pyrrhotite is veined by pyrite in section 23952 and in many sections pyrrhotite shows peculiar tarnishing effects of greyish cloudy material often streaked out parallel to the direction of layering or foliation.

Sphalerite is more abundant than pyrrhotite in certain
sections, occurring as tiny grains and larger irregular lensoid masses and trails. Layers of sphalerite trails in certain areas of section 23952 delineate isoclinal folding on a microscopic scale, and in other areas they wrap around large pyrite porphyroblasts in a similar fashion to micas wrapping around garnet porphyroblasts in the country schists.

Galena is never abundant and probably constitutes less than one per cent by volume of the total sulphides, occurring in tiny isolated grains set in compact chalcopyrite, some of them barely discernible under the microscope, and as inclusions in pyrite porphyroblasts. In some cases, e.g. 23953, galena, chalcopyrite and rare bornite inclusions are strongly aligned as small lens-like bodies along the cubic cleavage patterns in pyrite.

Ilmenite is an ubiquitous accessory mineral in the gangue at Murat, typically occurring in long blades (up to 0.5 mm long) and stubby prisms and exhibit a well-developed basal (0001) cleavage. Ilmenite is invariably aligned with its longest dimension parallel to the foliation in the silicates and characteristically is poikilitic, carrying tiny ovoid inclusions usually of silicates but also of pyrite (in section 23954) and chalcopyrite (23956). Twinning was observed in the form of multiple lamellae at high angles to the longest dimension of some ilmenite crystals, often tapering out along the lengths of the lamellae.

Magnetite was recorded in only one section (23956b) where it was found as a solitary irregular grain associated with silicates and ilmenite.

Malachite and azurite mainly form stains and growths around entrances and on the walls of adits, and is associated
with cavernous, limonitized schists. Covellite and chalcocite have not been identified in any sections collected by the author but would certainly be expected in more oxidized samples.

(6) Composition and Texture of the Mineral Deposits at Ao Mine

Eight polished sections have been made from sulphide mineralization at Ao but all specimens were found from old mine dumps.

Chalcopyrite is by far the most abundant sulphide constituting 60 to 70 per cent by volume in some samples, the remainder being made up of sphalerite, pyrite and lesser amounts of galena. Two Bi-bearing minerals have been identified in one section, 23512. Quartz is the most common gangue mineral together with a variety of carbonates including calcite, dolomite and magnesite.

Most samples completely lack any compositional layering or foliation but in certain areas of some sections there is a moderate degree of banding seen by trails, lenses and discontinuous bands of sphalerite- and galena-rich layers (more rarely of pyrite) in a compact chalcopyrite matrix. Several samples contain only a few patches of sulphides set in a massive quartz-carbonate gangue showing no foliation or compositional layering.

Common features observed are emulsion textures of chalcopyrite blebs and fine-grained spherical droplets arranged in cloud-like aggregates in sphalerite, best seen in sections 23516 and 23515. In many instances three different forms of chalcopyrite are embedded in sphalerite, even in the same crystal (Fig. 6.28):
The first type are minute ovoid droplets barely visible under the microscope and often concentrated in apparently randomly oriented aggregates in the central portions of sphalerite.

Chalcopyrite also forms tabular or lens-like bodies notably aligned and oriented parallel to certain crystallographic directions in sphalerite. Usually these are of slightly larger grain-size than those in the former case and also show a tendency to develop in the cores of sphalerite crystals.

The third form occurs in larger irregular blebs without any apparent orientation and characteristically are segregated on the rims of sphalerite crystals. In many cases they form lozenge-shaped bodies but in other instances they have an irregular shape.

The interpretation of these textural relations is discussed in a later section (p.388).

Pyrite generally has an anhedral form although a few show euhedral cubic faces and often appear broken up into island-like textures, annealed and recemented along fractures and cleavage planes by chalcopyrite, sphalerite, chalcocite and limonite. Peculiar structures are seen in section 23512, Fig. 6.29, where long, fractured "worms" of pyrite varying from 0.6 to 1.3 mm in length form an anastomosing network. Two of these "worms" have broader rounded "heads" and long "tails" fractured and cemented by narrow veins of chalcopyrite oriented along particular directions. Such structures appear reminiscent of trace fossils like pyritized worm borings or pyritized coprolites. On the other hand,
Fig. 6.28 Photomicrograph showing emulsion textures of chalcopyrite (white) in sphalerite (grey). Chalcopyrite forms blebs and fine-grained droplets. Ao Mine, X88, 23515.

Fig. 6.29 Photomicrograph of fractured "worms" of pyrite (greyish-white, high relief) set in massive chalcopyrite (grey) at Ao Mine, X44, 23512.
textures like this may have originated from fracturing of a formerly coherent pyrite grain or aggregate which has been annealed and recemented by chalcopyrite during deformation and metamorphism.

Two bismuth sulphosalts have been identified by electron probe analyses from section 23512 at Ao. Both are Cu Pb Bi S compounds and for reasons discussed later they have been designated merely as CuPbBiS-I and CuPbBiS-II. Comparative electron microprobe analyses between I and II indicated a considerably higher Bi component in II than I. Both minerals together constitute probably less than two per cent by volume in the section and CuPbBiS-I is very much more abundant than CuPbBiS-II. I occurs in irregular patches consisting of a compact mosaic or aggregate of grains whereas II usually forms thin lamellae, platelets and irregular blebs, always set in I. However, II does not seem to be an exsolution in I as the lamellae very often exceed in length the greatest dimensions of individual grains of I.

Presumably both bismuth sulphosalts have compositions belonging to the bismuthinite-aikinite series but optical properties of both minerals are quite distinct from either bismuthinite or aikinite. I is white, very similar to that of galena, moderately to strongly bireflectant in tints from pure white to light brownish-white, very strongly anisotropic with a much stronger anisotropism than Ramdohr (1969) records for aikinite. II is creamy-white with very strong anisotropism similar to I but no bireflection was visible to the writer - any determination of bireflection, if actually present, was possibly hampered because of a lack of two individual grains juxtaposed against each other.
Many names have been given to minerals in the bismuthinite-aikinite series, namely (data from Povarennykh, 1971): gladite, rezbanyite, lindströmite, hammarite, nuffieldite, cuplumbisulite. Padera (1956, in: Ramdohr, 1969) suggested that the intermediate members between bismuthinite and aikinite should not be considered different species but should all be represented by the common name rezbanyite. The bismuthinite-aikinite series was formerly not considered to be a continuous isomorphous series (Welm, 1968; Moore, 1967; Borodaev, 1970, 1971; in: Borodaev, 1971), but recently, Springer (1971), using synthetically prepared members of the series, proved that in fact it did show continuous isomorphism.

Consequently, I have merely used the names CuPbBiS-I and CuPbBiS-II to describe the two minerals at Ao with II containing a greater Bi component than I and lying closer to the bismuthinite end member of the series.

Other minerals identified include chalcocite and covellite which form large masses and characteristically infill cracks and fissures in chalcopyrite and occasionally in pyrite, sphalerite and galena. Tenorite occurs in section 23515 as small rhythmically banded colloform masses, closely associated with limonite which typically forms much larger patches surrounding tenorite - both minerals appear to be derived from the oxidation of chalcopyrite.

Gangue minerals calcite and dolomite are typically associated together, invariably with abundant quartz, and sometimes together with large dark red-brown to brown crystals of magnesite. It is possible that magnesite contains an appreciable Fe-content to give the brown colours, and hence
may perhaps have been mistakenly identified for siderite by Rossello (1962). Malachite and azurite are common, and malachite is generally the more abundant.

5. Metamorphism and Deformation of the Mineral Deposits

All the stratiform sulphide deposits in the Diahot region are believed to have been deposited during the Cretaceous, contemporaneously with the sediments in which they occur, and prior to regional metamorphism in the Oligocene. The metamorphism and accompanying deformation has variously modified the mineral deposits and some of these aspects will be discussed in this section, namely:

(1) Relict structures and textures.

(2) Changes in the fabric of the sulphide deposits as a result of metamorphic recrystallization:
   (a) Changes in the form or shape of sulphide minerals.
   (b) Grain size variation of pyrite crystals with variation in metamorphic grade.

(3) Mineralogical changes due to metamorphism.

(4) Fabrics due to deformation of the sulphides.

(5) Fabrics due to remobilization.

As mentioned previously, Mérétrice and Pilou mines are situated very close to the lawsonite isograd defined in pelitic assemblages, Fern-Hill lies approximately in the middle part of the lawsonite zone, Balade and Murat lie very close to the epidote isograd and Ao Mine is considered to be situated in a localized, detached schuppen structure of lawsonite grade metamorphism although in this case lawsonite zone rocks are not developed on a regional scale.
Relict Structures and Textures

Compositional banding or foliated structures in both sulphide and silicate minerals in ores are very common and characteristic even in the highly metamorphosed deposits of Balade and Murat. Such textural features have been described in detail in the previous section. Most significantly, the banding or foliation is also exactly parallel to the foliation in the wall rock schists whenever sulphide mineralization is seen in situ (e.g. Mérétrice, Balade, Murat), and in the wall rocks the foliation is presumed in most cases to represent relict bedding. Hence, the corollary is that the compositional banding and foliation in the ores is a relict bedding feature. Structures appearing to be cross-bedding in the massive sulphides at Mérétrice and Fern-Hill, and sedimentary slumping at Mérétrice, strongly support the hypothesis of a sedimentary or diagenetic origin.

Some of the sulphide minerals, i.e. cubanite, mackinawite, are additions to the original pre-metamorphic paragenesis, although the overall character and most probably the bulk rock composition of the sulphides and wall rocks would have remained much the same. For example, the pyrite-sphalerite-galena-chalcopyrite-arsenopyrite assemblage at Mérétrice most probably had a very similar original character and composition prior to metamorphism and in this case the effects of metamorphism are considered to be extremely slight and only produced, at most, minor modification of the form and shape of some of the sulphide minerals. The preservation of relict pyrite framboïds and pyrite-galena-sphalerite atoll structures of presumably sedimentary or
diagenetic origin in the massive sulphides at Mérétrice even at these medium grades of high pressure metamorphism has already been mentioned and very significantly proves an almost negligible effect of metamorphism on the textures and composition of these sulphide deposits. The presence of such relicts also strongly suggests that the overall banded fabric in the sulphide deposits is also a relict feature of the initial ore-forming process, rather than the result of later metamorphism.

A notable feature of the deposits in the Diahot region is that the dominantly Pb-Zn ores like those of Mérétrice and Fern-Hill are beautifully and intricately well-bedded while those of the dominantly copper ores, e.g. Balade, Murat, Ao, Pilou, are comparatively poorly bedded. This appears to be a feature peculiarly inherent to the original composition of the ores and has been pointed out by Stanton (1972) in similar stratiform sulphide deposits, e.g. Mt Isa. Also, the banding and layering in the dominantly Cu ores is developed to a very similar extent at Balade and Murat, at relatively higher metamorphic grades, as that at Pilou and Ao where the ores have been subjected to only relatively lower grades of metamorphism. Thus it can be concluded that progressive metamorphism from low to medium-high grades, has not significantly produced a better developed banding or foliation.

Relict colloform textures have been found in many metamorphosed ores, e.g. in the metamorphosed sulphides at Okuki and Kune Mines, Japan (Horikoshi, 1959; Yui, 1964; in: Kanehira and Tatsumi, 1970) but the only undoubted colloform textures in the Diahot region are those ascribed
to have formed from rhythmical deposition of oxides in the oxidation and cementation zones, e.g. tenorite at Balade, Ao.

(2) Changes in the Fabric of the Sulphide Deposits as a Result of Metamorphic Recrystallization

(a) Changes in the Form or Shape of Sulphide Minerals

Recrystallization produces characteristic crystal shapes and intergrowths in sulphides consequent upon the relative ability of an individual mineral to achieve idiomorphism. It has been noted throughout all the mineral deposits in the Diahot region that particular minerals usually have euhedral shapes, chiefly arsenopyrite and pyrite, others typically have subhedral to anhedral outlines, e.g. pyrrhotite, and many minerals like sphalerite, chalcopyrite and galena invariably have anhedral form and seldom develop crystal faces.

Stanton (1964) was probably the first English-language writer to interpret textures of regionally metamorphosed sulphide ores and proved that textures in ores of this type are not evidence of a paragenetical sequence, in which "late" matrix sulphides (e.g. sphalerite, chalcopyrite, galena) had "infilled" against early formed euhedral pyrite and arsenopyrite, but rather were expressions of part of a crystalloblastic series of metamorphic recrystallization, i.e. a function of the minimum interfacial free energies of these minerals and equilibrium between them. The crystalloblastic series noted in the Diahot deposits, in order of decreasing tendency to idiomorphism, is as follows: arsenopyrite, pyrite, pyrrhotite, sphalerite, chalcopyrite, galena. This order is a direct parallel with that proposed by Stanton (1964).
On the other hand, this order of idiomorphism could have commenced during diagenetic recrystallization (Amstutz, et al., 1964) and metamorphic recrystallization sensu stricto may have merely accentuated a pre-existing fabric, especially at Mérétrice, Pilou and Ao at low metamorphic grades. However, diagenesis grades imperceptibly into that of metamorphism, making any distinction hazardous in many instances, and many features attributed to metamorphism in this discussion could actually have formed during diagenetic recrystallization.

One exception to this order of idiomorphism is pyrite at Pilou Mine which is rarely euhedral and is usually rounded and granulated due to cataclastic deformation.

Also, the order of the last three matrix minerals (sphalerite, chalcopyrite, galena) should very often be grouped closely together as in many cases they have mutual grain boundaries and are difficult to separate consecutively. The matrix minerals show excellent metamorphic recrystallization textures in the Type (2) ores at Fern-Hill Mine (see Fig. 6.21, p.351), where sphalerite, galena, chalcopyrite, tetrahedrite and idaite are intimately intergrown in allotriomorphic mosaics and where adjacent grains meet in triple-point junctions. Although many cases are ambiguous, galena generally shows slightly cuspate grain boundary margins against all other sulphides, idaite shows slightly cuspate margins against all others except galena, and so on, and hence it is possible to determine a generalized crystallo-blastic sequence at Fern-Hill, in decreasing order: pyrite, sphalerite, tetrahedrite, chalcopyrite, idaite, galena. (Arsenopyrite is a very rare mineral but would most likely
precede pyrite, as is the case at Mérétrice.) The cuspate
grain boundaries of the sulphides low in the crystallobleastic
sequence are thus a metamorphic recrystallization texture
rather than due to replacement of one sulphide by another

In the Type (3) ore at Fern-Hill (also at Ao Mine), large
sphalerite grains form an intergrown mosaic and minor
chalcopyrite and galena crystals have been segregated into
lozenge-shaped grains along grain boundary margins of
sphalerite (Fig. 6.23). Such textures would be regarded
as resulting from metamorphic recrystallization by many
Etching of samples would also undoubtedly expose further detail
of recrystallization textures especially in the monomineralic
patches and layers.

(b) **Grain Size Variation in Pyrite Crystals**

In general, there is a progressive increase in the grain
size of sulphide minerals with increase in metamorphic grade.
This is best exemplified in the grain size of pyrite crystals
which are present at every deposit and afforded the best
sulphide mineral on which to study such a variation.

