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Shape as an outcome of formation history: Terrestrial Laser Scanning of shell mounds from far north Queensland, Australia

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Abstract

Terrestrial Laser Scanning (TLS) is a laser-based surveying system that enables rapid measurement of x,y,z coordinate points, creating an accurate representation of objects in three-dimensional space. We apply this technique to the survey and analysis of mounded shell matrix deposits (SMDs) near Weipa in far north Queensland, Australia. Eleven parameters were used to characterise the size and shape of 51 shell mounds all located in one geographical area. The results demonstrate substantial variation in mound size and shape, and suggest patterning in mound form related to age as well as position on the landscape. Radiocarbon chronologies developed for a sample of the 51 mounds demonstrate that the mounds do not conform to a model of linear formation of a shell deposit, suggesting mound histories are variable in both the nature of shell deposition as well as post-depositional processes. These results have important implications for interpreting the processes responsible for shell mound formation.

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1. Introduction

Terrestrial Laser Scanning (TLS) is a laser-based surveying system that enables rapid measurement of x,y,z coordinate points, creating an accurate representation of objects in three-dimensional space. It is non-contact, non-invasive and non-destructive, and the resultant data sets can be used to produce detailed and precise three-dimensional spatial images and models that can be analysed, measured and manipulated in a computer environment (Collins and Doering, 2009: 28). Currently, the majority of archaeological applications of TLS focus on the conservation and management of cultural heritage (e.g., Haddad 2011; Lerma *et al.* 2010; Yastikli 2007), particularly through a combination of TLS with photo-texturing to create realistic three-dimensional representations (e.g., Andrés *et al.* 2012; Domingo *et al.* 2013; Rodríguez-Gonzálvez *et al.* 2012). However, it is also possible to use the technique to create accurate and precise models that permit quantitative investigation of structures that are difficult with more traditional techniques that record spatial information. Here, we report on the analysis of the shape of shell matrix deposits (SMDs) that are a prominent feature of the landscape of Albatross Bay, Cape York Peninsula, Australia. There are estimated to be upwards of 500 SMDs in this region (Bailey 1999; Shiner *et al*. 2013). They are found in close proximity to the four rivers (Pine, Mission, Embley and Hey) that drain into Albatross Bay (Bailey *et al.* 1994; Wright 1964). The SMDs are predominantly composed of a single shellfish species, the bivalve *Anadara granosa* (Morrison 2003). In addition, the SMDs are very significant cultural sites for Traditional Landowners and whilst invasive research methods such as excavation have been permitted, the three-dimensional scanning of mounds prior to excavation creates a permanent digital record of the pre-excavation condition of mound that can then inform the post-excavation reconstruction of the mounds. This record can also be compared to similar records taken at future times allowing changes in mound size and form to be quantified. The ongoing preservation of the mounds and having a record for future generations is a key concern of the Aboriginal custodians.

The SMDs of Albatross Bay are an ideal setting to investigate how different processes have influenced the form of the deposits, since visually the mounds appear to vary in their shape and size as well as geomorphic contexts. The SMDs have previously been reported to show a range of forms (Bailey 1999; Morrison 2003), from small scatters to instances of *umådeligmødding* (megamiddens) or shell mounds of up to 14 metres in height (Bailey *et al.* 1994: 69) and up to 100 metres long (Morrison 2010). The SMDs are located on a variety of landforms, such as the bauxite plateau which is the dominant landform in the region, sandy and gravelly shore-parallel ridges, and estuarine mud flats. A small number have recently been found within the mangroves that fringe the estuaries (Shiner *et al*. 2013; Fanning *et al*. in prep.). The current chronologies show the SMDs date from the mid-Holocene to recent times (Fanning *et al*. in prep; Morrison 2013a, 2014).

This study focusses on 51 SMDs from Wathayn (Figure 1), an area approximately 25 km south east of Weipa. Since all of the deposits included in the analysis have some vertical relief, the term "shell mound" will be used hereafter to refer to the SMDs (after Morrison 2013b: 81).

2. Shell mound morphology and TLS

A number of techniques has previously been used to measure and quantify the morphology of shell mounds. In an early study, Bailey (1975, 1994) measured the height, base area and slope angles of 306 mounds in 1972, including a sample of the Wathayn sites, with a combination of tape measure, clinometer, eye-estimation and pacing, and calculated mound volumes using a variety of geometrical formulae based on standard shapes, and cross-sectional areas for more irregular shaped mounds. Theodolites have been used in the majority of more recent investigations to record a regular grid of three-dimensional co-ordinates (x,y,z), from which contours have been derived (e.g., Hiscock and Hughes 2001; Russo 2004; Sanger and Thomas 2010). Such records may provide a good approximation of shape for a large number of mounds in a variety of field settings but are often limited in their accuracy by the low density of measurements taken on any one mound. The difficulty is that complex shapes may require large numbers of points for accurate modelling, a problem that is also discussed in the literature documenting the ongoing attempts to create accurate three-dimensional representations of caves where important deposits and ancient rock art are found (e.g., González-Aguilera *et al*. 2009; Lerma *et al.* 2010; Núñez *et al.* 2013).

LiDAR (Light Detection And Ranging) provides a solution since it allows the rapid but accurate measurement of dense quantities of spatial information across large and morphologically complex areas. The spatial position of each data point is calculated using the known angle of the emitted laser, the speed of light, and the time of flight of the laser. Ground based LiDAR (Terrestrial Laser Scanning) can be used over distances from less than 1 m to over 100 m. Scans produce a large number of x,y,z points in a common coordinate system that form a point cloud. The speed and accuracy of TLS provides the capability to generate precise models of multiple mounds which can then be quantified and compared. However, TLS is also an indiscriminate recording technique, in that it records the surface of whatever the laser strikes. The technique does not differentiate between the object of interest and the surrounding landscape. Objects of interest must therefore be separated from the point cloud during the post-processing phase.

3. Data collection, processing and model construction

In the research reported here, a Leica Scanstation 2 was employed over two fieldwork seasons in 2010 and 2011, upgrading to a Leica C10 for the 2012 season. The two machines have a maximum scan rate of 50,000 points per second with a positional accuracy of 6 mm and 4 mm, respectively, in depth. For both machines, a laptop computer controlled the laser scanner, which facilitated the process of determining the area to be scanned, and allowed immediate review of completed scans to assess black-spots in the point cloud. Leica High Definition Survey (HDS) targets were employed as georeferencing tools. The targets were mounted on tripods and provided common points in multiple scans that could be used for automatic georeferencing. A field record of scanner and target attributes (height, GPS position) as well as scanner position relative to the mounds mitigated any difficulty in identifying mounds in different scans by allowing cross referencing of locations of scanner and target position in a GIS database. Cleaning of the surface of the mound through removal of vegetation, such as trees and grass, and small secondary features like termite mounds, allowed the scans to better represent the true mound surfaces.

