Movement of lithics by trampling: An experiment in the Madjedbebe sediments, northern Australia

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Understanding post-depositional movement of artefacts is vital to making reliable claims about the formation of archaeological deposits. Human trampling has long been recognised as a contributor to post-depositional artefact displacement. We investigate the degree to which artefact shape attributes can predict how an artefact is moved by trampling. We use the Zingg shape classification system to describe artefact shape. Our trampling substrate is the recently excavated archaeological deposits from Madjedbebe, northern Australia. Madjedbebe is an important site because it contains early evidence of human activity in Australia. The age of artefacts at Madjedbebe is contentious because of the possibility of artefacts moving due to trampling. We trampled artefacts in Madjedbebe sediments and measured their displacement, as well as modelling the movement of artefacts by computer simulation. Artefact elongation is a significant predictor of horizontal distance moved by trampling, and length, width, thickness and volume are significant predictors of the vertical distance. The explanatory power of these artefact variables is small, indicating that many other factors are also important in determining how an artefact moves during trampling. Our experiment indicates that trampling has not contributed to extensive downward displacement of artefacts at Madjedbebe.

Introduction

Claims for the first evidence of human activity, or of new types of activity, at many archaeological sites depend on a close stratigraphic association between culturally modified materials and dated materials. To be confident of these associations we need a robust understanding of the process of artefacts displacement from their original locations due to post-depositional processes. Examples of problematic vertical separation of artefacts that complicate the interpretation of archaeological deposits have been known for some time. For example, Villa and Courtin (1983) describe conjoinable artefacts up to 1 m vertically apart and in different deposits. Similarly, Cahen and Moeyersons (1977) report refitting artefacts up with to 1 m of vertical separation at Gombe Point in Zaire. At FxJj50, Koobi Fora, Kenya, Bunn et al. (1980) report conjoinable pieces up to 50 cm apart vertically in brief occupation deposits of alluvial sandy silt. At Cave Spring, Tenessee, Hofman (1986) recorded refitting artefacts over 20-40 cm of vertical distance. Richardson (1992) observed a maximum vertical separation of 30 cm for conjoining artefacts from different excavation units at Kenniff Cave (Queensland, Australia). In this paper we use geological methods to explore clast shape and size metrics to identify relationships that might help identify artefacts that have moved due to trampling, and given the

38 shape attributes of an assemblage, to understand the magnitude of movement that may have
39 occurred in an assemblage.

40 Our motivation for this study arises from claims of vertical movement of artefacts in debates
41 surrounding the timing of the first human occupation of Sahul, where the archaeological deposits
42 are often sandy and lacking well-defined stratigraphy. Investigations at archaeological sites in
43 northern Australia recovered small numbers of flaked stone artefacts from sandy rockshelter
44 deposits associated with Optically Stimulated Luminescence ages (OSL) 50-60 k BP. The
45 reliability of these associations has been questioned, with critics claiming that post-depositional
46 processes have brought the stone artefacts in association with much older sediments. At
47 Madjedbebe (formerly Malakunanja II), one of Australia's oldest sites, trampling of artefacts has
48 been frequently proposed as a possible cause of dislocation of artefacts through down through
49 the deposit into an association with sediments much older than the artefacts. In this paper we
50 describe a trampling experiment directly relevant to Madjedbebe and other sites with sandy
51 deposits in coastal or desert environments.

52 Because of the importance of their effect on the understanding artefact contexts and associations,
53 trampling experiments are a mainstay of archaeological science. For example, Eren et al. (2010)
54 summarised fourteen publications of trampling experiments, all aimed at understanding how
55 human and animal trampling contribute to the spatial displacement of, and damage to, object
56 commonly found in archaeological sites. The aim of our experiment was to understand how
57 artefacts move in a sandy deposit when trampled by walking. Specifically, we explored the
58 relationship between artefact shape parameters and the distance they were moved by trampling.
59 We follow Eren et al. (2010) in focusing on short-term trampling events, and by recording the
60 position, orientation and inclination of the artefacts between each trampling event.

61 The design of our experiment includes two novel elements not seen in previous trampling
62 studies. First, the substrate for our trampling experiment was the same sediment as the
63 archaeological site that motivated the experiment. A similar experimental setup was used by
64 Benito-Calvo et al. (2011), who simulated an archaeological sediment fabric by adding clasts to a
65 nearby non-archaeological deposit. In contrast, we conducted our trampling experiment directly
66 on the spoil heaps of archaeological sediment removed during the 2012 excavations at
67 Madjedbebe. The use of site specific archaeological sediment adds a degree of realism to our
68 trampling model. Interactions between the experimental artefact movement and trampling more
69 faithfully resemble what might have happened in the past because we used the archaeological
70 sediments. This ensures a close match for texture and penetrability between the experimental
71 setup and the archaeological site. Our experiment still has many differences from the
72 archaeological contexts; for example, we were not able to exactly match the compaction and
73 fabric, or directional properties, of particular archaeological layers. Furthermore, we cannot be
74 sure of the nature of the archaeological sediment at the time the artefacts were deposited and
75 trampled in prehistory, because post-depositional processes have likely altered the sediment
76 matrix. However, our field observations were that the spoil heaps closely resembled the
77 structure, cohesiveness, permeability and moisture content of the archaeological deposits at
78 Madjedbebe.

79 Our second novel element is the use of a system for classifying artefact shape that is derived
80 from geological studies of the effect of particle shape on their movement in sediments. Previous
81 studies have used artefact length or mass as a proxy for artefact size to investigate the

82 relationship between size and movement (e.g. Gifford-Gonzalez et al., 1985; Nielsen, 1991). As
83 Eren et al. (2010) note, previous studies are not unanimous in demonstrating a relationship
84 between artefact size and movement. This may be because length and mass by themselves are
85 not especially sensitive variables when considering artefact movement. In studying the natural
86 movement of clasts on the landscape, sedimentary geologists have developed a number of shape
87 quantification systems to investigate the transport history of sediments and characterize
88 depositional environments (Benn et al., 1992; Blott and Pye, 2008; Oakey et al., 2005; Woronow
89 and Illenberger, 1992). We adopted the simplest of these, the Zingg system, to quantify artefact
90 shape and investigate its relationship with movement resulting from trampling.

91 **Madjedbebe**

92 Previously known as Malakanunja II, Madjedbebe is a sandstone rockshelter at the edge of the
93 Magella floodplain in the Northern Territory, Australia. Archaeological excavations were
94 conducted at Madjedbebe in 1973 (Kamminga et al., 1973), 1989 (Clarkson et al., 2015; Roberts
95 et al., 1990), 2012 and 2015. The 1989 excavation produced Thermoluminescence (TL) and OSL
96 ages of 52 ± 11 and 61 ± 13 ka associated with the lowest artefacts in the deposit (Roberts et al.,
97 1990). The nearby site of Nauwalabila returned similar OSL ages, bracketing the ages of the
98 lowest artefacts at between 53 ± 5 and 60.3 ± 6 ka (Bird et al., 2002; Roberts et al., 1994).
99 These dates were questioned by Hiscock (1990) and Bowdler (1991), and later by Allen and
100 O'Connell (2003) and Allen and O'Connell (2014). We have previously discussed these concerns
101 in detail in Clarkson et al. (2015). Here we focus only on Hiscock's suggestion of the possibility
102 of downward displacement of artefacts into sterile layers through human treadage.

103 Hiscock cited previous work (e.g. Stockton, 1973) that documented vertical movement of
104 artefacts up to 16 cm. If movements of this magnitude are common in sandy deposits such as
105 Madjedbebe, then the artefacts associated with the 52 and 61 ka BP ages may have originally
106 been deposited on a much younger occupational surface, and then been displaced downward into
107 older deposits that are unrelated to human occupation. Hiscock's suggestion is that, for example,
108 an artefact at the level of the 52 ka age, 242 cm below the surface, may have originally been
109 deposited during occupation at c. 200 cm below. Using a loess regression on the ages published
110 in Clarkson et al. (2015), we can interpolate a calibrated age of 23.3 ka BP for 200 cm below the
111 surface. The difference in age of 29,000 years between 242 and 200 cm below the surface is
112 substantial, and the ages at each depth have very different implications for how we interpret the
113 stone artefact assemblage.

114 Previously, we reported on two factors that suggest this kind of downward displacement has not
115 been extensive at Madjedbebe (Clarkson et al., 2015). First, we noted that there are several
116 artefacts found within the same excavation unit that conjoin. We take these conjoins as evidence
117 that downward displacement has had only a small effect on this assemblage. Second, we showed
118 that there are clear changes in the abundance of raw materials over time. These changes would
119 be heavily obscured if there was substantial downward displacement of artefacts at Madjedbebe.
120 We believe it is unlikely that the all the artefacts associated with the 52 ka age are actually 23.3
121 ka old. However, we recognise the potential for artefact movement at the scale described by
122 Hiscock, and with this experiment we intended to get a better understanding of what components
123 of the lithic assemblage are most susceptible to this kind of downward displacement, and how
124 much of the assemblage was displaced to this extent.

