ARTICLES

Boulder Ridges on the Aran Islands (Ireland): Recent Movements Caused by Storm Waves, Not Tsunamis

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ABSTRACT

Ireland's Aran Islands are an excellent place to test whether coastal boulder deposits—including individual rocks weighing several tens of tonnes near sea level and clasts weighing several tonnes transported at tens of meters above sea level—require a tsunami for emplacement or whether storm waves can do this work. Elongate deposits of cobbles, boulders, and megagravel are strung along the Atlantic coasts of the Aran Islands. No tsunamis have affected this region in recent centuries, so if these deposits are forming or migrating at the present time, they must be storm activated. We find a diverse range of evidence for recent ridge activity. First, shells of *Hiatella arctica* (subtidal rock-boring bivalves preserved in life position within ridge boulders) yield radiocarbon ages from ≈200 AD to modern (post-1950 AD). Second, recent motion is attested to by eyewitness accounts that pin the movement of several individual 40–80-t blocks to a specific 1991 storm and by repeat photography over the last few field seasons (2006–2011) that captures the movement of boulders (masses up to ≈10.5 t) even in years without exceptionally large storms. Finally, geographic information system comparison of nineteenth-century Ordnance Survey maps with twenty-first-century orthophotos shows that in several areas the boulder ridges have advanced tens of meters inland since the mid-nineteenth century, overrunning old field walls. These advancing ridges contain boulders with masses up to 78 t at 11 m above high-water mark, so wave energies sufficient to transport those blocks must have occurred since the 1839 survey. Thus, there is abundant evidence for ridge activity since the 1839 mapping, and as there have been no tsunamis in the northeastern Atlantic during that time period, we conclude that the Aran Islands boulder ridges are built and moved by storm waves.

Online enhancement: appendix.

Introduction

Dramatic boulder ridges (fig. 1) up to 6 m high and tens of meters wide form a semicontinuous clastic collar along the Atlantic coasts of Ireland's Aran Islands. The cumulative length of the deposits is ≈15 km (table A1, available in the online edition or from the *Journal of Geology* office). They occur at elevations 1–40 m above high-water mark (AHWM) and at horizontal distances up to 250 m inland from the high-water line. Some ridges are perched on top of sheer cliffs, and others are at the back of wide, gently sloping ramps. The boulders come from seaward, eroded from cliff top or ramp surface and transported landward (Williams and Hall 2004). Clast size is variable: boulders weighing up to 78 t are incorporated into the ridges at lower elevation, with average boulder size decreasing at higher elevation. Isolated blocks up to 250 t have been measured on low-elevation ramps seaward of the ridges (Williams and Hall 2004; Scheffers et al. 2009). In aggregate, the size of the clasts, together with the extent and scale of the ridges, preserve an impressive record of high-energy wave action.

What type of wave could erode, transport, and pile up boulders of such magnitude in such quantity? Recent publications are polarized on this question. Some workers attribute the deposits to storm-wave emplacement (Williams and Hall 2004; Hall et al. 2006; Hansom et al. 2008), while others argue

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Figure 1. Boulder ridge on southwestern Inishmaan, looking south. The elongate boulder (11.5 m long) indicated in the image center is the 78-t block listed in table A5 (available in the online edition or from the *Journal of Geology* office) and shown in figure 8. The chimney cairn perched on the ridge crest in the midground marks the location of transect IM33. Transects IM34, IM35, and IM36 are at 50-m intervals between IM33 and the photographer, and the photo was taken at the site of transect IM37 (table A2, available in the online edition or from the *Journal of Geology* office). Ramp width in this area ranges from 140 to 220 m, and ridge base is 9–16 m above high-water mark.

that storm waves have insufficient power to move massive blocks at elevations well above sea level (or that storm waves of sufficient magnitude to do the work are improbable events) and that tsunamis are therefore required to explain the deposits (Kelletat 2008; Scheffers et al. 2009, 2010*a*). The Aran Islands are not the only location about which these questions are being asked: similar debates swirl about deposits on the Shetlands (Hall et al. 2006, 2008; Scheffers et al. 2009), Bonaire and nearby islands (Scheffers 2002; Morton et al. 2008), the Lesser Antilles (Spiske et al. 2008), and southeast Australia (Switzer and Burston 2010). As tsunamis clearly erode and transport large blocks (e.g., Goto et al. 2007, 2010*a*; Mastronuzzi et al. 2007)—even if their ability to produce organized linear deposits is doubtful (Morton et al. 2008)—we can therefore boil the question down to this: can megagravel (clast sizes in meters and tens of meters; Blair and McPherson 1999) be quarried and transported by storm waves?

Ideally, we would calculate an answer to this question using equations to determine the magnitude of forces exerted by various types of wave, but in fact a numerical solution is impeded by our limited understanding of wave hydrodynamics as they relate to boulder extraction and transport. Although several studies in recent years have made notable advances in this area (e.g., Nott 2003*b*; Hansom et al. 2008; Imamura et al. 2008; Benner et al. 2010; Nadesna et al. 2011), workers concur that the complexity of the dynamics precludes using equations to confidently predict the relationships between storm-wave size and excavation or transport of large clasts. This difficulty is compounded along steep coasts where shoaling is abrupt and where two additional complications apply. First, reflection of unbroken waves and consequent wave interference can locally enhance coastal wave height substantially, leading to very large and short-lived waves, the occurrence and behavior of which is not quantified in existing models (Hansom et al. 2008). Second, green-water overtopping, which can occur at steep cliffs (Hansom et al. 2008), generates ramp-crossing bores with hydraulic characteristics that differ from those of breaking waves (and for which the only current models are based on fixed-deck simulations; e.g., Ryu et al. 2007). Numerical estimates of the ability of storm waves to move boulders therefore probably represent minima rather than characteristic values and should be considered approximate at best.

In the absence of a quantitative solution, we can approach the question of storm-wave boulder transport by studying an area exposed to high-energy storms but with no recent tsunami history. The Aran Islands—like the situationally similar Shetlands (Hall et al. 2006, 2008; Hansom and Hall 2009)—are perfect for this purpose because they have not been subject to tsunamis in at least the last few hundred years. The most recent tsunami to affect northwestern Europe was caused by the 1755 Lisbon earthquake, and as it had vertical run-up of only 2 m in southern Britain (Baptista et al. 1998), its impact on western Ireland was small. Although older tsunami events caused by collapse events on the continental slope and rise—such as the 8.2-k.yr. Storegga slide (Dawson et al. 1988; Bryn et al. 2005)—could have influenced the Aran Islands on timescales of thousands to hundreds of years in the past (Scheffers et al. 2009), nothing of that scale has happened in the last 250 yr. Thus, if boulder ridges of the Aran Islands have been active in a recent time frame and if large boulders have moved in that time frame, then tsunamis are excluded as a candidate, and the only possible explanation is that the work was done by storm waves.

A number of observations supporting recent ridge activity on the Aran Islands are documented in the literature. Boulder orientations, for example, consistently parallel the prevailing storm-wave-approach direction (Williams and Hall 2004; Zentner 2009). Lichen coverage provides a qualitative measure of the length of time since ridge boulders were emplaced, because fresh limestone surfaces darken and are colonized by lichens within a few decades of exposure, and although back-ridge boulders and some large isolated clasts on the ramps are blackened and/or lichen covered (Williams and Hall 2004; Scheffers et al. 2009), the majority of ridge-front boulders have fresh, pale surfaces and little or no lichen growth (Williams and Hall 2004; Hall et al. 2006; Zentner 2009). Evidence for recent movement comes from fishing gear, rope, and other nylon and plastic debris found trapped inextricably beneath massive boulders (Williams and Hall 2004; Hall et al. 2006). These modern artifacts are pinned beneath boulders weighing up to 40 t (Zentner 2009) and strongly suggest very recent block movement.

