Research paper

The Holocene
2016, Vol. 26(3) 450–463

DOI: 10.1177/0959683615609754
hol.sagepub.com
SAGE

Modelling the palimpsest: An exploratory agent-based model of surface archaeological deposit formation in a fluvial arid Australian landscape

Benjamin Davies,[1] Simon J Holdaway[1,2] and Patricia C Fanning[3]

Abstract

Archaeologists make inferences about past human behaviour based on patterned material residues in various depositional contexts, including existing landsurfaces. These deposits are generated by processes that may obscure patterns at some observational scales while highlighting others, and interpretive differences can arise from a lack of explicit models of deposit formation. Here, an exploratory agent-based model based on the concept of the palimpsest is used to examine the effects of episodic sediment transport on the visibility and preservation of surface archaeological deposits in a fluvial context. Outcomes from the model indicate that the compound influences of preservation and visibility are capable of transforming a static radiocarbon record into one of increasing intensity towards the present, while simultaneously displaying periodic chronological gaps – features that have been used in our Australian study area to argue for demographic change driven by social or environmental factors. To differentiate between interpretations, expectations derived from the model are assessed against a second proxy from the same study area: Optically Stimulated Luminescence dates from hearth stones in surface contexts. Results indicate that patterns in the chronometric proxies from the study area are more consistent with episodic geomorphic change than explanations invoking changes in the local organization of human activity.

Keywords

agent-based modelling, formation, geomorphology, landscape archaeology, late Holocene, New South Wales, palimpsest, simulation

Received 20 May 2015; revised manuscript accepted 10 August 2015

Introduction

Archaeology uses enduring material remains that accumulate on or near the surface of the earth as proxies for past human behaviour. The condition of that material at the time of recording is largely determined by the same forces (climatic, geomorphological, etc.) that operate on the predominantly sedimentary landforms within which the material rests (Stein, 1987). Whatever relationships that exist among the material items have been transformed in the past and continue to be transformed in the present by processes that involve erosion, transport and deposition of sediment.

While a shared intellectual heritage between archaeology and geology has ensured that the physical formation of deposits incorporating cultural materials and sediments has long been of concern (Butzer, 1971; papers in Davidson and Shackley, 1976; Foley, 1981; Hassan, 1979; Lockerbie, 1954; papers in Nash and Petraglia, 1987; Schiffer, 1972; Stein, 2001; Stern, 1994; Waters and Kuehn, 1996; Wheeler, 1954; Wilson, 2011), the formation of archaeological deposits sometimes remains poorly understood and a source of contention in interpretation (see Rathje et al., 2013: 35). In some cases, the potential for post-depositional processes to have affected a deposit is proposed rather than demonstrated, and this potential is used to dismiss the value of a particular inference or promote an alternative interpretation (e.g. Gillespie and Brook, 2006; O'Connell and Allen, 1998). These interpretive differences may be attributed in part to ambiguities in data, but also point to a lack of explicit models of formation dynamics that may lead to less subjective interpretations of patterning within the archaeological record (Cosgrove, 2012; Ward and Larcombe, 2003).

Archaeological materials are almost never recorded in such a state that the precise sequence of depositional events is entirely known (Binford, 1980; Schacht, 1984; Stern, 1994). This means that almost all archaeological deposits are, in some way, palimpsests: products of multiple depositional events or actions. But despite their ubiquity, the label 'palimpsest' is often used for deposits considered disturbed or otherwise difficult to resolve because of limited chronological resolution or clear stratigraphic association (e.g. Carr, 1987; Gillespie and Brook, 2006; Henry, 2012; Sharon et al., 2014). 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 to be of use. The term is applied regularly in this sense to surface archaeological deposits, where artefacts and features from multiple depositional events may be lagged on to a common

[1]School of Social Sciences, University of Auckland, New Zealand
[2]School of Social Science, University of Queensland, Australia
[3]Department of Environmental Sciences, Macquarie University, Australia

Corresponding author:
Benjamin Davies, School of Social Sciences, University of Auckland, PB 92019, Auckland Central, Auckland 1142, New Zealand.
Email: b.davies@auckland.ac.nz

surface through deflation or sediment hiatuses (e.g. Bisson et al., 2014; Morgan et al., 2013). Archaeological deposits in present surface contexts have been a focus for archaeologists interested in the spatial organization of past human activity (Barrientos et al., 2014; Binford, 1980; Braun et al., 2008; Clarkson, 2008; Dunnell and Dancey, 1983; Ebert, 1992; Foley, 1981; Isaac, 1981; papers in Rossignol and Wandsnider, 1992; Shea, 2010), but concerns over the effects of weathering, mixing, and post-depositional disturbance on their integrity historically limited their use beyond that of indicating the possible presence of subsurface deposits (see papers in Schofield, 1991).

The palimpsest concept has also been used as part of a theoretical framework emphasizing how the condition of the archaeological record shapes the information that can be most gainfully extracted from it. By treating all archaeological deposits as palimpsests of one form or another, some emphasize how archaeological materials came together over time in whatever their stratigraphic context, and view any perceived loss of chronological resolution as an opportunity to explore processes operating over spatiotemporal scales greater than the ethnographic event (Bailey, 1983, 2007; Banning, 2002; Lucas, 2010; Wandsnider, 1996). There have been numerous efforts to incorporate these theoretical ideas into interpretations (e.g. Holdaway and Wandsnider, 2006; Malinsky-Buller et al., 2011; Vaquero, 2008), but practical applications have been few. Lucas (2012: 105), for example, comments that the palimpsest concept has been historically problematic because, while its symptoms can often be identified, a methodology is lacking that interfaces with formation processes explicitly (see also Bailey, 2008: 26). The lack of a strong proof-of-concept inhibits comparison between interpretations and enables the perpetuation of the irresolvable palimpsest label.

In this study, we present a model of palimpsest deposit formation that acts as a step towards answering Lucas' (2012: 121) call to '… foreground the processes of inscription and/or erasure, rather than the product …'; in other words, to evaluate how the combined effects of archaeological deposition and sediment transport over time might influence patterning in surface archaeological features (p. 121). Drawing on a case study from the arid rangelands in western New South Wales (NSW), Australia, the model is implemented as an exploratory agent-based simulation to assess the effects of episodic erosion and deposition on the condition of the surface archaeological record; specifically, the temporal distribution of chronometric data obtained from heat-retainer hearths. Simulation outcomes are then used to suggest additional tests grounded in formation which can help discern between different interpretations of that record.

Palimpsests, formation and models

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 deposition of new material, leaving only the most recent deposit behind. In theory, then, the opposite of a true palimpsest would be a true archaeological stratigraphy, in which each deposited object is immediately sealed within a distinct sedimentary layer, perfectly preserving the sequence of depositional events (Lucas, 2012). By these definitions, 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 for reconstructing behaviour at the event or ethnographic scale (Bailey, 2007; Stern, 1994). 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 as encountered by an archaeologist.

Numerous natural and anthropogenic processes contribute to the formation of an archaeological deposit over time, but those which would distinguish where a deposit fits between these two extremes are primarily sedimentary in nature. Sedimentation, from the perspective of an individual deposit, can be considered to occur along a continuum between completely depositional (true stratigraphy) and completely erosional (true palimpsest), and wherever the local regime falls along that continuum will strongly influence not only the condition of a deposit (Ward and Larcombe, 2003; Waters and Kuehn, 1996), but also, in surface surveys, its visibility. Archaeologists working at the scale of individual deposits are well aware that rates of sedimentation are crucial to interpreting the temporal resolution of archaeological deposits (e.g. Hunt et al., 2015; Ward, 2004); this awareness has prompted wider application of methods like age–depth modelling for subsurface deposits (e.g. Allen and Morrison, 2013; Armit et al., 2014). However, accounting for this becomes more complicated at the landscape scale, where the relative frequencies of deposition and erosion might vary not only over time or from place to place, but *over time from place to place*. The degree of geomorphic variability in any landscape is controlled by the capacity for sediment to move or settle, which is in turn largely dictated by landsurface gradient and intensity of erosive forces (e.g. gravity, wind and water) (Kirkby and Kirkby, 1976). On steep hills where there is frequent heavy rainfall, sediment may be more likely to erode and be transported downslope; in low gradient alluvial basins where sediments frequently collect, conditions are more likely to be uniformly depositional. But most landscapes occupied by humans do not feature such unimodal geomorphology, particularly over long spans of time (Barker et al., 1997; Brouwer Burg, 2013; Gouma et al., 2011), and the position of individual places within these landscapes along the spectrum between erosional and depositional may vary differently with time. Understanding how local depositional histories come together to produce larger scale patterning is fundamental to interpreting palimpsest archaeological landscapes.

Archaeologists who have used the palimpsest concept as a theoretical construct for interpreting the archaeological record, most frequently those associated with the time perspectivist paradigm, have argued that the incomplete nature of the archaeological record is not so much a hindrance as an intrinsic quality that can be used constructively to view processes operating over different temporal scales (Bailey, 1983, 2007; papers in Holdaway and Wandsnider, 2008; Hull, 2005; Murray, 1999; Vaquero, 2008; Ward, 2004). But while the theoretical implications of a palimpsest perspective have been considered in various contexts, explicit treatments of formation dynamics in the development of archaeological palimpsests are largely lacking (Bailey, 2008; Lucas, 2012; Murray, 1999). When we say explicit, we mean committed to a formal definition that can be articulated with data and compared with other formal definitions (e.g. Ward and Larcombe, 2003). This problem is not only limited to palimpsests and time perspectivism, but is also common elsewhere in the historical sciences where explanations and conceptualizations are largely expressed in verbal rather than formal terms (Doran, 1972; Epstein, 2008; Servedio et al., 2014). Such written articulations often feature assumptions which are left implicit and are open to challenge, sometimes simply on rhetorical grounds, or may be misconstrued in translation (O'Sullivan and Perry, 2013).