The raw point cloud data was processed using Cyclone, Leica's point cloud processing software, to create three-dimensional models of each mound. The initial step in model construction involved merging multiple scans. The quantity of data was reduced by removing unwanted and erroneous data ("noise"), including all point data outside the pre-defined mound perimeter. A smoothing function was used to highlight points on the mound surface and to delete points outside of this defined surface. A mesh was subsequently constructed using a Triangular Irregular Network (TIN), a vector based surface using a closest neighbour algorithm to connect vertices (points) with triangular polygons. A visual assessment of the final mesh allowed any erroneous polygons to be removed.

Mound perimeters were defined qualitatively in the field by visual inspection and mapped with a self-tracking Leica Total Station. Subsequently, the change in slope at the contact between the shell mound and the surrounding landsurface was used to refine the location of the mound perimeter and to construct a ground reference plane beneath the mound. The software function, ‘define cutplane at reference plane’, automatically created a line at the intersection of the TIN and the ground reference plane. The TIN outside this perimeter line was then deleted, effectively creating a representation of the mound in 3D space.

In addition to the terrestrial LiDAR data, airborne LiDAR data was used to provide a representation of the landscape in which the shell mounds were located. This airborne LiDAR data was recorded between 11th and 15th of September 2010 at an altitude of 1400 m, resulting in a minimum point density of 2 points per square metre and a spatial accuracy estimated to within 0.20 m. The spatial data was interpolated as 0.25 m contour lines. High resolution colour aerial photographs enabled mapping of key landform features, such as the position of the estuary and fringing mangroves. The aerial photographs were recorded during 2011 at an altitude of 2897 m with a sensor focal length of 62.7 mm, resulting in a pixel size of 30 cm.

4. Quantifying the form of shell mounds

Eleven size and shape variables were chosen to measure the form of the mounds: maximum height (m), long axis length (m), short axis length (m), volume (m^3), surface area (m^2), volume to surface area ratio (VSA), slope (two measures, in degrees), elongation ratio (ER) and axial symmetry (short and long axes). The variables utilise the numerous measuring functions programmed in Cyclone that are designed to aid measuring three-dimensional architecture.

Determining the maximum height of a mound seems intuitively obvious but this measure will vary depending on where it is obtained, particularly when the ground surface is irregular. Maximum height was therefore defined as the change in elevation (z-axis) between the lowest and highest point on the mound (Figure 2). The 'find highest point/ lowest point' tool in Cyclone was used to derive these points by placing a grid over the mesh surface at a set extent (100 m^2 for all the Wathayn mounds as this area included the surface areas of all of the mounds included in the analysis) and to locate the high and low points in the z-axis relative to this mesh.

The long axis was defined as the maximum distance between two points on the perimeter of the shell mound determined, as discussed above, by the change in slope at the edge of the mound. The short axis was then defined as the maximum distance between two points on the perimeter of the shell mound orthogonal to the long axis (Figure 2).

Cyclone calculates volume by sampling a surface and creating a volume from this surface. The density of the sample is defined by the user and can be increased when surfaces are complex. The sampling density used in this analysis was set at one point every 5 mm to achieve maximum accuracy without requiring long processing times. The reference plane created to identify the edge of the mound was used as an approximation of the pre-mound surface (i.e., the base of the mound). The measuring function 'volume above ref-plane' was then used to measure the volume of material between the ground mesh and the surface mesh. Surface area is the area, in m^2, of the surface of the mound within the perimeter identified during the mesh model construction. The surface area was estimated by using the 'measure surface area' tool in Cyclone.

Using these basic measurements, the shapes of the SMDs can be expressed as ratios that describe how the mounded material is distributed in space. The VSA ratio describes the relationship between mound volume and surface area and provides a measure of the 'flatness' of a mound. Thinking of mounds as cone-shaped, a mound with a flat cone shape has a large surface area and small volume while a mound with a tall cone shape has a small surface area and large volume. A second ratio, the elongation ratio (ER - short axis length divided by long axis length) represents the two dimensional elongation of the mound. Low values of the elongation ratio represent mounds that are long and thin since mounds are long relative to their width while high values represent mounds that are closer to a circle in outline. Because of the way the long and short axes are defined and the way that the ratio is calculated, values are always less than one.

Slope is the steepness of the sides of a mound, measured in two directions. These directions were chosen relative to the surrounding topography because many of the mounds were situated on linear landforms (either bedrock outcrops, or sandy and gravelly ridges of marine origin), oriented in a west to east direction. The S1 slope was measured on the side of the mound which faces the downslope direction, perpendicular to the ridge on which it is located, while the S2 slope was measured on the side of the mound orthogonal to the S1 slope. The slope direction of the topography around the mound was measured prior to the removal of mesh data outside the mound perimeter. The colour map of the mesh model including the mound and surrounding ground surface was modified to show elevation with 20 cm elevation contours (Figure 3). Points were selected on the perimeter of the mound in the downslope direction (S1) and across the slope (S2). A line created between the highest point and S1, and the highest point and S2 provided the geometry needed to calculate slope. The slope angle was measured using the 'elevation angle' tool in Cyclone, which measures the angle between the created lines and the horizontal plane.

Axial symmetry provided a measure of material distribution across the long and short axes based on estimates of volume. For long axis symmetry, the mound was sectioned vertically through the long axis and the volume of each half-section measured using the method outlined for estimating volume described above. The long axis symmetry was calculated as the ratio of the resulting half-section volumes. To calculate short axis symmetry, the procedure was repeated with the mound sectioned vertically through the short axis.

5. Results

Data from the 51 shell mounds at Wathayn were processed to create three dimensional models of each of the shell mounds and the eleven attributes described above were measured to quantify shell mound size and shape. Figure 4 provides examples of some of the mounds analysed.

Five variables describe size: maximum height, short axis length, long axis length, volume and surface area. The height of a shell mound describes how far above the ground surface the shell is currently mounded. The data in Table 1 show that most of the Wathayn mounds we surveyed are relatively low (around 1 m in height), with a small number of taller mounds. A comparable result was produced by Morrison (2013b: Table 3) from data on mound size and shape for the wider Albatross Bay region sourced from the work of Bailey (1975; 1994) and more recently from his own surveys (Morrison 2010).

Table1: Descriptive statistics of five variables that describe shell mound size at Wathayn (n = 51).

Variable	Minimum	Maximum	Median	Mean	Standard deviation
Maximum Height (m)	0.30	2.77	0.84	1.01	0.60
Long Axis Length (m)	4.11	76.66	17.34	19.43	10.93
Short Axis Length (m)	3.02	52.00	11.14	12.20	6.81
Volume (m^3)	0.41	846.08	29.11	64.49	128.42

Surface Area (m^2)	10.38	2135.53	161.36	235.50	302.79

The data are right skewed, emphasising a small number of mounds with large dimensions (Table 1). Some mounds with a large maximum height also have relatively large values for the long axis and short axis lengths reflecting significant (although not particularly strong) correlations between maximum height, long axis length and short axis length (max. height vs short axis length: Pearson correlation 0.592, n = 51, p <0.001; Spearman's rho 0.553, n = 51, p <0.001; max. height vs long axis length: Pearson correlation 0.599, n= 51, p < 0.001; Spearman's rho 0.435, n = 51, p = 0.001; long axis length vs. short axis length: Pearson correlation 0.852, n = 51, p < 0.001; Spearman's rho 0.635, n = 51, p <0.001).

