Lithics in Perspective

Indeterminacy, Simulation, and the Formation of Lithic Assemblages

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Abstract

Archaeologists cannot directly observe the past, meaning explanations are often subject to indeterminacy: the problem of distinguishing between any number of explanations for observed archaeological patterning. Using the example of mobility studies and the lithic record, it is shown that indeterminacy occurs because reconstructions of the past use static representations of behaviour. But the archaeological record is an emergent phenomenon, an outcome of variable accumulation histories of artefacts that is irreducible to proximate causal processes. An alternative approach is needed, one that dispenses with assumptions about the behaviours artefacts and assemblages are thought to represent, and instead investigates how patterning emerges in the archaeological record as observed in the present. Exploratory agent-based modelling is used as a means of achieving this, by simulating the interaction of simple processes of lithic production, reuse, and transport to generate independently derived expectations about assemblage patterning under a range of conditions that are then tested with empirical data. Two key areas of mobility-related research in lithic analysis provide case studies: the geological sourcing of artefacts, and the organisation of technology. A model called SourceSim explores how the distribution of artefacts deriving from different geological sources is affected by reusing material from deposits of previously discarded artefacts. Similarities between simulated outcomes and archaeological obsidian distributions from Aotearoa/New Zealand have implications for inferences about mobility based on distances to geological source. Another model called ClusterSim simulates agents producing and distributing artefacts under different mobility configurations, affecting the completeness of individual reduction sets, a measure of the physical movement of artefacts that serves as a proxy for human movement. Outcomes are tested using a late Pleistocene and a late Holocene assemblage from Australia, with similarities in place use suggested for both records, running counter to interpretations based on efficiency of raw material use and narratives of broad scale shifts in mobility. The results of the case studies highlight the importance of understanding how assemblage composition and distribution through time and space emerge from fundamental processes of lithic acquisition, transport, and reuse, serving as a foundation from which to build subsequent inferences.
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Chapter 1
Introduction

The inherent nature of archaeological research is such that archaeologists cannot directly observe past peoples or processes that are of interest. Instead, archaeologists deal primarily with materials left behind that survive sufficiently enough to be observed. Those material remains are subject to a range of formation processes, both human and natural, which structure the patterning observed by archaeologists (Schiffer 1972, 1976), and which operate at different temporal scales (Bailey 1981; Binford 1981; Foley 1981). Archaeologists do not have access to a singular ‘tape of history’ (Gould 1989) whereby they can trace back the precise historical sequence of events for a particular time or place. Consequently, archaeological inference is subject to the issue of indeterminacy: the problem of distinguishing between any number of explanations for observed archaeological patterning.

Indeterminacy is brought about by the joint issues of equifinality and underdetermination (Perreault 2019:1-2). Equifinality is the principle that, for any given system, a final state may be reached by different independent mechanisms and/or from more than one set of starting conditions. Underdetermination occurs when available data are insufficient to determine the probability of a particular outcome occurring over others (Perreault 2019:2). The indeterminacy issue spans all aspects of archaeological inquiry, from studies of mobility or faunal assemblage composition to inferences about cultural transmission and social interaction (e.g., Barrett 2019; Brantingham 2003; Graeber and Wengrow 2021:23-24; Lyman 2004; Premo 2010; White 2021).

The focus of this thesis is on how to address the problem of indeterminacy, which is itself a question about the construction of archaeological knowledge. In a recent volume, Perreault (2019) set out the indeterminacy issue as a mismatch between the microscale nature of archaeological theories, the perceived goals of archaeological inference, and what scholars have come to understand about the nature and formation of the archaeological record. Generally, much archaeological theory is borrowed from the contemporary social sciences, which draw upon information that is quite different from what archaeologists work with. That information consists of observations of contemporary human groups where behaviour and change are understood at the scale of an individual lifespan (Murray 2008:173). This aligns with the implicit goal of much archaeological research, which is to produce linear, proximate
narratives of the past, at the centre of which are individual people (Bailey 2008; Stern 2015). For some, such high-resolution reconstructions of past human behaviour, or ‘ethnographies of the past’, are seen as achievable through the analysis of material remains that accumulated over short time scales (e.g., Conard 1994; Mallol and Hernández 2016). As such, any problems with inferences derived from contemporary social theories are typically attributed to inadequate data and not the suitability of the theory (Murray 2008).

Archaeologists have recognised for some time that material remains from multiple behavioural events accumulate over long periods to form palimpsest deposits, in which successive depositional events erase evidence of previous activities or in which material accumulates in such a way that individual depositional episodes are indiscernible (Bailey 2007; Lucas 2005). Indeed, individual objects may themselves be palimpsests, acquiring different meanings over their use-lives (Bailey 2007:207-208). In this way, accumulations of material and individual objects form multi-temporal records of activity (Bailey 2007; Lucas 2005). As such, behavioural interpretations may not necessarily be resolvable down to the microscale. Thus, the ability of archaeologists to interpret archaeological remains in terms of social theory based on the microscale is limited (Holdaway and Wandsnider 2008). It is not the case that behavioural phenomena such as those described by present-day analogues did not occur in the past, but rather that the data with which archaeologists typically deal are not necessarily amenable to such interpretations, the implications of which are often acknowledged but rarely worked through (Bailey 2008; Holdaway and Wandsnider 2008; Lucas 2012; Perreault 2019).

For Perreault (2019), rather than attributing fault to archaeological data, addressing issues of equifinality and underdetermination lies in reconfiguring the kinds of questions that are asked of those data. This reconfiguration should account for the quality of the archaeological record, which encompasses four characteristics of archaeological data: scope (the total amount of time and space a dataset encompasses), sampling interval (the interval of time and space between each analytical unit), resolution (the amount of time and space represented by each analytical unit), and dimensionality (the number of independent dimensions of an object of study measured). The magnitude of underdetermination is dependent on the relative size or value of these aspects, each of which are affected by the mixing and loss of archaeological data. Mixing of archaeological data is brought about by various depositional processes, post-depositional disturbance, and analytical processes such as the lumping of data to create analytical units. Loss of data is a product of preservation loss (remains did exist but have
since been lost or eroded due to various processes) and observational loss (where remains are present but not discovered or recognised by archaeologists). Perreault (2019) argues taking full advantage of the archaeological record requires prioritising the reconstruction of cultural histories and emphasising macroscale patterns and processes, both of which are less susceptible to underdetermination: the former because it addresses low-level questions and processes, the latter because the larger the temporal or spatial scale at which some pattern emerges, the fewer the number of processes that might explain that pattern (Perreault 2019:164, 181). While both goals have much to contribute to archaeological enquiry, this thesis draws inspiration from Perreault’s (2019) argument and explores an alternative way to address the issue of indeterminacy, based on reassessing the fundamental treatment of archaeological data brought to light by concepts like ‘quality’, ‘mixing’, and ‘loss’.

When discussing the archaeological record in terms of these concepts, there is an implicit assumption that at some point in time that same record existed in some unmixed or complete, ‘original’ state, such that were it possible to re-reveal this original state, then microscale theories could be unproblematically applied. This perspective is symptomatic of many current interpretive approaches that treat the archaeological record as a static, inert representation of the past. Recent discourse surrounding archaeological metaphysics sees the reconstruction of the past as problematic since this assumes the past is something separate from the present, yet archaeological remains are inherently of the present such that they cannot be ‘filtered’ to reveal some ‘past as it was’ (e.g., Lucas and Olivier 2021). Instead, the recent past and present are parts of a sequence of augmentation or physical transformation of sites and artefacts (Olivier 2011). In this way, the archaeological record might be thought of as generative (sensu Epstein 2006) where material organisation is not an outcome of some initial state being transformed by various agents, but instead an emergent outcome of a long history of accumulation. In other words, the archaeological record is in a constant state of becoming (Bailey 1983; Binford 1981; Lucas 2012; Olivier 2011). Importantly, this emergent quality is not reducible to proximate causal processes (Bailey 2007; Davies et al. 2018). Thinking about the fundamental nature of the archaeological record in this way means terms such as ‘quality’, ‘mixing’, and ‘loss’ are no longer useful since there is no other iteration of the archaeological record against which these relative terms can be compared. The archaeological record simply is, not was.

An alternative approach to addressing the indeterminacy issue requires a method of analysing the archaeological record in a way that is open to the histories of relationships that form a
record that is ever in a state of becoming. One way to think about this is in terms of essentialist and materialist approaches to interpreting the archaeological record, and how these relate to the concept of emergence. Essentialist approaches to archaeological interpretation assume that material objects have an essential nature that defines what the object is, such that they can be used to represent some past event, process, or people (Fowler 2013). For instance, in calling an artefact a ‘scraper’ or ‘knife’ it is sometimes assumed past people intended to produce objects of these predetermined morphologies, which then forms the basis for inferences about site function and associated behaviours, or arguments concerning socio-cultural evolution (see discussion in Holdaway and Douglass 2012). Such an approach has been pervasive since the beginning of the discipline and contributes to the indeterminacy issue by locking objects into a priori categories of being (Holland-Lulewicz 2021; Van Oyen 2013). In doing so, they predetermine the outcome of analysis. Shott (2010:887) explains this with reference to assemblages of lithic artefacts:

When archaeologists contemplate sets of roughly coeval assemblages, they tend to accommodate them to essentialist preconceptions. By the presence of particular tool types...assemblages represent the norms or icons of identity-conscious groups...or patterns of historical descent; by the proportional abundance of types, assemblages represent activity sets or toolkits...for instance as “kills” or “camps” in forager societies...Once we decide what we are looking for, typically we find it in assemblage data.

In contrast, a materialist perspective recognises the multi-temporal nature of objects and how their meanings shift according to their relationships with other entities, including people in the past as well as the present (Lucas 2012). This way of conceptualising objects aligns more closely with an archaeological record that is emergent and generative. The value of a materialist perspective here is methodological (e.g., Holdaway and Phillipps 2021) in how it prompts a critical rethink of the assumptions of established interpretive norms and the way in which archaeological analysis is conducted.

Specifically, this thesis explores how the indeterminacy issue might be addressed by using the example of mobility studies, focusing on inferences drawn from the lithic record. Mobility is a prominent theme in archaeology (e.g., Barnard and Wendrich 2008; Binford 1980; Close 2000; Kahn 2013; Kelly 1992; Kuhn et al. 2016; Sobkowiak-Tabaka et al. 2022), marking it as a useful topic with which to explore the issue of indeterminacy. Lithics are equally suited for this purpose since they are ubiquitous in the archaeological record, often
the only remaining evidence of past human activity. In general, current approaches to lithics are, at their core, similar to those of the nineteenth/twentieth centuries, which typically focus on morphology (typology) and technology (manufacture) of the observed objects, or the central tendencies of collections of objects, when explaining patterns of variability (Dibble et al. 2017; Rezek et al. 2020). Many studies of mobility are no exception, such as those that link mobility to design concepts like flexibility and versatility and how these are expressed in the form of lithic objects (e.g., Bleed 1986; Parry and Kelly 1987; Torrence 1983), or those that link the presence of artefact types with the dispersal and migration of Homo sapiens (e.g., Goder-Goldberger et al. 2016; Mellars 2006).

However, such approaches are fundamentally essentialist in the way the morphology or technology of the observed artefacts reflects some final (and, as is often assumed, intentional) end product of manufacture to which behavioural meaning and significance is ascribed. Such assumptions are critiqued in lithic literature such as in Dibble’s discussion of the scraper reduction continuum (1984, 1995) or the ‘finished artefact fallacy’ (Davidson 2002). An increasing number of studies argue archaeologists need to consider the life-histories of lithics, looking beyond essentialised forms and instead thinking of them in more materialist terms (e.g., Assaf and Romagnoli 2021; Dibble et al. 2017; Holdaway and Phillipps 2021; Iovita et al. 2021; Rezek et al. 2020; Turq et al. 2013). This presents an opportunity to conduct analysis which foregrounds lithics not as essential objects but rather as contextually and historically contingent (Lucas 2012:166). One way is to shift focus away from pre-defined morphological and technological categories, in which lithics are treated as direct manifestations of behaviour, and towards practice of use, where lithics become proxies for past behaviours (Rezek et al. 2020). Rather than assuming the information to be gained from an artefact is present within the artefact itself, efforts should more productively turn to considering “the associations between the stone artefact and the systemic record reflecting the situations in which the artefact was made, used and abandoned” (Holdaway and Douglass 2012:102). This requires a reconceptualization of the process of lithic analysis, presenting the question of how this kind of analysis might be conducted.

Two key areas of mobility-related research in lithic analysis are explored in this thesis to highlight essentialist assumptions that lead to the patterns archaeologists observe and the subsequent inferences about mobility that are generated. The first is the sourcing of lithics and identification of trade/exchange and social interaction. The second is the investigation of mobility and settlement pattern based on lithic technology and principles of behavioural
ecology. Studies that draw upon raw material sourcing typically investigate the distribution of artefacts of particular raw material types relative to the geological source from which those materials originate, and use metrics such as frequencies and distance to the geological source to make inferences about trade and exchange, social networks, and territorial circumscription, all of which relate to mobility (e.g., Newlander and Lin 2017; Rindel et al. 2020; Smith 2010; Torrence et al. 2013). Since stone artefacts can be sourced to a geological origin, this property becomes important. In this way geological sources are also essentialised and treated as key components of resource procurement strategies and associated mobility regimes (Blair 2010; Brantingham 2003). Yet such assumptions belie, for instance, the many and varied ways in which artefacts can move from one location to another (Hughes 2011; Kelly 1992; Smith and Harvey 2018). In the case of mobility and technology, the density of artefacts and distribution of artefact forms are often used to make inferences about settlement pattern, usually as an indicator of occupation intensity. These are often linked with principles of optimisation. For example, residential or base camps should include artefacts from all stages of manufacture since people have more time to work on tool manufacture and maintenance, and artefacts used by groups who were highly mobile or using non-local raw materials should show evidence for a greater degree of curation or raw material conservation (Nelson 1991). Yet such assumptions do not mesh with the way in which artefacts accumulate in the archaeological record with varying temporalities and life-histories, throughout which the form and use of the objects may change significantly (e.g., Bailey 2007; Holdaway and Davies 2020; Shott 1989). Therefore, essentialist assumptions need to be scrutinised, rather than taken as given, lest evidential claims by necessity conform to expectations since the outcome is predetermined by top-down projection of interpretation onto artefacts (Chapman and Wylie 2016; Rezek et al. 2020).

A materialist perspective prompts a critical rethink of the validity of statements about the past based on essentialist approaches. Statements that foreground the techno-morphological attributes of stone artefacts say little in light of a record composed of artefacts that constantly form new associations (e.g., Turq et al. 2013; see also Lucas 2012:166). This becomes clear when considering, for instance, the process of reuse of stone artefacts (e.g., Amick 2007; Coco et al. 2020; Douglass et al. 2017; Holdaway and Phillipps 2021; Rezek et al. 2020; Schick 1987). Ethnographic examples from various places around the world suggest that the selection and reuse of previously discarded objects such as unretouched flakes were often as common, if not more so, than the manufacture of new artefacts with intended forms (e.g.,
Binford and O’Connell 1984; Hiscock 2004; Holdaway and Douglass 2012; McCall and Horowitz 2015; Sillitoe and Hardy 2003). Acquisition of artefacts from existing deposits has clear implications for inferences about mobility that are based on assumptions about access to geological sources of material or the manufacture of particular artefact forms.

One way to approach analysis is to break it down to a fundamental level by limiting assumptions through appeals to simple, lower-order propositions, thus going some way to addressing the indeterminacy issue by building analysis from the bottom-up. Analysing stone artefacts in this way means they can be used to test ideas about mobility where the outcome is not predetermined or limited by the use of microscale theories. However, this in turn raises the question of how to derive such tests. Understanding mobility in the manner suggested here requires data regarding the distribution and attributes of many artefacts located across the landscape in order to see patterning beyond that confined to a site or spatially restricted assemblage. To this end, agent-based modelling is used in this research as a mechanism for exploring processes of interest in an explicit computational framework to generate hypotheses about patterning in lithic data without appealing to the morphology of lithic objects or the way in which they were manufactured. The use of computational modelling also acknowledges the challenge of studying processes that are otherwise difficult to experiment with in an actualistic sense, be it in the laboratory or in the field. The hypotheses generated by the agent-based modelling may then be tested using real archaeological data.

This thesis presents two simple simulations of lithic acquisition, use, discard, and movement based on the sourcing and technology case studies, which are used to generate expectations about patterning in lithic assemblages under a range of conditions. These expectations are tested using empirical data from 1) late Holocene Aotearoa/New Zealand (henceforth: Aotearoa) for the sourcing case study, and 2) late Pleistocene and late Holocene Australia for the technology case study, to provide insight into the processes that govern assemblage accumulation. The two empirical cases are chosen not for their culture-historical significance but rather for their methodological value as useful examples of archaeological records to which common interpretive approaches outlined above are often applied, and for which appropriate data are available to test simulation outcomes.

1.1 Thesis Structure

This thesis is divided into seven chapters. Chapter 2 focuses on indeterminacy in the context of lithic studies. It begins with a discussion of how many current interpretive approaches in
lithic archaeology are fundamentally essentialist in nature, privileging the manufacture sequence and artefact form and treating lithics as emblematic of some form of behaviour in an *a priori* manner, such that lithics in effect act as both data and interpretation. The consequences of essentialist approaches to archaeological interpretation that contribute to the indeterminacy issue are outlined. A discussion of the emergent nature of the archaeological record follows, before setting out an alternative, materialist approach to lithics, emphasising how a materialist view allows researchers to dispense with the notion of stone artefacts as forms manufactured for a specific purpose and instead consider the histories of relationships that constitute the artefacts. Reuse of previously discarded artefacts is discussed as a key example of a phenomenon that emerges when considering lithics from a materialist perspective and that has implications for the validity of common inferences built on essentialist assumptions. The chapter then turns to the examples of sourcing and technological analyses, two common ways in which inferences about mobility are drawn. The implications of a materialist perspective for inferences about mobility are considered with reference to the sourcing and technology case studies, and an overview of the method of analysis for each case is provided.

Chapter 3 introduces the use of agent-based modelling in archaeology, explaining its suitability as a tool for conducting the type of analysis advocated in this thesis. The chapter explains the rationale for an ‘exploratory’ approach (*sensu* Premo 2007, 2010) where questions of interest are addressed by exploring a simple modelled world with clearly defined parameters and scenarios. The act of translating ideas into formal operational statements by design necessitates reflection on the underlying assumptions that structure those ideas. The simulation of simplified, lower-order processes generates output which serves as a set of hypotheses that can be tested using archaeological data. In this manner, simulation is a heuristic device with which to think about the archaeological record in particular ways.

The mobility and lithic sourcing case study is presented in Chapter 4. The process of lithic reuse calls into question the fixity of sources of stone raw material, requiring a reassessment of the kinds of inferences typically drawn from raw material source distributions. There may be many places between the geological origin of an artefact and its location of discard where artefacts are/were located. This case study considers the significance of those ‘in-between’ places by implementing a simple set of lithic production, reuse and movement behaviours in an agent-based model called SourceSim. A series of simulation experiments establishes the effect of different combinations of parameters on resulting distributions of lithics deriving
from different geological sources. Empirical data on obsidian artefact distributions from across Aotearoa are used to test simulation outcomes.

Chapter 5 presents the mobility and organisation of technology case study. A method of analysing the physical movement of artefacts, following the principles of geometry, is presented as an alternative to methods that rely on artefact morphology and technology. Based on the published simulations of Davies (2016; Davies et al. 2018), an agent-based model called ClusterSim is constructed to explore the effects of different lithic production and human movement behaviours on the composition of individual stone reduction sets and the extent to which they are either ‘complete’ or are missing artefacts. Simulation outcomes are considered in terms of the late Pleistocene lithic record of Lake Mungo (Stern 2015; Stern et al. 2013), which reflects a low-density accumulation of discrete, identifiable artefact reduction sets in a context where geological sources of raw material are not locally available. Results are compared with the extensively studied late Holocene surface record at Rutherfords Creek, a relatively high-density accumulation in a context of raw material abundance (Barrett 2014; Davies and Holdaway 2017; Davies et al. 2015, 2018; Douglass 2010; Douglass and Holdaway 2011; Fanning et al. 2009; Holdaway et al. 2012; Parker 2011). Analysis of the artefact assemblages is used to test simulation outcomes and compare the use of stone and formation of the archaeological record in the Mungo and Rutherfords Creek cases.

Chapter 6 begins with a summary of the findings from the previous two chapters and considers some local implications for the empirical cases studied. The evaluation of SourceSim outcomes using data on archaeological obsidian distributions from Aotearoa suggests the reuse of lithic material is a valid explanation for observed archaeological patterning, calling into question the extent to which behaviours such as trade and exchange and social interaction are directly interpretable from obsidian distribution data. For the Australia case, the comparison of ClusterSim outcomes with surface lithic assemblage data from Lake Mungo and Rutherfords Creek suggests a set of similar formational processes are in operation at both locations, reflecting similar place use histories on the whole. This has implications for common narratives of behaviour change from the late Pleistocene to the late Holocene. Following this, the discussion turns to some of the implications of the findings for the study of lithics, including the value of understanding place use through the practice of stone use (e.g., Rezek et al. 2020), rather than focusing analysis on techno-morphological categories. The chapter finishes with a brief discussion of the implications of this research for
indeterminacy and the construction of archaeological knowledge more broadly. Finally, Chapter 7 concludes the thesis with some remarks on the role of agent-based modelling in archaeological research, and some thoughts on future directions for archaeological analysis.
Chapter 2
Lithics in Perspective

Contemporary archaeological theory, or indeed accounts of the nature and purpose of archaeological knowledge, has not engaged with our changing understanding of the phenomenology of archaeological records. In fact, the opposite has been the case with much ‘archaeological theory’ being borrowed from sources that…comprise quite different types of information than archaeologists more generally understand they work with. (Murray 2008:173)

The passage above was written with reference to the concept of time in archaeology and the implicit goal of much archaeological research to produce linear, proximate narratives of the past, at the centre of which are individual people (Bailey 2008; Perreault 2019; Stern 2015). In the passage, Murray highlights the incommensurability of typical explanatory frameworks that are both founded on and seek to elucidate microscale (ethnographic scale) narrative when interpreting the archaeological record, and the much larger time spans over which the archaeological record accumulates, arguing archaeology requires its own theory that accounts for the unique nature of archaeological data. Part of that nature is how the archaeological record is an emergent outcome of many processes, human or otherwise, operating throughout the past and into the present such that it is in a constant state of becoming (Bailey 2007; Epstein 2006; Lucas 2012; Olivier 2011). Emergence provides a useful point of departure for thinking through the issue of indeterminacy with reference to the fundamental treatment and conceptualisation of artefacts and the assemblages they make up. From one perspective, artefacts and assemblages are locked into discrete categories of being that are thought to be direct manifestations of behaviour in themselves, which aids in anthropological reconstructions of the past. However, this ‘essentialist’ approach does not interface well with an archaeological record that is fundamentally emergent in nature. If the patterning in the archaeological record at the time of recording is the phenomenon to be explained, and this patterning cannot be divorced from the processes that generated it, then a different perspective is needed. A consideration of the history of associations that constitutes the material record allows for a record that is constantly in a state of becoming (Hamilakis and Jones 2017; Rezek et al. 2020). This materialist perspective emphasises process and change rather than fixed essences, which aligns more closely with an emergent archaeological record.
This chapter sets out the conceptual background for the approach to indeterminacy taken in this thesis, beginning first with a discussion of essentialism with reference to lithics, before outlining two main consequences for the indeterminacy issue: that material objects act as both data and interpretation, with implications for subsequent behavioural inferences; and a ‘short time’ perspective where interpretations do not adequately take into account the temporality of the archaeological record. Following this, the chapter turns to the contemporary understanding of the archaeological record as an emergent, generative phenomenon, before outlining the value of a materialist perspective in addressing the issues introduced above. The chapter concludes with a discussion of two common approaches to studying mobility using lithics which serve as useful examples of the indeterminacy issue: sourcing and technological organisation. The implications of a materialist perspective for each are considered, and the foundation for a method of addressing indeterminacy is laid out for the case studies in the chapters that follow.

2.1 Essentialism and Lithics

For the most part, archaeology builds from a modernist disciplinary legacy looking for essences and boundaries amongst things (Van Oyen 2016). Categories of being are a priori waiting to be found. Translated into archaeological practice, typological units exist as empirical truths, and consist of entities that have an essential nature or intrinsic characteristics defining what the object is (O’Brien and Lyman 2000:32). Objects and types are models (representations) that are treated as data, and are always confirmed since they are assumed prior to analysis (Griffiths 2017; Shott 2010).

The essentialist practice in archaeology is evident in many major interpretive approaches, from early twentieth century functionalist-empiricist thinking to postprocessualist notions. What they share is the leveraging of categories of things through the use of culture-historic/typological units to explain social change by situating artefacts and sites in time. This operates under the reasoning that such units have heuristic value. There is no issue with heuristic devices in and of themselves. Rather, the problem begins when typological units are treated as behaviourally meaningful analytical units, based on assumptions about the social, political, and economic relationships that underlie the categorical forms (Holland-Lulewicz 2021:538). From this perspective, things are immutable, locked into a state of being which potentially homogenises diverse histories of both people and artefacts.
The essentialist approach is pervasive among studies of stone artefacts, particularly in the way many studies privilege the form of artefacts and the way they were manufactured when making inferences about the past (for example, Bar-Yosef and Van Peer [2009] on predetermination of artefact form as it relates to socio-cultural evolution; or Parry and Kelly [1987] on how artefact forms reflect differing levels of mobility). Form refers to the morphology, dimensions, and attributes of artefacts, and manufacture the process of producing an artefact with selected or intended properties (Dibble et al. 2017; Rezek et al. 2020). The focus on form and manufacture is partly due to the assumption that individual stone artefacts represent intentional, finished products which often involved significant time and energy costs in manufacture (cf. Davidson 2002). This is evidenced by replicative experiments, which are common in lithic analysis (Dibble et al. 2017; Johnson 1978). The inferential leap that typically follows such experiments is that since the steps taken to manufacture a specific artefact form can be demonstrated, this reflects a causal link between some start and end states – initial raw material and finished object – which aids in reconstructions of the past. In this way, replicative experiments lead to an emphasis on manufacture in understanding technology and other behavioural phenomena such as social learning (Dibble et al. 2017:823-824).

However, in lieu of any critical scrutiny, replicative approaches result in a form of hindsight bias whereby the artefact seems inevitable since its creation can be traced back through time (Holdaway et al. 2015). This disregards a range of other processes that lead to the objects archaeologists observe in the present, such as post-depositional modification or change in form through use and resharpening (e.g., Davidson 2002; Dibble 1984). Hindsight bias is also related to the ‘fallacy of affirming the consequent’ in which it is argued that a particular set of conditions was responsible for patterning in past material since such conditions can produce those same patterns in the present (Wylie 1982:389-390). Inferential leaps based on preconceived ideas may also lead to multiple competing explanations for a particular phenomenon (equifinality), which raises questions about how to distinguish one explanation to the exclusion of others. It is important to separate the physical relationships identified experimentally from interpretations of past behaviour that resulted in the artefacts since while uniformity may be assumed in the former, the latter often reflects one of many processes that can result in the same outcome (Bailey 1981; Lin et al. 2018:681).

The ways in which stone artefacts and the assemblages they make up are currently conceptualised and explained are diverse. Yet at a fundamental level many are similar in that
they routinely regard stone artefacts as behaviour in and of themselves – that is, the form and manufacture of artefacts is thought to be directly reflective of the intention of people in the past (Dibble et al. 2017). Typologies, for instance, are often defined based on attributes of artefacts which are grouped into larger analytical units such as industries or technocomplexes. These units are then treated as manifestations of groups of people or even hominin species (Bisson 2000; Bordes 1961; Hilbert et al. 2017; Mellars 2005; Scerri 2013; Zilhão 2006). Similar reasoning applies to artefacts and assemblages interpreted in functional terms as models of adaptation (Rezek et al. 2020). ‘Points’, for example, may be defined as weapon tips according to their shape, or ‘scrapers’ named for their presumed functioning as such, though there is not necessarily a one-to-one relationship between form and function (e.g., Iovita and Sano 2016; Olszewski 2007). Assemblages of different artefact types in various proportions are then thought to reflect site function with reference to ethnographically derived models (see discussion in Holdaway and Davies 2020). This is despite studies suggesting the spatial association and frequency of artefacts in an assemblage is more reflective of discard behaviour and variation in use-lives, or is explained by sample size dependencies, rather than the existence of functional activity sites (e.g., Binford 1979; Phillipps et al. 2022a; Shott 1989; Wandsnider 2008). The assumption that artefacts are desired end products is also retained in more recent evolutionary explanations for variation in stone artefacts, such as cultural transmission and social learning (Eerkens and Lipo 2005). Different artefact forms and ‘traditions’ in manufacture are viewed as complex systems of cultural inheritance, where information is transmitted via social learning (Jordan 2014; Mesoudi and O’Brien 2008; Mithen 1994, 1999). The units of inheritance are the ideas regarding artefact attributes, not the physical objects themselves (Lycett and von Cramon-Taubadel 2015). Yet those units of inheritance are measured through the analysis of specific artefact traits (for example, flake scar patterning or overall shape) where similarities may be explained in terms of cultural transmission (e.g., Eren et al. 2015; Sholts et al. 2012; Turnes 2015). Thus, artefact traits are equated with cultural/behavioural traits (e.g., Jordan 2014).

Whether explanations be cultural identity/activity-related or similar, these are often problematic because stone artefacts can potentially undergo changes in form throughout their use-lives as they are reworked and resharpened (referred to as the ‘reduction thesis’ and ‘Frison effect’, e.g., Dibble 1984, 1987; Frison 1968), meaning the form of the artefact as observed by the archaeologist may bear little resemblance to that same piece of material at any other stage in its use-life, nor might they be intentionally shaped at all but rather the
result of post-depositional modification (Andrefsky 1997; Chase et al. 2009). This is significant because it suggests that typological and technological variability in stone artefacts is continuous, such that the construction of categories (be they cultural, functional, etc.) may simply be arbitrarily partitioning this variability and therefore in some cases may not hold any behavioural reality at all. Artefacts are seen as both the content of culture and the units with which to draw inferences about the social or evolutionary relationships between different groups, providing a means of achieving reconstructionist goals that are pervasive in the discipline.

2.2 Essentialism and Indeterminacy

Despite differences in terminology and method, whether approaches to lithics be about cultural affiliation, function, adaptation, or cultural transmission, all are similar in their treatment of artefacts as emblematic of some form of behaviour (Dibble et al. 2017). There are two interrelated consequences of essentialist approaches to archaeological interpretation which contribute to the indeterminacy issue: 1) material remains act as both data and interpretation; and 2) inferences do not adequately consider the temporalities and histories of artefacts, instead following what is referred to here as the ‘short time’ perspective. Each of these consequences are considered in turn.

2.2.1 Material Remains Act as Both Data and Interpretation

Stone artefacts are the consequences of human action, not human action in some intrinsic sense (Stern 2008, 2015). This distinction is significant because operating under the latter perspective results in the tautological treatment of stone artefacts as both data (units of analysis) and interpretation. For instance, consider the example of a stone artefact described in one manner as a *bifacially flaked object with lateral margins convex in shape and a total edge length of 80 mm*, and in another as a *broken projectile point*. Although somewhat contrived, the example demonstrates the difference between the observation of attributes and interpretation. The interpretation – broken projectile point – often becomes the unit of analysis or data for inferring, for example, the functioning of a location as a lithic workshop where the production of artefact forms occurred. The unit of observation is locked into a static category assumed to be real and analytically meaningful according to how archaeologists expect the past to behave (Jones 2012:7; Moore 2020:654). However, this treatment of artefacts creates a circular argument since data and interpretation are not
independent. As such, evidential claims by necessity conform to expectations since the outcome is predetermined (Chapman and Wylie 2016). Another example of predetermination is the use of Binford’s (1980) forager and collector model of hunter-gatherer land use. Though it is applied less as two dichotomous states and more as a spectrum (Barton and Riel-Salvatore 2014; Blair 2010), “by projecting it top-down onto archaeological data, there are high odds for circular reasoning in trying to fit the data to these predetermined categories and labels simply because they are known” (Rezek et al. 2020:907).

It is arguably the appeal to these ‘knowns’ that factors into the difficulty in distinguishing, for example, technological responses to constraints imposed by mobility, or determining whether an artefact was acquired via direct procurement from a source or through some mechanism of exchange (these examples are discussed further below). As noted at the beginning of this chapter, archaeological knowledge is typically generated by applying external theories to archaeological data – that is, theories derived from cognate disciplines such as the contemporary social sciences, or from lived experience, and not from within archaeology itself (Holdaway and Wandsnider 2006; Murray 2008; Rezek et al. 2020). Examples include the application of ethnographically observed exchange practices in explanations of the distribution of artefacts of different material types, or the use of modern functional tools as analogues for past stone tool use. Such behavioural phenomena are thought to be substantively uniform across different contexts – where past and present processes are uniform such that the present can be used to interpret the past (Bailey 1983, 2008) – leading to the conflation of data and interpretation (Rezek et al. 2020). Substantive uniformitarianism differs from methodological uniformitarianism, which “asserts a belief in the spatial and temporal invariance of general laws, essentially as a procedural principle for bringing past events within the scope of empirical investigation” (Bailey 1983:174).

With regards to mobility, an example of the distinction between substantive and methodological uniformitarianism is Close’s (2000) distinction between conceptual and archaeological mobility. Conceptual mobility refers to the ability to move and is based on assumptions about the contextual relationships between archaeological remains and mobility. These are often equated with or informed by ethnographically observed patterns of mobility. In contrast, archaeological mobility refers to actual human movement, as measured by the physical movement of objects from one point to another such as through refitting analyses or through proxies indicating occupation intensity/duration (Phillipps 2012:61-62). The use of materials and the archaeological consequences of processes like mobility vary according to
wider socio-natural contexts. Therefore, instead of using predetermined categories to interpret the archaeological record, archaeologists may be better served by taking “a ground-up perspective on the interplay between different processes of record formation…[using] external references from a theory that is uniformitarian in a methodological (as opposed to substantive) sense” (Rezek et al. 2020:907). This point is returned to towards the end of the chapter.

2.2.2 Short Time Perspective

Assemblages of material remains with immutable defined properties are often used to define cultural groups or site types. As Shott (2010:902) notes, the persistence of the ‘assemblage type’ concept is based in part on the projection of ethnographic data onto the archaeological record, linking to the implicit goal of much archaeological research to elucidate anthropological narratives about past peoples. This is what is meant by the ‘short time’ perspective. However, inferences about the past based on an essentialist treatment of material remains often struggle to reconcile interpretation with the variable temporalities and histories of those remains (Fowler 2013). The search for living/occupation floors or functional tool kits, for example, assumes the artefacts present were manufactured, used, and discarded over the course of a single event, and therefore assumes a degree of contemporaneity of the objects in question (Dibble et al. 2017; Holdaway and Wandsnider 2008). Yet this does not easily consider the potential changes in morphology and function artefacts underwent over the course of their use-lives due to processes such as resharpening, nor the differing rates of discard due to variable lengths of time over which artefacts were used prior to discard (e.g., Dibble 1984; Shott 1989). Therefore, assemblages of different artefact types with different life-histories do not necessarily reflect the “functional utility of a group of tools used at one particular instant but the outcome of combining many such scenarios through time. The pattern resides in the palimpsest, not the functional instant” (Holdaway and Wandsnider 2008:9, emphasis added).

The palimpsest concept relates directly to the temporality of the archaeological record. It is long recognised that the archaeological record is the product of a range of processes operating at different temporal scales (e.g., Bailey 1981; Binford 1981; Foley 1981). The concept of time perspectivism developed by Bailey (1983, 2007) states that time scales bring into focus different processes that are not necessarily visible at all scales, thus requiring a range of explanations (Bailey 2007). In this way, assemblages are multi-temporal records of human
activity (Bailey 2007; Lucas 2005). This is because the structure of the archaeological record is a palimpsest – an aggregate of the material products of past human action whose temporal resolution is typically coarser than that of the individual depositional episodes that contributed to its formation. In other words, the archaeological record more often than not reflects long-term trends in past human behaviour and is not necessarily separable into neat packages of discrete behavioural events.

Palimpsests are the result of time averaging. The time averaging concept is derived from palaeontology and articulated for archaeology by Stern (1993, 1994) as a disjuncture between the accumulation rates of sediments and the materials they envelop, such that an archaeological assemblage is an aggregate of materials derived from multiple separate events. Therefore, artefacts in the same assemblage and in the same depositional unit may never have operated together in the systemic context (sensu Schiffer 1972). This poses interpretive challenges particularly when attempting to generate inferences in terms of microscale processes (Perreault 2019). Importantly, time averaging does not imply that assemblages are average representations of the behavioural events or episodes that formed them (Stern 2008, 2015). For example, some infrequent activities might result in the deposition of a much greater amount of material than other more common activities, thus coming to dominate an assemblage. As Stern (2008:135) notes, an issue with “following through the logical implications of studying a time-averaged assemblage is that established analytical and interpretive procedures were not designed to deal with data characterised in this way”, requiring an alternative approach.

Despite awareness of the implications of time perspectivism and time averaging for archaeological interpretation, there is nonetheless a continued treatment of stone artefact assemblages as reflecting central tendencies in stone use as they formed over time through the deposition of material from succeeding occupations. While it is generally acknowledged that artefact assemblages tend to form over extended periods of time, Rezek and colleagues (2020) point out that interpretations usually remain unimodal, related to a single underlying cultural system, and in many instances are viewed as the sum of multiple cycles of manufacture and discard akin to the typical linear sequence outlined by Dibble and colleagues (2017:824, Figure 4), resulting in the deposition of many kinds of artefacts. However, there are several assumptions underlying this approach if the aim is to make inferences about behaviour at a specific time and place (Dibble et al. 2017). One assumption is that there is a degree of contemporaneity among objects in the assemblage. However, this
assumption is nullified by the palimpsest and time-averaging phenomena. A second assumption relates to the behavioural integrity of the assemblage – that the objects present were manufactured, used, and discarded in the same place. This assumption is the ‘complete reduction sequence fallacy’, where the artefacts present in an assemblage are assumed to represent the entire product of reduction sequences aimed at producing an intended product (Turq et al. 2013). However, many studies demonstrate how stone artefacts were often transported by humans into and away from the places where assemblages are located, such that the composition of a given assemblage may in fact be more reflective of activities occurring elsewhere (Dibble et al. 2017; Douglass et al. 2008; Holdaway and Davies 2020; Turq et al. 2013). A final assumption is the taphonomic integrity of the assemblage, such that the spatial distribution of artefacts reflects the distribution at the time of discard. However, this assumption may be invalidated by considering the range of natural formation processes that impact the accumulation of artefacts such as fluvial action, cycles of deposition and erosion, and animal activity (Dibble et al. 2017), as well as incidental human action such as trampling (e.g., Marwick et al. 2017).

The issues and limitations of a ‘short time’ perspective discussed thus far are demonstrated by a further example, derived from Davies and Holdaway’s (2017) investigation of late-Holocene land-use by Indigenous Australians. Based on measures of stone artefact movement, they showed how a pattern of regularity in land use emerged only with sufficient time elapsed. They analysed 93 surface stone artefact scatters of variable density occurring on a series of eroded patches of sediment along ca. 15 km of the Rutherfords Creek catchment in western New South Wales (for further context, see Appendix D). The cortex ratio was calculated for each scatter as a measure of artefact movement. Ratios above or below one reflect the movement of artefacts based on a deficit or surplus of cortex (outer surface of the rock formed by chemical and mechanical weathering processes) in an assemblage (the process for calculating cortex ratios is described further below). The movement of artefacts serves as a proxy for the movement of people in a methodologically uniform sense (cf. Close’s [2000] archaeological mobility).

Interpreted in isolation and as a synchronous unit, one might reason that a high-density accumulation of artefacts represents a prolonged occupation by a group of people, or perhaps a large gathering of people, with lower-density accumulations reflecting the opposite. In Australia, increases in the density and range of artefact forms in assemblages led to interpretations of greater sedentism among Indigenous Australians, thought to be a response
to drier and less predictable climatic conditions by investing more heavily in local resources (e.g., Smith and Ross 2008; Williams et al. 2015). Davies and Holdaway (2017) noted that the density of each accumulation of artefacts in their study area was positively correlated with the age of the surface on which they were exposed, determined through carbon dating of hearth charcoal and optically-stimulated luminescence (OSL) dating of sediments. The younger, less dense assemblages exhibited a greater variance in cortex ratio values with values ranging from close to zero to well above one. However, as the age/density of the surface assemblages increased, cortex ratios exhibited less variance, converging around a mean value of 0.53, reflecting overall a degree of artefact movement away from the area. The significance of this pattern is that while there appears to be local short-term variability, when viewed over the long term, accumulations of artefacts show remarkable regularities in place use (based on the convergence of cortex ratios and therefore similarity in the degree of artefact movement and by proxy human movement). Importantly, the pattern emerged only with enough time elapsed but also space – that is, processes were temporally variable across space such that patterning was inconsistent at a local scale, but the emergent pattern was visible at the landscape scale (Davies and Holdaway 2017).

The examples above demonstrate how the temporal and spatial scale of archaeological patterning often exceeds that directly related to individuals and their actions. A range of formation processes are implicated, such as the manufacture, repeated reworking and transport of an artefact, or the erosion and deposition of sediment which determines what artefacts are visible and whether surfaces are available to receive discarded artefacts. Understanding what kinds of processes lead to material organisation at a place through time (histories of accumulation) is therefore key, rather than the construction of linear narratives (Davies and Holdaway 2017).

2.3 Emergence

In his discussion of the temporality of the archaeological record, Olivier (2011:47) states:

The conventional approach to the archaeological past posits that history…is the only tangible identity of the past that artifacts express. It is widely believed that the past can be read from artifacts, and that this allows us to establish the reality of the past as it was; in other words, its historical identity.

But this is not at all so. There is no such thing as reading the past as it was…Its material remains come down to us truncated, or enlarged, or transformed, and we are at a loss to
distinguish what existed originally when the past was unfolding from the altered forms that evolved thereafter.

Olivier’s comment reinforces that the fundamental nature of the archaeological record is not one of a static, perfectly preserved record of behaviours as they happened in the past, but rather a generative phenomenon constantly in state of becoming that is not necessarily interpretable in terms of individual proximate processes. This idea developed over the course of several decades in archaeology, tracing its roots to formation studies and concepts such as palimpsests and time perspectivism (e.g., Bailey 2007).

Lucas (2012) reconceptualises the palimpsest in terms of the dual process of inscription and erasure, as opposed to the final product that archaeologists observe. This dual process operates between the two extremes of a true palimpsest, in which all previous material traces are erased upon deposition of new material, and a true stratigraphy, where material traces of activities are perfectly preserved in successive layers. Importantly, the palimpsest concept, and therefore inscription/erasure, is equally as applicable to objects or assemblages derived from a single distinct episode of activity as it is to deposits. Bailey (2007:208) refers to objects as ‘palimpsests of meaning’: “the succession of meanings acquired by a particular object, or group of objects, as a result of the different uses, contexts of use and associations to which they have been exposed”. He refers to assemblages as ‘temporal palimpsests’: assemblages of “materials and objects that form part of the same deposit but are of different ages and ‘life’ spans”, but part of the same episode of activity/deposition, like in Olivier’s (1999) example of the Hochdorf princely grave, a single, well-defined burial but a product of multiple instances of deposition of grave goods over time (Bailey 2007:207). Lucas (2012) builds upon the palimpsest concept further and links the process of inscription/erasure with the processes of materialisation and dematerialisation. These processes emphasise how objects come to be or cease to exist, as part of their very nature. A key point here, and one that is discussed further below, is that (de)materialisation switches the focus away from essential properties of things, as is common in much archaeological analysis, to objects as entities with histories and shifting associations (Lucas 2012).

The universality of the palimpsest concept brings to the fore the temporality and historicity of the archaeological record and material objects. While the archaeological record is the result of the long-term accumulation of material remains, archaeology is also of the present – that is, the material record archaeologists observe is situated in the present (Lucas and Olivier
2021; Olivier 2011). Olivier (2011) notes how the recent past and present are parts of a sequence that are added to the parts that preceded them, either by supplementing with new material or by transforming what is already there. Indeed, the past is “the very stuff of the present, at the same time that it holds, in the present, the seeds of what is to come, as surviving traces of what has been… [T]he world, as it appears to us and in its materiality, takes on new meaning, and its history reappears as potential memory” (Olivier 2011:85). Olivier goes further in conceptualising object palimpsests as ‘memory objects’ – material entities “in which the memory of a moment in time is recorded” (2011:132). That memory is unique to the moment it is recorded to the exclusion of others; paradoxically, memory is imprinted such that something else is forgotten or erased. Archaeologists deal in what has survived from the past, but that survival necessarily requires things having changed through processes of repetition and transformation (Lucas 2012:206-207). In this manner, history is now “a dynamic unfolding over time that is radically different from the time of conventional history” (Olivier 2011:85).

Here, parallels can be drawn with Lucas’ (2008) concepts of reversibility and irreversibility, which describe processes of material organisation. He notes how what archaeologists actually observe is surviving material organisation as opposed to surviving objects as ‘residues’ of an event, since some objects may have been involved in multiple events such that it is difficult to separate out sequences of those events (again, invoking the palimpsest). It is not trivial to state that many events will not leave any material trace. Of those that do, some will ‘erase’ previous events as if they had not happened. In this case material organisation is reversible, likened to a shelf of books where rearranging the order of those books erases evidence of the previous order (Lucas 2008). Change occurs easily in such assemblages, but leaves fewer material traces. Irreversible assemblages are composed of traces that are more persistent and difficult to change – analogous to traffic systems where the complexity of the material connections (signage, road markings, steering wheel positioning, traffic lights, etc.) would make shifting the side of the road driven on a major task. Lucas (2008) suggests the archaeological record is composed mainly of objects from assemblages that are irreversible – the results of reinforced and repeated patterning that are more likely to persist than those of ephemeral activities.

The concepts discussed in the preceding paragraphs – palimpsests, memory objects, temporality, historicity, reversibility, each of which speak to the very nature of the archaeological record – all relate to the notion of emergence. Simply put, the archaeological
record is a generative record. The material organisation witnessed in the patterning of the archaeological record is not simply the outcome of human or natural processes transforming the material products of some initial cultural system, since this essentialist view implies there existed at some point a ‘pristine’ record of a cultural system to be transformed (Davies and Holdaway 2017). Instead, the archaeological record is the outcome of many individual actions through time, and as such is constantly in a state of becoming (Bailey 1983; Binford 1981; Lucas 2012; Olivier 2011). Hence, the material organisation at the point of observation is the phenomenon to be explained.

The notion of emergence bears many similarities to complexity science. Human systems are examples of complex systems (Gifford-Gonzalez 1991), involving networks of lower-order individual actions that result in emergent and self-organising behaviour or patterning (Epstein 2006:31-33; Kohler 2012). Significantly, the process of emergence is non-linear, and the resultant patterning is difficult to predict based on the individual system components alone. Thinking about the archaeological record, this means explanations of the observed patterning cannot be separated from the formational processes that generated it (Davies 2016:64) nor may individual processes necessarily be discernible or ‘filtered out’. As stated above, understanding the forces that operate through time and that lead to the observed patterning at a place at a given point in time has precedence over constructing linear narratives (Davies and Holdaway 2017). This does not work with an essentialist approach since nothing is assumed a priori.

To summarise, appeals to essentialist notions, ethnographic analogues, and even actualistic studies cannot adequately explain an archaeological record that is a contemporary phenomenon constantly in a state of becoming, with a temporality that exceeds that of the explanatory mechanisms typically employed. The emergent nature of the archaeological record suggests it is not reducible to its individual formational components and therefore, it cannot necessarily be studied in terms of proximate processes or essentialised descriptions since doing so leads to underdetermination of any inferences generated at best, or at worst, incorrect statements about the past (Perreault 2019).

2.4 Towards Tackling Indeterminacy

The notion of artefacts as both data and interpretation and a ‘short time’ perspective are both interrelated consequences of essentialist approaches to archaeological interpretation which are direct contributors to the indeterminacy issue. Considering the problem through the lens
of essentialism suggests a way of addressing the indeterminacy issue lies in rethinking the fundamental way in which artefacts and assemblages are conceptualised in other than essentialist terms. As Assaf and Romagnoli (2021:284) suggest, “the remoteness of time tends to preclude non-technological considerations [when studying lithic artefacts]; therefore, lithic studies are mostly conceived in techno-typological and economic terms, creating a most probably false distinction between objects and their meanings”. A range of scholarship in the last decade interrogates the concepts of linear manufacture sequences and intentional end products in lithic analysis while highlighting the important role of selection, reuse, and variable life histories of lithics in shaping assemblage composition. However, the persistence of the essentialist approach suggests further exploration is warranted (e.g., Dibble et al. 2017; Holdaway and Douglass 2012; Holdaway and Phillipps 2021; Hussain and Will 2021; Iovita et al. 2021; Rezek et al. 2020; Turq et al. 2013).

A way to think about lithics in other than essentialist terms is through the concept of materiality. Discussions of materiality are increasingly common in archaeological discourse (Harris and Cipolla 2017). Broadly speaking, materiality encompasses a suite of approaches that advocate understanding and interpreting material remains in terms of the relations or associations that compose them, rather than in terms of essential properties (Alberti 2016; Fowler and Harris 2015; Govier and Steel 2021; Harris and Cipolla 2017:4; Lemke 2015; Witmore 2014). As such, focus is shifted away from passive objects that simply represent human behaviour to material objects as active in making a difference in the world. Material objects are entities with histories that both shape and are shaped by events in which they are involved (Fowler 2013; Hussain and Will 2021). Entities have no stable essences but rather are contextually and historically contingent (Lucas 2012).