One step towards making interpretations of the archaeological record more explicit is through the use of formal models. Models act as mediators between theory and reality, a heuristic space in which to evaluate assumptions and adjust expectations (e.g. Cartwright, 1999; papers in Clarke, 1972; Epstein, 2008; Morgan and Morrison, 1999). In a model-based approach, the real phenomenon or system becomes a target, and a theoretically informed description is implemented as a model system. The resemblance between outcomes from the model system and the target is then gauged, giving the modeller an opportunity to re-evaluate the model description (Godfrey-Smith, 2006; Kohler and Van der Leeuw, 2007). This differs from purely hypothetico-deductive approaches in that it is not a search for laws, but instead estimates the tendencies of different model systems to produce patterning while recursively informing on provisional interpretations (Giere, 1999). In archaeology and other historical disciplines, if a model can be established as a valid representation of the 'verbal logic' (Servedio et al., 2014), so to speak, 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.

Models in archaeology, particularly computational models, have not always been used in this way. Instead, archaeological models may attempt to reconstruct past human systems in a realistic way (see Costopoulos, 2010; Lake, 2014; Premo, 2010). Because the phenomena under study are not directly observable, this inevitably involves the use of variables that hold supposed, speculated or otherwise unknown influence on past systems as fully functioning, detailed components of a modelled system. When this is attempted using particularistic datasets as targets, or recourse to analogy without being grounded in well-established, *tested* 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; Premo, 2010). 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. As our case study below illustrates, archaeologists trying to compare interpretations might be better served by models that allow them to ask questions of the 'what *kinds* of processes might create this pattern?' type and hope to find a best answer among several possibilities, rather than models asking 'what *precisely* happened here?', expecting correct, metric answers in absolute terms (O'Sullivan and Perry, 2013).

As an alternative, Premo (2007, 2010) suggests 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). 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 patterning similar 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 (e.g. Brughmans et al., 2014; Crema, 2014; Premo, 2012; Wren et al., 2014). Because exploratory models can be built independently of particular datasets, they are often revealing about general dynamics that may help to eliminate particular model structures, narrow the parameters to those under which a model produces relevant patterning, and/or suggest additional tests that can be undertaken to discern between interpretations.

Exploratory modelling is often associated with the computational method of agent-based modelling. 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. These micro-level interactions can generate macro-level regularities over time, allowing the modeller to observe the emergence of larger patterns or entities as outcomes of smaller scale activities. Lake (2014) describes successful applications to archaeological problems emphasizing sociocultural evolution and human–environment interactions, with model outcomes that are frequently social, demographic or biophysical in nature. These applications, while in pursuit of the goal of model simplicity, may assume an unproblematic relationship between model outcomes and recorded archaeological residues (Barton and Riel-Salvatore, 2014: 335). At the same time, debates over the interpretation of observed archaeological signatures, particularly where the point of departure lies in aspects of formation, illustrate that the relationship between past human systems and the material record is anything but unproblematic. This is not an admonishment for abstract models of long-term sociocultural evolution to be grounded in specific depositional outcomes *in exemplum*, but rather a recognition that the level from which archaeological inferences are drawn (the formation of the deposit) has seen less theoretical attention when compared with the development of social and ecological theories than would seem warranted by the orientation of numerous archaeological debates. 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.

Even within the limited realm of formation models, which have prodigiously emphasized assemblage formation (e.g. Aldenderfer, 1981; Barton and Riel-Salvatore, 2014; Brantingham, 2003, 2006; Thomas, 1973), there has been little formal modelling of the coupled processes of cultural deposition and sediment movement. Examples of the form that models of deposit formation may take include the work of Kirkby and Kirkby (1976), who laid out early mathematical models for the geomorphology of mound features and artefacts in semi-arid locations, and that of Wainwright (1991, 1994), who used simulation to explore the effects of erosion on site formation and artefact displacement. In those studies, archaeological remains were considered as components within sedimentary systems, and the visibility and condition of archaeological remains was gauged after simulating rainfall events of varying intensities on different surfaces. A more recent simulation study by Clevis et al. (2006), using similar constructs and principles, demonstrated three-dimensional effects of aggradation and incision on subsurface deposits in an alluvial valley. In all of these cases, a range of outcomes were produced that were used to evaluate the logic of hypothetical formation scenarios (typically expressed as written conceptual models) rather than try to reconstruct specific depositional histories and serve as examples of the exploratory approach outlined above.

We draw on the spirit of this kind of work in this study, in which we use an agent-based model to explore how different combinations of two simplified processes, erosion and deposition, might influence an archaeological record that accumulates on the surface of the earth. Our model builds on observations from a case study from arid western NSW in Australia, where extensive sediment movement has exposed some ancient landsurfaces while masking others, and which has broader implications for the study of landscape archaeology and palimpsest deposits.

Surface archaeology in western NSW, Australia

The western NSW region consists of arid and semi-arid rangelands extending westward from the Western Slopes and Riverina areas of NSW, bounded on the north, west and south by the borders of Queensland, South Australia and Victoria (Figure 1). The land is predominantly flat (<200 m a.s.l.), with some limited areas of higher relief in the western Barrier Ranges. The primary drainage is the Darling River, which flows intermittently depending on precipitation in the headwaters far to the east. Mean annual rainfall in the region is between 150 and 350 mm, with pan evaporation typically exceeding precipitation.[1] 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 features episodically, often a result of low latitude exposure to

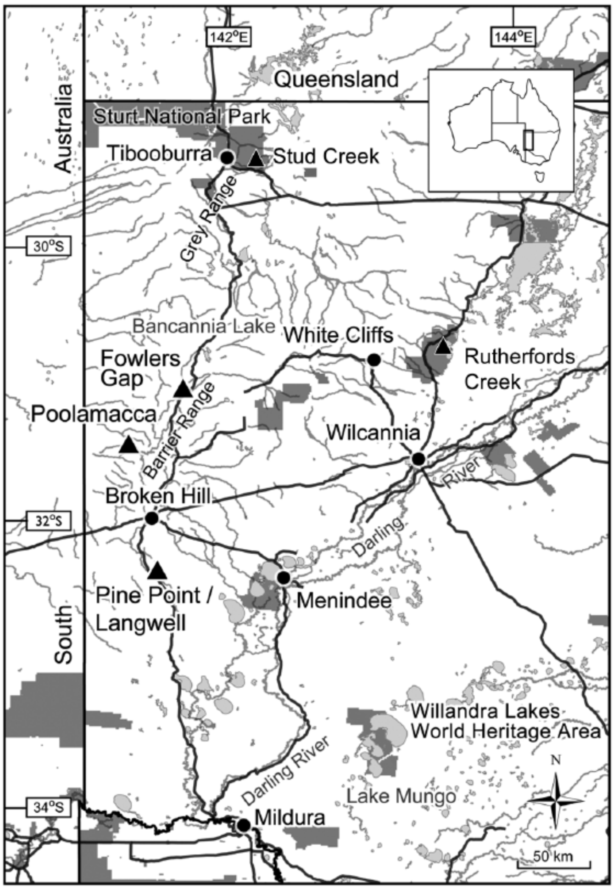

Figure 1. Map of western New South Wales. Locations of study areas are indicated by triangles.

monsoon troughs around the headwaters of the Darling and its tributaries (Bell, 1979).

The archaeology of the region, like many arid parts of Australia, is noteworthy for extensive surface exposures of archaeological materials, predominantly comprising lithic scatters and heat-retainer hearths. Stone artefacts, mostly unretouched cores and flakes of silcrete, quartz and quartzite, are present in varying densities across the surface (Douglass, 2010; Holdaway and Fanning, 2014; Holdaway et al., 2004; Witter, 1992). Heat-retainer hearths typically present as concentrations of fire-altered stone, in some cases preserving charcoal embedded within sediment beneath the hearth stones (Figure 2). It is thought that hearths were originally formed as pits lined with stone that acted as heat retainers and were used as earth ovens to cook game (Fanning and Holdaway, 2001b; Gould, 1967). As the sediments into which the pits were dug erode away, 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.

The exposure and visibility of archaeological objects in this region is heavily influenced by 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, 2001b; 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., 2009b; sensu Renwick, 1992) propose a model of 'episodic non-equilibrium', in which large-scale, intermittent erosional events relocate sediments within low relief creek valleys, with the effect of either masking or exposing archaeological materials lying on the surface. Since relatively shallow-gradient slopes in the study region prevent overland flow from reaching velocities capable of moving larger objects (>20 mm; Fanning and Holdaway, 2001a), the result is a set of lagged artefact deposits seated on 'a mosaic of differently aged surfaces many of which lie adjacent to one another' (Fanning et al., 2007: 284). 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 (Bull and Kirkby, 2002; Gould, 1980; Tooth, 2000).

