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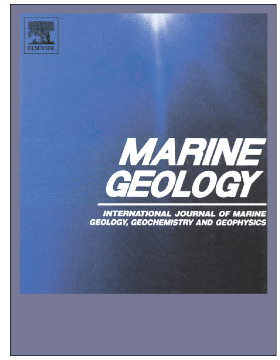

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Intertidal boulder-based wave hindcasting can underestimate wave size: Evidence from Yorkshire, U.K.

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Abstract

Large boulder-size clasts can represent important archives of high energy erosional wave activity at the coast. From tropical coral reefs to high-latitude eroding cliffs, boulders have been used to hindcast the frequency and magnitude (height) of waves produced by both storms and tsunami. Such reconstructions are based on the balance between the hydrodynamic forces acting on individual boulders and the counteracting resistive forces of friction and gravity. We test published models on over 900 intertidal boulders on the coast at Staithes in North Yorkshire, U.K., using repeat high-resolution topographic survey data. We quantified the predicted versus actual rates of boulder movement in the field over a 7-year period (2007 – 2014). We assessed the degree to which local geomorphology and biology may affect the resistive forces inhibiting transport. We found that 84% of intertidal boulders predicted to be mobile remained stationary over 7 years, suggesting that in some contexts boulder movement may be significantly less than predicted, regardless of boulder volume, shape or location. *In situ* cementation of boulders to the substrate by marine organisms appears to play a key role in retarding or preventing boulder transport. The implication is that boulder characteristics may not always provide a reliable estimation of wave height on the coast and reliance solely on hindcasting relationships may result in under prediction of the frequency and magnitude of past storm wave activity. We suggest here that more field studies that consider boulder movement are needed, set within specific site contexts, and that these data are used to improve the applicability and robustness of boulder transport models.

Keywords: boulders, storm, tsunami, palaeotempestology, rock coast, shore platforms, waves, bioprotection

Introduction

Coastal boulder deposits have been widely used to reconstruct the magnitude and frequency of high energy wave events produced by tropical (Goto et al., 2011) and high latitude cyclones (Knight and Burningham, 2011; Paris et al., 2011), and tsunami (Biolchi et al., 2016; Goto et al., 2010; Imamura et al., 2008; Yalciner et al., 2002) with hindcast models reaching back to the Last Interglacial period (Hearty, 1997; Kennedy et al., 2007). For boulders to be moved and deposited, bedrock lithology and structure must be conducive to producing clasts of this size, and wave energy must be sufficient for transportation (Kennedy et al., 2014; Stephenson and Naylor, 2011). These conditions are met in almost all coastal environments from tropical coral reefs (Goto et al., 2011) to high latitude rocky shores (Etienne and Paris, 2010), evidenced by boulders at both intertidal elevations (Chen et al., 2011) and at tens of metres above sea level (Hall et al., 2010).

To initiate boulder movement, the momentum forces of waves acting on a block must exceed the resisting forces of gravity and friction between the boulder and the foreshore and neighbouring clasts. Clasts can then be moved through sliding, rolling, saltation and, in extreme events, by suspension in the water flow (Nandasena et al., 2011; Nandasena and Tanaka, 2013; Nandasena et al., 2014). The greater the wave energy the larger the clast that is able to be transported. Despite this apparently relatively straight forward relationship, controversy exists over the transport mechanisms of many boulder deposits and the palaeotempestology and palaeotsunami inferred from them (e.g. Bryant and Nott, 2001; Dominey-Howes, 2007). Much of the debate is focussed on the dynamics of clast movement, and physics of the equations used to hindcast the hydrodynamic conditions during transport.

Considerable recent work on historical and recent boulder deposits which can be unequivocally related to specific events, such as the 2004 Indian Ocean Tsunami (Goto et al., 2007; Paris et al., 2010) or annual winter storms in the north Atlantic (Hall et al., 2008; Hall et al., 2010; Hansom et al., 2008), have related observed clast dynamics to known wave conditions, specifically wave heights. These results are not always conclusive. For example, Paris et al. (2009) found that during the 2004 Indonesian tsunami the available clasts moved were smaller than the waves were capable of transporting. Despite these investigations, no single relationship between wave characteristics and boulder size has yet been identified. This means that several disparate hydrodynamic hindcasting-equations remain in use worldwide for coastal-planning and risk assessment (e.g. Nott (Nott, 2003), Hansom (Hansom et al., 2008), and Benner-Goto (Benner et al., 2010; Goto et al., 2007; Goto et al., 2009; Imamura et al., 2008)). It remains that no unequivocal answer exists to the question of 'what wave height causes boulders of specific sizes to move'.

Site-specific geomorphology plays a significant factor in boulder movement and this complicates and limits the application of many hindcasting equations (Imamura pers. comm., in Benner et al., (2010)). For example, on the Glamorgan coast of Wales, boulders rapidly moved across the surfaces between topographic steps in the intertidal zone; whereas those that clustered and accumulated in front of these steps, of the same size, moved more slowly (Naylor et al., 2016). However, most work assumes that all boulders are mobile under the right hydrodynamic conditions and if wave forces are sufficient a boulder will always move. We test this specific inference by investigating a field of 900 intertidal boulders on the coast of North Yorkshire, U.K. (Fig. 1). The intertidal zone is chosen as boulders are exposed by the semi-diurnal tide and therefore have one of the highest chances of being moved over a given period, and so this location provides a useful field laboratory. Specifically, the study aims to quantify observed boulder movement over a 7-year period, and to compare this to the movement predicted by commonly used hydrodynamic relationships. It aims to test the theory that wave height hindcasting is not simply a direct function of boulder size and is significantly affected by a wider set of controls including geomorphic and biological conditions.

