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Storm Waves May Be the Source of Some “Tsunami” Coastal Boulder Deposits

Andrew B. Kennedy1, Ronadh Cox2,3, and Frédéric Dias4

1Department of Civil & Environmental Engineering & Earth Sciences, University of Notre Dame, Notre Dame, IN, USA, 2Geosciences Department, Williams College, Williamstown, MA, USA, 3School of Earth Sciences, University College Dublin, Dublin, Ireland, 4University College Dublin, Dublin, Ireland

Abstract Coastal boulder deposits (CBD) provide what are sometimes the only remaining signatures of wave inundation on rocky coastlines; in recent decades, CBD combined with initiation of motion (IoM) analyses have repeatedly been used as primary evidence to infer the existence of ancient tsunamis. However, IoM storm wave heights inferred by these studies have been shown to be highly inaccurate, bringing some inferences into question. This work develops a dimensionless framework to relate CBD properties with storm-wave hindcasts and measurements, producing data-driven relations between wave climate and boulder properties. We present an elevation-density-size-inland distance-wave height analysis for individual storm-transported boulders which delineates the dynamic space where storm-wave CBD occur. Testing these new relations against presumed tsunami CBD demonstrates that some fall well within the capabilities of storm events, suggesting that some previous studies might be fruitfully reexamined within the context of this new framework.

Plain Language Summary Coastal Boulder Deposits (CBD) are large rocks transported on land by storm or tsunami waves. Because CBD are very durable they can provide long term records of coastal inundation, but quantifying the strength and source of inundation remains controversial. This work uses many records of CBD found worldwide combined with wave climatology to determine the range of transport possible for storm-wave CBD, and then to compare present results to findings using older methodologies. It is found that these older methods can underestimate the potential for storm waves to create CBD, and some previously identified “tsunami” CBD may actually have been generated by storm waves.

1. Introduction

Coastal boulder deposits (CBD) are found worldwide on rocky coastlines (Abad et al., 2020; Cox et al., 2012; Engel & May, 2012; Gandhi et al., 2017; Kennedy et al., 2017; Lau et al., 2016; Shah-Hosseini et al., 2011), with boulders up to hundreds of tonnes generated by both tsunamis (Goto et al., 2012; Imamura et al., 2008) and storm waves (Cox et al., 2018). Over the past two decades, the number of CBD sites identified has grown rapidly, revealing transport at elevations as high as tens of meters (Cox et al., 2012) and 1-km inland (Paris et al., 2009). However, although transport by storms or tsunamis has been directly observed at some sites (Autret et al., 2018; Cox et al., 2018; Goto et al., 2012; Kennedy et al., 2016, 2017; May et al., 2015), CBD at many other locations have indeterminate origins (e.g., Engel & May, 2012; Medina et al., 2011; Shah-Hosseini et al., 2011) but direct implications for risk, safety, and coastal planning. The field has been plagued by two long-lived controversies: (a) Was a given CBD generated by a tsunami or by storm waves? and (b) What was the inundation magnitude leading to transport? Both questions are essential for calculating return intervals and for estimates of future risk. As most CBD have not been observed to move, we must use indirect analytical techniques, but serious flaws in existing methodologies (Cox et al., 2020; Gandhi et al., 2017) lead to interpretations tilted toward tsunami emplacement (Engel & May, 2012; Medina et al., 2011; S. R. Scheffers et al., 2008; Shah-Hosseini et al., 2011). This bias skews our understanding, impeding effective use of CBD as event records.

The most accurate estimates of storm wave or tsunami potential to transport boulders are likely from high-resolution hydrodynamic inundation models that dynamically transport model boulders based on Newton’s laws of motion (Imamura et al., 2008; Kennedy et al., 2016; Minamidate et al., 2020; Rovere
et al., 2017). However, these require high computational effort and large amounts of data for boulders, topography, and inundation climate, and are not suitable for all situations. A far more common analysis method is to calculate Initiation of Motion (IoM) criteria by solving a static balance equation to obtain minimum fluid velocities for motion (Nandasena et al., 2011; Nott, 2003). For a boulder with long, intermediate, and short axis dimensions \((a, b, c)\), and assuming level ground, this may be written as in Nandasena’s form as:

\[
\frac{U^2}{ge\left(\frac{\rho_s}{\rho_w} - 1\right)} = f\left(\frac{c}{b}, \text{coefficients}\right)
\]

