Cliff-top megaclast deposits of Ireland, a record of extreme waves in the North Atlantic—storms or tsunamis?

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Abstract

Past occurrences of major tsunami in the global record have often been inferred from the presence of megaclast accumulations at significant heights above sea level, which sometimes exhibit a pronounced seaward-directed imbricate fabric. The Aran Islands, off the west coast of Ireland, exist in a marine environment which is totally unprotected from the most extreme sea states encountered in the North Atlantic. Spectacular megaclast accumulations are found along the tops of vertical cliffs on these islands. The elevation of these deposits varies from 0 m to 50 m above mean sea level and they include clasts weighing 250 tonnes at sea level, over 117 tonnes at 12 m and 2.9 tonnes at 50 m above sea level. Imbrication measurements on these megaclasts indicate a well defined and consistent mean direction from the southwest for the emplacing waves, one that is consistent with the prevalent storm wind direction for the area. The megaclast accumulations are subject to episodic and on-going erosion by cliff retreat but the existing accumulations are estimated to record events since at least 1839. Recent emplacement and reworking is evidenced by trapped plastic detritus within the deposits and eyewitness accounts of large storms during which clasts have been emplaced. Similar deposits are found on the exposed coasts of the Shetland and Orkney islands off Scotland. There is at present no evidence of any tsunami in recorded history affecting the western Irish and Scottish coasts other than those generated by the Lisbon earthquake of 1755, where the wave effects were slight. Thus, the presence of megaclast accumulations at significant heights above sea level, on exposed coasts, and exhibiting imbrication should not be used as a definitive criterion for the past occurrence of tsunami. These deposits attest to extreme wave conditions occasionally encountered in the North Atlantic and act as a record of such events extending back at least 160 years. Such data on extreme wave conditions are essential for the prediction of the effects of deepwater waves on structures such as offshore drilling platforms.

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1. Introduction

Many authors have ascribed the presence of giant clasts at some heights above sea level in coastal environments to the activities of catastrophic waves, tsunami or tropical cyclones (e.g. Bryant, 2001; Bryant et al., 1996; Nott, 1997; Mastronuzzi and Sanso, 2000; Hearty and Neumann, 2001; Noormets et al., 2001). The Aran Islands off the western seaboard of Ireland (Fig. 1) display some of the most spectacular accumulations of megaclasts in an exposed coastal environment in the world; some
perched on the top of stepped sea cliffs 50 m above sea level. These accumulations were first named “The Block Beaches” by the Geological Survey of Ireland (Kinahan et al., 1871). This study aims at illustrating the mechanisms involved in the emplacement of such megaclasts and will address the controversy as to whether such deposits indicate the action of tsunamis or storm waves (e.g. Felton and Crook, 2003).

The three main Aran Islands consist of Carboniferous Limestone and represent the offshore continuation of the karstic landscape of the Burren to the southeast. The regional dip of the limestones is low from about 4° to 10° towards the SSW. Marine erosion has resulted in the formation of dramatic sea cliffs on the western margins of the two northern islands. The vertical cliffs rise to heights of 80 m in places. Cliff erosion is facilitated by the presence of at least two primary joint directions, one of which is at a high angle to the cliff margins (Gillespie et al., 2001), together with the presence of occasional thin shale horizons which lead to severe undercutting and eventual collapse of the cliff faces. Preferential erosion along these shale horizons has led to the formation of limestone terraces in places resulting in stepped cliff profiles in many localities.

During the Pleistocene, Ireland experienced at least three main glacial advances and retreats with the ice extending over the Aran Islands and as far as the edge of the continental shelf (McCabe, 1987). During the last ice advance, glacial erratics of the Galway Granite, derived from the northeast, were deposited on the limestones of the Aran Islands (Kinahan et al., 1871). Ice movements resulted in complex isostatic responses which are, as yet, not
fully understood (Shennan et al., 2002). Raised beaches up to 20 m above sea level are found primarily in the northeast and east of the country where they comprise sand and rounded gravel deposits, although no such beaches apparently exist on the west coast including the Galway Bay area (Mitchell, 1976). Due to these unequal isostatic responses to ice melting, Holocene changes in relative sea levels vary around the coasts. In the south and southwest, the increase in sea level has been 0.6–1.1 mm/year over the past 5000 years. Local anomalies exist, however, for example on the northern coast where relative sea level is falling at 2.4 mm/year (Carter et al., 1989). The absence of raised beaches at heights similar to those of the megaclast ridges precludes inheritance from earlier high sea levels and shows the ridges to be Holocene features.