Materiality has received comparatively less attention in lithic analysis than in archaeology more generally, particularly when interest lies in the deeper past (Assaf and Romagnoli 2021; Hussain and Will 2021). However, Holdaway and Phillipps illustrate what such an application means for lithic studies:

Artefacts, both individually and as groups, need not derive interpretation as forms solely manufactured for a particular purpose. Rather, materialisation is emphasised with relations among objects and people continually made and unmade… This leads to a different form of historical narrative, one based on artefact use-life histories…[A]rtefact identity comes from relationships among entities rather than the entities themselves. (2021:144)
Thinking about artefacts and assemblages from a materialist perspective allows that things are always in a state of becoming, their meanings and associations in a constant state of flux. From this perspective, views of the lithic record that privilege techno-morphological attributes of stone artefacts are no longer so informative (Iovita et al. 2021). Across their shifting associations, stone artefacts acquire a variety of attributes of which their current context is only one (Rezek et al. 2020). Focusing less on the manufacture of specific artefact forms and more on processes like (de)materialisation, reuse of stone material emerges as a key component of artefact life-histories and assemblage accumulation, and the changing associations they undergo.

Reuse of previously discarded material is long recognised by archaeologists (Amick 2007, 2015; Barkai et al. 2015; Camilli and Ebert 1992; Coco et al. 2020; Dibble et al. 2017; Holdaway and Douglass 2012; Rezek et al. 2020; Schick 1987; Turq et al. 2013; Vaquero 2011). Ethnographic accounts of various stone-using groups from places such as Namibia (e.g., McCall and Horowitz 2015), Papua New Guinea (e.g., Sillitoe and Hardy 2003; White and Thomas 1972) and Australia (e.g., Binford and O’Connell 1984; Gould et al. 1971; Hiscock 2004; Horne and Aiston 1924) demonstrate how selection of previously discarded artefacts was a key component of the acquisition of lithic material, and was often more common than the intentional production of particular artefact types or retouched tools that typically form the focus of lithic analysis. Such accounts suggest in many cases, suitable artefacts were simply those with an appropriate amount of usable edge. For instance, White and Thomas (1972) observed that the Duna-speaking people of the New Guinea Highlands did not distinguish between artefact ‘types’, but rather selected an object for a task if it possessed features suitable for that task. Similarly, Tindale (1965), upon collecting retouched tools in Australia, was instead supplied with primary flakes by a Ngadadjara man as they were considered more useful than ‘worn’ retouched tools (a point also suggested through the experimental work of Clarkson and colleagues [2015]). These ethnographic accounts highlight the temporal disjuncture between initial artefact production and subsequent selection and reuse. As Dibble and colleagues (2017) point out, this means that the person or people responsible for the final discard of an artefact need not necessarily be the same one(s) responsible for its manufacture, nor does it mean that people necessarily sought out or returned to geological raw material sources once artefacts in their possession had no utility remaining (however utility is defined). In contexts of use, lithic artefacts materialise as
Despite awareness of lithic reuse as a significant component in artefact accumulation histories, the implications and relative impacts for interpreting lithic assemblage patterning are often underappreciated (Amick 2007; Turq et al. 2013; Vaquero 2011). This is attributable in part to the historic emphasis on the role of manufacture in lithic analyses (Dibble et al. 2017), but also due to the difficulty of empirically identifying reuse behaviours archaeologically. For instance, many researchers turn to the identification of double patina on artefacts as hard evidence of reuse, since patinas require time to form. However, patina can be difficult to identify and can lead to overlooking other artefacts that were reused yet do not possess a double patina (Amick 2007).

Nonetheless, the process of lithic reuse calls into question linear conceptual models of stone artefact production that underlie many lithic analyses (e.g., as represented in Dibble et al. 2017: Figure 4). This is reflected in Turq and colleagues’ (2013) analysis of various Middle Palaeolithic assemblages from Western Europe, which suggests Neandertals chose to reuse already discarded artefacts and transport a wide variety of artefact forms, including unretouched flakes, which were chosen based on selection criteria different to those often assumed by lithic analysts. These observations are in line with Holdaway and Douglass’ (2012) suggestion that the artefacts people produced and used were determined more by context than procedural knapping rules. This points to the ‘fragmented’ nature of lithic reduction across the spatial, temporal and social domains, where material may be picked up, worked and used at different places, at different times, and by different people (Bleed 2002; Turq et al. 2013). Furthermore, in a recent study Coco and colleagues (2020) presented an agent-based model which simulated the production and reuse of lithic artefacts by two independent, technologically divergent populations. The populations acquired lithic material from existing deposits, the visibility of which was governed by simulated processes of sediment deposition and erosion. The results of the model demonstrated that ‘transitional’ stone industries such as those that occur across the Middle-Upper Palaeolithic boundary could be explained as by-products of long-term scavenging and reworking of artefacts acquired from visible archaeological deposits (Coco et al. 2020).

A further example of the exploration of reuse is Holdaway and Phillipps’ (2021) study from Aotearoa in which they question common fixed material culture categories and explore
indigenous Māori concepts for alternative interpretations of archaeological objects. In their two study locations, they found the distribution and use intensity of stone artefacts derived from various geological sources did not match predictions based on simple economic relationships between technology and distance to source. Rather, approached in terms of materialisation, the patterning in the lithic accumulations was structured by a complex history of artefact use, a significant component of which was the deposition of artefacts creating new sources from which material was subsequently acquired and reused. Thought of in this way, inconsistencies in the flaking of materials from different geological sources is not surprising, since appeals to linear reduction sequences and notions of economic efficiency (which, the authors note, is a western model) fail to consider varied histories of interactions among people and materials (Holdaway and Phillipps 2021).

Materiality therefore provides a way to think about accumulations of stone artefacts in other than essentialist terms, in a way that is open to the emergent properties of the archaeological record. The materialist perspective suggests archaeologists may be better served by analysing material remains in such a way that limits assumptions as much as possible and builds analysis from the ground-up. Holbraad (in Alberti et al. 2011) suggests a starting point for analysis is evaluating and questioning common assumptions which creates a space for redefining relationships with things. Similarly, others suggest the need to reconceptualise archaeological remains as “fragments situated in enchained networks of practice” where knowledge is built from the bottom-up, and what is of interest is the shifting associations between entities (Jones 2012:19; Lucas 2012). Emphasising processes like Lucas’ (2012) (de)materialisation brings to the fore how relations between people and objects are constantly changing, thus leading to a different form of historical narrative (Holdaway and Phillipps 2021; Lucas 2012).

The remainder of the chapter considers two common ways of inferring mobility from the lithic record which are used as examples for addressing the indeterminacy issue: sourcing studies, and the analysis of technological organisation. A brief intellectual history of each is sketched out, drawing attention to the impact of indeterminacy, before considering the implications of a materialist view of the lithic record in each case. The foundation for a method of addressing indeterminacy is then provided by way of introduction to the case studies in the chapters that follow.
2.5 Mobility, Lithics, and Indeterminacy

Mobility is fundamental to the way people use and interact with the landscapes they inhabit, and to mitigating spatial and temporal variability in access to resources necessary for survival (Grove 2009; Morales et al. 2009). Mobility is also implicated in the trade and exchange of objects and ideas, facilitating social interaction and economic practice (e.g., Calvo et al. 2011; Dallos 2011; Frachetti 2012; Kahn 2013:249; Kelly 1991; Sahlins 2004:33). Therefore, mobility is a common subject of archaeological enquiry (e.g., Barnard and Wendrich 2008; Binford 1980; Close 2000; Kahn 2013; Kelly 1992; Kuhn et al. 2016; Sobkowiak-Tabaka et al. 2022), marking it as a useful topic with which to explore the issue of indeterminacy.

The focus on manufacture and form in lithic analysis is particularly evident in studies of mobility. Two common ways of inferring mobility from the lithic record that emphasise the manufacture and form of artefacts include 1) the geological sourcing of stone artefacts; and 2) the study of technological organisation and the way in which different attributes of stone artefacts relate to mobility strategies. In the former, mobility is implicated in the way stone material is moved from its geological origin to the place where it is found by archaeologists, through measures such as distance to source and inferred processes such as trade and exchange or direct/indirect procurement (e.g., Hughes 2011; Nash et al. 2013; Renfrew 1969; see also examples in Kuzmin et al. 2020). In the latter, the structure and composition of assemblages of artefacts with particular attributes is related to different mobility strategies through principles of optimisation (for example, producing the maximum amount of cutting edge per unit of mass or producing tools that are multifunctional) and through functional site types that relate to wider settlement pattern (e.g., Bleed 1986; Nelson 1991).

2.5.1 Mobility and Sourcing

Modern replicative experiments along with ethnographic observation of the production of specific artefact forms (e.g., Binford and O’Connell 1984; Stout 2002) are the historical basis for assumptions about stone artefacts as intentional or desired products of the artefact production process. As Dibble and colleagues (2017) note, a consequence of this assumption is the conceptualisation of a linear, procedural manufacture process, the reconstruction of which characterises much of the literature such as studies focusing on lithic chaînes opératoires or reduction sequences (e.g., Bar-Yosef and Van Peer 2009; Shott et al. 2011; Tostevin 2011). This linear process begins with raw material acquisition, followed by core
preparation and the production and retouch of different kinds of flakes, resulting in the desired end product (e.g., Figure 4 in Dibble et al. 2017).

The common perception in lithic studies is that the first step of the manufacture process – raw material acquisition – involves the procurement of unworked pieces of rock gathered from a naturally-occurring geological source, such as an outcrop or gibber plain. It is often assumed that when in need of a stone artefact for some purpose, people would begin the manufacture process anew, returning to a geological source to acquire a new block of material to manufacture a new tool (Dibble et al. 2017). For decades, archaeologists have used a range of methods to determine the geological source of lithic raw materials such as volcanic rocks and silicates quickly and reliably (Sheppard 2004). The spatial separation of the geological source and the location where an artefact is found forms the basis for many common inferences about mobility, the relative extent of which depends on the distances involved (e.g., Hughes 2011, 2018; Smith and Harvey 2018).

Archaeological interest in sourcing lithic materials stems from the seminal work of researchers such as Renfrew (1969, 1977). Drawing on the economic anthropology of the time, Renfrew sought to quantitatively define lithic acquisition strategies and socioeconomic systems in his European case study by plotting the abundance of obsidian artefacts against distance from the geological source of those artefacts. The result was a series of distance decay curves that he related to different forms of acquisition and mechanisms of exchange (e.g., Renfrew 1977). This supported his statement that “it is clear that the application of the techniques of locational analysis to archaeological materials promises a deeper insight into the working of prehistoric economic systems (Renfrew 1969:157; see also Earle and Ericson 1977).

In the years since, understanding the geological sources of lithic raw materials has become important for explaining lithic assemblage variability (e.g., Andrefsky 1994; Clarkson and Bellas 2014; Ditchfield and Ward 2019; Doelman et al. 2001; Kuzmin et al. 2020; MacDonald 2008; McAnany 1988; Roth and Dibble 1998; Torrence et al. 2013; Will and Mackay 2017). Because it is possible to identify the geological origin of lithic materials, this property becomes essentialised in a similar fashion to how the ability to replicate the manufacture of artefacts leads to a focus on artefact form. Studies that draw on lithic sourcing tend to emphasise one of two ideas. The first is the distinction between local and non-local geological sources of material, which plays into inferences surrounding mobility and
What defines whether a geological source is local or non-local varies between studies, likely due to wider contextual factors such as geological source density and transport technology. For instance, in Aotearoa/New Zealand McCoy and colleagues (2010) distinguish ‘local’ from ‘long distance’ sources, the latter located at distances of almost 300 km from a given site, whereas Walter and colleagues (2010) consider local geological sources as within a range of 500 km. In their Great Basin USA study, Jones and colleagues (2003) consider ‘extra-local’ geological sources as beyond 150-200 km from a site; similarly in their Patagonia case Rindel and colleagues (2020:3) consider geological sources within 150 km of archaeological sites as “geographically close”. In Australia, Ditchfield and Ward (2019) define ‘non-local’ geological sources as those beyond 10 km from their study sites in the north-west, whereas in his case study in eastern Australia Shiner (2006:188), following Dibble and colleagues (1995:261), defines ‘local’ sources as “those that could be sourced within the immediate vicinity of the assemblage” with ‘non-local’ materials requiring “some amount of travel to procure”. While definitions of local and non-local geological sources vary, inferential paths with regards to mobility tend to be similar. For example, long distances between a geological source and the location where an artefact is discarded are often interpreted as either an indicator of mobility over great distances (e.g., Jones et al. 2003; Smith 2010) or as evidence of trade or exchange (e.g., Newlander 2012; Newlander and Lin 2017), both of which are processes documented ethnographically (Hughes 2011). While both interpretations are related to mobility, the relative magnitude of mobility differs in each. As Hughes (2011) suggests, these interpretations may be rooted in a problem of scale, where it seems reasonable to suggest materials found close to a geological source were procured directly, whereas for those located hundreds or thousands of kilometres away from the parent source, indirect procurement through trade and exchange seems more feasible.

A second related concept often emphasised by sourcing studies is the availability and accessibility of different geological sources of material. Raw material availability (in terms of abundance, distribution, and quality) factors in arguments about the use of lithic materials and mobility strategies based on economising models, where people try to maximise the utility or use life of an artefact while minimising costs such as time, risk, and energy, discussed further below (e.g., Andrefsky 1994; Bamforth 1986; Nelson 1991; Torrence 1983; Shott 1986; Wilson 2007). More pertinent here is that changes in geological source representation and use in lithic assemblages is also often interpreted in terms of territoriality
or restricted access to sources. For example, in Aotearoa many studies of pre-European contact Māori settlement and interaction networks draw upon the relative proportions of Tūhua (Mayor Island) obsidian in archaeological assemblages. Tūhua is one of over twenty unique sources of obsidian all located in northern Aotearoa. The relatively high proportion of Tūhua obsidian in early assemblages throughout the country is generally thought to reflect initial unrestricted access to the geological source. Later in time there is a decline in the proportion of Tūhua obsidian in assemblages located greater distances from the geological source (Green 1964; McCoy et al. 2014; Walter et al. 2010), a shift roughly correlated with the construction of major earthworks and pā (defended settlements), interpreted as increasing regionalisation of source use. These patterns are often explained in terms of direct or indirect access to geological sources, which factors into arguments surrounding trade and exchange, communication networks, and territorial circumscription (e.g., Brown and Pitman 2019; Ladefoged et al. 2019; Lawrence et al. 2014; Leach 1978; Moore and Coster 2015; McCoy and Carpenter 2014; McCoy et al. 2014; Walter et al. 2010). Seelenfreund-Hirsch (1985), for instance, suggested the linear distance decay trend observed for Tūhua obsidian implied direct access to the geological source. Walter and colleagues (2010) explored the relationship between Tūhua obsidian use and distance from Tūhua, noting a lack of economising behaviour at sites located closer to Tūhua (expressed as similarities in core size and large proportions of unused flakes) and more efficient use of Tūhua obsidian at sites located further away. They suggested this reflects increasing value placed on Tūhua obsidian as access to the geological source declined due to changes in social networks.

While there is no question that processes such as trade and exchange, territorial circumscription or mobility regimes involving variable distances were in operation at different times and places in the past, inferences about mobility based on sourcing artefacts need to be assessed in relation to indeterminacy. It has long been recognised that measures of distance to geological source only provide an indication of the minimum distance artefacts moved (e.g., Kelly 1992). Understanding the various vectors by which an artefact moved from its geological origin to the place it is recovered archaeologically remains difficult (Freund 2013; Hodder 1984; Smith and Harvey 2018). As Jackson and Ericson (1994:402) note, “one of the most perplexing issues regarding exchange in the context of distributional studies has to do with determining whether groups acquired commodities directly (as in direct access at a quarry) or indirectly by exchange. In many cases, it seems the answer is simply “yes” to both prospects”. This is a clear issue of equifinality – several different processes
might explain how an artefact moved from point A to B (e.g., Brantingham 2006; Close 2000; Graeber and Wengrow 2021:23-24; Hodder 1974, 1984; Hughes 2011:7; Kelly 1992; Smith and Harvey 2018). Further contributing to the indeterminacy issue is that often, the distribution of material deriving from different geological sources is conflated with the processes that led to that distribution, such that one phenomenon is used as a proxy for another, making it difficult to evaluate any subsequent interpretations. As Hughes (2011) notes, insofar as his Great Basin context is representative of other parts of the world, it is not surprising that archaeologists focus on trade/exchange or direct access to raw material sources as explanations for observed archaeological patterning since these are prominent amongst the ethnographic literature; however, while these are useful concepts for thinking about mobility and movement of material, Hughes (2011) cautions against the temptation to directly apply these as behavioural explanations.

2.5.2 Mobility and the Organisation of Technology

Many mobility studies draw on Binford’s (1978, 1980) forager and collector modes of resource acquisition and associated residential and logistical mobility strategies, in which functional site types link settlement pattern and mobility. Binford’s models were quickly adopted as direct explanations for archaeological patterning and were linked with ideas drawn from behavioural ecology and optimal foraging theory (Blair 2010; Surovell 2009:9-10), from which the study of lithic technological organisation (LTO) developed. LTO provides a framework for understanding how the structure and composition of stone artefact assemblages are related to constraints imposed by a cultural system, such as mobility (e.g., Kelly 1983; Nelson 1991; Shott 1986).

The optimisation of technology is often investigated with reference to artefact design (Nelson 1991). Artefact design is viewed as a strategy for dealing with spatial and temporal variation in resource distribution (Odell 1996; Barton 1997), such that modifying the design of an artefact can improve its performance in solving technological problems (Hayden et al. 1996). It is assumed that similarities in design reflect similarities in adaptive response to constraints imposed by the environment and cultural system (Odell 2001). So, in the context of evolutionary ecology, design theorists assume that as costs associated with performing a given task increase, people should invest more time and effort into tool designs that reduce costs for that task, helping to achieve returns above minimum requirements (Bleed 1986; Clarkson 2007).
Design theory postulates several different aspects of utility that contribute to variability in artefact form and assemblage composition. For instance, Bleed (1986) distinguishes between reliable and maintainable design alternatives, where reliable designs can be counted on when needed, and maintainable tools can be made to function when broken or not fully suited to the immediate task, which incorporates flexible and versatile (Nelson 1991; Shott 1986) or multifunctional (Hayden et al. 1996) designs. As such, more mobile groups may be expected to use multifunctional, maintainable tools with the most functionality per unit mass. In contrast, more sedentary groups may use single-function, reliable tools with less concern about function-mass efficiency (Bleed 1986; Nelson 1991). These differences are often framed in terms of more curated versus more expedient technology (Binford 1979; Shott 1996).

The differential proportions, quality, and treatment of raw material in assemblages is often thought to relate to the degree of mobility. For instance, it is often assumed highly mobile groups have access to more distant sources of material, whereas lower levels of mobility would lead to greater use of local sources (Close 1996:550; Surovell 2009). Jeske (1989) suggested that in situations where quality raw material is scarce (where ‘quality’ typically refers to the ease and predictability with which the material can be flaked) or the distance to raw material sources is great, raw material will be worked in the most optimal way. In cases where raw material is abundant, the need for efficient use of material would decrease since there would be no pressure to overcome potential future raw material limitations (Andrefsky 1994; Odell 1996; Parry and Kelly 1987).

The reasons for the rapid uptake and continued use of Binford’s (1980) residential-logistical model of group mobility lie in the relative ease with which they are relatable to visible archaeological data. Different site types expected under residential or logistical patterns relate to mobility which in turn relate to the kinds of artefacts that should be present. Nelson (1991), for instance, distinguishes residences/base camps and limited activity sites based on assemblage composition. At base camps, there is time to work on tool manufacture and maintenance, therefore all products of manufacture should be present. This contrasts with places where extractive activities occur and where comparatively little time is spent, such that retouch flakes or broken pieces from a transported toolkit would be present.

However, Nelson (1991) also notes that material consequences of a given mobility strategy are likely to be highly variable depending on the specific situation. There are a wide range of
technological strategies that may be employed for overcoming constraints yet no one strategy appears unique as a response to a given constraint. Assumptions about efficiency of use such as those underpinning LTO separates artefacts from the socio-natural contexts in which they were used (Rezek et al. 2020). The result is that the same set of observed attributes of artefacts and assemblages often lead to contrasting interpretations. For instance, Kuhn (1994) argues that carrying several small, finished artefacts is the most efficient way of transporting a useable cutting edge for mobile groups, yet Morrow (1996) argues the opposite, suggesting the transport of a smaller number of larger artefacts is the more economic strategy. Further, efficiency is likely to be context dependent. For instance, Parry and Kelly (1987) suggested highly mobile groups could not anticipate future tasks or raw material availability, and therefore required multipurpose tools that maximised utility per unit weight. They suggested bifaces, as they could act as both tools and cores. However, Prasciunas’ (2007) experimental work suggested bifacial cores did not necessarily produce more usable flake edge than other artefact forms, suggesting some other reason for the use of bifacial cores aside from flake production efficiency. Indeed, retouched, ‘finished’ artefacts may not even feature greatly in lithic assemblages at all. Douglass and colleagues’ (2008) investigation of late-Holocene stone artefact assemblages in Australia noted a comparative lack of retouched tool technology, with highly mobile groups instead opting to ‘gear up’ with ‘expedient’ flakes, since it could be shown that these were the types of artefacts removed from the study area by people in the past and not returned. Similarly, Turq and colleagues (2013) found that Neanderthals in western Europe transported a range of artefacts including small flakes, rather than only ‘finished’ retouched tools. Therefore, understanding artefact use, and by proxy mobility, requires a consideration of all components of an assemblage rather than solely those forms deemed to reflect intentional design choices.

2.6 Lithics and Mobility from a Materialist Perspective: The Case Studies

Thinking through materialist concepts brings to the fore processes such as the reuse of lithic artefacts which disrupts linear sequences of manufacture and use, with implications for the association of site types or mobility strategies with lithic reduction intensity, and behavioural inferences based on access to geological sources of material. Materialist concepts also provide a set of ideas for thinking through the analysis of lithic artefacts in a way that addresses the issues raised with regards to indeterminacy. The question of how to operationalise such an analysis is addressed in the overview of the case studies that follow.
2.6.1 Mobility and Sourcing

Often in lithic analyses the geological source of an artefact and associated properties relating to raw material are essentialised, forming the basis for interpretations of mobility based on the distance to the geological source. The relative size of these distances is then linked to procurement behaviours either directly from the source, or indirectly via processes such as trade and exchange. These in turn serve as the basis for inferences surrounding social interaction, territorial behaviour, and changes in communication networks. A key assumption in constructing these inferences is that people returned to a geological source when in need of lithic raw material. However, if raw material procurement is thought of from a materialist perspective, where the geological attribution of an object is no longer an essential property, lithic objects are conceived as undergoing a constant process of (de)materialisation as they are transported and used as functional objects by people before being discarded to form accumulations which, when made visible by local geomorphic processes, materialise as sources of raw material for the same or indeed different people to use in the future. This confounds the notion of fixed raw material sources, blurring local/non-local source distinctions and suggesting material acquisition may occur in the absence of any interaction between users.

The implications for the study of mobility lie in the varied ways material moved from a geological source to where it is found archaeologically over the course of one or more successive transport episodes, and the ability to distinguish between alternative transport mechanisms. Discarded artefacts create new sources of raw material at places in-between the geological origin and archaeological location of those artefacts. It is the significance of these ‘in-between’ places for patterning in archaeological distributions of stone materials that is explored in the first case study.

As noted above, the focus on the geological source of an artefact as an essential property often leads to the conflation of the distributions of artefacts of given material types with the processes that led to those distributions (Hughes 2011). However, if essentialist assumptions about the geological source and indeed, the production and use of (intentional) artefact forms are removed, it is possible to explore the effects of simple foundational processes of lithic acquisition, discard, and reuse on the distribution of artefacts deriving from different sources. Importantly, studying mobility requires an understanding of the interaction of these basic processes through time and over spatial scales exceeding those of individual assemblages or
sites. Agent-based simulation provides a method for achieving this, allowing a researcher to explore ideas drawn from relevant theory, with the results of that exploration serving as hypotheses that can be independently tested with empirical archaeological data (the conceptual and methodological background of this agent-based modelling approach is discussed further in Chapter 3).

The case study on mobility and sourcing is presented in Chapter 4 and explores the outcomes of a simple agent-based model that tests the assumption that people always returned to a geological source when in need of stone material, and the subsequent implications for inferences about mobility. Stone material deriving from different geological sources is discarded by simulated groups as they move around a landscape. These groups either always acquire new stone material from a geological source when in need (the essentialist perspective) or will first acquire material from visible accumulations of discarded artefacts – those ‘in-between’ places (based on the materialist perspective). Each of these produces patterning in the spatial distribution of stone material deriving from different sources which is tested using data on archaeological distributions of obsidian in Aotearoa.

There are several reasons why Aotearoa is an ideal case study for exploring the implications of discarded artefacts as sources of raw material. The chronology of occupation is limited to a few centuries, with East Polynesian ancestors of Māori arriving in the late thirteenth century AD (Jacomb et al. 2014). The country is a relatively isolated archipelago, providing natural bounds for the movement of stone material. Major stone sources, particularly obsidian, are well known, and upon arrival people had to discover these sources before extracting material and distributing it around the country (Figure 2.1). These conditions are advantageous compared to other locations where several thousand years of human occupation, artefact discard, reuse, and import and export of material have created artificial lithic landscapes (e.g., Foley and Lahr 2015) which make it difficult to determine the influence of anthropogenic creation of sources of material on assemblage patterning.
Figure 2.1 Geological sources of obsidian on Te Ika-a-Māui (North Island) of Aotearoa New Zealand. Red dots mark the location of assemblages analysed in Chapter 4, a complete list of which is provided in Appendix A.
Another advantage is the availability and widespread use of obsidian, the geological sources of which can be quickly and reliably determined using geochemical methods (McCoy and Carpenter 2014; Sheppard et al. 2011). As noted earlier in this chapter, obsidian has featured heavily in inferences about the development of social and exchange networks in Aotearoa (e.g., McCoy et al. 2010; Walter et al. 2010) since it appears in the earliest assemblages and is found in archaeological deposits throughout the country. There are 27 geological sources of obsidian in Aotearoa occurring only on Te Ika-a-Māui (the North Island) or its smaller offshore islands (Seelenfreund and Bollong 1989; Sheppard 2004; Figure 2.1), meaning it was transported great distances to the far corners of the country and places in between. Most obsidian artefacts are unretouched flakes, cores, and to a lesser extent, informal tools (Sheppard 2004; see also observations in Holdaway and Phillipps 2021:151-152). Ladefoged and colleagues suggest “this informal nature is analytically advantageous because social factors and matters of expediency might have often played more significant roles than the quality of obsidian in choosing source material” (2019:2). Additionally, obsidian is an inherently reusable material since it flakes easily and produces a very sharp edge, such that even small pieces may retain some usability (Elston 1990:156; Kelly 2011:192; Maning 1875; McAnany 1988:8).

2.6.2 Mobility and the Organisation of Technology

Essentialising the manufacture process and the form of stone artefacts leads to assumptions about what different types of artefacts, and accumulations thereof, represent in terms of mobility. However, the relationship between such observations and mobility strategies are shown to vary according to the wider socio-natural context (as exemplified by debates about mobility and tool size efficiency, for instance). As discussed above, part of the issue is how the essentialist treatment of artefacts conflates data and interpretation. Lessons from thinking through a materialist perspective, however, suggest archaeologists are better served by avoiding imposing meaning onto the form and manufacture of stone artefacts in an *a priori* manner, and instead they should approach them in a way that leaves open the varied histories of associations into which artefacts entered and exited. From this perspective, analysis should proceed in a way that limits essentialist assumptions and builds inferences from the bottom-up.

With regards to mobility, one way is to employ analytical techniques that are methodologically rather than substantively uniformitarian, in line with Close’s (2000) notion
of archaeological mobility where, rather than being treated as direct manifestations of behaviour (such as a ‘maintainable’ design representing a higher level of mobility), artefacts instead serve as proxies for mobility by identifying the physical movement of artefacts. The principles of ‘geometric approaches’ demonstrate this point. Geometric approaches in stone artefact analysis depart from essentialist notions about artefact form and function and instead draw upon principles of geometry and fracture mechanics to quantify the physical separation of products of stone reduction, through either the supplementation or loss of material from an accumulation of artefacts. In this way they do not rely on understanding precise manufacture sequences, nor are they concerned with the morphology or typology of intended products. This breaks the interpretive process down to a more fundamental level than other methods of lithic analysis (Holdaway and Davies 2020).

An example of a geometric approach is the cortex ratio, introduced briefly earlier in this chapter. Originally developed by Dibble and colleagues (2005), details of its rationale, calculation and validity are widely published (e.g., Douglass and Holdaway 2011; Douglass et al. 2008; Holdaway et al. 2012; Lin et al. 2010). The cortex ratio compares the observed amount of cortex in a collection of artefacts with how much cortex is expected to be present based on the average size of raw material nodules and the number of cores (one core representing one raw material nodule). When the amount of observed and expected cortical surface is expressed as a ratio, a value of one suggests no artefact movement since there is no difference between the observed and expected amount of cortex. A ratio below or above one indicates a deficit or surplus of cortex respectively, and therefore indicates the movement of artefacts. The method is applied in a range of temporal and geographic settings such as Middle Palaeolithic Morocco and France (Dibble et al. 2012; Lin et al. 2015), Middle-Late Stone Age and late Holocene Southern Africa (Davies et al. 2022; Lin et al. 2016a), mid-late Holocene Egypt and North America (Holdaway et al. 2010b, 2015; Neeley and Lee 2020; Phillipps 2012), and late Holocene Australia and the Pacific (Ditchfield et al. 2014; Douglass 2010; Douglass et al. 2008). The ability to quantify the physical separation of products of stone reduction (and therefore, human movement) rests on a set of simple assumptions based on uniformitarian principles: that there is a fixed relationship between the surface area and volume of a three-dimensional solid (which in the method acts as a proxy for original raw material nodule shape); that flaking is a reductive process so cobbles can only lose mass (and surface area and volume); that surface area and volume are lost at different rates depending on the shape of the nodule and the flaking strategy used; that an artefact can only exist in a
single spatial location in the archaeological context even though it may have moved over the course of its use-life; and that accumulations of artefacts can be supplemented or depleted by the movement of artefacts to or from a given location (Phillipps 2012:115).

In discussing knowledge construction in lithic studies, Rezek and colleagues (2020) suggest that rather than using categories defined from the form of the current material world to impose interpretations on the archaeological record, archaeologists should take a bottom-up perspective on the interplay of different processes of formation, using external references from theories (such as those founded on principles of mathematics or physics) that are methodologically uniformitarian. These references should ideally only be applied to understand possible proximate causations behind the emergent record, rather than for making final inferences about the role of stone artefacts in some behavioural system (Rezek et al. 2020). In this way, the references used also remain independent of interpretation. As such, geometric techniques like the cortex ratio are fundamentally different ways of investigating mobility compared to other typical approaches, since accumulations of artefacts are not viewed as bounded activity sets that reflect central tendencies in stone use at the time of their formation (Rezek et al. 2020). Rather, accumulations of artefacts at one location inform on activities that occurred elsewhere – what is of interest are the artefacts that are missing (Douglass et al. 2017; Holdaway and Davies 2020). Importantly, this way of approaching the lithic record is commensurate with its emergent nature since it allows for multiple forms of social, geomorphological, and other interactions that combine over time to form the lithic record archaeologists observe (Holdaway and Davies 2020; Rezek et al. 2020).

The case study exploring mobility and the organisation of technology is presented in Chapter 5 and considers surface accumulations of artefacts from two locations in Australia: one low-density accumulation from Lake Mungo dating to the late Pleistocene, and a higher-density surface record from Rutherfords Creek dating to the late Holocene. Both occur in similar semi-arid contexts and in association with bodies of water (Figure 2.2; for further archaeological and palaeoenvironmental contexts, see Appendix D). These two records are useful comparative cases for several reasons, one of which is their temporal differences, separated in time as they are by some six to sixteen thousand years. While the surface lithic record at Rutherfords Creek generally represents ca. 2000 years of accumulation and is largely inseparable into distinct behavioural episodes, lithic scatters and hearths within the Lake Mungo study area are preserved such that they arguably reflect single discrete episodes of activity or related sets of activities, like the one-off use of a hearth or the flaking of a core,
Figure 2.2 The location of Lake Mungo and Rutherfords Creek (red squares) in western New South Wales, Australia (figure adapted from Holdaway and Douglass 2012:111, Figure 1).
as determined through archaeomagnetic and refitting analyses (Stern 2014, 2015; Stern et al. 2013). Importantly, raw material contexts differ, with raw material locally abundant at Rutherford’s Creek but not at the Lake Mungo study area, such that all material had to be transported there by people. With these factors in mind, under the logic of typical lithic analysis frameworks like LTO, the Lake Mungo record should demonstrate marked differences in the use of stone, and potentially differences in mobility/settlement pattern, to that of Rutherford’s Creek.

Another way of making inferences about mobility that forgoes the essentialist assumptions of LTO but remains faithful to the principles of geometric approaches is to investigate the extent to which individual lithic reduction sets, like those recorded at Lake Mungo, retain all products of reduction, or whether some have been moved away. To this end, a simple agent-based model is constructed to explore the effects of basic lithic reduction, discard, and reuse behaviours on the composition of individual reduction sets under differing levels of mobility. The resulting patterns derived from the simulation experiments form hypotheses that are independently tested with the empirical data from Lake Mungo and Rutherford’s Creek. This provides a means of understanding mobility without appeals to essentialist assumptions about the form and manufacture of lithic artefacts and how these relate to different contexts of mobility.

It is important to note that insofar as this research is concerned, the Aotearoa and Australia cases are spatially and temporally disparate and otherwise unrelated aside from their shared methodological value for investigating the issues at hand. That is, the cases are not selected for their culture-historical significance. Despite the interest in mobility as a process that underpins other important behaviours like trade and exchange and forms of social interaction, this research is not about the extent to which Māori engaged in trade and exchange practices or maintained communication networks over time. Similarly, despite mobility being a key way in which people used the landscape and interacted with variable environments through time and space, this research is not about the relative mobility of Indigenous Australians at different times and places. Rather, the Aotearoa and Australia cases serve as useful examples of archaeological records to which common essentialist approaches are often applied, and as a result which suffer from indeterminacy; but also, for which appropriate data are available to test hypotheses about patterning in stone artefact assemblages derived from thinking through a materialist perspective.
2.7 Summary

This chapter argued that a large proportion of contemporary lithic analyses are fundamentally essentialist in nature, privileging the manufacture and form of stone artefacts when constructing inferences about past human behaviour. This is evident in studies of mobility and was described in relation to two key pieces of archaeological interpretation: mobility based on the sourcing of artefacts, and mobility based on the organisation of technology. Aspects of each of these highlight two problems that contribute to the wider issue of indeterminacy – the conflation of data and interpretation, and inferences built on a ‘short time perspective’. The latter does not adequately consider the varied histories of accumulation of lithic records, the outcomes of which result in an archaeological record that is emergent in nature and constantly in a state of becoming.

The concept of materiality provides an alternative way of thinking through the indeterminacy issue by approaching lithics in other than essentialist terms, highlighting the constantly shifting associations between people and lithic objects in the past and present. The value of such a perspective is methodological in the way it prompts a close consideration of essentialist assumptions on which many common approaches to archaeological analysis lie, at the core of which are the treatment of the archaeological record as a static representation of past human action and a desire to construct anthropological narratives by employing explanatory principles that rarely exceed the temporal scale of human observation (Murray 2008). From a materialist perspective, materials no longer act as both data and interpretation since nothing about the behavioural significance of materials is assumed a priori; instead, a bottom-up approach is advocated which considers the interaction of different foundational processes of lithic production, reuse, and discard and not the manufacture and form of specific artefact types. Through emphasising process rather than stasis with regards to the constitution of things, a materialist perspective does not necessarily entail a short time perspective, instead allowing for varied histories of accumulation in an archaeological record that is constantly in a state of becoming.

This leads to the question of how to operationalise the lessons learned to deal with and interpret an archaeological record that is the emergent outcome of a set of historical and ongoing relationships between the entities that comprise it. Two case studies, centred on mobility and lithic sourcing and the organisation of technology, provide the conceptual bases for such an approach, which involves departing from essentialist assumptions and instead
understanding the interaction of a fundamental set of processes and the patterning they produce. In the following chapter, agent-based modelling is presented as a mechanism for testing processes of interest in an explicit computational framework, to generate hypotheses about patterning in lithic data without appealing to the morphology of lithic objects or the way in which they were manufactured. These hypotheses are testable using archaeological data from the Aotearoa and Australian cases. The use of computational modelling acknowledges the challenge of studying processes that are otherwise invisible or difficult to experiment with in a laboratory or field-based setting, and has the advantage of requiring that any assumptions are made explicit through the process of codifying statements into a formal model.
Chapter 3
Agent-Based Simulation for Generating Testable Hypotheses

In the previous chapter it was argued that one way to address the indeterminacy issue is by considering the archaeological record in other than essentialist terms. The essentialist perspective is particularly evident in lithic studies, manifesting as a focus on the form and manufacture of artefacts which leads to the conflation of data and interpretation as well as difficulties in dealing with an archaeological record that is fundamentally emergent in nature. That is, artefacts and the assemblages they comprise are not simply static representations of past human behaviour but rather an emergent outcome of many processes operating over time and space and that cannot be separated into its proximate generative mechanisms. A materialist perspective was introduced as an alternative way of thinking about artefacts and assemblages by emphasising the varied relationships and histories of accumulation rather than locking them into static, a priori categories of being. Two key examples of inferring mobility from lithics – through the sourcing of raw materials, and through the organisation of technology – demonstrate the indeterminacy issue and provide useful case studies for operationalising an analysis informed by a materialist perspective.

Such an analysis should limit the number of assumptions about what artefact types or assemblages represent in terms of past human behaviour to avoid predetermining any outcomes, and instead build from the bottom-up by focusing on understanding the interaction of simple sets of processes which produces patterning that can then be assessed in relation to the empirical archaeological record. With regards to mobility, this somewhat paradoxically requires understanding how patterning (fundamental attributes and distribution of stone artefacts) is generated through time and over spatial scales exceeding those at which archaeological data are often observed (which is typically at the scale of a site, assemblage, or catchment), in order to understand how those archaeological data relate to the wider patterning. Computer simulation provides a means of achieving this by enabling experimentation with sets of theoretically grounded variables and processes in a way that is difficult if not impossible in an actualistic setting. It is possible to observe the interaction of these variables and processes to understand how resultant patterns are produced. These patterns are effectively virtual archaeological records which serve as hypotheses that can be independently tested using empirical archaeological data.
This chapter begins by establishing the epistemic link between models and the real-world systems they are meant to represent. Following this is a discussion of the method of agent-based simulation and how it will be applied in the two mobility case studies, focusing on the exploration of a few simple processes of interest rather than the replication of some empirical reality. The chapter concludes with a brief note on how to best document agent-based models for clarity and accessibility, acknowledging the often ‘black box’ nature of computer simulation (Evans et al. 2017).

3.1 On Models

As historical scientists, archaeologists move from observable effects to unobservable causes, the opposite direction in which experimental scientists work (Perreault 2019). Therefore, the past processes that lead to the patterns archaeologists seek to interpret require some form of analogue by which archaeologists can construct inferences about the past (Lin and Premo 2021). The use of analogues is inherently an act of modelling. Before turning to the utility of agent-based models for providing insight into past generative mechanisms that produce the emergent archaeological record, it is useful to first explore the epistemic links between models more generally and the real-world systems they represent.

Simply put, a model is a representation of a system of interest and is generally simplified to help the user better understand certain aspects of a system by excluding elements considered unimportant to the purpose for which the model is created (Contessa 2007). However, a model is only a representation of something if it is a) recognised as such by the model’s user, and b) it allows inferences to be made from the model to the entity it represents via a process of surrogative reasoning (sensu Contessa 2007). Whether the model facilitates surrogative reasoning depends on the purpose at hand (Contessa 2007, 2011; Giere 1999). For instance, to borrow an example from Contessa (2007), the Auckland Transport logo and network map both represent the Auckland Transport network (Figure 3.1). Yet unlike the map, the logo cannot be used to perform surrogative inferences to the wider network of stations and connections for the purpose of navigating Auckland. Therefore, the map is considered an epistemic representation of the Auckland Transport network whereas the logo is not.

Furthermore, when all inferences from the map to the network are sound (e.g., when using a new map rather than an outdated map), this constitutes a faithful epistemic representation (Contessa 2007). The map may only be a partial representation of the transport network (it does not include buildings, size of stations, railway signals, and so on) and may be of limited
accuracy (distances depicted on the map do not scale to real-world distances), but nonetheless it allows the user to perform valid inferences for the purpose of navigating the Auckland Transport system. Scientific models are best thought of as representational in this sense (Giere 1999).

Figure 3.1 The Auckland Transport logo (left) and network map (right). Both represent the Auckland Transport network, but unlike the map the logo cannot be used for the purpose of navigating Auckland. Images sourced from the Auckland Transport website (at.govt.nz).

While there are many reasons for constructing models, including for prediction and guiding data collection (Axelrod 1997; Edmonds 2017; Epstein 2008), one that is receiving increasing attention in archaeology is for the development of theory, particularly in cases where there are detailed data but a poor understanding of how a system works (Davies et al. 2018; O'Sullivan and Perry 2013; Premo 2007). Used in this way, models may be thought of as heuristic devices or “tools to think with” (O’Sullivan and Perry 2013:14). In such cases models are constructed to explore various hypotheses and compare outcomes with real empirical observations to help refine associated theory or clarify thinking about the world and prompt further questions. This process inverts traditional hypothetico-deductive approaches such as those promoted by processual archaeology (Kohler and van der Leeuw 2007).

Significantly, the act of model building itself is a learning process (Morrison and Morgan 1999). Constructing a model forces reflection on assumptions being made about a target system, and subsequent testing of the model may lead to refining some parameters or simply discarding others that are deemed irrelevant to the purpose at hand. Discovering what does not work is often enlightening itself (Premo 2007). Modelling therefore becomes an iterative process that is cyclical and reflexive in nature, with the potential for useful insights about a target system to be revealed at each stage of the process (Railsback and Grimm 2012:7).
Generally, all models begin as conceptual models of the causal mechanisms that lead to observable patterns of interest. As such, the act of interpreting observations of the archaeological record in terms of human behaviour or some other processes inherently draws upon conceptual models (Clarke 1972). These may be expressed verbally, mentally, or in diagrammatic form. While relatively easy to express, the inferences generated from conceptual models are often broad and built on implicit or hidden assumptions which may be difficult to parse out when attempting to evaluate the model (Epstein 2008).

Translating the conceptual model into a formal model has the advantage of making explicit the assumptions and relationships between different aspects of a model, making it easier to verify the logic of the model (Lake 2015; Servedio et al. 2014). Common examples of formal models include mathematical/equation-based models and computer simulation. These essentially codify the components of conceptual models into clearly defined operational statements. Simulations allow one to observe the changes in a system over time, since the state of a system is iteratively recalculated at defined intervals based on the current set of variables and relationships that describe that system (Lake 2015; O’Sullivan and Perry 2013). This allows one to explore how a system came to be, rather than simply how a system works (Lake 2015).

As noted in the preceding chapter, human systems are complex systems where simple behaviours on the part of individuals combine to produce emergent patterning that is difficult to predict based on the individual contributing mechanisms alone (Kohler 2012; McGlade 2014:295). A formal simulation enables experimentation with various conditions that may contribute to patterning of interest and which may not be visible in the real world (Morrison 2009; Premo 2007), nor practical to directly experiment with due to the temporal and spatial scales typically involved – such as in the case of mobility, lithic reuse, and the landscape-scale reorganisation of lithic resources. In this manner, simulation is well-suited to the study of complex systems and therefore archaeological questions, providing a heuristic tool with which to learn about a particular system, and a space in which to test and adapt ideas (Aldenderfer 1998; Barton 2014; Epstein 2008; Kohler 2000; O’Sullivan and Perry 2013:14). For these reasons, computer simulation is used in the case studies for this thesis as a means of exploring the interaction of simple variables and processes of interest to generate testable expectations about the kinds of archaeological patterns that might result.
3.2 Agent-Based Models

Specifically, this thesis uses agent-based modelling, a particular form of computer simulation that Premo and colleagues liken to a laboratory “capable of executing controlled, repeatable experiments and systematically exploring multiple parameters of hypothetical cultural processes” (2005:11). An agent-based model (ABM) involves the manipulation of behavioural rules or conditions governing the interaction of a single (e.g., Brantingham 2003) or many (e.g., Barcelo et al. 2015) autonomous agents with other agents and the environment. These usually simple, micro-level interactions combine over time to produce macro-level regularities which can be explored to help understand the effects of different variables on a simulated system (Lake 2015). Patterning emerges from the local interactions of agents and other system components, often in a way that cannot be predicted based on the individual behavioural mechanisms alone. ABMs can encompass large spatial and temporal scales, or remain spatially and temporally abstract, while making available every detail about the modelled system at any given time (Premo et al. 2005). Agents are also heterogeneous, with each having their own unique set of properties. The interaction of heterogeneous agents through space and time means agent-based simulations are subject to historical contingency. This facilitates the exploration of systems in which previous processes and interactions matter (Gilbert 2008; Premo 2010). As Kohler and colleagues (2012) note, archaeologists typically tack between past behaviour and observed patterning based on ethnographic analogy, environmental regularities, experimental archaeology, or simple intuition – a computer simulation like an ABM offers another method free of many of the limitations of these approaches. Each of these properties of ABMs led Cegielski and Rogers (2016:283) to argue that ABMs “offer a methodology to unify long-held discipline-based theoretical disjunctures and open the path to fundamental challenges to epistemological assumptions”.

Due to the inherent difficulties with investigating processes of interest to archaeologists through actualistic research, it is tempting to treat the use of agent-based models as an opportunity to imitate what is thought to have happened in the past, or to recreate specific empirical observations (e.g., Dean et al. 2000), particularly with increasing availability of high computing power and user-friendly software (Premo 2007). However, simply recreating or ‘emulating’ empirical observations in silico does not mean anything new will be learned about the target system. As Premo (2007:29) notes, often emulative models serve as “archaeological ‘explanation’ by default rather than by scientific merit”. By altering parameters enough, one will eventually produce output that replicates what is observed
empirically. However, the simulation configuration that yielded that result may not be the only explanation for how those real-world observations came to be (Lake 2015, Romanowska et al. 2021), echoing in some respect Perreault’s (2019) ‘test for consistency’ whereby archaeologists settle on an explanation simply because it is consistent with the data at hand, leading to ignorance of equipollence and underdetermination and therefore contributing to indeterminacy. Indeed, using agent-based models in an emulative sense is what Perreault (2019:17-18) cautions against:

In the end, the danger of simulations… is that they give us the illusion that they can patch up an incomplete historical record; and they can lead us to assume the very things we should be trying to find out. [They do not] offer any guarantee whatsoever of being accurate representations of the past, and because of that, they do not have the epistemological weight necessary to discriminate between competing hypotheses.

An alternative form of modelling is ‘exploratory modelling’ (Premo 2007, 2010) where simplified models are used to experiment with a range of conditions at broader theoretical levels. Using a simpler rather than more detailed model structure means it is easier to achieve a clearer understanding of what parameters may have been important to some past system and how they influence resultant patterning (O’Sullivan and Perry 2013; Premo 2007). Using simulation as something akin to a ‘behavioural laboratory’ reduces the impact of underdetermination since it is lower-level hypotheses that are of interest – what is important is understanding what kinds of processes might create a particular pattern, rather than determining exactly how a given pattern was produced (Lake 2015). Because of this, exploratory models can be constructed independent of specific data, and by exploring a range of different parameter settings, can therefore be used to “formulate expectations that can be tested with archaeological data collected from the field… [and thus] build archaeological inferences from the null-up” (Premo 2007:35; see also Barton 2014). As Davies (2016:87-88) notes, exploratory modelling operates similarly to appeals to methodological uniformitarianism (e.g., Bailey 1983; Binford 1981) by arguing from “well-understood principles derived from observations in the present [the simulation experiments] to unobserved processes in the past”.

The exploratory agent-based modelling approach is used in the case studies for this thesis, as a means for experimenting with the formation of lithic assemblages based on ideas and processes informed by a materialist understanding of the archaeological record. In both the Aotearoa and Australia examples, different combinations of simple lithic acquisition, discard,
reuse, and movement are simulated to better understand the operation of these processes and how they interact, producing a range of patterning in virtual lithic data which can then be tested using empirical lithic data.

### 3.3 Structuring the Agent-Based Models

There are an increasing number of simulation studies that investigate the formational dynamics of lithic accumulations, including how these relate to processes such as mobility, raw material choice, and discard behaviour (e.g., Barton and Riel-Salvatore 2014; Brantingham 2003, 2006; Coco et al. 2020; Davies et al. 2018, 2021; Haas and Kuhn 2019; Lin 2018; Lin and Premo 2021; Oestmo et al. 2016, 2020; Pop 2016; White 2021). The underlying structure of many of these simulations are based on principles of neutral models, which are themselves forms of exploratory models. The core premise of a neutral model is that “all same-level components of a system are equivalent both in terms of their innate behaviours and the impact that the environment has on the expression of those behaviours” (Brantingham 2003:491, original emphasis). In other words, components of a simulated system are uniform such that there are no extraneous factors biasing the interaction of those components and influencing resultant patterning. Applying the principles of a neutral model means any processes or variation considered unimportant to the operation of the target system being investigated are removed, making it easier to identify the effects of those processes of interest that are coded in by the researcher and systematically investigated in the exploratory framework.