Grain sizes of 500 pyrite crystals were measured at
each of Mérétrice, Pilou, Fern-Hill, Balade and Murat mines
and the results are shown in histograms in Fig. 6.30 and
are summarised in Table 6.8. Most grains were measured
parallel to the (100) cubic faces in pyrite, and rounded,
anhedral grains, where (100) cubic faces could not be
detected, were measured across their diameters.
Fig. 6.30 Histograms showing variation in grain sizes of 500 pyrite crystals at each of Mérétrice, Pilou, Fern-Hill, Murat and Balade Mines.
### TABLE 6.8 Grain Size Variation in Pyrite Crystals with Variation in Metamorphic Grade

<table>
<thead>
<tr>
<th>Mine</th>
<th>Range in grain size (mm)</th>
<th>Average grain size (mm)</th>
<th>Metamorphic grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mérétice</td>
<td>0.002 - 0.6</td>
<td>0.03</td>
<td>Lawsonite isograd</td>
</tr>
<tr>
<td>Pilou</td>
<td>0.006 - 1.4</td>
<td>0.07</td>
<td>Lawsonite isograd</td>
</tr>
<tr>
<td>Fern-Hill</td>
<td>0.005 - 0.8</td>
<td>0.08</td>
<td>Lawsonite zone</td>
</tr>
<tr>
<td>Balade</td>
<td>0.01 - 3.0</td>
<td>0.19</td>
<td>Epidote isograd</td>
</tr>
<tr>
<td>Murat</td>
<td>0.01 - 2.5</td>
<td>0.15</td>
<td>Epidote isograd</td>
</tr>
</tbody>
</table>

Fig. 6.30 and Table 6.8 clearly illustrate the increase in grain size of pyrite with increase in metamorphic grade. In particular, the wider ranges in grain size at Murat and Balade are a result of porphyroblastic growth of pyrite where some grains reach 2.5 to 3.0 mm. It is also possible to link this increase in grain size rather closely with the increase in grain size of the silicates in the enclosing rocks. At the lawsonite isograd the country rocks are fine-grained sericitic schists which grade progressively into medium-grained mica schists with porphyroblastic garnet, albite, etc. at the epidote isograd. This strongly implies, therefore, that the sulphide deposits have been metamorphosed and subjected to the same physical conditions as the enclosing wall rocks, whose mineral assemblages are also compatible with the regional grade of metamorphism.

Increase in the grain size of sulphide ores with progressive regional metamorphism is in parallel with what has been found to be the case in the sulphide deposits in the Norwegian Caledonides (Vokes, 1968), in the cupriferous
Pyrite deposits (Besshi-type) in the Sanbagawa metamorphic terrain in Japan (Doi, 1962; in: Kanehira and Tatsumi, 1970), and by many other authors reviewed by Vokes (1969).

(3) **Mineralogical Changes Due to Metamorphism**

As mentioned previously the variation of mineral assemblages of the sulphide ores is largely ascribed to the original composition of the ores. Nevertheless, progressive metamorphism has resulted in certain changes in the sulphide assemblages and has also caused variation in the composition of some of the constituent sulphides. A few of the variations and changes will be discussed in this section.

(a) **Pyrrhotite**

In the sulphide deposits in the Diahot region pyrrhotite becomes increasingly abundant in the ores of higher metamorphic grade and is a feature which is suggestive that this mineral may be, in itself, partly of metamorphic origin, derived from the high-temperature conversion of pyrite. Pyrrhotite has not been observed at Fern-Hill and Ao mines, is extremely rare at Mérétrice and Pilou, but is relatively abundant at Balade and Murat. A partly metamorphic origin for pyrrhotite in sulphide ores has been postulated previously by several authors, including Vokes (1968) in the Norwegian Caledonides, and Hutchinson (1965) in the Keewatin greenstone belts of the Canadian Precambrian Shield.

The composition of pyrrhotite from Murat Mine was calculated from X-ray diffraction data from repeated runs, using a Fe tube, Mn filter, 20mA, 30KV, scanning speed ½°/minute, and calibrated using a pure silicon standard.
was found to have the double $d(102)^\alpha$ reflection, indicating a monoclinic symmetry and the average $d(102)^\alpha$ values for the two peaks was 2.0616, corresponding to 60.7 weight percent Fe (or $0.938N_{FeS}$) according to the calculated curves of $d\alpha$ values versus pyrrhotite composition of Arnold (1962) and Toulmin and Barton (1964). Pyrrhotite constitutes only approximately one per cent of the sulphide assemblage at Balade and significantly pure samples could not be extracted for X-ray diffraction; presumably, it is also of the monoclinic type. Pyrrhotite at Balade and Murat was also analysed using an electron microprobe and the compositions are given in Table 6.9. Pyrrhotite is associated with pyrite at both Balade and Murat and consequently temperatures for the metamorphic recrystallization of pyrite-pyrrhotite and $\log f_{s2}$ values can be calculated using the pyrite-pyrrhotite solvus in the diagram of Toulmin and Barton (1964, Fig. 6, p.656). Results and ranges of temperatures and $\log f_{s2}$ values for recrystallization conditions at Balade and Murat are also shown in Table 6.9. Also, Table 6.9 shows the significantly variable values for the composition of pyrrhotite, and the corresponding wide variation in temperatures and $\log f_{s2}$, obtained by calculating the composition by direct ratio with a troilite standard, those obtained by linear regression analysis using troilite and pyrite standards, and those calculated by the X-ray diffraction method. The temperatures vary from 330 to 480°C but the "average" temperature of approximately 400°C is in relatively good agreement with the temperatures obtained by oxygen isotope geothermometry in the Ouégoa district for similar grade rocks (Taylor and Coleman, 1968; Black, 1974).
TABLE 6.9 Variation in Pyrrhotite Composition at Murat and Balade Mines

<table>
<thead>
<tr>
<th></th>
<th>Electron Microprobe Analyses</th>
<th>XRD Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculation by direct ratio with troilite standard</td>
<td>Calculation by linear regression analysis</td>
</tr>
<tr>
<td>Murat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>60.6</td>
<td>61.1</td>
</tr>
<tr>
<td>S</td>
<td>40.6</td>
<td>39.3</td>
</tr>
<tr>
<td>Total</td>
<td>101.2</td>
<td>100.4</td>
</tr>
<tr>
<td>T°C</td>
<td>440°C</td>
<td>335°C</td>
</tr>
<tr>
<td>( \log f_{s2} )</td>
<td>( 10^{-6.1} )</td>
<td>( 10^{-10.0} )</td>
</tr>
<tr>
<td>Balade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>61.0</td>
<td>60.4</td>
</tr>
<tr>
<td>S</td>
<td>40.7</td>
<td>39.4</td>
</tr>
<tr>
<td>Total</td>
<td>101.7</td>
<td>99.8</td>
</tr>
<tr>
<td>T°C</td>
<td>330°C</td>
<td>480°C</td>
</tr>
<tr>
<td>( \log f_{s2} )</td>
<td>( 10^{-10.2} )</td>
<td>( 10^{-4.8} )</td>
</tr>
</tbody>
</table>
Arnold (1962) found that the metal content of pyrrhotite formed in equilibrium with pyrite is virtually independent of confining pressure; certainly in this case where the compositions of pyrrhotite could not be determined with accuracy, any correction for confining pressure would be meaningless.

A very important assumption incorporated into the pyrite-pyrrhotite geothermometer is that equilibrium conditions apply. At these medium-high grades of metamorphism, equilibrium conditions, or conditions close to equilibrium, might be expected. However, the validity of the pyrrhotite geothermometer has been queried by a number of writers, e.g. Desborough and Carpenter (1965), Barton and Skinner (1967), who seriously doubted that strictly equilibrium conditions would necessarily be attained. Moreover, it is possible that the sulphides reequilibrated at lower temperatures during retrogressive metamorphism, especially possible at Murat where there has been later remobilization of sulphides, probably during retrogressive metamorphism, and that the calculated temperatures therefore represent only minimum temperatures. Sulphides are particularly inclined to retrograde reequilibration (Vokes, 1969).

(b) *Sphalerite*

Sphalerite occurs in all of the major sulphide deposits in the Diahot region. Compositions of sphalerite at Pilou, Mérétrice, Fern-Hill, Balade and Murat mines are presented in Table 6.10, determined from electron microprobe analysis using three sphalerites with variable amounts of FeS substitution as standards. Table 6.10 illustrates low amounts

<table>
<thead>
<tr>
<th></th>
<th>Mérétrice</th>
<th>Pilou</th>
<th>Fern-Hill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>67.1</td>
<td>66.3</td>
<td>68.5</td>
</tr>
<tr>
<td>Fe</td>
<td>1.2</td>
<td>1.3</td>
<td>0.1</td>
</tr>
<tr>
<td>S</td>
<td>32.7</td>
<td>32.6</td>
<td>32.6</td>
</tr>
<tr>
<td>Total</td>
<td>101.0</td>
<td>100.2</td>
<td>101.2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Balade</th>
<th>Murat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>57.4</td>
<td>58.1</td>
</tr>
<tr>
<td>Fe</td>
<td>8.7</td>
<td>8.4</td>
</tr>
<tr>
<td>S</td>
<td>33.3</td>
<td>33.6</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
<td>100.1</td>
</tr>
</tbody>
</table>
of FeS substitution in the ZnS-FeS system at Pilou, Mérétrice and Fern-Hill, subjected to lower grades of metamorphism, but significantly higher amounts of FeS substitution in the sphalerite at Balade and Murat at the higher metamorphic grades.

A similar increase in the amount of FeS incorporated into sphalerite mix-crystals with increasing metamorphic grade has been determined by a number of authors and is a common mineralogical change (Vokes, 1962; Mookerjee, 1964, in: McDonald, 1967; Schreyer, et al., 1964, in: Vokes, 1969).

However, the sphalerite geothermometer cannot be used to determine temperatures of metamorphic recrystallization for the following reasons. Firstly, the sphalerite geothermometer demands the equilibrium coexistence of hexagonal pyrrhotite with sphalerite (Barton and Skinner, 1967); at Fern-Hill, Pilou and Mérétrice, sphalerite coexists with pyrite but pyrrhotite is absent or extremely rare - the apparent absence of pyrrhotite at Fern-Hill (at medium grades of metamorphism) tends to cast doubt on whether the pyrrhotite at Pilou and Mérétrice (at lower grades of metamorphism) crystallized under equilibrium conditions. Also, the pyrrhotite at Murat (and presumably at Balade) is of the monoclinic type. Secondly, the recent data of Scott and Barnes (1971) have indicated that the total iron content in sphalerite, even when in equilibrium with pyrite and hexagonal pyrrhotite, cannot be used as a geothermometer below 550°C because below this temperature the ZnS-FeS solvus is vertical and there is no change in the iron content of sphalerite. Scott and Barnes (1971) have proved that the pressure effect of the FeS-content of sphalerite is large, making
sphalerite a useful geobarometer when in equilibrium with pyrite and hexagonal pyrrhotite, and if the temperature can be independently verified. At Balade and Murat, both the ores and the enclosing country rock should provide compatible data on the pressures and temperatures during metamorphism. At Balade, where sphalerite, pyrite and pyrrhotite (presumably of the monoclinic type as at Murat) occur, the sphalerite appears homogeneous and contains 15.0 mole per cent FeS. Assuming a temperature of 400°C and applying this possible geobarometer (Scott and Barnes, 1971, Fig. 5, p.663), the iron content of the sphalerite indicates a total pressure of 3.2 kb. The sphalerite at Murat also coexists with pyrite and monoclinic pyrrhotite and contains 14.3 mole per cent FeS which indicates a total pressure of 3.6 kb. From petrological and other evidence (Brothers, 1974; Black, 1974) this figure is much too low and the above authors have suggested lithostatic pressures approximately twice these values for the upper epidote zone rocks. In these deposits at Balade and Murat, the metamorphism should offer optimum conditions for equilibration and homogenization of mineral assemblages but it may be that re-equilibration took place during retrogressive metamorphism and the estimated pressures are only a minimum value representing the last stage of re-equilibration of sphalerite. It may be that these pressure estimates correspond to a much lower temperature during retrogressive metamorphism, perhaps about 200°C. Variation in the temperature of 400°C ± 100°C produces relatively small variations in the pressures of approximately 3.5 ± 1 kb, so even if the assumed temperature of 400°C is inaccurate, pressure values compatible with the country rocks
would not be attained. Also, coexistence with monoclinic rather than hexagonal pyrrhotite would probably invalidate an accurate application of this method. At Balade there is good evidence that retrogressive re-equilibration has occurred indicated for example by the presence of mackinawite in the sulphide assemblage and chloritization of garnets in the wall rocks, the latter also a notable feature in the wall rocks at Murat Mine.

Emulsion textures of chalcopyrite in sphalerite occur at several deposits, e.g. Ao, Pilou, and some of these textures may have been produced by unmixing of an originally iron-rich sphalerite during cooling. In many cases the chalcopyrite blebs are thought to be segregations along sphalerite grain boundary margins and not exsolution bodies, but in other instances, especially at Ao, some of the chalcopyrite blebs occur as tiny droplets in the cores of the sphalerite host and some appear to be oriented along crystallographic directions in sphalerite, and these latter types of emulsions are considered to be chalcopyrite exsolutions in sphalerite (Fig. 6.28). The restriction of certain chalcopyrite droplets to the cores of sphalerite grains may indicate a compositional zoning effect between core and rim of individual grains although compositions have not been determined to confirm this aspect. However, recent work by Fujii (1970) on the unmixing of sphalerite-chalcopyrite has shown that the temperature of homogenization of exsolation intergrowths cannot be used successfully as a geothermometer.
(c) **Cubanite, mackinawite**

Several mineral pairs which occur at Balade Mine are indicators of the temperature conditions of metamorphic recrystallization. For example, cubanite forms lamellae in chalcopyrite, most probably due to exsolution, and which is regarded as having crystallized at a minimum temperature of 235°C (Edwards, 1954). This may be cited as evidence for metamorphic recrystallization which had taken place at temperatures which reached or exceeded 235°C. Mackinawite forms tiny wormlets, bent T-shapes and is also regarded as an exsolution product in chalcopyrite but which implies a minimum temperature even less than that for chalcopyrite-cubanite exsolution. However, the presence of such phases in the sulphide assemblage as cubanite, mackinawite and monoclinic pyrrhotite most probably represent a retrograde assemblage. Monoclinic pyrrhotite may be produced by the retrograde reaction from iron-deficient pyrrhotite of the high-temperature form (Izawa and Mukaiyama, 1972) and mackinawite is a phase only stable below approximately 150°C (Zōka, et al., 1974). These minerals may have been derived from a retrograde metamorphic reaction similar to that suggested by Izawa and Mukaiyama (1972) which is characterized by a desulphurization process, with re-equilibration and recrystallization of the minerals, and is produced by the break-down of the intermediate Cu-Fe-S solid solution and a pyrrhotite phase into chalcopyrite, cubanite, monoclinic pyrrhotite and a small amount of mackinawite.

(d) **Idaite-like Minerals**

Two types of idaite-like minerals occur in the Diahot region, one type at Pilou, the other at Fern-Hill Mine. The
two types are optically, texturally and compositionally distinct:

(1) The idaite-like mineral at Pilou forms tiny (0.01 mm) compact granular grains which occur in cracks and fissures in chalcopyrite, rarely in galena, and is thought to be a product of supergene alteration of chalcopyrite. The cracks are irregular, cut across the overall foliation or banding of the sulphides and generally open out into limonitic cavities. This type of idaite is consistently more copper-rich, iron-poor in composition compared with that at Fern-Hill (see Table 6.11 and Fig. 6.31), and shows some similarities (although it is not identical) in its optical properties and composition to the Cu\textsubscript{5} Fe S\textsubscript{6}-type mineral at Nukundamu, Fiji, described as idaite by Frenzel and Ottemann (1967). Table 6.11 and Fig. 6.31 depict the variation in idaite composition and chemical formulae between the most Cu-rich patches (analyses 1 and 3) and the Cu-poor patches (analyses 2 and 4) at Fern-Hill and Pilou, although electron microprobe analyses indicated that some grains and patches had intermediate compositions between the compositions of (1) and (2), and (3) and (4).