Frequency distributions of radiocarbon data from western NSW study areas show curvilinear increases in hearth dates towards the present over the last 2000 years, particularly within the last five or six centuries (e.g. Figure 3). Surface sediment ages determined through the use of Optically Stimulated Luminescence (OSL) dating have been shown to correlate with the radiocarbon ages of heat-retainer hearths situated on them, such that older sediments retain hearth ages that span longer periods of time than do sediments deposited more recently, suggesting erosion may be driving this pattern in radiocarbon data (Holdaway et al., 2008). However, in this and other parts of Australia, similar patterns in the distribution of radiocarbon ages are interpreted to reflect late Holocene population growth and more intensive occupation in the region (Smith, 2013), an interpretation supported by continental-scale studies of summed radiocarbon data (Johnson and Brook, 2011; Williams et al., 2010).

In addition, gaps have been identified in the radiocarbon sequences obtained from several western NSW locations (Holdaway et al., 2005). Figure 3 shows a plot of 80 dates randomly sampled from a corpus of 93 dates obtained from the Rutherfords Creek study area falling within the last 2000 years (Holdaway et al., 2010). Adapting a method developed by Rhode et al. (2014) in which a uniform record of simulated radiocarbon ages for the time period in question is repeatedly resampled and tested for gap length distributions, the number of larger gaps (>75 years) seen in the Rutherfords Creek data is beyond what would be expected statistically from randomly sampling a uniform distribution of equal duration ($p = 0.006$), indicating that the gaps are extremely unlikely to be simply a product of sampling error (although questions of spatial autocorrelation remain to be examined; Rhode et al., 2014: 576). These gaps correlate roughly with broad-scale environmental changes that have been previously argued to have induced prolonged periods of human absence (Holdaway et al., 2010). Alternatively, it has been suggested that shifts in local vegetation may have dispersed foragers logistically over wider areas during some periods more than others, periodically decreasing the likelihood of hearth formation within creek valleys (Smith, 2013: 323). To date, it has not been suggested that the gaps might be the outcome of geomorphic processes.

In western NSW and other arid environments, event-driven erosion and sediment deposition processes have the respective capacities to erase or preserve archaeological materials deposited on the surface (Fanning, 1999; Wainwright, 1994; Ward and Larcombe, 2003). 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. Changes to visibility by burial will influence what is recorded by the archaeologist working in surface contexts (Foley and Lahr, 2015: 10). 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.

Figure 2. Heat-retainer hearths recorded at Rutherfords Creek in varying states of exposure. Following classification in Fanning et al. (2009a), top row are examples of partially exposed hearths. Bottom row are disturbed (left) and remnant (right).

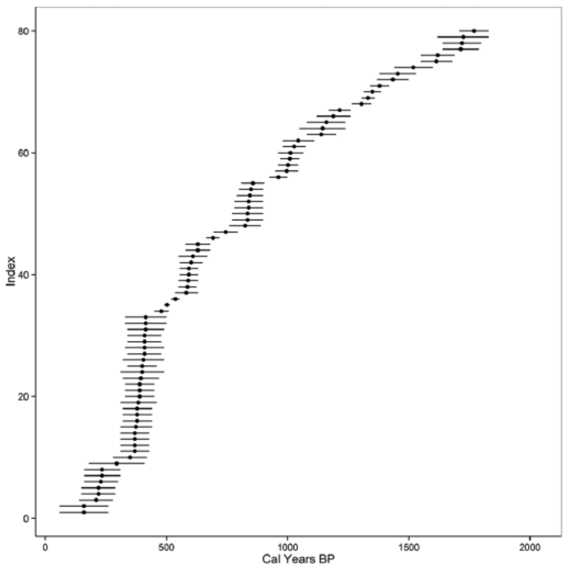

Figure 3. Sample (n=80) of calibrated radiocarbon dates obtained from surface hearths recorded at Rutherfords Creek.
Dates expressed as ordered set of means (dots) with 1 standard deviation (bars). Radiocarbon determinations processed at Waikato University, calibrated in OxCal using ShCal13 calibration curve (Hogg et al., 2013). Original data published in Holdaway et al. (2010).

An exploratory agent-based model of palimpsest formation and archaeological visibility

To explore the effects of differential erosion and deposition on a uniform record of hearth manufacture, an agent-based model was constructed using the NetLogo modelling platform (Wilensky, 1999; available online). The model, called HMODEL, is an exploratory model in the sense that Premo (2010) defines it; it is meant to be a mechanism that represents elements of the system in question but is simple enough so that the entire parameter space over which the model operates can be explored. The simulation begins with an $n \times n$ space of gridded cells. Each cell in the grid world contains an ordered list of numbers representing the ages of sedimentary layers in years before present. Computational agents within the simulation construct hearths at a constant rate over random points on the grid; these hearths contain a radiocarbon age, given in years before present. Any hearth that has a radiocarbon 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 sedimentary list) is considered visible on the surface while any that are older are hidden as part of a subsurface deposit.

At given intervals, a scheduled event will have one of two effects on cells: either erosion of surface sediments or deposition of new sediments on the surface (Figure 4). 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 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.

In this configuration of the model, the behaviour of agents is effectively neutral, producing a uniform record of activity in order to establish to what extent the patterns observed in the archaeological record are explainable in terms of directed human behaviour (for other examples of null or neutral agent-based models, see Brantingham, 2003; Lake, 2015; Premo, 2007; Rhode et al., 2014). Agents do not favour particular cells, nor do they deviate from their rate of construction. If no sedimentary events

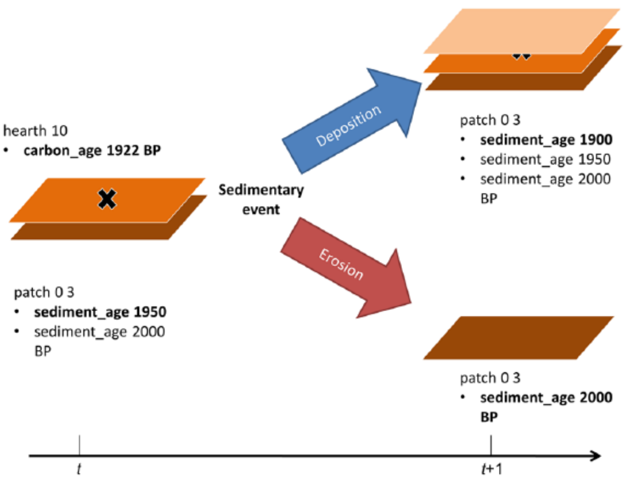

Figure 4. Diagram of typical cell-level behaviour in HMODEL at the threshold of a sedimentary event. At timestep *t* (in this case, 1900 years before present), a grid cell contains two layers of sediment deposited at 2000 and 1950 BP, respectively, and a single hearth deposited at 1922 BP. As the model moves on to *t* + 1, the cell might experience one of two processes: deposition, in which case a third layer of sediment is deposited atop the cell dated to the current timestep, obscuring the hearth; or erosion, in which case the top layer of sediment is removed along with the hearth charcoal situated in it, exposing the lower layer of sediment. Hearths obscured by deposition can become re-exposed through a subsequent erosion event.

were to occur at all, this model will produce a surface record of uniform occupation over time, with the total number of hearths equal to the number of timesteps during which hearth building occurs multiplied by the rate of construction. Only two variables are explored initially in this model: the proportion of cells experiencing erosion versus deposition during a given event and the time interval between these events.

The erosion/deposition proportion is expressed as a value between 0 and 1. 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 lower than the erosion/deposition proportion, the cell will experience deposition; otherwise, the cell will experience erosion. When the 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 per 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 the 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 per Bailey's (2007) definition). This variable is explored at increments of 0.1.

The other variable under consideration is the interval at which these events occur. It is not clear from the literature what level of fluvial intensity is required to effect geomorphic change in places like those under consideration in western NSW. 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'[2]); this pattern is corroborated by trends in local paleoclimate 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 (Fanning et al., 2007, 2009; Jansen and Brierley, 2004). Similar variation in frequency and intensity might also be accorded to droughts that bring wind-blown sediments into and out of a catchment (Holdaway et al., 2010). Therefore, to evaluate how the frequency of geomorphic events might affect the character of the surface record, in the model these were spaced at intervals of 10, 50, 100 and 200 years in order to observe differences in trends.

Because we are interested in late Holocene Australia, all simulations were run at a yearly timestep from 2000 years before present, with hearth building ceasing at 200 years before present to account for a decline in hearth building after European contact. Upon completion, dates were obtained from hearths visible on the surface. Each simulation was run 1000 times to assess variability in outcomes.

Learning from the model

Simulation results

The aim of this simulation is to establish broad trends that would be expected from a set of geomorphological processes on a behaviourally neutral archaeological record. To compare simulation outcomes, 1000 samples of 100 hearth ages were taken from each parameter configuration. These were ordered from youngest to oldest and plotted (Figure 5). In this configuration, a sample of an unaltered neutral record would fall along a diagonal line from 200 years before present at bottom left to 2000 years before present at top right. Curves falling to the left of this line are interpreted as being weighted towards the present, while curves falling to the right are interpreted as being weighted towards the past.

When sampled ages of surface hearths from all simulations are compared, generated records clearly display bias towards the present (Figure 5). As events become more frequent, the distributions become more weighted towards the present as more and more hearths are hidden or lost. 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, showing that the modelled surface archaeological record, under all configurations explored, is biased towards the present as a result of differential preservation and visibility.

Configurations that have inverse erosion/deposition ratios 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.