Consensus has not been reached, however, because these lines of evidence are seen as inconclusive by some. Scheffers et al. (2009) assert that although smaller boulders have been shown to move, there are no observations providing evidence for storm-wave dislocation of "very large boulders (>50 t) near the shoreline or smaller boulders found at altitudes of >20 m" (p. 571). Kelletat (2008) has asserted a lack of "direct observation of extremely large boulders being transported by storm waves to elevated positions and far from the shoreline—evidently because those observations do not exist" (p. 89). These workers have argued that boulder-pinned modern debris does not provide evidence for recent movement because they believe the items could have been jammed under the trapping blocks by wave impacts, long after block emplacement (Scheffers et al. 2009, 2010*a*). Furthermore, because hitherto-reported ^{14}C from marine shells (collected from growth position on boulders now incorporated in ridges) gives boulder-emplacement ages before the eighteenth century, some workers (Kelletat 2008; Scheffers et al. 2009, 2010*a*) argue that the boulder ridges must be uniformly old.

If the boulder ridges are exclusively old, as Scheffers, Kelletat, and coworkers claim, then a tsunamigenic origin is plausible. But if they have been active in recent decades and centuries, then—no matter how long their history and no matter whether tsunamis of the past have contributed to them—storms must build and move them.

Increasing numbers of studies suggest that both storm waves and tsunamis can contribute to coastal boulder deposits (e.g., Barbano et al. 2010; Richmond et al. 2010). Some boulder deposits can confidently be attributed to storms, either because of direct observation or because tsunamis can be excluded as a mechanism (e.g., Suanez et al. 2009; Etienne and Paris 2010; Khan et al. 2010). But of the described coastal boulder accumulations, only a few—the Aran Islands (Williams and Hall 2004), Shetland Islands (Hall et al. 2006), the Brittany coast (Suanez et al. 2009), and Iceland (Etienne and Paris 2010)—can be certified free of the effects of large-run-up tsunamis within the last few hundred years. And among these, the Aran Islands deposits

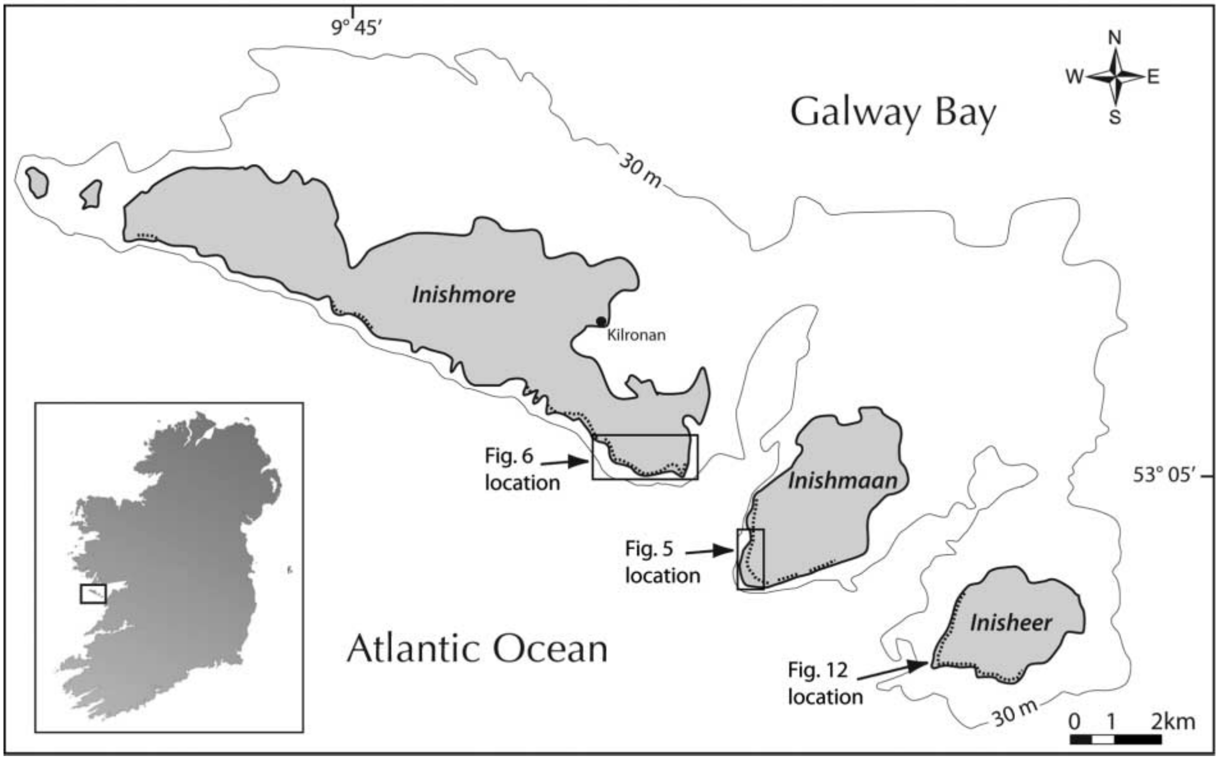

Figure 2. Map of Aran Islands. Dotted lines show locations of boulder ridge deposits on the Atlantic-facing coasts. The 30-m bathymetric contour is from a navigational chart of Galway Bay (GUNIO 2007).

stand out as having the largest clasts and tallest piles. Thus, the Aran Islands provide a good test case for isolating the effects of storm waves from those of tsunamis.

Determining whether the Aran Island ridges have been active in recent, tsunami-absent times is therefore important: to reliably distinguish past tsunami events from those of high-energy storms and to understand the limits of coastal wave energy, we need to resolve whether storm waves can move megaclasts and build massive ridges, and we need to know the magnitude of blocks that can be transported by storm events. If the Aran Islands ridges are storm activated, then we can use the block sizes in those ridges to inform our understanding of coastal wave dynamics and the boulder-transport capabilities of storm waves.

In this article, we present evidence for recent (decadal and centennial) movement of individual blocks and of ridge systems wholesale, including movement of the >50-t clast sizes designated by Scheffers et al. (2009) as the touchstone category. We present four kinds of data: photo comparisons showing movement of blocks between 2006 and 2011, eyewitness accounts of megagravel movement during a storm in 1991, new radiocarbon age data that reveal recent (post-1950) block movement, and geographic information system (GIS) analysis of nineteenth-century maps and twenty-first-century orthophotos showing landward migration of large sections of the ridge system over the last 1.5 centuries. As there have been no tsunamis in western Europe since the mid-nineteenth century, we conclude that storm waves must build and move the ridges.