2. The megaclast accumulations

The nature of these megaclast deposits varies, being at least partly dependent on the height of the deposit above sea level. The lithologies present are dominantly of the local Carboniferous limestone but occasional more rounded glacial erratics of the Galway Granite are also present. Normally, they are formed into ridges, which broadly follow the morphology of the coastline (Fig. 2). However, in some cases, erosion has overtaken the rate of formation of the ridges resulting in their collapse into erosional gullies and eventual destruction of parts of the ridges. Complete destruction of parts of the ridges is seen for example immediately south and north of the Black Fort on Inishmore where the ridge terminates abruptly against the margins of a large embayment (Williams, 2004). Ridges vary in thickness from about 1 to 6 m (Fig. 3) and the width varies considerably from 3 to about 35 m. The size of clasts, which form these ridges, varies from a sand grade to megaclasts with a longest dimension of 7 m. The ridges are separated from the cliff edges or the seaward edges of lower limestone benches by wave-scoured sub-horizontal platforms from 0 to 200 m wide. Only rarely is any detritus seen seaward of the ridges on these platforms presumably due to the high energy of the wave action over their surfaces. Clast roundness varies considerably. At low levels (0–5 m a.s.l.), smaller clasts are
frequently well rounded and resemble the more normal cobble-pebble storm beaches common on the western Irish seaboard. With increase in the elevation of the ridges above sea level, the percentage of rounded clasts decreases until at elevations of 20–50 m all clasts (with the exception of granitic glacial erratics) are highly angular.

The ridges typically have a steep seaward face with the largest clasts on this margin and demonstrate a landward reduction in clast size. However, the weight of some of the megaclasts within these deposits is extremely large. The heaviest clast measured was approximately 250 tonnes (approximately $6 \times 5 \times 3.2$ m with a limestone density of 2.6 kg/m$^3$) just above sea level on Inishmore, not adjacent to any cliff collapse and perched across a small ravine. The maximum weight of the clasts at any location is approximately related to their height above sea level.
The highest elevation ridge is found on the north coast of Inishmaan at about 50 m above sea level (Fig. 5). The maximum clast weight here is 2.9 tonnes. At heights of 15–25 m a.s.l. maximum weights can be up to 45 tonnes (Fig. 6). There is evidence of at least three separate megaclast ridges at a number of localities in the Irish case, for example the southern tip of Inishmore and at Crummel on Inishmaan shown in Fig. 7, each ridge separated from its neighbour by a zone clear of clasts and each ridge being thinner and narrower in a landward direction. These smaller ridges further...
inland probably represent the results of older and more extreme events formed in more distal locations when the cliff edge was further seaward than the present day. There is some evidence for older coastal deposits comprising partly lithified sand and gravel being overlain by more recent megaclast deposits (Fig. 8). These represent the oldest deposits on the cliff tops and may exist up to 25 m a.s.l. The origin of these deposits is as yet unproven.

3. Megaclast imbrication

Sedimentary clasts deposited in many different environments may exhibit an imbricate fabric. This is caused by the stacking of the clasts against each other so that one of the clast axes dips with respect to the horizontal. If the clasts possess a marked asymmetry of axial lengths with the $a$-axis (longest) significantly longer that the intermediate ($b$-axis) and

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Fig. 7. Sketch of multiple megaclast ridges at Crummel, Inishmaan. The ridge nearest the sea shows well-developed imbrication, which becomes weaker in the other ridges moving landward.

