Wave-Emplaced Coarse Debris and Megaclasts in Ireland and Scotland: Boulder Transport in a High-Energy Littoral Environment

Anja Scheffers, Sander Scheffers, Dieter Kelletat,[1] *and Tony Browne*

School of Environmental Science and Management, Southern Cross University, P.O. Box 157, Lismore, New South Wales 2480, Australia (e-mail: anja.scheffers@scu.edu.au)

ABSTRACT

Many coastlines of the world, particularly those at higher latitudes and those located in tropical cyclone belts, are regularly battered by strong storm waves. Drowning of low-lying areas by storm surges and storm floods has been thoroughly recorded; however, storm deposits at rocky shorelines or on cliffs have been underrepresented in the literature. This article presents observations of extraordinary wave deposits along the high–wave energy coastlines of western Ireland and the northern Scottish isles and discusses possible wave event types and time windows of the processes responsible. We used archaeological, geomorphological, and geochronological disciplines to compare our findings with earlier results published for these areas and to contribute to the debate on whether large clasts found well above sea level and/or a considerable distance inland were deposited by storms or by tsunamis.

Introduction

Until recently, coastal boulder deposits have not attracted any specific scientific interest, entering into mainstream discussion only with the development of paleotsunami field research. The debate regarding transport processes involved (storm or tsunami waves) therefore remains highly controversial. Coarse coastal deposits, including boulders of limited size, have mostly been reported from hurricane impacts on coral reefs (Stoddart 1974; Baines and McLean 1976; Hernández-Ávila et al. 1977; Scoffin 1993; Bries et al. 2004; Scheffers and Scheffers 2006; Scheffers et al. 2009*a*). However, during the past 20 years, tsunami boulder transport has been described, particularly for paleotsunamis from the late Holocene up to more recent times (Scheffers and Scheffers 2007; Bryant 2008; Scheffers et al. 2008, 2009*a*, 2009*b*). Some researchers dispute these results (e.g., Morton et al. 2006; Tappin 2007) and argue that these deposits were generated by storm processes. In general, information on boulder transport is scarce in review articles on tsunami deposits (Dawson 1996; Dawson and Shi 2000; Dawson and Stewart 2007).

Since the strong tsunamis in Nicaragua (1992), Papua New Guinea (1998), Peru (2001), and the Indian Ocean (Andaman-Sumatra; 2004), task forces have inspected the effects of boulder transport in near-time studies (Satake et al. 1993; Shi et al. 1995; Dawson et al. 1996; McSaveney et al. 2000; Lavigne et al. 2006; Moore et al. 2006; Richmond et al. 2006; Kelletat et al. 2007). Although most of the reports are entitled "tsunami deposits," they deal almost exclusively with fine-sediment transport. Large, freshly dislocated boulders, however, can be seen in photographs from these publications and have been described in modern tsunamis, such as the Andaman-Sumatra event of 2004 (Goto et al. 2007; Kelletat et al. 2007; Paris et al. 2007). Articles comparing tsunami and storm deposits (Nanayama et al. 2000; Goff et al. 2004; Tuttle et al. 2004) also mostly lack a discussion on coarse deposits. This leads to the false presumption that modern tsunamis have moved only fine sediments and that boulders moved by these tsunamis are not preserved or recognized.

In the debate on storm versus tsunami transport

Manuscript received November 2, 2008; accepted May 11, 2009.

[1] Institute of Geography, University of Cologne, Albertus-Magnus-Platz, Cologne, Germany.

[The Journal of Geology, 2009, volume 117, p. 553–573] 0022-1376/2009/11705-0006$15.00. DOI: 10.1086/600865

of very large boulders (20–50 t and more), the enigmatic deposits on coastlines of Ireland and Scotland play a key role. Here, Williams (2004), Williams and Hall (2004), Hall et al. (2006, 2008), Hansom et al. (2008), and Hansom and Hall (2009) have described deposits of megaclasts along steep, elevated coastlines (up to 50 m a.s.l.), so-called cliff-top megaclasts. These authors interpreted the deposits as congruent with modern and historical storm processes. This scenario is a key argument in the scientific debate supporting the storm hypothesis for boulder deposits along various coastlines.

This article presents observations and results from coastal sites in western Ireland and the west coasts of northern Scottish islands that highlight the extraordinary evidence of onshore boulder deposits mentioned by previous investigators. It seems very likely that these shorelines may hold the key to improving our understanding of megaclast transport by waves from either storms or tsunamis. This is not only an academic dispute; it has far-reaching consequences regarding processes of coarse coastal deposits and natural-hazard management in general. If the storm hypothesis for the deposition of large boulders at very high altitudes along western European shorelines can be verified, then wave power there must be far greater than has been reported for nearly all modern and paleotsunamis to date. With an open-minded approach and without any preconceived bias, we present observations on and discussion of boulder deposits along the western coastlines of the northern Scottish isles and Ireland.

Regional Setting and Methods

Looking for deposits from extreme events implies that field research may be selectively concentrated in special locations. To avoid this, our field survey was carried out in Ireland and Scotland, where sites were carefully selected to represent highly exposed areas as well as sheltered areas along shallow waters (fig. 1). Digital photographs from western Ireland at a scale of 1 : 4000 allowed for a continuous check of the complete coastline from southwestern to northeastern Ireland at a resolution of about 0.5 m. Many places were investigated personally, and topographic maps at scales of 1 : 25,000 and 1 : 50,000 were used. Further, old photographs, descriptions of archaeological or historical importance, and maps and charts from the nineteenth century were used to gain insight into coastal changes in more recent times. Field measurements included boulder axes (table 1), GPS orientation, and geologic and geomorphologic investigations of weathering state. Samples (table 2) were collected to date the deposition of large boulders or the formation of boulder ridges. However, this was mostly restricted to the limestone coasts of Aran and Galway Bay, where boring bivalves could be found in dislocated boulders. These samples were dated by the accelerator mass spectrometry (AMS) radiocarbon technique at Beta Analytic Laboratories in Florida. Additional samples (mollusk hash, single shells, or peat) were taken from coarse deposits. Open-ocean wave data for the North Atlantic and Western Europe are available (Shields and Fitzgerald 1989; Draper 1991; Lamb and Frydendahl 1991; Dolan and Davis 1994; Meeker and Mayewski 2002; Clarke and Rendell 2009), but data for wave heights at the coastline are rare. The literature on the geomorphology of coastal areas of Ireland and Scotland is extensive (e.g., Gray 1977; Wright et al. 1982; Carter and Orford 1984, 1993; Dawson et al. 2004), as is that on sea level history (Carter et al. 1989; Lambeck 1991; Gilbertson et al. 1999; Shennan and Horton 2002). Valuable information on the historical changes in the coastal environment since Neolithic times can be found in archaeological literature (e.g., Lamb 1980; Renfrew 1985; Ritchie 1988; Ashmore 1996; Wickham-Jones 1998). The development of the rural landscape of Ireland is also well documented in Aalen et al. (1997). Given a tidal range of 3–4 m and sea level variations (at least in Ireland) of no more than 3 m during the most recent millennium, it is possible to extrapolate the coast-forming parameters from modern aspects of geology and rock type, degree of exposure, bathymetry, coastal sloping, cliff height, and indicators for coastal changes in archaeological evidence. With the exception of southwestern Ireland, one complicating factor is the wide distribution of coarse clasts in the coastal environment left by the last glaciation.

Results

Coarse Coastal Deposits and the Intensity of Abrasion. The exposed coastlines of the Scottish isles and western Ireland have many aspects in common. Destructive wave forces are documented by the steepness and freshness of cliff profiles (including undermining). In many places, archaeological remains from Neolithic, Bronze Age, or Iron Age fortifications and medieval castles and monasteries give approximate data relating to coastline retreat. More precise wave impact data can be gained from coastal deposits. Beach ridges built by pebbles, cobbles, and small boulders (Carter and Orford 1984, 1993; Otvos 2000; fig. 2) mostly form a single crest

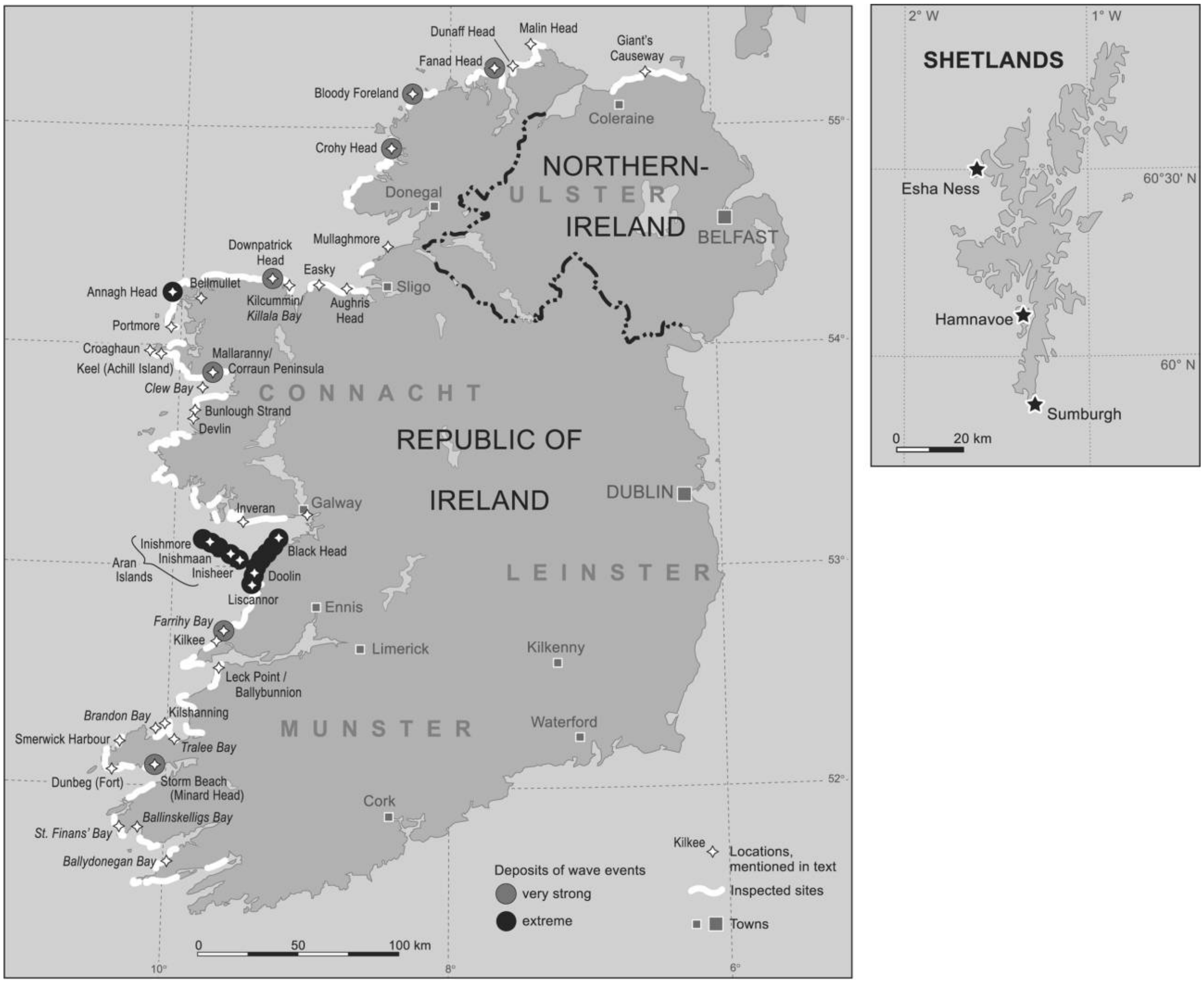

Figure 1. Field sites visited along the west and north coasts of Ireland and Scotland and the locations of extreme events with high and very high impact energy.

