COVER PAGE

Research article - How do we distinguish termite stone lines from artefact horizons? A challenge for geoarchaeology in tropical Australia.

Michael Alexander Smith[1,2], Ingrid Ward[3] and Ian Moffat[1,4]

1. Archaeology, CHASS, Flinders University of South Australia, Bedford Park SA 5042, Australia.

2. National Museum of Australia, Canberra ACT 2601, Australia.

3. School of Social Sciences, University of Western Australia, Perth WA 6009, Australia.

4. McDonald Institute for Archaeological Research, University of Cambridge, Cambridge CB2 3DZ, United Kingdom.

Corresponding author: Mike Smith, email: mike.smith@nma.gov.au

Orchid ID:

M. A. Smith 0000-0002-6177-8217.

I. Ward 0000-0002-0566-1479

I. Moffat 0000-0002-2171-7145

Short running title: Termite stone lines and artefact horizons.

How do we distinguish termite stone lines from artefact horizons? A challenge for geoarchaeology in tropical Australia.

M. A. Smith[1,2], I. Ward[3] and I. Moffatt[1,4]

1. Archaeology, CHASS, Flinders University of South Australia, Bedford Park SA 5042, Australia.

2. National Museum of Australia, Canberra ACT 2601, Australia.

3. School of Social Sciences, University of Western Australia, Perth WA 6009, Australia.

4. McDonald Institute for Archaeological Research, University of Cambridge, Cambridge CB2 3DZ, United Kingdom.

ABSTRACT

Can we distinguish stone lines created by termite bioturbation from genuine artefact horizons? This is a challenge for field archaeology and geoarchaeology in northern Australia, where termites are abundant. We review published data to (a) present a model of the evolution of stone lines and (b) develop guidelines for recognizing these bioturbation products in archaeological contexts. In case studies, we examine Madjedbebe and Nauwalabila, two sites in northern Australia. The early occupation levels at these sites are pivotal to ideas about initial human occupation of the Australian landmass but there are claims these are unrecognized stone lines. Our assessment is that neither Madjedbebe nor Nauwalabila contain termite stone lines, although both sites may have complex geomorphic and taphonomy histories.

Keywords: bioturbation, termites, artefact horizons, stone lines, Madjedbebe, Nauwalabila.

1 INTRODUCTION

Bioturbation should be treated as an integral part of the sedimentary history of archaeological sites, rather than as a *post hoc* explanation for anomalous dates or intrusive finds. Its potential impact on archaeological deposits has been evident since Darwin's book *The formation of vegetable mould through the action of worms* (1882). The fundamental role of bioturbation in soil formation and creation of a 'biomantle' is now widely acknowledged by soil scientists (Johnson, 1990; Lee & Wood, 1971a; Lobry de Bruyn & Conacher, 1990; Paton, 1978). The main vectors are ants, termites, earthworms, and burrowing mammals. Archaeologists have focused on the translocation of sediments by bioturbation and its consequences for luminescence dating (Bateman et al., 2007; Kristensen et al., 2015; Rink et al., 2013); for the displacement of organics and impact on ^{14}C dating (Bird et al., 2002; Tschinkel, Rink, & Kwapich, 2015); for the ways in which stone layers can mimic artefact horizons (Cahen & Moeyersons, 1977; Johnson, 1989; McBrearty, 1990; Moeyersons, 1978; O'Connell et al., 2018), and for the displacement of cultural material (Armour-Chelu & Andrews, 1994; Canti, 2003). The detection of burrowing activity by vertebrates (e.g., agamid and varanid lizards, rabbits, gophers, bettongs, or wombats) is straightforward and can usually be identified visually in the stratigraphy of a site. Disturbance by invertebrates is harder to identify or quantify but may be significant. For example, ants and termites can move large volumes of sediments (>300 kg/ha/yr, Whitford & Eldridge, 2013: table 2).

An extreme example of bioturbation is where an apparent subsurface stone layer is the secondary product of prolonged activity by invertebrates. This issue has been sharpened in a recent paper by O'Connell et al. (2018). Their paper is primarily a critique of anomalously early estimates of occupation at two sites in tropical Australia—Madjedbebe and Nauwalabila (Figure 1)—that are pivotal to ideas about initial human occupation of the Australian landmass. O'Connell et al. argue that apparent occupation horizons at both sites are unrecognized termite stone lines. Because they give no criteria for distinguishing genuine artefact horizons from bioturbation stone lines that potentially mimic artefact horizons, this proposition also represents a fundamental challenge to archaeology in tropical Australia.

Sharpe (1938:24) originally proposed the term "stone line" for "a line of angular to subangular fragments which parallels a sloping surface at a depth of several feet." This may be one stone thick, or a layer of coarse material. Armour-Chelu and Andrews (1994) describe them as "the lower members of two-layered and multilayered faunal-mantles." Early views on the origins of stone lines canvassed a range of causal factors (Nye, 1955; Ruhe, 1959) and foreshadowed current perspectives (Nehren, Kirchner, & Heinrich, 2016; O'Connell et al., 2018; Williams, 1968) that stone layers *sensu lato* are polythetic. They may be (a) secondary bioturbation products, produced by invertebrates or fossorial vertebrates, (b) geogenic layers produced by soil creep or mass movement, or (c) primary depositional units buried by younger sediments (e.g., a layer of colluvial gravel, a stony pavement, a buried erosional lag, or an artefact horizon). In this paper, our focus is not bioturbation *per se,* but specifically the creation of stone layers by termite bioturbation. We review published data on termite stone lines, develop guidelines for distinguishing them from artefact horizons, and return to the question of whether Madjedbebe and Nauwalabila contain termite stone lines.

2 IMPACT OF TERMITES ON PHYSICAL AND CHEMICAL PROPERTIES OF SOILS

Termites (Isoptera) are important soil organisms (Black & Okwakol, 1997) as they make up 40–65% of total biomass of soil macro-fauna in some regions (Jouquet et al., 2016). Approximately 263 species of termite occur in Australia. About 160 of these are found in northern Australia (Smith et al., 1998), primarily in sclerophyll forest, woodland, and savanna (Gray & Calaby, 1970; Jones & Eggleton, 2011). Termites live exclusively in colonies and often form large subterranean colonies containing millions of individuals (Ku, Su, & Lee, 2013). High densities of large mounds (termitaria) are found in savanna. Smaller mounds are abundant in both savanna and forest (Lee & Wood, 1971b). In northern Australia, termite mounds occur at densities ranging from 10–1000/ha (Holt, Coventry, & Sinclair, 1980; Lee & Wood, 1971b; Andersen, Jacklyn, Dawes-Gromadzki, & Morris, 2005; Williams, 1968). Regional richness of termite species is higher in the Top End, Northern Territory, than in either the Kimberley or Cape York Peninsula (Abensperg-Traun & Steven, 1997) but the Arnhem Land sandstones are species poor, with only 26 of the 50 species recorded in the Kakadu region (Braithwaite, Miller, & Wood, 1988).