Regional Setting

The coast at Staithes (54°33'37.61"N, 0°47'41.44"W), North Yorkshire, U.K. (Fig. 1) is composed of interbedded mud, silt and sandstones, with shales and ironstone units in the middle Lias formation of the lower Jurassic (Powell, 2010). The near-horizontal beds average c. 3 m in depth but can be up to 11 m in places (Lim et al., 2010), forming near-vertical cliffs up to 30 m high which are eroding at spatially averaged rates between 0.001 to 0.01 m/year (Rosser et al., 2013) (Fig. 2 a, b). The North Yorkshire coast has experienced negligible isostastic adjustment in the past 5 ka with sea level remaining relatively steady at present elevation since that time (Shennan et al., 2018). The contemporary morphology of the coast therefore reflects modern processes with no inheritance from earlier Pleistocene sea levels (Robinson, 1977a; Robinson, 1977b; Lim et al., 2010).

The coast is macrotidal (6 m range) with a mean significant wave height at the nearby Whitby wave buoy (20 km southeast) varying from 0.8 m in summer to 1.2 m in winter with a significant wave height of almost 7.5 m in January (NECO, 2018). Winter storms can produce winds in excess of 36.11 m/s (Lim et al., 2010), with monthly means ranging from 2.32m/s (July) to 6.20 m/s (January). During the period between 2010 to 2014 the maximum wave height at Scarborough was 10.99 m with nearly all waves approaching the coast from the NE quadrant (Fig. 3). This maximum height is greater than heights recorded between 2008 and 2010 (Norman, 2012). The average annual rainfall recorded by the Loftus Meteorological Office (3 km north of Staithes) is 567 mm. Frosts can occur during winter (average of 8.1 days of air frost), but minimum daily mean monthly temperatures do not fall below zero (minimum is 1.5°C in February) derived from weather data at Loftus between 1981 and 2010.

Methods

Time series terrestrial and airborne LiDAR were collected in 2007 and 2014 to establish whether boulders had moved or not during this 7-year period. We used rotary wing LiDAR at a flying height of approximately 150 m (TopoEye Mk II (2007) and RobinWings^{TM} (2014), to collect detailed foreshore topography. Flight lines for the intertidal boulder mapping were spaced at c. 200 m, with a usable swath width of c. 300 m, leading to a line overlap of c. 150

m, deriving a mean point spacing of c. 100 ppm^2. The survey precision was checked against planar targets also scanned in the survey areas and measured independently with GNSS, providing a plan and vertical precision of 0.05 and 0.06 m respectively. A regular DEM at 0.20 m resolution was derived from the point clouds using kriging. Fieldwork was conducted in August 2014 concurrent with the second LiDAR survey. Individual boulders were measured in the field using a tape and located with a hand-held GPS. Each boulder dimension (a- and b-axis) was also measured from the DEM and compared with field measurements. The c-axis (vertical) was calculated as the difference between the maximum and minimum heights within a 1 m buffer of the boulder edge. As some boulders were perched on bedrock pedestals, all boulders were surveyed in the field and the height of any pedestals measured. This pillar height was subtracted to calculate the true boulder c-axis. Boulder roundness was quantified using the visual technique of Powers (1953).

Once the two LiDAR surveys were compared, the boulders were divided into two categories: mobile or stationary. Mobility was classified as both lateral movement and/or rotation of a boulder. As the sample size was unequal (779 stationary and 132 mobile) a random subsample of 100 boulders from each category was selected for statistical analysis. Welch's t-test assumes unequal variance of the two sample groups and is therefore more robust than a Students' t-test. The statistical package R 3.2.0 was used with data checked for assumptions of normality via box plots and homogeneity of variance via plots of mean vs variance. Where these assumptions were not met the data was transformed ($y=\log(x)$) and assumptions checked again.

Wave hindcasting was conducted using the relationships of Nott (Nott, 2003), Hansom (Hansom et al., 2008), and Benner-Goto (Benner et al., 2010) modified from Goto and Imamura (Goto et al., 2009; Imamura et al., 2008). For each equation, a seawater density of 1.02 g/cm^3 and local rock density of 2.583 g/cm^3 was used (Lim et al., 2010). These equations were selected as combined they are the most widely used (c. 750 citations) and represent the principal relationships used by researchers (Table 1).

Results

Platform Morphology

The surveyed shore platform at Staithes is 7.5 ha in area, with a maximum width to mean low water spring of 230 m. The rear of the platform is delineated by a ramp of boulders accumulated at the base of a 30 m cliff (Fig. 1, 4). The ramp is 25 m wide and close to 2 m high with an elevation range of 0.8 – 3.0 m above MSL. The mean slope of the platform is < 1° and roughness is generally low, with a step (0.09 – 0.22 m high) daylighting across the centre of the boulder field (Fig 1b, 4a).

Boulder Sedimentology

911 individual boulders >0.5 m in size (a-axis) are scattered across the platform seaward of the toe of the boulder ramp at base of the cliff toe (Fig. 1). The clasts range in volume from 0.004 - 4.023 m^3 (mean 0.409 +/- 0.441 m^3) and the average a, b, and c-axes are 1.50 +/- 0.51, 1.01 +/- 0.33, and 0.29 +/- 0.12 m respectively (Fig. 5). The b-axes of boulders range from 0.304 – 2.236 m in length. These dimensions classify (Zing Class) 59% of the boulders as oblate (discoidal) in shape, with a further 40% being triaxial (bladed). The boulders also range from being well rounded (7%) to very angular (3%). The majority were classified as subrounded and subangular (28% each), with angular boulders accounting for 22% of the sample.