Fig. 8. Megaclast ridge at 20 m a.s.l. overlying a distinct and older deposit of partially lithified sand and gravel, 500 m southwest of Gort na gCapall, Inishmore. Trowel (circled) is 28 cm long.
shortest (c-axis) then the orientation of the a-axis can indicate the method of transport. The a-axis normal to the flow indicates a rolling or sliding mechanism of entrainment, whereas the a-axis parallel to the flow indicates an emplacement involving turbulent suspension or saltation (Collinson and Thompson, 1982). The original size of angular clasts in the Aran ridges is determined by the combination of bed thickness of the limestone and joint frequency since these are the discontinuities that determine the rate and nature of erosion of the cliff faces (Williams, 2004). As a result, the majority of clasts have much larger a- and b-axes than the c-axis, i.e. they are tabular clasts. In approximately 30% of cases, the a-axes of clasts are significantly larger than the b-axes. The megaclast ridges comprising angular clasts frequently exhibit a pronounced imbricate fabric (Fig. 9). This fabric is best developed on the seaward margins of the ridges and is replaced by a more chaotic clast arrangement in a landward direction. Measurement of the imbricate fabric involved establishing the dip direction of the a-axis if this was much larger than the b-axis, or the dip of the a–b plane if both axes were of similar dimensions. The amount of dip measured was between 5° and 30° to the horizontal. Fig. 10 shows imbrication directions for the three Irish islands. These directions have been modified occasionally on a local scale by reworking around progressively enlarging embayments so that the imbrication is arranged in a radially inward sense towards the embayment. In general, however, the imbrication orientation of the megaclasts reflects the direction of the regional wave patterns that created the ridges. Measurements of imbrication directions have been taken where the coastline is essentially linear to avoid the localized modifications described above. Fig. 10 shows clearly that the dominant imbrication direction of the deposits is towards the southwest coinciding with the dominant wind-driven wave direction from the Irish Meteorological Service Station at Belmullet where the principal wind direction is from approximately 250° both in fair-weather and storm conditions (Met Eireann, 2003).

The orientation of the megaclasts can yield evidence about their mechanism of emplacement. It is not possible in all cases to ascertain the way-up of many of the megaclasts. Some however are right way-up (Fig. 11), some partly overturned (Fig. 12) and some completely inverted (Fig. 13). The criteria for recognition of orientation include horizons of fossil concentrations and weathered surfaces of megaclasts. Thus, some megaclasts are apparently emplaced by

Fig. 9. Well defined seaward imbrication in megaclasts at about 5 m above sea level on the northwestern extremity of Inishmore, looking north, sea to the left. Notebook (circled) is 20 cm high.
sliding in a right way-up position within a column of water whilst others have been toppled and emplaced by the vertical component of water forces acting on them. Both modes of emplacement probably involve impacts of the megaclasts with the bedrock since crescentic percussion marks (Fig. 14) are occasionally found preserved on the limestone platforms seaward of the ridges suggesting an element of saltation and high velocity flow in their emplacement (Reineck and Singh, 1973). This mechanism is confirmed by the dip of the \( a \)-axes of the megaclasts, where this is distinguishable, as these dip approximately orthogonally to the strike of the ridges in a seaward direction indicating that the majority were not rolled along the rock platforms during emplacement. None of the ridges examined are backed by cliffs and are therefore not the products of cliff collapse.

Evidence for the sources of the megaclasts is provided by sockets at the cliff-top edges, by steps in the rock platforms and by scars at the rock bases of the ridges (Fig. 15). For example at Poll Dorchá, 2 km southeast of the Black Fort, a large socket associated with fresh debris measures \( 18 \times 11.5 \times 1.4 \) m. The lift and fragmentation of this rock mass has resulted in a group of megaclasts each approximately of \( 20 \) m\(^3\), a maximum horizontal transport distance of some 32 m and a vertical lift of some 1.4 m.

4. Timing of clast detachment, transport and emplacement

The blocks on the seaward side of the ridges are often fresh at levels below about 20 m above sea level. Surface darkening of fresh limestone and the growth of the bright orange lichen, *Caloplaca marina*, occurs within a few decades on the Aran Islands as shown by the surfaces of gravestones in the churchyard of Kilmurvy on Inishmore. Thus the most recent movement (at least at lower levels) of megaclasts is related to near-contemporary wave action. At a number of localities plastic or nylon objects (bottles, containers,
fishing nets, etc.) can be seen firmly trapped beneath megaclasts, especially along the seaward side of the ridges. Careful examination of these was made to discount any that could have been forced into crevices in the ridge deposits at a later time than that of the movement of any individual clast. This evidence supports the observation discussed earlier that these are not raised beach ridges of the Pleistocene, which

Fig. 12. Partial overturning of megaclast (arrowed) 2 km southwest of Crummel on Inishmaan. Weathered surface is on the right side of the clast. Compass (circled) is 20 cm.