Setting

The Aran Islands (Inishmore, Inishmaan, and Inisheer) form a linear array across the mouth of Galway Bay on the western edge of Ireland (fig. 2). They are constructed of Viséan-age limestones that dip gently (≈3°) toward the south-southwest (Langridge 1971), and the topography is dominated by bedding-plane surfaces that slope toward the Atlantic. Karstified bedrock is widespread, and high drystone walls protect thin soils (mostly man-made) from the onslaught of wind and salt spray. The updip sides of the islands—lying in Galway Bay—are more sheltered, and the islands' small populations cluster there. Downdip, the rugged western

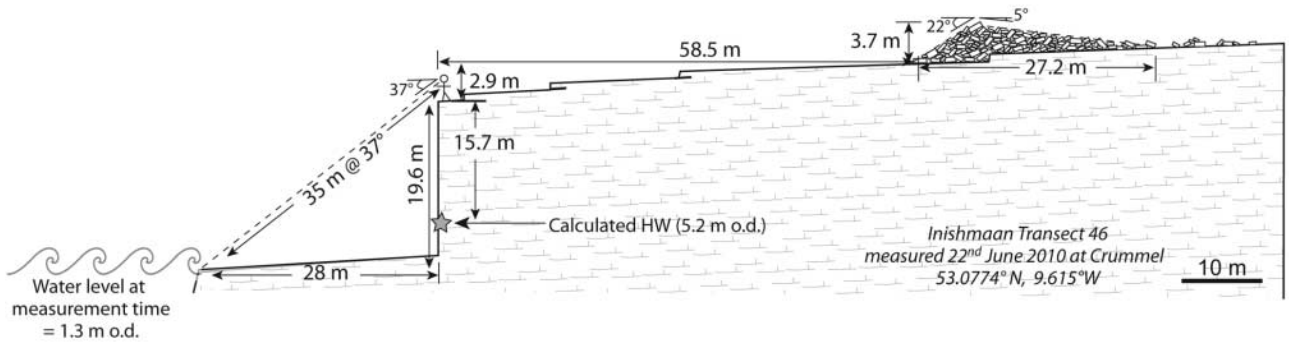

Figure 3. Surveyed topographic profile of a boulder ridge on a limestone ramp cliff top on Inishmaan, showing many of the common ridge features and illustrating our measurement methodology. See "Methods" for detailed descriptions of procedures. HW = high water, o.d. = over datum.

coasts—fully exposed to the Atlantic—are treeless, unpeopled, and rocky.

The Atlantic sides of the islands experience high wave energies, and erosion exploits bedrock stratigraphy and pervasive joint systems. The resistant limestones have occasional interbedded muddy units (a few centimeters to 1.4 m thick), referred to as shale bands or clay wayboards (Langridge 1971), and these are very susceptible to mechanical erosion. They also act as aquicludes, channeling groundwater out into coastal springs and promoting enhanced local dissolution of the overlying limestones. Wave attack preferentially carves out these weaker layers, forming deep horizontal incisions in ocean-facing surfaces. Where the shaley beds are thick and close to sea level, elongate, boxlike sea caves (Waterstrat et al. 2010) profoundly undercut the overlying rocks. The limestones are mechanically stronger than the clay wayboards, but they are dissected by vertical and subhorizontal fracture sets (Gillespie et al. 2001) that predispose them to block excavation. Joints are widened by dissolution, making it easier for wave action to wedge slabs apart and pry them loose.

Resultant Atlantic seaboards are of three main types: gently inclined bedding-parallel ramps that slope gradually into the sea (these are rare on Inishmore, common on Inishmaan, and dominate the coast on Inisheer), steeper descents via stairsteps through the stratigraphy (common on both Inishmore and Inishmaan, rare on Inisheer), and sheer cliffs with drops of 10–70 m (these predominate on Inishmore, dominate the western coast of Inishmaan, and are absent on Inisheer). The boulder ridges thread along the coastline (fig. 1; table A1), regardless of coast profile type.

The ridges are constructed of material wave-quarried from the sea's edge (Williams and Hall 2004; Hall et al. 2006). Displaced slabs will usually drop downward, but if the wave provides enough lift force, blocks are hoisted upward over the bedrock edge to lie on the coastal ramp. There they may lie, stranded on the ramp; or subsequent waves may drag them backward into the ocean. In some cases, however, the force of breaking wave jets and overtopping wave bores may shove them inland along the ramp (Hansom et al. 2008), ultimately to fetch up in a wave-bulldozed heap at the landward extent of wave action.

Methods

Field data were collected during 2008–2011. We surveyed topographic profiles of boulder ridges at 117 locations on the Atlantic coasts of Inishmore, Inishmaan, and Inisheer, using tape measures to measure distances, Brunton surveying compasses to sight angles, and trigonometry to calculate dimensions where necessary (fig. 3; table A2, available in the online edition or from the *Journal of Geology* office). On Inishmore, the 52 measured profiles were generally spaced 100 m apart, although there are two clusters at closer intervals (Zentner 2009). The 61 transects on Inishmaan and three on Inisheer were spaced uniformly 50 m apart.

We report ridge elevations and distances inland in meters above high-water mark (AHWM) because the high-water (HW) location provides a robust measure of ridge freeboard with respect to the ocean surface. We took the HW elevation as 5.2 m over datum (o.d.), on the basis of 2010 tide tables (the local mean sea level in the Aran Islands is above the national datum; the lowest low water for 2011 was −0.5 m o.d.). We recorded the time at which the exposures at water level were measured

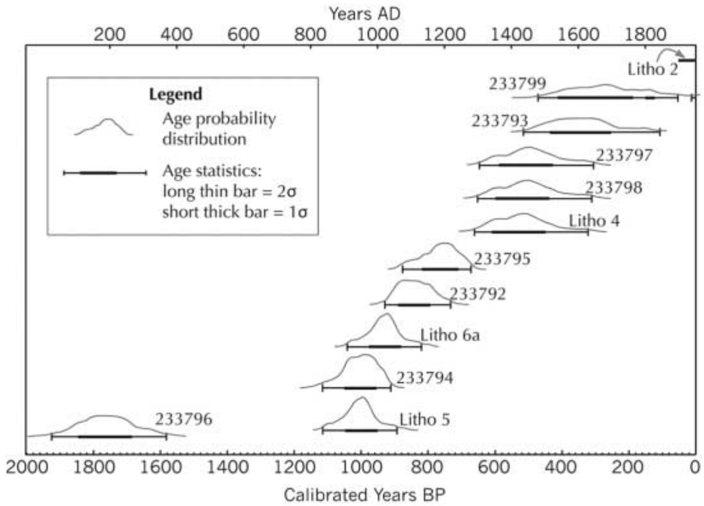

Figure 4. Age relationships among [14]C-dated boring-bivalve shells from boulder ridges on the Atlantic coasts of Inishmore, Inishmaan, and Inisheer. Data (table A3, available in the online edition or from the *Journal of Geology* office) include four samples dated for this study (with "litho" prefix) and eight from Scheffers et al. (2010*a*; recalibrated to include local ΔR correction). In this "Caltech plot," the *Y*-axis has no scale; the vertical stacking is to facilitate comparison of samples, which are arranged in order of decreasing age. The probability density distribution (PDD) for each calibrated age spectrum is shown (area beneath each curve sums to 1.000), along with both the 1σ and 2σ calibrated age ranges (see also table A3). Sample 233799 (Scheffers et al. 2010*a*) has two age ranges at 2σ because the age calibration produced a nonunique solution. Litho 2 has no PDD because it was too young to be calibrated; it is less than 60 yr old (postbomb).

and extrapolated from local tide tables to derive tide height at survey time (Aran Island tide data are based on a gauge at Kilronan on Inishmore). By calculating the difference between the HW elevation and tide height at the measurement time, we could locate the HW position on the surveyed transect (e.g., fig. 3). We take the base of the seaward face as the reference point, so ridge elevation refers to the location of the ridge base in vertical meters AHWM, and inland ridge location refers to the position of the seaward face in horizontal meters from HW.

