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Article abstract

A high-magnitude coastal flood event catastrophically affected the macrotidal Bristol Channel and Severn Estuary in southwest Great Britain, United Kingdom, on 30th January 1607 causing an estimated 2000 fatalities. Historical and physical evidence has provided a basis for the development of a theory that the flood may have been due to a tsunami rather than a storm. Previous studies have collected field data to test this hypothesis including a dataset of 136 wave-transported boulder clasts that was utilised to estimate minimum wave heights through hydrodynamic equations in 2007, but the dataset has hitherto remained unpublished in full. Since 2007 these equations have undergone refinement and for this paper minimum wave heights were recalculated from boulder measurements using revised hydrodynamic equations and presents the complete dataset for the first time. A recent study claiming that such equations are flawed is considered premature, given ongoing refinements to the equations. The results of the present study indicate that a tsunami 4.2 m high can explain the dislodgement of all boulders measured, equivalent to a storm wave height of 16.9 m, which is considerably greater than observed storm wave heights in the region. An up-channel increase in minimum wave height is also suggested by these data, generally corroborating the 2007 study, which may be due to wave amplification caused by the overall funnel-shape of the embayment. The areas worst affected by the 1607 flood are located in the coastal lowlands of the inner Bristol Channel and Severn Estuary, coinciding with the highest minimum estimated wave heights.

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Recalculation of minimum wave heights from coastal boulder deposits in the Bristol Channel and Severn Estuary, UK: implications for understanding the high-magnitude flood event of AD 1607

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ABSTRACT

A high-magnitude coastal flood event catastrophically affected the macrotidal Bristol Channel and Severn Estuary in southwest Great Britain, United Kingdom, on 30th January 1607 causing an estimated 2000 fatalities. Historical and physical evidence has provided a basis for the development of a theory that the flood may have been due to a tsunami rather than a storm. Previous studies have collected field data to test this hypothesis including a dataset of 136 wave-transported boulder clasts that was utilised to estimate minimum wave heights through hydrodynamic equations in 2007, but the dataset has hitherto remained unpublished in full. Since 2007 these equations have undergone refinement and for this paper minimum wave heights were recalculated from boulder measurements using revised hydrodynamic equations and presents the complete dataset for the first time. A recent study claiming that such equations are flawed is considered premature, given ongoing refinements to the equations. The results of the present study indicate that a tsunami 4.2 m high can explain the dislodgement of all boulders measured, equivalent to a storm wave height of 16.9 m, which is considerably greater than observed storm wave heights in the region. An up-channel increase in minimum wave height is also suggested by these data, generally corroborating the 2007 study, which may be due to wave amplification caused by the overall funnel-shape of the embayment. The areas worst affected by the 1607 flood are located in the coastal lowlands of the inner Bristol Channel and Severn Estuary, coinciding with the highest minimum estimated wave heights.

RÉSUMÉ

Une inondation côtière de forte ampleur a frappé de façon catastrophique le canal de Bristol et l'estuaire du Severn dans le sud-ouest de la Grande-Bretagne, au Royaume-Uni, le 30 janvier 1607, y causant un nombre estimatif de 2 000 décès. Des indices historiques et physiques ont donné lieu à la formulation d'une théorie supposant que l'inondation pourrait avoir été attribuable à un tsunami plutôt qu'à une tempête. Des études antérieures avaient comporté la collecte de données sur le terrain pour vérifier cette hypothèse, notamment un ensemble de données de 136 clastes de blocs rocheux transportés par des vagues qui a été utilisé pour l'estimation des hauteurs minimales des vagues au moyen d'équations hydrodynamiques en 2007. L'ensemble de données n'avait toutefois pas été publié dans son intégralité jusqu'ici. Les équations ont été raffinées depuis 2007 : on a recalculé pour le présent article les hauteurs minimales des vagues à partir des mesures des blocs rocheux au moyen d'équations hydrodynamiques révisées et l'ensemble de données complet est présenté pour la première fois. Une étude récente alléguant que les équations en question sont erronées est considérée comme prématurée compte tenu des améliorations courantes des équations. Les résultats de l'étude actuelle révèlent qu'un tsunami de 4,2 m de hauteur peut expliquer le déplacement de tous les blocs rocheux mesurés, ce qui équivaut à une onde de tempête de 16,9 m de hauteur, soit une hauteur considérablement supérieure à celles des ondes de

tempête observées dans la région. Les données laissent également supposer une augmentation en amont du canal de la hauteur minimale des vagues, corroborant de façon générale l'étude de 2007, qui pourrait être due à une amplification des vagues causées par la forme en entonnoir générale de l'échancrure. Les secteurs les plus affectés par l'inondation de 1607 se trouvent dans les basses terres côtières de l'intérieur du canal de Bristol et de l'estuaire du Severn, qui correspondent aux hauteurs estimatives minimales les plus élevées des vagues.

[Traduit par la redaction]

INTRODUCTION

In 2003, a theory was proposed that a widespread coastal flood event, which affected the Bristol Channel and Severn Estuary around the coasts of south Wales and southwest England on 30th January 1607, may have been due to the impact of a tsunami (Bryant and Haslett 2003). The theory was developed through a combination of, firstly, a re-reading of contemporary historical accounts published as pamphlets or chapbooks that provide ambiguous accounts of the weather with some stating that the day was "most fayrely and brightly spred" (Bryant and Haslett 2003, p. 164) and, secondly, coastal geomorphological and stratigraphic evidence potentially linked to the event. Haslett and Bryant (2005) undertook further historical research of accounts from Devon and Cornwall, and Bryant and Haslett (2007) and Haslett and Bryant (2007a, b) reported field evidence that was utilised to evaluate the theory.

The impact of the 1607 flood was extensive, affecting 570 km of coastline and flooding 518 km² of coastal lowlands causing great economic loss and an estimated 2000 fatalities (Bryant and Haslett 2007; Fig. 1) making it Great Britain's worst historical natural disaster. Although some authors considered the 1607 flood to have been caused by a storm surge (e.g., Horsburgh and Horritt 2006; see also Haslett 2007), Kerridge (2005), in a UK Government report, concluded that "the most credible source for a strong, potentially damaging tsunami reaching the UK coast is a large passive margin earthquake in the Sole Bank area (western Celtic Sea)" (p. 29) directly offshore of the Bristol Channel.