The quantity of material above the reference plain, measured by the volume parameter, is variable and is again right skewed. Volume and maximum height are significantly correlated (Pearson correlation 0.630, n = 0 51, P <0.001; Spearman's rho 0.650, n = 51, p< 0.001).

Volume and surface area are, in contrast poorly correlated, although the non-parametric rank test returns a significant result (Pearson correlation 0.254, n = 51, p = 0.072; Spearman's rho 0.353, n = 51, p = 0.011). Among the large mounds, five mounds (WPSM55, 58, 63, 76 and 77) have large surface areas as well as large volumes. With the exception of WPSM63, these mounds have surface area values greater than three times the interquartile range. However, WPSM100, which is also a large mound, has a large surface area but a relatively small volume (34.10 m^3). This suggests that the material that comprises WPSM100 is distributed very differently in space to the other large mounds.

Table 2: Descriptive statistics for the six variables that describe the shape of the Wathayn mounds (n = 51)

Variable	Minimum	Maximum	Median	Mean	Standard deviation
Volume/Surface Area Ratio (VSA)	0.04	0.82	0.18	0.22	0.17
Elongation Ratio (ER)	0.15	0.97	0.68	0.66	0.17
S1 Slope (degrees)	1.28	26.12	5.43	6.49	4.03
S2 Slope (degrees)	0.52	12.00	3.07	3.68	2.57
Short Axis Symmetry	0.29	3.74	0.99	1.13	0.70
Long Axis Symmetry	0.10	8.24	1.09	1.16	1.10

The variability in the way the volume of shell is distributed can be expressed using a ratio of volume to surface area (VSA) providing a measure of the relative "flatness" of the mounds. A low ratio represents a mound where most of the volume is accounted for by the long and short axis lengths rather than mound height. As indicated in Table 2, none of the mounds has a value greater than 1, with a mean of 0.22 (± 0.17), thus many of the mounds have a relatively large surface area relative to volume. The distribution of values is right skewed.

The elongation ratio (ER) compares the short and long axis values with low values reflecting elongated mounds and high values reflecting mounds that are close to circular in profile. The majority of mounds have elongation ratio values greater than 0.8 indicating that they are more circular in outline (Table 2).

The slope attributes describe the gradient of the sides of the mounds and were calculated relative to the surrounding topography. S1 is measured on the side of the mound which faces downhill. S2 is measured on the side of the mound orthogonal to the direction of S1.The results show that S1 median angle (5.43^0) is higher than the S2 median angle (3.07^0) and this difference is significant (Wilcoxon Signed Rank standardised statistic 5.287, $n = 51$, $p<0.001$). Forty six (90%) of the mounds have S1 values below 10^0 indicating relatively low slope angles even on the steepest faces of the mounds. Thus the form of the mounds appears to be influenced by their position in the landscape, with mound material being spread along the bedrock and marine ridges rather than perpendicular to them, although as discussed above, the elongation ratio indicates that the mounds we studied tend to be more circular than elongated in shape.

Axial symmetry quantifies how the material that constitutes a mound is distributed across two major axes (the long and short axes). It is calculated as the ratio of the volume of material either side of the long and short axes. Long axis (LA) symmetry and short axis (SA) symmetry have similar mean and median values suggesting that mounds are close to symmetrical (Table 2). However, the two measures are not correlated indicating that asymmetrical differences in volume distribution are randomly distributed. A small number of mounds show extreme asymmetry indicated by both high and low values for the ratios (LA symmetry WPSM55: 8.24, WPSM 105: 2.20, WPSM67: 0.10, WPSM92: 0.10; SA symmetry WPSM124: 3.74, WPSM62: 3.54, WPSM126: 0.36, WPSM67: 0.29). With the exception of WPSM67, these mounds are located in the western section of the study area and are located on a prominent bedrock ridge suggesting that topographic position has an impact on shell mound symmetry as reflected in the S1 measurements discussed above.

To summarise, the majority of mounds are more circular than elongated in shape, and have large surface areas relative to their volumes, i.e. they tend to be flat rather than high. Mound slope is steeper in the downhill direction relative to the surrounding topography. Thus, mound form appears to some extent to be influenced by position in the landscape, whereby mound material is distributed along the contours rather perpendicular to them. While the central tendency of the axial symmetry variables is symmetrical, there is considerable variability in both attributes and mounds with extreme values tend to occur in the same location. These results illustrate that the material that composes the mounds is distributed in space in variable ways.

6. Temporal and spatial variability in mound form

The age of the mounds is derived from radiocarbon determinations obtained from whole *Anadara granosa* shell by the Waikato Radiocarbon Laboratory (Fanning *et al*. submitted; Shiner *et al*. 2013). Samples were collected from vertical sequences in the end wall of a trench excavated to the centre of each mound. The determinations were calibrated using the Marine09 curve (Reimer *et al.* 2009) and a ΔR value of -103±16 14C years (Ulm 2006) in OxCal v. 4.1.7. The median calibrated ages of these dated samples provide an indication of the timing of mound formation, the assumption being that the shellfish were harvested live and processed almost immediately to access the meat, with the empty shells being discarded close by to where they were processed (Fanning *et al*., submitted). The temporal context provides a means to relate mound form to their age for 28 mounds for which we have both age determinations (since not all mounds were dated) and LiDAR data.

The youngest and oldest median ages from each mound are used as an approximation of the end and start points, respectively, of formation of the mound and so can be used to calculate the approximate time-span of mound formation. Maximum height and time-span are weakly correlated using the ranked correlation test (Pearson correlation 0.224, $n = 28$, $p = 0.251$; Spearman's rho 0.399, $n = 28$, $p = 0.036$). Correlations improve if time-span is limited to cases less than 1000 years although only the rank based correlation is significant (Pearson correlation = 0.394, $n = 23$, $p = 0.063$; Spearman's rho 0.669, $n = 23$, $p < 0.001$). There is also a weak rank correlation between time-span and volume for these mounds (Pearson correlation 0.325, $n = 23$, $p = 0.130$; Spearman's rho 0.644, $n = 23$, $p = 0.001$). As we discuss elsewhere (Fanning *et al*. submitted), some mounds display different periods of accumulation separated by a hiatus, indicating that mounds with the longest time-spans as determined from the overall start and end dates were not accumulating continuously.