2. On the other hand, idaite at Fern-Hill is a constituent of the typical mosaic of sulphides and exhibits triple-point junctions at grain boundary margins with hypogene sulphides including chalcopyrite, sphalerite and galena. In this case it appears to be a hypogene mineral.
### TABLE 6.11  Electron Microprobe Analyses Showing Variation in Composition of Idaite-like Minerals at Fern-Hill and Pilou Mines

<table>
<thead>
<tr>
<th></th>
<th>Fern-Hill (1)</th>
<th></th>
<th>Fern-Hill (2)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>49.8</td>
<td></td>
<td>46.5</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>14.1</td>
<td></td>
<td>15.2</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>34.2</td>
<td></td>
<td>35.3</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>98.1</td>
<td></td>
<td>97.0</td>
<td></td>
</tr>
</tbody>
</table>

Calculated formulae:

1. \( \text{Cu}_{3.11} \text{Fe}_{4.23} \)  
2. \( \text{Cu}_{2.69} \text{Fe}_{4.05} \)

<table>
<thead>
<tr>
<th></th>
<th>Pilou (3)</th>
<th></th>
<th>Pilou (4)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>57.2</td>
<td></td>
<td>52.8</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>10.6</td>
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<td>12.8</td>
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<tr>
<td>S</td>
<td>32.5</td>
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</tr>
<tr>
<td>Total</td>
<td>100.3</td>
<td></td>
<td>99.8</td>
<td></td>
</tr>
</tbody>
</table>

Calculated formulae:

3. \( \text{Cu}_{4.74} \text{Fe}_{5.33} \)  
4. \( \text{Cu}_{3.63} \text{Fe}_{4.66} \)
Fig. 6.31 Cu-Fe-S triangular diagram showing the variation in composition of idaite-like minerals at Fern-Hill and Pilou mines (from analyses, Table 6.11), and the composition of chalcopyrite and cubanite at Balade Mine (from analyses, Tables 6.6, 6.7). Analyses plotted as weight percent.
However, in most occurrences idaite is generally regarded as a supergene sulphide which is formed, characteristically, by the alteration of bornite (e.g. Sillitoe and Clark, 1969). Idaite has been recognized, in association with bornite, at Yauricocha, Peru (Kobe, 1961) – in this case the idaite is the Cu$_3$FeS$_4$-type and from studies of fluid inclusions and mineral parageneses it has been found to be a product of hydrothermal alteration of bornite, and coexists with normal covellite, chalcopyrite and enargite (pers. comm. Mr D.A. Weigel) – i.e. this appears to be an instance where idaite occurs as a hypogene sulphide. Bornite has not been observed at Fern-Hill except for a solitary inclusion in pyrite and there is no textural evidence to suggest that idaite is a decomposition product of bornite. Nevertheless, two further alternatives may be possible for the origin of idaite at Fern-Hill. Firstly, idaite may be the product of metamorphism or retrogressive metamorphism of bornite under conditions of high sulphur fugacity. However, bornite is a common sulphide in metamorphosed ores and has been reported as a particularly stable mineral under glaucophane schist facies metamorphism (Vokes, 1969). Secondly, bornite may be preferentially prone to supergene alteration by idaite, and idaite may have replaced bornite completely. Possibly the bornite inclusion is the only relic in these ores as a result of protection by the pyrite host. In this regard the textural relations described on p. 355 and Fig. 6.25 are interesting where idaite juxtaposed against quartz gangue is rimmed by a thin crust of a chalcopyrite-like phase which also forms small spindles penetrating inwards along cleavage directions in idaite. Possibly these textural
relations, very similar to those described in stages of the supergene alteration of bornite by Sillitoe and Clark (1969), represent a stage in the oxidation and alteration of bornite (now completely replaced) by idaite and the chalcopyrite-like phase, and where oxidizing solutions have gained access via microscopic cracks in the quartz gangue.

(e) Pyrite-arsenopyrite Geothermometer

The mineral pair pyrite-arsenopyrite supplies an upper temperature limit to the assemblage at Balade of 491°C according to Clark (1960), but is susceptible to pressure, estimated to increase at 18°C per kilobar. Brothers (1974) has indicated a lithostatic pressure of about 8 kb for the epidote isograd. This would mean an increment of 144°C and a total maximum temperature limit of 635°C for the pyrite-arsenopyrite assemblage.

Needless to say, the temperature limits for metamorphic recrystallization at Balade, i.e. a minimum of 235°C from chalcopyrite-cubanite exsolution, and a maximum of 635°C for the pyrite-arsenopyrite assemblage are rather meaningless. Metamorphic recrystallization temperatures at Balade of 400°C are considered most likely in view of the evidence of silicate assemblages, isotope data (Taylor and Coleman, 1968; Black, 1974) and the possible pyrrhotite geothermometry.
Fabrics due to Deformation of the Sulphides

The sulphide deposits in the Diahot region exhibit a wide range of textures which may be classed as deformational fabrics. Except for Murat Mine, the deposits in general are relatively little deformed on a macroscopic and even a microscopic scale in many cases. At Murat, multiple deformation, along with medium-high grades of metamorphism, is considered to be largely responsible for local remobilization of sulphides - this aspect is discussed in the next section.

On a microscopic scale, one of the most common effects of deformation is the cataclastic fracturing of pyrite crystals and the subsequent recementation and annealing of the deformed pyrite by softer matrix minerals, usually chalcopyrite, galena and sphalerite, and more rarely by gangue minerals, e.g. carbonates, and quartz. At Murat, pyrrhotite was also rarely observed partially cementing fractured pyrite. Cataclastic fracturing and recementation results in the island-like textures in pyrite and is not considered due to partial replacement of pyrite by matrix minerals. Individual fractured pyrite crystals often have straight outlines with respect to the sulphides which cement the pyrite, and if the cementation was absent, the pyrite crystals would "fit together" exactly; pyrite showing cuspat​e grain boundaries against the cementing sulphides have not been observed, as would be expected if the cementing sulphides were a replacement of pyrite. In other instances, fractured pyrite particles are rounded probably from deformational abrasion and then subsequently annealed. In some cases the effects of deformation only appear to cause
abrasion and rounding of pyrite without fracturing or shattering; this is particularly evident in the form and shape of pyrite at Pilou Mine where it seldom shows perfect idiomorphism. Intricately folded cleavages in galena at Pilou further demonstrates the deformational fabric in this deposit.

Microscopic isoclinal folding is observed in some of the ores and is depicted, for example, by phengitic muscovite in the gangue at Fern-Hill (23845) and folded discontinuous layers and trails of sphalerite at Murat (23952). Wrapping of the foliation (mainly defined by silicates) around pyrite porphyroblasts in the Balade and Murat ore also occurs and indicates pre-tectonic recrystallization of pyrite and a later flattening of the foliation.

Aspects of the mesoscopic and macroscopic folding deformation of both the sulphides and their country rocks have already been described in previous sections.

(5) **Fabrics due to Remobilization of the Sulphides**

Small scale remobilization, present to varying extents at all of the deposits studied, has been described in the previous section where matrix sulphides have cemented fractured pyrite crystals, but significant remobilization occurs on a larger mesoscopic scale particularly at Murat Mine.

At Murat there is clear evidence for at least two episodes of recrystallization of the sulphides, a primary phase of recrystallization which occurred contemporaneously with the development of foliation and a later coarser-grained phase of remobilization and recrystallization along strain-slip cleavages and small shear zones and fractures.
Remobilization of sulphides involving chalcopyrite, pyrite, pyrrhotite, during this latter phase takes place over varying distances, from a millimetre or two to probably several metres. In some instances, e.g. in sections 23956 (a), (b), there appears to be a thickening up in the crests and troughs of mesoscopic folds, coupled with thinning out along the limbs. However, the same effect may be produced by a stretching along the limbs without any movement of the sulphides relative to their wall-rocks. The most obvious mechanism for remobilization of this type is the plastic flow of sulphides under shear deformation (e.g. Mikkola and Väisänen, 1972).

Remobilization of sulphides at Murat is thought to be related to two factors: Firstly, both the sulphides and wall-rocks have been subjected to the highest grades of metamorphism of any of the deposits studied in the Diahot region and relative mobility would be expected to increase with progressive metamorphism. Secondly, Murat Mine is situated within a few metres of the post-metamorphic Col d'Amoss Fault and in a region where there is known to be post-metamorphic folding. The timing of this later faulting and folding probably occurred very shortly after the climax of metamorphism, taking place actually during retrogressive metamorphism which caused the chloritization of garnets at Murat. The evidence itself of remobilization of sulphides also implies that metamorphic conditions, at least lower grade retrogressive effects, must have still applied at the time of remobilization.

Late kink folds are ubiquitous over the entire Diahot region but no examples of remobilization associated with
late kinking have been observed; this means that the remobilization and recrystallization of the sulphide deposits occurred prior to kinking.

Remobilization is a common feature of metamorphosed stratiform sulphide deposits elsewhere, although it never occurs on a particularly large scale (rarely exceeding several metres), and has been fully reviewed by Vokes (1969, 1971).

6. Metallogenesis

Introduction

In this section the geological features of the mineral deposits of the Diahot region with regard to ore genesis will be discussed and summarized. The deposits occur in metasedimentary rocks and are clearly stratiform and conformable with the sequences that enclose them and may be classified as metamorphosed sedimentary-exhalative stratiform sulphide deposits. The deposits have similarities to one another in their genesis with the possible exception of Balade and Murat but are considered to belong to a single metallogenetic province.

The most important facts and their geological implications are enumerated as follows:

1. The deposits are mainly Cu-Pb-Zn sulphides with small amounts of Au and Ag.

2. The deposits south of the Gendarmerie Fault occur exclusively in a sedimentary-igneous sequence of Upper Cretaceous age. The age of the rocks north of the Gendarmerie Fault, incorporating the deposits at Balade and Murat, is uncertain but is considered on
structural and petrographical grounds to be Cretaceous as well.

3. The sulphide ores are generally well laminated and show relict sedimentary textures, and occur as layers and lenses which are stratiform and conformable with the host rocks.

4. The sulphide concentrations south of the Gendarmerie Fault at Pilou, Mérétrice and Fern-Hill, are situated in geologically well defined horizons where black phyllites are associated and interbedded with acid metatuffs.

5. The deposits at Balade and Murat also occur along definite horizons and are associated with rocks enriched particularly in Si and Fe. Rocks of volcanic origin have not been positively recognised associated with these deposits, although the green chloritic schists may have been partially derived from basic tuffs.

6. All of the deposits have been subjected to and variously modified by lawsonite-albite or glaucophanitic greenschist ("blueschist") regional metamorphism.

These points will now be discussed in more detail:

(1) **Constitution**

The mineral deposits in the Diahot region contain predominantly Cu-Pb-Zn with minor amounts of Au (at Fern-Hill and Balade) and Ag (at Mérétrice and Balade). Even though deposits such as Balade, Murat, Ao and Pilou were mined mainly for Cu, they still contain various, if minor, amounts of Pb and Zn, and Mérétrice and Fern-Hill
although basically Pb-Zn deposits, contain small quantities of Cu, and because of this consistency in their elemental constitution they are all regarded as belonging to a single metallogenetic province (as defined by Williams, 1960).

All the deposits are characteristically pyritic and the most highly metamorphosed deposits of Balade and Murat contain only one to two per cent pyrrhotite, subordinate to pyrite. Overall, next to S and Fe, Cu is the most abundant element (present mainly as chalcopyrite) followed probably by Zn and Pb and much less significantly by As, Sb, Ag, Bi and Au.

Of the minor elements, As is locally abundant especially at Mérétrice, occurring as arsenopyrite (and to a much lesser extent in tetrahedrite at Mérétrice and Fern-Hill). Sb has only been detected in tetrahedrite. Ag occurs in native form at Mérétrice and Balade, and as two Ag-sulphosalts-argentite and jalpaite, at Mérétrice Mine, and in argentiferous galena at Mérétrice. Bi has been found in two Cu Pb Bi-sulphosalts at Ao although it was suspected in native form as extremely small inclusions in pyrite at Mérétrice. Au has only been detected in native form and is most significant at Fern-Hill; native Au has also been found as a solitary grain at Balade Mine.

Segregation or stratigraphic zoning of Cu- (Fe) from Pb-Zn-(Fe-Cu) or an ordered sequence of compositional banding of sulphides has not been observed within individual deposits in these ores, in contrast to many stratiform deposits elsewhere in the world, e.g. Mount Isa, Australia; Kuroko ores, Japan, where it has been noted as a widespread
and constant feature. However, in this regard, possible segregation or stratigraphic zoning of ores, if present, cannot be determined at the mineral deposits of Pilou, Fern-Hill and Ao mines on account of the lack of mineralization in situ. This aspect is particularly unfortunate at Pilou Mine where some samples have been collected containing mainly chalcopyrite-sphalerite, or galena-sphalerite-chalcopyrite and it is possible that these different compositional ore types are representative of belonging to some sort of mineralization segregation or stratigraphic zoning, either in a lateral sense or perhaps more likely in a vertical stratigraphic sense with Pb-Zn increasing upwards stratigraphically. Also, as mentioned previously at Fern-Hill Mine, the type (2) and (3) ores are found from different mine dumps and may represent stratigraphically and spatially different types of ores. In this case, based on the stratigraphical zonal relationships of stratiform ore deposits elsewhere in the world (e.g. Braithwaite, 1969; in: Stanton, 1972) the type (2) Cu-rich ore characterized by chalcopryite-sphalerite-galena-(tetrahedrite-idaite-pyrite) would be expected to occur at a stratigraphically lower level than the sphalerite (galena-pyrite-chalcopyrite) type (3) Pb-Zn-rich ore.

(2) Restriction to Upper Cretaceous Rocks

The deposits south of the Gendarmerie Fault occur exclusively in an igneous-sedimentary sequence, dated by Espirat (1963) as being of Upper Cretaceous (Senonian) age on the basis of Inoceramus fossils. The age of the rocks north of the Gendarmerie Fault is uncertain but is also thought to be Cretaceous based on structural grounds.
and the general similarity of rock types on either side of the fault (see structural section).

In particular, the major deposits at Pilou, Mérétrice and Fern-Hill all lie along the same broad stratigraphic horizon, approximately 1 to 1.5 km stratigraphically below the Cretaceous-Tertiary boundary. The significant addition of Fern-Hill to this common broad stratigraphic horizon is based on structural grounds - that is, Fern-Hill is situated on a similar structural form line to that of Mérétrice or La Folle (see Fig. 1.9). However the continuation of a stratigraphic horizon from the vicinity of Mérétrice folded back to Fern-Hill involves the assumption that the structural form lines (based on regional mapping of the foliation) are in fact coincident with relict bedding in the stratigraphic sequence. However, assuming this hypothesis, the relationships of the stratigraphic position of Balade and Murat mines with respect to that of the broad stratigraphic horizon of Pilou-Mérétrice-Fern-Hill cannot be determined on account of the Gendarmerie Fault. The actual displacement along the Gendarmerie Fault is unknown but is considered to be of the order of several kilometres and any continuation of the structural form lines northeastwards from Fern-Hill across the fault would not be valid. Nevertheless, as mentioned previously, the deposits at Balade and Murat are postulated as belonging to the same metallogenetic province as those south of the Gendarmerie Fault and it is therefore possible that they too may lie along a somewhat similar stratigraphic level.

Many of the small mineral showings are also situated along this general stratigraphic horizon containing Pilou,
Mérétrice and Fern-Hill and include Lilas, Tchiengane, Tourris, Pilou Creek, Pilou West, Moyen Tchimbo, Espoir, Bas Tchimbo, La Folle, Sommet 206, Djavel, Eureka and Jack. Of particular metallogenetic significance is the concentration of rhyolitic metatuffs in this metalliferous horizon, which occur as thin bands stretching discontinuously from Balaguet Creek through to Pilou and Mérétrice and then with a northeast-southwest strike as far as Fern-Hill. The consistent association of mineralization with acidic metatuffs in all the major deposits and minor mineral showings south of the Gendarmerie Fault will be discussed further in a following section (4).