A good example of the application of such an approach is the simulation of Davies and colleagues (2018) called FMODEL, which explored the effects of variables relating to raw material availability, stone reduction, and movement tortuosity on the spatial patterning in cortex ratios across a synthetic landscape. The aim was to elucidate the theoretical relationship between cortex ratios and different movement configurations to contextualise the patterning in cortex ratios observed in their empirical assemblages from western New South Wales, Australia. In FMODEL, agents ‘behave’ but only in a simple manner by moving and producing, transporting, and discarding stone flakes and cores. The size of cores and flakes and the rate of discard are held at an arbitrary constant, and agent movement is random and undirected through a uniform landscape, allowing the authors to isolate the causal relationships between the variables of interest to address the question of what combination of processes produce different cortex ratios and how these vary across space. Another example
is the study of Haas and Kuhn (2019) which explored the significance of previously discarded artefacts as attractors for occupation. Following the premise that by discarding artefacts people are effectively reconfiguring resource locations on a landscape, Haas and Kuhn formalised a conceptual model in which people are attracted to locations with previously discarded material, which affects mobility decisions and results in emergent land-use patterns. In their model, an agent begins in an empty landscape, moving and depositing an artefact each time step. The agent may move either to a location with discarded artefacts or an empty location, which is determined with a probability that varies between simulation runs. In this way, only the presence of discarded artefacts potentially influences an agent’s movement choices. Other variables such as the rate of discard, different raw material types, remaining artefact utility, or other landscape features are not considered; not because they were unimportant in the past, but because including other variables not of immediate interest to the question at hand would increase model complexity, making it difficult to identify the core dynamics.

A common criticism of models like those just described is the relative simplicity and lack of realism, which effectively boil down to issues of representation. As noted above, the value of such models is not in recreating a real-world case under realistic settings. Indeed, as Lin and Premo (2021) ask, how can this be the purpose if it is reality we want to learn about? Rather, the aim is to generate hypotheses, based on the operation of processes of interest, which can be independently tested with archaeological, not simulated, data. The utility of a model therefore lies not in how ‘realistic’ it is, but rather in how well the underlying assumptions represent, however abstract or simplified, the essence of the real-world phenomenon under investigation (Cegielski and Rogers 2016). What that essence is should be grounded in relevant archaeological theory. Different research agendas will have different ideas about what that essence is, and this should be encouraged and tested (Lin and Premo 2021).

3.3.1 Agent-Based Modelling and Indeterminacy

As set out in the introduction to this thesis, equifinality and underdetermination are key principles contributing to indeterminacy (Perreault 2019). Indeed, the issue of equifinality in archaeology is highlighted by the results of many ABMs which provide demonstrably plausible alternative explanations for observed archaeological patterning, typically in contrast to conventional archaeological wisdom (e.g., Brantingham 2003; Coco et al. 2020; Lin 2018; Lin and Premo 2021). Equifinality, however, is also a characteristic inherent to models
themselves. “Equifinality means that a model’s fit with the data is never sufficient evidence for model truthfulness; it is possible, and in fact rather likely, that another model will eventually be devised that fits the data even better” (Romanowska et al. 2021:142). This is a characteristic of inductive reasoning more generally. While a model’s truthfulness can never be proven, its plausibility compared to other models can be quantified through a process of validation, where model predictions are compared to real data to establish whether the model is one correct representation of the target system (Romanowska et al. 2021). This is easier to achieve with simpler models. The issue of equifinality is precisely one reason why Premo (2010) argues in favour of exploratory ABMs. Equifinality places limitations on the explanatory power of emulative models, so archaeologists are better served by exploring the dynamics of simple, well-defined, and well-bounded processes, under the assumption that a better understanding of the wider system can be reached by better understanding the interaction of its parts (Premo 2010).

The question of representation, the distinction between emulative and exploratory models, and discussion of equifinality in simulations are all related to the construction of archaeological knowledge, evident in Perreault’s (2019) contrast between archaeology as a historical science with experimental sciences, where in the latter one moves from cause to effect by way of experimentation, but in the former one observes effects and must infer causes, which are themselves unobservable. This complicates the search for a ‘smoking gun’ – some piece of evidence or observation that successfully discriminates between different hypotheses (Perreault 2019:5).

However, if archaeologists focus their simulation efforts less on identifying a smoking gun and more on developing theory, then arguably, structuring analysis in an exploratory manner under an explicit modelling framework does help to address some of the contributors to the indeterminacy issue, such as the ‘test for consistency’ and the ease with which verbally defined hypotheses are confirmed. The act of coding a conceptual model into operational statements exposes any hidden or imprecisely defined assumptions, prompting their justification. The test for consistency and the logic of verbal hypotheses are then addressed through the systematic exploration and testing of a range of parameter combinations to identify which ones may contribute to the underlying structure of archaeological patterns. Importantly, this is more than simple pattern-matching. Whether the overall outcome of a particular simulation configuration matches observed archaeological patterning does not by itself distinguish between other simulation configurations that might also produce similar
pattern, nor does it mean that a given simulation configuration is the only explanation for observed archaeological patterning. However, structuring exploratory models as described above, independent of particular datasets, means a set of patterns that emerges in a given simulation configuration can be further tested by exploring the various sub-models or processes in operation in that simulation. For instance, if two simulation runs produce patterning in the distribution of lithics similar to an empirical case, but in one simulation run this occurred in the context of low reduction intensity and in the other, high reduction intensity, the reduction intensity in the empirical case can be investigated (assuming the data allow) as a way to discriminate between the two candidate explanations. In this way, these additional patterns serve as ‘filters’ for distinguishing between potential explanations (Davies 2016).

3.4 Summary

This chapter outlined the conceptual basis for constructing the agent-based simulations in this thesis, as part of a method that analyses the archaeological record in other than essentialist terms as a way of addressing the indeterminacy issue. Lin and Premo (2021) cogently sum up the modelling approach by stating that it is important to clarify how different processes affect archaeological patterning under a range of different settings and configurations before proposing a given explanation for that patterning. Using exploratory simulation, processes of interest, grounded in appropriate theory, are investigated in a bottom-up fashion which allows a set of patterns to emerge in the model (Railsback and Grimm 2012). Those patterns may or may not be observed in the real world. It bears repeating that the aim of exploratory simulation is not to replicate real historical events, but to explore the interaction of a range of processes that might influence observed archaeological patterns (Davies et al. 2021). The simulated patterns form hypotheses that can be tested with real archaeological data, but not simply in the sense of ‘pattern-matching’. Similarities between patterning in simulation output and the empirical archaeological record provide validation of the model (Romanowska et al. 2021). The key difference is that simulated patterning and the processes that produced that patterning are then used to contextualise archaeological data, suggesting further tests (such as in the reduction intensity example) that relate the empirical world to the modelled processes, thus providing theoretical insight into the possible generative mechanisms at play (Davies et al. 2021).
In the two chapters that follow, exploratory ABMs are constructed to assess processes and patterning in lithic accumulations related to mobility, based on a materialist understanding of the archaeological record. The sourcing case study (Chapter 4) questions the common essentialist assumption that people always returned to a geological source when in need of material to make artefacts. This assumption underlies many common inferences about trade and exchange practices, which are themselves underpinned by mobility and inferred from the observed distribution of lithic objects deriving from different geological sources. Instead, a materialist perspective highlights how the relationships between lithic objects and people constantly shift as discarded artefacts become sources of usable material themselves, occurring at places located between geological sources of raw material and where an artefact is recorded by the archaeologist. Therefore, an exploratory simulation called SourceSim is constructed to explore the significance of these ‘in-between places’ for inferences about mobility. Lithic material deriving from different geological sources is distributed around a simulated landscape by virtual stone-using groups who either always seek out a geological source when in need of stone material or will first resupply from deposits of previously discarded artefacts. The resultant patterning in the distribution of lithic material through time and space for each simulation run form hypotheses that are tested using data on the archaeological distribution of different obsidians through time and space in Aotearoa. The results of the analysis inform on the extent to which distributions of artefacts made from different raw materials are explained by the kinds of mobility underlying trade and exchange practices and social networks, or whether a simpler, more fundamental set of processes governs assemblage patterning.

The organisation of technology case study (Chapter 5) dispenses with essentialist assumptions about what tool types or assemblages thereof mean in terms of mobility and instead investigates mobility based on the extent to which all products of stone reduction are present in individual reduction sets, thus indicating whether stone material has left a given location, reflecting the movement of people. A simulation called ClusterSim is constructed based on the framework of Davies and colleagues’ (2018; Davies 2016) FMODEL (described above) to explore the effects of different mobility configurations on patterning in stone reduction sets under varying conditions of raw material availability. In the simulations, agents enter a window of observation carrying a varying amount of stone material, reducing and discarding material as they move through the window, while reusing previously discarded material if needed. The relative mobility of agents is determined by the tortuosity of their
movements which govern how long they spend in the window of observation, ranging from simply passing through in a fleeting visit, to potentially spending an extended period in the area before leaving. The resulting patterns in the size of simulated lithic reductions sets are used to contextualise the patterning in the late Pleistocene assemblage at Lake Mungo, which is compared with the extensively studied late Holocene assemblage from Rutherford's Creek in western New South Wales, to determine the extent to which these seemingly different records are explained by the same set of simple processes.

3.4.1 A Brief Note on Documenting Agent-Based Models

Throughout its history, the impact of agent-based modelling in archaeology has varied. While the number of practitioners and recognition of the potential for the method to make significant advances is growing (Cegielski and Rogers 2016; Davies and Romanowska 2018; Romanowska et al. 2021), it still receives a variable reception in the discipline, often couched in the perception that agent-based modelling is too complex and difficult to use (Cegielski and Rogers 2016; Lake 2014). Agent-based models are often likened to ‘black boxes’ where it is difficult for anyone but the developer or programming-savvy researcher (who are often not the sole intended audience of archaeological simulation research) to understand simulation inputs, processes, and resulting patterns (e.g., Evans et al. 2017; Lorscheid et al. 2012; Topping et al. 2010).

These criticisms can be addressed through clear, standardised documentation of model development, structure, processes, and implementation, and by making available the source code. Documenting models sufficiently also aids in reproducibility and replicability which are core aspects of the scientific method, enabling validation of the model and future development to generate novel interpretations (Lorscheid et al. 2012; Marwick 2017; Thiele and Grimm 2015). Davies (2016:88-94) highlights several exemplary studies that may be followed when developing models and summarises an approach to documenting them into four basic stages. These stages are used to structure the case studies in the chapters that follow. Model justification involves outlining the reasons for building the model, making explicit any assumptions, and identifying relevant parameters. Model conceptualisation provides the conceptual model which will be formalised in computer code and includes the decisions about what aspects of the target system will be modelled. Model implementation describes how the model operates, and includes specifying the initial state of the model, input data, parameter values, and stop conditions. It also includes verification and validation of the
model and describing how output is generated. Finally, *model exploration* lays out the model experiment, specifying the parameter values used and comparing simulated outcomes. Furthermore, one of the most widely used standards for documenting and communicating models in archaeology and more generally is the ODD protocol (Grimm et al. 2006, 2010, 2020). The ODD protocol was designed to provide a clear, standardised framework for describing models and therefore improving understanding and comparability, as well as encouraging replication – the idea being that the description is comprehensive enough that a conceptual model may be translated into a formal one by not only another user but during the initial model coding itself (Hauke et al. 2020). ODD documents for the simulations developed in this thesis are supplied in Appendices B and E, and source code is provided in Appendices C and F.
Chapter 4

Mobility and Sourcing: SourceSim

This chapter presents a justification for modelling based on interpretive differences regarding patterning in the distribution of lithic artefacts deriving from different geological sources. This patterning is typically assessed with respect to mobility that underpins lithic acquisition behaviours such as trade and exchange or direct procurement, which in turn factors into inferences about other processes such as the development of social networks and territoriality. Data that are key to deriving these inferences include measures of the frequency of artefacts of different raw material types and the distance to the geological source. As set out in Chapter 2, inferences derived in this manner are based on the essentialist assumption that when in need of artefacts, people would return to a geological source to acquire fresh material and begin the lithic manufacture process anew (Dibble et al. 2017). This contrasts with ethnographic and other studies that suggest raw material acquisition occurred just as much (if not more so) by accessing visible deposits of previously discarded artefacts (e.g., Camilli and Ebert 1992; Coco et al. 2020; Holdaway and Douglass 2012; Sillitoe and Hardy 2003). The extent to which these other source locations account for patterning in the distribution of lithic artefacts requires further investigation. A model is conceived in which agents move around a landscape discarding lithic material from different geological raw material sources, and who, when in need of material, either always return to a geological source, or attempt to acquire and reuse artefacts from the visible discard record. The conceptual model is translated into a formal exploratory simulation, the results of which demonstrate how the different modelled behaviours influence emergent patterning in the distribution of lithic material across the simulated landscape. These patterns serve as expectations which are explored using empirical data on archaeological obsidian distributions from Aotearoa.

4.1 Model Justification

The location of a stone artefact relative to its origin forms the basis for many inferences about mobility. One proxy for the origin of a stone artefact is the geological source from which the raw material used to manufacture the artefact derives. Depending on the material, the geological origin can be determined through physical and geochemical characterisation methods (Sheppard 2004). Once the geological origin of an artefact is known, the distance
between the artefact and its origin provides an indicator of movement from one point to another. The frequency and distribution of raw material types in an assemblage are used to make inferences about different procurement strategies, such as direct access to the geological source or indirect procurement through trade and exchange, which in turn factor into inferences about different forms of social interaction. While the occurrence of such processes in the past is not in question, inferences derived from measures based on fixed geological sources are subject to indeterminism. There are many ways in which an artefact can move from one point to another, which may or may not be knowable (Hodder 1984; Kelly 1992). This is an issue of equifinality. Furthermore, relative distances are often used to infer the mode of procurement, with longer distances implicating indirect procurement through trade and exchange and shorter distances suggesting direct procurement from the geological source (Hughes 2011). This often results in the conflation of the distribution of material deriving from different geological sources with the processes that led to that distribution.

The equifinality issue is demonstrated by several simulation studies that arrive at different explanations for patterning in distributions of lithic artefacts relative to fixed geological sources. For example, White (2021) considered the effects of technological changes on broad patterns of stone tool transport, as an alternative to distance to source as a proxy for the scale of group mobility. White presented an ABM to explore how three technological variables – use-life, inventory size, and frequency of use – affected the accuracy with which artefact transport distances reflected the scale of group mobility in a system based on seasonal dispersion and aggregation of groups centred on a fixed lithic source. Among other findings, White’s (2021) simulations demonstrated that parameters governing the use and discard of stone artefacts had significant effects on the maximum distance artefacts were transported. This has implications for interpretations of group mobility based on raw artefact transport distances or the identification of raw material conveyance zones often associated with group territorial ranges or interaction spheres (e.g., Jones et al. 2003; McCoy et al. 2010). In some cases, the use of multiple lines of evidence when interpreting changes in group mobility may be required (White 2021).

Lin and Premo (2021) specifically tested the effect of differential tool discard probability on distance to source measures, based on Shott’s discussion of how variable artefact use-lives result in differential rates of discard (in reply to Brantingham 2006). In their simulation, a set of agents move out from a central fixed source under different mobility configurations.
(specifically a Lévy walk – see Chapter 5 for a detailed explanation of this process),
discarding lithic material at regular intervals along their path according to a varying discard
probability. The simulation results suggested that decreasing probabilities of artefact discard
affected distance to source distributions in similar ways to mobility with longer step lengths
(i.e., more direct movement away from the source). This led Lin and Premo to conclude that
different lines of evidence are needed to differentiate the effects of tool discard probability
and mobility on raw material distributions with respect to a geological source of origin (Lin
and Premo 2021).

In a seminal lithic ABM study, Brantingham (2003) tested the possibility that much of the
variation in archaeological raw material frequencies is in fact of no adaptive or functional
significance by constructing a simple model in which behavioural assumptions were limited
to as few as possible. In his model, a forager moves in a random, undirected manner around a
uniform landscape while discarding units of raw material which are acquired upon chance
encounters with geological sources which are distributed randomly throughout the simulated
landscape. He found the resulting patterning in toolkit diversity was qualitatively similar to
commonly observed archaeological patterning, suggesting that in some instances it may not
be possible to reject his model as a hypothesis for patterning in raw material distributions in
archaeological assemblages. In an appraisal of Brantingham’s model, Pop (2016) noted how
processes that govern toolkit composition differ from processes that influence discard
records, which are what archaeologists actually observe. Pop reran Brantingham’s model
several times to investigate the discard records, increasing the length of the simulation runs
and varying the density of raw material sources and the maximum amount of material the
forager could carry. Based on the simulation outcomes, Pop (2016) made several predictions
about the character of discard records produced under otherwise neutral conditions, and what
deviations from these predictions might mean in terms of past human behaviour (such as
mobility, raw material preference, etc.). One such prediction was that maximum raw material
transport distances should be shorter under conditions of lower geological source density –
with any deviations from this pattern suggesting either biased mobility patterns or lithic
recycling behaviours (Pop 2016). Indeed, Pop suggested his simulations demonstrated how
the common practice of computing distance to source measures is flawed because the degree
to which sources are exploited depends in a large part on the local density of sources. Pop
(2016:1158) suggested it would therefore be useful to study the effects of lithic recycling
since this could result in locations with discarded artefacts being used as raw material
sources, and posed the question of whether, depending on different mobility strategies, archaeological variability actually reflects a need for constant access to lithic resources or other sites.

Pop’s (2016) suggestions about lithic recycling converge on the materialist alternative to lithic resource procurement discussed in Chapter 2, which highlights the reuse of previously discarded artefacts as a mechanism for acquiring and distributing material across a landscape and thus structuring assemblage composition and the artefacts themselves. Determining the geological origin of artefacts is one method of assessing assemblage composition and how this relates to mobility based on measures of distance to the geological source. However, thinking through the process of reuse means there are many other places between the geological source and the place an artefact is ultimately discarded where potentially usable material is located, thus confounding the notion of fixed sources. The implications of these ‘in-between places’ for distance to source measures and inferences about mobility require systematic investigation, warranting the development of a formal exploratory simulation to explore the effects of lithic reuse on artefact distributions.

The significance of previously discarded artefacts as sources of usable material has received some attention in simulation studies. As noted in the previous chapter, following the premise that by discarding artefacts people are effectively reconfiguring resource locations on a landscape, Haas and Kuhn (2019) formalised a conceptual model in which people are attracted to previously discarded material when in need of artefacts, which affects mobility decisions and results in emergent land-use patterns. This concept is somewhat akin to place-provisioning (sensu Kuhn 1995), though Haas and Kuhn (2019) note how place-provisioning in its original conception implies an element of intentionality and forward-planning. Their simulation, in contrast, considers the reuse of landscape locations and emergent patterning in the absence of planning. An agent begins in an empty landscape, moving and depositing an artefact each time step. The agent may move either to a location with discarded artefacts or an empty location, which is determined according to a probability that varies between simulation runs. Haas and Kuhn (2019) are therefore not concerned with the actual reuse of previously discarded artefacts and their distribution relative to geological sources of origin, but rather focus on how visible deposits of artefacts structure and restructure the use of landscape, with the need for usable stone resources providing the justification for the reoccupation of a place. From the simulation experiments Haas and Kuhn (2019) derived four
predictions for artefact distribution patterns, three of which were supported by their empirical test case of the Late Archaic Period settlement system in the Lake Titicaca Basin.

As Haas and Kuhn (2019) note, the reoccupation of a place is noted in anthropological and archaeological studies, such as in Yellen’s (1977) observations of !Kung groups regularly reusing existing brush structures in previously occupied camps. Binford (1982) refers to the knowledge and structure of such locations as ‘cultural geography’ which is as much a characteristic of landscapes as natural geography. This concept is also understood in terms of persistent places – features that “structure the use and reuse of the larger landscape” (Schlanger 1992:92) and which may be created in three ways: through the recognition of qualities of a place that mark it as suitable for certain activities; through visible remains that focus reoccupation and structure future activities; and through long term processes of occupation and revisitation (Schlanger 1992; see also Littleton and Allen 2007 for another example).

Whichever way one chooses to conceptualise cultural features that influence the reoccupation of a location, this rests on the assumption that markers of previous occupation are visible. If locations with previously discarded artefacts are to be exploited as sources of usable material, this also rests on the assumption that the material is reusable. The reusability of stone was explored in Chapter 2. Stone is an inherently reusable material given its durability and ability to be worked to produce a sharp edge. This includes obsidian which fractures easily to create a sharp edge such that even small pieces are potentially useful (e.g., Elston 1990:156; Kelly 2011:192; Maning 1875; McAnany 1988:8). The visibility of accumulations of stone artefacts, on the other hand, is not conditioned by physical properties of the material but rather by local geomorphological processes of erosion and deposition that operate in unison with cultural deposition (Camilli and Ebert 1992). For instance, in a case study from semi-arid Australia, it was shown that local geomorphological processes acted to condition the visibility of surface assemblages of stone artefacts such that a given exposure of artefacts may be removed in time from nearby hearths by an order of centuries (Davies et al. 2015; Fanning and Holdaway 2004; Fanning et al. 2009).

In the case of Aotearoa, in the centuries following initial occupation it is reasonable to suggest that locations with the potential to include deposits of artefacts were largely identifiable by people. The majority of archaeological sites in Aotearoa occur along the coastline or waterways, with widespread evidence of occupation of stable and forested dunes
Polynesian colonisation resulted in a relatively rapid reduction in native forest cover due to firing and the clearance of vegetation for the purpose of horticulture (Holdaway et al. 2018:4; McWethy et al. 2014; Wilmshurst 1997). These processes would clearly mark locations in the landscape where humans had some presence. Deforestation freed up sediment and led to the mobilisation of dunes, increasing the susceptibility to wind erosion and the potential for stratigraphic mixing (Hilton et al. 2018; McGlone 1983, 1989), implicating processes of erosion and deposition that acted locally to expose and bury accumulations of artefacts and other cultural features. Such processes were also not limited to dune systems.

For instance, in their analysis of an eroding escarpment exposing several thousand artefacts on Ahuahu/Great Mercury Island, Holdaway and colleagues (2018:11) suggest the extent of erosion caused by post-European farming activity indicates the area was equally susceptible to sediment movement in pre-European times, which in turn suggests the potential for visibility of artefacts in non-dune areas.

To summarise, archaeologists often use sourcing data and measures such as distance to source to make inferences about different degrees of mobility using stone artefact assemblages, which form the basis for inferences about trade and exchange and other processes of social interaction. The source is typically the geological origin of an artefact, and therefore inferences tend to implicitly assume that people accessed a geological source to acquire that artefact. However, stone artefacts were subject to reuse in the past, such that visible deposits of artefacts themselves served as sources of usable material. This calls into question the notion of fixed sources and the need to constantly access geological sources to acquire material. The extent to which acquisition of lithic material from places other than geological sources explains patterning in artefact raw material distributions and distance to source measures warrants systematic exploration. An exploratory simulation is therefore used to examine the influence of different source locations and raw material acquisition behaviours on resulting stone artefact distributions.

4.2 Model Conceptualisation

The model described in this section concerns the manner in which lithic raw material deriving from different geological sources is procured and subsequently distributed around the landscape. This is used to evaluate assumptions regarding the extent to which geological
sources of raw material were accessed to produce usable stone artefacts, and to explore the effects of exploiting deposits of stone artefacts as sources on resultant assemblage patterning.

Stone artefact assemblages around the world are a testament to the actions of past people who acquired, transported, and discarded stone material, resulting in anything from small, discrete accumulations of objects to entire anthropogenic landscapes covered in a continuous distribution of artefacts (e.g., Foley and Lahr 2015). Specific manifestations of each of these three processes provide a conceptual model for the distribution of stone material deriving from different sources.

For any given raw material type, people at some point had to initially acquire some quantity of that material from a geological source to then transport and distribute it across the landscape. Therefore, by default the geological sources of materials in question must have been visited at least once. One way in which raw material procurement can subsequently occur is by always obtaining material from a geological source when in need. Alternatively, people may opt to first acquire and reuse material from visible archaeological deposits, only accessing a geological source if no existing deposits of artefacts are available. Together these two processes form one set of parameters governing the acquisition of lithic raw material.

The Aotearoa context highlights other relevant parameters that should be considered in the conceptual model of lithic acquisition. As noted previously, Tūhua obsidian is present at most Aotearoa sites that contain an obsidian assemblage, and at all time periods (Seelenfreund and Bollong 1989). Generally speaking, Tūhua obsidian appears in higher proportions at earlier sites and declines in abundance at sites located far from the geological source (McCoy et al. 2014; Walter et al. 2010). Several explanations have been proposed for the ubiquity of Tūhua obsidian and the spatio-temporal patterning in abundance. One explanation is the increased desirability of Tūhua obsidian due to its better flaking properties than obsidian from other sources (e.g., Moore 2012). Another explanation suggests Tūhua obsidian may have been discovered first (and known about for longer) by settlers, accounting for its relatively large abundance compared to other obsidians (Green 1964). A further explanation relates to the physical manifestation of the source. Tūhua is an accessible offshore island that has massive outcrops of obsidian providing abundant large cobbles – or simply put, more material – than other sources that consist of low-density scatters of smaller cobbles some of which are difficult to access (Jones 2002; Moore 2012). As Holdaway and Phillipps (2021:152) explain,
…at first settlement of Aotearoa there were only the geological sources of obsidian available, since no transported obsidian assemblages yet existed. Therefore, abundance of obsidian in the earliest assemblages related to the size and form of material at the source… Because obsidian was much more abundant at Tūhaua than at any other geological sources it was relatively more abundant at the transported sources.

Based on the suggestions above, two other parameters regarding lithic acquisition are relevant to the model. One is the desirability of material from a given geological source, where people may preferentially access that source when in need of material rather than exploiting another closer or more convenient geological source. This would theoretically have the effect of increasing the total abundance of material from the desirable source relative to others due to the greater frequency at which it is accessed. The other parameter is an amalgam of the remaining explanations for the greater abundance of Tūhaua obsidian in Aotearoa assemblages. For the purposes of the model, a geological source being discovered first (and therefore potentially accessed a greater number of times before other sources) and a geological source providing a greater quantity of material than others both manifest as a potentially larger quantity of material initially entering the system, warranting their collapse into a single parameter. This is conceived in the model as people having a greater chance of ‘discovering’ a given geological source over others when accessing those sources for the first time to acquire material. Theoretically, any subsequent visits to the ‘larger’ geological source could result in more material being transported away than from other sources. However, for simplicity it is useful to hold the maximum amount of material groups can carry at some arbitrary constant, and to assume that when resupplying with material groups carried away that maximum amount regardless of the geological source being visited.

The movement of groups is the mechanism by which raw material is initially transported from a source and subsequently distributed across the landscape. As noted previously, understanding movement by analysing the stone artefacts reveals movement from some location to the place the artefact is observed in the archaeological record. Other movements may of course occur but are not captured by the discard record. Using artefact distributions as indicators of movement therefore implicitly assumes that the discard of artefacts is embedded in the movement patterns of people in the past to some extent (Binford 1979; Davies 2016:146-147). For the foregoing reasons, and for the purposes of simplicity when analysing model outcomes, movement in the model is conceived as groups making linear ‘jumps’ from one location on the landscape to another (akin to ‘camp’ moves). Of course, groups may also
occupy a given landscape location for some period of time rather than choosing to consistently move, therefore in the model movement is presented as a choice. In this way, the relative frequency and extent of movement will influence the distribution of raw material types in assemblages as material is moved to a greater or lesser extent throughout the landscape.

Finally, discard of artefacts can occur in several ways: purposefully after use or when the artefact is no longer needed; when purposefully caching material at a location for future use; or simply by accident. In the conceptual model, accidental discard is subsumed under the other forms of discard. When at a destination after a move, or indeed after choosing to remain at a location, groups can use and discard artefacts at varying rates, since hypothetically some tasks may result in a greater quantity of artefacts discarded than others. Groups may also decide to cache an amount of material at a location for future use if they are carrying sufficient material, in a process akin to place-provisioning (Kuhn 1995). Together, the processes of caching and discard after use capture the ways in which lithic material enters the archaeological record.

Based on the processes described above, a model is conceived in which groups move into an otherwise unpopulated landscape, initially extracting stone material from a limited number of geological sources randomly located in the landscape. In some cases, there may be a greater chance that one of those sources is discovered first by the groups, thus increasing the amount of material from that source initially entering the system. A geological source may also be considered more desirable than others, thus increasing the frequency with which it is potentially visited by groups when in need of material. After initially acquiring material from a geological source, groups disperse around the landscape by moving to a new location or remaining at their current location at each time step. They distribute material by discarding a number of artefacts after use and/or by caching a quantity of material at their current location. When they run out of material, in some cases groups may opt to always return to the nearest (or desirable) geological source of material, or instead opt to first acquire material from nearby visible accumulations of previously discarded artefacts if available. This conceptual model is formalised into an agent-based simulation to assess the influence of deposits of previously discarded artefacts as sources of material on raw material distributions and assemblage patterning.
4.3 Model Implementation

The model, called SourceSim, is constructed using the NetLogo modelling platform (Wilensky 1999) and output is analysed using R version 4.1.0 (R Core Team 2021) with the aid of the Tidyverse suite (Wickham et al. 2019) and ggpubr (Kassambara 2020) packages for data wrangling and visualisation. The model is of the exploratory form described by Premo (2007, 2010) and as described in Chapter 3. It constitutes a simplified version of the target system for the purposes of exploring the operation and consequences of mechanisms of interest, which in various combinations generate hypothetical lithic distributions that can be tested using real archaeological data. Importantly, SourceSim is not meant to replicate an empirical reality. Rather, it is a vehicle for working through the implications of the modelled processes – in this case, simple lithic acquisition, use, and discard behaviours that occur in the absence of any interaction between users. These insights are used as a tool with which to think about observed archaeological patterning (O'Sullivan and Perry 2013).

4.3.1 Model Initialisation

SourceSim begins with a bounded 33 x 33 grid of cells. Ten of these are randomly selected as geological sources of raw material, each defined by a unique identification number (0-9) and a variable that records how many extraction episodes occur at that source. An extraction episode can be thought of as a visit to the source, and involves the acquisition of some quantity of raw material in a single event. The locations of the geological sources are held constant across all simulation runs (Figure 4.1), except for the purposes of sensitivity analysis described below.

Each cell in the simulated world represents a location on the landscape that can contain an archaeological record in the form of discarded artefacts derived from any of the ten geological sources. The archaeological record for each cell is recorded as a list of numbers, where each number corresponds to a single artefact deriving from that geological source (0-9). Artefacts are distributed around the landscape by ten agents, each representing a group of people that can carry a maximum of 100 artefacts in their ‘toolkit’. This limit is needed to restrict the flow of material from geological sources into the simulated landscape to allow the potential for reuse of material. Groups follow a set of rules conditioning their movement and acquisition and use of material, and begin a simulation run with a full toolkit of artefacts derived from one of the geological sources.
Material from each geological source is treated as equal in terms of quality and (re)usability. Artefacts in SourceSim are simply considered as usable pieces of raw material and are abstract in terms of size and shape; for the purposes of the simulation experiment, specific features of artefacts other than the frequency of pieces and the geological sources from which they derive are unimportant. Each cell in the simulated landscape is considered uniform such that there are no extraneous factors biasing group movement, including previous occupation histories. Groups are treated as tireless and do not reproduce, die, or interact with each other. This neutrality (sensu Brantingham 2003) is important as the simulations effectively generate ‘null’ expectations, formed without recourse to any other processes not specified by the model. The simplicity of the model facilitates easier identification of underlying system dynamics that explain model outcomes, especially in the context of multiple interacting parameters.

4.3.2 Modelling Group Movement

The model procedures are presented in diagrammatic form in Figure 4.2. At each time step of the simulation there is a 25 % chance a group will move to a randomly determined target cell. Movement occurs as a ‘jump’ to the target cell regardless of the distance to that cell, with no visits or stops at intervening cells. In this way, movement is ‘directed’ in the sense that
groups move to a target destination (such as the movement of a ‘camp’) rather than moving progressively along a path (such as modelling forager movement) towards that destination. The 25% chance of moving at any given time step was selected as it allows for some mobility but with a bias towards remaining at a location for a longer period of time, a pattern not uncharacteristic of Māori settlement systems in Aotearoa (e.g., Allen 2012; Anderson and Smith 1996; Furey 2002; Phillipps et al. 2016).

Figure 4.2 Overview of SourceSim processes

4.3.3 Modelling the Acquisition, Discard, and Reuse of Material

After a group moves or opts to remain at their current location, if their toolkit is more than 50% full (i.e., contains a sufficient quantity of material), there is a 50% chance they will cache the material they are carrying at their current location if they have not already done so. This
simulates the process of a quantity of material entering a location for some reason other than immediate use in a task, the specifics of which are unimportant to the goals of the simulation experiment but could, for instance, reflect something akin to place provisioning (e.g., Kuhn 1995).

After moving and potentially caching, groups use up to five artefacts from their toolkit, randomly determined, for some arbitrary task. These artefacts are removed from the toolkit and added to the archaeological record of the current cell with a 50% chance of generating another piece of the same material, representing the products of striking a new sharp edge. It is assumed that only a sharp edge is needed for a task, therefore no distinction is made between flakes, cores, tools, or other formal artefact types, nor size and shape as described above. For the purposes of the simulation, it is also assumed all artefacts can always be reused, regardless of how many times they have previously been used. Of course, in reality there will be a point at which an artefact is no longer usable or is overlooked for use in favour of another artefact (such as a size cut-off, for example Lin 2018). However, it is possible that what is considered useful based on measures from stone artefact assemblages is in part influenced by archaeological collection and analysis strategies – for example, archaeologists often piece-provenience and fully analyse artefacts that are above a given size, with large quantities of smaller pieces or ‘shatter/debitage’ recorded based on raw count and weight alone (Holdaway and Phillipps 2021:148). Indeed, what archaeologists interpret as ‘useful’ may relate more to underlying essentialist notions which likely differ from the perspectives of people in the past (as discussed in Chapter 2). As noted previously, in the case of obsidian (assemblages of which provide the empirical test for SourceSim) even very small pieces potentially retain some utility. For these reasons – including the fact that the simulations here are exploratory, the amount of material groups can carry is set at the arbitrary value of 100, and what is of key interest is the distribution of materials relative to their geological origins – it is useful to exclude the added complexity of simulating limited artefact use-lives.

Since all material types are considered equal in terms of quality and (re)usability, the probability of an artefact of a given material type being discarded is dependent on the relative frequency of that material in the group’s toolkit (Brantingham 2003). If a group does not have enough material in their toolkit to complete a task, they will resupply with material. They do so by either accessing the nearest geological source to their current location, or by first seeking artefacts from nearby visible accumulations, only accessing a geological source if there are no visible accumulations available. Here, ‘nearby’ is defined as within a radius of
five grid cells from a group’s current location, reflecting a group’s ‘awareness’ of their local environment. When resupplying from a geological source, a group fills their toolkit to the maximum capacity of 100. When resupplying from an archaeological deposit, groups take as many artefacts as are available in that deposit, up to the amount required to reach the limit of 100 that can be carried (thus, if a group was carrying three artefacts and a deposit had 150 artefacts, they would pick up 97. If that deposit had 20 artefacts, they would pick up all 20). Similar to selecting an artefact to discard, the probability of selecting an artefact of a given material type from a deposit is dependent on the relative frequency of that material in the deposit. In the simulations, archaeological deposits of artefacts are considered visible when they contain a given minimum number of artefacts. For the simulation experiments here, that number is arbitrarily set at 25. The search radius of five grid cells and the 25-artefact minimum for visible deposits are chosen as it is necessary to impose some limit on the availability of material for reuse in order to allow for both reuse and visits to geological sources to occur. Theoretically, under the logic of the model increasing or decreasing these values would have the net effect of increasing or decreasing the availability of artefacts for reuse.

Three variables of interest are explored in the simulation experiments, which together capture the core aspects of the conceptual model outlined in the previous section. These are: 1) whether a group always returns to a geological source when in need of material, or first attempts to acquire material from visible archaeological deposits; 2) whether a given geological raw material source is discovered ‘first’ upon a simulation beginning, thus resulting in potentially larger quantities of material from that source initially entering the system; and 3) whether material from a given geological source is considered more ‘desirable’ than others, potentially resulting in that geological source being preferentially accessed by groups when acquiring material (Table 4.1). For the experiments here, the source ‘discovered’ first and the source that is ‘desirable’ are both set as source 0 (unless otherwise stated for the purpose of sensitivity tests described below). The same source is chosen for both parameters as this reflects ideas about the Tūhaua obsidian source in the Aotearoa empirical comparison (see Chapter 2). The simulation output relevant to the research goals here include patterning in the overall representation of different source materials over time, the distance of discarded artefacts to the geological source, the number of visits to each geological source, and the total number of artefacts produced. Lists of artefacts on each cell are recorded in a simulation every 50 time steps, along with the number of times a geological
The total number of artefacts in the discard record is recorded at the end of each simulation run.

### Table 4.1 SourceSim experiments and parameters

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Return to geological source (RTS)?</th>
<th>Discover?</th>
<th>Desirable?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>Always</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>1b</td>
<td>Always</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>1c</td>
<td>Always</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>1d</td>
<td>Always</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>2a</td>
<td>If needed</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2b</td>
<td>If needed</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>2c</td>
<td>If needed</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>2d</td>
<td>If needed</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>

1 Defines whether a group immediately returns to a geological source when in need of material
2 If yes, there is a 50% chance a group begins a simulation with material from source 0
3 If yes, when returning to a geological source, there is a 50% chance this will be source 0

### 4.3.4 Model Verification

A key procedure governing the distribution of material derived from different sources is the movement of the simulated groups. During each time step of the simulation, there is a 25% chance that a group will move to a randomly determined cell. To verify that the randomness and frequency of group movement were coded correctly and the processes were performing as intended, two tests were undertaken prior to running the simulation experiments. First, to assess the randomness of movement a single group was placed in the simulated world with a 100% chance of moving each time step. The simulated world was a square 33 x 33 cells in size, totalling 1089 cells. The simulation ran for 10,000 time steps with only the movement procedure active, and repeated 100 times, recording the number of times each cell was visited by the group at the end of each run. Theoretically, under conditions of randomness, over the course of 10,000 time steps the group should visit each of the 1089 cells an average of 9.2 times. Figure 4.3 presents the results of this verification test and shows that the number of visits to each cell are approximately normally distributed around a mean of 9.18 ± 3.0, conforming to expectations.

Second, to assess the frequency of movement a single group was placed in the same simulated world with a 25% chance of moving each time step. The simulation ran for 10,000 time steps with only the movement procedure active, and repeated 100 times, recording at the
end of each run the number of time steps in which the group moved. Theoretically, under these conditions the group should on average move during 2500 of the 10,000 time steps each run. Figure 4.4 presents the results of this verification test and shows how the number of group moves is evenly distributed around a mean of 2505.83 ± 45.1, conforming to expectations and indicating the movement procedure is operating as intended.

Figure 4.3 Histogram of number of visits per cell over 100 simulation runs. Red line marks the mean number of visits (9.18).

Figure 4.4 Histogram of number of group moves over 100 simulation runs. Red line marks the mean number of moves (2505.83).
It is also important to verify the functioning of the resupply procedure since this operationalises the assumption of people always returning to a geological source when in need of material, or first opting to reuse material. In the simulations, depending on the parameter setting a group will always access a geological source to gather material when their toolkit is empty, or alternatively will access a nearby visible accumulation of artefacts, only going to a geological source if no nearby accumulations are available.

To verify the groups were performing the resupply procedure as expected, three tests were performed. In each test, the model world was initialised with the following changes: all cells other than geological sources were seeded with 100 artefacts (1079 cells in total); the group search radius limit was removed; and a single group with an empty toolkit was created. The group remained in a fixed location for each test, and any material collected was instantly ‘used’ but not discarded, such that at the beginning of each time step the group’s toolkit was empty forcing them to resupply, and no new deposits of usable artefacts were created. Each test ran for 200 time steps.

In the first test, the group was set to always resupply from a geological source. It is expected that the nearest of the ten geological sources would receive 200 visits, and all other 1079 cells would still retain artefacts. The results in Table 4.2 show that expectations are met.

In the second test, the group first attempted to resupply from visible deposits of artefacts. Since in theory there is an ample number of cells containing artefacts, it is expected that no geological sources would receive visits, and 200 of the 1079 other cells would be depleted of artefacts. The results in Table 4.2 show that expectations are met.

In the third test, the group was set to first resupply from visible deposits of artefacts, though only 100 cells were seeded with artefacts. In this case, after 200 time steps it is expected that all cells would be empty of artefacts, and the nearest of the ten geological sources would receive 100 visits. The results in Table 4.2 show that expectations are met.

Further verification tests were performed as the model was written following guidance set out by Railsback and Grimm (2012) and Romanowska and colleagues (2021). Following protocols for clear communication of computer models set out at the end of Chapter 3, an Overview, Design concepts, and Description (ODD) document for SourceSim is provided in Appendix B, and model code is provided in Appendix C.
Table 4.2 Results of verification tests for the resupply procedure

<table>
<thead>
<tr>
<th>Test</th>
<th>No. visits to a geological source</th>
<th>No. cells with/without artefacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Always return to a geological source</td>
<td>200 (source 6) 0 (all others)</td>
<td>1079 / 0</td>
</tr>
<tr>
<td>Return to a geological source if needed</td>
<td>0 (all sources)</td>
<td>879 / 200</td>
</tr>
<tr>
<td>(ample visible deposits)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Return to a geological source if needed</td>
<td>100 (source 9) 0 (all others)</td>
<td>0 / 1079</td>
</tr>
<tr>
<td>(limited visible deposits)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.4 Model Exploration

The SourceSim experiments are outlined above in Table 4.1. Each simulation ran for 1000 time steps and was repeated 100 times to capture variation introduced by the stochastic elements of the model. While time and space are represented in each simulation, these are taken as abstract and not reflective of real-world time or distance. As noted, the simulations are exploratory, therefore it is the relative relationships between time, space, and resultant patterning in the distribution of artefacts of different material types that are of interest rather than a reconstruction of real-world conditions. The simulation output establishes broad patterns that are expected from a simple set of lithic acquisition and use behaviours in an otherwise behaviourally neutral situation.

4.4.1 Change in Geological Source Representation Over Time

Figure 4.5 plots the proportional representation of each material type in the total modelled assemblage over time, averaged across each of the 100 simulation runs. In instances where groups always return to a geological source when in need of artefacts (experiments 1a-d, upper row of Figure 4.5), on average proportions hold constant across the whole simulation run, with differences in proportions reflecting a combination of the position of a geological source in the modelled landscape and its location relative to others. For instance, leaving aside source 0 for a moment, source 8 is best represented proportionally due to its somewhat central (not an edge) location and relative isolation from other sources, meaning that for many locations in the modelled world, source 8 will be the closest source (Figure 4.1).
Figure 4.5 Change in overall proportions of the ten source materials over time, averaged across 100 simulation runs. The black line represents source 0. Refer to Table 4.1 for description of simulation experiment parameters.
However, in cases where source 0 is more desirable (experiments 1a and 1c), this material is invariably best represented simply because the geological source is accessed more frequently.

In instances where groups first attempt to obtain artefacts from archaeological deposits (experiments 2a-d, bottom row of Figure 4.5), the patterning is different when source 0 has a higher chance of first discovery but is not desirable (experiment 2b). In this case, the initial high representation declines over time before stabilising, with other materials increasing in abundance over time before stabilising. The inverse is true when source 0 has an equal chance of first discovery but is more desirable (experiment 2c), such that its proportional representation increases over time before stabilising. As before, preference for a particular material increases its relative representation in the total modelled assemblage. The initial discovery of a geological source affects initial proportions since an influx of material is introduced to the system, though this effect is only marked in cases where groups opt to source artefacts from visible deposits first (e.g., experiment 2b), since always returning to a geological source overrides any initial patterning by consistently introducing new material across a simulation run. Significantly, when more material of a particular type is initially introduced to the system due to being discovered first, while its relative representation declines over time, it nonetheless remains better represented overall than materials from other geological sources when material is primarily acquired from archaeological deposits (experiment 2b).

4.4.2 Geological Source Location Sensitivity

Geological source locations are held constant across all simulation runs. As noted above, the patterning in source representation shown in Figure 4.5 (in particular, experiments 1a-d, 2b, and 2d) suggests geological source location may be influencing patterning above and beyond the parameters of interest, since in the logic of the model access to a geological source is largely dependent on the distance from a group to that source. The impact of the spatial distribution of sources of material on archaeological patterning is also noted in other simulation studies. For instance, in his reworking of Brantingham’s (2003) original model, Pop (2016) found that the degree to which the geological sources in his simulation were exploited was dependent on the density and clustering of those sources – those sources that were more clustered were exploited less on the whole (Pop 2016:1144-1146). Similarly, in their model of small-scale transport of stone tools by primates, Reeves and colleagues (2021)
found that different spatial patterning in the archaeological record was created by varying the density of available resources even as the underlying agent behaviours were held constant.

For the above reasons, three further experiments were performed in SourceSim to test the sensitivity of simulated patterning to the location of the geological sources. These experiments were performed with the three main parameter settings according to one or both of experiments 2b and 2c since these experiments yielded unique results when compared with the others (Figure 4.5, Table 4.1).

The first sensitivity experiment (SE1) was performed using parameter settings from experiments 2b and 2c. In each case, source locations were held constant and then randomised for 100 simulation runs each, and the change in source representation over time was recorded. The results of SE1 are presented in Figure 4.6 and show how the relative relationships between proportions of the different sources stay the same regardless of whether source locations are held constant or randomised. When source locations are randomised, the average representation of sources other than source 0 is more constrained with proportions clustering more tightly around mean value. This is expected since source locations are randomised thus averaging out any differences caused by extreme locations.

The second sensitivity experiment (SE2) was performed using parameter settings from experiment 2b, and geological source locations were held constant. However, the source with a higher chance of first discovery was varied, with simulations running 100 times for each of the ten sources. The results are presented in Figure 4.7. Regardless of which source has a higher chance of being discovered first, the patterning in source representation remains the same in each case. Despite declining in proportion over time, the source that has a higher chance of first discovery is consistently best represented, with minor differences between sources due to the location of the source as discussed above. However, source location is not enough to change the relative patterning.

Finally, the third sensitivity experiment (SE3) was performed using parameter settings from experiment 2c, and geological source locations were held constant. However, the source considered more desirable was varied, with simulations running for 100 times for each of the ten sources. The results are presented in Figure 4.8. Similar to SE2, regardless of which source is considered desirable, the patterning in source representation remains the same in each case.
Figure 4.6 Results of SE1 showing the change in overall proportions of the ten source materials over time, averaged across 100 simulation runs, for experiments 2b (left) and 2c (right) when geological source locations are held constant (top) and randomised (bottom). The black line represents source 0.
Figure 4.7 Results of SE2 showing the change in overall proportions of the ten source materials over time, averaged across 100 simulation runs, for experiment 2b when geological sources are held constant but the source that has a higher chance of first discovery changes. The black line represents source 0.
Figure 4.8 Results of SE3 showing the change in overall proportions of the ten source materials over time, averaged across 100 simulation runs, for experiment 2c when geological sources are held constant but the desirable source changes. The black line represents source 0.
Overall, the geological source location sensitivity tests suggest that insofar as the world as modelled is concerned, the location and density of geological sources does not have a marked impact on patterning in source representation. Put another way, the three main parameters of interest override any effects of geological source location on the overall distribution of material deriving from those sources. It may be the case that the modelled geological source density is simply not high enough to have an impact on the resultant patterning in raw material distributions. This remains to be tested though this is beyond the scope of the purpose for which SourceSim was constructed, as set out in the earlier sections of this chapter.

4.4.3 Number of Visits to Geological Sources and Total Number of Artefacts

Whether existing deposits of artefacts are exploited as sources of usable material or not will impact the frequency with which people need to access a geological source of raw material. Unsurprisingly, in simulations where groups always return to a geological source to acquire material (experiments 1a-d), the total number of source visits is one or two orders of magnitude larger than when groups first attempt to exploit existing deposits of artefacts (Figure 4.9). In cases where source 0 is more desirable, it receives many more visits than other sources (experiments 1a, 1c, 2a, and 2c), with the average number of visits to other sources much lower and varying according to the location of the source within the modelled landscape. Under the modelled conditions, when groups opt to reuse artefacts only a handful of visits to geological sources is necessary to introduce sufficient material into the system for groups to use.

A similar pattern is true of the total assemblage size for each set of simulations. In cases where groups always return to a geological source to acquire raw material, the total number of artefacts produced is an order of magnitude larger than when groups reuse artefacts from visible deposits. This makes sense since under the logic of the model, each visit to a geological source introduces 100 new artefacts into the system, whereas reusing previously discarded artefacts may introduce one new object per artefact used (representing the product of resharpening) or indeed, may not create another artefact at all.

The figures for the number of visits to geological sources and total number of artefacts are reflective of the world as modelled and cannot be directly compared with empirical data. However, they nonetheless show how the need for access to geological sources is curtailed to a large degree when previously discarded artefacts are exploited as sources of usable
Figure 4.9 Number of visits to geological sources (bars) and total number of artefacts (centre of each plot) averaged across 100 simulation runs. Error bars and terms are one standard deviation. Note y-axis scales vary between rows.
material. The relative patterning in the simulated data is useful for contextualising the patterning in data from the empirical case, discussed further below.

4.4.4 Distance Decay

As discussed in Chapter 2, distance decay or fall-off patterns are often used in lithic sourcing studies to make inferences about the mode of raw material procurement, where it is generally expected that the frequency or proportion of artefacts of given raw material types will decline with increasing distance from the geological source. This appears to hold true for SourceSim in cases where groups always return to a geological source when in need of material (experiments 1a-d). Figure 4.10 displays the average proportion of source 0 material in grid cells (‘sites’) at increasing distances from the geological source. In the simulations where groups always return to a geological source (left half), a distance decay relationship is evident which tends to become more pronounced over time (moving down the rows). In each case, the results of Spearman’s rho tests suggest the negative correlation between the average proportion of material 0 and distance to source 0 is generally moderate, and statistically significant at $\alpha = 0.05$ in all cases bar two (experiment 1c at 100 and 250 time steps).