Termites have substantial impact on the physical and chemical properties of tropical soils, where they have been described as “neglected soil engineers” (Jouquet et al., 2016). In these regions they affect most pedogenic processes such as leaching, cycling of organic matter, eluviation and infiltration, diagenesis of secondary minerals (e.g., carbonates, clays, and salts), weathering of primary minerals, and translocation of particles. They also play a significant role in evolution of a pedogenic profile. Time fundamentally determines their impact on a profile (Paton, 1978). Not all bioturbation will produce either soil horizons or a stone line (both are a function of the duration of this process) but all termite stone lines are associated with significant pedogenesis because of the prolonged bioturbation required to produce a stone line.

2.1 Impact on physical properties of soils

Subterranean termites alter the fabric and textural characteristics of a soil. Their effects on the physical properties of soils are due mostly to translocation and sorting of particles, and creation of voids and galleries (Asawalam & Johnson, 2007; Cosarinsky, Bellosi, & Genise, 2005; Malaka, 1977). Greater porosity increases water infiltration, facilitates weathering of clays, and promotes formation of soil aggregates. Termites selectively move fine particles (<1–3 mm, depending on mandible size of the species). Most species select clay and silt in preference to sand for construction of mounds and other structures (Lee & Wood, 1971a: 405). Termite activity leads to gradual loss of fine material from lower horizons and its accumulation in upper horizons as fine textured sediment with elevated silt and clay content. Australian studies indicate that around 33% of material used in mound construction came from a soil depth within 30–45 cm (Lobry de Bruyn & Conacher, 1990). Over time, this process sorts the biomantle into two layers, an upper layer of fine material over a basal layer of coarser material.

One aspect that has concerned soil scientists—but is less relevant to archaeologists—is the action of termite bioturbation on weathered bedrock (e.g., granitic saprolite). Here, termite bioturbation creates a layer of rock fragments in the upper part of a saprolite zone by selectively removing fine material from *in situ* granular disintegration to produce a stone layer immediately above bedrock. Characteristically, this creates a three-layered soil with a surface mantle of sand, and a buried stone layer above a basal unit of weathered bedrock. As this process displaces fine sediments but leaves coarser material *in situ*, it creates a subsurface biogenic lag.

2.2 Effect on chemical properties of soils

Chemical changes are due largely to the incorporation of organic matter and increased infiltration of water. Studies beneath and around mounds show that termite activity creates elevated levels of N, Ca, K, Mg, and Na, (Asawalam & Johnson, 2007; Petts, Hill, & Worrall, 2009; Watson, 1962), sometimes down to 2–7 m. Other effects include changes in pH (from pH 4 to 6), an increase in organic C, as well as changes in the formation of carbonates, phosphates, and Fe oxyhydroxides. Although these chemical changes promote formation of biogenetic ferrimagnetic material (Maher, 1998), it has been difficult to identify this material in soil profiles (Lowe et al., 2018). Termite modification of wood can be detected by measuring cellulose percentage (for example, by using Fourier Transform Infra-Red spectroscopy analysis, or by Scanning Electron Microscope imaging) (Li, Lu, & Mo (2012).

2.3 Habitat and risk

Few depositional environments are devoid of bioturbation by termites. It is unlikely that particular habitats can be identified as having a higher risk of subsurface termite disturbance than others. All species require a well-drained aerobic substrate. Beyond this, data suggest species and sedimentation rate have more effect than substrate (Braithwaite, Miller & Wood, 1988; Buatois et al., 2007; Gingras et al., 2007). Different species have different feeding and nesting behaviors. Soil feeders, and species that build subterranean nests, have greatest potential impact on archaeological sites. The size of mound does not influence the depth of termite activity in a soil profile (Petts, Hill &Worrall, 2009). The Kakadu region has only 3–4 soil-feeding species (as opposed to grass harvesters). Only 9 species construct subterranean nests. The remainder nest in grass or dead trees, or build epigeal mounds (Braithwaite, Miller & Wood, 1988). High sedimentation rates potentially offset sediment turnover and mitigate the effects of termite activity.

In archaeological contexts, identifying the likelihood of disturbance is not straightforward. Most well-drained open locations, including many rock shelters, are potentially exposed to termite activity. We can, however, expect cave sites, dense shell middens, and active sand dunes to be free of termites, and that bioturbation will have been negligible wherever a deposit preserves features with good stratigraphic resolution (e.g., postholes, hearths, pits, laminated features). In principle, some degree of termite activity can be assumed to have occurred in most archaeological sites in northern Australia. The key questions, therefore, concern the intensity and duration of any bioturbation. These variables also determine whether or not bioturbation will produce a stone layer.

3 MODELING THE DEVELOPMENT OF TERMITE STONE LAYERS

3.1 Key variables

The evolution of a termite stone layer can be modeled from existing data. Stone lines are climax phenomena produced at one end of a trajectory of bioturbation. Their formation is determined by several variables: (a) time, (b) intensity, (c) size of objects, and (d) foraging depth. The density and content of these stone layers depends on the character of the parent material, which in an archaeological context is the range of materials on an occupation surface, and length of time that bioturbation has been active.

3.1.1 Time

The creation of a stone layer requires a prolonged period of bioturbation beneath a ground surface that is either stable or in equilibrium with respect to sediment accumulation and erosion. Published estimates indicate that >10 kyr are required to produce a stone layer at depths <1 m, with some evidence that these take 20–30 kyr to form. Field estimates for northern Australia (11.5 to greater than 17.7 kyr, Williams, 1968, 1978) are broadly consistent with global estimates of soil turnover by termites (Holt, Coventry & Sinclair, 1980; Nye, 1955; Whitford & Eldridge, 2013: table 2) and with experimental data on turnover rates (Salvador-Blanes, Minasny, & McBratney, 2007).