that does not show significant weathering or vegetation. Elevations are remarkably similar at coastal locations hundreds of kilometers apart, mostly between 2.5 and 4 m above mean high water (MHW). Differing from these average and widespread coastal settings, two types of site clearly show the impacts of higher energy in destruction/abrasion and the deposition of clasts. The first type of deposition consists of wide and smoothly formed beach ridges with crests 5–8 m above MHW; these contain significantly older sections, particularly at the landward margins, that are covered by dense lichen carpets, disappear under vegetation, soil, and even peat, and have certainly not moved from the seaside for centuries. Clusters of small boulders are deposited on soil or peat on flat ground and terraces 5–6 m above the MHW mark and 20–100 m farther inland than the boulder ridges. The second type clearly represents the strongest wave energy occurring along the western Scottish and Irish coastlines and consists of single, very large boulders (some of >100 t) or boulder fields or ridges extending for kilometers and ranging from 6 to 50 m above MHW. These exceptional deposits, however, are restricted to limited areas along the exposed coastlines of the western British Isles, in particular along southern Galway Bay and the Aran Islands (fig. 3) of western Ireland, at the Annagh Peninsula in County Mayo, and in the northwestern corner of mainland Shetland around Grind of the Navir. Most of these locations have been well described and mapped in detail by Williams and Hall (2004) and in particular by Hansom and Hall (2009). Our dating observations and conclusions differ from

Table 1. Dimensions of Some Boulders from Selected Coastal Sites in Ireland and Scotland

Location	Rock type	*a*-axis (m)	*b*-axis (m)	*c*-axis (m)	Volume (m^3)	Weight (t)	Altitude above MHW	Imbrication
Shetland Islands (western mainland and West Burra):								
Esha Ness	Ignimbrite	2.7	1.4	1.4	5.7	14	15	
Esha Ness	Granite	2.6	1.9	1.5	7.4	19	7	
Hamnavoe	Quartzite	2.6	1.2	.9	2.8	7.3	5	
Sumburgh	Quartzite	2.0	1.1	1.1	2.4	6.2	4.5	Seaward 29°
Northwestern Ireland:								
Dingle Bay	Quartzite	1.5	1.1	.9	1.5	>2	4	
Downpatrick Head	Granite	4.5	2.6	.7	8.2	21	5	Seaward 14°
Crohy Head	Granite	3.2	2.4	1.1	8.4	22	10	Seaward 34°
Fanad Head	Gneiss	4.0	2.0	1.2	9.6	24	5	
Annagh Head	Gneiss	3.1	3.0	1.1	10.2	26	11	Seaward 29°
Annagh Head	Gneiss	4.2	2.7	1.3	14.7	38	3	Seaward 22°
Western Ireland, Galway Bay, and Aran Islands:								
Inishmore, south coast	Limestone	4.8	3.3	1.4	22	57	6	Seaward 55°
Inishmore, south coast	Limestone	6.3	5.1	3.1	99	258	2	
Inishmore, south coast	Limestone	5.7	4.1	2.3	53	139	8	
Inishmaan, west coast	Limestone	9.2	2.6	1.1	26	68	10	Seaward 44°
Inishmaan, west coast	Limestone	2.8	1.8	.8	4	10.4	46	
Galway Bay, east	Limestone	4.3	2.2	2.0	18.9	49	7	
Galway Bay, east	Limestone	9.4	4.0	2.2	82.7	215	3	

Note. Except for Esha Ness on Shetland and some parts of the Aran Islands of western Ireland, all sites are in sheltered positions with wide, shallow water in the foreshore. The Inishmaan boulders are situated inland up to 220 m from the cliff. The density of granite, gneiss, quartzite, and limestone has been measured close to 2.6 g/cm^3; the density of ignimbrite has been measured to a little less than 2.5 g/cm^3. Boulders of 50 t and more are particularly widespread on the Aran Islands and along Galway Bay.

theirs in some respects, but comparisons can be made between their findings and the conclusions presented from this study.

For all the coastal features and deposits presented here, discussion is required regarding the amount of abrasion (we use the term "abrasion" rather than "erosion" because the latter is too general for wave destruction at cliffs by debris) that has occurred during the most recent millennium. Williams (2004) argued that "promontory forts" on Aran show signs of typical ring forts and that their appearance at cliff-top positions today is only incidental. He calculated the cliff retreat as 0.4 m/yr on average, for a total of about 1 km since the Iron Age (2500–2000 yr ago). Evidence from our observations and documentation suggests, however, that abrasion along steep coastlines must have been modest or even negligible at many sites:

1. The World Heritage Sites of Skara Brae, on the west coast of mainland Orkney, and Jarlshof, close to the southern tip of mainland Shetland, were occupied in Neolithic times >5000 yr ago, as evidenced by mid-Holocene shell middens in and under the settlements, the type of dwelling construction, and absolute age data. Because both coastal settlements show only minor signs of abrasion, coastal retreat during the most recent millennium here may be on the order of only 100–200 m.

2. The distribution of hundreds of shell middens close to sheltered and exposed shores in western Ireland and Scotland, most of them even presented on topographical maps at scales of 1 : 25,000 and 1 : 50,000, also point to limited abrasion since Neolithic times, again on the order of 100 m or less.

3. The dozens of Iron Age promontory forts constructed along the British and Irish coastlines (Lamb 1980) were attached to natural cliffs or headlands with narrow necks (fig. 4) and indicate that they are still in their original locations. Therefore, the conclusions of Williams (2004)—that the coast has retreated on the order of 1 km since Iron Age times and that the structures referred to as promontory forts are nothing but remnants of former inland ring forts—are questionable. Remnants from more recent historical times, such as Viking boathouses, medieval monasteries, and castles positioned on sheer cliffs, also indicate a limited amount of abrasion.

4. Old maps and charts can give information on former coastal configuration, such as the 1849 map of the "Isles of Arran" by Bedford or the 1839 map of Inishmore by James, revised by Johnston in 1899. Both maps show the cliff line around the Iron Age fort of Dun Duchathair on Inishmore, referred to in the main argument of Williams (2004) for significant coastal retreat, in the same configuration as it has today. In addition, Hall et al. (2008) measured and estimated cliff recession in hard rock (ignimbrite) on exposed headlands in the special case of Grind of the Navir in northwestern Shetland.

Table 2. Radiocarbon Data from Boulder Deposits from the West Coast of Ireland

Sample	Location	Material dated	$^{13}C/^{12}C$ ratio	^{14}C yr BP, conventional	Calibrated age (IntCal 04)	Remarks
Aran Islands and Galway Bay:						
236709	Inishmore, cape west of Black Fort	Mollusk hash	−.6	550 ± 40	1720 AD (1690–1820 AD)	Ridge, landward, 28 m above MHW
236711	Inishmore, cape east of Black Fort	Mollusk hash	.0	550 ± 40	1720 AD (1670–1880 AD)	Second ridge, 28 m above MHW
233799	Inishmaan, south coast	Boring bivalves	−2.1	610 ± 40	1680 AD (1640–1810 AD)	Ridge 6 m above MHW
233793	Inisheer, southwest coast	Boring bivalves	−1.5	670 ± 40	1650 AD (1540–1690 AD)	Behind large boulder ridge, 2 m above MHW
233783	2 km south of Black Head, Galway	Boring bivalves	+.6	830 ± 40	1480 AD (1440–1540 AD)	Lower ridge, from a boulder of 3 t 2 m above MHW
233797	Inishmaan, south coast	Boring bivalves	−.3	850 ± 40	1470 AD (1430–1520 AD)	From single boulder of 8–10 t on platform 3 m above MHW
233798	Inishmaan, south coast	Boring bivalves	−4.8	860 ± 40	1460 AD (1420–1520 AD)	Landward slope of ridge 5 m above MHW
233784	2 km south of Black Head, Galway	Boring bivalves	+.4	900 ± 40	1440 AD (1400–1480 AD)	Lower ridge, large platy boulder 2.4 m above MHW
233786	6 km north of Doolin	Boring bivalves	−.7	910 ± 40	1440 AD (1390–1480 AD)	Large ridge, central part with large boulder 6 m above MHW
236712	Inishmore, east of Puffing Hole	Mollusk hash	−1.9	950 ± 40	1420 AD (1330–1460 AD)	Second ridge over Puffing Hole, 30 m above MHW
233787	6 km north of Doolin	Boring bivalves	−10.0	1020 ± 40	1330 AD (1290–1420 AD)	Upper part of landward old slope of ridge 6 m above MHW
233795	Inishmore, west end	Boring bivalves	−1.0	1110 ± 40	1290 AD (1230–1330 AD)	Landward slope of ridge 6 m above MHW
233792	Inishmore, east of Wormhole	Boring bivalves	−.2	1190 ± 40	1230 AD (1150–1290 AD)	50 m from sea, large ridge 40 m wide, large boulders, 6 m above MHW
233790	Inishmore, west of Red Lake	Boring bivalves	−1.3	1210 ± 40	1210 AD (1110–1280 AD)	Crest of large ridge 4.5 m above MHW
233788	6 km north of Doolin	Boring bivalves	−1.6	1250 ± 40	1170 AD (1060–1250 AD)	Landward slope of large ridge 5 m above MHW
233794	Inishmore, west end	Boring bivalves	−1.4	1310 ± 40	1070 AD (1020–1190 AD)	Ridge with boulders >50 t, lichens, imbricated, 5 m above MHW
233791	Inishmore, west of Red Lake	Boring bivalves	−.9	1540 ± 40	860 AD (770–960 AD)	Crest of boulder ridge 4.5 m above MHW
236713	6.5 km north of Doolin	Mollusk hash	+3.1	2030 ± 40	360 AD (260–440 AD)	From brown soil 5 m above MHW
233796	Inishmore, southwest coast	Boring bivalves	−7.8	2070 ± 40	300 AD (220–410 AD)	In platy boulder on top of promontory 18 m above MHW
236708	Inishmore, west of Gort na gCapall	Mollusk hash	−.2	2210 ± 40	140 AD (60–240 AD)	West of Blind Sound, landward part of small ridge 18 m above MHW
236710	Inishmore, Black Fort	Mollusk hash	+1.0	3370 ± 40	1290 BC (1390–1190 BC)	Seaward ridge, seaward slope, under imbricated boulders 28 m above MHW
233782	2 km south of Black Head, Galway	Boring bivalves	−1.9	3620 ± 40	1580 BC (1670–1480 BC)	Seaward ridge, landward slope in imbricated boulder 28 m above MHW
236707	2 km south of Black Head, Galway	Mollusk hash	+1.2	4340 ± 40	2530 BC (2620–2440 BC)	Boulder ridge 70 m landward, from steep landward slope 5 m above MHW
Isolated locations on the west coast of Ireland:						
236726	Downpatrick Head, Donegal	Peat on boulders	…		690 AD	3.5 m above MHW
236962	North of Minard Castle	Peat	−28.5	1230 ± 50	780 AD (670–900 AD)	Base of upper peat 2.1 m above MHW
236961	North of Minard Castle	Peat	−28.4	2900 ± 50	1080 BC (1260–930 BC)	Top of lower peat .9 m above MHW
236715	Southern Annagh Peninsula, Donegal	Peat on boulders	…	3680 ± 40	2100–2040 BC	1 m under surface, 10 m above MHW

Note. All mollusk data were obtained by AMS dating. According to IntCal04 (Fairbanks et al. 2005; Ascough et al. 2006), the reservoir effect changes from about 385 ± 26 yr for ages 4000 BP to about 401 ± 25 yr for ages 600 BP. The peat samples dated were <2 cm thick.

Figure 2. A single steep, active cobble beach ridge at the Annagh peninsula, northwestern coast of Ireland.

Their estimated rate of recession of 5–6 mm/yr is in agreement with our conclusions, and such an abrasion rate would result in a recession of only 10–15 m over the past 2000–2500 yr.

Boulder Deposits. At both exposed and sheltered sites, boulder deposits and ridges are present that, judging from weathering and soil or peat cover, are at least partly not of recent origin. Following is a description of such sites located from southern Ireland's west coast to the north and the central parts of the Shetland Islands of Scotland (fig. 1).

Storm beach near Minard Castle, northern shoreline of Dingle Bay. This site has exceptional examples of perfectly rounded boulders of hard quartzitic sandstone up to 1.5 m long and weighing >2 t. These boulders form a 40-m-wide ridge covered by lichens on the crest and displaying a light roughness indicative of weathering. The 20-m isobath is 1.5 km away from the beach, and the 10-m isobath is at least 250 m away.