The boulders are scattered across the platform with the maximum seaward distance from the cliff toe being 172.84 m (mean 69.90 +/- 25.17 m). Apart from some grouping of clasts adjacent to the bedding steps on the platform, there does not appear to be any location on the platform where the boulders preferentially accumulate (Fig 4). The most seaward boulders are kelp covered and exposed only at spring low tides. The highest boulder is found at an elevation of

-0.01 m (with respect to Ordnance Datum at Newlyn) with a mean elevation of -0.85 +/- 0.28 m.

A small proportion (8%) of the boulders are perched on bedrock pedestals (Fig 2c). These pedestals range up to 0.68 m in height (average 0.01 m) and are on average about 73% of the diameter of the boulder above. Most boulders lie directly on the platform surface and are surrounded by benthic communities reflecting the degree of tidal inundation. Close to low water (below -1.5 m) a complete cover of macroalgae occurs (Fig 2d, e), while above this elevation encrusting coralline algae and barnacles are found in decreasing in abundance with elevation until the rock surface is virtually bare at the base of the landward cliff.

Boulder Movement & Hindcasting

Between 2007 and 2014, 132 (14.5%) boulders moved position with the remaining 85.5% stationary. Most observed boulder movement was < 5 m, although in some cases they could not be relocated and may have been fragmented or transported outside of the study area (Fig. 5). It was visually observed in the field in areas, especially in areas of high benthic covers, that where boulders had moved the rock surface at the original position was commonly characterised by an absence or a low density of intertidal encrusting communities (Fig. 2e). Critically, the aim of this paper was simply to quantify whether a boulder was stationary or not over the study period measurement of movement trails (Cullen & Bourke, 2018) or distance moved was not undertaken. The maximum volume of a boulder which moved position was 1.41 m^3, with 84.98% of boulders this size or less remaining stationary.

For the largest mobile boulder (1.41 m^3) a single wave with a height between 2.57 m (Hansom Equation), 2.73 m (Benner-Goto) and 7.80 m (Nott Equation) is hindcast. The wave height predicted to move the largest boulder found on the platform (4.02 m^3) is 2.85 m (Hansom), 3.08 m (Benner-Goto), to 7.29 m (Nott). The predicted wave heights from each equation were all significantly different from each other (ANOVA, α = 0.05, p<0.001, pairwise t test with

Bonferroni adjustment). A comparison of all the predicted wave heights, for both stationary and mobile boulders (Fig. 6) shows that the Nott equations predict significantly higher wave heights (average height 3.53 m ± 2.2) than the Benner-Goto (average height 1.52 m ± 0.4) and Hansom (average height 1.34 m ± 0.5) equations. The Nott equations produce a large scatter of points with poorer boulder volume / wave height relationships than the equations of Hansom and Benner-Goto, which display a better level of agreement and predictive potential over a range of boulder volumes, particularly where boulders were smaller. It is evident that boulder size is not the only parameter controlling movement, else all boulders of a similar volume would be mobile.

Discussion

The observations of clast mobility on the platforms at Staithes demonstrate that recorded wave energy, expressed as wave heights, is high enough to cause boulder movement. The important aspect of the observed mobility is that boulders up 1.41 m^3 in volume were moved by waves, however, of the boulders smaller than this size the overwhelming majority (84.98%) remained stationary. For those boulders which moved, we do not know if this was a single epoch of movement, or multiple iterations over time. Not unsurprisingly, all boulders significantly larger in volume than 1.41 m^3 (a and b axes) also remained stationary (Table 2). The boulders that moved were also found in both the 2007 and 2014 surveys at a significantly lower elevation and at a greater distance to the cliff than those that remained stationary which suggests a minimum water depth is required to initiate transport (Table 2). This implies that boulders are more likely to move if they are more frequently under the influence of waves.

The question arises as to what is controlling boulder mobility. For example, are the significant differences in volume, a axis or b axis contributing to the ease with which a wave drives the movement of the boulder as previous research suggests (e.g. Goto et al. 2011); or is local geomorphological control strongly modulating entrainment and transport (e.g. Naylor et al. 2016)? It may also be that wave height alone is not a nuanced enough measure of the efficacy of a wave in driving boulder movement, where the role of factors such as impulsive impacts as a function of wave shape are known to vary considerably yet have not been assessed in this context (Bullock et al., 2003; Muller et al., 2007). In addition, wave height on a platform may not be an adequate measure of wave power due to wave-wave interaction in shallow water both on and immediately off the shore platform (Massel, 2013). It is already established that the two groups (mobile and stationary) of boulders are different; one has been moved hydraulically and the other has not. Considering the amount of overlap in clast sizes between the two groups (Fig. 5) it is apparent that there may not be a specific hydraulic threshold that would enable movement, or any value that could be used to forecast the mobility boulders of a specific size. The significant results of slope, elevation and distance to the landward cliff indicate that there are additional factors that influence the ability of waves to move boulders, and so boulder size alone may not be the primary determinant than enables boulder movement.

One key variable that may affect boulder transport is the roughness of the surface over which the boulders are moved (Weiss and Diplas, 2015), which is analogous to the movement of bedload clasts in bedrock rivers (e.g. Ferguson et al., (2017)). In most studies, however, the roughness of the shore platform at millimetre-scale is poorly defined. At Staithes platform roughness is generally low (Fig. 4d) with steps (0.09 – 0.22 m high) present in the centre of the shore platform and boulder field providing the only topographic feature (Fig 4d). On the Glamorgan Peninsula in Wales, it has been established that bedrock steps can act to capture boulders moving across an intertidal shore platform, and that transport distance is more strongly linked to platform morphology than other commonly assessed parameters like clast size (Naylor et al., 2016). At Staithes, although there is some clustering of boulders near these steps, these features do not appear to trap boulders and inhibit transport in this manner.