Disney (2005a, b) referred to a second-hand report of an earth tremor being felt on the morning of the flood in 1607; however, it has not been possible to locate the historical source to support this statement. Nevertheless, Haslett (2011) identified from historical documents two previously uncatalogued seismic events that affected the region in 1607; the first occurred two weeks after the flood on 14th February and the second on 22nd May, suggesting that the year was a seismically active period. It is also possible that an earthquake may have triggered a submarine slide on the steep continental slope offshore Ireland (Kenyon 1987) that may have generated a tsunami, such as happened across the North Atlantic with a 13 m-high tsunami that struck the Burin Peninsula, Newfoundland, in 1929 (Heezen and Ewing 1952; Piper *et al.* 1999; Moore *et al.* 2007). Bryant and Haslett's (2007) field evidence collected to test the hypothesis included analysis of erosional coastal landforms and the dislodgement of boulders. They also acknowledged that the dating of coastal erosion features and boulder movement is challenging but were able to suggest a chronological link with the AD 1607 event based on a suite of evidence. For example, boulder dislodgement and transport at one site appears to have occurred in the period after AD 1590 but before AD 1634–1672, which overlaps with a significant episode of coastal erosion documented throughout the Bristol Channel and Severn Estuary that has been dated to the early seventeenth century (Allen and Rae 1987; Allen and Fulford 1992). Historical sources offer corroboration of extreme wave-energy during the 1607 event, such as the inland transport of a fully laden 60-t ship and the demolition of numerous buildings. Taken together, Bryant and Haslett (2007) suggested that a single catastrophic event is likely to account for this suite of features, which temporally excludes the Great Storm of 1703 as an alternative explanation. Nevertheless, additional field studies are required to expand the number of securely dated sites to test the hypothesis further. Boulders were investigated by Bryant and Haslett (2007) through the measurement of boulder clast axes (i.e. *a, b, c* for the longest to shortest axes, respectively) at a number of sites from which minimum wave heights required to initiate boulder movement (dislodgement) were derived based on the hydrodynamic equation of Nott (2003), which had been developed from previously published equations (Nott 1997).

Since 2007, a growing number of studies have analysed boulder deposits to investigate whether storm or tsunami waves have contributed to the evolution of coastlines around the World (e.g., Hansom *et al.* 2008; Spiske *et al.* 2008; Goto *et al.* 2009, 2010; Barbano *et al.* 2010; Scheffers *et al.* 2009, 2010; Costa *et al.* 2011; Lorang 2011; Paris *et al.* 2011; Erdmann *et al.* 2015, 2017; Watanabe *et al.* 2016; Cox *et al.* 2018; Haslett and Wong 2019a, b; Abad *et al.* 2020). However, some boulder studies have noted shortcomings in Nott's (1997, 2003) hydrodynamic equations (Bourgeois and MacInnes 2010; Switzer and Burston 2010; Gandhi *et al.* 2017; Kennedy *et al.* 2017; Piscitelli *et al.* 2017; Cox *et al.* 2020) and, indeed, we agree that Nott's versions of the equations are outdated and, therefore, should no longer be used. Subsequent studies have, however, further developed the hydrodynamic equations to refine them and to correct errors in previous versions of the equations, such as the work of Nandasena *et al.* (2011), Kain *et al.* (2012) and more recently Haslett and Wong (2019a). Yet despite ongoing refinements and corrections, Cox *et al.* (2020) claimed

Figure 1. Woodcut from a contemporary historic pamphlet (Anon 1607) depicting the aftermath of the 1607 flood in Monmouthshire, south Wales.

that all hydrodynamic equations derived from Nott's (1997, 2003) seminal work should be regarded as flawed.

Notwithstanding these ongoing developments, the present study aims to recalculate minimum wave heights derived from boulder clasts investigated by Bryant and Haslett (2007) using the revised formulae of Haslett and Wong (2019a) and to consider the significance for understanding the historical high-magnitude flood event of January 1607 in the Bristol Channel and Severn Estuary. The presentation of updated results, in light of the revised hydrodynamic equations, serves to better inform other researchers and the public. For example, public sources, such as newspaper articles (e.g., Barnes 2020), continue to refer to previous estimates of wave heights for the 1607 event; those earlier results are now refined and superseded by the present study.

METHODS

The study area is shown with principal sites in Figure 2, and details of the sites are presented in Table 1, categorised using the three zones defined by Bryant and Haslett (2007): the outer Bristol Channel, the inner Bristol Channel, and the Severn Estuary. Bryant and Haslett (2007) reported that

136 boulders were measured as part of their study, 129 of which appear to have been wave transported and seven clasts comprising an untransported boulder lag deposit derived from cliff retreat at Dunraven Bay (boulders DbL1-7), the significance of which for inclusion in their study was for dating boulder dislodgement (Bryant and Haslett 2007 pp. 264–266). From this dataset, Bryant and Haslett (2007) presented data for nine boulders only, being those from sites where the boulder was estimated to have the greatest resistance to flow within an area of each zone, both from storm and tsunami waves, as indicated by the formulae they used. Given that formulae are likely to continue to be developed and refined, the full dataset is presented here enable future use of these data (Appendix A, Table A1).

The formula used by Bryant and Haslett (2007) to test the hypothesis is for boulders in a submerged pre-transport setting (Nott 2003), as the 1607 event is known from historical sources to have struck the Bristol Channel and Severn Estuary at high tide, meaning that the extensive intertidal zone would have been submerged at the time. Therefore, for comparative purposes, for this paper, minimum storm and tsunami wave heights were recalculated using the revised hydrodynamic equation of Haslett and Wong (2019a) for boulders in a submerged