In cases where groups attempt to obtain material from existing deposits of artefacts (experiments 2a-d, right half of Figure 4.10), the average proportion of material 0 at sites does not tend to vary with increasing distance from the geological source. Spearman’s rho tests suggest correlations are generally weak to moderate and not statistically significant, with the slope of the trend lines generally flatter than in experiments 1a-d. Two cases stand out as different to the general trend, where experiments 2a and 2c show statistically significant, moderate-strength, positive correlations at the 1000 time step mark. In both of these experiments, source 0 is considered more desirable, thus proportionally more of that material will enter the system compared to other simulation runs, and be distributed further from the geological source via the process of reuse. Overall, the lack of any increase or decrease in proportions of material from source 0 with distance from the geological source demonstrates how distance decay effects are nullified and local/non-local source distinctions are obscured when ‘sources’ are simply visible accumulations of material.
Figure 4.10 Average proportion of material derived from source 0 at sites at increasing distances from geological source 0. Columns represent simulation experiments and rows represent time (as measured by time steps). Test statistics are Spearman’s rho.
4.4.5 Sites Where Material 0 is Dominant

In simulation runs where material from source 0 is more desirable (experiments 1a, 1c, 2a, and 2c) groups will on the whole access that geological source more frequently. As a result, material from source 0 is the dominant material at more sites than it is not, and this pattern holds true in all instances except earlier in simulations for experiment 2c (Figure 4.11). In all other simulation experiments, there a relatively few sites where material from source 0 is dominant, with the exception of experiment 2b (where groups first obtain artefacts from visible deposits, there is a greater chance of discovering source 0 first, and all sources are equally desirable). In this case, there are proportionally more sites where material from source 0 is dominant compared to other simulation runs, and the difference between the number of sites where it is dominant material and where it is not is smaller than for other simulation runs. This suggests that the initial greater influx of material deriving from source 0 (due to the higher chance of being discovered first) is enough to result in increased proportions at sites across the length of the simulation runs.
Figure 4.11 Average number of sites where material from source 0 is the dominant material type present. Error bars are one standard deviation.
To summarise, the results of SourceSim provide a set of predictions about what archaeological assemblages containing artefacts of different geological origins might look like were the simulated processes in operation:

- **When people always return to a geological source when in need of stone material**, geological source representation in the assemblage will remain relatively even and stable over time (experiments 1a-d), unless a given geological source is desirable in which case that material will always occur in a higher proportion than any other material type (experiments 1a and 1c).

- **Under conditions of reuse** (experiments 2a-d), geological source proportions in the assemblage will remain relatively even over time, except:
  - when a given geological source is discovered first and is desirable (therefore accessed more frequently), that material will occur in a stable higher proportion than other materials over time (experiment 2a); and
  - when a given geological source is discovered first but all material types are equally desirable, the initial proportion of the material discovered first will be high, declining over time but still remaining better represented than other material types (experiment 2b); and
  - when a given geological source is desirable, that material will increase in proportion over time relative to other material types (experiment 2c).

- **When people always return to a geological source when in need of stone material**, the proportion of different material types at sites will decline with increasing distance from their geological sources (experiments 1a-d).

- **Under conditions of reuse**, the representation of different material types at sites will remain relatively even and stable irrespective of the distance from their geological sources (experiments 2a-d).

- **When a given material is desirable**, it will generally be the dominant material type at sites over time (experiments 1a, 1c, 2a, 2c). In all other instances it will be the dominant material at few sites, except:
  - when artefacts are reused, when that given material is discovered first, and when all material types are equally desirable, that material will be dominant at a larger number of sites (experiment 2b).
In the following section, these predictions are tested in turn using empirical obsidian assemblage data from sites located across Aotearoa.

4.5 Comparison with Aotearoa Obsidian Distributions

The empirical Aotearoa obsidian data sets used here derive from several published sources, with each encompassing 58 to 65 assemblages and from 4942 to 13,184 artefacts in total (Table 4.3). These data are considered as three distinct data sets in the comparison with the SourceSim outcomes for three reasons, which prevent their aggregation into a single data set: 1) some assemblages appear in more than one data set as some of the published sources themselves constitute surveys of existing obsidian data; 2) data are presented in different ways in the original sources such that they cannot be amalgamated; and 3) geological sourcing protocols vary between the published sources, and therefore should be considered separately. Where possible, assemblages are divided into pre- and post-1500 CE (early and late) based on published radiocarbon dates, with the exception of data from Seelenfreund-Hirsch (1985) where the original tripartite scheme is retained (Table 4.3 footnote). The division at 1500 CE follows other Aotearoa literature and is roughly correlated with changes in material culture and art forms, and the construction of pā (defended settlements) (e.g., Walter et al. 2010). The names and locations of sites in each data set are available in Appendix A, along with descriptions for those sites specifically named in the text.

When analysing the proportional representation of stone artefacts, it is important to consider the methods by which those proportions are quantified. The abundance of material in a given assemblage can be quantified in a number of ways, but most often is done so in terms of counts or mass (Mears et al. 2022; Phillipps et al. 2022b). Phillipps and colleagues (2022b) discuss differences in stone artefact quantification methods using two assemblages from Aotearoa as examples, noting how artefact counts provide frequencies but are indifferent to artefact size, whereas mass does consider artefact size which is of use when absolute volumes of material are of interest. They demonstrate how the relative proportion of different raw material types in their study assemblages varies depending on the quantification method used (e.g., Phillipps et al. 2022b: Figure 1). This suggests there is no one ‘correct’ method for calculating abundance. What is important is understanding the basis for any differences when deriving interpretations based on the relative abundance of artefacts of different material types in an assemblage (Phillipps et al. 2022b).
Table 4.3 Aotearoa archaeological obsidian assemblage data sources

<table>
<thead>
<tr>
<th>Data source(s)</th>
<th>Pre-1500 CE assemblages</th>
<th>Post-1500 CE assemblages</th>
<th>Indeterminate date</th>
<th>Total assemblages</th>
<th>Total artefacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown and Pitman (2019); McBride (2019); McCoy et al. (2019)</td>
<td>31</td>
<td>16</td>
<td>12</td>
<td>59</td>
<td>6107</td>
</tr>
<tr>
<td>Seelenfreund-Hirsch (1985)¹</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>58</td>
<td>4292</td>
</tr>
<tr>
<td>Leach and de Souza (1979)</td>
<td>35</td>
<td>30</td>
<td>0</td>
<td>65</td>
<td>13,184</td>
</tr>
</tbody>
</table>

¹Assemblages split into three chronological groups: 630 BP and older (18), 630-350 BP (25), 350 BP to present (15), directly translated to BCE/CE format here as pre-1320 CE, 1320-1600 CE, and post-1600 CE.

Ideally, for comparison with simulation outcomes it would be useful to quantify the proportional abundance of different obsidian types in the empirical assemblages using both counts and mass, since raw frequencies of artefacts and volume of material are both important when considering artefact transport and the availability of material for reuse. However, among the three data sets artefact mass is not reported by Leach and de Souza (1979), is only reported for Tūhua obsidian by Seelenfreund-Hirsch (1985), and is reported for around only half of the assemblages from the remaining sources (Brown and Pitman 2019; McBride 2019; McCoy et al. 2019). For these reasons, frequency data are used in the empirical comparison with the simulation outcomes since this is the only abundance measure common to all data sources.

However, the assemblages where the mass of individual artefacts is recorded may be explored to determine the extent to which obsidian source proportions based on frequencies and mass are correlated, potentially providing a measure of confidence in the frequency measures alone. Figure 4.12 plots the proportional representation of different obsidians based on frequency and mass. The results of a Spearman’s rho test show a statistically significant strong correlation between the two variables (rho = 0.91, p < 0.001). This suggests that on the whole, using only frequency as the abundance measure when comparing the empirical and simulated data is not likely to yield significantly different results than if mass was also used.
4.5.1 Change in Geological Source Representation Over Time

Figure 4.13 shows the change in overall obsidian geological source representation over time for each of the three empirical data sets. In each case, the overall proportion of Tūhua obsidian (henceforth TO) declines over time while the proportion of obsidian deriving from other geological sources stays relatively constant or increases. While in the later periods the proportion of TO is equalled by other obsidians, it nonetheless remains one of the more dominant sources represented. This patterning is most similar to the outcome of simulation experiment 2b, in which groups obtained artefacts from visible deposits, where source 0 had a higher chance of first discovery, and where all materials were equally desirable.

4.5.2 Distance Decay

Depending on the data set and broad time period under consideration, the relationship between the proportion of TO at a site and distance from Tūhua varies (Figure 4.14). In general, the correlations are of weak to moderate strength but not statistically significant (based on Spearman’s rho tests – see individual plots in Figure 4.14 for test statistics). The exception is among the earliest sites in the Seelenfreund-Hirsch (1985) data set, where there
Figure 4.13 Average proportion of different obsidians at sites over time based on artefact counts. (A) Data from Seelenfreund-Hirsch (1985). Error bars are one standard deviation. C = Coromandel, I = Inland, FI = Fanal Island, GB = Great Barrier Island, H = Huruiki, MI-T = Mayor Island/Tūhua, N = Northland, O = Other, U = Unknown. (B) Data from Brown and Pitman (2019), McBride (2019) and McCoy et al. (2019). Error bars are one standard deviation. (C) Data from Leach and de Souza (1979) for Tūhua obsidian only. Test statistics are Spearman’s rho.
Figure 4.14 Change in proportion of Tūhua obsidian over time with increasing distance from the geological source, based on artefact counts. Distances are measured as Euclidean distance. (A) Data from Seelenfreund-Hirsch (1985). (B) Data from Brown and Pitman (2019), McBride (2019) and McCoy et al. (2019). (C) Data from Leach and de Souza (1979). All test statistics are Spearman’s rho.
is a statistically significant positive correlation of moderate strength (Figure 4.14 (A), leftmost plot). This patterning is consistent with some observations that early sites with less than 50% TO are rare, particularly on Te Waipounamu (South Island; e.g., Lawrence et al. 2014:160). However, the patterning overall (or lack thereof) runs counter to claims of a general distance decay trend amongst Aotearoa archaeological obsidian distributions (e.g., Walter et al. 2010; but see Leach 1978; Seelenfreund and Bollong 1989).

In the simulation experiments, a statistically significant distance decay pattern for material 0 was generally only observed when groups always returned to a geological source when in need of stone material (Figure 4.10, left half). The observed empirical patterning does not meet this expectation. Rather, the empirical Tūhua pattern most closely resembles that produced in simulation experiments 2a-d, when groups acquired artefacts primarily from visible deposits (Figure 4.10, right half).

4.5.3 Sites Where Tūhua Obsidian is Dominant

Figure 4.15 shows how the proportion of sites where TO is the dominant obsidian type decreases over time (note, data from Leach and de Souza (1979) are not included since only proportions of TO were supplied, therefore dominance of TO could not always be ascertained). This pattern follows general observations of increased abundance of TO in earlier relative to later sites (e.g., Furey 2002; Green 1964). However, based on the simulation results this patterning is not consistent with what would be expected were people always accessing a geological source when in need of material, as this would result in a dominance of TO in more assemblages than not (if ‘desirable’, experiments 1a and c) or the reverse (if not ‘desirable’, experiments 1b and 1d, Figure 4.11). Rather, the empirical patterning most closely resembles that produced in experiment 2b where groups acquired artefacts from visible deposits, and geological source 0 had a higher chance of first discovery.

However, the match is not as strong as for other measures reported above. In simulation experiment 2b, there are always more sites where material 0 is not dominant than where it is, and this difference becomes more pronounced over time (Figure 4.11). In the empirical data sets, TO is dominant at more sites than not in the earlier period(s), a trend which reverses later in time (Figure 4.15). Interestingly, the patterning in dominance of TO earlier in time resembles the pattern in simulation experiments 1a and 2a, where material from geological source 0 is considered ‘desirable’. In the context of the simulations, ‘desirability’ has the net effect of increasing the amount of material of a given type entering the system. This suggests
the possibility that the observed dominance of TO at earlier sites may be a simple function of the amount of material that was initially extracted compared to other geological sources, a suggestion supported by observations of large, readily available boulders of obsidian on Tūhua compared to other sources (e.g., Sheppard 2004).

4.5.4 Summary of SourceSim and the Empirical Comparison

The simulations presented above were constructed to test the effects of acquiring usable material from visible deposits of discarded objects – places other than geological sources – on archaeological distributions of material. The simulations yielded patterns in the distribution of stone artefacts from different geological sources that might be expected were the conditions as modelled in effect in some form. These expectations were tested using data on archaeological obsidian distributions in Aotearoa. Based on several measures including overall geological source representation, distance decay patterns, and the dominance of specific materials at different sites, it was found that empirical patterns most closely resembled the simulation experiment in which groups first acquired material from visible deposits of artefacts rather than always accessing a geological source, where one geological source had a higher chance of first discovery, and where all materials were equally desirable.
This finding runs counter to many studies that use sourcing data to make inferences about
mobility and forms of social interaction based on the nature of access to raw materials, which
are often based on the implicit, essentialist assumption that people always accessed a
geological source when in need of stone material. This is not to suggest that the
correspondence between specific simulation results and empirical patterning means such
processes were in operation in the past and others were not. Of course, the simulations are
highly simplified and not precise reconstructions of reality, but nor were they intended to be.
Instead, the simulations provide a sense of what kinds of processes lead to different types of
patterning, and are useful for contextualising observed empirical patterning and suggesting
further tests of the data.

4.6 Contextualising Archaeological Obsidian Use and Distributions in Aotearoa

In SourceSim, the ‘desirability’ parameter governs the amount of material of a given type that
tears the system upon groups accessing a geological source. There is ethnographic evidence
to suggest that in Aotearoa some obsidians were more desirable than others insofar as
different obsidians were used by Māori for different tasks. For example, White (1875)
observed how people used four different colours of Tūhua obsidian for specific tasks: black
for processing moa; light-coloured for cutting themselves when mourning the dead; green
when the dead were chiefs or children, or for cutting hair; and red when the dead were head
chiefs or priests. Colour may also have distinguished different obsidians for the purposes of
gifting, differentiating local from exotic material (McCoy and Carpenter 2014). Indeed, in
some contexts raw material acquisition or preference may not be viewable simply in terms of
rational, economic costs and benefits, but might be rooted in more complex social and ritual
values such as those enmeshed within Māori worldview and which may vary between
different kinship groups (hapū) and tribes (iwi) (see Allen 1996; Ladefoged et al. 2019;
Leach 1978; McCoy and Carpenter 2014; Sheppard 2004 for examples).

In the SourceSim experiment that most closely corresponds with empirical patterning,
‘desirability’ is not a factor. This raises the possibility that any preference for certain obsidian
types in the past was not a strong enough force such that its effects are detectable in empirical
archaeological artefact distributions. This is worth considering in the context of reuse of
material from visible deposits of previously discarded objects. Holdaway and Phillipps
(2021:151) note how when confronted with a deposit of objects derived from different
geological sources, the selection and treatment of raw material, as well as supposed
technological categories such as flakes and cores, may have been equal since the objects in the deposit now represent a single new source of material. Or, to return to Lucas’ (2012) terminology, once artefacts enter the archaeological record, they materialise as a new source, and any previous functional manifestations of those artefacts may dematerialise.

The ‘discover’ parameter in SourceSim governs the amount of material of a given type that initially enters the system. This parameter does factor in the SourceSim experiment whose results most closely approximate the empirical case. In the simulation, it is geological source 0 that has the higher chance of first discovery (i.e., potentially more groups enter the simulated landscape carrying this material). At first, the proportion of material 0 in the simulated assemblage is very high, but this declines over time as other source materials become better represented. Nonetheless, material 0 remains the dominant material type over time. In some respects, this patterning lends support to Green’s (1964) suggestion that the relative abundance of TO in early archaeological sites is due to the Tūhua geological source being the first discovered by people arriving in Aotearoa. However, in a later study Leach and de Souza (1979) explored Green’s idea in more detail with a larger data set and concluded that just as many assemblages conformed to expected patterning as did not, regardless of age or distance to Tūhua. Therefore, the proportion of TO in assemblages cannot be used for the basis of constructing relative chronologies as Green (1964) attempted to do. Leach and de Souza (1979) noted how the reason why some assemblages did or did not conform to the pattern of decreasing reliance on TO over time was not easy to determine. The results of the simulation experiments suggest that redistribution of material through reuse may be an explanation. Initially, proportions of different material types vary as different materials enter the system at different rates once they are discovered, but later in time the pattern stabilises as the materials simply become part of the landscape and are moved around through reuse.

The significance of the ‘discover’ parameter may be thought of in an alternative way. If ‘discover’ governs the amount of material entering the system from a given geological source, this prompts a consideration of the quantity of material available at a geological source for removal, since under the logic of the model the net effect of first discovery or greater quantity of material available are theoretically similar. As noted above, Tūhua is different from other geological obsidian sources due to its physical manifestation as a variety of nodules, boulders and seams, most easily accessible on beaches via water transport (Moore 2012; Sheppard 2004). Therefore, there was simply more TO available compared to other
geological sources, and more could enter the system in one go. Certainly, the simulation experiments suggest that in cases where people always returned to a geological source when in need of material, the abundance of material 0 (here a proxy for TO) remains very high compared to other materials and does not change in relative abundance over time (it should be noted that in the simulations, subsequent visits to geological sources result in the same amount of material extracted irrespective of the source – but extracting more material from source 0 would simply have the net effect of further increasing its relative abundance).

However, this patterning in relative abundance of different material types is not the case for the empirical Aotearoa obsidian patterning, where the relative abundance of TO declines over time and differences between source materials become less stark. This raises questions about the volume of material actually represented in the empirical assemblages, and the frequency with which new material from the geological sources was extracted.

When comparing simulations where groups always return to a geological source when in need of material (experiments 1a-d) with those where artefacts are first acquired from visible deposits (experiments 2a-d), there is a large difference between the total number of artefacts (volume of material) produced, resulting in around 210,000 versus 18,000 objects on average, respectively. Similarly, there is a large difference in the number of visits to geological sources, with experiments 2a-d resulting in only a handful of visits to each geological source (Figure 4.9). While the absolute numbers of artefacts and visits to geological sources in the simulations are not directly comparable with real-world quantities, these results nonetheless provide further context for the empirical obsidian assemblages in terms of the volume of material represented and the frequency of visits to geological sources required to account for the material present across the archaeological assemblages.

In considering the volume of obsidian represented in the Aotearoa assemblages, precise calculations are difficult but rough ball-park estimates are possible based on available data. For the combined Brown and Pitman (2019), McBride (2019) and McCoy et al. (2019) data sets, the average mass of an obsidian artefact based on those assemblages where mass was recorded is 5.15 g, resulting in an estimate of 31.5 kg of material based on 6107 artefacts across 59 assemblages in the data sets. Similarly, data from Seelenfreund-Hirsch (1985) suggest a mean mass of 6.06 g per artefact, resulting in an estimate of 26 kg of material based on 4292 artefacts across 58 assemblages. At Houhora, Furey (2002) reported over 3700 obsidian flakes totalling over 23 kg in museum collections, with a further 16 kg of excavated obsidian artefacts. At Kohika, a total of 8982 obsidian artefacts results in an estimate of 34.4
kg of material based on available data – an average mass per artefact of 3.83 g (Haysom 2009; Holdaway 2004). Further still, Holdaway and Phillipps (2021:145) report over 18,000 obsidian flakes greater than 20 mm in size at Waitapu, Ahuahu (for the location and description of named sites, see Appendix A). The Houhora, Kohika, and Ahuahu collections represent some of the largest obsidian assemblages from single locations in the country. Conservatively using the highest mean artefact mass estimate of 6.06 g as representative of all Aotearoa obsidian artefacts on average, the total mass of all objects across the assemblages mentioned above (in excess of 41,000 artefacts) is approximately 249 kg. Of course, this estimate is rough and does not include assemblages from unpublished commercial/consultant reports nor the often-unreported quantities of ‘shatter’ found at sites. However, the estimate includes several dozen assemblages from across Aotearoa, including some of the largest recorded in the country. Therefore, any additional assemblage information is unlikely to increase the total volume estimate considerably.

Put into this context, the total volume of archaeological obsidian in Aotearoa might be explained by only a few visits to geological sources, rather than reflecting a need to regularly access geological sources over time. The transport of large, heavy boulders with the potential to yield thousands of artefacts was certainly possible using canoe transport. Seelenfreund-Hirsch (1985:269) notes the recovery of a block of obsidian weighing 54 kg from North Canterbury on Te Waipounamu, and Leach and Manly (1982:100) note two blocks of Tūhua obsidian found on the Otago coast in the south of Te Waipounamu, describing them as ‘large’. These few cases are explicit examples of transported sources of raw material. The point of the hypothetical quantity exercise is not to suggest that people in the past never did return to a geological source of obsidian beyond the first visit, but rather suggests the need to carefully consider underlying, often hidden, assumptions about such processes and the extent to which they are responsible for structuring the patterning archaeologists observe.

Further in-depth testing of the simulation outcomes would require detailed technological analysis to help distinguish between competing explanations for observed patterning in obsidian distributions. Studies in Aotearoa that do include a technological component tend to report little beyond size and cortex retention. These variables are usually used to infer mode of procurement. For instance, McCoy and Carpenter (2014) suggest obsidian artefacts obtained via direct procurement from the geological source should be larger and include a significant amount of cortex (but see Moore 2015). However, this does not hold when considering sites close to Tūhua itself, with McBride (2019) suggesting the highest recorded
presence of cortex at sites located in close proximity to Tūhua was 15% in the Kohika assemblage (Holdaway 2004). This could reflect the collection of low quantities of cortical obsidian, removal of cortex before transport, or high availability of non-cortical cobbles on the island (Sheppard 2004). In a technological analysis of the Waitapu and Houhora obsidian assemblages that included variables beyond size and cortex retention, McBride (2019) found no difference in the treatment of Tūhua obsidian compared to other types. Based on measures of reduction intensity, he suggested the treatment of obsidian at Waitapu reflected a seemingly unrestricted supply. At Houhora, it seemed that people did not need to access Tūhua based on similarities in the reduction of obsidians from different geological sources. In an earlier technological analysis, Seelenfreund-Hirsch (1985:271) commented on the remarkable uniformity in artefact manufacture across Aotearoa irrespective of distance from the source, a pattern not unexpected in the context of reuse.

There are not sufficient data to conduct a detailed analysis of the empirical assemblages considered in this study. However, the simulation experiment of interest – experiment 2b – allows one to propose other tests of the data to further determine the extent to which the simulation parameters explain observed empirical patterning. For example, were reuse of obsidian artefacts occurring, as noted above one might expect to find no major differences in the treatment of obsidians from different geological sources regardless of distance to the source. Furthermore, one might expect disparities in the traditional linear reduction sequence continuum reflecting raw material acquisition, core preparation, production of primary flakes and debitage, and further working into retouched tools (e.g., Figure 4 in Dibble et al. 2017:824). For instance, there may be an overall lack of retouch in assemblages, with little differentiation in the use of flakes categorised as ‘complete’ or ‘broken’, and with usewear occurring on artefacts belonging to different technological categories.

Holdaway and Phillipps’ (2021:151-152) discussion of the Waitapu and Houhora obsidian assemblages provides an example of what such an analysis might look like. At Waitapu, Tūhua is the most commonly represented geological source of obsidian rather than the closer geological sources on the east coast of the mainland, whether by count or mass. There is also no correlation between the frequency and size of artefacts from different geological sources. The pattern is similar for Houhora, with closer geological sources underrepresented at the site compared to Tūhua (McBride 2019). Holdaway and Phillipps (2021) also report that at Waitapu, there is no significant difference in the mass and length of complete and broken flakes, and retouch is limited to only five artefacts. In another analysis of the Waitapu
assemblage, Young (2019) showed that approximately one third of the assemblage exhibited usewear. Based on these observations, Holdaway and Phillipps (2021) suggest that overall, the Waitapu assemblage is not heavily utilised in the sense of the production of formal retouched tools, but usewear does indicate obsidian was used to work a variety of materials. This use is no more intensive among obsidian from more distant geological sources, and there is no indication that usewear on broken artefacts occurred before breakage. Furthermore, a large proportion of cores occur on reused broken or complete flakes deriving from a range of geological sources, with no correlation between core size and geological source. While the results from the Houhora assemblage are more limited, Holdaway and Phillipps (2021) suggest on the whole they are similar to Waitapu. While only representing one example of an analysis (albeit from two of the largest obsidian assemblages in Aotearoa), Holdaway and Phillipps’ (2021) results generally support the expectations derived from thinking through the SourceSim outcomes. The lack of simple reduction sequences, such as the typical sequence noted by Dibble and colleagues (2017), suggests the obsidian artefacts at Waitapu and Houhora have complex life histories which include multiple episodes of use and reuse (Holdaway and Phillipps 2021).

4.7 Conclusion

Thinking about the lithic record from a materialist perspective prompted a reassessment of how lithic technology is used to infer mobility and associated behaviours based on the sourcing of lithic objects. One proxy for the source of an artefact is its geological origin, which is commonly used in interpretations of mobility and the mode of procurement of lithic material. However, the reuse of artefacts from visible deposits of previously discarded artefacts blurs local/non-local source distinctions and means there are places other than geological sources where usable raw material is found. This has an impact on inferences about mobility that underlies other behaviours such as trade and exchange or the development of social networks. An exploratory agent-based model was used to explore the simple acquisition and movement of artefacts made of different material types to and from different places in the landscape, and how the resultant distributions patterned in different ways. The simulation outcomes provided a set of expectations that were evaluated using data on archaeological obsidian assemblages from across Aotearoa. Similarities between simulation output and the empirical record suggest the processes implicated in the simulations are worthy of closer consideration.
Specifically, the closest correspondence between empirical assemblage patterning and simulated assemblage patterning occurred for simulations where groups acquired and reused artefacts from visible deposits when in need of material, as opposed to immediately returning to a geological source. Also of significance was the initial discovery of geological sources, which affected the amount of material of a given type entering the landscape and becoming available for reuse. Based on the simulation parameters, further tests of the empirical data were proposed and though data were limited, initial results also suggest a close correspondence.

That people did not necessarily return to a geological source when in need of raw material is not a revolutionary suggestion, and of course, the actual acquisition of material is likely to fall between the two extremes of always returning and never returning to a geological source. In the absence of any kind of social interaction in the simulations, the results of the SourceSim and empirical assemblage comparison may prompt the question of whether trade and exchange or the development of territorial behaviours and social networks occurred in the past, be it in Aotearoa or any other context where such behaviours might reasonably have taken place. Undoubtedly, they did. Indeed, the archaeological outcome of some form of exchange behaviour such as down-the-line exchange, as hypothesised by McCoy and Carpenter (2014:3-4) for instance, might potentially manifest in a similar way as artefacts that are distributed through reuse without any contact between individuals. The point is that fundamentally, both phenomena can be broken down to forms of mobility – an issue of equifinality – though they are based on different sets of assumptions. The significance of this study, and for addressing the wider indeterminacy issue, lies not in inferring any one mechanism exclusively over another, but rather in highlighting the need to carefully assess underlying assumptions and understanding the basic set of processes and generative mechanisms that influence the patterning archaeologists observe.
Chapter 5

Mobility and the Organisation of Technology: ClusterSim

This chapter presents a justification for modelling based on interpretive differences regarding the distribution of lithic artefacts of different technological types and how these relate to mobility. As discussed in Chapter 2, inferences based on the form of artefacts are founded on essentialist assumptions about the intentional manufacture of artefact forms and their presumed functioning in the past. Related to this is an incomplete understanding of the temporalities of artefacts and how they come to be associated in assemblages. The focus on the form and manufacture of lithic artefacts appeals to behavioural phenomena thought to be substantively uniformitarian, where past and present processes are considered similar enough that the present can inform on the past. The result is often multiple different explanations for the same observed patterning.

An alternative way to assess mobility is to build inferences from the ground-up, based on principles that are methodologically uniformitarian or in other words, hold constant through space and time. The use of methods employing geometric principles to quantify the physical movement of artefacts by identifying the supplementation or loss of stone material was advocated (Chapter 2) since these methods are not concerned with understanding precise manufacture sequences or the typology of lithic artefacts. In this chapter one such method for analysing the physical movement of artefacts is presented based on the association of flakes with their parent cores, and the extent to which all products of reduction are present or missing from an assemblage. A model, founded upon existing simulation work (Davies 2016; Davies et al. 2018), is conceived in which agents move within a window of observation to varying degrees while producing, discarding, and reusing flakes and cores, and potentially removing artefacts from the simulated assemblage, leaving behind flakes and parent cores that form reduction sets that are missing artefacts to varying degrees. The conceptual model is translated into a formal exploratory simulation to consider various combinations of these processes and how they impact the movement of lithic material into and away from the simulated assemblage and thus the ‘completeness’ of individual reduction sets. The resultant patterns serve as hypotheses that are tested using empirical data on stone artefact assemblages from Lake Mungo and Rutherfords Creek in Australia.
5.1 Model Justification

As discussed in Chapter 2, many mobility studies draw on Binford’s (1978, 1980) forager and collector modes of resource acquisition and associated residential and logistical mobility strategies, in which functional site types link settlement pattern and mobility. These are typically defined by the distribution and density of artefact forms thought to be intentionally manufactured as such (e.g., Torrence 1983; Wallace and Shea 2006). However, Binford developed his models to help understand the organisational structure of the material record, with his observations occurring at the ethnographic scale. Therefore, his models are not directly applicable as explanations for the long-term patterning characteristic of the archaeological record. Artefacts accumulate in the archaeological record with varying temporalities which may or may not be knowable and therefore may not be relatable to commonly used models of mobility (Bailey 2007; Lucas 2012; Holdaway and Davies 2020; Olivier 2011; Shott 1989). Furthermore, if accumulations of artefacts represent defined site types, this assumes the artefacts functioned as specified. But artefacts have different life-histories and are composed of shifting sets of relations rather than some essentialised properties (Dibble et al. 2017; Holdaway and Phillipps 2021; Iovita et al. 2021). Therefore, analysis and interpretation cannot focus solely on manufacture and assumed end-products.

A materialist perspective prompts a critical rethink of statements about the past based on common approaches to the lithic record. While such critiques are not new, they are expressed in recent literature that interrogates the concepts of linear manufacture sequences and intentional end products in lithic analyses, highlighting the important role of selection, reuse, and variable life histories of lithics in shaping assemblage composition (e.g., Amick 2007, 2015; Coco et al. 2020; Dibble et al. 2017; Holdaway and Douglass 2012; Holdaway and Phillipps 2021; Rezek et al. 2020). For example, in their discussion of Middle Palaeolithic assemblages, Turq and colleagues (2013) suggest that many types of artefacts including those typically considered ‘debitage’ were targeted for transport and use, and recycling of lithics was probably much more common than otherwise thought. Through refitting and proveniencing studies, they show how multiple episodes of stone working and reuse constantly formed new associations among artefacts through space and time, and suggest this should be of primary interest to researchers rather than complete reduction sequences. In other words, patterning in assemblage composition emerged from a range of lithic production, transport, reuse, and discard events (Rezek et al. 2020; Turq et al. 2013).
Studies like those just described touch on a different ontology for the definition of lithic assemblages and their formation compared to approaches that essentialise artefact form and the manufacture sequence. One way to operationalise the study of mobility is to forgo approaches that are based on variable contextual relationships between artefacts and mobility and instead determine the actual physical movement of artefacts as a direct proxy for human movement (cf. Close 2000). Geometric approaches are an option which depart from essentialist notions about artefact form and function, instead drawing upon principles of geometry and fracture mechanics to quantify the physical separation of products of stone reduction through the supplementation or loss of material from an assemblage of artefacts. Examples of such approaches include the cortex ratio and volume ratio, which quantify the movement of material based on the supplementation or loss of cortical surface area or volume of stone from an assemblage, respectively (e.g., Dibble et al. 2005; Douglass et al. 2008; Middleton 2020; Phillipps 2012; Phillipps and Holdaway 2016. See Chapter 2 for the logic and process of calculating cortex ratios).

Douglass and colleagues (2008) applied the cortex method to late Holocene surface stone artefact scatters from several locations surveyed as part of the Western New South Wales Archaeology Program (WNSWAP). Cortex ratios consistently below one, indicating a dearth of observed cortical surface compared to what was expected, were the result of selective removal of large (cortical) flakes from the assemblages on the whole (see also Douglass 2010; Holdaway and Fanning 2014; Holdaway et al. 2012; Parker 2011), suggesting people were highly mobile and gearing up with artefacts that provided a large amount of cutting edge per unit of mass, as a hedge against the unpredictable appearance of resources. For example, cortex ratios for surface assemblages from 93 scalds (patches of eroded sediment with lagged assemblages) distributed along ca. 15 km of the Rutherfords Creek catchment averaged at 0.53 ± 0.22 – the standard deviation suggesting considerable variability in the nature and degree of artefact movement with some scalds exhibiting cortex ratios above one, but the mean value reflecting a net export of material away from the area to elsewhere (Davies and Holdaway 2017). These findings serve as the basis for comparison with lithic assemblage patterning at Lake Mungo later in this chapter.

5.1.1 Lithic Geometry and Mobility in a Modelled World

Applications of the cortex ratio demonstrate movement occurred but do not necessarily establish the theoretical relationship between the two (Davies et al. 2018). As Lin and
colleagues (2015:102) conclude, “the relationship between cortex ratio variability and the various facets of occupation and mobility, such as the regularity and duration of (re)occupation or the frequency, velocity, and linearity of movement, need to be assessed”. Holdaway and Davies (2020:622) further commented that:

[cortex ratio] values measured at the level of individual assemblages need to be contextualised within wider systems of movement and discard. If we imagine a movable observation window delineating an archaeological assemblage, some lithic reduction products might enter the assemblage with others transported away. Increasing or decreasing the discard or manufacture events within the window plus the addition of objects from outside the window or removal of flaked objects from it creates the archaeological artifact assemblages. Obviously, movement in this case refers to activities related to the transfer of artifacts to, from, and within the window of observation, and movement unrelated to lithics is not visible.

Davies (2016; Davies et al. 2018) developed an exploratory agent-based simulation called FMODEL to assess the effects of variables relating to raw material availability, stone reduction, discard behaviour, and linearity of movement (tortuosity) on spatial patterning in cortex ratios across a synthetic landscape. The simulation was based on a simple conceptual model of how lithics might enter or leave an assemblage, broadly summarised in the quote above.

The use of computer modelling means the entire material product of a simulated behavioural system can be observed, allowing analysis of the range of patterning in that material at any stage and under any combination of parameters. In Davies’ (2016; Davies et al. 2018) FMODEL, agents ‘behave’ but only in a simple if trivial manner by moving and producing, transporting and discarding stone flakes and cores within the simulated world which acts as a ‘window of observation’ onto the stone artefact assemblage. Agents discard a flake or a core after each step they take, moving in either a highly linear pattern with extended step lengths, or a highly tortuous pattern where the movement path frequently intersects and doubles back on itself (Figure 5.1. The calculation of movement tortuosity is explained below). In this way, movement tortuosity governs how long an agent spends in the window. If agents are not carrying flakes or cores when they need to discard, they produce new ones to varying degrees from raw material that is of a uniform size and quality, and assumed to be readily available as needed. This is an important aspect of the model, based on the empirical case study of Rutherfords Creek where nodules of raw material are locally abundant in outcrops and gibber
beds (Douglass and Holdaway 2011). Upon flaking raw material, agents select a proportion of the products to transport. Importantly, agents may carry artefacts into and out of the window.

Figure 5.1 Example of increasingly tortuous moves (left to right). Figure adapted from Davies (2016:154, Figure 6.6).

The results of this highly simplified simulation of lithic production and movement suggest raw material availability and movement patterns explain much of the variation in cortex ratios. As movement becomes more tortuous and agents remain in the simulated landscape longer, cortex ratios tend to converge around one when there is raw material available, since there is a greater chance for all products of local stone reduction to be discarded in the window rather than transported away. Further, cortex ratios lower than one relate to higher mobility but the opposite association of high ratios with low mobility does not hold true – instead, both patterns appear to be “two sides of the same coin” (Davies 2016:168). Which pattern is expressed depends on how much stone material the agent carries into the simulated landscape. When tortuosity is low, material carried into the window has the effect of increasing cortex ratios since that material is deposited before flaking and discard of local material occurs, whereas when tortuosity is high, the effect of carry-in is nullified since increased flaking and discard of local material occurs. Davies (2016) also found that overall movement does not determine the value of the cortex ratios but rather controls the degree of variability around a mean value, since the degree of movement tortuosity determines the amount of time spent in the observational window – affecting the degree to which local or imported material is reduced and discarded.
Tortuosity is significant for the way it captures different aspects of mobility, without recourse to defining site types such as residential base camps or logistical extraction sites. For instance, for any given spatial extent, the relative frequencies of short- and long-distance movements made by an agent is akin to the intensity with which they occupy the landscape (Davies 2016). Indeed, movement tortuosity may be so high as to mimic sedentism, or so low as to reflect the briefest of visits to an area. Importantly, which pattern is expressed is determined by both the spatial and temporal scale of observation (Figure 5.2). With reference to patterning in cortex ratios described above, in cases of low tortuosity ratios would be variable, reflecting the depletion or supplementation of material as determined by the import of raw material from outside the area. However, by expanding the spatial or temporal scale at which the system is observed, more moves and discard events would be captured, causing the cortex ratio to converge around one, as expected in the high tortuosity scenario. This is similar to the modifiable areal unit problem (Openshaw and Taylor 1979) and Douglass’ model of radial movement (2010:258-259). In effect, the cortex ratio is always resolvable to one if the scale of observation is increased to some theoretical maximum. In this sense, time and space are equivalent, and both are simultaneously captured by tortuosity.

Figure 5.2 The spatiotemporal scaling of movement tortuosity. Figure adapted from Nathan et al. (2008:19053, Figure 1).
Taking tortuosity as a measure of both time and space with regards to landscape use, it follows that lithic assemblages may in fact form different parts of what is ultimately the same modelled world. Davies’ simulations showed how cortex ratios vary spatially following different movement (and raw material availability and lithic production) scenarios, irrespective of other contextual elements that are not part of the model. The size and location of the window of observation affects what elements of the system are captured and thus affects the observed assemblage composition. The outcome of Davies’ FMODEL suggests a combination of movement tortuosity and availability of raw material could strongly influence broad patterning in the composition of lithic assemblages, since raw material availability determines whether stone can be carried from one area to another, and tortuosity determines the extent to which different patterns in lithic assemblage composition are expressed (Holdaway and Davies 2020). In light of this, the surface stone artefact assemblage from Lake Mungo provides a useful comparative case to Rutherfords Creek.

There are several aspects of the Lake Mungo case study that make it a useful comparative case (for the archaeological and palaeoenvironmental contexts of Rutherfords Creek and Lake Mungo, see Appendix D). The archaeological record at Lake Mungo spans the late Pleistocene to the late Holocene (Bowler 1998; Bowler et al. 1970; Fitzsimmons et al. 2019; Jankowski et al. 2022; Stern 2014). The assemblage considered here, derived from a lunette dune, is late Pleistocene in age and separated from the late Holocene record of Rutherfords Creek by over a dozen millennia (Spry 2014; Stern et al. 2013). Where the surface lithic record at Rutherfords Creek generally represents ca. 2000 years of accumulation and is largely inseparable into distinct behavioural episodes, lithic scatters and hearths within the Lake Mungo lunette dune are preserved such that they arguably reflect single discrete episodes of activity or related sets of activities, like the one-off use of a hearth or the flaking of a core, as determined through archaeomagnetic and refitting analyses (Stern 2014, 2015; Stern et al. 2013). Importantly, unlike at Rutherfords Creek, raw material is not locally available at the Mungo study area, therefore all material had to be transported to the area, reflecting a ‘carry-in-only’ situation (Kurpiel 2017). With these factors in mind, under the logic of common lithic analysis frameworks like LTO, the assemblage at Lake Mungo should demonstrate marked differences in the use of stone, and potentially differences in mobility/settlement pattern, to that of Rutherfords Creek.

The Lake Mungo empirical data analysed here preclude calculating cortex and volume ratios, requiring another method by which artefact movement, and by proxy human movement, may
be investigated but in a manner that remains faithful to the principles of geometric approaches. Another way to understand the degree of artefact movement is to leverage the structure of the Mungo record and explore the extent to which all the products of flaking of individual nodules are present in observed reduction sets. This is based on the simple principle that holding all else constant, removing artefacts from a reduction set will reduce the size of that reduction set. Assessing this requires the ability to identify and associate individual artefacts in an assemblage with others derived from the same nodule of raw material – in essence, analytical nodule analysis (Larson and Komfeld 1997). As mentioned, it appears that stone artefact scatters on the Mungo lunette are preserved such that they reflect single distinct episodes of flaking (Stern et al. 2013). A large component of Spry’s (2014) research involved refitting and minimum analytical nodule analysis (MANA) to identify groups of artefacts detached from the same piece of raw material and assess their individual technological characteristics. Spry (2014), following Holdaway and Stern (2004), recorded a series of attributes for individual artefacts and identified which ones belonged to the same reduction sets. The analysis here uses these data courtesy of Caroline Spry, Nicola Stern and the Mungo Archaeology Project. What is also required is an understanding of the ways in which different lithic reduction, reuse, selection, and human movement behaviours impact the composition and distribution of lithic reduction sets, which is assessed here using computer simulation.

5.2 Model Conceptualisation

In total, Spry (2014) recorded 1508 artefacts belonging to 179 reduction sets. Eighty-two are associated with the Zanci depositional unit (ca. 19-16 kya, an envelope of time during which the lake level was reduced) and 97 are associated with sediments deposited after the decline of the lake (post-lake, from ca. 15 kya). Figure 5.3 shows the distribution of the number of artefacts in the Mungo reduction sets. Whether split according to depositional unit or considered as a whole, the distributions are right skewed with a large number of small clusters (< 10 artefacts in size) though some large reduction sets are present. The median size of the reduction sets is six. What is unknown based on assemblage size alone is whether these reduction sets are ‘complete’ or whether artefacts have been removed or disassociated from these sets, thus reducing their size to varying degrees. This requires an understanding of how different processes of lithic reduction, discard, and transport affect the ‘completeness’ of individual reduction sets under different mobility configurations.
As with the cortex ratio example, simulation provides a means to explore the interaction between raw material supply, lithic production, selection and movement as they impact reduction set composition. The basis for such a simulation has already been established. Following Knell (2012), Davies and colleagues (2018) note raw material may be reduced and all products discarded locally in the area, leaving ‘complete’ reduction sets. Alternatively, some or all products of reduction might be removed from the area, thus depleting the reduction sets or removing all trace of them. Of course, the intensity of reduction will affect how many artefacts are produced in a given reduction episode. Similarly, the amount of time people spend in the area will affect how much material is reduced. Importantly, previously discarded artefacts have the potential to be picked up and moved away at some later date by the same or different groups of people, or may be further worked in a separate reduction episode – simply put, existing artefacts may be collected and reused as long as they are visible as described in the previous chapter. Therefore, different sets of relationships between raw material supply, occupation duration, reduction intensity and selection of artefacts for reuse or transport elsewhere will lead to the discard of reduction sets of different sizes over time. Together, the foregoing statements form a conceptual model that is translated into a formal simulation below to explore the effects of different parameters of interest on the formation of lithic reduction sets.

Figure 5.3 Distribution of reduction set sizes (number of artefacts) at the Mungo study area, per stratigraphic unit and the assemblage as a whole. Data supplied courtesy of Caroline Spry, Nicola Stern, and the Mungo Archaeology Project.
5.3 Model Implementation

To understand changes in the spatial distribution of reduction sets (henceforth ‘clusters’) and their associated size, an exploratory agent-based model called ClusterSim was constructed based on the conceptual model outlined above and building on the structure and processes of FMODEL (Davies 2016; Davies et al. 2018), particularly the way in which movement is conceptualised and represented as varying degrees of tortuosity. The model is constructed using the NetLogo modelling platform (Wilensky 1999). Output is analysed using R version 4.1.0 (R Core Team 2021) with the aid of the Tidyverse suite (Wickham et al. 2019), ggpubr (Kassambara 2020), and janitor (Firke 2021) packages for data wrangling and visualisation.

In ClusterSim, agents representing individual foragers enter a window of observation carrying raw material in the form of cores and move around while flaking the cores to varying extents. All processes in the simulation are modelled simply and with a level of stochasticity (Brantingham 2003). If the simulations produce patterning in cluster sizes (i.e., reduction set sizes) similar to that observed empirically, this provides an alternative perspective on stone artefact assemblage formation without recourse to idealised manufacture sequences or a priori inferences about raw material types, quality and treatment. In this respect, simulation output generates hypotheses about stone reduction and past use of landscape which can be tested with the empirical data.

5.3.1 Model Initialisation

Figure 5.4 presents the ClusterSim processes in diagram form. Table 5.1 provides a description of the parameters and their associated values. A simulation run begins with an unbounded 33 x 33 grid of cells which acts as a window of observation. A forager is placed at a random location in the window carrying a number of cores according to the carry_in parameter which varies between simulation runs (Table 5.1). Foragers follow a set of rules conditioning their movement and acquisition and reduction of stone material. The simulated landscape is considered uniform such that there are no extraneous factors biasing forager movement, including the presence of discarded artefacts. Foragers are treated as tireless and do not reproduce, die, or interact with each other. If a forager would move outside of the window of observation, they are removed from the simulation with whatever material they are carrying, and a new forager enters.
Figure 5.4 Overview of ClusterSim processes

Table 5.1 ClusterSim parameter descriptions and values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>carry_in</td>
<td>The number of unworked cores carried into the window with a forager</td>
<td>5, 10, 20, 100</td>
</tr>
<tr>
<td>reduction</td>
<td>The degree to which a core is flaked in a reduction episode (1.00 = fully reduced)</td>
<td>0.25, 0.50, 0.75, 1.00</td>
</tr>
<tr>
<td>levy_mu</td>
<td>Controls the degree of movement tortuosity, where 1.0 = low and 3.0 = high tortuosity</td>
<td>1.0, 1.5, 2.0, 2.5, 3.0</td>
</tr>
<tr>
<td>selection</td>
<td>The proportion of flakes removed (transported) at the end of a simulation run</td>
<td>0.00, 0.25, 0.50, 0.75</td>
</tr>
</tbody>
</table>
5.3.2 Modelling Lithic Reduction

While present in the window, the forager first attempts to reduce a core according to a level of intensity determined by the *reduction* parameter, which represents a proportion of the flakes to be removed from a core. For the purposes of the simulation, a core represents a unit of raw material that will yield 20 flakes before it is exhausted (following Davies 2016). All cores are treated as uniform in terms of their initial size and material type/quality. So, an unworked core reduced under a *reduction* setting of 0.25 will yield five flakes, with a further 15 potential flakes remaining on the core.

When reducing a core, the forager first attempts to flake a core they are carrying. Following reduction, the core and flakes are discarded. If the forager is not carrying any cores, they look for the largest core (i.e., most potential in the flakes remaining) available in the discard record and reduces that, discarding the core and flakes (such that foragers can pick up and flake a core that was discarded by a forager that came before them). In this instance, if the *reduction* parameter would result in more flakes being removed than are available on the core, all possible flakes are removed and the core and flakes are discarded (for example, *reduction* is 0.75 which would result in 15 flakes removed from a core, however the largest available core has only five possible flakes remaining. In this case, five flakes would be removed and discarded along with the core). All flakes and cores are assigned a unique ID number which tracks the particular cluster to which they belong. Because the simulated world is considered a single window of observation, flakes and cores are not assigned to specific cells – rather, the discard record is a property of the entire window itself.

5.3.3 Modelling Forager Movement

After a reduction episode, the forager moves. Following Davies (2016; Davies et al. 2018) movement is modelled as a Lévy walk which represents movement to varying degrees of tortuosity, ranging from highly linear moves to highly tortuous moves where the movement path frequently doubles back on itself (Figure 5.1). A forager turns to a random heading before stepping forward. The length of a step is drawn from the equation

\[ P(l) = l^{-\mu} \]

where \( P(l) \) is the probability of selecting a step size of length \( l \) (Brantingham 2006). When \( \mu = 1 \), step lengths tend to be longer, and when \( \mu = 3 \), step lengths tend to be shorter (Figure 5.5). As described above, movement tortuosity affects the amount of time a forager spends in
the window and therefore affects the number of reduction episodes the forager will carry out – the higher the tortuosity, the greater the length of time spent in the window and the greater the number of potential reduction episodes.

![Figure 5.5 Probability of drawing step length \( l \) according to the Lévy equation. Note step length is log-transformed. Figure adapted from Davies (2016:154, Figure 6.6).]

### 5.3.4 Modelling Lithic Selection and Removal

Foragers follow the reduce-move cycle until a move takes them outside the window of observation. At this point, they are removed from the simulation and replaced by a new forager. Depending on the parameter settings, it is possible for a forager to leave the window carrying unused cores that they originally brought into the window (that is, a forager may not end up flaking all of the cores they originally carried in).

At the end of a simulation run, a random proportion of flakes is ‘selected’ according to the selection parameter (Table 5.1) and those flakes are removed from the window. This simulates the transport of flakes away from the assemblage for use elsewhere. For example, under a selection setting of 0.25, 25 % of all flakes present in the window will be removed.

The window in which foragers move acts as a single observation unit of an arbitrary size. Therefore, transport of flakes and cores within the window is not of interest per se, but rather interest is in the removal of these objects which impacts the size of individual clusters. Because previously discarded cores can be picked up and flaked again, and because any flake can potentially be selected for removal, it is an assumption of the model that all previously discarded material in the observation window is visible to foragers. Further, the choice to have selection happen to random flakes at the end of a simulation run means that reduction sets may be selected from differently. If selection occurred immediately after each reduction
episode, the same proportion of flakes would be removed each time producing similar-looking reduction sets of similar sizes. By removing flakes at the end of a simulation run, some reduction sets may be targeted more often and others less so, simulating variation in reduction products between nodules and the suitability of flakes for selection.