We believe that a tsunami event could have moved the boulders onshore but would have been unable to abrade them in this perfect manner. Data for a strong wave event are available from west of Minard Head, about 2 km from the boulder ridge, where a cliff section exhibits a chaotic sand and shell layer with pebbles between peat strata. The absolute age of the top of the lower peat was determined to be 1080 BC (calendar years; sample 236961), and the base of the upper peat was dated at 780 AD (sample 236962; table 2). This "sandwich dating" for a possible extreme-event deposit is only approximate because the basal peat layer has been eroded by an unknown amount.

Boulder ridges west of Mallaranny, County Mayo. Along the inner Clew Bay's north coast, from the Mallaranny Pier to the west, a boulder ridge about 3 m above MHW runs for a length of about 3 km. Red sandstone clasts are mostly well rounded, with diameters between 0.2 and 0.6 m; larger fragments are more angular. Bivalve borings show that the clasts had been moved several meters upward from the intertidal and subtidal belt. Rough surfaces resulting from weathering, dense lichen carpets, and embedding in soil and peat at the landward side indicate significant age. Storm waves can be excluded as the driving force for the movement of the large boulders located on the crest or farther inland because the water is shallow (~10 m deep at 700 m seaward) and the ridges are exposed to the inner part of Clew Bay toward the southeast and east.

Downpatrick Head, north coast of County Mayo (fig. 5). Along the north coast of County Mayo west of Downpatrick Head, a low, rocky shoreline lies exposed to the northwest. On the rock platform in front of 1–3-m-high cliffs, platy granite boulders

Figure 3. Boulder ridge at 12 m a.s.l. at the southwest corner of Inishmore, Aran Islands.

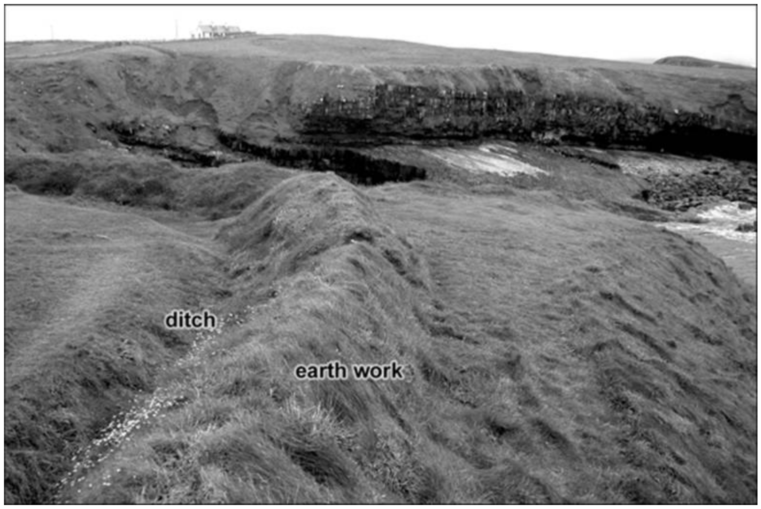

Figure 4. Remnant of an Iron Age promontory fort at Corraun Peninsula, County Mayo, western Ireland. An earthwork and ditch are preserved, whereas the main site (to the seaside at right) has been abraded.

up to 4.5 m in length, >2.5 m wide, 0.6–0.7 m thick, and weighing up to 21 t have been moved tens of meters. At the cliff, boulders of up to 3 t appear under a thin stratum of peat. Smaller boulders are distributed 40 m inland on and in peat. The dislocation of the large boulders from the cliff occurred before 690 AD, and movement of smaller boulders located on the vegetated cliff top occurred after that date, which was determined from the peat layer at the head of the cliff section (sample 236736; table 2). We believe that storm waves today are not able to transport coarse sediments into this area about 4 m above MHW because of the shallow water (10-m isobath ~400 m seaward).

North coast of Gweebarra Bay (Crohy Head), west coast of central Donegal. North of the entrance to Trawenagh Bay in the inner part of Gweebarra Bay, the coast inclines approximately 10° to the sea and is exposed to the south-southwest; the water is shallow (20-m isobath at 4 km seaward). The granite boulders (corestones; fig. 6) are mixed with cobble-sized fragments of hard sandstone. The width of these ridges range from 30 to 50 m, with a thicknesses of mostly <2 m, and the highest boulders are found up to 10 m above MHW. To the northwest, where a small promontory offers shelter, partly imbricated angular fragments weighing up to 20 t and >3 m long dominate. Those on higher ground exhibit significant pitting and are covered by lichens.

We believe that the weight of the boulders, the altitude of the deposit, and weathering may provide evidence of impacts larger than can be produced by modern storm waves. This is corroborated by the modeling of storm wave transport capacity in Benner et al. (2009) and Imamura et al. (2008).

Northwestern coast of Donegal, south of Bloody Foreland Head. Approximately 2 km south of Bloody Foreland in an exposure to the west, quartzite cobble beaches appear on peat at up to 4 m above MHW, and large granite boulders appear at up to 5 m above MHW. A profile in the cliff shows two different phases of onshore deposition after the formation of a podsol on till (fig. 7). On top of this soil, boulders of up to 2 t settled in a chaotic dump deposit and were covered by a peat layer 10–30 cm thick. On this peat, boulders of <1 t occur in several chaotic deposits. These deposits document strong events, with movement of large clasts in a shallow-water environment.

West of Fanad Head, northwestern coast of Donegal. At 2–3 km southwest of Fanad Head in western to northern exposures, another granite coast covered with large boulders lies along shallow water (10-m isobath at ~500 m seaward). Rounded granite fragments with single-boulder weights of up to 20 t and maximum lengths of 4 m accumulated 4–5 m above MHW to form an imbricated ridge at the top of a flat peat terrace (fig. 8). The boulders are covered by lichens and exhibit strong pitting. No signs of more recent movement or accumulation can be observed, suggesting the occurrence of a single strong dislocation event at least several hundred years ago.

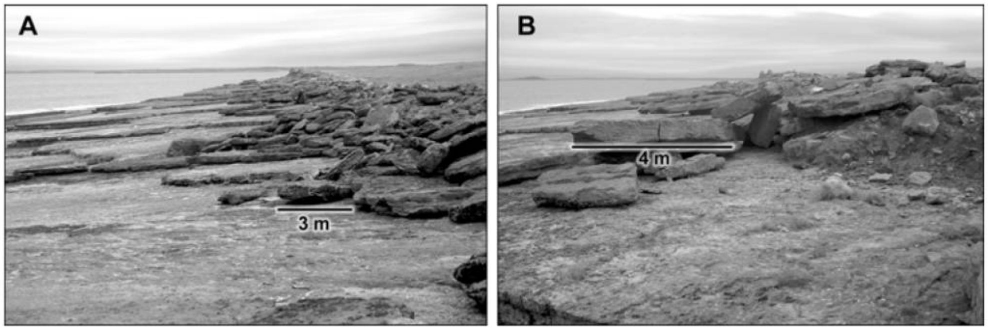

Figure 5. *A*, Platy boulders dislocated onshore west of Downpatrick Head, north coast of Ireland. *B*, Boulders of up to 10 t rest on a low cliff in weathered drift material.

Esha Ness, northwest coast of mainland Shetland. The Esha Ness area in northwest mainland Shetland exhibits signatures of most extreme events, such as Grind of the Navir, but also deposits that document lesser wave impacts. One such deposit ("the Burr") is a boulder ridge approximately 70 m wide and 4 m above MHW that separates Croo Loch from the open ocean. The most elevated parts of the barrier close to Croo Loch are deeply weathered and covered by vegetation that has seemingly not been affected by more recent accumulations. In the small bay between Gill Stacks and Burro Stacks, boulders are much larger (~10 t), weathered, and covered by lichens (fig. 9). Some large boulders are dislocated up to 60 m inland and ~6 m above MHW. Along the more exposed coastline closer to the high ridges of Grind of the Navir, the southwest-facing broad promontory at Head of Stanshi displays an old boulder ridge up to 14–15 m above MHW, with the largest and most deeply weathered fragments weighing ~1.5 t. Field evidence indicates the occurrence of a strong dislocating event hundreds of years ago that has not been equaled by wave energy since.

Hamnavoe Bay on West Burra Island, Shetlands. West Burra is separated near Hamnavoe into two branches. The southern branch shows evidence of extreme wave impacts (fig. 10). In the south-southwest, between Biargar and Pundsar, a nest of boulders accumulated up to 6–7 m a.s.l., but the main deposits form a broad ridge partly on base rock between Pundsar and Fugla Ness up to 80 m wide and steep along the seaward side because of the impact of surf during storms. In the southern section, two parallel ridges can be identified, and in the northern section, as many as three were identified. The highest parts of the ridge reach 5 m above MHW, with individual boulders 2.6 m in length and weighing ~7 t. The crest and the leeward slopes are densely covered by lichens, and the coarse granite is deeply pitted. The orientation of axes is random, imbrication is not well developed, and some boulders are unstable and balance on others. The deposit is undoubtedly old, only partly added to by the dislocation and movement of smaller boulders at the seaward slope.

Sumburgh peninsula, southern tip of mainland Shetland (fig. 11). The southern part of mainland Shetland is formed by two peninsulas approximately 3 km long: the Sumburgh peninsula on the east and the promontory of Scat Ness on the west. On the central west coast of Scat Ness, which is a deep-water environment with high exposure, boulders are deposited up to ~5 m above MHW as well as in the bay ("West Voe of Sumburgh") between the two peninsulas at the northwestern corner of Sumburgh, where Jarlshof is located. The strangest feature in this coastal landscape is a 5-m-high, 500-m-long, up to 200-m-wide tombolo of boulders on rocky outcrops at the northeastern corner of the Sumburgh peninsula that links the rocky head of Scult of Laward with the mainland at Grutness.

Figure 6. Large, well-imbricated granite boulders south of Crohy Head, west coast of Donegal, Ireland.

Figure 7. Large granite boulders south of Bloody Foreland rest chaotically on a podsol in drift material.

The steeper side is exposed to the southeast, where storm waves move smaller boulders up to a level 3–4 m above MHW. The quartzite boulders are well rounded, which can result only from wave action, but the relatively shallow foreshore and its sheltered position make it difficult to envisage a longer-lasting phase of wave impacts at this site. Many of the boulders have diameters or longest axes of >1 m (up to 2 m), with maximum weights of ~6 t. From evidence such as the onionlike foliation of boulder surfaces, continuous lichen carpets, and dense vegetation with peat between boulders from the crest to the leeward side, the ridge is undoubtedly ancient.

Galway Bay and the Aran Islands, Western Ireland. As demonstrated in more detail by Scheffers et al. (2008), Galway Bay and the Aran Islands represent the most extremely wave-impacted areas in Western Europe (also Williams and Hall 2004; Hall et al. 2006, 2008). Here, boulders of several hundred tons have been dislocated, with some of >50 t at least ~15 m above MHW. In addition, boulder ridges with very good imbrication extend >30 km, with the highest point near 50 m a.s.l. These deposits, commonly weathered, karstified, and covered by lichens, were dated by the AMS method from boring bivalves in boulders, mollusk hash in ridges, and peat (table 2). Ages cluster around 1650–1720 AD, 1420–1470 AD, early and late medieval times (1070–1290 AD), 140–300 AD, 1290 BC, 1580 BC, and even 2500 BC. Although the highest deposits occur at sites with exposure to the open ocean along sections with deep water, several others with ridges up to 10 m high and boulders of >100 t were found in the shelter of the Aran Islands and along inner Galway Bay (fig. 12). Only two other sites with coastal deposits point to similar wave impact energy and boulder dislocation: Grind of the Navir on the northwest coast of mainland Shetland (described in detail by Hall et al. 2006; Hansom and Hall 2009) and Annagh Head on the Annagh peninsula west of Belmullet in County Mayo, northwestern Ireland, which has not yet been surveyed.