In Figure 5, the presence of chronological gaps is clearly visible under configurations with longer intervals between geomorphic events. These gaps in the modelled radiocarbon chronology are an outcome of the system *as modelled*: since the geomorphic events affect all grid cells simultaneously, then all hearths sitting on the surface at those times (which includes all hearths accumulated since the last event) 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. Repeating this process produces interdigitating sets of surfaces containing hearths grouped by alternating time periods, with older hearths within those groups becoming rarer through time. If radiometric data were obtained from these surfaces at any given point in time, there would

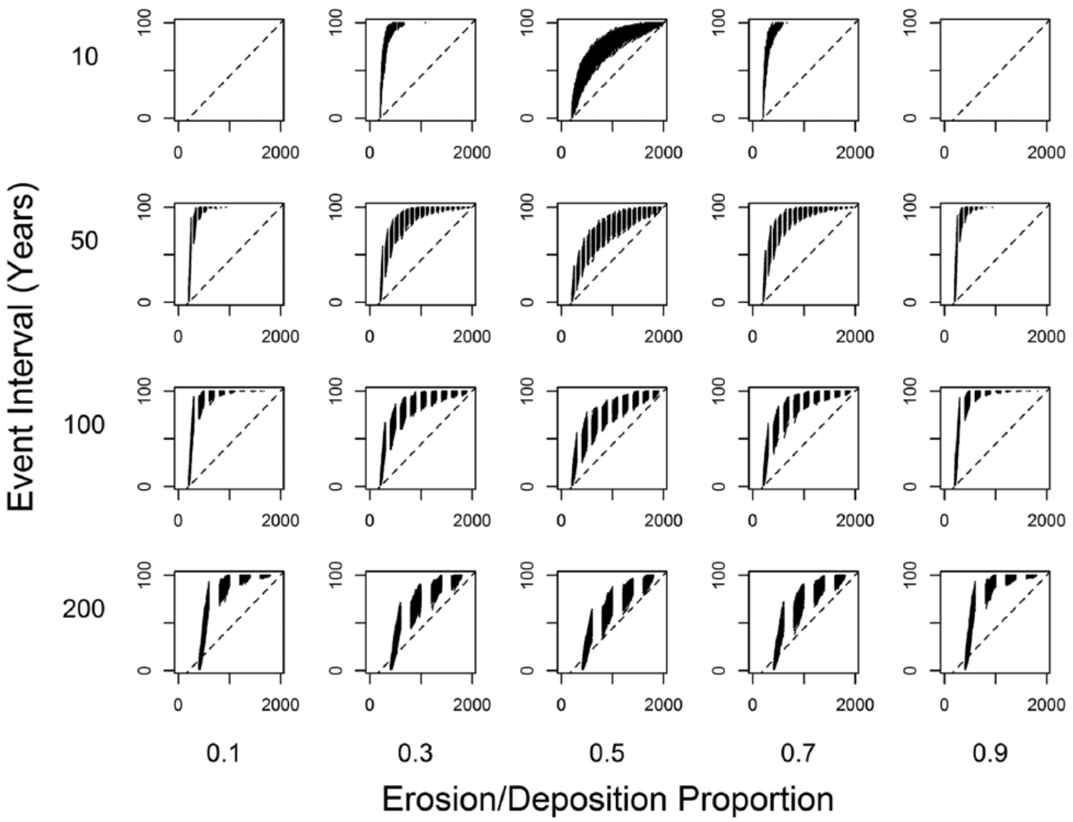

Figure 5. Output of initial HMODEL exploration. Individual graphs give yr BP on horizontal axis, hearths indexed in order by ascending age (1 being youngest, 100 being oldest) on vertical axis. Event intervals of 10 years do not produce enough hearths to generate a viable sample under highly depositional (0.1) and highly erosional (0.9) settings.

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 patches when they occur, then gaps in age frequencies would be less prominent. This can be accounted for in the simulation by relaxing the assumption that all patches are affected when events occur, which can be accomplished by adding a third variable: surface stability. 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 6, simulations were run using the same set of erosion/deposition proportion (0.5) and event interval (100 years) settings, but with different percentages of cells left stable through runs. In the original configuration ($s=0$), the plot shows an increasing density of hearths towards the present while also showing regular gaps in the record. As the proportion of stable cells increases, the surfaces upon which the hearths rest become less organized by the sedimentary process and the gaps begin to aggrade ($s=0.1$). As surface stability approaches 50% ($s=0.5$), the gaps are completely extinguished, but a record of increasing frequency towards the present remains. When stability reaches 100% ($s=1$), the record undergoes no geomorphic change and thus displays the uniform record of hearth generation. By exploring this additional parameter, we can infer that if the gaps or depressions in the curve are to be explained solely in terms of event-driven geomorphic change, a relatively large portion of the modelled landscape would need to be affected during these events.

Using the model to develop further tests

As it stands, the simulation is a simple mechanism derived from conceptual models that we have interpreted and used to evaluate the effects of periodic deposition and erosion on surface archaeological deposits. This has produced qualitative similarities to archaeological phenomena recorded from deposits in western NSW, particularly the increasing frequency of dates towards the present and episodic gaps in the chronometric record. Yet, these findings by themselves do not indicate that the patterning identified in the archaeological deposits in the western NSW study areas is solely the result of changes in preservation and visibility as is the case in the model. These outcomes do not even go so far as to adjudicate between this interpretation and other interpretations of intensified occupation, episodic human absence or changes in resource distributions. Instead, the outcomes from this exercise 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.

Because we have used a formal model (in the form of a simulation), and because we have found some similarities between outcomes from some parameter settings in the model and archaeological data from western NSW study areas, we can use the model structure to generate further expectations under those parameters, thereby 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 et al. (2005) refer to as ‘patterns for contrasting alternative theories’ in their pattern-oriented modelling framework.

The chronological gaps in modelled data are generated by sequential changes in preservation (a result of the vulnerability of charcoal to dispersal) and visibility (a result of sedimentary deposition obscuring surface deposits) operating over a substantial portion of the landscape. Such processes would not affect all proxies in the same way; for example, a proxy that was not dependent on the preservation of charcoal, such as OSL dates obtained from larger burned objects (Rhodes et al., 2010), would likely

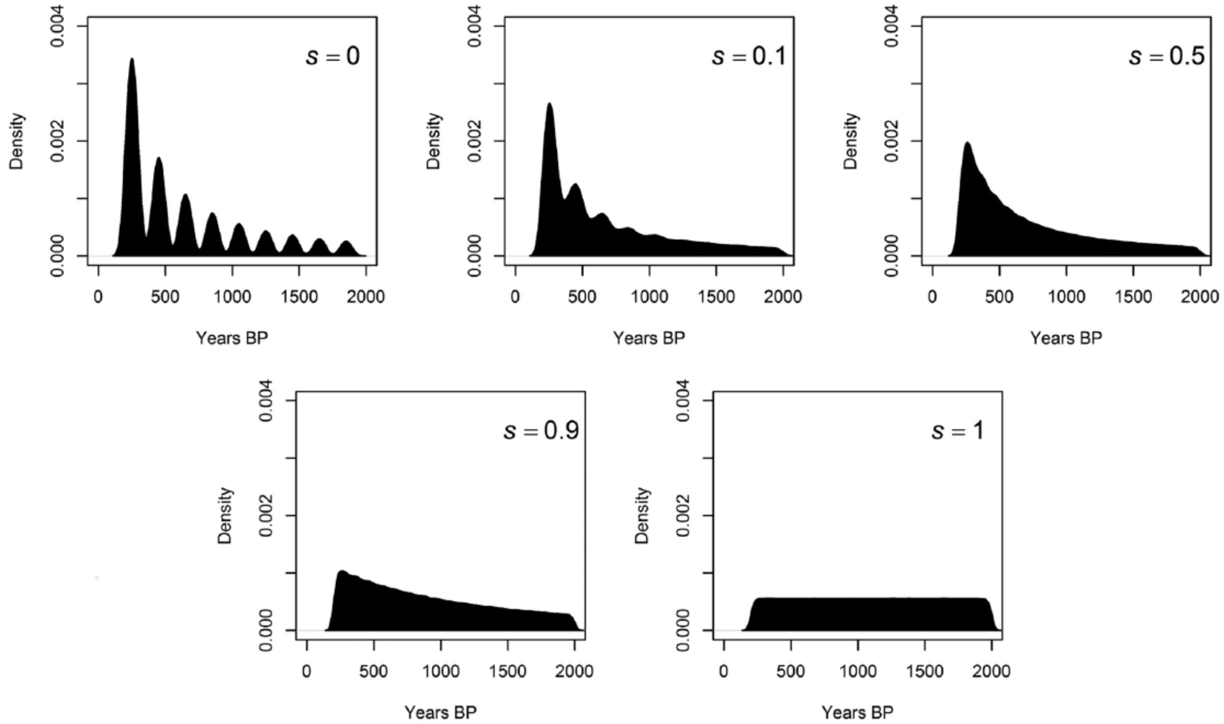

Figure 6. Influence of different surface stability (*s*) settings on the same output in HMODEL. Each plot shows kernel density of dates recorded from all simulated surface hearths with an event interval setting of 100 years and an erosion/deposition proportion setting of 0.5.

have different chronometric outcomes than those obtained from the charcoal-based assessment. Hearth stones, particularly those above a certain size threshold (Fanning and Holdaway, 2001a), are more resistant to dispersal by fluvial processes than charcoal, and thus, any gaps in the record caused by processes like those modelled should not occur with the same degree of intensity as would be seen in a charcoal record (if at all) if a process like that occurring in the model were operating. 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, thus falsifying the geomorphic interpretation developed in this study.