3.1.2 Intensity

Degree of bioturbation varies with intensity of termite activity and with species, as species differ in feeding and nesting behavior and foraging depth. In general, most subsurface biological activity is within 20 cm of the ground surface and declines with depth. Australian data indicate that ants and termites can modify the upper part of a soil profile in 200–430 years (Eldridge,1993; Holt, Coventry, & Sinclair, 1980; Humphreys, 1981).

There are no quantitative data on the relationship between termite abundance (population density) and soil turnover rate although these variables can be assumed to be positively correlated. In northern Australia, field estimates of turnover rates of 0.48 m^3/ha/yr (equivalent to 0.521 tonne/km^2/yr) (Williams, 1968) are of the same order as experimental approximations (~1.1 tonne/km^2/yr) and global estimates (300–3000 kg/ha/yr) (Whitford & Eldridge, 2013: table 2). Estimates of the rate of deposition of fine sediments on the ground surface in northern Australia vary but are mostly >2.5 mm / 100 yr (2.5–50 mm / 100 yr, Holt, Coventry and Sinclair, 1980; 10 mm / 100 yr, Lee & Wood, 1971b:251).

3.1.3 Object Size

The surface area of an object will determine its rate of displacement. Termite bioturbation displaces material >3 mm by removing fine particles beneath an object, and via collapse of voids or galleries. Displacement rate can be expected to be inversely proportional to the area of an object. An object 10,000 mm^2 (e.g., a 10 cm fragment of grindstone) will require >10 times as much sediment to be translocated as an object 100 mm^2 (e.g., a 1 cm flake) Small objects are also more readily translocated via termite galleries, which range 1–7 mm (Ali, Ahmed, Sheridan, & French, 2016:103). We predict, therefore, that the process of concentrating stones or artefacts in a stone layer will initially produce moderate size sorting, with smaller objects displaced faster than larger objects. Also, this suggests that the size distribution of original parent material will affect the rate at which a stone line will form, though there is no field or experimental data on whether this has a significant effect.

3.1.4 Depth

Stone layers eventually form at the base of foraging activity, the depth of which varies with termite species. We can assume that the greatest subsurface impact is by soil-feeders and species that build subterranean nests. Most biological activity—and translocation of fine sediments—occurs at depths <20 cm (Salvador-Blanes, Minasny, & McBratney, 2007), but termite foraging commonly extends to 0.4–1.2 m depth, and is affected by the depth of bedrock and presumably also the water table. Some termite activity has been observed at depths of 2–7 m (Lecomte, 1988; Stewart, Anand, & Balkau, 2012), but there are no data on its intensity, and field observations have not identified stone layers at >0.5 m depth. We also assume that stone layers at greater depth will take longer to form than those at <0.3 m depth.

3.2 Stages of formation

Our modeling predicts several sequential steps in the formation of a stone layer:

(1) *Local post-depositional disturbance*. The intensity of biological activity within the upper 20 mm of a soil profile (the biomantle) will rapidly affect objects on the surface. Translocation of objects within this biologically active zone may only require 2 kyr. Potentially, this can rework a discrete occupation surface creating an artefact spread over 20 cm. Wherever such rates (equivalent to 100 mm/kyr) exceed the rate of sediment accumulation, the net effect is a moving window of bioturbation, potentially degrading archaeological provenance to ±10 cm throughout a profile.

(2) *Dispersal*. Ongoing bioturbation will disperse surface and subsurface objects and stones throughout the profile (mostly within a zone 0.4–1.20 m) to produce an irregular distribution of material >3 mm, with some size sorting of larger objects (also noted by McBrearty, 1990).

(3) *Concentration*. With sufficient time (>10 kyr), bioturbation will concentrate objects >3 mm at the limits of foraging activity to form a stone layer. Such a concentration may mimic an archaeological horizon and will contain the same range of material as on the original occupation surface. A corollary of this process is creation of a stone-free mantle above the stone layer and significant pedogenesis throughout the profile. The concentration of rocks or artefacts in a stone layer depends on the duration of termite activity relative to a specific surface.

This process would be interrupted by any change in termite species (affecting foraging depth), or a change in site environment (wherever it affects termite activity), or by changes in rate of sediment accumulation. Changes in water table depth will change foraging depth.

Rapid sedimentation also changes the baseline for termite foraging depth and depth of any displaced material. If it takes 17.7 ka to concentrate stone at the limit of foraging activity, any ongoing sediment buildup during this period would alter relative foraging depth and thereby diffuse the formation of a stone line. There has to be a time step >10 kyr in sediment accumulation to give adequate time for a stone line to form. Stepwise sediment accumulation could be expected to create sequential stone lines, provided these time steps are >10 kyr. If, however, the sediment surface is actively aggrading, bioturbation should produce a more-or-less random distribution of stones or artefacts within a sediment profile.

4 DIAGNOSTIC CRITERIA FOR TERMITE STONE LAYERS

We suggest, therefore, that an array of interrelated attributes will best distinguish stone layers produced by termite bioturbation from genuine artefact horizons (Table 1). Individual attributes may be associated with an occupation layer—depending on its sedimentary history—but not as a systematic set of features.

4.1 An overlying fine-grained mantle

Sediments above a stone line are typically free of stones, artefacts, and coarse sediments >3 mm. The profile will also show changes in grain size in sand, silt, and clay fractions with the profile fining upwards. This fine-grained mantle should be evident irrespective of whether the size distribution of artefacts or the grain-size characteristics of sediment matrix are analyzed. Where it overlies bedrock, a stone line characteristically mantles a zone of saprolite.

4.2 Evidence for significant pedogenesis

There will be significant pedogenesis above a termite stone layer, evident in soil zonation within a profile. This typically involves mineral authigenesis; mobilization of clays and carbonates; elevated levels of organic C, N, P, and Ca; and the effects of illuviation. These effects in soils should be detectable by analyzing physical characteristics, geochemical properties, and micromorphology. Pedogenic processes appear to have only a limited effect on magnetic susceptibility (particularly frequency dependence) (Dalan & Banerjee, 1998) although translocation of fine-grained sediments into the mantle would be expected to enhance magnetic response, as this sediment fraction contains superparamagnetic grains. Pedogenesis may be hard to detect on siliceous sand sheets but is associated with significant translocation of medium and fine sand grains, which should be detectable in particle size analysis and in standard single-grain dispersal plots routinely used in OSL dating.