Materials and methods

Lithic assemblage

We collected nodules of white quartz from the landscape and used hard-hammer direct percussion to remove flakes, following a multi-platform reduction pattern. Quartz nodules occur in the local sandstone scarp formation. Quartz artefacts are abundant in the archaeological deposit, especially in the Holocene levels. We selected 30 flakes for the experiment, spray-painted the artefacts bright orange and numbered them to make them easy to identify after each trampling event. Metric data from the artefacts recovered in 1989 are not available, but we produced the artefacts to be within the size range of the artefacts we were recovering from the 2012 excavations (analysis of these artefacts is in progress).

Shape measurement

The overall shape of a clastic particle, such an artefact, is difficult to conveniently reduce to a single measurement with precision and accuracy. In attempting to summarise an artefact's shape, archaeologists have developed a variety of methods for producing multivariate descriptions of artefact shape in two- and three-dimensions (eg. Grosman et al., 2008; Lycett et al., 2006). While these methods have provided insights into reduction strategies and assemblage comparison, they require specialised equipment (such as a three-dimensional scanner or photogrammetry equipment) that was not available to us for our experiment. Instead, we used linear measurements of artefacts obtained with vernier calipers to compute indices of artefact shape. These linear measurements can be used with the Zingg system to summarize artefact shape. Although there is extensive discussion on the question of the best clast shape classification method amongst geologists, there is little agreement (Blott and Pye, 2008; Woronow and Illenberger, 1992). We chose the Zingg because it is the simplest and most widely used shape classification system for geological clasts (Figure 1).

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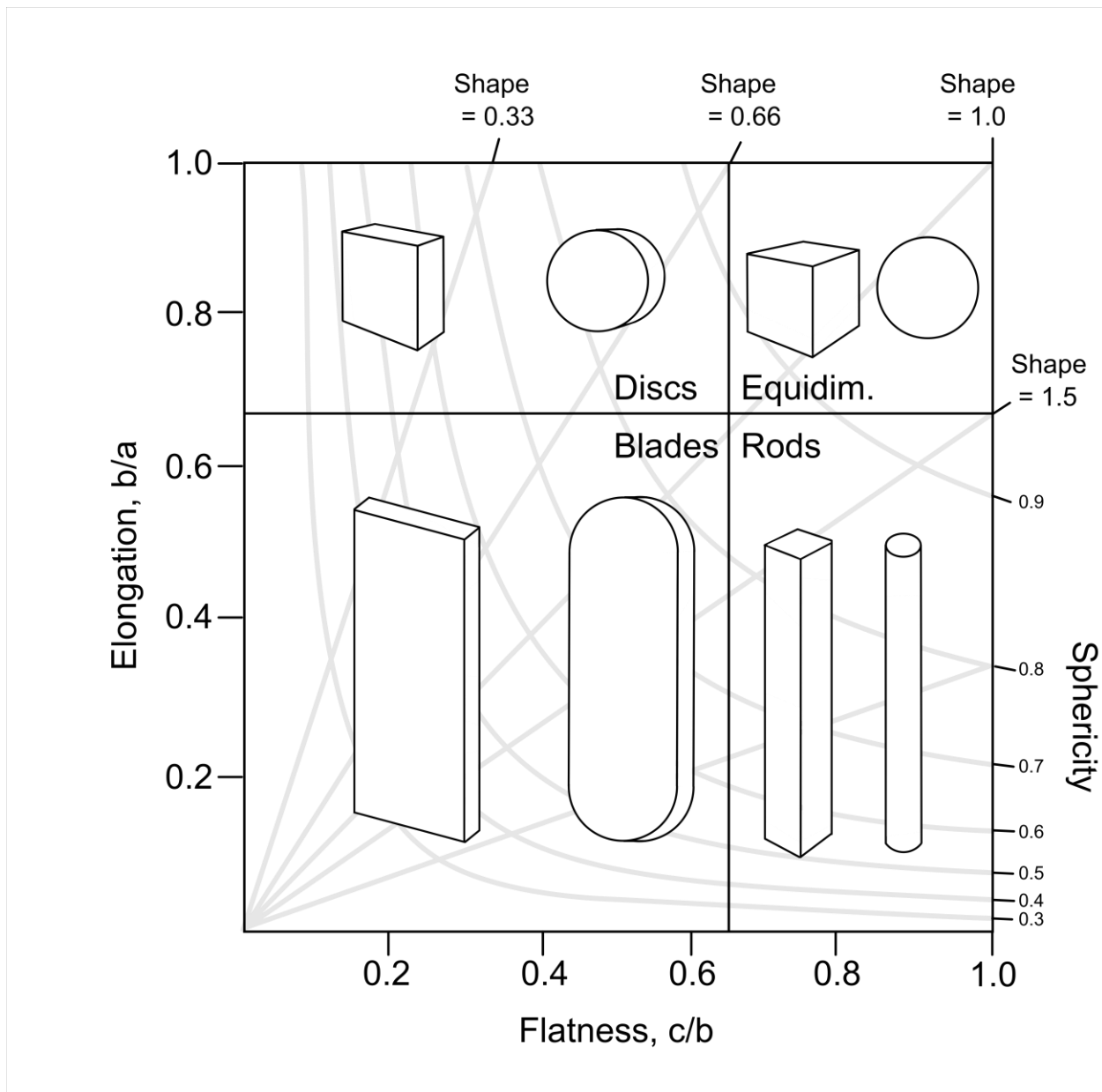
Figure 1: Schematic of the Zingg classification of geological clast shape
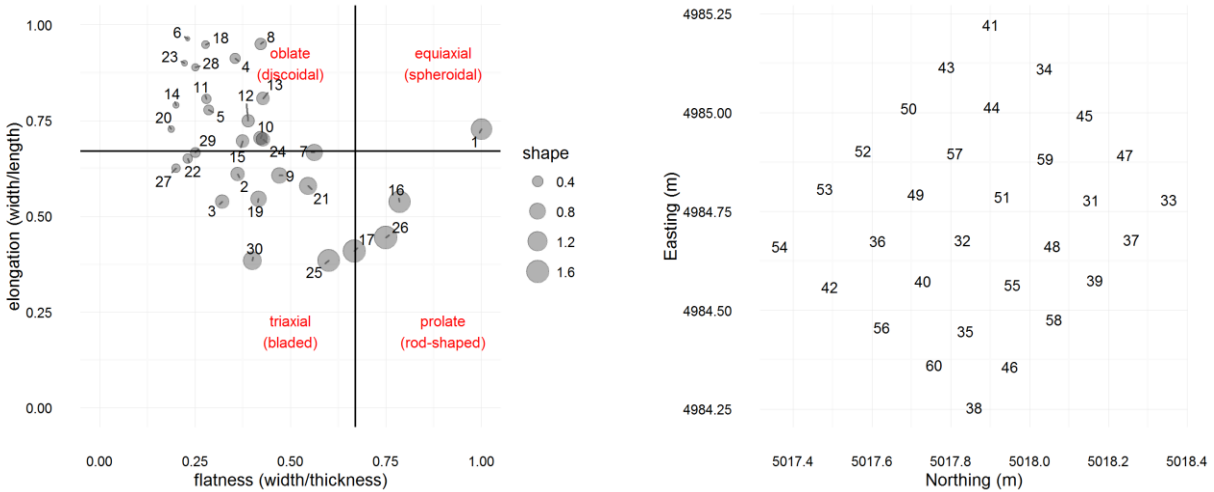
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Figure 2: Left: Zingg Diagram classifying the shape of the experimental artefacts. Right: Starting locations of the experimental artefacts before trampling.

Zingg indices are derived from the measurement of the three principal axes of the approximating tri-axial ellipsoid. The three principal axes are the longest axis (denoted as *a*), the second longest axis perpendicular to the longest axis (*b*), and the third longest axis perpendicular to both *a* and *b* (denoted as *c*). These measurements are not oriented with respect to the percussion axis of the artefact. This is because the percussion attributes have little relevance to how the artefact interacts with the sedimentary deposit during trampling. We simply measured the longest axis on the artefact without regard to the flaking attributes, and then the longest axis that is perpendicular to the first axis (the intermediate axis), and then the longest axis perpendicular to that (the short axis). Volume is taken as the log of the product of *a*, *b*, and *c*. To obtain the Zingg indices for a given artefact, we first determined the directions for principal axes of the artefact, then measured the axes, and finally computed the axis ratios *b*/*a* (Zingg's elongation ratio) and *c*/*b* (Zingg's flatness ratio). Zingg's shape factor is flatness divided by elongation. A round or cubic artefact will have a shape factor equal to 1, more elongated and thin artefacts will have a shape factor greater than 1, and a disc shaped artefact will have a shape factor less than 1 (Uthus et al., 2005). The Zingg classifications of the artefacts used in the trampling experiment are presented in Figure 2.

170

Figure 3: Views of the trampling area on the excavation spoil heaps.

