Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognize the author's right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form and Deposit Licence.
Logic and Landscapes:
Simulating Surface Archaeological Record Formation in
Western New South Wales, Australia

Benjamin Davies

A thesis submitted in partial fulfilment of the requirements for the degree of
ABSTRACT

Surface archaeological deposits are ubiquitous in arid Australia, but using them to reconstruct human behaviour and chronological sequences is made difficult by stratigraphic mixing. Contrasting interpretations of late Holocene human activity in the region have emerged, alternatively suggesting high levels of mobility and frequent hiatuses in occupation, or greater sedentism and population growth, based on equivocal archaeological patterning. The latter feature in narratives of socioeconomic intensification in Australian prehistory, prompting two questions that guide this thesis: is directional change needed to explain patterns in the surface record in western New South Wales and how can we know? Two simplified models of formation processes, formalised as agent-based simulations, are used to resolve differences in interpretations by evaluating their logic in an explicit framework and generating tests. The first, called HMODEL, is based on the concept of the archaeological palimpsest and demonstrates that infrequent, high intensity sedimentation events can generate patterning qualitatively similar to that explained elsewhere in behavioural terms. The second model, called FMODEL, features agents reducing stone and distributing it across a simulated space to examine the influence of movement patterns on the ratio of cortical to non-cortical stone (the Cortex Ratio) in flaked stone assemblages. Outcomes suggest that movement can influence the variability of ratio values, while systematic shifts depend on the consistent import or export of stone. Patterns observed in a large-scale surface survey at Rutherfords Creek, western New South Wales, are considered in light of simulation outcomes. Alternative models of hearth formation are compared to establish how each explains patterns in radiocarbon chronologies. Predictions from these models are tested against a second chronometric proxy, showing that patterning in the data is more aligned with geomorphological change operating on a consistent record of occupation than any detectable changes in population dynamics. The results of FMODEL further show that patterning in at Rutherfords Creek can be explained in large part by the relative abundances of raw material in the region. Both finds are consistent with a model of regularly occurring, short-term occupations over the course of the late Holocene. These demonstrate the potential for exploratory modelling of formation processes to resolve issues concerning contrasting interpretations of the past.
ACKNOWLEDGEMENTS

I acknowledge the indigenous Traditional Owners of the western Darling and pay respect to their Elders, past and present. The enduring traces of their truly unique history provided the motivation and material for this thesis.

This would have been a very different thesis if it were not for some long and lively discussions with my supervisors. Those held with Simon Holdaway of the School of Social Sciences convinced me to stray away from idyllic Pacific Islands to think differently about scattered stones in the Australian desert. Talking with David O’Sullivan, once of the School of Environment and now the Geography Department at University of California, Berkeley, introduced me to a wider world of modelling. Having turned up in New Zealand with some vague ideas about using simulation to address archaeological questions, I could not have asked for better supervision.

For sharing data, ideas, and consideration, I thank Trish Fanning, Matt Douglass, Tessa Bryant, Ed Rhodes, and Daniel Parker. I also thank former crews of WNSWAP for their roles in gathering and processing the data used to complete this project. My work was only possible because of their efforts, but any mistakes are mine.

Staff at Fowlers Gap Arid Zone Research Station and Paroo-Darling National Park provided access to the study areas we revisited in 2011, and their assistance is sincerely appreciated. Technical support provided by the University of Auckland Faculty of Arts IT and the New Zealand eScience Infrastructure (NeSI), the latter facilitated by Sina Masoud-Ansari, was immensely helpful for conducting simulation experiments. A debt of gratitude is also owed to the law offices of Preti Flaherty/New Zealand Consulate to New England in Concord, New Hampshire, USA for providing office space during an important part of the writing up phase.

This research was supported by a University of Auckland Faculty of Arts Doctoral Scholarship, for which I am very grateful.

I am lucky to have friends, colleagues, and teachers who supported this work and offered useful discussion regarding research and career over the years, particularly Tom Barker, Gerard O’Regan, Jen Huebert, Tom Brughmans, Iza Romanowska, Stefani Crabtree, Melinda Allen, George Perry, Mark Dickson (who also presided as co-supervisor), Nick Malone, Bruce Floyd, Alex Morrison, Peter Sheppard, and Harry Allen. The University of Auckland Archaeology PhD
reading group was a perpetual source of inspiration, as were the many students I have taught over the last few years. Deserving of special mention is the inimitable Simon Bickler, whose encouragement and assistance have been instrumental throughout my studies.

Finally, I thank my family, without whom I could not have completed this project (or any project for that matter). My brothers Phill, Nick, and Alex are my foundation and continually inspire me. Bill and Ellen Saturley have been unwavering enablers, and the importance of their support cannot be overstated. My mother, Carla, can take full credit for instilling the determination and curiosity that carried me through. Finally, I thank Kate, William, and Matilda: the most outstanding, resilient, helpful, and loving people I have ever known. Time I spent away from them working on this project was by far the greatest expense it extracted.
Table of Contents

ABSTRACT .................................................................................................................. I
ACKNOWLEDGEMENTS .............................................................................................. II

1 INTRODUCTION .................................................................................................... 1
  1.1 Thesis organisation ............................................................................................ 6

2 THE WESTERN NEW SOUTH WALES REGION .................................................. 11
  2.1 The western NSW environment ........................................................................ 11
     2.1.1 Recent human occupation history of western NSW .................................... 17
  2.2 History of prehistoric archaeology in western NSW .......................................... 20
     2.2.1 Willandra Lakes ......................................................................................... 22
     2.2.2 Menindee Lakes ......................................................................................... 25
     2.2.3 Northwest Corner ...................................................................................... 28
  2.3 Wider arid zone context .................................................................................... 34
  2.4 Synthesis ........................................................................................................... 37

3 FORMATION AND THE INTERPRETATION OF THE SURFACE ARCHAEOLOGICAL
   RECORD .................................................................................................................... 41
  3.1 The surface archaeological record ...................................................................... 42
     3.1.1 The spatial extent of the surface archaeological record .............................. 45
     3.1.2 The integrity of the surface archaeological record .................................... 46
  3.2 Formation .......................................................................................................... 49
     3.2.1 Criticisms of formation and related concepts in archaeology .................... 53
  3.3 Synthesis ........................................................................................................... 59
     3.3.1 On the conceptual barrier ......................................................................... 61
     3.3.2 On the methodological barrier .................................................................. 64
  3.4 Summary ............................................................................................................ 67

4 MODELS, SIMULATION, AND FORMATION IN ARCHAEOLOGY ...................... 69
  4.1 Models ............................................................................................................... 70
     4.1.1 Classifications of models based on medium .............................................. 73
  4.2 Simulation in archaeology ................................................................................. 76
     4.2.1 Critiques of archaeological simulation ...................................................... 79
  4.3 Formation, models, and analogues .................................................................... 82
     4.3.1 Exploratory modelling .............................................................................. 86
     4.3.2 Pattern-oriented modelling ...................................................................... 94
  4.4 Summary ............................................................................................................ 96

5 HMODEL: AN EXPLORATORY AGENT-BASED MODEL OF DEPOSIT FORMATION .98
7.3 Predicting additional patterns from simulation outcomes ........................................................................... 192
  7.3.1 Using HMODEL and HMODEL_A to simulate the effects of erosion and deposition on distributions of OSL determinations from hearth stones ........................................................................... 194
  7.3.2 Evaluating model expectations against an empirical record ................................................................. 196

7.4 Summary ....................................................................................................................................................... 201

8 DISCUSSION AND CONCLUSION .................................................................................................................... 203
  8.1 Interpreting late Holocene prehistory in arid Australia: lessons from the surface record ....................... 204
    8.1.1 Patterning in hearth ages and population dynamics at Rutherford Creek ....................................... 204
    8.1.2 Patterning in Cortex Ratios at Rutherford Creek ................................................................................. 208
  8.2 Implications for prehistoric narratives in western New South Wales and arid Australia ..................... 218
    8.2.1 Formation, reversibility, and resilience: engaging with a diversity of records in Australian prehistory 222
  8.3 On the role of models and simulation in understanding archaeological formation ............................... 226
    8.3.1 “Tools to think with”: reflections on the process of building and testing models .......................... 228
  8.4 Concluding remarks ..................................................................................................................................... 231

REFERENCES ......................................................................................................................................................... 234

APPENDIX A: OVERVIEW, DESIGN CONCEPTS, AND DETAILS FOR HMODEL .................................................. 266
APPENDIX B: HMODEL CODE .............................................................................................................................. 272
APPENDIX C: OVERVIEW, DESIGN CONCEPTS, AND DETAILS FOR FMODEL ............................................. 281
APPENDIX D: FMODEL CODE .................................................................................................................................. 286
APPENDIX E: PATTERN-ORIENTED TEST RESULTS ............................................................................................ 297
LIST OF FIGURES

Figure 2.1 Location of Far Western division in Australia (data source: abs.gov.au) ........ 12

Figure 2.2 Bioregions of western New South Wales. Studied areas discussed below are indicated with triangles (data sources: abs.gov.au, environment.gov.au) ........................................... 14

Figure 2.3 A western New South Wales landscape at Rutherfords Creek following a summer of heavy rain, with linear distribution of trees along creek edge................................. 16

Figure 2.4 Map of western New South Wales. Areas discussed below are indicated with triangles ........................................................................................................................................ 21

Figure 2.5 Typical scald scene at Rutherfords Creek, featuring lithic scatters of varying densities........................................................................................................................................ 31

Figure 2.6 Typical scald scene at Rutherfords Creek, featuring lithic scatters of varying densities........................................................................................................................................ 33

Figure 5.1 Summed probabilities of hearth ages at Rutherfords Creek (n=93). Calibrated and summed using OxCal 4.2 (Bronk-Ramsey 2009), using the ShCal13 calibration curve (Hogg et al. 2013). Grey gives raw sums, black line indicates smoothing spline (df=25). .................. 100

Figure 5.2 Calibrated radiocarbon determinations (n = 93) from the Rutherfords Creek study area dating to within the last 2000 years, plotted in order from youngest to oldest. Horizontal lines indicate one standard deviation from the calibrated mean. ......................... 101

Figure 5.3 Heat retainer hearths at Rutherfords Creek in various states of exposure..... 107

Figure 5.4 Spatial distribution of heat-retainer hearths at Rutherfords Creek (black). Red circles indicate hearths from which radiocarbon dates were obtained. ................................. 109

Figure 5.5 Frequency of radiocarbon dates from Rutherfords Creek in 100-year (black dots) and 300-year (white bars) bins to illustrate both the non-linear distribution and the overall trend of increasing frequency of determinations through time ................................. 110

Figure 5.6 Diagram of processes operating in HMODEL ................................................. 114

Figure 5.7 Multi-distance spatial clustering ($K_{obs}$) of surface hearths (black line) from five runs of HMODEL compared to the same for 100 instances of random points distributed in the same space according to a Poisson process (grey envelope). ................................................. 118

Figure 5.8 Comparing distributions in the numbers of list elements recorded in sediment_ages lists of cells using different settings of the erosion_proportion parameter.................................................................................................................. 119
Figure 5.9 Plotting convention used for HMODEL outcomes ............................................. 120
Figure 5.10 Outcomes from a single run of HMODEL (left) compared with envelopes generated from 1000 runs (grey envelope right) ........................................................................ 121
Figure 5.11 Outcomes of initial exploration of HMODEL. Envelopes generated by plotting the ages of samples of 100 simulated surface hearths from each run (horizontal axes of smaller plots) in chronological order from youngest to oldest (vertical axes of smaller plots). . 122
Figure 5.12 Diagram indicating how chronological gaps are form in HMODEL. Orange, green, and violet crosses indicate hearths constructed during the centuries following 2000, 1900, and 1800 BP, respectively while red and blue squares indicate erosion and deposition, respectively ...................................................................................................................... 124
Figure 5.13 An example of the effect of changing surface_stability ($s$) settings on modelled outcomes where the erosion_proportion parameter is set to 0.5 and the event_frequency is set to 100 years. .................................................................................. 126
Figure 5.14 Mean artefact densities recorded across different settings of erosion_proportion........................................................................................................................................ 128
Figure 6.1 Spatial distribution of cortex ratios for surface assemblages recorded at Rutherford Creek. Red points indicate cortex ratios less than or equal to 0.5. Yellow points indicate cortex ratios greater than 0.5 but less than or equal to 1. Green points indicate cortex ratios greater than 1. CNES/Spot Image obtained using Google Earth......................................................... 140
Figure 6.2 Cortex ratios calculated from surface lithic assemblages ($n=89$) from Rutherford Creek ........................................................................................................................................ 143
Figure 6.3 Schematic of processes contributing to the formation of lithic assemblages (after Knell 2013). ........................................................................................................................................ 145
Figure 6.4 Polyhedral models of cores and flakes used in FMODEL .................................. 150
Figure 6.5 Diagrammatic representation of the list structure used to store artefacts in patches and agents. Each row is an artefact attribute, while each column represents an individual artefact. In this case, artefact 200124 is a core with half of its cortex remaining (10/20 possible faces on an icosahedron)........................................................................................................... 184
Figure 6.6 Path resulting from an uncorrelated random walk on a two-dimensional surface beginning at the centre of the window of observation and ending outside of it. Dots indicate stops between moves. .................................................................................................................. 153
Figure 6.7 Top row: Random walks on a two-dimensional surface that begin and end outside of the window of observation, with step lengths drawn from the Lévy equation. Bottom row: Probability densities of drawing step lengths of length \( l \) corresponding to each of the walks above. Note that step length \( l \) is log-transformed in the density plots. Settings for \( \texttt{levy\_mu} \) are a) 1.1, b) 2.0, and c) 3.0. ................................................................. 154

Figure 6.8 Effect of varying estimates of the number of nodules used in cortex ratio calculations. Left graph derived from FMODEL, dot indicates the cortex ratio based on the actual number of nodules (33) used to produce the test assemblage, dashed line indicates a cortex ratio of 1. Right graph from Dibble et al. (2005:554), vertical line indicates number of nodules (33), dashed lines indicate 10% deviation from 1. ................................................................. 157

Figure 6.9 Effect of removing cortical flakes on cortex ratio calculations. Left graph derived from FMODEL, squares are values taken from an assemblage generated using a random reduction process, triangles indicate values when nodules are fully reduced. Right graph from Dibble et al. (2005:556). All were generated from 33 nodules. ................................................................. 158

Figure 6.10 Comparison between Douglass’ (2010) theoretical model of cortex distribution (left) and the result of a similar process simulated in FMODEL (right) ............. 159

Figure 6.11 Beanplots illustrating the distribution of cortex ratios from all simulation runs by \( \texttt{levy\_mu} \) settings when flakes are the objects being selected. Black horizontal lines indicate individual datapoints, while white curves represent the probability density of outcomes. ........ 160

Figure 6.12 Beanplots illustrating the distribution of cortex ratios from all simulation runs by \( \texttt{levy\_mu} \) settings when cores are the objects being selected. White horizontal lines indicate individual datapoints, while black curves represent the probability density of outcomes........ 162

Figure 6.13 Mean (dashed line) and 95% confidence intervals (grey) for cortex ratios obtained from simulations using varying degrees of \( \texttt{reduction\_intensity} \) and a \( \texttt{selection\_intensity} \) of 1 when flakes are the objects being selected ................................................................. 163

Figure 6.14 95% confidence intervals for cortex ratios obtained from simulations using varying degrees of \( \texttt{reduction\_intensity} \) (shown in upper right corner of each plot) and \( \texttt{selection\_intensity} \) (low to high = darker to lighter, outermost envelope showing \( \texttt{selection\_intensity} = 1 \)) when flakes are the objects being selected. ........................................... 164
Figure 6.15 Mean (dashed line) and 95% confidence intervals (grey) for cortex ratios obtained from simulations using varying degrees of `reduction_intensity` when cores are the objects being selected. ................................................................. 165

Figure 6.16 Cortex ratios obtained from simulations using `reduction_intensity` and `selection_intensity` settings of 1, and variable settings for `carry_in` (indicated in top right corner of each graph) when flakes are the objects being selected. Dashed line indicates a cortex ratio value of 1. .................................................. 166

Figure 6.17 Cortex ratios obtained from simulations using a `reduction_intensity` setting of 1, and variable settings for `carry_in` (indicated in top right corner of each graph) when cores are the objects being selected. Dashed line indicates a cortex ratio value of 1. 168

Figure 6.18 Mean (dashed line) and 95% confidence intervals (grey) for cortex ratios when cores are the objects being selected, and allowing for “overproduction” of a) 1, b) 5, and c) 20 cores per reduction event ................................................................. 169

Figure 6.19 Cortex ratios obtained from simulations using `reduction_intensity` and `selection_intensity` settings of 1, and variable settings for `carry_in` (indicated in top right corner of each graph) when flakes are the objects being selected. Grey dots indicate runs using 10 walkers, while black dots indicate runs using 100 walkers. Dashed line indicates a cortex ratio value of 1. .................................................. 170

Figure 7.1 Change in population over time (expressed as a multiple of the initial population) using different growth rates used in HMODEL_A .................................................. 176

Figure 7.2 Survival probabilities for charcoal in hearths of given ages based on decay rates used in HMODEL_A .................................................. 177

Figure 7.3 Outcomes of initial exploration of HMODEL_A. Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest. .................................................. 179

Figure 7.4 Outcomes of initial exploration of HMODEL_A at different settings of the `absence_interval` variable (numbers in upper left corners of plots). Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest. .................................................. 181
Figure 7.5 An example of the effect of changing absence_intensity (ai) settings on modelled outcomes where the pop_growth and decay parameters are set to 0.1, and the absence_interval is set to 100 years.

Figure 7.6 Proportions of gap lengths from Rutherford’s Creek (solid line) vs. expected gap lengths from a negative exponential distribution of gaps from same time period and date frequency (dashed line). Compare with Rhode et al. 2014:Fig 10.

Figure 7.7 Differences between sequential gap lengths at Rutherford’s Creek.

Figure 7.8 Outcomes of HMODEL simulations evaluating radiocarbon (black) and OSL (grey) samples. Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest.

Figure 7.9 Outcomes of HMODEL_A simulations evaluating radiocarbon (black) and OSL (grey) samples. Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest.

Figure 7.10 Comparing outcomes of HMODEL_A simulations using absence_intensity (ai) settings of 1 (left) and 0 (right), pop_growth and decay settings of 0.1 and absence_interval of 200 years. Envelopes generated by plotting samples of 100 simulated hearths from each run in chronological order.

Figure 7.11 Samples of calibrated radiocarbon dates (n = 93; black) and OSL dates (n = 93; grey) on hearth stones from Rutherford’s Creek. Dates expressed as ordered set of means (dots) with one standard deviation (bars).

Figure 7.12 Log-transformed OSL gap lengths (n=100) from Rutherford’s Creek imposed on 100 simulated samples from a uniform frequency model with same date frequency and time span (grey cloud).

Figure 8.1 Idealised logistical mobility structure, consisting of a central core featuring high movement tortuosity and peripheral areas of low movement tortuosity.

Figure 8.2 Constraints on potential Cortex Ratio distributions of cortex ratios imposed by tortuosity of movement.

Figure 8.3 Theoretical structures of curation and mobility configurations: a) ‘Logistical’ configuration with high levels of carry-in occurring at the core, b) ‘Logistical’ configuration with high levels of carry-in occurring at the periphery, c) ‘Residential’ configuration with levels of carry-in varying between locations. Graphs at right indicate effects on distributions of
assemblage level cortex ratios. Red circles indicate areas of high carry-in, while blue circles indicate areas of low carry-in. ................................................................. 212

Figure 8.4 Illustrations of different parameter settings for FMODEL_A: a) Distributions of raw material sources (red cells) generated from abundance settings modelling even raw material distribution (left) and stone-rich/stone-poor areas (right); b) Agent paths resulting from Lévy mu (μ) settings used to model a residential mobility configuration (left) with no differences in redundancy of place use and a logistical or ‘periphery-core’ configuration (right) with greater tortuosity of movement on the right side relative to the left. ......................................................... 214

Figure 8.5 Outcomes of the FMODEL_A exploration of the influence of raw material distribution on assemblage Cortex Ratios. Top row are logistic mobility configurations, bottom row are residential mobility configurations................................................................. 216

Figure 8.6 Relationship between scald area and Cortex Ratio (n=89)................................. 218

Figure 8.7 Two basins of attraction, illustrating the position of the system (black dot), its precariousness (Pr), and the latitude (L) and resistance (R) of the current basin (from Walker 2004)......................................................................................................................... 224
LIST OF TABLES

Table 6.1 Stone artefact classes recorded at Rutherfords Creek. Artefact classes showing retouch are shaded grey. ........................................................................................................... 141

Table 6.2 Proportions of cortex retention on cores recorded at Rutherford’s Creek ...... 149
Table 6.3 Proportions of cortex ratio outcomes for different settings of Levy_mu ...... 161
Table 7.1 Primary explanation for qualitative patterns in radiocarbon chronologies ..... 175
Table 7.2 Summary statistics from simulated uniform data and radiocarbon data from Rutherfords Creek ........................................................................................................... 186
Table 7.3 HMODEL_A and HMODEL curve test and cluster test outcomes with probability of success greater than 0.05 ................................................................. 191
Table 7.4 Summary statistics from simulated uniform data and OSL data from Rutherfords Creek ........................................................................................................... 199
Table 7.5 Outcomes of one-sample Kolmogorov-Smirnov test against uniform
distribution ..................................................................................................................... 201
Table 8.1 Parameter settings for FMODEL_A exploration ........................................ 215
1 INTRODUCTION

Modern humans have adapted to numerous changes in their physical and social environments since emerging in Africa over 200,000 years ago. In some cases, those adaptations have substantially reorganised the behavioural patterns of human groups and the ecological systems in which they exist. Archaeological research around the world has charted these adaptations and reorganisations through the geographic variability and temporal changes in the form and arrangement their material residues. It is the presence of arrangements of these residues for which there is no account that gives archaeology a purpose in the first.

Understanding transitions in human societies is of fundamental import to archaeology in the twenty-first century. Several recent agenda-setting papers have cited changes to mobility (physical organisation), subsistence change (economic organisation), and the emergence of social complexity (social organisation) as areas of critical development for the discipline (e.g. Smith et al. 2012; Kintigh et al. 2014). This is driven in part by the perceived potential for archaeologists to contribute to discussions of contemporary problems of socioecological adaptability and ecosystem management from their unique position as narrators of humanity’s long-term cultural history (e.g. van der Leeuw and Redman 2002; Redman 2005; Lane 2015). In many parts of the world, narratives featuring major directional changes that bear on the present trajectories of global societies have been developed over the past century.

In Australia, the identification of changes in Aboriginal societies before European contact has been stymied by enduring perceptions of cultural stasis. During the 18th and 19th centuries, European encounters with the economy, society, and material culture of Indigenous Australians were incorporated into comparative cultural evolution frameworks that were used to interpret archaeological patterning elsewhere in the world (Colwell-Chanthaphonh 2012:268). These frameworks were in turn used to promote the notion that contemporary Indigenous Australians shared similar lifeways to their Pleistocene forebears.
(Bowler 1992), demonstrating limited cultural evolution and reinforcing prevailing racial stereotypes (Hiscock 2008:4; Lourandos 1997:2).

The perception of Australian prehistory as uniform and unchanging has undergone substantial revision during the last century, due in part to developments in Australian archaeology. The temporal depth of Australia’s prehistory began to be understood in the 1960s (Mulvaney and Joyce 1965); today, colonisation is thought to have taken place sometime before 50,000 years ago (Clarkson et al. 2015; O’Connell and Allen 2012). Some early researchers sought to identify sequential changes in material culture that might indicate prehistoric migrations or cultural interactions (e.g. McCarthy 1948, 1958; Tindale 1957), but these efforts were hampered by limited sampling and consideration for the variability in material culture (Mulvaney 1966). More recently, concerted efforts to document archaeological variability in different parts of the continent have demonstrated a diversity of cultural expressions and adaptations in the past (e.g. Attenbrow 2006; Balme 1995; Barker 2004; Cosgrove 1999; David and Lourandos 1997; Head 1987; Hiscock 1986; Holdaway and Fanning 2014; Lourandos 1980, 1983; McBryde 1975; O’Connor 1999; Smith 2013; Ulm 2006; Veth 1993; White 1971; Williams 1988). Studies such as these have provided the basis for a range of regional narratives suggesting different cultural trajectories and emphasising change over the course of antiquity. However, major directional shifts akin to the Neolithic transition in Eurasia (e.g. Bar-Yosef and Belfer-Cohen 1992; Childe 1951; Zeder 2009) or the development of complex village and urban societies in the Americas (e.g. Flannery 1972; Kohler and Varien 2012) have not been demonstrated in Australia. The lack of clear evidence for food production and storage has remained a notable point of difference between Australia and other parts of the world, one that may have placed limitations on the development of lasting inequalities in prehistoric Australian societies (Edwards and O’Connell 1995; Keen 2006). But whatever the reason, major social reorganisation has been conspicuously absent from narratives of Australian prehistory.

In the past few decades, though, narratives have developed portraying the middle to late Holocene as a period of progressive changes to the social, economic, and technological organisation of human groups in many parts of Australia. Patterns identified in regional archaeology have been used to demonstrate decreasing mobility, increased territoriality,
elaboration in ritual and ceremonial activities, and higher populations in this period (Beaton 1983; Lourandos 1983; David 2002; Smith 1986, 2013; Williams 1988; Ross 1985, 1989). The mechanisms proposed to have stimulated these changes vary from place to place along with the forms of evidence used to demonstrate them, but many invoke combinations of changes in environmental productivity, technological developments, internal social dynamics, and demographic pressure as prime movers. In some cases, elements of these regional narratives have been combined to propose a continent-wide process of socio-economic intensification beginning around 4000 years ago and becoming amplified over the past two millennia (e.g. Lourandos 1983, 1997; David and Lourandos 1997; David 2002; Johnson and Brook 2011; Ross et al. 1992; Smith and Ross 2008; Williams et al. 2015a), prompting comparisons to intensification narratives developed in other parts of the world (Lourandos 1997:330-335; Williams et al. 2015b:12).

These narratives represent a substantial shift from earlier notions of a continent of hunter-gatherers unchanged since the Pleistocene. If a large-scale transition toward greater sedentism and higher population densities was underway in Australia during the late Holocene, this would also represent one of the most recent instances occurring in prehistory, offering archaeologists an unparalleled opportunity to study the preconditions and effects of such a transition. Such an opportunity warrants careful consideration of the evidence used to support the developing narratives, which some have noted has been hindered to a degree by inadequate priorities in theorising and data acquisition (e.g. Attenbrow 2006; Attenbrow and Hiscock 2015; Bird and Frankel 1995; Hiscock 2008; Holdaway et al. 2008; Robins 2005; Ulm 2013). Ulm (2013:184), for instance, recently critiqued complexity narratives in Australia, arguing that “the limits of archaeological variability, or at least their interpretation, have been predetermined by the expectations deriving from the continental narrative.” This was demonstrated in a tendency within Australian archaeology to focus research attention and chronology building primarily on stratified rockshelters rather than ‘open-sites’ and archaeological landscapes, despite the biases that such a focus involves (Ulm 2013). Human activity in the past was not constrained to those areas where archaeological evidence is abundant or well-preserved. Foragers, even those transitioning to food production systems, were likely wide ranging in their activities (Kelly 1992; Smith 2001). Patterns resulting from mobility configurations and population growth, then, are unlikely to be well documented in
rockshelters alone. Archaeological sampling at the scale of landscapes is needed to better understand human use of space.

Australia is uniquely situated for this purpose, as large areas have avoided extensive modern development, and many regions are rich in surface deposits. Surface archaeological deposits in a contemporary sense are collections of artefacts, features, and residues lying inert on the surface of the earth. Like subsurface deposits, surface deposits are formed through the actions and interactions of many processes over time. However, the particular combinations of processes that generate surface deposits inhibit or subsequently undo the formation of stratigraphic layers of sediment: the primary means by which archaeologists determine the chronological sequences of deposits. While this has meant that surface archaeology has been historically perceived as problematic for the purposes of reconstructing human behaviour (Roper 1976; papers in Schofield 1981), the past few decades have seen a broadening of this perspective as the potential for these deposits to inform on place use is increasingly recognised (e.g. Bailey 1983, 2007; Barrientos et al. 2015; Binford 1982; Clarkson 2008; Dunnell and Dancey 1983; Ebert 1992; Foley 1981; Foley and Lahr 2015; Holdaway and Fanning 2014; papers in Holdaway and Wandsnider 2008; Isaac and Harris 1975; papers in Rossignol and Wandsnider 1992; Stern 1993).

Distinguishing between models of prehistoric behaviour, whether from surface or subsurface deposits, lies in the ability to correctly identify mechanisms that generated definable patterning within archaeological deposits to the exclusion of others (Murray and Walker 1989). However, associating archaeological recordings with explicit formation processes is not straightforward, and this can present difficulties in the narrative-building process. As Binford (1992:47) puts it, “[a]rchaeologists are impatient. They want to transform their observations of contemporary phenomena into descriptive or even explanatory statements about the past.” In this case, the contemporary phenomena are the objects in the material record as recorded in archaeological contexts, and to explain those observations means to understand the processes that generated them. But implicit in Binford’s (ibid.) statement is a recognition that explanations are not empirically sufficient when based solely on the analysis of observations, even if they form patterns that may appear to be congruent with a conjectured generating process. Some processes may not produce a
wholly distinctive pattern in terms of the data being observed, leading to the dilemma of multiple interpretations that may not be complementary.

This can be illustrated by current interpretations of surface archaeological deposits in western New South Wales, Australia. Due to widespread erosion, many landscapes in the Australian deserts feature extensive, highly visible surface deposits, predominantly composed of lithic scatters and heat-retainer hearths. The visibility of these deposits is appealing for study of prehistoric human landscape use (Pardoe 2003:42), and surface archaeological deposits are often a major component of heritage archaeological surveys in the arid zone (e.g. Hughes et al. 2011; Bryant 2013). But it has also long been recognised that translating these deposits into interpretations is not straightforward given the influence of non-behavioural formation dynamics (e.g. Allen 1972; papers in Hope 1981; Webb 1994; Shiner 2004; Fanning et al. 2007). The archaeological landscapes of western New South Wales, like many places featuring extensive surface archaeology, are frequently considered to be a “complex palimpsest” of archaeological materials of varying ages (Smith 2013:323). Despite these difficulties, behavioural interpretations have emerged which incorporate patterning from surface deposits. Early interpretations continuous from the terminal Pleistocene (e.g. Allen 1972) contrast with regional and superregional models of population growth, greater sedentism, and socio-economic intensification (e.g. Balme 1995; Smith and Ross 2008; Smith 2013), while others still have constructed less directional models, arguing for low population densities, high levels of residential mobility, and episodic absences from the landscape (e.g. Holdaway et al. 2010; Holdaway and Fanning 2014). The role of non-behavioural agents of formation continues to play a central yet confounding role in the interpretation of the surface record in the region (Fanning et al. 2009).

Although archaeological interest in surface deposits has increased and brought abundances of new data, the forums in which archaeologists translate static observations of these deposits into dynamic processes have largely gone unchanged (Bailey 2008; Lucas 2012). Recognising patterning at these levels depends on linking potential generative mechanisms to observed patterns in an explicit way (Rossignol 1992:11; Ward and Larcombe 2003). For processes operating in the unobservable past, this requires analogical reasoning to processes assumed to be uniform. However, finding appropriate analogues for processes that
occur over long time spans, operate over large spatial extents, or involve more orders of organisation than are immediately observable in the present is difficult (Wobst 1974; Gifford-Gonzalez 1992). For surface archaeological deposits, which tend to be more intensively scrutinised over their formational histories than subsurface deposits (e.g. Shott 1995), interpretive differences are unlikely to be resolved without recourse to alternative means of assessing processes.

This thesis is aimed at resolving interpretive differences over the formation of surface archaeological deposits in western New South Wales by evaluating the logic on which they are built in explicit, computational modelling framework. In particular, it seeks to address whether patterns observed in this record are consistent with interpretations of increased sedentism and population growth as has been argued for in this and other parts of the arid zone. The emphasis on explicitness is a response to an ontological disjuncture that exists between the patterning in the archaeological record and the largely behavioural interpretations drawn from them (Lucas 2012; Stern 2015). Computer simulation is used as a method in recognition of the inability to directly observe past formational processes, as well as to account for processes beyond the scale of ethnoarchaeological or actualistic studies.

1.1 Thesis organisation

In Chapter 2, relevant literature concerning the western New South Wales region is reviewed. This begins with a discussion of western New South Wales as a human environment, followed by a concise history of archaeological research in the region. This will be used to illustrate the contrast between the opportunities presented by the region’s extensive surface deposits and general perceptions of that record as being distorted or disturbed, as well as provide the justification behind existing regional narratives. This research is then positioned within the wider context of the prehistory of Australian deserts, highlighting connections between current regional and continental interpretations. It is shown that multiple contrasting interpretations exist for archaeological phenomena in the region, and it is argued that, rather than a lack of data, this is due to an inability to constructively
Chapter 3 discusses the surface archaeological record and some of the challenges faced by archaeologists working in surface contexts. Surface records are expansive, and frequently regarded as palimpsests due to their low temporal resolution. In spite of this, some have used the concept of the palimpsest to argue that archaeological records of differing resolutions may be more suited for viewing processes operating at different spatio-temporal scales (e.g. Bailey 1983). It is maintained that the surface record provides a rich resource that is underutilised due to poor understanding of its formation: the means by which archaeologists infer processes operating in the past from the contemporary record. The primary mechanism by which archaeologists accomplish this is through analogical reasoning to processes observed in the present, assuming or reasoning a uniform relationship between their operation in the present and their operation in the past. However, as the record on the archaeological surface is the product of processes operating at scales that inhibit direct observation even in the present, suitable analogues for phenomena observed in surface contexts are generally lacking, contributing to underdetermination between contrasting interpretations in terms of the data available. This is further compounded by a view of formation as a spoiler to interpretations of archaeological patterning as outcomes of ethnographically-conceived behaviour. It is argued that in order to make strong inferences from the surface record in western NSW, formation must be considered not in terms of post-depositional “disturbances” but as a more holistic, generative process. Overcoming the problem of finding suitable analogues, on the other hand, requires recourse to analogues not necessarily constrained to ethnographically observable situations.

Chapter 4 begins by discussing the ways in which models are used in science and archaeology more specifically, emphasising the epistemological status of models relative to theory and empirical phenomena. One method of modelling, computer simulation, has been used in ways similar to ethnographic and experimental analogues, to understand theoretically what kinds of processes may have operated in the past by way of uniformitarian assumptions from processes observed in the present. However, it has been argued recently that archaeologists have regularly employed simulation for reconstructing past systems, leading
to overly complicated models with limited theoretical applicability. This has prompted a shift toward more generalised “exploratory” models (sensu Premo 2007), built with the aim of building theory in terms of well-understood, simplified processes. Efforts to date have by and large emphasised socio-ecological processes with limited consideration for the archaeological manifestations of these systems (Lake 2014), largely avoiding the task of comparing models in terms of archaeological data (Barton 2014:310). A case is made for using simulations systematically as a means of tacking between well-understood theoretical principles and empirical observations. A programme of exploratory agent-based modelling of simplified conjectured formation processes, followed by a pattern-oriented modelling approach to derive testable statements regarding simulated deposits, is recommended.

In Chapter 5, archaeological interpretations of late Holocene population dynamics in western New South Wales are presented through the lens of an archaeological proxy: distributions of radiocarbon data. Using patterns in chronometric data obtained from heat-retainer hearths at the Rutherfords Creek study area to constrain structure, an exploratory model of the formation of surface archaeological deposits in a fluvial environment is described. Based on the complimentary concepts of stratigraphy and palimpsests (Lucas 2012:120), the model is instantiated in an agent-based computer simulation called HMODEL, which models heat-retainer hearths as datable features constructed at a given rate that can be hidden, exposed, or destroyed by sediment deposition and erosion events occurring in different proportions. An exploration of model outcomes is undertaken that establishes how the model operates under various parameter configurations, and demonstrates how the combined effects of erosion and visibility through time can produce shifts in the temporal distribution of deposited materials. Outcomes from this exploration are considered in terms of the archaeological record at Rutherfords Creek.

In Chapter 6, interpretations of mobility among the foraging groups that inhabited western New South Wales in the past are discussed. It is contended that many of these interpretations are built upon conceptualisations of material culture for mobile versus sedentary lifeways rather than evidence for movement itself, and a distinction between conceptual mobility and archaeological mobility is drawn (sensu Close 2000). Stone artefacts, being both abundant and portable, are suggested among the potential sources of
information about the mobility of peoples in the past. Past studies in the region have utilised the Cortex Ratio, which compares the amount of cortical stone in an assemblage to that which would be expected for that assemblage. The Cortex Ratio acts as an archaeological proxy for mobility through the depletion or augmentation of cortical stone in local lithic assemblages, and is presented as an option for evaluating different archaeological mobility configurations in a simulation.

The remainder of the chapter describes an exploratory model of the formation of surface lithic assemblages through the processes of manufacture, transport, and discard to evaluate patterning in assemblage-level Cortex Ratios resulting from different combinations of these mechanisms. This is implemented in an agent-based simulation called FMODEL, in which stone artefacts, either carried with the agent or manufactured locally, are distributed within a given window of observation between steps of a correlated random walk used to model differing degrees of movement tortuosity. An exploration of this model illustrates the effects of different degrees of reduction, selection, movement tortuosity, and material carried in on the Cortex Ratios for generated assemblages, and these are considered in terms of Cortex Ratios from surface assemblages recorded at Rutherfords Creek.

Chapter 7 compares the outcomes one of these exploratory simulations, HMODEL, and outcomes from alternative models in a pattern-oriented framework geared toward model comparison in terms of patterning observed at Rutherfords Creek. Similarities between patterning in the field data and model outcomes from particular parameter configurations are demonstrated, allowing for the association of simulation patterning with different generative processes such as changes in occupation intensity and geomorphic activity. An additional pattern, in the form of optically-stimulated luminescence dates from hearth stones, is identified as a means of testing these models in terms of field data, and modifications to the simulations are made to accommodate these patterns. The results of these simulation exercises demonstrate divergence between models of population growth and geomorphic change in terms of the patterning of radiocarbon and luminescence chronologies, providing an expectation for comparison to field data. Patterning in radiocarbon and luminescence chronologies obtained from Rutherfords Creek is shown to be consistent with interpretations
of a dynamic geomorphic environment operating on a more or less uniform record of occupation, rather than population growth or episodic dispersal.

Chapter 8 closes the thesis with a discussion of these results in the context of surface archaeological deposit formation in western New South Wales and contemporary approaches to formation in archaeology more generally. The explorations and test of HMODEL provide the basis for an argument that the record in western New South Wales is consistent with a late Holocene prehistory characterised by regular, low-level occupation. The explorations of FMODEL are used to provide additional context for interpreting different possibilities for a mobility scheme in western New South Wales. It is suggested that Rutherfords Creek may represent only one component of a larger mobility scheme, but that use of Rutherfords Creek in terms of the net transport of lithic material is remarkably invariable. Both of these interpretations, of a regularly visiting population exploiting local stone resources for use elsewhere, are in keeping with a successful adaptation to a comparatively marginal environment through regular mobility and forward-planning. This is discussed in terms of developing narratives, suggesting that the record of Western New South Wales might be considered in terms of resilience and persistence of socio-ecological structures.

The current study provides one instance of how models, simulation or otherwise, can be used to develop expectations about the record given a set of generative mechanisms, and how these can be used in turn to discern between contrasting interpretations. It is argued that simulation is a tool that archaeologists can use to think about the archaeological record and develop theories, but that by grounding some simulations in the logic of uniformitarianism and experimentation, it provides another form of analogue against which archaeological data can be assessed, one that is more suited to phenomena formed at scales beyond those afforded by traditional inquiry.
2 THE WESTERN NEW SOUTH WALES REGION

In this chapter, western NSW will be considered as a human environment, and historical human occupation in the area will be outlined. This is followed by an overview of archaeological studies conducted there, focusing specifically on research in three areas: the Willandra Lakes, the Menindee Lakes, and the northwest corner. Research conducted in these areas is used to highlight the development of ideas regarding local social organisation and change, as well as difficulties inherent in drawing inferences from a primarily surface archaeological record. These western NSW studies are then contextualised within wider regional and continental interpretive frameworks, showing how different aspects of this research have been used to support or dispute established narratives. A synthesis of this literature illustrates reasons for using western NSW as a case for the study of surface deposit formation, with emphasis on the different ways in which this record has been interpreted and incorporated into regional and continental narratives.

2.1 The western NSW environment

The western NSW region, for the purposes of this study, roughly corresponds with Far West geographical divisions used by various state and federal institutions\(^1\), extending westward from the Western Slopes and Riverina regions of central NSW to the borders of South Australia, Queensland, and Victoria. The land is predominantly low (< 250 m asl) and flat, with most surface undulations surrounding creek catchments and lakes in the form of low hills and dunes. The Barrier and Grey Ranges in the far west provides some higher relief and separates the region from the Lake Eyre basin (Fig 2.1).

The Darling River is the primary drainage for the region. The headwaters of the river are located in the New England Fold of the Great Dividing Range, consolidating near Bourke.

---

\(^1\) The Far West region is an informal distinction that is defined differently by various organisations. The geographic area described here is similar in extent to the Far West division used by the Australian Bureau of Statistics, the Upper and Lower Western districts used by the Australian Bureau of Meteorology, and the Western Division identified under the NSW Crown Lands Act 1989.
and flowing south-southwest to its confluence with the Murray River at the Victorian border. Major tributaries within the region join the river from the north and include the Warrego and Paroo Rivers, while the Lachlan and Murrumbidgee Rivers flow through the southern part of the region directly into the Murray. The Great Darling Anabranch, the product of a major late Pleistocene avulsion event (Bowler et al. 1978), forms an intermittent parallel drainage from Willandra to the southwestern corner of the state. Unlike the continuously flowing Murray, the other major drainage within the wider basin, the Darling River flows intermittently depending on oscillations in precipitation in its Southern Queensland headwaters.

Ephemeral or extinct lakes are common throughout the region. Active ephemeral lakes, such as the Paroo Overflow Lakes, the Bulloo-Bancannia Lakes (part of a small endorheic basin in the northwest part of the state), and the Menindee Lakes, fill episodically with flooding from contributing channels, while truly extinct lakes, such as the Willandra
Lakes, are primarily found south of the river and are disconnected from contemporary major stream systems.

Local temperatures fluctuate seasonally, with hot summers (mean air temperature ~32°C) and mild to cool winters (mean air temperature ~18.5°C), and average annual rainfall across the region is approximately 245 mm², with pan evaporation typically exceeding precipitation. However, rainfall can be highly variable on a month-to-month or year-to-year basis. Droughts are recurrent, with increasing rates of incidence in coordination with the El Niño-Southern Oscillation (Marx et al. 2009). Flooding also features episodically, oftentimes resulting from low latitude exposure to monsoon troughs around the headwaters of the Darling and its tributaries (Bell 1979).

The alternation between desiccating drought periods and inundating floods has the capacity to rapidly change the condition of landsurfaces in the region. In the areas away from streams, local rainfall can cause flooding, moving loosely aggregated sediments downslope as sheetwash (Fanning 1994; Webb 1993). This rainfall can be highly localised, with marked differences in rainfall over short distances (e.g. Fanning et al. 2007:277). Aeolian transport of sediments is a common feature during dry periods, with heavier sediments accumulating locally while finer sediments are dispersed further afield (Marx et al. 2009). High magnitude windstorms can blanket areas in thick deposits of dust (Hesse and McTanish 2003; McTanish and Lynch 1996). Both fluvial and aeolian sediment transport has been accelerated by changes to surface vegetation following the introduction of grazing ungulates (Fanning 1999).

The large area of western NSW incorporates a good deal of regional variability in local ecosystems. The Interim Biodiversity Regionalisation of Australia (IBRA) scheme (Thackaway and Cresswell 1995) currently used by Environment New South Wales lists six distinct ecoregions covering the area (Fig 2.2):

---

2 Grand averages of historic weather data for Menindee (station no. 047019), Wilcannia (station no. 046043), Kayrunnera Station (station no. 046093), Broken Hill (station no. 047031), and Tibooburra (station no. 046037) Source: Australian Bureau of Meteorology http://www.bom.gov.au/climate/data/
• **Broken Hill Complex** Located on the far western edge of the state in a wide area surrounding the city of Broken Hill and the Barrier Ranges. This features a dry, desert climate, with stands of *Acacia* woodland situated within chenopod shrublands. Drainages in this ecoregion end primarily in the Bancannia basin.

• **Channel Country** Highly arid region in the northwest corner of the state, named for numerous streams flowing west into Lake Eyre basin. Rainfall is highly unpredictable. Channel valleys are dominated by quartz-heavy desert pavements (“gibbers”) and shallow soils. Some higher hills are found around the town of Tibooburra.

• **Darling Riverine Plains** Hot, arid-to-semi-arid alluvial plains extending along the corridor of the Darling River from Bourke to the Menindee Lakes. Very flat landscape, with the Darling River and its tributaries providing primary
relief. Rainfall, as well as alluvial deposition, is higher in the eastern reaches. Flooding is a common feature during heavy rains or monsoons in Darling headwaters. *Eucalyptus* and *Acacia* species are found along watercourses, while saltbush and Mitchell grass are prominent on open plains.

- **Murray-Darling Depression** Located on either side of the lower Darling River, extending northeast along the southern boundary of the Darling Riverine Plains corridor as far as Louth. Features hot semi-arid-to-arid dune fields, ephemeral or extinct lakes, and plains, with additional drainage through the Lachlan and Murrumbidgee Rivers. Lake edges feature lunette systems preserving Pleistocene stratigraphic sequences.

- **Mulga Lands** Semi-arid to arid table lands extending north from the northern banks of the Darling River to the Queensland border. *Acacia* (mulga) are the dominant woody species, but *Eucalyptus* species are also found along watercourses. Features silcrete formations and pavements, ephemeral streams, and sand plains. Partially-connected river systems like the Paroo and Warrego terminate into overflow lakes and wetlands. During wet periods, these areas support large communities of water birds. Artesian mound springs at Peery Lake are an essential habitat for several plant species in the region.

- **Simpson-Strzelecki Dunefields** Highly arid, linear dune country in the far northwestern corner of the state. Precipitation is highly variable, with droughts a regular feature. Dunes are of variable stability, especially since the advent of pastoralism in the region (see below). Following rainfall, water collects in ephemeral streams and claypans, which often support transient species of water birds.

Although each region has a distinctive character, there are some general qualities that are shared between these and with other arid parts of Australia. Much of the land is depleted of nutrients, a characteristic of the geologic age of the landscape, and those nutrients that do persist tend to collect in shallow soils near the surface and are distributed in an irregular manner (Stafford-Smith and Morton 1990). Intense flood events like those mentioned above have the capacity to regularly remove or relocate sediments, periodically altering the
distribution of nourishing soils (Prosser et al. 2001). This combination of a well-sorted landscape and irregular, intense precipitation encourage the presence of nutrient-deficient, high-carbohydrate plant taxa (Stafford-Smith and Morton 1990; Morton et al. 2011). Chenopod shrubs dominate regionally, occurring in a patchy coverage across the landscape. Trees, predominantly Acacia and Eucalyptus species, can be found distributed mostly along watercourses (Fig 2.3).

Vertebrate species present in the region have developed adaptations as consumers of low-nutrient resources with varying degrees of productivity. Water fowl, for example, make frequent long-distance moves between resource patches to counter local depletion (Roshier et al. 2006). Macropod species such as kangaroos and euros can obtain sufficient water from plant consumption (Dawson 1995), and have developed reproductive mechanisms for reducing fertility and delaying embryonic development during periods of resource stress (Tyndale-Biscoe 2005). Rodent populations fluctuate dramatically between periods of

Figure 2.3 A western New South Wales landscape at Rutherfords Creek following a summer of heavy rain, with linear distribution of trees along creek edge
drought and abundance, reflecting environmentally-mediated shifts in mortality and fertility (Dickman et al. 1999).

Arid environments are typically considered marginal habitats for human occupation, often featuring low population densities. Ethnographically-known groups occupying desert environments are frequently characterised as mobile foragers (e.g. Gould 1980; Myers 1991; Cane 1987; Tonkinson 1993; Kelly 2013), who use a strategy of high mobility and flexible social organisation as a means of survival (Kelly 1992). However, it has been argued that prehistoric human populations living in the Australian arid zone may have adopted behaviours that permitted greater degrees of sedentism and higher population densities, evidenced by different archaeological signatures (see discussion below).

2.1.1 Recent human occupation history of western NSW

Aboriginal groups traditionally associated with the western Darling Basin belong predominantly to the Paakantyi³ linguistic group (Allen 1972; Hercus 1993), with influence from Yarli- (western) and Karnic-speaking (northern) groups as well (Dixon 2007). In the far south near the Willandra Lakes, groups speaking Kulinic, Wiradhuric, and Lower Murray dialects were also present (McBryde 1978, 1984; Dixon 2007). These groups are the Traditional Owners of country in the western Darling and its surrounds. It has been proposed that Aboriginal systems of land tenure, particularly in marginal areas, were flexible in the past to accommodate episodic fluctuation in resource availability and to facilitate social network maintenance (Sutton 1995; Veth 2002). Despite this, fixed tribal boundaries based primarily on shared language have developed in Australia since the 19th century (e.g. Tindale 1974), and are a common part of the land tenure systems that currently exist⁴.

---

³ Paakantyi is a language group within the larger Pama-Nyungan family of languages, and is the name currently used by the Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS Code D12). In its usage here, it is synonymous with the names Paaktantji, Barkindji, Barkandji, Baagandji, Bogundgi, and the non-indigenous designation Darling, which are found in other texts (Hercus 1993). Dialects of Paakantyi include Kurnu, Wanyiwalku, Pantyilikali, Southern Paakantyi, Wilykali, Thangkaali, Parrintyi, Marawara, and Paaruntyi (AUSTLANG 2014).

⁴ “Mapping and spatial information play a key role in navigating native title...Mapping enables people to gain an understanding of where these matters are in relation to other things, such as towns, roads, farms, mining tenements, and local government areas.” Source: National Native Title Tribunal http://www.nntt.gov.au/assistance/Geospatial/Pages/default.aspx
European explorations along the Darling River were preceded by a wave of infectious disease from coastal settlements that greatly reduced populations. While exploring the upper Darling in 1829, Sturt (1833) noted that many of the indigenous inhabitants suffered from a disease with dermatological symptoms similar to smallpox, and that it was clear that populations had recently declined. Similar observations were made in 1831 by Mitchell (1838), who remarked that “the population of the Darling seemed to have been much reduced by smallpox, or some cutaneous disease which must have been very virulent.” The loss of regional populations due to the spread of disease has been estimated to be on the order of ninety percent (Butlin 1983).

The activities of Aboriginal groups were often recorded during these earliest phases of exploration, including notes on their social and economic organisation (e.g. Sturt 1833; Mitchell 1838; Eyre 1845; Beveridge 1883). Population densities observed by early European explorers varied widely, with some large gatherings (>120 individuals) contrasted against long stretches of apparently empty country (Sturt 1833; Mitchell 1838). Most noted that riverine resources were a regular part of the diet of groups living close to the river (Lawrence 1967) although vegetable foods were also important, especially in areas away from the river (Allen 1972). More detailed reviews of these sources can be found in Lawrence (1969), Allen (1972), and Keen (2004).

Pastoralism followed these expeditions, and accounts of early settlers begin to appear around 1850 (Hardy 1969; Allison 2003). Aboriginal groups occupying areas adjacent to the river were the first to be displaced by incoming settlements, and the establishment of river boats along the Darling simultaneously facilitated expansion of sheep farming and disrupted indigenous fish weirs (Heritage Office and Department of Urban Affairs and Planning 1996). Initial conflicts between Aboriginal and settler groups ultimately reinforced the marginalisation of Aboriginal lifeways in the region, while employment of Aboriginal people on large stations became commonplace during the late 19th century (Beckett 1958; Hardy 1976). Away from the river, mining became a primary industry, attracting large numbers of settlers to newly created settlements like White Cliffs, Broken Hill, and Milparinka (Eklund 2012).

Intense droughts in the late 19th and early 20th centuries devastated an oversized pastoral economy, with impacts most acutely felt in areas distant from the Darling River.
Low-lying vegetation had been removed by grazing pastoral stock and introduced pests across much of the region, while trees were removed for fencing and other industrial uses, leading to widespread erosion (Fanning 1999). Aboriginal populations, then largely dependent on pastoralism as well, declined further during this period, and remaining groups coalesced around settlements like Tibooburra, Milparkina, Wilcannia, and Menindee (Beckett 1958). Over time, pastoral reliance on local rainfall and fresh flows from upstream was eased by the drilling of bores around the countryside (White 1984), but stocking rates never again reached levels comparable with those in the 19th century (Roshier and Barchia 1993; Mabbutt 1973). Mining began to decline in the middle of the 20th century as mineral deposits became less productive, leading to the depopulation of many mining towns (Eklund 2012; although the city of Broken Hill has remained something of an exception, see Coulson 2012). In recent years, the economy of western NSW has waned as the primary industries of mining and pastoralism have become less sustainable, and populations in the region have been in steady decline since the 1970s (ABC News 2011,2012).

Several themes from this admittedly brief review of recorded history are relevant to studying the archaeological record in western NSW. First, the decline of Aboriginal populations and disruption of traditional lifeways during the 18th and 19th centuries almost certainly affected visible patterning in archaeological remains in the region. But it is also important to consider that ethnohistorical evidence, which has been used in the construction of models, is largely built upon observations occurring during this time. The demographic changes associated with the epidemics of this period, and the social and technological changes associated with European contact, would have almost certainly affected the organisation of activities recorded by European explorers and early settlers (Hiscock 2008:12). Finally, geomorphic change resulting from pastoral activities had a significant impact on the present condition of landsurfaces in the region, and will affect the visibility and overall condition of present archaeological deposits in both surface and subsurface contexts (Fanning 1999).
2.2 History of prehistoric archaeology in western NSW

In western NSW, as in most of Australia, archaeological studies in the early to mid-20th century consisted primarily of descriptive assessments of local material culture (e.g. Black 1949; Dow 1938) and the development regional cultural sequences (e.g. McCarthy 1958; Tindale 1957; although discussions of megafaunal extinctions also featured, see Tedford 1954). These studies often characterised changes to material culture as the result of diffusing ideas or population replacements. An early investigation of lakeshore deposits at Lake Menindee by Tindale (1955), for example, uncovered archaeological materials eroding from the lake shore which were grouped into successive occupations based on prevailing culture historical frameworks of the day. The absence of a transition from one culture (Mudukian) to another (Murundian) at Lake Menindee was explained as resulting from the isolation of the locale from centres of dispersal (Tindale 1955:293). While some patterns identified in these early studies, such as the late proliferation of small-backed artefacts, have been retained and continue to feature in the interpretation of archaeology in western NSW and beyond (e.g. Hiscock 1994, 2002; Veth et al. 2011), the comparative typologies used to support these narratives have gradually been replaced with more technologically-oriented artefact groupings (e.g. Mulvaney 1961, 1966; Gould 1969; Bowler et al. 1970; White 1977; Holdaway and Stern 2004; papers in Clarkson and Lamb 2005), and ideas about their associations and transitions have expanded beyond processes of diffusion and migration (e.g. Hiscock 1994; Veth et al. 2011; cf. Bowdler and O’Connor 1991; Flood 1995).

Most of the archaeological work conducted in western NSW since the 1960s has concentrated around three general areas: Willandra Lakes, Menindee Lakes, and the northwest corner of the state (Fig 2.4). In some respects, each of these studies represents a successive treatment of issues identified in previous studies. Research in these areas will be reviewed in turn, followed by a discussion of this region in the wider context of Australian desert archaeology.
Figure 2.4 Map of western New South Wales. Areas discussed below are indicated with triangles.
2.2.1 Willandra Lakes

The Willandra Lakes, located south of the river in the central part of the Murray Darling Depression bioregion, are a set of dry lakes currently disconnected from any major drainage, but once connected via a creek of the same name to the southern Lachlan River. Surveys in the Willandra Lakes area beginning in the 1960s provided some of the first evidence of Pleistocene occupation in western NSW (Bowler et al. 1970; Barbetti and Allen 1972). An eroding lunette on the leeward side of Lake Mungo exposed a series of distinct stratigraphic units that formed under different lake conditions: Golgol (basal layer, >100 kya), Lower Mungo (lake full to fluctuating, 55-40 kya), Upper Mungo (lake fluctuating to full, 40-35 kya), Arumpo (lake fluctuating to full, 35-20), Zanci (lake fluctuating to dry, 22-19 kya), and Mulurulu (lake dry, 19-17.5) (Bowler 1998; Stern 2014). Archaeological materials were encountered in all layers from the Lower Mungo onwards. In the Lower Mungo unit, a human burial consistent with cremation was recovered which at the time was estimated to be 30,000 years old (Bowler et al. 1970). These dates have been periodically revisited and revised (e.g. Gillespie 1998; Thorne et al. 1999; Bowler et al. 2003), and it is now clear that the skeletal remains in the Lower Mungo unit were deposited more than 40,000 years ago, making them both the oldest human remains in Australia and the oldest evidence for cremation in the world.

Other materials were also recovered from the Mungo Unit. Over two hundred stone artefacts were recorded; while some artefacts were found in situ, the majority (87%) were located atop eroded surface deposits nearby. Carbonate patination on surface artefacts suggested that they had originated from the carbonate-indurated soils of the Mungo unit, leading to the interpretation that they belonged to the same assemblage (Bowler et al. 1970:48). Most of the artefacts were either worked cores or flakes, with horsehoof cores and steep-edged scrapers being the most recurrent forms. This finding was consistent with other Pleistocene aged sites of the era (e.g. Mulvaney 1966). Charcoal-rich patches within the Mungo sediments were identified as hearths, and these contained some burned faunal remains. Spatial associations between the distributions of stone artefacts, hearths, and human remains were used to suggest that they were associated with the same occupation episode (Bowler et al. 1970:48).
A thorough review of ethnohistorical observations of Bagundji (Paakyanti) lifeways was conducted by Allen (1972) in order to develop a model of economic activity which could then be used to assess the evidence for prehistoric occupation in the region. This work portrayed groups inhabiting the region as mobile foragers exploiting seasonally available resources, positing that resources provided by the trunk rivers would have been the most desirable resource base, but that these resources were subject to fluctuations in rainfall at the rivers’ headwaters. Allen (1972) argued that the Willandra Lakes would have provided a similarly desirable resource base when full, but the onset of arid conditions during the late Pleistocene would have shifted economic focus away from these areas and back toward the rivers. Grasses and other cereals growing in the rangelands away from the main watercourses were observed to be important staples during lean times, leading Allen (1972, 1974) to surmise that late Pleistocene aridity may have prompted the development of seed-grinding technology to supplement dwindling riverine and lacustrine resources. This latter claim was evidenced through the association of grindstones showing carbonate patination with a cremation burial at Tandou Creek dating over 12,000 years old. Evidence for grindstones from the older deposits at Mungo, meanwhile, was conspicuously absent (Allen 1972), and it was argued that a pattern of movement between riverine and rangeland economies is evident in the archaeological record of the region from 15,000 years ago onward.

Allen (1972) also noted that surface collections of artefacts at the Willandra Lakes featured implements like those found in the eroding Pleistocene-aged Mungo deposit, but combined with artefacts such as backed blades that are associated elsewhere with later Holocene occupations. This provided motivation to seek out stratified deposits that could be used to establish chronological relationships between artefact forms, which could then be applied to lagged surface deposits to establish the duration of archaeological accumulations situated on them. Excavations at Burkes Cave in the Scropes Range south of the city of Broken Hill provided a stratified deposit, but one which only accumulated during the last 2000 years, making it insufficient for the task of assessing the deflated surface deposits in Willandra. However, from the excavation it was concluded that groups inhabiting Burkes Cave used the site as a semi-permanent base camp, but may have occasionally abandoned the area to access river resources during flood periods (Allen 1972:218). Similarities in artefact forms from the earliest deposits at Willandra to the more recent deposits at Burkes Cave were
used to suggest that the settlement pattern of western NSW groups had seen little change since the Pleistocene (Allen 1972), a conclusion similar to that later drawn by Gould (1977; 1980) from work in the Western and Central Deserts.

The original interpretations of Mungo and Willandra have been revisited over the years as more data has become available. Re-analysis of the dates of the Mungo burials have pushed back estimates by nearly 10,000 years, while the date of the lowest artefacts may be between 45,000 and 50,000 years old (Shawcross 1998; Bowler et al. 2003). Smith (1985) re-examined the evidence for Pleistocene seed grinding, concluding from an assessment of use-wear on grindstones that specialised grass seed grinding was a Holocene development associated with demographic and social reorganisation, and that earlier grindstones were amorphous, associated with a more generalised and opportunistic use of grinding technology. This interpretation was bolstered by findings at a variety of southern Darling locations (Balme 1991; discussed in the following section), which found that specialised millstones, thought to be used in processing seeds, were limited to Holocene deposits. Allen (1990, 1998) concurred with this, but cautioned that functional differences in grindstone technology would be more clearly demonstrated through the analysis of residues (per Gorecki et al. 1997). This evidence has been re-evaluated once again in light of recent excavations (Fullagar et al. 2015a), showing residues consistent with seed grinding in the late Pleistocene and leading to further debate over its role in the Pleistocene economy (Smith 2015; Fullagar et al. 2015b).

Since the time of the original work at Mungo began, the Willandra Lakes region has become one of most well-known archaeological sites in Australia and recognised internationally for its heritage value (Stern 2014). Work in the Willandra area continues up to the present, with Australian archaeologists collaborating with international teams to further assess the geomorphic processes contributing to the preservation of archaeological remains in other parts of the lake system (e.g. Fitzsimmons et al. 2014). The recent discovery of Pleistocene footprints at Lake Garnpung have been used to develop more event-oriented reconstructions of Pleistocene lifeways during the final drying-out phase in Willandra (Webb et al. 2006; Webb 2007; Westaway et al. 2013). Others have recently challenged the idea that the lake became less attractive during drying periods; for example, evidence from fish otoliths suggest that the drying of the lake may have made fish easier to catch, attracting
human groups rather than repelling them (Long et al. 2014). It has also been argued that, rather than lake resources representing a primary target for prehistoric foragers, it may instead represent a stable supplement to a terrestrial-based diet derived over a wider landscape (Stern 2014). These studies reflect the richness of the archaeological landscape present at Willandra, and illustrate that issues concerning the formation of surface deposits and their interpretation have persisted since their original investigation (e.g. Allen 1990; Webb 1994; Allen and Holdaway 2009; Stern et al. 2013; Stern 2015).

2.2.2 Menindee Lakes

The Menindee Lakes, northwest of Willandra along the Darling River, are a set of overflow lakes connected to the Darling River by a set of anabranch creeks. In the mid-20th century, the lakes were connected directly to the Darling to store water for agricultural use in surrounding areas, and the bed of Lake Tandou was converted into large-scale wheat and cotton cropping in the 1970s. Initial surveys such as those by Tindale (1955, 1964) and Tedford (1954, 1967) associated the lakes with Pleistocene human occupation through association with extinct megafaunal remains. A survey of Tandou Creek and the lunette near Lake Tandou was part of Allen’s (1972) thesis, revealing terminal Pleistocene-aged deposits which were associated with grindstones.

The lakes, along with some of the surrounding area (Teryawynia Creek, Talyawalka Creek and Lakes, and Anabranch Lakes), were surveyed in the late 1970s and early 1980s by teams out of the University of Sydney and the Australian National University, coming together as part of a larger regional survey known as the Darling Surveys (Balme and Hope 1990; papers in Hope 1981). Hope and colleagues (1983) initially aimed the project at resolving the stratigraphy and chronology of the lunette at Lake Tandou in order to help provide a local stratigraphic sequence before expanding to more regional surveys. They identified five distinctive stratigraphic units: Buntigoola, Kinchega, Packer, Tandou, and Bootingee. The most recent of these, the Bootingee, was initially dated to between 27,000 and 15,000 years ago, and was associated with extinct megafauna deposits such as Diprotodon and Procoptodon (Hope et al. 1983). More recently, the evidence for megafaunal remains in association with human activity at Lake Menindee has been reassessed using
multiple chronometric proxies, raising questions about the validity of the association but pushing back the date of initial occupation 44,000 years before present (Cupper and Duncan 2006).