There is no overall correlation between mound basal age (i.e., start date) and volume nor between mound upper age (i.e., end date) and volume. However, if median size values are compared between groups of mounds of different ages, excluding those mounds with large time-spans that likely reflect long periods of abandonment between periods of shell accumulation, then differences do exist. For mounds with time-spans less than 1000 years, the group of mounds with end dates older than 2000 years have smaller volumes and maximum heights than mounds with end dates younger than 2000 years BP. These differences have probabilities close to the 0.05 cut-off but are not significant (volume independent samples median test 4.102 (df = 1); Fisher exact probability = 0.063; maximum height independent samples median test 4.102 (df = 1); Fisher exact probability = 0.063). A significant difference is seen when the median values for the volume to surface area ratio (VSA) are compared between the two groups of mounds with different ages (independent samples median test = 8.856 (df =1); Fisher exact probability = 0.003). The median VSA ratio for the older mounds is 0.21 while the value for the more recent mounds is 0.37. As discussed above, these results indicate that the older mounds tend to be relatively “flatter” than the more recent mounds because most of the mound volume in the older mounds is accounted for by the long and short axis lengths rather than mound height. As discussed in more detail below, one interpretation of these results is that older mounds have evolved into flatter shapes as a result of fragmentation, dissolution, and compaction of the shell matrix. However, this temporal pattern is not universal: there are a number of older mounds that are relatively high and more conical in shape (e.g. WPSM77). Thus there is considerable variability within this overall temporal trend.

Figure 5a and b show the distribution of volume to surface area ratio values (VSA) and the elongation ratios (ER), together with the upper and lower median radiocarbon ages (where these were taken) for the 51 mounds surveyed. There is no simple geographic pattern in the index of mound flattening (i.e., the VSA) across the area. Mounds further from the present day shoreline are no more flattened as a group than those closer to the present day shoreline. Although there is, as noted above, considerable variability among the mounds studied, mound flattening is most closely associated with mound age. The slope and elongation results discussed above do show some geographic patterning, in that shell material is distributed along the length of ridges rather than across them. Mounds closest to the present day shoreline in the eastern Wathayn area (Figure 5b) show lower ER values and are therefore more elongated than those more distant from the shoreline. For example, the mean ER for mounds WPSM70, 76, 77, 79, 80, 82, 83, 85, 90, and 94 is 0.518±.189 and this is significantly different to the inland mounds located on a ridge, WPSM57, 60, 62, 63, 64, 68, 71, 72, 73, 91 and 92, mean 0.773±.071 ($t = 4.044$, $df = 11.145$ $p = 0.002$). The same is true for the mounds closest to the shore in the western Wathayn area (Figure 5a) (WPSM54, 55, 101, 105, 106, 107, 121, 124, 128, mean 0.519±0.143; mounds on the ridge WPSM59, 60, 61, 62, 104, 108, 119, 121, 126, 127, mean 0.732±.085, $t = 3.887$, $df = 12.742$, $p = 0.002$) .

Discussion

The 51 shell mounds analysed for this paper show variation in size and shape, with the five size attributes considered showing some positive correlations. Mound size is right skewed with a larger number of mounds showing lower values and a small number of unusually large mounds for this area. Mound age based on mounds from which we have both TLS data and radiocarbon ages is significantly correlated with mound shape, with older mounds more flattened relative to younger mounds. Mounds with a long duration of accumulation are exceptions since these exhibit periods when mound accumulation ceased and then recommenced (Fanning *et al*. submitted) and their shape and size likely reflects this.

It is possible to understand the relationship between mound volume, surface area and age by considering the geomorphological principles that define the morphology of the mound as shell is accumulated, as well as the cumulative effect of post-depositional processes. The act of deposition itself, plus plant and animal damage, the weight of overlying sediment, human trampling, and weathering processes, will act to fragment shells (Muckle 1985). Combined with sediment accession to the mound and pedogenesis within the mound, these processes will result in a decrease in mound mean particle size over time. The result is increased internal cohesion because smaller particles have increased inter-grain interactions (i.e., less space between particles) which produce an increased bond holding the sediment particles together (Anderson and Anderson 2010). The increased internal cohesion means the mound morphology will reflect the weathering processes that acted on the consolidated shell pile after formation rather than on the critical angles of repose of the freshly deposited shell (Huggett 2007).

A fundamental principle of geomorphology is that landforms become lower in relief over time (Huggett 2007). At least a portion of the contemporary shape of the Wathayn shell mounds likely reflects this principle. A preliminary study of the Wathayn mounds indicated variability in fragmentation, dissolution, and compaction of the shell matrix through time within individual mounds, as well as between mounds (Shiner *et al*., 2013). These processes act on the shell deposited by people to form mounds, and it is the combination of these processes that contribute to the shape and size of mounds that are recorded by archaeologists today. Therefore it is important to make formation studies a central focus of any comparative analysis of mound shape and size as well as the chronology of mound formation (Fanning et al. submitted). Detailed studies of the chemical and physical composition of the mounds at Wathayn are currently being undertaken that will allow assessment of the state of the shell material and the non-shell matrix that makes up individual mounds of different ages. As the results presented here indicate, classification of mounds on the basis of geometric shapes alone will add little to our understanding of their significance for human behaviour without detailed studies of what gives rise to mound shapes. What is critical to the contemporary shape of the shell mounds is an understanding of their formation history.

The S1 and S2 slopes were defined relative to the surrounding topographic slope. These measures, together with the elongation ratio, assess slope relative to landscape position of the mound, particularly the ridges on which the mounds are situated. Most of the mounds show some evidence of slope changes parallel to the ridges on which they rest but not so much that the mounds depart significantly from a largely circular outline. The S1 slope measurements perpendicular to the ridge orientation are larger than S2 slope measurements parallel to the ridge orientation, indicating how mound material is spread along the ridges rather than up and down hill. However, the elongation ratios indicate that for the mounds located on ridges this process has not produced particularly elongated mounds. Mounds that are elongated are located closer to the shore away from the rock ridges. It seems likely that these data reflect the interaction of the topographic location of mounds together with changes in mound shape due to weathering of the shells over time.

Obviously, the activity of people in the past created the mounds but this activity varied in duration, with some mounds accumulating relatively quickly while others accumulated more slowly and included one or more hiatuses in mound accumulation. Once formed, however, the mounds did not remain static entities but changed in shape due to a variety of internal and external weathering processes that changed the composition of the shells and the non-shell matrix. How mounds weathered likely reflected quite local conditions, including soil formation and vegetation cover, and these conditions may of course have varied through time on any one mound. Mound shape and size to some degree reflect their age but also their position within the local environment, particularly their location on and off ridges. The results presented in this study suggest that we need more detailed studies of mound composition to understand how these relationships interact to affect mound form. That said, the results do indicate that future comparative studies of mound shape will need to consider the outcome of varied formational histories. At least in the case of the Wathayn mounds reported here, the shape of the mounds that we see today is the result of a combination of both natural and cultural processes that need to be considered together if mound form is to be correctly interpreted.

7. Conclusions

The results of an analysis of shell mound size and shape data collected using a Terrestrial Laser Scanner show that there is considerable variability in the shape and size of shell mounds even from one relatively small geographic location. It is clear that there is no single causal factor for this variability, highlighting that the mounds must be conceived of as the result of multiple cultural and natural processes acting over time. In addition, mound shape has most likely changed markedly from when the mounds were originally deposited. The results indicate some patterning in mound form with the shape of mounds related to their age as well as the local position of the mounds in the landscape. As the material within the mounds weathered, the mounds tended to flatten and become more elongated across the slopes and ridges on which many of the mounds are situated. The mounds do not conform to a model of linear evolution of a pile of shell, suggesting mound histories are varied in both the nature of shell deposition as well as post-depositional processes.