172

Figure 4: Close-up of trampling area showing the arrangement of artefacts before trampling (left, grid spacing in 10 cm) and after five minutes (right, scale rod bars are 10 cm)

Trampling area, setup and events

The trampling area was a level surface on the spoil heap of sediment removed during the 2012 excavations at Madjedbebe (Figure 3). After excavation, the sediment was sieved through 7 mm and 3 mm sieves and dumped in a pile where it was stored until the excavation was backfilled. We used shovels to create a level surface on the spoil heap of about three by three meters. We waited until near the end of the excavation so that the trampling experiment could be conducted on sediments removed from the lowest artefact-bearing deposits at Madjedbebe. Waiting until the end of the excavation imposed time constraints on the experiment, limiting the scale of our

183 study, because our excavation permit required immediate backfilling at the end of the field
184 season.

185 The artefacts were arranged on a one meter grid in the centre of the trampling area (Figure 4).
186 The artefacts were positioned 10 cm from each other. The location of the artefacts was recorded
187 with a total station after they were placed on the grid, and after each trampling event. Of the
188 thirty artefacts, 12 were over two centimeters long and recorded using two points at either end of
189 their longest axis. The remaining 18 were recorded with a single point at their center of mass.

190 Each trampling episode consisted of an adult male walking barefoot at a constant natural slow
191 walking speed. Our subject walked continuously in a clockwise circuit that included the
192 trampling area for five minutes for each event. The walker crossed the trampling area in the same
193 direction each time. At the end of five minutes, we carefully exposed the artefacts in situ with
194 small leaf trowels, and used a total station to record their location, and for the larger ones,
195 orientation and inclination.

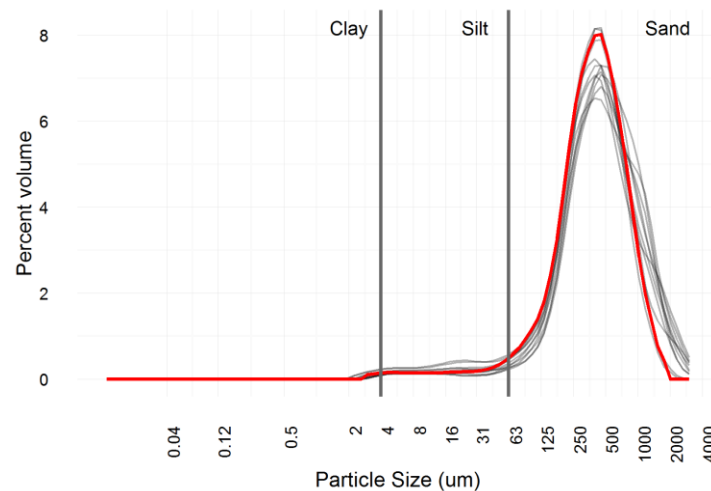196 Trampling substrate

197

198 *Figure 5: Particle size distributions of sediment collected from the trampling area (bold red*
199 *line) and sediment collected from the archaeological excvation, 3-4 m below the surface*

200 The trampling area was a levelled section of the excavation spoil heap. The sediments came from
201 3-4 m below the surface, and had passed through 7 mm and 3 mm sieves before being dumped
202 on the spoil heap. Although the sediment has been sieved, the texture of a sample taken from the
203 spoil heap sediment remains identical to samples taken from the archaeological deposit, 3-4m
204 below the surface (Figure 5). A permutation test for significant differences between any of these
205 samples returns a p-value of 1 (99% confidence interval: 0.999- 0.999 estimated from 10,000
206 Monte Carlo replications).

207 Regression models and model visualisations

208 To investigate how the artefacts' shape and size variables predicts their movements during
209 trampling, we computed linear models (Chambers, 1991) for each combination of artefact
210 attribute and movement. For each model we visually inspected the independence of residuals,
211 homoscedasticity (constant variance of the residuals), and the distribution of the residuals to

212   verify that our data are consistent with the assumptions of linear modelling. These plots are
213   available in our SOM. Here we present visual summaries of several models, following Wickham
214   et al. (2015). We introduce a new kind of plot, the model ensemble plot, to show model-level
215   summary statistics. These model ensemble plots are an information-dense visualisation that is
216   useful for exploring and comparing the importance of predictors in multiple models. These
217   scatterplots show the models' adjusted R^2 values, standardarised estimates and p-values. The
218   adjusted R^2 values (on the vertical axis) shows model fit as an estimate of the proportion of
219   variance explained by the variable under consideration (Faraway, 2014). Standardarised
220   estimates (on the horizontal axis) are useful as measures of relationship strength for each variable
221   because they can be interpreted as the change in response when the predictor changes by one
222   standard deviation, if all other variables are held constant (Wickham et al., 2015). Standardarised
223   estimates also show the slope of the regression line and thus the direction of the relationship
224   between the variables (i.e. a positive or negative relationship). Our model ensemble plots show
225   the models' p-value of the models as proportional to the size of the data points (larger points
226   indicate lower p-values), with $p < 0.05$ values indicated by hollow points to highlight models
227   with a very low probability of obtaining the observed data or more extreme data, given a
228   hypothesis of no association between the variables (Greenland et al., 2016).

229   Reproducibility and open source materials

230   To enable re-use of our materials and improve reproducibility and transparency according to the
231   principles outlined in Marwick (2016), we include the entire R code used for all the analysis and
232   visualizations contained in this paper in our SOM at http://dx.doi.org/10.17605/OSF.IO/7A6H6.
233   Also in this version-controlled compendium are the raw data for all the tests reported here, as
234   well as additional regression diagnostics and power tests. All of the figures, tables and statistical
235   test results presented here can be independently reproduced with the code and data in this
236   repository. In our SOM our code is released under the MIT licence, our data as CC-0, and our
237   figures as CC-BY, to enable maximum re-use (for more details, see Marwick, 2016).

0-5min

0-5-10 min

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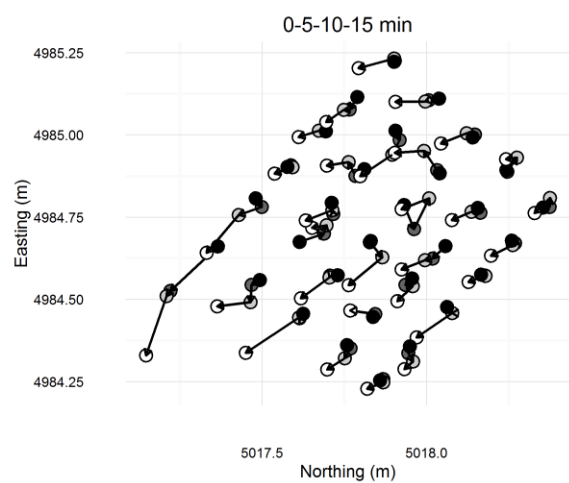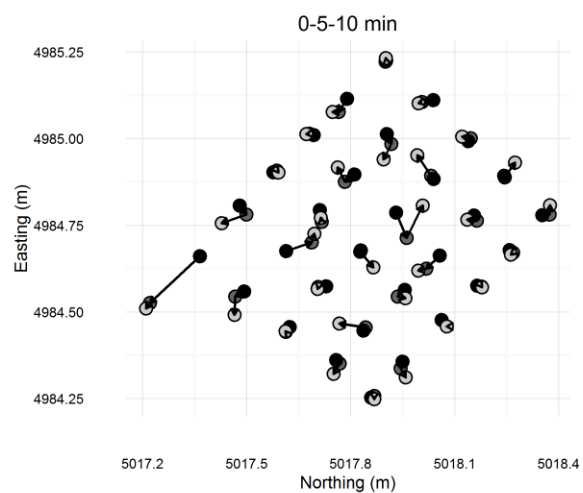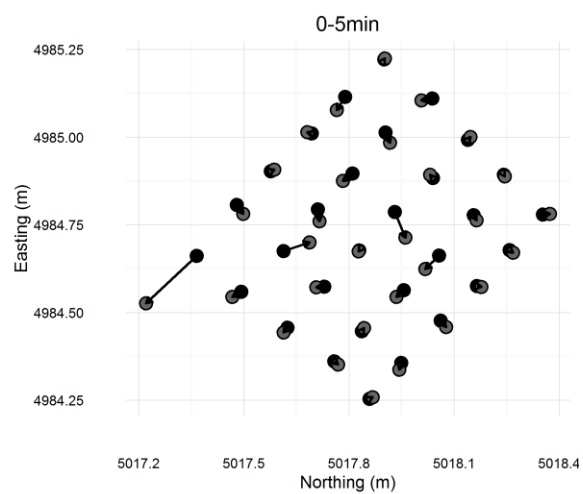
240　　*Figure 6: Plots of horizontal displacement of artefacts after 5, 10 and 15 minutes of*
241　　*trampling.*
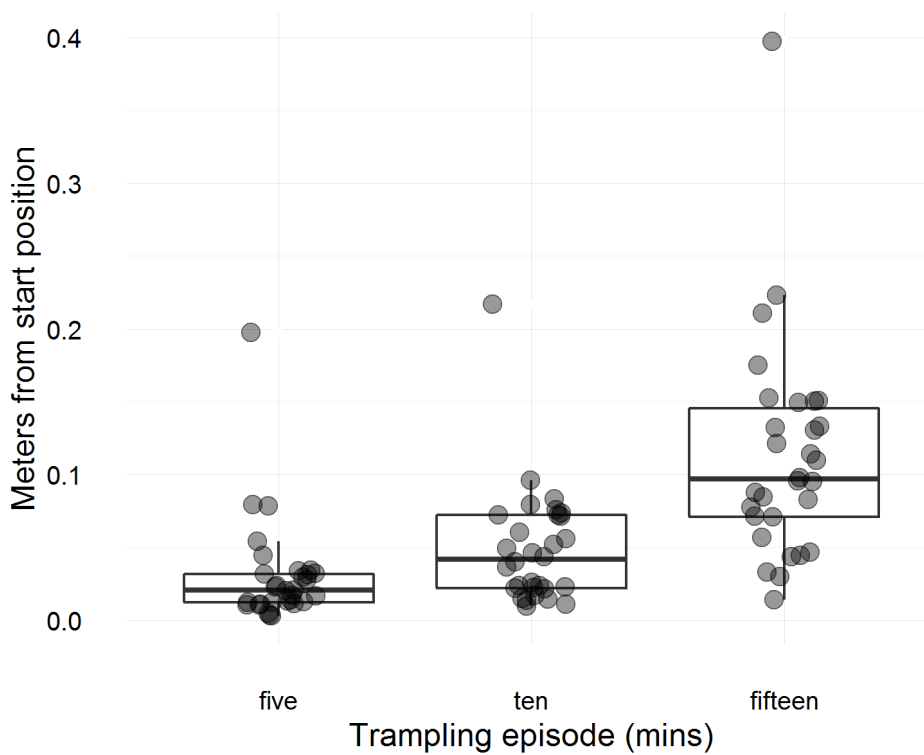
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243　　*Figure 7: Distributions of horizontal displacements of artefacts after 5, 10 and 15 minutes of*
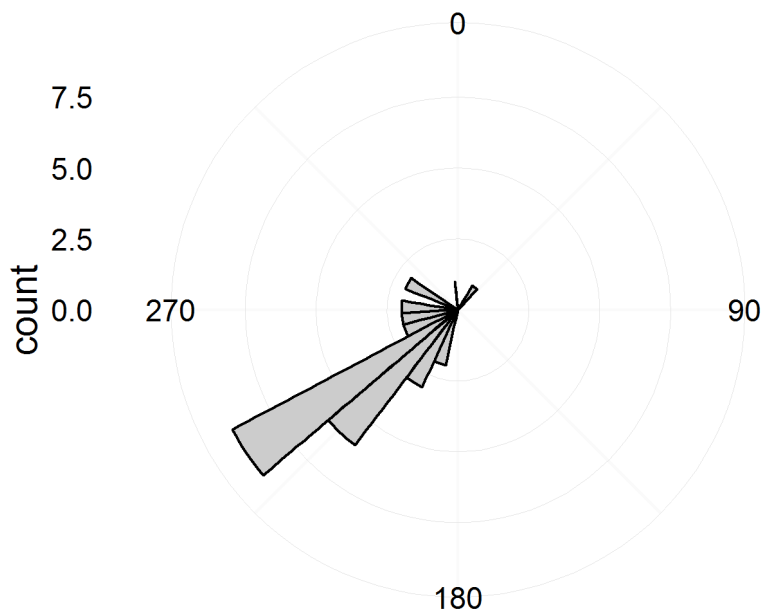244　　*trampling.*