The lack of boulder mobility appears to persist well beyond the 7-year observation period of this study. Some boulders appear to have remained stationary long enough for the platform surface to lower around them, resulting in boulders perched on top of pedestals up to 0.68 m in height (Fig. 2f) (Robinson, 1977a,b). Rates of erosion on North Yorkshire intertidal shore platforms have been measured in detail through microerosion meters and range from 1.09 – 1.14 mm/yr (Robinson, 1977a; Robinson, 1977b). Assuming that these downwearing rates are uniform spatially and temporally across this coast, the size of the smallest and largest boulder pedestals at Staithes suggests that the boulders may have been stationary for between 26 - 28 and 623 - 651 years respectively. Assuming zero platform inheritance, and a consistent Holocene cliff erosion rate, it is plausible that some of these boulders may have been in place since their location was exposed by the retreat of the cliff. A hypothesis which could be tested through quantitative dating.

Intertidal ecological communities are an important additional contributor to platform surface roughness (Naylor and Viles, 2000) and they also act as bioprotectors reducing the intensity of other earth surface processes such as mechanical rock decay (Coombes et al., 2017). At Staithes, coralline algal communities form millimetre-thick crusts across the rocky substrates in the intertidal zone (Fig. 2d) and are particularly noticeable where boulders have been recently moved, leaving the bedrock underneath exposed devoid of algal communities (Fig 2e). In the U.K. the red algae *Lithophyllum incrustans* is one of a number of intertidal species that bind sediment along with tube building annelids (Naylor and Viles, 2000) and macroalgae (e.g. red sand binding weed). *Lithophyllum incrustans* grows laterally at rates of 2.305 – 3.144 mm/yr and vertically at 0.234 – 0.298 mm/yr (Edyvean and Ford, 1987) and so the potential exists for boulders to become biologically reattached to the platform surface. *Lithophyllum* sp. was also found to protect platform surfaces from other erosion processes including boring by cyanobacteria, which may also limit fine-scale erosion of boulders by weathering agents (Naylor, 2001). Such encrustations increase the required shear stress to initiate boulder movement when they cement the boundary between clasts, as has been demonstrated to occur in gravel bed rivers (Rice et al., 2012). It remains likely that these encrustations as biological adhesives and contribute to immobility of smaller boulders that are otherwise predicted to move under hindcasted wave conditions. Hansom et al. (2008) based their field data and modelling of boulder detachment, transport and deposition on fresh boulders newly quarried from bedrock. Similar to boulder detachment and movement in the Aran Islands of Ireland (Cox et al., (2018), the work of Hall et al., (2006) and Hansom et al. (2008) also relates entirely to processes at tidal heights well in excess of those that would support the development of intertidal encrustation. In these contexts, the biological constraints on boulder movement, suggested by the Staithes data, are absent. However, for boulders in other settings such as coral reef flats, the biological encrustations may play a vital role.

Despite this, biological processes are also known to be highly scale dependant (Naylor, 2005) and whilst algae may provide localised bioprotection of the platform and secure boulders to the platform surface, the presence of biological binders does not completely inhibit bedrock erosion in the surrounding area (Fig. 2c, f). The implication is that boulder transport models need to take account of the variety of processes and their spatial variability that restrict the transport. For boulders on pedestals, the hydrodynamics required to initiate transport are also influenced by pedestal morphology as well as the strength and maturity of any encrustation. Subsequent movement of the boulder may then be a function of the lifespan of the bioprotective adhesive and the pedestal itself, along with any reduction of boulder mass through biological, chemical and physical rock decay processes (Naylor et al. 2012).

Conclusions

Hindcasting wave heights based on boulder dimensions has become a standard technique in coastal science despite issues with the accuracy of the techniques and their underlying assumptions. Nevertheless, a key underlying principle is that all boulders will be moved by specific wave heights. In this study 84% of the >900 blouders remained stationary despite wave conditions being theoretically sufficiently energetic to move them. There was a significant difference in the size of the clasts which did move: boulders that moved were statistically smaller, but a large degree of overlap existed between the two groups, so it was not possible to identify a threshold value of wave dimensions that could affect mobility. We therefore contend that hindcasting-derived palaeotempestology and palaeotsunami data should only be considered to produce minimum wave heights at the coast, since boulders may not move under the conditions predicted for them to be mobile. In addition, it needs to be considered, based on other studies, that wave height alone may not fully approximate energy at the rock surface. We also suggest that site specific conditions also play a significant role in enabling or inhibiting boulder movement, whether this be the morphology of the shore platform (i.e. geomorphological control), or the biological adhesion that encrustations provide by binding boulders to the foreshore surface. It follows that the magnitude of palaeostorms are therefore likely more intense than previous predictions based solely on boulder dimensions. We therefore recommend that further field and laboratory experiments are conducted to allow models predicting storm-wave boulder transport to be improved.

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Figures

Figure 1: (a) Staithes, North Yorkshire, is located on the eastern coast of the United Kingdom. (b) A digital elevation model of the field site derived from airborne LiDAR. Boulders on the platform are observable as high points on the shore platform surface.

Figure 2: (a) The intertidal platform at mid-high tide. All the studied boulders are subjected to wave action during each high tide. (b) The landward cliffs backing the shore platform at Staithes. These cliffs expose the lower Jurassic middle Lias formation which is the same rock type as the boulder-size clasts on the platform. (c) Boulders perched on bedrock pedestals. (d) Coralline algae encrustation on the platform. (e) Macroalgae dominated communities close to the mean low tide mark. The boulder in the foreground has recently shifted position exposing the bare bedrock that lay beneath its original position. A similar bare patch where a boulder was once positioned is also visible above this position, however the clast is absent having been recently detached and moved. (f) one the highest pedestals found at the study site which may be up to 650 years old. The ruler is 30cm long for scale.