These results have implications for comparative studies that seek to assess contemporary mound shape as a direct reflection of the activities of peoples in the past. Shell mounds were certainly created by people but their contemporary form reflects the outcome of a complex series of historical processes reflecting local environmental conditions. The contemporary size and shape of these mounds reflects the time over which these processes have operated as well as local variations in environmental conditions. Although the mounds from Wathayn come from only one location, it seems likely that formation processes like those discussed here have had some impact on mound size and shape more widely in the Albatross Bay region and in other regions of the world where mounded shell matrix deposits are found. If this proves to be the case then future studies will have to consider the impact of formation history on shell mounds as part of any assessment of the significance of mound size and shape.

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References

Anderson, R.S., Anderson, S.P. 2010. Geomorphology: The Mechanics and Chemistry of Landscapes. Cambridge University Press, Cambridge.

Andrés, A.N., Buill Pozuelo, F., Regot Marimón, J., de Mesa Gisbert, A. 2012. Generation of virtual models of cultural heritage. Journal of Cultural Heritage 13 (1), 103-106.

Bailey, G.N. 1975. The role of shell middens in prehistoric economies. Unpublished PhD Dissertation, University of Cambridge.

Bailey, G.N. 1994. The Weipa shell mounds: Natural or cultural? In Sullivan, M., Brockwell, S., Webb, A. (Eds.), Archaeology in the North: Proceedings of the 1993 Australian Archaeological Association Conference, pp. 107–129. North Australia Research Unit (ANU), Darwin.

Bailey, G.N. 1999. Shell mounds and coastal archaeology in northern Queensland. In: Hall, J., McNiven, I.J. (Eds.), Australian Coastal Archaeology. ANH Publications, Department of Archaeology and Natural History, RSPAS, The Australian National University, Canberra, Australia, pp. 105–112.

Bailey, G.N., Chappell, J., Cribb, R. 1994. The origin of *Anadara* shell mounds at Weipa, North Queensland. Archaeology in Oceania 29, 69–80.

Collins, L.D., Doering, T.F. 2009. High definition digital documentation at the Crystal River archaeological site (8Cl1). The Florida Anthropologist 62 (1-2), 23-44.

Domingo, I., Villaverde, V., López-Montalvo, E., Lerma, J.L., Cabrelles, M. 2013. Latest developments in rock art recording: Towards an integral documentation of Levantine rock art sites combining 2D and 3D recording techniques. Journal of Archaeological Science 40 (187), 1879-1889.

Fanning, P.C., Holdaway, S.J., Shiner, J.I., Petchey, F., Alley, K. In prep. The locations, ages and rates of accumulation of shell matrix deposits at Wathayn, Albatross Bay, northern Australia. For submission to *Journal of Island and Coastal Archaeology.*

González-Aguilera, D., Rodríguez-Gonzálvez, P., Gómez-Lahoz, J. 2009. An automatic procedure for co-registration of terrestrial laser scanners and digital cameras. ISPRS Journal of Photogrammetry and Remote Sensing 64 (3), 308-316.

Haddad, N.A. 2011. From ground surveying to 3D laser scanner: A review of techniques used for spatial documentation of historic sites. Journal of King Saud University-Engineering Sciences 23 (2), 109-118

Hiscock, P., Hughes, P. 2001. Prehistoric and World War II use of shell mounds in Darwin Harbour. Australian Archaeology 52, 41-45.

Huggett, R.J. 2007. Fundamentals of Geomorphology. Routledge, New York.

Lerma, J.L., Navarro, S., Cabrelles, M., Villaverde, V. 2010. Terrestrial laser scanning and close range photogrammetry for 3D archaeological documentation: The Upper Palaeolithic cave of Parpalló as a case study. Journal of Archaeological Science 37 (3), 499-507.

Morrison, M. 2003. Old boundaries and new horizons: The Weipa shell mounds reconsidered. Archaeology in Oceania 38 (1), 1-8.

Morrison, M. 2010. The shell mounds of Albatross Bay: An archaeological investigation of late Holocene production strategies near Weipa, north eastern Australia. Unpublished

Doctoral Thesis, Department of Archaeology, Faculty of Education, Humanities, Law and Theology, Flinders University, Adelaide.

Morrison, M. 2013a. From scatter to mound: a new developmental model for shell mound sites at Weipa. Queensland Archaeological Research 16, 165-184.

Morrison, M. 2013b. Niche production strategies and shell matrix site variability at Albatross Bay, Cape York Peninsula. Archaeology in Oceania 48, 78-91.

Morrison, M. 2014. Chronological trends in late Holocene shell mound construction across northern Australia: insights from Albatross Bay, Cape York Peninsula. Australian Archaeology 79, 1-13.

Muckle, R.J. 1985. Archaeological Considerations of Bivalve Shell Taphonomy. Unpublished Master of Arts thesis, Department of Archaeology, Simon Fraser University.

Núñez, M.A., Buill, F., Edo, M. 2013. 3D model of the Can Sadurní cave. Journal of Archaeological Science 40 (12), 4420-4428.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Talamo, J.R., Southon, S., Turney, C.S.M., van der Plicht, J., Weyhenmeyer, C.E. 2009. IntCal09 and Marine09 radiocarbon age calibration curves, 0-50,000 years cal BP. Radiocarbon 51,1111-1150.

Rodríguez-Gonzálvez, P., Mancera-Taboada, J., González-Aguilera, D., Muñoz-Nieto, Á., Armesto, J. 2012. A hybrid approach to create an archaeological visualization system for a palaeolithic cave. *Archaeometry* 54 (3), 565-580.

Russo, M. 2004. Measuring shell rings for social inequality. In: Gibson, J., Carr, P. (Eds.), Signs of Power: The Rise of Cultural Complexity in the Southeast. University of Alabama Press, Tuscaloosa, pp. 26–70.

Sanger, M., Thomas, D.H. 2010. The two rings of St. Catherines Island: Some preliminary results from the St. Catherines and McQueen shell rings. In: Thomas, D.H., Sanger, M. (Eds.), Trend, Tradition, and Turmoil: What Happened to the Southeastern Archaic? American Museum of Natural History Anthropological Papers, New York, pp. 45–70.

Shiner, J.I., Fanning, P.C., Holdaway, S.J., Petchey, F., Beresford, K., Hoffman, E., Larsen, B. 2013. Shell mounds as the basis for understanding human-environment interactions in far north Queensland, Australia. Queensland Archaeological Research 16, 65-92.

Ulm, S. 2006. Australian marine reservoir effects: A guide to ΔR values. Australian Archaeology 63, 57-60.

Wright, R.V. S. 1964. Probing Cape York’s past. Hemisphere 8 (7), 12-16.

Yastikli, N. 2007. Documentation of cultural heritage using digital photogrammetry and laser scanning. Journal of Cultural Heritage 8 (4), 423-427.