Figure 8: Histogram of directions of displacement of artefacts from their starting positions to their locations after fifteen minutes of trampling. Zero degrees is due North.
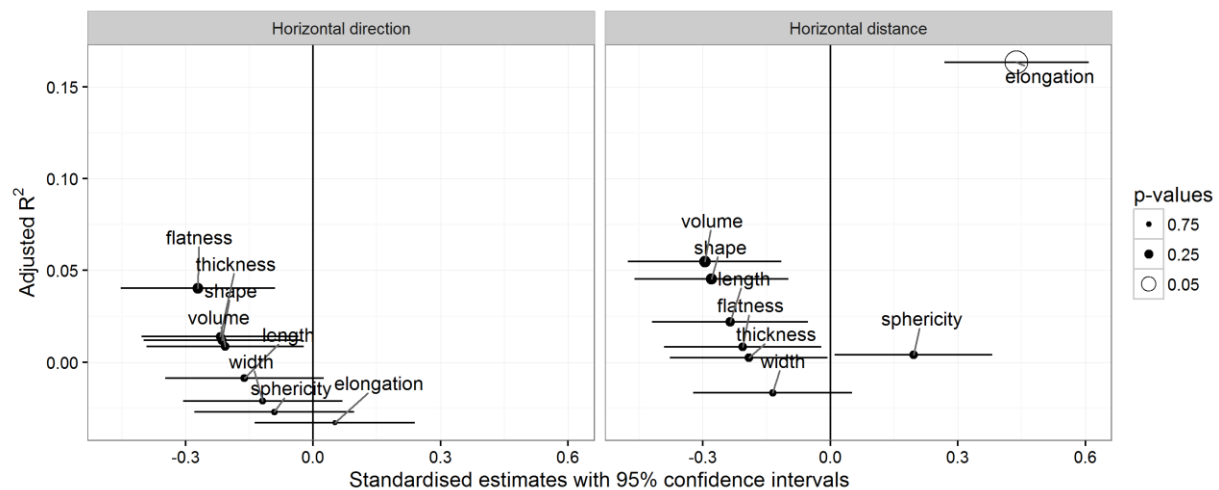

Figure 9: Linear models for a variety of predictors of the direction of horizontal direction (left) and distance (right) after fifteen minutes of trampling. Hollow data points indicate p < 0.05. Positive estimate values indicate positive correlations.

Horizontal displacement

Figure 6 shows maps of the horizontal displacement of artefacts after five, ten and fifteen minutes. A variety of trajectories are visible, with some artefacts moving in a relatively straight line, others changing direction at each move, and one returning almost exactly to its start

256 position. Figure 8 shows that after fifteen minutes, most artefacts have moved to a location
257 opposite to the direction of walking across the area. None of the Zingg shape variables are
258 effective predictors of the direction of horizontal displacement (Figure 9).

259 Figure 7 shows the distributions of displacements from each artefact's starting position after each
260 trampling interval. After fifteen minutes, the total horizontal displacement of all artefacts varied
261 from 0.014 m to 0.397 m with a median of 0.097 m, and median absolute deviation (a robust
262 measure of variation) of 0.057 m. Figure 9 provides a graphical summary of linear regression
263 models to identify how well the Zingg shape attributes predict the amount of horizontal
264 displacement for each artefact after fifteen minutes of trampling. Elongation is the strongest
265 predictor of horizontal displacement. The elongation relationship indicates that as width
266 increases relative to length, the artefacts are more likely to be moved a longer distance by
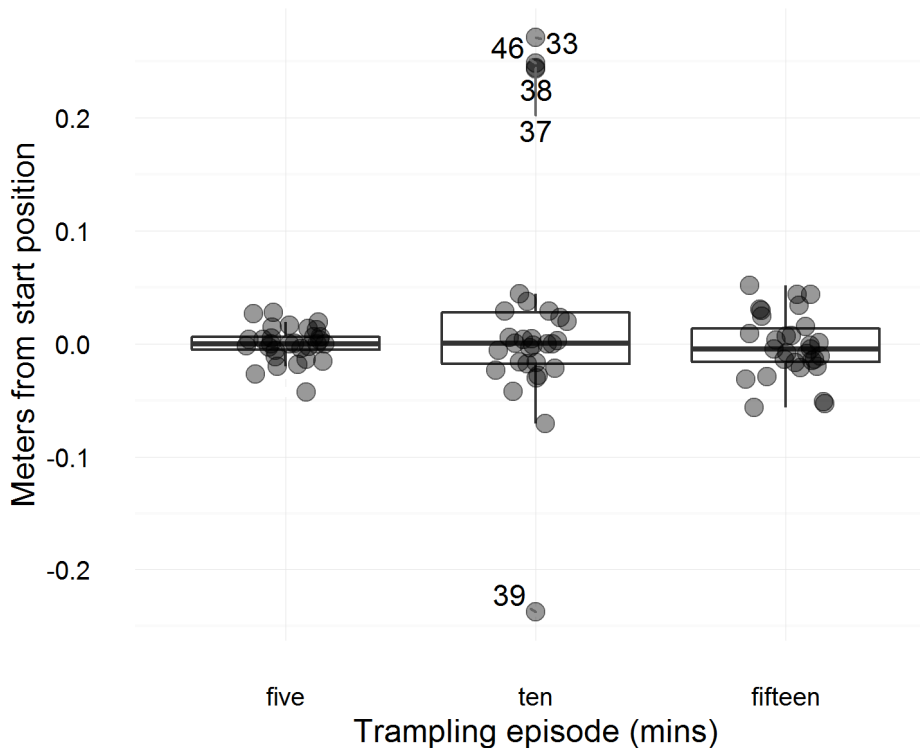267 trampling.