Fig. 13. Complete overturning of a megaclast (outlined) approximately 6 m long on Inisheer, 80 m south–southwest of the lighthouse. This clast lies inverted on top of its in-situ parent bedrock, both of which exhibit a nodular horizon.
have achieved their present elevations due to post-glacial uplift. It is usually in the ridges nearest the sea that modern debris has been found.

At present, the actual age at some localities of any megaclast accumulation is not known with certainty. However, eyewitness and other evidence do constrain the age of some of them. The first scientific description of the formation of these megaclast ridges on Inishmore (Kinahan et al., 1871) mentioned “a block 15 × 12 × 4 ft (approximately 20 m³) seems to have
been moved 20 yards (6 m) and left on a step 10 ft (3 m) higher than its original site”. The Black Fort (Fig. 10), known in Irish as Dun Duchathair, some 30 m a.s.l. on the cliff top of Inishmore contains within its circumference a number of ancient stone huts. Some of these were buried on the 5th of January 1839 (The Night of the Big Wind) by megaclasts, which today exhibit a pronounced imbrication. During the storm, the roofs of most houses on the Aran Islands were removed and some houses completely destroyed, with crusts of salt forming on trees 12 miles inland (Carr, 1993). A large proportion of the clasts at the Black Fort are extensively covered by *C. marina*, which is also prevalent on many of the high level clasts such as at 50m a.s.l. on Inishmaan. In areas of similar climatic conditions megaclasts with extensive growth of the lichen would have been emplaced and stabilized prior to those with little or no lichen growth. The megaclasts in the Black Fort may represent part of a relatively old suite of megaclast deposits still preserved on the islands, older deposits having been eroded by cliff recession which is quite rapid in places (Williams, 2004).

At the south end of Inisheer is a lighthouse (Fig. 10), constructed in 1857. In January 1941, a megaclast weighing approximately 84 tonnes was emplaced onto the seaward limestone platform 2 m above sea level during a storm. Wave heights are not recorded but were sufficient to flood the lighthouse (base at 5 m a.s.l.), trapping the keeper for 9 h (Scanlan, 1993). At many localities, some stone field walls can be seen to have been destroyed by the emplacement of megaclasts, whereas elsewhere such walls can be seen to have been built on top of the ridge deposits. In 1952, a slipway and access track were being constructed near a village on Inishmore (Gort na gCapall, Fig. 10). A storm early the following year (30th January 1953) resulted in the total destruction of the construction machinery together with the emplacement of a large number of megaclasts so that the slipway can no longer be accessed for boat launching from the landward side because the access road was completely buried under a megaclast ridge. Some of these clasts reached heights of 15 m a.s.l. Waves reached breaking heights of approximately 12–15 m at up to 150 m inland and transported megaclasts up to 2 m in longest dimension (Patrick Derrane, builder on the slipway project, pers. comm.). This storm was responsible for the sinking of the Princess Victoria in the Irish Sea with the loss of 132 people and the deaths of thousands of people in England and Holland. The storm was generated by an extreme depression over the eastern North Sea and was not accompanied by any tsunami (Kelman, 2003; British Broadcasting,

![Fig. 16. Rounding of clasts on a low level ridge (5 m a.s.l.) due to repeat wave action, 2 km southwest of Crummel, Inishmaan.](image-url)
Robinson (1986) noted the movement of a block of approximately 0.75 by 1.75 m during a storm in the winter of 1981.

Away from the high cliffs at low levels of 0–5 m a.s.l., there are storm beach deposits of well rounded boulders and cobbles at the front of shore platforms or at the foot of cliffs. In many cases, angular megaclasts can be seen deposited on top of such beaches. This suggests that the angular megaclasts are only transported even at low elevations by exceptional wave events. Once emplaced on low-level beaches, the megaclasts are reworked to produce progressively more rounded morphologies (Fig. 16). There is thus a spectrum of clast shape at low levels. Reworking at higher elevations is far less frequent resulting in clasts with more angular morphologies.

5. Wave climate in the adjacent North Atlantic

Weather data show the western Irish coast to experience the highest number of gales per annum in Europe. The 30-year average from 1961 to 1990 shows 30.5 gale-days/year with a maximum gust during this period of 93 knots. The maximum gust speed likely to be exceeded once in 50 years in the Aran Islands area is 112 miles/h, the dominant direction being from the southwest (Met Eireann, 2003).