We measured horizontal and vertical surfaces directly with tapes where practical and used a laser rangefinder for long distances and tall cliffs. Cliff heights were calculated by sighting the hypotenuse with a Brunton surveying compass and using the measured angle to calculate both the vertical drop (subtracting 1.5 m for the observer's eye height) and the width of any exposed ramp at the cliff base. We calculated the location of the HW mark (5.2 m o.d.) relative to the measured water level. In figure 3, the tide level at the time of surveying was 1.3 m, so AHWM is 3.9 m above the measured water level (indicated with a star), and cliff height AHWM is 15.7 m. The ridge elevation AHWM is the sum of cliff height AHWM plus the measured elevation change between the cliff edge and the ridge (2.9 m in the fig. 3 example). The ridge itself was surveyed trigonometrically by sighting the hypotenuse distances and angles landward and seaward from the ridge top. The surveyed angles are shown on figure 3 next to the ridge crest, and the derived height (3.7 m) and total length (27.2 m) are also indicated. The end of the ridge is defined as the extent of 100% ground cover by clasts and does not include the strewn boulders that extend landward. This procedure was followed for all ridge transects.

We measured sizes of the largest blocks at every transect site and made imbrication measurements and line counts of clast populations at a subset of the transects. The tabular shapes of the boulders, with their joint-bounded sides and sharp corners (fig. 1), lend themselves well to volume estimation. For each of the 114 transects, we measured the *X*-, *Y*-, and *Z*-axes of the five largest clasts (table A2) and estimated mass using a standard limestone density of 2.6 t/m^3. For 24 of the transects on Inishmore, we line-counted clast populations (Zentner 2009) to look at the overall distribution of grain sizes in the ridges and to examine their sorting characteristics. The line-counting methodology—by which we laid a tape across the ridge and measured all clasts ≥0.5 cm that lay beneath the tape—provided a complete transect sample of clasts in the ridge, unbiased by observer selection. Because

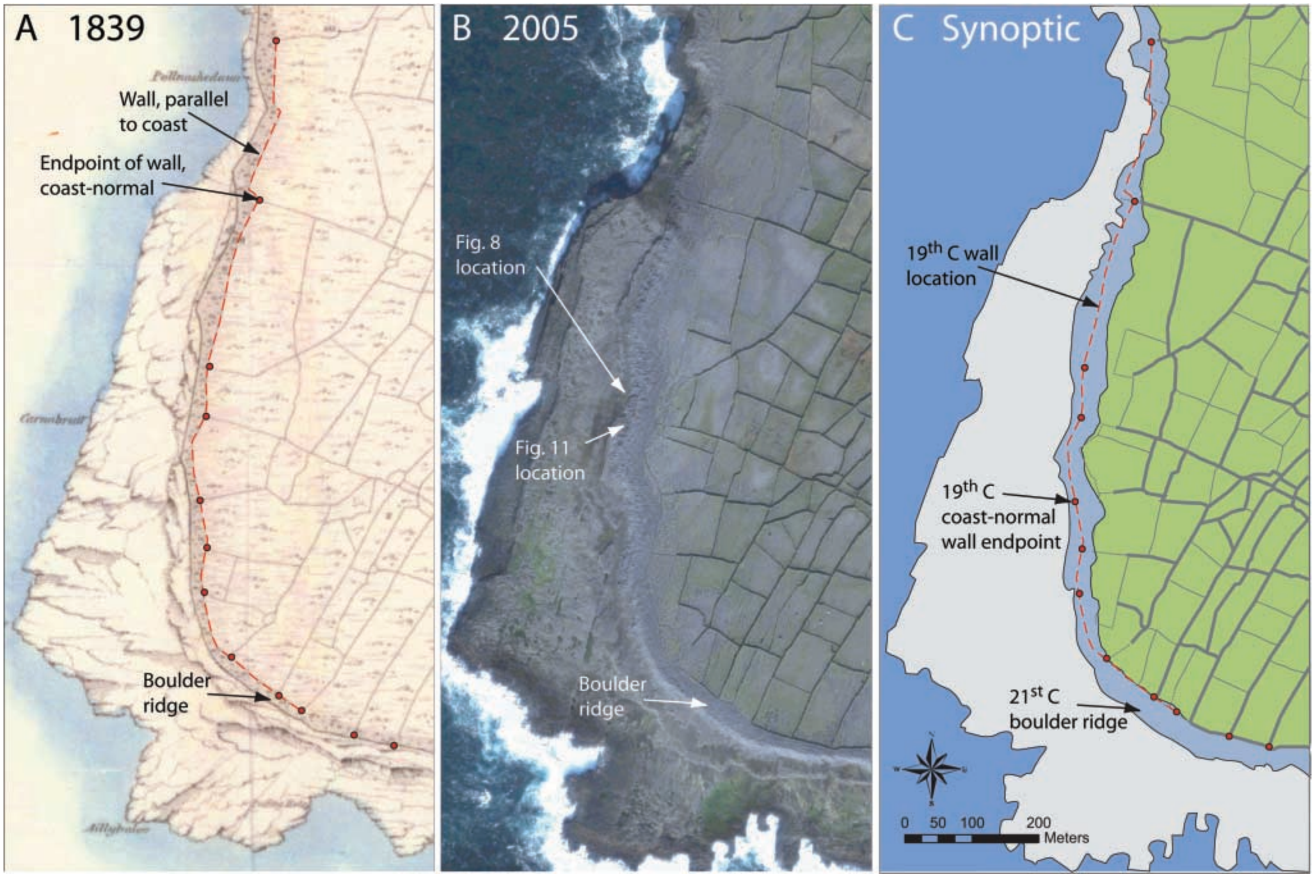

Figure 5. Southeastern Inishmore (see fig. 1) shown in geographic information system orthorectified nineteenth-century Ordnance Survey map (*A*) and 2005 orthophotos (*B*). The synoptic map (*C*) was constructed from the overlaid orthorectified images and from 2010 field mapping (see "Methods"). The heavier lines in *C* indicate old walls (mapped in the nineteenth century) still present today; the lighter lines are walls that were not on the Ordnance Survey map. In contrast to Inishmaan (fig. 6), the nineteenth-century boulder ridge is not strongly delineated in the 1839 Inishmore map, but we do know that it existed in this area from radiocarbon ages of constituent boulders (Scheffers et al. 2009, 2010*b*). The boulder ridge unit shown in *C* is the 2008 field-mapped limit of continuous clast cover.

the *X*-, *Y*-, and *Z*-axes of each clast were measured directly, the data are also unbiased by clast size or orientation. Clast-size distributions were analyzed using measures of Folk and Ward (1957) and implemented in the package GRADISTAT (Blott and Pye 2001). During the line counts, for all clasts with *X*-axis >40 cm we also recorded imbrication (trend and plunge of the steepest face).

Radiocarbon ages come from shells of *Hiatella arctica* (Linnaeus 1767; species confirmation by James T. Carlton, pers. comm.), which we collected from life position in burrows within ridge boulders. Whole shells were submitted to Beta Analytic (Miami, FL) for accelerator mass spectrometry analysis. The conventional radiocarbon dates thus produced (Stuiver and Polach 1977) were converted to calendar ages using the MARINE09 database implemented in the CALIB 6.0 application (Reimer et al. 2009). To correct for secular and regional variations in the marine carbon reservoir effect, we used age-specific Holocene ΔR values for western Ireland and the north Atlantic (Reimer et al. 2002; Ascough et al. 2006, 2009). We incorporated into our analysis the eight conventional ^{14}C ages for boring bivalves reported by Scheffers et al. (2009, 2010*a*) and calibrated them using the MARINE09 database and the local ΔR corrections (table A3, available in the online edition or from the *Journal of Geology* office) so that the existing data could be directly compared with our new ages. The combined data sets (table A3; fig. 4) provide an internally consistent synoptic overview of all available ^{14}C data from the Atlantic boulder ridges.