Grind of the Navir, Shetland. The west coast of Esha Ness (fig. 9*A*) exhibits individual sites of boulder deposits (mostly ignimbrites) located at high altitudes, from nearly 30 m a.s.l. south of Calder's Geo lighthouse to 20 m a.s.l. at Grind of the Navir. Grind of the Navir (fig. 13*A*), as well as the coastline north of it around Hamnavoe and at several sites in the eastern Shetland islands, has been mapped in detail by Hansom and Hall (2009). It represents two headlands with a gap between them. In this gap, a slot cave blowhole developed. Landward, a depression with water depths of about 3 m (fig. 13*B*) appeared, formed from plucked rock and surrounded by a steep, high ridge of large boulders (fig. 13*C*). This ridge has a maximum relative height of ~4.5 m and consists of angular and platy boulders approximately 3 m long and weighing up to 6 t. Hansom and Hall (2009) mapped eight ridges, one of which is an older, lower ridge that appears inland at the highest elevation (fig. 13*D*). Unstable setting and imbrication are typical in the main ridge (fig. 13*E*), where the setting of boulders seems to be chaotic. Although many of the boulders look remarkably fresh (places of fresh plucking of rock could be seen between 10 and 12 m a.s.l.; fig. 13*E*), the landward slope shows weathering and lichens in dense carpets, indicating no movement for decades or even longer (fig. 13*F*). For the lichen cover, Hall et al. (2006) found that the black *Verrucaria maura* takes about 100 years to cover rocks to be-

Figure 8. Boulder ridge (granite) settled in and on peat at 5 m above MHW west of Fanad Head, County Donegal, Ireland.

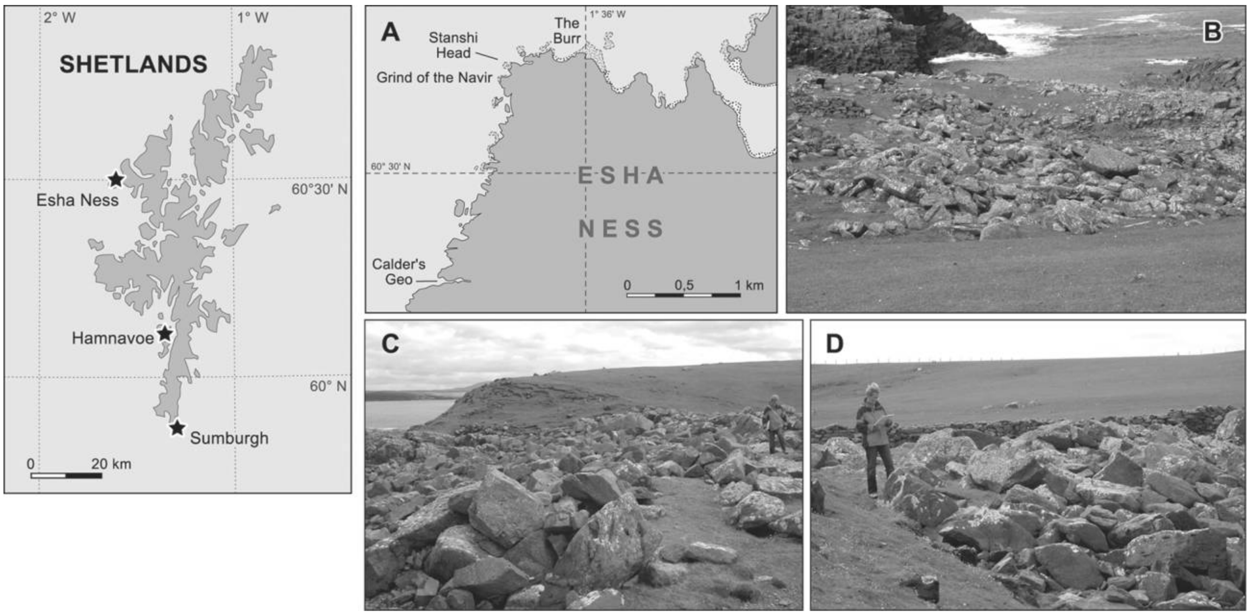

Figure 9. *A*, Topographical sketch of Esha Ness, northwest mainland Shetland. *B*, Strongly weathered ignimbrite boulders at 8 m a.s.l. near Stanshi Head, Esha Ness. *C*, Angular, weathered boulders may form ridges along the northwest coast of Esha Ness at 10 m or more a.s.l. *D*, The highest weathered ignimbrite boulders near Stanshi Head at Esha Ness partly disappear under peaty soils.

tween 50% and 100%. The site at Grind of the Navir is unique because of the freshness of the rocks, and with the occurrence of the slot cave, the ridge may be the result of a more recent event, probably related to the opening of the slot cave as a funneling process for large waves. Thus, it is questionable whether this site can be used as a general example to explain wave forces and their impacts on coastal deposition of boulders in Western Europe. There is no doubt that at Grind of the Navir, storm waves are able to quarry ignimbrite boulders nearly 15 m above MHW and dislocate them to the seaward edge of the boulder ridge. Remaining debatable, however, is whether storm waves could excavate the large pond as a closed depression at >10 m above MHW: because the pond is always filled with water, every boulder pushed in by waves would be stopped in its motion immediately. Hansom and Hall (2009) compare documents of changes in Grind of the Navir boulders over the past hundred years and cite extreme storms in 1900, 1953, 1992, 1993, and 2005 in the Shetland area. However, these storms affected some of the Grind boulders but evidently did not affect the deposits north of Stanshi Head and on the low barrier in front of Croo Loch, which are located <1 km north of Grind of the Navir. Contrary to this, Hansom and Hall (2009, p. 46) state that relative sea level rise over the late Holocene, together with present rates of sea level rise, led to "increasingly frequent intervals as a consequence of nearshore deepening," but did the effect of sea level rising only some centimeters to 2–3 dm during the past century have significant effects on increasing wave height and boulder deposition high above sea level?

Annagh Head, western Ireland. West of Belmullet in County Mayo and exposed to the open ocean, the narrow Annagh peninsula ends in the Annagh Head promontory up to 28 m a.s.l. (fig. 14*A*). The Annagh peninsula contains spectacular deposits due to extreme wave energy at both exposed and sheltered sites. Ramparts and boulder beaches exist, dominated by angular clasts partly weathered, covered with lichens, and weighing as much as 40 t (particularly in the north and northwest of the peninsula; fig. 14*B*). The most striking deposits, however, are boulder ridges comprised of schists and gneiss: one elevated up to 14 m and exposed directly to the west on the north coast of the peninsula (fig. 14*C*), with a back slope of several meters to leeward, and two on the other side of the peninsula, at Port Point and in the southern exposure of the promontory, with altitudes 10–14 m above MHW. These deposits appear to be ancient, are deeply weathered and covered at least partly by soil and vegetation, and disappear landward under

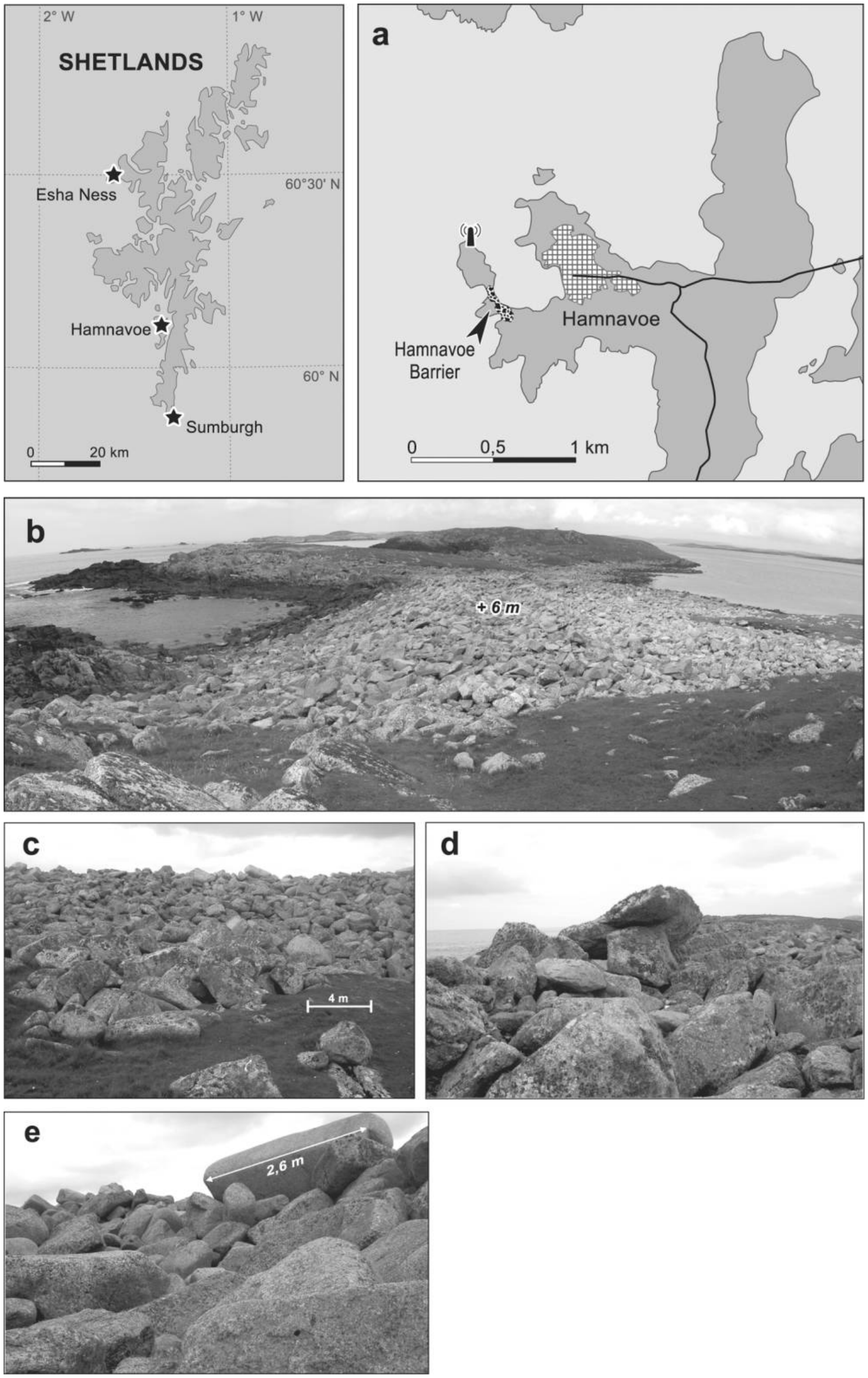

Figure 10. *a*, Topographical features at Hamnavoe on West Burra Island, Shetland. *b*, The 6-m-high Hamnavoe Barrier, seen from the east. *c*, Chaotic setting of large granite boulders at the leeward slope of the Hamnavoe Barrier. *d*, Weathering and lichens are typical for the crest of the Hamnavoe Barrier. *e*, Some boulders of many tons are nearly balancing on the crest of Hamnavoe Ridge.