(3) Relict Sedimentary Textures and the Stratiform Nature of the Deposits

All the primary mineral deposits in the Diahot region have a dominant feature in common although they vary somewhat in their individual compositions – that is, on a mesoscopic scale, they all show varying degrees of compositional banding of sulphides in layers and lenses which are consistently conformable with the foliation and schistosity of the enclosing host rocks. Moreover, all the mineralization is confined to particular layers, often with very definite sharp contacts against the host rocks and as such are stratiform rather than stratabound deposits as defined by Stanton (1972). Also, with the exception of a few minor and very localized cases, the foliation (and the dominant schistosity parallel to the foliation) is assumed to be parallel to relict bedding in the host rocks and consequently the mineral deposits are also assumed to represent a relict sedimentary feature, being deposited
contemporaneously with the sediments that enclose them.

The sedimentary nature is particularly emphasized by the Pb-Zn deposits where structures indicative of cross-bedding and sedimentary slumping are seen in the ore at Mérétrice and cross-bedding and possible scour and fill sedimentary structures at Fern-Hill.

In general the Pb-Zn ore is much more delicately and finely laminated than the Cu ore and although the Cu ore is restricted to definite layers in the schists e.g. at Balade, Murat, Pilou, it does not show such good bedding or compositional banding within those particular layers as does the Pb-Zn ore. This is a feature common to most stratiform ore deposits elsewhere in the world where the Pb-Zn ore is segregated from the Cu ore and has been recorded particularly by Stanton (1972).

One of the more convincing pieces of evidence for the sedimentary origin of the ore at Mérétrice is the presence of framboidal pyrite and atoll structures. Although it has recently been proved that a biologic origin is unnecessary for pyrite framboid formation, it is nevertheless generally consented that pyrite framboids and atoll structures are of sedimentary or diagenetic origin. The perfect preservation of such relict microscopic structures at the medium grades of high pressure metamorphism at Mérétrice is rather surprising but strongly proves the lack of significant overprinting effects of the metamorphism on destroying the original sedimentary or diagenetic features of the deposit - i.e. the other sedimentary features previously described as fine delicate bedding, cross-bedding and slumping are most likely to be true sedimentary or
diagenetic features and not due to any metamorphic modification.

At Balade and Murat the mineralization occurs in numerous thin layers intercalated with a variety of schists and although the mineralized layers were seen to be continuous only over the width of the outcrop (of the order of several metres), it is assumed that the thicker layers and bands extend along the strike of the foliation for very much greater distances - probably for hundreds of metres indicated by the lateral extension of the oxidation zone. At Mérétrice the ore occurs in lenses of compact sulphide which have extremely abrupt, sharp contacts with the enclosing black phyllites. The lenses occur as discrete bodies in an overall en echelon pattern within the host black phyllites. However, although the mineralized layers at Balade and Murat must pinch out laterally, they are also lensoid in a broad sense although they are much thinner than the Pb-Zn lenses at Mérétrice. Also, at Balade and Murat pyrite occurs disseminated within particular layers in silicate folia and very often it continues along horizons where thin chalcopyrite-rich layers have pinched out - at Mérétrice pyrite has not been observed disseminated in the country black phyllitic rocks.

These different aspects are considered to have metallogenetic significance in that different processes of deposition of sulphides were probably involved at Balade and Murat on the one hand and Mérétrice on the other. Sulphide deposition at Balade and Murat is thus thought to have occurred intermittently on a relatively flat but enclosed basinal part of the sea floor producing thin
extensive layers of sulphides intercalated with siliceous and iron-rich material. Sulphide deposition at Mérétrice, however, is postulated to have involved intermittent sudden inflow of sulphide muds into very small, localized, topographical depressions on the sea floor, which produced compact massive lenses of sulphides.

The sedimentary slumping and cross-bedding features mentioned above suggest that some of the ores have formed by slumping or sliding of accumulated sulphide masses during and after ore deposition. The environment of deposition and the origin of the sulphides is elaborated in the following section.

(4) Significance of the Black Phyllite - Acid Volcanism Association of the Deposits South of the Gendarmerie Fault

The major deposits south of the Gendarmerie Fault are consistently associated with black carbonaceous phyllites intercalated with rhyolitic metatuffs. Also, many of the minor showings of mineralization in this district have an association with similar rocks, e.g. Pilou West, Moyen Tchimbo, Sommet 206, Banianou, Euréka, Jack, Tirima. However, some of the showings are associated only with black, dark grey or greenish phyllites and not with rocks recognizable as necessarily tuffaceous e.g. Tourris, Pilou Creek, Bas Tchimbo, Espoir, while others are associated with acidic tuffaceous rocks although the phyllites and sericitic schists are neither black nor notably carbonaceous in appearance e.g. Tchiengane, Lilas, La Folle, Djavel, Henri.

Thus, the localization of sulphides appears to be spatially related with specific facies of sedimentation
and with volcanic activity. Metamorphism has not been sufficiently intense to obliterate the original features of the containing rocks, especially in the lawsonite and lowest grade rocks, and the environment of deposition of the associated sedimentary rocks can be deduced with fair accuracy.

At Pilou and Fern-Hill mines the rhyolitic metatuffs are finely intercalated in a vertical stratigraphic sense with the phyllitic rocks and the mineralization occurs mainly in the latter lithologies. The ore lenses at Mérétrice are restricted to the black carbonaceous phyllites but the intercalated rhyolitic tuffs occur several tens of metres along the strike from the mineralization.

The rhyolitic metatuffs are quite variable in their composition as shown by the chemical analyses - those at Fern-Hill are highly potassic, containing abundant microcline, others, particularly in the Pilou region contain abundant relict plagioclase porphyroclasts, and some are almost chert-like with rare relict plagioclase. The host black phyllites also vary considerably in composition and are most richly carbonaceous at Mérétrice and probably represent an original black shale, reducing environment of deposition. The abundance of carbon in the phyllites also indicates that this facies was originally laid down not far from a shoreline. The phyllites at Fern-Hill are notably siliceous, hard and flinty and represent a rather different original environment of ore deposition - i.e. one where deposition of siliceous material was accompanied by finely bedded organic-rich sediments.

There appears to be a correlation between the actual
size of individual deposits and the extent and thickness of the black phyllites. The sulphide deposits are always somewhat smaller in volume than that of the enclosing phyllites and also the form and shape of the layers and lenses of sulphide concentration depends dominantly on the outlines of the black phyllites (also to some extent together with greenish-grey and green phyllitic rocks at Pilou Mine).

This is particularly emphasized by a comparison of the extent and thickness of the black phyllites at the major deposits of Mérétrice, Pilou and Fern-Hill, with the minor showings scattered throughout the district. Black phyllites at the minor mineral showings are usually very thin units, never noted to exceed one metre in thickness and never extend along the strike for distances greater than several metres or apparently very much less in some cases. The minimum thickness of the black phyllites at Mérétrice, on the other hand, is six metres and they extend approximately 200 m laterally; also the siliceous phyllites at Fern-Hill are even more extensive than those at Mérétrice. The volume of black and green phyllites at Pilou Mine is uncertain although the clastic sediments are seen to be at least five metres thick.

The metals are thought to have been derived from hot springs emanating on the sea floor and the deposits formed by the accumulation of metalliferous chemical precipitates in a black shale, reducing environment. Although the evidence indicates that acid tuffaceous volcanism coincided with ore formation the genetic relation between these two factors may be either an indirect or a
direct one.

In the first case, volcanism may have only supplied the thermal energy necessary to circulate leaching thermal waters through country rock which may have provided the base metals. In this case a geothermal environment could be envisaged with similarities to the Red Sea Deeps (e.g. Craig, 1969; Bischoff, 1969; Kaplan, et al., 1969), the Salton Sea geothermal field (Skinner, et al., 1967) or the geothermal region of New Zealand (Brown and Ellis, 1970; Weissberg, 1969). For example, the hot metalliferous brines of the Red Sea have isotopic compositions indicating that their trace metal content is not derived from any volcanic or magmatic source (Craig, 1969; Kaplan, et al., 1969) — rather, it is thought that the various metals have been transported by groundwater which leached them out of the evaporites and other country rocks through which they passed for several hundreds of kilometres to the point of ultimate brine discharge. The brines then become heated on encountering hot basalt magma in the central part of the Red Sea rift zone and rise through fractures and restricted vents into basinal deeps on the sea floor (Craig, 1969; Kaplan, et al., 1969).

On the other hand the hot springs may have been directly related to submarine hydrothermal volcanic activity. In this case the mineralization would have some affinities with the Kuroko-type or the Cyprus cupriferous deposits with the important difference that neither of these types of deposits are spatially related to specific facies of sedimentation even though some of the ores are sedimentary in origin (e.g. Matsukuma, et al.,
1970; Hutchinson and Searle, 1971). The abundance of disseminated pyrite within many rhyolitic metatuff units and possibly rhyolitic flows near Mérétrice suggests a metalliferous hydrothermal stage associated with acid volcanism. However, pyrite is the only sulphide phase so far observed within the tuffs and there is a notable lack of galena, sphalerite or chalcopyrite, dominant minerals in the actual deposits. Nevertheless, it could be argued that the pyrite-bearing tuffs represent minor stockwork deposits or ancient feeder channels through which hydrothermal fluids and gases passed and many stockworks or feeder channels described in other deposits (e.g. Kuroko deposits at Shakanai Mine, Kajiwara, 1970) contain pyrite as the sole sulphide phase. However, while pyrite occurs in the tuffs, neither pyrite nor any cross-cutting veins of mineralization are present in the adjacent clastic sedimentary rocks outside the ores themselves. Thus it appears unlikely on the present evidence that the pyrite-bearing tuffs represent feeder channels.

Thus, in summary, the question of the role of volcanism in ore genesis, that is whether the genetic relationship of volcanism is a direct or an indirect one remains unanswered on the present evidence. I am inclined to the opinion that at Fern-Hill and Pilou, where there is an extremely close temporal and spatial relationship of mineralization with acid tuffs, i.e. where the tuffs are intimately intercalated with mineralization, there may be a direct relationship with volcanism.

At Mérétrice the mineralization is not so intimately spatially related with acid tuffs although there is a very
strong temporal relationship and I also favour a direct genetic relationship with volcanism in this case.

(5) **Significance of the Si- and Fe-rich Rocks Associated with the Deposits North of the Gendarmerie Fault**

The major deposits north of the Gendarmerie Fault at Balade and Murat are intercalated with a variety of schists, namely stilpnomelane-bearing quartzitic schists (at Balade only) chloritoid-bearing chlorite mica schists and chlorite mica schists; almandine garnet and ilmenite are abundant additional minerals. Also at Balade Mine, Lacroix (1941) has described magnetite-hematite-garnet schists the presence of which, however, could not be confirmed; it is assumed that this rock type was collected from a deeper section of the mine now completely inundated. Like the mineralization, stilpnomelane, chloritoid and presumably magnetite-hematite are confined to particular folia in the schists.

In comparison to the ordinary country mica schists and as shown by the chemical analyses (Table 6.4), the mineralization at Balade and Murat is spatially associated with rocks that are relatively enriched in Si and Fe. Mineralogically, this is expressed by the abundance of quartz and Fe-rich minerals respectively, e.g. stilpnomelane, almandine, garnet, Fe-rich chlorite, magnetite, ilmenite, hematite, chloritoid and possibly the grunerite of Lacroix (1941). Furthermore, it is evident from those layers rich in chloritoid that there is also a localized enrichment within those particular layers of Al.

In contrast with the rocks associated with the mineralization on the south side of the Gendarmerie Fault,
there are no rocks at Balade or Murat which are so far recognized as acid volcanics. In this regard it may be that at the higher metamorphic grades of the rocks in the Balade Mine region, acid volcanics are no longer recognisable as such and their original character is now obliterated by a greater degree of recrystallization. Nevertheless, a comparison of the chemical composition of the rocks at Balade and Murat as shown by ternary diagrams e.g. AFM, ACF plots (Fig. 6.15), and especially of the quartz-rich schists, indicates that none of the rocks at Balade or Murat have similar chemical compositions to those rocks known to be rhyolitic metatuffs or flows at lower metamorphic grades. The quartz-rich schists are consistently more Fe-rich than any of the rhyolitic metatuffs and are considered to be derived from chemically precipitated Si- and Fe-rich sediments.

However, green chloritic schists are conspicuous rocks at Balade and Murat mines, and are also present at most of the minor showings in the Balade region, and it is possible that these green rocks may be partly tuffaceous in origin. It could be argued that the green schists have been partially derived from basaltic tuffs rather than acidic tuffs and hence would have distinctly different compositions from those acidic tuffs analysed in the Mérétrice, Pilou and Fern-Hill regions. The question of whether such rocks are partially tuffaceous derived is particularly difficult to resolve and is compounded by the medium-high grades of metamorphism in the Balade region. On the present evidence there is an apparent absence of volcanic rocks at Balade and Murat mines, although I think
that the green chloritic schists could have been partially tuffaceous.

The only known volcanic rocks anywhere in the whole of the Balade Mine region are several small metabasalts exposed on the ridge between Murat Mine and Ouanélé Creek. These rocks are relatively coarse-grained, contain relict igneous augite, and have narrow zones of hard, siliceous, metasedimentary rocks along their contacts. This latter feature is interpreted to be a baking effect and the metabasalts are thought to be sills. Consequently (like the metabasalts in the vicinity of Mérétrice and Pilou mines) it follows that the intrusion of the basalts must have post-dated the sediments that enclose them. Moreover, as the mineralization is obviously stratiform in nature and the deposition of the sulphides occurred contemporaneously with the sediments, the intrusion of the basalts must have post-dated the mineralization and hence have no genetic relationship with the mineralization.

The mineral deposits at Balade and Murat are postulated to have been deposited originally by chemical precipitation. As regards their origin and genesis, the similarities with the Recent heavy metal deposits in the Red Sea is most striking. Very detailed work in the Red Sea (Degens and Ross, 1969) has dispelled all doubt that marine chemical precipitation can occur on a large and concentrated scale with significant quantities of sulphides - dominantly sphalerite with lesser amounts of chalcopyrite and pyrite (Bischoff, 1969). Assays of the metals in the sediment on the bottom of the Red Sea Deeps, apart from Cu, Zn and Fe, have also proved economic quantities of Ag,
Au and Pb (Emery, et al., 1969). Of particular interest as regards the similarity to the Balade and Murat deposits, is the chemical sedimentation in the Red Sea of sediments rich in Si, Fe, Al, Ca and Mn. An epidote-rich (i.e. a Ca-rich) rock has been collected from Balade Mine by Dr H.W. Kobe (pers. comm.) and only the relative enrichment in Mn is not observed at Balade or Murat. However, spessartine-rich garnets have been found by Black (1973) in an aegirine-magnetite metachert from Delaveuve Mine - the specimen of this rock comes from the original collection described by Lacroix (1941, p.70) and it is not known whether this sample actually comes from the mine itself and was in situ or represents part of the glaucophaneite assemblage in the fault zone passing very close to Delaveuve Mine. From examination of compositions of coexisting minerals, Black (1973) has shown that Mn is consistently concentrated in the garnets except for one rock (7985) which was not in situ and contained Mn-epidote (piemontite) as well as spessartine. The garnets from the chloritoid and stilpnomelane schists at Balade and Murat are almandine (Black, 1973) and the rocks at both of these major deposits are notably Mn-poor, MnO values never exceeding 0.38 weight per cent (see chemical analyses, Table 6.4). The apparent absence of manganiferous rocks is perhaps surprising; a possible explanation is that Mn is more mobile than Fe (e.g. Mason, 1958) and may have been deposited further away along the strike from the mineralized and iron-rich metasedimentary horizons, not so far discovered or recognised.