Emphasis on the faunal record was a feature of these studies, and it was argued to provide better controls on chronology than lithic scatters in a geomorphologically dynamic environment like western NSW. A review of radiometric dates from the region suggested a continuous presence through the arid periods of the late Pleistocene and early Holocene, a different signature to that identified at the Willandra Lakes. A review of radiometric dates found that aquatic resources continued to be exploited despite increasing aridity in the region during the late Pleistocene (Balme and Hope 1990), suggesting a shift away from the drying Willandra Lakes toward stable lacustrine environments in the Lower Darling and Anabranch (Hope 1993).

Balme (1991) re-evaluated Allen’s (1972, 1974) work on seed-grinding, finding that carbonate encrustation is not a definitive indicator of Pleistocene age as had previously been suspected, and contending that the limited association of grindstones in Pleistocene-aged surface assemblages in western NSW may in part be the product of stratigraphic deflation. Of those grindstones that could be of Pleistocene age, none were found to exhibit morphological characteristics specific to seed grinding; on the contrary, she found that seed-grinding technology is firmly associated with Holocene-aged sites, particularly those around the more well-watered lakes to the west (Balme 1991). It was therefore contended that there was not sufficient evidence to associate the advent of seed grinding with the decline of the Willandra Lakes, an argument that concurred with Allen’s (1990) coincidental assessment that the data used to generate the original formulation was inadequate.

Further investigations of fishing and mollusc-gathering practices in the Darling catchment found that, despite the onset of more arid conditions during the late Pleistocene and the drying of the Willandra Lakes, the main Darling channel and more proximate lakes remained active (Balme 1995). The mechanisms for catching fish appear to have undergone little change since the Pleistocene; however larger midden deposits with a wider range of species appear in the late Holocene, suggesting larger populations or longer habitation periods during this period. Coupling these findings to the argument that the onset of arid conditions was not a likely cause for the development of seed grinding in the Lower Darling,
and evidence for continuous occupation at locations around the river (Balme and Hope 1990), invited the notion that demographic or social change may have been the driver of Holocene economic shifts (Balme 1991:8, 1995:18). The general picture painted by these studies is one of greater diet breadth and increasing complexity in archaeological deposits from the mid Holocene, potentially explained as the outcome of greater investment in local resource exploitation to support larger social gatherings or longer occupations.

Near Lake Cawndilla in Kinchega National Park, Webb (1994) sought to evaluate the integrity of the surface record itself at a variety of scales, emphasising areas away from watercourses to establish whether differences in preservation might account for the appearance of a settlement pattern oriented around water availability (e.g. Allen 1972; Balme 1991; Veth 1993). Webb (1994) employed a ‘non-site’ approach to survey (sensu Thomas 1975), which treats the archaeological record as a more-or-less continuous distribution of artefacts across a surface, and various landforms in the park were surveyed in order to assess the formation of surface deposits in a range of geomorphic settings. An experimental component of this research involved replicating surface deposits of knapped stone objects in a semi-controlled setting to evaluate the movement of lithic artefacts, as well as repeated observations of known archaeological deposits near the study area (Webb 1994:86-98). The experimental study, while limited in scope and not repeated, indicated that the visibility of surface artefacts was highly variable over the short observation period, and the composition of assemblages was difficult to predict based on raw material or artefact morphology.

Among the other findings of this study are (Webb 1994:191-195):

- Landforms were of little use for predicting the function of assemblages, but were essential for considering the role of geomorphic change on the character of an assemblage.
- Lithic densities are not appropriate for evaluating patterns of land-use, as they are influenced significantly by the depositional context in which they are found.
- Based on a survey extending into adjacent sand plains, greater artefact accumulations around watercourses do not appear to be the result of sampling bias, but instead may reflect greater intensity of occupation in those areas.
However, artefacts were present in all areas surveyed, indicating that activities took place away from watercourses as well.

- Archaeological deposits at Lake Cawndilla feature cobbles of silcrete and quartzite which were likely imported from distant sources, and may have served not only as functional objects but also as caches of raw material in an area otherwise bereft of naturally-occurring stone (see also Webb 1993).
- Non-site recording methods were useful but ultimately very time consuming, preventing the recording of area samples adequate for answering some questions, but allowed for the recording of places where artefacts were not found, providing a better sense of the overall distributions of artefacts situated within the study area.

These studies, particularly those originating from the Darling Surveys project, were aimed at revising ideas developed from the earlier Willandra Lakes studies and working to establish a broader picture of the past economy. Most importantly, these demonstrated that ecological and occupational patterns observed at Willandra were not universal across the region (Balme and Hope 1990; Hope 1993). The greater stability viewed at Menindee presented a counterargument to an environmentally-mediated shift to seed processing (Balme 1991, 1995). At the same time, these studies confirmed some of the difficulties associated with the formation of surface deposits that had been identified previously. While Balme (1991) demonstrated that grindstones encountered from surface assemblages at the Menindee Lakes were likely of Holocene origins, her interpretation of these as dating to the earlier part of the Holocene has been questioned based on the “palimpsest” nature of surface deposits (Smith 2013:200). The study at Lake Cawndilla by Webb (1994) indicated highly dynamic surfaces and a strong connection between geomorphic change and the character of surface deposits. These issues would be explored in more detail over the following decade.

2.2.3  Northwest Corner

Until the 1990s, the bulk of archaeological research conducted in western NSW had taken place south of the Darling River (for exceptions, see Binns and McBryde 1972; Dury
and Langford-Smith 1970; McCarthy and Macintosh 1962; Riddell 1928). Changes in heritage management legislation, notably the NSW National Parks and Wildlife Act of 1974\(^5\), the NSW Heritage Act of 1977\(^6\), and the NSW Environmental Planning and Assessment Act of 1979\(^7\), brought more archaeological investigations to this part of the region (Bryant 2013), and greater regulatory interest in the archaeology of the northwest corner has bolstered academic interest in the region as well.

At three locations on a Northwest-Southeast transect across western NSW (Tibooburra, Cobar, and Boorowa, respectively), Witter (1992) worked to develop a regional-scale predictive model for surface surveys based on an appraisal of technological variability in different environments. Witter (1992:252-256) differentiated between two different technological traditions, microblade and non-microblade, which he argued showed distributions reflecting different adaptive strategies, but that these differences in distributions were consistent across the three different study areas. Analysis of lithic scatters also indicated a trend from a low-reduction, flake-oriented technological scheme in the west to a high-reduction, core-oriented scheme in the east, which was argued to be primarily a function of raw material availability (Witter 1992:258-264). The findings were further developed into a description of the variability in archaeology throughout the region (Witter 2004), and outcomes were used to make recommendations for the development of a research framework for heritage management applications.

The Western NSW Archaeological Program (WNSWAP), a joint research venture originally between La Trobe University and NSW Parks, and later between Macquarie University in Sydney and the University of Auckland in New Zealand, was initiated in 1995 to investigate geomorphic change and human occupation in the western Darling rangelands (Holdaway and Fanning 2014). This was developed in part out of earlier research on the geomorphology of region’s rangelands, which indicated that substantial changes to landsurfaces had occurred over time as a result of large scale sediment movement following European settlement (Fanning 1994). Surface surveys have been carried out at a number of locations throughout western NSW in order to gain a regional perspective on occupation and


surface deposit formation; these include Sturt National Park (Fanning and Holdaway 2002a; Holdaway, Shiner, and Fanning 2004; Holdaway et al. 1998), Fowlers Gap Arid Zone Research Station (Holdaway and Fanning 2003, 2014), Poolamacca Station (Rhodes et al. 2009), Paroo-Darling National Park (Holdaway, et al. 2012; Holdaway et al. 2006), Burkes Cave (Shiner et al. 2007), and the Pine Point and Langwell stations (Shiner 2004, 2009).

Among the goals of the WNSWAP project was the establishment of more efficient methods of recording archaeological data from spatially-dispersed surface assemblages. This was accomplished by combining advances in geospatial data management with portable computing (Holdaway et al. 1998; Gnaden and Holdaway 2000). At Stud Creek in Sturt National Park, the locations of artefacts were recorded in three-dimensions through the use of a digital theodolite, and these locations were then associated in a database with morphological and technological attributes recorded in the field. These measurements were then analysed and used to assess the formation of surface assemblages. For example, attribute data from Stud Creek was used to establish a relationship between artefact size and likelihood of lateral movement due to slopewash (Fanning and Holdaway 2001a), showing that clasts greater than 20 mm in maximum dimension were unlikely to have moved substantially unless flow was concentrated in streams or rills.

At the same time, the geomorphology and geochronology of the Stud Creek area was evaluated. A trench dug perpendicularly from Stud Creek revealed a discontinuous sedimentary record, indicating alternating periods of deposition and erosion (Fanning 1999; Fanning and Holdaway 2001b). A combination of charcoal and optically-stimulated luminescence determinations from these stratigraphic sections indicated periods of either sedimentary hiatus or (more likely) sediment loss occurred at various times throughout the history of the area. This places temporal limits on the ages of surface deposits, but also constrains what may be preserved beneath the soil as well (Fanning and Holdaway 2001b).

The methods developed at Sturt National Park were later applied at the Fowler’s Gap location north of Broken Hill. Not unlike the studies by Witter (1992) and Webb (1994), this approach sought to evaluate whether predictable statements about archaeological distributions, particularly regarding the age distributions and qualities of surface scatters, could be generated based on the types of landforms in which they were found (Holdaway and Fanning 2014:10). However, this study can be distinguished from earlier efforts by its
emphasis on the analysis of non-formal artefact types, meaning unmodified flakes and cores, and by developing chronologies for surface deposits.

One key finding of this study was that spatial proximity is not a reliable indicator of temporal proximity; that is, objects that are near to each other may not relate to the same time periods. This was made clear in the case of the FC (Fowlers Creek) location (Fig 2.5), a stony alluvial terrace overlooking a creek where one hearth\(^8\) (FC22) returned a calibrated radiocarbon determination of 6018 ± 181 cal. BP, while all other hearths at the location dated to within the last 4000 years (Holdaway et al. 2005). Hearths within 10 – 20 metres of each other on the surface were found to be upwards of 1600 years apart (Holdaway and Fanning 2014:91). The age distributions of hearths on a given surface, then, was illustrated not to be a signature of a common occupation, but rather a function of the age of the surfaces into which

\(^8\) Uncannily, this oldest hearth was later destroyed when the sediments into which it was built eroded in a later flood event (Fanning et al. 2007:277).
they were constructed. Similar patterning was also found elsewhere at Fowler’s Gap, suggesting that, if near hearths were not temporally associated, the same might be said for stone artefact scatters as well.

The FC location demonstrated another pattern which has since been identified at a number of other western NSW locations: the temporal clustering of hearth ages (Holdaway et al. 2010). From a sample of fourteen heat-retainer hearths FC, eight were dated to a period around 4000 and 3000 years ago (Holdaway et al. 2005), while the others were found to be separated by periods upwards of 1000 years. Given the finding that spatially proximate hearths might be distant to each other in time, the authors argued that it is unlikely that erosion might be targeting hearths of particular ages (Holdaway et al. 2010; Holdaway and Fanning 2014:91). This led to the interpretation that periods of occupation at Fowlers Gap and other western NSW locations may have been interspersed by periods of abandonment that could have lasted centuries (Holdaway et al. 2004; Holdaway and Fanning 2014:176).

While the original objective of determining a predictive relationship between landsystems and types of archaeological deposits preserved in them was largely unrealised, the Fowlers Gap research provided insight into the formation dynamics which contributed to the present condition of surface deposits. To evaluate this model, WNSWAP archaeologists intensively surveyed a single catchment at Rutherfords Creek, an ephemeral stream emptying into ephemeral Peery Lake in Paroo-Darling National Park. Approximately 13% of the creek valley has exposed saline subsoils, known locally as “scalds”, which form when wind or water action removes less compacted topsoils (Figs. 2.5 and 2.6), and a 4.5% sample of these was used as survey units (Holdaway et al. 2012). Thousands of stone artefacts, primarily cores and unmodified flakes, were recorded on these surfaces, along with hundreds of heat-retainer hearths.

The Rutherfords Creek surveys helped to confirm and further advance a number of the ideas developed at Fowlers Gap. Among these is the notion that geomorphological change is a major determining factor in the constitution of surface archaeological deposits. Chronologies obtained from surfaces, by means of OSL dating of sediments underlying deposits, demonstrated that the age of a given surface will determine the maximum age of material visible on them (Fanning et al. 2009a); in essence, this is equivalent to Stern’s (1994) “minimum stratigraphic unit”. These may vary over very short distances, as
demonstrated at the FC location at Fowlers Gap, presenting as “a mosaic of differently aged surfaces many of which lie adjacent to one another” (Fanning et al. 2007:284). This was shown at Rutherford’s Creek by clusters of adjacent hearths showing high degrees of variance in age ranges (Holdaway et al. 2008; Fanning et al. 2009). The episodic erosion and deposition of sediments which occurs in the region influences the visibility and preservation of archaeological materials on the surface.

This research has also been used to argue that mid-to-late Holocene landscape use in western NSW is characterised by high levels of mobility, shown through analyses of surface scatters of stone artefacts. Douglass and colleagues (2008; see also Douglass 2010), for example, showed that lithic scatters at western NSW study areas, on average, have a low ratio of cortical-to-non-cortical stone. It has been argued that this is evidence for the curation of large (and thus disproportionately cortical) flakes which were lightweight and had a high degree of utility in terms of cutting edge, transported out of Rutherford’s Creek as part of a
“gearing up” strategy (Douglass 2010:251; *sensu* Binford and O’Connell 1984; Kuhn 1992), without replacement by like materials from elsewhere. The evidence for movement was further corroborated by a study using isolating colour analysis at the Rutherfords Creek study area (Barker 2009), which showed that much of the material in surveyed exposures is of local origin, but the presence of rare, imported “orphan” artefacts within lithic scatters could occasionally be identified, indicating limited movement of stone into the catchment.

Finally, WNSWAP research has portrayed study areas as being occupied intermittently over time by relatively small groups of people. Hearth ages at Rutherfords Creek, like those at Fowlers Gap and Stud Creek, are often clustered together in time, suggesting that hearth-building and other activities were likewise clustered, interspersed with decades or centuries of apparent abandonment (Holdaway et al. 2002b; Holdaway et al. 2005). These clusters show positive correlation with sea-surface temperature anomalies associated with monsoon activity; inversely, gaps show correlation with deposits of wind-driven Australian dust in New Zealand peat bogs (Holdaway et al. 2010; Marx et al. 2009). This has been used as further evidence of late Holocene mobility, as well as periodic abandonment coinciding with declining resource availability during periods of increased aridity. The findings at the WNSWAP study areas have been described as more consistent with “visitation” behaviour than regular occupation (Holdaway and Fanning 2014: 170).

### 2.3 Wider arid zone context

The western NSW region is often cited as a regional case study for the archaeology of arid and/or semi-arid Australia (e.g. Flood 1995; Lourandos 1997; Mulvaney and Kamminga 1999; Hiscock 2008). Comparisons have been drawn between the region and other arid zone locations, such as the Western or Central Deserts, to support or contrast with various interpretations of the Australian desert archaeological record (Gould 1980; Hiscock 2008; Lourandos 1997; Smith 2013). It is useful, then, to contextualise the archaeological history outlined in the previous sections in terms of the interpretive frameworks developed in the surrounding regions and wider arid zone.

Archaeological research in the arid zone has been restricted when compared to coastal areas in Australia. The logistical difficulties of operating in remote areas away from major
settlements have historically inhibited research in the Australian desert (e.g. Thomson 1975; Gould 1980). Until the 1980s, prehistoric narratives of Australia’s deserts were largely built upon Gould and colleagues’ (1977) excavations at Puntutjarpa and Intirtekwerle (James Range East), and the aforementioned studies at Willandra (e.g. Bowler et al. 1970; Allen 1972; Barbetti and Allen 1972). These studies, heavily supplemented by ethnographic and ethnohistorical research concerning modern desert Aboriginal groups, converged on a model of cultural continuity from the Pleistocene onward, in which people remained highly mobile, opportunistic hunter-gatherers in a social system linked by long-distance ceremonial exchange. This was demonstrated by similarities in artefact forms and resource use through time (Allen 1972, 1974; Gould 1977). Gould (1980:61) in particular argued that the unpredictability of the Australian desert habitat demanded a conservative “desert adaptation”, and that deviation therefrom might have disastrous consequences for desert-dwelling people.

It is recognised today that the desert regions of Australia, occupying around two-thirds of the continent, represent a diversity of arid environments which would have been differentially habitable over the course of human prehistory in Australia (Morton et al. 2011; Smith 2013). Researchers working in the Carnavon Ranges in the Gibson Desert, for example, identified a long cultural hiatus between 23,000 years ago and 4700 years ago (O’Connor et al. 1998). A similar pattern has observed at several other arid zone locations (e.g. Thorley 1998), suggesting that parts of the deserts were abandoned in the late Pleistocene. Yet other locations exhibited evidence of continuous occupation from the Pleistocene onward (e.g. Lampert and Hughes 1987; Smith 1989), suggesting that people may not have abandoned the desert completely during the Last Glacial Maximum. This pattern showed correspondence with ethnographic observations of Martu-speaking groups in the Western Desert demonstrating shifts in aggregation and occupation intensity depending on the prevalence and persistence of water (e.g. Veth 1987; Tonkinson 1991).

Veth (1989, 1993, 2005) developed these ideas into a biogeographic model postulating that the permanence of water attracted greater degrees of sedentism or greater frequency of occupation. Places with permanent water were likely locations for more permanent base camps and offered opportunities for large gatherings, while places with ephemeral surface water were more likely to be occupied intermittently or used for functionally-specific extraction sites (Veth 1993:79-87). This model imagines the late
Pleistocene as a period of dramatic changes in human organisation and land use strategies, as human populations contracted around areas of higher relief which tended to be better-watered and offer a greater diversity of resources, while lower, arid plains presented barriers to occupation and movement (Veth 2005). The early Holocene, with its ameliorating climate, saw groups slowly re-inhabiting lowland areas and re-acclimatising themselves to the more marginal plains and dunefields, eventually increasing the intensity of occupation and social interactions during the late Holocene (Veth 1993; Thorley 1998; Veth 2005).

Holocene behavioural re-adjustment has been evidenced not only through features in lowland areas which can be dated to this period, but also through changes in material culture. The aforementioned proliferation of small, backed artefacts and points has been used variably. While some of these backed artefacts appear in earlier assemblages (e.g. Hiscock and Veth 1991), they become prominent only from the middle of the Holocene onward (Hiscock 1994, 2002; Clarkson 2007). This pattern, along with the abrupt appearance of the tula adze after 4000 years ago, has been explained as a response risk, in which resource availability became less predictable and thus prompted the invention of a versatile, easily maintained and long-lasting toolkit that could accompany highly mobile foragers (Hiscock 1994). Some have associated this technological shift with greater residential mobility along the lines of the “desert culture” adaptation (e.g. Veth et al. 2011), while others suggest that it may reflect risk associated with greater logistical mobility and more sedentary occupations (e.g. Smith 2013).

Work in the Central Australian deserts has produced a wealth of archaeological information contrasting Pleistocene and Holocene records (Smith 1986, 1987, 1989, 1993, 2013; Smith and Ross 2008). Increases in the number and diversity of lithic artefacts during the late Holocene at Purritjarra and other sites have been used to argue for greater degrees of sedentism, along with higher frequencies of grindstones indicative of grass-seed processing (Smith 1986; Smith and Ross 2008). This latter pattern, when considered in association with the onset of drier, less predictable ENSO conditions during the late Holocene, is suggested to indicate greater investment in marginal resources to support larger aggregations of people (Smith 2013), a behaviour also indicated by increased use of marginal areas away from lakes and channels (Veth 2005). Increases in the sizes and numbers of visible rock art sites have
also suggested larger groups, while diversification of rock art forms has been used to suggest greater degrees of social fragmentation and territoriality (Smith and Ross 2008).

These patterns are used as evidence of late Holocene socioeconomic intensification in the desert (*sensu* Lourandos 1983; Lourandos and Ross 1994, drawing parallels to ‘broad spectrum’ transitions identified in other parts of the world (Smith 2013). Human habitation during this period is viewed in terms of greater investment in local resource extraction, and greater degrees of social complexity as groups sought to manage resources for expanding population in an increasingly marginal environment. This model is corroborated by continental-scale studies of radiocarbon determinations, which show greater frequencies during the mid to late Holocene (Smith et al. 2008). Williams (2012), after applying a taphonomic correction to a broad suite of dates from the arid zone, found that archaeological signatures are consistent with exponential population growth during the late Holocene. Simulations by Johnson and Brook (2011), compared with a separate set of radiometric and luminescence dates from arid and non-arid contexts, likewise found that the increasing frequency of radiocarbon dates toward the present is most parsimonious with continent-wide population growth. These studies have been used as further evidence of late Holocene population growth and economic intensification in Australia’s deserts.

### 2.4 Synthesis

Combinations of erosion, restricted surface vegetation, and slow encroachment of modern infrastructure development in western NSW have left archaeologists with an “unparalleled view of the distribution of archaeological materials” (Pardoe 2003:42). This high visibility means that surface deposits can be surveyed and sampled over large areas, on an order which landscape-scale interpretations are often derived and, as Webb (1994:192) points out, are likely to display patterning driven by larger scale processes rather than discrete events (see also Bailey 1983, Lucas 2008). This rich surface record has encouraged archaeologists working in the region to orient research around patterns in the spatial organisation of human activity (e.g. Allen 1972, Douglass 2010; Fanning et al. 2009; Holdaway and Fanning 2014; papers in Hope 1980; Webb 1994; Witter 1992). At the same time, the difficulties of inferring past human behaviour from surface deposits have become
an increasingly prominent feature of archaeological research in the region (Allen 1990; Allen et al. 2008; Balme 1991; Balme and Hope 1990; Holdaway et al. 2004; Johnston and Clark 1998; Stern 2015). It is now well recognised that the geomorphic forces which make these deposits visible to archaeologists also contribute significantly to their present distribution (Fanning et al. 2009; Stern et al. 2013), and that these forces in the past as well as the present (Fanning et al. 2007).

Despite the identified challenges, archaeologists have used these surface records, supplemented with data from excavations and ethnohistorical sources, to develop behavioural models for human prehistory in the region. Western NSW presents as an environment of marked fluctuation in resource availability and geomorphic dynamics. Infrequent but high-intensity oscillations between periods of drought and flood have shaped the land and its available resources, and the relative frequencies of these shifts in aridity have been considered a primary motivator behind the behavioural patterns of past peoples in the region (e.g. Allen 1974; Balme 1995; Holdaway et al. 2010). Allen’s (1972, 1974) ethnoarchaeological study of Bagundji (Paakantyi) lifeways has provided a baseline against which nearly all subsequent analyses have been evaluated (e.g. Hope et al. 1982; Balme and Hope 1990; Balme 1991; Webb 1994; Holdaway and Fanning 2014). His original formulation of a consistent seasonal economy (Allen 1974), in particular its emphasis on the importance of seed-grinding during the late Pleistocene and socioeconomic continuity, contrasts with subsequent studies that propose a model of directional change during the middle to late Holocene (e.g. Balme 1991, 1995; Lourandos 1997). These models are borne in part out of an expansion of datasets beyond the initial archaeological studies of Australia’s deserts, which have brought to light variability in the prehistory of the region, but also reflect a reaction to portrayals of prehistoric Australians as unchanging (Hiscock 2008:4–8; Allen 2015). Others have questioned the empirical basis for claims of intensification in arid Australia, arguing that the geomorphological conditions that have come to shape the record in the region are not being accounted for in these narratives (e.g. Holdaway et al. 2008; Robins 2005; Stern 2015). Beyond the bounds of the region, archaeologists have been developing overarching ideas about human occupation of Australia’s deserts, and the data from western NSW has been variously incorporated into these narratives (e.g. Smith et al. 2008; Smith 2013; Veth 1993; Williams et al. 2015b).
Ideally, differences between narratives reflect different models through which archaeological patterning has been interpreted. In some cases, the patterns being used to argue for alternative models are different; for example, the case for greater mobility as a late Holocene risk aversion strategy is made in terms of changes in portable implements (e.g. Veth et al. 2011), while arguments for increased logistical mobility emphasise artefacts which are more difficult to carry or imply greater investment in local resources (e.g. Balme 1995:19; Smith 1986, 2013). In other instances, the same pattern may be interpreted in different ways. Increasing frequencies of radiometric determinations during the late Holocene have been viewed as evidence of population growth and/or greater occupation intensity (e.g. David and Lourandos 1997; Johnson and Brook 2011; Smith 2013; Smith et al. 2008), or alternatively a product of archaeological preservation (e.g. Holdaway et al. 2008; Marwick 2009; Robins 2005). The density of artefacts in surface deposits, or the diversity of artefacts in an assemblage, is commonly viewed as a product of occupational intensity or site function (e.g. Veth 2005; Williams 1998 cf. Clarkson 2008), yet surface assemblages throughout the region have been recognised as being palimpsests, time-averaged to varying degrees by sedimentary processes (e.g. Shiner 2004; Smith 2013:323; Webb 1994).

While differing interpretations are not problematic unto themselves, if it is an objective of archaeology to make authoritative statements about the past then resolving these differences and adjudicating between interpretations is fundamental to achieving that objective (Dunnell 1982). In some cases, limitations imposed by the data used in drawing inferences and building models prevent alternative interpretations from being successfully compared. It is sometimes argued that either the existing data is too degraded or disturbed to draw secure inferences (e.g. Gillespie and Brook 2006; O’Connell and Allen 2004), or that the amount or type of data collected is insufficient to make a secure inference (e.g. Gorecki et al. 1997; Smith 2015). Alternatively, it may be that the inferential models are imperfectly understood in terms of how they are expected to have generated the patterning (Dunnell 1992:102; Lucas 2012:87). The ways in which proposed formation processes present themselves outside of a given archaeological context (whether behavioural, geomorphic, or otherwise), in terms of the patterning of archaeological data, is rarely known or assessed (Ward and Larcombe 2003). When this is the case, then additional data or singlular findings are unlikely to be of much assistance in determining between explanatory models.
There is no doubt that if the intention of the archaeologist is to reconstruct past human behaviour in detail, then datasets obtained from archaeological deposits suffer limitations not only through the metamorphosis of archaeological materials through time (Bailey 2007), but also because the data available are only likely to reflect a limited suite of activities (Binford 1980; Pettitt 1997). But given the long history of research programmes in western NSW focused on large-scale interregional comparison, and the broad differences in these interpretive models (intensifying or not, residential or logistic, etc.), a lack of appropriate data is less concerning. It is argued here and in subsequent chapters that it is an emphasis on site contents and spatial associations, disconnected from explicit models of formation, that has prevented archaeologists working in western NSW from discerning between different interpretations of palimpsest deposits there, and that making considerable headway toward resolving these differences requires reorientation of these interpretations around formation.
3 FORMATION AND THE INTERPRETATION OF THE SURFACE ARCHAEOLOGICAL RECORD

Between 1966 and 1967, Richard Gould (1967, 1968, 1969, 1980) spent a three-month period with a group of Ngaatjatjara-speaking Aboriginal people in the southern Gibson Desert. During that time, the group moved their camp six times, spending no more than three weeks at a given location and covered a total distance of 185 kilometres (Gould 1980:64). At one of the campsites, Tikatika, he observed a range of behaviours with material consequences, including the construction of windbreak shelters and campfires, the manufacture and maintenance of stone, wood, and fibre implements, and the processing and consumption of foraged plants and animals, and many other activities that left no material trace. Five months following his ethnographic observations at Tikatika, after the group had moved on to stay at the regional mission station, Gould (1980:23) returned to re-survey the material remains. He noted that the organic and earthen components of the campsite were either decaying or in the process of being destroyed. However, stone artefacts were still present on the surface, and in fact, the number of them had multiplied by an average of eight times (Gould 1980:26-27). This was attributed not to an intermediate occupation, but to the geomorphology of the sandplains around the Warburton Ranges, where desiccated topsoils are easily eroded by wind and water action. In many places, those processes remove soil but leave larger, heavier objects, including stone artefacts, more or less in place horizontally, producing an amalgamated assemblage of artefacts discarded during multiple occupation events on a common surface. Gould (1980:27) lamented that “the apparently greater richness of the site in stone artifacts is in fact a sign of stratigraphic disturbance and mixing that renders the site almost useless for any later attempt to sort out its chronology or to discover former loci or most of the activities that produced this debris.”

This juxtaposition between richness and distortion is characteristic of past and present discussions of surface archaeological deposits. Methodological and theoretical developments developed over the past few decades have improved data collection in surface contexts and transformed notions of the value of these deposits. However, the perception of the surface deposits as irresolvably disturbed still lingers, hindering comparison between interpretations.
Some reasons for this are conceptual, such as the pursuit of explanations at an ethnographically-oriented temporal resolution or in terms of sequential, behaviourally-resonant narratives. Others are methodological, such as the inability of archaeologists to either observe archaeological deposit formation or experiment directly with many suspected formational processes, allowing for the perpetuation of a loosely-defined notion of equifinality. Together, these impede the use of formation as a means of discerning between interpretations of archaeological patterning, especially at spatiotemporal and organisational scales beyond direct observation. To overcome the conceptual barrier, theoretical concepts are borrowed from time perspectivism, framing the surface archaeological record as a generative phenomenon that is one of constrained set of possible outcomes, and patterning within in it is in terms of reversibility. The goal of studying such a record is to explain archaeological patterns in terms of summative generating processes rather than trying to filter the effects of some processes from others or to reconstruct material organisation at some moment in the past. Appropriate analogues for large-scale processes may be difficult to find in the real world, but abstract models are suggested as a suitable substitute.

3.1 The surface archaeological record

The surface archaeological record consists of archaeological deposits exposed on existing landsurfaces. This distinction is made in relation to subsurface deposits, which are covered (or sealed) by at least one layer of sediment. Surface archaeological deposits are typically associated with geomorphological conditions that limit the obscuring effects of sediment deposition. In places where soil formation is slow or infrequent, discarded archaeological objects may remain visible on the surface over extended periods of time (e.g. Close 1997; Olszewski et al. 2005) Alternatively, surfaces that have experienced erosion or that are actively eroding can also exhibit surface archaeology by exposing objects that were previously buried (e.g. Fanning et al 2007; see also Brown 1997). Other forces, such as freeze/thaw cycles, the drying and wetting of subsurface clays, or animal burrowing are also known to push buried objects to the surface (Wood and Johnson 1978), while human earth-moving activities may likewise bring artefacts to the surface.
The survey of surface deposits is viewed as useful for detecting stratified archaeological deposits, and is often considered among “the first steps to be taken in deciding where to dig” (Binford 1992:47). Systematic field walks, for example, are designed to identify concentrations of archaeological remains on the surface which are used as an indicator of subsurface deposits (Ammerman 1981; Drewett 1999:44). The concept of “plough zone” archaeology, or surveys of recently ploughed fields where shallow archaeological deposits might be turned up, is regularly used as a means of identifying sites (Roper 1976; Allen 1991:39). Sites, in a traditional sense, are considered to be loci of past human behaviour based either on the simple presence of archaeological artefacts or on their relative density, and have been a fundamental concept in archaeology during the last century (Dunnell 1992b).

Studies of the spatial organisation of activity in contemporary human societies sometimes contrasts with the concept of sites. Gould (1980), for example, reported that the Western Desert Aboriginal groups he observed dispersed the vast majority (>90%) of their artefacts over large areas away from camps. In an ethnoarchaeological study of Arandic-speaking groups in central Australia, O’Connell (1987:104) noted that, in order to obtain a reasonable approximation of place use, multiple large exposures on an order “at or beyond” the largest known at the time would need to be surveyed. Peterson (1971:246) similarly suggests that the patterning of archaeological artefacts in surface deposits or “open sites” is more likely to reflect the spatial organisation of Australian Aboriginal foragers than isolated excavations. Other studies of hunter-gatherer groups, especially in lower latitudes, report similarly high frequencies of movement (Yellen 1977; Hayden 1979; Kelly 1983). While the mobility of human groups has varied over time and space, these studies indicate that the scale of human activity is not necessarily well-represented in constrained settings.

As this kind of ethnographic knowledge was increasingly used to interpret archaeological phenomena in the 1970s, the surface record began to be considered in its own right as a source of information distinct from that obtained from subsurface deposits, and one in which defined sites were of limited relevance. Geographic approaches developed in the 1970s to evaluate site distributions (e.g. Thomas 1972; Hodder and Orton 1979) gave way to ‘off-site’ (Foley 1980, 1981), ‘non-site’ (Thomas 1975; Isaac and Harris 1980), ‘siteless’
(Dunnell and Dancey 1983) or ‘distributional’ (Ebert 1992, Wandsnider and Camilli 1992) approaches which eschewed archaeology’s site-oriented programme. More recently, these ideas have merged with the more general notion of landscape archaeology (David and Thomas 2008), developing parallel concepts such as “lithic landscapes” (e.g. Clarkson 2008; Barrientos et al. 2014; Foley and Lahr 2015). On the whole, these approaches share a view of the archaeological record as a more or less continuous distribution of discarded materials on or near the surface of the earth (Boismier 1991:14-15; Dunnell and Dancey 1983), and the intensity of place use and human activity is viewed in terms of the accumulation of materials in some locations relative to others (Binford 1982; Foley 1981). This has provided a foundation for archaeologists to interpret the surface record in terms of behaviour which is spatially disaggregated and variable (e.g. Binford 1980, 1982; Foley 1981; Wandsnider 1996; Shiner 2004; Foley and Lahr 2015).

The unique value of surface archaeological deposits lies primarily in their high visibility over large areas. Subsurface deposits impose logistical limits on the spatial scales of archaeological studies by the need to excavate. The high degrees of visibility in surface deposits afford archaeologists opportunities to examine the distributional properties of the archaeological record. This was summarised by Dunnell and Dancey (1983:270):

“There can be little doubt that surficial deposits retain considerable distributional information at least on a gross scale... It is our contention that the surficial distribution of artifacts constitutes an appropriate source of archaeological data independent of subsurface remains. As long as surface distributions contain patterned information that is analytically separable from post-depositional patterning, they are useful data.”

The idea that surface archaeological deposits can be used to make inferences about past human activity is predicated on the same idea used by archaeologists working in subsurface contexts, that patterning in archaeological objects can be correctly associated with processes that formed them. However, there are some qualifiers in the above assessment that are worth highlighting: first, the idea that surface distributions may contain patterns at a ‘gross scale’ (i.e. at a low temporal or spatial resolution); and second, that signals in patterning that indicate past human behavioural organisation must be separable from patterning derived from non-anthropogenic forces in order for surface archaeological finds to
be used effectively. These are common threads in discussions of surface archaeology, made in recognition of interpretive challenges viewed as inherent to (or at least accentuated in) the surface record (Ebert 1992). Two primary challenges that have been discussed are logistical constraints imposed by the large spatial extent of some surface archaeological assemblages and interpretive constraints imposed by a lack of integrity in surface deposits.

3.1.1 The spatial extent of the surface archaeological record

The distributions of objects that compose the surface archaeological record can be expansive. Depending on the mode and frequency of movement, archaeological materials may be dispersed over large areas or far removed from their points of origin (e.g. Webb 1993; McBryde 1997; Barker 2009; Tibbett 2002). At the Rutherfords Creek study area, for example, it has been estimated that over 480,000 artefacts may be present upon 1,675,982 m² of exposed surfaces (Fanning et al. 2009). These can also be of varying density. The average density of artefacts at Rutherfords Creek is 0.58 artefacts/m² (Bryant 2013:136), while densities upwards of six artefacts/m² have been encountered on exposures that range in area between a two square metres to two hectares. Surveys around Olympic Dam near Lake Eyre have turned up surface deposits with densities up to 100 artefacts/m², leading to estimates of surfaces assemblages ranging from hundreds of thousands to millions of artefacts (Hughes et al. 2011), estimates that are roughly in line with those found in other parts of the world where surface exposure is high (e.g. Foley and Lahr 2015).

Historically, recording archaeological data across large areas has been an expensive endeavour producing limited datasets (Foley 1981). This problem was discussed by O’Connell (1987:104, emphasis added), who surmised that:

“[p]laying greater attention to the recovery of very small objects while at the same time radically expanding the scale of exposure will definitely increase the cost of archaeological research. This can only be justified in cases where commensurate gains in information about past human behavior can reasonably be expected. To anticipate such gains, and to plan and conduct the archaeological research necessary to achieve them, archaeologists must have a better basis than currently available for predicting the patterns
likely to be present in site structure, the scales at which they will appear, and the information about past behavior they may convey.”

Methodological approaches over the past two decades that have significantly reduced both financial and temporal costs in the collection of data. Archaeological survey using remote sensing methods, electronic range finding, portable computing, and geographic information systems have helped to cut down on recording time and manage large-scale datasets (e.g. Wandsnider 1992; McPherron and Holdaway 1996; Galaty 2005; Wheatley 2011; Smith and Levy 2012; De Reu et al. 2013; Austin 2014). While the costs associated with excavation remain an impediment to studies of subsurface deposits, these technical advances have permitted archaeologists working in surface contexts to amass datasets from study areas many times larger than traditional, site-based archaeological investigations at a lower cost (e.g. Holdaway and Fanning 2008; Barrientos et al. 2014; Foley and Lahr 2015).

Overcoming the practical issues of recording data over large areas reduces the urgency for predictive models as a prerequisite to justify expenditures. This is potentially a very positive development, as interpretation of large scale phenomena can only stand to benefit from the identification of variability within large-scale patterning (Kelly 2015:17). But amassing data is not a replacement for the kind of theoretical understanding advocated in the passage above. This conundrum is currently faced by the transdisciplinary “Big Data” movement (Bar-Yam 2013), and reflects the adage “data do not speak for themselves” (Bailey 1983:179 Wylie 1993:21). In the absence of a strong theoretical understanding of pattern formation, and a corresponding empirical basis for such theories, large datasets can be made to serve any number of interpretive agendas (Stern 2015). So even though there has been significant progress in addressing the logistical challenges identified by O’Connell (1987), the persistence of contrasting interpretations developed for western NSW surface archaeology, and for surface archaeology more generally, suggests that commensurate gains have not been made toward meeting the theoretical challenges they impose.

3.1.2  The integrity of the surface archaeological record
Being comprised of artefacts and features combined on a common surface, the primary mechanism by which archaeologists establish chronology, vertical stratigraphy, cannot be used as typically conceived (Harris 1979; cf. Fanning et al. 2008). Additionally, geomorphic and weathering agents, as well as modern human activities, shape the landscape in the present and influence the condition of archaeological deposits on the surface. Some of these forces have the capacity to displace artefacts and rearrange patterning within assemblages. The combination of low temporal resolution and potential for post-depositional movement has led to characterisation of surface archaeological deposits as lacking integrity when compared to subsurface deposits (Ebert 1992:6).

Surface deposits are frequently described as *palimpsests*, meaning that they are the products of multiple depositional events or actions which might blend or erase original patterning (e.g. Binford 1981; Bailey 2007; Clarkson 2008; Morgan, Cannon, and Fowler 2013; Bisson et al. 2014). Archaeological materials, whether in surface or subsurface deposits, are almost never recorded in such a state that the precise sequence of depositional events is entirely known (Schacht 1984; Stern 1994). However, the label “palimpsest” is often reserved for deposits considered disturbed or otherwise difficult to resolve due to limited chronological resolution or clear stratigraphic association (e.g. Gillespie and Brook 2006; Henry 2012). This usage implies that there is an ideal deposit type on which to build archaeological inference, and that palimpsest deposits must be disentangled or otherwise transformed into this ideal state to be of use to archaeologists (e.g. Egeland et al. 2004; Henry 2012; Machado et al. 2013).

Concern over the formation of surface deposits has led some researchers to intentionally avoid them, directing attention toward stratified archaeological deposits that are considered to be less disturbed (e.g. David and Lourandos 1997; Johnsson and Brook 2011). Whether these deposits represent a truer reflection of historical occupation is questionable. Working in the semi-arid Keep River region of northwestern Australia, Ward and colleagues (2006) demonstrated that sedimentation rates within rockshelters was variable, preserving the more recent Holocene record more effectively than earlier deposits. Conversely, open sites on sandplains adjacent to these rockshelters displayed better preservation of Pleistocene remains through more regular sedimentation during that period. In a similar vein, Hunt et al.
(2015) illustrated that sedimentation in caves is rarely straightforward, and that sampling of radiometric dates in stratified deposits is not necessarily sufficient for establishing the history of sedimentation and its influence on the appearance of temporal appearance of occupation. At Mackintosh and Nunamira Caves in southwestern Tasmania, Stern (2008) demonstrated that deposits exhibiting gross similarities in assemblage composition had accumulated over vastly different time spans. These studies illustrate that universal claims for improved resolution in rockshelters are not necessarily merited. However, even if it were the case that rockshelters or other stratified deposits provide higher resolution archaeological data, relying solely on well-preserved rockshelters would necessarily provide a limited window into the diversity of places occupied during the past. As Pettitt (1997:220) argues, “sophisticated preservation and recovery of archaeology does not necessarily imply a sophistication of behaviour that left it there in the first place.” Ignoring some parts of the archaeological record in favour of others in order to avoid interpretive difficulties only trades a potentially resolvable bias for a systematic one.

Much of the emphasis on the integrity of the surface record stands out against a comparatively uncritical view of subsurface deposits. It has been repeatedly noted that nearly all subsurface archaeological deposits were at one time surface deposits (Dunnell and Dancey 1983; Ebert 1992; Wandsnider and Camilli 1992), implying that any distinction between surface and subsurface deposits should be qualified on actual depositional histories. In a review of the differences between surface and subsurface archaeological deposits, Ebert (1992:7-14) notes that the recovery of archaeological materials from buried strata can give the impression of being “intact” or “sealed”, giving license to ethnographic-scale interpretation, when their depositional history may only be known superficially. Such illusions are typically absent from a study of surface archaeology as the effects of non-anthropogenic formational processes are more noticeable; indeed, they often control the observability of archaeological phenomena in the first place (e.g. Gould 1980:27; see also Foley 1980:178; Waters and Kuehn 1996; Ward and Larcombe 2003; Fanning et al. 2009a). In other words, the visible condition of surface deposits forces an honest appraisal of formation processes beyond those which immediately preceded their discard by people in the past.
The surface record is data-rich and accessible, and archaeologists possess the ability to amass large datasets from it, encouraging inferences about the activities of human groups in past landscapes. However, drawing inferences from surface deposits is hampered by a limited understanding of their formational dynamics. Surface records have been regularly characterised as irresolvable palimpsests, yet the difference between surface and subsurface deposits, typically expressed in terms of integrity or disturbance, only exists as a matter of degree. There is no documented threshold between the integrity of surface and subsurface deposits. Instead, patterning in the surface record, like that in the subsurface record, is formed by a number of processes operating in the past. These processes are the keystone to any construction of behavioural narratives.

3.2 Formation

In a short treatment on his work East Africa, Foley (1980:39) compares surface archaeology to the study of plant communities, in that they both involve “sampling small objects (i.e. plants, artefacts) over large areas.” Archaeological data often come in the form of populations of artefacts. This is especially true of the surface archaeological record, where artefacts exist in a more or less continuous distribution across the surface of the earth (Cherry 1984). Being large populations of discrete things, studies of the archaeological record are often statistical in nature, usually requiring the use of sampling techniques rather than the accumulation of complete datasets (Salmon 1975:459).

Foley (1980) leaves the comparison between plant ecology and archaeology at their shared orientation around populations of things. However, this analogy could be extended in light of the concerns identified above. For example, the patterning observed in plant communities is the emergent product of individual plant behaviours in given contexts over time; in other words, the ecology of the plant. Because some plants will disperse and grow differently from others, and the same plant might disperse or grow differently in different environments, the patterning of plants in a given area can be used to infer something about the processes which formed them (e.g. Barot et al. 1999). However, the generative
mechanisms forming patterns are often difficult to observe directly, so the ontological connection between macro-scale patterns in plant communities and processes which produced them is not always straightforward and frequently depends on the use of abstract representations (Levin 1992).

Essentially the same could be said for the patterns observed by archaeologists with one very important caveat: the behavioural processes sought by plant ecologists almost always concern the plants from patterns in observations of the plants themselves, while archaeologists are almost always seeking the behavioural processes of humans not from observations of humans, but of materials discarded by humans. Thus, there is an intervening step in the chain of causality between patterning in the archaeological record and the activities of past human actors that might be thought of as the ecology of archaeological objects. In archaeology, this ‘ecology’ has largely been subsumed under the heading of formation. To study formation is to study the processes which influence patterning within archaeological deposits. Connecting present-day archaeological patterning to processes operating in the past has been a clear aim of archaeological research for decades (Ascher 1961; Bailey 1981, 1983; Binford 1981; Gifford-Gonzalez 1991; Schiffer 1972, 1987) and consistently features in introductory descriptions of the discipline (Scarre 2013:1; Renfrew and Bahn 2012:11).

Patterns consist of one or more objects or observations that, taken together, share some identifiable relationship or relationships (Resnik 1981:532). These objects and their relationships are “the discernible outcomes or signatures of the processes operating in a given system” (O’Sullivan and Perry 2013:30). The term discernible outcomes can be understood to mean that the organisation of, or relationships between, the recorded data falls outside an acceptable range of variability for observed outcomes from a random generation process (Grimm et al. 2005:991). That observable patterns exist within a real and knowable world is a fundamental assumption in any scientific endeavour. A process is a set of actions which, when taken in order, achieve a particular outcome. From the perspective of the archaeological record, processes are mechanisms which move, physically transform or change relationships between deposited artefacts and features (Schiffer 1987:11). The current configuration of artefacts and features, their attributes, and their relationships as observed by
an archaeologist is the outcome of some combination of sustained, episodic, or transient mechanical processes (Lucas 2008:62). The processes that form patterning in any observed archaeological data can occur over any span of time prior to and including the moment of recording by the archaeologist (Bailey 1983).

In the context the surface archaeological deposits in western NSW, patterning might be found in any aspect of the deposit the archaeologist observes, such as the spatial arrangements of artefacts, frequencies of artefacts featuring a given attribute, or temporal sequences of datable objects. The specific processes which operated in the past to form any archaeological pattern, by contrast, cannot be directly observed by researchers in the present, and in that sense they must remain theoretical. But if the goal of archaeology is to explain or interpret patterning in archaeological deposits with some authority, with the parallel anthropological aim of implicating some human behaviour in that explanation, then the task of the theorising archaeologist must be to develop a strong inferential link between those patterns and suspected generating processes (Murray 1999:24).

It is not empirically sufficient to interpret processes operating in the past solely from analysis of patterns. There are several reasons why this is the case, which tend to be subsumed under the heading of equifinality. First, patterns may not be intuitively recognisable as the outcome of a given process. Such a situation might arise because the pattern itself lacks a unique structural isomorphism (Cale et al. 1989) or the observer lacks a referent pattern for comparison. But perhaps more pernicious is the inverse notion that the same pattern might be generated by more than one process (Levin 1992; Dincauze 2000; Beven 2002; Premo 2010). There are numerous cases where archaeologists have developed multiple models to explain the same phenomena; the interpretations derived from western NSW discussed in the previous chapter would qualify as an example.

A further example comes from Cape York in Northern Queensland, Australia, where large shell mounds there have been variously considered to have been formed through long-term, low-intensity predation on reliably available Anadara granosa shellfish beds (Bailey 1975); short-term, high-intensity predation to support ceremonial activities (Morrison 2003); long-term intense exploitation resulting in diminishing returns and temporary abandonment (Faulkner and Clark 2004); or the amalgamation of multiple, spatially discrete events.
associated with shifting availability of resources (Morrison 2014; Shiner et al. 2014). It could be argued that these different interpretations constitute an instance of equifinality as, from the perspectives of the different archaeologists promoting each of these interpretations, each could potentially explain the phenomenon.

Interestingly, explanations of shell mounding caused by avifaunal burrowing, for which identification criteria have been developed, have been dismissed (Hiscock 2008:175). While this has done little to eliminate any of the archaeological explanations, this would suggest that defining archaeological instances such as this as equifinal is questionable because their status as such may only be fleeting. Rogers (2000) notes this, differentiating between a mathematical definition of equifinality (sensu von Bertalanffy 1949:15) that declares generative mechanisms as equifinal only when they produce precisely the same outcome, and a more colloquial definition used by archaeologists in which outcomes are not the same, but only similar (e.g. Dincauze 2000). If archaeological interpretations such as these were truly equifinal, then there would be no hope of discerning between the proposed generating processes, nor much need to. Alternatively, if outcomes are only equifinal in the sense that it is difficult to compare generating archaeological models in terms of the available data, they might be better described as provisionally underdetermined by the data at hand (Laudan and Leplin 1991). This may be in part due to a lack of comparable data, and to that extent calls for more data (or more appropriate data) may be correct. This may also be due to a lack of appropriate mechanisms for discerning between patterns in existing data. In both of these cases, the problem of underdetermination between presented alternative explanations is potentially a resolvable one.

In order to associate a pattern with a presumed process, the acceptable range of variability for outcomes of the process in question, with respect to the pattern observed in the archaeological record, must be established: in other words, its material signature. This is what Binford (1981:26) calls “criteria of recognition” for the operation of past processes, and speaks to “performance” standards identified by Dunnell (1992a) as fundamental for empirical studies. In nomothetic sciences, this is typically done through experimentation. Experimental archaeology is aimed at replicating processes presumed to have occurred in the past in order to parameterize the variables associated with those processes (Coles 1979).
Flintknapping experiments, for example, may involve the careful manipulation of raw materials, angles, and forces to produce stone implements with certain qualities (e.g. Dibble and Rezek 2009). Natural processes, such as the influence of fluvial action on the displacement of artefacts, can be experimented with in either laboratory (e.g. Schick 1987) or field settings (e.g. Stockton 1973; Webb 1994; Texier et al. 1998; Fanning 1994). Alternatively, living cultural systems engaging in behaviours similar to those supposed to be occurring in the past might be used to establish the material signatures of a past process. Ethnoarchaeology uses the methods of ethnography to observe and record archaeologically-relevant behaviours (e.g. Binford 1967, 1977b; Skibo 2009). Gould’s (1980) study at Tikatika, discussed in the opening passage of this chapter, is an example.

The application of either ethnoarchaeological observation or experimentation relies on analogical reasoning. In order for inferences regarding past processes to made securely (sensu Wylie 1985:105), the causal relationships between the analogue process and the analogue pattern are assumed to be uniform through time and space. For example, an individual dismembering an ungulate using sharp stone flakes might be expected to generate definitive patterns of wear on the implements being used. While this process might be expected to vary between instances, the uniformitarian assumption holds for the durability of both the stone and the ungulate. The variability, then, can be estimated through repeated experimentation or observation, which can then be compared to patterning observed in archaeological contexts. In instances where such uniformitarian assumptions are warranted, archaeologists can evaluate “how an object interacted with its environment [in the past] with exactly the same certainty as if it were moving in front of us” (Dunnell 1992:215). Analogical reasoning by uniformitarian concept lies at the heart of many approaches to archaeological formation (e.g. Bailey 1981; Binford 1981; Schiffer 1987).

3.2.1 Criticisms of formation and related concepts in archaeology

A shared intellectual heritage between archaeology and geology has ensured that the physical formation of deposits has long been of concern (Butzer 1971; papers in Davidson
and Shackley 1976; Foley 1981; papers in Nash and Petraglia 1987; Schiffer 1972; Stein 2001; Stern, 1994; Waters and Kuehn 1996; Wheeler 1954; Wilson 2011; Wood and Johnson 1978), but the theoretical treatment of formation of archaeological deposits is largely attributed to the later days of the New Archaeology. One of the overarching principles of Schiffer’s (1972; 1976) behavioural archaeology is that archaeological objects were once part of active cultural systems, referred to as the systemic context, but have since passed out of use and into an archaeological context in which they are encountered by the archaeologist. The intervening natural and cultural processes that occur between the original condition of an object in the systemic context and its recording in the archaeological context, referred to as transformations, occur during the life history of the object (Schiffer 1976, 1987). A primary goal of behavioural archaeology is to develop generalised principles from combinations of behaviours occurring in the systemic context and transformations occurring in the archaeological context (La Motta 2012). Binford (1977a; 1981) likewise considered the matter of connecting archaeological remains in the present to cultural systems in the past in his initial conceptualisation of ‘middle-range’ theory, which viewed the contemporary archaeological record as static but past systems as dynamic, and that theoretical constructs were needed that could provide a means of bridging this ontological divide. The middle-range approach embraced the use of actualistic studies, particularly ethnoarchaeological research among contemporary societies (e.g. Binford 1977b; Binford and O’Connell 1984; Longacre 1985) as a means of providing analogies for the processes operating in the past that formed archaeological patterning as encountered in the present.

Middle-range theory, Shott (1998) argues, was rejected by many archaeologists for a number of reasons: underdevelopment of methods, confusion of terms with the sociological definition of middle-range theory (Raab and Goodyear 1984), and an implied exclusive alignment with a materialist theoretical orientation (Wylie 1989) top the list. Others still disapproved of what was viewed as an uncritical use of analogical reasoning (Gould 1980; Gould and Watson 1982). The main critique was based around whether archaeologists were employing a substantive form of uniformitarianism that projected entire cultural systems into the past based on a limited number of observed similarities (Wobst 1978). Questions were also raised about whether anything novel could be learned by such extrapolation, as the analogue is necessarily better understood than the phenomenon under study (Gould 1980:32).
This led to a vigorous review of analogy and its use in archaeological inference (e.g. Gould and Watson 1982; Salmon 1982; Wylie 1982, 1985). While many now contend that analogy in some form is necessary to the task of interpreting a phenomenon that cannot be observed (e.g. Dunnell 1992; Gifford-Gonzalez 1991; Johnson 2010:50; Murray and Walker 1996; Wylie 1985), actual methods for applying analogies, especially from ethnographic contexts, remain tenuous (for example, see Allen 1996; Hiscock 2008; Skibo 2009; Spriggs 2008).

Schiffer’s approach (1976) was criticised prominently by Binford (1981b), who claimed that behavioural archaeology, in its view of post-depositional processes forces as distorting behavioural signals, sought to reconstruct ethnographic behaviours from the archaeological record. This reconstructionist viewpoint, which has been at times pervasive in archaeology (see Murray 1999), was initially critiqued by Ascher (1961) who likened it to archaeologists seeking ethnographic moments frozen in time; this became known as the ‘Pompeii premise’. Binford (1981:200) argues that behavioural archaeology, and its definition of formation through sets of transformations, conceives of the archaeological record as distorted images of cultural systems that can be reconstructed, and counters that “a pattern or arrangement among artifacts at an archaeological site can only be viewed as distorted if one is not interested in the cultural system as manifest, but rather in some property of a cultural system chosen a priori to receive special inferential attention.” While the actual content of Binford and Schiffer’s approaches may not be as different as portrayed in the debates (Kelly 2011), this speaks to a fundamental conceptual schism regarding the proximate and ultimate goals of archaeology: to explain the arrangement of objects in the archaeological record and to explain human behaviour in the past (Clarke 1973; Hodder 1988).

Since the ‘Pompeii premise’ debate, however, general attitudes toward formation approaches have not been overly hostile or critical, at least not relative to other bodies of theory (for examples, see Johnson 2010, 2012). But nor have they been universally receptive or responsive. While the actual feelings of archaeologists are difficult to gauge, there is a sense that archaeologists on the whole give limited attention to formation. This sentiment is encapsulated in an informal exchange between Michael Shanks and Michael Schiffer (Rathje,
Shanks, and Witmore 2013:35). Schiffer, when asked why formation studies had not been more enthusiastically embraced by archaeologists, responded:

“All although I really don’t know, I can furnish one facile answer. Archaeologists do get it, but they recognize that taking into account formation processes complicates the research process, burdening us with labor- and thought-intensive activities. Many archaeologists are willing to take shortcuts because accolades flow swiftly and surely to those who craft fascinating and far-reaching inferences consistent with the latest theoretical fashions – regardless of how firmly they have been grounded in archaeological principles and archaeological evidence.”

This notion, that many archaeologists will choose more-interesting-but-empirically-shaky research over less-interesting-but-empirically-sound research, could be read simply as cynicism, although it has been suggested that similar types of decisions in other disciplines are endemic to the contemporary academic research climate (e.g. Nosek et al. 2012). But it also echoes an earlier dilemma discussed in Wylie’s (1985) treatment on the use of analogy in archaeology, in which the search for meaningful interpretations is contrasted with the more menial task of accounting for physical arrangements of artefacts. According to this characterisation of the dilemma, formation studies in isolation represent an intellectually sterile form of “artifact physics” to be contrasted with a more fulfilling interpretive archaeology which is ultimately more speculative (DeBoer and Lathrap 1979:103). Rather than operating as a common interpretive framework for the study of the archaeological record, the study of formation is viewed a ‘spoiler’, highlighting the ontological disconnect between the informational content of archaeological deposits and the interpretations made therefrom (Shott 1998:321; McGuire 2002:174; Wood and Johnson 1978:369). This is demonstrated most acutely in those instances when the potential for post-depositional processes to have affected a deposit in a certain way is proposed, and this potential is used to dismiss the value of an inference or promote an alternative interpretation.

Bailey (2008) discusses further concerns over appropriate interpretive scales and their value in reconstructing human behaviour (what he terms “the problem of the individual” and “the problem of the narrative”). Individual-level behaviour, the emphasis of which being a hallmark of agency-oriented approaches (e.g. papers in Dobres and Robb 2000), becomes
largely moot if the archaeological record is a palimpsest that aggregates archaeological residues over periods potentially well beyond the lifetime of individuals (Lucas 2008). Additionally, if these palimpsests consist of materials from potentially unrelated events, determining a sequential narrative of events from these data becomes a limited endeavour (Stern 1994). This initially led to criticisms that, in suggesting that short-term events would lack definition in a palimpsest archaeological record and thus more informative about correspondingly long-term, large-scale processes (of which environmental changes were used as an example, see Bailey 1983), these approaches square with environmental determinism and deny agency to people in the past (e.g. Shanks and Tilley 1987:122; see Murray 1999 and Bailey 2007 for reviews of these criticisms). In this respect, regarding archaeological deposits as palimpsests acts as a spoiler to linear, ethnographic-scale interpretation (Lucas 2012:107).

These criticisms highlight some barriers to the application of formation theory to archaeological phenomena in surface contexts. As noted above, and elsewhere (e.g. Gould 1967; Johnson 2010:50), analogical reasoning of some sort is necessary for an observer in the present to infer past phenomena. The power of such reasoning depends on whether the causal mechanisms between pattern and process in the present operate uniformly through time and space. However, methods that have normally been used to generate analogical inferences in archaeology (predominantly actualistic and ethnoarchaeological research) are not likely to provide suitable analogues for processes operating over larger spatiotemporal scales or higher orders of organisation as they are limited in their ability to represent qualities that emerge from aggregate instances of such activities. Gifford-Gonzalez (1991:226), for instance, touts the success of these methods in the identification of taphonomic agents in zooarchaeological studies (e.g. Behrensmeyer 1978; Blumenschine 1988; Shipman and Rose 1983), but also notes that this line of inquiry has a scalar limit:

"...actualistic investigations into the causes and contexts of production of various marks on bone have successfully distinguished the distinctive “signatures” of various agents. However, these solid relational analogies may not be enough to get us where we ultimately want to go [interpretations of ecological, cultural, and social relationships]. We should not assume that if we keep doing the same kind of work in the future that we will obtain cumulatively greater and equally confident knowledge about events and states in the prehistoric past."
The point here is that processes that generate discrete phenomena, like cut marks on bone, can be observed in actualistic studies and that knowledge of the causal relationship between pattern and process can be effectively leveraged via uniformitarian assumptions to interpret the signatures of some causal mechanisms to the exclusion of others. But understanding higher-order phenomena, such as why different frequencies of cut marks occur in different places, or why the relative frequencies of different kinds of cut marks changes over time, is not simply a matter of doing more bone modification experiments. The systems that generate these kinds of patterns may be composed of individual instances of bone modification, but are connected by relationships that may or may not be linear, or may be connected to elements that do not bear directly on the formation of modification signatures but influence other components of the larger archaeological pattern. The resultant phenomena exhibit emergent qualities that are not captured by a study of the proximal causal mechanics alone. On this matter, Gifford-Gonzalez (1991) argues that persisting in using middle-range analogues of lower-order phenomena to directly assess higher-order phenomena will inevitably result in more instances of equifinality (at least as understood archaeologically, see above). By extension, ignoring formational mechanisms altogether would similarly facilitate underdetermination (Shott 1998).

The scale and organisation of the phenomena being studied have implications for how it might be effectively treated by an analogy, and these may be preventative when analogies are sought directly from the real world. Physical experiments which recreate landscape-scale archaeological patterning are often impractical because the logistical constraints (geographical, financial, etc.) of replicating an archaeologically-relevant process at the landscape scale are extraordinary (Jermann 1981:1-2). While ethnoarchaeological studies and natural experiments achieve this by recording the operation of analogous processes in living systems (e.g. Binford and O’Connell 1986; Faith and Behrensmeyer 2006; Schiffer and Skibo 1997), they are unable to be present in all places at all times (Wobst 1978), limiting observations to those places and times where they are present. Furthermore, conducting experiments or observations over long time spans, which are often those of interest to archaeologists and certainly pertinent for post-depositional processes, is difficult or in many
cases impossible (Shiner 2004:15). Studies which extend beyond the lifetime of the researcher are presently rare, and ensuring their maintenance is complicated. Finally, experimenting with more complex systems (social or natural) is not always practical or ethical, but these systems are also largely path dependent, with their state at any given time being one of many possible outcomes of contingent on historical precedence (Gifford-Gonzalez 1991; McGlade 2014). At these levels of organisation, individual observations may not lead to robust insights into system mechanics. The processes that can be most comprehensively observed (and thus parameterised) are those which operate at smaller spatio-temporal scales, those occurring in “ethnographic” time (Binford 1981). In the absence of experimentation or observation extending beyond these bounds, understanding large-scale processes must be done by extrapolating carefully from processes operating on smaller scales with reference to the variability within those processes and changes they may undergo through time and across space (Bailey 1983; Binford 1964; Dunnell and Dancey 1983; Ebert 1992; Fanning and Holdaway 2001a; Jermann 1981;). Such information may not be readily available to the archaeologist, leaving relationships between variables or components in the system uncertain.

3.3 Synthesis

The preceding sections have laid out both reasons for studying the surface record and problems faced by archaeologists who venture to do so. These issues are not entirely unique to surface archaeology, but are perhaps exaggerated by, or at the very least made more obvious by, their visibility on a dynamic surface. In this way, a study of surface deposits highlights the problems of conflicting formation models more strongly than a study of subsurface deposits. All archaeological records, regardless of their degree of stratigraphic control, are ultimately some form of palimpsest (Bailey 1981; Binford 1981). Surface records, like those in western NSW being studied here, are merely an extremely obvious example of this.
Archaeological theory-building, including theories developed to explain social or ecological entities, depends on the association of patterns of material objects observed in the present with formation processes that occurred in the past. However, formational processes that occurred in the past cannot be observed, only the patterns they leave behind. Nor can archaeologists experiment directly with many suspected generative processes, because they occurred over long periods of time and involved subjects that are logistically or ethically impossible to constrain. This is especially true when human behaviour is considered at the landscape scale, where substantial variation might be expected to occur over both time and space; interpretations at this scale are precisely those for which surface archaeological deposits are considered to be most useful.