Wave buoy data off the west coast of Ireland is only of relatively recent usefulness (3 years). However, a non-continuous record of wave data recorded by passing ships off the west coast of Ireland extends back to 1870. These data, obtained from Met Eireann (The Irish Meteorological Service), shows that deep water wave heights (up to 1995) in excess of 14 m occur on a regular basis in this part of the Atlantic. It must be borne in mind that the most exceptional waves are less likely to be recorded since many ships are unlikely to be sailing under such conditions. However, large waves recorded include some of 20 m. Most of the larger waves are naturally recorded in the winter months and in relatively deep water although some exceptions to this are notable from the data set of 2837 points. For example, between 1879 and 1934, there were 20 large wave events (14 m wave heights or greater) recorded (by two or more ships) in the summer months (May through August).

Wave height estimations for this region have focussed on a 50-year hindcast (the maximum wave height which may be exceeded on average once every 50 years). Carter (1993) showed that storm-generated waves in excess of 20 m are statistically likely off the west coast of Ireland once in 50 years. A more localised study in the area of the Skerd Rocks (some 12 km northwest of Inishmore) concluded that the maximum deepwater generated wave in this area for a 1 in 50-year storm from the west was 21.6 m (Aqua-Fact International, 2002). These studies have been conducted without long-term data from wave buoys. In the North Sea where such data from wave buoys and offshore structures have become available over the past 20 years, predicted maximum wave heights have been increased and the return period for large waves reduced from previous estimates (Lawton, 2001). By analogy, in the deep water off the Aran Islands, it is suggested that maximum wave heights of 15–25 m can be expected in storms with return periods of less than 20 years.

The light vessel Lima located off the northwest coast of Ireland (57°N 20°W) provided data for a wave period versus wave height scatter plot between the years 1975 to 1983 (Draper, 1991). This shows that over this relatively short time interval wave heights of approximately 17 m were actually occurring typically at wave periods of 11–13 s. West of Shetland, in the Schiehallion area, modelling of extreme wave heights showed that they may reach 24 m (BPX, 1995).

6. Comparison with Scottish cliff-top deposits

These features preserved on the Aran Islands are comparable in many respects with similar deposits on the Scottish islands of Shetland and Orkney where the geology is more varied than that of the Arans (Wilson et al., 1935; Mykura, 1976; Hansom, 2001). Here, the cliff-top deposits often form low ridges up to 3.5 m high parallel to the coast and are composed of imbricate boulders with maximum axes of 2.1 × 1.0 × 0.3 m. At Grind of the Navir, Eshaness, Shetland, large slabs of ignimbrite have been quarried from the adjacent cliff-top edge and transported 50 m landwards and emplaced 15 m above sea level in one
of three megaclast ridges, the largest of which is 3.5 m thick. Many megaclasts that comprise these ridges are fresh with sharp serrated edges that can be matched perfectly to fresh scars on the cliff edges (Hansom, 2001).

On Shetland one of us (A.M.H.) demonstrated block removal had occurred during the storms of 1/1/1992 and 17/1/1993. The storms of the early 1990s were associated with two of the highest wind speeds in the 20th century and occurred without the action of any tsunami activity.

7. Wave mechanisms

High level megaclast marine deposits such as those on the Irish and Scottish Islands may be formed by exceptional storm waves or by tsunami (e.g. Hearty, 1997; Mastronuzzi and Sanso, 2000; Noormets et al., 2001). The rate of occurrence of tsunami in the North Atlantic is very many factors lower than that of very large storms (Bondevik et al., 1997, 2003; Dawson et al. 2000). In fact, the largest seismically generated waves to have affected Ireland and Britain in the historical past were those generated by the 1755 earthquake in Lisbon, Portugal. The waves generated by this event affected Cork (Ireland) and Cornwall (England) amongst other places. The magnitude of the waves in Cork is not known but the run-up height in Cornwall (approximately the same horizontal distance from the epicentre) was 2 m (Baptista et al., 1998). On the Scilly Isles, in the English Channel, the maximum wave height was estimated at 3 m above high tide level (Dawson, 2000). These tsunami wave heights, generated by the most significant earthquake experienced in northern Europe in historical times, are quite insufficient to emplace megaclasts, such as those of the Arans at tens of metres above sea level.