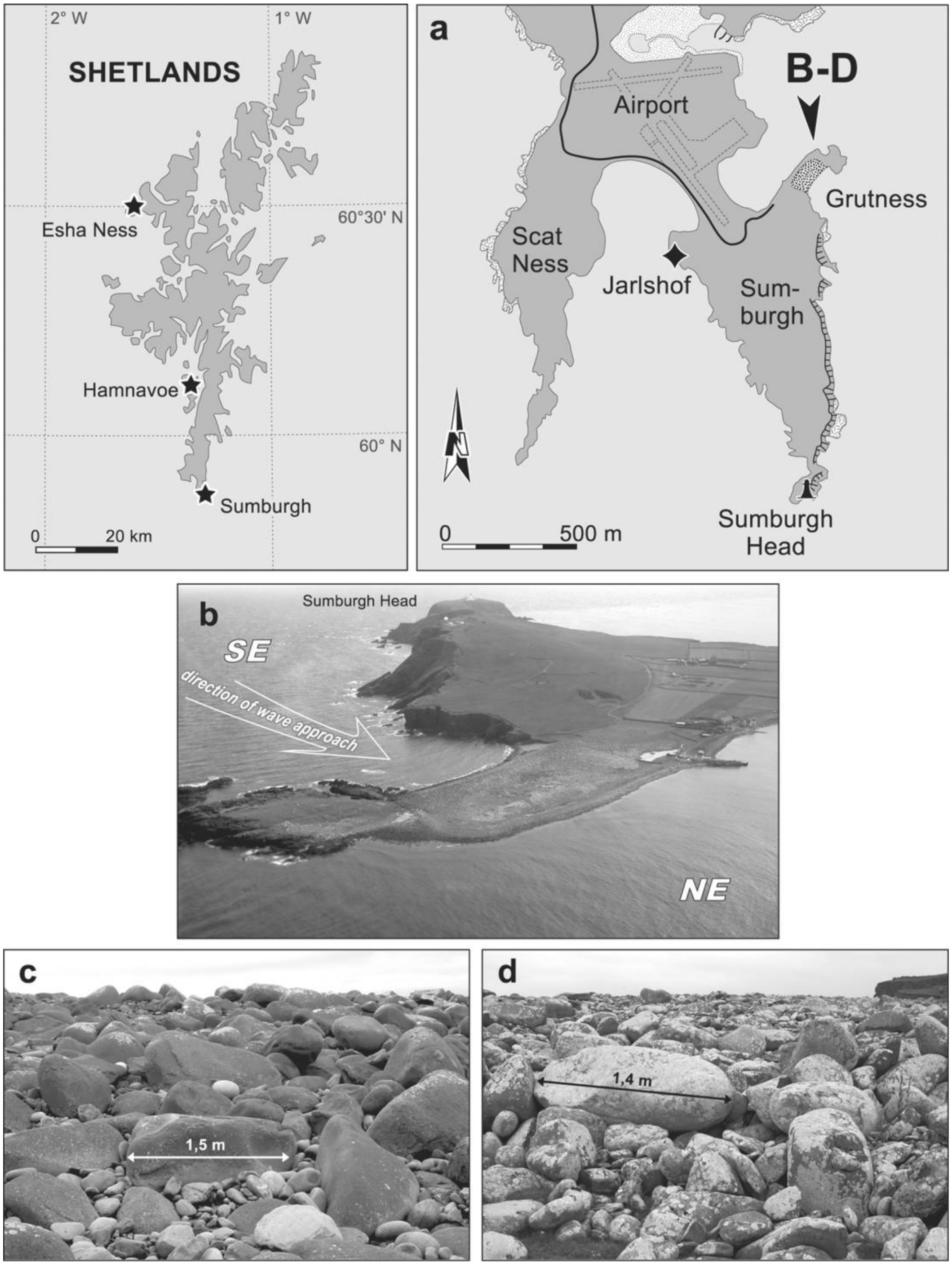

Figure 11. *a*, Topographic features at the southern tip of mainland Shetland. *b*, Sumburgh Ridge as seen from the air. Open sea is to the left (south). *c*, Large, well-rounded quartzite boulders near the crest of the Sumburgh ridge at 5.5 m above MHW. *d*, Sumburgh boulders covered up to 100% by lichens along the leeward (northern) slope.

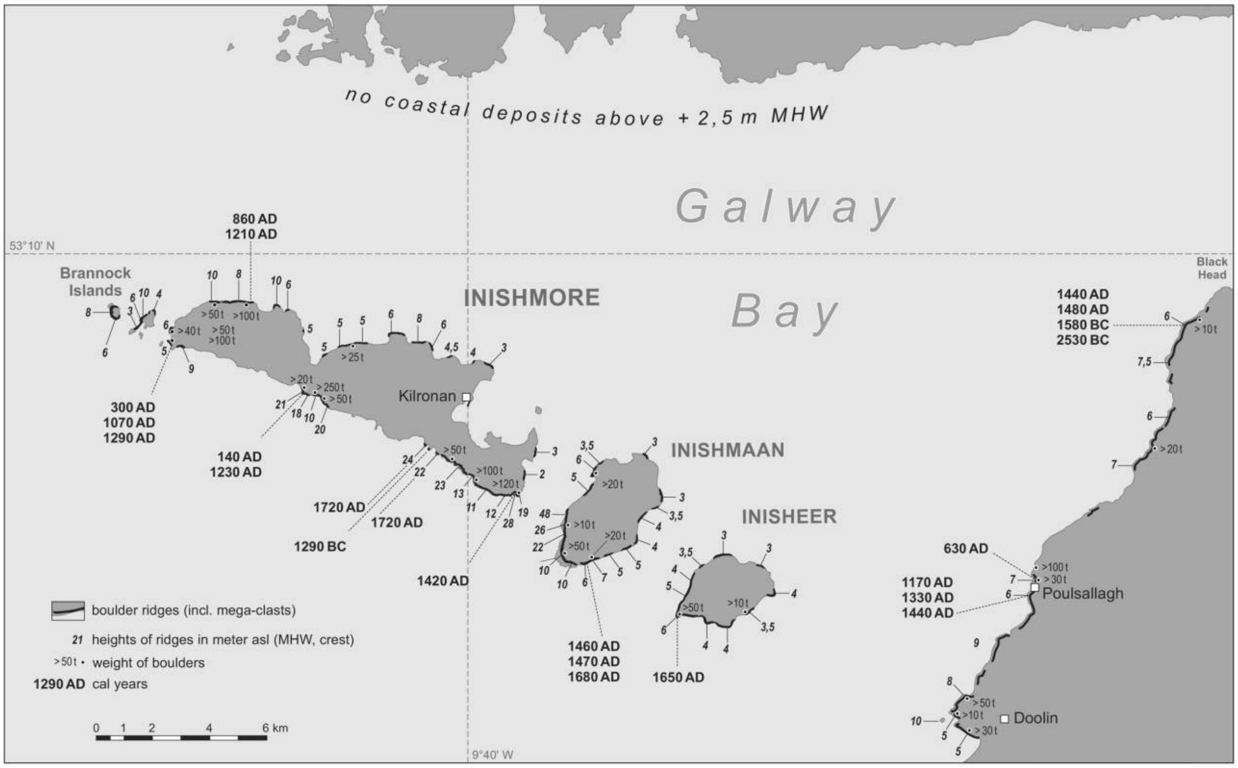

Figure 12. Distribution of boulder ridges and dating of coarse wave deposits on the Aran Islands and the east coast of Galway Bay, central west coast of Ireland (modified from Scheffers et al. 2008).

a thick carpet of peat (fig. 14*D*). With their distribution even in sheltered places, such as along the southern shorelines of Annagh peninsula, the ridges have not been reached by waves for a considerable time. Peat accumulation 1 m below the surface on the boulders of these ridges, after their deposition, was dated at 2100–2040 BC, limiting the minimum age for the boulder deposit (table 2).

Discussion

Historical reports on extreme wave events are still scarce, and paleoclimatology and wave modeling of the open ocean do not give answers to questions relating to coastal morphology and sedimentology (e.g., Shields and Fitzgerald 1989; Draper 1991; Lamb and Frydendahl 1991; Carter and Orford 1993; Lozano et al. 2004). It is not enough to survey selected sites with remarkable deposits and forms. To judge extraordinary signatures and their sources, information from the wider environment, including the "normal" or "everyday" situation over a larger area, must be considered. Tsunamis may be restricted to a single site or a small area (good examples of the "hit-or-miss" scenario are coral reefs during the 2004 tsunami event in the Indian Ocean), whereas extreme storms cover a much wider area even at landfall (e.g., for hurricane Katrina near New Orleans, storm surges of 4–7 m occurred over 260 km measured in direct line), with very large waves being the result of strong, long-lasting storms caused by significant depressions over a longer time period. Therefore, these waves do not work selectively along similar coastal geomorphologies but impact wider coastal sections. For this to occur, however, deep water at the coast is essential, because shallow water significantly diminishes the height and energy of waves at a coastline (cf., e.g., Kirkgoz 1992). Local conditions such as rock type, exposure, and inclination of coastal slopes, availability of sediments, and so on must also be considered. If such conditions are similar in areas that have differing geomorphology and deposits, then the possible interpretations for these differences are restricted. If the most extreme coastal deposits in Scotland and Ireland are believed to have resulted from storms, then western Ireland and Scotland represent the most extremely storm wave–impacted coastlines in the world, because similar deposits are unknown elsewhere. In addi-

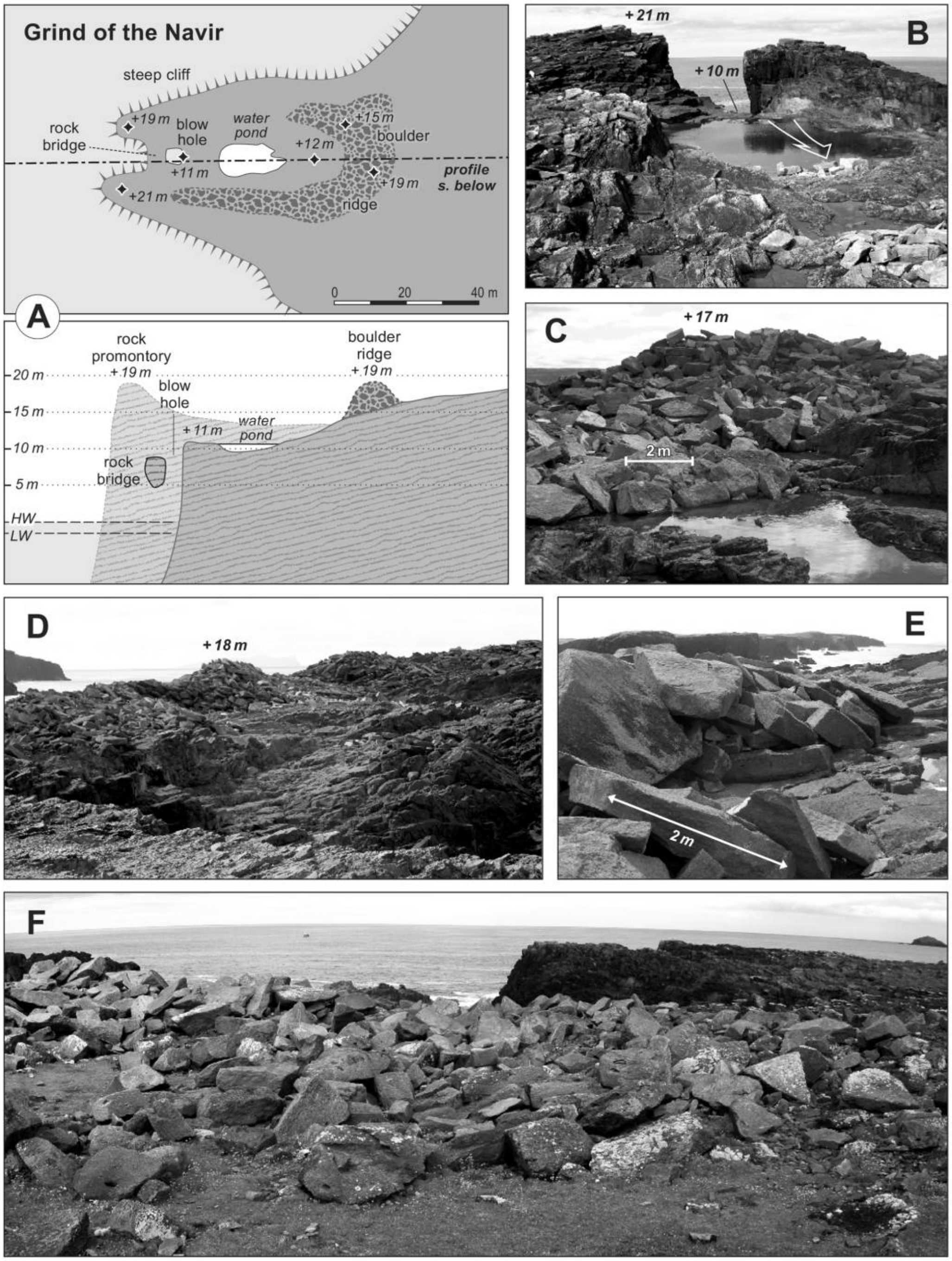

Figure 13. *A*, Schematic sketch and profile of Grind of the Navir, Esha Ness, northwest mainland of Shetland. *B*, Geo and rock base quarried by waves at Grind of the Navir, seen from the landward side. *C*, Seaward inner slope of the high ignimbrite ridge, with some fresh boulders. *D*, The main ridge at Grind of the Navir, at about 15 m a.s.l., consists of at least three boulder hills. *E*, Sharp, angular boulders with imbrication at the inner slope of the ridge. *F*, The most landward boulders of the Navir ridge are clearly much more weathered and covered by lichens than those on the main ridge crest and the seaward slope.