To overcome the ontological disjuncture between observed patterns and suspected processes, many theoreticians have emphasised the need for appropriate middle-range analogues. Indeed, analogical reasoning by way of uniform processes is the only means of effectively addressing causal relationships in past phenomena (Bailey 1983; Dunnell 1992a; Gould 1965). But faced with the expansive and temporally inconsistent nature of surface archaeology, some difficult questions arise. Most immediately, what analogues exist for landscapes, particularly analogues that are capable of being observed simultaneously? And furthermore, how does one find substitutes for the time it takes for long-term generative processes to operate? If the surface archaeological record is truly a time-averaged palimpsest (*sensu* Bailey 1983; Stern 1994), processes of this nature are supposed to be those most responsible for patterning in the surface archaeological record, yet there are currently no established mechanisms for observing how they influence variability in that patterning. The processes that operate at these scales (social, ecological, formational, or otherwise) produce emergent phenomena, and as such cannot be simply reduced into their constituent parts, nor can it be assumed that they can be collapsed to a past snapshot comparable with an ethnographic scene. But even if it were the case that such a reconstruction was possible, the combinations of processes which came together to produce an observed pattern are but one outcome from a host of possible historical contingencies that different combinations of processes might produce (Gifford-Gonzalez 1991; McGlade 2014). Outside of case-specific statements, how would such an analogy inform on general theory?
In order to make inferences regarding the formation of patterning in surface archaeological landscapes such as those in western NSW, while maintaining a commitment to explanation, two barriers discussed above must be overcome. The first is a conceptual barrier which exists between understandings of what the archaeological record is versus what archaeologists can learn from it. The second is a methodological barrier which exists between observations of a static record, unobserved processes which generated it, and observations of processes operating in the present that might serve as appropriate analogues.

### 3.3.1 On the conceptual barrier

As stated earlier, an archaeological record that is a palimpsest of multiple depositional events is not consistent with the goals of reconstructing a preconceived notion of a past behavioural system. Engaging in a successful behavioural interpretation of the record through the filtering of intervening formational processes, at least at any resolution that would *not* be synonymous with a coarser grain palimpsest, the record must be not only dissectible (that is, configurations occurring at one time must be able to be extracted from configurations occurring at other times), but it must also be conservative, such that elements from earlier periods which continued to exist into subsequent periods remain present throughout. This would not be unlike a roll of motion picture film, in which the changes between frames is minute and incremental, so that any single frame could be extracted and viewed as an independent image. While a record of this type would be supremely useful for documenting sequential changes through time, such a record cannot exist in reality. Conceptualising any archaeological record as distorted or disturbed necessitates a preconceived notion of an ideal record that cannot be met in reality, whether that record is presently on the surface or buried.

The palimpsest concept has also been used as a theoretical framework emphasising how the condition of the archaeological record shapes the information that can be most gainfully extracted from it, an idea most frequently associated with the time perspectivist paradigm (Bailey 1983, 2007; Wandsnider 1996; Banning 2002; Lucas 2010). A “true” archaeological palimpsest, as defined by Bailey (2007), is a situation in which the
archaeological record is generated in such a way that all traces of any previous deposits are removed prior to the deposit of new material, leaving only the most recent deposition behind. In theory, the opposite of a true palimpsest would be a true stratigraphy, in which each deposited object is immediately sealed within a distinct sedimentary layer, perfectly preserving the temporal sequence of depositional events (Lucas 2012). This definition implies that anything less than a true stratigraphy is some form of palimpsest, and is subject to some processes, geophysical or otherwise, that blend or blur the temporal resolution of the recordable data, reducing their usefulness at reconstructing behaviour at the ethnographic scale (Bailey 2007). While neither a “true” palimpsest nor stratigraphy may exist in reality, these archetypes serve as useful bookends for describing the process of deposit formation, and its influence on the character of the record encountered by an archaeologist.

By treating all archaeological deposits as palimpsests of one form or another, time perspectivism emphasises how archaeological materials came together over time in whatever their stratigraphic context. Similar ideas are raised in Stern’s (1994) use of the palaeontological concept of time averaging. Established in the context of Lower Palaeolithic assemblages in East Africa, this is the idea that the contemporaneity of materials within a given deposit is determined by the timespan represented in their shared sedimentary context. From this perspective, in the absence of overlying strata or finer-grained stratigraphic information (e.g. Stern 2015), surface archaeological deposits can be considered to be a summative record of the depositional inputs and outputs occurring since the time that the landsurfaces on which they rest were laid down (sensu Fanning and Holdaway 2001).

If archaeological patterns are not distorted images of past events or previously existing cultural systems, then what are they? Although a deposit may be time averaged, this does not necessarily translate to its being behaviourally averaged, as the materials preserving and their rates of accumulation are unlikely to be uniform through time (Stern 2015:236). Lucas (2008:63) introduces the concepts of “reversibility” and “irreversibility”, using the metaphors of book collections (highly reversible) and traffic systems (highly irreversible) to discuss how patterns of material organisation which are reinforced and repeated are more likely to persist and be visible over time than those produced by more ephemeral or individualised activities. From this perspective, seeking to construct dissectible linear
narratives would be subordinate to establishing material organisation occurring at a place through time (Schlanger 1992; Lucas 2008; Shiner 2009), and the identification of that organisational force depends on its persistence through time (Balley 1983). Activities that do not leave traces that preserve well are unlikely to persist over long time spans, while activities that change frequently in terms of their depositional outcomes are unlikely to leave a discernible pattern. The most persistent patterning, then, would be that which leaves durable material traces and is reinforced through repetition. There are strong similarities between this and Binford’s (1982:16) notion of “tempo of land use”, and Bailey’s (1983) idea that patterns observed in a palimpsest archaeological record are more likely to be informative about longer-scale processes. Reversibility is measured in terms of a concentrated effort that would be required to disorganise the signatures of these structural influences.

While organisation that is reinforced by higher-order structures is likely to increase the resilience of patterning within the archaeological record, Lucas’ (2008) examples imply that the forces of material reorganisation are predominantly anthropogenic (e.g. where and when a person leaves an artefact or feature). However, external forces do not simply act as disorganising agents, but can reorganise archaeological materials in different ways that are also structurally reinforced. An example of this is size-sorting on slopes, where topography can systematically reorganise archaeological objects through the action of water, wind, or gravity moving artefacts downslope (e.g. Schick 1987; Fanning and Holdaway 2001). Like a traffic system, the patterning generated by topographic size sorting could be reversed, but it would require substantial shifts in either the local topography or the velocity of fluid moving over it. While not disqualifying the possibility of sudden change, transitions that disorganise well established patterns are more likely occur over long time spans. In a situation where irreversible internal and external organising forces were both in operation, the intertwining of these processes might in fact produce patterning which is distinctive from the patterning generated by either force alone, or even patterning that resembles the signature of some other unrelated phenomenon (see examples in Wood and Johnson 1978).

Conceived of in this way, the archaeological record, surface and subsurface, could be thought of as a generative record (sensu Epstein 2006; see also Lucas 2005:41; Lake
in which the material organisation of archaeological patterning is not the combined outcome of human and natural processes transforming the signature of an idealised cultural system, or the persistence of structural residues against forces of erasure or reorganisation, but the emergent outcome of many individual actions through time, human-mediated and otherwise, which might change the condition of one or more elements of the archaeological record. This concurs with the general idea shared by nearly all theoreticians discussed thus far that the record or deposit is constantly in a state of becoming (Ascher 1961; Schiffer 1976; Binford 1981; Bailey 1983; see also Pred 1984). It maintains that the patterning in the archaeological record itself at the time of recording is the phenomenon to be explained (after Binford 1981), and that explanation cannot be separated from the formational processes which generated it.

The concept of reversibility in organising forces (e.g. Lucas 2008, 2010) can be retained under a generative perspective, although it is extended to account for processes not directly influential to the original acts of inscription. Ultimately, meaningful patterning in the archaeological record is likely to be dominated by less reversible organising forces, but those which are most irreversible might not be internally generated. This is not to say that more reversible patterning is not visible in the archaeological record, or that patterns cannot be broken down into constituent, more reversible parts. But when this occurs the result is decontextualized from its emergent whole, and thus stands apart as a phenomenon to be understood in terms of a more individualised set of formational processes. This perspective is in-line with Gifford-Gonzalez’ (1991) call for archaeologists to recognise that the phenomena of interest to them exhibit emergent qualities that are not captured by lower-order analogies.

3.3.2 On the methodological barrier

While maintaining a generative view of the record helps to clarify what might be expected to be learned from it, it does not address the shortcomings of a middle-range approach based on ethnographic observation or actualistic studies addressed at the start of
this section. Without finding different ways to construct analogical relationships, competing explanations of higher-order phenomena cannot be effectively arbitrated.

An objective of actualistic studies is to understand the influence of different variables on a given system. But in a system where the condition is for the most part historically contingent, such as a social institution or landscape, the influence of variables in the observable system only occurs once, preventing assessment of variability in the process. Gifford-Gonzalez (1991:240) recognises this when she suggests that, where emergent phenomena are concerned, causal uniformitarian assumptions are likely to take a probabilistic rather than deterministic form. In some instances, it may be possible to observe enough analogous real-world cases to sufficiently establish these statistical relationships. This would seem to be a goal of Binford’s (2001) “constructing frames of reference” from a wide-ranging comparative study of hunter-gatherer ethnographies. But as mentioned earlier, achieving this becomes less likely when the emergent properties of the system extend beyond the practical limits of observation (Wobst 1978). In such cases, natural analogues may not exist, and physical experiments may not be possible that capture the essential components of the system. However, because the relationship is analogous to begin with, the comparison between the two systems need not be one-to-one. Indeed, assuming that substantive uniformitarian assumptions apply wholesale to situations in the past was a primary critique of the use of analogy in archaeology (Gould 1980; Wobst 1978; Wylie 1985). To make archaeological inferences from analogies that are applicable beyond their originating case studies, a certain amount of generality would be preferable.

The relationship between a phenomenon and an analogue is representational (Sloman 1971); in the absence of the real phenomenon, the analogue acts as a stand-in. For uniformitarian assumptions to hold, the analogue need not be precisely the same, but must only be similar enough to the original in order for the inference hold with respect to the question being asked about the original phenomenon (Giere 1988; Suárez 2004). For example, if we wished to know how long a grapeshot slug might have taken to reach a target when dropped from a 15-metre medieval tower in comparison to a large calibre cannonball, we might obtain replicas of these objects, run them up a tower and drop them, recording the time it takes each to reach the ground. But to simply determine which of two falling objects
of unequal weight would reach the ground first (assuming drag is not a consideration), it may suffice to use other objects of unequal weight: a marble and a bowling ball, for instance. The specificity of the analogue depends largely on the specificity of the question being asked (Cartwright 1983). The coarse grain of archaeological data and the limited attention that can be allotted to a diverse range of research topics mean that researchers often have restricted resources with which to evaluate competing interpretations. Archaeologists trying to compare interpretations of surface formation processes might be better served by analogues that allow them to ask questions of the “what kinds of processes might create this pattern?” type and hope to be able to find a best answer among several possibilities, rather than analogues aimed at answering “what precisely happened here?”, expecting correct, metric answers in absolute terms (Isaac 1981; O’Sullivan and Perry 2013).

Analogies based on phenomenological entities are typically limited to a given level of abstraction. Referring back to the example, if we wished to move from the more general question to the more specific one, our marble cannot easily be made to have the same aerodynamic qualities as a grapeshot slug. This lack of flexibility makes understanding how historical contingency influences record formation difficult. But because the analogic relationship is representational, there is no a priori reason why a ‘real’ entity needs to be used in the first place (Callender and Cohen 2006). Provided the questions being asked are not highly case-specific (and the debates over the use of analogy in archaeology suggest that they should not be), suitable analogues might be found in more abstract model systems (Godfrey-Smith 2006).

A model is a representation of a real-world entity which might be a discrete object or being, a relationship, or a system. Models are often used when manipulating or measuring the entity in question is not a practical course; therefore, producing a model typically involves some kind of transformation of the original entity in order to make it more accessible. For example, scale models such as model locomotives alter the size of the entities they represented, make them fit within spaces they would be otherwise restricted from. Oftentimes models are simplifications, reducing the nature or complexity of the original entity in order to highlight key relationships or processes. In archaeology and other historical disciplines, if a model can be a representation of the “verbal logic” (Servedio et al. 2014) of a
process or system presumed to have operated in the past, it can function as a laboratory where that logic can be experimented with and outcomes can be compared.

3.4 Summary

Surface archaeological deposits are characterised by objects which are spatially dispersed and of uncertain temporal association. Archaeologists have sought to use patterning in surface deposits to assess the organisation of past human activity at the landscape scale, but this is complicated by the formational histories of surface deposits. An unwillingness to engage with these histories is evident in the branding of surface archaeological deposits as palimpsests to the exclusion of subsurface deposits. This is further compounded by a desire to resolve archaeological deposits at the level of ethnographic description and in terms of sequential narratives.

Inferential frameworks for understanding formation dynamics in archaeology are mainly built around the use of analogical reasoning between an observable phenomenon in the present and an unobservable phenomenon in the past. If the causal mechanism in the observed phenomenon does not change over time and space, then the past phenomenon can be assessed in terms of that mechanism. This becomes problematic when the phenomenon under study emerges through the interactions of multiple, disassociated components such as is the case of the surface archaeological record. The inability to resolve formational mechanisms can lead to conflicting interpretations that may be treated as instances of equifinality, but reflect inadequate inferential frameworks rather than patterning with multiple, truly indistinguishable generating mechanisms.

In this chapter, it has been argued that in order to make use of surface archaeological deposits, the record needs to be considered not as a moment in time that can be reconstituted by filtering out formational processes, but as a generative phenomenon with no defined starting point and many potential outcomes. Doing so means that methods that are dependent on analogues developed in observational contexts alone, at least as conceived of in ethnoarchaeological and actualistic studies, will be insufficient to resolve patterning in
surface contexts. In the next chapter, the use of models in archaeology will be reviewed in terms of their ability to bridge the gap between processes and patterning, as well as between theory and empirical observations, and a method for developing models for evaluating the formation of surface archaeological patterning will be presented.
4 MODELS, SIMULATION, AND FORMATION IN ARCHAEOLOGY

In the previous chapter, it was noted that archaeologists often seek analogues for interpreting processes operating in the past from contemporary ethnographic and experimental settings. Noting a general criticism that ethnoarchaeology cannot always provide appropriate analogues for many of the kinds of systems that may have generated archaeological deposits, Skibo (2009:39) responds by stating that “[a]nalogical reasoning without analogs is not possible”, going on to argue that understanding any archaeological record must be based on relationships between humans and material objects. This assertion foregrounds the importance of a strong empirical basis for inferring the mechanisms responsible for patterning in present day archaeological deposits, but in contrasting the mechanism of analogical reasoning with what he (ibid:39) refers to as “nonmaterial-based” theoretical frameworks, a tacit assumption is made that analogues used to understand material phenomena in the archaeological record must come directly from material phenomena observed in the present. This presents something of a paradox, and problems for finding analogues suitable to draw inferences about large-scale, emergent phenomena. It is argued here that while Skibo’s claim regarding analogical reasoning is correct, analogues need not be directly obtained from phenomenological settings, but that strong inferences can be made from many classes of models.

In this chapter, modelling is presented as a means of addressing the problems associated with comparing archaeological interpretations of surface archaeological deposits in terms of proposed formational histories. The merits of a model-based approach are discussed. These include providing a pragmatic framework for reducing the complexity of a system, offering a reflexive praxis of model-building and testing, and operating as theoretical scaffolding from which to test expectations. One method of modelling, computer simulation, has stood out as capable of handling the complex phenomena archaeologists deal in, and the history of simulation methods in archaeology is briefly reviewed. It is argued that, considering their shared purpose of understanding past dynamics and shared use of surrogative reasoning (sensu Contessa 2007) to achieve that purpose, contemporary model-based studies in archaeology are in many ways continuing the work of earlier formation-
oriented studies. A formation study based on simulation has the distinct advantage of being able to operate outside the limits of actualistic research, and examine how historical contingency can influence the evolution of record-generating phenomena. Furthermore, recent developments in simulation that emphasise the emergence of patterning through the actions of disaggregated agents provide a natural avenue for studying surface deposits as generative phenomena. However, the flexibility of these tools also invites the possibility of building models that are behaviourally rich but difficult to test, inhibiting model comparison. A strategy for building and using simulations to evaluate formation processes is presented as a staged process, combining an exploratory agent-based approach advocated for use in archaeological theory-building (Premo 2010) with elements of a pattern-oriented approach drawn from ecology (Grimm et al. 2005), in order to test the bridge between general theory and empirical observations. This methodology will be used in further chapters to address some of the interpretive differences discussed for western New South Wales archaeology.

4.1 Models

The concepts of what a model is and the role of models in scientific inquiry have been the subject of ongoing philosophical discussion (e.g. Hesse 1963; Suppes 1961, 1969; Cartwright 1983, 1999; Giere 1988, 1999; van Fraassen 1980, 2008). Contessa (2011) contrasts two different concepts of scientific models: theoretical models and representational models. Theoretical models are systems about which certain theoretical statements are true (Giere 1988:79). For example, if Lewis Carroll’s book Alice in Wonderland were taken to be a model, then the statement “Cats can become invisible of their own accord” would be true of that model, even if it is not true of cats in the known world. A representational model, on the other hand, is used to represent elements of a target system (Godfrey-Smith 2006). A street map of Auckland, for instance, can be used to represent elements of the city of Auckland, as long as a user of the map interprets the map in terms of the city. It is by virtue of that interpretation that user is or is not able to make valid inferences from map to city (Contessa 2007, 2011). By these definitions, Alice in Wonderland could also be taken to be a representation of the city of Auckland, albeit not an especially faithful one (not least because
of its disappearing cats). Between these concepts, models might be constructed for many reasons that balance these qualities of theoretical truth and representational faithfulness.

One reason to build models is to exchange a complex or otherwise intractable phenomenon for a more accessible one. While some phenomena are amenable to controlled experimentation, others, including many of those of interest to archaeologists, are not. Models, through the representational relationship described above, can allow for inferences to be made about something which exists at spatial, temporal, or organisational levels beyond that controllable in a laboratory setting. This quality of accessibility also drew middle-range theorists to ethnoarchaeology and experimental studies in the first place (Binford 1977b:24). However, the relationship in both cases is an indirect one (Godfrey-Smith 2006); reasoning is used to interpret the model in terms of the real phenomenon (Contessa 2007).

Models are also heuristic devices for learning more about a system or theory. Learning from models is accomplished at two stages: the building of the model and the testing of the model (Morrison and Morgan 1999). In order to build a model, the modeller must determine the elements of the entity being modelled to be included (or excluded), and describe the relationships between those elements. Making the model in the medium used for its construction forces decisions regarding the inclusion or exclusion of particular elements in a model which are made based on assumptions about the relative importance of those elements to the nature of the entity in question (Giere 1988:77). When a model is tested, it provides the modeller with an opportunity to evaluate the implications of their assumptions. This occurs as an iterative process in which the modeller might test a newly-constructed model and then change assumptions (and the structure of the model) based on disagreements between the model and the entity in question (Railsback and Grimm 2012:7). Watt (1968:371) summarises this with regard to computational model-building:

“Of fundamental importance... is the self-teaching side effect. That is, if we build a simple model of a phenomenon into the computer system by means of a program, observe the discrepancy between the behaviour of real and “model” systems, and improve the model on this basis. While we may start with inadequate and unrealistic assumptions, the pattern of the output will quickly suggest to us how assumptions must be modified to make the model more realistic... Such computer experimentation is an ideal means of suggesting how key experiments to obtain new data can clarify our
understanding of a phenomenon with a minimum amount of actual experimentation.”

Developing a model therefore has its own heuristic value, as the configurations of assumptions and variables under which the conceived system or function might produce the desired outcome (or those that do not) become clearer with each completed cycle. This mechanism has the capacity to bring neglected elements of the process which may have relevance to the attention of the modeller. Although Watt (1968) describes this as a side effect, others have reached the conclusion that this is a fundamental part of model-based research (Morrison and Morgan 1999:32; Epstein 2008; Railsback and Grimm 2012:7).

This praxis is not limited to learning about real systems through representational models, but theoretical systems as well. For instance, Giere (1988:68-80) makes an example of the simple harmonic oscillator, noting that even though this object as imagined cannot exist in reality because other forces that would operate on it are not accounted for in the theory from which they are derived, they are useful nonetheless for illustrating Newtonian mechanics because they simplify the relationships between objects in a system. But the recognition of this simplification itself leads to inferences about both the complex nature of oscillations in a real setting, and the relative importance of parameters needed to make an inference about a given phenomenon.

A final objective of building scientific models is applying theoretical principles to make predictions about some real phenomenon. For example, physicists may use theoretical relationships between mass, distance, and gravitational acceleration developed from observations on earth to evaluate gravitational acceleration in relation to other planets. In such a model, the theoretical relationship remains the same, but the conditions (planet size, proximity, and mass) have changed. Being able to derive correct predictive statements from such a model depends heavily on the uniformity of the causal mechanisms in the theory and their correct transposition to the new case; in the case of gravity and laws of motion, predictions derived therefrom have been borne out in decades of successful space exploration.

This list of reasons for building models is not exhaustive (for more, see Epstein 2008; Miller and Page 2007:78-89), but it highlights a core concept in scientific representation; that
models can share relationships with theory and reality than can facilitate inferences between them. If some models can be considered to be instantiations of theory (such as the harmonic oscillator), and sets of modifications on such models can be made with respect to an analogous relationship to a real phenomenon with the aim of representing it (such as the example of modelling gravitational acceleration near extra-terrestrial bodies), then the separation between these two types of models can be considered in terms of degrees of model faithfulness (Giere 1988:80; Contessa 2011:122). In this sense, models can act as mediators between theory and reality: simultaneously a heuristic space in which to evaluate and adjust theoretical assumptions (Cartwright 1999; Morgan & Morrison 1999; Epstein 2008), and a means of providing expectations about real-world phenomena given a set of assumptions about how the world works (Morrison 2009). A model-based approach that emphasises systematic evaluation of these assumptions presents the potential to help resolve the different interpretations of surface archaeology described in the previous chapters, as these are at their core disagreements over how components of the world work (or worked).

4.1.1 Classifications of models based on medium

The description of models above is not very strict in terms of how models are made manifest. Models are constructed in many different ways, and these different mediums have strengths and weaknesses. For example, physical models (alternatively hardware or material models) are tangible representations of the entity in question. A model locomotive is a physical model, as are other scale models. Physical models are often used to examine the effect of a set of conditions on a similar physical entity. In archaeology, physical models are most often used in various forms of experimentation. For example, butchering experiments will often make use of modern stone tools which provide a model for prehistoric artefact types (e.g. Walker 1978; Jones 1980; Blumenschine 1988; see Clarke 1972:13). A physical model might also be used to visualise a complex process or phenomena in order to gain a better understanding. William Phillips’ MONIAC computer (Bissell 2007), which uses hydraulics to model the flow of revenue within a nation’s economy, is an example of this use. However, because they are material entities, physical models are not very flexible and are
rarely, if ever, used in this visualisation capacity in archaeology. The representation of complex processes is usually done using more abstract models.

Conceptual models, specifically models which are conceptual rather than models of concepts, are a broad class of abstract models which are not necessarily dependent on quantitative information (Tooby and DeVore 1987). These include mental models, causal-loop diagrams, flow charts, and verbal descriptions. Building conceptual models is often the first step in a modelling process, giving the modeller an opportunity to visualise the model before committing to a more formal definition (O’Sullivan and Perry 2013:4). Binford’s (1980) diagrams of collector and forager subsistence-settlement systems are examples of conceptual models, as are Flannery’s (1972) flow charts of control hierarchies. These are used as mechanisms for connecting and clarifying ideas about the ways in which systems operate. Conceptual models are ubiquitous in research (and life more generally), but often make use of assumptions which are for the most part implicit, which can create problems for using them to clarify systemic relationships. Epstein (2008) describes this same sentiment:

“Anyone who ventures a projection, or imagines how a social dynamic—an epidemic, war, or migration—would unfold is running some model. But typically, it is an implicit model in which the assumptions are hidden, their internal consistency is untested, their logical consequences are unknown, and their relation to data is unknown.”

This problem is not limited to archaeology, but is also common elsewhere in the historical sciences where explanations and conceptualizations are largely expressed in verbal rather than formal terms data (Doran 1972; Epstein 2008; Servedio et al. 2014). Such written articulations may feature assumptions which are open to challenge on rhetorical grounds or be misconstrued in translation. One step toward making abstract models more explicit is through the use of formal models (Servedio et al. 2014), such as mathematical or computational models.

Mathematical models are those generated using formal logic and expressed using mathematical notation. A well-known example of a mathematical model is the simple linear regression model in statistics, which is used to examine the relationship between a dependent variable and an explanatory variable based on measurements taken from a sample population (Orton 2000). Mathematical models are often a preferred means of addressing a problem as
they are an elegant expression of a relationship between variables; however, problems involving many variables or being otherwise complex or complicated may be difficult to subdue strictly using mathematical equations (Salmon 1978, Miller and Page 2007:61; Premo 2010:31; Railsback and Grimm 2012:10).

Computational modelling, often synonymous with the term *simulation*, involves the use of computer programs to model an entity. In that sense, they sit somewhere between physical and abstract models. Algorithms, or ordered lists of commands which are used to compute a function, are a key component of a dynamic computational model and provide a means of simulating a process. A command or indeed an entire algorithm might be composed of one or more mathematical equations, but the need to implement these within a computer arises from intractability in the complexity or volume of the equations. The computer is instructed to complete these tasks to produce output, which may either be the sought result or be incorporated into another algorithm operating within the program. The inclusion of elements that are determined probabilistically is a common feature in simulation, often implemented using pseudo-random number generation (Knuth 2014).

It has been argued that simulation in particular is well-positioned to address archaeological questions (Kohler 2000; Kohler and van der Leeuw 2007; Lake 2015). Simulation is often conceived of as a mechanism for experimenting with inaccessible subjects in a ‘virtual’ or ‘behavioural’ laboratory (Kohler et al. 1996; Premo 2007). Computational methods offer a more explicit abstraction of processes than formal mathematical models, allowing for greater degrees of ontological correspondence between model and theory or model and reality (Doran 1970:297; Aldenderfer 1991; Gilbert 2008). Additionally, the complexity that is considered part and parcel to human systems (Gifford-Gonzalez 1991; Smith et al. 2012) can be more effectively assessed computationally than using other mechanisms which rely on top-down explanations (Miller and Page 2007; Kohler 2000). It is primarily on these grounds that Kohler and van der Leeuw (2007) propose that archaeology might be repositioned as a ‘model-based science’, using simulation as a primary component in the archaeologist’s inferential toolkit.
4.2 Simulation in archaeology

It is difficult to pin down the beginning of the overt use of “models” in archaeology, at least in the broader sense of the term. Several histories (e.g. Aldenderfer 1991; Wylie 2002; Kohler 2012) trace the origins of a declared archaeological modelling paradigm to Clarke’s (1972) edited volume, Models in Archaeology. However, in the opening chapter of that book, Clarke argues that models exist in archaeology whether archaeologists would like them to or not. Archaeologists, as humans, use cognitive models to help them to understand the world around them (Clarke 1972:2; see also Jelec 2014:39). By comparison, it is a far easier task to track the history of the use of simulation in archaeology; indeed, there have now been several surveys of that topic which could be referred to (e.g. Aldenderfer 1998; Kohler 2012; Lake 2010, 2014). These tend to break up the history into three successive waves of development, each reflecting the historical circumstances and intellectual climates in which they were developed. To avoid being repetitive, this section will provide an abridged history to provide context for addressing some of the issues discussed in the previous chapter.

Computational models were being used more frequently by anthropologists and archaeologists beginning in the 1960s (e.g. Ammerman and Cavalli-Sforza 1971; Gilbert and Hammel 1965; Kunstadter et al. 1963; Thomas 1972). The appeal of simulation was immediately apparent to some archaeologists, who saw it as a means to build models of social and formational systems as they might have existed in the distant past. In a prescient excerpt (especially given the technology available at the time), Doran (1970:297) describes a hypothetical simulation which would allow archaeologists to experiment with socio-ecological systems:

“Suppose that a certain large island has been extensively excavated and has produced a considerable amount of archaeological evidence… the simulation might have as its main components: (a) a fixed ‘map’ of the island including information about climate, vegetation and fauna, together with (b) specification of the type of settlement characteristic of each population, including... size, material products and demand upon the natural environment, and (c) rules specifying the dynamics of the system – the rules which determine when settlements are founded, when a settlement
is abandoned, what forms of trade and conflict there are between
settlements, and in what ways the material cultures of the populations
evolve.”

Doran’s (1970) description of a virtual island highlights some of the elements of
simulation which have been long been attractive to archaeologists. First, the capacity to
approximate controlled conditions, similar enough for the purpose of answering an
archaeological question, within the constructs of a simulated reality (Antweiler 1991:159).
Secondly, the ability to play out hypothesized scenarios through simulated time, such that
they can be a dynamic “recitation of the history of the operation of physical laws on the
phenomenon in question” (Dunnell 1992:212). Finally, that simulation can combine these
conditions and dynamics to produce outcomes which are comparable to observed
archaeological phenomena means that simulation can act as a vehicle between theory and
reality (Contessa 2007), not unlike that sought in ethnographic analogy by the Middle Range
Theory programme (Binford 1981). Doran’s (1970) imagined simulation is in recognition of,
and a proposed solution to, the limitations identified in the previous chapter regarding the
linking of process and pattern.

Clarke’s (1972) original exposition in Models in Archaeology did not single out
computer simulation as a primary modelling method. His treatment was more generally
focused on models as mechanisms archaeologists could use to mediate between theory and
reality, and promotes a general modelling strategy over a specific implementation of
computational methods. However, in other publications, Clarke (1968, 1973), like Doran
(1970) and others subsequently (Hamond 1978; Lake 2015), recognizes that simulation may
provide the only means of modelling the complex systems thought to be responsible for
archaeological patterning. These early recommendations were followed by the publication of
numerous simulation studies in the 1970s and early 1980s (e.g. papers in Hodder 1978;
papers in Sabloff 1981). Many of these were aimed at evaluating outcomes of hypothetical
human behaviours within a simulated environment. Levinson, Ward, and Webb’s (1973)
simulation of drift voyages in the South Pacific, for example, was used to evaluate
hypotheses of accidental settlement using (what was at the time) detailed wind and current
data from the South Pacific. Steward’s (1955) model of Shoshonean seasonal subsistence
practices was tested by Thomas (1972) using a simulation of resource use that incorporated
geographic information on the distribution of different resources. These are examples of what Aldenderfer (1998) refers to as “whole-society modelling”, which were characteristic in which the first wave of simulation studies developed in the context of the New Archaeology (see Lake 2014).

The 1980s and 1990s saw increased fragmentation among processual archaeological studies and greater particularism in archaeological modelling (Costopolous 2010). Simulation studies in archaeology saw a decline during this period, which has been variously interpreted as reflecting archaeologists’ fickle tastes in method and theory (Chippendale 1993), lack of training in simulation methods and evaluation (Wobst 2010), and the broader dissatisfaction with quantitative approaches following the post-processual critique (Kohler 2012). Despite these setbacks, there were some exceptions which are noteworthy. One is the penultimate publication of the Guila Naquitz project (Flannery 1986), in which Reynolds (1986) employed the use of “cultural algorithms” aimed at modelling how individuals share information in order to mitigate unpredictability in resource availability. Another is the EOS project (Doran et al. 1994), which was an implementation of Mellars’ (1985) ecological model of cultural changes in Western Europe during the Upper Palaeolithic. This used a method known as “distributed artificial intelligence,” an early foray into object-oriented programming which developed into the method known today as agent-based modelling. Finally, Mithen’s (1989, 1990) simulations of forager-prey encounters and individual decision-making, which were in turn inspired by optimal-foraging theory (Bird and O’Connell 2006). These models were significantly different in that they sought to generate macro-scale phenomena through the actions and interactions of individual agents through time.

Developments like cultural algorithms, distributed artificial intelligence, and decision-optimisation were intellectually tied to developments in mathematics and computer science pertaining to the assessment of complex systems (Kohler 2012:101). Simple computational systems such as cellular automata (Wolfram 1984), agent-based models (Schelling 1978), and adaptive networks (Barabási and Albert 1999) which are capable of generating emergent structures through the self-organisation of interacting individual components, began to be applied with some success to social phenomena (e.g. Epstein and
Axtell 1996; Axelrod 1997), and helped to spur a renewed interest in archaeological modelling and simulation during the last two decades (e.g. Kohler et al. 1996; papers in Kohler and Gumerman 2000; papers in Bentley and Machner 2003; Barceló 2008; papers in Costopolous and Lake 2010; Kohler and Varien 2012). Lake (2014) notes that these more recent studies differ from earlier archaeological applications of simulation in that they are often oriented around a simulation, rather than being a component to a wider research programme. This represents a considerable shift from earlier studies in which archaeological simulations are used as a means of confirming existing ideas, to more prominent roles for simulation in the generation of archaeological knowledge.

4.2.1 *Critiques of archaeological simulation*

One of the recurring themes in the literature of computer simulation in archaeology is how arduous the process of building computer simulations is and how this has hindered its wide-scale adoption by archaeologists (Aldenderfer 1991; Wobst 2010). While computer programming is a technical skill, recent technological solutions have made this far less daunting (Grimm and Railsback 2012). This allows programming to occur closer to the speed of thought, making possible for simulation to be used as a means of recursively testing ideas against data. Rather than simulations being strictly limited to hard-won end products in a dedicated study, these developments move models closer to what O’Sullivan and Perry (2013:14 *sensu* Waddington 1977) describe as “tools to think with”; mechanisms by which the modeller can make sense of the world.

A general criticism of simulation that has been applied to archaeology is that computational methods are potentially more complicated or cumbersome than other approaches such as equation-based models. Doran and Hodson (1975), for example, argued that several early simulations were used unnecessarily in situations where mathematical models would have served. While there can be no mistaking that simple equation-based models do not require hardware or software to be used and therefore are less cumbersome in this respect, these criticisms seem poorly justified by the need to optimise clarity. If this were
truly the case, then diagrammatic models might be argued to be even easier to communicate
than mathematical ones, particularly to wider audiences not versed in mathematical
formalisms (Fawcett and Higginson 2012). A computer simulation, like an equation or a
diagram, will require expression of the interpretation on the part of the user. Some have
argued that the expression of some forms of simulation like agent-based models as object-
oriented dynamic processes might be better suited for representing archaeological
phenomena (Lake 2015:10; see also Gilbert 2008). Miller and Page (2007:61) suggest that
the critique may be more sentimental than substantial:

“We often have attachments to particular tools even when they produce the
same outcomes… Perhaps we could argue that an axiomatic proof is still
superior because it may provide some additional insight into the underlying
processes or new theoretical directions in other domains. Whatever the
merits of these types of justifications, they implicitly assume that no such
insights or directions will be forthcoming from the enumerative approach –
an assumption that does not hold in practice.”

The initial embrace of modelling and simulation in the 1970s was met with some
cautions that coincided with broader concerns over explanation in archaeology (e.g. Fritz and
Plog 1970; Salmon 1975; Sullivan 1978; Watson et al. 1971). Some argued that the formal
models being constructed at the time were too simple for complex archaeological phenomena
(Doran and Hodson 1975; Salmon 1978). This is something Wobst (2010) would later
describe these as symptomatic of simulation’s natural range of effectiveness lying between
highly abstract and moderately complex models. Some worried that computer simulation, in
putting what are at best theoretical abstractions within a formal, explicit quantitative
framework, might lead researchers toward the “heuristic error” of believing the world mimics
their simulation, ignoring the potential for other models that might explain the phenomenon
equally well (Dyke 1981:202). But perhaps the most substantive criticism of the early use of
simulation was that while the potential for archaeological use of simulation was clearly
recognised and in some cases applied, concurrent theoretical developments were lacking
(Doran and Hodson 1975:306; Hamond 1978:2). Bell (1987), for instance, criticises several
simulation studies, including Thomas’ (1972) Shoshone study, for adopting models from
geography which, being developed outside of archaeology, offer limited opportunities for
new theoretical insights within the discipline. These critical works emphasised taking a
cautious approach to modelling in archaeology, especially in computer simulation which was still a relatively young method.

The criticism of limited theoretical development has been countered to some extent over the past two decades by the adoption of concepts of nonlinear dynamics and ideas associated with research in complex systems (papers in McGlade and van der Leeuw 1999; Kohler 2012; Barton 2014). Among the main tenets of complex systems theory are the notions of self-organisation and emergence; in other words, that complex, higher-order structures that are identifiable, describable, and in many cases quantifiable entities unto themselves can emerge from simpler, lower-order interactions of individual system components (Anderson 1972; Bak et al. 1987; Weaver 1948:539). Being properties of evolving systems, defining emergent structures necessitates the incorporation of time and space, operating at scales both synchronous with, and different from, those of their parts (Levin 1992:1950; Goldstein 1999:50). These ideas correspond well with contemporary conceptualisations in archaeology of the relationships between individual agency within socio-ecological systems (e.g. McGlade 1995; Bintliff 2008:160), facilitating the application of simulation methods to these systems, although it has been argued that these ideas have not translated easily to inferences regarding the formation of patterning in the material record on which archaeological inference is made (Barton 2014:310-311).

More recently, archaeological simulation has seen critical examination from within in terms of its approach to theory-building and hypothesis testing. Numerous practitioners have pointed to a tendency among archaeologists to build overly specific models aimed at replicating past process (Aldenderfer 1998; Lake 2015; McGlade 2014; Premo 2007, 2010;), and it has been argued that this has yielded few models that are used beyond their initial application (Costopolous 2010:25). This is closely tied to the problem of underdetermination discussed in the previous chapter: Many models, simulations or otherwise, could be used to produce an outcome, and archaeological theories are rarely well-developed enough to differentiate between them empirically. Some have suggested, though, that by grounding interpretation in simpler, more thoroughly understood models considered in an experimental framework, simulation can be used to evaluate the ways in which these different models fit
4.3 Formation, models, and analogues

It is fair to say that many simulating archaeologists employ computational models to overcome the ontological barrier of being unable to observe or experiment with processes occurring in the past (Aldenderfer 1991; Kohler 2000; Premo 2010), which is much the same reason that middle-range approaches make use of ethnographic analogy and actualistic studies (Binford 1981, 2001; Gifford-Gonzalez 1992; Schiffer 1987; Wylie 1985). This resemblance, however, has rarely been made explicit in recent years (but see Premo 2007), and in fact has been downplayed in a number of instances. Kohler and van der Leeuw (2007) draw some distinctions between scientific approaches developed as part of the New Archaeology, and those employed by a model-based archaeology in more recent years. Chief among these is a difference in approaches to explanation. Where New Archaeologists sought to derive law-like statements about archaeological systems through a deductive hypothesis-testing regime, the model-based approach is aimed at generating models that “fits some portion of the world” (Kohler and van der Leeuw 2007:3). This latter description bears strong similarity to the definition of representational models in science given at the start of this chapter (see also Hughes 1997). But while generating Hempelian “covering laws” was once a stated goal of that period (e.g. Fritz and Plog 1970, Watson et al. 1971), it is also true that the many practitioners of middle-range approaches abandoned the deductive-nomological model of science in favour of less stringent models (Wylie 1992; Hegmon 2003), and that much of what has actually been practiced in the interim by archaeologists taking a ‘scientific’ approach is far closer to descriptions of model-based science.

Differences certainly exist between earlier formational approaches and more recent conceptualisations of archaeology as model-based science, but many of these are arguably superficial when compared with the obvious similarities. Specifically, the language adopted by model-based archaeological studies is primarily experimental (Kohler et al. 1996 cf.
Binford 1981:29). Simulation is used for much the same arena for which formation-based approaches such as middle-range theory and behavioural archaeology were originally conceived: to generate a better understanding of variability in the outcomes of processes that formed the archaeological record (Aldenderfer 1991:222). Premo (2007:27, emphasis in original) notes this when he refers to exploratory agent-based simulation as a form of “experimental ethnoarchaeology”, and argues that:

“Exploratory agent-based models start with theory. They allow us to build a set of expectations that can then be evaluated with observed empirical data. As a result, they can facilitate tests (of our assumptions or of a particular hypothesis) that do not suffer from the same pernicious circularity that confounds studies that use the same set of archaeological data both to formulate hypotheses about archaeological formation processes and to test them.”

This recognition of the need for independence between hypotheses built from theoretical understanding, and the data used to test predictions therefrom, bears striking similarities to descriptions of the goals of middle-range approach (e.g. Binford 1981:29). What is being argued for in these cases, then, is not the use of simulation as either a replacement for ethnographic analogy or actualistic studies, nor that simulation is somehow a different path to theory-building that does not involve developing theoretical expectations and testing them. Instead, simulation acts as an additional experimental apparatus to explore variability in the outcomes of archaeologically-relevant processes. Simulation models, being surrogate representations just as actualistic or ethnographic analogies are meant to be, provide a potential means of addressing the methodological barrier discussed in the previous chapter.

Middle-range theory and other formational approaches are meant to act as an ontological bridge between archaeological observations and what is frequently but unhelpfully referred to as “general theory”, and models are likewise considered to operate in this liminal space. Giere (2004:744), for example, while focusing on the power of models as representational tools, describes them as “artful specifications of the very abstract models defined by [theoretical] principles,” fitting between theory and the real world in both a representational and active role. This follows closely along the lines of a depiction of models by Clarke (1972:3), in which theory is used to define explicit models as “formalized, skeletal
expressions” which can be both explored in their own right to examine the dynamics of a
given system and also tested in some circumstances against archaeological observations. In
both of these definitions, general theories can themselves be considered models, albeit at the
extremely abstract end of model specifications, while the other end of that spectrum are
detailed models in the form of case-specific interpretations, narratives, and other devices
meant to replicate a system or conditions in reality and that might be used to predict its
behaviour.

Put another way, in an ideal world, between completely unfaithful abstraction and
precise replication (or, even more precisely, reality) exist models in many shades of
abstraction. Ethnographic analogies, thought of as models from this perspective, are very
difficult to extract from their context, making the information gained from them frequently
case-specific. Models built on controlled experiments are more easily applied outside their
specific cases, but are limited to processes which can be effectively constrained. Simulations,
which can be constructed with varying degrees of direct input from observed phenomena,
might fit anywhere along this spectrum, from hardly less abstract than those models we
might call general theory, to highly-specified models that use particular datasets and
parameter configurations.

For example, optimal foraging theory (OFT) is a basic concept in foraging theory
(Stephens and Krebs 1986), and operates as very general component under the theoretical
umbrella of human behavioural ecology used to evaluate human foraging societies (e.g.
O’Connell and Hawkes 1984; Smith and Winterhalder 1992; Bird and O’Connell 2006).
According to OFT, a predator will try to maximize its energetic returns from prey, meaning
that the prey which provides the most energy for the least cost (that is, time spent hunting and
processing) would be the most preferable, and all others would be preferred in descending
order based upon this equation. Based on this, it could be predicted that as preferred species
become less abundant, the number of prey species exploited should increase. This last notion
is what has composed a theoretical model known as the prey choice or diet breadth model
(Stephens and Krebs 1986:13).

A very basic agent-based simulation based on OFT could be imagined in which a
world consisted of human foragers and patches of varying degrees of productivity. Assuming
that no other force was influencing the behaviour of the agents (e.g. taste preference), the deductive logic of the model is as follows: IF there is a patch nearby the agent with greater productivity than the patch the agent is presently located on (such that the cost of moving is outweighed by the benefit) THEN the agent will move to that patch. This model, while entirely explicit, is not far removed from general theory. In the universe encompassed by the simulation, the propositions of Optimal Foraging Theory are all true. While it provides confirmation of the general principles of OFT, it does little to expand on our understanding or make any more specific predictions that those already stated.

An experimental variant on this might be used to assess how the population dynamics of different prey species operating under the rules of an OFT model might be affected given different distributions of habitats. In some cases, patterning expected from the previous model might hold; in other configurations, it might not, leading to further insights about the operation of such a system. Much like the example of the harmonic oscillator used above, the findings generated from this instantiation of the theory can inform recursively on the theory itself. If the question became more focused upon the expectations under more specific circumstances, simulated environments could be derived from existing geographic datasets, including the distribution and productivity of a set of habitats. The decision-making of individual foragers might also be made more nuanced, with choices made based not exclusively on immediate needs, but on perceived needs based on historical knowledge of changing conditions. At some point, enough specifications could be made that the observations obtained from the virtual foragers becomes closer to that which might be expected to be obtained from an ethnographic study of an actual group of foragers in the environment in question.

The example described here is admittedly ad hoc (although not without precedent, see Simon 1956; Mithen 1989, 1990; Lake 2000), but it presents an idealised way in which simulation could be used to move inference between general theory and empirical phenomena. Binford (1981:24) quotes Amsterdamski (1975) as stating that “the distinction between ‘empirical’ and ‘theoretical’ may only be a relative one” in justification for using middle-range apparatus. By making trade-offs that come from adding or subtracting parts of a model (Winterhalder 2002), the representational strength of the analogy (the simulated
system) can be reconfigured. There is no defensible methodological reason for preferring extremely general or extremely specific models to the exclusion of the other, as they serve different purposes in terms of the knowledge they might be expected to generate.

However, as Callender and Cohen (2006:79) note, models can “succeed along the dimension of representation but fail along the dimension of truth.” For example, adding clouds or the sound of buzzing insects might go some way toward making the above model based on OFT more realistic, but such changes are unlikely to improve the model’s capacity to inform about forager behaviour or its role in archaeological record formation. The specificity of a model does not guarantee its faithfulness to the phenomenon under study, and highly specific models are not always needed for hypothesis-testing. Models used for this purpose need only be specific enough to speak to the specificity of the question they are being used to address (Contessa 2011).

Grimm and colleagues (2005:987) discuss choosing a level of model specification in terms of return on investment, arguing that highly specific models may be too rigid to be widely useful, and overly simplistic models may be too abstract to make reliable predictions. While prediction is not the sole value of a modelling enterprise, models are conventionally gauged according to a fit, formal or informal, to real phenomena (Giere 1999), and models that omit key system components are unlikely to produce non-spurious similarities or may not be able to be assessed empirically at all. Conversely, models that are highly complex make analysis difficult, and may generally be less informative as their specificity may limit their application beyond the cases for which they were developed (Grimm 2005:987; Wainwright and Millington 2008). Optimising the return on investment in this case means finding a point between these two extremes that accounts for both the quality of the data and the knowledge of the system that generated it. For practical purposes, and given the limited understanding of formation dynamics, simpler models have been argued to be a more logical place to start.

4.3.1 Exploratory modelling
Because the specific mechanisms that generated the archaeological record are not directly observable, this inevitably involves the investigation of variables that hold supposed, speculated, or otherwise unknown influence on past systems. In an ethnographic analogy, these are painstakingly observed, left implicit, extrapolated from observables, or omitted entirely. In simulation, by contrast, these can be incorporated as fully-functioning, detailed components of a modelled system. When this is attempted using specific datasets as targets or recourse to analogy without being grounded in well-established theory, the resulting models can be very complicated or esoteric, making it difficult to clearly associate outcomes with variable configurations or to compare with models constructed using different structures or datasets (Lake 2015). Such a process would serve to promote underdetermination rather than alleviate it.

As an alternative, Premo (2007, 2010) promotes another form of modelling – exploratory modelling – in which highly simplified models are used to test hypotheses at more general theoretical levels (see also O’Sullivan 2008:2). The objective of an exploratory model is not to determine the precise historical sequence of events that produced a given dataset, but instead to experiment with a range of conditions that may (or, perhaps more tellingly, may not) produce similar patterning to that observed or expected (Morrison,2009). This is accomplished through exploring parameter spaces, the multitude of outcomes that can be produced by running a model under different configurations of variables (Premo 2012; Brughmans, Keay, and Earl,2014; Crema 2014; Graham and Weingart 2014; Wren et al. 2014). Because exploratory models can be built independently of particular datasets, they are often more revealing about dynamics that may help to eliminate some model structures, narrow parameters to those under which a model produces relevant patterning, and/or suggest additional tests that can be undertaken to discern between interpretations. The primary argument for using simple exploratory models rather than more detailed model structures is that the behaviour of such models can be more clearly understood in terms of possible outcomes and interactions (O’Sullivan and Perry 2013:265). Exploratory models in this case act as building blocks of theory, allowing for hypothesis testing at a lower level (Premo 2010) and providing firmer theoretical grounding for making inferences about more complex phenomena. This operates in much the same way as the appeals to methodological uniformitarianism by Bailey (1983), Binford (1981) and others; in both cases, the objective is
to argue from well-understood principles derived from observations in the present (either through ethnographic observation, experimentation, or, in the case of simulation, experimentation in silico) to unobserved processes in the past.

Exploratory modelling is often associated with the computational method of agent-based modelling (ABM). In this approach, individual system components (often in the form of autonomous computational “agents”) interact with each other and/or their environment according to a given set of rules (Gilbert 2008). These micro-level interactions can generate macro-level regularities over time, allowing the modeller to observe the emergence of these larger patterns or entities as outcomes of smaller-scale activities (Miller and Page 2007). Lake (2014) describes numerous successful applications to archaeological problems emphasizing sociocultural evolution and human-environment interactions, with model outcomes that are frequently social, demographic, or biophysical in nature (see also Barton 2013). These applications, while in pursuit of the goal of model simplicity, may assume an unproblematic relationship between model outcomes and recorded archaeological residues (Barton 2013; Barton and Riel-Salvatore 2014:335). At the same time, debates over the interpretation of observed archaeological signatures, where points of departure are rooted in formation, illustrate that the relationship between past human systems and the material record is anything but unproblematic. This is not to say that abstract models of long-term sociocultural evolution need to be grounded in specific depositional outcomes as a rule, but that the level from which archaeological inferences are drawn (the formation of the deposit) has seen less theoretical attention from archaeological simulators when compared with the development of social and ecological theories. The ability to evaluate the emergent properties of a system through the interactions of individual system components seems as well suited for studying complex archaeological formation as it is for studying complex sociocultural interactions, complementing the generative conceptualisation of surface record formation described in the previous chapter.

This study will use exploratory agent-based models as a means of experimenting with processes supposed to be of influence in the development of archaeological patterning in surface archaeological contexts in arid Australia. Guidelines for developing exploratory models have not been formalised, but studies in archaeology that exemplify the exploratory
approach (e.g. Brantingham 2003; Premo 2012; Crema 2014) tend to follow four basic stages, described here as justification, conceptualisation, implementation, and exploration. Many general frameworks for building agent-based models emphasise this as a cyclical process (e.g. O’Sullivan and Perry 2013:244; Railsback and Grimm 2012:6). In addition, Grimm and colleagues (2010) provide a protocol on how one might document agent-based models at large: the Overview, Design concepts, and Details (ODD) protocol. The ODD was designed to standardize descriptions in order to improve understanding of modelling studies and encourage replication. For describing the process employed here in familiar terms, the ODD provides a useful guide as well.

_model justification_

It has already been noted that there are numerous reasons for building models, but the specific reasons should be known before embarking on a model-based study to avoid leaving assumptions about the problem being investigated implicit. The problems of implicit assumptions in modelling has been discussed earlier (see Epstein 2008) and this is a primary motivation for the use of formal models in the present study, but even the most well-defined and explicit models exist within frameworks of existing theory. In the ODD protocol (Grimm et al. 2010), this justification corresponds to the “Purpose” component of the Overview section. For this study, the presence of multiple competing interpretations of archaeological patterning in WNSW surface deposits involving phenomena that are difficult to experiment with provides this justification, so it is the details of these interpretations which will be used to justify models. Brantingham (2003) likewise identifies a number of potential explanations for a distance-decay relationship between lithic sources and distributions of products obtained from them before suggesting that the process might simply reflect the spatial structure of resource availability. Premo (2012) points to perceived shortcomings in an existing model of cultural transmission between residentially-vs.-logistically mobile foragers, demonstrating the concept with a simpler model. These justifications provide the modellers’ perspective on the problem and help to identify the suite of parameters that have or have not been considered relevant historically and might be considered relevant for the present study.
Model conceptualisation

As discussed above, many existing models in archaeology are expressed in verbal form, and computer simulation is offered as a means of formalising these models to reduce their dependence on implicit assumptions. This does not replace the need for verbal expressions of models, however, as simulations can likewise act as “black boxes” if their functioning is not generally understood by non-simulators (Topping et al. 2010). This stage more or less maps on to the remainder of the Overview section of the ODD protocol, which is based around agent-based systems of particle and grid cell objects, but expectations from the model behaviour (such emergent phenomena) or reasoning for chosen abstractions (such as modelling a variable as random) that fall under the Design Concepts component might also be considered part of model conceptualisation. Because models are abstractions, conceptualising a model involves deciding which elements are germane to the process in question and those which are not, making the assumptions going into the model as explicit as possible. Many existing studies do this by first describing the system as conceived in the literature, and then re-describing it in algorithmic form, explicating in detail each step in the process (e.g. Brantingham 2003:492-493; Premo 2012:647). As the primary aim in exploratory modelling is limiting the parameter space while capturing shifts in model dynamics (Crema 2014:394), the number of potential explanatory variables is kept as few as possible. An extreme form of this is use of null or neutral models, which assume a minimal behavioural in order to establish the necessity of more complex behaviour in generating patterns (Brantingham 2003; Lake 2015:26; Premo 2007; O’Sullivan and Perry 2013:43). In conceptualising an exploratory model, then, the objective is to give a verbal account of the process which the model represents as conceived by the modeller. This provides a more explicit bridge between the problem given in the justification above, and a map for implementing the simulation as computer code.
Model implementation

Translating a conceptual model into a computational one requires the chosen elements to be coded into an explicit set of algorithmic instructions. This requires additional decisions to be made about how to represent the phenomena identified in the model conceptualisation as computational entities. There are many different techniques that a modeller might employ to do so. The ODD protocol offers some guidelines for implementation in terms of the descriptions of model elements in the Detail section, such as the condition of the model at initialisation, any input data that might be used, and the functioning of submodels within the overall model (for example, how prey movement is modelled in the example above of an optimal foraging model). Crema (2014:323) notes that parameters that are circumscribed by natural limits are usually the easiest to implement and explore, as these can be worked through systematically in defined intervals. Some parameters may need to be represented probabilistically rather than as discrete values; Monte-Carlo methods are a set of commonly-used computational mechanisms for assessing uncertainty in model parameters. If there is some degree of variability in a process, a computer simulation can be used to generate multiple outcomes from that process over a range of values, and distributions or ‘envelopes’ of uncertainty can be established through repeated random sampling of the modelled data (Robert and Casella 2004; see Crema 2012 for an archaeological example).

A computer simulation is software, and an important part of any software development is verification: the act of ensuring that the operations performed by the computer are those which are expected from the program as written (Sargent 2010). In computational models, this is typically done through a process of debugging and testing of computer code. An example might be a piece of code which tabulates skeletal elements as a ratio by dividing the number of cranial elements by the number of postcranial elements. In the event that several cranial elements but no postcranial elements are recovered, the existing calculation would involve division by zero, which invariably produces a program error. While some programming languages offer some debugging tools such as exception handling, and source code editors in some development environments offer syntax highlighting or other features, this process is usually done through a process of trial and error (associated with the
praxis notion above). One way to reduce the potential for models to fail during this stage is to limit the number of parameters in the model. It is canon within the modelling literature to use as few explanatory variables as possible when building a model (Miller and Page 2007:46), and as discussed above this is a key feature in exploratory approaches. In addition to simplifying the verification process, this also reduces the number of permutations needed to effectively explore the sensitivity of models to changes in conditions.

Even if a simulation does not produce errors under the settings used to define the parameter space, this does not necessarily mean that errors will not ever occur or that the outcomes are those which should be expected. More proactive mechanisms can also be employed to verify model functioning. These might include visual diagnostics (including plots, numerical monitors, and other visual output to evaluate model functioning), code traces (variables with values that change when specific processes occur), and stress tests (checking the functioning of the model when unrealistically extreme parameter values are used), and known-value tests (checking the model using outputs for which the output should be known) among others (Gilbert 2008; Railsback and Grimm 2012; Sargent 2010). It also suggested that, to improve accountability in computational studies, code be made freely available to facilitate external reviews and encourage reuse and replication. In that respect, the code used in the simulations built for this study will be made available along with the document.

It is important to distinguish verification from validation, which is a process that establishes whether the software adequately performs the task. In the case of a model, this would be achieved if a model accurately predicts the operation of the system which it is meant to represent. An exploratory model should be verified as much as possible, but by strict definition it should not be possible to validate an exploratory model as it is meant to produce a range of outcomes, many of which may not reflect observable phenomena in any coherent way. This is not to say that exploratory models cannot generate outcomes with satisfactory predictive power, but only that this is not a prerequisite for using an exploratory model.
**Model exploration**

Model exploration consists of running the simulation under a set of parameter configurations in the parameter space and comparing outcomes. As discussed earlier, the parameter space is defined by the number of parameters, and the number of settings for each parameter. For example, if the model has five parameters, each with three settings, then the defined parameter space is $3^5$, or 243 individual parameter settings. If some parameters represent continuous variables, then it may be necessary to choose intervals at which the parameter is investigated. For example, a bounded variable that exists between 0 and 1 might be explored in increments of 10%. This entire process is akin to the model assessment process of sensitivity analysis (Gilbert 2008:44), although the aim here is to understand the relationships between parameters generally rather than estimating specific parameter settings that produce empirically plausible outcomes (O’Sullivan and Perry 2013:201). The actual labour of running the simulation is left to the computer. The size of the parameter space, the need to account for stochastic elements by repeating simulations, and the complexity of the computational mechanics of the modelled process itself can influence the resources required to complete the enumeration. The use of supercomputing facilities can aid in reducing computation time or increasing the scale or complexity of simulations.

Once outputs are generated, comparison of outputs is often done graphically, making use of templates that can demonstrate the outcomes associated with multiple parameter settings within a single graph. For example, in examining the effect of fission-fusion dynamics on the rank-size distribution of settlements, Crema (2014) demonstrates the effects of changing spatial, demographic, and fitness parameter inputs as a gridded set of 108 scatterplots, with each grid square illustrating the outcomes of a single parameter setting. Premo (2012) likewise uses a gridded set of line charts with different symbology to illustrate the influence of residential movement on the frequency of forager interaction in terms of different resource distributions, interaction rules, and combinations of foraging parameters. As mentioned earlier, outcomes of Monte Carlo simulations are often presented as envelopes, and these can be presented to demonstrate the variability in model outcomes.

The outcomes of the exploratory exercise allow causal statements to be made that hold in the modelled world. For example, if a parameter change results in a noteworthy
change in model outcomes, as long as the mechanism by which that parameter change influences model behaviour is fully understood, it can be said that the relationship between parameter change and outcome in the modelled world is a causal one. The simulation therefore operates like a theoretical model as described earlier; a model in which given theoretical statements are true. Based on the definitions of representation given above, there is no inherent relationship between a model and an entity it might represent, but rather that relationship is defined by the model’s users. For scientific models, or really any model on which the representational relationship is depended upon to make a decision of consequence, that relationship is typically defined through its capacity to make meaningful expectations about the phenomenon being represented (Callender and Cohen 2006).

4.3.2 Pattern-oriented modelling

On the subject of bridging archaeological theory and the empirical world, existing literature is somewhat ambiguous. Aldenderfer (1998:112) notes that the success of more specialised models is “highly dependent upon how well theory is articulated with empirical expectations derived from that theory.” This speaks to the need for theoretically well-understood “building block” models generated using an exploratory approach like that advocated above in cases where that articulation is not strong. This approach grounds models in theoretically sound components, along the lines of the methodological uniformitarianism upon which approaches like time perspectivism and middle-range theory were constructed. But while the use of overly specific models may be criticised as a retreat from theory (e.g. Gremillion et al. 2014), a unified method for developing strong empirical connections from exploratory models has not been forthcoming.

The systems of interest to archaeologists are often manifold, and the wedded generative structures are not necessarily indicated by a corroborating signal in a set of data. A single pattern, then, has greater danger of having more than one process which might account for it, described earlier as under-determination (Beven 2002; Premo 2010; Rogers 2000). This principle was illustrated by Attenbrow (2006), whose study of Upper Mangrove Creek
near Sydney utilised the temporal distribution of multiple proxies to assess the hypothesis of increasing population growth through the Holocene. This work concluded that while some patterning, such as the number of habitations in use per millennium, were consistent with unidirectional population growth, other patterning such as the rate of artefact discard were not parsimoniously explained this way (Attenbrow 2006).

Models which account for more than one observed pattern, on the other hand, give more leeway in comparing multiple explanations (Dincauze 2000:31; Gifford-Gonzalez 1991:245). However, adding more patterns to be explained will necessarily increase the complexity of model construction and analysis, which may diminish the return on investment if it obscures the relationship between theory and empirical observation. To address this, Grimm and colleagues (2005) recommend a “pattern-oriented” approach to modelling, in which a model produces patterning using multiple proxies. These patterns need not be strictly quantitative, as many interpretations of archaeological phenomena rely on qualitative or impressionistic physiognomies (e.g. the concentric rings of henge features in Western Europe). Restricting an archaeological model to account for only those phenomena which can be quantified would ignore potentially rich sources of information. Grimm and Railsback (2012; sensu Platt 1964) identify differences between “strong” and “weak” patterns, and these generally fall on the respective sides of the divide between quantitative and qualitative. A strong pattern is a conspicuous regularity that is amenable to statistical measures like correlation and regression. A weak pattern is more ambiguous, may be represented through isomorphic comparison or written description. While a strong pattern is preferred to a weak pattern in a singular sense, multiple weak patterns, or combinations of strong and weak patterns, might provide for a better approximation of the real world system than a single strong pattern. Since archaeological patterning, spatial or otherwise, occurs at multiple scales of observation (artefacts, features, concentrations or “sites”, regions, etc.), it is important that modelled processes are consistent with observation at multiple scales (Levin 1992).

Matching additional patterns provides a “filter” for identifying the structure of the generating system by eliminating other potential explanations. For instance, if one wished to identify a reduction strategy used to generate a specific stone artefact assemblage, doing so simply by tabulating the number of flakes would not be of much help. Using other patterns
(e.g. frequency of flake classes, direction of flake removal, cortex retention, etc.) can help to narrow down the ways in which the assemblage could have been generated. The objective of a pattern-oriented modelling study in archaeology, then, is to create a model based on a set of submodels which generate multiple patterns consistent with that observed in the archaeological record at multiple scales, which can be used to evaluate multiple competing hypotheses (Bailey 1983:176; Wylie 2002:95).

4.4 Summary

Up to this point, it has been argued that comparing archaeological interpretations like those developed for surface deposits in western New South Wales depends on the ability to assess how those interpretations account for the generation of that patterning of material remains in the present. It has been suggested that, rather than reflecting different models that are equally capable of explaining the phenomena in question, these competing interpretations exist due to underdetermination of their outcomes in terms of patterning in the record. Analogues obtained from ethnoarchaeological and actualistic studies provide mechanisms for understanding variability in archaeological patterning, but the extent to which such variability can is limited in terms of the physical and organisational scale at which phenomena are observable.

This chapter has presented computer simulations as analogues for making empirically-grounded statements about the operation of formation processes. Because the formation of surface archaeological deposits is poorly understood, an approach that begins by examining basic theoretical concepts about the relationships between formational agents is recommended to guide further investigation. Exploratory agent-based simulation was suggested as a means of establishing baseline expectations from the logic of theoretical sets of formation processes considered relevant to surface archaeology. The exploratory approach favours using simple, well-defined models which might be expected to produce outcomes discernible in terms of changes to their parameter inputs. The objective of the exploratory approach used here is to develop a better understanding of proposed formational dynamics in
terms of formalised models. In the following chapters, exploratory models will be presented to model the formation of two different archaeological phenomena: heat-retainer hearths and stone artefact assemblages. To further exploit the ability of models to of the analogies they provide, a pattern-oriented approach will be used, in which multiple observed patterns are used to build and compare model outcomes.
5 HMODEL: AN EXPLORATORY AGENT-BASED MODEL OF DEPOSIT FORMATION

Following the prescription for building simulations for the purpose of model comparison outlined in Chapter 4, a justification for modelling is made based upon interpretive differences and uncertainties regarding the formation of surface archaeological deposits in relation to the patterning in chronological data obtained from heat-retainer hearths. A verbal model is constructed in which a ‘neutral’ uniform model of human occupation is coupled with a model of rangeland geomorphology based on the concept of ‘episodic disequilibrium’, using the theoretical concepts of stratigraphy and palimpsests to flank the continuum between total deposition and total erosion. In the model, the visibility and preservation of hearths on the surface is differently affected by local deposition and erosion of sediments. The verbal model is translated into an exploratory computer simulation, with a parameter space defined between a measure of erosion and deposition, a measure of landsurface stability, and the frequency of geomorphic events. Model outcomes versus expectations are used to verify the functioning of the model. The results of the simulation exercise are presented, demonstrating how the system as modelled influences the distribution of surface hearth ages under different parameter configurations. Further tests are devised to investigate how deposits of stone artefacts, which are differently affected by geomorphic change, as well as the effects of the modelled processes on the chronological distributions of subsurface hearths. These outcomes are used to formulate ideas about the formation of surface deposits and propose patterns to investigate in a later stage of modelling.