(1)

where \(U\) is depth-averaged fluid velocity near the boulder, \(g\) is gravitational acceleration, \(\rho_s / \rho_w\) is the ratio of rock and water densities, and “coefficients” defines various parameterized processes. The function \(f(c/b, \text{coefficients})\) is an expression that varies depending on the mode of motion (sliding, overturning, or lifting) (Nandasena et al., 2011). Central to this approach is assumption that the local emplacing wave height, \(H\), can be determined if the Froude number, \(Fr\), is known, or asserted

\[
Fr^2 = \frac{2}{gH}
\]

(2)

It has become standard practice to use the assumption of Nott (2003), which recasts \(Fr^2\) as a “wave parameter” \(\delta\), arbitrarily set such that \(Fr = 1\) for storm waves and \(Fr = 2\) for tsunamis. This means that, for any given boulder size, calculated storm-wave heights necessary for transport are always four times larger than calculated tsunami heights (Cox et al., 2020; Nott, 2003). The emplacing wave height at the CBD site, \(H\), is then usually taken to be equal to the offshore significant wave height, \(H_s\) (Medina et al., 2011; Shah-Hosseini et al., 2011). Unsurprisingly, computed storm wave heights are often deemed unrealistically large relative to local wave climate, leading to “discoveries” of previously unknown tsunamis (e.g., A. Scheffers et al., 2009). However, the link between calculated velocities and offshore wave height has little validity because \(Fr\) is not constant as assumed but instead strongly variable (Cox et al., 2020), and because emplacing wave heights at the boulder location will almost certainly be very different from those offshore. The inability to link estimated CBD entrainment velocities to offshore wave heights is perhaps the greatest conceptual gap in this field, and the Froude number assumption is perhaps its greatest untested hypothesis.

2. Boulder Dynamics

A more defensible link to local wave climate begins by generalizing (1) to

\[
\frac{U^2}{gl\left(\frac{\rho_s}{\rho_w} - 1\right)} = f_1(\text{shape, coefficients, setting})
\]

(3)

where \(l\) is a representative boulder length scale, and \(f_1\) and subsequently introduced \(f_2 = f_3\) are not-yet-determined dimensionless functional relationships. “Shape” and “setting” refer to properties of the boulder and its environment that may affect transport. We adopt \(l = \sqrt[3]{V}\) as our representative length scale, where \(V\) is boulder volume; other choices are possible. Combining Equation 3 with a function \(U^2 = gHf_2(Z/H_s, X/H_s, \text{topography, bathymetry})\) relating fluid velocity at the boulder to \(H_s\), local elevation above high tide, \(Z\), and inland distance from the high tide shoreline, \(X\), gives

\[
\frac{H_s}{\left(\frac{\rho_s}{\rho_w} - 1\right)l} = f_3\left(Z / H_s, X / H_s, \text{topography, bathymetry, shape, coefficients, setting}\right)
\]

(4)

where \(f_3 = f_1 / f_2\). In the most straightforward case, where waves directly approach unsheltered coasts with a steep foreshore or cliff, the system may be rewritten as:

\[
l' = \frac{H_s}{l\left(\frac{\rho_s}{\rho_w} - 1\right)} = f_4\left(Z / H_s, X / H_s, c / b\right)
\]

(5)
where $f_4$ is a simplification of $f_3^{-1}$. Thus, the dimensionless boulder size for storm-generated CBD is a function of dimensionless elevation, distance onshore, and aspect ratio. Data at different locations and for different storm deposits may be used to delineate the envelope of Equation 5, within which storm CBD occur and outside of which they are currently unknown. The simplifications required here are necessary to be able to compare results from many sites, but neglected processes may be important in some instances.

The question of what $H_s$ value to use now becomes important, as wave heights vary strongly in time and space. Here, we take $H_s$ at 1.5 km offshore wherever available, as heights in deeper water are not subject to the dramatic changes that can be caused by shallow bathymetry and irregular coastlines, and may be available from wave measurements or large-scale wave hindcasts. For boulders moved by storms during a known time period, we take the maximum $H_s$ over that period. For CBD where transport mechanisms are unobserved (and for which the question of storm vs. tsunami activation often remains open), we adopt $H_{100}$, the 100-year significant wave height, to represent extreme conditions.