Figure 3: (a) Maximum and (b) mean significant wave height in the Staithes region taken from the Scarborough buoy for the period 2010 – 2014.

Figure 4: A series of data derived from the aerial survey (2014) used to determine boulder character. (a) aerial image, (b) digital elevation model, (c) slope and (d) rugosity, for the same section of platform.

Figure 5: Histograms of the a/b/c dimensions and volume as well as the distance from the landward cliff of mobile and randomly-selected stationary boulders that were statistically analysed. There is significant overlap in the populations for all dimensional parameters.

Figure 6: Hindcast wave height as a function of boulder volume for the hydrodynamic relationships predicted by the equations of Nott (Nott, 2003), Hansom (Hansom *et al*, 2008), and Benner-Goto (Benner *et al.,* 2010) tested in this study. Boulders which were observed to move position (solid symbols) overlap with stationary boulders (empty symbols) for the same predicted wave height.

Table Captions

Table 1: Citations of published hindcasting relationships (from GoogleScholar, July 2018).

Table 2: Results of Welch's t test between 100 randomly selected boulders from each group of boulders (mobile or stationary). Numbers in bold indicate significant differences between stationary boulders and those that moved. Data was checked for normality and homogeneity of variance and transformed (y=log(x)) where indicated with a *.

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Table 1

Hindcasting Article	**Citations**
Brenner, 2010	61
Goto et al., 2007	173
Imamura et al., 2008	148
Subtotal	**382**
Nott, 2003	264
Hansom et al., 2008	103
TOTAL	**749**

Table 2

Factor	**p-value**	**Mean mobile**	**Mean stationary**
Axis A* (m)	**0.008**	1.300 ± 0.4	1.468 ± 0.5
Axis B (m)	**0.013**	0.878 ± 0.3	0.984 ± 0.3
Axis C* (m)	0.137	0.252 ± 0.1	0.274± 0.1
Volume* (m^3)	**0.014**	0.253 ± 0.2	0.342 ± 0.3
Roundness	0.403	3.75 ± 1.0	3.61 ± 1.3
Elevation (m)	**0.028**	-0.796 ± 0.3	-0.894 ± 0.3
Distance to cliff (m)	**<0.001**	57.8± 22.3	73.6 ± 25.6
Slope (°)	**0.022**	1.88 ± 0.6	2.10 ± 0.6

Highlights

- The mobility of over 900 clasts were analysed to test theories of wave hindcasting.
- 84% of clasts which are predicated as mobile are in fact stationary based on analysis of aerial LiDAR data.
- Standard hindcasting relationships provide a minimum value of storm wave intensity
- Site-specific benthic communities are a major determinate of boulder mobility.