This effect can be demonstrated in HMODEL by keeping track of all surface hearths, differentiating between those that have had charcoal removed following an erosion event and those that have not. In these cases, radiocarbon dates may only be obtained from those still containing charcoal, while luminescence dates may be obtained from any hearth visible on the surface. Results of this exercise illustrate how the process as modelled would generate different records for comparable samples of radiocarbon- and OSL-dated hearths (Figure 7). In more depositional environments, the radiocarbon and OSL dates track well together as fewer hearths are destroyed but many are not visible. 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. 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 like that seen under the highly depositional settings, but the OSL distribution straightens out, reflecting the actual record of hearth ages produced by the agents which is now almost entirely visible. Gaps that are clear in the radiocarbon chronologies under settings with no surface stability (Figure 7, $s=0$) are effectively absent from those in the OSL record.

To evaluate whether such a pattern might occur in a real setting, OSL dates were obtained from stones found in surface hearths 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 Rutherfords 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. A randomly drawn subsample of 80 determinations from the corpus of OSL dates falling within the last 2000 years were then compared with the randomly drawn subsample of 80 dates from the corpus of radiocarbon dates from the same area dating to within the last 2000 years.

Plotting the radiocarbon and OSL ages together shows a difference in plot steepness similar to that predicted by the simulation (Figure 8). The difference between these two curves suggests that erosion is having a different impact on the charcoal from hearths compared with the hearth stones. As a consequence of erosion, the chronologies produced by the two techniques appear to differ in a way that is similar to some of the mixed-regime models illustrated in Figure 7. Furthermore, gaps that are visible in the radiocarbon sample are less pronounced, and in most cases altogether absent, in the OSL sample (Figure 8). In particular, pronounced gaps at ~800–600 and ~600–400 cal yr BP in the radiocarbon chronology are well represented in the OSL record. If the gaps were the result of a stoppage in hearth building activities (due to expanded ranges or otherwise), then there is no reason to expect continuity in the OSL chronology where gaps are present in the radiocarbon chronology. That the OSL sample from Rutherfords Creek shows such continuity means that a geomorphic interpretation of gaps in the radiocarbon chronology cannot be ruled out, and that any alternative interpretations that explain these gaps through changes in human behaviour would need to account for differences between these proxies.

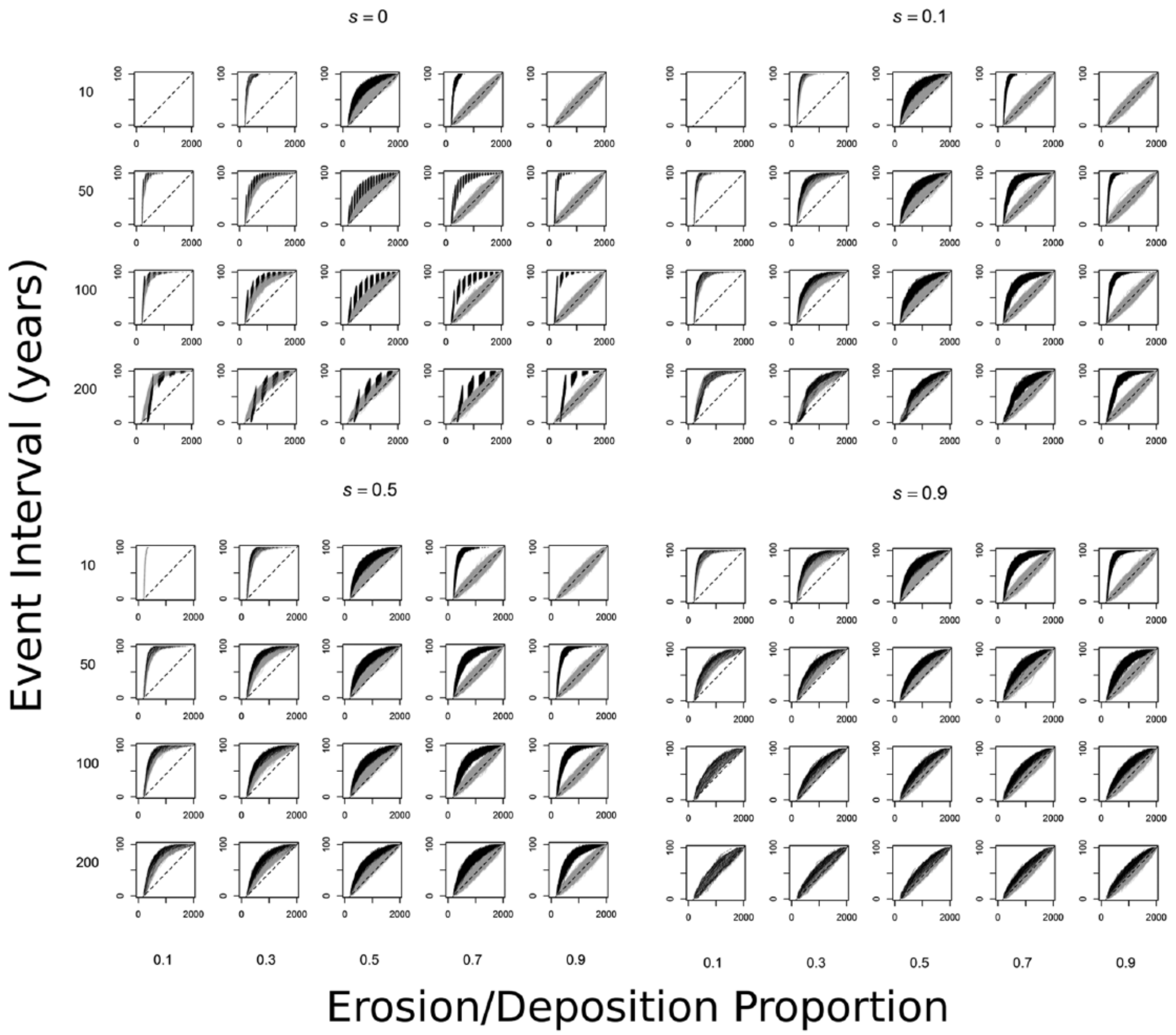

Figure 7. Output of HMODEL exploration with radiocarbon (black) and OSL dates (grey) at different levels of surface stability (s).
OSL: Optically Stimulated Luminescence. Individual graphs give yr BP on horizontal axis, hearths indexed in order by ascending age (1 being youngest, 100 being oldest) on vertical axis.

Discussion

The validity of archaeological interpretations is often questioned based on the perception that post-discard processes may have influenced the patterning within a deposit to such an extent that the patterning does not reflect the original interpretation. We contend that while interpretations themselves may be flawed, the usual methods by which interpretations are questioned and compared is even more problematic. When interpretations or invalidations are made without recourse to explicit models of the formational processes being attributed and how they come together to generate patterning within a deposit, they operate effectively as common sense inferences and do little to advance our understanding of archaeological phenomena (Dunnell, 1982). Here, we have used an explicit model of formation to evaluate a depositional record generated by an unchanging set of human behaviours occurring within a context of event-driven episodes of sediment deposition and erosion. The assumptions made by the model used here are derived directly from conceptual models in archaeological and associated literature used to explain a given phenomenon (Fanning et al., 2007; Holdaway and Wandsnider, 2008; Holdaway et al., 2010; Smith, 2013). The exploratory model described here has been constructed using as few assumptions as possible (but as many as necessary) while at the same time making them explicit by building them into a computer simulation (Costopoulos, 2009; Lake, 2015; Premo, 2010). This exercise demonstrates how exploratory agent-based models can be used effectively as mechanisms for generating insights into a hypothesized system, and how those can in turn be used to develop archaeological tests for comparing interpretations. Moreover, it shows that the types of problems to which agent-based modelling methods are suited are not limited to sociocultural or socio-ecological phenomena, but may also 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.

In striving to maintain a simple model structure and limit the parameter space being explored, decisions were made which eliminated components of the formation process that, while relevant, were not deemed necessary to represent the logic of the process. For example, HMODEL does not consider the effects of trampling on surface hearths, 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 was not meant to reconstruct the precise sequence of events and processes occurring at Rutherfords Creek, but rather to explore a simple theoretical model with the aim of establishing broad trends in archaeological patterning. With some reconfiguration, other processes like trampling could be incorporated into the model to

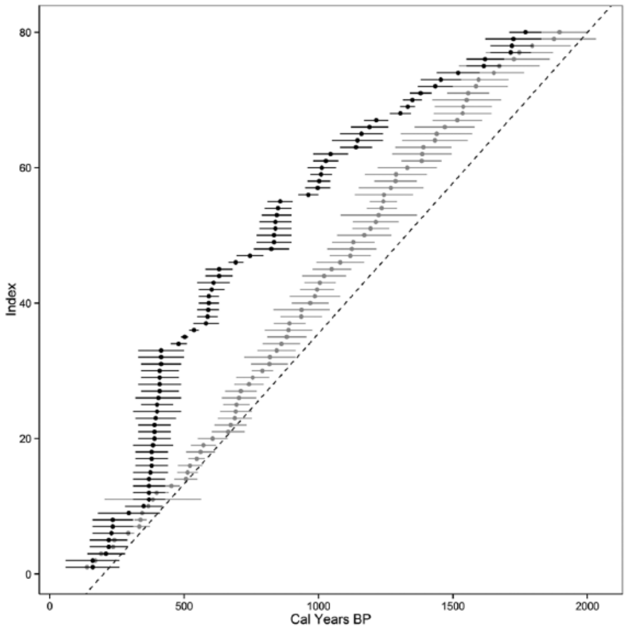

Figure 8. Samples of calibrated radiocarbon dates ($n=80$; black) and OSL dates ($n=80$; grey) on hearth stones from Rutherfords Creek.
OSL: Optically Stimulated Luminescence. Dates expressed as ordered set of means (dots) with 1 standard deviation (bars). Radiocarbon dates calibrated in OxCal using ShCal13 calibration curve (Hogg et al., 2013). Original radiocarbon data published in Holdaway et al. (2010). Original OSL data published in Rhodes et al. (2010).