Manganese concentrations and especially iron-rich
non-sulphide country sediments and even rocks which could be called ironstones (as defined by James, 1966) have been recorded by many authors in association with stratiform deposits elsewhere in the world e.g. some Kuroko deposits and bedded cupriferous iron sulphide deposits in Japan (Watanabe, et al., 1970; Matsukuma and Horikoshi, 1970), the cupriferous pyrite deposits in Cyprus (Hutchinson and Searle, 1971), and the massive sulphide deposits in the Spanish-Portuguese Pyrite Belt (Strauss and Madel, 1974).

Typically, the iron-rich units occur on the hanging-wall side of the sulphide deposits and according to Stanton (1972), associated iron-rich non-sulphides are characteristic features of stratiform copper ores rather than the stratiform lead-zinc ores in regions where the two ore types are spatially segregated. The latter feature is certainly also evident at both Balade and Murat mines although the most iron-rich metasedimentary units are intercalated with sulphide layers rather than restricted to the hanging- or foot-wall side of the sulphide deposits. As mentioned previously in the structural section, it is considered by the author that the sequence in the Balade Mine Stream area is stratigraphically inverted and the hanging-wall side or stratigraphic top of the sequence is therefore the upstream side of the mineralization - i.e. tops are to the east.

The Si- and Fe-rich chemical sediments appear thickest in the section seen in Balade Mine Stream and gradually thin out along the strike in both directions on either side of the stream where clastic sedimentation becomes dominant -
the latter now evident as the typical dark grey mica schists. Thus it appears that chemical sedimentation occurred within localized basins, being of greater extent at Balade than Murat.

Taking the model of the Recent Red Sea heavy metal deposits, it is envisaged that hot brines emanated into a restricted basin on the sea floor. Base-metal sulphides precipitated in the overlying water column by cooling and releasing of metal from chloride complexes and were sedimented within the basin. At Balade, this resulted in sediments relatively enriched in Si and Fe, local enrichment in certain layers of Al and Ca, and significant quantities of copper and iron sulphides, with lesser amounts of Zn, Pb, As, Ag and Au. Chemical sedimentation then ceased abruptly for a period and clastic sedimentation predominated. This is evident by the sudden progression in the sequence immediately upstream from the iron-rich formation at Balade Mine where the Si and Fe-rich rocks are overlain by typical mica schists. Later, after a considerable period of clastic sedimentation, hot brine or hot spring activity resumed, accompanied by chemical precipitation and sedimentation, producing Si and Fe-rich rocks again at Murat with dominantly copper and iron sulphide mineralization and minor deposition of Zn and Pb sulphides.

Thus it seems that for the deposits in the vicinity of Balade Mine Stream at Balade and Murat and also the minor mineral showings at Delaveuve, 26e Soldat, Moonta and Bruat, there was intermittent hot spring activity on the sea floor, associated with subaqueous chemical precipitation
and sedimentation, and periodic normal clastic sedimentation. The typical mica schists are laminated in places and the laminations are presumed to be relict bedding of alternating fine and medium-grained material, probably originally mudstones and siltstones; such structures are best seen in Jacques Creek and are illustrated on p. 97, Fig. 3.47.

Helgeson and others (reviewed in White, 1968), have shown that metals can be transported as metal-chloride complexes in Na-(Ca)-Cl brine solutions, and Bischoff (1969) suggested that sulphides, e.g. sphalerite, in the Red Sea deposits were precipitated by the reaction of soluble zinc chloride complexes with H₂S formed by bacterial sulphate reduction or reduction of dissolved sulphate by organic matter in shales (Kaplan, et al., 1969). Stanton (1962) also considered that silver and lead were transported together to the depositional site as chloride complexes which were subsequently sulphidized. Such a mechanism possibly also occurred at Balade and may help explain why rare native silver is spatially very closely associated with galena within discrete laminae.

Assuming that hot brines were the transporting agency for the metals, it is still possible that the metalliferous solutions may have been derived or partially derived from a volcanic source even though volcanic material has not been positively identified.

In consideration of the broad similarities of the Balade and Murat deposits to those at Mérétrice, Pilou and Fern-Hill, I am inclined to the opinion that the origin of the metalliferous solutions were at least partially
derived from a volcanic source.

The chlorite-talc schists at Balade Mine are an unusual rock type but are thought by the author to possibly be of some metallogenetic significance. They occur on the footwall side (downstream side) of the mineralized horizon as pod-like bodies associated with large quartz masses and contain rhombohedral spaces where porphyroblasts, possibly magnesite, have weathered out. A number of authors, for example Watanabe (1970) at the Hitachi mining district in Japan, Strauss and Madel (1974) at La Zarza Mine in Spain, have described stockwork-type mineralization in the footwall accompanied by strong Mg- and Si-metasomatism and corresponding depletion of alkalis. In the Hitachi district, part of the Abukuma metamorphic terrain, Watanabe has interpreted that the cordierite-anthophyllite schists associated with cupriferous iron sulphide deposits were produced by regional metamorphism of hydrothermally-altered rocks rich in magnesian chlorite. It is possible, therefore, that the chlorite-talc schists (containing magnesian chlorite) at Balade are also metamorphosed altered rocks and represent a relict stockwork type Mg- and Si-metasomatized alteration zone in the footwall where hot metalliferous brines passed up through the country wall rocks.

Alternatively, the chlorite-talc schists may represent a magnesium-rich parent lithology not associated with any stockwork or feeder channel - similar rocks have been observed elsewhere in the Diahot region but only in fault zones where they constitute a part of the glaucophanite assemblage.
Post-depositional Changes

From the evidence cited previously, it is postulated that all the deposits in the Diahot region were deposited during the Cretaceous, contemporaneously with the sediments in which they occur, and prior to lawsonite-albite, glauconphanic greenschist or "blueschist" regional metamorphism during the Oligocene. The metamorphism and deformation has variously modified the deposits and these aspects have been discussed in a previous section - only a summary of these features is given here.

However, it should be emphasized that some of the features interpreted to be post-depositional may in fact be due to diagenesis rather than to metamorphism. For example, the features reminiscent of sedimentary slumping at Mérétrice probably occurred during diagenesis. Also, although the ores at Mérétrice are relatively fine-grained, the grain size has most probably increased from what was originally an extremely fine-grained sulphide mud, and the increase in grain size could have resulted from a combination of diagenesis and metamorphism. Thus, especially with regard to the deposits of Mérétrice and Pilou which have been subjected to low grade metamorphism, the origin of the post-depositional changes may be ambiguous. At higher grades of metamorphism, diagenetic effects may have been completely overprinted by the effects of metamorphism.

The general hypothesis that the sulphide deposits are of the stratiform type inherently implies that their deposition pre-dates the metamorphism and all of the deposits have been subjected to the same grades and physico-chemical conditions of metamorphism as the country
Some textural evidence indicative of recrystallization and deformation of the deposits is enumerated below:

1. The sulphides show an overall foliated structure which is parallel to the foliation in the silicate wall rocks. This structure is largely a relict sedimentary or diagenetic feature, little modified by metamorphism.

2. Many samples of ores show excellent granoblastic or allotriomorphic mosaic textures where adjacent grains meet in triple-point junctions. Many authors, for example Stanton (1964), Spry (1969), Vokes (1969), would regard such textures as unequivocal evidence of recrystallization, and are classically seen in the Type (2) ore at Fern-Hill. Very few grains of minor phases, with the exception of exsolved phases, e.g. cubanite, occur within the bodies of grains of the major phases - most of them occur along grain boundaries and appear as lozenge-shaped grains. This is again regarded as evidence of recrystallization by the above authors, and is best shown by the segregated chalcopyrite blebs in sphalerite in the Type (3) ore at Fern-Hill and at Ao Mine. Strictly, however, such textures merely prove recrystallization has occurred and they do not by themselves prove that the recrystallization was a metamorphic process - similar textures may also occur in magmatic ore deposits, hydrothermal deposits, etc., and in this case recrystallization probably commenced during diagenesis.
3. The crystal shapes of the sulphides generally conform to the metamorphic crystalloblastic series in sulphides. The series is based on the relative tendencies to idiomorphism and is a function of the interfacial free energies of the sulphides and is not evidence of any paragenetical sequence or selective replacement (Stanton, 1964). Also, there is a progressive increase in the grain size of sulphide minerals with increase in metamorphic grade.

4. Metamorphism has produced a number of mineralogical changes. These include (a) an apparent increase in the abundance of pyrrhotite at higher metamorphic grades (presumably derived from high temperature conversion of pyrite, Vokes (1969)); (b) an increase in FeS substitution in sphalerite with increase in metamorphic grade.

5. The effects of deformation, accompanying metamorphism, vary widely and has produced cataclastic fracturing and rounding of sulphides and oxides, and penecontemporaneous recementation and annealing of the fractured grains, folding, shearing and small-scale faulting.

6. Deformation and metamorphism has caused localized remobilization of pre-existing sulphides on a small mesoscopic scale at most. Remobilization of sulphides and subsequent recrystallization probably occurred by plastic flow along cleavage planes, shear zones and minor fractures.
Hydrothermal Replacement Hypothesis

The general hypothesis developed by the author is that the origin of the sulphides of the ores in the Diahot region is syngenetic. Nevertheless, there is an alternative epigenetic school of thought to account for the origin of stratiform sulphide deposits like those in this region.

In the concept of an epigenetic origin, the component sulphides are derived from intrusive granitic rocks, transported to their present positions in solutions, and precipitated by substitution or replacement of pre-existing rock materials (Stanton, 1972).

The most important evidence against an epigenetic origin is detailed below:

1. The mineralization occurs in layers and lenses which show a remarkable degree of bedding control observed on both megascopic and microscopic scales. Discrete sulphide laminae parallel the foliation in the wall rocks, best seen at Balade Mine where they have been traced along the strike for approximately ten metres. This represents convincing evidence that the sulphides were formed contemporaneously with the country wall rocks and it seems unlikely that replacement could occur selectively and be totally restricted to certain folia. This point carries the generally upheld assumption that the foliation is parallel to relict bedding.

2. There is a lack of channelways up through which hydrothermal ore-bearing fluids might have passed,
and apart from Murat, there is a general absence of any discordancy of the sulphides. The only veins observed in the ores (apart from those derived from oxidation or cementation infilling minor fractures in the primary ore) are pyrite-chalcopyrite-pyrrhotite veins at Murat. These veins are very narrow (less than five millimetres wide) and occur along strain-slip cleavages, small shear zones and fractures. However, although they are epigenetic, they are considered to have originated from remobilization of pre-existing sulphides during metamorphism and deformation and are not regarded as the channelways of hydrothermal ore solutions. Veins are ubiquitous over the whole of the Diabhot region and the majority of them are constituted of quartz, some of quartz-calcite or quartz-albite. Mineralized veins are very rare and have been found at Fern-Hill where quartz-pyrite and quartz-jarosite veins occur (the jarosite is possibly derived from oxidation of pyrite). No other sulphides apart from pyrite and no alteration effects in the country rock have been observed associated with veins. Most of the veins appear to be of metamorphic origin and are not considered to have any metallogenetic significance.

3. There are no major faults passing through any of the major mineral deposits and the only showing of mineralization associated with a fault or shear zone is that in Pilou Creek. In the latter case, copper mineralization occurs in siliceous schists which are very crenulated and deformed. The mineralization is
of very minor extent and possibly originated from metamorphic remobilization of sulphide mineralization at depth, passing up along the preferred path of a shear zone.

Major faults occur in the broad vicinity (within several hundred metres) of the major deposits of Balade, Murat, Fern-Hill and possibly Pilou Mine but there is no evidence of sulphide mineralization directly associated and occurring within these fault zones.

4. The only intrusive rocks known in the region are metabasalt sills and there does not appear to be any correlation in general between distribution of the deposits and distribution of the metabasalts. They occur nearly adjacent to the mineral deposits at Pilou and Mérétrice, approximately 600 m away from the mineralization at Balade and Murat, but are not found in situ anywhere near Fern-Hill Mine. This evidence plus the absence of any mineralization within or along the contacts of the metabasalts would seem to discount the metabasalts as source rocks of hydrothermal ore solutions.

5. Wall-rock alteration, an ubiquitous characteristic of epigenetic deposits, has not been observed associated with any deposits in the Diahot region. This is best exemplified at Mérétrice where the in situ Pb-Zn ore lens has an abrupt, sharp contact against the country wall rocks and there is no evidence of any alteration. It could be argued by some
geologists that the quartzose and iron-rich wall rock schists at Balade and Murat were derived by Si-Fe metasomatism but a derivation from deposition as chemical sediments is favoured.

Overall, the hydrothermal replacement concept is inadequately supported by the geological data.

Two more theories are possible for the origin of the sulphides – firstly, a combination of the syngenetic and epigenetic theories and secondly, the sulphides were derived by metamorphic processes.

In the first case, non-ferrous metals could be derived from plutonic intrusions and/or by lateral secretion from sediments, and deposited by selective replacement of the iron of pre-existing sedimentary iron sulphide. However, at Mérétlice for example, there is an absence of pyrite or any iron sulphides in the black phyllites outside the ore lenses, and similarly at the other deposits and showings, pyrite is never abundant in the wall-rocks and has not been found in massive form like the Cu-Pb-Zn mineralization.

In the second case, it has been suggested (e.g. Stanton, 1955, in: Stanton, 1972) that there could be expulsion of heavy metals as halides in pore waters, with increasing burial and compaction of sedimentary rocks, e.g. tuffs, during diagenesis and low grade metamorphism. Some of these pore waters might then encounter iron sulphide lenses, and metals such as Cu, Pb, Zn displace some of the iron from the sulphide, thus precipitating as sulphides themselves. However, there does not seem to be good evidence that metamorphic processes could concentrate sufficient metal
to yield large ore deposits and such replacements are not needed at all for metal-sulphide precipitation.

**Stratiform Deposits and Exploration**

There are several significant criteria for exploration to help find further deposits or extensions of known deposits. As Croxford and Jephcott (1972, pp. 22-23) and others have pointed out, a mass of geochemical and mineral laboratory data on known deposits will have only limited value unless it is fitted into a paleogeographic framework.

Some of the factors that may assist the exploration geologist in narrowing the field of Cu-Pb-Zn ore search in New Caledonia are enumerated below:

1. The Cu-Pb-Zn mineralization, as far as is known at present, is restricted to the sedimentary-igneous Cretaceous sequence. This criterion could be extended to include lithologies of possibly different ages but which are similar to those of the Cretaceous rocks.

2. In particular, the mineral deposits are restricted in their paleogeographic association to definite stratigraphic horizons and distinctive lithologies. Thus, geological exploration could be further reduced by searching for lithologies such as carbonaceous and pyritic shales and siltstones, siliceous and iron-rich chemical sediments, acid volcanic tuffs, and all their metamorphosed equivalents.

3. The mineral deposits are not controlled by any
specific structural feature. Faults, shear zones, folds, schistosity and cleavage planes may be the sites of mineralization from metamorphic remobilization of pre-existing sulphide deposits although such mineralization would be expected to be only on a relatively minor scale.

At the same time, it is possible that a showing of mineralization from metamorphic remobilization may indicate the presence of a much larger primary deposit at depth which is not exposed at the surface.

An accurate structural knowledge of the region would be necessary on a very detailed scale in order to trace particular lithological horizons in view of the conformable stratiform nature of the mineral deposits which occur in a metamorphic terrain of great structural complexity involving multiple folding and faulting.