The famous Grand Banks earthquake in November 1929 generated a tsunami at the Newfoundland coast achieving heights of 30 m above sea level. No effects of this event were experienced in Britain or Ireland (Dawson, 2000).

The data presented here shows that some storm generated waves are clearly capable of quarrying joint-bounded blocks of 45 m$^3$ and moving them tens of metres across rock platforms at heights in excess of 20 m a.s.l. On Eleuthera, in the Bahamas, blocks resulting from Holocene hurricanes and storms reach 10 m a.s.l. with an average size of 22 m$^3$ (Hearty, 1997), dimensions comparable to, but generally less than, those found on the Aran Islands. The physical characteristics of such deposits are not particularly helpful in distinguishing between the two mechanisms. Imbrication of clasts for example can be generated by either mode (Mastronuzzi and Sanso, 2000) or indeed by any high competence flow. Because of the physical characteristics of the waves, tsunami have been modelled as being more effective than storm waves of similar dimensions at transporting megaclasts (Nott, 1997). The megaclast accumulations of these Irish and Scottish islands are important not only as a record of extreme wave conditions in the North Atlantic dating back at least 160 years in the case of Aran, but also for their contribution to the debate concerning evidence for tsunami activity in coastal areas of the world.

The fact that the seaward side of these ridges show well developed imbrication compared to the landward margins suggests that the fabric is developed by the repeated influence of waves affecting the ridge and not by a short-lived wave event such as a tsunami, the landward sides of the ridges being more protected from wave action. The imbricating action of repeated wave action is confirmed by comparing imbricate fabrics at various heights above sea level (Fig. 17). Higher level ridges show a poorer development of fabric than those at lower levels which would be re-worked more frequently by storm wave action. Such pronounced imbrication with a low spread of directions has been employed by some authors as evidence for formation during an isolated large wave event, that is a tsunami (e.g. Mastronuzzi and Sanso, 2000; Nott, 1997, 2003; Young et al., 1996). This feature however may contribute to a circularity of argument where the very presence of imbrication and of clasts at high elevations above sea level is used as actual evidence for tsunami action (e.g. Bryant, 2001; Whelan and Kelletat, 2002) rather than examining deposits which are already known to have been generated by tsunami and determining their imbricate fabric, if any, and heights above sea level.

Calculations of wave properties necessary for the mobilization and transport of joint-bounded blocks such as those found on the Aran Islands have been
attempted by Nott (2003). The equations governing the wave heights necessary to lift such blocks show that storm waves would have to be approximately four times the height of tsunamis to lift a block of the same dimensions. The equations are:

\[
H_t = 0.25 \frac{(\rho_s - \rho_w)}{\rho_w} a / C_l
\]

\[
H_s = \frac{(\rho_s - \rho_w)}{\rho_w} a / C_l
\]

Where \(H_t\) is the height of tsunami and \(H_s\) the height of storm wave; \(\rho_s\)—density of clast (2.6 g/cm\(^3\) in the case of the limestone), \(\rho_w\)—density of seawater (1.02 g/cm\(^3\)); \(a\)—\(a\)-axis length of clast; \(C_l\) coefficient of lift 0.178.

Applying the equations to an example from the Aran Islands to a clast (approximately 200 m north-west of Gort na gCapall, Fig. 10) with an \(a\)-axis of 3.5 m at 15 m above sea level results in a storm wave height necessary for lifting of 25.28 m above the 15-m platform, i.e. a total height of 40.28 m and a necessary tsunami total height of approximately 21 m. Neither of these values are realistic since the waves impacting with the Aran Island cliffs are deep water waves and have not been enhanced by constriction in bays. Such waves would have over-run the ridges and deposited material further inland, a situation for which there is no evidence.