5.1 Model justification

The late Holocene population history of western New South Wales, and the arid zone of Australia more generally, has been a matter of disagreement among archaeologists. Based in part on ethnographic observations of Aboriginal foragers in the 19th and 20th centuries, it was argued that the behaviour of prehistoric desert-dwelling groups would have been significantly constrained by the arid zone environment, promoting the maintenance of an
unchanging desert adaptation (e.g. Gould 1980). Since at least the 1980s, however, it has been contended that greater population growth may have occurred during the late Holocene in the context of a wider-scale social and economic intensification (Balme 1995; Smith 1989; Smith and Ross 2008; Williams et al. 2015b). Alternatively, some have suggested that population growth is not indicated by the archaeological signatures cited (e.g. Bird and Frankel 199; Marwick 2009; Robins 2005), and that the population history of this and other arid regions may not be as unidirectional as intensification models suggest (e.g. Holdaway et al. 2008). The differences between these models of human behaviour, as argued in Chapter 2, are based ultimately on different interpretations of the formation of archaeological patterning.

One pattern frequently used by archaeologists to demonstrate population change is summed radiometric data. These studies bring together large sets of (predominantly radiocarbon) determinations in order to produce a frequency or sum probability plot. The number or density of determinations at any given time period compared to others is argued to be a proxy for relative human population levels at that time. Radiocarbon chronologies from western New South Wales study areas exhibit exponential increases in hearth dates toward the present over the last two thousand years, particularly within the last five or six centuries (Fig. 5.1) (Holdaway et al. 2008; Holdaway et al. 2010; Smith 2013). Studies of surface sediment ages have shown that these correlate with the radiocarbon ages of heat retainer hearths such that sediments of older ages retain hearths that span longer periods of time than do sediments that have more recent ages. This suggests that declining survivorship of hearths containing charcoal may be driving the growth pattern in radiocarbon data (Holdaway et al. 2008). However, in this and other parts of Australia similar patterns in the distribution of hearth ages are interpreted to reflect late Holocene population growth and more intensive occupation in the region, an interpretation supported by changes in assemblage composition and rock art (e.g. Smith and Ross 2008), as well as continental-scale studies of summed radiocarbon data (e.g. Williams et al. 2010; Johnson and Brook 2011; Williams 2012, 2013). It has been proposed that the patterning of hearth ages in western NSW surface deposits is consistent with this interpretation (Smith 2013:323).
Figure 5.1 Summed probabilities of hearth ages at Rutherfords Creek (n=93). Calibrated and summed using OxCal 4.2 (Bronk-Ramsey 2009), using the ShCal13 calibration curve (Hogg et al. 2013). Grey gives raw sums, black line indicates smoothing spline (df=25).

Trends in radiocarbon data are not the only means used to assess population dynamics. In several western New South Wales locations, gaps in radiocarbon sequences have been identified and used to argue for periods of human absence (Holdaway et al. 2005; Fig. 5.2). These gaps are correlated with periods of climate deterioration (Holdaway et al. 2010), suggesting that populations, rather than intensifying their occupation, may not have been routinely resident during the late Holocene. Others have maintained that these gaps are not necessarily inconsistent with models of population growth and intensification. Smith (2013:323), for example, suggests that naturally-shifting local vegetation regimes may have dispersed foragers over wider areas for periods of time, reducing the likelihood of building
hearth within creek valleys where surveys have been concentrated. To date, it has not been suggested that this pattern may be the result of geomorphic changes (Holdaway et al. 2005).

Most of these interpretations are predicated on the idea that changes in the abundance of datable materials (or absences of it altogether) in a given area are primarily derived from changes in the intensity of human activity in that area. This, in turn, depends on a number of assumptions regarding the nature of radiocarbon determinations as data related to human activity, the formation of deposits bearing datable organic remains, their recording in the field, and their subsequent analysis. These issues will be reviewed in the following subsection.

Figure 5.2 Calibrated radiocarbon determinations ($n = 93$) from the Rutherfords Creek study area dating to within the last 2000 years, plotted in order from youngest to oldest. Horizontal lines indicate one standard deviation from the calibrated mean.
5.1.1 *Radiocarbon data as a proxy for human population*

Radiocarbon dating is based on the beta decay of the carbon-14 isotope, which is a naturally occurring radioactive carbon isotope present within earth’s atmosphere, as well as living things and their organic remains. A radiocarbon determination, once processed and calibrated to account for historic changes in the atmospheric concentration of carbon-14, is meant to be a statement of probability that the death of the organism from which datable material is obtained (or, in the case of long-lived plant species, the death of some tissue derived therefrom) took place at a given time, as this is the point at which the organism ceases to accrue carbon-14 from the surrounding environment and carbon-14 remaining within the organism decays without replacement. In archaeological contexts, it is assumed that the difference in time between the death of an organism (e.g. tree felling, shellfish harvesting) and its use and discard by humans is likely to be insignificant, at least at the resolution of the radiocarbon method, thus, a radiocarbon determination taken from an archaeological context is often considered to be roughly contemporaneous with a behavioural event (Bronk-Ramsey 2008). There are additional considerations, such as the differential accumulation of carbon-14 in marine environments (Stuvier et al. 1986), that can influence the estimation of age. However, the connection between the temporal probability distributions obtained from the remains of an organism and the timing of its use or discard by humans in the past represents the core of the logic behind the radiocarbon dating method in archaeology.

It is instructive to think of a hearth where wood is burned, as wood charcoal is one of the most common sources of organic remains used by archaeologists for dating purposes. As long as the species of wood is not long-lived (e.g. Schiffer 1986), there is a good reason to believe that the time elapsed between the death of the plant from which the wood was obtained and its eventual use in a hearth is relatively short. Therefore, the time elapsed between the death of the organism and its recovery by archaeologists (as determined by the rate of beta decay of carbon-14), is likely to also be a reasonably good estimate of the time elapsed since the wood was burned by humans.
If a single radiocarbon determination is taken to reflect the probable timing a single event, then, all other things being equal, the number of determinations falling within the same time period could be considered to reflect the number of events occurring during that time period. Of course, the number of determinations obtained from archaeological deposits is only a sample from the total population of objects capable of being used for radiocarbon dating in existence at any given time, so any inference regarding the number of events represented by radiocarbon determinations falling within a given time period can only be made in comparison with numbers of radiocarbon determinations from other time periods. In this way, frequencies of radiocarbon determinations can theoretically provide a relative measure of the frequencies of events occurring during different time periods.

The method of using frequencies or summed probabilities of radiocarbon determinations as proxies for the intensity of human activity is typically attributed to Rick (1987), who laid out some explicit assumptions regarding the ontological connection between the datable materials recovered from archaeological sites and the relative intensity of activity represented by their different frequencies. One of the fundamental assumptions underlying Rick’s (1987) approach is that when large numbers of determinations from many different locations are used, the overall effects of biases introduced by local-scale, non-random sampling and differential preservation should be minimised, allowing archaeologists using large radiocarbon datasets to make interpretations regarding prehistoric populations or occupation intensity with a reasonable amount of confidence. With the increasing availability of published radiocarbon dates, this method has seen greater use worldwide and increasingly over the past decade (e.g. Gamble et al. 2004; Collard et al. 2008; Mulrooney 2013; Delgado et al. 2015).

In an early application in Australia, Lourandos (1983) proposed that, in addition to other evidence obtained from a regional survey, late Holocene increases in the numbers of radiocarbon determinations in southwestern Victoria demonstrated a significant shift in population during the late Holocene. The data used by Lourandos was later supplemented by Bird and Frankel (1991), who contested the interpretation of intensification by demonstrating that date distributions varied between different site types. Using summed probabilities of radiocarbon dates from inland rockshelter sites in Tasmania, Holdaway and Porch (1995)
showed cyclical patterns of occupation during the late Pleistocene, suggesting a relationship with climatic fluctuations. Additional studies have employed this method to investigate population trends in other regions such as Cape York (David and Lourandos 1997), and the arid zone (Smith et al. 2008; Smith 2013), while still further studies have been used to address population changes at the continental scale (e.g. Johnson and Brook 2011; Williams 2013; Williams et al. 2015b). The contrasting opinions over these patterns in western NSW have already been discussed.

Histograms and summed radiocarbon distributions, such as those developed for regional scale analyses, regularly show greater frequencies of dates in more recent periods than in the more distant past. This issue was raised by Surovell and Brantingham (2007), who noted that this trend is similar to decay trends observed in geological records. Some of the exponential increase in radiometric data, they argue, can be attributed to taphonomic processes that break down archaeological deposits containing datable organic material over time, resulting in a curve that appears to be increasing toward the present but is actually decaying over time. Surovell and Brantingham (2009) later used information obtained from geological proxies to establish an equation by which a summed radiocarbon record might be “corrected” for this preservation bias.

As the method has become more common in recent years, the use of summed radiocarbon data for reconstructing population history has come under greater scrutiny. Williams (2012), using a large dataset of dates from Australia, identified a set of best practices for archaeologists using this method. He identified five key concerns when it comes to the use of this data: non-random intra-site sampling, overall sample size, calibration effects, taphonomic loss (sensu Surovell and Brantingham 2007), and comparison with other proxies. These all concern assumptions that are made about the representativeness of the sample used to produce the curve. Like Rick (1987), Williams (2012:587) argues that larger samples help to overcome the sampling concerns, and sets 500 dates as a minimum threshold for using Australian sequence. To account for taphonomic loss, Williams (2012) adopts the data correction developed by Surovell et al. (2009), modifying it slightly to account for the vagaries of the Australian dataset. Finally, the use of multiple proxies to corroborate
observed patterns is advocated as a check on the summed probability curves (Williams 2012; see also Attenbrow 2006).

Contreras and Meadows (2014) likewise outline explicit assumptions that should accompany any use of summed radiocarbon data as a proxy for human population history, many of which overlap with concerns identified by Williams (2012). However, foremost among their concerns is that researchers using summed radiocarbon data must be able to demonstrate that “the link between production, preservation, and analysis of datable organic material and population in that case is sound” (Contreras and Meadows 2014:606, emphasis in original). Here, production is taken to mean the actual mechanisms by which datable material enters the archaeological record, preservation is taken to mean intervening effects between the original deposition of the datable material and the present that may prevent datable material from being recovered, and analysis is taken to mean the sampling, calibration, and interpretation of patterning in radiocarbon data. Many studies have emphasised the links between production and sampling using simulated datasets (e.g. Williams 2012; Contreras and Meadows 2014; Rhode et al. 2014; Brown 2015). The issue of preservation, on the other hand, has been primarily handled through the use of data modelling and transformations (e.g. Surovell and Brantingham 2009; Williams 2013).

Whether or not a link between these three aspects of demographic reconstruction from summed radiocarbon data has been made, and made soundly, for surface deposits western NSW is debatable. For instance, while Smith (2013) promotes the use of data transformations to account for differential preservation in western NSW surface deposits, taphonomic corrections, such as those developed by Surovell and Brantingham (2009), assume a decay relationship between time and age that does not incorporate the specific effects of formational processes on the condition of deposits at the time of recording. On this point, Williams (2012:585) states, “[w]here site visibility is strongly constrained by the age of specific landforms or depositional units. an assumption of exponential time-dependent taphonomic loss may not be strictly valid.” If this is the case, then it is necessary to understand how formation processes affect not only the preservation of these deposits through time, but also their visibility in the present, if radiometric dates obtained from surface deposits in western NSW are to be used in reconstructing population histories.
These two properties, preservation and visibility, are in large part controlled by the sedimentary history of the deposit, as the local rate of sedimentation determines whether a deposit is buried or exposed, and whether it is subject to surface geomorphic processes or not (Waters and Kuehn 1992; Ward and Larcombe 2003). Differences in the relative frequencies of erosion and deposition of sediment over time and space are likely to produce different patterning within the chronological distribution of discoverable features in surface deposits (to say nothing of subsurface features). Without considering these formational dynamics explicitly, differences in interpretations regarding the prehistoric population history of western NSW estimated from the frequencies of dated materials are unlikely to be resolved.

To summarise, the use of radiocarbon data as a proxy for prehistoric populations is dependent on a number of assumptions regarding the context from which the datable material entered the archaeological record, the formation of deposits bearing datable material, and the methods by which these materials are sampled and analysed. At the very least, suppositions regarding the influence of formational dynamics have not been convincingly argued, and ultimately may not hold in the case of surface deposits in western NSW, and multiple interpretations are likely to persist as long these formational dynamics are not considered explicitly within the conceptual models used to link chronometric data patterning with population. To establish whether the distribution of radiocarbon determinations recovered from these study areas represents a reasonable proxy for population change in the region, it is necessary to assess how formation processes may affect the chronometric signal present in the surface archaeological record. Following the prescription in Chapter 4, and in line with recommendations made by other researchers (e.g. Contreras and Meadows 2014; Brown 2015; Attenbrow and Hiscock 2015), computational modelling will be used to evaluate the influence of these processes on a record of hearth construction.

5.2 Model conceptualisation

The model described here concerns the effects of differential erosion and deposition on the formation of surface archaeological deposits, shown through the chronological
distribution of heat-retainer hearth features. This is used to assess whether patterning within the archaeological record can be accounted for by such processes. As the preservation of faunal remains in these surface deposits is extremely limited, the charcoal in these hearths presently offer the only material suitable for radiometric dating and thus the natural source of data used in reconstructing population histories using the method described in the previous section.

Figure 5.3 Heat retainer hearths at Rutherfords Creek in various states of exposure
5.2.1 Patterns for model structure: Heat-retainer hearths at Rutherfords Creek

Heat-retainer hearths typically present as concentrations of fire-altered stone, in some cases preserving charcoal embedded within sediment beneath the hearth stones (Fig 5.3). It is thought that the hearths were originally formed as pits lined with stone that acted as heat retainers, and were used as earth ovens to cook game (Gould 1967; Fanning and Holdaway 2001a). As the sediments into which the pits were dug erode away, the more stable baked sediments of the hearths sometimes convert into convex features on the surface covered with hearth stones (Fanning et al. 2009a). Left to the elements, these eventually disintegrate, dispersing any charcoal-bearing sediment and leaving behind loose congregations of fire-altered rock.

Surface surveys were conducted to identify heat-retainer hearths along the Rutherfords Creek valley floor. A total of 979 heat-retainer hearths were recorded from the creek valley at Rutherfords Creek (Fig 5.4). A sample of more than a quarter of these (n=256) were sectioned in order to obtain charcoal samples, and 96 of these contained sufficient charcoal to produce a radiocarbon determination using accelerator mass spectrometry (Fanning et al. 2009). Of these, 93 fall within the last 2000 years. All radiocarbon determinations on charcoal samples were processed at the University of Waikato Radiocarbon Dating Laboratory in Hamilton, New Zealand. Calibration of radiocarbon determinations was performed in OxCal 4.2 (Bronk-Ramsey 2009) using the SHCal13 Southern Hemisphere curve (Hogg et al. 2013).
Figure 5.4: Spatial distribution of heat-retainer hearths at Rutherfords Creek (black). Red circles indicate hearths from which radiocarbon dates were obtained.
The distribution of dates from Rutherfords Creek shows fluctuations over time, but a general trend of increasing frequency in the number of determinations is present (Fig 5.1). This is particularly clear when data are aggregated into larger temporal bins (Fig 5.5). For example, when represented in sets of 300 years, there is a four-fold increase in the number of dates from 1800 to 300 BP, including a doubling of the number of dates between 600 and 300 BP.

5.2.2 Modelling the formation of surface deposits

The exposure and visibility of archaeological objects in this region, including heat-retainer hearths, is largely the product of fluvial and aeolian sediment transport. Disconformities observed in the sedimentary profiles at Stud Creek near Tibooburra suggest alternating periods dominated by erosion or deposition throughout the Holocene (Fanning...
and Holdaway 2001a; Holdaway et al. 2004), a process that was accelerated by the introduction of grazing ungulates to the region in the late 19th century (Fanning 1999). Fanning et al. (2007; Fanning et al. 2009a; sensu Renwick 1992) propose a model of “episodic non-equilibrium” to describe the processes forming the surface archaeological record in western NSW, in which large-scale, intermittent geomorphic events relocate sediments within low relief creek valleys, with the effect of either masking or exposing archaeological materials lying on the surface. Since shallow slopes prevent overland flow from reaching velocities capable of moving larger objects (>20 mm; Fanning and Holdaway 2001b), the result is a set of lagged artefact deposits seated on top of “a mosaic of differently aged surfaces many of which lie adjacent to one another” (Fanning et al. 2007). This description contains many of the features of palimpsest deposits outlined by Bailey (2007) and is not dissimilar to geomorphic conditions described for arid and semi-arid regions elsewhere (Gould 1980; Tooth 2000; Bull and Kirkby 2002).

The concepts of the true stratigraphy and true palimpsest discussed in Chapter 3 are relevant here. Sedimentation, from the perspective of an individual deposit, can be considered to occur along a continuum between completely depositional (Lucas’ (2012) true stratigraphy) and completely erosional (Bailey’s (2007) true palimpsest). Wherever the local regime falls along that continuum will have a strong influence not only on the condition of the deposit (e.g. Waters and Kuehn 1992; Ward and Larcombe 2003), but also on its visibility. In western NSW and other arid environments, event-driven erosion and sediment deposition have the respective capacities to erase or preserve archaeological materials deposited on the surface, but sediment deposition events that preserve remains by burying them may also obscure them from view, while subsequent erosion events may reveal them yet again. Differential visibility by burial will influence what is recorded by the archaeologist working in surface contexts. Combinations of intermittent erosion and deposition, as described in the episodic non-equilibrium model above, will produce a surface record that is partly eroded and partly hidden, one that falls somewhere between the true palimpsest and true stratigraphy states.

Within this framework, the processes related to the formation of heat-retainer hearth features situated on the surface can be broken down into a series of mechanistic statements.
Hearth features are constructed by digging into an existing landsurface and engaging in an activity (e.g. burning vegetation and cooking food) that leaves datable material embedded within the feature. If the landsurface into which the hearth is constructed is currently in the process of eroding, then at the next geomorphic event, the hearth should begin to disintegrate, dispersing the charcoal it contains along with sediments and smaller clasts while simultaneously revealing any features situated on the underlying layer. However, if the landsurface on which it is situated is currently in the process of aggrading, then the hearth should begin to be covered with sediment during the next geomorphic event, obscuring it from the view of a surface observer. Assuming limited influences of chemical and biological weathering processes that might break down charcoal within hearths during the interim, hearths should remain more or less intact until the surfaces into which they are dug are eroded. Over time, these forces combined will influence both the visibility and the survivorship of hearths situated on the surface.

This verbal description represents a blunt simplification of a process that is likely to be far more complex and nuanced, especially at the level of individual deposits. However, it is an explicit statement of the theorized operation of a process, and the number of assumptions made in order to make is held to a minimum and, wherever possible, are built upon known uniformitarian principles. As such, it provides a framework for building a computational model in which the number of parameters under investigation is relatively small, facilitating the thorough exploration of the parameter space created therefrom.

5.3 Model implementation

The simulation described here is an exploratory model in the sense that Premo (2007, 2010) defines it. It is meant to be a mechanism that represents elements of the system in question but is simple enough that the entire parameter space over which the model operates can be explored. This structure suits the needs of the current study, which is aimed at understanding the ramifications of a broad set of processes rather than the emulation of
particular circumstances or sequences of events. State variables used within the model are written in **Lucida Console** font.

To explore the effects of differential erosion and deposition on a uniform record of hearth manufacture, an agent-based model, called HMODEL, was constructed using the NetLogo modelling platform (Wilensky 1999). The simulation begins with a \( w \times w \) space of uniformly gridded cells wrapped as a toroid such that the bottom of the grid connects to the top and vice versa, and left side of the grid connects to right and vice versa. The cells in the grid world contain a sequence of values called `sediment_ages` representing an ordered list of sedimentary layers. Time moves forward in the simulation in annual steps, tracked in reverse order as a state variable `years_BP`.

Computational agents within the simulation construct hearths at a constant rate of once per year at random points on the grid. These hearths contain a variable called `age`, given in years before present, indicating the time-step when it was generated. Hearths also contain a Boolean variable called `hidden?` that determines whether or not the hearth is visible on the surface. Any hearth that has an `age` younger than or equal to the age of the most recent layer of sediment of the cell upon which it rests (that is, the lower bound of the cell’s `sediment_ages` list) is considered visible on the surface while any that are older are hidden as part of a subsurface deposit.

At given intervals (`event_interval`), a scheduled event will have one of two effects on cells: either erosion of surface sediments or deposition of new sediments on the surface. If erosion occurs, the uppermost layer of sediment is removed and any hearths visible on the surface are destroyed (or more appropriately, the charcoal particles they contain are dispersed). If deposition occurs, a layer of sediment is added to the cell’s `sediment_ages` list, and any hearths currently visible on the surface are hidden from view. Following subsequent erosional events, hidden hearths can become re-exposed through the removal of overlying sediments. This process is illustrated in Fig 5.6. Over time, repeated deposition events will produce a stratified record interspersed with occupation events, while repeated erosion events will remove any previously lain layers of sediment and evidence of occupation.
In this configuration of the model, the behaviour of agents is neutral, producing a uniform record of activity in order to establish to what extent the patterns observed in the archaeological record are explainable in the absence of directed human behaviour (Brantingham 2003; Premo 2007; Lake 2015). Agents do not favour any cells more than others, nor do they deviate from their rate of construction. Only three variables are explored initially in this model: the proportion of cells experiencing erosion versus deposition during a given event, the percentage of cells that remain stable through a given event, and the time interval between these events.

Figure 5.6 Diagram of processes operating in HMODEL
The erosion/deposition proportion, called \textit{erosion\_proportion}, is expressed as a value between 0 and 1. This is described by a Bernoulli distribution, where the probability of hearths “successfully” experiencing erosion \( n \) is given as:

\[
P(n_j) = \begin{cases} 
1 - p, & \text{for } n_j = 0 \\
p, & \text{for } n_j = 1 
\end{cases}
\]

where \( p \) is the value of the \textit{erosion\_proportion} parameter. During a run of the simulation, each cell draws a random number from a uniform distribution between 0 and 1, and if that number is greater than the value of \textit{erosion\_proportion}, the cell will experience deposition; otherwise, the cell will experience erosion. When \textit{erosion\_proportion} is set to 0, all cells will experience only deposition at every interval, burying archaeological deposits in all cells beneath the same sequential layers of sediment (i.e., a true stratigraphy following Lucas’ (2012) definition). As the value increases, a greater proportion of cells will erode rather than aggrade, with the actual sequence of erosion and deposition varying from cell to cell. When \textit{erosion\_proportion} is set to 1, all cells will experience only erosion, simulating stripping surfaces down to bedrock and removing all previous archaeological deposits (i.e., a true palimpsest following Bailey’s (2007) definition). This variable is explored at increments of 0.1.

A second variable, \textit{surface\_stability}, controls the probability that a cell will undergo geomorphic processes during events. Values for surface stability range between 0 and 1, and this is likewise described by the Bernoulli equation above. At each event, each cell generates a random, floating point value between 0 and 1, and if that value falls below the \textit{surface\_stability} threshold, then the cell undergoes geomorphic change as determined by the erosion/deposition proportion. Otherwise, the cell undergoes no change during the present event. When set to 0, all cells undergo geomorphic change when events occur. If all cells are held stable (e.g. \textit{surface\_stability} = 1), then no changes should occur in terms of the preservation or visibility of surface hearths, producing the unaltered uniform record of occupation generated by the agents.

The final variable under consideration is the interval at which these events occur, controlled in the simulation by the variable \textit{event\_interval}. It is not clear from the
literature what level of fluvial intensity is required to affect geomorphic change in places like those under consideration in western New South Wales. Storms of magnitudes known to carry large loads of sediment downslope occur sporadically (Fanning et al. 2007), with higher magnitude events referred to by their probability of recurrence (e.g., “one in 50 years” or “one in 100 years”); this pattern is corroborated by trends in local palaeoclimate data (Holdaway et al. 2010). However, heavy rains might occur in as little as one in 10 years, while regime-shifting super-floods are occasionally cited in the geomorphological literature that may occur at intervals beyond the scope of recorded weather data (Jansen and Brierley 2004; Fanning et al. 2007; Fanning et al. 2009). Similar variation in frequency and intensity might also be accorded to droughts that bring wind-blown sediments into and out of a catchment (Marx et al. 2009). This is likely to vary from place to place in any event, therefore to evaluate how the frequency of geomorphic events might affect the character of the surface record, these were spaced at intervals of 10, 50, 100, and 200 years in order to observe differences in trends.

The simulations were run over a period from 2000 years to 200 BP, making the assumption that hearth building would substantially decrease after this time as Aboriginal populations suffered the effects of introduced disease and disruptions from colonisation. These three variables (erosion_proportion, surface_stability, and event_interval) are used to capture essential characteristics of the verbal model described in section 5.2, and the combinations of settings described above will constitute the parameter space to be explored below. However, before continuing with the model exploration, the methods used to verify that the model is a successful implementation of the conceptual model are discussed.

---

9 This date is meant to be a heuristic guideline. Aboriginal populations were decimated during the contact period, but documented events are limited to coastal areas. The timing of population declines in the interior is poorly understood.
5.3.1 Model verification

During each time step of the simulation, the agent moves to a random point on the grid and generates a hearth. The modelling of agent behaviours as spatially random is done to evaluate the effects of a spatially variable geomorphic process on a record of undirected human activity, which acts as a null versus the idea that resultant patterning depends on more complex behaviours. To test the randomness of the spatial distribution of agent behaviour, the model was run under a stability setting of 1, preventing any change in surface visibility and preservation, and hearth locations were recorded at the end of simulation. These coordinates were examined using Ripley’s $K$ function, which provides a measure of spatial clustering or uniformity by averaging the number of occurrences at distance intervals from reference points within a given space. For a given distance interval, $d$, the calculation of $K$ is:

$$K(d) = \frac{\sum_{i=1}^{n} \# [S \in C(s_i, d)]}{n\lambda}$$

where $C(s_i, d)$ is a circle of radius $d$ centred at $s_i$ (O’Sullivan and Unwin 2010). Simulation outcomes were then compared to 100 simulations of 2000 points distributed in the same space using a Poisson process. These results were used to produce an envelope circumscribing values expected from a spatially random distribution. Figure 5.7 shows a typical result of those simulations, along with values obtained from hearths in HMODEL.

To assess whether the erosion/deposition process was behaving appropriately, the simulation was run over the 2000 year time period with geomorphic events occurring at intervals of 10, 50, 100, and 200 years, and different erosion/deposition proportions. Following a run of the simulation, the number of elements in the sediment sequences of the grid cells, representing layers of sediment, were recorded to assess the effects of geomorphic events. Sets of simulations in which only deposition occurs should produce grids in which each cell possesses a sediment_ages list with 200, 40, 20, and 10 elements, respectively,
as these represent the number of years over which the simulation is run divided by the
interval length (in other words, one layer per interval over 2000 years). Simulations in which
only erosion occurs should have lists with no elements at all, as there are no depositional
events to produce them. The boxplots in Figure 5.8 show the average number of elements in
sediment_ages lists for simulation grids following 99 simulations under each
configuration. These illustrate that the extreme conditions (total deposition and total erosion)
produce the outcomes expected. The plots for intermediate erosion/deposition values show
how the average number of elements decreases as the rate of erosion increases, while the
range of sediment ages increases toward a maximum as the erosion/deposition proportion
approaches 0.5.

Further debugging efforts comparing visual outputs with expectations were made to
verify the functioning of the model and ensure that results obtained from it are not spurious
outcomes of faulty computer code; however, the spectre of coding errors is omnipresent.
Following best-practice protocols for documenting agent-based models, an Overview, Design

Figure 5.7 Multi-distance spatial clustering ($K_{obs}$) of surface hearths
(black line) from five runs of HMODEL compared to the same for
100 instances of random points distributed in the same space
according to a Poisson process (grey envelope).
5.4 Model exploration

The objective of this exercise is to explore the effects of differential erosion and deposition over time on the surface signature of a uniform record of occupation as expressed through datable features. It is worth repeating that this is not meant to be a digital reconstruction of the surface archaeological record in western NSW or anywhere else. Rather, it is meant to be a test the logic of the verbal formation model described in section 5.2, recording outcomes within the parameter space defined to allow for comparison between different model settings and with archaeological data.

Following the exploratory approach outlined in Chapter 4, simulations were run under all combinations of parameter settings listed in section 5.3. Simulations were run 999 times.
under each parameter setting in order to capture the variability in outcomes from the stochastic erosion/deposition proportion and the random movement of the agent. All simulations were run using the New Zealand eScience Infrastructure Pan Cluster high performance computing system, which links multiple processing cores together in a network in order to run programs in parallel. These resources were made available for the present study through the University of Auckland Centre for eResearch. It is worth noting that NetLogo, at least at the time of writing using release version 5.05, cannot be distributed across multiple cores; therefore, each core within the cluster was used to run a single instance of NetLogo under a given parameter configuration. So although high performance computing was used to reduce processing time, these resources are not required to run HMODEL. After each run of the simulation, data, in the form of visible hearth ages, were output as commaseparated text files.

\subsection*{5.4.1 Overall distribution of hearth ages}
Samples of 100 hearth ages were taken from each run, and these were ordered from youngest to oldest and plotted to form a Lorenz curve. In this configuration, a sample of the uniform record would fall along a diagonal line from 200 BP at bottom left to 2000 BP at top right (Fig. 5.9 and 5.10). Curves falling of the left of this line are interpreted as being weighted toward the present, while curves falling to the right are interpreted as being weighted toward the past. These provide a sense of how the interactions of these different variables over time work to produce visible archaeological patterning in the present.

When sampled ages of surface hearths from all simulations are compared, it is clear that all records generated by the modelled process are biased toward the present (Fig 5.11). As events become more frequent, the distributions are weighted more heavily toward the present as greater numbers of hearths are hidden by deposition or lost to erosion. Increasing the frequency of events produces a record that is younger on average, while more mixed regimes tend to feature a wider range of dates on the surface. As events become less frequent, the mean age of mixed-regime surface hearths tends to increase, but the variability decreases as the number of exposing events is fewer. However, in all cases, the upper quartile age of surface hearths falls within the last 400 years.
Figure 5.11 Outcomes of initial exploration of HMODEL. Envelopes generated by plotting the ages of samples of 100 simulated surface hearths from each run (horizontal axes of smaller plots) in chronological order from youngest to oldest (vertical axes of smaller plots).
Configurations that have inverse `erosion_proportion` settings ironically feature more or less identical distributions. This is because, under more erosional conditions, older hearths are less likely to survive destruction and thus the record is mostly younger, while under more depositional conditions, older hearths will be hidden by layers of sediment, with only the most recent hearth constructions being visible on the surface. This suggests that the surfaces featuring similar distributions of radiocarbon hearth ages may have been formed under highly divergent geomorphological regimes.

5.4.2 Gaps in chronology of surface hearths

The presence of chronological gaps is clearly visible under configurations with longer intervals between geomorphic events. The number of gaps decreases, and the duration of these gaps becomes longer, as the stretches of time between sedimentary events becomes greater. These gaps in the modelled radiocarbon chronology are an outcome of the system as modelled: since the geomorphic events in the model affect all grid cells simultaneously, then all hearths sitting on the surface at that time (including all hearths from the most recent interval) will either be obscured by deposition or destroyed by erosion, leaving only hearths from previous intervals exposed on the surface to be joined by hearths from the upcoming interval.

Figure 5.12 illustrates how event-driven geomorphic processes create chronological gaps in HMODEL. Here, events occur once every 100 years, and `erosion_proportion` is set to 0.5 such that when an event occurs, a cell might experience erosion or deposition with equal probability. At the start of the model at 2000 BP there are no hearths, but as time goes on, the grid world fills with hearths (Fig 5.12 orange crosses). When the event occurs at 1900 BP, all cells experience either deposition (Fig 5.12 blue cells) or erosion (Fig 5.12 red cells). Hearths on depositional cells become hidden from view, while hearths on eroding cells are destroyed, thus producing a surface with no visible hearths from the interval 2000 – 1901 BP. From this point, the process of hearth construction begins anew (Fig 5.12 green crosses).
At the second event in 1800 BP, all cells once again experience either deposition or erosion, and all hearths presently situated on the surface are either destroyed or obscured. Meanwhile, hearths from the previous time period that were previously hidden can become visible again, although far fewer than were visible in 1901 BP. As time moves forward, there are opportunities for hearths from the 1800 – 1701 BP time period (Fig 5.12 violet crosses) to be constructed alongside hearths from the 2000 – 1901 BP time period. If a sample of surface hearths were taken at 1701 BP, there would be appear to be a substantial increase in the number of hearths through time but with a conspicuous gap between 1900 and 1801 BP. Repeating this process produces interdigitating sets of surfaces containing hearths grouped by alternating time periods, with older hearths within those groups becoming rarer through

Figure 5.12 Diagram indicating how chronological gaps are form in HMODEL. Orange, green, and violet crosses indicate hearths constructed during the centuries following 2000, 1900, and 1800 BP, respectively while red and blue squares indicate erosion and deposition, respectively.
time. If radiometric data were obtained from these surfaces at any given point in time, there would appear to be gaps in the record, but these would be purely the result of geomorphic activity.

This also means that if events were not affecting all cells when they occur, then the gaps in age frequency would be less prominent. This can be accounted for in the simulation by relaxing the assumption that all cells are affected when events occur through the third variable accounting for surface stability. Surface stability, given as the state variable `surface_stability`, can be expressed as a percentage of the total gridded space; in real terms, this would be akin to a percentage of the surface remaining stable or residual through a geomorphic event. In Figure 5.13, simulations were run using the same set of `erosion_proportion` and `event_interval` settings but different percentages of cells were left stable through runs. In the original configuration (Fig 5.13, s=0), the plot shows an increasing density of hearths toward the present while also showing regular gaps in the record. As the percentage of stable cells increases, the surfaces upon which the hearths rest become less organised by the sedimentary process and the gaps begin to aggrade (Fig 5.13, s=0.1). As the value for `surface_stability` approaches 50% (Fig 5.13, s=0.5), the gaps are completely diminished but a record of increasing frequency toward the present remains. When stability reaches 100% (Fig. 5.13, s=1), the record undergoes no geomorphic change, and thus displays the uniform record of hearth generation.

5.5 Summary: Learning from HMODEL

The results of this exploratory exercise provide indications of how a sedimentary system, operating under varying parameterisations of the ‘episodic disequilibrium’ model (Fanning et al. 2007), might affect the archaeological signal of a uniform model of human activity. Sequential sedimentation and/or erosion events over time can transform a steady chronological signal into a record that is biased toward the present. While this is partly an outcome of decay by post-depositional processes operating on deposits over time, the combined effects of differential visibility and preservation has the capacity to produce
Figure 5.13 An example of the effect of changing surface_stability (s) settings on modelled outcomes where the erosion_proportion parameter is set to 0.5 and the event_frequency is set to 100 years.

If sedimentary events are of sufficient intensity, features of different ages may end up grouped together on interdigitating sets of extant surfaces, producing apparent gaps in the surface record which are actually a product of geomorphic activity rather than any change in behaviour. In the model, increasing landsurface stability through events can mitigate the gap-producing effect, allowing for the preservation of more ‘gap hearths’ within the record. Further, surfaces under divergent geomorphological regimes may present similar chronometric records using radiocarbon on charcoal. A surface record that is obscured by sediment deposits, or one that has been scoured by erosion, may have similar effects on the temporal distributions of hearth features.
In addition to hearths, stone artefact scatters are a common feature in WNSW archaeology. These occur in varying densities, which have been interpreted by some as evidence of intensity of place use. Unlike charcoal from hearths, stone artefacts are unlikely to be destroyed by episodic geomorphological activity, and experimental and field research has suggested that clasts larger than 20mm are unlikely to be moved by wind or sheetwash (Fanning and Holdaway 2001b). To include the deposition of artefacts in HMODEL, cells were modified to include an additional state variable called artefacts. Whenever agents visit a cell and generate a hearth, they update the artefacts list with a date derived from years_BP. Artefacts, like hearths, were only considered visible if their date of discard was younger than that of the most recent date in the cell’s sediment_layers list; however, unlike hearths, visible artefacts were not removed if they experience erosion. In this way, stone artefacts deflate onto a common surface as sediments beneath them erode away. Additional sets of 99 simulations under each parameter configuration were used to examine the outcomes of this added module.

When the mean density of artefacts on the surface is plotted against the erosion/deposition proportion (Fig 5.14), the resulting graphs for each of the event frequency settings follows a sigmoid curve, wherein the inflection point between low and high density lies at the boundary between conditions dominated by deposition to conditions dominated by erosion. When events are spaced closely together (e.g. event_frequency = 10), the rate of increase is slow across the more depositional settings, but artefact density rapidly increases at the switch between depositional and erosional conditions. As events are spaced further apart (e.g. event_frequency ≥ 50), the curve becomes shallower, with increases in density under highly depositional conditions resulting from greater amount of time for artefacts to accumulate between events.

The ideas that more erosion exposes more artefacts and more time between depositional events allows for greater build-up of artefacts are fairly intuitive. But when they are considered in tandem with the age profiles for the surface hearths shown in Fig 5.10 what becomes apparent is that, in the system modelled here, different densities of surface artefacts might accompany distributions of hearth ages of roughly the same age distribution. If this pattern were considered from a purely behavioural standpoint, denser deposits might be
presumed to reflect more intensive place use within roughly contemporary deposits; however, it may be that these differences instead reflect the adjacency of more erosional and more depositional surfaces.

To make sense of archaeological palimpsests, Lucas (2012:121) argues that archaeologists would do well to “...foreground the processes of inscription and/or erasure, rather than the product.” As it stands, HMODEL has been used to do this by exploring the effects of periodic sedimentation and erosion on the formation of surface archaeological deposits across a range of parameter configurations. The outcomes from the model exploration provide a baseline for the operation of the system as modelled; that is, the statements given above regarding causal mechanisms are only strictly applicable within the

Figure 5.14 Mean artefact densities recorded across different settings of erosion_proportion
modelled world. Some of the parameter configurations used in this exercise produce patterns that exhibit some qualitative similarities to archaeological phenomena recorded from deposits in western New South Wales, chiefly an increasing frequency of dates toward the present and episodic gaps. The model demonstrates that these patterns can be achieved in the absence of directed human activity, emerging from simple rules governing geomorphic change that are based in principles of stratigraphy. In Chapter 7, the patterns generated from this exploratory exercise will be revisited in the spirit of developing tests based on expectations from the model.
6  FMODEL: AN EXPLORATORY AGENT-BASED MODEL OF LITHIC ASSEMBLAGE FORMATION

Following the prescription for building simulations outlined in Chapter 4, a justification for modelling is made based upon interpretive differences and uncertainties regarding the formation of patterning in the ratio of expected cortex to cortex observed in surface lithic scatters. A verbal model is constructed in order to explore how the spatial distribution of flakes and cores influences the expression of the cortex ratio within a given window of observation. In the model, agents move between points on a simulated landscape, manufacturing artefacts on an as-needed basis and discard them between moves. The verbal model is translated into an exploratory computer simulation, with a parameter space defined by the degrees of reduction and selection occurring in the model, the proportion of artefacts entering or leaving a catchment relative to those made locally, and the distribution of spatial displacements between manufacturing and discard events. Model outcomes versus expectations derived from previously published literature are used to verify the functioning of the model. The results of the simulation exercise are presented, demonstrating how the system as modelled influences the distribution of cortical stone under different parameter configurations. These outcomes are used to formulate ideas about the formation of lithic landscapes and propose patterns to investigate in a later stage of modelling.

6.1  Model justification

Like variations in population, the mobility of past peoples in arid Australia during the late Holocene is of interest to archaeologists interested in studying transitions. While it is generally agreed that the ancestors of modern desert Aboriginal groups were foragers who ranged across large territories and social networks, the degree to which the mode and frequency of movements changed substantially during the last few millennia remains contentious. Models of social intensification hold that during this period groups became larger and began to occupy places for longer durations, making greater use of local resources while at the same time becoming more territorial (e.g. Smith et al. 2008; Smith 2013;
Williams et al. 2015b). It is also suggested that residential mobility was high during this period, with the degree of mobility influenced by environmental shifts which would attract or deter visitation rates in some parts of the country (e.g. Holdaway et al. 2010; Veth et al. 2011). The ethnographic and ethnohistorical records are used to support of both these models. For example, accounts of large Aboriginal gatherings witnessed by early European explorers are cited to demonstrate permanent occupations and decreased mobility (e.g. Williams 2015a:3). Other 20th century studies of desert-dwelling Aboriginal groups show a lifestyle of frequent, long-distance movement (e.g. Gould 1980; Thomson 1975; Tonkinson 1993)

Shifts toward greater sedentism are frequently associated with shifts in subsistence practices. For instance, transitions from large-game hunting to more broad-spectrum resource bases, or from foraging economies to agriculture, are implicated in settlement pattern changes in Europe, the Americas, Northern Africa, and Southwest Asia (Bar-Yosef 1998; Zeder 2012). In arid Australia, a late Holocene shift toward greater use of marginal resources, particularly grass and acacia seeds is shown by an increased number of grindstones associated with wet seed-milling (Smith 2013). These grindstones, often referred to as *millstones*, are recorded in late Holocene deposits chiefly in Central Australia (Smith 2004). Grindstones in general are large, heavy objects not considered easily portable (e.g. Gould 1980; Cane 1989), while the grasses and other seeds processed with millstones have a low caloric value relative to their processing costs (O’Connell and Hawkes 1984). An increase in their use therefore suggests lower residential mobility as groups used locally abundant resources in response to decreases in higher-ranked resources and greater social obligations (Smith 2013:202).

Despite the logic of this interpretation, seed-grinding implements are not found exclusively or even primarily in late Holocene contexts. Grindstones are known from a number of Pleistocene and early Holocene assemblages (e.g. Balme 1991; Gorecki et al. 1997; Fullagar and Field 1997), some with residue analyses indicating the grinding of seeds (Balme et al. 2001; Fullagar et al. 2015). Considering the difficulty in obtaining comparable samples of Pleistocene-aged deposits (Edwards and O’Connell 1995), the available evidence challenges interpretations of subsistence change in the late Holocene. But regardless of
whether seed grinding was limited to the late Holocene or not, determining mobility using heavy-duty grinding equipment is difficult as it relies on artefacts that were supposedly rarely moved. In effect, a conceptual relationship is proposed between an archaeological phenomenon (grindstones) and a behaviour which would not directly affect it (movement). Close (2000) argues that archaeologists often approach mobility using a perceived capacity to move, rather than evidence of actual movement. The capacity to move is thereby conflated with evidence for movement. Conceptual mobility is illustrated using features or artefacts similar to ethnographic cases in which people were either sedentary or mobile (Phillipps and Holdaway 2015).

Associations of certain artefact types with degrees of mobility are not always supported by archaeological data. For example, architectural features are often classed as permanent, semi-permanent, or temporary based on the investment in labour, and this is used to infer the degree of sedentism of the people responsible for the architecture (e.g. Rafferty 1985:129; Williams 1987). However, investment in building does not necessarily preclude prior or subsequent movement (Boyd 2006; Clarke 1994). For instance, Boyd (2006) argues that the development of stone architecture at the end of Levantine Epipalaeolithic may indicate investment in place, but this does not equate to time spent at that place. It may instead reflect places to which people returned rather than places where sedentary people resided. Interpretations based on conceptual mobility will change when the conceptual model concerning the role of the artefacts changes. If formational models are to be used, proxies associated with movement are needed rather than models based on conceptual mobility.

Evidence for residential features in Australia is limited (but see Williams 1987; O’Connor 1987; Clarke 1994; Builth 2002) and is absent from the arid zone. However, like architecture, grindstones are considered to be part of a sedentary lifestyle (Belfer-Cohen and Bar-Yosef 2000) and abundances of these in archaeological deposits are taken to show decreased mobility (Smith et al. 2008; Smith 2013). But while increased frequencies of grindstones are associated with known or presumed instances of sedentism, and are conceptualised as part of sedentary lifeways, their presence or absence does not directly indicate whether any movement has occurred. Since they do not reflect movement, they cannot be related to the formational history of a deposit that concerns movement, and these
instead reinforce essentialist models of behaviour (Allen 2015). To compare interpretations of movement, proxies are required that bear directly on whether movement occurred or not, and ideally indicate something about the nature of such movements.

Among the artefacts present in archaeological deposits in western New South Wales, stone artefacts are the most likely candidate, as they are portable, durable, and ubiquitous in the region. A substantial body of theoretical research exists concerning stone artefacts and movement (e.g. Andrefsky 1991; Shott 1986, 1996; Nash 1996; Close 2000). Changes in the frequencies of some artefact forms are used to argue that groups were more or less mobile during prehistory. For example, in Australia, greater abundances of tula (a stout, semi-discoidal adze flake with a pronounced percussion bulb and a retouched, convex cutting edge; see Holdaway and Stern 2004:253-256) found in assemblages dating from the mid to late Holocene are used to indicate higher residential mobility during this time. Tula are seen as versatile, general purpose tools incorporated as part of a risk-management strategy (Hiscock 1994) adopted at the onset of greater climatic variability due to El Niño-Southern Oscillation intensification (Veth et al. 2011). Alternatively, tula, along with the wooden toolkit manufactured with the implement, are taken to represent part of a strategy of greater logistical mobility to offset depletion of local resources from longer occupations (Smith 2013). Both of these interpretations, like those used for grindstones, depend on an association of the object with a conceptual context of use, and are therefore not amenable to formation modelling.

Methods that are less reliant on functional conceptualisations tend to focus on variability in the attributes of the artefacts rather than the presence of some forms. Geochemical sourcing of artefacts is used to reconstruct point-to-point distances when raw material sources can be readily identified (e.g. Nash et al. 2013; Allen and McAllister 2013). Other studies emphasise the reductive nature of stone artefact manufacture. Close (2000), for example, demonstrates how refitting studies of stone artefacts can be used to reconstruct movements by re-connecting the products of a reduction sequence back into an original whole (see also López-Ortega et al. 2011). However, both sourcing and refitting studies have logistical constraints which make their application to cases like Rutherfords Creek problematic. Potential sources of silcrete, the predominant raw material in the region, occur
in creek beds, gibbers, and outcrops across wide expanses of the region (Doelman et al. 2001, Shiner et al. 2005). While artefacts might be shown to have a geochemical signature statistically similar to that obtained from silcrete sources in one or more locations, any interpretations would depend on the extent to which all other potential areas could be demonstrated to be statistically different. Large scale refitting studies are currently arduous to undertake, and the outcomes are dependent on the skill of the refitter (Laughlin and Kelly 2010). Alternative methods are less prone to observer bias. For example, one study applied at the Rutherfords Creek used a method that quantified artefact colour, and demonstrated statistically probable conjoining artefacts within and between assemblages. One probable refit spanned a distance of over 8 km (Barker 2009). However, even if the analytical component of this method were automated, it would still require researchers to photograph each artefact under carefully controlled lighting conditions, hampering larger scale applications.

An alternative approach uses the geometric attributes of artefacts to evaluate the extent to which expected reduction products are present within a given assemblage. In western New South Wales, surface stone artefact assemblages are deficient in cortex, the outer weathered surface of unworked stone, and this is used to argue for high mobility and low redundancy in place use as stone artefacts bearing cortex are removed from the area. The logic of this argument is reviewed in the following section.

6.1.1  The cortex ratio as an indicator of archaeological mobility

Naturally occurring stone often features an outer rind known as cortex. Cortex forms as the result of natural weathering processes or mechanical processes (Andrefsky 2005). Following lithic reduction, cores will retain a percentage of their original cortical surface, while cortex will also be present to varying degrees on the dorsal surface of some flakes. The relative level of core reduction or the reduction stage at which a flake was removed may be expressed by the amount of cortex remaining on the dorsal surface of the artefact (e.g.
Andrefsky 2005:103; Blades 2001:95). Cortex is by necessity removed upon reduction, and usually early in reduction sequences.

For a given assemblage of stone artefacts, the cortex ratio is the proportional relationship between 1) the cortical surface area observed from the artefacts in the assemblage and 2) the cortical surface area that is expected for that assemblage. The surface area of a flake covered by cortex can estimated by using the axial dimensions (length x width) to approximate the total surface area, and multiplying this by the percentage covered in cortex, which is usually estimated at intervals (Dibble et al. 2005). The cortical surface area of cores can be approximated by using the axial dimensions of the core to calculate the surface area of a geometric proxy (like a prism or spheroid) and then multiplying this again by the percentage covered in cortex. The expected cortical surface area is based upon a geometric model of nodules used to produce the assemblage, which in turn is calculated using a theoretical average nodule volume (Dibble et al. 2005). Ideally, this theoretical nodule represents an average size and shape of nodules used to produce the flakes and cores in an assemblage.

The cortex ratio is used as a measure of movement by estimating, on average, how much cortical material was moved in or out of an assemblage given the cortex expected from the number of cores and the average dimensions of local raw material. This is calculated in slightly different ways based on the material encountered and the questions being asked. The evolution of thought around the cortex ratio is charted in its use over time:

- The original estimation by Dibble et al. (2005) was based on an experimental dataset derived from 33 nodules of stone. This study divided the total volume from the assemblage (calculated from artefact weight and material density) by the number of cores present in the assemblage to estimate average nodule volume, which was then input into equations for different geometric solids (e.g. sphere, rectangular prism, etc.) to obtain an estimate of average nodule surface area. The experimental assemblage was used to evaluate the effects of varying average nodule size and shape, nodule counts, and the removal or addition of cores and flakes on cortex ratio outcomes.
- A similar approach was used by Douglass et al. (2008) in a study of assemblages from locations in western New South Wales. A scalene ellipsoid was used to approximate cores surface area. The model was tested using two
experimental datasets, one using six quartz nodules and the second using seven silcrete nodules. Cortex ratio calculations for all recorded assemblages returned values consistently lower than one. The authors suggest that individuals “gearing up” with cortical flakes before departing might explain this patterning.

- Following Braun (2006), Douglass (2010) sought to improve estimates of average nodule size through the use of experimental datasets. In these, the original volume of nodules is known prior to flaking, and attributes of reduced cores can then be used to predicting the percentage of original nodule mass lost during flaking. Douglass (2010:169-180) developed two alternative methods for estimating this value for the purpose of reconstructing original nodule volume; one based on a linear regression using the percentage of cortex remaining on the surface, and a second based on a multiple linear regression based on flake scar counts, core area, and exploitation surface interactions. These refined calculations were used to show variability in cortex ratios at Rutherfords Creek, with values for the most part lower than one.

- Lin et al. (2010) used laser scanning of recorded artefacts to test the reliability of cortical surface area estimates. Findings suggest that the methods applied in the earlier studies by Dibble et al. (2005) and Douglass et al. (2008) produced precise assessments, with errors averaging out as sample size increases.

- Douglass and Holdaway (2011), recognising that the cortex ratio calculation depends on an accurate estimate of nodule size, evaluated how underestimates of nodule size might account for the low cortex ratios at western New South Wales locations. The size of a single nodule large enough to account for the surface area represented in assemblages was calculated, and a Wolman pebble count (Wolman 1954) was applied to several raw material sources at Rutherfords Creek and other western New South Wales study areas in order to establish the likelihood of selecting cobbles of this size randomly. The frequency of large cobbles within all areas surveyed was never greater than 0.03% (Douglass and Holdaway 2011:50). Minimum Analytical Nodule Analysis (Larson and Finley 2004) was also undertaken to assess whether each core was derived from a unique nodule, and findings were consistent with this hypothesis.

- At Contrebandiers Cave in Morocco, Dibble et al. (2012) found cortex ratios lower than one for low density Middle Palaeolithic assemblages. The authors used two methods for calculating average nodule size: assemblage mass divided the number of cores, and the average mass of cores with 60% cortical surface. Disparities in cortex ratios calculated using these two methods were used to indicate greater assemblage volume relative to the number of cores.
present for coarse-grained materials (e.g. quartzite), suggesting the transport of cores away from the site.

- Parker (2012) examined the effects of selection of flake morphology using a computer simulation. The simulation generated large assemblages through bootstrapping an experimental dataset. Results of this study suggested that core reduction and selection of cortical flakes would need to be substantial, on the order of >20% of largest flakes ranked by size, in order to produce cortex ratios comparable to those recorded at Rutherfords Creek.

- Phillipps (2012) noted variability in cortex ratios from multiple surface assemblages in eastern Egypt, and found cortex ratios to be inflated at several locations with suspect flake-to-core ratios. To assess this, she applied a secondary calculation based on the ratio of observed-to-expected volume of artefacts to establish whether the high cortex ratios were the result of an influx of flakes or the removal of cores. Results of her analysis of the cortex and volume ratios were consistent with the hypothesis of transported cores and secondary removal of flakes (see also Phillipps and Holdaway 2015).

- Working on assemblages of basalt artefacts from the island of Aitutaki in the central Pacific, Ditchfield and colleagues (2014) used the cortex and volume ratios in an adze manufacturing site. Resulting high cortex ratios and low volume ratios from that study were consistent with the interpretation of regular removal of de-cortified adze preforms.

- Lin et al. (2015), dealing with the potential problem of multiple cores per original nodule, calculated average nodule size for Middle Palaeolithic assemblages in the Dordogne region of France using a linear regression based on maximum width or length of flakes in the assemblage. This study also accounted for naturally-occurring non-cortical surfaces by estimating their frequency in local raw material, and recommended the use of bootstrapped experimental data to establish whether the uncertainty in average nodule volume estimates could account for high or low cortex ratios.

Several researchers have suggested that differences in foraging behaviours might influence the distribution of cortex among mobile hunter-gatherers. Douglass (2010) argues that movement patterns which result in lower redundancy of place use will produce assemblages deficient in cortex, while Holdaway et al. (2012:287) suggest that “all things being equal, fewer moves will tend to produce increased cortex ratio values and more moves the opposite.” At present, this theoretical relationship between movement and cortex ratios remains untested. For instance, Phillipps (2012:241) discusses the implications of varying cortex and volume ratios at Egyptian locations as an outcome of different movement patterns.
across space, but expresses this in terms of “loss” of either surface or volume from assemblages. Patterning in cortex ratios obtained from excavated Middle Palaeolithic assemblages at Roc de Marsal, Pech de l’Aze IV, and Combe Capelle Bas in France by Lin et al. (2015:102) is likewise suggested to be indicative of changes to movement patterns through time, but they note that these outcomes may be explained in other ways and ultimately contend that “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.”

When compared to individual assemblages, interpreting cortex ratios at the landscape scale becomes more complicated, as assemblages can no longer be considered in isolation but as part of the net flow of artefacts across a surface. Douglass (2010), for example, assesses the consistently low cortex ratios obtained from assemblages recorded at Rutherfords Creek as evidence as the patterned outcome of a low redundancy in place use and a preference for large (and thus disproportionately cortical) flakes selected for use away from the creek valley. This contrasts with increased logistical movement during the late Holocene promoted for this and other parts of the Australian arid zone, which as discussed above are based on proxies associated with the capacity to move rather than proxies affected directly by the act of moving (e.g. Smith 2013). Until patterned variability in cortex ratios can be connected to patterns of movement, rather than strictly the removal or addition of materials to a given assemblage, interpretations of mobility or sedentism in late Holocene contexts cannot be compared in terms of their formational expectations.

In sum, archaeologists have debated the nature of mobility in arid Australia during the late Holocene, but most arguments depend on proxy data consistent with conceptual rather than archaeological mobility (Phillips 2012:6; post Close 2000). Such proxies are ill-suited for comparing models in terms of formation as they are context dependent. In contrast, the cortex ratio is a proxy of archaeological mobility which indicates movement patterns for stone artefact assemblages in western New South Wales through the augmentation of assemblage components. It is theorised, but not demonstrated, that different patterns of movement will have predictable formational outcomes that pattern cortex ratios both within and between assemblages. To better understand where cortex ratios at Rutherfords Creek fit
along a continuum between nomadism and sedentism, cortex ratio outcomes from different mobility regimes need to be assessed within a common framework. An exploratory model of surface assemblage formation will therefore be used to examine the influence of different movement patterns on assemblage-level cortex ratios.

6.2 Model conceptualisation

The model described here is used to evaluate the effects of differential manufacture, transport, and discard of stone artefacts on the formation of lithic assemblages. The resultant assemblages will be used to calculate the ratio. This is used to assess how different movement patterns might produce noticeable deviations in ratios at the assemblage level.

The model described here concerns the effects of differential erosion and deposition on the formation of surface archaeological deposits, shown through the chronological distribution of heat-retainer hearth features. This is used to assess whether patterning within the archaeological record can be accounted for by such processes. As the preservation of faunal remains in these surface deposits is extremely limited, the charcoal in these hearths presently offer the only material suitable for radiometric dating and thus the natural source of data used in reconstructing population histories using the method described in the previous section.

6.2.1 Patterns for model structure: Surface lithic assemblages at Rutherfords Creek

Lithic assemblages produced through hard-hammer percussion are composed of two primary components: cores and flakes. Flakes have a ventral surface where shear stress splits the flake from its parent stone. Cores are the remnants from nodules of stone with negative scars from the flakes removed, and have no ventral surface. Cores or flakes might be converted into many different forms through retouch. A complete breakdown of artefact classes, following a classificatory scheme in Holdaway and Stern (2004), can be found in
Table 6.1. While a range of artefacts were recovered from the Rutherfords Creek including formal tools, unretouched flakes and cores account for 93% of recorded flaked artefacts, a finding in line with other western New South Wales locations (Holdaway et al. 2004; Shiner et al. 2005; Holdaway and Fanning 2014).

Surface surveys were conducted on exposures of indurated subsurface sediments known locally as “scalds”. Scalds form beneath upper layers of sediment through the leaching of siliceous materials, creating an impermeable subsurface sedimentary layer that can become exposed through the erosion of finer overlying sediments. The location of each scald within the Rutherfords Creek catchment was mapped and its area was recorded. A total of 2271 scalds were mapped, representing a total area of approximately 1.8 km$^2$, or 13% of the total surface area of the valley floor (Fig. 6.1). A total of 24,179 stone artefacts were recorded from a random sample of 107 scalds representing approximately 5%. The dominant raw material was silcrete (89.4%), followed by quartzite (10.3%), while remainder consisted of a handful of quartz, sandstone, and petrified wood (<1%). Archaeologists recorded attributes for each artefact in situ, including artefact class, maximum dimensions, platform
width and thickness, exterior angle, cortical surface and cortex type, number of retouched edges, number of dorsal flake scars, probable nodule source, and number of core scars. During one field season, weight was recorded using a portable digital scale; this data was used to generate a regression formula based on artefact volume (Douglass 2010).

Table 6.1 Stone artefact classes recorded at Rutherfords Creek. Artefact classes showing retouch are shaded grey.

<table>
<thead>
<tr>
<th>Artefact class</th>
<th>% of total recorded</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete Flake</td>
<td>44.53</td>
<td>10768</td>
</tr>
<tr>
<td>Distal Flake</td>
<td>13.45</td>
<td>3251</td>
</tr>
<tr>
<td>Angular Fragment</td>
<td>9.91</td>
<td>2397</td>
</tr>
<tr>
<td>Proximal Flake</td>
<td>8.44</td>
<td>2041</td>
</tr>
<tr>
<td>Complete Split</td>
<td>6.77</td>
<td>1636</td>
</tr>
<tr>
<td>Core</td>
<td>5.77</td>
<td>1394</td>
</tr>
<tr>
<td>Complete Tool</td>
<td>4.11</td>
<td>993</td>
</tr>
<tr>
<td>Medial Flake</td>
<td>2.75</td>
<td>666</td>
</tr>
<tr>
<td>Distal Tool</td>
<td>1.09</td>
<td>264</td>
</tr>
<tr>
<td>Proximal Split</td>
<td>0.82</td>
<td>199</td>
</tr>
<tr>
<td>Angular Fragment Tool</td>
<td>0.61</td>
<td>147</td>
</tr>
<tr>
<td>Broken Split</td>
<td>0.45</td>
<td>109</td>
</tr>
<tr>
<td>Proximal Tool</td>
<td>0.35</td>
<td>84</td>
</tr>
<tr>
<td>Broken Complete Flake</td>
<td>0.33</td>
<td>79</td>
</tr>
<tr>
<td>Complete Split Tool</td>
<td>0.16</td>
<td>38</td>
</tr>
<tr>
<td>Medial Tool</td>
<td>0.14</td>
<td>35</td>
</tr>
<tr>
<td>Milling Slab Fragment</td>
<td>0.11</td>
<td>26</td>
</tr>
<tr>
<td>Hammerstone</td>
<td>0.07</td>
<td>17</td>
</tr>
<tr>
<td>Muller</td>
<td>0.06</td>
<td>15</td>
</tr>
<tr>
<td>Pestle</td>
<td>0.03</td>
<td>7</td>
</tr>
<tr>
<td>Proximal Split Tool</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>Complete Bipolar Core</td>
<td>0.01</td>
<td>3</td>
</tr>
<tr>
<td>Medial Split Tool</td>
<td>0.01</td>
<td>2</td>
</tr>
<tr>
<td>Chopper</td>
<td>0.01</td>
<td>2</td>
</tr>
<tr>
<td>Axe</td>
<td>&lt;0.01</td>
<td>1</td>
</tr>
<tr>
<td>Block</td>
<td>&lt;0.01</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td>24179</td>
</tr>
</tbody>
</table>
Of the assemblages surveyed, 89 met the minimum requirement of containing at least one core needed to produce a cortex ratio. Calculating the cortex ratio for a given assemblage requires knowledge of the volume (which can be approximated using mass) and the cortical surface area of the assemblage. For flakes and fragments, surface area is estimated by multiplying maximum length by maximum width. The surface area of cores could be estimated using a number of different geometric proxies; following Douglass (2010), the equation for the surface area of an oblate spheroid is used:

\[ S = 4\pi \left( \frac{a^p b^p + a^p c^p + b^p c^p}{3} \right)^{1/p} \]

where \( a, b, \) and \( c \) correspond to three axial dimensions and \( p \approx 1.6075 \). Once the surface area has been estimated, cortical surface area is estimated by multiplying the surface area by the decimal value of the mid-point of cortex estimate (0 for none, 0.25 for 1-50\%, 0.75 for 50-99\%, and 1 for 100\%). The values for observed surface area and observed cortical surface area for all artefacts can then be summed to give assemblage-level values.

The volume of nodules used by people in the past is not known. To estimate this value, the summed assemblage volume is divided by the number of cores present in a given assemblage to give an average nodule volume. To obtain artefact volume, artefact mass is divided by the density of the material; for silcrete artefacts, this is approximately 2.53 t/m³ (Tracey and Direen 2002). In the absence of a mass recording, Douglass (2010:110) provides as a set of regression equations which can be applied using maximum dimensions. The surface area of an average nodule can then be estimated by substituting average nodule volume into the equation for surface area of a sphere:

\[ S = 4\pi \left( \frac{3V}{4\pi} \right)^{2/3} \]
This value is multiplied by the number of cores in the assemblage to give the expected cortical surface area for the assemblage. Finally, the cortex ratio is obtained by dividing the observed cortical surface area by the expected cortical surface area. If all products of reduction are present, the cortex ratio should approximate one. Cortex ratios below one suggest that there is less cortex than should be present for the assemblage, while cortex ratios higher than one indicate that there is more than should be present.

The distribution of values for Rutherfords Creek assemblages is plotted in Fig. 6.2. Overall, cortex ratios recorded from surface lithic assemblages at Rutherfords Creek are low; in fact, all but two low-density scalds produce cortex ratios lower than 1. The average cortex ratio for the area is approximately 0.56, with a standard deviation of 0.18. Low cortex ratios from Rutherfords Creek and other locales have been used as evidence of the regular transport of cortical flakes, and this forms the basis for Douglass’ (2010) interpretation of landscape mobility during the late Holocene.
6.2.2 Model structure

In its simplest manifestation, the cortex ratio is a measure of the amount of cortical surface present on cores and flakes in an assemblage, divided by the amount of cortical surface expected from that assemblage. As a nodule of stone is reduced, the amount of cortical surface present on the resultant core decreases, while the amount of cortex present in the form of flakes produced from that core increases. Once flakes are removed from cores, the products might be discarded locally or transported away. Removing cortical flakes or adding cores will decrease the cortex ratio for a given assemblage, while adding cortical flakes or removing cores increases the cortex ratio for a given assemblage (Dibble et al. 2005). These imbalances are used to illustrate whether flaked material has been removed or supplemented within a given assemblage.