refine existing model outcomes or challenge the inferences already drawn from them, and such reconfigurations would be welcome. However, 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 in order to increase the likelihood of commensurate gains (Grimm et al., 2005). Likewise, there are other configurations of the modelled process which, for the sake of space, were not explored here. Of particular 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 model as it exists now, but this highlights how, even using very small numbers of variables, parameter spaces can be expansive and multiscalar. Ideally, the parameter settings used in the exploration here that best fit a particular 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 modelling results support assertions made in earlier studies that the chronology presented by the surface hearth record in western NSW study locations is biased towards the present primarily because of geomorphic processes acting on it. 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 landsurfaces in one catchment, we have previously documented isolated places where hearths with older dates were both visible and preserved and places where only more recent hearths could be found (Holdaway et al., 2008). As the results from the modelling experiments presented here demonstrate, in order for older charcoal to be both visible and preserved alongside more abundant recent material, depositional and erosional processes must occur in mixed proportions. What was not able to be predicted from previous studies was that heavily erosional and heavily depositional surfaces may produce very similar chronometric patterning when radiocarbon is the only proxy in use. Nor could it be predicted that erosion and deposition alone could also lead to a discontinuous pattern of radiocarbon ages like that shown in Figure 3. Both of these results have important implications for interpreting chronologies derived from surface hearths.

We think it is important to recognize that if the patterning observed in the two chronometric proxies from Rutherfords Creek is the result of processes like those modelled here, this does not necessarily imply that the same chronometric signals exist beyond the landforms studied here. Different landforms will face different degrees of erosion, deposition and stability based on their particular characteristics (e.g. slope, local rainfall intensity, proximity to channel), creating different depositional conditions for archaeological materials. However, 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 model's parameter space. It would be instructive, then, to examine hearths from different kinds of depositional environments (e.g. valley margins, ridges) and compare the resulting chronometric data derived from both proxies used here to that generated by the model.

At a more general level, the simulation results caution against the use of summed radiocarbon probability distributions 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 nonexistent. This is why some have correctly pointed out 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 taphonomically corrected radiocarbon data as a proxy for population dynamics is dependent on the extent to which places exist where archaeological visibility is not of concern. The effects of sediment transport on visibility in surface contexts are not likely confined to rare studies where they have been clearly identified (e.g. Fanning et al., 2009b; Ward et al., 2006, 2015). Archaeologists may attempt to overcome issues of differential visibility and preservation by targeting places that may be less affected by sediment transport such as rockshelters (David and Lourandos, 1997; Johnson and Brook, 2011), although it has been demonstrated that these are not necessarily immune from changing rates of sedimentation (Hunt et al., 2015; Ward, 2004; Ward et al., 2006). Furthermore, focusing on one kind of occupation setting is not likely to provide an appropriate proxy for human activity as it effectively swaps one bias for another (Ulm, 2013: 187). Instead, following on the findings from the simulation, it is suggested here that the archaeological proxies used to demonstrate change, and the kinds of change (high magnitude, directional) that have been historically sought from them, might benefit from reconsideration in some instances (see also Attenbrow and Hiscock, 2015; Ulm, 2013). Changes can occur at a variety of spatiotemporal scales, and the record we have in some places may be suited for viewing some changes better than others.

Conclusion

If the archaeological record is truly a palimpsest, in the sense that there are events or processes that blend, distort or erase patterning of recordable archaeological objects as might be expected from an ordered set of synchronic depositional events, then understanding the formational dynamics which generated it is crucial to any interpretation (Cosgrove, 2012). Patterns that appear behaviourally driven could be partly or predominantly the result of time-dependent geomorphic processes, for example. This has implications for the behaviours we might expect to interpret from a deposit and the methods used to assess those behaviours.

Here, a simple simulated world was presented and fully explored; a world in which the visibility and preservation of deposited items are differently affected by episodic, localized sediment transport. The outcomes of the simulation suggest that such a process 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 proxies with different formational properties, radiocarbon and OSL, suggests a counterargument to existing interpretations of social intensification or periodic abandonment and warrants further investigation. The model presented here has been used as a form of theoretical scaffolding to aid in discerning between interpretations of the record, and upon which additional arguments can be made and further models could be constructed.

Acknowledgements

We are indebted to the Indigenous Traditional Owners of country in western New South Wales (NSW) for their permission to undertake research and their help and support with fieldwork. Students from La Trobe, Auckland and Macquarie Universities provided invaluable labour in the field. We thank the NSW National Parks and Wildlife Service for permission to conduct the research at Rutherfords Creek. All radiocarbon determinations were performed by the University of Waikato Radiocarbon Dating laboratory, and we thank Alan Hogg and his colleagues for their help with the samples. Optically Stimulated Luminescence (OSL) determinations were carried out by Ed Rhodes. Finally, we thank two anonymous reviewers for their helpful comments on the original manuscript.

Funding

Funding was provided by the University of Auckland, Macquarie University, La Trobe University, the NSW National Parks and Wildlife Service and the Australian Research Council.

Notes

1. Based on historical rainfall data obtained from Wilcannia Reid St weather station (No. 046043), Australian Bureau of Meteorology http://www.bom.gov.au/climate/data
2. http://www.bom.gov.au/water/designRainfalls/rainfallEvents/why100years.shtml

Supplementary files

All simulations were conducted in NetLogo (v.5.05), and all graphs were produced using the R statistical platform (v3.0.2), both of which are freely available software packages. The NetLogo simulation (hmodel.nlogo) and the R script used to produce the graphs (hmodel_output.R) are available as supplemental files with the web version of this paper, along with the chronometric data used in the analysis. These can also be obtained by contacting the corresponding author.

References

Aldenderfer MS (1981) Creating assemblages by computer simulation: The development and uses of ABSIM. In: Sabloff JA (ed.) *Simulations in Archaeology, School for American Research Seminar Series*. Albuquerque: University of New Mexico Press, pp. 67–117.

Allen MS and Morrison AE (2013) Modelling site formation dynamics: Geoarchaeological, chronometric and statistical approaches to a stratified rockshelter sequence, Polynesia. *Journal of Archaeological Science* 40(12): 4560–4575.

Armit I, Swindles GT, Becker K et al. (2014) Rapid climate change did not cause population collapse at the end of the European Bronze Age. *Proceedings of the National Academy of Sciences of the United States of America* 111(48): 17045–17049.

Attenbrow V and Hiscock P (2015) Dates and demography: Are radiometric dates a robust proxy for long-term prehistoric demographic change? *Archaeology in Oceania* 50: 30–36.

Bailey G (1983) Concepts of time in quaternary prehistory. *Annual Review of Anthropology* 12: 165–192.

Bailey G (2007) Time perspectives, palimpsests and the archaeology of time. *Journal of Anthropological Archaeology* 26: 198–223.

Bailey G (2008) Time perspectivism: Origins and consequences. In: Holdaway SJ and Wandsnider L (eds) *Time in Archaeology: Time Perspectivism Revisited*. Salt Lake City, UT: University of Utah Press, pp. 13–30.

Banning EB (2002) *Archaeological Survey: Manuals in Archaeological Method, Theory, and Technique*. New York: Springer.

Barker G, Creighton O, Gilbertson D et al. (1997) The Wadi Faynan Project, Southern Jordan: A preliminary report on geomorphology and landscape archaeology. *Levant* 29(1): 19–40.

Barrientos G, Catella L and Oliva F (2014) The spatial structure of lithic landscapes: The late Holocene record of east-central Argentina as a case study. *Journal of Archaeological Method and Theory*. Available at: http://link.springer.com/article/10.1007/s10816-014-9220-0. (accessed 27 November 2014).

Barton CM and Riel-Salvatore J (2014) The formation of lithic assemblages. *Journal of Archaeological Science* 46: 334–352.

Bell FC (1979) Precipitation. In: Goodall DW and Perry RA (eds) *Arid Land Ecosystems: Structure, Functioning, and Management*. Cambridge: Cambridge University Press, pp. 373–392.

Binford LR (1980) Willow smoke and dogs' tails: Hunter-gatherer settlement systems and archaeological site formation. *American Antiquity* 45(1): 4–20.

Bisson MS, Nowell A, Cordova C et al. (2014) Dissecting palimpsests in a Late Lower and Middle Paleolithic flint acquisition site on the Madaba Plateau, Jordan. *Quaternary International* 331: 74–94.

Brantingham PJ (2003) A neutral model of stone raw material procurement. *American Anthropologist* 68(3): 487–509.

Brantingham PJ (2006) Measuring forager mobility. *Current Anthropology* 47(3): 435–459.

Braun DR, Rogers MJ, Harris JWK et al. (2008) Landscape-scale variation in hominin tool use: Evidence from the Developed Oldowan. *Journal of Human Evolution* 55(6): 1053–1063.