4.3 Direct evidence of termites

On micromorphological examination, termite activity can be identified by the presence of galleries with smooth, curved walls that contain fecal pellets, plant remains, or fragments of termite cuticle (Corarinsky,Bellosi & Genise, 2005; Cosarinsky, 2011). These may also include microaggregates of clay, sometimes welded with striated cement made from body fluids. Abandoned galleries may be filled with termite corpses (Sun, Haynes, & Zhou, 2013). For wood-dwelling termite species, we can also expect fecal pellets with a distinctive shape (Adams, 1984). Termites like other soil invertebrates (worms, mites, ants, and wasps), increase the porosity of soils and create crumb, microaggregate, or granular microstructures (Cosarinsky, Bellosi & Genise, 2005; Sarcinelli et al., 2009). Unlike packing voids between quartz grains in a sediment, voids from invertebrate activity are typically chamber, channel, or vug voids, sometimes with clay or organic coatings (Mujinya, et al., 2013: fig. 5). Blocky soil aggregates can be distinguished from fragments of termite mounds, which usually have inner galleries ((Villagran, Strauss, Alves, & de Oliveira, in press). The presence of clay is not sufficient indication of termite activity, unless it also preserves traces of galleries as termites typically recycle existing clay in their constructions. Not all termite material in an archaeological site will derive from *in situ* termite activity, as people are known to have used termite mounds for a range of purposes (e.g., as heat retainers in hearths).

4.4 Presence of time steps in site sedimentation >10 ka

Stone lines should be associated with discrete time steps in sedimentation (each >10 kyr). Stone layers produced from a contemporary ground surface require this surface to have been stable or in equilibrium for >10 kyr. Stone layers produced from earlier surfaces should each be associated with a significant temporal hiatus in sediment accumulation. This time step will occur around 0.3–1.2 m <u>above</u> a termite stone layer, unlike a temporal hiatus associated with an occupation layer. In the latter, occupation debris is usually associated with a palaeosurface, or with an erosional surface if this debris constitutes a lag.

4.5 Absence of stratigraphic detail

The prolonged bioturbation by termites required to produce a stone layer will erase most stratigraphic detail. In contrast, occupation units may include residual traces of features (pits, postholes, hearths), spatial patterning in occupation activities, and fine stratigraphic features evident in micromorphological analyses (e.g., laminations, evidence of trampling, lens of ash, or heating of sediments). Unlike a stony layer produced by bioturbation, the micromorphology of an occupation horizon may also show fragments of cultural material <1–2 mm. Elevated levels of phosphate and other bioavailable elements (Fe, Ca, Mg, Zn, Mn, Cu, P, organic C) may represent a cryptic stratigraphy associated with occupation, and can be distinguished from termite activity if they are vertically localized within a profile. We can also expect differences in magnetic susceptibility. Stone lines should exhibit depleted magnetic susceptibility because of preferential removal of fine-grained (superparamagnetic) sediments. In contrast, artefact horizons may show enhanced magnetic susceptibility (particularly frequency dependence) because of the effects of fires associated with occupation, and the introduction of Fe-rich materials (e.g., hematite and ochres). This is shown in other studies in northern Australia, where magnetic susceptibility has been successfully used as a proxy for rock shelter occupation (Lowe et al., 2016; Lowe, Mentzer,Wallis, & Shulmeister et, 2018).

4.6 Size sorting

In its intermediate stages, the formation of a termite stone layer can be expected to produce moderate sorting of material within a profile, with smaller objects moving farther than larger objects. Occupation horizons are polymorphic phenomena but are essentially heterogeneous accumulations of food or manufacturing refuse, without size-sorting unless reworked.

5 AN ASSESSMENT OF MADJEDBEBE AND NAUWALABILA

On these criteria, neither Madjedbebe nor Nauwablabila contain termite stone layers. However, we do not discount the possibility that the early levels at these sites may have complex geomorphic and taphonomic histories. Our working assumption is that any occupation horizon may have been degraded to some degree—but not necessarily erased—by a range of processes including (a) disturbance during accumulation (e.g., by tread age and scuff age, digging of pits, clearing of debris), (b) subsequent erosion (surface wash or aeolian deflation), or (c) by post-depositional disturbance after burial (reworking of deposits, and bioturbation).The key question for a field archaeologist is not the presence or absence of post-depositional disturbance but rather the extent of this and its impact on primary context. At Madjedbebe and Nauwalabila our assessment is that any reworking of these deposits by termites has not been sufficient to create simulacra of artefact horizons.

5.1 Madjedbebe

The deposit at Madjedbebe is an extension of massive alley-fill sand sheets in the western Arnhem Land region, and is composed of poorly sorted medium–coarse quartz sand (Roberts, Jones, & Smith, 1990; Clarkson et al., 2017). At Madjedbebe, this sand mantle is ~5 m deep and is capped by an earthy midden of mangrove gastropods associated with the last marine transgression. Within this sand sheet, stone artefacts are distributed down to 2.6–2.8 m, with three distinct bands of artefacts at depths of 2.15–2.60 m, 0.95–1.55 m and 0.35–0.70 m. The lowest of these (Phase 2) is dated by Clarkson et al. (2017) between 65.0 ± (3.7, 5.7) kyr and 52.7 ± (2.4, 4.3) kyr and this is the focus of critical attention by O’Connell et al. (2018). Several lines of evidence indicate that the band of artefacts in Phase 2 is not a stone layer produced by termite bioturbation.

- Invariably, termite stone layers are overlain by fine-grained mantles. This is absent at Madjedbebe, where pieces of broken bedrock and rock spall occur throughout the sand sheet. The deposits above each of the artefact bands have substantial numbers of artefacts - including flaked stone artefacts, grindstones, pieces of hematite and stone axes (Clarkson et al., 2017: Extended Data figs. 1 & 2, Supplementary Tables 13 &14). Overall density of stone artefacts at this site ranges from 0.06-10.93 artefacts/ litre/ spit (Clarkson et al., 2017: Supplementary Data).

- There is some evidence of pedogenesis at Madjedbebe but no indication this has led to the soil zonation typically associated with prolonged termite bioturbation. The limited micromorphology available shows that micro-faunal galleries are absent and that there are few voids. Grain-size analysis shows that the sand sheet is relatively homogenous, with a multimodal distribution, and only small amounts of clay (<2.5%). There is a minor fining upwards trend, although silt is most common within the estuarine shell midden layer, where it might be expected. There is no evidence in single-grain OSL D_e distributions for substantial translocation of sand particles (Clarkson et al., 2017: Extended Data figs. 9 & 10). However, micromorpholgy also shows that microstratigraphy is not preserved and that several types of pedo-relicts (grain coatings and small aggregates) are present (Clarkson et al., 2017: Extended Data fig. 7).