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Figure
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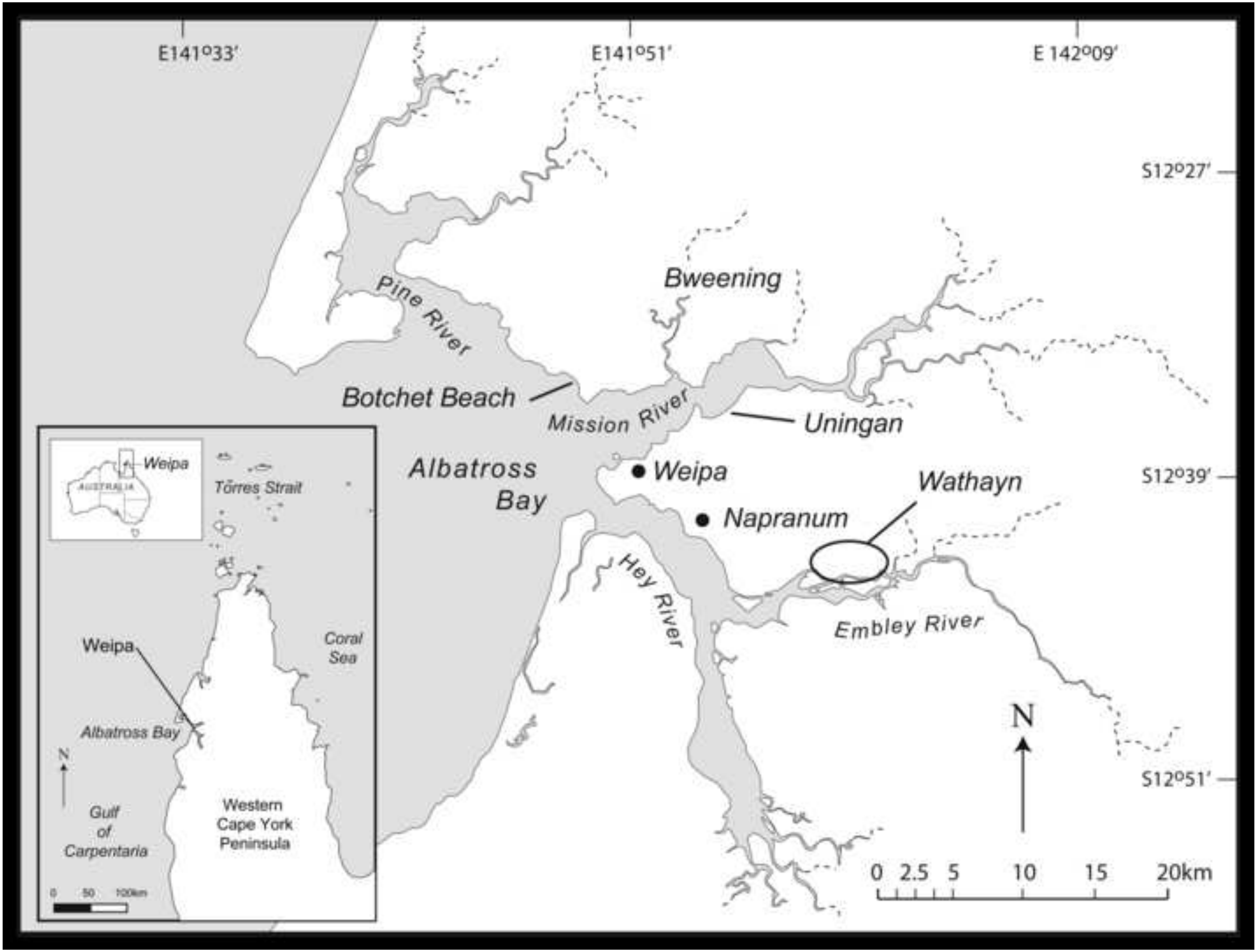

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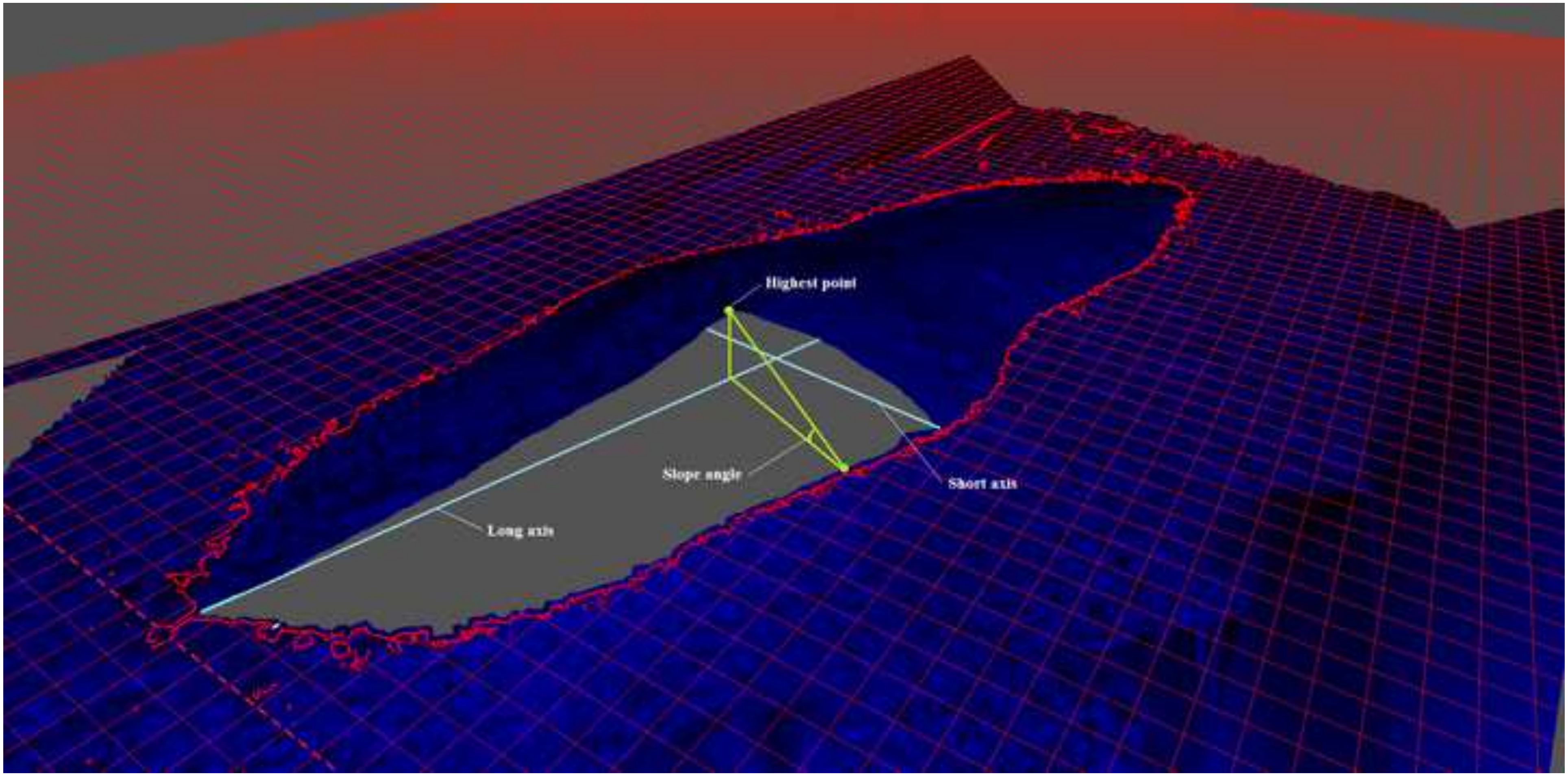