Brouwer Burg M (2013) Reconstructing 'total' paleo-landscapes for archaeological investigation: An example from the central Netherlands. *Journal of Archaeological Science* 40(5): 2308–2320.

Brughmans T, Keay S and Earl G (2014) Introducing exponential random graph models for visibility networks. *Journal of Archaeological Science* 49: 442–454.

Bull LJ and Kirkby MJ (2002) *Dryland Rivers: Hydrology and Geomorphology of Semi-arid Channels*. New York: John Wiley & Sons.

Butzer KW (1971) *Environment and Archeology: An Ecological Approach to Prehistory*. 2nd Edition. Chicago, IL: Walter de Gruyter, Inc.

Carr C (1987) Dissecting intrasite artifact palimpsests using Fourier methods. In: Kent S (ed.) *Method and Theory for Activity Area Research*. New York: Columbia University Press, pp. 236–291.

Cartwright N (1999) *The Dappled World: A Study of the Boundaries of Science*. Cambridge: Cambridge University Press.

Clarke DL (1972) *Models in Archaeology*. London: Methuen.

Clarkson CJ (2008) Lithics in the landscape. In: David B and Thomas J (eds) *Handbook of Landscape Archaeology*. Walnut Creek, CA: Left Coast Press, pp. 490–501.

Clevis Q, Tucker GE, Lock G et al. (2006) Geoarchaeological simulation of meandering river deposits and settlement distributions: A three-dimensional approach. *Geoarchaeology* 21(8): 843–874.

Cosgrove R (2012) Comment. *Australian Archaeology* 74: 23–24.

Costopoulos A (2009) Simulating society. In: Bentley RA, Maschner HDG and Chippindale C (eds) *Handbook of Archaeological Theories*. Lanham, MD: Rowman & Littlefield, pp. 273–281.

Costopoulos A (2010) For a theory of archaeological simulation. In: Andre Costopoulos A and Lake MW (eds) *Simulating Change: Archaeology Into the Twenty-First Century, Foundations of Archaeological Inquiry*. Salt Lake City, UT: University of Utah Press, pp. 21–27.

Crema ER (2014) A simulation model of fission – Fusion dynamics and long-term settlement change. *Journal of Archaeological Method and Theory* 21(2): 385–404.

David B and Lourandos H (1997) 37,000 years and more in tropical Australia: Investigating long-term archaeological trends in Cape York Peninsula. *Proceedings of the Prehistoric Society* 63: 1–23.

Davidson DA and Shackley ML (1976) *Geoarchaeology: Earth Science and the Past*. London: Duckworth and Co.

Doran JE (1972) Computer models as tools for archaeological hypothesis formation. In: Clarke DL (ed.) *Models in Archaeology*. London: Methuen, pp. 425–451.

Douglass MJ (2010) *The archaeological potential of informal lithic technologies: A case study of assemblage variability in western New South Wales, Australia*. Unpublished PhD Thesis, The University of Auckland.

Dunnell RC (1982) Science, social science, and common sense: The agonizing dilemma of modern archaeology. *Journal of Anthropological Research* 38(1): 1–25.

Dunnell RC and Dancey WS (1983) The siteless survey: A regional scale data collection strategy. *Advances in Archaeological Method and Theory* 6: 267–287.

Ebert JI (1992) *Distributional Archaeology*. Albuquerque, NM: University of New Mexico Press.

Epstein JM (2008) Why model? *Journal of Artificial Societies and Social Simulation* 11(4). Available at: http://jasss.soc.surrey.ac.uk/11/4/12/12.pdf.

Fanning PC (1999) Recent landscape history in arid western New South Wales, Australia: A model for regional change. *Geomorphology* 29: 191–209.

Fanning PC and Holdaway SJ (2001a) Stone artifact scatters in Western NSW, Australia: Geomorphic controls on artifact size and distribution. *Geoarchaeology* 16(6): 667–686.

Fanning PC and Holdaway SJ (2001b) Temporal limits to the archaeological record in arid western NSW, Australia: Lessons from OSL and radiocarbon dating of hearths and sediments. In: Jones M and Sheppard P (eds) *Australasian connections and new directions: Proceedings of the 7th Australasian archaeometry conference* (Research in Anthropology and Linguistics, vol. 5). Auckland: University of Auckland, pp. 85–104.

Fanning PC, Holdaway SJ and Phillips RS (2009a) Heat-retainer hearth identification as a component of archaeology survey in western NSW, Australia. In: Fairbairn A, O'Connor S and Marwick B (eds) *New Directions in Archaeological Science* (Terra Australis). Canberra: ANU E Press, pp. 13–22.

Fanning PC, Holdaway SJ and Rhodes EJ (2007) A geomorphic framework for understanding the surface archaeological record in arid environments. *Geodinamica Acta* 20(4): 275–286.

Fanning PC, Holdaway SJ, Rhodes EJ et al. (2009b) The surface archaeological record in arid Australia: Geomorphic controls on preservation, exposure, and visibility. *Geoarchaeology* 24: 121–146.

Foley R (1981) Off-site archaeology: An alternative approach for the short-sited. In: Hodder I, Isaac GL and Hammond N (eds) *Pattern of the Past: Studies in Honour of David Clarke*. Cambridge: Cambridge University Press, pp. 157–183.

Foley RA and Lahr MM (2015) Lithic landscapes: Early human impact from stone tool production on the central Saharan environment. *PLoS ONE* 10(3): 1–15.

Giere RN (1999) *Science Without Laws*. Chicago, IL: University of Chicago Press.

Gillespie R and Brook BW (2006) Is there a Pleistocene archaeological site at Cuddie Springs? *Archaeology in Oceania* 41(1): 1–11.

Godfrey-Smith P (2006) The strategy of model-based science. *Biological Philosophy* 21: 725–740.

Gould RA (1967) Notes on the hunting, butchering, and sharing of game among the Ngatajara and their neighbors in the West Australian desert. *The Kroeber Anthropological Society Papers* 36: 41–66.

Gould RA (1980) *Living Archaeology*. Cambridge: Cambridge University Press.

Gouma M, van Wijngaarden GJ and Soetens S (2011) Assessing the effects of geomorphological processes on archaeological densities: A GIS case study on Zakynthos Island, Greece. *Journal of Archaeological Science* 38(10): 2714–2725.

Grimm V, Revilla E, Berger U et al. (2005) Pattern-oriented modeling of agent-based complex systems: Lessons from ecology. *Science* 310(5750): 987–991.

Hassan FA (1979) Geoarchaeology: The Geologist and Archaeology. *American Antiquity* 44(2): 267–270.

Henry D (2012) The palimpsest problem, hearth pattern analysis, and Middle Paleolithic site structure. *Quaternary International* 247: 246–266.

Hogg AG, Hua Q, Blackwell PG et al. (2013) SHCal13 Southern Hemisphere calibration, 0–50,000 years cal BP. *Radiocarbon* 55(2): 1–15.

Holdaway SJ and Fanning PC (2014) *Geoarchaeology of Aboriginal Landscapes in Semi-arid Australia*. Collingwood: CSIRO Publishing.

Holdaway SJ and Wandsnider L (2006) Temporal scales and archaeological landscapes from the eastern desert of Australia and intermontane North America. In: Lock G and Molyneaux B (eds) *Confronting Scale in Archaeology: Issues of Theory & Practice*. New York: Springer Science and Business Media, pp. 183–202.

Holdaway SJ and Wandsnider L (2008) *Time in Archaeology: Time Perspectivism Revisited*. Salt Lake City, UT: University of Utah Press.

Holdaway SJ, Fanning PC and Rhodes EJ (2008) Challenging intensification: Human-environment interactions in the Holocene geoarchaeological record from western New South Wales, Australia. *The Holocene* 18: 403–412.

Holdaway SJ, Fanning PC and Shiner JI (2005) Absence of evidence or evidence of absence? Understanding the chronology of indigenous occupation of western New South Wales, Australia. *Archaeology in Oceania* 40: 33–49.

Holdaway SJ, Fanning PC, Rhodes EJ et al. (2010) Human response to palaeoenvironmental change and the question of temporal scale. *Palaeogeography, Palaeoclimatology, Palaeoecology* 292: 192–200.

Holdaway SJ, Shiner JI and Fanning PC (2004) Hunter-gatherers and the archaeology of discard behavior: An analysis of surface stone artifacts from Sturt National Park, Western New South Wales, Australia. *Asian Perspectives* 43(1): 34–72.

Hull KL (2005) Process, perception, and practice: Time perspectivism in Yosemite native demography. *Journal of Anthropological Archaeology* 24(4): 354–377.

Hunt CO, Gilbertson DD, Hill EA et al. (2015) Sedimentation, re-sedimentation and chronologies in archaeologically-important caves: Problems and prospects. *Journal of Archaeological Science* 56: 109–116.

Isaac GL (1981) Stone Age visiting cards: Approaches to the study of early land use patterns. In: Hodder I, Isaac GL and Hammond N (eds) *Pattern of the Past: Studies in Honour of David Clarke*. Cambridge: Cambridge University Press, pp. 131–155.

Jansen JD and Brierley GJ (2004) Pool-fills: A window to palaeoflood history and response in bedrock-confined rivers. *Sedimentology* 51(5): 901–925.

Johnson CN and Brook BW (2011) Reconstructing the dynamics of ancient human populations from radiocarbon dates: 10 000 years of population growth in Australia. *Proceedings of the Royal Society of London B: Biological Sciences*. Available at: http://rspb.royalsocietypublishing.org/content/early/2011/05/06/rspb.2011.0343. (accessed 26 January 2015).