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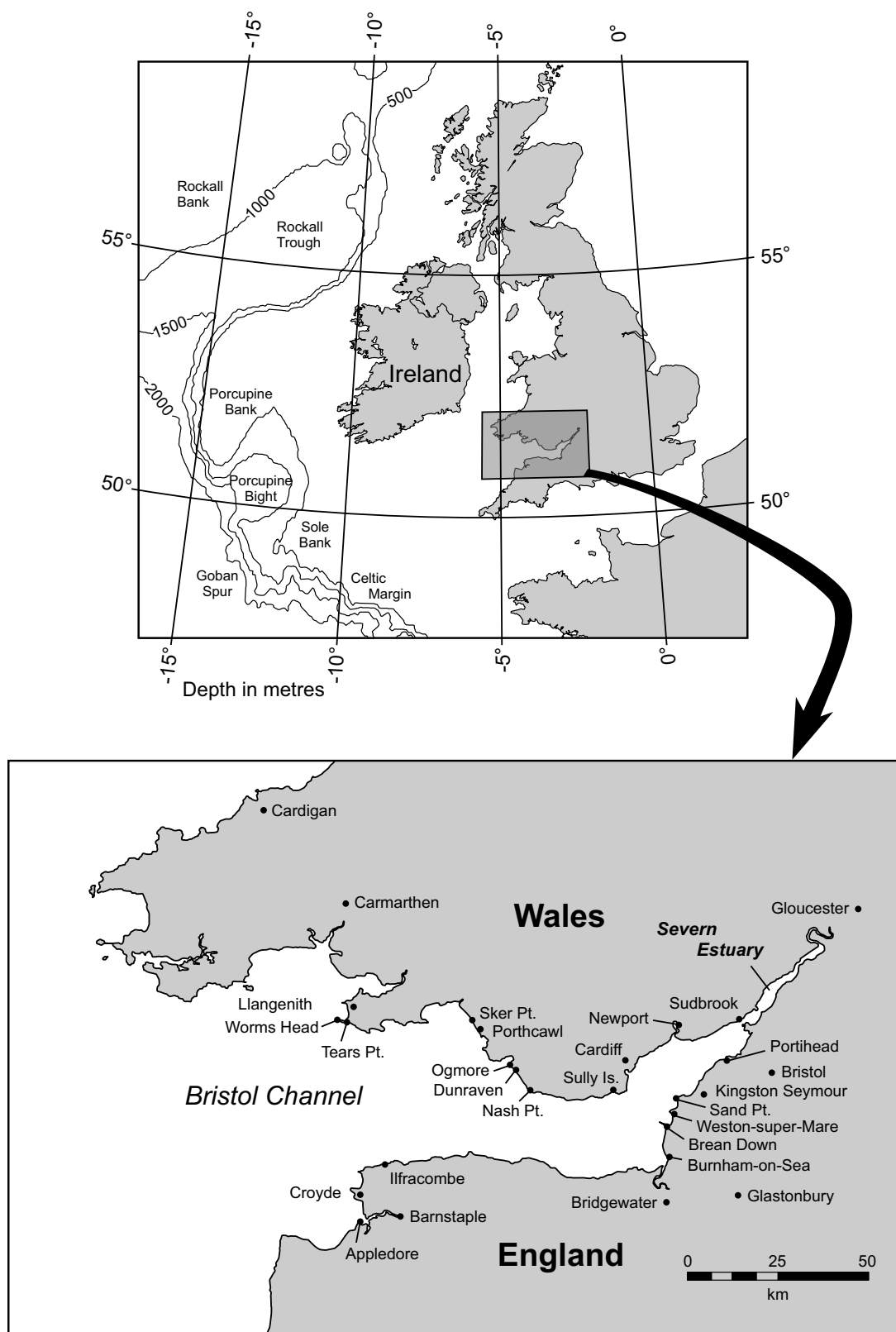**Figure 2.** The macrotidal Bristol Channel and Severn Estuary in southwest Britain indicating the principal localities where boulder clasts were investigated (redrawn after Bryant and Haslett 2007).

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Table 1. Details of sites investigated by Bryant and Haslett (2007) in the Bristol Channel and Severn Estuary (see Figure 2 for locations).

Region	Area/Site	Sub-site and (Code)	Distance (km)[1]	Lithology	Density (kg/m³)	Visit Date	Surveyor
Severn Estuary	Sudbrook	Sudbrook (Sb)	45	sandstone	2323	10th Sept. 2004	EAB, SKH
	Portishead	Kilkenny Bay (Kb)	56	sandstone	2323	8th June 2005	SKH
	Portishead	Clevedon (Cd)	62	limestone	2611	8th June 2005	SKH
Inner Bristol Channel	Weston-Super-Mare	Swallow Cliff (Sc)	73	limestone	2611	14th Oct. 2004	SKH
	Brean Down	Brean Down (Bd)	81	limestone	2611	14th Oct. 2004	SKH
	Sully Island	Sully Island (Si)	85	sandstone	2323	11th Oct. 2004	SKH
	Dunraven	Dunraven Bay (Db)	106	limestone	2611	14th Sept. 2004	EAB, SKH
	Ogmore	Ogmore-by-Sea (Os)	107	limestone	2611	13th Sept. 2004	EAB, SKH
	Sker Point	Newton Point (Np)	109	limestone	2611	19th April 2005	SKH
	Sker Point	Sker Point (Sp)	112	dolomite	2751	19th April 2005	SKH
Outer Bristol Channel	Ilfracombe	Combe Martin (Cm)	145	slate	2675	20th July 2005	SKH
	Tears Point	Tears Point (Tp)	147	limestone	2611	13th Sept. 2004	EAB, SKH
	Ilfracombe	Hele Bay (Hb)	148	slate	2675	20th July 2005	SKH
	Ilfracombe	Lee Bay (Lb)	158	slate	2675	20th July 2005	SKH
	Croyde	Croyde (Cr)	162	slate	2675	8th Sept. 2004	EAB, SKH

Notes: [1]Approximate distance (km) seaward of tide limit at Gloucester. Abbreviations: EAB = Edward A. Bryant; SKH = Simon K. Haslett.

pre-transport setting. To provide an estimate for an upper limit of the minimum wave height required, calculations for joint-bound boulders were also made (Nandasena *et al.* 2011; Haslett and Wong, 2019a). Consequently, a range of minimum wave heights is presented for each boulder where an estimated range is provided by the formulae for submerged and joint-bound pre-transport settings.

For clarity, the equations used in this study are given here as equations 1 and 2 for boulders in submerged and joint-bound pre-transport settings (equations 6b and 8d of Haslett and Wong, 2019a) respectively:

$$H \geq \frac{2}{\delta} c \left(\frac{\rho_s - \rho_w}{\rho_w} \right) \frac{\left[cos\,\theta + \left(\frac{c}{b} \right) sin\,\theta \right]}{\left[\left(\frac{c^2}{b^2} \right) C_d + C_l \right]} \quad (1)$$

and

$$H \geq \frac{2}{\delta} c \left(\frac{\rho_s - \rho_w}{\rho_w} \right) \frac{[cos\,\theta + \mu_s\,sin\,\theta]}{C_l} \quad (2)$$

where H is wave height (m); b and c are the measurements (m) of the intermediate and shortest axes of a boulder; C_l is the lift coefficient of 0.178; C_d is the drag coefficient of 1.2; ρ_s is the density of a boulder (kg m⁻³); ρ_w is the density of water (1020 kg m⁻³); θ is the shore slope angle, estimated here to be

10˚; μ_s is the static friction coefficient of 0.7; and δ is a wave-type parameter, which is $\delta = 4$ for tsunami and $\delta = 1$ for storm waves (for a full explanation see Haslett and Wong 2019a). The minimum speed/velocity (u, m s⁻¹) at which a wave impacts a boulder is also calculated for a submerged pre-transport setting derived from Equation 6a of Haslett and Wong (2019a).