- No direct evidence of termite activity (e.g., galleries and sheeting) is evident in the micromorphology. O'Connell et al. (2018) argue that the clay in these sediments is "derived from the disintegration of defunct termite mounds." We disagree. The proportion of clay is low (<2.5%), much lower than recorded in termite mounds. In any case, presence of clay alone is not diagnostic of termite activity as termites use local clay in a substrate for their constructions. At Madjedbebe, the clay must be authigenic even if it were recycled by termites. Some evidence of small-scale disturbance is shown in the micromorphology, artefact conjoins, and radial plots of OSL D_e values (Clarkson et al., 2017). This appears to be of the order of ±10 cm. Whether this is due to bioturbation by invertebrates, disturbance by roots, or treadage and scuffage during occupation has not been determined.

- The sand sheet at Madjedbebe does not show any time steps >10 ka in site sedimentation. Neither the luminescence dates (60 OSL; 9 TL) nor the radiocarbon dates (36 ^{14}C) (Clarkson et al. 2017: Fig. 3, Supplementary Tables 1-2, 5-6) show a pattern of episodic sedimentation. Rather, the dates indicate quasi-continuous sediment accretion throughout the history of the site. Sediment accumulation within the sand sheet ranges from 2.6 ± 0.2 cm/kyr to 4.4 ± 0.4 cm/kyr—which implies that foraging depth would change >28–70 cm during the requisite time for termites to concentrate artefacts at the limit of their foraging range. Under such conditions a stone layer will not form.

- Size sorting is a stage in development of a stone line. At Madjedbebe there is no evidence for size sorting of artefacts down the stratigraphic profile (Clarkson et al., 2017:547). The larger artefacts, including grinding stones (N = 128) and ground-edge axes (N = 10) are distributed throughout the deposits and not restricted to the three artefact bands.

- Data on fine-scale stratigraphic structure is equivocal but sufficient to confirm other evidence against large-scale turnover of sediments. At Madjedbebe, hearths (N = 14) do not preserve fine structure and their stratigraphy, if any, has not been published. Nor do they preserve combustion products, such as calcitic ashes, phytoliths, burned bone fragments, rubified earth, or secondary phosphate. Other data suggest a cryptic stratigraphy is intact. For example, conjoining analyses (N = 17) found refits within artefact bands but not between them, although there is a mean vertical displacement of 10 cm. Mass-specific, low-frequency magnetic susceptibility data show peaks associated with artefact bands, which suggests that these sediments have not been significantly disturbed following deposition (Clarkson et al., 2017: Extended Data: Fig. 7, & Online Data).

5.2 Nauwalabila

Nauwalabila 1 is an open rock shelter formed by a large inclined block of sandstone detached from the southern escarpment of Deaf Adder Gorge (Jones & Johnson, 1985). The level floor of the shelter is a horizontally bedded sheet of quartz sand representing an extension of the sand apron in the gorge. The sedimentary sequence consists of 2.5 m of poorly-sorted medium sand, underlain by 0.4 m of heavily weathered rubble resting on a bedrock with interstitial pockets of oxidized red sand. The lowest artefacts were recovered within the basal rubble (at 277 cm), bracketed by OSL dates of 53.4 ± 5.4 kyr and 60.3 ± (5.8, 6.7) kyr (Roberts et al., 1994). This rubble cannot be a termite stone layer for the following reasons.

- Nowhere in this profile is there any evidence of a mantle of fine-grained, stone-free sediments above a stone line. Stone artefacts occur throughout the profile with peaks at 30 cm, 100 cm, 150 cm, and 240 cm. Between 2.15–2.50 m the sands contain pisoliths (pea-sized ironstone concentrations >5 mm) transported from a nearby laterite formation. Rocks and stones (>5 cm) are irregularly distributed throughout the profile, often lying flat in bands (e.g., at 0.8, 1.2, and 1.5 m; Jones & Johnson 1985: Fig. 9.11) and contributing ~10–20% of total sediment weight.

- Particle-size analysis shows the absence of systematic trends, with only minor textural variation within this sand sheet (Bird et al., 2002: Fig. 5). Silt and clay comprise 5–10% of the rock-shelter sediments throughout this profile. The principal grain size trend is a decrease in gravel-sized material from 2.0–2.5 m in the lower part of the sand sheet. Above 2 m, the stratigraphy is dominated by sand, with a significant increase in the ratio of silt and clay ratio from 0–1.50 m This pattern suggests a dominance of source and transport processes rather than post-depositional bioturbation.

- A key issue is whether the rubble at the base of the profile is termite-modified saprolite. This cannot be the case as the underlying bedrock is intact and forms large blocks of sandstone (>1 m). OSL dates confirm that the interstitial pockets of red sand are allochthonous, rather than products of *in situ* disintegration of base rock. The overlying rubble unit is a heavily weathered layer with granular disintegration of rocks and artefacts (6–10 cm), and mobilization of ferric oxides. This degree of weathering has no counterpart elsewhere in the profile. The rubble (likely roof fall) appears to be restricted to the rock shelter as it was not detected in a deep (>4 m) auger hole on the sand sheet 30 m outside the shelter. These patterns are not diagnostic of termite stone layers developed on a saprolite.

- There is little data on pedogenesis or micromorphology of the sediments, or direct evidence of termite activity at Nauwalabila. Although the basal rubble unit shows signs of heavy weathering, stratigraphy and particle-size data of the overlying sandy unit suggest that pedogenesis of these sediments has not been marked. It has not been determined whether any of the silt and clay in these sediments derives from illuviation down the profile. Silt and clay could also derive from *in situ* weathering of feldspars and silicates in these sediments, or be present in small amounts in local sandstones.

- The age–depth relationships of luminescence (6 OSL, 2 TL; Roberts et al., 1994: Table 2) and radiocarbon ages (n = 51; Bird et al., 2002: Table 1) do not indicate any time steps in sedimentation >10 ka, although radiocarbon data show numerous smaller reversals below 110 cm. A significant temporal hiatus between deposition of the sand sheet and the heavily weathered rubble unit might be expected on geomorphic grounds but is only accommodated by the OSL data if the outside range of uncertainties is taken. Bird et al. (2002) estimate overall sedimentation rates within the sand sheet of 4.3–12 cm/kyr, which implies that a stable ground surface has not been in place for sufficient time for a termite stone line to form.