As discussed above, in addition to the measured cortical surface of the assemblage under study, the equation itself requires an estimated number of nodules used to produce the assemblage, as well as an approximation of average nodule shape and volume. These components are typically derived from the assemblage itself, or from an assessment of locally available raw material, and several studies have focused on developing better estimates for this (e.g. Lin et al. 2010; Ditchfield et al. 2014; Phillipps and Holdaway 2015). Additionally, the number of artefacts present, as well as the actual attributes of the artefacts themselves, will influence patterning in an assemblage. For example, using a computer simulation, Parker (2012) demonstrated that biasing selection based on maximum dimension would have a stronger tendency to produce lower cortex ratios than other attributes. However, if the questions being addressed are exploratory in nature and less specific to any particular case study, then specific nodule or artefact properties are not essential to perform the calculation as long as the basic relationship between original surface area and products of reduction is preserved.

Cortex ratios are calculated from lithic assemblages formed through the accumulation of discarded artefacts over a given span of time, spatially circumscribed by an observational window determined by the archaeologist. Over time, stone might be worked and discarded locally, or might move into or out of an assemblage as either unworked raw material or
reduction products (i.e. cores or flakes). Knell (2012; post Sellet 1999) illustrates this process using a series of five scenarios (Fig 6.3):

1) Raw material is reduced and discarded locally.
2) Raw material is reduced locally and some products are removed from the assemblage.
3) Raw material is imported and worked locally, potentially breaking and being discarded locally or being transported away as finished artefacts.
4) Finished artefacts are carried into the assemblage area, are maintained through retouch, and then removed from the assemblage area.
5) Finished artefacts are carried into the assemblage area and discarded locally.

This scheme provides a general sense of the processes which might generate an assemblage of stone artefacts. Calculations of the cortex ratio do not differentiate between
maintenance and manufacturing activities, but rather treat both as forms of flake removal. Therefore, for the purposes of this study, scenarios 3 and 4 might be collapsed into a single scenario where flaked material is brought in, flaked again locally, and transported away. A further scenario might be envisioned in which discarded material from a local existing assemblage is removed from the observational window on a subsequent occasion; however, even though the constituent behaviours are divided between two separate events, this behaviour is captured from a formational standpoint by Scenario 2.

These scenarios assume a relationship between the amount of movement occurring within a window of observation and opportunity for discard, and provide some limits to the process of artefact dispersal. On one end is total technological expedience (Nelson 1991), where all products of reduction are deposited at the same place they were made. On the other is total curation, where artefacts are moved immediately out of the window of observation without discard. Between these two are movements punctuated by selection and discard events. Movements resulting in greater linear displacement between events are more likely to move an individual located within a given window beyond its boundaries, while movements that are shorter in distance are more likely to result in redundancy in place use. Within this framework, the processes related to the formation of lithic assemblages of flakes and cores can be broken down into a series of mechanistic statements which comprise a conceptual model. Cores and flakes are produced through the reduction of nodules of stone, with the number of flakes relative to cores corresponding to the intensity of reduction. Some of the products of reduction events might enter an archaeological assemblage immediately, while others might be selected for transported to other locations. Movement between selection and discard events with respect to a given window of observation will determine the character of the assemblage within that window by increasing or decreasing the number of opportunities for discard or manufacture, while also serving to introduce additional flakes or remove flaked objects from the window.

While the model simulates “movement” by an individual agent, this movement is expressed as linear moves between discard events, an activity with an archaeologically visible residue. Movements may occur that are not accounted for in the discard record. A cortex ratio of one might indicate either complete technological expedience, or it could
indicate a balance between import and export (Lin et al. 2015). Individuals could make and discard artefacts in the same location but carry them for use somewhere else. Such movements would leave no trace in cortex ratios. While the cortex ratio allows us to see the positive image created by the dispersal of lithic artefacts, the negative image of human movements between discards cannot be assessed using this proxy. It is therefore an assumption of studies using the cortex ratio that the discard of archaeological artefacts is embedded to some extent in the movement patterns of individuals in the past (Binford 1979). This study seeks to evaluate the kinds of patterning a system with these properties might produce. The formational processes considered here are certainly less complex than those they purport to represent but simplifications are made intentionally with the aim of fully exploring the parameter space created by them.

6.3 Model implementation

To address changes in the spatial distribution of flakes and cores, and therefore in the cortex ratio, an exploratory agent-based model was constructed based on the conceptual model above. Unlike simulations of deposit formation, assemblage-generating simulations have a legacy in archaeology. These models are often used to investigate how groupings of specific attributes of artefact assemblages emerge through repeated manipulation and discard, which in turn are seen to be reflections of the organisation of activities (e.g. Aldenderfer 1981; Barton and Riel-Salvatore 2014; Brantingham 2003; Lake 2000; Schick 1986; Thomas 1972; Wandsnider 1992; Varien and Potter 1997). This study draws inspiration from these efforts, applying similar methods to the measurement of a geometric property of lithics within continuous spatial distributions rather than bounded into spatially discrete sites. As in the previous chapter, a more detailed description of the model can be found in Appendix B, along with the code used in the simulation program and that used to produce the graphics in this chapter. State variables used within the model are written in Lucida Console font.

The model, instantiated using the NetLogo modelling platform (Wilensky 1999) as a computer simulation called FMODEL, begins with an \( n \times n \) space of gridded cells. The
gridded space operates as an observation window. Any activity taking place outside the window is not considered directly. During the course of a simulation run, a computerised agent moves into the window following a set of movement rules and, given the parameter settings, may stop somewhere within the window. If the agent is carrying artefacts, then a stop will result in a discard event. If the agent has no artefacts, then artefacts will be manufactured according to a set of reduction and selection rules, and products of the reduction will either enter the record or not depending on the rules used in the simulation.

6.3.1 Simulating lithic reduction and selection

Nodules of stone are modelled in the simulation as icosahedra (20-sided polygons), while flakes are modelled as triangular prisms. Each flake represents an equal portion of the surface area of the nodule (5%) and an arbitrary but near constant volume which equates to less than 5% of the original nodule volume so that some component of the core is left (Fig 6.4). An icosahedron was chosen to give balance between control over cortical surface reduction and mathematic simplicity. In reality, differences in flake morphology will have an influence on the relative degrees of cortex removed during reduction (Douglass 2008; Parker 2012), and estimations of volumetric relationships between assemblage contents and original nodules will influence cortex ratio calculations (e.g. Phillipps and Holdaway 2015; Lin 2015). For the time being it is useful to hold this variability constant in order to understand the influences of spatial behaviour on outcomes.

Douglass (2010) uses a preferential selection of cortical flakes for use away from the catchment in his explanation of the distribution of cortex ratios for recorded assemblages at Rutherford Creek. However, studies conducted elsewhere have suggested the transport of cores (e.g. Phillipps 2012) and the transport of cores is not unknown elsewhere in the region (e.g. Webb 1993). Because this study seeks to explore the influence of the parameters rather than try to recreate a specific situation, it is not assumed a priori that flakes or cores were targeted. Instead, each set of parameter settings is explored for both cores and flakes as the desired product of reduction. When an agent makes an artefact in the model, they do so to a
single, pre-set reduction level, given as a proportion of cortical surface removed from a nodule (\textit{reduction\_intensity}). Actual assemblages typically reflect a range of patterning in reduction. For example, Table 6.2 shows the degree of cortex retention present on cores at Rutherford's Creek for which this value was recorded ($n = 1383$). Following reduction, flakes are selected from the local assemblage, modelled as a proportion of the number of flakes generated in the preceding reduction episode (\textit{selection\_intensity}). Thus, with a \textit{reduction\_intensity} setting of 0.5 and a \textit{selection\_intensity} setting of 0.8, an agent will remove 10 of the 20 possible flakes from the nodule (leaving 10 of 20 possible flakes remaining on the core, or \texttt{core\_rem} = 10), and then select eight flakes for transport away. Under simulation configurations where cores are the desired product of reduction, cores are always selected, leaving behind the flakes produced from the knapping event. In the foregoing reduction scenario, an agent targeting cores would select the core for transport, leaving behind 10 flakes.

Table 6.2 Proportions of cortex retention on cores recorded at Rutherford’s Creek

<table>
<thead>
<tr>
<th>Cortex remaining</th>
<th>% of assemblage</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>50-99%</td>
<td>20.2</td>
<td>20.2</td>
</tr>
<tr>
<td>1-50%</td>
<td>54.2</td>
<td>54.2</td>
</tr>
<tr>
<td>None</td>
<td>27.1</td>
<td>27.1</td>
</tr>
</tbody>
</table>
Figure 6.4 Polyhedral models of cores and flakes used in FMODEL
Cores and flakes are not stored as objects (i.e. agents or patches) within the simulation architecture, but as indices within lists kept by grid cells and agents (Fig 6.5). Each grid cell contains lists that keep track of individual artefacts (artefact_id), given by a unique identification number added sequentially to artefact type (artefact_type), where cores are represented by 0s and flakes represented by 1s, and the amount of cortical surface remaining on each artefact (cortex_rem), given as 1 for flakes, and a value between 0 and 20 depending on the reduction strategy currently in use. Agents have analogous lists for flakes and cores in which artefacts currently being carried are kept (cur_id, cur_type, cur_cortex). When a flake or core is added to a cell or an agent, it takes a position within the corresponding list. When it is removed from a cell or an agent, the index at which that artefact is listed is deleted across all corresponding lists. The reason for using this structure is strictly computational. Because the condition of each artefact does not need to be updated at every time step, NetLogo’s list architecture allows for the fast generation of large assemblages on a commercial grade computer (Bagwell 2000).

Because the simulation models movement within a given window of observation, artefacts carried by the agent departing the window are not considered part of the local assemblage. Interpretations of low cortex ratios suggest that artefacts are leaving catchments and not returning, thus the capacity for objects to leave the window is a crucial component of assemblage formation models. But it is also possible that an individual might move into the window already carrying objects. A parameter called carry_in therefore gives a proportion of the total number of artefacts an agent might be carrying given the reduction_intensity and selection_intensity settings in use. This defines the point in the agent’s discard cycle when it in enters the window. Thus, if the parameter settings in the previous example were used along with a carry_in setting of 0.5, then agents would enter the window of observation with four flakes on hand. The reduction_intensity, selection_intensity, and carry_in parameters are varied in increments of 0.1.
6.3.2 Modelling agent movement and artefact discard

The objective of the model is compare outcomes of movement patterns ranging between highly tortuous and highly linear movements within a given observation window. To do this, an agent must enter the observational window, follow a path through the window which may or may not involve discard events, and, eventually, leave the window. A commonly-used method for modelling the movement of individuals within a landscape is a random walk. For a simple random walk on a two-dimensional surface, an individual turns in a randomly determined direction and takes a step forward at a set distance, and then repeats this set of actions (also known as Brownian motion, Codling et al. 2008). The result is a high degree of tortuosity in movement and a corresponding redundancy in the coverage of terrain (Fig 6.6).

Simple random walk models offer a null model against which expectations regarding spatial behaviour can be compared. Random walks can be altered to model less tortuous
movement by changing the frequency of directional change, length of steps, or the probability distribution from which step-lengths or directional changes are drawn (Renshaw and Henderson 1981). These walks, called correlated random walks, can give control over the degree of linearity of movement. A special instance of this is the Lévy walk, in which the length of the step is selected from a distribution determined by the equation:

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

where \( P(l) \) is the probability of selecting a value with length \( l \) (Tsallis 1997). When \( \mu \) is greater than or equal to 3, the likelihood of selecting step lengths greater than 2 becomes increasingly small, and thus movement approaches Brownian motion with higher values of \( \mu \) (Fig 6.7c). As \( \mu \) approaches 1, the probability of longer step lengths (termed “Lévy flights”) becomes greater as the distribution develops a long tail, eventually resulting in the possibility
of taking a step of infinite length (Fig 6.7a). In a study of raw material procurement in Palaeolithic societies, Brantingham (2003, 2006) used Lévy walks as part of a neutral model of hunter-gatherer mobility, arguing that patterning in modelled spatial distributions of discarded artefacts using different values of \( \mu \) can be used to evaluate planning depth in movement indicated by the greater frequency of long-distance, linear moves. The relative frequencies of short and long distance movements produced by the equation could be viewed as the intensity with which the agent occupies a landscape. Some settings of the \( \mu \) parameter, for example, optimise searches in unfamiliar spaces (Viswanathan et al. 1999). This parameter, \texttt{levy\_mu}, is explored at values of 1.1, 1.5, 2.0, 2.5, and 3.
The model conceives of movement as occurring continuously through the window of observation (as in Fig 6.6), meaning that the first movement must begin outside of the window. To model this with respect to a given value of \( \text{levy}_\mu \), a step length value is drawn using the Lévy equation above. This value is then multiplied by a random value between 0 and 1, producing a fraction of the length of the original step. Next, a point along the outer edge of the grid world is selected randomly, and a direction is chosen from a 180° arc with its origin at the location of the agent and its base parallel to the edge of the grid world where the agent is entering from. The agent then moves forward the fraction of the step generated above to complete its first step. The length of each subsequent step is generated using the Lévy equation only, and direction chosen randomly from a 360° arc with its origin at the location of the agent. If the length of a step in the chosen direction will take the agent outside of the grid world, the agent is removed from the model and a new agent begins the process again. Each simulation consists of 100 iterations of this process.

The four variables used here, \text{reduction}_\text{intensity}, \text{selection}_\text{intensity}, \text{carry}_\text{in}, \text{and levy}_\mu, are used to capture essential characteristics of the verbal model described in section 6.2, and the combinations of settings described above will constitute the parameter space to be explored below. However, before continuing with the model exploration, the methods used to verify that the model is a successful implementation of the conceptual model is discussed.

6.3.3 Model verification

Unlike HMODEL, the conceptual basis for FMODEL has a history of experimental work, and the results from these experiments can be used to help verify model function. The original study by Dibble and colleagues (2005) provides a set of outcomes from known experiments which can be used to derive expectations from this model to evaluate whether it is functioning correctly. Not all tests in the paper are relevant to this model. For example, Dibble et al. (2005) examined the effects of eliminating non-cortical flakes from the calculation of a spherical cortex ratio. Because the current simulation treats all flakes as
cortical and holds variation in core dimensions and flakes constant, a comparable test could not be conducted using the current model. However, two of the tests are suitable for replication with FMODEL: varying estimates of the number of nodules and removing cortical flakes.

First, the simulation was configured such that all reduction activity was limited to a single grid cell. This was accomplished by temporarily making sections of code that control the movement of the agent inactive, compressing all activity down to a single grid cell. To generate their experimental assemblage, Dibble et al. (2005) had multiple knappers reduce 33 nodules. To replicate this, an agent reduced 33 nodules to random levels of reduction. This was accomplished by asking agents to draw a random number between 0 and 1, which was then rounded to the nearest multiple of 0.05 to determine the degree of reduction. Next, the cortex ratio for the simulated assemblage was calculated by dividing the observed cortical surface area (the total number of flakes produced added to the sum of the core_rem values for the assemblage) by the expected cortical surface area (33 cores multiplied by 20 possible flakes per core = 660). Finally, this same calculation was performed but varying the number of cores between 1 and 100. The result closely matches that of Dibble et al. (2005), although there are significant differences in the magnitude of the effect on cortex ratios (Fig. 6.8). These differences can be attributed to the fact that the original study used the assemblage itself to estimate not only the number of nodules but also the average nodule volume. Reducing the number of nodules concurrently increases the average nodule volume, and vice versa, thereby constraining cortex ratio values closer to 1. In this study, the volume is held constant (not unlike approaches employed by Dibble et al. 2012 and Phillips and Holdaway 2015), therefore the magnitude of change in cortex ratios better reflects the true size of the simulated “raw” material. However, in both cases, reducing the estimated number of nodules pushes the cortex ratio up, reaching an asymptote as the number of nodules approaches zero, while increasing the number of nodules pushes cortex ratios lower than 1.

A second test which can be compared to the experiments by Dibble et al. (2005) involves the removal of cortical flakes from generated assemblages. In the original study,
flakes were selected for removal based on their cortical coverage (e.g. all flakes with >90% cortex coverage). In FMODEL, all flakes are fully cortical; however, a similar effect can be achieved simply by removing percentages of cortical flakes from the assemblage (Fig 6.9). Using the assemblage generated for the previous tests, cortex ratios decline from 1 when all cortical flakes are present, to a value of 0.47 when all but 10% of cortical flakes are selected. This value reflects the cortex remaining in the form of flakes (0.1) as well as the cortex remaining on cores in the simulated assemblage (~0.37). A second assemblage was generated in which all cortical flakes were removed from cores. As expected, the resultant values track perfectly with their removal levels.

Finally, Douglass’ (2010) model of radial movement argues that under a flake transport scenario, cortex ratios should increase with distance from a point of production as more material from reduction events is encountered. To simulate this in FMODEL, an agent begins at a central point in the gridded world, manufactures flakes using full reduction_intensity and selection_intensity settings, and then repeatedly moves out to random points within a set radius from the central location and discards them. After this was repeated 500 times, cortex ratios were calculated for radii increasingly distant from the central location, and grid cells within those radii were coloured according to the
smallest radii within which they were included (Fig 6.10). The agreement between the theoretical expectation and the simulated outcome lend additional support for the model.

Further visual debugging, including assessment of step length distributions obtained using the Lévy function (see Fig 6.7), were conducted to ensure the model is functioning as intended. As in Chapter 5, an Overview, Design concepts, and Description document is made available with this thesis in Appendix C, while the code is available in Appendix D.

6.4 Model Exploration

The objective of this exercise is to examine the effects of different patterns of movement on a random discard of flaked artefacts. This model is not meant to be a digital reconstruction of lithic scatters in western NSW or anywhere else. Rather, it is meant to be a test the logic of the verbal formation model described in section 6.2, recording outcomes within the parameter space defined to allow for comparison between different model settings and archaeological data. Following the exploratory approach outlined in Chapter 4, simulations were run under all combinations of parameter settings listed in section 6.3. Simulations were run 1000 times under each parameter setting in order to capture the variability in outcomes from the stochastic components of the model (in this case, the probability draw used to generate step length in the Lévy equation). All simulations were run using the New Zealand eScience Infrastructure Pan Cluster high performance computing.
system, which links multiple processing cores together in a network in order to run programs in parallel. These resources were made available for the present study through the University of Auckland Centre for eResearch. As stated earlier, these resources help to speed processing, but are not necessary to run FMODEL.

6.4.1 Overall distribution of outcomes with respect to movement

Figure 6.11 illustrates the distributed cortex ratios of all simulation runs in which flakes were the transported objects, separated according to \( \text{levy}_\text{mu} \) settings. A trend is present, in which cortex ratios at the lowest settings for this parameter (that is, low tortuosity of movement) are the most variable, becoming less so with increasing values of \( \text{levy}_\text{mu} \). Some cortex ratios produced under the \( \text{levy}_\text{mu} = 1.1 \) setting are several times higher than the highest values recorded for assemblages at Rutherfords Creek.
Despite these striking visual disparities between low and high tortuosity outcomes, simulated cortex ratios at all settings are evenly spread on either side of a value of one, and the majority are situated between 0.5 and 1.5 (Table 6.3). At the $\text{levy\_mu} = 1.1$ setting, cortex ratios are lower than 1 for about half (50.5%) of simulations while the cortex ratios are greater than or equal to one nearly as often. By comparison, cortex ratios reach values greater than or equal to 1.5 in only a small percentage of all simulation runs at this level (8.9%), and even fewer reach cortex ratios are less than or equal to 0.5 (1.8%). Percentages of simulations featuring cortex ratios greater than or equal to 1.5 and percentages less than or equal to 0.5 decrease exponentially as the setting of the $\text{levy\_mu}$ parameter increases. At the same time the balance of cortex ratios shifts slightly toward values under 1 as movement tortuosity increases. Across all simulation settings, the overall effect of increasing tortuosity of

Figure 6.10 Beanplots illustrating the distribution of cortex ratios from all simulation runs by $\text{levy\_mu}$ settings when flakes are the objects being selected. Black horizontal lines indicate individual datapoints, while white curves represent the probability density of outcomes.
Table 6.3 Proportions of cortex ratio outcomes for different settings of \texttt{Levy\_mu}

<table>
<thead>
<tr>
<th>Levy_mu setting</th>
<th>Cortex Ratio ≤ 0.5</th>
<th>Cortex Ratio &lt; 1</th>
<th>Cortex Ratio ≥ 1</th>
<th>Cortex Ratio ≥ 1.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.018</td>
<td>0.505</td>
<td>0.495</td>
<td>0.089</td>
</tr>
<tr>
<td>1.5</td>
<td>0.010</td>
<td>0.511</td>
<td>0.489</td>
<td>0.048</td>
</tr>
<tr>
<td>2.0</td>
<td>0.006</td>
<td>0.513</td>
<td>0.487</td>
<td>0.027</td>
</tr>
<tr>
<td>2.5</td>
<td>0.003</td>
<td>0.515</td>
<td>0.485</td>
<td>0.02</td>
</tr>
<tr>
<td>3.0</td>
<td>0.001</td>
<td>0.516</td>
<td>0.484</td>
<td>0.017</td>
</tr>
</tbody>
</table>

...movement on assemblage composition appears to be a concurrent decrease in the variability of cortex ratio outcomes, and a slight increase in the proportion of cortex ratios less than 1.

When cores are selected rather than flakes, the variability in outcomes decreases substantially across all settings of \texttt{Levy\_mu}, and is more or less normally distributed at all settings of \texttt{Levy\_mu} (Fig. 6.12). The decrease in variability can be attributed to artefact manufacture occurring on single nodules, meaning agents only carry one core at a time. Because of this, each discard event under this setting is immediately followed by a manufacturing event and vice versa, keeping most products of reduction within the observation window and thus maintaining cortex ratios close to one. In fact, as currently configured, only one core can ever enter or leave the window of observation in any given movement sequence. Lower settings of \texttt{Levy\_mu} mean less time spent inside the window, making the impact of adding or subtracting a single core on cortex ratio values more substantial, while higher settings are more likely to leave greater numbers of complete reduction sets within the window. Relaxing this assumption would have an effect on distributed outcomes; however, doing so has implications for interpretations of technological organisation (see section 6.5 below).

6.4.2 Effects of reduction and selection on modelled outcomes

The degree of reduction controls the amount of cortex remaining on cores relative to that available on flakes (Fig. 6.13). At lower values of \texttt{reduction\_intensity}, fewer...
flakes are produced, meaning that if flakes are the object being targeted, most of the cortex is remaining on the cores themselves, and these are discarded locally following a manufacturing event. Flaking occurs more regularly than when levels of reduction are higher, allowing for greater build-up of locally-produced material as reduction sets are cycled through more rapidly. At a setting of 0.1, for instance, each event produces two flakes, meaning only two discard events occur between manufacturing events. At this level, the discard of these complete reduction sets locally strongly outweighs the impact of material being imported or exported from the window of observation.

At higher levels of reduction_intensity, more flakes are removed and thus become available for transport, while the time between reduction events becomes longer as more stops between moves involve discard. At a setting of one, each event produces 20 flakes, meaning only two discard events occur between manufacturing events. At this level,
the discard from these complete reduction sets outweighs any material being imported or exported from the window of observation.

Breaking these curves down according to selection_intensity settings shows how the process of artefact selection can further influence cortex ratios (Fig 6.14). Selection itself is constrained by reduction, so the effects of differential selection are only apparent when reduction is sufficient. Under cases, greater degrees of selection allow for greater variability in cortex ratios as the number of candidate flakes that might be potentially separated from parent cores grows larger. This result is corroborated by the simulation work of Parker (2012), who estimated that at least 20% of the longest (and therefore most cortical)

Figure 6.12 Mean (dashed line) and 95% confidence intervals (grey) for cortex ratios obtained from simulations using varying degrees of reduction_intensity and a selection_intensity of 1 when flakes are the objects being selected
flakes at Rutherfords Creek would need to be selected in order to account for cortex ratios at Rutherfords Creek. Similar patterning is evident when cores are the objects selected, albeit at a subdued level (Fig 6.15). Higher variability in cortex ratios coincides with greater levels of reduction as more cortex might remain behind in an assemblage either within the window, or beyond it (in the case of greater carry_in). While the previous section demonstrated that variability in cortex ratios around a value of one is influenced by movement patterns, the extent to which that variability can be realised is dependent upon the degree of reduction and selection. As more potential cortical flakes stay on cores, lower or higher cortex ratios become harder to achieve as fewer flakes are available to be added to or removed from assemblages. Likewise, if flakes are not being selected, then they remain as part of the local assemblage, keeping cortex ratios closer to one. Similar patterning is observable in the case
of cores, although the effect is muted by the more frequent recycling of cores assumed in the model. Nonetheless, assemblages featuring cortex ratios that deviate substantially from one require that reduction and selection occur in significant quantities.

### 6.4.3 Effects of carry-in on modelled outcomes

When `reduction_intensity` and `selection_intensity` are held constant at one, further trends can be observed. The distribution of cortex ratios shifts from below 1 to above 1 as `carry_in` is increased (Fig 6.16). This is most pronounced when tortuosity of movement is low. For example, when `levy_mu` is set to 1.1, the mean cortex
ratio of outcomes with a carry_in setting of 0 is 0.21, while the mean cortex ratio of outcomes with a carry_in setting of 1 is 1.95. Distributions at these two different settings do not cross the threshold of one, indicating that they are statistically distinguishable from a situation where no flaked material was moved at all. At the other end of the tortuosity spectrum, a similar pattern in cortex ratios can be observed, albeit at a significantly reduced level of variability. Low levels of carry_in still produce cortex ratios lower than 1. The mean cortex ratio for simulation runs with a carry_in of 0 and a levy_mu setting of 3 is around 0.51, suggesting that about half of the locally produced cortex is leaving the window of observation at this setting. This is somewhat counterintuitive, given the expectation expressed in section 6.1.4 for cortex ratios at high levels of mobility to be situated around one, but the lower cortex ratios under these settings are an outcome of the process as

Figure 6.15 Cortex ratios obtained from simulations using reduction_intensity and selection_intensity settings of 1, and variable settings for carry_in (indicated in top right corner of each graph) when flakes are the objects being selected. Dashed line indicates a cortex ratio value of 1.
modelled. The following thought experiment provides an explanation. An agent, carrying no artefacts and adhering to a movement pattern determined by a \texttt{levy\_mu} setting of 3.0 (approximately Brownian motion) enters the window of observation. The initial movement is some fraction of a value generated using the Levy equation with a mu of 3, which by definition will be close to one. This means that the first movement into the window will be relatively short, leaving the agent close to the edge of the world. If no artefacts are carried, then the first action will be to reduce a nodule of stone to produce flakes. If both \texttt{reduction\_intensity} and \texttt{selection\_intensity} are set to one (as they are in the anomalous situation described above), then the nodule is fully reduced and all of the twenty flakes are selected for transport away. On the agent’s next move, it draws a random heading between 0 and 359 degrees and takes another step of a length generated from the Lévy equation. Based on the agents’ current position, about half of the potential headings the agent might assume would point the agent further into the window, while the other half would point it back out again. If the heading carries the agent into the window, the agent will discard a flake at its next location, raising the local cortex ratio. However, if the movement takes the agent back out of the window, then the flakes depart with the agent. Over time, the resulting assemblage will be a mix of discard events formed by agents that carried on a path through the window, and others that moved into and out of the window relatively quickly (effectively ‘grazing’ it) as part of their tortuous movement from elsewhere.

When cores are targeted, the shift is once again far less pronounced, but displays the opposite trend (Fig. 6.17). A \texttt{carry\_in} of 0 produces cortex ratios higher than one, decreasing with greater movement tortuosity, while a \texttt{carry\_in} value of 1 produces cortex ratios lower than 1, increasing with greater movement tortuosity. Removing cores through transport reduces the estimated number of nodules used to calculate the cortex ratio, decreasing the number of cores relative to flakes and thereby producing higher cortex ratios. Adding cores increases the estimated nodules, resulting in decreased cortex ratios. The reduced variability when compared to flake-targeted assemblages is also a product of the regular cycling of reduction sets occurring using the settings for the model, keeping most outcomes close to 1.
The results of this exploratory exercise provide indications of how cortex ratios of lithic assemblages, operating under varying parameterisations of reduction, selection, and carry-in, are affected by the displacement of artefact-carrying individuals. While cortex ratios significantly lower than one might be comfortably associated with higher mobility, an inverse assumption that high cortex ratios are indicative of lower levels of mobility would be false. Instead, cortex ratios lower or higher than one appear to be two sides of the same coin.

In the model, attaining assemblage cortex ratios either side of one depends primarily on where the agent is in its discard cycle at the time it moves into the window of observation (modelled using the \texttt{carry\_\_in} parameter).

In the logic of the model, rather than specifying the position of cortex ratio calculations above or below one, movement seems to control the magnitude of variability around a mean value that might be expected over all. Assuming reduction and selection are sufficient enough to permit such variability to emerge, patterns of low tortuosity movement

\textbf{Figure 6.16} Cortex ratios obtained from simulations using a \texttt{reduction\_intensity} setting of 1, and variable settings for \texttt{carry\_\_in} (indicated in top right corner of each graph) when cores are the objects being selected. Dashed line indicates a cortex ratio value of 1.

\section*{6.5 Summary: Learning from FMODEL}

The results of this exploratory exercise provide indications of how cortex ratios of lithic assemblages, operating under varying parameterisations of reduction, selection, and carry-in, are affected by the displacement of artefact-carrying individuals. While cortex ratios significantly lower than one might be comfortably associated with higher mobility, an inverse assumption that high cortex ratios are indicative of lower levels of mobility would be false. Instead, cortex ratios lower or higher than one appear to be two sides of the same coin. In the model, attaining assemblage cortex ratios either side of one depends primarily on where the agent is in its discard cycle at the time it moves into the window of observation (modelled using the \texttt{carry\_\_in} parameter).

In the logic of the model, rather than specifying the position of cortex ratio calculations above or below one, movement seems to control the magnitude of variability around a mean value that might be expected over all. Assuming reduction and selection are sufficient enough to permit such variability to emerge, patterns of low tortuosity movement
Figure 6.17 Mean (dashed line) and 95% confidence intervals (grey) for cortex ratios when cores are the objects being selected, and allowing for “overproduction” of a) 1, b) 5, and c) 20 cores per reduction event

In the case of core transport, the general pattern holds but the relationship between low import and high import areas reverses, with cortex ratios decreasing in areas with greater amounts of imported materials and increasing with loss of cores. The influence of core transport demonstrated within the structure of FMODEL is less striking than that generated for flakes: this can be attributed to the way in which the model uses a “one-nodule-at-a-time” routine, preventing mass import or mining of cores. Relaxing this assumption by allowing agents to “overproduce” cores shows how a system based on greater use of cores would likewise be affected by movement as the amount of cortex capable of being carried or left behind increases (Fig.6.18). Elsewhere in the region where stone is not as readily available, this kind of core transport has been suggested as a means creating raw material sources.
As Phillipps (2012) demonstrates, this kind of behaviour can have a significant influence when cortex ratios are being calculated using core counts and volumes as a means of estimating average nodule volume. But the effect of such “overproducing” is limited by the logistical constraints imposed by moving rock; from the formational standpoint presented in the model, it is easier to create imbalances with flakes than with cores.

Finally, tortuosity of movement has an overall effect on comparative assemblage density; that is, greater tortuosity will by and large produce more artefacts in an assemblage. However, given the findings generated so far, it is not clear that creating denser assemblages by regularly cycling through local material under a high tortuosity scheme will produce the same signature as denser assemblages formed through repeated instances of occupation under

Figure 6.18 Cortex ratios obtained from simulations using reduction_intensity and selection_intensity settings of 1, and variable settings for carry_in (indicated in top right corner of each graph) when flakes are the objects being selected. Grey dots indicate runs using 10 walkers, while black dots indicate runs using 100 walkers. Dashed line indicates a cortex ratio value of 1.
a lower tortuosity setting. Likewise, the more diffuse assemblages formed at low tortuosity may not bear directly on assemblages that are mostly locally generated. This can be explored in FMODEL by running it using the same set of parameters as the exploration above, but with only 10 agents performing walks through the window rather than 100 (Fig 6.19).

At higher levels of carry_in, cortex ratios and their variance at low levels of tortuosity are suppressed in less dense assemblages (walkers = 10 mean = 2.3 standard deviation = 0.78, coefficient of variation = 33.91) when compared to denser assemblages (walkers = 100, mean = 4.72, standard deviation = 2.58, coefficient of variation = 54.66), while the opposite can be said at high levels of tortuosity between less dense (walkers = 10 mean = 1.7, standard deviation = 0.67, coefficient of variation = 39.41) and denser assemblages (walkers = 100 mean = 1.34, standard deviation = 0.13, coefficient of variation = 9.7). Under high tortuosity settings, the difference in distribution of cortex ratio values can again be attributed to the stochastic component of the model, which are more acutely felt when fewer events are considered. In low tortuosity scenarios (i.e. levy_mu = 1.1), the differences between distributions of cortex ratio values at the two density settings is likewise attributable to stochastic elements of the model, although for quite different reasons. The reduction in mean values between less dense and denser assemblages at low tortuosity reflects the capacity for more walkers (and thereby more discard events) to result in greater numbers of discarded flakes, inflating cortex ratios.

However, it is also worth noting that when carry_in is high but the number of walkers is low, the probability that an agent moving into the window will actually remain there long enough to discard all of their flakes and then reduce a nodule is very small. This means that as the number of individuals decreases, there is an increasing probability that a core will not be generated, producing an assemblage composed entirely of flakes. In the simulation above where the number of walkers is 10, the probability of producing an assemblage without cores is around 20% for a levy_mu setting of 1.1, dropping to about 6% with a levy_mu of 3.0. Core-free assemblages would not be able to be used in a cortex ratio calculation directly as the presence of at least one core is needed as a proxy for the number of nodules being reduced. This has some ramifications for survey strategies and cortex ratio interpretations that will be discussed in greater detail in Chapters 7 and 8.
Like HMODEL in the previous chapter, FMODEL has been used to evaluate the logic of conceptual models, in this case pertaining to the relationships between mobility and the formation of patterning in surface assemblages of stone artefacts. The findings of the model at present are only relevant to the system as modelled, but similarities between modelled outcomes and recorded patterns can be used to develop further expectations, potentially providing opportunities for tests of the archaeological record. Patterning generated from the exploratory modelling in this chapter will be used for this purpose in the next chapter.
7 COMPARING MODELS OF THE FORMATION OF THE CHRONOMETRIC RECORD AT RUTHERFORDS CREEK

In their current states, HMODEL and FMODEL are simple mechanisms derived from conceptual models that have been used to explore abstract notions regarding the formation of deposits and assemblages, respectively. The exploratory framework used to construct these two simulations has permitted the assessment of outcomes from a variety of parameter configurations. Under some configurations these have produced patterns with qualitative similarities to archaeological phenomena recorded from deposits in western New South Wales; their “patterns for model construction” (Railsback and Grimm 2012). As noted earlier, though, alternative interpretations of these and other archaeological patterns in the western New South Wales surface record have been advanced concerning the population dynamics and mobility of past human inhabitants. The findings of HMODEL and FMODEL by themselves do not indicate that the patterning identified in the archaeological deposits in the western NSW study areas is the result of the processes like those operating in the models (Grimm et al. 1996), or even go so far as to adjudicate between existing interpretations of the archaeological record of western New South Wales. Instead, these exercises provide only a sense of what an archaeological record would be like if the processes as modelled, or processes sufficiently like them, were operating in reality.

Adding further interpretations based on the outcomes of the simulation exercises, while valuable heuristically (in the sense of Aldenderfer’s (1981) “conceptual” and “developmental” utility to the developer; see also Lake 2010), is somewhat counterintuitive to the primary goal of this study, which is to compare interpretations in terms of their formational outcomes with the hope of eliminating one or more of them. But because formal models were used (in the form of computer simulations), and because some similarities between outcomes from some parameter settings in the model and archaeological data from western NSW study areas were found, the model structure can be used to generate further expectations, potentially suggesting tests that, when applied to the archaeological record, might help to compare different interpretive models (Servedio et al. 2014). This is along the lines of what Grimm and colleagues (2005) refer to as “patterns for contrasting alternative theories” in their pattern-oriented modelling framework.
This chapter will take a pattern-oriented approach to evaluating these competing interpretations in terms of their ability to generate observed chronometric patterning from heat-retainer hearths at Rutherfords Creek. First, alternative generating mechanisms will be conceptualised and implemented within an exploratory simulation similar to that developed for HMODEL, demonstrating their capacity to generate similar patterning. The patterns, discussed in qualitative terms up to this point, will be characterised more precisely, providing some means of gauging fit between data and model outcomes, and models will be compared in these terms. Finally, these different models will then be used to make predictions regarding a hitherto unexamined pattern: the temporal distribution of optically-stimulated luminescence dates obtained from hearth stones.

7.1 Conceptualising, implementing, and exploring alternative models

Of the two proxies explored so far, the patterning in chronometric data is best suited to the goal of comparison. Unlike the Cortex Ratio, which has only been used to demonstrate high levels of residential mobility in the region (Douglass 2008), the different interpretations of human population dynamics and geomorphic processes discussed herein have been expressed in terms of their capacity to generate the same patterning in the radiocarbon data present in the archaeological record (Holdaway et al. 2008; Smith 2013; Smith et al. 2008).

One of these alternative interpretations is that of extended occupations and population growth in the late Holocene. The overall exponential curve is used to argue for increased population, while gaps are thought to be the product of extended lateral movements occurring periodically with changes in logistical foraging areas. For the purposes of this discussion, this can be called the “intensification” model (sensu Smith 2013; Williams et al 2015b). Another alternative view is that the overall curve is the product of time-dependent loss of radiometric data (Robins 2006, Holdaway et al. 2008), while the gaps are a product of long-term hiatuses in occupation coinciding with cyclical environmental degradation (Holdaway et al. 2010). This can be called the “mixed” model. Finally, the model presented in Chapter 5, in which both the curve and the gaps are caused by changes in preservation and visibility resulting
from episodic disequilibrium in the geomorphology of region, can be called the “geomorphic” model.

<table>
<thead>
<tr>
<th>Model</th>
<th>Curve explained by</th>
<th>Gaps explained by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intensification</td>
<td>population dynamics</td>
<td>population dynamics</td>
</tr>
<tr>
<td>Mixed</td>
<td>preservation/visibility</td>
<td>population dynamics</td>
</tr>
<tr>
<td>Geomorphic</td>
<td>preservation/visibility</td>
<td>preservation/visibility</td>
</tr>
</tbody>
</table>

These different models explain the archaeological patterning in terms of the primary forces driving the patterning (those which are ultimately invoked in narratives), and conceptually these show overlap in some respects (Table 7.1). Both the intensification and mixed models explain the gaps as a product of waxing and waning human presence; the difference between the two lies in whether this is a change in logistical behaviour, which maintains human occupational continuity in the long-term, or periodic abandonment, which does not. Furthermore, while the mixed and the geomorphic model differ in terms of what is causing the gaps, both assume that the mechanisms driving the exponential curve are time dependent changes in preservation and/or visibility. Interpretations that align with the intensification model also tend to recognise that a time-dependent loss of potential radiometric data is operating concurrently, but this is not considered to be strong enough to account for the superlinearity of the curve, leaving the remainder to be explained by population growth (e.g. Johnson and Brook 2011; Williams 2013). Each model differently emphasises the relative importance of these factors in shaping the archaeological patterning. While it has been demonstrated using HMODEL that the geomorphic model is logically capable of producing pattering with qualities similar to those observed at Rutherford's Creek, providing insights into how this occurs according to the logic of the modelled system, this has not been done explicitly for the intensification or mixed models. Following Grimm and Railsback (2012), a simulation can be constructed that can accommodate these alternative mechanisms. This implementation can be called HMODEL_A.
7.1.1 Computational implementation of HMODEL_A

Using HMODEL as a baseline, HMODEL_A relaxes the assumption that populations remain steady, adds a new mechanism for modelling human absence, and an optional mechanism to account for loss of charcoal is created: a time-dependent decay of hearth data. Population growth estimates for the late Holocene in Australia vary substantially. Attenbrow (2006), studying accumulation rates of numerous archaeological proxies at Upper Mangrove Creek in eastern New South Wales, suggests that these might represent growth rates around 0.1% per annum. Rates between 0.04% and 0.09% per annum have been suggested in other modelling studies based primarily on radiocarbon evidence (Johnson and Brook 2011; Williams 2012), although short periods of higher growth have been proposed in some of these studies as well (Williams 2013). To model population growth, the number of agents was increased at each time step according a set growth rate variable called `pop_growth`,

![Figure 7.1 Change in population over time (expressed as a multiple of the initial population) using different growth rates used in HMODEL_A](image-url)
which is a function of the population level at the previous time step and was explored at increments of 0.05, 0.1, 0.15, and 0.2 percent per annum. Differences in the relative populations that are produced from these settings are shown in Figure 7.1. The setting of 0.05% per annum results in a population about 2.7 times larger than that at 2000 BP, while a growth rate of 0.2% would produce a population over 50 times larger. As discussed earlier, populations would be expected to decline around the contact period as Aboriginal groups suffered the depopulating effects of large-scale epidemics (Butlin 1983); therefore, as in the original configuration in HMODEL, this is accounted for by not generating hearths after 200 BP.

Estimates of time-dependent taphonomic loss of archaeological data have been made, but these are poorly understood for surface deposits. Formulas used to correct radiocarbon chronologies for taphonomic bias based on stratigraphically identified tephra deposits produce an estimate between 0.03 and 0.05% per annum on average over the late Holocene period (Williams 2012). However, given historically documented topsoil erosion rates in the
region (e.g. Fanning 1994, 1999), these rates could be substantially higher in surface contexts. In HMODEL_A, time-dependent decay was modelled as a compound probabilistic determination of charcoal loss through time, implemented as a parameter called \textit{decay\_prob}. For each hearth, a random number between 0 and 1 is generated, and hearths for which a number below the \textit{decay\_prob} value is generated are removed. Unlike the sedimentation mechanism used in the original model, the decay process affects both visible and hidden hearths. The \textit{decay\_prob} variable was likewise explored in increments of 0.05, 0.1, 0.15, and 0.2 percent per annum.

To model periodic human absence, a third parameter was added which prevents agents from building hearths during a given time interval. This parameter, called \textit{absence\_interval}, is like HMODEL’s \textit{event\_interval} parameter in that it operates as a trigger for a change in model behaviour, but in this case it triggers the start or cessation of hearth building. If the \textit{absence\_interval} parameter is set to 200 years, for example, agents will build hearths from 2000 to 1800 BP, stop building hearths between 1800 and 1600 BP, resume building them between 1600 and 1400 BP, and so on. This parameter, like the \textit{event\_interval} parameter, was explored at intervals of 10, 50, 100, and 200 years. Finally, because the gaps in the record are not always interpreted in terms of absolute abandonment, but often as a waxing and waning human presence, the model uses a parameter called \textit{absence\_intensity} that controls the percentage of agents that cease building hearths during an absence period. Like the stability parameter in FMODEL, this is given as a value between 0 and 1 and was explored in intervals of 0.1.

\subsection{7.1.2 Exploring HMODEL\_A}

The programmatic differences between HMODEL\_A and HMODEL are described in more detail in Appendix A. Simulations were run 999 times under each parameter setting in order to capture the variability in outcomes from the stochastic components of the model. All simulations were run using the New Zealand eScience Infrastructure Pan Cluster high performance computing system. When sampled ages of surface hearths from HMODEL\_A
simulations without human absences are compared, patterning in the simulated chronological data is clearly biased toward the present (Fig 7.3). As the degree of decay or population increases, the distributions become weighted more heavily toward the present as greater numbers of hearths are either lost with age or constructed through time. Increasing both the decay rate and the population growth rate simultaneously compounds this effect.

As periods of human absence are introduced into the simulation, gaps predictably appear in the record, and the size of these gaps increases with the duration of the absences (Fig 7.4). Similarities between these outcomes and those obtained from the mixed regime configurations of HMODEL are striking. When the influence of the absence_interval parameter is tempered by reducing the absence_intensity parameter, gaps are less

---

**Figure 7.3 Outcomes of initial exploration of HMODEL_A.** Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest.
pronounced, not unlike the effect of increasing the `surface_stability` parameter in HMODEL (Fig 7.5). It suffices to say that some configurations that are consistent with the intensification and mixed models are likewise capable of reproducing the qualitative patterns of increased frequencies of radiocarbon dates, while periodic absences under either model are capable of producing episodic gaps.
Figure 7.4 Outcomes of initial exploration of HMODEL_A at different settings of the absence_interval variable (numbers in upper left corners of plots). Envelopes generated by plotting samples of 100 simulated surface hearths from each run in chronological order from youngest to oldest.
This exercise has not alleviated the persistence of multiple, competing interpretations, although it was not suspected that it would. Building these into simulations does, however, help to clarify the mechanisms by which these different processes generate the patterning. Both the curve and the gaps in the simulated data from HMODEL are present when differential preservation and differential visibility are more or less in balance (0.3 > erosion_prop > 0.7) and operate over a substantial portion of the landscape. Gaps are more pronounced when geomorphological events occur less frequently (erosion_freq >= 50) and when events affect a greater portion of the landscape (surface_stability < 0.5). Conversely, gaps become less noticeable when events are not sufficiently spaced (erosion_freq < 50 years) or when fewer cells are affected by sedimentary events (surface_stability >= 0.5). In HMODEL_A, superlinear curves are present under conditions where population growth and/or decay occur (pop_growth > 0, decay_prob > 0), while gaps become visible when human absences are more intense.
(absence_intensity > 0) and occur for longer stretches of time (absence_interval > 10).

7.2 Characterising patterns in the chronometric data from Rutherfords Creek

The simulations HMODEL and HMODEL_A are explicit instantiations of verbal logic (as interpreted above) upon which different interpretations of archaeological patterning are built. They demonstrate not only that these different formation processes are capable of producing said patterning, but they also make explicit the mechanisms by which they do so. A pattern-oriented approach, introduced in Chapter 4 as a means of comparing models, uses the capacity of the model to generate qualitative as well as quantitative patterns as a means of discerning between generative models. Two qualitative temporal patterns were captured in the outputs of both HMODEL and HMODEL_A: the overall superlinear curve of the distribution of hearth ages through time, and the presence of episodic gaps in that curve. The presence or absence of these patterns is currently insufficient to discern between potential generating models. It can say that these kinds of processes can produce the patterns, but provide no guidance toward discerning between models. The qualitative patterns discussed so far are what are characterised as weak patterns by Grimm and Railsback (2012). Stronger patterns involve some form of quantification. In the following section, methods for quantifying both the curve and the gaps are discussed.

7.2.1 Characterising the curve

In previous chapters, radiocarbon data has been displayed by ordering dates from youngest to oldest and plotting them by their age. Displaying data this way has the advantage of allowing samples of similar sizes to be compared in terms of their deviance from a uniform distribution, indicating the extent to which the chronometric data are biased toward one end of the chronology or the other. This deviance can be quantified by establishing the
difference between the actual dataset and a set of data points of equivalent size, spread at equal intervals across the diagonal span between 2000 to 200 BP. This is accomplished by calculating the sum of squared errors:

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2$$

where \(y_i - \hat{y}_i\) is the difference between the observed and expected (uniform) value. To express this as a proportional value, this can be divided by the sum of squared errors for a dataset at maximum deviation (similar to the calculation of a Gini coefficient of inequality; Dixon et al. 1987). Sampled distributions lying close to the diagonal line would present a value closer to 0, while an extreme case where all dates were clustered at either end of the date range (200 or 2000) produces a value of 1. For radiocarbon data obtained from Rutherfords Creek falling within this temporal window (\(n=90\)), the value of this proportion is approximately 0.11.

7.2.2 Characterising the gaps

Gaps in a radiocarbon record can be considered strictly as spans of time between dates within a sequence. Proportions of gaps of greater or lesser lengths may differ between sequences as a result of sampling the underlying distribution, or may be genuine components of the population of radiocarbon ages. The gaps observed at Rutherfords Creek present as periods of greater or less clustering of dates over time (Holdaway et al. 2010). When the data are considered together (see Fig 5.2), clusters of dates are visibly apparent in the distribution, interspersed with periods with lower frequencies of dates. Gap lengths generally appear to increase over time, while dates are more clustered in the recent past.

Recent work by Rhode et al. (2014) provides a means of assessing regional radiocarbon chronologies in terms of the gaps and clusters of mean age determinations that might be expected from sampling an underlying distribution. The study noted that, assuming that the generative mechanism is uniform (e.g. behaviourally neutral), the lengths of gaps in a
sequenced sample should approximate a negative exponential distribution. When the lengths of gaps from the Rutherfords Creek chronology are plotted proportionally alongside an expected outcome from a negative exponential distribution (Fig. 7.6), the comparison suggests that the data from Rutherfords Creek broadly follows this trend.

A set of summary statistics can be used to evaluate distributions of gap lengths against values expected from a negative exponential distribution. Rhode et al. (2014) note that the ratio between the median gap length and the expected average gap length should be approximately ~69%, with values below this level indicating clustering of dates (and the coincident presence of larger gaps). Additionally, standard deviations of gap lengths drawn from a negative exponential distribution tend to approximate the average gap length. To obtain these measures, uniform distribution of data were simulated within the temporal window available in the Rutherfords Creek data, and sampled at the same frequency.
The values for Rutherfords Creek, perhaps unsurprisingly, vary from the strict expectations of the negative exponential distribution. Specifically, the standard deviation is larger than the average gap length, and the ratio of median to average gap length is lower than would be expected. These differences may indicate that the overall frequency of radiocarbon dates at Rutherfords Creek is otherwise distributed in such a way that some periods of time are more likely to be sampled than others (for instance, increasing in frequency through time), producing clusters of dates at some time intervals and consequential gaps in others. Alternatively, these values may be consistent with the interpretation that one or more of the gaps in the sequence may be a genuine component of the record.

Table 7.2 Summary statistics from simulated uniform data and radiocarbon data from Rutherfords Creek

<table>
<thead>
<tr>
<th></th>
<th>Uniform distribution (1000 simulations)</th>
<th>Rutherfords Creek (OSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiocarbon date span</td>
<td>1790 – 162 BP (1628 years)</td>
<td>1790 – 162 BP (1628 years)</td>
</tr>
<tr>
<td>Date frequency</td>
<td>0.057 (93 dates/1628 years)</td>
<td>0.057 (93 dates/1628 years)</td>
</tr>
<tr>
<td>Average gap length (estimated)</td>
<td>17.51 years</td>
<td>17.51 years</td>
</tr>
<tr>
<td>Standard deviation gap length</td>
<td>17.32 (14.4-21.7)</td>
<td>22.1 years</td>
</tr>
<tr>
<td>Standard deviation/average</td>
<td>0.99</td>
<td>1.26</td>
</tr>
<tr>
<td>Median gap length</td>
<td>11.93 ± 1.25</td>
<td>9</td>
</tr>
<tr>
<td>Median/average ratio</td>
<td>0.69</td>
<td>0.51</td>
</tr>
<tr>
<td>Maximum gap length</td>
<td>92.66 ± 19.85</td>
<td>106</td>
</tr>
<tr>
<td>Maximum/average ratio</td>
<td>5.29</td>
<td>5.99</td>
</tr>
<tr>
<td>% total &gt; 50 years</td>
<td>5.4%</td>
<td>7.6%</td>
</tr>
<tr>
<td>% total &gt; 75 years</td>
<td>1.3%</td>
<td>4%</td>
</tr>
<tr>
<td>% &lt; average</td>
<td>64%</td>
<td>66%</td>
</tr>
<tr>
<td>% &lt; 1 – 3 x average</td>
<td>32%</td>
<td>27%</td>
</tr>
<tr>
<td>% &gt; 3 x average</td>
<td>4%</td>
<td>7%</td>
</tr>
</tbody>
</table>

Finally, Rhode et al. (2014) provide a set of equations for assessing the likelihood that a set of large gaps of a specific length might be obtained from a uniform frequency sequence.
First, a cumulative negative exponential distribution is used to provide the probability of a time interval between two dated events of uniform probability:

\[ f(t) = 1 - e^{-t/\beta} \]

where \( \beta \) is the reciprocal of the number of dates expected per year (in other words, the total time interval divided by the number of dates minus one). This value is then used to calculate the probability of obtaining a gap greater than or equal to a given length:

\[ p_N(n_1) = \frac{N!}{n_1!(N-n_1)!} p^{n_1} q^{N-n_1} \]

where \( q \) is the probability of attaining a gap of a given length, \( p \) is the inverse probability, \( N \) is the total number of gaps in the sequence and \( n_1 \) is the number of gaps less than length of the gap under consideration. The longest gaps in the sequence from Rutherford's Creek are 106 (1742-1636 BP), 95 (1307-1212 BP), 94 (1137-1043 BP), and 83 (961-878 BP) years. Using the above calculations, the probability of gaps of this length co-occurring in a sample of 93 dates drawn from uniform distribution over 1628 years is approximately 0.0051, so it is extremely unlikely that the gaps at Rutherford's Creek are the product of sampling an underlying uniform distribution. The alternative explanation is that the gaps observed at Rutherford's Creek are more likely caused either by the presence of actual gaps in the population of radiocarbon dates at Rutherford's Creek, or sampling an underlying distribution of variable frequency.

The Rutherford's Creek data roughly follow this trend, but exhibit a conspicuous sequence of 25 dates between 367 and 422 BP, each separated from adjacent dates in the sequence by gaps of less than 8 years. When the sequential gap lengths are differenced, this appears as a distinctive flat region (Fig 7.7), contrasting with patterning that would be expected from an exponential decay curve. Rhode et al. (2014) caution that clustering could be a product of spatiotemporal autocorrelation in the ages of sampled features, whereby features sampled in close spatial association may also be temporally proximate. There is reason to suspect that autocorrelation is not a primary cause of the clustering of dates observed in the radiocarbon record at Rutherford's Creek. Holdaway et al. (2008) have previously demonstrated that there is substantial variability in hearth ages over short
distances, which has been used to argue against an interpretation of spatially-clustered hearths as contemporaneous occupations. Further sampling of the surface record would be needed to fully account for this. However, even after averaging sequential hearth ages from the same area (defined as hearths connected by overlapping 20-metre buffers, see Holdaway et al. 2008; Bryant 2013), an unbroken sequence of 16 data points separated by 15 gaps of 6 years or less remains. This provides a second pattern that can be used to evaluate the radiocarbon data from Rutherfords Creek.

7.2.3 Pattern-oriented testing

Pattern-oriented modelling was developed as a means of making stronger inferences from agent-based models, using the juxtaposition of patterns as a means of filtering between variant model structures (Grimm et al. 2005). Some studies employ rigorous statistical
mechanisms such as multi-model inference methods for evaluating different model structures (e.g. Martinez et al. 2011; Topping et al. 2010). Others suggest that the approach can be much more informal, employing visual inspections of patterns and basic summary statistics in the process (Grimm and Railsback 2012; O’Sullivan and Perry 2013). This study takes a middle-of-the-road approach: a 95 percent confidence range is used to accept or reject models using the quantified measures of the patterns identified in the Rutherfords Creek data. Neither of these patterns is highly specific, as the objective of this exercise is still to establish what kinds of patterns produce a given result, rather than specifically parameterising any of the models. It is assumed for the time being that the parameter configurations used here will only be able to approximate these patterns; therefore, the measures described above indicate whether gaps, clusters, and curvature are occurring on the order of that encountered at Rutherfords Creek. For curves, deviance values for each parameter setting were obtained for 100 simulated samples of equivalent size (n=90) following the method described above, and the probability density for the Rutherfords Creek value (0.11) was obtained from the distribution of outcomes from the simulated curves. In terms of gaps or clustering, models were assessed on their probability of producing a single long cluster within the sequence. Given concerns over sampling discussed above, the more conservative estimate of 15 sequential gaps of less than 6 years was used.

The results of this assessment, which tested 70 parameter configurations of HMODEL and 625 configurations of HMODEL_A, are presented in Appendix E. Individually, these patterns turn up inside of the 95 percent confidence interval under many different settings; this reflects the generality of the patterns being sought. The index used to describe the curve was achieved with regularity in many instances of HMODEL where geomorphic events were well spaced, regardless of their stability setting. Likewise, HMODEL_A runs produced this pattern in cases where the combined effects of decay and population growth fell between 0.1% and 0.15% per annum with little respect to the presence or absence of gaps. On the other hand, the pattern of finding at least 15 sequential gaps of 6 years or less occurs reliably in many model configurations that are highly biased toward the present (providing greater resolution of dates closer to the present) or have large embedded gaps (leaving sampling to occur in the remaining clustered temporal spans).
Even though these patterns turned up regularly in both HMODEL and HMODEL_A, the forces in the model that generate one pattern will frequently prevent it from producing the other, and this can be used for filtering between model structures (Grimm and Railsback 2012). For HMODEL, the only settings to pass the test are those at the 200-year event_interval with no stability (Table 7.3). As noted earlier, erosion_proportion settings between 0.3 and 0.7 appeared the most likely to reveal this pattern, and this was the case in terms of the pattern-oriented test as well. For HMODEL_A, patterns are captured within confidence intervals for a similarly small set of configurations. These include decay_prob setting of 0.05 and a pop_growth setting of 0.1 (or vice versa), or decay_prob setting of 0 and a pop_growth setting of 0.15 (or vice versa), with absence_intervals set to 100 years and absence_intensity set to 1. These settings are broadly consistent with the visual inspection made earlier. More importantly, they give some indication of the kinds of conditions that might be required to produce patterning like that at Rutherfords Creek. In support of the geomorphic model, the patterns are best explained in terms of large-scale sedimentary events involving mixed proportions of erosion and deposition, interspersed with long timeframes of inactivity. In support of the intensification or mixed models, the outcomes are consistent with either exponential growth or decay on the order of 0.15% per annum, or mixed proportions of 0.05% and 0.1% each, coupled with century-scale absences or extremely broad dispersals that create notable gaps in the record. It is worth noting that the population growth and taphonomic decay settings used here as consistent with an intensification model are in-line with those advocated in other estimates of demographic change during the late Holocene (e.g. Williams 2013), while the lower or higher settings are unable to reliably reproduce these two patterns. While not an indicator of model fit, this speaks to the sound logic on which these previous models were constructed.
Table 7.3 HMODEL_A and HMODEL curve test and cluster test outcomes with probability of success greater than 0.05

**HMODEL A**

<table>
<thead>
<tr>
<th>decay_prob</th>
<th>pop_growth</th>
<th>absence_interval</th>
<th>absence_intensity</th>
<th>Curve Test</th>
<th>Cluster Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>0.387</td>
<td>0.073</td>
</tr>
<tr>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>0.333</td>
<td>0.094</td>
</tr>
<tr>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>1</td>
<td>0.302</td>
<td>0.086</td>
</tr>
<tr>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>0.287</td>
<td>0.1</td>
</tr>
</tbody>
</table>

**HMODEL**

<table>
<thead>
<tr>
<th>event_frequency</th>
<th>erosion_proportion</th>
<th>stability</th>
<th>Curve Test</th>
<th>Cluster Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.3</td>
<td>0</td>
<td>0.351</td>
<td>0.144</td>
</tr>
<tr>
<td>200</td>
<td>0.5</td>
<td>0</td>
<td>0.233</td>
<td>0.326</td>
</tr>
<tr>
<td>200</td>
<td>0.7</td>
<td>0</td>
<td>0.219</td>
<td>0.346</td>
</tr>
</tbody>
</table>
7.3 Predicting additional patterns from simulation outcomes

The records generated in HMODEL and HMODEL_A have been shown to be qualitatively similar to those found at Rutherfords Creek, and the preceding section demonstrated how they can also produce quantitative similarities under certain settings. However, the mechanisms by which they produce these patterns are quite different. This is evident in the case of the gaps: two models suggest that the gaps are caused by cessation in hearth construction, while the other suggests that the hearths were created, but cannot be dated because their charcoal is no longer present. This difference is intrinsic to the way in which the proxy of charcoal in heat-retainer hearths has been represented in the simulation: as susceptible to burial (in the event of localised deposition) and dispersal (in the event of localised erosion), and occurring only in the presence of an occupying human population.

Charcoal in hearths is affected by burial because it is a small object that would not remain visible on the surface assuming a sufficient volume of sediment were laid on top of it (see Fanning 1994 for estimates of sediment movement at Fowlers Gap). This also true of nearly all of the material objects known to be created by desert-dwelling Aboriginal groups in Australia (e.g. Gould 1980, Tonkinson 1993) and those associated with human groups occupying desert regions in the past (Gould 1969; Holdaway and Stern 2004; Mulvaney and Kamminga 1999; Hiscock 2008; Smith 2013; Witter 1992). Similarly, charcoal objects are affected by erosion because they are typically lightweight, allowing them to be carried away by wind or water moving over the surface. However, unlike deposition, wind or water driven-erosion would not necessarily affect heavier objects used by Aboriginal peoples in the same way. Fanning and Holdaway (2001), for example, were able to demonstrate that low velocity overland flow in western New South Wales was unlikely to cause substantial lateral displacement for stone artefacts with a maximum dimension greater than 20mm, a finding consistent with experimental studies (e.g. Schick 1987). A chronometric proxy that met these criteria (durable object larger than > 20mm) would be expected to show different formational properties than charcoal.

Such a proxy is available in the form of optically-stimulated luminescence (OSL) dates obtained from hearth stones (Roberts and Jacobs 2008; Rhodes et al. 2010). Broadly
speaking, the OSL method measures the amount of radiation absorbed by a mineral matrix since the last time stored charges within the matrix were released through exposure to sufficient sunlight or heat (Aitken 1985). In the case of buried sediments, which are commonly used in OSL studies, this is used to indicate the time since the sediments were last exposed to sunlight. For fired objects such as hearth stones or pottery, this is taken to measure the time since their burning. Archaeologists frequently make use of radiocarbon and luminescence dates in tandem, often in instances where the ages of sedimentary matrices are sought in geomorphic reconstructions (e.g. Roberts et al. 2001; Clarkson et al. 2015). Despite this, there has been limited consideration given to the formational difference in these two proxies, which are likely to be considerable given the different properties of objects that might be dated using these two techniques.

In addition to having different formational properties, hearth stones and charcoal are also associated with the same activity, the construction of a heat-retainer hearth. A calibrated date from wood charcoal obtained from a hearth reflects the age of the death of the plant used to provide the wood, an event which most archaeologists recognise as acceptably close to the date of the burning activity provided the wood is obtained from a short-lived species. An OSL date from a hearth stone, assuming the stone has been sufficiently emptied of its charge during the burning process, also reflects the date of the burning. Therefore, in theory, the dates from either component should both reflect the time that a surface hearth was constructed.

In surface contexts, hearths can only be dated if they are visible, but being visible also makes them susceptible to erosion. Hearths can only be dated using the radiocarbon method where sufficient charcoal can be obtained. However, hearths which have lost their charcoal can be dated using OSL as long as they can be identified as hearths. This means that any proportion of hearths that are absent from the radiocarbon record as a result of erosion would be accessible using the OSL method. Any gaps in the record caused by geomorphic processes like those in HMODEL should not occur with the same degree of intensity as would be seen in a charcoal record (if at all), while gaps caused by sparser human presence in the landscape would be expected to appear in both proxies.
Using HMODEL and HMODEL_A to simulate the effects of erosion and deposition on distributions of OSL determinations from hearth stones

The differential effects of the modelled formational process on a charcoal-based and stone-based chronometric proxy can be demonstrated using the HMODEL and HMODEL_A simulations by keeping track of all surface hearths, but differentiating between those that have had charcoal removed following an erosion event and those that have not. In this version of the model, radiocarbon dates may only be obtained from those still containing charcoal.
charcoal (hidden? = false, dispersed? = true), while luminescence dates may be obtained from any hearth visible on the surface (hidden? = false, dispersed? = {true, false}). Simulations were run 99 times for each setting used in the explorations of HMODEL and HMODEL_A thus far.