It may be that other factors need to be considered in the movement of the megaclasts. Amplification of wave heights may be generated by constructive interference of incoming waves with waves reflected from a vertical non-porous barrier, i.e. the cliffs. This effect has been demonstrated in work by Hu et al. (2000) where modelled waves of initial height 0.4 m and period approximately 20 s developed heights of 0.8 m after reflection from a vertical wall. Also green-water overtopping, for example, occurs when a wave does not break until it comes into contact with an object such as the top of a sea wall, the deck of a ship or oil platform, or natural platforms at cliff tops such as the Aran Islands. It has been shown experimentally that a green-water overtopping of a fixed deck (by analogy a cliff-top platform in this case) results in wave collapse onto the deck and the development of a bore whose velocity may be up to 2.4 times that of the original wave (Cox and Ortega, 2002). The bore thus develops the characteristics of a forward moving mass of water rather than a circular wave, so storm wave water velocities are considerably increased under such conditions and the heights necessary for megaclast movements are decreased. Such a process may also help explain the presence of megaclasts well above the possible action of a simple wave colliding with a single vertical cliff. Modelling of a wave surge crossing an underwater step has been carried out by Hu et al. (2000). This shows that the effect of such a step is to increase the forward velocity of the surge, in the quoted case, by up to 40% upon crossing over the step. In the case of the platforms of the Aran Islands forward wave velocities will be increased progressively by crossing platform margins (steps) thus enhancing the waves’ capabilities for clast transport at progressively higher levels. For example the megaclast ridges at 50 m above sea level on Inishmaan are separated from the sea by a number of limestone platforms (Fig. 5) which may have accelerated incoming waves sufficiently to emplace clasts at this height. At other localities however, such as...
the promontory of the Black Fort where such seaward platforms are absent in water depths of approximately 18 m, megaclasts have been moved by waves directly impacting platforms at 30 m above sea level without such amplification over platform steps.

8. Conclusions

The megaclast ridges of western Ireland and northern Scotland form a record of extreme storm-generated wave activity in this North Atlantic region. In this paper we have shown that these waves have been capable of moving large clasts directly at heights of 30 m above sea level and by surge enhancement over platform steps up to 50 m above sea level. The method of transport of these clasts has been by uplift and suspension or by saltation but generally not by rolling along the substrate. Clasts are plucked from wave-washed platforms just prior to entrainment and sometimes overturned in the emplacement process. These transport and depositional processes have resulted in a well-defined imbricate fabric in many parts of these ridges. A number of eyewitness accounts relate to the emplacement of these clasts on the Aran Islands namely in 1839, 1871, 1941, 1953 and 1981 (1992 and 1993 in Scotland). All these accounts attest to the activity of large storm waves with no records of any tsunami activity in the North Atlantic during these events. The only historic tsunami proven to have affected the region (in 1755) produced waves just 3 m high on English coasts, quite insufficient, for example, to emplace clasts weighing 45 tonnes at 12 m above sea level such as found on the Aran Islands. Thus, we must conclude that the megaclast ridges of western Ireland and Scotland were formed over an extensive period of time by extreme storm events, such events having been active in the recent past. Additionally the study shows that well developed imbricate fabrics of such megaclast ridges are not necessarily an indication of the action of tsunami in fact imbrication is a common feature of all storm beaches, which consist of flat pebbles/boulders (Collinson and Thompson, 1982). Megaclast accumulations at high levels on exposed coasts, and sometimes exhibiting imbrication, in other areas and considered to be the result of large tsunami, notably Australia and the Caribbean, should be re-examined with regard to their origins (e.g. Bryant, 2001; Bryant and Nott, 2001; Scheffers, 2002). Some of the parameters employed by some of these authors have been questioned (Felton and Crook, 2003). It is unlikely for example that isolated tsunami events will have a greater effect on the general morphology of coastlines than persistent storm activity, one of the primary controlling factors of coastal recession. Maximum wave heights in the North Atlantic may reach well in excess of 20 m and result in the stepwise velocity increases over seaward platforms necessary to achieve clast movement on 50 m high cliffs. It is not possible to be precise at the moment with regard to the frequency of such events, but, in the case of the Aran Islands, it would appear that an event affecting cliff heights possibly exceeding 30 m a.s.l. occurred in the last 160 years (Night of the Big Wind) and that events involving the emplacement of clasts weighing tens of tonnes at heights of 15 m above sea level have certainly occurred since the widespread use of plastic probably between the 1970s and present. The significance of the occurrence of such waves for deep-water and coastal structures is important especially in view of the fact that hydrocarbon production off the west coast of Ireland is now beginning.

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