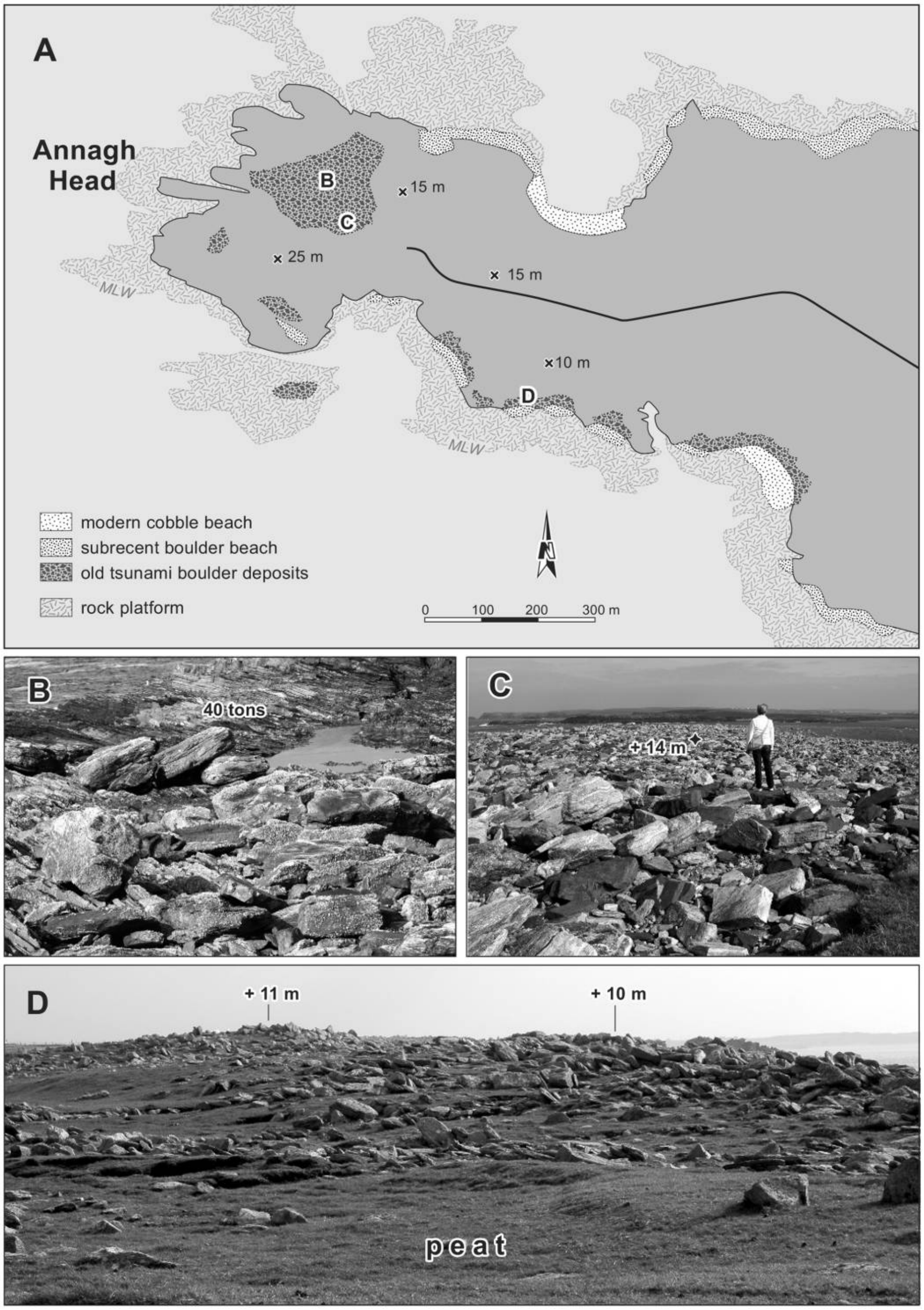

Figure 14. *A*, Topographic features of the Annagh peninsula, County Mayo, west coast of Ireland. *B*, Large, imbricated boulders, some larger than 30 t, north of Annagh Head. *C*, Top of the broad ridge north of Annagh Head at 14 m above MHW, about 200 m from the sea. *D*, Old boulder ridge at 10–11 m a.s.l. at the south coast of Annagh Head, on the landward side, covered by thick peat.

tion, storms in these areas would then represent more energy than do nearly all known modern and ancient tsunamis worldwide. The existence of enough evidence for these conclusions (as argued by Williams and Hall 2004; Hall et al. 2006, 2008; Hansom and Hall 2009) would undoubtedly have significant consequences for our knowledge of coastal geomorphology. Interestingly, these authors give several hints that large cliff-top megaclasts are different from normal storm deposits in several respects, stating that older ridges "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" (Williams and Hall 2004, p. 105–106). This would indicate that in spite of rising storm energy, deeper water at the cliff foot, and ongoing coastal erosion, the geomorphologic effects of modern or historical storms are significantly surpassed by those of older events. Because physical restrictions limit wave heights, wind speed, and storm energy, it is surprising that tsunamis have never been taken into consideration. Hall et al. (2006, p. 132) stated that the "angularity, lack of sorting and large size of the boulders … are not features commonly associated with modern storm beaches." They also found that during the extreme storms in the Shetland Islands in 1992 and 1993, only small boulders were moved in the direction of the seaward ridge fronts and that earlier storms must have been much stronger than those in modern times. What can be discounted now are storm surges and extremely high spring tides during dislocation, because Shaw and Carter (1994) state that no storm surge higher than 1 m may occur within 1000 years.

Evidence presented in this article does not support the argument that the most remarkable deposits along the exposed coastlines of western Ireland and Scotland can be explained by storms alone, in particular by storms from modern times or the past several centuries. Older boulder ridges several meters or tens of meters landward of frontal ones have never been affected by waves, although they are indisputably older than the frontal ridges by >2000 years (table 2). Under conditions of ongoing significant cliff retreat and strong storm impacts, it should be expected that the frontal (i.e., most seaward) ridges have been shifted to landward and have incorporated the material of the older deposits. Hall et al. (2006) and Hansom and Hall (2009) regard plastic artifacts in the ridges as indicators of recent events, but these also could have been entrained by wave pressure in gaps of an existing ridge. It is difficult to understand how very high waves with extreme power could dislocate large boulders and a light inflatable buoy at the same time and to the same place (Hansom and Hall 2009). Like floatable objects, mollusk hash can easily be entrained in old ridges by recent storm events, which do not have the wave power required to move boulders. Therefore, the reliability of their ages may differ from that of materials found attached to or even in boulders, such as boring bivalves.

Data from sites with very high wave energy indicate that only very few events of extraordinary power have taken place in these areas during the recent Holocene, that is, during the past several thousand years. These events may well have been combinations of extraordinary wave energy from extraordinary storm events so rare that they would occur only at intervals of millennia (e.g., the "perfect storm"), but it is doubtful that this explanation is correct for the deposits at sheltered sites. The argument that the large, elevated deposits are the result of storms and that these extraordinary storms are quasi-normal features along the exposed coastlines of Ireland and Scotland is in direct contrast to historical and modern infrastructure at the coasts. For example, boathouses from Viking times are preserved at 5–6 m above MHW in Skipi Geo at the northwest corner of mainland Orkney and at the Voe of Dale along the southwestern coast of mainland Shetland; on the west coast of the Orkney Islands (Ronaldsay) near Wind Wick, at exposed sites in the Outer Hebrides on Lewis's west coast near the causeway from Harris to Eriksay and in the northwest of South Uist, cemeteries still in use are situated at 5 m above MHW or lower; and the new schoolhouse at the exposed west coast of Benbecula was constructed without protective works at a level of about 3 m above MHW.

The singularity of the forms and deposits found on the Shetland Islands at Grind of the Navir or in Ireland near Annagh Head, in the outer Galway Bay, and on the Aran Islands (fig. 12) raises serious questions about the displacement of boulders by storm events. No calculations of possible storm wave heights, storm wave physics, or ages of the deposits and no descriptions of extraordinary storms are sufficient to explain these displacements. Hansom et al. (2008), however, describe experiments showing extreme velocities of bore flow conditions at cliff tops, with up to 2.4 times the velocity of the incoming waves, and also that at several steps this kind of acceleration may repeat (see also Williams and Hall 2004). Taking into account that extremely high waves (12–15 m) at plunging deep-water cliffs may have a maximum velocity of 8–9 m/s, an acceleration of 2.4 times this velocity, or several such accelerations, would produce flow conditions of far more than 100 km/h, with sufficient energy to transport even the largest boulders to extreme altitudes. The question, however, is whether these conditions are in harmony with natural-scale processes. Over decades of coastal research and observations during tropical and extratropical storms, we have never observed flow velocities on cliff tops higher than 9 m/s, and EurOtop (2007) gave only 5–8 m/s for this process as a maximum. The only logical conclusion for the dislocation of extremely large boulders to extreme altitudes is the impact of wave events with much more power than extreme storms.

Another main argument for the storm hypothesis in previous articles is that big waves affect only the upper section of the cliffs, from which they break the boulders to form cliff-top megaclast ridges, and that it is not necessary to imagine that storm waves have lifted large boulders far against gravity. If this is a sound explanation, then it is difficult to explain why boulders with boring bivalves, bore holes of these bivalves, sea urchin erosion marks, or attachments of calcareous algae and vermetids., undoubtedly derived from tidal or subtidal levels, can be found at least as high as 30 m a.s.l. Another argument against the hypothesis that only the upper section of cliffs is affected is the fact that the best-developed and highest continuous ridges, with very large boulders at very high altitudes, can be found along perpendicular or even overhanging cliffs with undermining of up to 20 m at their base, such as those along most of the southwest coast of Inishmore and the west coast of Inishmaan in the Aran Islands and along the east coast of Galway Bay (figs. 3, 15).

Undoubtedly, arguing for tsunami impacts along the coastlines of Western Europe is crucial. Only 20 years ago in the coastal sciences, nearly all researchers would have excluded tsunamis in the North Atlantic, except for the Grand Banks event of 1929 AD near Newfoundland and the Lisbon event of 1755 AD, neither of which had significant imprints in our research area. With the detection of the Storegga Slide (Bugge et al. 1988; Dawson et al. 1988), the picture changed dramatically. Now tsunamis of extreme size and far-reaching consequences in the European Atlantic region can no longer be excluded. More recent research of this event, initially dated at ~8000 BP, has shown that at ~5500 BP (the Garth event, on the east coast of mainland Shetland) and ~1500 BP (the Basta Voe event on Yell Island; also Bondevik et al. 2005; Dawson et al. 2006), tsunamis occurred in the same area, leaving significant signatures in the geological record. The latest results are reported by Bryant and Haslett (2003, 2007), Haslett and Bryant (2005, 2007*a*, 2007*b*, 2008), and Haslett (2008) for the Bristol Channel area, where they found deposits that can be explained only by a tsunami event reaching far inland, most probably in 1607 AD, and more evidence for times before the seventeenth century has been published from North Wales (Haslett and Bryant 2007*a*, 2007*b*). Therefore, because of their extension into extreme altitudes with extremely large boulders even in sheltered positions and the lack of any signature directly from neighboring coasts, such as the northern coast of Galway Bay, at least the Annagh Head features in County Mayo and those from the Galway Bay and the Aran Islands (see "Galway Bay and the Aran Islands, Western Ireland") are the result of tsunami impacts. At Annagh Head, these events would have occurred >4000 years ago. In the Galway area, the data show more events (table 2), and these time clusters are in general agreement with the occurrence of three to five ridges found at several locations.