Importantly, most aspects of ClusterSim are neutral. ‘Cores’ are simply equal units of raw material that do not differ in type or quality, such that all cores of a given size (having equal numbers of potential flakes remaining) have an equal chance of being chosen for reduction; in the same manner all flakes have an equal chance of being selected for removal. The window itself is empty such that forager movement is not biased by any extraneous factors. Raw material enters and exits the window with foragers, but from where the raw material originates and where it goes is irrelevant to the modelled world – like in Davies’ FMODEL, the window of observation is conceived as a movable lens of arbitrary size, and may change its contents as it shifts in size and location – but nonetheless, it provides a view into the flow of lithics across the (simulated) land.

Of course, in the real world, differences in raw material quality and size will influence the way in which stone is reduced, just as cycles of sediment erosion and deposition will influence what artefacts are visible for selection, and the distribution of subsistence resources and other landscape features will impact landscape use by humans. However, since the simulations are exploratory, it is useful to hold this variability constant to better understand the impact of various processes of interest on resultant stone artefact distributions. The results of Davies’ FMODEL simulations suggest movement and distribution of material are controlling assemblage composition and emergent patterning. Removing the notion of ‘artefacts as artefacts’ as well as other landscape-related variables limits behavioural assumptions, facilitating easier testing of the key processes of interest and assessment of the extent to which other processes are needed to explain assemblage patterning.

5.3.5 Model Verification

To verify the forager movement and lithic production and selection procedures were operating correctly, a series of tests were conceived along with expected outcomes. For each of the verification tests, the simulation runs were limited to a single forager carrying 100 cores.
To assess the movement procedure was operating as expected, the movement procedure was isolated and three simulation runs were performed at a \textit{levy\_mu/tortuosity} setting of 1.0, 2.0, and 3.0. Each simulation ran for 10,000 time steps and the step length for each move was recorded. The distribution of step lengths for the two simulation runs are presented in Figure 5.6, and approximate the theoretical distributions for the Lévy equation, suggesting the movement procedure was performing as expected.

To assess the reduction and selection procedures were operating correctly, the forager was confined to a single grid cell. Simulations ran for 100 time steps with \textit{reduction} and \textit{selection} parameters set at the values in Table 5.1. This resulted in the reduction of all 100 cores the forager was carrying with a single reduction episode per core, and no removal of artefacts, facilitating the ease of calculating expected frequencies. For example, under a \textit{reduction} setting of 0.25 and a \textit{selection} setting of 0.00, the reduction of 100 cores should result in 600 artefacts (five flakes per core = 500 flakes, plus 100 cores). If in this example \textit{selection} was set at 0.50, this should result in 350 artefacts (250 flakes removed leaving behind 250 flakes, plus 100 cores). The expectations and actual results for each test are presented in Table 5.2. There are no differences, demonstrating the procedures are operating as expected.

![Figure 5.6 Results of the verification experiment for the ClusterSim movement procedure. Step length distributions match the theoretical distributions from the Lévy equation (inset). Note step length is log-transformed.](image)

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Further verification tests were performed as the model was written. Following protocols for clear communication of computer models, an Overview, Design concepts, and Description (ODD) document for ClusterSim is provided in Appendix E, and model code is provided in Appendix F.

### 5.4 Model Exploration

Individual simulations end once 100 foragers have passed through the window, and simulations are repeated 50 times for each combination of parameters to capture variability introduced by the stochastic elements of the model. Three sets of data relevant to the research goals here are output at the end of each simulation run: the frequency of clusters (reduction sets) of different sizes (the number of artefacts forming the cluster/reduction set), the number of cores carried out of the window by foragers, and the total number of artefacts remaining in the window.

Figures 5.7-5.10 show the distribution of cluster sizes for each combination of parameters, averaged across 50 simulation runs. Clusters of all sizes are produced resulting in a range of distributions of different shapes. Regardless of other parameter settings, when *selection* is 0.00, only cluster sizes of 6, 11, 16 and 21 are produced since flakes are generated in multiples of five and discarded along with one core per cluster, and under this setting no flakes are removed at the end of a simulation run.
Figure 5.7 Distribution of cluster sizes for ClusterSim runs where \( \text{reduction} = 0.25 \), averaged across 50 simulation runs. Red numbers indicate \textit{selection} values. For each subplot, rows represent \textit{carry in} (5, 10, 20, 100) and columns represent \textit{levy_mud/tortuosity} (1.0, 1.5, 2.0, 2.5, 3.0). Error bars are one standard deviation. Note y-axis scales vary between plots.
Figure 5.8 Distribution of cluster sizes for ClusterSim runs where reduction = 0.50, averaged across 50 simulation runs. Red numbers indicate selection values. For each subplot, rows represent carry_in (5, 10, 20, 100) and columns represent levy_mu/tortuosity (1.0, 1.5, 2.0, 2.5, 3.0). Error bars are one standard deviation. Note y-axis scales vary between plots.
Figure 5.9 Distribution of cluster sizes for ClusterSim runs where \textit{reduction} = 0.75, averaged across 50 simulation runs. Red numbers indicate \textit{selection} values. For each subplot, rows represent \textit{carry in} (5, 10, 20, 100) and columns represent \textit{levy_mutation/tortuosity} (1.0, 1.5, 2.0, 2.5, 3.0). Error bars are one standard deviation. Note y-axis scales vary between plots.
Figure 5.10 Distribution of cluster sizes for ClusterSim runs where reduction = 1.00, averaged across 50 simulation runs. Red numbers indicate selection values. For each subplot, rows represent carry_in (5, 10, 20, 100) and columns represent levy_mu/tortuosity (1.0, 1.5, 2.0, 2.5, 3.0). Error bars are one standard deviation. Note y-axis scales vary between plots.
5.4.1 Reduction Intensity

Overall, increasing values of *reduction* has the net effect of shifting the centre of cluster size distributions to the right. As *reduction* increases, more flakes are generated per core, therefore on average cluster sizes are larger. Under higher *reduction* settings of 0.75 and 1.00 (Figures 5.9 and 5.10) cluster sizes tend to be approximately normally distributed. However, at lower *reduction* settings there is more variation in the shape of the distributions, with many being right-skewed or bimodal, particularly at lower *selection* and *levy_mu (tortuosity)* settings (Figures 5.7 and 5.8).

5.4.2 Raw Material Supply

When *carry_in* is set at 100, the centre of the cluster size distributions (the modal average cluster size) sits to the left of those distributions where fewer cores are brought into the window with the foragers. This occurs across all levels of reduction intensity except for complete reduction (Figure 5.10). This happens because under the logic of the model, if more fresh cores are available to be reduced, reuse of discarded cores is less likely overall compared to situations where there is a diminished supply of fresh cores which prompts further flaking and reuse of cores. Therefore, with minimal continued flaking of a core, cluster sizes are smaller on average.

5.4.3 Movement Tortuosity

In general, *tortuosity* does not affect the distributions of cluster sizes to a large degree except when it is low (1.0-1.5, meaning that forager paths intersect infrequently) or when *carry_in* is set to 100 and *reduction* is low (0.25 or 0.50). Distributions shift slightly to the right with increasing tortuosity which makes sense since increased tortuosity means more time spent in the window, meaning potentially more reduction can occur before a forager leaves and fresh material is brought in. Conversely, low tortuosity represents less time spent in the window on average which leads to larger numbers of small clusters but with some larger clusters still occurring, or bimodal distributions particularly at lower *selection* settings (0.25). That this patterning occurs at all *tortuosity* settings when *carry_in* is high (100) also makes sense since there is a consistent supply of fresh material, meaning the need for continued flaking or reuse of cores is diminished.
5.4.4 Selection Intensity

Increasing values of selection has the net effect of driving cluster size distributions to the left since more artefacts are removed, therefore reducing cluster sizes. That is, for each combination of parameters, increasing the value of selection lowers the modal average cluster size but the shape of the distributions remain largely the same. The greatest change in distributions occurs at low to mid values of selection (0.25-0.50) in conjunction with lower reduction (0.25 and 0.50, Figures 5.7 and 5.8) and tortuosity (1.0-1.5) settings. Under these conditions there are fewer flakes produced overall resulting in greater variation in cluster size distributions for the selection process to act upon.

In sum, the most variation in cluster size distributions occurs at lower reduction settings (0.25-0.50) and when tortuosity is low (1.0-1.5), or when carry_in is large (100) in which case there is variability across all tortuosity levels. Increasing values of selection on the whole tends to uniformly reduce average cluster sizes, though the clearest variability occurs in the low to mid-range (selection value 0.25-0.50).

Table 5.3 presents the average number of unworked cores carried out of the window by foragers (that is, unworked pieces of material that a forager carried in but did not discard before leaving the window). The number of cores leaving the window decreases as tortuosity increases. As tortuosity increases, forager paths frequently intersect, resulting in more time spent in the window and therefore a greater potential for foragers to flake and discard more of the cores they are carrying. Increasing the number of cores carried in results in more cores leaving the window with foragers. However, reduction intensity does not have a marked effect on how many cores leave the window with foragers. In most cases (except when 100 cores are carried in or when 20 cores are carried in but at lower tortuosity settings) very few cores on average (< 4) are carried out of the window with each forager. In most instances except where carry_in is 100, standard deviations are high, often exceeding the mean value. So in some cases more cores may be carried out of the window or indeed no cores may be carried out at all.

Figure 5.11 presents the total number of artefacts remaining at the end of simulation runs for each combination of parameters. Generally, as reduction and tortuosity increase, total assemblage size increases. Holding all else constant, increasing values of selection reduces the total number of artefacts as more flakes are removed at the end of each simulation. Intuitively, increasing values of carry_in also leads to larger final assemblage sizes as there
are simply more cores available to produce flakes. Total assemblage size tends to number in the several thousands on average when 20 cores are carried in with each forager, whereas it is several times larger when 100 cores are carried in.

Table 5.3 Average number of unworked cores carried out of the window by foragers. Error terms are one standard deviation. Shaded cells denote reduction settings.

<table>
<thead>
<tr>
<th>carry_in</th>
<th>levy_mu/tortuosity</th>
<th>1.0</th>
<th>1.5</th>
<th>2.0</th>
<th>2.5</th>
<th>3.0</th>
</tr>
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<tr>
<td>0.25</td>
<td></td>
<td>0.550 ± 1.15</td>
<td>0.145 ± 0.64</td>
<td>0.034 ± 0.31</td>
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<td>5</td>
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<td></td>
<td>10</td>
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<td></td>
<td>100</td>
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<td>87.977 ± 9.82</td>
<td>70.171 ± 22.09</td>
<td>47.367 ± 29.47</td>
<td>29.783 ± 28.59</td>
<td>19.350 ± 24.65</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.560 ± 1.16</td>
<td>0.133 ± 0.61</td>
<td>0.030 ± 0.30</td>
<td>0.006 ± 0.13</td>
<td>0.002 ± 0.06</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.536 ± 3.14</td>
<td>0.711 ± 1.93</td>
<td>0.179 ± 1.00</td>
<td>0.046 ± 0.51</td>
<td>0.010 ± 0.23</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>9.503 ± 6.40</td>
<td>3.619 ± 5.55</td>
<td>1.049 ± 3.27</td>
<td>0.297 ± 1.77</td>
<td>0.068 ± 0.83</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>88.051 ± 9.68</td>
<td>70.010 ± 21.98</td>
<td>47.638 ± 29.49</td>
<td>29.767 ± 28.64</td>
<td>19.288 ± 24.76</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.576 ± 1.18</td>
<td>0.136 ± 0.62</td>
<td>0.032 ± 0.31</td>
<td>0.008 ± 0.15</td>
<td>0.002 ± 0.08</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>2.531 ± 3.12</td>
<td>0.719 ± 1.94</td>
<td>0.198 ± 1.05</td>
<td>0.052 ± 0.55</td>
<td>0.008 ± 0.20</td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>9.438 ± 6.43</td>
<td>3.579 ± 5.55</td>
<td>1.045 ± 3.24</td>
<td>0.302 ± 1.78</td>
<td>0.062 ± 0.77</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>87.827 ± 9.85</td>
<td>70.379 ± 21.78</td>
<td>47.484 ± 29.57</td>
<td>29.760 ± 28.46</td>
<td>19.075 ± 24.70</td>
</tr>
</tbody>
</table>
Figure 5.11 Total number of artefacts at the end of the simulations, averaged across 50 simulation runs. Red numbers indicate selection values. For each subplot, rows represent carry-in (5, 10, 20, 100) and columns represent levy_mu/tortuosity (1.0, 1.5, 2.0, 2.5, 3.0). Error bars are one standard deviation. Note y-axis scales vary between plots.
5.5 Comparison with Mungo Clusters

To summarise so far, the simulations presented here, derived from a simple conceptual model of the creation of lithic reduction sets, demonstrate the effects of the interaction between raw material supply \( (carry\_in) \), movement tortuosity (length of time spent in the observation window), reduction intensity, and artefact transport \( (selection) \) on highly simplified stone reduction systems and resulting cluster/reduction set sizes. Importantly, the outcomes apply to the simulated world as modelled – insofar as the empirical archaeological record is concerned, the simulated outcomes only provide a sense of what an archaeological record might look like were the modelled processes operating in reality (Davies et al. 2015).

Nonetheless, there are qualitative similarities between some simulated outcomes and archaeological patterning from Lake Mungo. The cluster size distribution for the Mungo assemblage is right skewed with many small clusters (median size = 6 artefacts) tailing off sharply with fewer large clusters (Figure 5.3). Several simulations result in average cluster size distributions that are similar in shape to that for Mungo. In general, those that most closely match on visual inspection are when \( carry\_in \) is 20 with low \( tortuosity \) (1.0) and \( reduction \) (0.25-0.50) but varying levels of \( selection \) (0.25-0.75); or when \( carry\_in \) is 100, \( tortuosity \) is 1.5-2.0, \( reduction \) is low (0.25-0.50) and \( selection \) varies (0.25-0.75). In no instances when \( reduction \) is high (0.75-1.00), \( tortuosity \) is high (2.5-3.0) or \( selection \) is zero do simulated average cluster size distributions approximate the empirical Mungo distributions (note that visual rather than statistical comparisons between simulation outcomes and the empirical data were carried out because the results of the simulations as presented are average frequencies of cluster sizes over 50 simulation runs).

Though similarities between the empirical record and simulation outcomes are apparent, this does not mean to suggest that only the simulated processes were in operation in the past, nor do the simulations help distinguish between any given interpretation of the Mungo assemblage. However, that a simplified set of processes produces qualitatively similar patterning to what is observed empirically suggests they are worthy of further consideration (Brantingham 2003). The use of the exploratory simulations as heuristic devices in this sense is analytically advantageous as it facilitates the exploration of different patterns suggested by the simulations to help distinguish alternative ideas about the empirical world (Grimm et al. 2005).
5.6 Testing Simulation Outcomes: Stone Use at Lake Mungo and Rutherfords Creek

As Davies and colleagues (2015:7) note, because a formal model was used and because some similarities between simulated outcomes and archaeological data were observed, the model structure can be used to suggest other tests of the archaeological data to help understand the extent to which processes similar to those in the simulations might have been in operation in reality. For example, the simulations suggest both smaller and larger amounts of material carried in to the window can produce patterning in cluster (reduction set) sizes similar to what is observed in the Mungo assemblage. One way to distinguish between these carry_in settings is to compare the total number of artefacts produced in the simulations with the approximately 10,000 recorded across all fieldwork on the Mungo lunette. This would suggest greater support for the simulations where carry_in is relatively small (Figure 5.11). However, this measure is only interpretable in a relative sense.

The simulations also predict that low to medium reduction intensities (reduction values of 0.25-0.50) in conjunction with low tortuosity movement (that is, less time spent in an area) and the transport of a small to large quantity of artefacts away from an area (selection values of 0.25-0.75) will result in a distribution of cluster sizes similar to the empirical stone artefact record at Lake Mungo. These predictions can be tested using empirical artefact data by exploring various technological attributes related to stone reduction. For example, evidence of low reduction intensity might be found in various technological measures such as artefact size, flake to core ratios, and the analysis of different core types, cortex proportions, and flake production methods. Similarly, artefact transport might be inferred from the size distribution of objects in the assemblage (e.g., Phillipps et al. 2022b; section 5.6.3 this study) or from the relationships between flakes and their respective cores in the individual reduction sets (section 5.6.5 this study).

For comparative purposes data from Rutherfords Creek (RC) are also included. As described above, extensive study at Rutherfords Creek has led to a good understanding of the formational history of the lithic record and nature of artefact transport and human mobility, providing a useful benchmark for comparison. Additionally, artefact attributes at Lake Mungo and Rutherfords Creek were recorded in similar ways such that the data are comparable.

Of interest are the modelled scenarios where 100 cores are transported in to the window with foragers and which produce similar patterns to the empirical Mungo record. Though in these
scenarios there is still a limit on the amount of material entering the window with each forager, under the logic of the model this is somewhat akin to a readily available, abundant supply of raw material. In a way, the carry_in 100 scenarios are more reflective of the Rutherfords Creek case and carry_in 20 more reflective of Mungo, raising interesting questions about the similarities in assemblage composition on the basis of two contrasting contexts of raw material availability. This is explored further below.

5.6.1 Overview of Assemblages

The Mungo dataset analysed here consists of 1508 artefacts, 731 of which are from the earlier Zanci unit and the remaining 777 from the post-lake unit. The majority of artefacts are manufactured from fine-grained silcrete, with coarser-grained silcrete, quartzite and sandstone making up the remaining proportion. The RC dataset consists of 27,106 artefacts. Like those at Mungo, the majority are manufactured on silcrete with quartzite, quartz, sandstone and other materials making up the remaining proportion (Table 5.4). For the purposes of comparing the Mungo and RC assemblages, only artefacts greater than or equal to 20 mm in maximum dimension are considered (because at RC, only artefacts greater than or equal to 20 mm were analysed). Resulting assemblage sizes are 1041 for Mungo (483 in Zanci unit, 558 post-lake) and 26,912 for RC (Table 5.4).

| Table 5.4 Raw material types and proportions in the Mungo and Rutherfords Creek assemblages |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|
| **MUNGO** | **Zanci (N (%)** | **Post-lake (N (%)** | **TOTAL (N (%)** | **RUTHERFORDS CREEK (N (%)** | **Silcrete** | **Ochre** | **Quartz** | **Petrified Wood** | **Quartzite** | **Sandstone** | **TOTAL (N (%)** |
| FGS | 419 (86.7) | 472 (84.6) | 891 (85.6) | 23,951 (89.0) | | | | | | | | |
| MGS | 51 (10.6) | 27 (4.8) | 78 (7.5) | 1 (< 0.1) | | | | | | | | |
| CGS | 6 (1.2) | 17 (3.0) | 23 (2.2) | 26 (0.1) | | | | | | | | |
| Quartzite | 7 (1.4) | 33 (5.9) | 40 (3.8) | 29 (0.1) | | | | | | | | |
| Sandstone | 0 (0.0) | 9 (1.6) | 9 (0.9) | 17 (< 0.1) | | | | | | | | |
| **TOTAL** | **483** | **558** | **1041** | **26,912** | | | | | | | | |

Both the Mungo and RC assemblages are dominated by complete unretouched flakes (64.0 and 45.5 % respectively), with cores representing approximately 8 % and 6 % of each assemblage respectively. In both cases, retouched artefacts (tools) constitute a small
proportion of the total assemblage (Table 5.5). Therefore, at a broad level the Mungo and RC assemblages are similarly composed in terms of raw materials and general artefact types.

However, on average artefacts from Mungo are smaller than those from RC (Table 5.6) and this difference is statistically significant at $\alpha = 0.05$ (Mann-Whitney $U = 12,253,890$, $p < 0.001$). At Mungo, there is no significant difference in the size of artefacts from the Zanci unit and Unit F (Mann-Whitney $U = 133,330$, $p = 0.768$). At both Mungo and RC, the size distribution for all artefacts is positively skewed reflecting an abundance of smaller artefacts and a declining frequency of larger artefacts (Figure 5.12). For Mungo this decline is not as regular or consistent as for RC, a pattern that is potentially related to sample size.

Cortex proportions are similar for the two Mungo units (Table 5.7). Overall, proportionally more artefacts at Mungo have no cortex compared to RC, though in both cases artefacts without cortex constitute over 50% of each assemblage. At RC, raw material was predominantly cortical to begin with (Douglass and Holdaway 2011). Therefore, assuming cortical nodules were flaked on the Mungo lunette, the difference in cortex proportions could reflect a greater degree of transport of cortical artefacts away from the assemblage than at RC, or greater reduction intensity. However, other studies of Mungo artefact technology (e.g., Spry 2014) and raw material sources (e.g., Kurpiel 2017) suggest material was transported to the lunette in both ‘prepared’ (fully or partially decortified) and unprepared form, which is likely influencing the cortex proportions. Nonetheless, further exploration of artefact attributes can help shed light on reduction intensity and artefact movement.

### Table 5.5 General artefact types and proportions in the Mungo and Rutherford's Creek assemblages

<table>
<thead>
<tr>
<th>MUNGO</th>
<th>Zanci N (%)</th>
<th>Post-lake N (%)</th>
<th>TOTAL N (%)</th>
<th>RUTHERFORDS CREEK N (%)</th>
<th>TOTAL N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angular frag.</td>
<td>17 (3.5)</td>
<td>14 (2.5)</td>
<td>31 (3.0)</td>
<td>Angular frag.</td>
<td>2632 (9.8)</td>
</tr>
<tr>
<td>Complete flake</td>
<td>301 (62.3)</td>
<td>365 (65.4)</td>
<td>666 (64.0)</td>
<td>Complete flake</td>
<td>12,251 (45.5)</td>
</tr>
<tr>
<td>Broken flake¹</td>
<td>90 (18.6)</td>
<td>82 (14.7)</td>
<td>172 (16.5)</td>
<td>Broken flake</td>
<td>8887 (33.1)</td>
</tr>
<tr>
<td>Core</td>
<td>37 (7.7)</td>
<td>47 (8.4)</td>
<td>84 (8.1)</td>
<td>Core</td>
<td>1488 (5.5)</td>
</tr>
<tr>
<td>R/ED²</td>
<td>38 (7.9)</td>
<td>50 (9.0)</td>
<td>88 (8.5)</td>
<td>Complete tool</td>
<td>1122 (4.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Broken tool</td>
<td>470 (1.7)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Other³</td>
<td>62 (0.2)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>483</td>
<td>558</td>
<td>1041</td>
<td>TOTAL</td>
<td>26,912</td>
</tr>
</tbody>
</table>

¹ Includes proximal, medial, distal, and split pieces
² Artefact with retouch and/or edge damage
³ Includes Axe (1), Block (1), Chopper (2), Hammer (18), Mill slab frag. (26), Muller (14)
Table 5.6 Average maximum length for all artefacts ≥ 20 mm in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Average maximum length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mungo: Zanci</td>
<td>483</td>
<td>32.7 ± 11.7</td>
</tr>
<tr>
<td>Mungo: Post-lake</td>
<td>558</td>
<td>32.5 ± 10.7</td>
</tr>
<tr>
<td>MUNGO ALL</td>
<td>1041</td>
<td>32.6 ± 11.2</td>
</tr>
<tr>
<td>RUTHERFORDS CREEK$^1$</td>
<td>26,870</td>
<td>35.3 ± 13.4</td>
</tr>
</tbody>
</table>

$^1$ Excludes artefacts > 200 mm as outliers

Table 5.7 Proportion of cortex on artefacts in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th>MUNGO</th>
<th>Zanci N (%)</th>
<th>Post-lake N (%)</th>
<th>TOTAL N (%)</th>
<th>RUTHERFORDS CREEK</th>
<th>TOTAL N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>221 (59.7)</td>
<td>254 (56.3)</td>
<td>475 (57.9)</td>
<td>None</td>
<td>14,267 (53.1)</td>
</tr>
<tr>
<td>1-32 %</td>
<td>89 (24.1)</td>
<td>107 (23.7)</td>
<td>196 (23.9)</td>
<td>1-50 %</td>
<td>8840 (32.9)</td>
</tr>
<tr>
<td>33-66 %</td>
<td>30 (8.1)</td>
<td>47 (10.4)</td>
<td>77 (9.4)</td>
<td>50-99 %</td>
<td>2819 (10.5)</td>
</tr>
<tr>
<td>67-99 %</td>
<td>25 (6.8)</td>
<td>36 (8.0)</td>
<td>61 (7.4)</td>
<td>Complete</td>
<td>881 (3.3)</td>
</tr>
<tr>
<td>Complete</td>
<td>5 (1.4)</td>
<td>7 (1.6)</td>
<td>12 (1.5)</td>
<td>N/A</td>
<td>49 (0.2)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>370</td>
<td>451</td>
<td>821</td>
<td>TOTAL</td>
<td>26,856</td>
</tr>
</tbody>
</table>
Figure 5.12 Lake Mungo and Rutherfords Creek artefact size distribution. Note y-axis scales vary between plots.

5.6.2 Complete and Broken Flakes

Comparing the number of complete to broken flakes in an assemblage provides an indication of the degree of fragmentation. There is a greater proportion of complete flakes than broken at Mungo compared to RC, suggesting the assemblage at Mungo is less fragmented (Table 5.8). This association is statistically significant ($X^2 = 187.83$, df = 1, $p < 0.001$). Within the Mungo assemblage, there is no statistically significant association between stratigraphic unit and fragmentation ($X^2 = 2.766$, df = 1, $p = 0.096$). At both Mungo and RC, complete flakes are larger than broken flakes (Table 5.9).

A number of factors could explain the differences in fragmentation at Mungo and RC. In addition to breakage during flaking and post-depositional processes which may lead to increased fragmentation, the patterning may also be related to artefact density or artefact
Table 5.8 Frequency of complete and broken flakes in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>Complete flake N (%)</th>
<th>Broken flake N (%)</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mungo: Zanci</td>
<td>339 (79.0)</td>
<td>90 (21.0)</td>
<td>429</td>
</tr>
<tr>
<td>Mungo: Post-lake</td>
<td>415 (83.5)</td>
<td>82 (16.5)</td>
<td>497</td>
</tr>
<tr>
<td>MUNGO ALL</td>
<td>754 (81.4)</td>
<td>172 (18.6)</td>
<td>926</td>
</tr>
<tr>
<td>RUTHERFORDS CREEK</td>
<td>13,373 (58.8)</td>
<td>9357 (41.2)</td>
<td>22,730</td>
</tr>
</tbody>
</table>

Table 5.9 Average maximum length of complete and broken flakes ≥ 20 mm in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>Average max. length (mm)</th>
<th>Average max. length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complete flakes</td>
<td>Broken flakes</td>
</tr>
<tr>
<td>Mungo: Zanci</td>
<td>32.1 ± 10.2</td>
<td>29.7 ± 8.6</td>
</tr>
<tr>
<td>Mungo: Post-lake</td>
<td>31.9 ± 10.0</td>
<td>28.4 ± 7.1</td>
</tr>
<tr>
<td>MUNGO ALL</td>
<td>32.0 ± 10.1</td>
<td>29.1 ± 7.9</td>
</tr>
<tr>
<td>RUTHERFORDS CREEK</td>
<td>36.2 ± 12.8</td>
<td>32.0 ± 10.5</td>
</tr>
</tbody>
</table>

1 Excludes artefacts > 200 mm as outliers

movement. The density of the Mungo assemblage is low compared to RC, therefore artefacts may have been less prone to fragmentation through trampling or other similar processes. Alternatively, assuming the amount of usable cutting edge was the primary criterion for flake selection, and assuming edge length is positively correlated with artefact size, the transport of large complete flakes in quantity away from RC may explain the lower ratio of complete to broken flakes. This contrasts with Mungo where, assuming once again that people targeted large complete flakes for transport, a higher ratio of complete to broken flakes may suggest lower levels of flake movement away from the assemblage.

The distributions of flake sizes at Mungo and RC are positively skewed with a high peak at smaller values which rapidly declines with increasing artefact size (Figure 5.13). This is typical for archaeological flake size distributions in general with a large quantity of smaller objects and fewer larger elements (Brown 2001; Lin et al. 2016b). However, the steep decline in frequency of large flakes may suggest a relative absence of large flakes, which were the target of transport away from the RC catchment (Douglass 2010; Douglass et al. 2008; Parker 2011). A similar flake size distribution at Mungo may suggest similar artefact selection processes, albeit at a smaller scale.
Notably, broken flakes at RC are larger on average, and approximately the same size as complete flakes at Mungo. This suggests several possible scenarios: a) initial cobble sizes at RC were larger than those at Mungo thereby producing large flakes that were transported away but where remaining flakes are still larger; b) the Mungo assemblage was heavily picked over for large flakes; c) larger artefacts at Mungo are still buried or were not recorded; or d) some combination of these. While it is almost certain that artefacts remain buried or undiscovered on and around the lunette dune at the Mungo study area, the addition of these to the assemblage is unlikely to significantly affect any technological measures since the density of material on the lunette overall appears relatively low (Stern et al. 2013). Scenario B, while also possible, appears unlikely since if many large flakes were removed from the area (at least to the extent seen at RC), the ratio of complete to broken flakes would likely be smaller, holding all else constant. Scenarios A and B can be explored further by examining other technological aspects of the Mungo and RC assemblages.
5.6.3 Assemblage Completeness Based on Artefact Size Distributions

Another method with which to consider artefact size distributions and ‘completeness’ of assemblages is by fitting data to theoretical distributions (Brown 2001; Lin et al. 2016b; Phillipps et al. 2022b). Adding or removing artefacts from an assemblage will change shape of the size distributions, therefore it is possible to compare size distributions with what would be expected given all products of core reduction are present (Lin et al. 2016b). One useful theoretical distribution is the fractal distribution, a power-law distribution which Brown (2001) notes closely predicts rock fragmentation. Following the work of Turcotte (1997), the fractal relation is defined as

\[ N(> r) = r^{-D} \]

where \( N(>r) \) is the number of artefacts with maximum dimension greater than \( r \), and \( D \) is the fractal dimension. \( D \) is a measure of the relative abundance of objects of specific sizes, defined by taking the logarithm of both sides of the equation above:

\[ D = -\frac{\ln(N(> r))}{\ln(r)} \]

Following Brown (2001) and Phillipps and colleagues (2022b), Table 5.10 shows how \( \ln(N>r) \) and \( \ln(r) \) are calculated for Lake Mungo and RC flakes and flake fragments. The frequency of artefacts in size interval bins that characterise variance in maximum dimension is calculated. The value of \( r \) is the lower bound of each size interval bin. The cumulative frequency for artefacts in bins greater than that value of \( r \) is calculated, giving \( N(>r) \). The natural logarithms of both \( r \) and \( N(>r) \) are calculated.

\( \ln(r) \) and \( \ln(N>r) \) are plotted and the linear regression calculated, the slope of which approximates the fractal dimension, \( D \). Importantly, the plot must be linear for the relation between the two variables to be fractal. Figure 5.14 displays the fractal plots for the Mungo and RC assemblages, the high linear regression \( R^2 \) values showing how the regressions comfortably capture much of the variance in the data. The resulting estimate of \( D \) for the Mungo assemblage is 3.8, and for RC it is higher at 4.4.
Table 5.10 Variables for the fractal plot of the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th>Size interval (mm)</th>
<th>Lower bound (r)</th>
<th>Frequency</th>
<th>Cumulative frequency (N&gt;r)</th>
<th>ln(r)</th>
<th>ln(N&gt;r)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mungo: Zanci</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-25</td>
<td>20</td>
<td>149</td>
<td>446</td>
<td>2.996</td>
<td>6.100</td>
</tr>
<tr>
<td>25-30</td>
<td>25</td>
<td>89</td>
<td>297</td>
<td>3.219</td>
<td>5.694</td>
</tr>
<tr>
<td>30-35</td>
<td>30</td>
<td>77</td>
<td>208</td>
<td>3.401</td>
<td>5.338</td>
</tr>
<tr>
<td>35-40</td>
<td>35</td>
<td>58</td>
<td>131</td>
<td>3.555</td>
<td>4.875</td>
</tr>
<tr>
<td>40-50</td>
<td>40</td>
<td>48</td>
<td>73</td>
<td>3.689</td>
<td>4.290</td>
</tr>
<tr>
<td>50-60</td>
<td>50</td>
<td>18</td>
<td>25</td>
<td>3.912</td>
<td>3.219</td>
</tr>
<tr>
<td>60+</td>
<td>60</td>
<td>7</td>
<td>7</td>
<td>4.094</td>
<td>1.946</td>
</tr>
<tr>
<td><strong>Mungo: Post-lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-25</td>
<td>20</td>
<td>159</td>
<td>511</td>
<td>2.996</td>
<td>6.236</td>
</tr>
<tr>
<td>25-30</td>
<td>25</td>
<td>120</td>
<td>352</td>
<td>3.219</td>
<td>5.864</td>
</tr>
<tr>
<td>30-35</td>
<td>30</td>
<td>92</td>
<td>232</td>
<td>3.401</td>
<td>5.447</td>
</tr>
<tr>
<td>35-40</td>
<td>35</td>
<td>60</td>
<td>140</td>
<td>3.555</td>
<td>4.942</td>
</tr>
<tr>
<td>40-50</td>
<td>40</td>
<td>56</td>
<td>80</td>
<td>3.689</td>
<td>4.382</td>
</tr>
<tr>
<td>50-60</td>
<td>50</td>
<td>17</td>
<td>24</td>
<td>3.912</td>
<td>3.178</td>
</tr>
<tr>
<td>60+</td>
<td>60</td>
<td>7</td>
<td>7</td>
<td>4.094</td>
<td>1.946</td>
</tr>
<tr>
<td><strong>MUNGO ALL</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-25</td>
<td>20</td>
<td>308</td>
<td>957</td>
<td>2.996</td>
<td>6.864</td>
</tr>
<tr>
<td>25-30</td>
<td>25</td>
<td>209</td>
<td>649</td>
<td>3.219</td>
<td>6.475</td>
</tr>
<tr>
<td>30-35</td>
<td>30</td>
<td>169</td>
<td>440</td>
<td>3.401</td>
<td>6.087</td>
</tr>
<tr>
<td>35-40</td>
<td>35</td>
<td>118</td>
<td>271</td>
<td>3.555</td>
<td>5.602</td>
</tr>
<tr>
<td>40-50</td>
<td>40</td>
<td>104</td>
<td>153</td>
<td>3.689</td>
<td>5.030</td>
</tr>
<tr>
<td>50-60</td>
<td>50</td>
<td>35</td>
<td>49</td>
<td>3.912</td>
<td>3.892</td>
</tr>
<tr>
<td>60+</td>
<td>60</td>
<td>14</td>
<td>14</td>
<td>4.094</td>
<td>2.639</td>
</tr>
<tr>
<td><strong>RUTHERFORDS CREEK</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-30</td>
<td>20</td>
<td>10910</td>
<td>25328</td>
<td>2.996</td>
<td>10.140</td>
</tr>
<tr>
<td>30-40</td>
<td>30</td>
<td>7720</td>
<td>14418</td>
<td>3.401</td>
<td>9.576</td>
</tr>
<tr>
<td>40-50</td>
<td>40</td>
<td>4116</td>
<td>6698</td>
<td>3.689</td>
<td>8.810</td>
</tr>
<tr>
<td>50-60</td>
<td>50</td>
<td>1651</td>
<td>2582</td>
<td>3.912</td>
<td>7.856</td>
</tr>
<tr>
<td>60-80</td>
<td>60</td>
<td>804</td>
<td>931</td>
<td>4.094</td>
<td>6.836</td>
</tr>
<tr>
<td>80-100</td>
<td>80</td>
<td>102</td>
<td>127</td>
<td>4.382</td>
<td>4.844</td>
</tr>
<tr>
<td>100+</td>
<td>100</td>
<td>25</td>
<td>25</td>
<td>4.605</td>
<td>3.219</td>
</tr>
</tbody>
</table>
In Brown’s (2001) archaeological examples, a higher value of $D$ (i.e., steeper regression line) reflects assemblages dominated by smaller artefacts with relatively few large artefacts, such as assemblages derived from the production of bifaces and projectile points. Lower values of $D$ tend to occur in assemblages that include the full range of reduction products (and therefore a higher proportion of larger artefacts) such as those located at geological raw material sources where test flaking of large cobbles occurred (Brown 2001). The fractal dimensions for the Mungo and RC assemblages approach the higher values that in Brown’s (2001) examples are associated with biface reduction. Therefore, the fractal distribution analysis provides a further indication that the assemblages are dominated by smaller artefacts, suggesting the loss of larger artefacts.

Figure 5.14 Fractal plot of broken and complete flake size-frequency relation for the Mungo and Rutherfords Creek assemblages
The higher value of $D$ for RC suggests there are proportionally more smaller artefacts and fewer larger ones than at Mungo, a finding in line with the notion of transport of quantities of large (cortical) flakes away from the area (Douglass 2010; Douglass et al. 2008; Parker 2011), with a similar process occurring at Mungo but to a lesser degree.

5.6.4 Raw Material Reduction

It is possible to further distinguish between different simulation parameter settings by assessing the manner and degree of raw material reduction, which provides an indication of what an assemblage would look like under those conditions and given no material was removed or added. This information may then be used to make further inferences about the movement of artefacts.

The flake to core ratio provides a rough indicator of the degree of raw material reduction, with values lower for Mungo than for RC (Table 5.11). At face value this suggests less reduction at Mungo. However, there is no significant difference between the minimum number of flakes (MNF) and cores in each assemblage ($X^2 = 2.617 \, df = 1, \, p = 0.106$). Further, interpreting flake to core ratios in terms of reduction intensity assumes initial raw material size and reduction strategy were similar at both locations. Research shows flake to core ratios are affected by initial raw material size, reduction intensity, and artefact movement (Barrett 2014). Therefore, any interpretations need to consider the potential influence of these variables.

The cores from both Mungo units retain similar proportions of cortex (Table 5.12). There is a greater proportion of non-cortical cores at Mungo than RC, which may suggest increased reduction intensity since they had to be worked such that all cortex was removed. However, this assumes all raw material transported to the lunette was cortical to begin with, which is probably not the case (Kurpiel 2017; Spry 2014). Nonetheless, completely and/or partially cortical cores did make their way to the Mungo lunette in some quantity. Approximately 60% of all cores retain some cortex, with a roughly equal proportion retaining zero or 1-32% cortex. At RC, approximately 74% of cores retain cortex, a larger proportion than at Mungo. Of these, the majority retain 1-50% cortex.
Table 5.11 Flake to core ratios for the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>MNF¹</th>
<th>Cores</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mungo: Zanci</td>
<td>389</td>
<td>37</td>
<td>10.5</td>
</tr>
<tr>
<td>Mungo: Post-lake</td>
<td>459</td>
<td>47</td>
<td>9.8</td>
</tr>
<tr>
<td>MUNGO ALL</td>
<td>845</td>
<td>84</td>
<td>10.1</td>
</tr>
<tr>
<td>RUTHERFORDS CREEK</td>
<td>18,233</td>
<td>1488</td>
<td>12.3</td>
</tr>
</tbody>
</table>

¹Calculated as the total number of complete and proximal flakes and tools, plus half the number of complete split flakes and tools, and half the number of proximal/distal split flakes and tools, whichever is larger.

Table 5.12 Cortex remaining on cores in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th>MUNGO</th>
<th>Zanci N (%)</th>
<th>Post-lake N (%)</th>
<th>TOTAL N (%)</th>
<th>RUTHERFORDS CREEK</th>
<th>TOTAL N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>14 (37.8)</td>
<td>19 (41.3)</td>
<td>33 (39.8)</td>
<td>None</td>
<td>390 (26.2)</td>
</tr>
<tr>
<td>1-32 %</td>
<td>15 (40.5)</td>
<td>17 (37.0)</td>
<td>32 (38.6)</td>
<td>1-50 %</td>
<td>796 (53.5)</td>
</tr>
<tr>
<td>33-66 %</td>
<td>8 (21.6)</td>
<td>9 (19.6)</td>
<td>17 (20.5)</td>
<td>50-99 %</td>
<td>296 (19.9)</td>
</tr>
<tr>
<td>67-99 %</td>
<td>0 (0.0)</td>
<td>1 (2.2)</td>
<td>1 (1.2)</td>
<td>Complete¹</td>
<td>3 (0.2)</td>
</tr>
<tr>
<td>Complete</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
<td>N/A</td>
<td>3 (0.2)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>37</td>
<td>46</td>
<td>85</td>
<td>TOTAL</td>
<td>1488</td>
</tr>
</tbody>
</table>

¹Possibly represents a recording error since by definition a fully cortical nodule has not been worked.

Despite having proportionally fewer cortical cores than RC, the fact that there are so many cortical cores at Mungo is interesting as it suggests not all cores were fully worked despite the lack of naturally occurring raw material on the lunette. However, this broad measure may not be reflective of the true extent of core reduction since a) cortex is recorded in intervals, such that a core with 1-32 % cortex may only retain 1 % cortex; and b) cores lose cortex at different rates depending on how they are reduced. For example, given two cortical cores of the same shape and size, one may be rotated a few times to generate a few flakes, so volume is retained yet all cortex (surface area) is removed, whereas the other may be unifacially flaked (flaked from one platform and in one direction) to the point of exhaustion, yet still retain cortex on a large proportion of its surface area. This may be further explored by investigating the relationships between cortex proportions and core size and type.

Core type indicates the way in which cores were reduced and may reflect reduction intensity. Several core types are present at Mungo and RC (Table 5.13). At both Mungo and RC, unifacial and multiple cores make up most cores. Unifacial cores are flaked from a single platform in a single direction, whereas multiple cores are flaked from multiple platforms in
multiple directions. While multiple cores are the most frequent core type at both locations, at Mungo they are proportionally more abundant. This may reflect a greater intensity of reduction at Mungo since multiple cores are rotated, and it is often assumed cores were rotated to generate as many flakes as possible. However, as stated above this relationship is not straightforward, and there may be other factors influencing whether a core was rotated or not, including original raw material shape and size (Baumler 1988:260; Phillipps 2012).

Table 5.13 Core types in the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th>Core Type</th>
<th>Mungo N (%)</th>
<th>Post-lake N (%)</th>
<th>Total N (%)</th>
<th>Rutherford Creek N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bidirectional</td>
<td>7 (18.9)</td>
<td>12 (25.5)</td>
<td>19 (22.6)</td>
<td>30 (2.0)</td>
</tr>
<tr>
<td>Bifacial</td>
<td>0 (0.0)</td>
<td>1 (2.1)</td>
<td>1 (1.2)</td>
<td>103 (6.9)</td>
</tr>
<tr>
<td>Conical</td>
<td>1 (2.7)</td>
<td>0 (0.0)</td>
<td>1 (1.2)</td>
<td>3 (0.2)</td>
</tr>
<tr>
<td>Horsehoe</td>
<td>2 (5.4)</td>
<td>3 (6.4)</td>
<td>5 (6.0)</td>
<td>110 (7.4)</td>
</tr>
<tr>
<td>Microblade</td>
<td>0 (0.0)</td>
<td>1 (2.1)</td>
<td>1 (1.2)</td>
<td>16 (1.1)</td>
</tr>
<tr>
<td>Multiple</td>
<td>11 (29.7)</td>
<td>17 (36.2)</td>
<td>28 (33.3)</td>
<td>526 (35.3)</td>
</tr>
<tr>
<td>Opposed</td>
<td>1 (2.7)</td>
<td>0 (0.0)</td>
<td>1 (1.2)</td>
<td>44 (3.0)</td>
</tr>
<tr>
<td>Other</td>
<td>1 (2.7)</td>
<td>0 (0.0)</td>
<td>1 (1.2)</td>
<td>5 (0.3)</td>
</tr>
<tr>
<td>Radial</td>
<td>2 (5.4)</td>
<td>3 (6.4)</td>
<td>5 (6.0)</td>
<td>119 (8.0)</td>
</tr>
<tr>
<td>Unifacial</td>
<td>12 (32.4)</td>
<td>10 (21.3)</td>
<td>22 (26.2)</td>
<td>519 (34.9)</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>37</strong></td>
<td><strong>47</strong></td>
<td><strong>84</strong></td>
<td><strong>1488</strong></td>
</tr>
</tbody>
</table>

This is apparent when examining core size. Cores at Mungo are significantly smaller than at RC (Table 5.14, Mann-Whitney U = 52,142, p = 0.013), again suggesting a greater degree of reduction assuming original nodules were similarly sized. However, this difference could reflect different original nodule sizes, with larger nodules occurring at RC (Douglass and Holdaway 2011). From a logistical perspective, cobble size at RC was unlikely to be significant since raw material is locally abundant and therefore transport of mass in the form of unworked cobbles was not necessary. In contrast, raw material in some form had to be transported to the Mungo lunette, presumably imposing some limits on the mass and quantity moved. As noted above, it is suggested that cobbles were ‘prepared’ at the geological sources, the closest of which are silcrete outcrops located several kilometres from the lunette (Kurpiel 2017). Workable stone does not seem to have been available in closer proximity whether in creek beds or gibber plains (N. Stern, pers. comm., Jan 2022), though it is unclear
whether water transport was used across the lake or along the lake margins, which would impact the validity of the economy of transport argument.

Table 5.14 Core size by type for the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>MUNGO</th>
<th>RUTHERFORDS CREEK¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean core maximum length (mm)</td>
<td>Mean maximum corescar length (mm)</td>
</tr>
<tr>
<td>All Cores</td>
<td>47.4 ± 15.5</td>
<td>26.6 ± 11.5</td>
</tr>
<tr>
<td>Multiple</td>
<td>54.5 ± 15.7</td>
<td>34.0 ± 11.5</td>
</tr>
<tr>
<td>Unifacial</td>
<td>43.0 ± 11.7</td>
<td>20.2 ± 8.3</td>
</tr>
</tbody>
</table>

The impact of original nodule size is also apparent when examining the size of unifacial and multiple cores. At Mungo, multiple cores are significantly larger than unifacial cores in both maximum length (Mann-Whitney U = 427, p = 0.020) and longest core scar length (Mann-Whitney U = 487, p < 0.001). This suggests that at least at Mungo, core rotation is not necessarily reflective of reduction intensity but some other factor (some researchers suggest rotation to remove cortex, e.g., Spry 2014; Tumney 2011; Vick 2012). A sequence of reduction from unifacial to multiple is not suggested. In contrast, at RC multiple cores are significantly smaller than unifacial cores in terms of maximum length (Mann-Whitney U = 121,661, p = 0.003) but significantly larger in terms of longest core scar length (Mann-Whitney U = 82,267, p = 0.028).

Holding all else constant, cores with the least cortex should be the smallest on average, since cortex is removed as reduction progresses. This pattern tends to hold at Mungo and RC but cores with 67-99 % cortex at Mungo and complete cortex at RC are smaller on average than those with less cortex (Table 5.15. Completely cortical ‘cores’ at RC are either errors in recording since by definition cores cannot be completely cortical, or they represent unworked cobbles). However, in both cases these groups are only represented by three or fewer artefacts. Cores with no cortex are by definition multiple cores (since rotation is required to remove all cortex), unless cores were not cortical to begin with. At RC, a greater proportion of cores with 50-99 % cortex are unifacial, whereas a greater proportion of cores with less cortex are multiple cores (Table 5.16). When considered alongside core sizes, a flaking
### Table 5.15 Core size by cortex for the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>MUNGO</th>
<th>RUTHERFORDS CREEK¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean core maximum length (mm)</td>
<td>Mean maximum corescar length (mm)</td>
</tr>
<tr>
<td>None</td>
<td>46.2 ± 16.3</td>
<td>26.2 ± 10.2</td>
</tr>
<tr>
<td>1-32 %</td>
<td>46.1 ± 15.2</td>
<td>25.3 ± 12.1</td>
</tr>
<tr>
<td>33-66 %</td>
<td>52.1 ± 14.9</td>
<td>30.7 ± 12.9</td>
</tr>
<tr>
<td>67-99 %</td>
<td>42.3</td>
<td>26.0</td>
</tr>
<tr>
<td>Complete</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Mean core maximum length (mm)</td>
<td>Mean maximum corescar length (mm)</td>
</tr>
<tr>
<td>None</td>
<td>46.3 ± 13.7</td>
<td>30.4 ± 11.6</td>
</tr>
<tr>
<td>1-50 %</td>
<td>51.5 ± 16.5</td>
<td>31.9 ± 13.1</td>
</tr>
<tr>
<td>50-99 %</td>
<td>61.4 ± 22.7</td>
<td>33.5 ± 14.4</td>
</tr>
<tr>
<td>Complete³</td>
<td>53.7 ± 10.6</td>
<td>65.0</td>
</tr>
<tr>
<td>Complete</td>
<td>N/A</td>
<td>49.3 ± 9.5</td>
</tr>
</tbody>
</table>

¹For RC cores > 150 mm removed as outliers
²Possibly represents a recording error since by definition a fully cortical nodule has not been worked

### Table 5.16 Core cortex by type for the Mungo and Rutherfords Creek assemblages

<table>
<thead>
<tr>
<th></th>
<th>MUNGO N (%)</th>
<th>RUTHERFORDS CREEK N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>None</td>
<td>1-32 %</td>
</tr>
<tr>
<td>Multiple</td>
<td>11</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(33.3)</td>
<td>(31.2)</td>
</tr>
<tr>
<td>Unifacial</td>
<td>11</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>(33.3)</td>
<td>(12.5)</td>
</tr>
<tr>
<td>Other</td>
<td>11</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>(33.3)</td>
<td>(56.3)</td>
</tr>
</tbody>
</table>

strategy where multiple cores are an indicator of increased reduction intensity cannot be ruled out. The same does not hold for Mungo, however, since while there is a greater proportion of multiple cores overall, they tend to be larger than other core types and retain more cortex. Taken together, this suggests a lower intensity of reduction on average and/or variation in initial cobbles sizes at Mungo, where multiple cores were made on larger cobbles and rotated early in the reduction sequence (cf. Spry 2014). Stern suggests variation in initial cobbles size could have been significant, with observations in the field suggesting nodules may have ranged from fist-sized cobbles to larger boulders (N. Stern, pers. comm., Jan 2022).