Conclusions

In summary, the deposits at Mérétrice, Pilou and Fern-Hill are thought to be both sedimentary and volcanic in origin, derived from acid-volcanic metalliferous exhalations which have undergone chemical precipitation and sedimentation in black shale, euxinic environments on the sea floor.

The deposits at Balade and Murat are thought to be derived from the chemical precipitation of localized exhalations of hot metalliferous brines in enclosed basins on the sea floor, similar to those found in the Red Sea. Volcanic or volcanic-derived rocks have not been positively identified but the green chloritic schists may represent
metamorphosed rocks of partly tuffaceous origin.

All of the deposits have been subjected to and modified by lawsonite-albite and glaucophanitic green-schist regional metamorphism.
CHAPTER 7
CONCLUSIONS

General statement

High-pressure metamorphic terrains occur principally around the margins of the Pacific Ocean, in the island arcs of the Caribbean and Indonesia, and are conspicuous in the Alpine-Himalayan foldbelt (Ernst, 1971; 1972). The constituent rock types are known collectively as glaucophane schists or blueschists although they also include other mineral assemblages not characterized by the presence of sodic amphiboles. Glaucophane schist belts are generally thought to be generated by relatively high-pressure, low temperature physical conditions that characterize convergent lithospheric plate boundaries (Dewey and Bird, 1970; Coleman, 1971; Ernst, 1972).

High-pressure regional metamorphism has produced an elongated schist belt measuring 170 x 25 km along the northeastern part of New Caledonia. A comprehensive regional study of the metamorphic belt has been made by Brothers and Blake (1973) and Brothers (1974). The present investigation in the Diahot region covers only a very small portion of this terrain and it is realised that some of the conclusions may not apply to other areas of the metamorphic belt. However, before the discussion of the tectonic environment of northern New Caledonia, the observed and inferred structural, petrological and time relations will be summarized to emphasize the constraints imposed on possible tectonic theories.
Lithologies, mineral parageneses and age of metamorphism

The rocks in the region studied consist dominantly of a metamorphosed Cretaceous sedimentary-igneous sequence of carbonaceous claystones, siltstones and sandstones, with intercalated basaltic rocks and rhyolitic tuffs. Additional minor members of the sequence include calcareous schists, metacherts, intermediate meta-igneous rocks, basic metatuffs, and extremely rare conglomerate and concretionary horizons.

The Cretaceous rocks contain fragments of *Inoceramus* in the stratigraphically upper parts of the sequence, dated as Senonian by Espirat (1963), and in general become stratigraphically older towards the east coast. The Cretaceous sequence is flanked to the southwest by Eocene rocks consisting mainly of siliceous argillites, phtanites (massive cherts) and limestones. To the south, the Cretaceous-Eocene sedimentary rocks overlie Permian-Jurassic greywackes (Lillie and Brothers, 1970).

The stratigraphic thickness of the Cretaceous-Eocene strata is not known with any accuracy. If the regional isoclinal fold in the Balade region is accepted, the original stratigraphic thickness for the whole of the Cretaceous rocks in the Diahot region is calculated to be only about 4.5 kilometres. Lillie (1970, p. 84-5) has postulated that the Eocene cover was approximately 9 km although he pointed out that there may be much repetition of the Eocene strata west of Crève Coeur. Consequently the minimum stratigraphic thickness for the Cretaceous-Eocene sequence of 12 km given by Brothers and Blake (1973) and Brothers (1974) is thus an
acceptable figure.

The tectonic thickness of the Cretaceous-Eocene sequence, however, is very much greater than the stratigraphic thickness and I have determined it to be at least about 26 km, i.e. 12 km for the Eocene and 14 km for the Cretaceous. Espirat (1963) was the first to observe that the metamorphic zones cut across the structure which therefore implies that the overburden at the climax of metamorphism must be calculated on the basis of tectonic thickness rather than stratigraphic thickness.

Brothers (1974) has postulated that the Cretaceous-Eocene paraschists were deposited in a trench as a sedimentary apron which was peripheral to the Permian-Jurassic basement of the island and extended eastwards across oceanic crust. The Cretaceous sediments probably accumulated in relatively shallow water, as indicated by carbonaceous material and rare conglomerate lenses, but the site must have been well offshore since the dominant lithologies are fine-grained and lack sedimentary features like graded or current bedding. Eocene sedimentation probably occurred in relatively deeper water conditions since it is dominated by phtanites, silicaceous argillites and limestones. Basaltic and rhyolitic volcanism was concurrent with sedimentation in the Cretaceous although only the basaltic volcanism continued into Eocene time. Stratiform Cu-Pb-Zn-Ag-Au mineralization is restricted to definite stratigraphic horizons in the Cretaceous sequence and some of the mineralization, e.g. at Pilou, Mérétrice and Fern-Hill, is genetically related in space and time to rhyolitic volcanism associated with localized black shale reducing
environments. Other sites of mineralization, e.g. Balade and Murat, can be attributed to hot springs emanating within localized basins on the sea floor.

The high-pressure metamorphism has affected both the Eocene and Cretaceous rocks and has been radiometrically dated at 38-21 m.y. (Oligocene-lowermost Miocene) by Coleman (1967). These dates were deduced by potassium-argon determinations on coexisting muscovite and glaucophane from "high-grade blueschists" near Ouégoa. However, no further information is given by Coleman and it is not known whether these "blue-schist" rocks were sampled in situ or belong to the allochthonous glaucophane assemblage. In the latter case, if the dated rocks were glaucophanites (analogous to the "knockers" of Californian geologists), then ages slightly older than the in situ rocks may be expected (Coleman and Lanphere, 1971).

Metamorphism increases progressively in grade towards the northeast. The distribution of the regional isograds for the whole of the New Caledonian metamorphic belt is depicted by Brothers (1974, Fig. 3). In the Diahot region, lowest grade rocks occur in the southwest near the Cretaceous-Tertiary boundary and the highest grade rocks are exposed along the east coast and tectonically emplaced in fault zones around Ouégoa and the main divide. In the present study, four metamorphic zones have been mapped from assemblages in pelitic parents which in order of increasing metamorphic grade are: (1) lowest grade rocks; (2) lawsonite zone; (3) transitional zone; (4) epidote zone; in addition, Brothers (1974) has mapped a highest grade Ca-amphibole zone developed in rocks along the east coast, outside the area of this study.
The progression of metamorphic zones has been expressed in terms of metamorphic facies by Brothers (1974, p. 118) as follows: the lawsonite zone represents the lawsonite-albite facies; the transitional zone (as defined by Brothers for a zone containing both lawsonite and epidote) spans the passage from the lawsonite-albite facies to glaucophanitic greenschists which form most of the epidote zone; the deeper part of the epidote zone containing omphacite-almandine is denoted by eclogitic glaucophanitic greenschists, and the Ca-amphibole zone represents eclogitic glaucophanitic albite-epidote amphibolites.

**Physical conditions of metamorphism**

Previous workers in the New Caledonian metamorphic belt, e.g. Espirat (1963), Coleman (1967), Brothers (1970; 1974), Brothers and Blake (1973), Lillie (1970), Black (1970a; 1974) are agreed that metamorphism was dominated by relatively high pressure, low temperature conditions and this is in accord with other blueschist terrains elsewhere in the world (e.g. Ernst, 1971). Evidence for this is shown by experimentally determined and computed phase relations for mineral assemblages in blueschist terrains, for example: jadeite + quartz (Birch and Le Comte, 1960; Newton and Smith, 1967), glaucophane II (Ernst, 1963), phengitic muscovite (Velde, 1965), lawsonite in the presence of excess silica (Newton and Kennedy, 1963; Crawford and Fyfe, 1965; Liou, 1971; Nitsch, 1972), and aragonite (Jamieson, 1953; Clark, 1957; Crawford and Fyfe, 1964; Boettcher and Wyllie, 1968; Newton, et al., 1969; Goldsmith and Newton, 1969; Johannes and Puhan, 1971). In the New Caledonian metamorphic belt
jadeite is absent and aragonite is confined to the northern sector of the belt (Brothers, 1974); in the Diahot region I found aragonite coexisting with lawsonite in only two rocks, both of which were orthoschists of intermediate composition. Fig. 7.1 is a P-T diagram based on some critical univariant equilibria and shows the approximate field for P-T conditions attending metamorphism in the Diahot region.

Brothers (1974, Fig. 4) has compiled a tentative PT curve depicting the development of progressive zonation at the climax of metamorphic recrystallization and has drawn separate curves for the northern and southern ends of the schist belt. Brothers' diagram incorporates a number of PT criteria including:

1. the data for facies boundaries after Liou (1971) on the assumption that the mineral stability fields correspond roughly to facies boundaries.
2. the broadened calcite-aragonite inversion field after Newton, et al. (1969) and Johannes and Puhan (1971).
3. the absence of jadeite and the ubiquitous occurrence of albite throughout the metamorphic belt.
4. the general hypothesis concerning blueschist paragene-
sis that $P_{\text{total}} = P_{\text{load}}$ and that temperature gradients were abnormally low.

Brothers (1974) deduced from petrological evidence that:
(a) below the garnet-epidote horizon the T:P was notably higher in the northern sector than in the southern sector of the belt; (b) there was a deeper regime of metamorphism and higher maximum temperatures in the northern sector of the schists than were attained further south; and (c) the greater
Fig. 7.1 P-T diagram showing some critical univariant equilibria in low grade metamorphic rocks. Cross-hatched area represents the approximate field for P-T conditions attending metamorphism in the Diahot region.

1. Liou (1971)
2. Newton & Kennedy (1963)
3. Nitsch (1972)
4. Ernst (1968)
5. Newton & Smith (1967)
thickness of the transition zone in the southern part was possibly a result of a lower temperature gradient at the southern end. Brothers also found that the metamorphic isograd patterns were constricted, especially opposite Tao, where the outcrop between first lawsonite and first Ca-amphibole in pelitic assemblages is only 7.5 km in width; he favoured fluctuation in the physical environment of metamorphism as the most likely cause for this variation in the distribution of the regional isograds. Petrological reasons related to regional differences between the northern and southern ends of the schist belt cited by Brothers (1974, p. 117) are: paraschist omphacite has been found only in the north; glaucophanites are much more abundant in the north and are thought by Brothers to represent the metamorphosed oceanic basement of the Cretaceous-Eocene trench; in situ orthoschists are more widespread in the north; aragonite, while not necessarily an indicator of high total pressures (Newton, et al., 1969), has nevertheless been found only in the most northerly section (Brothers, 1970).

Three significant factors in the regional distribution of the isograd patterns have been observed in the Diahot region in addition to those proposed in Brothers' model. They are:

(a) the isograd patterns in the Pilou district are much more constricted than in the section from Col de Crève Coeur to Ouégoa and this is explained by a number of steep, westerly-dipping post-metamorphic faults which strike subparallel to both the regional foliation and the metamorphic isograds. Post-metamorphic faults also occur in the Ouégoa
Col d'Amoss region (Espirat and Millon, 1965; Lillie, 1970) and the largest of them, the Gendarmerie Fault, separates rocks of the lawsonite zone from transitional and epidote zone rocks. These faults are thought to have occurred during retrogressive metamorphism, after the metamorphic maximum. Hence, it may be that some of the constrictions in the isograd patterns mapped by Brothers on a much larger regional scale could be explained by post-metamorphic faulting, striking subparallel to the regional isograds.

(b) in most cases the isograds cut across the structure and are independent of it, but in the Balade Mine region north of Ouégao, the epidote isograd is strongly folded and the folding is considered to be contemporaneous with post-metamorphic faulting. However, post-metamorphic folding of the isograds occurs only on a relatively small macroscopic scale and would not noticeably affect the distribution of the isograds on the larger scale mapped by Brothers. A more pronounced late regional flexure is described by Lillie (1970) in the region between Ouégao and Bondé and is a synformal fold, plunging southwest, which has produced a late warping of the epidote isograd.

(c) the transitional zone in the Diahot region, characterized by lacking both lawsonite and epidote, is a unique zone of about 1 km in width and appears to be represented by anomalous Ca-poor rocks, containing less than 0.90 weight percent CaO (from 21 chemical analyses in Balade Mine Stream). Elsewhere in the metamorphic belt the transitional zone is demarcated by containing both lawsonite and epidote in relatively Ca-rich parent lithologies. While the
variation in width of the transitional zone may be a result of variation in the physical environment of metamorphism as suggested by Brothers (1974), the actual presence or absence of the critical minerals, lawsonite and epidote, may also be likely to be dependent on very small changes in bulk rock chemistry within the compositional field of pelites. In support of the latter view is the crossing over of the Na-amphibole and lawsonite isograds defined in pelitic assemblages in a 4 km-long section between Forêt d'Ougne and Pouagone Creek. Normally, Na-amphibole appears after lawsonite in the metamorphic progression but in this section Na-amphibole appears before lawsonite in an apparently particularly favourable pelitic lithology which forms a thin lens 4 km long and several metres thick.

Estimates of the pressures attained during metamorphism in the Diahot region are rather tenuous. Recent experimental determinations of the lower stability limit of lawsonite + quartz (Liou, 1971; Nitsch, 1972) suggest pressures of approximately 3 kb at 250°C (i.e. at the temperature determined by Black (1974) for the lawsonite isograd). Taylor and Coleman (1968) and Black (1974) have determined that the upper stability limit of lawsonite in the Ouégoa district is approximately 400°C and using the data of Nitsch (1972, p. 125, Fig. 5), this temperature corresponds to a pressure of at least 6.5 kb. However, as already pointed out by Black (1974) for the Ouégoa district and Brothers (1974) for the whole of the metamorphic belt, there is a major anomaly between the pressures as calculated by experimental data, and the P increment that can be deduced
from field work - i.e. lithostatic load for the tectonic thickness of the lawsonite zone. The tectonic thickness of the lawsonite zone (between Crève Coeur and Paala River, beyond Bondé) is approximately 7.5 km (Lillie, 1970, and confirmed in this study), and assuming an average density of 2.8, these rocks provided a lithostatic pressure increment of only 2.1 kb, or approximately half that required from the experimental data.

Estimations of the tectonic thickness of the Eocene phtanites, argillites and limestones from the 1:50,000 map of Espirat and Millon (1965) indicate a thickness possibly in excess of 12 km, which is compatible with the experimental data for the lawsonite isograd at 3 kb (assuming, for computational purposes, that 1 kb load pressure represents 4 km of compacted sedimentary overburden (after Brothers, 1974)). This also assumes, as Lillie (1970) pointed out, that repeated layers were placed one over another to make a considerable load.

However, in the Cretaceous rocks there is the anomaly cited above for the tectonic thickness of the lawsonite zone (only 7.5 km) and also for the tectonic thickness for the whole of the Cretaceous-Eocene pile which has been estimated to be at least 26 km (6.5 kb) - certainly much less than that required by a lithostatic load hypothesis alone for the formation of the glaucophanitic greenschists and eclogitic rocks, estimated to have been metamorphosed in an environment of about 11 kb or 44 km of load by Brothers (1974).

A possible explanation favouring a load hypothesis for metamorphism is that post-metamorphic faulting has removed significant parts of the Cretaceous-Eocene sequence. As
already mentioned, post-metamorphic faults have been mapped in the Pilou district and possibly explain the constricted nature of the isograd patterns. Also, in the Ouégoa district, the Gendarmerie Fault has removed either the lower part of the lawsonite zone or the upper part of the epidote zone, or both. It could well be that the Gendarmerie Fault has removed several kilometres of the original metamorphic pile, although in the region to the south near Bondé no major post-metamorphic faults have been mapped and the lawsonite zone grades into the epidote zone with no apparent structural break in the sequence (Lillie, 1970). Only one post-metamorphic fault has been observed along R.T. 7 between Col de Crève Coeur and the Diablot River and has been mapped to extend from the Djavel River to pass just south of Ouébé Stream; this is regarded as a surface of décollement (Lillie, 1970) with a dominantly transcurrent sinistral offset. Nevertheless, this fault, like the Gendarmerie Fault, might also have removed a significant increment in the sequence, and if extended to the southeast, may correct the anomalous spacing between the lawsonite and epidote isograds. It should also be borne in mind that while there is relatively good structural control along the section of R.T. 7, there may be other post-metamorphic faults striking subparallel to the foliation as in the Pilou district, either not yet observed or not exposed. The latter seems quite likely, especially in certain sections of the road where there are wide gaps between exposures.