To map the ridges we used a combination of GPS

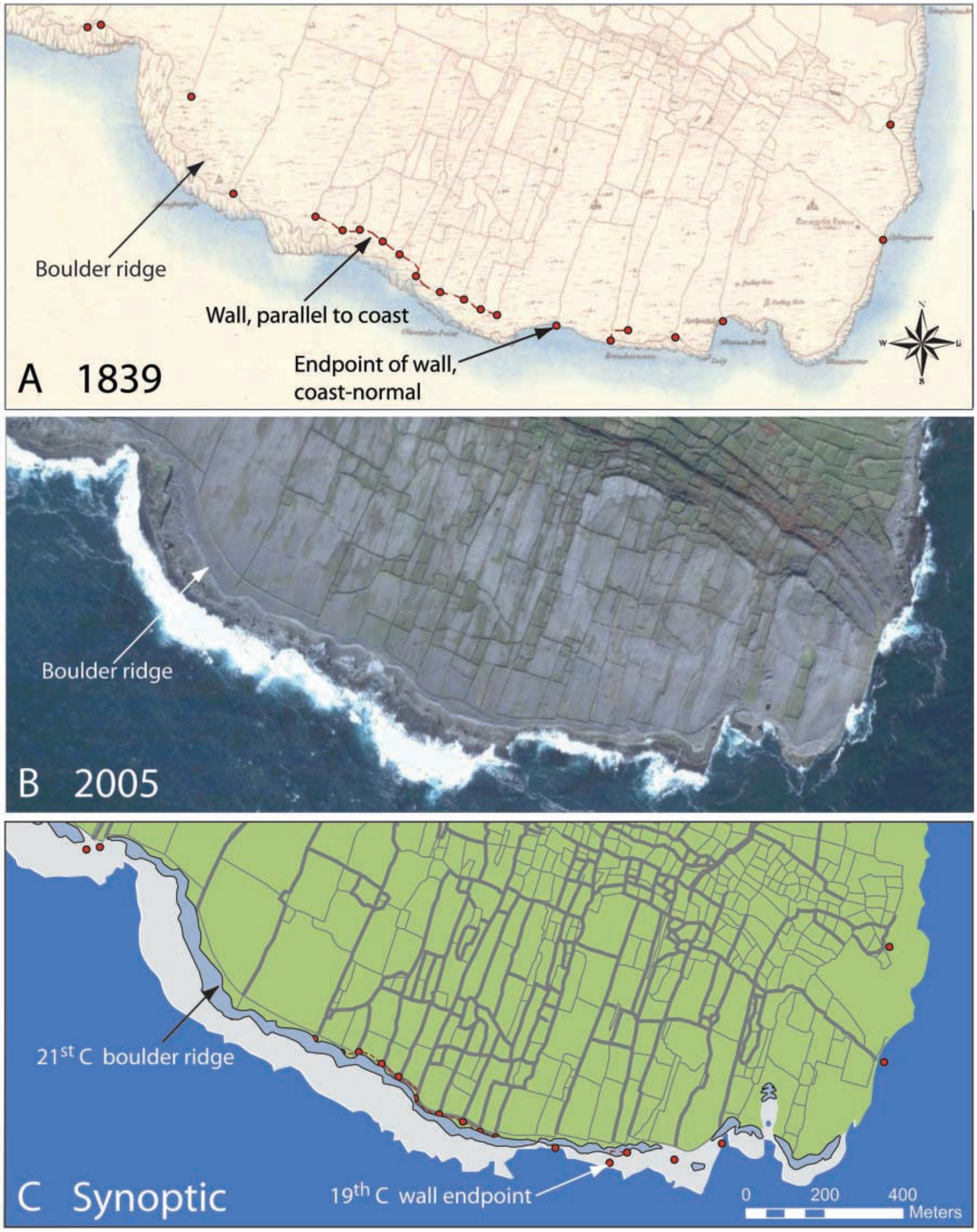

Figure 6. Southwestern Inishmaan (see fig. 1) shown in geographic information system–orthorectified nineteenth-century Ordnance Survey map (*A*) and 2005 orthophotos (*B*). The synoptic map (*C*) was constructed from the overlaid orthorectified images and from 2010 field mapping (see "Methods"). Heavier lines in *C* indicate old walls (mapped in the nineteenth century) still present today; the lighter lines are walls that were not on the Ordnance Survey map. Dotted light lines represent recently destroyed walls, as mapped in the field. The synoptic map shows that although there has been substantial reorganization of field boundaries in a few places, many walls are unchanged and can be used to precisely georectify the old map to the modern image; this permits us to quantify changes in the boulder ridge location relative to the old walls. The twenty-first-century boulder ridge unit shown in *C* is the field-mapped

tracks and good old-fashioned field-map inking. Our field sheets were printouts of 2005 orthophotos (1 : 10,000), in which the boulder ridges are clearly visible as mounds of loose debris between the walled fields and the bedrock of the coastal ramps. The seaward limit of the ridges is clear in the images because coastal ramps are generally bare of clasts and the front of the ridge is abrupt (fig. 1), often with flat-lying blocks shoved kerblike to the base. On the landward side, however, the boundaries are more diffuse, as there is often a gradation from the boulder ridge to a zone of scattered clasts inland. We defined the landward boundary of the ridge proper as the extent of 100% ground cover by contiguous or overlapping blocks, and we mapped that by walking along the ridges and inking the boundary location on the field sheets as we went. We also recorded GPS tracks outlining the ridges. We transferred the field data into ArcMap 9.3 and created polygons to delineate the twenty-first-century ridge locations for GIS analysis.

Repeat photography allowed us to identify clasts that had moved between field seasons. We documented each transect using a series of photographs, then in subsequent years returned to those locations, bringing the previous seasons' field photographs on a tablet computer. By looking at the older photographs while standing on site, we were able to reoccupy the exact positions from which we had taken the original photographs and rephotograph the ridges from the identical viewpoints. Comparing the original photograph with the more recent view, we could spot clasts that had either moved or been newly emplaced. We measured all moved clasts of more than ≈200 kg and (where possible) measured the distance they had traveled. Data from the largest moved clasts are compiled in table A4, available in the online edition or from the *Journal of Geology* office.

Comparison between the present-day ridge location and extent and that recorded in nineteenth-century maps of the Aran Islands (Ordnance Survey 1841) was implemented using ArcMap. Orthophotos (Ordnance Survey Ireland's Trailmaster Series 2006; 1 : 50,000, 2.5 m/pix) served as a base map, on top of which we overlaid and georeferenced higher-resolution 2005 orthoimages (1.5 m/pixel) from Google Earth covering the coastal areas of interest. We digitized the nineteenth-century Ordnance Survey maps, imported them to ArcMap, and georeferenced them.

The wonderful level of detail in the nineteenth-century maps allowed us to accomplish precise image matching with the 2005 orthophotos. The Ordnance Survey field mappers meticulously recorded the web of stone walls crisscrossing the islands. Although walls were added over time as large fields and landholdings were subdivided, the new walls were usually built within the existing field system, preserving the shapes of the older enclosures (figs. 5*B*, 6*B*). This conservative agricultural landscape presented plenty of good control points for exact registration of the nineteenth-century and twenty-first-century images, and image rectification was based entirely on the ubiquitous stone wall network. The nineteenth-century map was very accurate: lengths, locations, and orientations of field walls in the old maps were the same as those measured on the 2005 orthophotos. Testament to the precision of the nineteenth-century mappers, we found that their maps overlaid the twenty-first-century orthophotos very closely, with little need for image warping (total root mean square error on the transformation was 0.00421). In consequence, we were able to use the overlay of old and new maps to quantify changes in ridge location.