268 Vertical displacement

269

270 *Figure 10: Distributions of vertical displacements of artefacts from their initial location to*
271 *their location after 5, 10 and 15 minutes of trampling. Negative values indicate that the*
272 *artefact is below its starting location.*

273 The distributions of vertical displacements are shown in Figure 10. Five artefacts stand out as
274 outliers, having moved > 0.2 m from their starting positions after ten minutes of trampling.
275 These artefacts are located on the edge of the trampling area (Figure 2) and their high vertical
276 displacement is a result of heavier steps taken while walking over the edge of the trampling area
277 as the walker adjusted their stride after ascended the slope onto the sand pile where the trampling
278 area was located. At the end of the third trampling episode these outlying artefacts had returned
279 closer to their starting locations, in part because the trampling moved them horizontally further

280   from the edge of the trampling area and away from the slope. Excuding these outliers, the
281   vertical displacement of the artefacts is summarised in Table 1.

282   *Table 1: Summary of absolute (ie unsigned) vertical displacement of trampled artefacts (units*
283   *are meters, MAD = median absolute deviation)*

time	Minimum	Maximum	Median	MAD
five	0.000	0.043	0.006	0.009
ten	0.000	0.071	0.018	0.018
fifteen	0.001	0.056	0.016	0.016

284   Figure 11 shows that unsigned (or absolute, without respect to the upwards or downwards
285   direction) vertical displacement have no strong predictors among artefact shape and size
286   variables. However, artefact volume, width, length and thickness are all signficant predictors
287   when the direction of vertical movement is considered. Bigger artefacts tend to move above their
288   starting position, and smaller artefacts tend to move below it.

289   The vertical angles of artefact displacement cluster close to horizontal (Figure 12). This is
290   expected given that the horizontal displacement values are much greater than the vertical
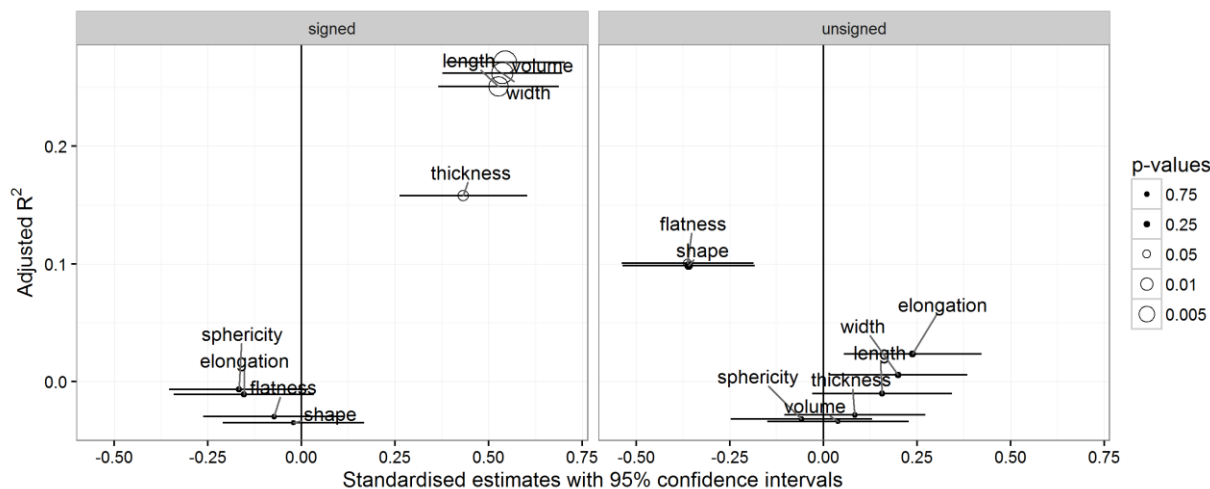291   displacement values.

292

293   *Figure 11: Linear models for a variety of predictors of signed and unsigned (ie. absolute)*
294   *vertical displacement after fifteen minutes of trampling. Hollow data points indicate p < 0.05.*
295   *Positive estimate values indicate positive correlations.*

296   *Table 2: Summary of correlations of artefact size and shape variables with the displacement*
297   *below starting position after 15 minutes.*

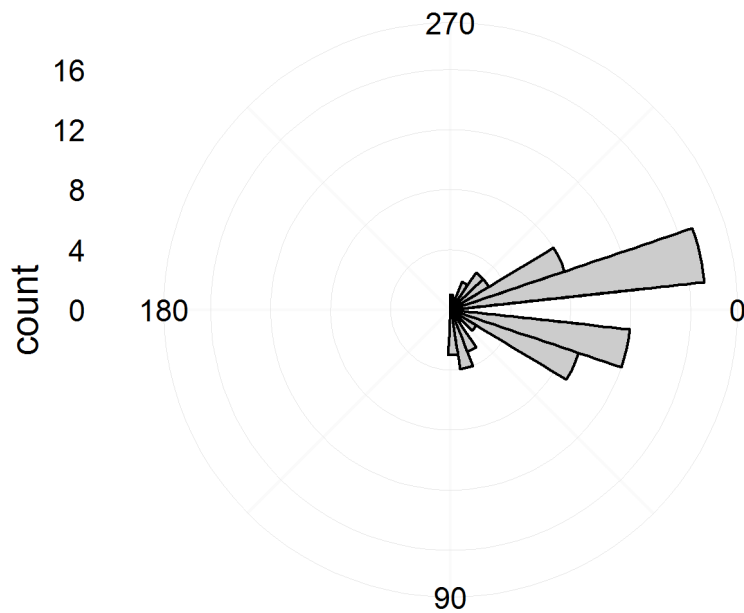| Variable	Pearson correlation	p-value
Thickness	0.432	0.017
Length	0.526	0.003
Width	0.536	0.002
Volume	0.544	0.002

Figure 12: Vertical angles of artefact displacement, or the vertical angle that the artefact moved from its starting point to its location after each trampling event. Zero degrees is horizontal

Orientation and Plunge

Our sample includes 14 artefacts with two or four total station points, enabling measurements of changes in the orientation of the artefact (ie. changes in the bearing of the long axis of the artefact) and plunge (ie. the vertical angle from the horizontal plane of the long axis of the artefact). Figure 13 shows that these changes are generally small, with most changes clustered around zero degrees (ie the bearing/plunge angle that the artefact was at before trampling). Only changes in orientation are significantly predicted by artefact shape and size attributes; there are no significant predictors for changes in artefact plunge angle (Figure 14). Similar to vertical displacement, artefact volume, width, length and thickness are all significant predictors of the magnitude of change in artefact orientation. Bigger artefacts tend to be rotated further from their original bearing.

Correlations of these changes in orientaton and plunge with horizontal and vertical distances and angles are shown in Table 3. Orientation and plunge are not strongly correlated with any other measurements of artefact movement. Increased distances of artefact displacement do not appear to have any effect on artefact orientation and plunge. Vertical angle is strongly negatively correlated with horizontal distance and vertical distance. This indicates that as the artefact moves further from its starting location, the vertical angle is smaller (i.e. closer to horizontal). Vertical and horizontal distance have a moderately strong positive relationship, indicating that the magnitude of displacement is proportional in both horizontal and vertical axes.
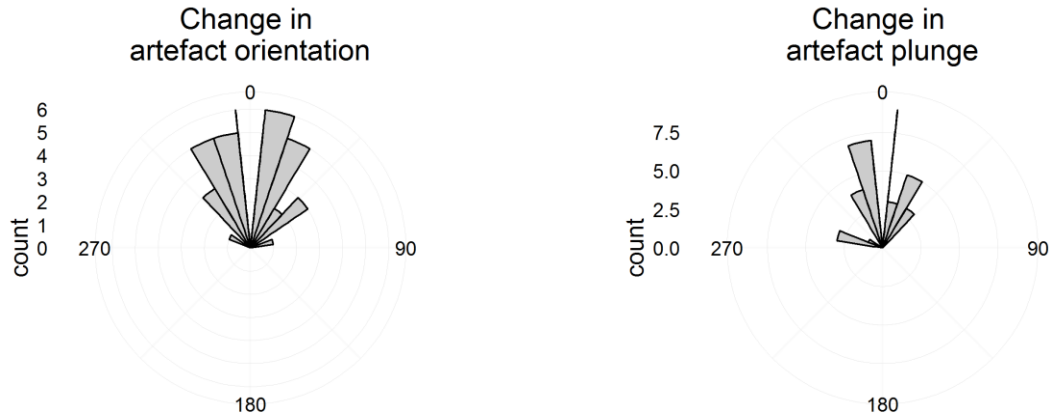
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Figure 13: Histograms of changes in artefact orientation (left) and artefact plunge (right)
after each trampling event. Zero degrees refers to the starting orientation bearing or plunge
angle for each artefact. For artefact plunge, a change 0-180 degrees is a change towards a
more vertical orientation, and a change 180-360 is a change towards a more horizontal
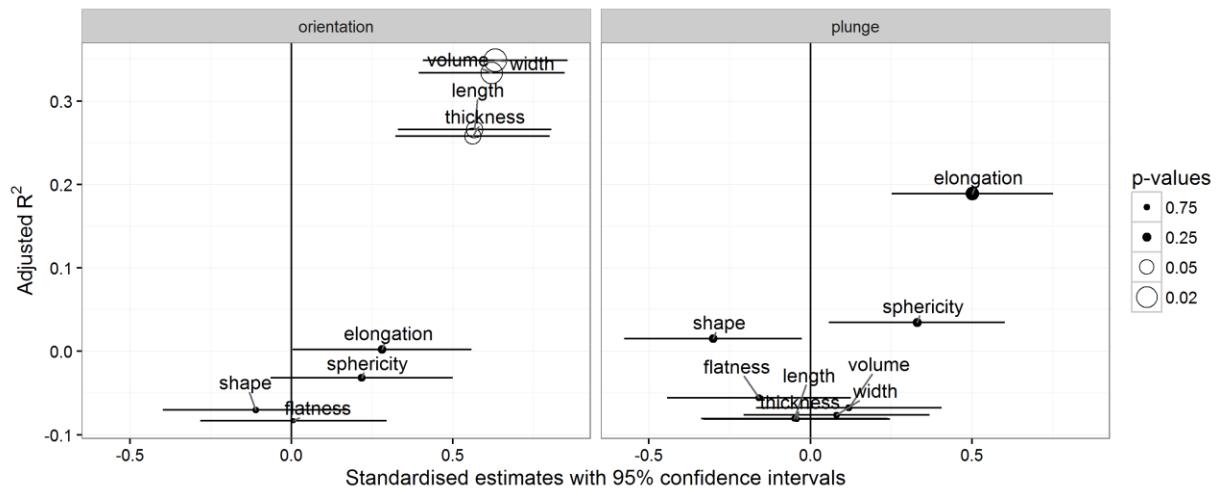*orientation.*