In their analysis, Bryant and Haslett (2007) referred to observed wave height data to provide the modern context for comparison with calculated minimum wave heights derived from boulder measurements. In the eastern North Atlantic area, the maximum deep-water wave height is 35 m with a 50-yr return period (NERC 1991), but the continental shelf shallows eastwards so that wave heights become ≥10 m in the outer Bristol Channel. However, in the shallower and more protected inner Bristol Channel and Severn Estuary, 50-yr return period waves of 4.7 m and 3.5 m, respectively, occur (McLaren et al. 1993). These observed wave heights are utilised in the present study for comparative purposes. However, the caution of Stephenson and Naylor (2011) should be noted in that some "boulders used to reconstruct past energy regimes [along the South Wales coast] may underestimate wave energies, if the blocks have been broken since detachment" (p. 23).

RESULTS AND DISCUSSION

Dimensions of the 136 boulders measured in the field are presented in Appendix A (Table A1) along with the measured imbrication direction for each boulder, as reported by Bryant and Haslett (2007). Imbrication is considered an indication of the direction from which the flow responsible for transport, and subsequent deposition, originated (see Fig. 3 for examples). Mean imbrication was analysed by Bryant and Haslett (2007) who concluded that at their nine sites "wave refraction is not efficient, a feature of tsunamis more than storm waves" (p. 263); the matter is not revisited further in the present study. From these data the range of recalculated minimum wave heights under storm (H_{storm}) and tsunami (H_t) scenarios are derived for each site and presented in Table 2 along with wave velocity (u). These wave height data are also plotted in Figure 4 against approximate distance (km) seaward from the tide limit at Gloucester, along with observed wave heights for the outer and inner Bristol Channel and Severn Estuary from McLaren *et al.* (1993). In the outer Bristol Channel five sites were investigated. Boulders measured at Hele Bay, Coombe Martin, and Croyde indicate a similarly low range of minimum wave heights required to initiate movement, whereas boulders at Lee Bay and Tears Point indicate a much higher range. However, in each case the threshold for boulder dislodgement in a submerged pre-transport setting is less than observed storm wave heights for the zone of ≥ 10 m (McLaren *et al.* 1993). Therefore, although all the boulders at the outer Bristol Channel sites may have been dislodged by $H_t \geq 2.3$ m, dislodgement at each site may also be explained by $H_{storm} \geq 9.3$ m.

Bryant and Haslett (2007) also concluded that it is theoretically possible that boulders at the outer Bristol Channel sites may have been dislodged by storm waves but recognised that in the "inner Bristol Channel and in the Severn Estuary, the required H_{storm} [for boulder dislodgement] is significantly greater than observed storm wave heights" (p. 263). The present study corroborates this observation; in these two zones, results from all sites yield H_{storm} greater than observed storm wave heights reported by McLaren *et al.* (1993) and the dislodgement of all boulders may be explained by $H_t \geq 4.2$ m or $H_{storm} \geq 16.9$ m (Fig. 4). This result is derived from Brean Down, located on the boundary between the inner Bristol Channel and the Severn Estuary, and as such may reasonably be taken to represent both zones.

Given observed storm wave heights (50 yr return period) of 4.7 m and 3.5 m in the inner Bristol Channel and Severn Estuary, respectively (McLaren et al. 1993), which are significantly lower than Hstorm ≥ 16.9 m, the recalculations presented here agree with Bryant and Haslett's (2007) conclusion that boulder dislodgement in these zones was "achieved not by storm waves but by tsunamis" (p. 263). Clearly, if this is the case for the inner Bristol Channel and the Severn Estuary, then boulders in the outer Bristol Channel could also have been dislodged by $H_t \geq 4.2$ m but reworking by subsequent storm waves and/or meteorological tsunami remains a possibility for boulders at these outer Bristol Channel sites (see Haslett and Bryant 2009).

Accepting that boulder dislodgement in the Bristol Channel and Severn Estuary is more likely to have been due to a tsunami than storm waves, Bryant and Haslett (2007) were able to recognise an up-channel increase in H_t, due to wave height amplification conjectured to have been caused by the overall funnel-shape of the embayment, an observation that is fundamentally replicated in this study. However, details vary between the two studies in that Bryant and Haslett (2007) recognised an increase from $H_t \geq 4$ m in the outer Bristol Channel, to $H_t \geq 5$ m in the inner Bristol Channel, to $H_t \geq 6$ m in the Severn Estuary. In the present study, H_t increases from ≥ 2 m in the outer Bristol Channel to ≥ 4 m in the inner Bristol Channel and the Severn Estuary.

Data from Sker Point, however, suggest that $H_t \geq 3$ m was experienced close to this site near the boundary between the outer and inner Bristol Channel. From these data, interpolation of minimum wave heights between the key sites of Lee Bay, Sker Point, and Brean Down is plotted on Figure 4. Extrapolation beyond the end sites permits reconstruction of the possible up-channel increase in wave height, relocating the 5 m and 6 m theorised tsunami wave height of Bryant and Haslett (2007) further up-channel to approximately 55–60 km and 25–30 km seaward from Gloucester, respectively. These results, embracing those of Bryant and Haslett (2007) that were derived from an earlier outdated version of the equation (Nott 2003), represent the minimum threshold for boulder dislodgement and, therefore, do not discount the possibility that a higher tsunami wave affected these sites.