We believe that large boulders may be the best markers in the geological record. Bryant and Haslett (2003, 2007), Haslett and Bryant (2007*a*, 2007*b*, 2008), and Haslett (2008) found boulders on high ground a considerable distance inland from the Bristol Channel and in North Wales. Boulders from the Storegga Slide and later tsunamis (the Garth event and the Basta Voe event) have never been described, although these tsunamis occurred over very large areas, from southwestern Norway to the Shetland and Orkney Islands as well as along the north and east coasts of mainland Scotland. Is it possible that these extraordinary events, with run-up heights of >20 m (sea level was about −20 m at the time of the main Storegga event, 8000 BP) did not dislocate boulders? Or is it possible that the undated cliff-top megaclasts on the Shetland and Orkney Islands (in eastern exposures to the North Sea) described by Hall et al. (2006) are, at least partly, signatures of one or another tsunami event in that part of the North Atlantic Ocean? Coastal scientific research can only partially discern between storm and tsunami deposits. Modern tsunamis (e.g., the Andaman-Sumatra event of 2004) have shown that with regard to fine sediments, nearly all aspects of the deposits may be typical for either storm waves or tsunami waves (see contributions in Shiki et al. 2008). Therefore, coarse deposits hold the evidence for reasonable discrimination, and boulder deposits can be defined as tsunamigenic if the following conditions (also the most significant characteristics in Scheffers et al. 2009*a*) are met:

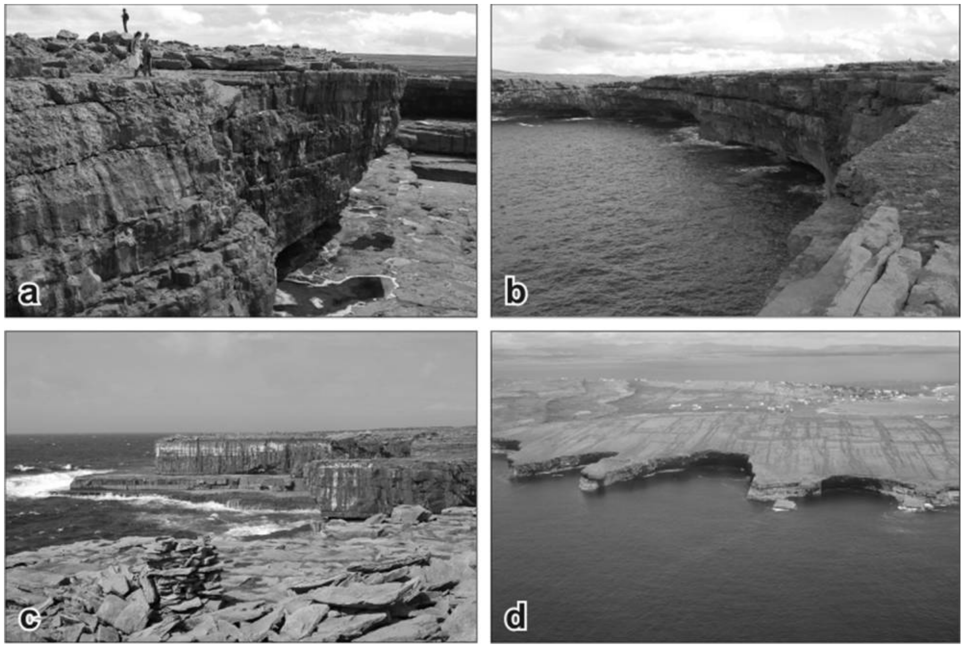

Figure 15. Typical vertical and undermined cliffs with heights of 20–30 m above MHW and cliff-top megaclasts in the form of boulder ridges (examples from the south coast of Inishmore, Aran Islands, central west coast of Ireland).

1. The size and weight of boulders are far beyond what can be moved by storm waves, based on modern modeling and physical calculations (Nott 2003; Imamura et al. 2008) as well as direct observations of boulder movement and the expertise of coastal engineers (EurOtop 2007); the threshold may be on the order of 10–20 m^3.
2. Evidence suggests that large boulders have been moved onshore along coastlines with very shallow water (e.g., fringing reefs), where wave heights, even during strong storm surges, are very limited.
3. The transport of boulders is much farther inland than inundation by extreme storm waves.
4. The height of deposition is far above the reach of strong storm waves and transport capacity by water against gravity.
5. In areas with regular strong storm impacts, large boulders can be found within old vegetation, soil, or even peat, which exclude the possibility of storm waves for many centuries.
6. Dating of boulder deposits within the past 6000 years lacks any regularity in intervals known for extreme historical storms; that is, these deposits are definitely rarer than so-called thousand-year-storms events.

In addition, the lack of accumulations of large boulders along deep-water coasts in areas hit by category 5 cyclones as well as along very extended coastlines with winter storm impacts, where boulders are available for transport in large numbers, indicates that onshore dislocation of boulders of extreme size forming long and high ridges is not a typical indicator of storm waves.

Hansom and Hall (2009) have also compared their data with indicators of greater storminess in the North Atlantic determined from Greenland ice cores, which exhibit a marked rise in Na^+ during the Little Ice Age (LIA) from about 1450 AD onward (see also Sommerville et al. 2003, 2007). This method, however, is not flawless. First, it is not clear that high Na^+, which suggests more storms, reflects either a greater number of large storms or extreme wave heights, both of which are necessary to explain the boulder deposits found in the western British Isles (Hansom and Hall 2009). Second, how higher storminess in the west-wind drift could raise the Na^+ in Greenland's ice cores, positioned to the west of the storms, must be explained. A relationship between high Na^+ in Greenland ice cores and extremely high and large boulder deposits during the LIA seems plausible, but similar boulder dislocations have also been dated for medieval times, the late Roman epoch, and the Bronze Age (table 2; fig. 12; Sommerville et al. 2007). This does not support the theory of combining the ice core and boulder deposit archives for an explanation. If sea ice cover was more extended during the LIA, fetch would have been reduced as well. Therefore, the combination of higher Na^+ and more extensive sea ice would not enhance storminess in the eastern North Atlantic. Being aware of the uniqueness of cliff-top megaclasts (Hansom and Hall 2009), we believe that the debate on their origin, in particular at sheltered sites with shallow water where storm waves are limited in height and energy, is well worth continuing.

Conclusions

To date, no evidence—such as observations or indisputable documents—exists for storm wave dislocation of very large boulders (>50 t) near the shoreline or smaller boulders found at altitudes of >20 m a.s.l. Calculations of boulder transport by Nott (2003) and Imamura et al. (2008) clearly exclude storm wave transport as well. Sedimentary evidence along the shorelines of western Ireland and Scotland, where an explanation of recent storm wave origin for extended boulder ridges on the Aran Islands, inside Galway Bay, and along Grind of the Navir on mainland Shetland has been presented by Williams and Hall (2004), Hall et al. (2006, 2008) and Hansom and Hall (2009), requires reassessment. Because of the uniqueness of these sites with respect to the amount of the coarse deposits and their position in both limited areas exposed to strong waves and very sheltered sites, alternative explanations, such as tsunamis, should be considered. To define an exact source, submarine surveys of potential areas of slides at the shelf edge are necessary, as are absolute data gained from deep trenches in the most extended ridges and the relation of the boulder deposits to peat and soil development before and after the event. The question remains as to whether cliff-top megaclasts on the eastern coasts of Scottish isles may be connected to sand layers from younger tsunamis, such as the Garth or Basta Voe events. All of this may help to support or disprove the exclusive storm wave hypothesis.

ACKNOWLEDGMENT

We would like to thank the German Research Foundation (Deutsche Forschungsgemeinschaft) for funding this project.

REFERENCES CITED

Aalen, F. H. A.; Whelan, K.; and Stout, M., eds. 1997. Atlas of the Irish rural landscape. Cork University Press, Cork, 352 p.

Ascough, P. L.; Cook, G. T.; Church, M. J.; Dugmore, A. J.; Arge, S. V.; and McGovern, T. H. 2006. Variability in North Atlantic marine radiocarbon reservoir effects at *c.* AD 1000. The Holocene 16:131–136.

Ashmore, P. J. 1996. Neolithic and Bronze Age Scotland. London, Batsford, 99 pp.

Baines, G. B. K., and McLean, R. F. 1976. Sequential studies of hurricane deposit evolution at Funafuti Atoll. Mar. Geol. 21:M1–M8.

Benner, R.; Browne, T.; Brueckner, H.; Kelletat, D.; and Scheffers, A. 2009. Boulder transport by waves: progress in physical modeling. Z. Geomorphol., forthcoming.

Bondevik, S.; Mangerud, J.; Dawson, S.; Dawson, A.; and Lohne, O. 2005. Evidence for three North Sea tsunamis at the Shetland Islands between 8000 and 1500 years ago. Quat. Sci. Rev. 24:1757–1775.

Bries, J. M.; Debrot, A. O.; and Meyer, D. L. 2004. Damage to the leeward reefs of Curaçao and Bonaire, Netherlands Antilles from a rare storm event: Hurricane Lenny, November 1999. Coral Reefs 23:297–307.

Bryant, E. 2008. Tsunami: the underrated hazard. 2nd ed. Chichester, Praxis, 325 p.

Bryant, E. A., and Haslett, S. K. 2003. Was the AD 1607 coastal flooding event in the Severn Estuary and Bristol Channel (UK) due to a tsunami? Archaeol. Severn Estuary 13:163–167.

———. 2007. Catastrophic wave erosion, Bristol Channel, United Kingdom: impact of tsunami? J. Geol. 115: 253–269.

Bugge, T.; Belderson, R. H.; and Kenyon, N. H. 1988. The Storegga Slide. Philos. Trans. R. Soc. A 325:357–388.

Carter, R. W. G.; Devoy, R. J. N.; and Shaw, J. 1989. Late Holocene sea levels in Ireland. J. Quat. Sci. 4:7–24.

Carter, R. W. G., and Orford, J. D. 1984. Coarse clastic barrier beaches: a discussion of their distinctive dynamics and morpho-sedimentary characteristics. Mar. Geol. 60:377–389.

———. 1993. The morphodynamics of coarse clastic beaches and barriers: a short and long-term perspective. J. Coast. Res. Spec. Issue 15:158–179.

Clarke, M. L., and Rendell, H. M. 2009. The impact of North Atlantic storminess on western Europe coasts: a review. Quat. Int. 195:31–41.

Dawson, A. G. 1996. The geological significance of tsunamis. Z. Geomorphol., N.F., Suppl. 102:199–210.

Dawson, A. G.; Dawson, S.; and Bondevik, S. 2006. A Late Holocene tsunami at Basta Voe, Yell, Shetland Isles. Scott. Geogr. J. 122:100–108.

Dawson, A. G.; Long, D.; and Smith, D. E. 1988. The Storegga Slides: evidence from eastern Scotland for a possible tsunami. Mar. Geol. 82:271–276.

Dawson, A. G., and Shi, S. 2000. Tsunami deposits. Pure Appl. Geophys. 157:875–897.

Dawson, A. G.; Shi, S.; Dawson, S.; Takahashi, T.; and Shuto, N. 1996. Coastal sedimentation associated with the June 2nd and 3rd, 1994 tsunami in Rajegwesi, Java. Quat. Sci. Rev. 15:901–912.

Dawson, A. G., and Stewart, I. 2007. Tsunami deposits in the geological record. Sediment. Geol. 200:166–183.

Dawson, S.; Smith, D. E.; Jordan, J.; and Dawson, A. G. 2004. Late Holocene coastal sand movements in the Outer Hebrides. Mar. Geol. 210:281–306.

Dolan, R., and Davis, R. E. 1994. Coastal storm hazards. J. Coast. Res. 12:177–187.

Draper, L. 1991. Wave climate atlas of the British Isles. Offshore Technology Report OTH 89-303. Her Majesty's Stationery Office, London.

EurOtop. 2007. Wave overtopping of sea defences and related structures: assessment manual. Die Küste 73. 178 pp.