- Size sorting of artefacts has not been explicitly addressed at Nauwalabila. However, Jones and Johnson (1985: Table 9.19) examined the distribution of different size classes of flakes as part of their typological analysis of the Nauwalabila assemblage. The size distribution of quartzite flakes is the reverse of that expected for termite bioturbation: quartzite flakes <1 cm^2 declined at depths below 100 cm, and flakes 1–4 cm^2 and >4 cm^2 increase at these depths.

- Fine stratigraphic structures are evidently not preserved in this deposit but there is an indication that some stratigraphy is present. Organic bands within the upper 1 m of the profile are associated with peaks in artefact concentrations and cannot be pedogenic overprinting. The pisolith layer (2.15–2.50 cm) must also be a genuine depositional unit, as pisoliths are allochthonous in this site, and not found at higher levels. Pisoliths are associated with Cenozoic laterized surfaces in this region. Their presence suggests that the initial phase of sand sheet accumulation at Nauwalabila involved stripping of nearby laterite surfaces.

6 CONCLUSION

If termite stone lines can mimic archaeological artefact horizons, they pose a fundamental problem for field archaeology in tropical Australia. We argue that, although bioturbation is a polythetic process, termite stone layers have diagnostic signatures that allow archaeologists to distinguish them from primary or reworked artefact horizons. Post-depositional displacement of artefacts and other coarse material by termites invariably creates a fine-grained, stone-free mantle above a stone line. High levels of termite activity also produce substantial translocation of fine sediments and are associated with pedogenesis, which can be detected in standard grain-size analyses, micromorphology, and OSL grain-dispersal plots. Termite stone lines are unlikely to be accompanied by any increase in magnetic susceptibility (particularly frequency dependence), whereas this is often the case with artefact horizons. Where termite activity has been intense, we expect any residual organic material to be finely comminuted and dominated by invertebrate fecal material. Where a stone line is produced on a saprolite, translocation of finer sediments effectively produces a biogenic sub-surface lag, leaving rocks (or artefacts) largely *in situ*.

Stone lines generally form within 0.4–1.2 m of a stable surface, at the foraging limit of termites. Estimates of the time required for bioturbation to produce a stone line range from 11.5–33 kyr and are consistently >10 kyr, indicating that prolonged bioturbation from a quasi-stable surface is a prerequisite for their formation. In a stratigraphic sequence, this will manifest as time steps >10 kyr in sediment accumulation about 0.2–1.2 m above a stone line. The absence of a time step does not imply that termite bioturbation is absent, only that it has not been sufficiently prolonged to produce a stone line.

Our assessment of the early archaeological horizons at Madjedbebe and Nauwalabila is that neither are consistent with their identification as stone lines produced by termite bioturbation (O'Connell et al., 2018). These two sites may have complex geomorphic and techonomic histories but we disagree that available data show that termite turnover of sediments has produced these artefact horizons.

ACKNOWLEDGMENTS

Both IW and IM are recipients of Australian Research Council Discovery Early Career Awards, respectively DE180100601 and DE160100703, funded by the Australian Government. IM also holds a Commonwealth Rutherford Fellowship funded by the Commonwealth Scholarships Commission, and thanks Homerton College, University of Cambridge, for hosting him as a Research Associate during the writing of this manuscript. We are grateful to Tom Musselman for his assistance with proof reading and editing this manuscript.

CONFLICT OF INTEREST STATEMENT

IW and IM declare no conflict of interest in writing this paper. MS advises that he was a member of excavation teams at Madjedbebe in 1989, 2012 and 2015, a member of the 1989 field team that reopened the trench at Nauwalabila to obtain OSL samples, and was co-author of publications on the chronology and stratigraphy of these sites.

REFERENCES

Adams, K.R. (1984). Evidence of wood-dwelling termites in archaeological sites in the southwestern United States. *Journal of Ethnobiology,* 4, 29-43.

Abensperg-Traun, M., & Steven, D. (1997). Latitudinal gradients in the species richness of Australian` termites (*Isoptera*). *Australian Journal of Ecology,* 22, 471-476.

Ali, I.G., Ahmed, B.M., Sheridan, G. & French, J.R.J. (2016). The effect of termite activity on soil profile in a laboratory test tank. *IOSR Journal of Agriculture and Veterinary Science,* 9, 97-108.

Andersen, A., Jacklyn, P., Dawes-Gromadzki, T., & Morris, I. (2005). *Termites of Northern Australia.* Alice Springs: CSIRO and Tropical Savannas CRC.

Armour-Chelu, M. & Andrews, P. (1994). Some effects of bioturbation by earthworms (*Oligochaeta*) on archaeological sites. *Journal of Archaeological Science,* 21, 433-443.

Asawalam, D.O. & Johnson, S. (2007). Physical and chemical characteristics of soils modified by earthworms and termites. *Communications in Soil Science and Plant Analysis,* 38, 513-521.

Bateman, M.D., Boulter, C.H., Carr, A.S., Frederick, C.D., Peter, D. & Wilder, M. (2007). Preserving the palaeoenvironmental record in drylands: bioturbation and its significance for luminescence-derived chronologies. *Sedimentary Geology,* 195, 5-19.

Bird, M.I., Turney, C.S.M., Fifield, L.K., Jones, R., Ayliffe, L.K., Palmer, A., Cresswell, R.,. & Robertson, S. (2002). Radiocarbon analysis of the early archaeological site of Nauwalabila I, Arnhem Land, Australia: implications for sample suitability and stratigraphic integrity. *Quaternary Science Reviews* 21, 1061–1075.

Black, H. I. J., & Okwakol, M. J. N. (1997). Agricultural intensification, soil biodiversity and agroecosystem function in the tropics: the role of termites. *Applied Soil Ecology,* 6, 37–53.

Braithwaite, R.W., Miller, L. & Wood, J.T. (1988). The structure of termite communities in the Australian tropics. *Australian Journal of Ecolog*y, 13, 375-39.

Buatois, L.A., Uba, C.E., Gabriela, M.M., Hulka. C. & Heubeck, C. (2007). Deep and intense bioturbation in continental environments: evidence from Miocene fluvial deposits of Bolivia. *SEPM Special Publications,* 88, 123-136.

Cahen, D. & Moeyersons, J. (1977). Subsurface movements of stone artifacts and their implications for the prehistory of Central Africa. *Nature,* 266, 812-815.

Canti, M.G. (2003). Earthworm activity and archaeological stratigraphy: a review of products and processes. *Journal of Archaeological Science,* 30, 135–148.