The nineteenth-century maps show boulder deposits on all three islands, but there are clear differences in cartographic approach from island to island. On the Inishmaan map the ridge location is distinct, with the seaward edge indicated by an inked line (fig. 5); however, for Inishmore the ridges are less clearly shown, and the boundaries are ambiguous (fig. 6). We therefore used the seaward walls of coastal fields as markers for the maximum possible inland extent of nineteenth-century ridges. The walls were (then as now) inland of the ridge in all cases. We plotted coast-parallel field walls by a red dashed line. Many ocean-facing fields on the Aran Islands do not have a coastal wall, however;

2010 limit of continuous block cover. The locations of nineteenth-century coast-parallel walls are indicated by the dashed line, and filled circles show the coastal endpoints of coast-normal walls. In the nineteenth-century map (*A*), field walls were all inland of the ridge. Along the southern coast the wall location is unchanged (see, e.g., the red dots marking nineteenth-century coastal wall endpoints exactly overlying the modern wall endpoints). Along the western coast, however, the location of the old wall has been overrun by the boulder ridge, which has moved up to 40 m inland in places (measured as the distance between the nineteenth-century wall location and the present position of the ridge's inland edge). The location of figure 11 is shown in *B*: the large boulder in figure 11 sits at the approximate location of a nineteenth-century field wall.

often, two walls run down to the coast, but the seaward end is open. We therefore marked the end of coast-normal side walls with a red circle (figs. 5, 6), and in many cases that denotes the seaward extent of the field. These wall-location markers provide a maximum nineteenth-century landward limit of the boulder ridges and also show the oceanward extent of nineteenth-century agriculture.

Measuring in ArcMap the distance between the locations of nineteenth-century coastal walls (and wall endpoints) and the twenty-first-century locations of the same, we were able to identify areas where ridge location and nearshore infrastructure had changed between the mid-nineteenth century and the early twenty-first century (figs. 5, 6).

Results

Sorted, Organized Deposits. The ridges are asymmetric clast piles ranging from small accumulations (0.5 m high and a few meters wide) to massive structures measuring 6 m from bedrock ramp to ridge crest and spanning 50 m from front to back. In some places, especially at high elevation or as the coast curves away from the Atlantic, the ridges occur as loosely arranged wave-bulldozed boulder piles. The classic ridge, however, is a well-organized structure, sloping steeply in the upflow (seaward) direction (average = 20°, range = 6°–35°), and with a gentle downflow (landward) incline (average = 5°, range = 2°–12°). In most places there is a single ridge, but many locations have a series of 2–4 distinct ridges, diminishing in size landward (e.g., fig. 3). Each ridge element has the same overall form (steepest slope upflow), and all have small wavelength-to-height ratios, ranging from 4 to 6.

The boulder ridges rise abruptly from a clean-swept ramp that may be a few meters wide or may extend more than 250 m from HW. Stranded blocks sometimes occur on the ramp between the ridge and the ocean, but in general loose material has either been incorporated into the structure or removed out to sea (fig. 1). Often the ridge is localized at a bedrock step, which would have served to halt and trap clasts in transport. Characteristically, a sharp crest separates the seaward and landward faces of the ridge. The landward side of the ridge grades from the main boulder pile (sometimes through two or three smaller subsidiary ridges) into a diffuse boulder-strewn zone that in some cases extends for many tens of meters into the fields beyond.

Most ridge boulders are derived from the directly underlying strata, which can be demonstrated by comparing boulder lithology with the coastal stratigraphy: the largest blocks generally come from the topmost units and usually are not far removed from their bedrock sockets. Other blocks can be lithologically correlated with beds farther down in the stratigraphy, meaning that they have been transported greater distances both vertically and horizontally. Some blocks have traveled up to 12 vertical meters. The far-traveled population includes intertidal blocks (showing characteristic tide-pool karst, sometimes with barnacles, mussels, and coralweed still attached) and even some subtidal boulders (evidenced by abundant burrows of the boring bivalve *Hiatella arctica*, sometimes with shells still in life position). Subtidal boulders can be found in ridges up to about 6 m AHWM (i.e., >11 m above low water). As *Hiatella*-bearing rocks are not exposed at low tide, their presence in the ridge indicates excavation from the subtidal zone, so their elevation above low water is a minimum transport distance. The far-traveled population is small, usually only a few clasts in any one ridge. In general, the clast population is dominated by supratidal blocks, with the uppermost 3 m of the local stratigraphy yielding the majority of the rocks (Zentner 2009).

The deposits are well imbricated, especially on their seaward faces (fig. 7). The imbrication directions are predominantly to the southwest and south-southwest, which matches the prevailing wave-approach direction (Williams and Hall 2004). Imbrication directions on the landward sides of the ridges are more variable. The dominant direction is still south-southwest, but there is a greater range, and a higher proportion of clasts have easterly tilts. We interpret the imbrication differences between the seaward and landward faces (fig. 7) as being due to some clasts being transported up the ridge face and then toppling over the back side, where they may come to rest leaning landward. This interpretation is supported by observations of balanced horizontal and sometimes back-tilted clasts along the ridge crest, which appear to be arrested in trans-ridge transport. That the majority of clasts slant seaward, however, suggests that the ridge is subject to strong unidirectional forcing overall.

Pebbles, cobbles, boulders (0.25–4.1 m), and megagravel (>4.1 m; sensu Blair and McPherson 1999) are the grain-size categories that make up the ridges. Occasional pockets of sand occur trapped in cracks and crevices, but by and large there is no matrix, and the framework is open. Clast counts along 24 transects on Inishmore (Zentner 2009; data summarized in table A2) reveal size distribu-

Figure 7. Rose diagrams showing imbrication directions for boulder ridges on Inishmore (Zentner 2009). Measurements (direction of maximum clast dip) were made systematically along transects Z1–Z24 (table A2, available in the online edition or from the *Journal of Geology* office) and represent all clasts from those transects >40 cm in X dimension. The dominant imbrication direction in the seaward faces (≈190°–260°) matches the dominant wave-approach direction for the islands (Williams and Hall 2004) and reflects emplacement by incident waves. The more variable trends for clasts on the landward side of the ridges result because clasts that crest the ridge topple over into the back-ridge environment, and their orientation is therefore influenced by the size and shape of the clasts onto which they fall, as well as some reworking by turbulent flows behind the ridge.

tions with a relatively small standard deviation. Clast sizes in the transects range from about -2 to -11 Φ (4 mm to 2.05 m in Y-axis length), but the average sorting parameter (σ_Φ) is only 0.69 Φ. On the basis of the criteria of Folk and Ward (1957), the deposits are on average moderately well sorted.

The upper end of the clast-size distribution ranges from merely impressive to mind-bogglingly stupendous (table A5, available in the online edition or from the *Journal of Geology* office). The largest clast in table A5, a 78-t tabular block (fig. 8), is also the most striking in terms of wave emplacement dynamics: it sits at an elevation 11 m AHWM (17 m above sea level), 145 m inland from HW. It is not transported far (lithologically it matches the underlying bed, appearing to have been lifted up, swung around through ≈50°, and shoved upward and inward), but that a rock of this mass could be incorporated into the boulder ridge at this horizontal and vertical distance from HW is impressive. Local information indicates that this block was moved during a 1991 storm. The largest clast we measured (at Gort na gCapall on Inishmore) weighed 87 t and was situated 4 m AHWM and 32 horizontal meters inland. Larger clasts (≥250 t) have been reported by others (Williams and Hall 2004; Scheffers et al. 2009), although in general these exceptionally large blocks are stranded on the seaward ramp and are not incorporated into the ridges. All of the clasts listed in table A5, however, are constituents of boulder ridges.