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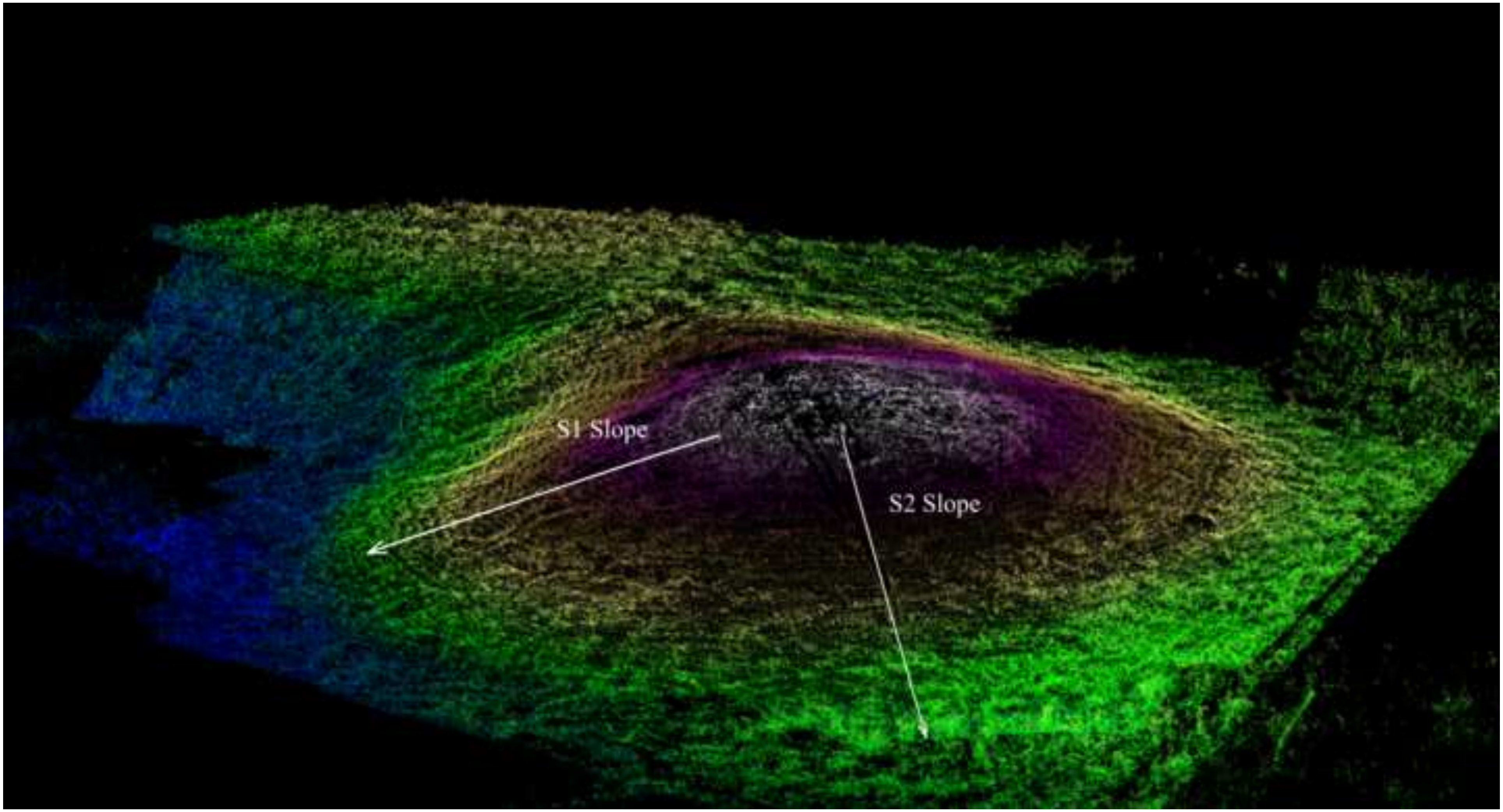

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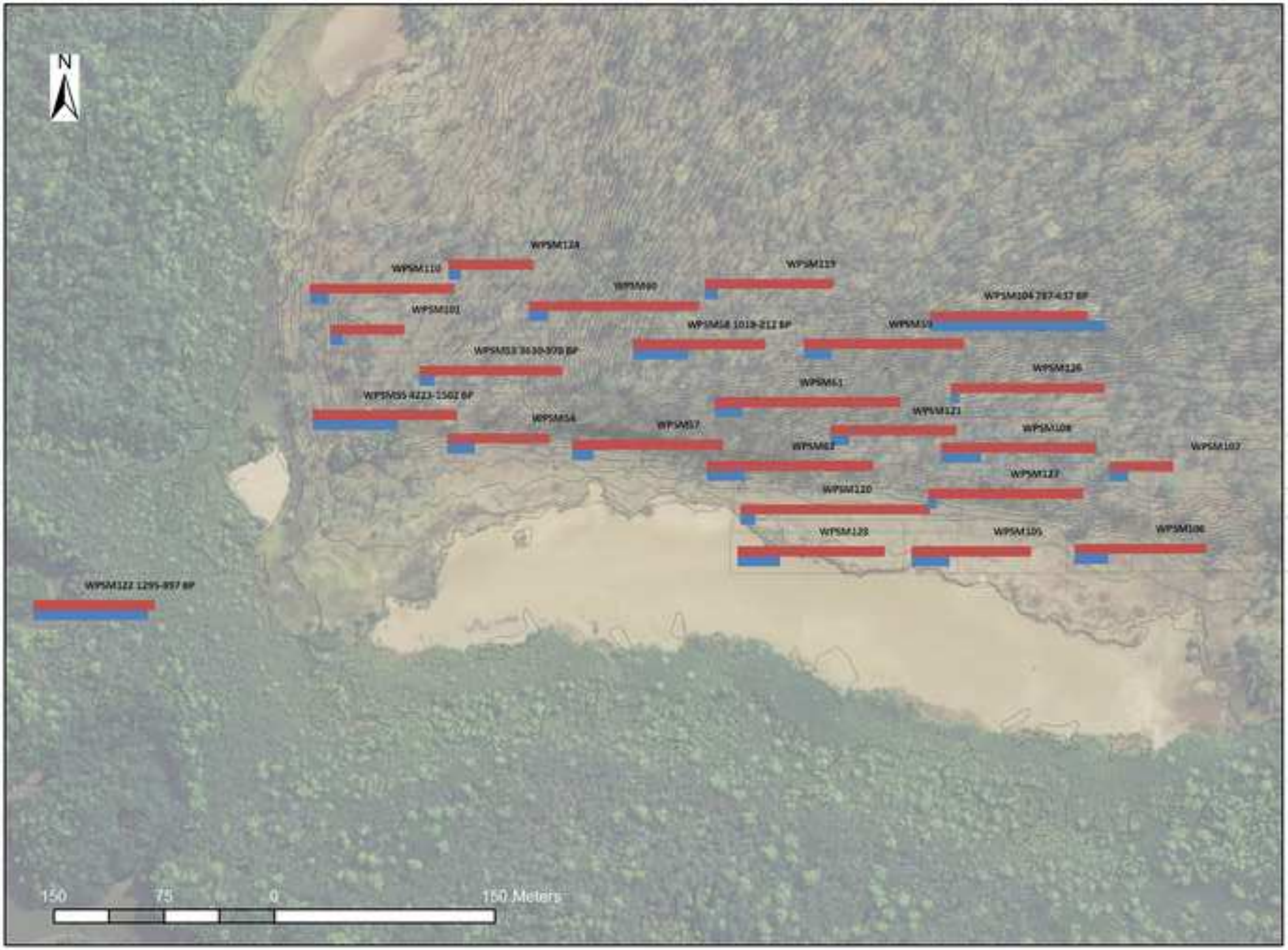