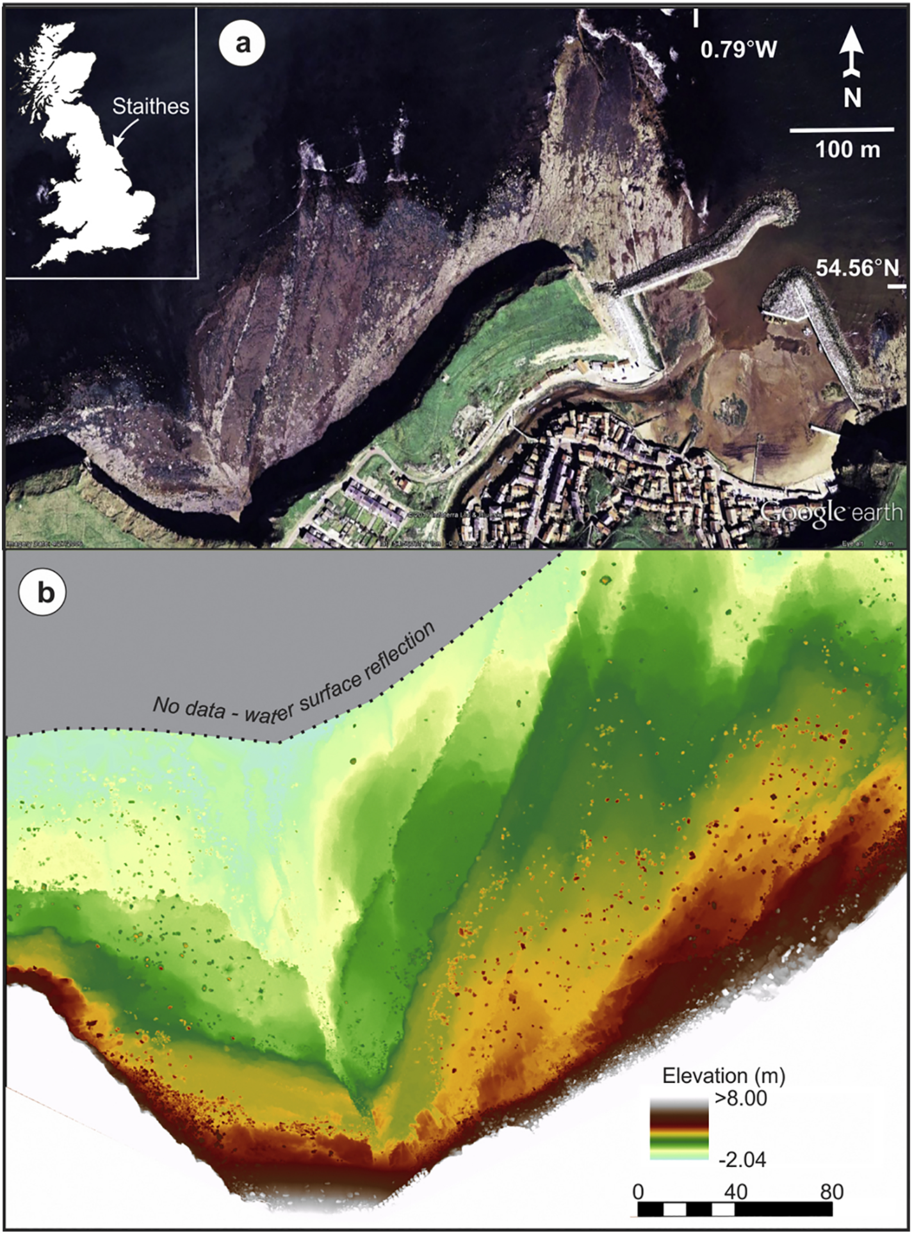

a
Staithes
0.79°W
N
100 m
54.56°N
Google earth
b
No data - water surface reflection
Elevation (m)
>8.00
-2.04
0
40
80