The detailed form of Equation 5 is not known, but can be estimated using boulder data combined with storm wave hindcasts and measurements. Once the functional form has been outlined, it may be used to test tsunami inferences: results falling outside the storm wave envelope may have the tsunami inference strengthened, while those overlapping with the storm wave data may be suitable for reevaluation.

3. Data Used

Figure 1 and Table 1 show data used here, divided into three subsets: A. Individual boulders observed to have been moved by storms; B. CBD with inferred storm genesis but without verified observation; C. CBD with inferred or observed tsunami genesis. There are many more published CBD measurements than reported here; the primary limitation on inclusion was the availability of inshore $H_s$ measurements or hindcasts. For observed and inferred tsunami boulders, we show several examples to demonstrate how the techniques to be developed in the next section may be applied to test the storm wave hypothesis.
4. Results

4.1. Type A. Observed Storm Transport for Size-Elevation

As a first approach, we neglect inland distance and shape in Equation 5 and examine directly the dimensionless size-elevation relationship for observed storm transport of individual boulders (Type A: Table 1). A clear relationship is seen with the largest boulders moving only at lower elevations and the upper size limit decreasing at higher elevations (Figure 2a). This allows us to quantify a dimensionless parameter space for storm-transported boulders, and in particular, to predict the limiting elevation for a given boulder size. The size-elevation envelope is approximated by

\[ Z / H_s = 0.75 t^* - 0.7 \tanh^{0.25} \left(3 \left( t^*_{\text{max}} - t^* \right) / t^*_{\text{max}} \right) \]  

(6)

where here \( t^*_{\text{max}} = 0.9 \). Data set limits cover the size range \( t^* = [0, t^*_{\text{max}}] \) and to dimensionless elevation \( Z / H_s = 2.5 \). The extremes of the distribution in Figure 2a are poorly defined, particularly for higher elevations and larger boulders, reflecting the paucity of direct boulder-movement observations. Thus, it is very possible that storm wave CBD may exist outside this range; this is tested in the next section. Additionally,
the form of Equation 6 should not be considered as set in stone, but as a reasonable fit to available data. Nontrivial uncertainty is introduced by errors in estimating $H_s$ at the Equation 6 limit (Figure 2a), and for some locations may prove a significant source of error.

One boulder in Figure 2a lies outside the envelope. This may be a true outlier, but its location on the graph is imprecise because parameters for this clast were given in rounded numbers (23): $(a, b, c) = (5, 2.5, 2.5)$ m, $Z = 15$ m, $\rho_s = 2000$ kg/m$^3$. Note also that the envelopes are not necessarily defined by the largest boulders or those at the highest elevations, as both dimensionless size and elevation vary with $H_s$ for given boulder properties.

### 4.2. Type B. Inferred (but not Directly Observed) Storm Transport

Data from deposits in which motions have not yet been directly observed (Type B: Table 1, Figure 2b), are consistent with Equation 6 derived from Type A deposits, but include data at higher dimensionless elevations. These high elevation Type B deposits are located at short alongshore distances from lower elevation Type A boulders (with directly observed motion), and are consistent with the interpretation that higher
elevations record only the most extreme events, while lower elevation deposits may be more regularly active. Their concordance with Figure 2a supports use of $H_{s100}$ as the representative wave height, and extends the apparent upper limit for dimensionless elevation to $z/H_s = 3.8$. We point out that reliable data are still sparse at the extremes, and limits for both elevation and size could well be exceeded.

### 4.3. Topographic Distribution of Types A and B CBD

Wave power attenuates with both elevation and distance inland from the shoreline. Figure 3 illustrates how these affect boulder transport, showing combined Type A and B datasets separated into six dimensionless size bins. Integrated elevation-distance controls on storm-wave CBD are clear. Small boulders define the dimensionless limits of storm-wave boulder transport (Figure 3a): they are found both at high elevations close to the shoreline and also at large distances inland for low elevations. The binned data also show the dramatic effect of size on transportability: the largest boulders can only be moved close to sea level and near the shoreline. This is no surprise, as only the smallest clasts will be mobile at the extremes.