The results from these simulations illustrate how the processes as modelled would generate different records for comparable samples of radiocarbon- and OSL-dated hearths. In HMODEL, radiocarbon and OSL date sequences track well together in more depositional
environments as fewer hearths are destroyed. As conditions become more erosional, both curves become less steep, but the curve of the radiocarbon data remains steeper than that obtained from the OSL dates (Fig 7.8). This is because hearths that have lost their charcoal in erosional events can still be sampled using the OSL method. Meanwhile, hearths that are obscured by overlying sediments are still invisible in both samples. When conditions become completely erosional, the radiocarbon distribution returns to the exponential curvature also seen under the highly depositional settings, but the OSL distribution straightens out, reflecting the actual record of hearth ages produced by the agents. Gaps that are clear in the radiocarbon chronologies under settings with no surface stability (7.8, top left) are effectively absent from those in the OSL record.

For HMODEL_A (Fig 7.9), differences between radiocarbon and OSL sequences are only apparent when hearths are affected by time-dependent loss of charcoal. Increases in population growth, on the other hand, have no influence on the distribution of radiocarbon and OSL date frequencies. Gaps that are the result of reduced human presence, meanwhile, persist in both proxies, as the forces which are creating the gaps are not intrinsic to the type of proxy being assessed. These are ameliorated equally in both proxies as the intensity of absences decreases (Fig 7.10). The findings of the pattern-oriented test above suggest that the most probable scenarios for both HMODEL and HMODEL_A involve minimal stability or maximal absence intensity, respectively.

7.3.2 Evaluating model expectations against an empirical record

The simulation results above show that, assuming the processes forming both the curve and the gaps are at least broadly similar with those used in one of the alternative model configurations used here, there should be different expectations in terms of the patterning in these two proxies. If the gaps present in the radiocarbon chronology from Rutherfords Creek were the product of geomorphic processes like those simulated in HMODEL, gaps should not be present (or at least, not as in a chronometric proxy based on an erosion-resistant proxy such as OSL-dated hearth stones). On the other hand, if observed gaps were an outcome of
human absence or dispersal, then gaps present in the radiocarbon record should also be present in the luminescence record of the hearth stones as the generating mechanism for both charcoal and concentrations of stone would be the same, thus falsifying the geomorphic interpretation developed in the present study.

To test this expectation, OSL dates obtained from stones found in surface hearths were used for comparison with radiocarbon dates from surface hearths. Rhodes et al. (2010) discuss the issues involved in obtaining OSL determinations from hearth stones but also note the relatively close correlation between OSL and radiocarbon dates obtained from the same hearths. In this study, OSL dates are not meant to act as a check on radiocarbon dates, but instead are used as a separate proxy with different formational properties from charcoal deposits. From a total of 979 hearths recorded on the surface at the Rutherford’s Creek study area near Peery Lake, 135 were selected randomly, and hearth stones were removed for OSL dating (Rhodes et al. 2010); of these, 101 have a mean age determination that falls within the last 2000 years.

Figure 7.11 Comparing outcomes of HMODEL_A simulations using absence_intensity (ai) settings of 1 (left) and 0 (right), pop_growth and decay settings of 0.1 and absence_interval of 200 years. Envelopes generated by plotting samples of 100 simulated hearths from each run in chronological order.
To compare the two proxies qualitatively, a random subsample of 93 OSL determinations were drawn and plotted alongside the 93 radiocarbon dates dating to within the last 2000 years. This a difference in plot steepness similar to that predicted by HMODEL, as well as some of the settings in HMODEL_A (Fig 7.11). The difference between these two curves suggests that the having a different impact on the charcoal from hearths compared to the hearth stones. Furthermore, gaps that are visible in the radiocarbon sample are less pronounced, and in most cases altogether absent, in the OSL sample. In particular,
pronounced gaps in the radiocarbon chronology are well represented by ages in the OSL record. The period between 367 and 422 BP, represented by 25 radiocarbon dates, contains only four dates in the OSL record. When summary statistics are calculated for the distribution of gap lengths in the OSL sequence (Table 7.4), values are far closer to those expected from a uniform distribution. Notably, the ratio between standard deviation of gap lengths and average gap length and the ratio of median to average gap length are both in line with expectations. This is also apparent when the observed gap lengths are plotted against cumulative time and compared to simulated dates drawn from a uniform distribution (Fig 7.12).

Table 7.4 Summary statistics from simulated uniform data and OSL data from Rutherfords Creek.

<table>
<thead>
<tr>
<th></th>
<th>Uniform distribution</th>
<th>Rutherfords Creek (OSL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiocarbon date span</td>
<td>1896 – 66 BP (1830 years)</td>
<td>1896 – 66 BP (1830 years)</td>
</tr>
<tr>
<td>Date frequency</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>Average gap length (estimated)</td>
<td>18.12 years</td>
<td>18.12 years</td>
</tr>
<tr>
<td>Standard deviation gap length</td>
<td>17.15 (12.3 – 24.7) years</td>
<td>16.96 years</td>
</tr>
<tr>
<td>Standard deviation/average</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td>Median gap length</td>
<td>12.48 (9 – 18.5)</td>
<td>12</td>
</tr>
<tr>
<td>Median/average ratio</td>
<td>0.7</td>
<td>0.66</td>
</tr>
<tr>
<td>Maximum gap length</td>
<td>191</td>
<td>81</td>
</tr>
<tr>
<td>Maximum/average ratio</td>
<td>10.54</td>
<td>4.47</td>
</tr>
<tr>
<td>% total &gt; 50 years</td>
<td>5%</td>
<td>8%</td>
</tr>
<tr>
<td>% total &gt; 75 years</td>
<td>1.2%</td>
<td>1%</td>
</tr>
<tr>
<td>% &lt; average</td>
<td>64%</td>
<td>60%</td>
</tr>
<tr>
<td>% &lt; 1 – 3 x average</td>
<td>32%</td>
<td>35%</td>
</tr>
<tr>
<td>% &gt; 3 x average</td>
<td>4%</td>
<td>5%</td>
</tr>
</tbody>
</table>
The differences between the Rutherfords Creek radiocarbon and OSL data can be further demonstrated using a Kolmogorov-Smirnov test of the null hypothesis that samples are drawn from a uniform distribution. While the null hypothesis can be rejected in the case of the radiocarbon data, the OSL cannot be discerned as different from a uniform distribution (Table 7.5). Both this test and the summary statistics calculated above for gap lengths indicate that the OSL sample is uniformly distributed, suggesting the presence of neither conspicuous gaps or a statistically significant change in the frequency of dates over time.

Figure 7.13 Log-transformed OSL gap lengths (n=100) from Rutherfords Creek imposed on 100 simulated samples from a uniform frequency model with same date frequency and time span (grey cloud).
Table 7.5 Outcomes of one-sample Kolmogorov-Smirnov test against uniform distribution

<table>
<thead>
<tr>
<th></th>
<th>Rutherfords Creek $^{14}$C (n=93)</th>
<th>Rutherfords Creek OSL (n=101)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.233</td>
<td>0.1045</td>
</tr>
<tr>
<td>$p$</td>
<td>0.00008</td>
<td>0.2198</td>
</tr>
</tbody>
</table>

7.4 Summary

To review, this study has sought to make empirical assessments of alternative explanatory models for the formation of surface archaeological deposits in western NSW. The verbal logic of these models, at least in terms of how they are meant to form patterning within a radiocarbon chronology obtained from charcoal in surface hearths, was interpreted and formalised as correspondent computer simulations in order to make the assumptions of each model clear for comparison. By quantifying the patterning visible in the record at Rutherfords Creek, statistical comparisons between simulation outcomes and observed data were able to be made that provided an indication of whether the patterning was a likely outcome of a given model. By combining multiple patterns, this narrowed the field of potential parameter configurations within each model. The different candidate models were shown to demonstrate similar patterning, albeit using different mechanisms to do so, and these different mechanisms were used as a means of developing contrasting expectations for a further pattern: the distribution of OSL dates obtained from hearthstones. Given the absence of gaps in OSL chronology, which would be expected under the intensification and mixed models, these models can be considered to be provisionally falsified. The geomorphic interpretation, derived from notion of episodic disequilibrium (Fanning et al. 2007), predicts this final pattern and can therefore be retained.

The falsification is only provisional, of course, because the models used here are interpretations of verbal models; in other words, the findings only hold true as long as these alternative generative mechanisms are faithfully described by HMODEL and HMODEL_A. Given that verbal models can be far more nuanced than computer programmes, it is possible for objections to be raised over the representation of the alternative models used here. If it
were the case that a key component of one of these alternatives was omitted, then a new round of modelling would be warranted. As long as models are committed to formal definition, there is no reason why reframed or refined versions of the alternative models already described, or other alternatives altogether, could not be likewise compared. The model-based approach employed here, with its emphasis on explicitness, invites this kind of critical re-assessment (Premo 2010:34).

The simulations employed here are noteworthy not for their specificity, but for their generality. Neither HMODEL nor HMODEL_A are overly complicated in their representation of the generative mechanisms responsible for patterns in simulated chronometric data; at most, they employ four or five variables, and the behaviour of the agents is neutral for all intents and purposes. These variables were aimed at capturing the most important dynamics of the formational systems purported to be creating the “patterns for model structure” (Grimm et al. 2005). While model simplicity does not translate directly to model reliability (O’Sullivan and Perry 2013:216), it makes it easier to understand how the models produce their patterning, and then to deduce from logic of the models expectations that might be applied in another area altogether. The results presented here provide further support for the idea that population dynamics are not required to explain the patterns in the two chronometric proxies. Instead, the presence of strong clustering of dates in the radiocarbon data coupled with a comparatively flat OSL distribution are better explained as differential effects of geomorphic processes occurring over a large portion of the sampled landscape. These findings have implications for the ways in which patterning in archaeological data is used to construct prehistoric narratives, how western NSW can be accommodated by existing prehistoric narratives, and as how archaeologists working in the region might approach further collection of data. These ideas, in combination with the outcomes of the exploratory FMODEL outcomes, will be explored in more detail in Chapter 8.
In studies of landscape history there is an established tradition of ‘reading’ landscapes (David and Wilson 1999; Hart 1995; Watts 1975). The metaphor is that the land is inscribed with the collective marks of nature and humanity which, through keen observation, can be read like a text. In a seminal paper on the topic, Lewis (1979) describes a set of guidelines, in the form of ‘axiomatic’ statements, for interpreting cultural landscapes. These promote treating the ordinary as equally important to the extraordinary (the Axiom of Cultural Unity and Landscape Equality), stress the need to understand the operation of physical and historical processes that give rise to landscape entities (the Mechanical Corollary and the Historic Axiom), and highlight the importance of geographic and environmental contexts (the Geographic Axiom and the Axiom of Environmental Control). These ideas have been echoed in this study by emphasising the significance of all archaeological records (even those deemed difficult to interpret), drawing out the mechanisms of formation are key to discerning between explanatory models for emergent landscape patterns, and underscoring the roles of environment and space on the formation of deposits and assemblages. But it is the final axiom, the Axiom of Landscape Obscurity, which is most relevant to the discussion of the western NSW surface record. The idea is that while information is encoded in landscapes, the encoding is not likely to be a message that is straightforward or intuitive, but rather one that reflects processes without intended consequence for patterning in landscapes of the present. This is encapsulated in Lewis’ (1979:13, emphasis in original) oft-repeated line: “Like books, landscapes can be read, but unlike books, they were not meant to be read.”

The findings from the modelling exercises are considered in this chapter with respect to different readings of the archaeological landscapes in western NSW. Tacking back forth between model outcomes and observations from the surface record, it is argued that patterning at Rutherfords Creek is the result of a consistent set of behaviours over the course of the late Holocene, providing additional hypotheses for testing and making recommendations for further data collection. The modelling exercises, combined with the empirical observations at Rutherfords Creek, provide an experimental test of some of the formational logic upon which prehistoric narratives in arid Australia are built. The test itself demonstrates that the reasoning used to support some narratives does not hold in the case of...
Rutherfords Creek, demonstrating a need to carefully scrutinise the formational histories of archaeological deposits and landscapes. The problematic position of the prehistory of Rutherfords Creek as an exception to these narratives is then assessed. A framework that puts trajectories of persistence and transition on equal footing is sought, and one such framework, that of socioecological resilience, is briefly explored. The role of models in the study is reviewed and a short reflection on the model-building process is provided to illustrate how models were used here as both formal theory building mechanisms and “tools to think with” (O’Sullivan and Perry 2013:14). Finally, future directions for the study of formation in archaeological landscapes in Australia are considered.

8.1 Interpreting late Holocene prehistory in arid Australia: lessons from the surface record

8.1.1 Patterning in hearth ages and population dynamics at Rutherfords Creek

Population dynamics in Australia are often demonstrated using the frequency of dated objects, especially radiocarbon determinations on organic or calcareous materials in archaeological contexts (Attenbrow and Hiscock 2015). Studies in the Australian arid zone have pointed to increased frequencies of radiocarbon dates through time as evidence for increasing populations in the late Holocene. Abundances of surface deposits dating to this period, with limited numbers of earlier deposits, promote this idea (Lourandos 1997:185; Smith 2013:323).

Heat-retainer hearths were used as the primary source of chronometric data for this study as they are the most abundant among the potential sources of radiometric data available. A heat-retainer hearth as identified in the present is a collection of stones that were once exposed to a heat source. These may also be conglomerated with fire-altered sediments and charcoal. From these different components, depending on their state of preservation, chronometric determinations are obtained from both wood charcoal (radiocarbon) and hearth stones (OSL). At Rutherfords Creek, a pattern of increasing frequency toward the present is
observed in radiocarbon determinations and this has been variously ascribed to population dynamics and differential preservation. Periodic gaps evident in this record have been argued to show fluctuations in the intensity of occupation, either through a process of expanding and contracting logistical foraging areas or through alternating periods of occupation and abandonment.

In HMODEL and HMODEL_A, differences between the two chronometric curves are products of differential preservation in the proxies they are constructed from. Hearths that lose their charcoal, either to erosion or some other taphonomic process, can still be dated using the OSL method as hearth stones are more durable and less prone to dispersal. This means that the OSL proxy is somewhat immune to the time-dependent processes that drive charcoal dispersal. The extent to which such dispersal occurred during the formation of the simulated record determines the degree of distinction between the two curves.

If substantial differences were not present in the distributions of dates between the chronometric proxies at Rutherfords Creek, then based on the outcomes of the simulations it might be argued that these were not strongly affected by processes that led to the loss or obscuring of charcoal data sources, but that any curvature was instead due chiefly to changes in the frequency of hearth construction. However, this would be difficult to reconcile with the geomorphic reality in western NSW, where event-driven fluvial and aeolian processes cause extensive changes to the character of landsurfaces (Fanning 1999; Jansen and Brierly 2004). Strong similarities between these two proxies might also be expected under highly depositional conditions, which prevents the loss of charcoal in HMODEL. But the surveyed parts of the Rutherfords Creek catchment are not thought to have experienced conditions dominated by deposition over the past 2000 years (Fanning et al. 2009; Bryant 2013), and in any event, the curves in both proxies are far too shallow for either proxy to be associated with conditions akin to the deposition-dominated HMODEL outcomes.

The differences observed between these two proxies supports assertions made in some earlier studies that the chronology presented by the surface hearth record in western NSW study locations is biased toward the present due to time dependent loss of information, which itself is a function of the geomorphology of the landscape. As shown by Holdaway et al. (2008), there is a correlation between the ages of hearths and the ages of the depositional
surfaces on which these hearths rest, such that older geomorphic surfaces feature a greater range of hearth ages than do more recently deposited surfaces. By considering specific land surfaces in one catchment, isolated places where hearths with older dates were both visible and preserved and places where only more recent hearths could be found have been documented (Holdaway et al. 2008). The results from the experiments presented here likewise indicate that for older charcoal to be both visible and preserved alongside more abundant recent material, depositional and erosional processes must occur in mixed proportion, presenting a wider range of surface ages that could be built on over time.

Other assertions, however, are not supported. If the observed gaps in the Rutherford's Creek radiocarbon sequence were the result of periodic stoppages in hearth building activities, due to expanded foraging ranges or periods of abandonment, then there is no reason to expect concomitant continuity in the OSL chronology. Both are the product of the same activity (hearth-building), subject to effectively the same set of geomorphic forces, and there is no appreciable difference between the hearths selected for OSL and radiocarbon dating. Therefore, any gaps caused by changes in the frequency of hearth construction at Rutherford's Creek would be intrinsic to the population of hearths and not the hearths’ components, as seen in the HMODEL_A outcomes. On the other hand, if the gaps were the product of geomorphic processes like those explored in HMODEL, then continuity in the OSL record where gaps are present in the radiocarbon record would be entirely expected because these formational processes affect these two proxies differently. That the OSL sample from Rutherford’s Creek shows such continuity suggests that a geomorphic interpretation of gaps in the radiocarbon chronology cannot be ruled out and that retaining any alternative interpretations that explain these gaps through changes in the population dynamics of the area would require accounting for the observed differences between these proxies.

At a general level, the HMODEL and HMODEL_A simulation results, combined with the patterning observed in the chronometric proxies studied here, caution against the use of frequency distributions of summed radiocarbon data from surface contexts as a proxy for estimating past human population dynamics in the absence of explicit formation models. If erosion differentially affects not only the preservation of hearths, but also their visibility, the
compound effect may give the appearance of exponential growth when in fact growth was limited or non-existent. Some have already noted that in places where visibility is a concern, mathematical corrections of summed radiocarbon data to account for post-depositional changes may not be applicable (Williams 2012: 586). Accepting this condition, however, means that proper use of radiocarbon data as a proxy for population dynamics, taphonomically-corrected or otherwise, depends on the extent to which places exist where archaeological visibility is not of concern. The differential effects of sediment transport on visibility and preservation in archaeological contexts are not likely confined to rare studies where they have been clearly identified (e.g. Fanning et al 2009; Ward et al. 2006, 2015; Stern 2008, 2015). This is not to say the summed radiocarbon data cannot be used as a means of generating insights into population dynamics, but rather that their interpretations should be couched firmly in formational as well as demographic logic. As others have suggested (e.g. Contreras and Meadows 2014), simulation can be helpful in providing context for assessing radiometric distributions going forward.

It has been noted in previous studies that fluctuations evident in the radiocarbon data at Rutherfords Creek correlate with proxies for broad-scale environmental changes. Holdaway et al. (2010) have shown that periods featuring greater numbers of hearth ages correspond to some extent with increased frequencies of sea-surface temperature anomalies evident in tropical marine sediment cores, which are used as proxy for greater presence of monsoonal troughs reaching eastern Australia. Additionally, some correspondence has also been demonstrated between gaps and records of Australian dust transported to New Zealand, a proxy for extreme aridity (Marx et al. 2009; Holdaway et al. 2010). While it has been previously argued that these may correspond with fluctuations in human activity (contraindicated here by the comparison to the OSL record), the same forces of drought and flooding would also be those presumably driving the geomorphological shifts in the condition of the surface of the valley floor that are promoted. This view would be also consistent with interpretations of charcoal records derived for the continent of Australia that characterise fluctuations as being primarily correlated with climatic changes (e.g. Mooney et al. 2011; Mooney et al. 2012).
Even though the patterning observed in the two chronometric proxies from Rutherfords Creek is best explained as the outcome of geomorphic processes on a fairly uniform record of occupation, this does not imply that the same chronometric signals exist beyond the landforms studied here, nor that occupational continuity should be expected for all places and times. Different landforms will face different degrees of erosion, deposition, and stability based on their given characteristics (e.g., slope, local rainfall intensity, proximity to channel, etc.), creating different depositional conditions for archaeological deposits. Nevertheless, under situations where event-driven geomorphic activities were a driving force in the exposure of archaeological remains, findings might be expected to fall somewhere within the spectrum captured by the parameter space of HMODEL. It would be instructive, then, to examine hearths from different kinds of depositional environments (e.g. valley margins, ridges, etc.) and compare the resulting chronometric data derived from both proxies used here to that generated by the model.

8.1.2 Patterning in Cortex Ratios at Rutherfords Creek

Archaeological discussions of changes in the mobility regimes of Australia’s desert-dwelling peoples often focus on the extent to which populations were residentially or logistically mobile (Douglass 2010; Smith 2013; Smith and Ross 2008; Veth 1993; Veth et al. 2011). While defining these concepts is complicated by the relationships between behaviour and material expressions (Kelly 1992), they can be boiled down to the frequency with which individuals return to a base residence (Binford 1980; Kelly 1983). For ‘logistical’ foragers, areas around a base residence can be considered a ‘core’, while forays into an outlying ‘periphery’ might be taken for the purpose of exploiting resources (e.g. Smith and Ross 2008:384; Veth 1993) (Fig. 8.1). This is often associated with more intensive use of local resources and higher populations. In a ‘residential’ foraging scheme, distinctions between core and peripheral areas are less important as groups use places with equal redundancy. These mobility configurations can be considered as points along a continuum. At one end of this continuum are groups that make very few logistical forays from a base at
which they are otherwise resident; at the other end are groups that never stop moving (e.g. Lourandos 1997:20; Perrault and Brantingham 2011).

The Cortex Ratio was chosen as a measure of mobility in this study as it indicates movement by considering the physical separation of constituent parts of a lithic reduction sequence (Dibble et al. 2005; Douglass et al. 2008). The Cortex Ratios recorded from surface assemblages at Rutherfords Creek are predominantly lower than one; in fact, while a few Cortex Ratios are higher than 1, the distribution of these values is primarily clustered around a value of 0.55. This kind of patterning might be expected from either the removal of cortical flakes or the addition of reduced cores. At Rutherfords Creek, raw material is abundant in creek beds, stony desert pavements, and rocky outcrops. Nearly all of the material being encountered in surface scatters is indiscernible from local material (Barker 2009).
Furthermore, the raw material being worked has been shown to be of a size consistent with locally available raw material (Douglass and Holdaway 2011), begging the question of why equivalent material would be brought from a distance. This would suggest that Cortex Ratio patterning within the creek catchment is not due to the addition of reduced cores but rather the transport of cortical flakes away from the valley floor.

In the context of FMODEL, a forager that was concentrating activity within a single catchment would be expected to produce a range of assemblages featuring different Cortex Ratios distributed around a value of 1. The extent of that variation should be approximately determined by the degree of redundancy in discard locations, which is described in FMODEL by the tortuosity of movements between discard events (Fig. 8.2). Higher tortuosity means greater frequency of local discard events, reducing the influence of added or subtracted material as the majority of reduction products remain local. Conversely, lower tortuosity
means fewer reduction events might occur before an individual moves beyond the window of observation, with the increased possibility of shifting Cortex Ratios higher or lower than one.

Differences in the tortuosity of movement might be expected between core and peripheral areas within a logistical movement scheme, with higher tortuosity at the core and lower tortuosity in peripheral areas (Fig. 8.3 a and b). Greater redundancy in place use at the core would have the effect of reducing cortex variability. Higher velocity of movement at the periphery, meanwhile, would be expected to produce more variable Cortex Ratios. Yet as long as carry-in and carry-out behaviours were not significantly different between core and peripheral areas, the distributions of Cortex Ratios in both areas should still fall roughly around one.

The extent to which the assemblages in a core versus a peripheral area exhibit Cortex Ratios that are distributed around a value that is above or below one, then, would be due to the differences in the transport and discard of stone between the two areas. For example, if stone resources were regularly being carried from peripheral areas into the core (such as in a quarrying scenario), then it might be expected that Cortex Ratios would highlight this imbalance by falling below one in peripheral assemblages and above one in core assemblages, while still reflecting the difference in the different tortuosity models (Fig 8.3a). On the other hand, if provisioning of stone resources was occurring within the core areas for use in the periphery, then the opposite patterning might be expected, with Cortex Ratios inflated at the periphery and depressed at the core (Fig 8.3b). Finally, if there were no substantial differences in the redundancy of place use, but the amount of stone carried in versus carried out differed between places, then this might be expected to generate imbalances in Cortex Ratios as well. However, as long as redundancy in movement patterns are similar across the landscape, variability should be consistent between locations (Fig 8.3c). Each of these is a verbal model that provides some expectations of what might be expected from assemblage Cortex Ratios if mobility and procurement were organised in a given way.
Figure 8.3 Theoretical structures of curation and mobility configurations: a) ‘Logistical’ configuration with high levels of carry-in occurring at the core, b) ‘Logistical’ configuration with high levels of carry-in occurring at the periphery, c) ‘Residential’ configuration with levels of carry-in varying between locations. Graphs at right indicate effects on distributions of assemblage level cortex ratios. Red circles indicate areas of high carry-in, while blue circles indicate areas of low carry-in.
All of the alternative scenarios discussed above strongly suggest that the spatial distribution of raw material in the landscape could have the potential to influence patterning in Cortex Ratios, as the availability of raw material will largely determine whether stone can be carried out of a given location and into another or vice versa. As mobile foragers move through the landscape, “gearing up” at places that have stone would provide the forager with a ready kit (Kuhn 1992). As long as there is a ready supply of stone, foragers should generate a range of assemblage-level Cortex Ratios balanced around a value of 1. Eventually, foragers carrying stone from material-rich places may reach places where raw material availability is diminished. This restricts the forager from replenishing a kit with new flakes, while potentially involving the discard of imported material into local assemblages as they become worn or broken. The result over time is a build-up of imported flakes without comparable loss of cortex from local sources through replenishment. This would be akin to a high carry-in/low carry-out situation. These same foragers, faced with a situation of a dwindling kit in a place with limited stone resources, might return to places where stone resources are more readily accessible, replenishing their kit upon arrival and continuing to forage. This would be akin to the inverse: a low carry-in/high carry-out situation.

This can be illustrated in a simulation using the FMODEL framework. Like the original configuration, agents move through the world following a Lévy walk discarding artefacts, manufacturing them when they have an empty kit according to a set level of reduction, and adding them to their mobile kit according to a pre-set selection level. However, instead of modelling movement paths of multiple individuals through the window, the world is wrapped as a torus, such that the left side of the world is connected to the right, the right side of the world and the bottom is connected to the top, mimicking a continuous space. In this model, agents move through an environment which is divided into equal areas of high and low raw material availability. Any cell within the world can be a raw material source, but the frequency of these raw material cells on each side of the model world is determined as a percentage of the total number of cells selected at random (by variables called left_abundance and right_abundance, respectively, Fig 8.4a). Unlike the previous incarnation of FMODEL, an agent cannot replenish its kit until it encounters a raw material source. Finally, the mobility of the agents can be differentiated by using different settings of mu (μ) for the two sides of the world (left_mu and right_mu, respectively),
allowing the model to simulate differences in tortuosity between core (high \( \mu \)) and periphery (low \( \mu \)) areas (Fig 8.4b). Each simulation was run until 100 reductions had occurred, and Cortex Ratios were calculated for assemblages on the left and right sides. Parameter settings

Figure 8.4 Illustrations of different parameter settings for FMODEL_A: a) Distributions of raw material sources (red cells) generated from abundance settings modelling even raw material distribution (left) and stone-rich/stone-poor areas (right); b) Agent paths resulting from Lévy mu (\( \mu \)) settings used to model a residential mobility configuration (left) with no differences in redundancy of place use and a logistical or ‘periphery-core’ configuration (right) with greater tortuosity of movement on the right side relative to the left.
used in this brief model exploration are listed in Table 8.1, and a more detailed treatment of this model variation, called FMODEL_A, can be found in Appendix C.

Table 8.1 Parameter settings for FMODEL_A exploration

<table>
<thead>
<tr>
<th>Model configuration</th>
<th>left_mu</th>
<th>right_mu</th>
<th>left_abundance</th>
<th>right_abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Periphery-Core (even)</td>
<td>1.1</td>
<td>3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Landscape (even)</td>
<td>1.1</td>
<td>1.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Stone Poor Core</td>
<td>1.1</td>
<td>3</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Landscape (uneven)</td>
<td>1.1</td>
<td>1.1</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>Stone Rich Core</td>
<td>1.1</td>
<td>3</td>
<td>0.1</td>
<td>0.9</td>
</tr>
</tbody>
</table>

When this null model is explored (Fig 8.5), settings with no difference in abundance between the two sides (‘Periphery-Core (even)’ and ‘Residential Mobility (even)’) produce Cortex Ratios distributed around 1. Where the tortuosity of movement differs between the two sides (‘Periphery-Core (even)’), Cortex Ratios are more variable in areas of lower tortuosity. Changing the abundances in raw material availability pushes distributions away from one, creating distinctions between the two modelled regions. Cortex Ratios decrease where raw material is more abundant and increase where it is scarcer (‘Residential Mobility (uneven)’). The disparity between stone rich and stone poor areas becomes more exaggerated as the tortuosity of movement changes (‘Stone Poor Core’ and ‘Stone Rich Core’).

What this demonstrates is that while the carry-in and carry-out components are the proximate determinant of the degree of deviation in assemblage level Cortex Ratios, these can be imposed on a forager moving randomly and gearing up on an as-needed basis by introducing disparities in the availability of raw material within the landscape. It could be that what made Rutherford’s Creek different was not any particular environmental attractor, but the widespread availability of raw stone material. Stone resources would be unlikely to attract people to Rutherford’s Creek in particular, as they can be found in great abundances throughout the area surrounding Peery Lake and points beyond. But Rutherford’s Creek and these other areas together are different from areas with little in the way of stone resources.
Stone-poor areas can be found surrounding Rutherford’s Creek in several directions (e.g. Darling floodplains to the south, dunefields in the Simpson-Strzelecki Desert to the northwest, Bulloo basin to the north, etc.). If foraging took people through Rutherford’s Creek and on into areas without stone, those areas could be absorbing transported flakes as a low density scatter that might be difficult to detect in a casual archaeological survey.

Under this scenario, the degree to which places that are rich or poor in raw material availability are differentiated by Cortex Ratios would be determined by the relative value of these places as foraging environments. Areas with high degrees of overlap between abundant raw material and subsistence resources might be expected to produce a core area for foraging activities. In such a scenario, the shift in the distribution of Cortex Ratios might not be

Figure 8.5 Outcomes of the FMODEL_A exploration of the influence of raw material distribution on assemblage Cortex Ratios. Top row are logistic mobility configurations, bottom row are residential mobility configurations.
substantial as the local cycling of manufacture and discard would be expected to outweigh the overall loss of material to resource poor areas. In other words, a pattern generated through intense local use would be more difficult to reverse than patterning resulting from net import-export by occasional occupants. The result would be Cortex Ratios that were marginally depressed at the core, while inflated and highly variable Cortex Ratios would be encountered in peripheral areas (the “Stone Rich Core” configuration in Fig 8.5). Rutherfords Creek, given its broad distribution of values around a mean value considerably lower than 1, is not suggestive of this. Based on the observed data in the context of the simulation outcomes, Rutherfords Creek assemblages might be better described by low tortuosity movement patterns similar to those in a model that put the stone-rich creek at the periphery (the “Stone Rich Core” configuration in Fig 8.5), or a model of high residential mobility where the zones of resource use and stone availability were of different sizes, prompting disproportionate loss of cortical stone from stone rich areas to stone poor areas. However, determining more precisely how the variability might be expected to vary given these different spatial relationships would be of fundamental importance going forward.

This brings up an important final caveat. Because the spatial definition of assemblages affects how Cortex Ratios are calculated, finding patterns elsewhere that make sense in terms of mobility will require careful consideration of survey methods. Calculating the Cortex Ratio depends on the presence of at least one core, therefore a landscape dominated by low density scatters of cortical flakes may require survey over a large expanse in order to incorporate a single core. However, if assemblages are targeted for survey as areas immediately adjacent to cores, then these might demonstrate deflated Cortex Ratios when inflated ratios are present at a wider spatial scale. This is an example of the classic ‘modifiable areal unit problem’ in geography (Openshaw 1983), and recalls Douglass’ (2010) radial model of the relationship between Cortex Ratios and space (see section 6.3.3), which would suggest that Cortex Ratios should increase as the area around a core becomes larger.

At Rutherfords Creek, surveys were conducted on a randomly chosen set of 107 exposures of varying sizes, ranging from 10 to over 5000 square metres. Among surveyed scalds, 82% contained at least one core, and a linear relationship between exposure size and Cortex Ratio could not detected ($p = 0.511$, adjusted $R^2 = -0.006453$; Fig 8.6), indicating that the Cortex Ratios are not directionally biased with respect to core proximity in samples from
8.2 Implications for prehistoric narratives in western New South Wales and arid Australia

How do narratives operate in the construction of archaeological knowledge? A recent paper by Williams and colleagues (2015a:12) describes an intensification narrative for Australia, based foremost on radiocarbon evidence, as a “first-order framework for researchers to test.” Narratives in archaeology are built from observing and interpreting patterning in archaeological data, and some suggest that tests of large-scale narratives like late Holocene intensification will come from gathering more data to flesh out regional studies (Ulm 2013:189; Williams et al. 2015b:106). But if testing is “a matter of comparing a forecasted outcome with an empirical realization under a specified set of tolerance limits” (Dunnell 1992:210), then any testing of such a framework must assume that the ‘tolerance
limits’, the conditions under which the conjectured mechanisms hold, are known and can be applied independently. Obtaining more data will not necessarily serve the purpose of testing unless the patterning in that data can not only be associated with the range of outcomes of a suspected process but that it can also be used to test expectations of what will be found that are independent of the original formulation (Kosso 2001:71). Even if sound reasoning provides the former, confirming evidence will not provide a test of whether the system responds or not according to expectations.

Rutherfords Creek provides a motivating example of this. Observations of the local geomorphology have prompted some to suggest that patterns in the surface record at Rutherfords Creek are largely a product of natural forces that control the preservation of archaeological materials such as stone artefacts and hearths (Holdaway et al. 2008). On the other hand, the surface record at Rutherfords Creek possesses several traits commonly associated with intensification narratives, such as radiocarbon chronology dominated by late Holocene dates; indeed, if sampling is indicative, Rutherfords Creek alone may have more than 700 hearths dating to within the last 2000 years visible on the surface (not to mention others beneath it). Deposits of lithic artefacts of varying densities associated with hearths dating to this period are situated around the creek watercourse, which have been cited elsewhere as being indicative of more lasting occupations (Veth 1993; Williams 1998 cf. Shiner 2004). From an alternative perspective (e.g. Smith 2013:323), the patterning at Rutherfords Creek therefore provides further confirmation of a late Holocene intensification narrative.

While these different interpretations of the surface archaeology in western NSW diverge in the causal mechanisms they assign, it is not difficult to see that the logical foundations on which these interpretations are based are all quite reasonable. This may not be true in every case where the data are underdetermined by models, but it is worthwhile recognising that it is in fact the reasoned nature of the interpretation logic that makes narratives compelling. As verbal models (sensu Servedio et al. 2014), they provide mechanisms by which a pattern or set of patterns could have formed. This is one of the primary reasons why formal, exploratory models were employed in this study: to evaluate
this logic in a common framework that clarifies how the mechanisms produce patterning with the record.

Here, simple simulated worlds were created and fully explored, worlds in which the visibility and preservation of deposited items are differently affected by episodic, localized sediment transport, and where artefacts were distributed across a surface according to a consistent set of reduction, selection, and movement rules. The outcomes of the simulations suggest that such processes might produce several characteristics in simulated landscapes that are qualitatively similar to patterns seen within recorded surface archaeological deposits in western NSW. Demonstrating that these processes can generate patterns similar to those observed in two chronometric proxies with different formational properties, charcoal and hearth stones, suggests a counterargument to existing interpretations of social intensification or periodic abandonment.

If a narrative were to be constructed solely from the patterning discussed here, the emerging picture is one of continuity during the late Holocene at Rutherfords Creek. Assuming a causal relationship between human population dynamics and the frequencies of chronometric dates (Rick 1987), the temporal distribution of OSL hearthstone dates, in contrast to the charcoal record, suggests that the creek valley was occupied regularly, without much in the way of directional or cyclical change in the frequency, duration, or size of occupations over time. And while variability in the manufacture and discard of stone artefacts is evident at Rutherfords Creek, the overall pattern is remarkable for its consistency in the patterns of flake removal. Assemblages at Rutherfords Creek indicate significant loss of cortical material without evidence for its re-deposition elsewhere within the catchment or replacement with similar material from elsewhere, indicating that individuals regularly left Rutherfords Creek with more stone than they brought with them (a pattern potentially explainable through the geographic distribution of raw material). In short, these signs would seem to indicate that Rutherfords Creek was a place that was occupied habitually, and that the activities taking place there exhibited in the archaeological proxies discussed here showed little variation over the last 2000 years.

Such an interpretation runs contrary to narratives of late Holocene population growth and increasing sedentism, and may raise the question of how different Rutherfords Creek is
from other places. Some of the specifics that make the region unique, such as the presence of coordinate drainage, likely played a role in shaping the historical trajectory of human groups in western NSW, but this is an unsatisfying explanation for the differences observed in the archaeological proxies at Rutherfords Creek and other locations where patterning is used to support intensification narratives. As noted above, the patterning observed in the archaeological record at Rutherfords Creek is in many ways similar to that found in surface contexts elsewhere in the arid zone used to support intensification narratives. Many of the changes that are thought to have coincided with intensification elsewhere, such as increased aridity from 1500 to 600 BP followed by terminal Holocene climate amelioration, also occurred at Rutherfords Creek and the surrounding area. And while social dynamics were likely different between the ancestral peoples occupying the Darling River basin and other parts of arid Australia, ethnohistorical records of Barkindji (Paakantyi) settlement patterns and economy are sometimes cited as an example of an observed outcome of the intensification process (Williams et al. 2015a:12). In short, by the logical reckoning of existing intensification narratives, there is no reason why Rutherfords Creek should not have undergone the kinds of changes the narrative purports to have taken place during the last 2000 years. However, the radiocarbon date frequencies only appear to indicate this in the context of the narrative.

This is a reinforcing example of the Axiom of Landscape Obscurity (Lewis 1979): that patterning within the archaeological record may not be intuitive, and that interpretations should be carefully scrutinised in terms of how they account for the formation of archaeological patterning (see also Hiscock 1985; Wandsnider 2004). Archaeologists may attempt to overcome the influences of differential visibility, preservation, and accumulation that confound sequential narratives by targeting places that may have been less affected by sediment transport such as rockshelters (Lourandos and David, 1998; Johnson and Brook 2011), although it has been demonstrated that these are not necessarily immune from differential rates of sedimentation (Hunt et al. 2015; Ward 2004; Stern 2008). Furthermore, focusing on one kind of occupation setting effectively swaps one bias for another (Langley et al. 2011), and preferring some datasets over others reinforces the “predetermination of the variability” identified by Ulm (2013).
8.2.1 Formation, reversibility, and resilience: engaging with a diversity of records in Australian prehistory

The findings discussed above suggest that some reconsideration of the nature of the data on which such narratives are built is warranted. But supposing for the moment that the patterns observed elsewhere used to support narratives of late Holocene intensification do in fact reflect genuine trends, how should the record at Rutherfords Creek be reconciled? The development of intensification narratives creates a somewhat uncomfortable space for this, as alternatives are almost by necessity put into contrast with the ‘progressive’ interpretation of intensification (Hiscock 2008:249; Allen 2015). This conjures parallels to difficult discussions regarding cultural evolution in Tasmania (e.g. Jones 1977; Bowdler 1980; Horton 1980), begging questions along the lines of ‘if intensification was happening in so many other places, why was it not happening here?’ Should separate narratives be constructed to accommodate the exceptions? Or are there ways of interpreting the record that might accommodate both trends and exceptions without relying on a progressive model of change?

The consistency seen in the record at Rutherfords Creek harkens back to interpretations that positioned regular mobility and demographic conservatism as parts of a long-standing adaptation to a desert environment that is by most accounts marginal for human habitation (e.g. Allen 1974; Gould 1977, 1980). These models argued that maintaining mobile, disaggregated populations, particularly during times of resource stress, provided a failsafe against unpredictable shortfalls in local environmental productivity. But environmental unpredictability, along with demographic and social pressures, can create problems that require solving (e.g. David and Lourandos 1998), and solutions that are considered successful may be accompanied by reorganisations of socio-ecological systems. Such state changes often trigger knock-on effects that, in the short term or over the long run, may require additional solutions, creating positive feedbacks within a system (Scheffer 2009:25; Morton et al. 2011:325). The panoply of social elaborations seen in many parts of the world, such as that observed from the Neolithic period onward, are frequently attributed
to these types of feedback systems (e.g. Zeder 2009), and the role of such feedbacks is increasingly implicated in Australian prehistory (e.g. Smith 2013:337).

An ideal framework for incorporating the variability of patterns of land use would focus on these feedbacks and transitions rather than attempt to fit a single trajectory. One such framework, presented here as food for thought, is the concept of resilience. Resilience is variably defined but typically refers to the capacity for a system to withstand or adapt to change while maintaining its core functions (Holling 1973). This is often expressed in terms of basins of attraction (Walker et al. 2004). A system in equilibrium has a single basin of attraction, so that if the system is pushed away from the equilibrium, counteracting forces will return the system to its equilibrium state. However, some systems may have more than one basin of attraction, and certain forces, internal or external, can push these systems into an alternative basin, forcing a reorganisation of system components. These transitions may not be linear, but instead may occur following a substantial disruption or when a tipping point is reached through the influence of sustained, low amplitude forces (the sort that might arise from a positive feedback loop). Increasing resilience, then, is accomplished by either widening the preferred basin of attraction (termed “latitude”), or altering the probability of transitioning between basins (termed “resistance”) (Fig 8.7).

Resilience frameworks have unsurprisingly found applicability among studies of prehistoric responses to disasters such as floods or volcanic eruptions, as these kinds of catastrophic shocks are more likely to push the adaptive capacity of socio-ecological systems to an extreme. Resilient cases, often demonstrated through cultural continuity following disasters, emphasise the adaptive capacity exhibited by groups through diversifying resource exploitation, actuating social memory, or exploiting social networks (e.g. Sheets 2012; Torrence 2015). Others have focused more on the role of management in the resilience of socio-ecological systems. Redman and Kinzig (2003:14), for example, treat the successions of city-states and empires in Mesopotamia as stages within adaptive cycles, suggesting that policies and practices aimed at capitalising on short-term gains for elites that allowed for the establishment of the Sumerian empires could not be sustained by the local environment, leading to a systemic reorganisation into regional social entities.

All of these kinds of processes have implications for the formation of archaeological residues. If changes occurred frequently and cyclically, then patterning in the record might be
expected to settle into a general pattern reflecting this. Feedbacks of substantial amplitudes, like those suggested between population growth, social organisation, and environmental productivity as part of intensification narratives, would be expected to shift archaeological patterning directionally given enough time to operate on the record, producing intermediate forms during the earliest stages of this transition. But by this same token, small-scale changes employed strategically to increase overall resilience may leave a more reversible pattern in the wake of the continuity such resilience supports. These notions recall Lucas’ (2008) notion of reversibility, which would suggest that different parts of the record would be differently reversible depending on their role in either the maintenance of resilience, or the systemic components which are being retained by that resilience (see also Bailey 1983, 2007).

During the late Holocene, the occupants of Rutherfords Creek employed a strategy of high mobility, evidenced by the net loss of cortical flakes from lithic assemblages. Cortical flakes tend to be removed earlier in reduction sequences (Dibble et al. 1995), producing large, flat flakes that balance the utility of cutting edge and manual leverage with artefact weight (see Douglass 2010; Kuhn 1994, 1996; Morrow 1996). This pattern suggests a
strategy of regular mobility, as well as the regular provisioning of a mobile toolkit with high utility flakes. Such a strategy may have aided, or at the very least did not impede, the ability of groups to occupy Rutherfords Creek on a regular basis despite irregular fluctuations in the availability of resources. The stability evident in the OSL chronology may indicate that adaptations such as high degrees of mobility and frequent re-provisioning may have maintained a wide-enough latitude to prevent transitions into substantially different basins of attraction. Alternatively, they may have given foragers enough flexibility to transition into and out of an alternative basin of attraction with enough ease and speed to negate any sustained shift in the processes that generate archaeological patterning. Whatever the case, these strategies allowed humans to maintain a presence at Rutherfords Creek despite frequent, unpredictable changes in the suitability of the foraging environment it presented.

An estimation of stability and resilience during the late Holocene would not indicate a lack of change at Rutherfords Creek; on the contrary, a resilience-based framework would assume some kind of change being a necessary component of a resilient system. But archaeologically, it suggests that the magnitude of any behavioural changes that may have occurred at Rutherfords Creek was not sufficient enough to perceptibly shift the patterning in the selected proxies given the resolution of the data under examination (Bailey 1983). For example, it could be that episodic periods of abandonment were occurring as part of a low resistance strategy but that these abandonments were of durations short enough not to register in the patterning of the chronometric data. Other proxies may be indicative of changes at other levels. For example, it could be that Rutherfords Creek saw an increase in the use of grinding technology or diversification of rock art styles as has been documented for Holocene deposits elsewhere in arid Australia (Smith and Ross 2008). These proxies are not always available in surface contexts (although see Shiner 2004:267) but this does not mean that they did not occur or were not part of wider cultural systems in operation at Rutherfords Creek over this period of time. It could be that changes in these proxies identified elsewhere reflect adaptive processes operating at other scales within a socio-ecological system which may or may not contribute directly to their resilience. But there is no reason to assume that these patterns as perceived indicate changes in population dynamics or movement configurations. It is only when these are conceptualised within the context of an ethnographically-oriented model that they take on these associations (Boyd 2006).
Based on the outcomes from the simulations, it is argued that some of the archaeological proxies used to demonstrate change, and the kinds of change (high magnitude, directional) that have been historically sought from them, would benefit from reconsideration (see also Hiscock 2008; Attenbrow and Hiscock 2015; Ulm 2013). Changes can occur at a variety of spatiotemporal scales and the record in some places may be suited for viewing some changes better than others.

Prehistoric narratives typically represent big picture trends and trends will always have exceptions. Hiscock (2008), for example, has documented numerous exceptions to Australian narratives invoking broad-scale directional changes in prehistory, making the alternative case that the archaeology of the continent is better characterised as a diverse set of regional and local trajectories. Yet as long as these are viewed as exceptions, pointed to as failings of the broader narrative, they can be dismissed as spoilers, cautionary tales, or forms of particularism that misses the forest for the trees (Davidson 2009:217). Finding perspectives that balance between trends and variability is difficult but important as archaeological narratives are incorporated into discourse beyond the sphere of the discipline (Allen 2015).

8.3 On the role of models and simulation in understanding archaeological formation

In February of the year 2000, a low pressure system moved across western NSW, bringing heavy rains to many parts of the region, including the Nundooka study area near Fowlers Gap Arid Zone Research Station. Archaeologists working in the area had surveyed the surface archaeology during the previous year, and returned to survey again in the following winter (Fanning et al. 2007). In their follow-up survey, they noted an abundance of vegetation that obscured many parts of the study area that were once highly visible. They also noted that erosion in some places had winnowed away topsoils, exposing a greater abundance of smaller artefacts, while concentrated flows in other parts of the study area decreased the number of small flakes. This serendipitous co-occurrence of an archaeological survey and a large-scale fluvial event is an example of a ‘natural experiment’; an opportunity to evaluate the effects of a natural process that is otherwise difficult or impossible to control.
(Tucker 2009). The effects observed at Nundooka were not uniform across Fowlers Gap landscape: for example, stream action in another study area knocked out previously recorded surfaces dating back to the mid-Holocene. However, these are only two expressions of this process within a range of settings that went mostly unobserved. Additionally, the event-driven natural processes that condition the surface record in western NSW such as large scale flooding and aeolian sediment transport are fairly rare occurrences, and being in a position to measure their effect on the archaeological record at all is even rarer given their unpredictability. The next such opportunity would not come for another decade, after the field seasons for the project had already ceased.

Natural experiments such as these are useful for providing primary observations and generating hypotheses in systems that are otherwise difficult to experiment with, but relying on these to understand large-scale processes would make building and testing theories about landscape formation untenable (O’Sullivan and Perry 2013). The primary role that models served in this study was that of analogies for processes that are unwieldy for experimentation. Patterning in archaeological landscapes emerges out of sequences of inscription and erasure that may vary over time and space (Lucas 2010), but that are ultimately unobservable. The exploratory modelling process used in Chapters 5 and 6 (and briefly in Chapters 7 and 8) was aimed at evaluating the logic of how a given set of formational processes produces patterning with the record. Modelling of both deposit and assemblage formation was done “from the null up” (Premo 2007), making as few assumptions as possible about the role of human behavioural variability in order to assess the extent to which this is needed to explain the patterning. In HMODEL, the outcomes suggest that many of the patterns seen in the record of heat retainer hearths on the surface could be formed in large part by the episodic disequilibrium in geomorphic processes operating on a fairly undifferentiated record of occupation through time. FMODEL examined the effects of different patterns of mobility on the formation of Cortex Ratios, suggesting that deviation from one is largely determined by the balance between stone import and export, something facilitated but not determined by mobility. The exploratory outcomes of HMODEL and HMODEL_A demonstrated how different processes could produce qualitatively similar signatures in the surface radiocarbon record, but allowed expectations about the record to be
developed into a set of tests that were used to effectively rule out some suspected formation processes.

Given the above, it would not be inconceivable to suggest if the logical outcomes of the processes could be generated within the model, then it could have been done within the mind of a clever individual, circumventing the need for the computer or a model at all. This presents the question of whether building simulations is actually necessary to understand the systems or formulate a test. Such a question gets at the heart of not only what models are for, but what a model is. In a canonical treatment on the role of models in science, Hesse (1963) portrays a similar position several times in a fictional dialogue between an individual sympathetic to models (the “Campbellian”) and an individual disposed to view models as unnecessary (the “Duhemist”). In that account, models are dismissed by the antagonist as useful but ultimately superfluous items to the task to theorising. Similar sentiments were questioned recently by Barton (2013:153) in regard to the role of computational models in archaeology, who wondered how confident his colleagues were in the validity of their assumptions without formulating explicit models. Granting the possibility of working out a simple exploratory model without the aid of a computer or other mechanism, how would the result of such a process be conveyed? If the answer is either “as a written description” or “as a model”, then we have come either halfway around or full circle. If ‘worked out’ theories are given an unambiguous definition, they will come to look more and more like formal models. As long as verbal models are capable of being misunderstood, formal models act as “proofs-of-concept” (Servedio et al. 2014). The very presence of underdetermination between alternative verbal models suggests that some kind of more formal model is needed, if for no other reason than to lay bare the assumptions on which those verbal models are based to determine the specific conditions under which their logic might hold true.

8.3.1 “Tools to think with”: reflections on the process of building and testing models

The presentation of the finalised models here may give the impression that the model-building process was straightforward, unwavering in its course from model conceptualisation through to exploration and finally to pattern-oriented comparisons. Such an impression
would be very misleading. While the written descriptions of the models are meant to provide clarity and justification for the modelling decisions that were made, the actual modelling process undertaken here was iterative, often involving significant re-conceptualisation and reconfiguration. As discussed in Chapter 4, the model-building process can be as informative as the model itself when it comes to understanding the process under investigation (perhaps even more so). In that spirit, a short reflection here is meant to provide some context for the model development process.

During their development, both HMODEL and FMODEL saw swings from simplified models built primarily as tests of different code structures to highly detailed models with complicated behavioural procedures and high levels of data integration (similar in character to Premo’s (2010) description of “emulative models”), and finally a stripping back of processes to core dynamics within a well-defined parameter space. This was partly an outcome of exposure to different modelling philosophies during the research process, but also in large part due to the frustrations and enlightenments that come from the model-building process itself (which, for better or worse, helped to solidify the author’s philosophical bent on the matter).

FMODEL, for example, was initially built to assess Douglass’ (2010; see also Section 6.3.3) conceptual model of Cortex Ratio formation through radial movement patterns. At the time, the model structure was very simple: agents began at a central location, made flakes by means of a stochastic generation process, and distributed them at random distances within a given maximum distance away from the centre. Although the calculations in this initial model structure were highly flawed, it displayed general patterning consistent with expectations, suggesting that the model was on the right track. Once the calculation errors were corrected and a few different movement structures were tested, it was decided that the effects of travel time and deposition rate might be fruitfully examined within a geographically realistic space. A grid world of 499 by 499 cells was integrated with GIS data from Rutherford’s Creek (including elevation, vegetation, locations of watercourses, etc.) by way of NetLogo’s GIS extension (Wilensky 1999). Water resources in the model came in the form of local rains (which filled creek lines but not the lake) and floods (which filled the lake but not the creek lines), the frequency of which were modelled based on historical
meteorological data. Agents within the model moved into the landscape each year and searched for water. If no water was found, agents would move out of the landscape; if water was found, agents would establish a foraging camp and make logistical movements. Downtime at hunting blinds or camps was spent making flaked artefacts. The model’s structure began to look less theoretical and more like a digital reconstruction of ethnographies from the Australian deserts (e.g. Cane 1984; Gould 1980; Tonkinson 1993).

Faced with decisions about parameters and agent behaviours, such as what kinds of plant foods to gather, different kinds of movements associated with foraging behaviours, hunting encounter and success rates, and so on, it became clear there would be a lot of work that was not immediately concerned with the formation of the record. Building in these superfluous parameters also constrained learning from the model, as they involved increasingly intensive computation and thus became cumbersome for testing. This made it difficult to verify the functioning the model, let alone use them for addressing the theoretical questions at hand. All of these factors forced a critical re-examination of the problem and the components of the conceptualised process that would be necessary to model it effectively (as in Watt 1968). After some time, it was resolved to begin from known, controllable principles in an abstract space and work forward from there (Brantingham 2003; Premo 2010). From that point, the resulting model, and model-building process, resembled that presented in Chapter 6. This process of iterating between “complication and consolidation” is not uncommon in simulation practice and in this case helped to draw attention to the fundamental elements needed to address the questions (see O’Sullivan and Perry 2013:246).

Along with this praxis effect of the model-building process, the models also afforded learning moments when they were tested and occasionally produced outcomes that were not expected. This is something which is often discussed in the literature on simulation and agent-based models (e.g. Axelrod 1997:4; Gilbert and Terna 2000:67), though rarely discussed in the context of published modelling studies. Of these, the clearest case was the presence of temporal gaps occurring under the initial configuration of the HMODEL simulation. While in hindsight the process causing the gaps in the record makes sense, at the time the model was constructed it was not foreseen that gaps would be an outcome of the process. This outcome, and the process that generated it, provided an alternative explanation
for their presence which, as demonstrated in Chapter 7, can withstand a test of its core dynamics against recorded archaeological patterns.

Models in this study were used along these lines as “tools to think with” at all stages of the research. Prototype models used to understand the ramifications of model assumptions in this study eventually gave way to more effective models that could be used to help develop expectations about the systems these models represent. Sometimes, the refined models were not much more complicated or technically-sophisticated than the prototypes, but their operation, and connection to empirically-observed phenomena, was far more clearly understood by virtue of the models that came before them. The prototype models and their development, like initial sketches made by an architect before blueprints are produced, were valuable as heuristic devices in this endeavour (see Lake 2010:14), and without passing through those stages of the model-building process, it is not clear that the modelling enterprise would have been a successful one. In the broader modelling literature there have been calls to improve the documentation of these prototypes (Grimm et al. 2010). For the time being, this reflection provides some account of the processes used in the present study, with the hopes of it joining a more explicit discussion of how models work within the framework of archaeological inquiry.

8.4 Concluding remarks

In the growing literature on agent-based models, the modelling venture is often viewed as a cyclical process in which the analytical process returns eventually to formulating new questions (e.g. Railsback and Grimm 2012:7). In striving to maintain simple model structures and limit parameter spaces being explored, decisions were made which eliminated components of formation processes that, while relevant, were not deemed necessary to represent the logic of the process. For example, neither HMODEL nor FMODEL considers the effects of trampling on surface hearths and lithics, something which undoubtedly occurred as both humans and animals traversed the landscape, and this might be pointed to as a shortcoming of the modelling enterprise. However, as stated earlier in the paper, HMODEL
and FMODEL were not meant to reconstruct the precise sequences of events and processes occurring at Rutherfords Creek, but rather to explore simple theoretical models with the aim of establishing broad trends in archaeological patterning. With some reconfiguration, other processes like trampling could be incorporated into the model to refine existing model outcomes or challenge the inferences already drawn from them, and such reconfigurations would be welcome. Doing so would necessarily increase the complexity of the model and the size of the parameter space being explored, and it remains to be seen whether such reconfigurations would significantly alter the findings made here; therefore, modification should be done strategically with reference to observed patterns (Grimm et al. 2005).

Additionally, there are other configurations of the modelled processes which, for the sake of time and space, were not explored here. Of interest is the question of temporal autocorrelation in the modelled sedimentation process. While some of the stochastic settings used here capture this to some extent, there are patterned sequences of erosion and deposition which might better resolve observed patterns. These could be assessed through different parameter settings of the models as they exist now, but this highlights how, even using very small numbers of variables, parameter spaces can be expansive and multi-scalar. Ideally, the parameter settings used in the exploration here that best fit a dataset might be used to limit the search for more precise sequences of deposition and erosion for individual landscapes, especially when connected with additional simulated patterns.

The expectations generated from the exploration of FMODEL in Chapter 6 suggest that Cortex Ratios might be fruitfully applied to other places in the western NSW landscape that might serve as strong attractors or to places where stone resources are limited. High density deposits would be expected in the former; while low density scatters dominated by flakes would be expected in the latter. If these showed consistent distribution about a value of 1, then the model or sampling strategy used at Rutherfords Creek will need to be revised. However, if these indicated Cortex Ratios consistently higher than 1, then it could be expected that these locations are absorbing the material carried out of places like Rutherfords Creek.

The differences identified between the OSL and the radiocarbon data at Rutherfords Creek, and also in the HMODEL study, offer potential for assessing environmental change
and formational processes in archaeological landscapes where these proxies might be found. These could be used to distinguish between depositional environments operating over large scale areas, giving insight not only into the reliability of the radiocarbon chronology, but also into the kinds of recording that might be expected.

All of this leads to the inevitable conclusion that further research in western New South Wales archaeology is needed. However, if this study has demonstrated nothing else, it is that further research cannot be oriented exclusively around gathering data and constructing narratives. Theory-building, at all levels of abstraction, and the empirical assessment of those theories in terms of their capacity to generate observed patterns are also needed. As both tools to think with and test with, models are part of a toolkit that archaeologists can employ to aid in theory-building. Used as mechanisms for experimentation, models can generate theoretical insights into a hypothesised system that can in turn be used to develop archaeological tests for comparing interpretations. This study expands on this by demonstrating that the types of problems to which agent-based modelling methods are suited are not limited to socio-cultural or socio-ecological phenomena, but can and should include questions concerned with the way the archaeological record formed within sedimentary deposits and may be used to discriminate between formational models with geophysical components. Not all theorising in archaeology needs to be formational, but no archaeological theory can be applied to the past absent a theory of formation for it stand on.

The people who inhabited Rutherfords Creek during the past left their marks in the form of lithic scatters and hearths, unwittingly writing a history of their presence in the landscape. That signature reveals a remarkable consistency over the last 2000 years, a feat made all the more remarkable in light of the highly unpredictable environmental conditions of the region. But during that same time the land itself has also been writing, occasionally but forcefully fixing the indelible marks of humanity with its own signature. The result is indeed a palimpsest, but not in the sense of a hopeless jumble or a distorted record that needs to be fixed, but as the generative outcome of entwined socioenvironmental processes that are no less important to understanding and contextualising the past than that visible in any other record.
REFERENCES


Beveridge, P. 1884. *Of the Aborigines Inhabiting the Great Lacustrine and Riverine Depression of the Lower Murray, Lower Murrumbidgee, Lower Lachlan and Lower Darling* / by Peter Beveridge. Sydney: Govt. Printer.


David, B., and M. Wilson. 1999. Re-Reading the Landscape: Place and Identity in NE Australia During the Late Holocene. Cambridge Archaeological Journal 9, no. 02 (October): 163–188.


Ditchfield, K., S.J. Holdaway, M.S. Allen, and A. McAlistier. 2014. Measuring Stone Artefact Transport: The Experimental Demonstration and Pilot Application of a New Method to a


———. 2008. Why Model? *Journal of Artificial Societies and Social Simulation* 11, no. 4: Published online.


Eyre, E.J. 1845. *Journals of Expeditions of Discovery into Central Australia, and Overland from Adelaide to King George’s Sound, in the Years 1840-1: Sent by the Colonists of South Australia, with the Sanction and Support of the Government: Including an Account of the Manners and Customs of the Aborigines and the State of Their Relations with Europeans*. Goldsmiths’-Kress Library of Economic Literature ; No. 34180. London: T. and W. Boone.


Holdaway, S.J., M. Douglass, and P.C. Fanning. 2012. Landscape Scale and Human Mobility: Geoarchaeological Evidence from Rutherfords Creek, New South Wales, Australia. In Landscape Archaeology Between Art and Science: From a Multi- to an Interdisciplinary Approach, ed. S.J. Kluivig and E. Gutman-Bond. Amsterdam: Amsterdam University Press.


250


Ross, A. 1985. Archaeological Evidence for Population Change in the Middle to Late Holocene in Southeastern Australia. Archaeology in Oceania 20: 81–89.


Sabloff, J.A. 1981. Simulations in Archaeology. Santa Fe: University of New Mexico Press.


261


Veth, P. 2002. ‘Abandonment’ or Maintenance of Country? A Critical Examination of Mobility Patterns and Implications for Native Title / Peter Veth. *Australian Institute of Aboriginal and Torres Strait Islander Studies. Native Title Research Unit* 2, no. 22. Issues Paper (Australian Institute of Aboriginal and Torres Strait Islander Studies. Native Title Research Unit) ; v. 2 No. 22. 1326-0316: 1326–0316.


———. 2002. ‘Abandonment’ or Maintenance of Country? A Critical Examination of Mobility Patterns and Implications for Native Title. In . Geraldton, WA.


http://rspb.royalsocietypublishing.org/content/280/1761/20130486.


APPENDIX A: OVERVIEW, DESIGN CONCEPTS, AND DETAILS FOR HMODEL

The following description of HMODEL, introduced in Chapter 5, follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006, Grimm et al. 2010).

1. Purpose

The purpose of the model is to:

1. Explore surface archaeological formation dynamics by modelling the interaction of individual hearth features within a shifting sedimentary environment.
2. Evaluate the combined influence of preservation and visibility on the chronological distribution of surface archaeological features based on the concept of episodic disequilibrium discussed in Fanning et al. 2007.

Additional configurations, discussed in section 7, are used to examine the effects of periodic absence, population growth, and taphonomic decay on the simulated data, as well as the impact of these forces on the surface visibility of stone artefacts.

2. Entities, state variables, and scales

To model the effects of episodic changes in landsurfaces on surface archaeology, two primary entities are used: hearths and patches. A hearth is an archaeological feature from which chronometric data might be obtained. In the model, hearths are modelled as agents that contain a date, given as the variable age, which is the number of time steps that have occurred at the time of its construction subtracted from the total number of time steps over which the model is run $(T - t)$. Hearths can exist in one of four states: hidden and intact, hidden and dispersed, visible and intact, and visible and dispersed. Hidden hearths are not considered part of the surface record and are thus cannot be sampled in an archaeological survey. Dispersed hearths cannot be sampled using the radiocarbon method.

A patch is a discrete unit of space within a gridded toroidal space (referred to using the more generic term ‘cells’ in the text but using the NetLogo specific term ‘patches’ here). Hearths contain an ordered list of sedimentary layers called sediment_ages. Each sediment layer is associated with the date it was deposited. The visibility of any hearths within the patch is determined by their age in relation to the most recent sedimentary later on the patch (i.e. only hearths younger than the youngest sedimentary layer are visible).
A third group of entities, *humans*, are modelled as behaviourally neutral actors that move between random points on the landscape, building hearths at a constant rate of one per year. The use of behaviourally-neutral humans is part of a strategy of model-building aimed at determining the degree of human agency or social complexity required to explain a given phenomenon.

Three parameters are used to control the sedimentary process within the model: the *event_interval* parameter determines the frequency of geomorphic events; the *stability* parameter controls the probability that a patch will undergo some kind of change during an event; and the *erosion_proportion* parameter determines the relative probabilities of a patch undergoing geomorphic change.

The passage of time in the model occurs at yearly intervals, which are tracked forward from a number of years before present using a state variable called *years_bp*. While the simulation is ostensibly meant to model processes at the scale of the ‘landscape’, the spatial relationships are abstract and not reflective of any particular scale.