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Figure 14: Linear models for a variety of predictors of changes in artefact orientation bearing
and plunge angle after fifteen minutes of trampling. Hollow data points indicate p < 0.05.
Positive estimate values indicate positive correlations.

Table 3: Pearson's correlation coefficients for changes in artefact plunge and orientation, and
for values of horizontal and vertical distance, horizontal bearing and verticle angle after
fifteen minutes. Values in parentheses are p-values. Strong significant correlations are in bold.

	Plunge	Horizontal distance	Horizontal bearing	Vertical distance	Vertical angle
Orientation	-0.02 (0.94)	0.1 (0.74)	-0.22 (0.44)	0.11 (0.71)	-0.15 (0.61)

Plunge	0.28 (0.33)	0.37 (0.19)	0.33 (0.25)	-0.31 (0.28)
Horizontal distance		0.27 (0.35)	0.62 (0.02)	**-0.74 (0)**
Horizontal bearing			0.49 (0.07)	-0.44 (0.12)
Vertical distance				**-0.88 (0)**

Discussion

Comparison with previous experimental results

336 Previous trampling studies show little agreement about the relationship between artefact size and
337 displacement due to trampling. Stockton (1973) identified moderate size sorting resulting from
338 trampling, with mean artefact mass decreasing with depth. Conversely, Moeyersons' (1978)
339 wetting-drying experiments in Kalahari sands at Gombe found that the heaviest aretfacts moved
340 the largest distances downward in the deposit. Wilk and Schiffer (1979) reported a similar
341 relationship on paths in vacant lots, with larger artefacts having been more frequently trampled
342 off the paths. Similar patterns have been observed in more general studies of site formation. For
343 example, smaller rather than larger pieces of flaked stone, bone and charcoal are more likely to
344 be found *in situ* after sweeping and other site maintainance activities have occurred (Keeley,
345 1991; Stevenson, 1991).

346 On the other hand, Villa and Courtin (1983) reported from their trampling experiment that
347 artefacts lighter than 50 g were relatively mobile, moving vertically more than pieces heavier
348 than 50 g, which tended to stay on or near their original location. They report no obvious
349 correlations for horizontal movement and artefact size, but observed that while many lighter
350 artefacts did not move far from their original locations, lighter pieces tended to move further than
351 heavier artefacts. Gifford-Gonzalez et al. (1985) found that none of the artefact metric variables
352 they recorded correlated significantly with depth below surface (although no summary statistics
353 or raw data are provided to support this claim). However, they note that their results may not be
354 decisive because of the rarity of very large and very small artefacts in their sample (their
355 artefacts had a maximum unoriented length of 3-13 mm, the majority were 3-6.5 mm). They
356 further propose that the high dynamic range of trampling (i.e. highly vigorous) in their
357 experiment may have prevented patterns from emerging in the interaction between the artefacts
358 and the moving sediment.

359 In a trampling experiment conducted by Driscoll et al. (2015) vertical movements of artefacts
360 were mostly less than 1 cm, with rare occurrences of greater than 2 cm. They observed no clear
361 relationship between artefact size and vertical distance. In their low foot-traffic zone the largest
362 artefacts had the greatest change in mean depth, while in the high traffic zone the smallest
363 artefacts moved further. For horizontal movement, Driscoll et al. noted a clear pattern of the
364 largest, thickest, and heaviest artefacts moving the greatest mean distance. But when they
365 excluded the largest artefacts from the analysis (i.e. those with a maximum length of 35-40 mm,
366 out of a total range of 10-40 mm in their sample), the relationship between distance and artefact
367 size became very weak. Eren et al. (2010) also report no relationship between artefact size and

368 horizontal displacement, and only a weak positive correlation between artefact size and vertical
369 displacement.

370 *Table 4: Summary of significant (p < 0.05) and strong (r > 0.6 or r < -0.6) correlations of*
371 *artefact size and shape variables with the Cook's Distance values for each linear model.*

Variable	Movement	Pearson correlation	p-value
Length	Orientation	0.854	0.000
Length	Plunge	0.648	0.012
Thickness	Orientation	0.789	0.001
Thickness	Plunge	0.676	0.008
Volume	Plunge	0.637	0.014
Width	Plunge	0.663	0.010

372 Our results similarly showed weak, non-significant relationships between artefact length, width
373 and thickness (as defined above) and horizontal distance, horizontal direction of movement, and
374 unsigned (ie. absolute) vertical displacement after trampling. However, if we consider the
375 direction of vertical movement, we found a positive significant relationship with length, width,
376 thickness and volume, indicating that trampling causes larger artefacts to move above their
377 starting position. That said, the adjusted R^2 values on these relationships are low (0.1-0.3),
378 indicating that these artefact metrics predict only 10-30% of the observed variation in vertical
379 distance moved after trampling.

380 Our artefacts ranged in maximum unoriented length from 8 mm to 108 mm, a much greater
381 range than reported by Gifford-Gonzalez et al. (1985) and Driscoll et al. (2015). While Driscoll
382 et al. noted a strong effect of larger artefacts in horizontal movement, we did not find a similar
383 effect. Table 4 shows that in our experiment the larger artefacts have an outsize influence only
384 on the models describing artefact orientation and plunge (full details are reported in the SOM).
385 We computed the Cook's (1979) distance for each artefact in each model to identify the artefacts
386 whose removal from the model would change the model coefficients the most (Fox and
387 Weisberg, 2010). Then we computed the correlation between an artefact's volume (as a measure
388 of artefact size) and its Cook's distance value in each model. Strong significant correlations were
389 found in the models using artefact length and thickness to predict change in artefact orientation,
390 and for using length, thickness, width and volume to to predict change in artefact plunge. There
391 were no signficant correlations between artefact volume and Cook's distance in models
392 predicting horizontal or vertical movement, so bigger artefacts do not seem to have had an
393 unusual influence on these relationships.

394 Artefact shape variables have received limited consideration in previous studies. In his
395 experiment with five artefacts, Moeyersons (1978) observed how artefacts with the highest
396 weight/vertical projection surface ratio moved the greatest vertical distance. Gifford-Gonzalez et
397 al. (1985) similarly examined the orientation of the artefact edge and the ground surface, but did
398 not identify any relationship between this orientation and vertical displacement due to trampling.
399 In their experiment to investigate post-depositional processes on an experimental knapping
400 assemblage deposited on sand dunes, Barton and Bergman (1982) observed that wider, flatter
401 artefacts moved less, and artefacts that moved further down the deposit tended not to be
402 horizontally oriented.

403 In our experiments artefact shape variables were significant predictors for horizontal distance
404 (elongation has a positive relationship) and signed vertical distance (volume, width, length and
405 thickness). Artefacts with high elongation values are more disc-like or equidimensional
406 (depending on their flatness values), and artefacts with high volume, width, length and thickness
407 are larger overall (Figure 2). These results agree with those from from Barton and Bergman's
408 (1982) observations that wider, flatter (i.e. discoidal) artefacts moved less. However, the adjusted
409 R^2 values for our models range between 0.1 and 0.3, indicating that although shape variables
410 have a statistically significant role in influencing artefact movement during trampling, they have
411 limited value for making specific predictions how far artefacts with certain shape attributes have
412 moved due to prehistoric trampling. Our results indicate that it is not possible to use artefact
413 shape and size to identify artefacts that have been trampled away from their original location.