Shape analysis of these wave-transported boulders (excluding the seven boulders from the Dunraven Bay lag deposit) is presented here using the Zingg (1935) method, c/b and b/a results derived from the measurements of 129 wave-transported boulders in Table 2 are plotted on a Zingg diagram in Figure 5. It is clear from these data that disc-shaped boulders dominate the sample with 71 clasts (55.04% of sample), followed by 49 blades (37.98%), with minor components of seven rods (5.43%), and two spheres (1.55%). The dominance of discs and blades within the sample is not surprising given the mainly sedimentary geology of the region and the prevalence of well-bedded stratigraphic units that are predisposed to produce tabular clasts upon erosion/quarrying from bedrock. Furthermore, disc-shaped clasts are more likely to be evidently imbricated, meeting the field criteria for wave-transported boulders and, therefore, selected for measurement.
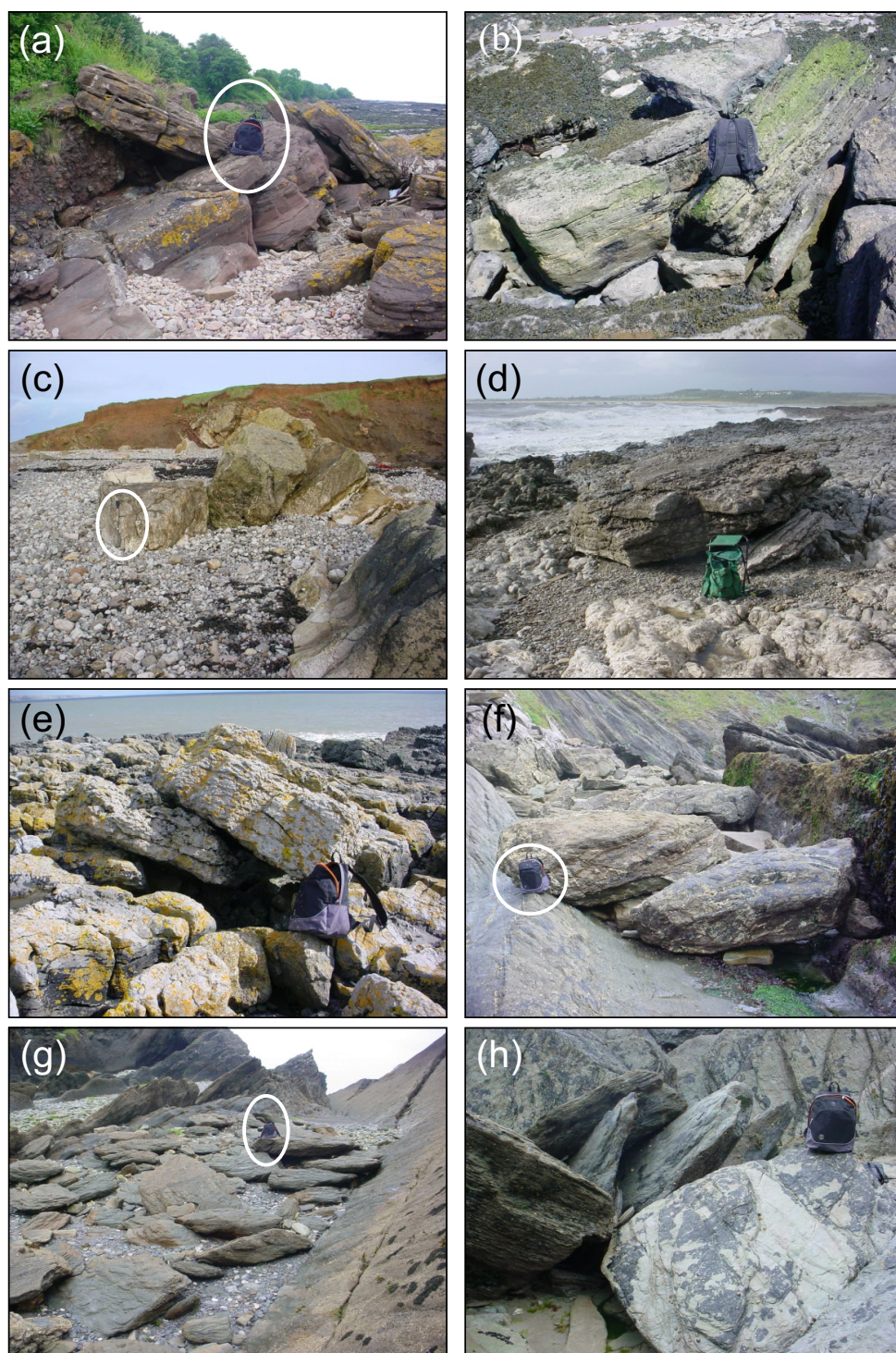
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Figure 3. Examples of boulder deposits from sites in the inner and outer Bristol Channel additional to those illustrated by Bryant and Haslett (2007): (a) imbricated boulders at Kilkenny Bay, Portishead (down-channel view); (b) imbricated boulders at Clevedon (up-channel view); (c) imbricated boulders at Swallow Cliff (up-channel view); (d) large boulder at Ogmore-on-Sea (down-channel view), (e) imbricated boulders at Newton Point (up-channel view); (f) imbricated boulders at Coombe Martin, near Ilfracombe (down-channel view); (g) ascending boulder train at Hele Bay, near Ilfracombe (up-shore view), and (h) imbricated boulders at Lee Bay, near Ilfracombe (up-channel view). Scale: for (a), (b), (e–h) backpack is 0.4 m high, for (c) spade circled is 1 m high, and (d) backpack is 0.5 m high.
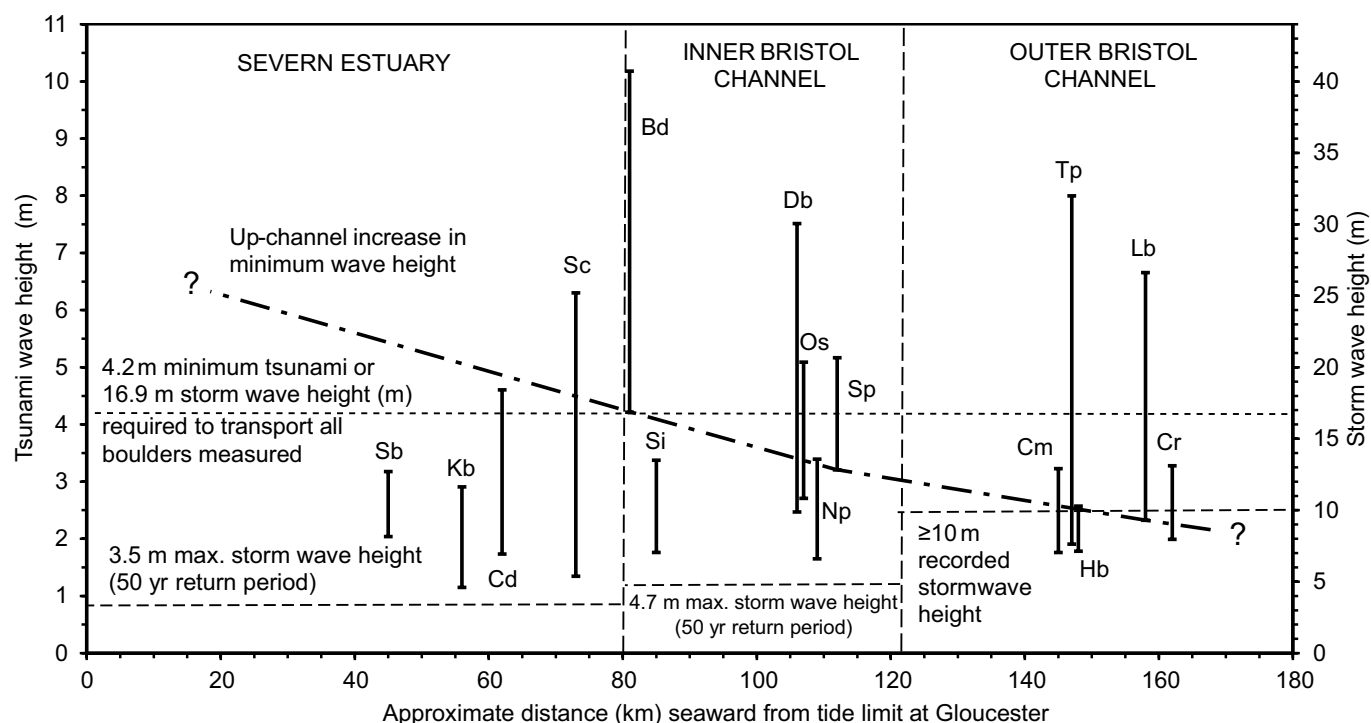
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Figure 4. Ranges in minimum wave heights for storm wave (H_{storm}) and tsunamis (H_t) derived from the recalculation of boulder data (see Table 2 for summary data and site codes) for each site investigated using the revised equations of Haslett and Wong (2019a). Sites are plotted according to approximate distance (km) seaward from the tide limit at Gloucester and the zones of the outer and inner Bristol Channel and the Severn Estuary are indicated. Observed storm wave heights from McLaren *et al.* (1993) are indicated as well as the minimum wave height required to explain the dislodgement of all boulders. A line representing interpolation and extrapolation using three key sites (Lee Bay, Sker Point, and Brean Down) is plotted suggesting an up-channel increase in recalculated wave heights.