3. Process overview and scheduling

During each year, each of the humans moves to a random point within the world and generates a hearth which is visible on the surface and contains an *age* value equal to the current value of *years_BP*. At given intervals, determined by the *event_interval* parameter, an event occurs which affects a subset of all patches. Membership in the subset is determined for patches individually using the *stability* parameter as the probability of change occurring. Patches undergoing geomorphic change determine whether that change is erosion or deposition from a Bernoulli probability draw based on the *erosion_proportion* parameter (see section 6), and this will affect whether hearths on the surface become buried or dispersed, or whether any hearths lying directly beneath the uppermost layer of sediment in the patch become visible. Finally, the *years_BP* value is decreased by one.

4. Design concepts

4.1 Basic Principles

HMODEL is based on idealised geological and archaeological concepts of stratigraphy and palimpsests. In the model, archaeological deposits exist within stratigraphic layers of sediment. Sediment is transported into and out of a given location by geomorphic processes (e.g. water or wind action). These forces have the capacity to obscure or disperse different elements of surface archaeological deposits.
4.2 Emergence

Regularities in the chronometric distribution of sampled data emerge through the individual-level interactions between patches and hearths. These include super- or sub-linear changes in the frequency of hearth ages, as well as the presence or absence of chronological gaps.

4.3 Interaction

Human agents within the model interact with their environment by adding cultural residues (hearths, artefacts). Patches interact with hearths and artefacts by making them visible or invisible through changes in the sedimentary layers of the patches. Patches also interact with surface hearths by dispersing them in the event of erosion.

4.4 Stochasticity

The movement of agents was modelled as completely random under the neutral assumption of no behavioural bias in the formation of the record. Other elements, such as the probabilities of patches undergoing geomorphic change and the probability of that change being erosional or depositional, are based on Bernoulli distributions, and random number draws are to establish whether these probabilities have been met.

4.5 Collectives

Humans do not form any collective beyond all following the same behavioural rules. Hearths can be grouped based on their visibility and dispersal status.

4.6 Observation

Data was primarily collected at the end of a simulation run. The ages of intact hearths on the surface were recorded to simulate sampling of a radiocarbon record based on charcoal. The ages of all hearths on the surface were recorded to simulate sampling of an OSL record based on hearth stones. For instances where artefacts were included, the mean numbers of artefacts for each patch were recorded. Other data used for debugging purposes included the ages of intact and dispersed hearths that are hidden, spatial distribution of hearths and the number of sedimentary layers in patches.

5. Initialization

When the model begins, all patches contain sediment_ages lists with a single value for the start of the modelled time period, equal to the initial value of years_BP. The humans within the model are distributed randomly within the modelled space.

Table 1 Parameter settings used in HMODEL
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>world_size</td>
<td>$32 \times 32$</td>
</tr>
<tr>
<td>years_BP</td>
<td>2000</td>
</tr>
<tr>
<td>starting_population</td>
<td>5</td>
</tr>
<tr>
<td>event_interval</td>
<td>10, 50, 100, 200 years</td>
</tr>
<tr>
<td>erosion_proportion</td>
<td>0 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>stability</td>
<td>0 – 1 (0.1 intervals)</td>
</tr>
</tbody>
</table>

6. Submodels

6.1 Geomorphic event model

During an event, affected patches will either undergo erosion or deposition, determined individually using a Bernoulli draw:

$$P(n_j) = \begin{cases} 
1 - p, & \text{for } n_j = 0 \\
p, & \text{for } n_j = 1 
\end{cases}$$

where $p$ is the value of the erosion_proportion parameter. Patches undergoing erosion will lose the youngest member of their sediment_ages list. Visible hearths situated on patches experiencing erosion will become dispersed (dispersed? = true), while any hidden hearths situated on an eroding patch that are younger than the youngest member of the patch’s updated sediment_ages list will become visible (hidden? = false). Patches undergoing deposition will add a new value to their sediment_ages list, equal to the current value of years_BP. Any visible hearths (hidden? = false) situated on a patch experiencing deposition become hidden (hidden? = true).

7. Alternative configurations

7.1 Stone artefacts

While the original configuration of the model is aimed at understanding these effects of these geomorphic processes on the formation of chronometric processes, the model can be naturally extended to examine how they affect the visibility of stone artefacts on the surface. To do this, patches were given an additional list variable, called artefacts. At each time step, after an agent builds a hearth, it adds a value to the artefacts list equal to the current value of the years_BP. The number of visible artefacts on the surface of a patch at
any given time in the model can be calculated as the number of values in the artefacts list that are younger than the youngest value in the sediment_ages list.

7.2 HMODEL_A

HMODEL was reconfigured into HMODEL_A to examine the effects of population growth, periodic absence, and a ‘taphonomic decay’ process as alternative mechanisms for generating patterning in chronometric data. In this model, the geomorphic submodel is removed along with their controlling variables. Four parameters are used to control the formational process within the reconfigured model: the pop_growth parameter determines the annual growth of the agent population over time; the decay parameter controls the annual probability that a given hearth will lose its charcoal (e.g. become dispersed); the absence_interval parameter controls the frequency and duration of periodic agent absences (determined by the agent variable absent?, set to true or false accordingly); and the absence_intensity parameter determines the proportion of the population that leaves during an absence period.

When the model begins, the humans within the model are distributed randomly within the modelled space. During each year, humans that are currently present in the model world move to a random point within the world and generate a hearth which is visible on the surface and contains an age value equal to the current value of years_BP. At given intervals, determined by the absence_interval parameter, an event occurs in which either a) a subset of all humans become ‘absent’ (absent? = true), or b) all humans that are currently absent return (absent? = false). Membership in the subset is determined for humans individually using the absence_intensity parameter as the probability of leaving during an absence period. Humans that leave do not contribute to the generation of archaeological remains during their absence.

At the end of each time step, population growth and taphonomic decay occur. The population of humans is increased incrementally by taking the current number of humans, multiplying that by the pop_growth parameter. The number of humans added is the difference between this value and the number of humans rounded down to the nearest whole number. Hearth decay (dispersed?=true) is determined probabilistically for each individual using the value of the decay parameter. Finally, the years_BP value is decreased by one.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>world_size</td>
<td>32 × 32</td>
</tr>
<tr>
<td>years_BP</td>
<td>2000</td>
</tr>
<tr>
<td>starting_population</td>
<td>5</td>
</tr>
</tbody>
</table>
8. References

APPENDIX B: HMODEL CODE

The following code is written using the NetLogo platform (Wilensky 1999). To use, copy the code below into a text file and save with the extension “.nlogo”, then open in NetLogo. This version was implemented in NetLogo version 5.2.1, but is backward compatible to at least version 5.0.4. A complete version of the code, along with code used to produce graphics, can be obtained by contacting the author.

To obtain NetLogo, visit https://ccl.northwestern.edu/netlogo/

;;HMODEL: an exploratory simulation of surface archaeological formation
;;written by Benjamin Davies, The University of Auckland
;;Comments within the code are preceded by two semi-colons (;;)
;;declares two agent types: humans and hearths
breed [ humans human ]
breed [ hearths hearth ]
;;declares hearth attributes
hearts-own [ 
age          ;;the age the hearth was deposited
dispersed?  ;;indicates whether a hearth still possesses charcoal
]
;;NOTE: NetLogo has an in-built agent variable, hidden?,
;;which is used below to indicate whether a hearth is visible on the surface
;;declares grid cell ("patch") attributes
patches-own [ 
sediment_ages  ;;an ordered list representing ages of sediment layers on a grid cell
]
;;declares global variables
globals [ 
years_BP ;;reverse time counter to get years before present
c14_hearth_ages ;;records the ages of visible hearths ("hidden? = false") still possessing charcoal
("dispersed? = true")
osl_hearth_ages  ;;records the ages of all visible hearths ("hidden? = false")
]
to setup
;;clears all information from the model
clear-all
;;set years before present to 2000
set years_BP 2000
;;create empty lists for c14 and osl ages
set c14_hearth_ages []
set osl_hearth_ages []
;;makes patches coloured white, gives them each a sediment_ages list with 2000 as the first element
ask patches [ 
set pcolor white
set sediment_ages (list (years_BP))
]
;;creates the agents, the number determined by the slider "number_of_ages" on the interface
ask one-of-patches [ 
sprout-humans number_of_agents [ 
set color blue
set shape "person"
]
]
;;make the hearths x-shaped
set-default-shape hearths "x"
to go
; when the simulation reaches 0 years BP, records the existing data and then stops the simulation
if years_BP = 0 [
plot-hearth-ages
stop
]

; human agents move to a random point on the grid and, if it is prior to 200 years BP, build a hearth
(see below)
ask humans [
set xy random-xcor random-ycor
if years_BP > 200 [
build-hearth
]
]

; at each interval, checks erosion (see below)
if ticks > 0 and ticks mod event_interval = 0 [
check-erosion
]

; subtracts one year from the years before present counter
set years_BP years_BP - 1

; advances time step
tick
end

to build-hearth
; generates one hearth, colors it black, gives it an age, and gives it charcoal
hatch-hearths 1 [
set color black
set age years_BP
set dispersed? true
]
end

to check-erosion
; first, a number of cells are chosen randomly, the number decided by the total number of cells minus the percentage of "stable" cells
ask n-of (count patches) * (1.00 - surface_stability) patches [
; next, those cells choose a random number between 0 and 1
; if that number is less than than the erosion_proportion
; proportion (a slider in the interface), then erosion occurs:
; (1) as long as there is more than the base sediment layer
; to remove, it will remove a sediment layer
; (2) all hearths younger than that sediment layer
; lose their charcoal, and
; (3) any hearths with ages older than that sediment layer
; become visible.
; (4) if there are no sediment layers to remove, then any hearths currently visible lose their charcoal
ifelse random-float 1.000 < erosion_proportion [
ifelse length sediment_ages > 1 [
let y item 0 sediment_ages
let z item 1 sediment_ages
set sediment_ages remove-item 0 sediment_ages
ask hearths-here with [ age <= y and dispersed? = true ] [
set dispersed? false
set color pink
]
ask hearths-here with [ age <= z and age > y ] [
set hidden? false
]
]
ask hearths-here with [ dispersed? = true ] [
set dispersed? false
set color pink
]
]
; if that number is less than than the erosion_proportion
; proportion then deposition occurs:
; (1) a sediment layer is added to the sediment_ages list for that cell, and
; (2) any hearths currently visible on that cell become hidden
set sediment_ages fput years_BP sediment_ages
ask hearths-here with [ age > years_BP ] [
set hidden? true
]
]
; color the patches based on their relative degree of sedimentation
;(white = no sedimentation, dark orange = full sedimentation)
ask patches [ set pcolor scale-color orange (length sediment_ages) ((2000 / event_interval) * 1.5) 1 ]
end
to plot-hearth-ages
let c14_sample []
let osl_sample []
ask n-of 100 hearths with [ hidden? = false and dispersed? = true ] [ set c14_sample fput age c14_sample ]
let cumulative_c14ages []
let counter 0
while [ counter < 2001 ] [ repeat ((length (filter [ ? <= counter ] c14_sample)) / length c14_sample) * 100 [ set cumulative_c14ages lput counter cumulative_c14ages ]
set counter counter + 1 ]
ask n-of 100 hearths with [ hidden? = false ] [ set osl_sample fput age osl_sample ]
let cumulative_oslages []
let counter 0
while [ counter < 2001 ] [ repeat ((length (filter [ ? <= counter ] osl_sample)) / length osl_sample) * 100 [ set cumulative_oslages lput counter cumulative_oslages ]
set counter counter + 1 ]
set-current-plot "Hearth Ages"
set-plot-x-range 0 2000
set-plot-y-range 0 10
set-histogram-num-bars 2000
set-current-plot-pen "c14"
histogram cumulative_c14ages
set-current-plot-pen "osl"
histogram cumulative_oslages
end
to record-data
;;NOTE: this code only runs when the "hmodel_test" experiment is run using Tools->Behaviorspace
;;compiles all ages for all surface hearths (osl) as well as those still possessing charcoal (c14), then prints them out to comma-delimited text files
set osl_hearth_ages []
ask hearths with [hidden? = false ] [ set osl_hearth_ages fput age osl_hearth_ages ]
set c14_hearth_ages []
ask hearths with [hidden? = false and dispersed? = true ] [ set c14_hearth_ages fput age c14_hearth_ages ]
file-open (word "e" event_interval "_g" erosion_proportion "_s" surface_stability ".txt")
foreach c14_hearth_ages [ file-write ? ]
file-close
file-open (word "e" event_interval "_g" erosion_proportion "_s" surface_stability ".by run.txt")
foreach c14_hearth_ages [ file-write ? ]
file-close
file-open (word "OSLe" event_interval "_g" erosion_proportion "_s" surface_stability ".txt")
foreach osl_hearth_ages [ file-write ? ]
file-close
file-open (word "OSLe" event_interval "_g" erosion_proportion "_s" surface_stability ".by run.txt")
foreach osl_hearth_ages [ file-write ? ]
file-close
file-write ?
]
file-print ""
file-print "###"
flush
end
GRAPHICS-WINDOW
210
10
649
470
1
-1
13.0
1
10
1
1
0
0
0
1
32
0
32
0
1
ticks
30.0
SLIDER
6
69
173
102
number_of_agents
number_of_agents
1
10
5
1
1
NIL
HORIZONTAL
SLIDER
6
182
177
215
event_interval
event_interval
5
200
100
5
1
years
HORIZONTAL
BUTTON
9
11
73
44
NIL
Setup
NIL
1
T
OBSERVER
NIL
NIL
NIL
NIL
1
BUTTON
81
11
144
44
NIL
Go
T
1
T
<experiments>
  <experiment name="hmodel_test" repetitions="999" runMetricsEveryStep="false">
    <setup>setup</setup>
    <go>go</go>
    <final>record-data</final>
    <enumeratedValueSet variable="number_of_agents">
      <value value="5"/>
    </enumeratedValueSet>
    <enumeratedValueSet variable="event_interval">
      <value value="10"/>
      <value value="50"/>
      <value value="100"/>
    </enumeratedValueSet>
    <enumeratedValueSet variable="erosion">
      <value value="0.1"/>
      <value value="0.3"/>
      <value value="0.5"/>
      <value value="0.7"/>
      <value value="0.9"/>
    </enumeratedValueSet>
    <enumeratedValueSet variable="surface_stability">
      <value value="0"/>
      <value value="0.1"/>
      <value value="0.5"/>
      <value value="0.9"/>
    </enumeratedValueSet>
  </experiment>
</experiments>
APPENDIX C: OVERVIEW, DESIGN CONCEPTS, AND DETAILS FOR FMODEL

The following description of FMODEL, introduced in Chapter 6, follows the ODD (Overview, Design concepts, Details) protocol for describing individual- and agent-based models (Grimm et al. 2006, Grimm et al. 2010).

1. Purpose

The purpose of the model is to:

1. Explore the formation of time-averaged surface stone artefact assemblages by modelling the manufacture, transport, and discard of lithic artefacts.
2. Evaluate the relationships between movement tortuosity, curation, and ratio of observed cortical surface area to expected cortical surface area (the Cortex Ratio) in surface assemblages (see Douglass et al. 2008).

Additional configurations, discussed in section 7, are used to examine the effects of raw material availability and spatial differences in movement patterns.

2. Entities, state variables, and scales

To model the effects of artefact manufacture, transport, and discard on the composition of lithic assemblages, two primary entities are used: a single mobile agent and patches representing a known space. The agent operates as a transport vehicle for stone artefacts, moving in an uncorrelated random walk, discard artefacts between moves, and manufacturing artefacts on an ‘as needed’ basis. A patch is a discrete unit of space within a gridded toroidal space (referred to using the more generic term ‘cells’ in the text but using the NetLogo specific term ‘patches’ here).

Artefacts are modelled as two discrete types: cores and flakes. Cores are modelled as icosahedra (20-sided polyhedral solids), while flakes are modelled as triangular prisms. The triangular cortical surface of the dorsal side of each flake corresponds to 1/20th of the surface area of a cortical surface area of a core. The relationship between the amount of cortical surface area present in a local assemblage

The spatial relationships in the model are abstract and could be taken to represent any number of scales that reflect an archaeologically meaningful ‘window of observation’ such as a surface exposure. Time advances between agent movements but is not explicitly represented here.

3. Process overview and scheduling
In the model, agents manufacture artefacts to a set reduction level determined by the reduction parameter. That value is a fraction of the total surface area of a core rounded to the nearest 1/20th, and this fraction is divided into equal parts to represent flakes. Both cores and flakes are added to a list variable called assemblage in the patch immediately beneath the agent. Each core is added to the list as a 0, while each flake is added as a 1.

Following a reduction event, the agent will select the core, or a portion of the flakes produced by the reduction based on the selection parameter. The model is designed to evaluate strategies that target either flakes or cores, so the targeted artefact type in the model is determined by the target parameter. These are tabulated and stored in a variable called carry_count. The agent then moves in a random direction with step lengths to model different degrees of tortuosity in movement, established with the levy_mu parameter. Between each step, agents will discard an artefact by subtracting one from their carry_count and, depending on what kind of element is being targeted in the model, adding a flake or core to the patch’s assemblage. This is repeated until either a) the agent runs out of artefacts (carry_count = 0), prompting the agent to manufacture more artefacts, or b) the agent leaves the window of observation, in which case that agent is removed and a new agent is added to the model. Agents may start off carrying a set number of artefacts, determined using the parameter carry_in. Simulations are run until a set number of agents, determined using the parameter walkers, is reached.

4. Design concepts

4.1 Basic Principles

FMODEL is based on basic concepts of forager technological organisation, viewing the discard and procurement of stone artefacts as embedded within the movement routines of the forager. The forager moves with a degree of tortuosity of movement across a space given the intensity of the foraging activity. Greater tortuosity movement results in greater redundancy in place use, producing more opportunity for local discard and potentially limiting the amount of stone material that might be taken away from a place.

4.2 Emergence

Regularities in the ratio of cortical surface area to expected cortical surface area occur through the additional and removal of flakes and cores to patches within the window of observation.

4.3 Interaction

Agents within the model interact with patches by adding artefacts to the local assemblage, and obtaining artefacts from generated assemblages.

4.4 Stochasticity
Agent movement directions were determined randomly to assume no directional bias in movement. Movement lengths were drawn randomly from a Lévy distribution (see section 6) to model different degrees of tortuosity in movement.

4.6 Observation

Data was primarily collected at the end of a simulation run. Cortex ratios were calculated from accumulated assemblages by multiplying the number of cores (0s) in patch assemblage lists by 20, multiplying that value by the reduction parameter setting, and then adding the total number of flakes (1s) to get the observed cortical surface area, and then dividing this by the number of cores (0s) multiplied by 20 (taken to be the expected cortical surface area).

5. Initialization

At the start of the model, there are no agents, and all patches contain no artefacts. When the first agent moves into the world following the movement submodel, it will either begin by discarding an artefact or making new artefacts, depending on the value of the carry_in parameter.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>world_size</td>
<td>32 x 32</td>
</tr>
<tr>
<td>Walkers</td>
<td>10, 100</td>
</tr>
<tr>
<td>Reduction</td>
<td>0.1 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>Selection</td>
<td>0.1 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>levy_mu</td>
<td>1 &lt; μ ≤ 3</td>
</tr>
<tr>
<td>Stability</td>
<td>0 – 1 (0.1 intervals)</td>
</tr>
</tbody>
</table>

6. Submodels

6.1 Movement submodel

The probability of the agent taking a step of length is determined using the parameter levy_mu, which is the μ variable in a heavy-tailed probability distribution using the equation:

\[ P(l) = l^{-\mu} \]
where $\mu$ is a value equal to $1 < \mu \leq 3$. At the start of the model, the agent draws a value from the above distribution, and a random fraction of that value is obtained. The agent then moves into the world by that fraction from a random point at the edge of the world. All subsequent moves are taken using the full value of the draw until a move carries the agent out of the world.

7. Alternative configurations

7.1 FMODEL_A

FMODEL was reconfigured in FMODEL_A in order to examine the effects of differences raw material distribution on a forager whose stone procurement was embedded in foraging movements, as well as the influence of imbalances in the intensity of place use between ‘stone-rich’ versus ‘stone-poor’ region. In this model variant, the world is split evenly into two sides, right and left. In each side, raw material is identified by the agent based on patch colour; red patches have raw material which black patches do not. The number of patches in a side that contain raw material is determined as a proportion of the total number of patches on the side using the parameters left_abundance and right_abundance, respectively. While agents continue to discard between steps, they are constrained in their ability to manufacture new artefacts by the presence of raw material in the patch at which they are located.

In addition, instead of moving to a single level of tortuosity, movement tortuosity is governed depending on what side of the world the agent is located on, using the parameters left_mu and right_mu as the $\mu$ parameter in the movement submodel above. This was used to model the differences between a residential mobility pattern where there was no substantial difference in the redundancy of place use, and a logistic mobility pattern where the redundancy of place use was higher in some places and lower in others.

Table 2 Parameter settings used in FMODEL_A

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>world_size</td>
<td>32 x 32</td>
</tr>
<tr>
<td>walkers</td>
<td>100</td>
</tr>
<tr>
<td>reduction</td>
<td>0.1 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>selection</td>
<td>0.1 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>left_abundance, right_abundance</td>
<td>0 – 1 (0.1 intervals)</td>
</tr>
<tr>
<td>left_mu, right_mu</td>
<td>$1 &lt; \mu \leq 3$</td>
</tr>
</tbody>
</table>
8. References

APPENDIX D: FMODEL CODE

The following code is written using the NetLogo platform (Wilensky 1999). To use, copy the code below into a text file and save with the extension “.nlogo”, then open in NetLogo. This version was implemented in NetLogo version 5.2.1, but is backward compatible to at least version 5.0.4. A complete version of the code, along with code used to produce graphics, can be obtained by contacting the author.

To obtain NetLogo, visit https://ccl.northwestern.edu/netlogo/

;;;FMODEL: an exploratory simulation of assemblage formation
;;;written by Benjamin Davies, The University of Auckland

;;;Comments within the code are preceded by two semi-colons (;;)

;;;declares agent attributes
 turtles-own [  real_x ;;real x-position relative to window  real_y ;;real y-position relative to window  carry_count ;;number of artefacts carried by the agent  ]

;;;declares grid cell ("patch") attributes
 patches-own [  artefact_x ;;list containing artefact x-coordinates relative to window  artefact_y ;;list containing artefact y-coordinates relative to window  ]

;;;declares global variables
 globals [  turtle_count ;;count of all agents that have appeared in model (using NetLogo primitive "turtle")  exp_csa ;;expected cortical surface area for window  obs_csa ;;observed cortical surface area for window  cortex_ratio ;;cortex ratio for assemblage for window  ]

to setup
 ;;clears all information from the model
 clear-all

 ;;clears sets up patch variables as empty lists
 ask patches [  set assemblage []  set artefact_x []  set artefact_y []  ]

 ;;sets count of agents to 0
 set turtle_count 0

 ;;resets the clock
 reset-ticks
end
to go
when the number of agents reaches the value of the walkers variable,
 calculates the cortex ratio if there is at least one core (exp_csa > 0)
 otherwise, sets the cortex ratio to NA
 then the model stops
 if turtle_count >= walkers [
   set exp_csa (sum [ length filter[ ? = 0] assemblage ] of patches) * 20
   ifelse exp_csa = 0 [
     set cortex_ratio "NA"
   ]
   set cortex_ratio obs_csa / exp_csa
   stop
 ]

if turtle_count turtle_count + 1
crt 1 [ creates a local variable "d" which is a random floating-point value between 0 and 1
 let d random 1.000

if a coinflip turns up heads, the agent moves to a random patch on the
left or right side of the screen
if it comes up tails, the agent moves to a random patch on the
top or bottom of the screen
the agent then faces a random direction within a 180 degree arc
from whatever side of the screen they end up on
ifelse random 2 = 0 [
   setxy (one-of (list (max-pxcor ) (min-pxcor ))) random-ycor
   ifelse xcor = max-pxcor [
     set heading 270
     right -90 + random 181
   ]
   set heading 90
   right -90 + random 181
   ]
   setxy random-xcor (one-of (list (max-pycor ) (min-pycor )))
   ifelse xcor = max-pycor [
     set heading 180
     right -90 + random 181
   ]
   set heading 0
   right -90 + random 181
   ]
]

creates a local variable s as a random number from a Levy distribution
if this number is greater than 500 (which will by definition take the agent
well outside the window of observation), then a value of 500 is set to prevent
movements of extraordinary length that can slow the functioning of the model
this value can be reset to accommodate larger windows if needed
let s (random-float 1.000) ^ (-1 / mu )
if s > 500 [ set s 500
]

agent moves into window according to the prechosen direction
at a length of a fraction d of the distance s, drawing a line behind them
pd fd s * d
pu

agent updates its true coordinates relative to the window
set real_x xcor
set real_y ycor

agent sets the number of artefacts it is carrying to some percentage
of the number of artefacts that an agent operating within the window
would carry following a manufacturing event

```lisp
(ifels target = "Flakes"
    set carry_count 0 + round ((20 * reduction) * selection) * carry_in)
)

(set carry_count 0 + round (overproduce * carry_in))
)

;; while the agent is still inside the window of observation, it will continue
;; to take steps, replenishing its kit if it runs out of artefacts
;; Once the agent leaves the window, it is removed from the simulation
ask turtles [;
    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) ] [;
        if carry_count = 0 [;
            make-flakes
        ]
        step
    ]
    die
]
tick
end

to make-flakes
    ;; if the target artefacts are flakes, then the agent removes a percentage
    ;; of the the cortical surface to the nearest 1/20th, then selects a percentage
    ;; of those produced. The remaining material gets added to the local assemblage.
    ;; if target = "Flakes"
        set carry_count round ((20 * reduction) * selection)
        ask patch-here [;
            set assemblage lput 0 assemblage
            set artefact_x lput ([ xcor ] of myself) artefact_x
            set artefact_y lput ([ ycor ] of myself) artefact_y
            repeat ((20 * reduction) - (([ carry_count ] of myself)) [;
                set assemblage lput 1 assemblage
                set artefact_x lput ([ xcor ] of myself) artefact_x
                set artefact_y lput ([ ycor ] of myself) artefact_y
            ])
        ]
    ;; if the target artefacts are cores, then the agent removes a percentage
    ;; of the the cortical surface to the nearest 1/20th, then selects the core.
    ;; The remaining material gets added to the local assemblage. Note: the
    ;; "overproduction" variable relaxes the "as needed" production assumption
    ;; if target = "Cores"
        repeat overproduce [;
            set carry_count carry_count + 1
            ask patch-here [;
                repeat ((20 * reduction)) [;
                    set assemblage lput 1 assemblage
                    set artefact_x lput ([ xcor ] of myself) artefact_x
                    set artefact_y lput ([ ycor ] of myself) artefact_y
                ]
            ]
        ]
    end

to step
    ;; agent faces a random direction, creates a local variable step-length
    ;; as a random number from a Levy distribution
    set heading random-float 360
    let step-length (random-float 1.000) ^ (-1 / mu )
    while [ step-length > 500 ] [;
        set step-length (random-float 1.000) ^ (-1 / mu )
    ]
    ;; agent updates its true coordinates relative to the window
    set real_x real_x + (dx * step-length)
    set real_y real_y + (dy * step-length)
    ;; agent takes a step of the length drawn above, drawing a line behind it
    pd
    fd step-length
    pu
```
;; if the agent is still inside the window, it adds an artefact to the
;; local assemblage and reduces the number of artefacts it is carrying by 1

if real_x <= (max_pxicor + 0.5) and real_x >= (min_pxicor - 0.5) and
real_y <= (max_pycor + 0.5) and real_y >= (min_pycor - 0.5) and carry_count > 0 [
    ifelse target = "Flakes" [
        set assemblage lput 1 assemblage
    ]
    set assemblage lput 0 assemblage
]
set artefact_x lput real_x artefact_x
set artefact_y lput real_y artefact_y
set carry_count carry_count - 1
]
end
148
195
181
selection
selection
0
1
1
0.1
1
NIL
HORIZONTAL

BUTTON
24
23
87
56
NIL
setup
NIL
1
T
OBSERVER
NIL
NIL
NIL
NIL
1

BUTTON
96
24
159
57
NIL
go
T
1
T
OBSERVER
NIL
NIL
NIL
NIL
1

MONITOR
431
71
512
116
Walkers
turtle_count
3
1
11

MONITOR
431
18
514
63
Cortex Ratio
cortex_ratio
3
1
11

SLIDER
22
189
194
222
carry_in
carry_in
0
1.0
1
0.05
<experiment name="fmodel_test" repetitions="99" runMetricsEveryStep="false">
  <setup>
    setup
  </setup>
  <go>
    <go>
    </go>
  </go>

  <metric>obs_csa</metric>
  <metric>exp_csa</metric>
  <metric>cortex_ratio</metric>
  <enumeratedValueSet variable="walkers">
    <value value="10"/>
    <value value="100"/>
  </enumeratedValueSet>
  <enumeratedValueSet variable="mu">
    <value value="1.1"/>
    <value value="1.5"/>
    <value value="2"/>
    <value value="2.5"/>
    <value value="3"/>
  </enumeratedValueSet>
  <enumeratedValueSet variable="reduction">
    <value value="0.1"/>
    <value value="0.3"/>
    <value value="0.5"/>
    <value value="0.7"/>
    <value value="0.9"/>
    <value value="1"/>
  </enumeratedValueSet>
  <enumeratedValueSet variable="selection">
    <value value="0.1"/>
    <value value="0.3"/>
    <value value="0.5"/>
  </enumeratedValueSet>
</experiment>
APPENDIX E: PATTERN-ORIENTED TEST RESULTS

The outcomes of the HMODEL and HMODEL_A simulations were exposed to tests to evaluate their fit to two patterns: a measure of the deviance between the curve and a uniform distribution, and a test of the probability of obtaining result. Each parameter setting was run 99 times. For CURVETEST, the result is the probability density for the actual value for Rutherfords Creek (0.11) within the distribution of outcomes from that simulation, and was considered acceptable if the density was greater than 0.05. CLUSTERTEST gives the probability of obtaining 16 or more consecutive dates separated by gaps of 6 years or less, and was considered acceptable if the probability was greater than 0.05.

NA values indicate instances where a viable sample could not be obtained from the data produced in the model.
### HMODEL RAW SCORES

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>0.1</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.1</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.1</td>
<td>0.5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>0.1</td>
<td>0.9</td>
<td>3.69E-62</td>
<td>0.982</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>0.3</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>0.3</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>0.3</td>
<td>0.5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>8</td>
<td>10</td>
<td>0.3</td>
<td>0.9</td>
<td>2.03E-07</td>
<td>0.354</td>
</tr>
<tr>
<td>9</td>
<td>10</td>
<td>0.5</td>
<td>0</td>
<td>0.008775</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>0.5</td>
<td>0.1</td>
<td>0.008454</td>
<td>0.111</td>
</tr>
<tr>
<td>11</td>
<td>10</td>
<td>0.5</td>
<td>0.5</td>
<td>0.010994</td>
<td>0.114</td>
</tr>
<tr>
<td>12</td>
<td>10</td>
<td>0.5</td>
<td>0.9</td>
<td>0.02169</td>
<td>0.084</td>
</tr>
<tr>
<td>13</td>
<td>10</td>
<td>0.7</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>14</td>
<td>10</td>
<td>0.7</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>15</td>
<td>10</td>
<td>0.7</td>
<td>0.5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>16</td>
<td>10</td>
<td>0.7</td>
<td>0.9</td>
<td>2.60E-07</td>
<td>0.36</td>
</tr>
<tr>
<td>17</td>
<td>10</td>
<td>0.9</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>18</td>
<td>10</td>
<td>0.9</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>19</td>
<td>10</td>
<td>0.9</td>
<td>0.5</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>0.9</td>
<td>0.9</td>
<td>5.90E-64</td>
<td>0.99</td>
</tr>
<tr>
<td>21</td>
<td>50</td>
<td>0.1</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>22</td>
<td>50</td>
<td>0.1</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>23</td>
<td>50</td>
<td>0.1</td>
<td>0.5</td>
<td>5.82E-72</td>
<td>0.988</td>
</tr>
<tr>
<td>24</td>
<td>50</td>
<td>0.1</td>
<td>0.9</td>
<td>0.061252</td>
<td>0.006</td>
</tr>
<tr>
<td>25</td>
<td>50</td>
<td>0.3</td>
<td>0</td>
<td>3.52E-21</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td>50</td>
<td>0.3</td>
<td>0.1</td>
<td>3.53E-15</td>
<td>0.81</td>
</tr>
<tr>
<td>27</td>
<td>50</td>
<td>0.3</td>
<td>0.5</td>
<td>6.34E-07</td>
<td>0.321</td>
</tr>
<tr>
<td>28</td>
<td>50</td>
<td>0.3</td>
<td>0.9</td>
<td>0.358574</td>
<td>0</td>
</tr>
<tr>
<td>29</td>
<td>50</td>
<td>0.5</td>
<td>0</td>
<td>0.008426</td>
<td>0.696</td>
</tr>
<tr>
<td>30</td>
<td>50</td>
<td>0.5</td>
<td>0.1</td>
<td>0.021952</td>
<td>0.184</td>
</tr>
<tr>
<td>31</td>
<td>50</td>
<td>0.5</td>
<td>0.5</td>
<td>0.04285</td>
<td>0.062</td>
</tr>
<tr>
<td>32</td>
<td>50</td>
<td>0.5</td>
<td>0.9</td>
<td>0.398803</td>
<td>0</td>
</tr>
<tr>
<td>33</td>
<td>50</td>
<td>0.7</td>
<td>0</td>
<td>3.12E-19</td>
<td>0.997</td>
</tr>
<tr>
<td>34</td>
<td>50</td>
<td>0.7</td>
<td>0.1</td>
<td>1.94E-16</td>
<td>0.839</td>
</tr>
<tr>
<td>35</td>
<td>50</td>
<td>0.7</td>
<td>0.5</td>
<td>1.11E-06</td>
<td>0.347</td>
</tr>
<tr>
<td>36</td>
<td>50</td>
<td>0.7</td>
<td>0.9</td>
<td>0.364569</td>
<td>0.003</td>
</tr>
<tr>
<td>37</td>
<td>50</td>
<td>0.9</td>
<td>0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>38</td>
<td>50</td>
<td>0.9</td>
<td>0.1</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>39</td>
<td>50</td>
<td>0.9</td>
<td>0.5</td>
<td>1.69E-76</td>
<td>0.993</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>40</td>
<td>50</td>
<td>0.9</td>
<td>0.9</td>
<td>0.059158</td>
<td>0.007</td>
</tr>
<tr>
<td>41</td>
<td>100</td>
<td>0.1</td>
<td>0</td>
<td>4.03E-108</td>
<td>1</td>
</tr>
<tr>
<td>42</td>
<td>100</td>
<td>0.1</td>
<td>0.1</td>
<td>8.71E-83</td>
<td>0.998</td>
</tr>
<tr>
<td>43</td>
<td>100</td>
<td>0.1</td>
<td>0.5</td>
<td>9.04E-19</td>
<td>0.642</td>
</tr>
<tr>
<td>44</td>
<td>100</td>
<td>0.1</td>
<td>0.9</td>
<td>0.162925</td>
<td>0</td>
</tr>
<tr>
<td>45</td>
<td>100</td>
<td>0.3</td>
<td>0</td>
<td>1.15E-08</td>
<td>0.961</td>
</tr>
<tr>
<td>46</td>
<td>100</td>
<td>0.3</td>
<td>0.1</td>
<td>4.02E-06</td>
<td>0.59</td>
</tr>
<tr>
<td>47</td>
<td>100</td>
<td>0.3</td>
<td>0.5</td>
<td>0.003871</td>
<td>0.059</td>
</tr>
<tr>
<td>48</td>
<td>100</td>
<td>0.3</td>
<td>0.9</td>
<td>0.046522</td>
<td>0</td>
</tr>
<tr>
<td>49</td>
<td>100</td>
<td>0.5</td>
<td>0</td>
<td>0.008587</td>
<td>0.644</td>
</tr>
<tr>
<td>50</td>
<td>100</td>
<td>0.5</td>
<td>0.1</td>
<td>0.039929</td>
<td>0.203</td>
</tr>
<tr>
<td>51</td>
<td>100</td>
<td>0.5</td>
<td>0.5</td>
<td>0.129922</td>
<td>0.015</td>
</tr>
<tr>
<td>52</td>
<td>100</td>
<td>0.5</td>
<td>0.9</td>
<td>0.028349</td>
<td>0</td>
</tr>
<tr>
<td>53</td>
<td>100</td>
<td>0.7</td>
<td>0</td>
<td>7.04E-09</td>
<td>0.935</td>
</tr>
<tr>
<td>54</td>
<td>100</td>
<td>0.7</td>
<td>0.1</td>
<td>2.62E-06</td>
<td>0.622</td>
</tr>
<tr>
<td>55</td>
<td>100</td>
<td>0.7</td>
<td>0.5</td>
<td>0.002488</td>
<td>0.074</td>
</tr>
<tr>
<td>56</td>
<td>100</td>
<td>0.7</td>
<td>0.9</td>
<td>0.034897</td>
<td>0</td>
</tr>
<tr>
<td>57</td>
<td>100</td>
<td>0.9</td>
<td>0</td>
<td>1.06E-104</td>
<td>1</td>
</tr>
<tr>
<td>58</td>
<td>100</td>
<td>0.9</td>
<td>0.1</td>
<td>3.90E-08</td>
<td>0.997</td>
</tr>
<tr>
<td>59</td>
<td>100</td>
<td>0.9</td>
<td>0.5</td>
<td>1.50E-20</td>
<td>0.643</td>
</tr>
<tr>
<td>60</td>
<td>100</td>
<td>0.9</td>
<td>0.9</td>
<td>0.17698</td>
<td>0</td>
</tr>
<tr>
<td>61</td>
<td>200</td>
<td>0.1</td>
<td>0</td>
<td>2.71E-12</td>
<td>0.961</td>
</tr>
<tr>
<td>62</td>
<td>200</td>
<td>0.1</td>
<td>0.1</td>
<td>5.35E-15</td>
<td>0.07</td>
</tr>
<tr>
<td>63</td>
<td>200</td>
<td>0.1</td>
<td>0.5</td>
<td>9.58E-05</td>
<td>0.069</td>
</tr>
<tr>
<td>64</td>
<td>200</td>
<td>0.1</td>
<td>0.9</td>
<td>8.71E-07</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>200</td>
<td>0.3</td>
<td>0</td>
<td>0.219496</td>
<td>0.346</td>
</tr>
<tr>
<td>66</td>
<td>200</td>
<td>0.3</td>
<td>0.1</td>
<td>0.180313</td>
<td>0.006</td>
</tr>
<tr>
<td>67</td>
<td>200</td>
<td>0.3</td>
<td>0.5</td>
<td>0.13789</td>
<td>0.005</td>
</tr>
<tr>
<td>68</td>
<td>200</td>
<td>0.3</td>
<td>0.9</td>
<td>3.03E-08</td>
<td>0</td>
</tr>
<tr>
<td>69</td>
<td>200</td>
<td>0.5</td>
<td>0</td>
<td>0.351268</td>
<td>0.144</td>
</tr>
<tr>
<td>70</td>
<td>200</td>
<td>0.5</td>
<td>0.1</td>
<td>0.387053</td>
<td>0.005</td>
</tr>
<tr>
<td>71</td>
<td>200</td>
<td>0.5</td>
<td>0.5</td>
<td>0.339674</td>
<td>0.002</td>
</tr>
<tr>
<td>72</td>
<td>200</td>
<td>0.5</td>
<td>0.9</td>
<td>2.41E-08</td>
<td>0</td>
</tr>
<tr>
<td>73</td>
<td>200</td>
<td>0.7</td>
<td>0</td>
<td>0.233785</td>
<td>0.326</td>
</tr>
<tr>
<td>74</td>
<td>200</td>
<td>0.7</td>
<td>0.1</td>
<td>0.165892</td>
<td>0.01</td>
</tr>
<tr>
<td>75</td>
<td>200</td>
<td>0.7</td>
<td>0.5</td>
<td>0.152976</td>
<td>0.002</td>
</tr>
<tr>
<td>76</td>
<td>200</td>
<td>0.7</td>
<td>0.9</td>
<td>8.15E-08</td>
<td>0</td>
</tr>
<tr>
<td>77</td>
<td>200</td>
<td>0.9</td>
<td>0</td>
<td>1.44E-12</td>
<td>0.963</td>
</tr>
<tr>
<td>78</td>
<td>200</td>
<td>0.9</td>
<td>0.1</td>
<td>4.35E-14</td>
<td>0.078</td>
</tr>
<tr>
<td>79</td>
<td>200</td>
<td>0.9</td>
<td>0.5</td>
<td>0.000148</td>
<td>0.062</td>
</tr>
<tr>
<td>80</td>
<td>200</td>
<td>0.9</td>
<td>0.9</td>
<td>1.02E-06</td>
<td>0</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>1.28E-90</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0.1</td>
<td>1.93E-93</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
<td>4.66E-89</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0.9</td>
<td>4.20E-88</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>1.0</td>
<td>6.11E-94</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>5.22E-112</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0.1</td>
<td>6.24E-99</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0.5</td>
<td>1.44E-96</td>
</tr>
<tr>
<td>9</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>0.9</td>
<td>1.29E-84</td>
</tr>
<tr>
<td>10</td>
<td>0</td>
<td>0</td>
<td>50</td>
<td>1.0</td>
<td>2.84E-82</td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>2.30E-80</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0.1</td>
<td>6.61E-109</td>
</tr>
<tr>
<td>13</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0.5</td>
<td>5.91E-75</td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>0.9</td>
<td>2.69E-62</td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0</td>
<td>100</td>
<td>1.0</td>
<td>7.26E-49</td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>9.22E-101</td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0.1</td>
<td>1.47E-93</td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0.5</td>
<td>2.94E-89</td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>0.9</td>
<td>1.07E-58</td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0</td>
<td>200</td>
<td>1.0</td>
<td>1.51E-54</td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>3.69E-86</td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>0</td>
<td>2500</td>
<td>0.1</td>
<td>1.54E-108</td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>0</td>
<td>2500</td>
<td>0.5</td>
<td>9.40E-96</td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>0</td>
<td>2500</td>
<td>0.9</td>
<td>1.12E-105</td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0</td>
<td>2500</td>
<td>1.0</td>
<td>1.33E-88</td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>0.005</td>
<td>10</td>
<td>0</td>
<td>3.35E-06</td>
</tr>
<tr>
<td>27</td>
<td>0</td>
<td>0.005</td>
<td>10</td>
<td>0.1</td>
<td>6.05E-07</td>
</tr>
<tr>
<td>28</td>
<td>0</td>
<td>0.005</td>
<td>10</td>
<td>0.5</td>
<td>4.95E-07</td>
</tr>
<tr>
<td>29</td>
<td>0</td>
<td>0.005</td>
<td>10</td>
<td>0.9</td>
<td>1.68E-06</td>
</tr>
<tr>
<td>30</td>
<td>0</td>
<td>0.005</td>
<td>10</td>
<td>1.0</td>
<td>2.54E-06</td>
</tr>
<tr>
<td>31</td>
<td>0</td>
<td>0.005</td>
<td>50</td>
<td>0</td>
<td>3.55E-06</td>
</tr>
<tr>
<td>32</td>
<td>0</td>
<td>0.005</td>
<td>50</td>
<td>0.1</td>
<td>8.85E-07</td>
</tr>
<tr>
<td>33</td>
<td>0</td>
<td>0.005</td>
<td>50</td>
<td>0.5</td>
<td>3.85E-07</td>
</tr>
<tr>
<td>34</td>
<td>0</td>
<td>0.005</td>
<td>50</td>
<td>0.9</td>
<td>2.83E-09</td>
</tr>
<tr>
<td>35</td>
<td>0</td>
<td>0.005</td>
<td>50</td>
<td>1.0</td>
<td>5.70E-09</td>
</tr>
<tr>
<td>36</td>
<td>0</td>
<td>0.005</td>
<td>100</td>
<td>0</td>
<td>1.72E-06</td>
</tr>
<tr>
<td>37</td>
<td>0</td>
<td>0.005</td>
<td>100</td>
<td>0.1</td>
<td>3.97E-07</td>
</tr>
<tr>
<td>38</td>
<td>0</td>
<td>0.005</td>
<td>100</td>
<td>0.5</td>
<td>1.79E-08</td>
</tr>
<tr>
<td>39</td>
<td>0</td>
<td>0.005</td>
<td>100</td>
<td>0.9</td>
<td>3.59E-12</td>
</tr>
<tr>
<td>40</td>
<td>0</td>
<td>0.005</td>
<td>100</td>
<td>1.0</td>
<td>2.74E-11</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>41</td>
<td>0</td>
<td>0.005</td>
<td>200</td>
<td>0</td>
<td>3.07E-06</td>
</tr>
<tr>
<td>42</td>
<td>0</td>
<td>0.005</td>
<td>200</td>
<td>0.1</td>
<td>5.12E-07</td>
</tr>
<tr>
<td>43</td>
<td>0</td>
<td>0.005</td>
<td>200</td>
<td>0.5</td>
<td>7.31E-06</td>
</tr>
<tr>
<td>44</td>
<td>0</td>
<td>0.005</td>
<td>200</td>
<td>0.9</td>
<td>3.35E-05</td>
</tr>
<tr>
<td>45</td>
<td>0</td>
<td>0.005</td>
<td>200</td>
<td>1</td>
<td>0.001157</td>
</tr>
<tr>
<td>46</td>
<td>0</td>
<td>0.005</td>
<td>2500</td>
<td>0</td>
<td>5.19E-06</td>
</tr>
<tr>
<td>47</td>
<td>0</td>
<td>0.005</td>
<td>2500</td>
<td>0.1</td>
<td>7.18E-06</td>
</tr>
<tr>
<td>48</td>
<td>0</td>
<td>0.005</td>
<td>2500</td>
<td>0.5</td>
<td>6.45E-06</td>
</tr>
<tr>
<td>49</td>
<td>0</td>
<td>0.005</td>
<td>2500</td>
<td>0.9</td>
<td>3.27E-06</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>3.69E-06</td>
</tr>
<tr>
<td>51</td>
<td>0</td>
<td>0.01</td>
<td>10</td>
<td>0</td>
<td>0.275885</td>
</tr>
<tr>
<td>52</td>
<td>0</td>
<td>0.01</td>
<td>10</td>
<td>0.1</td>
<td>0.232688</td>
</tr>
<tr>
<td>53</td>
<td>0</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
<td>0.231187</td>
</tr>
<tr>
<td>54</td>
<td>0</td>
<td>0.01</td>
<td>10</td>
<td>0.9</td>
<td>0.220558</td>
</tr>
<tr>
<td>55</td>
<td>0</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>0.252349</td>
</tr>
<tr>
<td>56</td>
<td>0</td>
<td>0.01</td>
<td>50</td>
<td>0</td>
<td>0.249608</td>
</tr>
<tr>
<td>57</td>
<td>0</td>
<td>0.01</td>
<td>50</td>
<td>0.1</td>
<td>0.246188</td>
</tr>
<tr>
<td>58</td>
<td>0</td>
<td>0.01</td>
<td>50</td>
<td>0.5</td>
<td>0.191868</td>
</tr>
<tr>
<td>59</td>
<td>0</td>
<td>0.01</td>
<td>50</td>
<td>0.9</td>
<td>0.138266</td>
</tr>
<tr>
<td>60</td>
<td>0</td>
<td>0.01</td>
<td>50</td>
<td>1</td>
<td>0.154601</td>
</tr>
<tr>
<td>61</td>
<td>0</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>0.283351</td>
</tr>
<tr>
<td>62</td>
<td>0</td>
<td>0.01</td>
<td>100</td>
<td>0.1</td>
<td>0.241689</td>
</tr>
<tr>
<td>63</td>
<td>0</td>
<td>0.01</td>
<td>100</td>
<td>0.5</td>
<td>0.203068</td>
</tr>
<tr>
<td>64</td>
<td>0</td>
<td>0.01</td>
<td>100</td>
<td>0.9</td>
<td>0.080683</td>
</tr>
<tr>
<td>65</td>
<td>0</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>0.078066</td>
</tr>
<tr>
<td>66</td>
<td>0</td>
<td>0.01</td>
<td>200</td>
<td>0</td>
<td>0.271156</td>
</tr>
<tr>
<td>67</td>
<td>0</td>
<td>0.01</td>
<td>200</td>
<td>0.1</td>
<td>0.215713</td>
</tr>
<tr>
<td>68</td>
<td>0</td>
<td>0.01</td>
<td>200</td>
<td>0.5</td>
<td>0.337926</td>
</tr>
<tr>
<td>69</td>
<td>0</td>
<td>0.01</td>
<td>200</td>
<td>0.9</td>
<td>0.393155</td>
</tr>
<tr>
<td>70</td>
<td>0</td>
<td>0.01</td>
<td>200</td>
<td>1</td>
<td>0.392296</td>
</tr>
<tr>
<td>71</td>
<td>0</td>
<td>0.01</td>
<td>2500</td>
<td>0</td>
<td>0.282783</td>
</tr>
<tr>
<td>72</td>
<td>0</td>
<td>0.01</td>
<td>2500</td>
<td>0.1</td>
<td>0.270067</td>
</tr>
<tr>
<td>73</td>
<td>0</td>
<td>0.01</td>
<td>2500</td>
<td>0.5</td>
<td>0.259954</td>
</tr>
<tr>
<td>74</td>
<td>0</td>
<td>0.01</td>
<td>2500</td>
<td>0.9</td>
<td>0.261218</td>
</tr>
<tr>
<td>75</td>
<td>0</td>
<td>0.01</td>
<td>2500</td>
<td>1</td>
<td>0.26358</td>
</tr>
<tr>
<td>76</td>
<td>0</td>
<td>0.015</td>
<td>10</td>
<td>0</td>
<td>0.178396</td>
</tr>
<tr>
<td>77</td>
<td>0</td>
<td>0.015</td>
<td>10</td>
<td>0.1</td>
<td>0.193094</td>
</tr>
<tr>
<td>78</td>
<td>0</td>
<td>0.015</td>
<td>10</td>
<td>0.5</td>
<td>0.190951</td>
</tr>
<tr>
<td>79</td>
<td>0</td>
<td>0.015</td>
<td>10</td>
<td>0.9</td>
<td>0.226924</td>
</tr>
<tr>
<td>80</td>
<td>0</td>
<td>0.015</td>
<td>10</td>
<td>1</td>
<td>0.197351</td>
</tr>
<tr>
<td>81</td>
<td>0</td>
<td>0.015</td>
<td>50</td>
<td>0</td>
<td>0.20157</td>
</tr>
<tr>
<td>82</td>
<td>0</td>
<td>0.015</td>
<td>50</td>
<td>0.1</td>
<td>0.206481</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>83</td>
<td>0</td>
<td>0.015</td>
<td>50</td>
<td>0.5</td>
<td>0.233095</td>
</tr>
<tr>
<td>84</td>
<td>0</td>
<td>0.015</td>
<td>50</td>
<td>0.9</td>
<td>0.29</td>
</tr>
<tr>
<td>85</td>
<td>0</td>
<td>0.015</td>
<td>50</td>
<td>1</td>
<td>0.278599</td>
</tr>
<tr>
<td>86</td>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>0</td>
<td>0.177904</td>
</tr>
<tr>
<td>87</td>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>0.1</td>
<td>0.210891</td>
</tr>
<tr>
<td>88</td>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>0.5</td>
<td>0.250803</td>
</tr>
<tr>
<td>89</td>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>0.9</td>
<td>0.348474</td>
</tr>
<tr>
<td>90</td>
<td>0</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>0.354681</td>
</tr>
<tr>
<td>91</td>
<td>0</td>
<td>0.015</td>
<td>200</td>
<td>0</td>
<td>0.180891</td>
</tr>
<tr>
<td>92</td>
<td>0</td>
<td>0.015</td>
<td>200</td>
<td>0.1</td>
<td>0.191315</td>
</tr>
<tr>
<td>93</td>
<td>0</td>
<td>0.015</td>
<td>200</td>
<td>0.5</td>
<td>0.110594</td>
</tr>
<tr>
<td>94</td>
<td>0</td>
<td>0.015</td>
<td>200</td>
<td>0.9</td>
<td>0.064618</td>
</tr>
<tr>
<td>95</td>
<td>0</td>
<td>0.015</td>
<td>200</td>
<td>1</td>
<td>0.035444</td>
</tr>
<tr>
<td>96</td>
<td>0</td>
<td>0.015</td>
<td>2500</td>
<td>0</td>
<td>0.187023</td>
</tr>
<tr>
<td>97</td>
<td>0</td>
<td>0.015</td>
<td>2500</td>
<td>0.1</td>
<td>0.189081</td>
</tr>
<tr>
<td>98</td>
<td>0</td>
<td>0.015</td>
<td>2500</td>
<td>0.5</td>
<td>0.186714</td>
</tr>
<tr>
<td>99</td>
<td>0</td>
<td>0.015</td>
<td>2500</td>
<td>0.9</td>
<td>0.188187</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>0.015</td>
<td>2500</td>
<td>1</td>
<td>0.185505</td>
</tr>
<tr>
<td>101</td>
<td>0</td>
<td>0.02</td>
<td>10</td>
<td>0</td>
<td>0.003828</td>
</tr>
<tr>
<td>102</td>
<td>0</td>
<td>0.02</td>
<td>10</td>
<td>0.1</td>
<td>0.005683</td>
</tr>
<tr>
<td>103</td>
<td>0</td>
<td>0.02</td>
<td>10</td>
<td>0.5</td>
<td>0.00828</td>
</tr>
<tr>
<td>104</td>
<td>0</td>
<td>0.02</td>
<td>10</td>
<td>0.9</td>
<td>0.006254</td>
</tr>
<tr>
<td>105</td>
<td>0</td>
<td>0.02</td>
<td>10</td>
<td>1</td>
<td>0.005412</td>
</tr>
<tr>
<td>106</td>
<td>0</td>
<td>0.02</td>
<td>50</td>
<td>0</td>
<td>0.004289</td>
</tr>
<tr>
<td>107</td>
<td>0</td>
<td>0.02</td>
<td>50</td>
<td>0.1</td>
<td>0.005097</td>
</tr>
<tr>
<td>108</td>
<td>0</td>
<td>0.02</td>
<td>50</td>
<td>0.5</td>
<td>0.007007</td>
</tr>
<tr>
<td>109</td>
<td>0</td>
<td>0.02</td>
<td>50</td>
<td>0.9</td>
<td>0.015836</td>
</tr>
<tr>
<td>110</td>
<td>0</td>
<td>0.02</td>
<td>50</td>
<td>1</td>
<td>0.01009</td>
</tr>
<tr>
<td>111</td>
<td>0</td>
<td>0.02</td>
<td>100</td>
<td>0</td>
<td>0.005763</td>
</tr>
<tr>
<td>112</td>
<td>0</td>
<td>0.02</td>
<td>100</td>
<td>0.1</td>
<td>0.005031</td>
</tr>
<tr>
<td>113</td>
<td>0</td>
<td>0.02</td>
<td>100</td>
<td>0.5</td>
<td>0.01119</td>
</tr>
<tr>
<td>114</td>
<td>0</td>
<td>0.02</td>
<td>100</td>
<td>0.9</td>
<td>0.025966</td>
</tr>
<tr>
<td>115</td>
<td>0</td>
<td>0.02</td>
<td>100</td>
<td>1</td>
<td>0.032219</td>
</tr>
<tr>
<td>116</td>
<td>0</td>
<td>0.02</td>
<td>200</td>
<td>0</td>
<td>0.005656</td>
</tr>
<tr>
<td>117</td>
<td>0</td>
<td>0.02</td>
<td>200</td>
<td>0.1</td>
<td>0.007373</td>
</tr>
<tr>
<td>118</td>
<td>0</td>
<td>0.02</td>
<td>200</td>
<td>0.5</td>
<td>0.002593</td>
</tr>
<tr>
<td>119</td>
<td>0</td>
<td>0.02</td>
<td>200</td>
<td>0.9</td>
<td>0.000409</td>
</tr>
<tr>
<td>120</td>
<td>0</td>
<td>0.02</td>
<td>200</td>
<td>1</td>
<td>0.000138</td>
</tr>
<tr>
<td>121</td>
<td>0</td>
<td>0.02</td>
<td>2500</td>
<td>0</td>
<td>0.004511</td>
</tr>
<tr>
<td>122</td>
<td>0</td>
<td>0.02</td>
<td>2500</td>
<td>0.1</td>
<td>0.00611</td>
</tr>
<tr>
<td>123</td>
<td>0</td>
<td>0.02</td>
<td>2500</td>
<td>0.5</td>
<td>0.004525</td>
</tr>
<tr>
<td>124</td>
<td>0</td>
<td>0.02</td>
<td>2500</td>
<td>0.9</td>
<td>0.003983</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSENTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>125</td>
<td>0</td>
<td>0.02</td>
<td>2500</td>
<td>1</td>
<td>0.005386</td>
</tr>
<tr>
<td>126</td>
<td>0.005</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>1.48E-06</td>
</tr>
<tr>
<td>127</td>
<td>0.005</td>
<td>0</td>
<td>10</td>
<td>0.1</td>
<td>5.64E-07</td>
</tr>
<tr>
<td>128</td>
<td>0.005</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
<td>6.15E-07</td>
</tr>
<tr>
<td>129</td>
<td>0.005</td>
<td>0</td>
<td>10</td>
<td>0.9</td>
<td>1.99E-07</td>
</tr>
<tr>
<td>130</td>
<td>0.005</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>3.50E-07</td>
</tr>
<tr>
<td>131</td>
<td>0.005</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>8.33E-07</td>
</tr>
<tr>
<td>132</td>
<td>0.005</td>
<td>0</td>
<td>50</td>
<td>0.1</td>
<td>1.71E-06</td>
</tr>
<tr>
<td>133</td>
<td>0.005</td>
<td>0</td>
<td>50</td>
<td>0.5</td>
<td>1.68E-07</td>
</tr>
<tr>
<td>134</td>
<td>0.005</td>
<td>0</td>
<td>50</td>
<td>0.9</td>
<td>1.91E-08</td>
</tr>
<tr>
<td>135</td>
<td>0.005</td>
<td>0</td>
<td>50</td>
<td>1</td>
<td>1.26E-09</td>
</tr>
<tr>
<td>136</td>
<td>0.005</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>3.89E-06</td>
</tr>
<tr>
<td>137</td>
<td>0.005</td>
<td>0</td>
<td>100</td>
<td>0.1</td>
<td>2.87E-07</td>
</tr>
<tr>
<td>138</td>
<td>0.005</td>
<td>0</td>
<td>100</td>
<td>0.5</td>
<td>2.19E-07</td>
</tr>
<tr>
<td>139</td>
<td>0.005</td>
<td>0</td>
<td>100</td>
<td>0.9</td>
<td>1.90E-10</td>
</tr>
<tr>
<td>140</td>
<td>0.005</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>2.44E-14</td>
</tr>
<tr>
<td>141</td>
<td>0.005</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>2.46E-07</td>
</tr>
<tr>
<td>142</td>
<td>0.005</td>
<td>0</td>
<td>200</td>
<td>0.1</td>
<td>1.13E-06</td>
</tr>
<tr>
<td>143</td>
<td>0.005</td>
<td>0</td>
<td>200</td>
<td>0.5</td>
<td>2.92E-06</td>
</tr>
<tr>
<td>144</td>
<td>0.005</td>
<td>0</td>
<td>200</td>
<td>0.9</td>
<td>7.42E-05</td>
</tr>
<tr>
<td>145</td>
<td>0.005</td>
<td>0</td>
<td>200</td>
<td>1</td>
<td>0.00259</td>
</tr>
<tr>
<td>146</td>
<td>0.005</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>5.26E-07</td>
</tr>
<tr>
<td>147</td>
<td>0.005</td>
<td>0</td>
<td>2500</td>
<td>0.1</td>
<td>3.71E-07</td>
</tr>
<tr>
<td>148</td>
<td>0.005</td>
<td>0</td>
<td>2500</td>
<td>0.5</td>
<td>6.41E-07</td>
</tr>
<tr>
<td>149</td>
<td>0.005</td>
<td>0</td>
<td>2500</td>
<td>0.9</td>
<td>1.01E-06</td>
</tr>
<tr>
<td>150</td>
<td>0.005</td>
<td>0</td>
<td>2500</td>
<td>1</td>
<td>6.22E-07</td>
</tr>
<tr>
<td>151</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
<td>0</td>
<td>0.251277</td>
</tr>
<tr>
<td>152</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
<td>0.1</td>
<td>0.218257</td>
</tr>
<tr>
<td>153</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
<td>0.5</td>
<td>0.231365</td>
</tr>
<tr>
<td>154</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
<td>0.9</td>
<td>0.185359</td>
</tr>
<tr>
<td>155</td>
<td>0.005</td>
<td>0.005</td>
<td>10</td>
<td>1</td>
<td>0.239396</td>
</tr>
<tr>
<td>156</td>
<td>0.005</td>
<td>0.005</td>
<td>50</td>
<td>0</td>
<td>0.249435</td>
</tr>
<tr>
<td>157</td>
<td>0.005</td>
<td>0.005</td>
<td>50</td>
<td>0.1</td>
<td>0.210482</td>
</tr>
<tr>
<td>158</td>
<td>0.005</td>
<td>0.005</td>
<td>50</td>
<td>0.5</td>
<td>0.212116</td>
</tr>
<tr>
<td>159</td>
<td>0.005</td>
<td>0.005</td>
<td>50</td>
<td>0.9</td>
<td>0.14279</td>
</tr>
<tr>
<td>160</td>
<td>0.005</td>
<td>0.005</td>
<td>50</td>
<td>1</td>
<td>0.155708</td>
</tr>
<tr>
<td>161</td>
<td>0.005</td>
<td>0.005</td>
<td>100</td>
<td>0</td>
<td>0.247786</td>
</tr>
<tr>
<td>162</td>
<td>0.005</td>
<td>0.005</td>
<td>100</td>
<td>0.1</td>
<td>0.207155</td>
</tr>
<tr>
<td>163</td>
<td>0.005</td>
<td>0.005</td>
<td>100</td>
<td>0.5</td>
<td>0.168815</td>
</tr>
<tr>
<td>164</td>
<td>0.005</td>
<td>0.005</td>
<td>100</td>
<td>0.9</td>
<td>0.080843</td>
</tr>
<tr>
<td>165</td>
<td>0.005</td>
<td>0.005</td>
<td>100</td>
<td>1</td>
<td>0.079849</td>
</tr>
<tr>
<td>166</td>
<td>0.005</td>
<td>0.005</td>
<td>200</td>
<td>0</td>
<td>0.257647</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>167</td>
<td>0.005</td>
<td>0.005</td>
<td>200</td>
<td>0.1</td>
<td>0.214526</td>
</tr>
<tr>
<td>168</td>
<td>0.005</td>
<td>0.005</td>
<td>200</td>
<td>0.5</td>
<td>0.301915</td>
</tr>
<tr>
<td>169</td>
<td>0.005</td>
<td>0.005</td>
<td>200</td>
<td>0.9</td>
<td>0.37672</td>
</tr>
<tr>
<td>170</td>
<td>0.005</td>
<td>0.005</td>
<td>200</td>
<td>1</td>
<td>0.398936</td>
</tr>
<tr>
<td>171</td>
<td>0.005</td>
<td>0.005</td>
<td>2500</td>
<td>0</td>
<td>0.251895</td>
</tr>
<tr>
<td>172</td>
<td>0.005</td>
<td>0.005</td>
<td>2500</td>
<td>0.1</td>
<td>0.262833</td>
</tr>
<tr>
<td>173</td>
<td>0.005</td>
<td>0.005</td>
<td>2500</td>
<td>0.5</td>
<td>0.262644</td>
</tr>
<tr>
<td>174</td>
<td>0.005</td>
<td>0.005</td>
<td>2500</td>
<td>0.9</td>
<td>0.265938</td>
</tr>
<tr>
<td>175</td>
<td>0.005</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>0.262601</td>
</tr>
<tr>
<td>176</td>
<td>0.005</td>
<td>0.01</td>
<td>10</td>
<td>0</td>
<td>0.185907</td>
</tr>
<tr>
<td>177</td>
<td>0.005</td>
<td>0.01</td>
<td>10</td>
<td>0.1</td>
<td>0.215925</td>
</tr>
<tr>
<td>178</td>
<td>0.005</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
<td>0.205106</td>
</tr>
<tr>
<td>179</td>
<td>0.005</td>
<td>0.01</td>
<td>10</td>
<td>0.9</td>
<td>0.225796</td>
</tr>
<tr>
<td>180</td>
<td>0.005</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>0.194728</td>
</tr>
<tr>
<td>181</td>
<td>0.005</td>
<td>0.01</td>
<td>50</td>
<td>0</td>
<td>0.185404</td>
</tr>
<tr>
<td>182</td>
<td>0.005</td>
<td>0.01</td>
<td>50</td>
<td>0.1</td>
<td>0.2092</td>
</tr>
<tr>
<td>183</td>
<td>0.005</td>
<td>0.01</td>
<td>50</td>
<td>0.5</td>
<td>0.226502</td>
</tr>
<tr>
<td>184</td>
<td>0.005</td>
<td>0.01</td>
<td>50</td>
<td>0.9</td>
<td>0.275953</td>
</tr>
<tr>
<td>185</td>
<td>0.005</td>
<td>0.01</td>
<td>50</td>
<td>1</td>
<td>0.274961</td>
</tr>
<tr>
<td>186</td>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>0.209371</td>
</tr>
<tr>
<td>187</td>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>0.1</td>
<td>0.206944</td>
</tr>
<tr>
<td>188</td>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>0.5</td>
<td>0.250245</td>
</tr>
<tr>
<td>189</td>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>0.9</td>
<td>0.351771</td>
</tr>
<tr>
<td>190</td>
<td>0.005</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>0.356723</td>
</tr>
<tr>
<td>191</td>
<td>0.005</td>
<td>0.01</td>
<td>200</td>
<td>0</td>
<td>0.167549</td>
</tr>
<tr>
<td>192</td>
<td>0.005</td>
<td>0.01</td>
<td>200</td>
<td>0.1</td>
<td>0.227696</td>
</tr>
<tr>
<td>193</td>
<td>0.005</td>
<td>0.01</td>
<td>200</td>
<td>0.5</td>
<td>0.123867</td>
</tr>
<tr>
<td>194</td>
<td>0.005</td>
<td>0.01</td>
<td>200</td>
<td>0.9</td>
<td>0.054541</td>
</tr>
<tr>
<td>195</td>
<td>0.005</td>
<td>0.01</td>
<td>200</td>
<td>1</td>
<td>0.042478</td>
</tr>
<tr>
<td>196</td>
<td>0.005</td>
<td>0.01</td>
<td>2500</td>
<td>0</td>
<td>0.187613</td>
</tr>
<tr>
<td>197</td>
<td>0.005</td>
<td>0.01</td>
<td>2500</td>
<td>0.1</td>
<td>0.188728</td>
</tr>
<tr>
<td>198</td>
<td>0.005</td>
<td>0.01</td>
<td>2500</td>
<td>0.5</td>
<td>0.190791</td>
</tr>
<tr>
<td>199</td>
<td>0.005</td>
<td>0.01</td>
<td>2500</td>
<td>0.9</td>
<td>0.189111</td>
</tr>
<tr>
<td>200</td>
<td>0.005</td>
<td>0.01</td>
<td>2500</td>
<td>1</td>
<td>0.17435</td>
</tr>
<tr>
<td>201</td>
<td>0.005</td>
<td>0.015</td>
<td>10</td>
<td>0</td>
<td>0.004104</td>
</tr>
<tr>
<td>202</td>
<td>0.005</td>
<td>0.015</td>
<td>10</td>
<td>0.1</td>
<td>0.00741</td>
</tr>
<tr>
<td>203</td>
<td>0.005</td>
<td>0.015</td>
<td>10</td>
<td>0.5</td>
<td>0.00638</td>
</tr>
<tr>
<td>204</td>
<td>0.005</td>
<td>0.015</td>
<td>10</td>
<td>0.9</td>
<td>0.005232</td>
</tr>
<tr>
<td>205</td>
<td>0.005</td>
<td>0.015</td>
<td>10</td>
<td>1</td>
<td>0.007856</td>
</tr>
<tr>
<td>206</td>
<td>0.005</td>
<td>0.015</td>
<td>50</td>
<td>0</td>
<td>0.003493</td>
</tr>
<tr>
<td>207</td>
<td>0.005</td>
<td>0.015</td>
<td>50</td>
<td>0.1</td>
<td>0.006879</td>
</tr>
<tr>
<td>208</td>
<td>0.005</td>
<td>0.015</td>
<td>50</td>
<td>0.5</td>
<td>0.007154</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>209</td>
<td>0.005</td>
<td>0.015</td>
<td>50</td>
<td>0.9</td>
<td>0.013246</td>
</tr>
<tr>
<td>210</td>
<td>0.005</td>
<td>0.015</td>
<td>50</td>
<td>1</td>
<td>0.016053</td>
</tr>
<tr>
<td>211</td>
<td>0.005</td>
<td>0.015</td>
<td>100</td>
<td>0</td>
<td>0.00469</td>
</tr>
<tr>
<td>212</td>
<td>0.005</td>
<td>0.015</td>
<td>100</td>
<td>0.1</td>
<td>0.00598</td>
</tr>
<tr>
<td>213</td>
<td>0.005</td>
<td>0.015</td>
<td>100</td>
<td>0.5</td>
<td>0.016022</td>
</tr>
<tr>
<td>214</td>
<td>0.005</td>
<td>0.015</td>
<td>100</td>
<td>0.9</td>
<td>0.02774</td>
</tr>
<tr>
<td>215</td>
<td>0.005</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>0.033119</td>
</tr>
<tr>
<td>216</td>
<td>0.005</td>
<td>0.015</td>
<td>200</td>
<td>0</td>
<td>0.004793</td>
</tr>
<tr>
<td>217</td>
<td>0.005</td>
<td>0.015</td>
<td>200</td>
<td>0.1</td>
<td>0.005369</td>
</tr>
<tr>
<td>218</td>
<td>0.005</td>
<td>0.015</td>
<td>200</td>
<td>0.5</td>
<td>0.00177</td>
</tr>
<tr>
<td>219</td>
<td>0.005</td>
<td>0.015</td>
<td>200</td>
<td>0.9</td>
<td>0.000675</td>
</tr>
<tr>
<td>220</td>
<td>0.005</td>
<td>0.015</td>
<td>200</td>
<td>1</td>
<td>0.000158</td>
</tr>
<tr>
<td>221</td>
<td>0.005</td>
<td>0.015</td>
<td>2500</td>
<td>0</td>
<td>0.005383</td>
</tr>
<tr>
<td>222</td>
<td>0.005</td>
<td>0.015</td>
<td>2500</td>
<td>0.1</td>
<td>0.004835</td>
</tr>
<tr>
<td>223</td>
<td>0.005</td>
<td>0.015</td>
<td>2500</td>
<td>0.5</td>
<td>0.004577</td>
</tr>
<tr>
<td>224</td>
<td>0.005</td>
<td>0.015</td>
<td>2500</td>
<td>0.9</td>
<td>0.004067</td>
</tr>
<tr>
<td>225</td>
<td>0.005</td>
<td>0.015</td>
<td>2500</td>
<td>1</td>
<td>0.005642</td>
</tr>
<tr>
<td>226</td>
<td>0.005</td>
<td>0.02</td>
<td>10</td>
<td>0</td>
<td>3.05E-05</td>
</tr>
<tr>
<td>227</td>
<td>0.005</td>
<td>0.02</td>
<td>10</td>
<td>0.1</td>
<td>7.44E-06</td>
</tr>
<tr>
<td>228</td>
<td>0.005</td>
<td>0.02</td>
<td>10</td>
<td>0.5</td>
<td>1.22E-05</td>
</tr>
<tr>
<td>229</td>
<td>0.005</td>
<td>0.02</td>
<td>10</td>
<td>0.9</td>
<td>3.79E-05</td>
</tr>
<tr>
<td>230</td>
<td>0.005</td>
<td>0.02</td>
<td>10</td>
<td>1</td>
<td>1.16E-05</td>
</tr>
<tr>
<td>231</td>
<td>0.005</td>
<td>0.02</td>
<td>50</td>
<td>0</td>
<td>8.73E-06</td>
</tr>
<tr>
<td>232</td>
<td>0.005</td>
<td>0.02</td>
<td>50</td>
<td>0.1</td>
<td>2.43E-05</td>
</tr>
<tr>
<td>233</td>
<td>0.005</td>
<td>0.02</td>
<td>50</td>
<td>0.5</td>
<td>1.72E-05</td>
</tr>
<tr>
<td>234</td>
<td>0.005</td>
<td>0.02</td>
<td>50</td>
<td>0.9</td>
<td>7.25E-05</td>
</tr>
<tr>
<td>235</td>
<td>0.005</td>
<td>0.02</td>
<td>50</td>
<td>1</td>
<td>0.000102</td>
</tr>
<tr>
<td>236</td>
<td>0.005</td>
<td>0.02</td>
<td>100</td>
<td>0</td>
<td>2.88E-05</td>
</tr>
<tr>
<td>237</td>
<td>0.005</td>
<td>0.02</td>
<td>100</td>
<td>0.1</td>
<td>1.61E-05</td>
</tr>
<tr>
<td>238</td>
<td>0.005</td>
<td>0.02</td>
<td>100</td>
<td>0.5</td>
<td>4.16E-05</td>
</tr>
<tr>
<td>239</td>
<td>0.005</td>
<td>0.02</td>
<td>100</td>
<td>0.9</td>
<td>0.000134</td>
</tr>
<tr>
<td>240</td>
<td>0.005</td>
<td>0.02</td>
<td>100</td>
<td>1</td>
<td>0.000365</td>
</tr>
<tr>
<td>241</td>
<td>0.005</td>
<td>0.02</td>
<td>200</td>
<td>0</td>
<td>8.18E-06</td>
</tr>
<tr>
<td>242</td>
<td>0.005</td>
<td>0.02</td>
<td>200</td>
<td>0.1</td>
<td>3.51E-05</td>
</tr>
<tr>
<td>243</td>
<td>0.005</td>
<td>0.02</td>
<td>200</td>
<td>0.5</td>
<td>1.59E-06</td>
</tr>
<tr>
<td>244</td>
<td>0.005</td>
<td>0.02</td>
<td>200</td>
<td>0.9</td>
<td>2.37E-07</td>
</tr>
<tr>
<td>245</td>
<td>0.005</td>
<td>0.02</td>
<td>200</td>
<td>1</td>
<td>9.04E-08</td>
</tr>
<tr>
<td>246</td>
<td>0.005</td>
<td>0.02</td>
<td>2500</td>
<td>0</td>
<td>2.50E-05</td>
</tr>
<tr>
<td>247</td>
<td>0.005</td>
<td>0.02</td>
<td>2500</td>
<td>0.1</td>
<td>8.53E-06</td>
</tr>
<tr>
<td>248</td>
<td>0.005</td>
<td>0.02</td>
<td>2500</td>
<td>0.5</td>
<td>1.59E-05</td>
</tr>
<tr>
<td>249</td>
<td>0.005</td>
<td>0.02</td>
<td>2500</td>
<td>0.9</td>
<td>2.69E-05</td>
</tr>
<tr>
<td>250</td>
<td>0.005</td>
<td>0.02</td>
<td>2500</td>
<td>1</td>
<td>1.07E-05</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>251</td>
<td>0.01</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0.236927</td>
</tr>
<tr>
<td>252</td>
<td>0.01</td>
<td>0</td>
<td>10</td>
<td>0.1</td>
<td>0.230579</td>
</tr>
<tr>
<td>253</td>
<td>0.01</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
<td>0.212029</td>
</tr>
<tr>
<td>254</td>
<td>0.01</td>
<td>0</td>
<td>10</td>
<td>0.9</td>
<td>0.212588</td>
</tr>
<tr>
<td>255</td>
<td>0.01</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>0.226048</td>
</tr>
<tr>
<td>256</td>
<td>0.01</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>0.222242</td>
</tr>
<tr>
<td>257</td>
<td>0.01</td>
<td>0</td>
<td>50</td>
<td>0.1</td>
<td>0.207421</td>
</tr>
<tr>
<td>258</td>
<td>0.01</td>
<td>0</td>
<td>50</td>
<td>0.5</td>
<td>0.207032</td>
</tr>
<tr>
<td>259</td>
<td>0.01</td>
<td>0</td>
<td>50</td>
<td>0.9</td>
<td>0.151059</td>
</tr>
<tr>
<td>260</td>
<td>0.01</td>
<td>0</td>
<td>50</td>
<td>1</td>
<td>0.123709</td>
</tr>
<tr>
<td>261</td>
<td>0.01</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0.227143</td>
</tr>
<tr>
<td>262</td>
<td>0.01</td>
<td>0</td>
<td>100</td>
<td>0.1</td>
<td>0.225463</td>
</tr>
<tr>
<td>263</td>
<td>0.01</td>
<td>0</td>
<td>100</td>
<td>0.5</td>
<td>0.167288</td>
</tr>
<tr>
<td>264</td>
<td>0.01</td>
<td>0</td>
<td>100</td>
<td>0.9</td>
<td>0.085714</td>
</tr>
<tr>
<td>265</td>
<td>0.01</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>0.028455</td>
</tr>
<tr>
<td>266</td>
<td>0.01</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0.203795</td>
</tr>
<tr>
<td>267</td>
<td>0.01</td>
<td>0</td>
<td>200</td>
<td>0.1</td>
<td>0.225344</td>
</tr>
<tr>
<td>268</td>
<td>0.01</td>
<td>0</td>
<td>200</td>
<td>0.5</td>
<td>0.303282</td>
</tr>
<tr>
<td>269</td>
<td>0.01</td>
<td>0</td>
<td>200</td>
<td>0.9</td>
<td>0.368304</td>
</tr>
<tr>
<td>270</td>
<td>0.01</td>
<td>0</td>
<td>200</td>
<td>1</td>
<td>0.398614</td>
</tr>
<tr>
<td>271</td>
<td>0.01</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>0.211238</td>
</tr>
<tr>
<td>272</td>
<td>0.01</td>
<td>0</td>
<td>2500</td>
<td>0.1</td>
<td>0.212377</td>
</tr>
<tr>
<td>273</td>
<td>0.01</td>
<td>0</td>
<td>2500</td>
<td>0.5</td>
<td>0.240775</td>
</tr>
<tr>
<td>274</td>
<td>0.01</td>
<td>0</td>
<td>2500</td>
<td>0.9</td>
<td>0.237122</td>
</tr>
<tr>
<td>275</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>0.245398</td>
</tr>
<tr>
<td>276</td>
<td>0.01</td>
<td>0.005</td>
<td>10</td>
<td>0</td>
<td>0.189541</td>
</tr>
<tr>
<td>277</td>
<td>0.01</td>
<td>0.005</td>
<td>10</td>
<td>0.1</td>
<td>0.218492</td>
</tr>
<tr>
<td>278</td>
<td>0.01</td>
<td>0.005</td>
<td>10</td>
<td>0.5</td>
<td>0.205185</td>
</tr>
<tr>
<td>279</td>
<td>0.01</td>
<td>0.005</td>
<td>10</td>
<td>0.9</td>
<td>0.209185</td>
</tr>
<tr>
<td>280</td>
<td>0.01</td>
<td>0.005</td>
<td>10</td>
<td>1</td>
<td>0.200555</td>
</tr>
<tr>
<td>281</td>
<td>0.01</td>
<td>0.005</td>
<td>50</td>
<td>0</td>
<td>0.178389</td>
</tr>
<tr>
<td>282</td>
<td>0.01</td>
<td>0.005</td>
<td>50</td>
<td>0.1</td>
<td>0.223614</td>
</tr>
<tr>
<td>283</td>
<td>0.01</td>
<td>0.005</td>
<td>50</td>
<td>0.5</td>
<td>0.223971</td>
</tr>
<tr>
<td>284</td>
<td>0.01</td>
<td>0.005</td>
<td>50</td>
<td>0.9</td>
<td>0.277562</td>
</tr>
<tr>
<td>285</td>
<td>0.01</td>
<td>0.005</td>
<td>50</td>
<td>1</td>
<td>0.285832</td>
</tr>
<tr>
<td>286</td>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>0</td>
<td>0.193733</td>
</tr>
<tr>
<td>287</td>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>0.1</td>
<td>0.224644</td>
</tr>
<tr>
<td>288</td>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>0.5</td>
<td>0.262239</td>
</tr>
<tr>
<td>289</td>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>0.9</td>
<td>0.336439</td>
</tr>
<tr>
<td>290</td>
<td>0.01</td>
<td>0.005</td>
<td>100</td>
<td>1</td>
<td>0.349897</td>
</tr>
<tr>
<td>291</td>
<td>0.01</td>
<td>0.005</td>
<td>200</td>
<td>0</td>
<td>0.196608</td>
</tr>
<tr>
<td>292</td>
<td>0.01</td>
<td>0.005</td>
<td>200</td>
<td>0.1</td>
<td>0.219152</td>
</tr>
</tbody>
</table>