Comparing the ratio of average length of the longest core scar to the average oriented flake length (CS/L ratio) can also provide an indication of reduction intensity and/or artefact transport. Kurpiel (2017:232) suggests higher ratio values above one may reflect either selective transport of many large flakes or particularly low levels of core reduction. Higher
ratio values likely reflect the former, since under low levels of reduction core scar lengths and oriented flake lengths would be similar, bringing the ratio closer to one. At Mungo and RC, the average longest core scar is larger than the average oriented flake length, and both CS/L ratios are the same at 1.09, relatively close to one (Table 5.17). Low ratios could reflect minimal reduction intensity (because in cases of high reduction intensity with all products present, average oriented flake length would be larger than the average core scar length, and therefore the CS/L ratio would be below one). At RC, there was transport of large flakes away from the area, therefore it may be that to some degree, the ratio close to one reflects the flake products that were not selected for transport which are smaller, closer in size (on average) to the last flakes to be struck from cores before the cores were discarded (assuming the large flakes were large in terms of oriented length). Given the CS/L ratio, a potentially similar situation may exist at Mungo.

**Table 5.17 Average longest core scar and average oriented flake length in the Mungo and Rutherfords Creek assemblages**

<table>
<thead>
<tr>
<th></th>
<th>Mean Core Scar Length (mm)</th>
<th>Mean Oriented Flake Length (mm)</th>
<th>CS/L Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mungo: Zanci</td>
<td>27.71 ± 11.7</td>
<td>24.49 ± 9.2</td>
<td>1.13</td>
</tr>
<tr>
<td>Mungo: Post-lake</td>
<td>25.75 ± 11.3</td>
<td>24.44 ± 9.4</td>
<td>1.05</td>
</tr>
<tr>
<td>MUNGO ALL</td>
<td>26.62 ± 11.5</td>
<td>24.46 ± 9.3</td>
<td>1.09</td>
</tr>
<tr>
<td>RUTHERFORDS CREEK</td>
<td>31.88 ± 13.2</td>
<td>29.24 ± 12.2</td>
<td>1.09</td>
</tr>
</tbody>
</table>

For Mungo, other measures above suggest that a level of flake removal on par with RC is unlikely, therefore the ratio may be more reflective of lower reduction intensity with some flake transport, more so than a great number of flakes transported alone.

Thus far, assemblage-level technological measures from Mungo have been compared with a known case from RC providing useful context for their interpretation. Overall, artefacts are smaller at Mungo with a greater proportion being non-cortical. This may reflect greater reduction intensity at Mungo or greater removal of cortical artefacts from the area. However, the size and cortex measures are likely due to the reduction of smaller and less cortical cobbles to begin with. This may be reflected in the size and ratio of complete and broken flakes. At RC, the ratio is smaller. At both locations, complete flakes are larger than broken, with broken flakes at RC larger than complete flakes at Mungo. These indicators suggest larger initial cobbles sizes at RC and that the large flakes were targeted for transport were
likely complete flakes. Artefact size distributions at Mungo and RC are similar for both the assemblages as a whole and for complete flakes only, suggesting potentially similar reduction strategies and/or selection and transport processes, albeit at different scales. At face value, various reduction measures, particularly core attributes, point to a high reduction intensity at Mungo. However, when considered alongside the RC data the assemblage-level patterning at Mungo may be explained by variation in initial cobble sizes and a range of reduction intensities with some artefact transport, tending towards a lower reduction intensity on average. These findings generally agree with predictions derived from ClusterSim, which suggested that patterning in cluster size distributions like that observed for the Lake Mungo assemblage would occur under conditions of low reduction intensity and low tortuosity (passing through the area relatively quickly), with low to medium selection intensity (i.e., quantity of artefacts transported away from the assemblage).

5.6.5 Individual Reduction Sets

Taken together, a range of assemblage-level measures agree with expectations derived from the simulations. Therefore, at minimum, the hypotheses derived from the simulations regarding the creation of reduction sets and transport of artefacts cannot be rejected. One advantage of the Mungo data set is the detailed record of reduction sets to which individual artefacts belong (Foley et al. 2017; Spry 2014). Following Spry (2014), this provides an opportunity to assess reduction intensity and artefact transport at the level of individual reduction sets (‘clusters’). The simulations suggest combined instances of low reduction intensity together with the selection of artefacts for transport interact to generate clusters that exhibit a range of different sizes and reduction intensities. Therefore, it is expected that individual clusters at Mungo were subject to a range of different reduction intensities, and in general, larger clusters should on average reflect higher reduction intensities than smaller clusters. In the following analysis, the Mungo data set is no longer limited to artefacts ≥ 20 mm as was necessitated by the comparisons with Rutherfords Creek.

When the maximum length of cores is plotted against cluster size, there is a weak negative relationship though this is not significant, whether the data are split by stratigraphic unit or considered together (Figure 5.15), suggesting core size is not reflective of reduction intensity (as per the assemblage-level analysis above). This is expected given the hypothesised variation in initial raw material size.
Figure 5.15 Relationship between core maximum length and cluster sizes in the Zanci and post-lake units (top) and the Mungo assemblage as a whole (bottom). Test statistics are Spearman’s rho.

As noted above, when the ratio of the longest core scar to oriented flake length (CS/L) is greater than one, this might suggest selective removal of large flakes from a cluster. A ratio close to one might reflect a low level of reduction since the length of the longest core scar is similar to oriented flake length. Conversely, ratios below one might suggest higher levels of reduction. Artefact movement may also affect the CS/L ratio. For example, if small flakes were selected for transport, this would decrease the CS/L ratio since larger flakes would be left behind. At a broad level, CS/L ratios closer to one might be expected in smaller clusters (those that are less intensively reduced according to the simulations) and lower than one in larger clusters (more intensively reduced). However, removal of some large artefacts from the clusters would increase the ratios while removal of many large artefacts would dramatically increase the ratios. If clusters were selected from relatively consistently, then ratios may change in absolute value but the relative relationships for different cluster sizes should still hold.
When CS/L ratios are calculated for each cluster using *average* oriented flake length and plotted against cluster size, there tends to be a negative relationship though it is weak and not significant (whether data are split by stratigraphic unit or grouped together, Figure 5.16). However, plotting the same measures but using the *maximum* oriented flake length for each cluster provides a better sense of reduction intensity and/or flake removal since it provides a ‘bookend’ for the ratio, testing the largest possible flake given what is present against the largest possible flake removed from a core given its current state. A similar negative relationship is apparent but in each case the relationship is stronger and significant (Figure 5.17). The CS/L ratio decreases with increasing cluster size as per the expectations outlined above.

Figure 5.16 Relationship between CS/L ratio and cluster size in the Zanci and post-lake units (top) and the Mungo assemblage as a whole (bottom), using average oriented flake length for each cluster. Test statistics are Spearman’s rho.
There is a degree of variance in the CS/L ratio values, particularly amongst the smaller cluster sizes ($n \leq 10$ artefacts). This suggests that while on average, small clusters show minimal reduction intensity (CS/L ratios around one), some clusters deviate from this expectation. As outlined previously, ratios above one might reflect the removal of large flakes from the cluster (and therefore a higher reduction intensity), whereas clusters with CS/L ratios around one should exhibit less flake removal, or in other words exhibit a range of flake sizes including larger and smaller examples. While total numbers of flakes are low, in general this expectation holds when comparing the size distribution of complete flakes for different values of the CS/L ratio (Table 5.18). There are proportionally fewer large flakes among clusters with a CS/L ratio higher than 1.5, with no flakes greater than 40 mm in maximum dimension.

The extent to which variance in CS/L ratios amongst small clusters is due to reduction intensity is also reflected to a degree in the number of core scars present on cores, where larger numbers of core scars represent a greater number of flake removals. Table 5.19 shows
how cores in clusters with a CS/L ratio close to one tend to have fewer core scars compared to those with a higher (and to a lesser extent, lower) CS/L ratio.

Table 5.18 Complete flake size distribution according to CS/L ratio for small clusters (≤ 10 artefacts) in the Mungo assemblage

<table>
<thead>
<tr>
<th>Flake size class (mm)</th>
<th>CS/L ratio &lt; 0.75 N (%)</th>
<th>CS/L ratio 0.75-1.5 N (%)</th>
<th>CS/L ratio &gt; 1.5 N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10-20</td>
<td>4 (13.8)</td>
<td>22 (28.9)</td>
<td>3 (23.1)</td>
</tr>
<tr>
<td>21-30</td>
<td>13 (44.8)</td>
<td>35 (46.1)</td>
<td>7 (53.8)</td>
</tr>
<tr>
<td>31-40</td>
<td>7 (24.1)</td>
<td>13 (17.1)</td>
<td>3 (23.1)</td>
</tr>
<tr>
<td>&gt; 40</td>
<td>5 (17.2)</td>
<td>6 (7.9)</td>
<td>0 (0.0)</td>
</tr>
</tbody>
</table>

Table 5.19 Number of core scars on cores according to CS/L ratio for small clusters (≤ 10 artefacts) in the Mungo assemblage

<table>
<thead>
<tr>
<th>N core scars</th>
<th>CS/L ratio &lt; 0.75 N (%)</th>
<th>CS/L ratio 0.75-1.5 N (%)</th>
<th>CS/L ratio &gt; 1.5 N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6 (37.5)</td>
<td>0 (0.0)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>2</td>
<td>1 (6.3)</td>
<td>6 (20.0)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>3</td>
<td>3 (18.8)</td>
<td>2 (6.7)</td>
<td>0 (0.0)</td>
</tr>
<tr>
<td>4</td>
<td>1 (6.3)</td>
<td>2 (6.7)</td>
<td>1 (11.1)</td>
</tr>
<tr>
<td>5</td>
<td>1 (6.3)</td>
<td>3 (10.0)</td>
<td>1 (11.1)</td>
</tr>
<tr>
<td>6+</td>
<td>4 (25.0)</td>
<td>17 (56.7)</td>
<td>7 (77.8)</td>
</tr>
</tbody>
</table>

In sum, analysing the reduction of individual units of raw material shows broad agreement with the assemblage-level analysis. In general, larger cluster sizes reflect more intensively worked material. However, there are also small clusters that appear more intensively reduced but have had some artefacts removed. This agrees with the expectations derived from the simulations. The outcome of the simulations leads to the hypothesis that cluster sizes are a result of multiple instances of reduction of raw material nodules combined with selection of artefacts for transport elsewhere. Patterning in the Mungo stone artefacts at both the assemblage-level and reduction set-level fail to reject this hypothesis.

This result, and indeed the similarities between the Mungo and RC lithic assemblages, raises the possibility of Type II error. The sample size for the Mungo assemblage is relatively small in comparison to RC. As such, a larger sample size would help to assess the degree to which the conclusions presented reflect Type II error. However, given the notable similarities between the Mungo and RC assemblages, and between the Mungo assemblages and
simulation output (itself a product of simplified, lower-order processes), it is expected that an increased sample size would not dramatically affect the conclusions generated here.

5.7 Mobility and Lithic Technology: Revisited

The size and composition of lithic reduction sets were explored to understand the extent to which artefacts were missing, as a broad indicator of human movement. The results of the simulations show that qualitatively similar patterning to the distribution of Mungo reduction set sizes occurs under different combinations of parameters, specifically the carry-in of a small amount of material combined with a relatively low reduction intensity, relatively low tortuosity of movement, and a varying proportion of artefacts selected for removal. In no instance does patterning similar to the observed archaeology occur under conditions of consistently high reduction intensity – that is, where a core is flaked almost entirely in a single episode. This alone suggests caution is required when interpreting reduction intensity in terms of mobility and occupation duration in a traditional economic sense.

Certainly, there are instances of high reduction intensity of nodules at Mungo as the technological analysis suggests. Undoubtedly some of these were the result of a single knapping episode, but it is not easy to differentiate these instances from the reuse of a core in several brief but unrelated knapping episodes since the net outcome of both processes is the same. This is interesting because in the simulations, high tortuosity – where foragers spend more time in the window on average – results in greater reduction intensity as reflected by cluster sizes. This result makes intuitive sense from the perspective of economising arguments such as those derived from behavioural ecology. However, in the simulation runs of interest (Figures 5.7 and 5.8), the perceived high reduction intensity is a result of multiple occurrences of striking a few flakes from a core. There is greater variability in cluster sizes at lower tortuosity settings with patterning showing less fluctuation at higher tortuosity settings.

In some ways the change in patterning in cluster sizes with increasing tortuosity is reminiscent of the time-dependent patterning in cortex ratios noted by Davies and Holdaway (2017). Davies and Holdaway (2017) relate patterning in cortex ratios at RC to artefact density. As noted above, in many settlement pattern studies, artefact density is assumed to be positively correlated with occupation intensity and duration, with high densities reflecting the presence of more people or longer occupations, and therefore the potential for greater numbers of artefact types to occur. At RC, scalds with older hearths have higher densities of artefacts, and the higher density scalds also have greater numbers of artefact types (Davies
and Holdaway 2017). However, as Davies and Holdaway show, the relationship between artefact density and age may equally be the result of accumulation of material from unrelated occupations over time, leading to more deposition in some places than others. This suggests an alternative interpretation to typical settlement pattern approaches.

The mean cortex ratio for 93 scalds distributed along the length of the RC catchment is $0.53 \pm 0.22$. The mean value below one indicates a net export of material, but the standard deviation suggests considerable variability in the nature and degree of artefact movement, with some scalds exhibiting cortex ratios above one (Davies and Holdaway 2017). When plotted against artefact density (age of exposure), there is a slightly negative relationship, but this is weak (Figure 5.18). This suggests an overall lack of change in cortex ratios with age/density. As time passes there is greater opportunity for artefact movements to be captured by the cortex ratio, therefore variability in ratio values decreases (Davies et al. 2018). Younger/less dense assemblages are more variable because they are the result of fewer discard events. In other words, the relationships between artefact density, exposure age, and cortex ratios are relatively invariant. Younger/less dense assemblages, while more variable, are simply more diffuse versions of older/denser assemblages, reflecting relatively consistent lithic procurement, discard, and place use behaviours across the catchment over time (Davies and Holdaway 2017). It is therefore problematic to directly relate artefact density to settlement pattern in terms of site types or mobility.

![Figure 5.18 Cortex ratios plotted against log-transformed density for scalds from Rutherfords Creek (p = 0.086, adjusted $R^2 = 0.021$). Figure taken from Davies and Holdaway (2017:23, Figure 6).](image-url)
Regarding the simulations presented here, outcomes where the \textit{reduction} setting is low (0.25-0.50, Figures 5.7 and 5.8) show that cluster sizes become larger and less variable on average as tortuosity increases. Resulting assemblages from simulations where tortuosity is high are ‘denser’ since more flakes tend to be produced and discarded for each core present in the assemblage – cores overall are more heavily reduced. Conversely, when tortuosity is low assemblages are more variable in terms of cluster size with some large clusters present, but overall, they are less ‘dense’ since the majority of clusters are smaller, reflecting \textit{on average} the production of less flakes per core in the assemblage. The differences in average cluster size, despite suggesting \textit{different} lithic use behaviours at face value, are the result of \textit{regularity} in lithic use behaviours, similar to Davies and Holdaway’s (2017) cortex ratio example. That is, the same reduction behaviours that produce on average small but more variable cluster sizes scale up into larger, less variably sized clusters. Like in the cortex ratio example, the key is time, except that in the simulations time is manifest as how long foragers are present in the area to enact their reduction behaviours (modelled as tortuosity). The simulations show how a suite of variables including raw material supply, core reduction, artefact transport, and movement tortuosity combine to produce different reduction sets that from an LTO perspective, for instance, suggest differing material use and occupation duration, but from a perspective that is less concerned with manufacture, reflect regularities in behaviour over time. Therefore, archaeological patterning at Mungo may equally be explained as the result of accumulation of material from a set of unrelated, yet on the whole invariable, occupations/behavioural events over time.

The results of the simulations also showed that patterning in reduction set sizes similar to the Mungo record is produced under conditions of low tortuosity and reduction intensity but with an abundance of raw material (\textit{carry\_in} = 100). In effect, 100 cores entering the window with each forager is akin to the RC situation where raw material nodules are locally abundant and readily accessible. From the perspective of raw material availability, the fact that in the simulations raw material is ‘transported’ into the area is irrelevant – the key point is that unworked nodules of material are readily accessible as needed. That the patterning occurs only under conditions of low tortuosity is a finding congruent with the results of Davies’ simulations (2016; Davies et al. 2018) and interpretations of mobility and use of landscapes similar to those found at RC in general (Holdaway et al. 2012). This result is significant because at least in a world where lithic assemblage composition governed by geometry and
movement is concerned, use of raw material is similar *despite* marked differences in geological raw material availability. Translated across to the empirical world, this has implications for the extent to which stone raw material as a variable has a detectable influence on patterning in assemblage composition. Additionally, in the context of issues raised in Chapter 2, this result further highlights how indigenous peoples’ perception and use of lithic resources might be different to common archaeological assumptions where patterns of stone use relate to the distance to the geological source and the production of particular artefact types, rather than the reuse of artefacts (Dibble et al. 2017). This is similar to the findings from the Aotearoa example in the previous chapter.

Of course, the patterning discussed thus far is largely based on the outcomes of computer simulations that are themselves based on highly simplified processes and are not necessarily representative of a true reality. Again, this simplicity is a conscious decision, where the aim is to elucidate any causal relationships between processes of interest and the archaeological outcomes, rather than replicate some reality. The exploratory nature of the simulations, combined with the analysis that suggests the empirical lithic record is qualitatively similar to simulated outcomes, means the exercise is useful heuristically for thinking about observed archaeological patterning.

One interesting observation noted in studies of Mungo lithic technology is how indicators of reduction intensity and treatment of different raw material types suggests a lack of economising behaviour where it would otherwise be expected under a behavioural ecological framework, particularly given that geological sources of raw material are not locally available. For example, Tumney (2011:190) noted how the lack of conservation of non-local fine-grained silcrete in an assemblage from the central Mungo lunette dune associated with fluctuating lake levels was surprising, and from this inferred a level of mobility in which distances of at least 15 km were traversed regularly such that supplies of fine-grained silcrete were predictable. Spry (2014:147) similarly notes a surprising lack of raw material economisation in her study assemblages, suggesting the distances between the lunette and closest geological raw material sources at the time were still within the range generated from economic models of stone use. However, thinking through the implications of the simulations, economy of use manifests differently when previously discarded artefacts are reused. Raw material was most certainly transported to the Mungo study area in some form and quantity, but artefacts left behind by people when they left the area become a source of raw material themselves. To use Lucas’ (2012) terms, artefacts are consistently in a process
of (de)materialisation – materialising as functional objects in one form, then re-materialising as a source of raw material for future people when discarded. This is an acknowledgement of the archaeological record as generative and emergent, providing an alternative artefact use and place use history, and a different form of historical narrative (Holdaway and Phillipps 2021; Lucas 2012).

What, then, might be reasonably inferred about why mobility and the use of place was structured as it was? One way to think about this is in relation to the ‘ecology of place’. Holdaway and colleagues (2015) provide useful comparative cases in their discussion of place use in western New South Wales and the Great Plains in North America. In western New South Wales, the general lack of fertility and unpredictable rainfall meant the availability of food and water resources varied spatially and temporally but in unpredictable ways (Holdaway et al. 2013). This meant resource patches were not continuously attractive for occupation, leading to low redundancy in place use. Though raw material was locally abundant, unpredictable appearance of resources meant stopping to produce artefacts had a cost (Holdaway et al. 2013). As described above, this is reflected in a surface archaeological record consisting of stone artefact scatters and hearths that vary in age, and suggests high mobility of groups in a landscape where the ecology leads to the widespread dispersal of material remains but where no one place saw more use than any other (Davies and Holdaway 2017; Holdaway et al. 2015). Indeed, “people who came to Rutherfords Creek made hearths and manufactured artefacts. But they did this only intermittently and when they left, carrying the most efficient stone artefacts possible, they did not return until environmental conditions were suitable” (Holdaway et al. 2013:62).

The Australian example contrasts with the Oglala National Grasslands (ONG) in the Great Plains of North America, which is characterised by a system of permanent and intermittent streams with variable rainfall, broad seasonal changes in climate, and limited stone sources (Holdaway et al. 2015). A range of sampling locations were studied. Like at Rutherfords Creek, stone artefact assemblages on the whole show a pattern of local raw material use with material leaving, but with some variation in raw material use between sampling locations. For example, locations with smaller artefacts showed higher rates of non-local material deposition, and these locations tend to be in upland margins removed from water courses (Holdaway et al. 2015). Overall, unlike in Australia, the ecology of the ONG meant a greater degree of resource predictability and more opportunities for resource exploitation, resulting in high redundancy of place use evidenced by differences in assemblage composition in
different landscape contexts (Holdaway et al. 2015). In both the Australian and Great Plains examples, human movement and place use relates to the long-term ecology of the environment but in different ways – meaning that the evidence for reuse is different.

Holdaway and colleagues (forthcoming) go further in relating material culture to the ecology of place. In Australia, increased frequency of heavy grindstones in the late Holocene is often thought to reflect increased sedentism or population (e.g., Smith 2013). But grindstones are heavy and are left behind when people move as they cannot be easily transported. An alternative interpretation is that over time, visible grindstones are returned to for use as they become indicators of places that are suitable for grinding when grasses and seeds are available for grinding – they become (or materialise as) part of the ecology of the place. The grindstones are not fixed destinations or places of permanent occupation but rather if suitable conditions coalesce, people passing through will make use of them. If conditions do not allow, people will pass by. Similarly, concentrations of hearths and stone artefacts might not indicate fixed ‘sites’ but rather places where resources and raw materials converge to allow time for stone reduction and selection of artefacts for transport elsewhere (Holdaway et al. 2017). Importantly, this patterning is emergent, accumulating over time (Holdaway et al. forthcoming).

In some ways, Mungo bears similarities to the ONG example. Where the ONG is characterised by a network of water courses and an ecology of predictable resources, at Mungo there is a lake that provided resources to a greater or lesser degree depending on the lake level (Long et al. 2014), a lunette into which small marsupials burrowed, and surrounding plains that provided an opportunity to hunt, as evidenced by the remains of marsupials and avifauna contained in isolated hearths in the Mungo study area (Stern 2015; Stern et al. 2013). In the ONG, place use is characterised by long sequences of intermittent occupation. The analysis of ClusterSim and stone artefacts suggest occupations on the Mungo lunette were also intermittent and of variable length, but on average relatively short, leading to a low-density record. Given the coalescence of the right conditions, Mungo was a suitable place to stop to hunt or forage for resources and construct a hearth to cook, and even to flake stone that was carried with people to the area (Stern et al. 2013). Like the Rutherford's Creek example, the presence of hearths and scatters of artefacts would suggest locations suitable for such activities, with the potential for reuse of stone if needed. But Mungo is also part of a wider landscape ecology that consists of riverine corridors and other lakes (see Appendix D) which people also exploited – the evidence of removal of artefacts from the stone reduction
sets at the Mungo study area suggesting activities occurring elsewhere. In this way, Mungo is not conceived of as a fixed destination, but a place people passed through, taking advantage of if conditions permitted, and where behaviours retained a marked regularity over time. Reflecting on stone use, raw material supply and economy of use was perhaps indeed not of concern as suggested by other researchers (cf. Tumney 2011; Spry 2014), but for a different set of reasons. Taken together, an alternative place use history emerges, one that becomes apparent as the archaeological record accumulates and pattern emerges over time. Behaviour at some places in this sense is less about mobility relative to the place itself, but rather about frequency and redundancy of place use as the ecology allows, which also informs on activities that occurred elsewhere.

5.8 Conclusion

Thinking about the lithic record from a non-essentialist, relational perspective prompted a reassessment of how lithic technology is used to infer mobility and settlement pattern in a way that is not based on a priori statements about the manufacture sequence or artefact forms and their meaning within a behavioural system. An approach founded on geometry and grounded in uniformitarian principles was used to assess the extent to which all products of lithic reduction are present in an observed assemblage, thus indicating human movement. An exploratory agent-based model was used as a way of interrogating the empirical record by investigating the effects of simple variables of raw material availability, lithic production and movement on simulated assemblages. Simulation outcomes provided a set of hypotheses that were tested using lithic assemblage data from two contrasting contexts of late Pleistocene Lake Mungo and late Holocene Rutherfords Creek. Similarities between simulation output and the empirical records suggest the simple variables and processes modelled in the simulation may explain much of the lithic assemblage patterning at these locations.

The results of the assemblage analysis juxtaposed with the simulation output suggest the Mungo and RC cases appear to be two different parts of the same modelled world. That is, they can be thought of as two different ‘windows’ into a lithic record whose composition at different times and locations is explainable in terms of the same simple set of variables. Thought of in these terms, the archaeological residues of short-term events, like those in the Mungo case, are patterned in much the same way as longer-term accumulations like in the RC case. It therefore appears that lithic patterning in both locations is emergent along stable
lines, despite several millennia and different contexts of resource availability separating the two records.

This is an interesting result since according to conventional wisdom, the Mungo and RC records should show distinct differences in lithic assemblage patterning. Yet what the results presented in this chapter suggest is that, at least from the perspective of the lithic record, contrasting factors often given much interpretive weighting, such as Pleistocene-Holocene distinctions or differences in landscape and resource contexts, may actually have less explanatory power than previously thought, particularly when used in an *a priori* manner as a starting point for analysis and interpretation. Insofar as they provide overarching explanations for patterning in the lithic record, these contextual variables might only matter peripherally. For instance, landscape features like lakes may draw people to an area, but that effect is not large enough to influence patterning in the lithic record over time – this is not what the emergent patterning relates to. This is not, of course, meant to suggest that wider contexts in which people moved and lived are unimportant and should be ignored. Rather, it is a question of how they are incorporated into analyses of the lithic record. The investigation of how to interrogate the lithic record to answer questions about mobility in a way that does not essentialise artefacts highlights the need to understand the fundamental nature of lithic assemblages and what structures their composition. This point is returned to in the following chapter.
Chapter 6
Discussion

The focus of this thesis is on how to address indeterminacy in archaeological inference: the problem of distinguishing between any number of explanations for observed archaeological patterning. As a historical science, archaeology is subject to indeterminacy since it is not possible to directly observe the operation of processes of interest. Instead, unobservable causes must be inferred from observable effects. Recently, Perreault (2019), drawing on established literature on the temporal scale of the archaeological record (e.g., Bailey 1981, 2007, 2008), articulated the root of indeterminacy as a mismatch between the use of theories of human behaviour operating at the scale of an individual lifespan to explain an archaeological record which accumulates at much larger temporal scales. His solution was to reconfigure the kinds of questions that are asked of the archaeological record that is subject to the mixing and loss of data, focusing instead on the reconstruction of cultural histories and seeking macroscale patterns and processes (Perreault 2019).

This thesis took inspiration from Perreault’s (2019) discussion of the relationship between archaeological data and archaeological interpretation, arguing the fundamental treatment of archaeological data is a large contributor to indeterminacy (Chapter 1). Concepts such as ‘mixing’ and ‘loss’ carry with them implicit assumptions about the existence of an ‘unmixed’ or ‘complete’ archaeological record at some point in time that, were it possible to reveal this state, would allow the application of microscale theories to reconstructions of the past. However, this does not fit with contemporary understanding of the archaeological record as an emergent phenomenon that is constantly in a state of becoming. In this understanding of the archaeological record, observed patterning is not an outcome of some original state being transformed by various agents, but rather the product of a long history of accumulation involving human and non-human agents that is not reducible to proximate causal processes (Bailey 1983, 2007; Davies et al. 2018; Olivier 2011). Thus, it was suggested that an alternative approach to addressing indeterminacy requires analysing the archaeological record in a way that is open to the histories of relationships that contribute to its emergent quality.

This was approached in terms of essentialist and materialist perspectives in archaeological interpretation, specifically with reference to lithic studies (Chapter 2). Essentialist approaches assume material objects have an essential nature that defines what the object is, locking them
into *a priori* categories of being. In this way, artefacts are treated as direct representations of the past (Holland-Lulewicz 2021; Fowler 2013; Van Oyen 2013). Many lithic studies are essentialist in the way they privilege the form and manufacture of artefact types that are thought to represent intentional, finished products emblematic of some form of behaviour (Dibble et al. 2017). Two consequences of essentialist approaches for the indeterminacy issue were discussed. One consequence is that *material remains are treated as both data and interpretation*. Units of observation are often locked into static categories thought to be real and analytically meaningful according to how archaeologists expect the past to behave. Consider, for example, the naming of objects based on their presumed function, such as ‘scraper’ or ‘projectile point’, which are at once both units of analysis and interpretations about the role the artefacts played in the past behavioural system. Evidential claims based on such data conform to expectations by default since data and interpretation are not independent (Chapman and Wylie 2016). This makes it difficult to distinguish between alternative explanations for the same observed archaeological patterning. The second consequence of essentialist approaches for the indeterminacy issue is a *short time* perspective in which assemblages of material remains with immutable properties are used to define cultural groups or site types, which are subsequently used to form anthropological narratives about the past. However, such approaches often fail to consider the variable life histories of the artefacts in the assemblages and the changes in morphology and function they underwent (e.g., Dibble 1984). Nor do they account for the rate at which material accumulates in the archaeological record forming palimpsest deposits, in which assemblages are not necessarily interpretable as synchronous units or in terms of central tendencies in stone use or site function (Bailey 2007; Rezek et al. 2020; Stern 2008).

A materialist perspective, by contrast, recognises the multi-temporal nature of objects and sees them as composed of shifting sets of relations with other entities. This understanding of objects and the assemblages they comprise aligns more closely with the concept of an emergent archaeological record. In Chapter 2 it was argued that a materialist perspective prompts a critical rethink of the validity of statements about the past based on essentialist approaches, emphasising the understanding of histories of accumulation rather than the construction of linear narratives. Archaeologists may therefore be better served by analysing material remains in a way that limits assumptions about the behavioural significance of those remains as much as possible. Instead, analysis should be built from the ground-up, focusing on simpler, lower-order propositions that are methodologically uniformitarian rather than
substantively uniformitarian (*sensu* Bailey 1983; see section 2.2.1). Exploratory agent-based modelling was introduced as a way of implementing this kind of analysis by experimenting with processes of interest under a range of parameter settings, grounded in appropriate theory, to derive hypotheses about archaeological patterning that can be independently tested using empirical data (Chapter 3).

Two case studies based on common ways of inferring mobility from lithics through raw material sourcing and the study of technological organisation were used to demonstrate how the approach to addressing indeterminacy set out in the first two chapters might be operationalised. In the following section, the findings from each case study are summarised and some key insights are highlighted. The chapter then considers some of the implications of the findings for the study of lithics before turning to the indeterminacy issue more broadly.

### 6.1 Learning from the Case Studies

In the SourceSim and ClusterSim studies, lithic reuse was the unifying theme, based on a materialist view of lithic objects and the shifting sets of relations they undergo across their use-lives. Many approaches to mobility using lithics are based on essentialist understandings of the manufacture sequence which begins with raw material acquisition at a geological source and ends with the production of intentional artefact forms (Dibble et al. 2017). In light of the suggestion that archaeologists should analyse material remains in a way that limits assumptions about the behavioural significance of those remains as much as possible, it was argued that lithic reuse provided a minimal assumption regarding the acquisition of raw material or indeed immediately usable artefacts, rather than people always returning to the geological source and/or beginning the manufacture process anew. Lithic reuse therefore breaks down the notion of a linear manufacture sequence, with implications for inferences about mobility based on access to raw material which form the basis for lithic sourcing and technological organisation studies. These implications were explored in the SourceSim and ClusterSim studies, briefly summarised here.

#### 6.1.1 Mobility and Sourcing: SourceSim

In lithic studies, mobility is often inferred based on information about the geological origin of the raw material from which artefacts are manufactured. The relative quantities and the intensity or economy with which different raw materials are reduced is assessed against distance to the geological source of those materials, forming the basis for inferences about
trade and exchange or differential access to resources, which in turn often factor into interpretations about wider social organisation. While distance to the geological source provides an indication of the minimum distance artefacts moved, this measure alone does not record the complete set of movements an artefact underwent, which is often unknowable (Hodder 1984; Kelly 1992). However, the geological origin of stone is only one proxy for sources of usable material exploited by people in the past. In thinking about lithic reuse, it becomes apparent that as lithic material was procured, moved around, and discarded, it manifested as new sources of material at different places in the landscape (e.g., Potts 1984; Schick 1987). These human-made sources were located somewhere in between the geological origin of stone and the location of the artefacts when found by archaeologists. The existence of anthropogenic sources of usable stone changes the meaning of what is a ‘local’ and ‘non-local’ material, which has implications for behavioural inferences based on distances to geological sources.

An exploratory agent-based model called SourceSim (Chapter 4) was constructed to investigate the effects of raw material procurement from exclusively geological or a combination of geological and anthropogenic sources on patterning in archaeological raw material distributions, in a simplified scenario where groups acquire, move, and discard quantities of artefacts across an otherwise empty simulated landscape. Simulation outcomes were tested using empirical data on archaeological obsidian assemblages from locations across Aotearoa. The socio-natural properties of the Aotearoa case lend itself to testing alternative explanations for patterning in archaeological raw material distributions. To recap, given the large size but also geographic boundedness of Aotearoa, its short settlement chronology (relative to elsewhere in the world), and robust information about available obsidian sources, archaeologists should in theory be able to see patterns in lithic assemblages according to traditional models of mobility, such as distance decay, and their relationship to trade and exchange or other social behaviours.

The SourceSim experiment tested various combinations of parameters: whether groups always accessed a geological source when in need of artefacts or whether they first obtained material from visible deposits of artefacts; whether a given geological raw material source had a higher chance of being discovered first, thus initially introducing more of that material into the simulated landscape; and finally, whether a given raw material type was considered more desirable than others, the geological source of which would therefore potentially be accessed more frequently than others. Relevant simulation output included patterning in the
overall archaeological representation of different raw material types over time, the distance between discarded artefacts and their geological origin, the number of visits each geological source received, and the total number of artefacts produced.

When testing simulation outcomes using the Aotearoa obsidian data, the closest correspondence was between the simulation where groups first obtained material from visible deposits rather than always accessing a geological source, where one geological source had a higher chance of being discovered first, and where all materials were considered equally desirable. Geological source representation amongst artefact assemblages initially fluctuates but largely reflects initial access to those sources, before levelling out as lithic artefacts enter the system and become part of the landscape, forming new associations as sources of material for reuse. As discussed in Chapter 4, this finding runs in opposition to typical inferences about mobility using sourcing data which are often based on the implicit, essentialist assumption that people always accessed a geological source when in need of stone material.

Correspondence between a simulated and empirical pattern does not mean the processes modelled in the simulation were necessarily in operation in the past. That is not the point of the exploratory approach (Premo 2007, 2010). However, treated as tools with which to think about the real world (O’Sullivan and Perry 2013:14), the simulations prompted further tests of the empirical data based on patterns that might be expected were something akin to the simulated processes in operation in reality. For example, it was suggested that under conditions of reuse, there should be no major differences in the treatment of different obsidian types in terms of reduction intensity or economising behaviour, and there should be disparities in linear reduction sequences reflecting raw material acquisition, core preparation, production of primary flakes and debitage, and ultimately retouched tools. A lack of available attribute data for the empirical assemblages did not allow a detailed test of these expectations. However, support was found based on the technological analyses from other studies (e.g., Holdaway and Phillipps 2021; McBride 2019). Together these results suggest the importance of recording a full suite of attributes when analysing assemblages to better understand their formational histories. This includes analysing the full range of objects and measures of use beyond size, cortex retention, and the presence of retouch, such as use-wear on different artefact types (Phillipps et al. 2022b).

As noted in Chapter 2, in Aotearoa the distribution of obsidian artefacts deriving from different geological sources often forms the basis for inferences about trade, exchange, and
associated procurement behaviours (e.g., Brown and Pitman 2019; McCoy and Carpenter 2014; Moore 2012; Scott 2007; Walter et al. 2010); social networks and interaction spheres (e.g., Ladefoged et al. 2019; Leach 1978; McCoy and Robles 2016; McCoy et al. 2010; Moore and Coster 2015); territoriality and regionalisation of source use (e.g., Lawrence et al. 2014; McCoy et al. 2014); and, in combination with other proxy evidence, warfare (e.g., McCoy and Ladefoged 2019). Many such studies reference the proportion of Tūhua obsidian in assemblages, considered an important material based on its presence at sites throughout the country and its high-quality flaking properties (e.g., Moore 2012). For example, Walter and colleagues (2010) suggest the ubiquity of Tūhua obsidian at early sites, combined with the apparent lack of economical use at sites located large distances from Tūhua itself, indicates a ‘coloniser’ mode of exchange (sensu Irwin 1991) in which people had access to a common distribution system. A decline in long-distance transport of Tūhua obsidian over time is thought to reflect changes in social networks and increasing regionalisation of material use from different geological sources (McCoy et al. 2014; Walter et al. 2010). Alternatively, the results of the SourceSim analysis suggest patterning in the distribution of different source materials over space and time may be explained by redistribution through reuse, not exclusively by changes in access to the geological sources of obsidian. Similarly, thinking through the SourceSim results suggests the relative ‘value’ of Tūhua obsidian compared to other obsidian types may not be directly interpretable from assemblage data since any patterning may relate more to the geological expression and availability of the material – on Tūhua, obsidian is easily accessible and abundant compared to obsidian from other geological sources (Holdaway and Phillipps 2021; Moore 2012; Sheppard 2004).

Other studies consider patterning in the distribution of all obsidians in addition to Tūhua. For example, Ladefoged and colleagues (2019) employed a social network analysis of obsidian artefacts from 15 assemblages, for which the geological sources had been identified, to investigate changes in social interaction and affiliation amongst Māori over time. They set up the null hypothesis that people accessed the closest/easiest geological source in terms of travel time when procuring material (i.e., the least cost economically). They found a discrepancy between the rank order of geological source frequency and least cost travel to geological sources for many sites, suggesting material procurement strategies were tied to social considerations rather than purely least-cost distances (Ladefoged et al. 2019). However, the results of the SourceSim analysis indicate the reuse of discarded lithic material in the absence of any social interaction can also explain assemblage patterning. It may be the
case that social factors are not necessarily visible in lithic assemblage patterning – nonetheless, reuse is a valid alternative hypothesis that requires consideration.

The question of the degree to which social behaviours such as trade and exchange are interpretable from archaeological patterning and sourcing data has precedence in other studies of obsidian assemblages such as in Melanesia, which has a longer settlement history than Aotearoa. Fortunately, the generality of the patterns investigated in the empirical Aotearoa data facilitates comparison with published studies of early Lapita lithic assemblages. For instance, Specht (2002), in his evaluation of early Lapita obsidian assemblages from the Reef/Santa Cruz Islands (from Sheppard 1993), reached the conclusion that for some sites it may not be necessary to invoke long-distance exchange networks when explaining assemblage patterning. Lapita obsidian assemblages have historically been used to infer trade and exchange practices characterising ‘coloniser’ and ‘post-colonisation’ phases in the settlement of the Pacific as people reached new islands and established themselves (e.g., Irwin 1991). Sheppard (1993) reported on 972 pieces of obsidian for which the geological source was determined, derived from three sites in the Reef/Santa Cruz Islands, east of the main Solomon Islands group, dating from 1200 BCE (Figure 6.1; Table 6.1). Of these artefacts, 97.5 % were derived from the Talasea geological obsidian source in the Bismarck Archipelago, located over 2000 kilometres to the northwest, with the remainder of the obsidian originating from local sources. The total mass of artefacts analysed amounted to a little over two kilograms which, when extrapolated for all three sites based on sediment volumes, resulted in estimates of 245 kg of obsidian for SZ-8, 9.5 kg for RF-2, and 26.44 kg for RF-6 (Table 6.1). Specht (2002) noted that for the largest estimate at SZ-8, this only amounted to the importation of less than one kilogram of obsidian per year on average. Similarly, a single importation event was suggested as enough to provision people at RF-2 for the duration of occupation at the site, and that reuse of material occurred (Sheppard 1993). Various measures of reduction intensity suggested distance to geological source and material scarcity had a minor influence on reduction and discard behaviour at each site, providing little support for economising models of stone use (Sheppard 1993). These findings are similar to the results from assemblages from Aotearoa (e.g., Holdaway and Phillipps 2021). Sheppard ultimately concluded that for his study assemblages, archaeologists “might well be seeing only the mundane utilitarian commodity part of the game and not the big picture where differential access and social economizing may have played an important role” (1993:135). Albeit a broad comparison, the similarities between the Aotearoa and Lapita
obsidian assemblages suggest similar processes may account for archaeological patterning more generally, and warrants further comparison with assemblages from other parts of the world.

Figure 6.1 The location of the Reef/Santa Cruz Islands east of the Solomons in Melanesia. Note the location of the Talasea obsidian source in the Bismarck Archipelago to the northwest. Aotearoa is located approximately 3500 km to the south. Figure reproduced from Sheppard (1993:122, Figure 1).

Table 6.1 Obsidian assemblages from three Lapita sites on the Reef/Santa Cruz Islands reported by Sheppard (1993).

<table>
<thead>
<tr>
<th>Site</th>
<th>Approximate age (BCE)</th>
<th>Total number of obsidian artefacts</th>
<th>Total mass of obsidian artefacts (kg)</th>
<th>Estimated mass of obsidian for the site (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SZ-8</td>
<td>1200-770</td>
<td>335</td>
<td>0.87</td>
<td>245.00</td>
</tr>
<tr>
<td>RF-2</td>
<td>1050-900</td>
<td>642</td>
<td>1.32</td>
<td>9.50</td>
</tr>
<tr>
<td>RF-6</td>
<td>700-550</td>
<td>28</td>
<td>0.05</td>
<td>26.44</td>
</tr>
</tbody>
</table>

1 As reported by Sheppard (1993:124, 127). 2 As reported by Specht (2002:40).
Overall, the results of the comparison of Aotearoa obsidian assemblages with the outcomes of SourceSim call into question inferences about past human behaviour that are based on assumptions about the essential role geological sources of material played in the acquisition of raw material and production of lithic artefacts. The question is not about the existence of these behaviours in the past but rather the extent to which they are ‘visible’, so to speak, in lithic assemblage data. Thought of in relation to the reuse of existing artefacts, the assumption of accessing a geological source to acquire fresh raw material and begin the manufacture process anew (see Dibble et al. 2017) needs to be assessed rather than taken as a given before generating subsequent behavioural inferences.

6.1.2 Mobility and the Organisation of Technology: ClusterSim

Many mobility studies using lithics seek to identify patterns relating to Binford’s (1978, 1980) residential and logistical mobility strategies, the material expressions of which are based on optimality models from behavioural ecology (Blair 2010; Nelson 1991). These models predict that efficiency of raw material use, artefact design, and resultant patterning in lithic assemblages are influenced by resource density, quality, risk, uncertainty in resource availability, and mobility (e.g., Barton et al. 2013; Bleed 1986; Clarkson 2007; Kuhn 1995; Morrow 1996; Parry and Kelly 1987). However, the relationship between the expression of lithic technology and mobility strategies varies according to wider socio-natural contexts leading to contrasting interpretations, such as Kuhn (1995) and Morrow’s (1996) debate about mobility and tool size efficiency or Parry and Kelly (1987) and Prasciunas’ (2007) interpretations of biface reduction. This is unsurprising in the context of lithic reuse. As noted above, the process of reuse changes the meaning of raw material availability, highlighting the formation of new associations among artefacts and people through space and time, and breaking down linear manufacture sequences that begin with raw material acquisition at the geological source and end with the production of retouched tools (Dibble et al. 2017).

Analysis of lithic assemblages based on the principles of geometric approaches such as the cortex ratio (e.g., Dibble et al. 2005; Douglass et al. 2008) was suggested as a way of identifying the physical movement of stone artefacts as a direct proxy for human movement, thus avoiding assumptions about how the form and manufacture of stone artefacts relates to different types of mobility. This approach to analysing lithic assemblages is not concerned with specific artefact forms or lithic assemblages as bounded activity sets reflecting what occurred at a location, but rather evaluates all components of assemblages and what is
missing from them irrespective of artefact form, thus informing on movement and activities occurring elsewhere (Douglass et al. 2017). However, interpreting patterns in geometric measures requires an understanding of how these values relate to different mobility configurations, availability of raw material, and stone reduction behaviours.

An exploratory agent-based model called ClusterSim (Chapter 5) was constructed to investigate the effects of various combinations of these processes on the movement of lithic material into and away from a simulated assemblage, as measured by the ‘completeness’ of individual reduction sets (clusters) comprising of some number of flakes plus a parent core. ClusterSim was based on FMODEL which was originally developed by Davies (2016; Davies et al. 2018) to calculate cortex ratios but adapted for this study to allow the reuse of lithic material and to track the composition of individual clusters. The choice to model the composition of lithic reduction sets rather than the quantification of cortical surface area or volume of stone was based on the availability of data from an empirical lithic assemblage at Lake Mungo, which along with data from Rutherfords Creek in Australia, were used to test the outcomes of ClusterSim. These two records are ideal cases for testing the simulation outcomes for several reasons. To recap, the Lake Mungo record is late Pleistocene in age, and while it represents several thousand years of accumulation, the lithic record is of relatively low density and individual reduction sets are identifiable (Spry 2014; Stern et al. 2013). By contrast, the record at Rutherfords Creek is late Holocene in age but is of a much higher density reflecting ca. 2000 years of accumulation (Fanning et al. 2009; Holdaway et al. 2012). At Lake Mungo, raw material had to be imported from elsewhere whereas at Rutherfords Creek, raw material was locally available. Therefore, under common interpretive frameworks such as those based on optimality principles, the two cases should demonstrate marked differences in the use of stone and the formation of the assemblages.

The ClusterSim experiment explored the interaction of various combinations of raw material supply (carry_in), reduction intensity, selection intensity, and forager movement tortuosity (effectively modelling the length of time spent in an area), and the resultant effects on the distribution of cluster sizes. Qualitative similarities were found between the cluster size distribution shape for Lake Mungo and those simulations where reduction intensity and tortuosity were low, selection intensity was low to high, and carry_in was set at either 20 or 100. Like with SourceSim, qualitative similarities between a simulated and empirical pattern does not mean the processes modelled in the simulation were necessarily in operation in the past. However, the simulation parameters of interest served as the basis for tests of the Lake
Mungo and Rutherfords Creek stone artefact analysis data, enabling exploration of the extent to which those processes were reflected in the empirical data, thus strengthening the explanatory power of the simulations. A low to medium reduction intensity was suggested by the simulations, along with a small to large amount of material in the form of flakes and cores leaving the window. Based on a range of attribute measures, the assemblage level analysis of the two empirical data sets found broad agreement with expectations derived from the relevant ClusterSim outcomes, with further support suggested by the analysis of individual reduction sets from Lake Mungo.

As noted in Chapter 5, a carry-in setting of 100 in the context of the simulations is effectively a proxy for abundant, readily available raw material, mirroring the Rutherfords Creek situation and standing in contrast to the Lake Mungo context. Thus, it appears that at least for the empirical cases considered here, use of raw material is similar despite differences in geological raw material availability. This does not make intuitive sense from the perspective of optimality models and common conceptions of the manufacture process like those that underpin many studies of lithic technological organisation, yet does make sense from a reuse perspective since reuse effectively changes raw material availability. This finding is similar to the lack of efficient reduction of obsidian with increasing distance from the geological source noted for obsidian assemblages in Aotearoa (Chapter 4; e.g., Holdaway and Phillipps 2021).

Thus, measures of reduction intensity and how they relate to occupation duration and mobility are called into question, such as the assumption that with increasing occupation duration assemblages will exhibit a greater degree of raw material consumption (Shott 2003). No similarities were found between ClusterSim runs with high reduction intensity and the empirical records analysed. There are certainly empirical instances of high reduction intensity of cores, and high reduction intensity of cobbles does occur in the simulation runs of interest – but these might also be explained as the result of multiple episodes of flaking through the reuse of cores, and not some linear manufacture process. At Lake Mungo and Rutherfords Creek, these episodes occurred over time, resulting in the accumulation of material from a set of unrelated but relatively invariable occupations/behavioural events. This is congruent with findings from a recent simulation study by Davies and colleagues (2021) who built upon FMODEL to assess how sensitive cortex ratios are to differences in occupation intensity versus repeated visitation and accumulation. They ran two models: an ‘occupation’ model, in which a constant number of agents moved at a random level of tortuosity making and
discarding flakes; and an ‘accumulation’ model, in which a random number of agents moved at a constant level of tortuosity (in this case, low tortuosity) making and discarding flakes. In the occupation model, the number of occupation episodes does not vary, whereas in the accumulation model it does. When plotting simulated cortex ratios against assemblage density, for the accumulation model cortex ratios were distributed around a mean value that remained consistent across density values, a pattern remarkably similar to the empirical distribution of cortex ratios at Rutherfords Creek (Davies and Holdaway 2017). This suggests a pattern of repeated visitation combined with consistency of stone use across the landscape over the long term (Davies et al. 2021). Together, the results of ClusterSim and Davies and colleagues’ (2021) accumulation model challenge mobility inferences based on reduction intensity and variable assemblage density.