However, on the present evidence, especially the lack of data concerning the amounts of displacement on the post-
metamorphic faults, the problem of lack of lithostatic load pressure remains conjectural.

Brothers (1974) and Black (1974) also found that values for total pressure in the metamorphic system cannot be explained solely as a function of lithostatic load and suggested that intergranular fluid pressure could have exceeded lithostatic load. Such high fluid pressures may be related in part to dehydration reactions at deep metamorphic levels and would make a significant addition to the total pressure (Brothers, 1974). There seems no doubt that there was a widespread fluid phase during metamorphism, both in New Caledonia and in blueschist terrains elsewhere (Nitsch, 1972; Ernst, 1972), but experimental observations on strain rates, effects of temperature and the strength of rocks have shown that rock strengths decrease with slower, geologically reasonable strain rates and also decrease with increase in both temperature and $P_{H_2O}$ (Brace, et al., 1970). Hence, because of a permeating fluid phase, the rocks, especially such fine-grained pelites, must have been relatively weak and therefore any increment in pressure due to "tectonic overpressure" seems rather remote.

Similarly, I consider that rock strengths at moderately high temperatures (say 400°C) may not be able to tolerate conditions where $P_{H_2O}$ or $P_{fluid}$ was considerably in excess of lithostatic load pressure ($P_{load}$) for any period of time without rupture occurring and consequent loss of fluid pressure out of the system, especially in an essentially dynamic metamorphic environment. The situation of $P_{fluid} >> P_{load}$ would seem to require special conditions that might not be geologically feasible and I tend to favour a purely
lithostatic load hypothesis where significant parts of the sequence have been removed by post-metamorphic faulting.

Temperature gradients determined from the P-T diagram in Fig. 7.1 by plotting on the trend of mineral assemblages, give an average value of approximately 15°C/km (assuming 1 kb = 4 km), varying from about 10-20°C/km. These figures are generally compatible with those cited by Brothers (1974) who suggested an average gradient of 12-13°C/km, with variation from 5-30°C/km, and 20°C/km across the lawsonite zone in the Ouégoa district given by Black (1974). These geothermal gradients represent the climax of metamorphism and were probably very much lower during this time than during the Cretaceous and Eocene when rhyolitic and basaltic volcanism occurred concurrently with sedimentation.

Brothers (1974, p. 124) has already noted that total depth for metamorphism could be reduced from about 40 km to nearer 30 km by adjusting the PT gradients within some limits of the field and laboratory data, "which, on the structural and stratigraphic synthesis of the New Caledonia trench, seems geologically quite possible". Nevertheless, while such an adjustment reduces the total pressure required, it does not correct the anomalous spacing between the lawsonite and epidote isograds which I prefer to explain by post-metamorphic faulting.

Tectonic implications

The tectonic environment of New Caledonia has been discussed in recent literature by many authors including Lillie and Brothers (1970), Lillie (1970), Brothers and

It is not intended to discuss tectonic theories at length, but rather it is proposed to modify present ideas in the light of the detailed structural and petrological observations in the Diahot region. Neither is it intended to incorporate into this discussion the origin and emplacement of the ultrabasic massifs which form a great belt along the west coast of the island and a huge nappe in the south; for a discussion on the tectonics of the ultrabasic rocks the reader is referred to Avias (1967, 1973), Guillon and Routhier (1971), Guillon (1972), Rodgers (1972), Lillie and Brothers (1970), Lillie (1970), Brothers and Blake (1973), Brothers (1974).

Any tectonic theory must take into account a number of significant structural features observed in the Diahot region - these are enumerated below and are summarised in a general diagram in Fig. 7.2:

(1) The Cretaceous rocks are highly folded and the major folding is characterized by steeply plunging folds trending southwest down the dip of the regional northwest-southeast foliation, with axial planes striking northwest-southeast and dipping southwest. This folding occurred largely synchronously with high-pressure metamorphism. On a regional scale the major structure is an open to isoclinal, asymmetric, reclined fold, somewhat drag-like, with a
Fig. 7.2 Generalised diagram showing the major structural features in northern New Caledonia.
sinistral vergence. The southwesterly-plunging folds are considered to have been formed originally in a subhorizontal attitude, trending northeast-southwest, prior to westwards rotation of the Cretaceous-Eocene sequence and uplift to expose the highest grade metamorphics along the east coast. Thus, folding with attitudes trending northeast-southwest implies a direction of major transport either to the northwest or to the southeast, and the vergence sense favours the northwesterly alternative. This view has already been proposed by Lillie (1970, p. 110) who implied that the chief penetrative movement was directed in a roughly northwest-southeast direction although he interpreted the origin of smaller-scale folds otherwise.

(2) During retrogressive metamorphism, large-scale transcurrent sinistral movement occurred on faults, striking dominantly northwest-southeast and dipping southwest, subparallel to the axial planes of the regional inclined folds. Similarly, the faulting probably also occurred prior to rotation and uplift and hence is regarded to have originated by thrust movements. The transcurrent movement sense also implies a maximum movement component directed either northwest or southeast. These faults typically form wide zones up to 2 km thick occupied by high-grade ortho- and paragneisses (glaucophanites) and serpentinites. These high-grade rocks possibly represent slices and slivers of deep-seated metamorphic rocks which have been tectonically or diapirically emplaced into higher levels in the metamorphic pile, and indicate that the displacement on the fault must also have a dip-slip component. In the Ouégoa-Col
d'Amoss district the faults form an anastomosing network, sometimes enclosing lensoid packets of country rocks.

(3) On the other hand, the Tertiary rocks to the southwest are folded about generally subhorizontal axes, trending northwest-southeast with roughly sub-vertical axial planes, in strong contrast to the steeply-plunging southwesterly trending folds of the Cretaceous rocks in the deeper-seated metamorphic environment. This implies a principal movement component directed either northeast or southwest, at right angles to that postulated for the maximum movement component in the Cretaceous rocks. Southwesterly-dipping faults seamed with serpentinites also occur in the Tertiary rocks (and in the Cretaceous rocks near the Cretaceous-Tertiary boundary) and one such fault observed on the main road near Col de Petit Crève Coeur had a dominantly dip-slip displacement, again in contrast to the dominantly transcurrent faults in the Cretaceous rocks around Ouégoa. The Tertiary strata form part of the "mélange zone" of Brothers and Blake (1973) and Brothers (1974) in which they have also recorded southwesterly shear surfaces. Their "mélange zone" is characterised by a strong horizontal component of compression which was relieved by eastward-directed thrusts forming a regional imbricate structure; lawsonite was generated sporadically at deeper levels within the imbricate structure, below the soles of individual thrust surfaces (cf. Blake, et al., 1969).

However, it is a major problem that there is no well-defined boundary between these two domains of contrasting tectonic style. Any theory must take into account a dom-
inant movement component directed northwest in the deeper-seated Cretaceous rocks and northeast-southwest in the upper metamorphic levels of the "mélange zone".

**Regional setting for plate tectonics**

Many writers (e.g. Isacks, et al., 1968, 1969; Dewey and Bird, 1970; Avias, 1973; Brothers and Blake, 1973) have shown a complex system of island arcs and associated seismic Benioff zones, connected by transcurrent faults and extending southeast from New Guinea through New Britain, Solomon Islands, New Hebrides, Tonga-Kermadec, New Zealand, Macquarie Island and then south to the Indian-Antarctic rise. This structure, named the Outer Melanesian Arc by Avias (1973), is believed to outline the boundary between the Indian (or Australian) plate on the west and the Pacific plate on the north and east. The present apparent movements or relative velocity vectors are known along parts of this structure and these data, together with geological information and plate tectonic theory, support the general concept that the Indian plate is converging with the Pacific plate along a series of opposite-facing subduction zones and transcurrent faults (Brothers and Blake, 1973). The main transcurrent faults are the dextral Alpine Fault in New Zealand and the system of sinistral faults in the Fiji area, connecting the Tonga-Kermadec and New Hebrides trenches (Green and Cullen, 1973).

New Caledonia forms part of a now "dead arc", named the Inner Melanesian Arc by Avias (1973), and includes New Britain, the Louisiade Archipelago, through New Caledonia.
and possibly linked to New Zealand by the submerged Norfolk Ridge.

A series of marginal basins, underlain by oceanic crust, lies behind these island arc systems and is believed to be of extensional origin; it has been divided into actively spreading inter-arc basins and older inactive basins (Karig, 1971). During the Cretaceous and Paleocene (80-60 m.y. BP) New Caledonia formed part of a sialic foreland moving northeastwards under the influence of a spreading system located within the marginal basin of the Tasman Sea (Hayes and Ringis, 1973). These processes have been dormant within the Central Tasman Basin for about the past 60 m.y. and the area is now aseismic (Hayes and Ringis, 1973), although the Indian-Pacific plate junction, along which New Caledonia was presumably cited, must have been active during the Oligocene at the time of high-pressure regional metamorphism.

Brothers and Blake (1973) and Brothers (1974) have postulated that Cretaceous-Eocene sediments were deposited in a deep active trench lying to the east of the New Caledonian sialic foreland and related to a northwest-southeast-trending subduction zone, dipping to the northeast. Brothers (1974, Fig. 2) has drawn a diagrammatic series of tectonic and metamorphic events in New Caledonia, showing in the southern end, northeastwards underthrusting of the New Caledonian sialic foreland (part of the Indian plate) below a southwestwards overthrusting of the eastern oceanic crust (part of the Pacific plate). At the northern end, and coeval with obduction in the south, there was a strong horizontal component of compression which was relieved by eastward-directed thrusts and developed a regional imbricate structure,
named the "mélange zone". However, such a system would produce folds oriented northwest-southeast together with dip-slip faulting or thrusting, which is compatible with the structures observed in the "mélange zone" in the upper metamorphic regime but not with the southwesterly trending folds and transcurrent sinistral faulting in the deeper metamorphic levels of the Cretaceous rocks near the east coast. There are four possible hypotheses which may explain this anomaly and are diagrammatically represented in Fig. 7.3-

(1) Firstly, seismic first motion studies have indicated that the relative velocity vector or drift of the Pacific plate is at the present time directed approximately to the west or northwest (Le Pichon, 1968; Isacks, et al., 1968; Denham, 1973) and this direction has been relatively constant during the past 40 m.y. (Morgan, 1972). Possibly, therefore, the southwesterly trending folds and transcurrent sinistral faulting (or rather prior to rotation and uplift, northeast-southwest trending folds and thrust faulting) were related to an older subduction system trending northeast-southwest and dipping northwest formed by underthrusting of the Pacific plate. Later, this subduction system ceased or slowed with the cessation or slowing of drift of the Pacific plate, and renewed or faster northeastwards drift of the Indian plate commenced with underthrusting and down-going of the Indian plate in a subduction system trending northwest-southeast and dipping northeast. This later system associated with eastward-directed thrusting in the north and subduction in the south formed the mélange zone of Brothers and Blake (1973) and Brothers (1974) in the northern end of New Caledonia and produced northwes-
Fig. 7.3

Diagrammatic plan of New Caledonia illustrating four possible hypotheses of tectonic events in the interval 38-21 m.y. before present.
southeast trending folds and dip-slip faulting. This hypothesis incorporates two subduction systems oriented approximately at right angles to each other. There is no petrological evidence or any great tectonic break indicating two separate phases of metamorphism and these interacting systems must have occurred in continuous sequence during a single metamorphic episode. The section of progressive metamorphic zones now exposed after westwards rotation and uplift is thus both a rotated dip section, normal to the earlier subduction system, and also a rotated strike section normal to the slightly later northwest-southeast subduction zone.

There is a remote possibility that the direction of subduction was actually opposite to that deduced from the vergence of the folds in the Cretaceous - such a situation could arise if the folds produced by the subduction verge away from the trench towards the foreland instead of into the trench as is usually the case. However, the size of these folds and the association of the folds with sinistral serpentinite-bearing faults favours the conventional interpretation.

(2) In the second hypothesis, the southwesterly-trending folds and sinistral transcurrent faults may be related to a major sinistral transcurrent system which in mid-Tertiary time was a former westwards continuation of the Hunter Fracture zone or other fractures parallel to the Hunter Fracture zone (the Fiji Fracture Zone and the Kandavu Fracture zone of Green and Cullen, 1973). At present, these sinistral transcurrent faults connect the opposite-facing
subduction zones of the New Hebrides and Tonga-Kermadec arcs (Isacks, et al., 1969). However, in mid-Tertiary time, similar transcurrent faulting may have occurred further west in the New Caledonian region. The faults in the Fiji region strike approximately east-west (Green and Cullen, 1973, Fig. 7) and to explain the northwest-southeast transcurrent faulting and southwest trending folds in the Diahot region, either New Caledonia must have undergone 45° clockwise rotation during upper Tertiary time or the faults may have curved from an east-west strike in the east near Fiji to a northwest-southeast strike in the west near New Caledonia. Such a swing from east-west to northwest-southeast is shown by the general trend of the metamorphic belt as illustrated by Brothers and Blake (1973, Fig. 3) and Brothers (1974,Fig. 3).

On regional structural grounds there may be a large northwest-southeast striking transcurrent sinistral fault running along the east coast, parallel to the Gendarmerie Fault, and may have a greater displacement than the Gendarmerie Fault. This has already been suggested by Lillie (1970) and Lillie and Brothers (1970).

Sinistral transcurrent faulting ceased abruptly and a northwest-southeast trending subduction system, dipping to the northeast, became the dominant structural feature as described in the latter part of hypothesis (1). As in hypothesis (1), the northwest-southeast subduction system must have followed without a significant break after the wrench faulting regime, maintaining continued metamorphism throughout both tectonic cycles. Furthermore, the former
regime of transcurrent sinistral faulting only affected rocks close to the wrench faults along the northeastern sector, and the later regime of eastward-directed thrusting only affected rocks to the west in the mélange zone.

On the other hand, the faults in the mélange zone could have changed their character over a period of time and may have been originally wrenches, lubricated with serpentinites, and later changed to normal faults or thrusts due to a northeast-southwest compressive component.

This hypothesis implies that there was comparatively little westwards rotation of the island but comparatively large uplift, and the steeply plunging folds were produced in a wrench regime.

Tectonics analogous to wrench faulting have been favoured by Lillie (1970) to account for the formation of mesoscopic folds in the Ouégoa district and he argued it was unlikely that the whole of the Cretaceous-Eocene strata could be rotated en bloc with little internal modification. This hypothesis assumes that regional high-pressure blue-schist facies metamorphism can occur in an environment of wrench (or transform?) faulting.

(3) A possible third hypothesis involves a single subduction zone with either a strongly curving trend or a sinistrally offset jog along part of its length at depth, analogous to a minor sinistral transform fault. This is a particularly complicated case requiring a movement directed roughly northwest-southeast at deep levels in the metamorphic pile where the trend of the subduction zone was most curved or where it was sinistrally faulted, and a concurrent
or slightly later movement in the upper levels of the metamorphic environment, directed northeast-southwest and where the trend of the subduction zone was roughly rectilinear, trending northwest-southeast. Some support for this hypothesis comes from the regional swing in the metamorphic isograd patterns depicted by Brothers (1974) where the general strike in the northern sector is northwest-southeast but swings around to an east-west strike in the southern sector. Subsequent to cessation of the subduction system, westwards rotation and uplift occurred and preserved en bloc the southwesterly trending, steeply plunging folds in the deeper levels and subhorizontal northwest-southeast oriented folds in the upper levels.