Kirkby A and Kirkby MJ (1976) Geomorphic processes and the surface survey of archaeological sites in semi-arid areas. In: Davidson DA and Shackley ML (eds) *Geoarchaeology: Earth Science and the Past*. London: Duckworth and Co., pp. 229–253.

Kohler TA and Van der Leeuw SE (2007) Introduction: Historical socionatural systems and models. In: Kohler TA and Van der Leeuw SE (eds) *The Model-Based Archaeology of Socionatural Systems*. Santa Fe, NM: School for Advanced Research Press, pp. 1–12.

Lake MW (2014) Trends in archaeological simulation. *Journal of Archaeological Method and Theory* 21(2): 258–287.

Lake MW (2015) Explaining the past with ABM: On modelling philosophy. In: Wurzer G, Kowarik K and Reschreiter H (eds) *Agent-based Modeling and Simulation in Archaeology, Advances in Geographic Information Science*. New York: Springer International Publishing, pp. 3–35.

Lockerbie L (1954) Stratification in Otago archaeological sites. *Journal of the Polynesian Society* 63(2): 141–146.

Lucas G (2010) Time and the archaeological archive. *Rethinking History: The Journal of Theory and Practice* 14(3): 343–359.

Lucas G (2012) *Understanding the Archaeological Record*. Cambridge: Cambridge University Press.

Malinsky-Buller A, Hovers E and Marder O (2011) Making time: ‘Living floors’, ‘palimpsests’ and site formation processes – A perspective from the open-air Lower Paleolithic site of Revadim Quarry, Israel. *Journal of Anthropological Archaeology* 30(2): 89–101.

Marx SK, McGowan HA and Kamber BS (2009) Long-range dust transport from eastern Australia: A proxy for Holocene aridity and ENSO-type climate variability. *Earth and Planetary Science Letters* 282: 167–177.

Morgan C, Cannon MB and Fowler B (2013) Statistical means for identifying hunter–gatherer residential features in a lithic landscape. *Journal of Archaeological Science* 40(8): 3117–3128.

Morgan MS and Morrison M (eds) (1999) *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge: Cambridge University Press.

Morrison M (2009) Models, measurement and computer simulation: The changing face of experimentation. *Philosophical Studies* 143(1): 33–57.

Murray T (1999) A return to the ‘Pompeii Premise’. In: Murray T (ed.) *Time and Archaeology*. London: Routledge, pp. 8–27.

Nash DT and Petraglia MD (1987) *Natural Formation Processes and the Archaeological Record* (BAR international series). Oxford: Archaeopress.

O’Connell JF and Allen J (1998) When did humans first arrive in greater Australia and why is it important to know? *Evolutionary Anthropology: Issues, News, and Reviews* 6(4): 132–146.

O’Sullivan D (2008) Geographical information science: Agent-based models. *Progress in Human Geography* 32: 541–550.

O’Sullivan D and Perry GLW (2013) *Spatial Simulation: Exploring Pattern and Process*. West Sussex: Wiley.

Premo LS (2007) Exploratory agent-based models: Towards an experimental ethnoarchaeology. In: Clark JT and Hagermeister EM (eds) *Digital Discovery: Exploring New Frontiers in Human Heritage. CAA 2006*. Budapest: Archaeolingua Press, pp. 29–36.

Premo LS (2010) Equifinality and explanation: The role of agent-based modeling in postpositivist archaeology. In: Costopoulos A and Lake M (eds) *Simulating Change: Archaeology Into the Twenty-First Century, Foundations of Archaeological Inquiry*. Salt Lake City, UT: University of Utah Press, pp. 28–37.

Premo LS (2012) The shift to a predominantly logistical mobility strategy can inhibit rather than enhance forager interaction. *Human Ecology* 40(4): 647–649.

Rathje WL, Shanks M and Witmore C (eds) (2012) *Archaeology in the Making: Conversations through a Discipline*. London: Routledge.

Renwick WH (1992) Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. *Geomorphology* (Proceedings 23rd Binghamton Symposium in Geomorphology) 5: 265–276.

Rhode D, Brantingham PJ, Perreault C et al. (2014) Mind the gaps: Testing for hiatuses in regional radiocarbon date sequences. *Journal of Archaeological Science* 52: 567–577.

Rhodes EJ, Fanning PC and Holdaway SJ (2010) Developments in optically stimulated luminescence age control for geoarchaeological sediments and hearths in western New South Wales, Australia. *Quaternary Geochronology* (12th International Conference on Luminescence and Electron Spin Resonance Dating (LED 2008)) 5: 348–352.

Rossignol J and Wandsnider L (eds) (1992) *Space, Time and Archaeological Landscapes*. New York: Springer.

Schacht RM (1984) The contemporaneity problem. *American Antiquity* 49(4): 678–695.

Schiffer MB (1972) Archaeological context and systemic context. *American Antiquity* 37(2): 156–165.

Schofield AJ (ed.) (1991) *Interpreting Artefact Scatters: Contributions to Ploughzone Archaeology* (Oxbow Monograph). Oxford: Oxbow Books.

Servedio MR, Brandvain Y, Dhole S et al. (2014) Not just a theory – The utility of mathematical models in evolutionary biology. *PLoS Biology* 12(12): e1002017.

Sharon G, Zaidner Y and Hovers E (2014) Opportunities, problems and future directions in the study of open-air Middle Paleolithic sites. *Quaternary International* 331: 1–5.

Shea JJ (2010) Stone age visiting cards revisited: A strategic perspective on the lithic technology of early hominin dispersal. In: Fleagle JG, Shea JJ, Grine FE et al. (eds) *Out of Africa I: Vertebrate Paleobiology and Paleoanthropology*. Amsterdam: Springer, pp. 47–64.

Smith MA (2013) *The Archaeology of Australia’s Deserts*. Cambridge: Cambridge University Press.

Stein JK (1987) Deposits for archaeologists. *Advances in Archaeological Method and Theory* 11: 337–395.

Stein JK (2001) A review of site formation processes and their relevance to geoarchaeology. In: Goldberg P, Holliday VT and Ferring CR (eds) *Earth Sciences and Archaeology*. New York: Springer, pp. 37–51.

Stern N (1994) The implications of time-averaging for reconstructing the land-use patterns of early tool-using hominids. *Journal of Human Evolution* 27(1–3): 89–105.

Thomas DH (1973) An empirical test for Steward's model of Great Basin settlement patterns. *American Antiquity* 38(2): 155–176.

Tooth S (2000) Process, form and change in dryland rivers: A review of recent research. *Earth-Science Reviews* 51: 67–107.

Ulm S (2013) 'Complexity' and the Australian continental narrative: Themes in the archaeology of Holocene Australia. *Quaternary International* 285: 182–192.

Vaquero M (2008) The history of stones: Behavioural inferences and temporal resolution of an archaeological assemblage from the Middle Palaeolithic. *Journal of Archaeological Science* 35(12): 3178–3185.

Wainwright J (1991) *Erosion of Semi-arid Archaeological Sites: A Study in Natural Formation Processes*.

Wainwright J (1994) Erosion of archaeological sites: Results and implications of a site simulation model. *Geoarchaeology* 9(3): 173–201.

Wandsnider L (1996) Describing and comparing archaeological spatial structures. *Journal of Archaeological Method and Theory* 3(4): 319–384.

Ward I (2004) Comparative records of occupation in the Keep River region of the eastern Kimberley, northwestern Australia. *Australian Archaeology* 59: 1–9.

Ward I and Larcombe P (2003) A process-orientated approach to archaeological site formation: Application to semi-arid Northern Australia. *Journal of Archaeological Science* 30: 1223–1236.

Ward I, Fullagar RLK, Boer-Mah T et al. (2006) Comparison of sedimentation and occupation histories inside and outside rock shelters, Keep-River Region, Northwestern Australia. *Geoarchaeology* 21: 1–27.

Ward I, Larcombe P and Veth P (2015) A new model for coastal resource productivity and sea-level change: The role of physical sedimentary processes in assessing the archaeological potential of submerged landscapes from the northwest Australian continental shelf. *Geoarchaeology* 30(1): 19–31.

Waters MR and Kuehn DD (1996) The geoarchaeology of place: The effect of geological processes on the preservation and interpretation of the archaeological record. *American Antiquity* 61(3): 483–497.

Wheeler M (1954) *Archaeology from the Earth*. Oxford: Clarendon Press.

Wilensky U (1999) *NetLogo 5.0.4*. Evanston, IL: Center for Connected Learning and Computer-Based Modeling, Northwestern University. Available at: http://ccl.northwestern.edu/netlogo.

Williams AN (2012) The use of summed radiocarbon probability distributions in archaeology: A review of methods. *Journal of Archaeological Science* 39: 578–589.

Williams AN, Ulm S, Goodwin ID et al. (2010) Hunter-gatherer response to late Holocene climatic variability in northern and central Australia. *Journal of Quaternary Science* 25(6): 831–838.

Wilson L (2011) The role of geoarchaeology in extending our perspective. *Geological Society, London, Special Publications* 352(1): 1–9.

Witter DC (1992) *Regions and resources*. Unpublished PhD Thesis, Australian National University.

Wren CD, Xue JZ, Costopoulos A et al. (2014) The role of spatial foresight in models of hominin dispersal. *Journal of Human Evolution* 69: 70–78.