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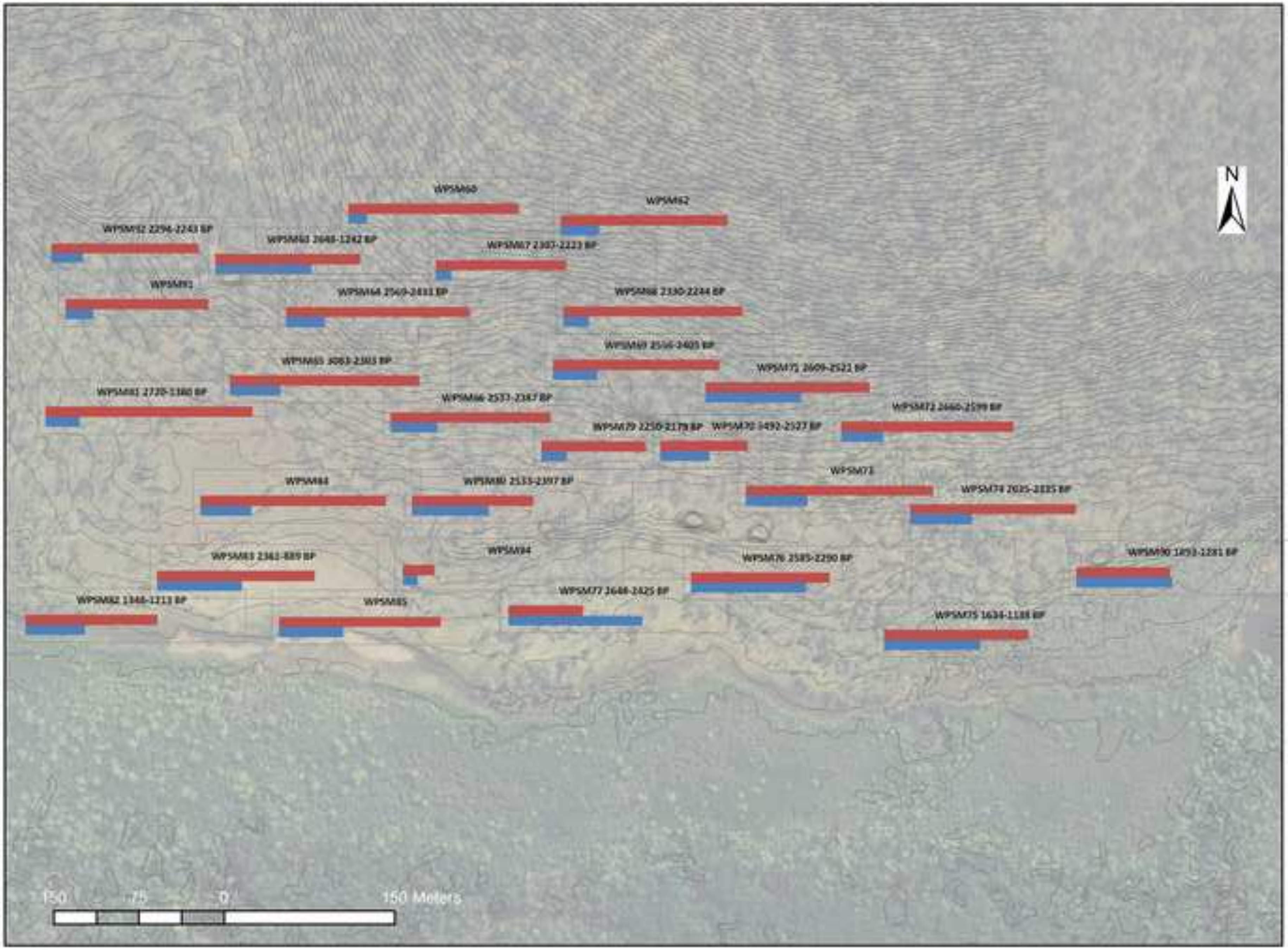

***Detailed Response to Reviewers**

Reviewer #1 asked that the paper should be published with some minor revisions.

It would be useful especially for the international reader to have one or two photos of the mounds for comparison with the schematic results. NEW FIGURE ADDED (NEW FIGURE 4) AND REFERRED TO ON PAGE 11

On Pg 15 Para under 6 It is not quite clear if all 51 mounds were dated or 28. NEW TEXT ADDED TOINDICATE THAT NOT ALL MOUNDS WERE DATED ON PAGE 16

It might be useful to include a brief sentence or two on how the results could be useful in the long term monitoring and management of these sites. NEW TEXT ADDED ON PAGE 3-4

Clearly a lot of data has been collected and it might be useful to provide a little more of a hint as to what will be covered in Fanning et al in Prep. THE PAPER OUTLINING THE DATING RESULTS IS SUBMITTED. WE HAVE ADDED SOME MORE TEXT TO THE DISCUSSION PAGE 18-19

Referencing

Check et al sometimes italics sometimes not. DONE

Anderson et al 2010 is 2001 on pg 18 DONE

Gonzalez-Aquilera 2009 should be et al on page 6 DONE

Russo 1994 is not in the text DELETED

Shennan 1997 is not in the text. DELETED

Reviewer #2: This is a great paper, well written with all the necessary details, explanations and data. The section on the technological application is clear and objective so anybody can follow it and apply it. The stats are clear, simple and correct. The conclusions seem perfectly reasonable based on the data. I found particularly interesting the results on the relation between thickness, width and time elapsed for the shellmounds. It would be interesting to apply a dating program to the changes in chronology in the horizontal dimension of the mounds to verify the hypothesis of changing shape due to time. I believe that one single change could be made: the inclusion of a figure with site photos of the most common shapes found in the region.
NEW FIGURE (NEW FIGURE 4) ADDED