The results derived from this study overall are consistent with those of Bryant and Haslett (2007) and the historical contemporary accounts of the 1607 flood (e.g., Anon 1607). Although some locations in the outer Bristol Channel were badly affected, such as north Devon where $H_t \geq 2$ m (Haslett and Bryant 2005), the most catastrophically affected areas were the coastal lowlands of the Somerset Levels in the inner Bristol Channel ($H_t = 3$–4 m), as far inland as Glastonbury (Fig. 2), and the Severn Estuary ($H_t \geq 4$ m, possibly rising to 5–6 m up-channel), from around Cardiff and Weston-Super-Mare up-channel towards Gloucester (Fig. 2; see also Skellern *et al.* 2008). It is in these areas that most of the ca. 2000 fatalities occurred on the morning of 30th January, 1607, due to the direct impacts of the catastrophic flood and its aftermath.

CONCLUSIONS

The entire dataset of 136 boulder clasts employed by Bryant and Haslett (2007) as part of their investigation into the impact of the 1607 flood in the Bristol Channel and Severn Estuary are used here to recalculate minimum wave heights for both storm waves and tsunamis using the revised hydrodynamic equations of Haslett and Wong (2019a). The results provide overall corroboration of the Bryant and Haslett (2007) study in that the data suggest that boulder dislodgement in the region was achieved not by storm waves but by tsunamis. The present study also corroborates an up-channel increase in tsunami wave height most likely due to wave amplification in the funnel-shaped embayment. The new results suggest that a tsunami ≥ 4.2 m high accounts for the dislodgement of all measured boulders (excluding a lag deposit) in the sample. Extrapolation suggests that a tsunami wave height up to 5–6 m is possible within the Severn Estuary where the impact of the 1607 flood on the coastal lowlands was most catastrophic.

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Table 2. The range of minimum storm (H_{storm}) and tsunami (H_t) wave heights required for boulder dislodgement at each site, with minimum wave speed (velocity) on impact with a boulder (u, m s-1), recalculated using the revised hydrodynamic equations for submerged and joint-bound boulders of Haslett and Wong (2019a; for the purpose of the analysis shore slope angle is estimated to be 10˚). Photographs of examples of boulders are referenced from Bryant and Haslett (2007) and this paper (see Figure 3).

Region	Site/sub-site and (Code)	Distance (km)[1]	H_{storm} (m)	H_t (m)	Example Figure
Severn Estuary	Sudbrook (Sb)	45	10.43 ± 2.27	2.61 ± 0.57	Bryant and Haslett (2007; fig. 14)
	Kilkenny Bay (Kb)	56	8.12 ± 3.52	2.03 ± 0.88	This paper (Fig. 3a)
	Clevedon (Cd)	62	12.68 ± 5.74	3.17 ± 1.44	This paper (Fig. 3b)
	Swallowcliff (Sc)	73	15.29 ± 9.91	3.82 ± 2.48	This paper (Fig. 3c)
Inner Bristol Channel	Brean Down (Bd)	81	28.79 ± 11.93	7.20 ± 2.98	Bryant and Haslett (2007; fig. 13)
	Sully Island (Si)	85	10.27 ± 3.23	2.57 ± 0.81	Bryant and Haslett (2007; fig. 12)
	Dunraven Bay (Db)	106	19.97 ± 10.09	4.99 ± 2.52	Bryant and Haslett (2007; fig. 11)
	Ogmore-by-Sea (Os)	107	15.59 ± 4.77	3.90 ± 1.19	This paper (Fig. 3d)
	Newton Point (Np)	109	10.09 ± 3.49	2.52 ± 0.87	This paper (Fig. 3e)
	Sker Point (Sp)	112	16.75 ± 3.92	4.19 ± 0.98	Bryant and Haslett (2007; fig. 10)
Outer Bristol Channel	Coombe Martin (Cm)	145	9.98 ± 2.93	2.49 ± 0.73	This paper (Fig. 3f)
	Tears Point (Tp)	147	19.81 ± 12.18	4.95 ± 3.05	Bryant and Haslett (2007; fig. 9)
	Hele Bay (Hb)	148	8.71 ± 1.58	2.18 ± 0.39	This paper (Fig. 3g)
	Lee Bay (Lb)	158	17.96 ± 8.66	4.49 ± 2.17	This paper (Fig. 3h)
	Croyde (Cr)	162	10.54 ± 2.57	2.63 ± 0.64	Not available