306
<table>
<thead>
<tr>
<th>DECAY</th>
<th>POPGROWTH</th>
<th>ABSENCE</th>
<th>ABSINTENSITY</th>
<th>CURVETEST</th>
<th>CLUSTERTEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>293</td>
<td>0.01</td>
<td>0.005</td>
<td>200</td>
<td>0.5</td>
<td>0.149985</td>
</tr>
<tr>
<td>294</td>
<td>0.01</td>
<td>0.005</td>
<td>200</td>
<td>0.9</td>
<td>0.077135</td>
</tr>
<tr>
<td>295</td>
<td>0.01</td>
<td>0.005</td>
<td>200</td>
<td>1</td>
<td>0.043484</td>
</tr>
<tr>
<td>296</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>0</td>
<td>0.184988</td>
</tr>
<tr>
<td>297</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>0.1</td>
<td>0.199661</td>
</tr>
<tr>
<td>298</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>0.5</td>
<td>0.184981</td>
</tr>
<tr>
<td>299</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>0.9</td>
<td>0.188559</td>
</tr>
<tr>
<td>300</td>
<td>0.01</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>0.177462</td>
</tr>
<tr>
<td>301</td>
<td>0.01</td>
<td>0.01</td>
<td>10</td>
<td>0</td>
<td>0.006189</td>
</tr>
<tr>
<td>302</td>
<td>0.01</td>
<td>0.01</td>
<td>10</td>
<td>0.1</td>
<td>0.007136</td>
</tr>
<tr>
<td>303</td>
<td>0.01</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
<td>0.00699</td>
</tr>
<tr>
<td>304</td>
<td>0.01</td>
<td>0.01</td>
<td>10</td>
<td>0.9</td>
<td>0.008492</td>
</tr>
<tr>
<td>305</td>
<td>0.01</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>0.006826</td>
</tr>
<tr>
<td>306</td>
<td>0.01</td>
<td>0.01</td>
<td>50</td>
<td>0</td>
<td>0.005881</td>
</tr>
<tr>
<td>307</td>
<td>0.01</td>
<td>0.01</td>
<td>50</td>
<td>0.1</td>
<td>0.005374</td>
</tr>
<tr>
<td>308</td>
<td>0.01</td>
<td>0.01</td>
<td>50</td>
<td>0.5</td>
<td>0.013226</td>
</tr>
<tr>
<td>309</td>
<td>0.01</td>
<td>0.01</td>
<td>50</td>
<td>0.9</td>
<td>0.010032</td>
</tr>
<tr>
<td>310</td>
<td>0.01</td>
<td>0.01</td>
<td>50</td>
<td>1</td>
<td>0.019348</td>
</tr>
<tr>
<td>311</td>
<td>0.01</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>0.005213</td>
</tr>
<tr>
<td>312</td>
<td>0.01</td>
<td>0.01</td>
<td>100</td>
<td>0.1</td>
<td>0.004913</td>
</tr>
<tr>
<td>313</td>
<td>0.01</td>
<td>0.01</td>
<td>100</td>
<td>0.5</td>
<td>0.009499</td>
</tr>
<tr>
<td>314</td>
<td>0.01</td>
<td>0.01</td>
<td>100</td>
<td>0.9</td>
<td>0.025507</td>
</tr>
<tr>
<td>315</td>
<td>0.01</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>0.033285</td>
</tr>
<tr>
<td>316</td>
<td>0.01</td>
<td>0.01</td>
<td>200</td>
<td>0</td>
<td>0.007671</td>
</tr>
<tr>
<td>317</td>
<td>0.01</td>
<td>0.01</td>
<td>200</td>
<td>0.1</td>
<td>0.008034</td>
</tr>
<tr>
<td>318</td>
<td>0.01</td>
<td>0.01</td>
<td>200</td>
<td>0.5</td>
<td>0.002198</td>
</tr>
<tr>
<td>319</td>
<td>0.01</td>
<td>0.01</td>
<td>200</td>
<td>0.9</td>
<td>0.000274</td>
</tr>
<tr>
<td>320</td>
<td>0.01</td>
<td>0.01</td>
<td>200</td>
<td>1</td>
<td>0.000118</td>
</tr>
<tr>
<td>321</td>
<td>0.01</td>
<td>0.01</td>
<td>2500</td>
<td>0</td>
<td>0.005272</td>
</tr>
<tr>
<td>322</td>
<td>0.01</td>
<td>0.01</td>
<td>2500</td>
<td>0.1</td>
<td>0.004517</td>
</tr>
<tr>
<td>323</td>
<td>0.01</td>
<td>0.01</td>
<td>2500</td>
<td>0.5</td>
<td>0.0048</td>
</tr>
<tr>
<td>324</td>
<td>0.01</td>
<td>0.01</td>
<td>2500</td>
<td>0.9</td>
<td>0.006794</td>
</tr>
<tr>
<td>325</td>
<td>0.01</td>
<td>0.01</td>
<td>2500</td>
<td>1</td>
<td>0.004786</td>
</tr>
<tr>
<td>326</td>
<td>0.01</td>
<td>0.015</td>
<td>10</td>
<td>0</td>
<td>1.41E-05</td>
</tr>
<tr>
<td>327</td>
<td>0.01</td>
<td>0.015</td>
<td>10</td>
<td>0.1</td>
<td>1.04E-05</td>
</tr>
<tr>
<td>328</td>
<td>0.01</td>
<td>0.015</td>
<td>10</td>
<td>0.5</td>
<td>1.29E-05</td>
</tr>
<tr>
<td>329</td>
<td>0.01</td>
<td>0.015</td>
<td>10</td>
<td>0.9</td>
<td>7.17E-06</td>
</tr>
<tr>
<td>330</td>
<td>0.01</td>
<td>0.015</td>
<td>10</td>
<td>1</td>
<td>1.57E-05</td>
</tr>
<tr>
<td>331</td>
<td>0.01</td>
<td>0.015</td>
<td>50</td>
<td>0</td>
<td>2.46E-05</td>
</tr>
<tr>
<td>332</td>
<td>0.01</td>
<td>0.015</td>
<td>50</td>
<td>0.1</td>
<td>1.06E-05</td>
</tr>
<tr>
<td>333</td>
<td>0.01</td>
<td>0.015</td>
<td>50</td>
<td>0.5</td>
<td>2.62E-05</td>
</tr>
<tr>
<td>334</td>
<td>0.01</td>
<td>0.015</td>
<td>50</td>
<td>0.9</td>
<td>4.98E-05</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
<td>---------</td>
<td>--------------</td>
<td>------------</td>
<td>-------------</td>
</tr>
<tr>
<td>335</td>
<td>0.01</td>
<td>0.015</td>
<td>50</td>
<td>1</td>
<td>0.000107</td>
</tr>
<tr>
<td>336</td>
<td>0.01</td>
<td>0.015</td>
<td>100</td>
<td>0</td>
<td>1.07E-05</td>
</tr>
<tr>
<td>337</td>
<td>0.01</td>
<td>0.015</td>
<td>100</td>
<td>0.1</td>
<td>1.07E-05</td>
</tr>
<tr>
<td>338</td>
<td>0.01</td>
<td>0.015</td>
<td>100</td>
<td>0.5</td>
<td>2.93E-05</td>
</tr>
<tr>
<td>339</td>
<td>0.01</td>
<td>0.015</td>
<td>100</td>
<td>0.9</td>
<td>0.000211</td>
</tr>
<tr>
<td>340</td>
<td>0.01</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>0.000278</td>
</tr>
<tr>
<td>341</td>
<td>0.01</td>
<td>0.015</td>
<td>200</td>
<td>0</td>
<td>9.93E-06</td>
</tr>
<tr>
<td>342</td>
<td>0.01</td>
<td>0.015</td>
<td>200</td>
<td>0.1</td>
<td>1.88E-05</td>
</tr>
<tr>
<td>343</td>
<td>0.01</td>
<td>0.015</td>
<td>200</td>
<td>0.5</td>
<td>4.73E-07</td>
</tr>
<tr>
<td>344</td>
<td>0.01</td>
<td>0.015</td>
<td>200</td>
<td>0.9</td>
<td>8.38E-07</td>
</tr>
<tr>
<td>345</td>
<td>0.01</td>
<td>0.015</td>
<td>200</td>
<td>1</td>
<td>5.20E-08</td>
</tr>
<tr>
<td>346</td>
<td>0.01</td>
<td>0.015</td>
<td>2500</td>
<td>0</td>
<td>1.66E-05</td>
</tr>
<tr>
<td>347</td>
<td>0.01</td>
<td>0.015</td>
<td>2500</td>
<td>0.1</td>
<td>1.23E-05</td>
</tr>
<tr>
<td>348</td>
<td>0.01</td>
<td>0.015</td>
<td>2500</td>
<td>0.5</td>
<td>1.41E-05</td>
</tr>
<tr>
<td>349</td>
<td>0.01</td>
<td>0.015</td>
<td>2500</td>
<td>0.9</td>
<td>1.10E-05</td>
</tr>
<tr>
<td>350</td>
<td>0.01</td>
<td>0.015</td>
<td>2500</td>
<td>1</td>
<td>2.42E-05</td>
</tr>
<tr>
<td>351</td>
<td>0.01</td>
<td>0.02</td>
<td>10</td>
<td>0</td>
<td>7.66E-09</td>
</tr>
<tr>
<td>352</td>
<td>0.01</td>
<td>0.02</td>
<td>10</td>
<td>0.1</td>
<td>2.81E-09</td>
</tr>
<tr>
<td>353</td>
<td>0.01</td>
<td>0.02</td>
<td>10</td>
<td>0.5</td>
<td>2.22E-09</td>
</tr>
<tr>
<td>354</td>
<td>0.01</td>
<td>0.02</td>
<td>10</td>
<td>0.9</td>
<td>6.31E-09</td>
</tr>
<tr>
<td>355</td>
<td>0.01</td>
<td>0.02</td>
<td>10</td>
<td>1</td>
<td>4.44E-09</td>
</tr>
<tr>
<td>356</td>
<td>0.01</td>
<td>0.02</td>
<td>50</td>
<td>0</td>
<td>4.44E-09</td>
</tr>
<tr>
<td>357</td>
<td>0.01</td>
<td>0.02</td>
<td>50</td>
<td>0.1</td>
<td>3.75E-09</td>
</tr>
<tr>
<td>358</td>
<td>0.01</td>
<td>0.02</td>
<td>50</td>
<td>0.5</td>
<td>6.60E-09</td>
</tr>
<tr>
<td>359</td>
<td>0.01</td>
<td>0.02</td>
<td>50</td>
<td>0.9</td>
<td>2.98E-08</td>
</tr>
<tr>
<td>360</td>
<td>0.01</td>
<td>0.02</td>
<td>50</td>
<td>1</td>
<td>1.94E-08</td>
</tr>
<tr>
<td>361</td>
<td>0.01</td>
<td>0.02</td>
<td>100</td>
<td>0</td>
<td>2.40E-09</td>
</tr>
<tr>
<td>362</td>
<td>0.01</td>
<td>0.02</td>
<td>100</td>
<td>0.1</td>
<td>1.48E-08</td>
</tr>
<tr>
<td>363</td>
<td>0.01</td>
<td>0.02</td>
<td>100</td>
<td>0.5</td>
<td>3.73E-08</td>
</tr>
<tr>
<td>364</td>
<td>0.01</td>
<td>0.02</td>
<td>100</td>
<td>0.9</td>
<td>1.34E-07</td>
</tr>
<tr>
<td>365</td>
<td>0.01</td>
<td>0.02</td>
<td>100</td>
<td>1</td>
<td>1.49E-07</td>
</tr>
<tr>
<td>366</td>
<td>0.01</td>
<td>0.02</td>
<td>200</td>
<td>0</td>
<td>1.00E-08</td>
</tr>
<tr>
<td>367</td>
<td>0.01</td>
<td>0.02</td>
<td>200</td>
<td>0.1</td>
<td>7.78E-09</td>
</tr>
<tr>
<td>368</td>
<td>0.01</td>
<td>0.02</td>
<td>200</td>
<td>0.5</td>
<td>1.18E-11</td>
</tr>
<tr>
<td>369</td>
<td>0.01</td>
<td>0.02</td>
<td>200</td>
<td>0.9</td>
<td>8.93E-12</td>
</tr>
<tr>
<td>370</td>
<td>0.01</td>
<td>0.02</td>
<td>200</td>
<td>1</td>
<td>1.09E-13</td>
</tr>
<tr>
<td>371</td>
<td>0.01</td>
<td>0.02</td>
<td>2500</td>
<td>0</td>
<td>6.13E-09</td>
</tr>
<tr>
<td>372</td>
<td>0.01</td>
<td>0.02</td>
<td>2500</td>
<td>0.1</td>
<td>3.85E-09</td>
</tr>
<tr>
<td>373</td>
<td>0.01</td>
<td>0.02</td>
<td>2500</td>
<td>0.5</td>
<td>9.58E-10</td>
</tr>
<tr>
<td>374</td>
<td>0.01</td>
<td>0.02</td>
<td>2500</td>
<td>0.9</td>
<td>8.23E-09</td>
</tr>
<tr>
<td>375</td>
<td>0.01</td>
<td>0.02</td>
<td>2500</td>
<td>1</td>
<td>7.38E-09</td>
</tr>
<tr>
<td>376</td>
<td>0.015</td>
<td></td>
<td>0</td>
<td>10</td>
<td>0.021718</td>
</tr>
</tbody>
</table>

308
<table>
<thead>
<tr>
<th>DECAY</th>
<th>POPGROWTH</th>
<th>ABSENCE</th>
<th>ABSINTENSITY</th>
<th>CURVETEST</th>
<th>CLUSTERTEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>377</td>
<td>0.015</td>
<td>0</td>
<td>10</td>
<td>0.1</td>
<td>0.236456</td>
</tr>
<tr>
<td>378</td>
<td>0.015</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
<td>0.213825</td>
</tr>
<tr>
<td>379</td>
<td>0.015</td>
<td>0</td>
<td>10</td>
<td>0.9</td>
<td>0.206871</td>
</tr>
<tr>
<td>380</td>
<td>0.015</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>0.239519</td>
</tr>
<tr>
<td>381</td>
<td>0.015</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>0.231255</td>
</tr>
<tr>
<td>382</td>
<td>0.015</td>
<td>0</td>
<td>50</td>
<td>0.1</td>
<td>0.215656</td>
</tr>
<tr>
<td>383</td>
<td>0.015</td>
<td>0</td>
<td>50</td>
<td>0.5</td>
<td>0.238862</td>
</tr>
<tr>
<td>384</td>
<td>0.015</td>
<td>0</td>
<td>50</td>
<td>0.9</td>
<td>0.27948</td>
</tr>
<tr>
<td>385</td>
<td>0.015</td>
<td>0</td>
<td>50</td>
<td>1</td>
<td>0.325747</td>
</tr>
<tr>
<td>386</td>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0.229728</td>
</tr>
<tr>
<td>387</td>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>0.1</td>
<td>0.205386</td>
</tr>
<tr>
<td>388</td>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>0.5</td>
<td>0.283686</td>
</tr>
<tr>
<td>389</td>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>0.9</td>
<td>0.336609</td>
</tr>
<tr>
<td>390</td>
<td>0.015</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>0.382371</td>
</tr>
<tr>
<td>391</td>
<td>0.015</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0.22284</td>
</tr>
<tr>
<td>392</td>
<td>0.015</td>
<td>0</td>
<td>200</td>
<td>0.1</td>
<td>0.203396</td>
</tr>
<tr>
<td>393</td>
<td>0.015</td>
<td>0</td>
<td>200</td>
<td>0.5</td>
<td>0.145079</td>
</tr>
<tr>
<td>394</td>
<td>0.015</td>
<td>0</td>
<td>200</td>
<td>0.9</td>
<td>0.092428</td>
</tr>
<tr>
<td>395</td>
<td>0.015</td>
<td>0</td>
<td>200</td>
<td>1</td>
<td>0.053845</td>
</tr>
<tr>
<td>396</td>
<td>0.015</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>0.228298</td>
</tr>
<tr>
<td>397</td>
<td>0.015</td>
<td>0</td>
<td>2500</td>
<td>0.1</td>
<td>0.207684</td>
</tr>
<tr>
<td>398</td>
<td>0.015</td>
<td>0</td>
<td>2500</td>
<td>0.5</td>
<td>0.213466</td>
</tr>
<tr>
<td>399</td>
<td>0.015</td>
<td>0</td>
<td>2500</td>
<td>0.9</td>
<td>0.227942</td>
</tr>
<tr>
<td>400</td>
<td>0.015</td>
<td>0</td>
<td>2500</td>
<td>1</td>
<td>0.202636</td>
</tr>
<tr>
<td>401</td>
<td>0.015</td>
<td>0.005</td>
<td>10</td>
<td>0</td>
<td>0.00399</td>
</tr>
<tr>
<td>402</td>
<td>0.015</td>
<td>0.005</td>
<td>10</td>
<td>0.1</td>
<td>0.006847</td>
</tr>
<tr>
<td>403</td>
<td>0.015</td>
<td>0.005</td>
<td>10</td>
<td>0.5</td>
<td>0.005144</td>
</tr>
<tr>
<td>404</td>
<td>0.015</td>
<td>0.005</td>
<td>10</td>
<td>0.9</td>
<td>0.007299</td>
</tr>
<tr>
<td>405</td>
<td>0.015</td>
<td>0.005</td>
<td>10</td>
<td>1</td>
<td>0.008869</td>
</tr>
<tr>
<td>406</td>
<td>0.015</td>
<td>0.005</td>
<td>50</td>
<td>0</td>
<td>0.005342</td>
</tr>
<tr>
<td>407</td>
<td>0.015</td>
<td>0.005</td>
<td>50</td>
<td>0.1</td>
<td>0.00723</td>
</tr>
<tr>
<td>408</td>
<td>0.015</td>
<td>0.005</td>
<td>50</td>
<td>0.5</td>
<td>0.006577</td>
</tr>
<tr>
<td>409</td>
<td>0.015</td>
<td>0.005</td>
<td>50</td>
<td>0.9</td>
<td>0.013284</td>
</tr>
<tr>
<td>410</td>
<td>0.015</td>
<td>0.005</td>
<td>50</td>
<td>1</td>
<td>0.010211</td>
</tr>
<tr>
<td>411</td>
<td>0.015</td>
<td>0.005</td>
<td>100</td>
<td>0</td>
<td>0.005023</td>
</tr>
<tr>
<td>412</td>
<td>0.015</td>
<td>0.005</td>
<td>100</td>
<td>0.1</td>
<td>0.006521</td>
</tr>
<tr>
<td>413</td>
<td>0.015</td>
<td>0.005</td>
<td>100</td>
<td>0.5</td>
<td>0.011298</td>
</tr>
<tr>
<td>414</td>
<td>0.015</td>
<td>0.005</td>
<td>100</td>
<td>0.9</td>
<td>0.02902</td>
</tr>
<tr>
<td>415</td>
<td>0.015</td>
<td>0.005</td>
<td>100</td>
<td>1</td>
<td>0.024077</td>
</tr>
<tr>
<td>416</td>
<td>0.015</td>
<td>0.005</td>
<td>200</td>
<td>0</td>
<td>0.005354</td>
</tr>
<tr>
<td>417</td>
<td>0.015</td>
<td>0.005</td>
<td>200</td>
<td>0.1</td>
<td>0.004729</td>
</tr>
<tr>
<td>418</td>
<td>0.015</td>
<td>0.005</td>
<td>200</td>
<td>0.5</td>
<td>0.003184</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>419</td>
<td>0.015</td>
<td>0.005</td>
<td>200</td>
<td>0.9</td>
<td>0.000858</td>
</tr>
<tr>
<td>420</td>
<td>0.015</td>
<td>0.005</td>
<td>200</td>
<td>1</td>
<td>0.000212</td>
</tr>
<tr>
<td>421</td>
<td>0.015</td>
<td>0.005</td>
<td>2500</td>
<td>0</td>
<td>0.004472</td>
</tr>
<tr>
<td>422</td>
<td>0.015</td>
<td>0.005</td>
<td>2500</td>
<td>0.1</td>
<td>0.004921</td>
</tr>
<tr>
<td>423</td>
<td>0.015</td>
<td>0.005</td>
<td>2500</td>
<td>0.5</td>
<td>0.005347</td>
</tr>
<tr>
<td>424</td>
<td>0.015</td>
<td>0.005</td>
<td>2500</td>
<td>0.9</td>
<td>0.007442</td>
</tr>
<tr>
<td>425</td>
<td>0.015</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>0.005399</td>
</tr>
<tr>
<td>426</td>
<td>0.015</td>
<td>0.01</td>
<td>10</td>
<td>0</td>
<td>8.59E-06</td>
</tr>
<tr>
<td>427</td>
<td>0.015</td>
<td>0.01</td>
<td>10</td>
<td>0.1</td>
<td>1.14E-05</td>
</tr>
<tr>
<td>428</td>
<td>0.015</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
<td>1.03E-05</td>
</tr>
<tr>
<td>429</td>
<td>0.015</td>
<td>0.01</td>
<td>10</td>
<td>0.9</td>
<td>3.90E-05</td>
</tr>
<tr>
<td>430</td>
<td>0.015</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>1.42E-05</td>
</tr>
<tr>
<td>431</td>
<td>0.015</td>
<td>0.01</td>
<td>50</td>
<td>0</td>
<td>1.65E-05</td>
</tr>
<tr>
<td>432</td>
<td>0.015</td>
<td>0.01</td>
<td>50</td>
<td>0.1</td>
<td>7.88E-06</td>
</tr>
<tr>
<td>433</td>
<td>0.015</td>
<td>0.01</td>
<td>50</td>
<td>0.5</td>
<td>1.89E-05</td>
</tr>
<tr>
<td>434</td>
<td>0.015</td>
<td>0.01</td>
<td>50</td>
<td>0.9</td>
<td>4.25E-05</td>
</tr>
<tr>
<td>435</td>
<td>0.015</td>
<td>0.01</td>
<td>50</td>
<td>1</td>
<td>4.99E-05</td>
</tr>
<tr>
<td>436</td>
<td>0.015</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>2.90E-05</td>
</tr>
<tr>
<td>437</td>
<td>0.015</td>
<td>0.01</td>
<td>100</td>
<td>0.1</td>
<td>2.33E-05</td>
</tr>
<tr>
<td>438</td>
<td>0.015</td>
<td>0.01</td>
<td>100</td>
<td>0.5</td>
<td>4.08E-05</td>
</tr>
<tr>
<td>439</td>
<td>0.015</td>
<td>0.01</td>
<td>100</td>
<td>0.9</td>
<td>0.000162</td>
</tr>
<tr>
<td>440</td>
<td>0.015</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>0.000173</td>
</tr>
<tr>
<td>441</td>
<td>0.015</td>
<td>0.01</td>
<td>200</td>
<td>0</td>
<td>1.33E-05</td>
</tr>
<tr>
<td>442</td>
<td>0.015</td>
<td>0.01</td>
<td>200</td>
<td>0.1</td>
<td>4.15E-05</td>
</tr>
<tr>
<td>443</td>
<td>0.015</td>
<td>0.01</td>
<td>200</td>
<td>0.5</td>
<td>3.78E-06</td>
</tr>
<tr>
<td>444</td>
<td>0.015</td>
<td>0.01</td>
<td>200</td>
<td>0.9</td>
<td>3.98E-07</td>
</tr>
<tr>
<td>445</td>
<td>0.015</td>
<td>0.01</td>
<td>200</td>
<td>1</td>
<td>8.97E-09</td>
</tr>
<tr>
<td>446</td>
<td>0.015</td>
<td>0.01</td>
<td>2500</td>
<td>0</td>
<td>1.51E-05</td>
</tr>
<tr>
<td>447</td>
<td>0.015</td>
<td>0.01</td>
<td>2500</td>
<td>0.1</td>
<td>6.53E-06</td>
</tr>
<tr>
<td>448</td>
<td>0.015</td>
<td>0.01</td>
<td>2500</td>
<td>0.5</td>
<td>7.48E-06</td>
</tr>
<tr>
<td>449</td>
<td>0.015</td>
<td>0.01</td>
<td>2500</td>
<td>0.9</td>
<td>6.82E-06</td>
</tr>
<tr>
<td>450</td>
<td>0.015</td>
<td>0.01</td>
<td>2500</td>
<td>1</td>
<td>1.47E-05</td>
</tr>
<tr>
<td>451</td>
<td>0.015</td>
<td>0.015</td>
<td>10</td>
<td>0</td>
<td>1.02E-09</td>
</tr>
<tr>
<td>452</td>
<td>0.015</td>
<td>0.015</td>
<td>10</td>
<td>0.1</td>
<td>8.85E-09</td>
</tr>
<tr>
<td>453</td>
<td>0.015</td>
<td>0.015</td>
<td>10</td>
<td>0.5</td>
<td>3.96E-09</td>
</tr>
<tr>
<td>454</td>
<td>0.015</td>
<td>0.015</td>
<td>10</td>
<td>0.9</td>
<td>9.12E-09</td>
</tr>
<tr>
<td>455</td>
<td>0.015</td>
<td>0.015</td>
<td>10</td>
<td>1</td>
<td>7.72E-10</td>
</tr>
<tr>
<td>456</td>
<td>0.015</td>
<td>0.015</td>
<td>50</td>
<td>0</td>
<td>2.12E-10</td>
</tr>
<tr>
<td>457</td>
<td>0.015</td>
<td>0.015</td>
<td>50</td>
<td>0.1</td>
<td>1.75E-08</td>
</tr>
<tr>
<td>458</td>
<td>0.015</td>
<td>0.015</td>
<td>50</td>
<td>0.5</td>
<td>1.12E-08</td>
</tr>
<tr>
<td>459</td>
<td>0.015</td>
<td>0.015</td>
<td>50</td>
<td>0.9</td>
<td>1.96E-08</td>
</tr>
<tr>
<td>460</td>
<td>0.015</td>
<td>0.015</td>
<td>50</td>
<td>1</td>
<td>2.11E-08</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>100</td>
<td>0</td>
<td>1.54E-09</td>
<td>0.131</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>100</td>
<td>0.1</td>
<td>3.32E-09</td>
<td>0.113</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>100</td>
<td>0.5</td>
<td>4.77E-09</td>
<td>0.166</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>100</td>
<td>0.9</td>
<td>1.07E-07</td>
<td>0.669</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>2.26E-07</td>
<td>0.893</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>200</td>
<td>0</td>
<td>3.57E-09</td>
<td>0.141</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>200</td>
<td>0.1</td>
<td>5.02E-09</td>
<td>0.167</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>200</td>
<td>0.5</td>
<td>2.70E-10</td>
<td>0.372</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>200</td>
<td>0.9</td>
<td>3.08E-13</td>
<td>0.738</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>200</td>
<td>1</td>
<td>3.57E-12</td>
<td>0.842</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>2500</td>
<td>0</td>
<td>8.19E-10</td>
<td>0.128</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>2500</td>
<td>0.1</td>
<td>7.11E-10</td>
<td>0.13</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>2500</td>
<td>0.5</td>
<td>7.51E-09</td>
<td>0.133</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>2500</td>
<td>0.9</td>
<td>3.32E-09</td>
<td>0.119</td>
</tr>
<tr>
<td>0.015</td>
<td>0.015</td>
<td>2500</td>
<td>1</td>
<td>4.03E-09</td>
<td>0.115</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>10</td>
<td>0</td>
<td>1.34E-13</td>
<td>0.283</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>10</td>
<td>0.1</td>
<td>9.69E-14</td>
<td>0.257</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>10</td>
<td>0.5</td>
<td>2.78E-13</td>
<td>0.219</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>10</td>
<td>0.9</td>
<td>1.17E-13</td>
<td>0.05</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>10</td>
<td>1</td>
<td>1.01E-12</td>
<td>0.001</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>50</td>
<td>0</td>
<td>6.55E-14</td>
<td>0.265</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>50</td>
<td>0.1</td>
<td>5.74E-13</td>
<td>0.24</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>50</td>
<td>0.5</td>
<td>4.40E-14</td>
<td>0.381</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>50</td>
<td>0.9</td>
<td>4.86E-12</td>
<td>0.811</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>50</td>
<td>1</td>
<td>1.33E-12</td>
<td>0.925</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>100</td>
<td>0</td>
<td>1.34E-13</td>
<td>0.267</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>100</td>
<td>0.1</td>
<td>6.38E-13</td>
<td>0.297</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>100</td>
<td>0.5</td>
<td>2.53E-13</td>
<td>0.269</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>100</td>
<td>0.9</td>
<td>1.28E-11</td>
<td>0.839</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>100</td>
<td>1</td>
<td>2.45E-11</td>
<td>0.973</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>200</td>
<td>0</td>
<td>8.42E-15</td>
<td>0.259</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>200</td>
<td>0.1</td>
<td>4.71E-13</td>
<td>0.235</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>200</td>
<td>0.5</td>
<td>6.04E-15</td>
<td>0.58</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>200</td>
<td>0.9</td>
<td>1.60E-17</td>
<td>0.868</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>200</td>
<td>1</td>
<td>5.63E-19</td>
<td>0.928</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>2500</td>
<td>0</td>
<td>1.51E-14</td>
<td>0.288</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>2500</td>
<td>0.1</td>
<td>9.60E-16</td>
<td>0.251</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>2500</td>
<td>0.5</td>
<td>7.51E-15</td>
<td>0.277</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>2500</td>
<td>0.9</td>
<td>2.07E-13</td>
<td>0.274</td>
</tr>
<tr>
<td>0.015</td>
<td>0.02</td>
<td>2500</td>
<td>1</td>
<td>1.50E-13</td>
<td>0.253</td>
</tr>
<tr>
<td>0.02</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>0.007338</td>
<td>0.012</td>
</tr>
<tr>
<td>0.02</td>
<td>0</td>
<td>10</td>
<td>0.1</td>
<td>0.007837</td>
<td>0.009</td>
</tr>
</tbody>
</table>

311
<table>
<thead>
<tr>
<th>DECAY</th>
<th>POPGROWTH</th>
<th>ABSENCE</th>
<th>ABSINTENSITY</th>
<th>CURVETEST</th>
<th>CLUSTERTEST</th>
</tr>
</thead>
<tbody>
<tr>
<td>503</td>
<td>0.02</td>
<td>0</td>
<td>10</td>
<td>0.5</td>
<td>0.005651</td>
</tr>
<tr>
<td>504</td>
<td>0.02</td>
<td>0</td>
<td>10</td>
<td>0.9</td>
<td>0.007301</td>
</tr>
<tr>
<td>505</td>
<td>0.02</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>0.006874</td>
</tr>
<tr>
<td>506</td>
<td>0.02</td>
<td>0</td>
<td>50</td>
<td>0</td>
<td>0.006483</td>
</tr>
<tr>
<td>507</td>
<td>0.02</td>
<td>0</td>
<td>50</td>
<td>0.1</td>
<td>0.005073</td>
</tr>
<tr>
<td>508</td>
<td>0.02</td>
<td>0</td>
<td>50</td>
<td>0.5</td>
<td>0.007129</td>
</tr>
<tr>
<td>509</td>
<td>0.02</td>
<td>0</td>
<td>50</td>
<td>0.9</td>
<td>0.008662</td>
</tr>
<tr>
<td>510</td>
<td>0.02</td>
<td>0</td>
<td>50</td>
<td>1</td>
<td>0.015202</td>
</tr>
<tr>
<td>511</td>
<td>0.02</td>
<td>0</td>
<td>100</td>
<td>0</td>
<td>0.005121</td>
</tr>
<tr>
<td>512</td>
<td>0.02</td>
<td>0</td>
<td>100</td>
<td>0.1</td>
<td>0.004573</td>
</tr>
<tr>
<td>513</td>
<td>0.02</td>
<td>0</td>
<td>100</td>
<td>0.5</td>
<td>0.01311</td>
</tr>
<tr>
<td>514</td>
<td>0.02</td>
<td>0</td>
<td>100</td>
<td>0.9</td>
<td>0.02202</td>
</tr>
<tr>
<td>515</td>
<td>0.02</td>
<td>0</td>
<td>100</td>
<td>1</td>
<td>0.040981</td>
</tr>
<tr>
<td>516</td>
<td>0.02</td>
<td>0</td>
<td>200</td>
<td>0</td>
<td>0.008616</td>
</tr>
<tr>
<td>517</td>
<td>0.02</td>
<td>0</td>
<td>200</td>
<td>0.1</td>
<td>0.007593</td>
</tr>
<tr>
<td>518</td>
<td>0.02</td>
<td>0</td>
<td>200</td>
<td>0.5</td>
<td>0.002925</td>
</tr>
<tr>
<td>519</td>
<td>0.02</td>
<td>0</td>
<td>200</td>
<td>0.9</td>
<td>0.000461</td>
</tr>
<tr>
<td>520</td>
<td>0.02</td>
<td>0</td>
<td>200</td>
<td>1</td>
<td>0.000285</td>
</tr>
<tr>
<td>521</td>
<td>0.02</td>
<td>0</td>
<td>2500</td>
<td>0</td>
<td>0.006698</td>
</tr>
<tr>
<td>522</td>
<td>0.02</td>
<td>0</td>
<td>2500</td>
<td>0.1</td>
<td>0.008161</td>
</tr>
<tr>
<td>523</td>
<td>0.02</td>
<td>0</td>
<td>2500</td>
<td>0.5</td>
<td>0.007839</td>
</tr>
<tr>
<td>524</td>
<td>0.02</td>
<td>0</td>
<td>2500</td>
<td>0.9</td>
<td>0.00603</td>
</tr>
<tr>
<td>525</td>
<td>0.02</td>
<td>0</td>
<td>2500</td>
<td>1</td>
<td>0.008221</td>
</tr>
<tr>
<td>526</td>
<td>0.02</td>
<td>0.005</td>
<td>10</td>
<td>0</td>
<td>3.01E-05</td>
</tr>
<tr>
<td>527</td>
<td>0.02</td>
<td>0.005</td>
<td>10</td>
<td>0.1</td>
<td>2.54E-05</td>
</tr>
<tr>
<td>528</td>
<td>0.02</td>
<td>0.005</td>
<td>10</td>
<td>0.5</td>
<td>1.41E-05</td>
</tr>
<tr>
<td>529</td>
<td>0.02</td>
<td>0.005</td>
<td>10</td>
<td>0.9</td>
<td>1.72E-05</td>
</tr>
<tr>
<td>530</td>
<td>0.02</td>
<td>0.005</td>
<td>10</td>
<td>1</td>
<td>8.94E-06</td>
</tr>
<tr>
<td>531</td>
<td>0.02</td>
<td>0.005</td>
<td>50</td>
<td>0</td>
<td>1.62E-05</td>
</tr>
<tr>
<td>532</td>
<td>0.02</td>
<td>0.005</td>
<td>50</td>
<td>0.1</td>
<td>2.42E-05</td>
</tr>
<tr>
<td>533</td>
<td>0.02</td>
<td>0.005</td>
<td>50</td>
<td>0.5</td>
<td>8.00E-06</td>
</tr>
<tr>
<td>534</td>
<td>0.02</td>
<td>0.005</td>
<td>50</td>
<td>0.9</td>
<td>4.61E-05</td>
</tr>
<tr>
<td>535</td>
<td>0.02</td>
<td>0.005</td>
<td>50</td>
<td>1</td>
<td>0.00105</td>
</tr>
<tr>
<td>536</td>
<td>0.02</td>
<td>0.005</td>
<td>100</td>
<td>0</td>
<td>8.42E-06</td>
</tr>
<tr>
<td>537</td>
<td>0.02</td>
<td>0.005</td>
<td>100</td>
<td>0.1</td>
<td>4.02E-05</td>
</tr>
<tr>
<td>538</td>
<td>0.02</td>
<td>0.005</td>
<td>100</td>
<td>0.5</td>
<td>3.33E-05</td>
</tr>
<tr>
<td>539</td>
<td>0.02</td>
<td>0.005</td>
<td>100</td>
<td>0.9</td>
<td>0.00011</td>
</tr>
<tr>
<td>540</td>
<td>0.02</td>
<td>0.005</td>
<td>100</td>
<td>1</td>
<td>0.000438</td>
</tr>
<tr>
<td>541</td>
<td>0.02</td>
<td>0.005</td>
<td>200</td>
<td>0</td>
<td>1.84E-05</td>
</tr>
<tr>
<td>542</td>
<td>0.02</td>
<td>0.005</td>
<td>200</td>
<td>0.1</td>
<td>1.42E-05</td>
</tr>
<tr>
<td>543</td>
<td>0.02</td>
<td>0.005</td>
<td>200</td>
<td>0.5</td>
<td>1.99E-06</td>
</tr>
<tr>
<td>544</td>
<td>0.02</td>
<td>0.005</td>
<td>200</td>
<td>0.9</td>
<td>1.53E-07</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>200</td>
<td>1</td>
<td>1.19E-07</td>
<td>0.652</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>2500</td>
<td>0</td>
<td>1.17E-05</td>
<td>0.049</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>2500</td>
<td>0.1</td>
<td>9.68E-06</td>
<td>0.061</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>2500</td>
<td>0.5</td>
<td>1.31E-05</td>
<td>0.059</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>2500</td>
<td>0.9</td>
<td>1.21E-05</td>
<td>0.047</td>
</tr>
<tr>
<td>0.02</td>
<td>0.005</td>
<td>2500</td>
<td>1</td>
<td>7.04E-06</td>
<td>0.064</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>10</td>
<td>0</td>
<td>3.52E-10</td>
<td>0.114</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>10</td>
<td>0.1</td>
<td>4.02E-09</td>
<td>0.156</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>10</td>
<td>0.5</td>
<td>1.64E-09</td>
<td>0.104</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>10</td>
<td>0.9</td>
<td>1.54E-08</td>
<td>0.021</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>1.34E-08</td>
<td>0.001</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
<td>0</td>
<td>1.15E-09</td>
<td>0.125</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
<td>0.1</td>
<td>5.08E-09</td>
<td>0.15</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
<td>0.5</td>
<td>8.79E-09</td>
<td>0.226</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
<td>0.9</td>
<td>2.94E-08</td>
<td>0.623</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>50</td>
<td>1</td>
<td>7.18E-08</td>
<td>0.815</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>1.52E-09</td>
<td>0.155</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>100</td>
<td>0.1</td>
<td>2.38E-09</td>
<td>0.119</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>100</td>
<td>0.5</td>
<td>1.20E-08</td>
<td>0.158</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>100</td>
<td>0.9</td>
<td>4.49E-07</td>
<td>0.677</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>100</td>
<td>1</td>
<td>2.61E-07</td>
<td>0.881</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>200</td>
<td>0</td>
<td>1.49E-09</td>
<td>0.13</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>200</td>
<td>0.1</td>
<td>3.05E-09</td>
<td>0.12</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>200</td>
<td>0.5</td>
<td>1.27E-10</td>
<td>0.405</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>200</td>
<td>0.9</td>
<td>4.97E-12</td>
<td>0.732</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>200</td>
<td>1</td>
<td>2.15E-13</td>
<td>0.856</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>2500</td>
<td>0</td>
<td>1.27E-09</td>
<td>0.138</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>2500</td>
<td>0.1</td>
<td>4.80E-09</td>
<td>0.14</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>2500</td>
<td>0.5</td>
<td>3.00E-09</td>
<td>0.146</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>2500</td>
<td>0.9</td>
<td>3.40E-09</td>
<td>0.122</td>
</tr>
<tr>
<td>0.02</td>
<td>0.01</td>
<td>2500</td>
<td>1</td>
<td>4.95E-09</td>
<td>0.137</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
<td>0</td>
<td>2.89E-13</td>
<td>0.272</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
<td>0.1</td>
<td>6.69E-13</td>
<td>0.285</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
<td>0.5</td>
<td>1.57E-14</td>
<td>0.208</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
<td>0.9</td>
<td>1.09E-14</td>
<td>0.037</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>10</td>
<td>1</td>
<td>2.39E-13</td>
<td>0.0</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>50</td>
<td>0</td>
<td>7.36E-15</td>
<td>0.256</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>50</td>
<td>0.1</td>
<td>2.71E-14</td>
<td>0.283</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>50</td>
<td>0.5</td>
<td>7.35E-13</td>
<td>0.348</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>50</td>
<td>0.9</td>
<td>9.52E-13</td>
<td>0.817</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>50</td>
<td>1</td>
<td>7.61E-13</td>
<td>0.93</td>
</tr>
<tr>
<td>0.02</td>
<td>0.015</td>
<td>100</td>
<td>0</td>
<td>3.86E-15</td>
<td>0.269</td>
</tr>
<tr>
<td>DECAY</td>
<td>POPGROWTH</td>
<td>ABSENCE</td>
<td>ABSINTENSITY</td>
<td>CURVETEST</td>
<td>CLUSTERTEST</td>
</tr>
<tr>
<td>-------</td>
<td>-----------</td>
<td>---------</td>
<td>--------------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>587</td>
<td>0.02</td>
<td>0.015</td>
<td>100</td>
<td>0.1</td>
<td>1.73E-14</td>
</tr>
<tr>
<td>588</td>
<td>0.02</td>
<td>0.015</td>
<td>100</td>
<td>0.5</td>
<td>1.01E-13</td>
</tr>
<tr>
<td>589</td>
<td>0.02</td>
<td>0.015</td>
<td>100</td>
<td>0.9</td>
<td>6.51E-12</td>
</tr>
<tr>
<td>590</td>
<td>0.02</td>
<td>0.015</td>
<td>100</td>
<td>1</td>
<td>2.73E-11</td>
</tr>
<tr>
<td>591</td>
<td>0.02</td>
<td>0.015</td>
<td>200</td>
<td>0</td>
<td>1.59E-14</td>
</tr>
<tr>
<td>592</td>
<td>0.02</td>
<td>0.015</td>
<td>200</td>
<td>0.1</td>
<td>2.66E-14</td>
</tr>
<tr>
<td>593</td>
<td>0.02</td>
<td>0.015</td>
<td>200</td>
<td>0.5</td>
<td>2.70E-16</td>
</tr>
<tr>
<td>594</td>
<td>0.02</td>
<td>0.015</td>
<td>200</td>
<td>0.9</td>
<td>7.80E-18</td>
</tr>
<tr>
<td>595</td>
<td>0.02</td>
<td>0.015</td>
<td>200</td>
<td>1</td>
<td>9.79E-21</td>
</tr>
<tr>
<td>596</td>
<td>0.02</td>
<td>0.015</td>
<td>2500</td>
<td>0</td>
<td>4.72E-14</td>
</tr>
<tr>
<td>597</td>
<td>0.02</td>
<td>0.015</td>
<td>2500</td>
<td>0.1</td>
<td>3.52E-13</td>
</tr>
<tr>
<td>598</td>
<td>0.02</td>
<td>0.015</td>
<td>2500</td>
<td>0.5</td>
<td>2.28E-14</td>
</tr>
<tr>
<td>599</td>
<td>0.02</td>
<td>0.015</td>
<td>2500</td>
<td>0.9</td>
<td>4.20E-15</td>
</tr>
<tr>
<td>600</td>
<td>0.02</td>
<td>0.015</td>
<td>2500</td>
<td>1</td>
<td>2.51E-14</td>
</tr>
<tr>
<td>601</td>
<td>0.02</td>
<td>0.02</td>
<td>10</td>
<td>0</td>
<td>1.14E-20</td>
</tr>
<tr>
<td>602</td>
<td>0.02</td>
<td>0.02</td>
<td>10</td>
<td>0.1</td>
<td>5.10E-19</td>
</tr>
<tr>
<td>603</td>
<td>0.02</td>
<td>0.02</td>
<td>10</td>
<td>0.5</td>
<td>1.38E-20</td>
</tr>
<tr>
<td>604</td>
<td>0.02</td>
<td>0.02</td>
<td>10</td>
<td>0.9</td>
<td>8.46E-20</td>
</tr>
<tr>
<td>605</td>
<td>0.02</td>
<td>0.02</td>
<td>10</td>
<td>1</td>
<td>7.41E-20</td>
</tr>
<tr>
<td>606</td>
<td>0.02</td>
<td>0.02</td>
<td>50</td>
<td>0</td>
<td>1.23E-20</td>
</tr>
<tr>
<td>607</td>
<td>0.02</td>
<td>0.02</td>
<td>50</td>
<td>0.1</td>
<td>5.45E-20</td>
</tr>
<tr>
<td>608</td>
<td>0.02</td>
<td>0.02</td>
<td>50</td>
<td>0.5</td>
<td>3.33E-19</td>
</tr>
<tr>
<td>609</td>
<td>0.02</td>
<td>0.02</td>
<td>50</td>
<td>0.9</td>
<td>8.58E-19</td>
</tr>
<tr>
<td>610</td>
<td>0.02</td>
<td>0.02</td>
<td>50</td>
<td>1</td>
<td>4.88E-19</td>
</tr>
<tr>
<td>611</td>
<td>0.02</td>
<td>0.02</td>
<td>100</td>
<td>0</td>
<td>1.62E-19</td>
</tr>
<tr>
<td>612</td>
<td>0.02</td>
<td>0.02</td>
<td>100</td>
<td>0.1</td>
<td>5.19E-19</td>
</tr>
<tr>
<td>613</td>
<td>0.02</td>
<td>0.02</td>
<td>100</td>
<td>0.5</td>
<td>3.97E-19</td>
</tr>
<tr>
<td>614</td>
<td>0.02</td>
<td>0.02</td>
<td>100</td>
<td>0.9</td>
<td>7.32E-17</td>
</tr>
<tr>
<td>615</td>
<td>0.02</td>
<td>0.02</td>
<td>100</td>
<td>1</td>
<td>4.08E-17</td>
</tr>
<tr>
<td>616</td>
<td>0.02</td>
<td>0.02</td>
<td>200</td>
<td>0</td>
<td>1.65E-20</td>
</tr>
<tr>
<td>617</td>
<td>0.02</td>
<td>0.02</td>
<td>200</td>
<td>0.1</td>
<td>5.42E-20</td>
</tr>
<tr>
<td>618</td>
<td>0.02</td>
<td>0.02</td>
<td>200</td>
<td>0.5</td>
<td>4.00E-22</td>
</tr>
<tr>
<td>619</td>
<td>0.02</td>
<td>0.02</td>
<td>200</td>
<td>0.9</td>
<td>8.28E-26</td>
</tr>
<tr>
<td>620</td>
<td>0.02</td>
<td>0.02</td>
<td>200</td>
<td>1</td>
<td>7.39E-25</td>
</tr>
<tr>
<td>621</td>
<td>0.02</td>
<td>0.02</td>
<td>2500</td>
<td>0</td>
<td>2.00E-18</td>
</tr>
<tr>
<td>622</td>
<td>0.02</td>
<td>0.02</td>
<td>2500</td>
<td>0.1</td>
<td>8.64E-21</td>
</tr>
<tr>
<td>623</td>
<td>0.02</td>
<td>0.02</td>
<td>2500</td>
<td>0.5</td>
<td>3.70E-20</td>
</tr>
<tr>
<td>624</td>
<td>0.02</td>
<td>0.02</td>
<td>2500</td>
<td>0.9</td>
<td>2.89E-19</td>
</tr>
<tr>
<td>625</td>
<td>0.02</td>
<td>0.02</td>
<td>2500</td>
<td>1</td>
<td>1.07E-19</td>
</tr>
</tbody>
</table>