Presented with the Lake Mungo and Rutherfords Creek records – two archaeological assemblages of differing densities and different contexts of raw material availability – similar formational processes and similar forms of mobility are implicated when viewed over the long term, where one might reasonably expect these to be different. This has implications for common narratives of past indigenous lifeways in Australia. Such narratives tend to relate to broad scale shifts in settlement, or indeed lack of change, between the late Pleistocene and late Holocene. For instance, early narratives described a highly mobile hunter-gatherer culture that remained relatively unchanged from the late Pleistocene onwards, in what Gould (1980) referred to as a ‘conservative desert culture’. This was based on the projection of ethnographic data onto the archaeological record (e.g., Allen 1972) and the supposed persistence of an ‘Australian Core Tool and Scraper Tradition’ until the late Holocene (e.g., Bowler et al. 1970). As the number of archaeological investigations in Australia increased, Veth (1989) found little support for Gould’s notion of a stable adaptation and instead proposed a biogeographic model in which late Pleistocene people inhabited better watered, elevated areas, with arid lowlands representing barriers to movement. With climatic amelioration in the Holocene, people expanded into the lowland areas resulting in increased occupation intensity and social interactions (Veth 1989).

More recently, based on increasing archaeological evidence of a variety of cultural expressions in different parts of Australia (e.g., Dortch et al. 2019), the narrative has shifted to one of directed change in economic, technological, and social adaptations in the Holocene (Ulm 2013). A range of evidence is used to argue for greater sedentism in the Holocene than in the Pleistocene, including shifts in stone technology. For example, Veth (2005) notes how
evidence from sites in the Western Desert suggests a shift from low reduction intensity in the
Pleistocene to high reduction intensity in the Holocene. Similarly, he notes an increase in the
diversity of artefacts over time suggesting decreasing mobility, based on the inverse
relationship between assemblage diversity and level of mobility noted by other scholars (e.g.,
Shott 1986). Smith (1989, 2013) also identifies an increase in the number and diversity of
artefacts in the late Holocene (see also Williams 1998) and suggests the presence of grinding
stones indicates a greater reliance on marginal resources such as seeds, reflecting greater
sedentism (though grinding stones are present in the Pleistocene, e.g., Fullagar et al. [2015].
See also Holdaway et al. [forthcoming] for an alternative interpretation). Evidence for greater
sedentism is linked with notions of late Holocene intensification (e.g., Lourandos 1983;
Lourandos and Ross 1994), supported by increased numbers of radiocarbon dates thought to
be indicative of population growth and more intensive occupation at this time (e.g., Williams
et al. 2015, but see Attenbrow and Hiscock 2015).

Despite changes in mobility being central to inferences about Pleistocene and Holocene
lifeways, these are interpreted in different ways. For instance, tula adzes, a distinctive tool
type used for working wood, are interpreted on the one hand as versatile tools associated with
frequent residential movement (e.g., Veth et al. 2011), and on the other as part of a strategy to
offset resource depression resulting from longer occupations in one place (e.g., Smith 2013).
Other studies demonstrate that formation processes and the influence of geomorphology on
artefact distributions needs to be considered (e.g., Holdaway and Fanning 2008, 2014; see
also Allely et al. 2021 for an example with shell deposits). As noted above, recent work
analysing late Holocene stone artefact assemblages from western New South Wales suggests
patterns of high mobility with repeated visitation to the area (Davies et al. 2018, 2021;
Douglass et al. 2008). Furthermore, simulation work investigating the distribution of hearth
ages suggests radiocarbon dates deriving from these kinds of features may be biased towards
the present as a result of geomorphic processes acting to bury, expose, or destroy hearths,
running counter to interpretations of population growth/intensive occupation (Davies et al.
2015).

The results of the research for this thesis suggest that in the cases considered, patterning in
late Pleistocene and late Holocene stone artefact assemblages is emergent over time in a
similar way, reflecting on the whole similar forms of place use. This finding is significant for
understanding change in mobility and place use over time using stone artefact assemblages.
However, it would be inaccurate to simply suggest this result reflects a shift in the narrative
back to earlier ideas about mobility in Australia. Rather, the implication is that the magnitude of any behavioural changes that might have occurred were not sufficient to shift patterning in the proxies under investigation (e.g., Davies et al. 2021:63).

Viewed from a materialist perspective, the composition of lithic assemblages in terms of different proportions of tool types and relative densities are not interpretable in terms of traditional narratives about human behaviour. Nor do environmental factors like the presence of water features necessarily relate to assemblage composition except in the broadest sense. It appears the lithic record is not sensitive enough to the types of variables archaeologists often consider important when making inferences about mobility and use of landscape. Rather, a more fundamental set of simple processes interact to produce the record observed by archaeologists in the present. As stated at the end of the previous chapter, this does not mean the wider contexts in which people lived and moved should be ignored, but instead raises the question of how they are incorporated into analyses of the lithic record. The impact of different variables on the structure of the archaeological record must first be assessed, not taken as given.

6.2 Implications for the Study of Lithics

Lithics are often the only surviving remains of past human behaviour and are therefore considered key evidence about past peoples’ social identity, environmental knowledge, technological and cognitive capabilities, subsistence economy, and mobility (Anghelinu et al. 2020). These aspects are typically inferred based on analysis of patterns in the form and manufacture of lithics, the materials they are made from, their distribution, and relative density in the assemblages they make up. The focus on form and manufacture sees lithic objects as inert, direct representations of the past where information about behaviour is contained within the artefact itself. This view of lithics has not fundamentally changed since the late nineteenth/early twentieth century (Dibble et al. 2017; Holdaway and Douglass 2012; Rezek et al. 2020).

In thinking about general understandings of how different systems work, Premo (2018) references Sloman and Fernbach’s (2017) notion of the ‘knowledge illusion’. The knowledge illusion posits that humans as a collective know more about how the world works today than at any other time, yet humans as individuals know less about how the world works than ever before. For instance, humans invented lightbulbs and flushable toilets, but how easily can individuals describe how these seemingly mundane objects work (Premo 2018)? The
relevance of the knowledge illusion for science and research is that, given time constraints and the limits of individual expertise, it is tempting to accept someone else’s answer to a problem, particularly if it means one can move on to other important questions or problems. However, as Premo (2018) notes, the act of recounting someone else’s solution does not necessarily require an understanding of that solution. Applying existing knowledge in this way may lead to new insights but can also lead to “intellectual cul-de-sacs populated by shambling “zombie” explanations that live far beyond their usefulness” (Premo 2018:26).

The relevance of the knowledge illusion for lithic studies is how it highlights the need to critically think about and understand the role of lithics in past behavioural systems and how patterning in assemblages is produced, rather than taking anything as given. For instance, before making inferences about forms of mobility that existed in the past, it is important to understand how patterning in lithic assemblages derives from different mobility configurations (Holdaway and Davies 2020). Paradoxically, if lithics are often the sole surviving material residues of some past peoples, then achieving this understanding often depends on studying the lithics themselves (Anghelinu et al. 2020). This research demonstrated a way of getting around this issue by using simulation and by considering lithic artefacts in light of contemporary understandings of the archaeological record, rather than those that were formed decades ago (Holdaway and Douglass 2012). The results of the research in this thesis reinforce that, as others have noted (e.g., Dibble et al. 2017; Rezek et al. 2020), lithic artefacts and assemblages cannot be treated as direct representations of past behaviour but rather, patterning is an emergent outcome of a range of processes, human or otherwise. This is evident when taking a materialist view of the lithic record, which sees lithics as composed of shifting sets of relations throughout life histories that are characterised by use and reuse through time and across space.

In this respect, it is also useful to consider the relationship between lithics and other types of material culture. Lithics preserve well but are one among many types of material that were used by people in the past which may not survive to be studied, as suggested by ethnographic research like that among the Wola of Papua New Guinea for whom flaked stone was “an integral but secondary part” of their material culture (Sillitoe and Hardy 2003:556; Hardy and Sillitoe 2003). Thought of in this way, the interpretive weighting given to lithics may, in many cases, be over-inflated, especially when essentialising the form and manufacture of lithic objects. Of course, stone is an important if not essential material for cutting and other tasks requiring a strong, durable tool. It is therefore unsurprising that the acquisition of stone
plays a large role in many inferences about past mobility. But perhaps more important to
people’s mobility decisions were the acquisition of food and other economic resources, an
idea captured by the concept of ‘embedded procurement’ (Binford 1979) but the implications
of which are often overlooked when analysing lithics in terms of linear manufacture
sequences beginning with raw material procurement from a geological source (Dibble et al.
2017).

As the results of this research suggest, the process of reuse accounts for patterning in
assemblages that might typically be explained in terms of mobility with respect to distance to
geological sources of raw material or use of stone material based on optimality models. This
has implications for the definition of ‘embedded procurement’. In its original form embedded
procurement refers to the acquisition of stone raw material occurring during other foraging
activities, rather than being the sole purpose of a trip. An assumption of distance decay
models used to infer geographic ranges of mobile groups is that raw material procurement is
embedded in other activities (Brantingham 2003). Binford (1979) developed the concept of
embedded procurement based on ethnographic observation of the Nunamiut. He noted how
the Nunamiut had little to no costs for procuring raw materials for manufacturing tools since
procurement was embedded in subsistence runs, such as the collection of quartz nodules for
making flakes during trips for which the primary purpose was to set animal traps. It is this
form of embedded procurement that most studies assume – acquisition of raw material from a
geological source. However, a naturally occurring outcrop is only one kind of material source
Binford (1979) was referring to, the other being anthropogenic sources – in Binford’s case,
these were materials cached by the Nunamiut in anticipation of reuse at some later date if
needed. Perhaps the clearest example of this is what Binford (1979) refers to as situational
gear – materials gathered or put together to accomplish a specific task. These materials may
be sought from direct sources but also from caches, through scavenging sites for lost or
abandoned gear, or by modifying gear on hand for reuse – the latter of which Binford
(1979:266) refers to as “expediently drafted sources of raw material”.

There is no doubt that access to geological sources of material occurred in the past since all
archaeological stone material had to be procured at some point and distributed throughout the
landscape to a greater or lesser extent. Early in the settlement history of a place, distance to a
geological source would be interpretable as a proxy for mobility to a degree, since at that
point no other locations with usable stone material (i.e., deposits of abandoned artefacts)
would exist. Upon abandonment, however, lithic artefacts materialise (sensu Lucas 2012) as
exploitable sources of raw material and, reasonably assuming that reuse occurred, would immediately overwrite any patterning in distance to the fixed geological source in a direct sense. The results of the simulation studies in this thesis suggest the patterning in lithic assemblages in the Aotearoa and Australia cases may be explained in part by the procurement of lithic material from landscape locations other than the geological sources of material. Yet, the generality of the simulations means they can easily be adapted, and resultant patterns can be tested elsewhere. This would be a worthwhile endeavour given ethnographic evidence (e.g., McCall and Horowitz 2015; Sillitoe and Hardy 2003; papers cited in Holdaway and Douglass 2012) and the increasing number of other archaeological analyses (e.g., Coco et al. 2020; Holdaway and Phillipps 2021; Turq et al. 2013) that suggest this kind of procurement behaviour may be the general rule rather than the exception. For instance, Douglass and colleagues (2018) note this kind of pattern for several assemblages from late Holocene western New South Wales, Australia (included among them, Rutherfords Creek). In upland locations where there is abundant stone in outcrops but little else to attract visitation such as water, faunal and floral resources, cores exhibited lower reduction intensities than in assemblages on the floodplain, where important subsistence resources would be intermittently available. Douglass and colleagues (2018) suggest ecological conditions would limit the frequency of visits to upland locations and abundance of stone would mean little need for reuse of cores. In contrast, higher reduction intensities in the floodplain assemblages were likely related to place use histories that involved repeated visitation with repeated use of cores exposed by erosion or simply not yet buried. What all these lines of research indicate is a shift in the meaning of ‘embedded procurement’ – lithic procurement is indeed embedded but in a different way to what is traditionally assumed, but it also means that sometimes usable material is passed by.

Approaching the study of mobility in the way advocated by this research reinforces a point that others have suggested (e.g., Holdaway and Davies 2020; Rezek et al. 2020) – that what is important is understanding the use of place through the practice of stone use, rather than constructing narratives about specific activities occurring at different times and places based on the raw material or techno-morphological form of lithic artefacts, the meaning of which vary according to different contexts. Practice of stone use refers to the “combination and interrelationship of selecting, flaking, transporting, reusing, maintaining, discarding, etc., inferred from emergent properties at different scales of time and space” (Rezek et al. 2020:899-900). Focusing on practice of use includes investigating whole assemblages and
what was taken away, not just what was left behind. However, the processes involved in the practice of stone use need to be contextualised in wider systems of movement to understand how assemblage formation emerges through different combinations of these processes, over the often vast timescales at which the archaeological record accumulates. Due to the spatial and temporal scales involved, this is often difficult to achieve in an actualistic sense (Holdaway and Davies 2020). This was the role of simulation in this thesis – to circumvent archaeological sampling issues, and to explore the interaction of different processes and how they produce emergent patterns. These patterns are then used to derive independent tests of the archaeological record in a way that analyses based on essentialist understandings are unable to.

It should be noted that this structure of deriving and testing expectations is similar to other methods of analysis discussed in Chapter 2 such as those based on optimality principles, including studies of lithic technological organisation or those that infer mode of procurement based on distance to a geological source. These approaches also generate predictions about archaeological patterning under different circumstances and test them using archaeological data. The distinguishing factor is the set of assumptions on which such approaches lie. For example, much theory about technological strategies and tool design derives directly from ethnographic observation (e.g., Binford 1980; Lee 1979). However, projecting contemporary expectations onto the past runs the risk of employing assumptions that predetermine what will be found (Chapman and Wylie 2016). This explains in part why any given conclusion cannot be supported to the exclusion of others, leading to contrasting interpretations of archaeological patterning such as Kuhn (1994) and Morrow’s (1996) debate over the optimal strategy for provisioning highly mobile people with usable stone cutting edge. Instead, analysing assemblages based on uniformitarian principles in a methodological sense (Bailey 1983) and simple, fundamental processes of movement, stone artefact production, reuse, and discard, allows the investigation of patterning unrelated to the morphology (in an intentional sense) or presumed functioning of artefacts in different contexts (Douglass et al. 2008, 2017). Of course, the reasons why movement patterns occurred are still open to explanation (Davies et al. 2018), but importantly any patterns are established independent of the data used to infer them.

All things considered, the kind of approach used in this research is a different way of thinking about the lithic record, one that gives primacy to understanding the interrelationships between simple processes of interest rather than listing and counting the number and variety of lithic
objects and how these compare between different places and times (Dibble et al. 2017; Rezek et al. 2020). This research highlights how it is important that archaeologists do not over-essentialise the lithics they are looking at and do not take for granted how lithic objects came to be associated together. There is ground to be gained by deconstructing technomorphological categories that are ultimately not real but an artefact of analysis, moving beyond simple description of what assemblages look like which is ultimately biased by what archaeologists think was important in the past. Instead, analysis should be geared towards understanding formational histories of lithic artefacts and assemblages, rather than what the artefacts and assemblages represent in an essentialist sense. This distinction is subtle, but one that opens an alternative way of approaching the archaeological record true to its emergent qualities, by emphasising the materialisation of the record as it appears in the present (Bailey 2007; Lucas 2012; Olivier 2011).

6.3 Implications for the Indeterminacy Issue and the Construction of Archaeological Knowledge

Taking indeterminacy as the problem of distinguishing between any number of explanations for observed archaeological patterning, has this problem been addressed? Are the explanations presented in the Aotearoa and Australia case studies not just other instances of equifinality? Indeterminacy is not solved in the sense of absolutely falsifying one explanation over another, but this is the wrong question to ask. Indeterminacy is more productively thought of as an issue of the construction of archaeological knowledge – understanding the nature of archaeological data and the types of inferences that can be constructed based on those data (Perreault 2019:1-3).

While addressing indeterminacy is not about the ability to absolutely falsify one explanation for some phenomena over another, being presented with contrasting explanations nonetheless raises the question of which one to carry forward in subsequent research and interpretation. That the analysis here suggests alternative explanations for assemblage patterning in the cases studied does not mean those explanations are “exclusively and exhaustively ‘right’” (Gero 2007:313), nor is it productive to present them as such. Of course, people in the past moved objects through trade and exchange and established social networks. For instance, in Aotearoa Maning (1875) observed that “blocks [of obsidian] were usually brought from the island of Tuhua by the Ngapuhi, when returning from the southern expeditions, and were articles which fetched a considerable price in the way of barter”. And of course, different
landscape features affected peoples’ mobility decisions. For instance, Krefft (1856-7, cited in Allen 1972:52) observed how Indigenous groups in the Murray River region in Australia established temporary shelters along swamps around February/March, and “towards the end of March [when] creeks and lagoons are at their lowest…they gather in large numbers at rich waterholes…Here they abide until the rain sets in, when other sources supply them with food, again in different localities either on the river or on the plains”. The existence of these kinds of behaviours in the past is not under debate — rather, the argument is about the nature of the evidence available to archaeologists, the assumptions on which inferences lie, and how conclusions are reached. The ethnographic examples above are just two examples of past behaviours, the full suite of which is likely to be complex and vary with the diverse indigenous groups that performed them. Thus, do archaeologists progress with higher-order explanations that are based on assumptions about how different types of evidence are thought to relate to past behaviour, or do they begin with an understanding of the patterning in material remains based on simpler, lower-order processes?

In considering this question it is useful to revisit Lucas’ (2008) concept of reversibility. As Lucas notes, many behaviours or events\(^1\) of the type archaeologists are typically interested in do not leave a material residue. Objects from specific behaviours or events do indeed survive but are often implicated in several other events and behaviours prior to their deposition. These residues then become involved in subsequent behaviours, often leaving no trace of the former (Lucas 2008). In this way, the archaeological record might be thought of in terms of patterns of material organisation, where material organisation that is reinforced and repeated is more likely to persist and be visible over time than that produced by ephemeral or individualised activities.

Following Lucas (2008), material organisation can be described as somewhere between reversible or irreversible. Reversible organisation is where changes in material organisation occur easily, such that subsequent events erase evidence of previous ones. Lucas provides the example of rearranging the order of books on a shelf, where the new order of books leaves no indication of the previous order. Lithics-wise, we might think about the residues of specific instances of trade/hand-to-hand exchange or the reworking of artefacts resulting in different

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\(^1\) ‘Event’ has many meanings in archaeological discourse; indeed, this is the subject of Lucas’ (2008) paper. It is beyond the scope of this thesis to parse out the varied meanings of the term and their significance for archaeological analysis and interpretation. For the purpose of discussion here, ‘event’ refers to an instance of behaviour defined in terms of conventional, everyday understanding of the term, and where various collections of events contribute to constructing microscale narratives of the past (per Murray 2008).
forms: retouching a stone object may erase any indications of the previous shape and function of the object, and trade/exchange practices themselves may leave no indication of the previous owners of objects nor material traces of the specific way in which the objects arrived at a location. Irreversible organisation, by contrast, is where patterns of material organisation are reinforced by what occurred in the past such that reorganisation or change occurs less easily. Here Lucas provides the example of changing the side of the road driven on in a traffic system which would require large-scale systemic shifts in infrastructure.

Lithics-wise, we might think about assemblage patterning that is the cumulative result of many individual instances of artefact movement – an accumulative process meaning that over time patterning becomes less sensitive to small-scale changes and more reflective of larger-scale, long-term processes (e.g., Davies et al. 2021:63). Lucas (2008) suggests the material organisation archaeologists observe is mainly composed of residues of objects from assemblages with low reversibility, since greater reversibility means less visibility. Importantly, this does not deny the existence in the past of the kinds of behaviours archaeologists are typically interested in. Though acknowledging that the archaeological record reflects material organisation with high irreversibility “may seem restrictive, especially if we want to write archaeological narratives that mimic history or ethnography, [it seems that] this is in fact rather liberating” – understanding material organisation in this way simply leads to a different type of narrative of the past (Lucas 2008:63).

In many ways Lucas’ (2008) comment, and indeed the question of competing explanations discussed at the beginning of this section, evoke anxieties over the apparent incongruity of empirical, scientific inquiry and the production of meaningful anthropological statements about the past. Over three decades ago, Murray and Walker (1988:250) commented that “the archaeological record is an ontologically singular record of human action, i.e., that it is not the subject of commonsense understandings”, and that many archaeologists ignore this so they can still apply “conventional interpretations and explanations of archaeological data thereby gaining meaning and plausibility which ‘trickle down’ from the contemporary social sciences”. This does not appear to have shifted in any significant way since (e.g., Murray 2008; Perreault 2019). This is perhaps due in part to the fear that by focusing solely on empirical justification based on the structural properties of the archaeological record, archaeologists in some way ‘dehumanise’ the past (Stern 2015:235). Wylie (1985, 2002, 2007) framed this tension as a ‘two-horned interpretive dilemma’. At one extreme is the ‘narrow empiricist’ horn which reflects a commitment to epistemic responsibility (Wylie
2007), whereby little is offered beyond simple description of the archaeological record (what is also termed ‘artefact physics’, particularly with reference to stone artefacts) and is typically seen as resulting in behaviourally sterile conclusions (DeBoer and Lathrap 1979; Watson 1986). The opposite extreme is the ‘speculative’ horn which forgoes empirical rigour in favour of the construction of “archaeological narratives that are understood to be a form of interpretive fiction in which contemporary expectations and preoccupations are projected onto the past” (Wylie 2007:519). The question is how to operate between the horns: “if archaeologists set their sights on establishing claims that are empirically irreproachable they may foreclose (some) risk of error but at the expense of abandoning the very questions that make archaeology worth doing, and if they do not self-limit in this way they may have nothing to offer but speculation” (Chapman and Wylie 2016:7).

The method for analysing lithics presented in this research – using appeals to methodologically uniformitarian principles and fundamental processes of lithic reduction, reuse, and movement – might appear to lean closer to the narrow empiricist horn of the interpretive dilemma by removing behaviour from the artefacts and reducing them to simple pieces of stone that can only be described in terms of measurable attributes and simple processes that result in their distribution at a place or across the landscape. However, behaviour has not disappeared – all artefacts reflect behaviour in some sense since the presence of observable features like platforms and bulbs of percussion most often means they were produced by human action. The point is that based on current understanding of the processes that underlie variation in stone artefacts (e.g., Dibble et al. 2017; Rezek et al. 2020) and the understanding of the nature and temporality of the archaeological record more generally (e.g., Bailey 2007; Lucas 2012; Olivier 2011), a shift is required from essentialising the manufacture and form of objects to instead focusing on inferences that are grounded in something testable and falsifiable. In doing so, this allows past behaviour to emerge rather than being defined by predetermined categories and understandings of what different patterns represent.
Chapter 7

Indeterminacy, Simulation, and the Formation of Lithic Assemblages

The analysis of SourceSim and ClusterSim and the Aotearoa and Australia cases suggests that simple, fundamental processes of lithic acquisition, transport, and reuse contribute to patterning in lithic assemblage composition and distribution through time and space. This was only possible to see when considering lithics free of essentialist assumptions about the way the distribution of artefacts of different types and forms relates to past behaviour. The two exploratory simulations used to generate testable hypotheses were different in the way mobility was measured but were constructed according to similar principles and ultimately based on similar underlying processes such as lithic reuse. It appears that similar fundamental forces contribute to the emergent patterning in the archaeological record in different places whereas by all accounts the assemblages from these places should exhibit differences in patterning with respect to mobility. If archaeologists are interested in mobility as the basis for many important human behavioural strategies (Kuhn et al. 2016; see also Kintigh et al. 2014), then it is important to understand the operation of these fundamental processes as a foundation from which to build further inferences, rather than a priori statements about how assemblage patterning relates to different behaviours. This approach, based on a reconsideration of the fundamental way archaeological data are conceptualised and treated, is one solution to Perreault’s (2019) challenge of indeterminacy.

7.1 On Agent-Based Modelling and Archaeological Research

In any modelling enterprise, there is a trade-off between generality, realism, precision, and tractability (ability to use the model productively). It is not possible to create a model that is sufficiently general, realistic, and precise, but that also maintains tractability – and if a model is intractable, then what is the point of constructing the model? (Bullock 2014:305-306). In an article aptly titled Models are stupid, and we need more of them, Smaldino (2017) notes a common criticism of models is their crudeness, simplicity, and lack of realism. In this sense, models are indeed ‘stupid’, but nonetheless useful in the way they formalise a system of interest to advance understanding of that system (Smaldino 2017).

Nonetheless, there is often a correlation between the complexity of a simulation and the “perceived level of authoritativeness” of that simulation (McGlade 2014:295). It is becoming
increasingly easier to incorporate many variables into simulations as greater computing power and user-friendly software become more accessible. However, the more complex a simulation, the more difficult it becomes to independently verify and validate the simulation and its outcomes (Premo 2010). Though as McGlade (2014:297) notes, the real issue is not about what simulations can or cannot do, but rather is about ensuring that the ontology of the model structure will allow significant insight into the unpredictable, contingent operation of socio-natural systems.

In the case of both SourceSim and ClusterSim, model development underwent several cycles that included the addition and removal of various parameters, shifting the models between different levels of complexity and perceived ‘realism’. The relatively simple models ultimately presented were the result of a conscious decision to keep the simulations as simple as possible while maintaining their usefulness for exploring the question at hand. This inevitably led to a number of processes not being explicitly modelled in the simulations which may bear significance for patterns in the target systems – those patterns being the distribution of artefacts of different raw material types (SourceSim) and presence/absence of products of stone reduction (ClusterSim). For example, both SourceSim and ClusterSim do not explicitly model waterways such as rivers, lakes, or the coast, which would influence the speed at which stone material moved, the quantity that moved, and the relative distances involved in raw material transfers (Blair 2010). Indeed, no landscape features that potentially affected peoples’ movement decisions were explicitly modelled. Similarly, the decision was made to exclude modelling processes affecting the visibility of artefacts such as cycles of erosion or deposition, or incidental processes such as trampling by people or animals, each of which would impact the distribution of artefacts in the real world. Other processes relating to stone use were also excluded, such as the change in size of artefacts with reuse, attributes governing the selection of artefacts, or the influence of different aspects of raw material variation with respect to reduction. Future research might conduct further experiments to assess the impact of such variables on simulated patterning and their effect on conclusions drawn with respect to the research question at hand.

It bears repeating that the point of the simulation exercise for this research was not to reconstruct some sequence of events to formulate narrative histories of the past. Rather, the aim was to explore how processes of interest produced different kinds of patterns and to evaluate these with respect to the empirical archaeological record. As Davies (2016:232) notes, adding extra processes may well help to refine simulation outcomes or challenge
existing inferences. Indeed, extending models in this manner is a hallmark of cumulative science, and exactly why agent-based models should be documented clearly and consistently (productive examples of archaeological model extensions include, but are not limited to, Carney and Davies’ [2020] reimplementaton of Davies and colleagues’ [2015] model of surface archaeological deposit formation, or Oestmo and colleagues’ [2016, 2020] and Pop’s [2016] extensions of Brantingham’s [2003] neutral model of raw material procurement). However, extending models by adding more processes necessarily increases the complexity of the models. The benefit of increased complexity in terms of new knowledge gained would need assessing on a case-by-case basis.

A key aspect of indeterminacy is equifinality. Equifinality is a common criticism of computer simulation but in fact relates to all models, computational or otherwise: it is simply not possible to prove a given model is the best possible representation of a system of interest (Romanowska et al. 2021:89). The problem of equifinality in archaeological simulation is mitigated by using an exploratory approach interested in understanding what kinds of processes create different types of patterns rather than recreating some empirical reality (Premo 2007, 2010). It is also mitigated by the strength of the underlying conceptual model, which should be constructed with reference to relevant theory and informed by appropriate information regarding the target system if necessary. Nonetheless, no archaeological simulation can conclusively answer a research question no matter how carefully constructed, since there is always the possibility that a future model will better explain some archaeological data or falsify existing knowledge. This is the reason why the results of simulation studies should be considered arguments, rather than definitive solutions to research problems of interest (Romanowska 2017:204-205). Therefore, agent-based modelling is best thought of in this sense as a tool for experimenting with different ideas to generate new hypotheses about archaeological phenomena, which can then be tested with appropriate empirical data – so long as those data are not used to construct the model!

7.2 Some Thoughts on ‘Where to Next?’

This thesis provided an alternative way of thinking about the archaeological record inspired by Perreault’s (2019) challenges about indeterminacy. It did so by thinking through the assumptions underlying common approaches to archaeological interpretation – specifically, the way mobility is inferred from the lithic record. As with most academic inquiry that builds on the shoulders of previous research, it is one thing to critique a theory, perspective, or
method as new ones develop and enter the discourse. It is another thing entirely to answer the question ‘where to next?’, and to provide clear, implementable alternative approaches – an important consideration, as criticism is intended to improve future practice, not belittle the past. Arguably this research is part of the way there, having provided a method for interrogating the archaeological record to answer some of the challenges of indeterminacy. However, the question of ‘where to next?’ remains unanswered.

In the present context, this question relates to what the goals of archaeology as a discipline are. Upon closer inspection, the textbook definition of archaeology taught in introductory courses around the world – ‘the study of the human past through material remains’ (e.g., Fagan and Durrani 2018:2; Renfrew and Bahn 2020:12; Scarre 2018:25) – is not as simple as it first sounds. Is archaeology about revealing past human behaviour, and the story of its operation and development at different times and in different places (“…archaeology is anthropology or it is nothing” [Willey and Phillipps 1958:2])? Or is archaeology about understanding the materials that relate to past human behaviour, and the various forces that produce emergent patterning in those remains (“Archaeology is, of course, the discipline of things par excellence” [Olsen 2003:89])? Or perhaps it is both? These questions are by no means new, and the continued discussion of the topic suggests further research and exploration are needed (e.g., Bailey 2007; Johnson 2015; Lucas 2012; Murray 2008; Nativ 2018; Olivier 2011).

It is beyond the scope of this thesis to address these fundamental questions in any detail, but the results of the analyses presented here nonetheless warrant some comment. If, for instance, information about raw material sources does not necessarily inform us in a direct sense about trade and exchange practices or social interaction, as suggested by the results of the SourceSim analysis; and if lithic technology and assemblage patterning are not sensitive enough to the influence of spatiotemporal differences in ecologies or resource availability on past human behaviour, as suggested by the results of the ClusterSim analysis; then what kind of prehistory is it possible for archaeologists to write? Insofar as the lithic record is concerned, if that record is not a direct representation of human behaviour, then the outcome is not a linear evolutionary history of the human past. Instead, what takes precedence are the interactions of diverse histories of archaeological remains and how these pattern in the archaeological record to tell us something about place use history – but not by imposing meaning in the form of functional site types or bounded spheres of interaction, based on some
properties of artefacts thought to be important and to have operated in certain ways in the past.

Perhaps, then, traditional archaeological narratives need to be unthought – or more precisely, the basis for such narratives requires continued critical consideration. Bailey (2008) comments on this in his discussion of the impact of time perspectivism in archaeology, though his point is equally salient here: as a historical discipline, archaeologists typically expect the primary output of analysis to be some form of narrative history about a trajectory of development that explains how humans came to be in the world they inhabit. However, concepts like time perspectivism and indeed, the research presented in this thesis, question the degree of correspondence between the traditional form of narrative and the character of the material record. Bailey goes further in considering the implications for the archaeological endeavour, noting that by questioning the degree of correspondence between the traditional form of narrative and the material record and instead thinking through alternative forms of analysis, what is presented is “an alien intellectual landscape where most of the familiar landmarks and signposts are missing”. However, “such a landscape is full of liberating possibilities for new exploration and the discovery of new knowledge, but it requires us to work out the “maps” for ourselves” (2008:28).

This research has contributed towards such a map, through a critical consideration of traditional approaches to archaeological interpretation which often impose meaning onto the material record, instead emphasising the need to understand material remains themselves, their interrelationships, and how different processes combine over time to produce the emergent patterning archaeologists observe. In doing so, this arguably situates archaeological analysis somewhere between empirical rigour and speculative enquiry by providing an understanding of material remains that serves as a foundation upon which to write a multi-scalar history from a range of perspectives.
Appendix A – Aotearoa (New Zealand) Site Map and Descriptions

Figure A1 Location of sites on Te Ika-a-Māui (North Island) from which the obsidian assemblages analysed in Chapter 4 derive. Site details are listed in Table A1. Black dots are the geological obsidian sources (see Figure 2.1 for names). The black star is the Tūhua (Mayor Island) geological source.
Figure A2 Location of sites on Te Waipounamu (South Island) from which the obsidian assemblages analysed in Chapter 4 derive. Site details are listed in Table A1.
Table A1 Sites from which the obsidian assemblages analysed in Chapter 4 derive

<table>
<thead>
<tr>
<th>Map Ref.</th>
<th>Site</th>
<th>NZAA Site Number</th>
<th>Chronology</th>
<th>Island</th>
<th>Assemblage Size (n)</th>
<th>Source</th>
</tr>
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<tbody>
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<td>1</td>
<td>Houhora</td>
<td>N03/59</td>
<td>Pre-1500 CE</td>
<td>N</td>
<td>525</td>
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</tr>
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<td>Pre-1500 CE</td>
<td>N</td>
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<td>N05/302</td>
<td>Pre-1500 CE</td>
<td>N</td>
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<td>3</td>
<td>Patunui Bay</td>
<td>P05/986</td>
<td>Pre-1500 CE</td>
<td>N</td>
<td>34</td>
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<td>4</td>
<td>Moturua Island: Mangahawa Bay</td>
<td>Q05/39</td>
<td>Pre-1500 CE</td>
<td>N</td>
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<td>47</td>
<td>Pararaki Oven Area</td>
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<td>J43/11</td>
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<td>S</td>
<td>36</td>
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<td>S</td>
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<td>Seelenfreund-Hirsch (1985)</td>
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</table>

**N.B.** Map Reference numbers refer to those in Figures A1 and A2. Site names are as presented in the sources listed, though in some cases Māori names are provided in addition to European names. The New Zealand Archaeological Association (NZAA) site numbers are given in the current metric system format (the site numbers provided by Leach and de Souza [1979] and Seelenfreund-Hirsch [1985] use the previous imperial system). Dates are as presented in the sources listed, and in the case of data from Seelenfreund-Hirsch (1985), are directly converted from BP to BCE/CE format. Island: N = North, S = South.
Site Descriptions

The following descriptions are for the sites explicitly mentioned in the body of the thesis text. The location of each site is highlighted in the labels in Figure A1.

Houhora

Houhora is in the far north of Te Ika-a-Māui at the harbour entrance at the foot of Mount Camel. Excavations at Houhora in the 1960s and 1970s revealed extensive material culture including stone and bone artefacts, fishing gear, and ornaments; faunal remains including terrestrial and marine fauna; and features such as hangi (subsurface ovens) (Furey 2002). A range of activities are thought to have occurred at the site leading to its interpretation as a village (e.g., Walter et al. 2006). Houhora is among the earliest known sites in the country with radiocarbon dates placing it in the early 14th century CE (Petchey 2000). Lithic artefacts are made from a range of materials including local and non-local basalt, argillite, gabbro, mudstone, siltstone, sandstone, and various cherts. The obsidian artefact assemblage is large, with an estimated 16 kg of excavated artefacts and another 23 kg of surface collected obsidian present in museum collections (Furey 2002). Furey (2002) reports on over 3700 obsidian artefacts from the assemblage, a portion of which was subsequently analysed in detail by McBride (2019).

Ahuahu

Ahuahu (Great Mercury Island) is the largest of seven islands in the Mercury group and is located approximately 6 km off the eastern coast of the Coromandel Peninsula. Both European (Salmond 1991:193, 197) and local Māori (Johnston 2000:35-40) accounts describe seasonal occupation for gardening in the eighteenth century and prior by people who otherwise lived on the mainland. A sandy tombolo in the centre of the island connects the more fertile northern region with the rhyolitic southern region. Ahuahu was subject to archaeological investigation in the 1950s (Golson 1955), 1970s (Edson 1973) and 1980s (Furey 1983; Irwin 2015). It is currently the location of a long-term archaeological research project by The University of Auckland, in collaboration with Ngati Hei ki Wharekaho and Sir Michael Fay, running from 2012 to the present (Furey et al. 2013, 2017; Phillipps et al. 2014). Several parts of the island have been investigated. Those from which the obsidian assemblages analysed in Chapter 4 derive include Waitapu, Tamewhera, and Oneroa. Waitapu lies on the east coast of tombolo and represents a dune system. Extensive
excavations revealed an array of features and thousands of artefacts including fire-cracked rock and basalt, chert and obsidian artefacts, the latter of which number more than 18,000 (Holdaway and Phillipps 2021:145). The site dates to the early 14th century CE. Tamewhera lies in the northwest portion of the island and is a large area consisting of stone rows, stone enclosures, and terraces with domestic features, all forming part of a larger horticultural and residential system. A swamp system lies at the base of Tamewhera Pā. Radiocarbon dates from the terraces suggest occupation from the mid-17th to early 18th century CE (Jorgensen 2018:169). Oneroa is on the foreshore of a beach on the west coast of the tombolo. Excavations revealed a large cultural deposit consisting of charcoal, stone artefacts, fire-cracked rock, bone, and shell, as well as fire features. These materials likely accumulated during the 15th century CE (Jorgensen 2018:122).

*Kohika*

Kohika is located on the Rangitaiki Plains on the central-eastern coast of Te Ika-a-Māui, and was first excavated in the 1970s, with subsequent fieldwork occurring in the 1980s and 2000s (Irwin et al. 2004). Kohika is interpreted as a permanently occupied lakeside village, lightly defended by a palisade wall, but with easy access to and from the area in all directions via water transport on rivers or the coast (Irwin 2005; Irwin et al. 2004). There is evidence for social differentiation with one elaborate house suggesting the residence of people of chiefly status (Irwin 2005). The site dates to the late 17th century CE and was occupied for approximately two generations before abandonment after a large flood (Irwin and Jones 2004). The material culture is extensive due to preservation in the anaerobic swamp environment and includes organic and inorganic objects relating to house construction, food acquisition and preparation, gardening, fibre-working, music, canoe-building, wood carving, and other domestic activities. The obsidian artefact assemblage is large, totalling 8982 artefacts or the equivalent of approximately 34.4 kg of material (Haysom 2009; Holdaway 2004).
Appendix B – Overview, Design Concepts, and Details for SourceSim

This ODD document (following Grimm and colleagues 2006, 2010, 2020) describes the simulation SourceSim, presented in Chapter 4.

1. Purpose and Patterns

The purpose of SourceSim to explore the effects of lithic acquisition, discard, and reuse behaviours on the distribution of different raw material types in individual assemblages and across the landscape.

The main patterns of interest are the overall proportions of different raw material types in the simulated landscape, and the spatial distribution of artefacts with respect to the geological sources from which they ultimately derive (what are referred to as distance decay patterns). Other relevant patterns include the frequency of visits to geological sources and the total number of artefacts produced. Various parameters, chief among them whether material is acquired only from geological sources or from deposits of previously discarded material, influence the patterns of interest in different ways. These patterns serve as hypotheses or expectations that can be tested with empirical archaeological data.

2. Entities, State Variables, and Scales

The model has three main entities: agents representing groups of people of an arbitrary size, geological sources, and patches. Throughout the simulation groups move randomly to different locations acquiring, carrying, and discarding artefacts. Patches (a term specific to NetLogo) are cells in a bounded grid that constitutes the modelled world. Patches can hold discarded artefacts (i.e., a virtual archaeological record) but are otherwise empty and uniform.

Some patches are geological raw material sources which are modelled as agents for ease of programming but are not agents in a conceptual sense. All geological raw material sources are randomly placed in the simulated world and assigned a unique identification number but are otherwise considered equal in terms of quality and quantity of accessible material. Artefacts represent equal units of raw material and are stored as numbers in a list, where the number is the geological source from which that artefact derives.
### Table B1 SourceSim state variables

<table>
<thead>
<tr>
<th>Group State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>toolkit</td>
<td>A list of numbers representing artefacts of different raw material types in the group’s possession. Maximum size is 100.</td>
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<tr>
<td>cached?</td>
<td>A variable representing whether the group can cache artefacts at a location when presented with the opportunity (true = already cached at this location so cannot yet cache again)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>visits</td>
<td>Records the number of times a geological source is visited by groups to extract material</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Patch State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>assemblage</td>
<td>A list of numbers representing artefacts from different geological sources that have been discarded on the patch</td>
</tr>
<tr>
<td>material_freq</td>
<td>A list of frequencies of material types, calculated from assemblage at defined intervals during a simulation run</td>
</tr>
</tbody>
</table>

Time passes in the simulation but is taken as abstract and not reflective of real-world time. Space is also represented and is analytically important for defining the distances different material types move and for differentiating discard assemblages (see below). However, space is also taken as abstract and not reflective of real-world space.

### 3. Process Overview and Scheduling

Groups begin the simulation carrying a full toolkit of artefacts made of one material type. During a time step, groups have a 25% chance of moving straight to a randomly determined patch. After a group moves or opts to remain at their current location, they may attempt to cache artefacts at their current location (see section 7.1).

After the movement and caching actions, groups use up to five randomly chosen artefacts from their toolkit, the exact number of which is also randomly determined (see section 7.2). These are removed from the toolkit and added to the assemblage of the current patch, with the potential to generate more artefacts of the same materials (representing the reworking an artefact). If there is not sufficient material in the toolkit to use, a group resupplies either from the nearest geological source, or from the nearest visible deposit of previously discarded material (see section 7.3).

The simulation ends when the number of time steps reaches a user-defined value.
4. Design Concepts

4.1 Basic Principles

Patterning in the distribution of artefacts made of different raw materials is often used as an indicator of trade and exchange or for identifying past social or communication networks, based on measures of material frequencies and distance to the geological source. These inferences assume that people always accessed a geological source when in need of usable material. However, deposits of previously discarded artefacts also serve as sources of (re)usable material. SourceSim explores the consequences of both forms of lithic material acquisition for patterning in archaeological raw material distributions.

4.2 Emergence

Patterns in the distribution of artefacts of different raw material types emerge as groups move and discard artefacts throughout the landscape. These patterns vary according to whether groups acquire material from geological sources or visible deposits of artefacts; whether a given geological source is ‘discovered’ first, which affects the amount of that material initially entering the simulated world at the beginning of a simulation run; and whether a given geological source is ‘desirable’ which affects the frequency with which new objects of that material type enter the simulated world during simulation runs. The relative influence of each parameter on patterning in raw material distributions depends on the specific combination of parameters.

4.3 Adaptation

Groups have one main adaptive behaviour which occurs when the RTS parameter (see section 5) is set as ‘if needed’: choosing whether to resupply with material from a geological source or a visible deposit of discarded artefacts.

Other adaptive behaviours for groups include choosing to resupply, which is based on if the group has enough artefacts to use and discard; choosing the geological source or visible deposit from which to resupply the toolkit, in which case the nearest is selected; and attempting to cache material which depends on the quantity of artefacts currently in the toolkit and whether the group has already cached at that location.

4.4 Objectives
The objective measure used by foragers to decide how to resupply is whether there is a visible deposit of discarded artefacts within a given radius of the group’s current location. If there is not, a geological source is accessed.

4.5 Learning

Learning is not implemented.

4.6 Prediction

Prediction is not implemented.

4.7 Sensing

Groups can sense visible deposits of artefacts within a defined radius of their current location and can sense which geological source is nearest to their current location.

4.8 Interaction

Groups interact with patches by discarding and picking up artefacts from the patches and interact with geological sources by extracting material from them.

4.9 Stochasticity

Stochasticity is used at several points in the model:

- At the first simulation run, the location of geological sources is randomly determined then held constant for subsequent runs
- At the beginning of a simulation run, groups are placed at random locations in the simulated landscape
- The geological source groups initially supply themselves from is randomly determined
- If the `discover` parameter is active, there is a 50% chance groups initially supply themselves with material from source 0
- During a time step, there is a 25% chance groups will move. If they do move, the destination is randomly determined.
- After a move, assuming groups can cache there is 50% chance they will do so
• When using artefacts, the number of artefacts used is a randomly determined between 1 and 5 inclusive. The artefacts selected from the toolkit for use are randomly determined.

• When discarding artefacts, for each artefact there is a 50 % chance another piece of the same material will be generated

• When resupplying from a geological source, the choice of geological source is random if two or more sources are equally near to the group’s current location

• If the desirable? parameter is active, there is a 50 % chance groups will resupply with material from source 0

• When resupplying from a visible deposit, the choice of deposit is random if two or more deposits are equally near to the group’s current location

• When resupplying from a visible deposit, the choice of artefacts is random.

4.10 Collectives

The model includes no collectives.

4.11 Observation

Data are generated at regular intervals during each simulation run (such as every 50 time steps) and saved in several .csv files. For each patch, the frequency of each material type in its assemblage is calculated (material_freq) and recorded in its own .csv file. These are summed to determine the total frequency of the different material types for the whole simulated assemblage and are written to another file. Proportions are calculated from these frequencies and written to a separate file.

At the end of a simulation run, the total number of visits to each geological source and the total number of artefacts produced are recorded.

5. Initialisation

When the model is initialised, the assemblage and material_freq lists for each patch are emptied. Ten geological sources are created and assigned a unique ID number. They are placed randomly in the simulated landscape but these locations are held constant across simulation runs, except for the purposes of sensitivity tests. Ten groups are created and
placed randomly in the landscape. The *toolkit* is filled to capacity with material from one of the geological sources. Several parameters are set according to user-defined values (Table B2). These parameters remain constant throughout a simulation run.

### Table B2 SourceSim parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>world_size</em></td>
<td>The number of patches (cells) forming the simulated landscape</td>
<td>33 x 33</td>
</tr>
<tr>
<td><em>end_after</em></td>
<td>The number of time steps at which the simulation ends</td>
<td>1500</td>
</tr>
<tr>
<td><em>chance_move</em></td>
<td>The probability of a group moving to another location during a time step</td>
<td>0.25</td>
</tr>
<tr>
<td><em>RTS</em></td>
<td>Defines whether a group immediately returns to a geological source when resupplying with material, or if they first seek material from a visible deposit</td>
<td>always, if needed</td>
</tr>
<tr>
<td><em>discover?</em></td>
<td>Defines whether a geological source has a greater chance of being ‘discovered’ by groups first. If true, there is a 50 % chance that groups begin with material from source 0 at the beginning of a simulation.</td>
<td>true, false</td>
</tr>
<tr>
<td><em>desirable?</em></td>
<td>Defines whether a geological source is preferred over others when resupplying. If true, when resupplying from a geological source there is a 50 % chance that groups go to source 0.</td>
<td>true, false</td>
</tr>
</tbody>
</table>

6. **Input Data**

No input data are required for the model.

7. **Submodels**

7.1 **Cache submodel**

Groups attempt to cache material if the *toolkit* is at least half full, and if they have not yet cached at their current location since they moved there. When groups attempt to cache material, there is a 50 % chance they will do so, in which case all material they are carrying is cached.

7.2 **Use-discard submodel**
A number of artefacts required for some arbitrary task is randomly determined, but falls between 1 and 5 inclusive. If there are enough artefacts in the toolkit, they are randomly selected and discarded. For each artefact discarded, there is a 50% chance of generating a new artefact of the same material type.

If there are not enough artefacts to perform the task, any available artefacts in the toolkit are used as above, then the groups resupply per the resupply submodel (section 7.3) before using and discarding the remaining number of artefacts required.

7.3 Resupply submodel

Upon attempting to use and discard artefacts, if a group does not have enough artefacts they will resupply with material. If the RTS parameter is set to ‘always’, groups will always resupply from the nearest geological source, except when the desirable parameter is active in which case there is a 50% chance groups will resupply from source 0. When resupplying from a geological source, the toolkit is completely filled.

If the RTS parameter is set to ‘if needed’, groups first attempt to resupply from a nearby visible deposit of discarded artefacts. If none are available, they resupply from a geological source as above. A ‘visible’ deposit is defined as one consisting of 25 or more artefacts, and ‘nearby’ is defined as within a radius of five grid cells from the group’s current location. When resupplying from a visible deposit of artefacts, as many artefacts as are available and can be carried are acquired.

References


Appendix C – SourceSim Model Code

The following code was written in NetLogo version 6.2, available as a free download from https://ccl.northwestern.edu/netlogo/.

Comments in the code are marked by a double semi-colon (;;).