The eye and the measuring device are drawn inevitably to the charismatic megagravel, but in fact those blocks are not representative of the overall grain-size distribution in the deposits: substantially smaller material constitutes the bulk of the ridges (fig. 9). Examination of the clast-size data emphasizes the deceptive visual effects of the large blocks (table A2). The mass of the largest clast in any transect is generally about twice the median of the five largest clast masses in that transect—that is, the largest couple of blocks are significantly larger than the other largest blocks in the system. The difference is even more dramatic when we consider the grain-size population as a whole: the median for all the clasts counted in a transect is smaller than the largest clast by one to four orders of magnitude. Taking transect Z1 as an example, the largest clast is almost 2 t in weight, but the median clast size is only 0.009 t (9 kg). The most extreme example in our database is transect Z8, where the largest clast weighs >3 t but the median clast size is only 0.0009 t (900 mg). The clast-count data show that populations tend to be skewed toward finer grain sizes (i.e., the mean is significantly fine relative to the median; Folk and Ward 1957). Of 24 transects, only two are coarse skewed; seven are symmetrical, and 15 are either fine or very fine skewed.

Elevation sets upper limits on ridge occurrence. Ridges top out at 38 m AHWM on Inishmaan and at 28 m AHWM on Inishmore (elevation is not a limiting factor on Inisheer, which has no coastal elevations greater than a few meters). Cliffs on both Inishmaan and Inishmore extend to higher eleva-

Figure 8. The largest within-ridge clast that we measured on the Aran Islands, shown here with two people for scale, is $11.5 \times 4 \times 0.65$ m^3 and has a mass of about 78 t. It is located on Inishmaan (table A2, available in the online edition or from the *Journal of Geology* office). The block was quarried from the bed that forms the base of the bedrock step (on top of which it now leans). It broke along joint surfaces, was uplifted enough to clear both the bed from which it detached and the overlying bed, rotated about 50°, and slid inland by several meters. The original block size was larger—a piece broke off during or after emplacement (visible behind the small boy at the top of the clast). Inishmaan residents say that this block, as well as other nearby megaclasts (not shown in this photo), was emplaced during a 1991 storm.

tions but without wave-excavated boulders on top. The high-elevation ridges are smaller, narrower, and contain smaller clasts; in general, both clast size and ridge volume decrease as cliff height increases.

The descriptive sedimentology outlined here places some constraints on how the ridges might be emplaced but does not amount to a mechanistic theory. Clearly, the ridges are traction deposits representing bedload movement. Although they are wave emplaced, oscillatory flow is probably insignificant in shaping them: they may experience bidirectional flow from bore run-up and return, but experiments and modeling indicate that unidirectional flow is the predominant forcing mechanism (Hansom et al. 2008). To date, however, most work on these and similar deposits has focused on clast erosion, initiation of motion, and grain-transport mechanism (Nott 2003*a*; Williams and Hall 2004; Hall et al. 2006; Hansom et al. 2008). Future work should consider the processes operating at the ridge itself, so that we can understand the way in which the ridges build and migrate.

In summary, the boulder ridges are well-structured and moderately well-sorted deposits, constructed from cobbles and boulders and decorated with dramatic megagravel, derived mostly (but not exclusively) from immediately subjacent outcrops. The clasts have a strongly imbricate texture, with a predominantly (although locally variable) northwesterly trend (Williams and Hall 2004; Zentner 2009). The clast trends reflect the prevailing emplacement flow direction and match the average wave-approach direction for the islands (Williams and Hall 2004).

Two Millennia of History from Radiocarbon Dating of Endolithic Bivalves. Some ridge boulders preserve shells of the rock-boring bivalve *Hiatella arctica* entombed in their burrows. The living organism inhabits the low intertidal to subtidal zone (Trudgill and Crabtree 1987), so radiocarbon dates of the bivalve shells therefore provide a maximum age for excavation and ridge emplacement of the host boulder, and the distribution of shell ages can provide an overview of the long-term history of the ridge system. Dated bivalves from within ridge boulders range from about 1800 yr old to modern (post-1950; table A3; fig. 4). The oldest ages come from Scheffers et al. (2010*b*) and include one boulder emplaced at 1760 (−76/+91) B.P. (i.e., sometime

Figure 9. This photograph, showing transect location Z15 on Inishmore (view northwest) at 12 m above high-water mark, shows the range of clast sizes that make up this segment of ridge. The largest clast measured on this transect was 1.2 t in mass (table A2, available in the online edition or from the *Journal of Geology* office); the median of the five largest clasts was 0.26 t, but the median of the 97 clasts counted along the transect was only 0.6 kg. This deposit is typical of the boulder ridges in being very fine skewed and moderately well sorted.

between 114 and 281 AD). Thus, ridge history recorded by these organisms spans almost 2 millennia.

Recurrent activity over many centuries is the clear message in the spread of boulder-emplacement ages (fig. 4). With only 12 individual ages, we must be circumspect about any interpretation of periodicity, especially as many of the samples are statistically identical at the 2σ level (fig. 4). There is, however, some age clustering at the 1σ level, which—bearing in mind the caveats appropriate to the low level of statistical confidence—may reflect large events with widespread effects in the ridges. Gaps in the 2σ ranges indicate a minimum of four separate events: the oldest nearly 2000 yr ago, an event (or set of events) between about 1100 and 700 yr ago, another one or more events between 700 and about 200 yr ago, and finally the post-1950 boulder emplacement. We think it pointless to attempt connecting age clusters with specific storms, because of both the uncertainties in the ^{14}C ages (table A3) and the uncertainties inherent in pre-eighteenth-century storm chronologies (Lamb and Frydendahl 2005). And although the (apparent) clustering may suggest periodic large events, we emphasize that it is statistically likely that there is no clustering and that all ages reflect separate events (i.e., the maximum number of events is equal to the number of samples). To determine the extent to which ridge history is periodic would require a much larger age data set. Finally, it is important to note that the ridges could well have an even longer history than the ≈1800-yr record that has been revealed to date: older bivalves may be sitting out there waiting to be found, tweezed out of their burrows, and dated.

A key result from the new data is demonstration of recent ridge activity. Our youngest sample (litho 2; table A3) is too young to be dated by radiocarbon: its conventional radiocarbon age (400 B.P.) is younger than the local reservoir age (414 B.P.). We know therefore that it postdates the reference year 1950. This is considerably younger than the youngest previously dated emplacement, which was 280 (+234/−132) B.P. (table A3; Scheffers et al. 2010*a*). The new radiocarbon data thus confirm that the ridges are gaining mass at the present day.

The radiocarbon ages give us a good first-order sense of the spread of ridge history, but only the intertidal or subtidal blocks contain bivalve shells. In most cases, therefore, these tend to be blocks less than a couple of tonnes in mass (with the exception of the one 40-t block; table A3). Most of the truly colossal blocks in the ridges (table A5) do not come from the subtidal realm and do not contain datable material. We need other data to establish large-block movements, to determine when and by how much the ridge deposits have migrated.

GIS Analysis Shows Ridge Migration between the Nineteenth and Twenty-First Centuries. GIS analysis of recent and older maps allows us to track the evolution of the ridges en masse, including the full range of constituent boulder sizes. Comparing nineteenth-century ordnance survey maps with twenty-first-century orthophotos shows that some boulder ridge sections sit tens of meters inland from their nineteenth-century location and that the sites of nineteenth-century walls have been buried beneath boulder deposits. For example, a 900-m section along the west coast of Inishmaan has moved inland as much 40 m (fig. 6), destroying the coastal field walls that existed along this stretch in the nineteenth century. On southeastern Inishmore (fig. 5), a section of ridge ≈700 m long has completely overrun the nineteenth-century wall locations, pushing up to 50 m inland. For the 166-yr period of record—the nineteenth-century maps (Ordnance Survey 1841) were surveyed in 1839, and the orthophotos were taken in 2005—sections of the ridge have advanced inland at average up to 3 m/decade.