Boulder motion is also affected by impediments to transport such as uphill slopes, stepped topography, backing cliffs, preexisting deposits, and other obstacles not considered in this analysis. Field data (references in Table 1) show that the furthest inland boulders are on relatively smooth shore platforms, where waves and boulders have fewer impediments to travel. The limiting value $X/H_s = 19$ seen in our data (Figures 3a and 3b) implies an upper limit for storm-wave transport of boulders as $X \approx 380m$ at extreme wave height $H_s = 20 m$, or shorter distances for less severe conditions. Tsunamis are known to transport boulders much further inland: 1 km for a “less than 1 m” boulder (Paris et al., 2009), or 390–1290 m for boulders averaging 2.5 m$^3$ (Goto et al., 2010). Thus, dimensionless transport distance can be used as another test to evaluate CBD origins.

**Figure 3.** Dimensionless storm-boulder inland distance and elevation data from studies in Table 1, binned into six dimensionless size groups. (*) Types A, B data; (*) Type C data for limiting cases of Section 4.5, plotting $H_s$ or $H_{s100}$ using the methodology developed here. Values for Crete and Morocco are both near the origin.
As a way to test whether boulder shape might affect the distributions, we examined whether a different length scale would affect the results, using $l = \sqrt{V}$ rather than $l = 3V$ (Figure 2c); we note that numerous boulders have computed $V$ but not $(a, b, c)$ so data are sparser. There is a strong similarity between overall shapes for both length scales (Figures 2a–2c). Direct comparison of $3V$ and $b$ (Figure S1) shows good correlation ($r^2 = 0.86$), yielding $b = 31.18V$. Thus, if $V$ is unavailable but $b$ can be determined (e.g., from aerial photos), it may still be possible to use these relations.

Next, we tested whether boulder shape (measured by the $c/b$ aspect ratio) had any influence on the distribution. Binned data (Figure 4) show a little dependence on the shape for either dimensionless size and elevation, with the notable exception that few very large boulders are observed for thin clasts with $c/b < 0.25$. This lack of sensitivity may be because for large $c/b$, drag forces will be large and lift forces small, and vice-versa for small $c/b$. Thus, driving processes are offsetting to some degree.

4.5. Type C. Testing CBD of Inferred Tsunami Origin

We now have tools to test whether CBD of indeterminate origin, or for which tsunami emplacement has been proposed based on IoM criteria, may in fact fall within the range of storm deposits. Two cases exist: Case (i) If $H_{100}$ or representative $H_s$ at the site is known, and if the largest boulders are within storm wave ranges shown in Figures 2 and 3, then storms cannot be excluded as an emplacement mechanism, even if that contradicts previous interpretations based on IoM criteria. If they are out of range, then the storm wave emplacement hypothesis is unlikely to be valid. Case (ii), which is more common, has wave climate data insufficient to evaluate inshore $H_{100}$. Here, the limiting $H_{100}$ that fits both Equation 6 and Figure 3 may be determined for specific boulders, and evaluated relative to local wave data: often it will be immediately clear whether these wave heights are possible. Several examples follow, all using CBD inferred or observed

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**Figure 4.** Dimensionless boulder size and elevation distribution binned by aspect ratio $c/b$, using $l = \sqrt{V}$ as length scale.
to originate from tsunamis. Figures 2d and 3 show how each of our examples fits into the dimensionless framework as wave heights vary, and for representative heights chosen, while Table S1 gives a summary of boulder data and findings.

Makran, Iran: Previous work estimated that 15 m storm wave heights were necessary for IoM, far greater than the stated $H_s = 8.8$ m maximum local wave heights; thus the CBD were interpreted as having as tsunami origins (Shah-Hosseini et al., 2011). However, using $H_s = 8.8$ m as representative per Case (i), the largest boulder fits well within Equation 6 envelope and Figure 3 limits. This suggests that storm genesis for these boulders is possible, and reevaluation would be indicated.

Rabat, Morocco: The largest boulder from Table 1 of Medina et al. (2011) would fit within Equation 6 envelope with $H_s^{100} \geq 7.25$m (Case [ii], Figure 2d). It is located within the intertidal zone, so onshore distance and elevation fit well within Figure 3. The authors had estimated that a 44m storm wave height was necessary to move this boulder. No known $H_s^{100}$ exist within 1.5 km of shore, but NOAA climatological wave computations on a 0.5° grid yield $H_s^{100} = 7.6$m at 60 km from the site (Chawla et al., 2013; NOAA, https://polar.ncep.noaa.gov/waves/hindcasts/nopp-phase2.php), consistent with Case (ii) $H_s^{100}$ inference. Although this hindcast is both coarse and far away, storm genesis does appear possible pending more detailed analysis of local conditions. We also note that storm-related CBD transport was directly observed further south in Dahomey Beach during 2011–2012 (Chiguer & Fida, 2019).