;; SourceSim: modelling the distribution of artefacts deriving from different geological sources and the creation of anthropogenic sources
;; by Matthew Barrett, The University of Auckland, 202

;; Define agent types: geological sources (programmed as agents for ease of manipulation) and 'groups' of people
breed [sources source]
breed [groups group]

;; Define geological source variables, group variables, and patch variables
sources-own [visits]
groups-own [toolkit cached?]
patches-own [assemblage material_freq]

to setup
  ;; Clear the simulation window
  clear-all
  ;; Create an empty assemblage list (i.e. archaeological record) for each patch. Reset the list of material frequencies.
  ask patches [ set assemblage [] set material_freq [] ]
  ;; Create 10 geological sources. 'with-local-randomness' ensures the sources are the same each simulation run.
  with-local-randomness [ random-seed 137 create-sources 10 [ setxy (precision random-xcor 0) (precision random-ycor 0) set visits 0 set label who ] ]
  ;; Create 10 groups. They 'discover' a geological source at random and supply themselves with 100 artefacts from that source.
  ;; If discover? = true, there is a 50% chance a group will start with artefacts from source 0, otherwise the source is randomly determined.
  create-groups 10 [ setxy random-xcor random-ycor set toolkit [] set cached? false ifelse discover? = true [ ifelse random-float 1.000 < 0.5 [ repeat 100 [set toolkit lput 0 toolkit] ask source 0 [set visits visits + 1] ] [ let x random 10 repeat 100 [set toolkit lput x toolkit] ask source x [set visits visits + 1] ] ] [ let y random 10 repeat 100 [set toolkit lput y toolkit] ]]
ask source y [set visits visits + 1]
]

;; Reset the clock
reset-ticks
end
to go
;; Every 50 time steps, record material frequencies for each patch
if (ticks mod 50 = 0 and ticks > 0) {
  ask patches {
    let material_freq (map [ i -> frequency i assemblage] {n-values 10 [i -> i]})

    let src0 (sum [item 0 material_freq] of patches)
    let src1 (sum [item 1 material_freq] of patches)
    let src2 (sum [item 2 material_freq] of patches)
    let src3 (sum [item 3 material_freq] of patches)
    let src4 (sum [item 4 material_freq] of patches)
    let src5 (sum [item 5 material_freq] of patches)
    let src6 (sum [item 6 material_freq] of patches)
    let src7 (sum [item 7 material_freq] of patches)
    let src8 (sum [item 8 material_freq] of patches)
    let src9 (sum [item 9 material_freq] of patches)

    ;; Record overall material frequencies in a .csv file
    file-open (word "run" behaviorspace-run-number "_totals.csv")
    file-type src0 file-type "," file-type src1 file-type "," file-type src2 file-type ","
    file-type src3 file-type "," file-type src4 file-type "," file-type src5 file-type ","
    file-type src6 file-type "," file-type src7 file-type "," file-type src8 file-type ","
    file-type src9 file-type "," file-type src10 file-type
    file-close

    ;; Record overall material proportions in a .csv file
    file-open (word "run" behaviorspace-run-number "_prop.csv")
    let total (src0 + src1 + src2 + src3 + src4 + src5 + src6 + src7 + src8 + src9)
    file-type (src0 / total * 100) file-type "," file-type (src1 / total * 100) file-type ","
    file-type (src2 / total * 100) file-type "," file-type (src3 / total * 100) file-type ","
    file-type (src4 / total * 100) file-type "," file-type (src5 / total * 100) file-type ","
    file-type (src6 / total * 100) file-type "," file-type (src7 / total * 100) file-type ","
    file-type (src8 / total * 100) file-type "," file-type (src9 / total * 100)
    file-close

    ;; Record material frequencies for each patch ('site') in a .csv file
    file-open (word "run" behaviorspace-run-number "_sites.csv")
    foreach sort patches [the-patch ->
      ask the-patch [file-type ticks file-type "," file-type pxcor file-type "," file-type pycor file-type "," file-type (round(distance source 0)) file-type "," file-type (round(distance source 1)) file-type "," file-type (round(distance source 2)) file-type "," file-type (round(distance source 3)) file-type "," file-type (round(distance source 4)) file-type "," file-type (round(distance source 5)) file-type "," file-type (round(distance source 6)) file-type "," file-type (round(distance source 7)) file-type "," file-type (round(distance source 8)) file-type "," file-type (round(distance source 9)) file-type "," file-type (item 0 material_freq) file-type "," file-type (item 1 material_freq) file-type "," file-type (item 2 material_freq) file-type "," file-type (item 3 material_freq) file-type "," file-type (item 4 material_freq) file-type "," file-type (item 5 material_freq) file-type "," file-type (item 6 material_freq) file-type "," file-type (item 7 material_freq) file-type "," file-type (item 8 material_freq) file-type "," file-print {item 9 material_freq}]
    ]
    file-close
  }
}

;; Stop condition. When the clock reaches a user-defined value, record the total visits to each geological source and final number of artefacts in a .csv file and end the simulation.
if ticks >= end after [
  file-open (word "run" behaviorspace-run-number "_visits.csv")
  foreach sort sources [the-source ->
    ask the-source [file-type visits file-type ""]
  ]
  file-type (sum [length assemblage] of patches)
  file-close
stop

;; Simulation procedures: groups move, then cache artefacts if possible, then use/discard artefacts
ask groups
  move
  cache
  use-discard
end

;; Advance the clock one time step
tick
end
to move
  ;; Determine if groups will move. If so, they move to a random location. If they do move, allow them to cache artefacts again.
  if random-float 1.000 < chance_move [
    setxy random-xcor random-ycor
    set cached? false
  ]
end
to cache
  ;; Determine whether groups cache all their artefacts (a 50% chance of caching only if their toolkit is > 50% full and they have not yet cached at their current location)
  if (cached? = false) and (length toolkit >= 50) and (random-float 1.000 < 0.5) [
    while [length toolkit > 0] [
      let artefact item 0 toolkit
      set assemblage lput artefact assemblage
      set toolkit remove-item 0 toolkit
      set cached? true
    ]
  ]
end
to use-discard
  ;; First determine how many artefacts (x) will be needed for the task (1-5)
  let x ((random 5) + 1)
  ;; If there are sufficient artefacts in the toolkit, discard artefacts with a 50% chance of generating a new artefact for each one discarded (represents flaking to create a sharp edge)
  ifelse length toolkit > x [
    repeat x [
      let index random (length toolkit)
      let artefact item index toolkit
      set assemblage lput artefact assemblage
      if random-float 1.000 < 0.5 [set assemblage lput artefact assemblage]
      set toolkit remove-item index toolkit
    ]
  ]
  ;; If there are not sufficient artefacts, determine the shortfall and discard what is currently in the toolkit as above
  let y x - (length toolkit)
  while [length toolkit > 0] [
    let artefact item 0 toolkit
    set assemblage lput artefact assemblage
    if random-float 1.000 < 0.5 [set assemblage lput artefact assemblage]
    set toolkit remove-item 0 toolkit
  ]
  ;; Then resupply (see below)
  resupply
  ;; Then discard the remaining artefacts to cover the shortfall as above
  repeat y [
    let index random (length toolkit)
    let artefact item index toolkit
  ]
set assemblage lput artefact assemblage
if random-float 1.000 < 0.5 [set assemblage lput artefact assemblage]
set toolkit remove-item index toolkit
]
end
to resupply

;; If groups always return to a geological source when needing artefacts, go to the nearest one and fill the toolkit
if RTS = "always" [ 
let target min-one-of sources [distance myself]
if desirable = true [if random-float 1.000 < 0.5 [set target source 0]]
repeat 100 [set toolkit lput [who] of target toolkit]
ask target [set visits visits + 1]
]

;; Otherwise, determine if there is a nearby visible deposit of previously used artefacts and resupply from there by taking as many artefacts as possible
if RTS = "if needed" [ 
let target-patch one-of patches with [length assemblage >= 25] in-radius 5
ifelse target-patch != nobody [ 
while [[length assemblage] of target-patch > 0 and length toolkit < 100] [ 
let index random ([length assemblage] of target-patch)
let artefact item index ([assemblage] of target-patch)
set toolkit lput artefact toolkit
ask target-patch [set assemblage remove-item index assemblage]
]
]
];; If there is no visible deposit nearby, then go to the nearest geological source as above
[
let target-source min-one-of sources [distance myself]
if desirable = true [if random-float 1.000 < 0.5 [set target-source source 0]]
repeat 100 [set toolkit lput [who] of target-source toolkit]
ask target-source [set visits visits + 1]
]
end

;;; A function to calculate the frequency of different items in a list
to-report frequency [a-item a-list]
  report length (filter [ i -> i = an-item] a-list)
end
Appendix D – Palaeoenvironmental and Archaeological Background for Lake Mungo and Rutherfords Creek

Lake Mungo

Lake Mungo is one of five large and several smaller interconnected lakes in the Willandra Lakes Region World Heritage Area (WLRWHA) in southeast Australia (Figure D1). The Willandra region contains a record of human activity that spans the entire known history of human occupation in Australia, from the late Pleistocene ca. 45 kya to the establishment of pastoralism in the nineteenth century (Fitzsimmons et al. 2019; Stern 2014). The significance of Lake Mungo to continental and world narratives regarding human settlement was recognised upon the discovery in the late 1960s of human remains dating to ca. 40 kya, which remain among the oldest known in Australia (Bowler et al. 1970, 2003; Stern 2014).

Palaeoenvironmental Background

The WLRWHA is located on the margin of the semi-arid zone of Australia. Annual rainfall is unpredictable, relief is low, and vegetation is primarily shrubland (Bowler et al. 1970). The lakes were fed by the Willandra Creek, a former channel of the Lachlan River which originates in the southeastern highlands (Bowler et al. 1970; Jankowski et al. 2020). Therefore, filling of the lake system was dependent on precipitation in the highlands and water availability in the wider region. Lake Mungo is a terminal lake with no outflow except for evaporation, and was therefore particularly sensitive to changes in the hydrological system, only filling when Lake Leaghur immediately to the north was at capacity and drained into Lake Mungo via a shallow sill (Jankowski et al. 2020).

Sustained high lake levels at Mungo occurred until approximately 30 kya, linked to regional environmental conditions including increased snowfall, seasonal runoff and river connectivity during the Last Glacial Maximum (LGM) and/or increased rainfall in the highlands (Jankowski et al. 2020:20-21). From ca. 30-16 kya local conditions in the Willandra decoupled from the wider region. Lake Mungo began its drying trend despite more northern lakes and the wider basin remaining well-watered, with permanent drying occurring approximately 15 kya following the LGM. This shift does not appear to be linked to regional
climatic conditions but rather a reactivation of tectonic processes along nearby faults which obstructed water flow to Lake Mungo (Jankowski et al. 2020).

On the eastern shore of Lake Mungo lies a 33 km transverse lunette dune (Figure D1) which provides a sedimentary marker of environmental and hydrological conditions over time (Bowler 1998; Fitzsimmons et al. 2014; Jankowski et al. 2020). The dune also preserves a proportion of the Pleistocene archaeological record dating from over 40 kya onwards (Bowler 1973, 1998). Layers of clean quartz sands in the dune sediments reflect prolonged high lake levels when waves washed sediment to the shore creating high-energy beaches, sands from which were transported by wind and created low foredunes. When lake levels were low exposing the lake bed, salts precipitated from saline groundwater which cracked the lake bed clays. The cracked clay was transported by wind as sand-sized pellets forming pelletal clay dunes (Jankowski et al. 2020; Stern 2015). Soils were able to form when the landscape was stable, typically between pelletal clay and quartz sand dune formation when lake levels rose.
but beach sands had not sufficiently accumulated, or in the absence of water but in a period of relative humidity (Bowler 1998). Archaeological materials embedded in these sediments allow the association of human occupation with differing lake conditions.

Bowler (1998; Bowler et al. 2012) studied the southern portion of the Mungo lunette, identifying several stratigraphic units, the chronology for which has recently been reassessed (Jankowski et al. 2020). Those units in which archaeological material occur are the Lower Mungo (ca. 65-33 kya), Upper Mungo (30-21 kya), Arumpo (21-19 kya), and Zanci units (19-16 kya). Fitzsimmons and colleagues (2014) investigated the central portion of the lunette aiming to correlate sediments with those identified by Bowler. Direct association was not possible since the accumulation of sediment varies across the lunette, such that in some places stratigraphic units differ in thickness or are absent entirely (Jankowski et al. 2020). The assemblage analysed in Chapter 5 comes from the Zanci (19-16 kya) unit, during which lake levels were low as the lake dried, and the post-lake unit (ca. 14.5-8 kya), when the lake had completely dried (Fitzsimmons et al. 2019).

**Archaeological Background: Early Investigations**

Archaeological research at Lake Mungo began with the discovery of Pleistocene burials and associated stone artefacts in the late 1960s/early 1970s (Bowler et al. 1970; Johnston and Clark 1998). These early studies were characterised by culture-historical approaches to artefact analysis and appealed to ethnographic analogy in making interpretations about the past. In the original excavations of what was interpreted as a transient lake-shore settlement, 200 surface and 27 in situ stone artefacts were recovered. Analysis focused primarily on the form of cores and tools. Three main artefact types were identified alongside unmodified flakes – core tools (in particular horsehoof cores), steep-edge scrapers, and flat scrapers (Bowler et al. 1970). At the time, the assemblage was recognised as consistent with other Pleistocene Australian assemblages and on this basis the Australian Core Tool and Scraper Tradition (ACTST) was proposed. This tradition was thought to have occurred from approximately 30 to 6 kya, when it was replaced by point, microlith and adze technology (Bowler et al. 1970).

Early studies regarding past lifeways of Australia’s First Nations examined subsistence in terms of continuity or change based on technology (Allen 1998). Based on faunal remains, similarities in proposed diet of the Pleistocene Mungo inhabitants and ethnographically observed groups in the nineteenth century were identified. This was argued to reflect the
presence of a “distinctively Australian culture” that had remained largely unchanged since the original occupation at Lake Mungo (Bowler et al. 1970:58). Allen (1972) subsequently drew upon ethnographic observations to develop a model of subsistence activity against which archaeological evidence for past occupation could be assessed. This model described mobile foragers exploiting seasonally available resources along desirable rivers. When full, the Willandra Lakes and the surrounding area would have also provided a desirable resource base, but people would have shifted their activity back to river systems like the Darling when the lakes began to dry with the onset of arid conditions in the late Pleistocene. Grasses and cereals were observed as important fall-back foods during leaner times which led Allen (1972) to suggest seed grinding technology developed with the onset of late Pleistocene aridity to supplement faltering aquatic resources, reflected archaeologically by the presence of grinding stones after 15 kya (though recent work determined that grinding stones were present prior to the Last Glacial Maximum [Fullagar et al. 2015]).

Allen (1972) investigated other stone artefact assemblages from stratified contexts using a formal approach to determine chronological relationships between different artefact forms. Several sites were studied, some much younger than the Pleistocene deposits at Lake Mungo, such as Burkes Cave (< 2000 years old). Similarities in faunal remains and stone artefact assemblage composition (particularly the observed dominance of hoof cores and steep-edge scrapers) across all sites was interpreted as evidence for long-term cultural continuity, a view reflected in later syntheses of Australian prehistory (e.g., Gould 1980). It was therefore concluded that ethnographic observations were a suitable analogy for past lifeways in the Willandra.

Further work in the late 1970s was conducted on the southern portion of the Mungo lunette and included excavation of two large trenches and survey of surface material (Shawcross 1998). In particular, this work aimed to acquire a known Pleistocene assemblage to independently substantiate the ACTST, and to investigate activities that occurred at the edge of Lake Mungo by searching for ‘living floors’. Other student-led work followed, examining the effects of erosion in exposing and conditioning the archaeological record (Robinson 1980), and investigating the adaptive significance of technology with respect to artefact reduction and distance to source (Muhlen-Schulte 1985). However, no systematic interdisciplinary research occurred at Lake Mungo from the late 1970s until the Mungo Archaeology Project in 2007 (below).
Allen and others have revised the original interpretations of the Mungo assemblages on several grounds (Allen 1998; Allen and Holdaway 2009; Allen et al. 2008; Hiscock and Allen 2000). One issue was with scale, both in terms of the palaeoenvironmental data and ethnographic observations used to interpret archaeological materials. Earlier studies sought to extrapolate palaeoenvironmental information to the entire Willandra system from only a few well-studied locations and failed to understand the difference in temporal and spatial scale of the geomorphic setting and the relatively small amount of archaeological data available (Allen et al. 2008; Stern et al. 2013:46-47). Allen and Holdaway (2009) note how the ethnographic record originally used to interpret material was based on scarce and patchy observations across an entire region, and therefore provided insufficient information. Issue was also taken with imposing the ethnographic record on the archaeological record without due consideration of time and scale in each (e.g., Murray 1992), since archaeological patterning is often the result of repeated occupation over periods of time that far exceed the scale of ethnographic observation (Allen et al. 2008). Equally, there is no reason to assume a priori that people observed in the present or very recent past behave or react to the environment in similar ways to other people past or present, especially in cases like Australia where indigenous groups were impacted by the arrival of Europeans and introduction of exotic diseases (Hiscock 2008).

Attention was also brought to the lack of consideration of raw material source proximity and differential core reduction on assemblage variability. Stone artefacts at Lake Mungo are predominantly made from silcretes of varying texture (grain size and sorting), with quartzite and sandstone occurring in lesser quantities. Significantly, raw material is not available on the Mungo lunette. The closest silcrete source lies 7 km away on the western shore of the lake, a distance which would be longer by land when the lake was full (Kurpiel 2017). Other silcrete sources occur within 18 km of the lunette. These sources yield stone generally considered poor to medium quality based on grain size. Finer-grained silcretes and quartzite are found further afield at distances ranging from 28-77 km from the central portion of the lunette (Kurpiel 2017).

Based on studies like that of Hiscock (1986) that indicated the characteristics of stone artefacts were related to the nature of raw material and its availability, Allen, noting how horsehoof cores and steep-edge scrapers could not be unambiguously assigned as either cores or core tools, argued that “their number in the Willandra sites suggests an absence of rationing and correlates with the proximity of raw materials. The association of horsehoof
cores and irregular steep-edge scrapers and the use of silcrete as a raw material makes their presence on sites in the region of any age of little note” (1998:211). Therefore, such artefacts could not be used in claims for cultural continuity. Instead, Allen (1998) plausibly suggested perceived similarities may be the result of Pleistocene-age artefacts being reused through time.

Hiscock and Allen (2000) later re-examined the original typological data from a technological perspective, focusing on overall assemblage structure rather than individual artefact types. The positive correlation of some artefact types with assemblage size suggested factors like sampling were conditioning observed variation, further calling into question the notion of cultural continuity. Like Allen (1998), the potential impact of recycling of artefacts was also noted though not explored in any detail. From a spatial point of view, the Willandra assemblage pattern was argued to reflect distance to source. Hiscock and Allen (2000) therefore suggested the ACTST be abandoned as it obscured otherwise significant variation present in the stone assemblages.

*Archaeological Background: Mungo Archaeology Project (MAP)*

The Mungo lunette was and is subject to ongoing processes of erosion, exacerbated by nineteenth-century vegetation clearing and stock grazing. These contribute to dune mobility and expose underlying archaeological material which often disintegrates within one to three years (Stern 2014, 2015; Stern et al. 2013). The effects of erosion are variable but rapid. Robinson (1980) investigated various processes influencing the rate of exposure and movement of archaeological material, particularly wind activity. Some locations saw a loss of surface sediment at a rate of up to 5 cm per year, while areas immediately adjacent accumulated sand at a higher rate (Robinson 1980). Similarly, Balme (1991, 1995) noted how erosion destroyed features like middens and uncovered new ones within a period of 18 months. The Lake Mungo lunette is therefore “a dynamic landform and ongoing erosion, even over the several seasons [of the MAP] during which the archaeological foot surveys were undertaken, continually exhumes both sediments and archaeological traces. Consequently, the record...represents a snapshot of traces exposed during the period of survey” (Fitzsimmons et al. 2014:351). This has clear implications for archaeological interpretation.

The archaeological traces are combustion features (such as hearths, rake-outs, and patches of burned animal bone or shell), stone artefacts, and faunal remains found on the surface of the
lunette. Like with other surface records it is often difficult to determine the stratigraphic origin of these materials (Tumney 2011). Remains of hearths, isolated scatters of artefacts and other materials also remain buried in sediments or are partially exposed, such that their precise stratigraphic origin can be determined, along with the approximate condition of the lake at the time of their deposition. This also extends to recently exposed clusters of artefacts for which sufficient time has not passed for them to weather and disintegrate (Stern et al. 2013). Most of the hearths and scatters of artefacts are preserved such that they arguably reflect single distinct episodes of activity or related sets of activities, like the one-off use of a hearth or the flaking of a core, as determined through archaeomagnetic and refitting analyses (Stern 2014, 2015; Stern et al. 2013). As Stern and colleagues note, “few of these activity traces have been documented or studied in any detail [early investigations notwithstanding] … reflecting the difficulty of studying archaeological remains scattered through vast landforms that have complex depositional and erosional histories, but which are also part of an active landscape” (2013:36-37). While archaeological traces reflect discrete sets of activities, those embedded in the same sedimentological unit nonetheless combine to form an aggregated, time-averaged sample (Stern 2015).

Archaeological remains occur in sediments reflecting a range of lake conditions, but when considering area of exposure, more tend to occur than predicted in sediments reflecting oscillating lake levels, with around half of all hearths embedded in the clean sands representing high lake levels, and half in the pelletal clays reflecting lower lake levels. Based on this, Stern and colleagues (2013) argue that contrary to previous interpretations of settlement history, people were not attracted to the lake system only when it was full, nor were aquatic resources the main form of subsistence (e.g., Allen 1998; see also Johnston 1993). Rather, people were attracted to the lake during oscillating conditions. This is in line with Bowler’s (1998) supposition that the Willandra lakes were a fall-back when the wider region dried out. When lake levels were high, surface water would have been present in the surrounding area, relaxing constraints on mobility. Pulses of fresh water when the lakes oscillated would enhance the biological productivity of the lakes, and aquatic resources would potentially be easier to find and exploit than at times when the lakes were full (Long et al. 2014; Stern 2015; Stern et al. 2013). Though fish remains are present in hearths, the faunal assemblages suggest exploitation of predominantly terrestrial animals from the surrounding plains (Stern 2015).
Current archaeological research at Mungo aims to address the difficulties imposed by the scale and structure of an archaeological record consisting primarily of small scatters of material exposed by erosion, departing significantly from previous studies (Stern et al. 2013). Research focuses largely on the central portion of the Mungo lunette, though the southern portion is also being studied (e.g., Jankowski et al. 2020; Tumney 2018). A number of postgraduate dissertations associated with the MAP have been completed (e.g., Bandurski 2018; Roy 2013; Tickle 2016; Vick 2012). However, for brevity the following only includes doctoral research and results in published articles and chapters. Major research interests include establishing the stratigraphic origin of stone artefacts (Foley et al. 2017; Tumney 2018), understanding discrete refitting sets and knapping clusters and how these relate to the wider aggregated assemblages (Foley et al. 2017; Spry 2014), locating, characterising, and understanding the use of raw material sources (Kurpiel 2017; Kurpiel et al. 2019), and investigating change in technological organisation over time, particularly across the LGM and post-LGM boundary and with respect to the local lake conditions (Spry 2014; Tumney 2011, 2018).

Tumney (2011) analysed three surface stone artefact assemblages from the central portion of the lunette to make inferences about technological organisation with respect to lake full and lake fluctuating conditions (see also Stern et al. 2013). Mobility levels were inferred based on the intensity of use of local (coarse-grained silcretes) and non-local materials (fine-grained silcretes, quartzite). The relationship was not clear-cut. Contrary to expectations, the two assemblages associated with fluctuating lake conditions exhibited the greatest difference in terms of exploitation of material, suggesting two different levels of mobility under similar environmental conditions. Analysis of the assemblage associated with lake full conditions suggested mobility levels at this time fell somewhere between those inferred from the two later assemblages. Tumney (2011) therefore linked changes in mobility to changes in landscape stability irrespective of the lake condition. Stern et al. (2013) further suggested the differences might be explained in terms of lake productivity, with a shift from high to fluctuating levels increasing its attractiveness, and sustained drying reducing productivity and resulting in higher mobility levels as the lake became peripheral.

Refitting is used to identify artefacts struck from the same nodule which are assessed in relation to topographic features and stratigraphic boundaries to help assign artefacts to a specific stratigraphic unit (Foley et al. 2017) and investigate changes in technological organisation across the LGM (ca. 25-14 kya) and post-LGM (ca. 14.5 -8 kya) boundary,
reflecting fluctuating and drying lake conditions respectively (Spry 2014). Like Tumney (2011), mobility levels were inferred on the basis of the intensity of use of local and non-local materials. The presence of more heavily reduced fine-grained silcrete cores and more abundant quartzite in the later assemblage was interpreted as reflecting a shift to higher mobility post-LGM once the lake dried, though notably there was also evidence to suggest raw material conservation was not always a concern like in the earlier assemblage. A shift from the transport of unprepared, less portable forms in the earlier assemblage to the selection of blade blanks as a more efficient and versatile form also suggested a change to greater mobility (Fitzsimmons et al. 2019; Spry 2014).

The results of the foregoing technological studies suggest inferring mobility from the Mungo assemblages is not straightforward, though some changes in technology are apparent. Raw material appears to have been transported to the lunette predominantly as cobbles during the LGM (lake fluctuating), with flake core blanks and more portable cores preferentially transported post-LGM (lake drying). This suggests provisioning the landscape with raw material (sensu Kuhn 1995) was the predominant strategy when people were less mobile when lake levels fluctuated, which changed to provisioning individuals when mobility increased upon the lake drying (Fitzsimmons et al. 2019). A lack of cortex in the assemblages is thought to reflect the preliminary working of material elsewhere, such as at the source (Spry 2014; see also Vick 2012). Kurpiel’s (2017) investigation of assemblages at stone sources suggests people were working material at the source – decortifying stone and preparing large flakes and cores for transport. Despite evidence for increased mobility post-LGM, people did not completely abandon the area once the lake permanently dried as there is evidence for activity in the post-lake sediments (Fitzsimmons et al. 2019), thus contradicting earlier models of regional abandonment in favour of riverine corridors (e.g., Allen 1974).

**Rutherfords Creek**

Rutherfords Creek lies in the northwest corner of New South Wales (Figure D2). It is an ephemeral stream system and tributary of Peery Lake in Paroo-Darling National Park. It has an overall catchment area of 62.5 km² and includes patches of eroded sediment which expose archaeological material consisting primarily of lithic scatters of varying densities and the remains of heat-retainer hearths (Holdaway et al. 2012).
Figure D2 The northwest corner of New South Wales, Australia. The red box highlights the location of Rutherford's Creek. Note the location of Lake Mungo towards the south (adapted from Holdaway and Douglass 2012:111, Figure 1).

Palaeoenvironmental Background

The western New South Wales region lies on the arid margin of Australia where resource distribution is patchy and of low density, due in part to low soil fertility (Holdaway et al. 2012). Rainfall averages at less than 250 mm per year against a pan evaporation of over 2000 mm. Rain episodes are infrequent and unpredictable, fluctuating according to El Niño and La
Niña cycles (Holdaway et al. 2002). Based on palaeoenvironmental records for the inland Australia, it appears there was a time of climatic amelioration in the Holocene up to around 4000 years ago, when increasing desiccation set in until 1500 years ago (Holdaway et al. 2002). The records for the last 1500 years generally suggest increasing moisture in most areas, though western New South Wales is still prone to local climatic variability (Douglass 2010:28).

There are limited permanent water sources in the northwest corner though water collects in dry creek beds or other such features after highly localised rain events and can be retained for weeks, whereas Peery Lake can hold water for months to over a year following heavy rainfall (Douglass 2010). Larger vegetation in the region is limited to watercourses with other parts of the landscape covered in sparse shrubland. Subsistence resource availability is linked to rainfall and is equally unpredictable (Holdaway et al. 2012). Larger terrestrial animals such as kangaroo or emu occur in small, dispersed groups or as individuals, and smaller animals burrow into the ground. There is a small range of edible plant resources, such as seed grasses, from which energy returns are relatively low (Gould 1991; O’Connell and Hawkes 1984).

**Archaeological Background**

Since the 1990s archaeological investigations in the northwest corner of New South Wales have been conducted by the Western New South Wales Archaeology Program (WNSWAP), a joint project originally between LaTrobe University and New South Wales Parks and Wildlife, and later between Macquarie University and the University of Auckland. The project initially aimed at developing an understanding of the geoarchaeological context of record formation, including identifying processes that led to the exposure of extensive surface accumulations of artefacts, developing methods for recording the artefacts, and establishing methods for generating chronologies (Holdaway and Fanning 2014). Later work investigated a range of other geomorphic environments in the region to determine if variation in the formational history of the archaeological record differed across space (Holdaway and Fanning 2014). Consequently, many locations in the northwest corner have been surveyed (Douglass et al. 2008; Holdaway and Fanning 2014; Holdaway et al. 2004; Shiner 2004; Shiner et al. 2007), among them Rutherfords Creek (Holdaway et al. 2012).

Surface stone artefact scatters of varying densities and the remains of heat-retainer hearths (shallow earth ovens expressed archaeologically as concentrations of heat-altered stones) dominate the archaeological record in the region. The exposure and visibility of
archaeological remains is due to the erosion of sediments by fluvial action after periods of heavy rain and aeolian transport of loose surface sediments during dry periods, both of which occurred throughout the Holocene (Fanning and Holdaway 2001; Marx et al. 2009). Erosion was exacerbated due to overgrazing and drought conditions in the late nineteenth century. Thus, the surface archaeological record is a result of both ancient and contemporary local-scale geomorphological processes (Fanning et al. 2008; Holdaway et al. 2004).

At Rutherford's Creek, systematic surveys were conducted along the stream for over 15 km from its headwaters to its outflow in Peery Lake. The eroding valley floor margin encompasses an area of 37.8 km² and is characterised by exposed patches of hardened sediment locally known as scalds, which constitute around 2 km² of the valley floor. Archaeological surveys occurred on a randomly selected sample from 2300 mapped scalds, totalling 4.5% of the valley floor area (Holdaway et al. 2012). The spatial extent of each scald was recorded along with the 3D location of every stone artefact over 20 mm in maximum dimension, a size below which artefacts are subject to movement by fluvial action and displaced from the location they were discarded (Fanning and Holdaway 2001). In total over 27,000 artefacts were piece-provenienced and their attributes recorded. In excess of 1000 hearths were also recorded, 256 of which were excavated with a third of those providing datable charcoal (Holdaway et al. 2012).

A regional chronology was developed using radiocarbon determinations from hearth charcoal and optically-stimulated luminescence (OSL) dates from the sediments into which the hearths were dug. These dates provide envelopes of time in which the archaeological record accumulated on an exposed surface (Fanning et al. 2009; Holdaway et al. 2005). Ancient and recent deposits in some instances were spatially adjacent, thus archaeological remains do not reflect a synchronous settlement system (Holdaway and Fanning 2008). Dates stretch as far back as 3000 BP, with the majority falling within the last 2500 years (Holdaway et al. 2010a, 2012). Gaps in the radiocarbon sequences were identified which roughly correlated with broad-scale environmental changes thought to have led to human absence in the area (Holdaway et al. 2010a). Recent simulation work by Davies and colleagues (2015; Davies 2016) showed how the patterning in radiocarbon sequences could be explained by geomorphic processes of erosion and deposition, running counter to interpretations of periodic abandonment or indeed, social intensification arguments (e.g., Williams et al. 2015).
At Rutherfords Creek, raw material is locally abundant in the form of silcrete and quartz cobbles found in creek beds and gibber pavements, as well as outcrops (Douglass and Holdaway 2011). Analysis of the Rutherfords Creek assemblage and others from the region suggest a technological strategy based on a generalised toolkit carried as a ‘hedge’ against unforeseen needs (Holdaway et al. 2012). Significantly, this toolkit did not include a large retouched tool component, instead being dominated by ‘expedient’ flakes and cores. The cortex ratio was used as a method for assessing the movement of artefacts as a proxy for human movement and returned values consistently below one for assemblages in the western New South Wales region, indicating cortex is underrepresented (e.g., Douglass et al. 2008). This underrepresentation could be explained by the addition of non-cortical flakes to the assemblages, but the context of raw material availability makes material importation unlikely (Douglass and Holdaway 2011). Rather, the low cortex ratios can be explained by people transporting large cortical flakes for use elsewhere, an interpretation supported by simulations conducted by Parker (2011) which demonstrated the size of flakes alone as a criterion for selecting artefacts could account for the low ratios. The interpretation of flake movement was supported by a study using colour analysis to identify exotic materials (Barker 2009), and by exploration of the flake to core ratio, another independent measure of artefact movement (Barrett 2014). Overall, the results of mobility research based on cortex ratios and analysis of the lithic assemblage suggest past people were highly mobile as a way of dealing with the unpredictable appearance of resources, gearing up with large, ready-to-use flakes with an efficient mass-to-cutting edge ratio (Holdaway et al. 2010b, 2012).

On the whole, occupation in the Rutherfords Creek area (and indeed, other WNSWAP study locations) is described as intermittent, more consistent with visitation behaviour rather than regular, prolonged occupation (Holdaway and Fanning 2014:170; Holdaway et al. 2012). Cortex ratios at Rutherfords Creek vary, each reflecting different degrees of movement. However, this variance is attributable to the age and density of the assemblages – older, denser assemblages exhibiting less variance than younger, less dense assemblages (Davies and Holdaway 2017). Cortex ratios fall around a mean of 0.53, reflecting movement of artefacts away from the area. Played out over time, this reflects a regularity in place use in the form of repeated, and relatively invariable, visits to the area (Davies and Holdaway 2017). This is supported by recent simulation work which demonstrates the low cortex ratio values are produced under conditions of low tortuosity movement (highly linear moves akin to passing through an area), and patterning in the values over time occurs under conditions of
Appendix E – Overview, Design Concepts, and Details for ClusterSim

This ODD document (following Grimm and colleagues 2006, 2010, 2020) describes the simulation ClusterSim, presented in Chapter 5.

1. Purpose and Patterns

The purpose of ClusterSim is to explore the effects of various combinations of agent movement patterns and the manufacture, transport, and discard of lithic artefacts on the composition of individual lithic reduction sets (clusters). The composition of individual clusters is used as an indicator of artefact movement which in turn serves as a proxy for human movement.

The main pattern of interest is the distribution of cluster sizes. Clusters comprise a number of flakes and a parent core. The number of flakes produced per core varies according to the simulation parameters, but flakes are removed at random at the end of a simulation run, representing transport of artefacts away from the area, thus altering cluster sizes. The resulting cluster size distributions from each combination of parameters serve as hypotheses or expectations that can be tested with empirical archaeological data.

2. Entities, State Variables, and Scales

The model has two main entities: agents and patches. The agent, thought of as a mobile forager, moves randomly throughout the simulated landscape carrying units of raw material representing cores. The forager produces and discards artefacts using those units of raw material and may reuse units of raw material that have previously been discarded. Patches (a term specific to NetLogo) are cells in a grid that forms the modelled world (‘window’). Patches can hold discarded artefacts (i.e., a virtual archaeological record) but are otherwise empty and uniform.

Two types of artefacts are represented in the model: cores and flakes. Both are modelled as agents for ease of programming, though neither are agents in a conceptual sense. Cores are equal units of raw material, each of which can yield 20 flakes before they are exhausted. All flakes are also equal units of material.
## Table E1 ClusterSim state variables

<table>
<thead>
<tr>
<th>Forager State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>core_kit</td>
<td>The number of cores currently in the forager’s possession</td>
</tr>
<tr>
<td>real_x</td>
<td>Coordinate calculated as previous x coordinate plus the distance moved according to a step length determined by the Lévy equation. Used to determine if the forager has left the window.</td>
</tr>
<tr>
<td>real_y</td>
<td>Coordinate calculated as previous y coordinate plus the distance moved according to a step length determined by the Lévy equation. Used to determine if the forager has left the window.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Core State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cluster</td>
<td>A unique ID number representing the cluster to which the core belongs</td>
</tr>
<tr>
<td>flakes_remaining</td>
<td>A number representing how many flakes can still be struck from the core</td>
</tr>
<tr>
<td>total_in_cluster</td>
<td>How many artefacts in the window make up the cluster to which the core belongs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flake State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>cluster</td>
<td>A unique ID number representing the cluster to which the flake belongs</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Observer State Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>total_foragers</td>
<td>The number of foragers that have passed through the window</td>
</tr>
<tr>
<td>next_id</td>
<td>The next number to assign as a cluster ID</td>
</tr>
<tr>
<td>cluster_size_list</td>
<td>A list of all total_in_cluster (cluster size) values, generated at the end of a simulation run</td>
</tr>
<tr>
<td>cluster_size_freq</td>
<td>A list of frequencies of cluster sizes, calculated from cluster_size_list at the end of a simulation run</td>
</tr>
<tr>
<td>flakes_remaining_list</td>
<td>A list of all flakes_remaining values, generated at the end of a simulation run</td>
</tr>
<tr>
<td>flakes_remaining_freq</td>
<td>A list of frequencies of flakes_remaining values, calculated from flakes_remaining_list at the end of a simulation run</td>
</tr>
<tr>
<td>cores_removed</td>
<td>A number representing how many unworked cores leave the window with foragers</td>
</tr>
<tr>
<td>flakes_removed</td>
<td>A number representing how many flakes are removed from the window at the end of a simulation run</td>
</tr>
</tbody>
</table>

The simulated world represents a single window of observation that is of an abstract size. Spatial relationships between artefacts are not modelled – instead, all artefacts present in the window are considered a single assemblage. Time advances in the model but is also taken as abstract and not reflective of the real-world passage of time.

### 3. Process Overview and Scheduling
During a time step, a forager enters the window at a random location carrying a number of cores defined by the *carry_in* parameter. The forager then flakes a core it is carrying according to the *reduction* parameter. If it is not carrying cores, the forager flakes the largest available previously discarded core. The core and any flakes produced are discarded.

The forager then moves by turning to a random heading and stepping forward with a step length calculated using the Lévy equation, where the relative size of the step length is determined by the value *levy_mu* which results in a more or less tortuous movement. The flaking, discard, and movement processes are repeated until the forager steps outside the window, at which point it is removed from the simulation and the number of cores it was carrying is recorded. Time advances by one step and a new forager enters the window beginning cycle anew.

At the beginning of a time step, if *total_foragers* has reached the value of *walkers* defined at the beginning of a simulation run, the simulation ends. A number of flakes are removed from the simulation window according to the *selection* parameter. All necessary data are recorded in *csv* files.

4. Design Concepts

4.1 Basic Principles

Similar to Davies’ (2016; Davies et al. 2018) FMODEL on which ClusterSim is based, the model assumes the acquisition and discard of stone material is embedded within a forager’s wider movement strategy. The degree of tortuosity of movement simulates anything from brief visits to an area where the forager passes through, to more intensive occupation. Greater tortuosity or intensity of occupation results in more intensive use of raw material, so that depending on how much raw material enters the area with a forager, cores may be reused more often, and more flakes may be produced per core on the whole.

4.2 Emergence

Patterns in the distribution of cluster sizes emerge from the production and discard of cores and flakes which varies according to the interaction of the different model parameters.
4.3 Adaptation

Foragers have one adaptive behaviour: choosing what core to flake. This decision is modelled as direct objective seeking: a forager chooses a core based on whether its objective measure (below) is satisfied or not.

4.4 Objectives

The objective measure used by foragers to decide what core to flake is whether there are any cores currently in their possession. If there are no cores in their possession, the forager chooses at random the largest available core from the discard record. If there are no cores that can be flaked, flaking does not occur.

4.5 Learning

Learning is not implemented.

4.6 Prediction

Prediction is not implemented.

4.7 Sensing

It is an assumption of the model that all previously discarded flakes and cores are visible such that the forager can sense what is available when attempting to flake a core.

4.8 Interaction

Foragers interact with patches insofar as patches hold flakes and cores that are discarded and can be acquired by the forager.

4.9 Stochasticity

Stochasticity is used in several ways. When a forager enters the simulation, they are placed at a random location. When acquiring cores from the discard record to make flakes, foragers select a core at random from the largest ones available. Forager movement direction and step length is determined randomly to ensure no directional bias in movement. At the end of each simulation run, a number of flakes are removed at random from the window according to the selection parameter.
4.10 Collectives

The model includes no collectives.

4.11 Observation

Data are generated at the end of a simulation run and saved in several .csv files. For each core in the window, the number of artefacts belonging to its cluster is added to a list and the frequency of cluster sizes is calculated. The number of potential flakes remaining on each core is also added to a list, and frequencies of these values are calculated. Other output data include the total number of artefacts present in the window, the total number of cores transported away with foragers, and the total number of flakes removed.

5. Initialisation

Upon initialisation the window of observation is empty and there are no foragers or artefacts until a forager enters at the beginning of the first time step. All lists are emptied, and several parameters are set according to user-defined values (Table E2). These parameters remain constant throughout a simulation run.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>world_size</td>
<td>The number of patches (cells) forming the window</td>
<td>33 x 33</td>
</tr>
<tr>
<td>walkers</td>
<td>The number of foragers that will pass through before the simulation ends</td>
<td>100</td>
</tr>
<tr>
<td>carry_in</td>
<td>The number of unworked cores carried into the window with an agent</td>
<td>5, 10, 20, 100</td>
</tr>
<tr>
<td>reduction</td>
<td>The degree to which a core is flaked in a reduction episode (1.00 = fully reduced)</td>
<td>0.25, 0.50, 0.75, 1.00</td>
</tr>
<tr>
<td>levy_mu (tortuosity)</td>
<td>Controls the degree of movement tortuosity, where 1.0 = low and 3.0 = high tortuosity</td>
<td>1.0, 1.5, 2.0, 2.5, 3.0</td>
</tr>
<tr>
<td>selection</td>
<td>The proportion of flakes removed (transported) at the end of a simulation run</td>
<td>0.00, 0.25, 0.50, 0.75</td>
</tr>
</tbody>
</table>

6. Input Data

No input data are required for the model.
7. Submodels

7.1 Movement submodel

When moving, the forager turns to a random heading then moves forward a step whose length is drawn from a probability distribution defined by the Lévy equation

\[ P(l) = l^{-\mu} \]

where \( \mu \) is the value of the \textit{levy\_mu} parameter. Higher values of \( \mu \) increase the probability of drawing shorter step lengths, resulting in more tortuous movement. The movement submodel ends when a move takes a forager outside the window, and begins again when a new forager enters the window.

References


Appendix F – ClusterSim Model Code

The following code was written in NetLogo version 6.2, available as a free download from https://ccl.northwestern.edu/netlogo/.

Comments in the code are marked by a double semi-colon ( ;; ).

;; ClusterSim: modelling the formation of lithic reduction sets under different mobility configurations
;; by Matthew Barrett, The University of Auckland, 2022

;; Define agent types: foragers, and flakes/cores which are programmed as agents for ease of manipulation
breed [foragers forager]
breed [cores core]
breed [flakes flake]

;; Define global variables, forager attributes, and flake and core attributes
globals [total_foragers next_id cluster_size_list cluster_size_freq flakes_remaining_list flakes_remaining_freq cores_removed flakes_removed]
foragers-own [core_kit real_x real_y]
cores-own [cluster flakes_remaining total_in_cluster]
flakes-own [cluster]

;; Model initialisation procedure: clears the simulation window, sets beginning values for variables, empties all lists, resets the clock
to setup
    clear-all
    set next_id 1
    set total_foragers 0
    set cluster_size_list []
    set cluster_size_freq []
    set flakes_remaining_list []
    set flakes_remaining_freq []
    set cores_removed []
    set flakes_removed 0
    reset-ticks
end

to go
    ;; Model stop condition: when a given number of foragers have passed through...
    if total_foragers >= walkers [
        ;; ...remove (transport) a portion of all flakes produced...
        let x (count flakes)
        ask n-of (round (selection * (count flakes))) flakes [die]
        set flakes_removed (x - (count flakes))

        ;; ...record the number of artefacts in each individual reduction set (cluster)...
        ask cores [ set total_in_cluster (count turtles with [cluster = [cluster] of myself]) ]

        ;; ...then record all necessary data and end the simulation.
        get-data
        stop
    ]

    ;; Add a new forager to the simulation and give them a number of cores according to the value of carry_in
    set total_foragers total_foragers + 1
create-foragers 1 |
setxy random-xcor random-ycor
set core_kit carry_in
}

;;;; While still in the window, foragers flake a core and then move...
ask foragers [  
while [real_x <= (max-pxcor + 0.5) and real_x >= (min-pxcor - 0.5) and real_y <= (max-pycor + 0.5) and real_y >= (min-pycor - 0.5)] [  
make-flakes
step
]
;;;; ...but if a move takes them outside the window, record the number of cores transported with them, then remove them from the simulation.
set cores_removed lput core_kit cores_removed
die
]
;;;; Advance the clock one time step
tick
end
to make-flakes
;;;; First attempt to make flakes from a core currently in possession:
ifelse core_kit > 0 [  
;;;; Determine how many flakes are generated according to the reduction parameter and remove these from the core...
let x (20 * reduction)
hatch-cores 1 [  
set total_in_cluster 0
set cluster next_id
set flakes_remaining (20 - x)
]
set core_kit core_kit - 1
;;;; ...and add the flakes generated to the archaeological record
hatch-flakes x [  
set cluster next_id
]
set next_id next_id + 1
]
;;;; If the forager does not have a core in its possession, look for the biggest discarded core and reduce that
[  
let target one-of cores with-max [flakes_remaining]
let value [flakes_remaining] of target
if value > 0 [  
let x (20 * reduction)
if x > value [set x value]
ask target [  
set flakes_remaining flakes_remaining - x
]
hatch-flakes x [  
set cluster [cluster] of target
]
]
]
to step
;;;; Turn to a random heading...
set heading random-float 360
;;;; ...then determine how far forward the forager will move according to the levy equation...
let step-length (random-float 1.000) (-1 / levy_mu)
if step-length > 500000 [set step-length 500000]
set real_x real_x + (dx * step-length)
set real_y real_y + (dy * step-length)
;;; ...and move forward that far.
fd step-length
end

;;; A function to calculate the frequency of different items in a list
to-report frequency [an-item a-list]
  report length [filter i -> i = an-item a-list]
end
to get-data

;;; For each core, record the number of artefacts in its reduction set in the
core_remaining_list, and the number of potential
foreach core [the-core ->
  ask the-core []
    set core_remaining_list 1put total_in_cluster cluster_size_list
    set flakes_remaining_list 1put flakes_remaining flakes_remaining_list
  ]

;;; Calculate the frequency of different cluster sizes (20 potential flakes per core, so
possible cluster sizes of 1-21)
set cluster_size_freq (map i -> frequency i cluster_size_list) (n-values 22 [i -> i])

to report
  let size1 item 1 cluster_size_freq
  let size2 item 2 cluster_size_freq
  let size3 item 3 cluster_size_freq
  let size4 item 4 cluster_size_freq
  let size5 item 5 cluster_size_freq
  let size6 item 6 cluster_size_freq
  let size7 item 7 cluster_size_freq
  let size8 item 8 cluster_size_freq
  let size9 item 9 cluster_size_freq
  let size10 item 10 cluster_size_freq
  let size11 item 11 cluster_size_freq
  let size12 item 12 cluster_size_freq
  let size13 item 13 cluster_size_freq
  let size14 item 14 cluster_size_freq
  let size15 item 15 cluster_size_freq
  let size16 item 16 cluster_size_freq
  let size17 item 17 cluster_size_freq
  let size18 item 18 cluster_size_freq
  let size19 item 19 cluster_size_freq
  let size20 item 20 cluster_size_freq
  let size21 item 21 cluster_size_freq

;;; Record cluster size frequencies to .csv file
file-open (word "run" behaviorspace-run-number "_cluster_sizes.csv")
file-type "n=1" file-type "," file-print size1 file-type "n=2" file-type "," file-print
size2 file-type "n=3" file-type "," file-print size3 file-type "n=4" file-type "," file-
print size4 file-type "n=5" file-type "," file-print size5 file-type "n=6" file-type "," file-
print size6 file-type "n=7" file-type "," file-print size7 file-type "n=8" file-type
"n=9" file-type "," file-print size8 file-type "n=10" file-type "," file-print size9 file-type
"n=11" file-type "," file-print size10 file-type "n=12" file-type "," file-print size11 file-type
"n=13" file-type "," file-print size12 file-type "n=14" file-type "," file-print size13 file-type
"n=15" file-type "," file-print size14 file-type "n=16" file-type "," file-print size15 file-
type "n=17" file-type "," file-print size16 file-type "n=18" file-type "," file-print size17 file-type
"n=19" file-type "," file-print size18 file-type "n=20" file-type "," file-print size19 file-type
"n=21" file-type "," file-print size20 file-type
file-close

;;; Calculate frequency of different flakes remaining values
set flakes_remaining_freq (map i -> frequency i flakes_remaining_list) (n-values 21 [i -> i])

let rem0 item 0 flakes_remaining_freq
let rem1 item 1 flakes_remaining_freq
let rem2 item 2 flakes_remaining_freq
let rem3 item 3 flakes_remaining_freq
let rem4 item 4 flakes_remaining_freq
let rem5 item 5 flakes_remaining_freq
let rem6 item 6 flakes_remaining_freq

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let rem7 item 7 flakes_remaining_freq
let rem8 item 8 flakes_remaining_freq
let rem9 item 9 flakes_remaining_freq
let rem10 item 10 flakes_remaining_freq
let rem11 item 11 flakes_remaining_freq
let rem12 item 12 flakes_remaining_freq
let rem13 item 13 flakes_remaining_freq
let rem14 item 14 flakes_remaining_freq
let rem15 item 15 flakes_remaining_freq
let rem16 item 16 flakes_remaining_freq
let rem17 item 17 flakes_remaining_freq
let rem18 item 18 flakes_remaining_freq
let rem19 item 19 flakes_remaining_freq
let rem20 item 20 flakes_remaining_freq

;; Record flakes remaining frequencies to .csv file
file-open (word "run" behaviorspace-run-number "_flakes_remaining.csv")
file-type "n=0" file-type "," file-print rem0 file-type "n=1" file-type "," file-print rem1
file-type "n=2" file-type "," file-print rem2 file-type "n=3" file-type "," file-print rem3
file-type "n=4" file-type "," file-print rem4 file-type "n=5" file-type "," file-print rem5
file-type "n=6" file-type "," file-print rem6 file-type "n=7" file-type "," file-print rem7
file-type "n=8" file-type "," file-print rem8 file-type "n=9" file-type "," file-print rem9
file-type "n=10" file-type "," file-print rem10 file-type "n=11" file-type "," file-print rem11
file-type "n=12" file-type "," file-print rem12 file-type "n=13" file-type "," file-print rem13
file-type "n=14" file-type "," file-print rem14 file-type "n=15" file-type "," file-print rem15
file-type "n=16" file-type "," file-print rem16 file-type "n=17" file-type "," file-print rem17
file-type "n=18" file-type "," file-print rem18 file-type "n=19" file-type "," file-print rem19
file-type "n=20" file-type "," file-print rem20
file-close

;; Record total number of artefacts to .csv file
file-open (word "run" behaviorspace-run-number "_total_artefacts.csv")
file-type ((count flakes) + (count cores))
file-close

;; Record total number of cores transported away to .csv file
file-open (word "run" behaviorspace-run-number "_cores_removed.csv")
file-type cores_removed
file-close

;; Record total number of flakes transported away to .csv file
file-open (word "run" behaviorspace-run-number "_flakes_removed.csv")
file-type flakes_removed
file-close
end
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