Clarkson, C., Jacobs, Z., Marwick, B., Fullagar, R., Wallis, L., Smith, M., Roberts, R.G., Hayes, E., Lowe, K., Carah, X., Florin, A., McNeil, J., Cox, D., Arnold, L.J., Hua, Q., Huntley, J., Brand, H.E.A., Manne, T., Fairbairn, A., Shulmeister, J., Lyle, L., Salinas, M., Page, M., Connell, H., Park, G., Norman, K., Murphy, T. & Pardoe, C. (2017). Human occupation of northern Australia by 65,000 years ago. *Nature,* 547, 306-31.

Cosarinsky, M.I. (2011). The nest growth of the Neotropical mound-building termite, *Cornitermes cumulans:* a micromorphological analysis. *Journal of Insect Science,* 11, 122.

Cosarinsky, M.I., Bellosi, E.S. & Genise, J.F. (2005). Micromorphology of modern epigean termite nests and possible termite ichnofossils: a comparative Analysis (Isoptera). *Sociobiology,* 45, 1-34.

Dalan, AR. & Banerjee, S.K. (1998). Solving archaeological problems using techniques of soil nagnetism. *Geoarchaeology*, 13, 3-36.

Darwin, C. (1882). *The formation of vegetable mould through the action of worms.* London: John Murray [Corrected edition].

Eldridge, D.J. (1993). Effect of ants on sandy soils in semi-arid eastern Australia - Local distribution of nest entrances and their effect on infiltration of water. *Australian Journal of Soil Research,* 31, 509-518.

Gingras, M.K., Bann, K.L., MacEachern, J.A., Waldron, .J & Pemberton, G.S. (2007). A conceptual framework for the application of trace fossils. In: J.A., MacEachern, K.L., Bann, M.K., Gingras & S.G., Pemberton (Eds.), *Applied Ichnology*, SEPM Short Course Notes, 52, 1–25.

Gray, F.J. & Calaby, J.H. (1970). Termites from the Australian Region. In K., Krishna & F.M., Weesner (Eds.) *Biology of Termites*, pp. 393-448.New York: Academic Press.

Holt, J.A., Coventry, R.J. & Sinclair, D.F. (1980). Some aspects of the biology and pedological significance of mound-building termites in a red and yellow earth landscape near Charters Towers, north Queensland. *Australian Journal of Soil Research,* 18, 97–109.

Humphreys, G.S. (1981). The rate of ant mounding and earthworm casting near Sydney, New South Wales. *Search,* 12, 129–131.

Johnson, D.L. (1989). Subsurface stone lines, stone zones, artifact-manuport layers, and biomantles produced by bioturbation via Pocket Gophers (*Thomomys bottae*). *American Antiquity,* 54, 370-389.

Johnson, D.L. (1990). Biomantle evolution and the redistribution of earth materials and artifacts. *Soil Science,* 149, 84-102.

Jones, D.T. & Eggleton, P. (2011). Global biogeography of termites: a compilation of sources. In D.E. Bignell, Y,Roisin & N. Lo (eds.), *Biology of Termites: A Modern Synthesis*, pp. 477–498. Dordrecht, Springer Netherlands.

Jones, R. & Johnson, I. (1985) Deaf Adder Gorge: Lindner Site, Nauwalabila I. In R. Jones (ed.) *Archaeological research in Kakadu National Park*, pp. 165- 227. Australian National Parks & Wildlife Service, Special Publication 13. Canberra: Commonwealth of Australia.

Jouquet, P., Bottinelli, N., Shanbhag, R.R., Bourguignon, T., Traoré, S. & Abbasi, S.A., (2016). Termites: the neglected soil engineers of tropical soils, *Soil Science.* 181 , 157-165.

Kristensen, J.A., Thomsen, K.J., Murray, A.S., Buylaert, J-P., Jain, M. & Breuning-Madsen, H. (2015). Quantification of termite bioturbation in a savannah ecosystem: Application of OSL dating, *Quaternary Geochronology, 3*0, 334-341.

Ku, S.J., Su, N-Y. & Lee, S-H. (2013). Movement efficiency and behavior of termites (Isoptera) in tunnels with varying pore sizes, *Florida Entomologist,*. 96, 810–817.

Lecomte, P. (1988). Stone line profiles: importance in geochemical exploration, *Journal of Geochemical Exploratio,* 30, 35–61.

Lee K.E. & Wood, T.G. (1971a). Physical and chemical effects on soils of some Australian termites, and their pedological significance. *Pedobiologia*, 11, 376-409.

Lee, K.E. & Wood, T.G. (1971b). *Termites and Soils*. New York: Academic Press.

Li, H., Lu, J. & Mo, J. (2012). Physiochemical lignocellulose modification by the Formosan subterranean termite *Coptotermes formosanus shiraki* (Isoptera: Rhinotermitidae) and its potential uses in the production of biofuels, *BioResources*, 7, 675–685.

Lobry de Bruyn, L.A. & Conacher, A. (1990). The role of termites and ants in soil modification: A review, *Australian Journal of Soil Research*, 28, 55-93.

Lowe, K. M., Cole, N., Burke, H., Wallis, L. A., Barker, B., & Hatte, E. (2018). The archaeological signature of 'ant bed' mound floors in the northern tropics of Australia: Case study on the Lower Laura (Boralga) Native Mounted Police Camp, Cape York Peninsula. *Journal of Archaeological Science: Reports*, 19, 686–700.

Lowe, K. M., Mentzer, S. M., Wallis, L. A., & Shulmeister, J. (2018). A multi-proxy study of anthropogenic sedimentation and human occupation of Gledswood Shelter 1: exploring an interior sandstone rockshelter in Northern Australia. *Archaeological and Anthropological Sciences*, 10, 279–304.

Lowe, K. M., Shulmeister, J., Feinberg, J. M., Manne, T., Wallis, L. A., & Welsh, K. (2016). Using Soil Magnetic Properties to Determine the Onset of Pleistocene Human Settlement at Gledswood Shelter 1, Northern Australia. *Geoarchaeology*, 31, 211–228.

Maher, B. A. (1998). Magnetite biomineralization in termites. *Proceedings of the Royal Society of London*. Series B: Biological Sciences, 265, 733–737.

Malaka, S.L.O. (1977). A note on bulk density of termite mounds, *Australian Journal of Soil Researc,* 15, 93-94.