Figure 1

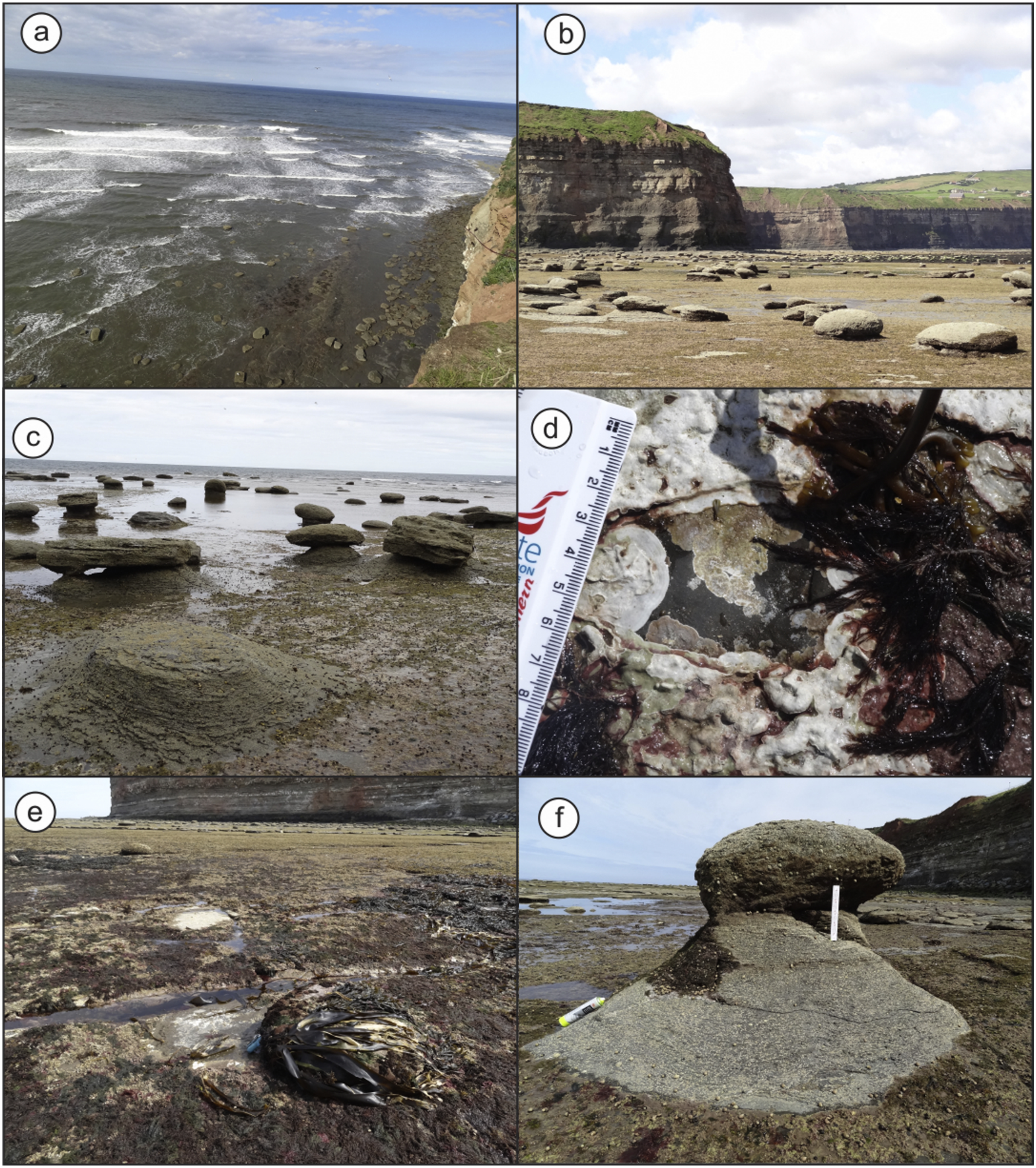


Figure 2

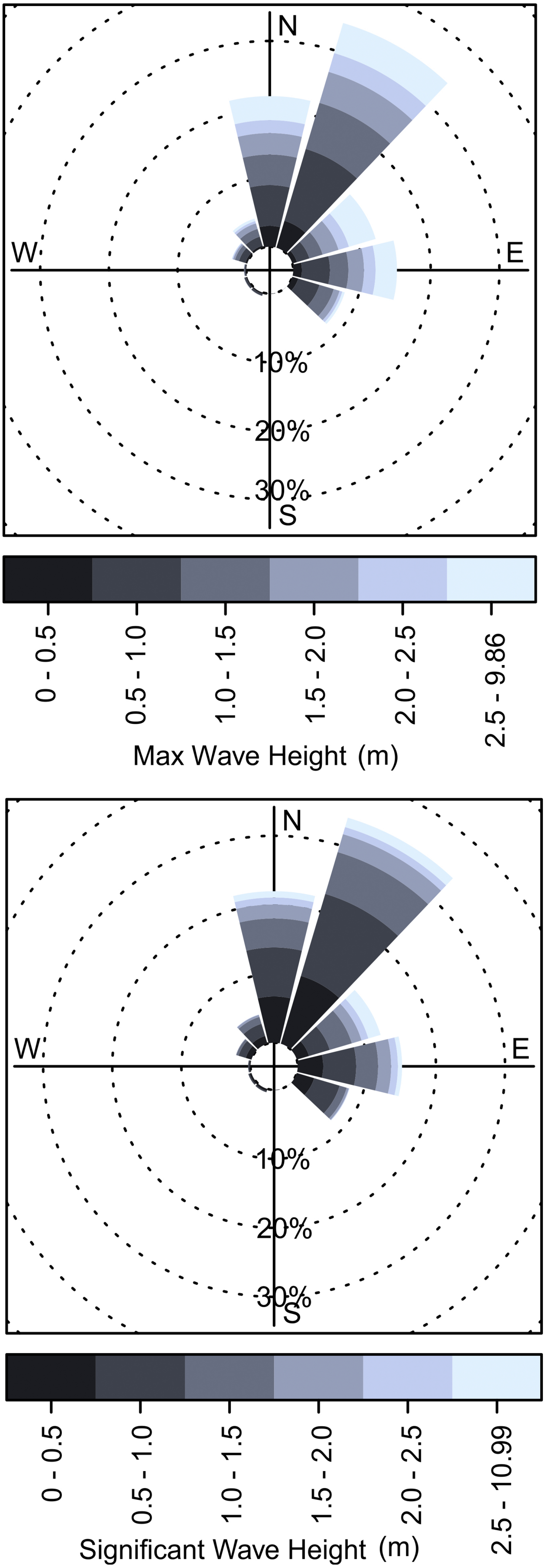

N
W
E
S
10%
20%
30%
0 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 9.86
Max Wave Height (m)
N
W
E
S
10%
20%
30%
0 - 0.5
0.5 - 1.0
1.0 - 1.5
1.5 - 2.0
2.0 - 2.5
2.5 - 10.99
Significant Wave Height (m)