Fairbanks, R. G.; Mortlock, R. A.; Chiu, T.-C.; Cao, L.; Kaplan, A.; Guilderson, T. P.; Fairbanks, T. W.; Bloom, A. L.; Grootes, P. M.; and Nadeau, M.-J. 2005. Radiocarbon calibration curve spanning 0 to 50,000 years BP based on paired $^{230}Th/^{234}U/^{238}U$ and ^{14}C dates on pristine corals. Quat. Sci. Rev. 24:1781–1796.

Gilbertson, D. D.; Schwenninger, J. L.; Kemp, R. A.; and Rhodes, E. J. 1999. Sand-drift and soil formation along an exposed North Atlantic coastline: 14,000 years of diverse geomorphological, climatic and human impacts. J. Archaeol. Sci. 26:439–469.

Goff, J.; McFadgen, B. G.; and Chagué-Goff, C. 2004. Sedimentary differences between the 2002 Easter storm and the 15th-century Okoropunga tsunami, southeastern North Island, New Zealand. Mar. Geol. 204: 235–250.

Goto, K.; Chavanich, S. A.; Imamura, F.; Kunthasap, P.; Matsui, T.; Minoura, K.; Sugawara, D.; and Yanagisawa, H. 2007. Distribution, origin and transport process of boulders deposited by the 2004 Indian Ocean tsunami at Pakarang Cape, Thailand. Sediment. Geol. 202:821–837.

Gray, J. M. 1977. Low-level shore platforms in the southwest Scottish Highlands: altitude, age and correlation. Trans. Inst. Br. Geogr., N.S., 3:151–164.

Hall, A. M.; Hansom, J. D.; and Jarvis, J. 2008. Patterns and rates of erosion produced by high energy wave processes on hard rock headlands: the Grind of the Navir, Shetland, Scotland. Mar. Geol. 248:28–46.

Hall, A. M.; Hansom, J. D.; Williams, D. M.; and Jarvis, J. 2006. Distribution, geomorphology and lithofacies of cliff-top storm deposits: examples from the high-energy coasts of Scotland and Ireland. Mar. Geol. 232: 131–155.

Hansom, J. D.; Barltrop, N.; and Hall, A. 2008. Modelling the processes of cliff-top erosion and deposition under extreme storm waves. Mar. Geol. 253:36–50. doi: 10.1016/j.margeo.2008.02.015.

Hansom, J. D., and Hall, A. M. 2009. Magnitude and frequency of extra-tropical North Atlantic cyclones: a chronology from cliff-top storm deposits. Quat. Int. 195:42–52. doi:10.1016/j.quaint.2007.11.010.

Haslett, S. K. 2008. 400 years on! report of a public conference commemorating the 400th anniversary of the 1607 flood in the Bristol Channel and Severn Estuary, UK. Archaeol. Severn Estuary 18:115–118.

Haslett, S. K., and Bryant, E. A. 2005. The AD 1607 coastal flood in the Bristol Channel and Severn Estuary: historical records from Devon and Cornwall (UK). Archaeol. Severn Estuary 15:163–167.

———. 2007*a*. Evidence of historic coastal high-energy wave impact (tsunami?) in North Wales, United Kingdom. Atl. Geol. 43:137–147.

———. 2007*b*. Reconnaissance of historic (post-AD 1000) high-energy deposits along the Atlantic coasts of southwest Britain, Ireland and Brittany, France. Mar. Geol. 242:207–220.

———. 2008. Historic tsunami in Britain since AD 1000: a review. Nat. Hazards Earth Syst. Sci. 8:587–601.

Hernández-Ávila, M. L.; Roberts, H. H.; and Rouse, L. J. 1977. Hurricane-generated waves and boulder rampart formation. Proc. 3rd Int. Coral Reef Symposium. Miami, FL, Rosenstiel School of Marine and Atmospheric Science, University of Miami, p. 71–78.

Imamura, F.; Goto, K.; and Ohkubo, S. 2008. A numerical model for the transport of a boulder by tsunami. J. Geophys. Res. 113:C01008, doi:10.1029/ 2007JC004170.

Kelletat, D.; Scheffers, S. R.; and Scheffers, A. 2007. Field signatures of the SE-Asian mega-tsunami along the west coast of Thailand compared to Holocene paleotsunami from the Atlantic region. Pure Appl. Geophys. 164:413–431.

Kirkgoz, M. S. 1992. Influence of water depth on the breaking wave impact on vertical and sloping walls. Coast. Eng. 18:297–314.

Lamb, H., and Frydendahl, K. 1991. Historic storms of the North Sea, British Isles and northwest Europe. Cambridge, Cambridge University Press, 204 p.

Lamb, R. G. 1980. Iron Age promontory forts in the northern isles. Oxford, British Archaeological Reports.

Lambeck, K. 1991. Glacial rebound and sea-level change in the British Isles. Terra Nova 3:379–389.

Lavigne, R.; Paris, R.; Wassmer, P.; Gomez, C.; Brunstein, D.; Grancher, D.; Vautier, F.; et al. 2006. Learning from a major disaster (Banda Aceh, December 26th, 2004): a methodology to calibrate simulation codes for tsunami inundation models. Z. Geomorphol., N.F., Suppl. 146:253–265.

Lozano, I.; Devoy, R. J. N.; May, W.; and Andersen, U. 2004. Storminess and vulnerability along the Atlantic coastlines of Europe: analysis of storm records and of a greenhouse gases induced climate scenario. Mar. Geol. 210:205–225.

McSaveney, M. J.; Goff., J. R.; Darby, D. J.; Goldsmith, P.; Barnett, A.; Elliott, S.; and Nangkas, M. 2000. The 17 July 1998 tsunami, Papua New Guinea: evidence and initial interpretation. Mar. Geol. 170:81–92.

Meeker, L. D., and Mayewski, P. A. 2002. A 1400-year high-resolution record of atmospheric circulation over the North Atlantic and Asia. The Holocene 12:257–266.

Moore, A.; Nishimura, Y.; Gelfenbaum, G.; Kamataki, T.; and Triyono, R. 2006. Sedimentary deposits of the 26 December tsunami on the northwest coast of Aceh, Indonesia. Earth Planets Space 58:253–258.

Morton, R. A.; Richmond, B. M.; Jaffe, B. E.; and Gelfenbaum, G. 2006. Reconnaissance investigation of Caribbean extreme wave deposits: preliminary observations, interpretations, and research directions. U.S. Geol. Surv. Open-File Rep. 2006-1293.

Nanayama, F.; Shigeno, K.; Satake, K.; Shimokawa, K.; Koitabashi, S.; Miyasaka, S.; and Ishii, M. 2000. Sedimentary differences between 1993 Hokkaido-nansei-oki tsunami and 1959 Miyakojima typhoon at Taisei, southwestern Hokkaido, northern Japan. Sediment. Geol. 135:255–264.

Nott, J. 2003. Waves, coastal boulders and the importance of the pre-transport setting. Earth Planet. Sci. Lett. 210:269–276.

Otvos, E. G. 2000. Beach ridges: definitions and significance. Geomorphology 32:83–108.

Paris, R.; Lavigne, F.; Wassmer, P.; and Sartohadi, J. 2007. Coastal sedimentation associated with the December 26, 2004 tsunami in Lhok Nga, west Banda Aceh (Sumatra, Indonesia). Mar. Geol. 238:93–106.

Renfrew, A. C. 1985. The prehistory of Orkney. Edinburgh, Edinburgh University Press.

Richmond, B. M.; Jaffe, B. E.; Gelfenbaum, G.; and Morton, R. A. 2006. Geologic impacts of the 2004 Indian Ocean tsunami on Indonesia, Sri Lanka, and the Maldives. Z. Geomorphol., N.F., Suppl. 146:235–251.

Ritchie, A. 1988. Scotland BC. Historic Scotland series. Edinburgh, Scottish Development Department, 80 p.

Satake, K.; Abe, K.; Abe, K.; Bourgeois, J.; Estrada, F.; Iio, Y.; Imamura, F.; Katao, H.; Noguera, E.; and Tsuji, Y. 1993. Tsunami field survey of the 1992 Nicaragua earthquake. EOS: Trans. Am. Geophys. Union 74:145, 156–157.

Scheffers, S. R.; Haviser, J.; Browne, A.; and Scheffers, A. 2009*a*. Tsunamis, hurricanes, the demise of coral reefs and shifts in pre-historic human populations in the Caribbean. Quat. Int. 195:69–87. doi:10.1016/j.quaint.2008.07.016.

Scheffers, A., and Scheffers, S. R. 2006. Documentation of the impact of Hurricane Ivan on the coastline of Bonaire (Netherlands Antilles). J. Coast. Res. 22:1437–1450.

———. 2007. Tsunami deposits on the coastline of west Crete (Greece). Earth Planet. Sci. Lett. 259:613–624.

Scheffers, A.; Scheffers, S. R.; Kelletat, D.; Browne, T.; and Haslett, S. 2009*b*. Coastal boulder deposits in Galway Bay and the Aran Islands, western Ireland Z. Geomorphol., forthcoming.

Scheffers, S. R.; Scheffers, A.; Kelletat, D.; and Bryant, E. A. 2008. The Holocene paleo-tsunami history of West Australia. Earth Planet. Sci. Lett. 270:137–146.

Scoffin, T. P. 1993. The geological effects of hurricanes on coral reefs and the interpretation of storm deposits. Coral Reefs 12:203–221.

Shaw, J., and Carter, R. W. G. 1994. Coastal peats from northwest Ireland: implications for late-Holocene relative sea-level change and shoreline evolution. Boreas 23:74–91.

Shennan, L., and Horton, B. P. 2002. Holocene land- and sea-level changes in Great Britain. J. Quat. Sci. 17:511–526.

Shi, S.; Dawson, A. G.; and Smith, D. E. 1995. Coastal sedimentation associated with the December 12th, 1992 tsunami in Flores, Indonesia. Pure Appl. Geophys. 144:525–536.

Shields, L., and Fitzgerald, D. 1989. The "Night of the Big Wind" in Ireland, 6–7 January 1839. Ir. Geogr. 22: 31–43.

Shiki, T.; Tsuji, Y.; Yamazaki, T.; and Minoura, K., eds. 2008. Tsunamiites: features and implications. Amsterdam, Elsevier, 411 p.

Sommerville, A. A.; Hansom, J. D.; Sanderson, D. C. W.; and Housley, R. A. 2003. Optically stimulated luminescence dating of large storm events in northern Scotland. Quat. Sci. Rev. 22:1085–1092.

———. 2007. Optically stimulated luminescence (OSL) dating of coastal aeolian sand accumulations in the Orkney Islands, Scotland. The Holocene 17:627–637.

Stoddart, D. R. 1974. Post-hurricane changes on the British Honduras reefs: resurvey of 1972. *In* Proc. 2nd Int. Coral Reef Symposium. Brisbane, Great Barrier Reef Committee, 2:473–483.

Tappin, D. R. 2007. Sedimentary features of tsunami deposits: their origin, recognition and discrimination: an introduction. Sediment. Geol. 200:1–4.

Tuttle, M. P.; Ruffman, A.; Anderson, T.; and Jeter, H. 2004. Distinguishing tsunami from storm deposits in eastern North America: the 1929 Grand Banks tsunami versus the 1991 Halloween storm. Seismol. Res. Lett. 75:117–131.

Wickham-Jones, C. R. 1998. Orkney, a historical guide. Edinburgh, Birlinn.

Williams, D. M. 2004. Marine erosion and archaeological landscapes: a case study of stone forts at cliff-top locations in the Aran Islands, Ireland. Geoarchaeology 19:167–175.

Williams, D. M., and Hall, A. M. 2004. Cliff-top megaclast deposit of Ireland, a record of extreme waves in the North Atlantic: storms or tsunamis? Mar. Geol. 206:101–117.

Wright, L. D.; Short, A. D.; and Nielsen, P. 1982. Morphodynamics of high energy beaches and surf zones: a brief synthesis. Coastal Studies Unit, University of Sydney, Rep. 82(5), 64 pp.