(4) Another model is possible involving oblique subduction where the deeper levels of deformation record the actual direction of convergence of plate boundaries whereas the upper levels are conformable to the geometry of the trench-arc system, the trend of which is not necessarily at right angles to the direction of convergence (e.g. the eastern part of the Aleutian Arc, Atwater and Menard, 1970; Peter, et al., 1970). Such a model is practically ruled out due to the fact that the two fold axis orientations are at 90° to each other.

Discussion

The four hypotheses outlined above are speculative and there is no clear evidence favouring any particular model. A significant problem common to all hypotheses presented here is the lack of overprinting of the contrasted trends in fold axes, oriented at right angles. Hence the
time relations of the differently oriented fold regimes cannot be positively determined although on general grounds tectonic disturbance of the deeper levels of the Cretaceous-Eocene sequence would seem most likely to have preceded that in the stratigraphically and tectonically upper portion.

A question arises here as to the time relations of the kink folds – in the Diahot region the kink folds are late structures, overprinting the steeply plunging folds, and I consider them to be associated with uplift and possibly with westwards rotation of the island. However, the kink folds trend northwest-southeast with subhorizontal plunges, parallel to the orientation of the folds seen in the mélange zone, and it is possible that both the kink folds and the folds in the mélange zone belong to the same tectonic regime. If this were the case, then clearly the folds in the mélange zone post-date the steeply plunging folds in the Cretaceous rocks.

Nevertheless, I do not favour the alternative that the kink folds are associated and contemporaneous with the subhorizontal folds in the mélange zone on the following grounds. It seems more likely that the large-scale subhorizontal folding in the mélange zone was associated with eastwards-directed thrusting; evidence for this, as already mentioned, is based on the parallelism of the strike of the thrusts with trend and plunge of the folds. The thrusts are seamed with serpentinites and locally lawsonite has been generated below their soles. Thus, during folding and thrusting, metamorphism was continuing
and it has been clearly shown from field relationships, chronological and petrological studies that the kink folds post-date the metamorphism, occurring when the rocks were in a cold brittle state. Also, if these folds are related, it is curious that such strong folding should occur in the Eocene rocks in the mélange zone which on the whole are extremely competent strata, whereas the relatively incompetent phyllites and schists of the Cretaceous rocks are merely kinked on a small mesoscopic scale.

It is also surprising that within the time span of a single metamorphic episode there should be such contrasted tectonic movements directed approximately at right angles. This assumes that the deep-seated regional metamorphism and localized generation of lawsonite below the soles of individual thrust surfaces in the mélange zone belong to a single, penecontemporaneous metamorphic episode. It may be that the latter occurred during a distinctly later, separate metamorphic event and the PT conditions of the two metamorphic episodes were analogous. Alternatively, there may have been a gradual migration of metamorphism. Brothers (1974) has postulated a single episode of metamorphism which was continuous over a time span of 38-21 m.y. (Coleman, 1967); however, this age was determined on rocks in the Ouégoa district and no dates are yet available for the age of the lawsonite generated below the soles of thrust surfaces in the lawsonite-bearing metagreywackes in the southern sector, or elsewhere in the metamorphic belt. This is a comparatively short time span for documented blueschist metamorphism (cf. Ernst, 1972) if in
fact these dates indicate the total period of metamorphism, but many authors consider this type of metamorphism as almost a "shock metamorphism" of short duration and it is possible that two distinct metamorphic events could have occurred over 17 m.y.

Another problem with hypothesis (1) is that there is no oceanographic morphologic lineament suggesting a relict northeast-southwest subduction system - all the oceanographic data indicate northwest-southeast trending structures at the present day. It could be argued that later northwest-southeast trending structures have subsequently obliterated all trace of previous structures oriented at right angles although this is highly conjectural.

Westwards rotation accompanied with isostatic buoyant uplift must have taken place, to account for the regional steep southwesterly dips. This is documented by Brothers (1974) and the westerly tilt is also evidenced by regional geomorphological considerations (Davis, 1925). Regional tilting and uplift occurred no later than the Miocene as shown by the horizontal or very gently dipping shelly, littoral and coral Miocene limestones which are the last marine strata known in the stratigraphic column, apart from coastal and river alluvial deposits, piedmont gravels and coral reefs (Lillie and Brothers, 1970).

In conclusion, it is felt that the hypotheses proposed here are modifications of the earlier tectonic models of previous writers, (mainly Brothers and Blake, 1973; Brothers, 1974), although their broader syntheses cannot yet adequately explain the most significant structural features
observed and deduced in the Diahot region. These features are the steeply-plunging reclined folds and the complex system of transcurrent sinistral faults. The area studied forms only a small part of the metamorphic terrain and a great deal of further structural and petrological work is necessary to elucidate the geology of the New Caledonian metamorphic belt in detail.
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APPENDIX 1

COMPREHENSIVE LISTS OF MINERAL ASSEMBLAGES OBSERVED IN PELITIC SCHISTS, CALCAREOUS SCHISTS, METACHERTS, METABASALTS, INTERMEDIATE METAIGNEOUS ROCKS AND RHYOLITIC METATUFFS

Mineral Assemblages in Metasedimentary Rocks

A wide variety of mineral assemblages occur in the metasedimentary rocks and for purposes of description they are subdivided into: (a) pelitic assemblages including assemblages in psammites and siliceous schists, (b) calcareous schists - rocks containing one or more carbonate minerals, and (c) metacherts.

The following are comprehensive lists of mineral assemblages in metasedimentary rocks depicting the variation with metamorphic grade.

(a) Pelitic Schists

Zone 1

The total assemblage in pelites from zone 1 is quartz-albite-phengitic muscovite-paragonite-chlorite +Na-amphibole=sphe-needles-opaques.

The following assemblages have been noted (sphene and opaque minerals are common additional phases):

quartz-phengitic muscovite
quartz-phengitic muscovite-chlorite
quartz-phengitic muscovite-paragonite-chlorite
quartz-chlorite
quartz-albite-phengitic muscovite
quartz-albite-phengitic muscovite-chlorite
quartz-albite-chlorite
quartz-albite-phengitic muscovite-paragonite-
chlorite
quartz-albite-Na-amphibole-phengitic muscovite-
chlorite

Zone 2

The total assemblage is: quartz-albite-phengitic
muscovite-paragonite-chlorite-lawsonite-Na-amphibole
&garnet&sphene&apatite&zircon&opaques&tourmaline.

Assemblages are (with possible additional minerals:
sphene, apatite, zircon, opaques):
quartz-lawsonite-phengitic muscovite-chlorite
quartz-lawsonite-phengitic muscovite-paragonite
quartz-lawsonite-chlorite
quartz-lawsonite-Na-amphibole-phengitic muscovite
quartz-lawsonite-Na-amphibole
quartz-lawsonite-Na-amphibole-muscovite-paragonite
quartz-lawsonite-albite-chlorite
quartz-lawsonite-albite-Na-amphibole
quartz-lawsonite-albite-Na-amphibole-phengitic
muscovite-chlorite
quartz-lawsonite-albite-phengitic muscovite-paragonite-
chlorite
quartz-lawsonite-albite-phengitic muscovite-chlorite
quartz-lawsonite-albite-Na-amphibole-garnet-phengitic
muscovite-chlorite
quartz-albite-Na-amphibole-phengitic muscovite-chlorite
quartz-Na-amphibole-phengitic muscovite-chlorite
quartz-Na-amphibole-phengitic muscovite-paragonite
+chlorite
quartz-Na-amphibole-garnet-phengitic muscovite
-tourmaline
quartz-albite-Na-amphibole-garnet-phengitic muscovite
-chlorite

Zone 3

The total assemblage of minerals in the transitional zone is: quartz-albite-phengitic muscovite-paragonite ±chlorite±stilpnomelane±Na-amphibole±garnet±chloritoid ±sphene±apatite±zircon±opaques.

Assemblages are (with possible additional minerals: sphene, apatite, zircon, opaques):
quartz-albite-phengitic muscovite-chlorite
quartz-albite-phengitic muscovite-chlorite-garnet
quartz-albite-phengitic muscovite-Na-amphibole±chlorite
quartz-albite-phengitic muscovite-Na-amphibole-garnet ±chlorite
quartz-albite-phengitic muscovite-paragonite-Na-amphibole ±garnet-chlorite
quartz-phengitic muscovite-paragonite-Na-amphibole -garnet-chlorite
quartz-phengitic muscovite-chlorite
quartz-phengitic muscovite-chlorite-garnet
quartz-phengitic muscovite±chlorite-garnet-Na-amphibole
quartz-phengitic muscovite-chlorite-Na-amphibole
quartz-chloritoid-phengitic muscovite-chlorite±garnet
quartz-stilpnomelane-phengitic muscovite-chlorite-garnet
Zone 4

The total mineral assemblage in the epidote zone is: quartz-albite-phengitic muscovite-paragonite chlorite-Na-amphibole-garnet-epidote-sphene-apatite opaques-zircon-chloritoid.

Assemblages are (with possible additional minerals: sphene, apatite, zircon, opaques):
- quartz-epidote-albite-Na-amphibole-garnet-phengitic muscovite-chlorite
- quartz-epidote-albite-Na-amphibole-garnet-phengitic muscovite-paragonite
- quartz-epidote-phengitic muscovite-paragonite-chlorite
- quartz-epidote-Na-amphibole-garnet-phengitic muscovite chlorite
- quartz-albite-phengitic muscovite-Na-amphibole-garnet
- quartz-albite-phengitic muscovite-Na-amphibole
- quartz-albite-phengitic muscovite-garnet-chlorite
- quartz-albite-phengitic muscovite-chlorite
- quartz-albite-phengitic muscovite-paragonite-Na-amphibole-garnet-chlorite
- quartz-phengitic muscovite-chlorite-Na-amphibole-garnet
- quartz-phengitic muscovite-chlorite-chloritoid-garnet

(b) Calcareous Schists

Calcareous schists are fairly rare occurrences in the Cretaceous sequence and consequently only a small number of mineral assemblages have been noted. Calcareous schists are absent in the transitional and epidote zones in the region of this investigation. Additional minerals are sphene and opaques.
Zone 1
quartz-calcite-albite-phengitic muscovite-chlorite
quartz-calcite-phengitic muscovite-chlorite
quartz-calcite-dolomite-phengitic muscovite-chlorite

Zone 2
quartz-calcite-lawsonite-albite-phengitic muscovite
quartz-calcite-lawsonite-phengitic muscovite-chlorite

(c) Metacherts
Only four metacherts have been sampled, mainly from
the Pilou district and only from the lowest grade
rocks. They have very simple assemblages:

Zone 1
quartz-phengitic muscovite-opaques
quartz-phengitic muscovite-chlorite-opaques
quartz-chlorite-sphene-opaques

Mineral Assemblages in Metaigneous Rocks and Metatuffs
Metaigneous rocks vary in composition from basic to
acidic and the mineral assemblages have been divided into
three categories:

(a) Metabasalts - the name metabasalt is used here in a
broad sense and incorporates basalts, green veins
cutting basalts and green rocks possibly derivatives
of basaltic tuffs.

(b) Intermediate metaigneous rocks - a rather rare group
of rocks dominantly composed of relict igneous
plagioclase and one or more carbonate phases.
Petrographic evidence indicates these rocks were possibly originally trachytes or andesites.

(c) Rhyolitic metatuffs - this category includes rocks which were probably originally rhyolitic flows.

(a) Metabasalt Assemblages - possible additional minerals are sphene, quartz, opaques (mainly limonite, pyrite), apatite, phengitic muscovite, calcite, dolomite, and relict igneous plagioclase (approximately up to zone 2) and relict igneous clinopyroxene and amphibole.

 Zone 1
 chlorite
 albite-chlorite
 pumpellyite-chlorite
 pumpellyite-chlorite-albite
 pumpellyite-Na-amphibole-chlorite
 pumpellyite-Na-amphibole-chlorite-albite
 pumpellyite-Na-amphibole-chlorite-stilpnomelane
 Na-amphibole-chlorite-stilpnomelane

 Zone 2
 Na-amphibole-chlorite
 Na-amphibole-chlorite-pumpellyite-lawsonite
 Na-amphibole-chlorite-pumpellyite-lawsonite-albite
 Na-amphibole-chlorite-pumpellyite-lawsonite-omphacite
 Na-amphibole-chlorite-pumpellyite-omphacite-stilpnomelane
 Na-amphibole-chlorite-lawsonite-omphacite
 Na-amphibole-chlorite-lawsonite-omphacite-albite
 Na-amphibole-chlorite-lawsonite-albite
pumpellyite-chlorite-lawsonite-albite

In situ metabasalts are absent in the transitional zone but several metabasalt bodies occur approximately 150 m inside the epidote isograd.

Zone 4
Na-amphibole-chlorite-epidote
Na-amphibole-chlorite-epidote-albite
Na-amphibole-chlorite-epidote-lawsonite
Na-amphibole-chlorite-epidote-lawsonite-albite
Na-amphibole-chlorite-epidote-omphacite-albite
Na-amphibole-chlorite-epidote-omphacite-lawsonite-albite
Ca-amphibole-chlorite-epidote

(b) Intermediate Metaigneous Assemblages

Possible additional minerals are sphene, opaques, phengitic muscovite. Quartz is generally a minor constituent, and most rocks contain abundant relict igneous plagioclase.

Zone 1
chlorite-albite-calcite
chlorite-albite-dolomite
chlorite-albite-dolomite-pumpellyite
chlorite-albite-aragonite-pumpellyite-lawsonite

Zone 2
chlorite-albite-calcite
chlorite-albite-calcite-pumpellyite
chlorite-albite-lawsonite
chlorite-albite-lawsonite-Na-amphibole
chlorite-albite-lawsonite-aragonite-calcite-pumpellyite
chlorite-albite-aragonite-calcite

Intermediate metaigneous rocks are absent from the transitional and epidote zones in the region of this investigation.

(c) **Rhyolitic Metatuffs**

Possible additional minerals are sphene, apatite, jarosite, opaques (mainly limonite, pyrite), zircon, opal (only recorded in the lawsonite zone) and relict igneous plagioclase.

**Zone 1**

quartz-albite-phengitic muscovite
quartz-albite-phengitic muscovite-calcite
quartz-albite-phengitic muscovite-chlorite
quartz-phengitic muscovite
quartz-phengitic muscovite-chlorite
quartz-phengitic muscovite-calcite
quartz-phengitic muscovite-pyrophyllite-chlorite
quartz-pyrophyllite-chlorite-albite-epidote-calcite
-magnesite

**Zone 2**

quartz-albite
quartz-phengitic muscovite
quartz-albite-phengitic muscovite
quartz-albite-phengitic muscovite-chlorite
quartz-albite-phengitic muscovite-pyrophyllite
quartz-albite-phengitic muscovite-Na-amphibole
quartz-microcline-phengitic muscovite
quartz-microcline-phengitic muscovite-albite
quartz-phengitic muscovite-chlorite-lawsonite

The author has not found any rocks recognisable
as originally rhyolitic tuffs or flows in the transi-
tional or epidote zones but Black (1970) has recorded
interesting assemblages from Bouehndep in rocks mapped
as leptynites by Espirat and Millon (1965) and probably
with an acid volcanic parent composition. This
locality lies to the north of the area of this study
in the epidote zone and assemblages in leptynites
contain: (9995, 7948) quartz-albite-phengitic
muscovite-omphacite-epidote-Na-amphibole-microcline
-sphene-apatite.