Figure 3

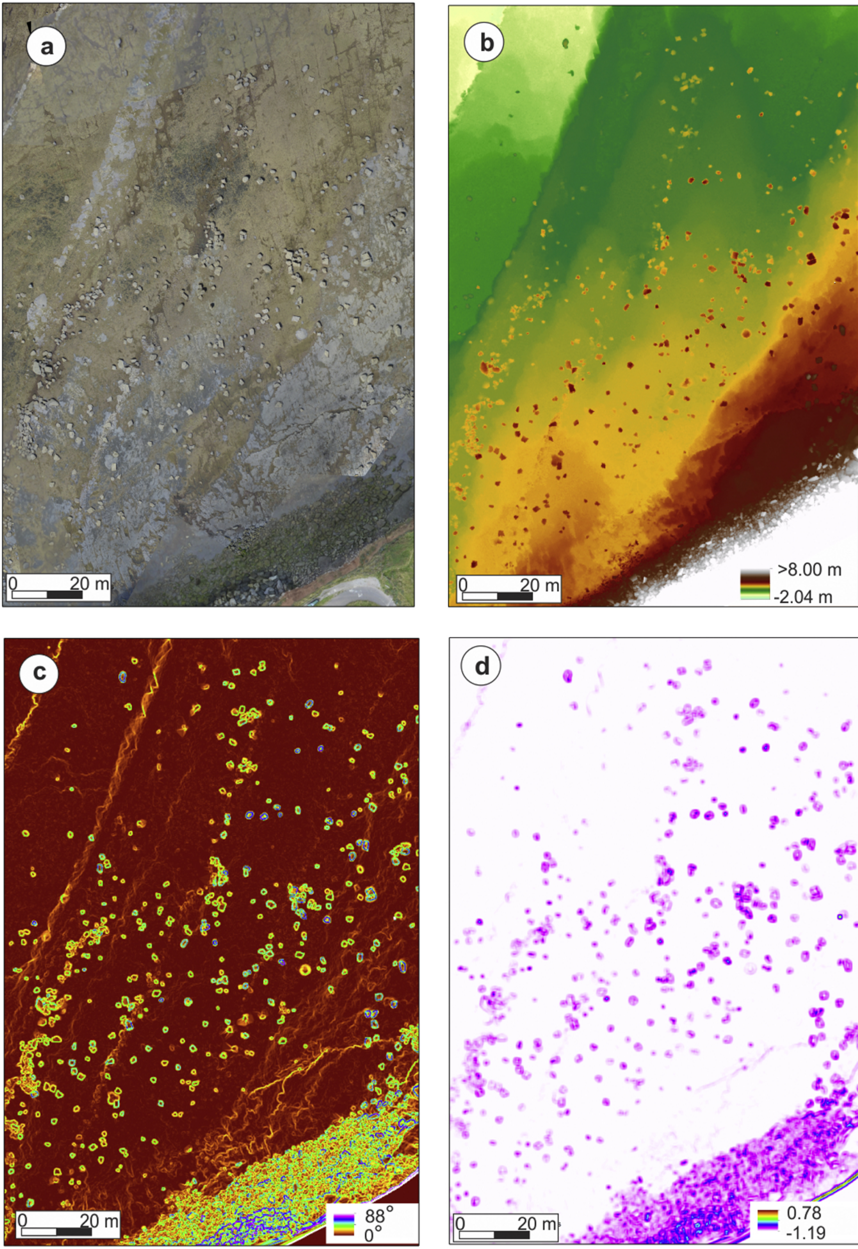
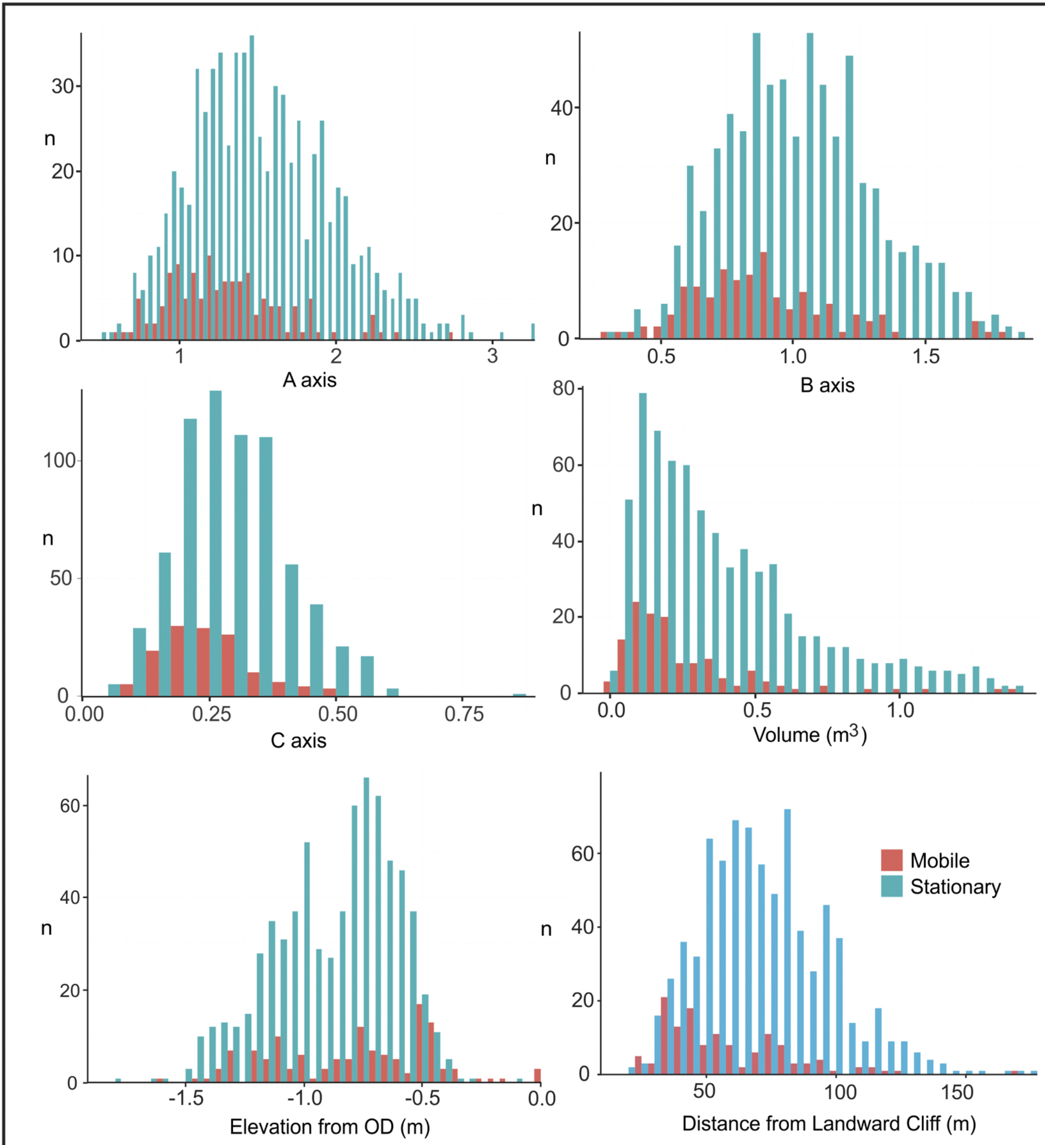


Figure 4



n
30
20
10
0
1
2
3
A axis
n
40
20
0
0.5
1.0
1.5
B axis
n
100
50
0
0.00
0.25
0.50
0.75
C axis
n
80
60
40
20
0
0.0
0.5
1.0
Volume (m3)
n
60
40
20
0
-1.5
-1.0
-0.5
0.0
Elevation from OD (m)
n
60
40
20
0
50
100
150
Distance from Landward Cliff (m)
Mobile
Stationary

Figure 5

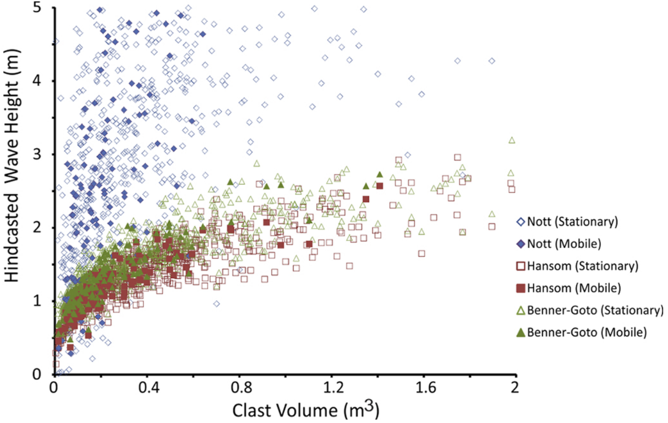

Hindcasted Wave Height (m)
0
1
2
3
4
5
0
0.4
0.8
1.2
1.6
2
Clast Volume (m3)
Nott (Stationary)
Nott (Mobile)
Hansom (Stationary)
Hansom (Mobile)
Benner-Goto (Stationary)
Benner-Goto (Mobile)

Figure 6