McBrearty, S. (1990). Consider the humble termite: termites as agents of post-depositional disturbance at African archaeological sites, *Journal of Archaeological Science*, 17, 111-143.

Moeyersons, J. (1978). The behaviour of stones and stone implements buried in consolidating and creeping Kalahari sands*, Earth Surface Processes,* 3, 115-128.

Mujinya, B.B., Mees, F., Erens, H., Dumon, M., Baert, G., Boeckx, P., Ngongo, M. & Van Ranst, E. (2013). Clay composition and properties in termite mounds of the Lubumbashi area, D.R. Congo, *Geoderma,* 192, 304–315.

Nye, P.H. (1955). Some soil-forming processes in the humid tropics. IV. The action of the soil fauna*, Journal of Soil Science,* 6, 73-83.

Nehren, U., Kirchner, A. & Heinrich, J. (2016). What do yellowish-brown soils and stone layers tell us about Late Quaternary landscape evolution and soil development in the humid tropics? A field study in the Serra dos Órgãos, Southeast Brazil, *Catena,* 137, 173–190.

O'Connell, J.F., Allen, J., Williams, M.A.J., Williams, A.N., Turney, C.S.M., Spooner, N.A., Kamminga, J., Brown, G. & Cooper, A. (2018). When did Homo sapiens first reach Southeast Asia and Sahul?, *PNAS.* doi/ 10.1073/pnas.1808385115.

Paton, T.R. (1978). *The formation of soil material,* London: George Allen and Unwin.

Petts, A.E., Hill, S.M. & Worrall, L. (2009). Termite species variations and their importance for termitaria biogeochemistry: towards a robust media approach for mineral exploration, G*eochemistry: Exploration, Environment, Analysis,* 9, 257-266.

Rink, W.J., Dunbar, J.S., Tschinkel, W.R., Kwapich, C., Repp, A., Stanton, W. & Thulman, D.K. (2013). Subterranean transport and deposition of quartz by ants in sandy sites relevant to age overestimation in optical luminescence dating, *Journal of Archaeological Science,* 40, 2217-2226.

Roberts, R.G., Jones, R. & Smith, M.A. (1990). Thermoluminescence dating of a 50,000 year-old human occupation site in northern Australia, *Nature.* 345,153-6.

Roberts, R.G., Jones, R., Spooner, N.A., Head, M.J., Murray, A.S. & Smith, M.A. (1994). The human colonisation of Australia: optical dates of 53,000 and 60,000 years bracket human arrival at Deaf Adder Gorge, Northern Territory, *Quaternary Geochronology (Quaternary Science Reviews),* 13, 575-583.

Ruhe, R.V. (1959). Stone lines in soils, *Soil Science,* 87, 223-231.

Salvador-Blanes, S., Minasny, B. & McBratney, A.B. (2007). Modelling long-term *in situ* soil profile evolution: application to the genesis of soil profiles containing stone layers, *European Journal of Soil Science,* 58, 1535–1548.

Sarcinelli, T.S., Schaefer, C.E.G.R., Lynch, L.D.S., Arato, H.D., Viana, J.H.M., Filho, M.R.D.A., & Gonçalves, T.T. (2009). Chemical, physical and micromorphological properties of termite mounds and adjacent soils along a toposequence in Zona da Mata, Minas Gerais State, Brazil. *Catena,* 76, 107–113.

Sharpe, C.F.S. (1938). *Landslides and Re-lated Phenomena.* New York: Columbia University Press.

Smith, G.B., Roach, A.M.E., Rentz, D.C.F., Miller, L.R., Abbey, H.M., Watson, J.A.L., Balderson, J., Cassis, G. & New, T.R. (1998). *Zoological Catalogue of Australia, Volume 23, Archaeognatha, Thysanura, Blattodea, Isoptera, Mantodea, Dermaptera, Phasmatodea, Embioptera, Zoraptera.* Australia: CSIRO/ABRS.

Stewart, A.D., Anand, R.R. & Balkau, J. (2012). Source of anomalous gold concentrations in termite nests, Moolart Well, Western Australia: implications for exploration, *Geochemistry: Exploration, Environment, Analysis*,12, 327-337.

Sun, Q., Haynes, K.F. & Zhou, X. (2013). Differential undertaking response of a lower termite to congeneric and conspecific corpses, *Scientific Reports,* 3: 1650.

Tschinkel, W.R., Rink, W.J. & Kwapich, C.L. (2015). Sequential subterranean transport of excavated sand and foraged seeds in nests of the Harvester Ant, *Pogonomyrmex badius*, *PLoS One.* 10(10): e0139922. *doi:10.1371/journal.pone.0139922.*

Villagran XS, Strauss A, Alves M, and de Oliveira RE. (in press) Complementing micromorphology: the application of micro CT scanning for identification of termite mounds in archaeological sediments. *Journal of Archaeological Sciemce Reports* (in press).

Watson, J.P. (1962). The soil below a termite mound, *European Journal of Soil Science*, 13, 46-51.

Whitford, W.G. & Eldridge, D.J. (2013). Effects of ants and termites on soil and geomorphological processes. In J. Shroder, D.R. Butler & C.R. Hupp (eds.) *Treatise on Geomorphology*, pp.281-292. San Diego CA: Academic Press.

Williams, M.A.J. (1968). Termites and soil development near Brocks Creek, Northern Territory, *Australian Journal of Science*, 31, 153-154.

Williams, M.A.J. (1978). Termites, soils and landscape equilibrium in the Northern Territory of Australia**.** In J.L. Davies & M.A.J. Williams MAJ (eds.) *Landform Evolution in Australas*

Figure 1. Madjedbebe and Nauwalabila. (a) Location, showing the two sites in relation to the Arnhem Land plateau. (b) Stratigraphic profile for Madjedbebe (after Clarkson et al., 2017: Extended Data fig 1a). (c) Stratigraphic profile for Nauwalabila (after Bird et al, 2002: fig 2).

Table 1. Diagnostic criteria for termite stone layers. Depending on sedimentary history, individual attributes may occur in a profile containing an occupation horizon but not as an array of inter-related attributes.

Table 1: Diagnostic criteria for termite stone layers. Depending on sedimentary history, individual attributes may occur in a profile containing an occupation horizon but not as an array of inter-related attributes.

- An overlying fine-grained mantle
- Evidence of pedogenesis above the stone layer
- Evidence of termite activity
- Time steps >10 kyr in sedimentation above a stone layer
- Absence of stratigraphic detail and micro-cultural material