414 <u>Simulation of long-term trampling by resampling</u>

415 A common limitation of experimental studies of taphonomic processes such as trampling is the
416 short time scale of experimental observations relative to the long time scales often represented by
417 archaeological sites. The duration of our experiment was particularly short due to the unique use
418 of the archaeological sediments in the spoil heap as the trampling substrate. In general, we lack
419 experimental data on what patterns might emerge after years of occasional trampling that might
420 result from, for example, seasonal use of a rockshelter. To explore what might have happened if
421 our experiment had run for a long time, we can simulate the effects of a large number of
422 trampling events by resampling many times from the observed trampling event measurements.
423 Yorsten et al. (1990) used this approach to the study the effect of ploughing on horizontal
424 distributions of ceramic sherds. They observed sherd locations at the Butser Ancient Farm
425 Research Project over six years, and simulated locations for various time intervals up to 200
426 years to show that ploughing can substantially alter surface distributions of ceramics.

427 Taking a similar approach, we computed the difference in co-ordinates of each artefact's location
428 after each of the three trampling events that we observed. The difference in co-ordinates are the
429 co-ordinates of an artefact's starting location minus the co-ordinates of its position at the end of
430 the trampling event. To simulate artefact movement by trampling, we take each artefact in our
431 sample and we randomly select one of its three observed differences in co-ordinates, and
432 compute a new position for the artefact by adding these randomly selected co-ordinates to the
433 artefact's starting co-ordintates. Then at this new position, we make another random selection
434 from the three co-ordinate pairs, and add these co-ordinates to compute a new position. In each
435 iteration we are taking the observed measurements specific to each artefact, and using them to
436 compute new theoretical, but plausible, positions after a simulated trampling event. This differs
437 slightly from Yorsten et al. (1990), who used a probability distribution to displace each artefact
438 in their simulation. Instead, we use the observed displacement values directly, because the
439 displacement of the artefacts is determined, in part, by the specific shape and size of each
440 artefact. If we repeat this process of computing new positions many times, we can simulate the
441 movement of artefacts after a large number of events, which is challenging to do in practice.

442 Simulations such as this are a trade-off between a desire to be relevant to real-world conditions,
443 and the limitations imposed by assumptions and simplifications necessary to make the modelling
444 tractable (Aldenderfer, 1991; Kohler, 2015; Lake, 2014). In our model we assume that the
445 surface that the artefacts rest on is clear, stable and flat, and that there is not acclumuuation or
446 erosion of the substrate. Obviously this is unrealistic, but because we do not have high resolution

447 data on the relationship between sediment accumulation rates and site occupation rates (e.g. was
448 the site was visited one week every ten years, or three hours every month? Were sedimentation
449 rates continuuous or strongly seasonal? Were there cycles of erosion and deposition, or contant
450 deposition?), we prefer not to speculate about these details in our simulation.

451 One detail that is important for improving the realism of this simulation is that the impact of
452 trampling activity declines with depth from ground surface, such that an artefact may eventually
453 be trampled so deep below the surface that it is no longer in range of trampling disturbance. To
454 identify a realistic value for this depth, we computed the parameters for a gamma distribution to
455 fit the distribution of observed values of artefact displacement below their starting locations
456 (several other distributions were also explored, details are available in the SOM). Using this
457 distribution, we determined that 99.9% of observations are above a depth of 0.151 m below the
458 surface. This depth is consistent with our field observations of the depth of the upper 'dry layer'
459 of mobile sands in the alluvial soils of Magella floodplain where Madjedbebe is located. It is also
460 close to the value of 16 cm for the maximum depth of the glass artefacts observed by Stockton
461 (1973) in his experiment in the sandy deposits of Shaw's Creek rockshelter. Other experiments
462 report lower values for maximum vertical displacement of trampled artefacts, for example, 3 cm
463 observed by Gifford-Gonzalez et al. (1985), 8 cm by Villa and Courtin (1983), 1.5 cm by Nielsen
464 (1991), and 21 cm by Eren et al. (2010, where trampling was by buffalo rather than humans). We
465 used this gamma distribution to scale down the intensity of trampling as the depth of the artefact
466 increased during the simulation. As an artefact in the simulation moves deeper, we multiplied the
467 displacement co-ordinates of each iteration by the inverse probability of finding an artefact at
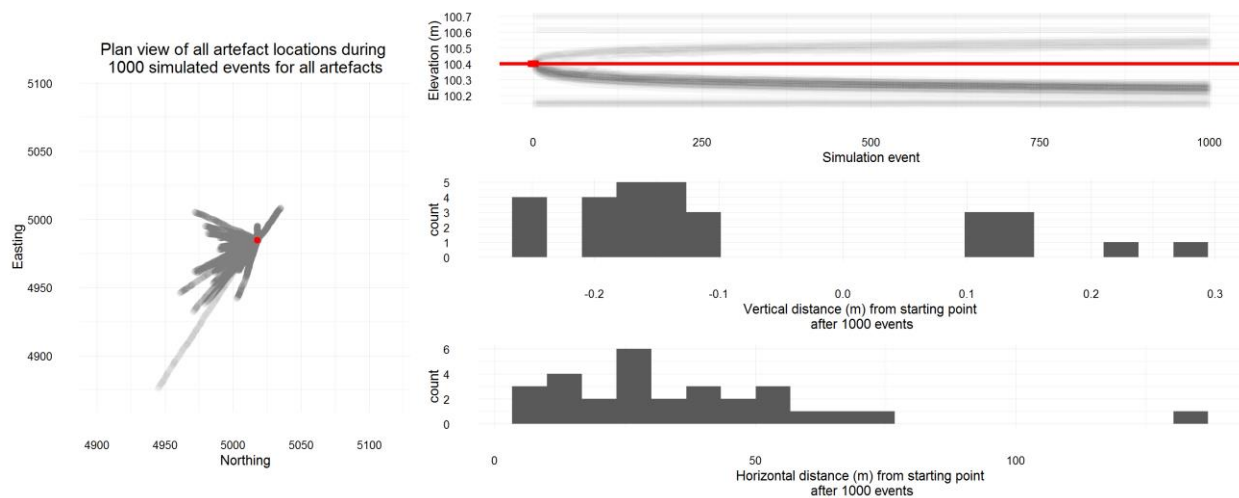468 that depth.

469

470 *Figure 15: Summary of a simulation of artefact trampling. Left panel shows the plan view of*
471 *artefact locations during the simulation, the red area indicates the starting locations of the*
472 *artefacts. Upper right panel shows change in artefact elevation during the simulation, the*
473 *horizontal red line shows the mean starting elevation of the artefacts, and the short vertical*
474 *red line shows the range of starting elevations for the artefacts. Middle right panel shows the*
475 *distribution of vertical displacement of artefacts after 1000 simulated trampling events.*
476 *Lower right panel shows distribution of horizontal displacement of artefacts after 1000*
477 *simulated trampling events.*

478 Figure 15 summarises the results of our simulation (additional figures are included in the SOM).
479 Horizontal movement is strongly determined by the direction of walking, with most artefacts
480 between 0 and 50 m from their original location. In the left panel of Figure 15 we can see two
481 diffuse scatters to the upper and lower left of the starting location. This simulation demonstrates
482 how trampling of a concentrated artefact scatter can result in low density scatters over a large
483 area, and isolated finds of artefacts up to 100 m from their original location. The vertical
484 distribution of artefacts at the end of the simulation shows that most artefacts end up 0.1 to 0.2 m
485 below their starting positions. Most artefacts in the simulation move quickly towards the
486 asymptotic depth where they are out of range of further trampling, and do not change their
487 vertical location much after the first few hundred trampling events.

488 This simulation has two implications for artefacts in sandy deposits. First is that the horizontal
489 patterning of artefacts may be strongly determined by the directions and duration of tramping
490 events. This means that horizontal clusters of artefacts observed on real-world archaeological
491 surfaces may be the result of trampling rather than prehistoric behaviour. Secondly, the vertical
492 distribution of artefacts is also altered by trampling, but rarely more than 0.1 to 0.2 m above or
493 below their starting locations. These findings are consistent with the observations of Gifford-
494 Gonzalez et al. (1985) and Villa and Courtin (1983) who report a turbulent 'zone of constant
495 circulation' of loose, mobile substrate where trampling affects the location of artefacts. They also
496 report artefacts migrating down to a stable zone where they are out of reach from further
497 trampling, just as we observed here. One real-world application of this is that in a weakly
498 stratified sandy deposit an assemblage of artefacts representing an archaeological instant (i.e. a
499 few hours or days) may, after some trampling, be distributed across a depth of up to 0.1 to 0.2 m
500 below its original position.