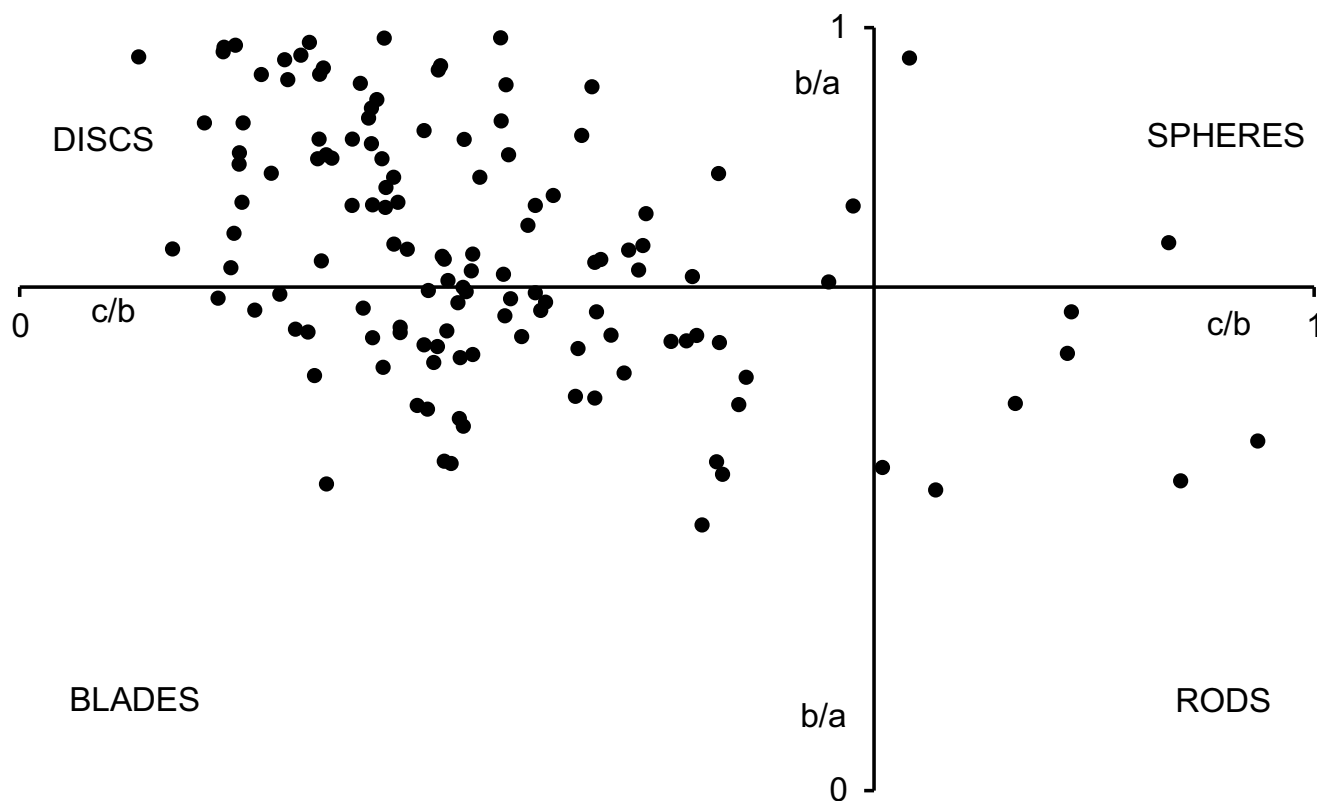Notes: [1]Approximate distance (km) seaward of tide limit at Gloucester.

Figure 5. Shape analysis using the classification of Zingg (1935) of 129 boulders (Appendix A, Table A1) from the Bristol Channel and Severn Estuary, excluding those of the lag deposit at Dunraven Bay (boulders DbL1-7).

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Table A1. Previously unpublished measurements of *a*. *b* and *c* axes and imbrication direction of all 136 boulders investigated by Bryant and Haslett (2007) in the Bristol Channel and Severn Estuary (see Figure 2 for locations).