Bonaire: These CBD have emplacement ages up to several thousand years and were interpreted as tsunami deposits because IoM calculations required storm wave heights up to $H_s = 36$ m (Engel & May, 2012), which is impossible. Our approach (Case [ii]) indicates that $H_s^{100} = 10.6$ m, which is possible during a hurricane, would be sufficient to emplace the boulders (Figures 2d and 3). However, the interpretation is not simple because, as noted by Engel and May, hurricanes are relatively uncommon around Bonaire, whereas the region is seismically active and tsunamigenic. Probabilities thus become a task for a team of seismologists, climatologists and modelers, but our analysis shows that storms cannot be excluded from consideration, particularly given the long depositional history of these CBD.

Diplomo Petris, Crete: A 690 tonne boulder, the largest clast in CBD identified by Boulton and Whitworth (2016), was interpreted as having tsunami origin since the $H_s = 12.7$ m wave height they estimated for emplacement was much larger than the $H_s^{100} = 5.5$ m estimated locally. Using 5.5 m for a Case (i) scenario, this boulder lies far outside the storm wave envelope in Figure 2d. If Case (ii) were assumed, a locally unlikely height of $H_s^{100} = 14$ m (not plotted) would be required to meet Figure 2d limits. Thus, a storm wave origin appears improbable, strengthening the original analysis.

Ishigaki Island, Japan: The famous Amatariya-Suari boulder, with dimensions ($a$, $b$, $c$) = (11, 9, 6) m, was transported 545m to its present position during the 1771 Meiwa tsunami (Imamura et al., 2008). Although the boulder requires only $H_s^{100} = 8$ m to fit within Equation 6 size-envelope curve (Figure 2d), taking $X = 545$ m would require an implausible $H_s^{100} = 28.7$ m to fit within the inland wave transport boundaries (Figure 3). Thus, this boulder appears clearly outside the range of what is possible for storm waves.

5. Discussion and Conclusions

This new dimensionless approach to CBD analysis directly links field observations of boulders to wave climate. In contrast, many IoM techniques rely on derived wave height estimates that are known to be faulty (Cox et al., 2020). It is crucial to adopt more reliable methods because CBD that may have been improperly interpreted are currently being used to estimate tsunami occurrence and risk (Long, 2018; Mastronuzzi et al., 2004; Papadopoulos et al., 2014). Application of this more defensible technique will provide increased clarity about possible CBD emplacement mechanisms, thus allowing increased confidence in future planning against both storm and tsunami inundation, particularly critical at this time of sea level rise and climate change-induced variations in wave climate.

Significant simplifications were made to arrive at the present results: ground slope, and details of topography and bathymetry were neglected; future work including their effects may increase accuracy (e.g., Weiss & Diplas, 2015). It should also be noted that computation of $H_s^{100}$ at 1.5 km from the CBD requires data from either a high resolution multidecadal hindcast (Accensi & Maisondieu, 2015; Boudiere et al., 2013; Clancy
et al., 2016), or local measurements. Thus, wave data remain a limiting factor for application of this method. Single storm or seasonal results are much more feasible (Mori et al., 2014). Additionally, sites with deposits much older than 100 years (e.g., Engel & May, 2012; Cox et al., 2012) raise the question of whether $H_{100}$ is the proper measure for older deposits, or whether the return period should be more closely tied to CBD age.

We emphasize that this methodology alone does not provide conclusive proof of emplacement mechanism, and forms only one part of a more complete analysis including geomorphologic, climatological, and seismic data. Additional inundation signatures, specimen dating, historical records, sea level reconstructions, and further hydrodynamic modeling. Finally, a process similar to that introduced here is very possible for tsunami-generated CBD and identification of tsunami boulder limits would be immensely valuable.

Data Availability Statement

Datasets for this research are included in references of Table 1 with the exceptions of: Boulder datasets for Banneg Island, Iceland, and Brittany may be found at: https://doi.org/10.1594/PANGAEA.930539. Results of Irish wave hindcasts may be found at https://www.doi.org/10.17603/ds2-w421-ex78.

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