501 <u>Implications for the age of artefacts at Madjedbebe</u>

502 To return to the archaeological question that motivated this experiment, we can investigate the
503 effect of 0.1 to 0.2 m of vertical spread of artefacts on determining the age of artefacts at
504 Madjedbebe. The 0.4 m vertical migration proposed by Hiscock for artefacts Madjedbebe is
505 much greater than what experimental data indicates would result from trampling. We
506 acknowledge, of course, that trampling is not the only process that can vertically migrate
507 artefacts, and may even be one of the least disruptive of post-depositional processes (Stein, 1983;
508 Wood and Johnson, 1978). Using the data published in Clarkson et al. (2015) and the results of
509 this trampling experiment we can estimate new ages for the lowest artefacts at Madjedbebe. For
510 example, Clarkson et al. (2015) report the lowest artefacts at a depth of 2.87 m below the
511 surface. Using the loess regression described above, we can compute an age of 65.2 ka for those
512 sediments. If those artefacts were actually deposited on a surface 0.1 to 0.2 m above that depth,
513 we can compute ages of 64.3 ka to 62.1 ka for those surfaces. The error term (two standard
514 deviations) on the nearest OSL sample to these lowest artefacts is 8.2 ka (KTL-162), so the
515 variation in the age of the artefacts due to trampling (3.1 ka) is less than half of the error on the
516 OSL age. This finding does not conclusively resolve the debate about the age of the oldest
517 artefacts at this site -- questions remain about the effects of other post-depositional processes,
518 and the degree of mixing of the sediment grains used in the OSL analysis (Allen and O'Connell,
519 2014; allen2003colonised; O'Connell and Allen, 2004). However, it does help us to understand
520 the magnitude of the effect of trampling at this site, which seems to be low, relative to
521 uncertainties in ages produced by OSL methods.

Conclusion

Trampling is as an important post-depositional process that influences spatial patterning of artefacts in surface and stratified deposits. Our experiment used the Zingg system of quantifying clast shape to investigate the relationship between artefact size and shape attributes and movement resulting from trampling. We used a trampling substrate made from the sediments of the Madjedbebe excavations to increase the relevance of our results to the debate about artefact movement in the Pleistocene deposits at Madjedbebe. Artefact elongation is a significant predictor of the horizontal distance an artefact is moved by trampling. Length, width, thickness and volume are significant predictors of the vertical distance an artefact is moved by trampling, when direction is considered. They are also predictors for changes in artefact orientation, but there are no significant predictors of artefact plunge. For overall vertical displacement, only shape and flatness are significant predictors. However, the explanatory power of these artefact shape and size variables is small, indicating that many other factors are also important in determining how an artefact moves during trampling. It is not possible to use artefact size and shape to reliably identify artefacts in an archaeological assemblage that have been moved the most by trampling.

Our experiment is limited by the short duration of the trampling events, and the small number of events. To explore the impact of long-term trampling on archaeological deposits, we used our observed data as inputs to a simulation of a large number of trampling events. The simulation resulted in extensive horizontal movement, but only limited vertical movement, rarely more than 0.1 to 0.2 m below the surface. We applied the results of the simulation to the archaeological stratigraphy at Madjedbebe, a site in northern Australia with controversial evidence of early human occupation. We find that when the effects of trampling are considered, the age of the lowest artefacts in the deposit remains within the error range of the OSL ages used to date the deposit. We conclude that trampling has probably not contributed to extensive downward displacement of artefacts at Madjedbebe.

Future directions in experimental studies of post-depositional artefact movement might explore the relationship between the body mass, foot size and gait of the person trampling. While we controlled these variables by using a single person for all the trampling, it is possible that variations in the physical attributes of the person and how they walk might be predictive of artefact displacement. A second important question is how variations in the texture of the deposit could be used to predict artefact movement. Our experiment was conducted on loose, well-sorted sand, and this might result in higher values of artefact displacement compared to other types of deposit. For example, highly compact deposits, or deposits with a high percentage of angular gravel might be predicted to have much smaller distances that artefacts move due to trampling. The more compact sediment requires higher energy for artefacts to penetrate, and the larger clasts would act as barriers to artefact movement. By experimenting with a range of different deposit textures it may be possible to identify how much texture variation can predict artefact movement due to trampling.

572 Colophon

573 This report was generated on 2016-10-20 21:54:02 using the following computational
574 environment and dependencies:

```
575 ## Session info -------------------------------------------------------------
576 -
577 ##   setting  value
578 ##   version  R version 3.3.1 (2016-06-21)
579 ##   system   x86_64, mingw32
580 ##   ui       RTerm
581 ##   language (EN)
582 ##   collate  English_Australia.1252
583 ##   tz       America/Los_Angeles
584 ##   date     2016-10-20

585 ## Packages -----------------------------------------------------------------
586 -
587 ##   package       * version    date       source
588 ##   assertthat      0.1        2013-12-06 CRAN (R 3.3.1)
589 ##   bookdown        0.1.1      2016-08-03 Github (rstudio/bookdown@902a670)
590 ##   broom         * 0.4.1      2016-06-24 CRAN (R 3.3.1)
591 ##   codetools       0.2-14     2015-07-15 CRAN (R 3.3.1)
592 ##   colorspace      1.2-6      2015-03-11 CRAN (R 3.3.1)
593 ##   DBI             0.5-1      2016-09-10 CRAN (R 3.3.1)
594 ##   devtools        1.12.0     2016-06-24 CRAN (R 3.3.1)
595 ##   digest          0.6.10     2016-08-02 CRAN (R 3.3.1)
596 ##   dplyr         * 0.5.0.9000 2016-08-03 Github (hadley/dplyr@8b28b0b)
597 ##   evaluate        0.9        2016-04-29 CRAN (R 3.3.1)
598 ##   fitdistrplus  * 1.0-7      2016-07-02 CRAN (R 3.3.1)
599 ##   formatR         1.4        2016-05-09 CRAN (R 3.3.1)
600 ##   ggfortify     * 0.2.0      2016-06-02 CRAN (R 3.3.1)
601 ##   ggplot2       * 2.1.0      2016-03-01 CRAN (R 3.3.1)
602 ##   ggrepel       * 0.5        2016-02-08 CRAN (R 3.3.1)
603 ##   gridExtra     * 2.2.1      2016-08-03 Github (baptiste/gridextra@478a7d2)
604 ##   gtable          0.2.0      2016-02-26 CRAN (R 3.3.1)
605 ##   highr           0.6        2016-05-09 CRAN (R 3.3.1)
606 ##   htmltools       0.3.5      2016-03-21 CRAN (R 3.3.1)
607 ##   httpuv          1.3.3      2015-08-04 CRAN (R 3.3.1)
608 ##   knitr         * 1.14       2016-08-13 CRAN (R 3.3.1)
```

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609  ##  lattice       0.20-33   2015-07-14 CRAN (R 3.3.1)
610  ##  lazyeval      0.2.0     2016-06-12 CRAN (R 3.3.1)
611  ##  magrittr      1.5       2014-11-22 CRAN (R 3.3.1)
612  ##  MASS        * 7.3-45    2016-04-21 CRAN (R 3.3.1)
613  ##  Matrix        1.2-6     2016-05-02 CRAN (R 3.3.1)
614  ##  memoise       1.0.0     2016-01-29 CRAN (R 3.3.1)
615  ##  mime          0.5       2016-07-07 CRAN (R 3.3.1)
616  ##  miniUI        0.1.1     2016-01-15 CRAN (R 3.3.1)
617  ##  mnormt        1.5-4     2016-03-09 CRAN (R 3.3.0)
618  ##  munsell       0.4.3     2016-02-13 CRAN (R 3.3.1)
619  ##  nlme          3.1-128   2016-05-10 CRAN (R 3.3.1)
620  ##  perm        * 1.0-0.0   2010-07-29 CRAN (R 3.3.1)
621  ##  plyr          1.8.4     2016-06-08 CRAN (R 3.3.1)
622  ##  psych         1.6.6     2016-06-28 CRAN (R 3.3.1)
623  ##  purrr       * 0.2.2     2016-06-18 CRAN (R 3.3.1)
624  ##  R6            2.1.3     2016-08-19 CRAN (R 3.3.1)
625  ##  Rcpp          0.12.7    2016-09-05 CRAN (R 3.3.1)
626  ##  readxl      * 0.1.1     2016-03-28 CRAN (R 3.3.1)
627  ##  reshape2      1.4.1     2014-12-06 CRAN (R 3.3.1)
628  ##  rmarkdown     1.0.9001  2016-08-03 Github (rstudio/rmarkdown@7769342)
629  ##  scales        0.4.0     2016-02-26 CRAN (R 3.3.1)
630  ##  shiny         0.14      2016-09-10 CRAN (R 3.3.1)
631  ##  stringi       1.1.1     2016-05-27 CRAN (R 3.3.0)
632  ##  stringr     * 1.1.0     2016-08-19 CRAN (R 3.3.1)
633  ##  survival    * 2.39-4    2016-05-11 CRAN (R 3.3.1)
634  ##  tibble        1.2       2016-08-26 CRAN (R 3.3.1)
635  ##  tidyr       * 0.6.0.9000 2016-09-17 Github (hadley/tidyr@3c9335b)
636  ##  withr         1.0.2     2016-06-20 CRAN (R 3.3.1)
637  ##  xtable        1.8-2     2016-02-05 CRAN (R 3.3.1)
638  ##  yaml          2.1.13    2014-06-12 CRAN (R 3.3.1)

639  ##
640  ## Attaching package: 'git2r'

641  ## The following objects are masked from 'package:purrr':
642  ##
643  ##      is_empty, when
```

The current git commit of this file is af776ae93bdbe390d8e85a59531f01c3ff7c7969, which is on the master branch and was made by Ben Marwick on 2016-10-20 16:03:43. The current commit message is "add orcid". The repository is online at https://github.com/benmarwick/mjbtramp

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