Site/sub-site	Boulder ID	*a*-axis (m)	*b*-axis (m)	*c*-axis (m)	Imbrication	Site/sub-site	Boulder ID	*a*-axis (m)	*b*-axis (m)	*c*-axis (m)	Imbrication
Brean Down	BdA1	3.13	2.20	0.77	234˚SW	Newton Point	NpA1	2.53	2.16	0.50	231˚SW
Brean Down	BdA2	2.60	1.80	0.80	189˚S	Newton Point	NpA2	1.77	1.52	0.66	242˚WSW
Brean Down	BdA3	2.05	1.55	0.75	n/a	Newton Point	NpA3	2.48	1.05	0.70	233˚SW
Brean Down	BdA4	3.30	1.30	0.92	227˚SW	Newton Point	NpA4	1.76	1.06	0.35	223˚SW
Brean Down	BdA5	3.85	2.95	1.90	n/a	Newton Point	NpA5	1.87	1.73	0.65	195˚SSW
Brean Down	BdA6	5.15	4.75	2.10	n/a	Newton Point	NpA6	2.01	1.65	0.28	198˚SSW
Clevedon	CdA1	2.20	1.05	0.36	230˚SW	Ogmore	OsA1	4.85	3.10	1.05	246˚WSW
Clevedon	CdB1	2.30	1.35	0.73	309˚NW	Ogmore	OsA2	3.02	2.50	0.70	260˚WSW
Clevedon	CdB2	3.02	1.56	0.67	281˚WNW	Ogmore	OsA3	2.15	2.10	0.35	291˚WNW
Clevedon	CdB3	2.18	1.95	0.53	307˚NW	Ogmore	OsA4	2.07	1.96	0.46	262˚W
Clevedon	CdB4	2.32	1.98	0.68	n/a	Ogmore	OsA5	2.62	1.65	0.30	240˚WSW
Clevedon	CdB5	2.25	1.45	0.55	279˚W	Portishead	KbA1	2.15	1.65	0.45	347˚NNW
Clevedon	CdC1	1.49	1.07	0.95	n/a	Portishead	KbA2	2.05	1.75	0.45	346˚NNW
Clevedon	CdC2	2.05	1.04	0.80	n/a	Portishead	KbA3	2.60	2.50	0.23	318˚NW
Clevedon	CdD1	2.25	1.36	0.29	287˚WNW	Sker Point	SpA1	3.30	2.53	0.65	311˚NW
Clevedon	CdD2	1.80	1.38	0.55	n/a	Sker Point	SpA2	3.20	1.56	0.53	217˚SW
Clevedon	CdD3	1.20	0.80	0.50	n/a	Sker Point	SpA3	3.06	1.99	0.40	284˚WNW
Coombe Martin	CmA1	3.30	1.65	0.52	272˚W	Sker Point	SpA4	2.80	1.70	0.50	302˚WNW
Coombe Martin	CmA2	2.78	1.93	0.45	277˚W	Sker Point	SpA5	3.15	3.05	0.48	288˚WNW
Coombe Martin	CmA3	2.80	1.95	0.64	291˚WNW	Sker Point	SpA6	1.95	1.16	0.45	289˚WNW
Croyde	CrA1	3.01	2.30	0.65	n/a	Sker Point	SpA7	2.55	2.50	0.56	285˚WNW
Dunraven	DbA1	2.40	1.67	0.75	353˚N	Sker Point	SpA8	3.17	2.65	0.45	273˚W
Dunraven	DbA2	3.34	2.37	0.71	319˚NW	Sker Point	SpA9	4.35	2.75	0.73	288˚WNW
Dunraven	DbA3	1.92	1.68	0.29	0/360˚N	Sker Point	SpA10	3.77	2.46	0.98	n/a
Dunraven	DbA4	2.50	1.36	0.31	289˚WNW	Sker Point	SpA11	4.40	4.10	0.85	n/a
Dunraven	DbA5	3.75	2.36	0.95	267˚W	Sudbrook	SbA1	2.50	1.60	0.65	233˚SW
Dunraven	DbA6	3.30	1.92	0.62	259˚W	Sudbrook	SbA2	3.50	2.45	0.80	n/a
Dunraven	DbA7	2.53	1.95	0.57	273˚W	Sudbrook	SbA3	2.45	2.15	0.80	215˚SW
Dunraven	DbA8	2.53	1.51	0.69	261˚W	Sudbrook	SbA4	1.85	1.60	0.50	209˚SSW
Dunraven	DbA9	2.94	2.76	0.64	237˚WSW	Sudbrook	SbA5	2.80	2.25	0.65	247˚WSW
Dunraven	DbA10	2.77	2.67	0.58	270˚W	Sudbrook	SbA6	1.75	0.90	0.40	247˚WSW
Dunraven	DbA11	3.38	2.42	0.70	306˚NW	Sudbrook	SbA7	2.80	2.45	0.35	n/a
Dunraven	DbA12	2.39	0.97	0.87	263˚W	Sudbrook	SbA8	4.45	3.60	0.70	112˚ESE
Dunraven	DbA13	2.70	1.68	0.63	291˚WNW	Sudbrook	SbA9	4.15	3.20	0.55	146˚SE
Dunraven	DbA14	3.29	1.66	0.51	279˚W	Sudbrook	SbA10	4.55	1.95	0.65	231˚SW
Dunraven	DbA15	2.80	2.25	0.80	0/360˚N	Sudbrook (west)	SbW1	3.50	2.90	0.70	219˚SW
Dunraven	DbA16	3.55	2.87	1.55	33˚NNE	Sudbrook (west)	SbW2	2.05	1.90	0.50	225˚SW
Dunraven	DbA17	2.80	1.16	0.63	309˚NW	Sully Island	SiA1	2.70	1.78	0.61	237˚WSW
Dunraven	DbA18	2.90	1.90	0.60	249˚WSW	Sully Island	SiA2	3.45	2.35	0.82	260˚W
Dunraven	DbL1	3.35	2.41	0.83	199˚SSW	Sully Island	SiA3	2.20	1.63	0.64	244˚WSW
Dunraven	DbL2	3.52	2.86	0.64	268˚W	Sully Island	SiA4	2.60	1.53	0.77	213˚SSW
Dunraven	DbL3	4.22	2.48	0.95	350˚N	Sully Island	SiA5	2.11	1.98	0.37	197˚SSW
Dunraven	DbL4	2.93	1.87	0.58	207˚SSW	Sully Island	SiB1	4.09	2.32	0.79	n/a
Dunraven	DbL5	5.55	3.00	1.26	280˚W	Sully Island	SiB2	2.40	1.70	0.80	224˚SW
Dunraven	DbL6	3.68	3.05	0.38	284˚WNW	Sully Island	SiB3	3.21	1.78	0.50	238˚WSW
Dunraven	DbL7	4.22	2.89	0.83	264˚W	Sully Island	SiB4	2.70	2.25	0.85	n/a
Hele Bay	HbA1	3.81	2.29	0.51	n/a	Sully Island	SiB5	4.25	2.55	0.75	269˚W
Lee Bay	LbA1	3.13	2.02	0.31	317˚NW	Sully Island	SiC1	2.15	1.57	0.26	245˚WSW
Lee Bay	LbA2	3.77	2.54	1.32	n/a	Sully Island	SiC2	1.17	1.14	0.18	278˚W
Lee Bay	LbA3	3.90	2.55	0.88	n/a	Sully Island	SiC3	1.43	0.98	0.16	286˚WNW
Lee Bay	LbA4	3.10	2.20	0.26	n/a	Sully Island	SiC4	1.37	0.80	0.25	268˚W
Lee Bay	LbB1	4.45	1.92	0.63	n/a	Sully Island	SiC5	1.01	0.89	0.24	255˚WSW

Table A1. Continued.

Site/sub-site	Boulder ID	*a*-axis (m)	*b*-axis (m)	*c*-axis (m)	Imbrication	Site/sub-site	Boulder ID	*a*-axis (m)	*b*-axis (m)	*c*-axis (m)	Imbrication
Swallow Cliff	ScA2	1.10	0.63	0.51	279˚W	Tears Point	TpA11	1.68	1.31	0.54	255˚WSW
Swallow Cliff	ScA3	2.51	1.15	1.10	0/360˚N	Tears Point	TpB1	2.14	2.05	0.42	233˚SW
Swallow Cliff	ScA4	1.89	1.35	0.65	261˚W	Tears Point	TpB2	1.44	1.42	0.40	226˚SW
Swallow Cliff	ScA5	1.80	1.63	0.45	0/360˚N	Tears Point	TpB3	1.81	0.98	0.55	175˚S
Swallow Cliff	ScA6	1.78	0.90	0.50	0/360˚N	Tears Point	TpB4	2.79	1.75	0.78	239˚WSW
Tears Point	TpA1	2.30	1.95	0.53	n/a	Tears Point	TpB5	2.50	2.40	1.65	n/a
Tears Point	TpA2	2.80	1.65	0.85	236˚SW	Tears Point	TpB6	2.28	1.90	0.45	219˚SW
Tears Point	TpA3	1.70	1.15	0.43	269˚W	Tears Point	TpB7	2.78	1.65	0.45	n/a
Tears Point	TpA4	1.80	1.70	0.55	n/a	Tears Point	TpC1	3.60	1.97	0.92	173˚S
Tears Point	TpA5	2.10	1.66	0.47	255˚WSW	Tears Point	TpC2	3.12	1.75	0.56	173˚S
Tears Point	TpA6	2.15	1.78	0.41	283˚WNW	Tears Point	TpC3	3.16	1.10	0.58	199˚SSW
Tears Point	TpA7	1.81	0.78	0.42	218˚SW	Tears Point	TpC4	2.20	2.09	0.68	207˚SSW
Tears Point	TpA8	1.50	1.48	0.55	218˚SW	Tears Point	TpC5	2.10	1.20	0.42	228˚SW
Tears Point	TpA9	2.17	1.45	0.48	261˚W	Tears Point	TpC6	2.36	1.61	0.77	187˚S
Tears Point	TpA10	2.52	1.46	0.63	262˚W	Tears Point	TpC7	2.18	1.30	0.68	239˚WSW

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