As the boulder ridge advances in the most dynamic areas it demolishes field walls. Field mapping shows that many ridge-adjacent walls appearing on the twenty-first-century orthophotos but not on the nineteenth-century map have been knocked down. The destroyed modern field walls (dotted lines inland of the migrating ridge in fig. 6*C*) are associated with strewn boulders and boulder clumps that extend tens of meters and, in some cases, >100 m into the adjacent fields. The fallen walls occur in the area along the Inishmaan west coast, where the ridge has shown the greatest inland advance. We note also that many of the intact coastal walls along these stretches, especially those close to the ridges, show indications of recent rebuilding, and this was confirmed by conversations with local people. Some ridges have abrupt inland margins corresponding to the locations of well-maintained walls, suggesting that some landowners may modify the inland edge of the ridge as part of wall rebuilding and reinforcement. The overall picture is one of a dynamic system.

The active ridges on Inishmaan appear also to have widened: in places where the landward edge of the ridges has migrated inland, the seaward edge remains near its nineteenth-century location (fig. 6). (We make this evaluation only for Inishmaan because the nineteenth-century mappers indicated but did not quantitatively map the ridge on Inishmore; see fig. 5.) It makes sense that active ridges should widen as well as migrate: during successive events, blocks on the ridge can migrate up and over the ridge into the back-ridge zone, and new blocks can be added to the front of the ridge. The landward force of the transporting bore is far stronger than the backwash, so larger blocks can have net movement landward only. Smaller blocks may be washed back into the ocean, but they will also be trapped in the ridge if they become armored by an overlay of larger blocks (and we do see on the ridges that the blocks beneath the surface layer tend to be smaller). The tendency, therefore, will be for the boulder piles to get higher and wider over time as their leading edges advance landward.

Not all of the ridges have been this active, however. The GIS analysis also shows long ridge segments that have experienced no net movement since the mid-nineteenth century (figs. 5, 6). In the field, one can see clear contrasts between stretches of ridge with fresh, clean gray blocks and stretches where many blocks have been thoroughly coated with several species of lichen (Williams and Hall 2004; Zentner 2009), which is a testament to protracted dormancy. We note that a lack of landward migration is not the same as complete ridge inactivity, because it does not preclude the transport and addition of new boulders on the oceanward side of the ridges, and even the most lichen-rich ridge segments often have fresh, clean blocks lying on the seaward face. There is no doubt, however, that large portions of the boulder ridge have been fairly stable since the mid-nineteenth century.

Nineteenth-Century Observations of Boulder Movement. Our conclusion that different sections of the ridge have different activity levels is not new. Kinahan et al. (1871) also observed dramatic differences in ridge activity from place to place on the islands. They described sites where "great quarrying seems to be going on here during the gales. Blocks 30 × 15 × 4 feet"—that is, 57 t—"tossed and tumbled about … have all the appearance of being yearly tossed about by the waves, while more are added," which they contrasted with other, less active locations, where "the blocks seem not to have been stirred or added to, by the sea, for years" (p. 33).

Late nineteenth-century Geological Survey of Ireland geologists were convinced that the ridge boulders were moving on short timescales and reported block-socket relationships as evidence. Specific examples given by Kinahan et al. (1871) are

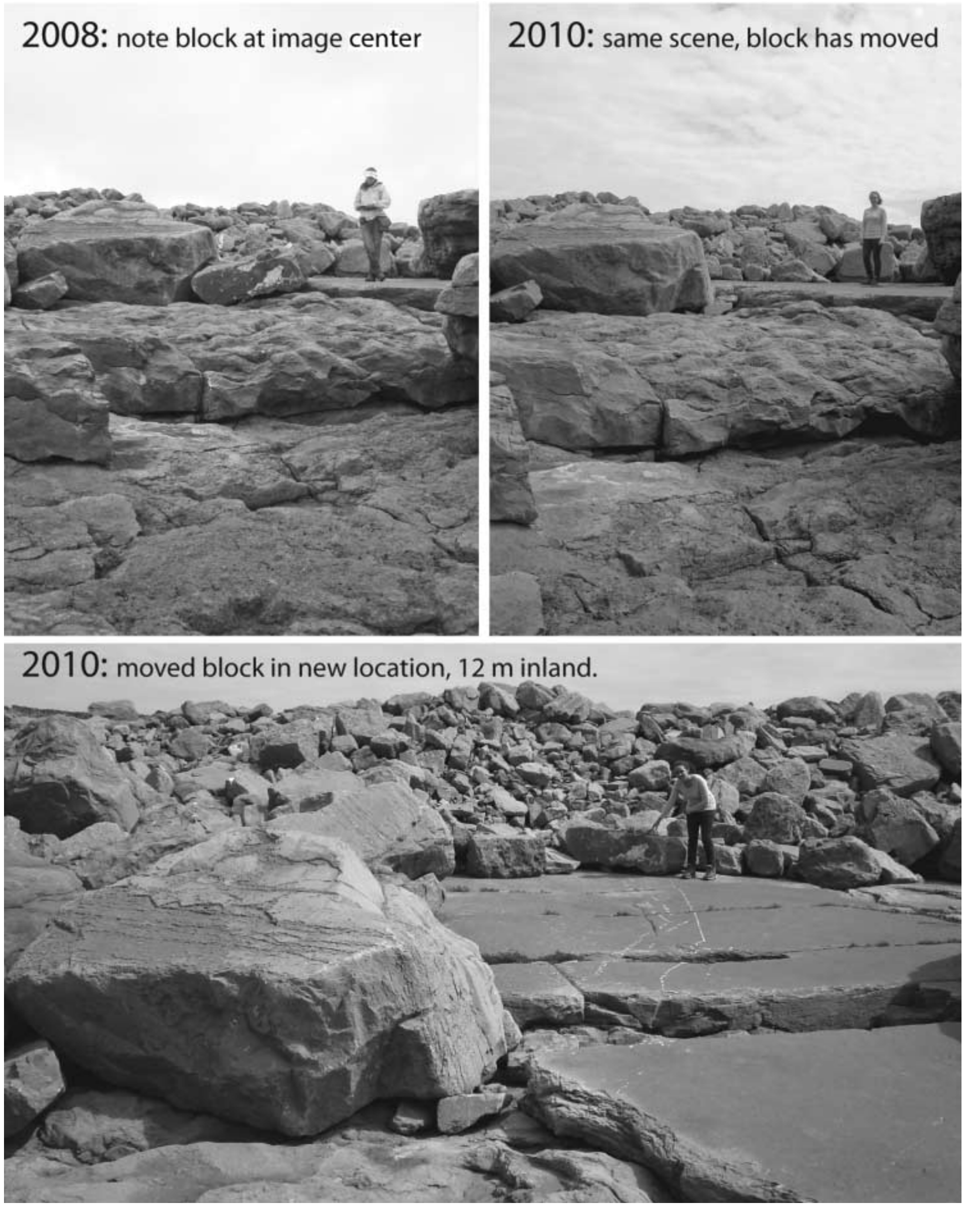

Figure 10. Recent block movement west of Gort na gCapall on Inishmore (lat 53.1216°N, long 9.7486°W). The block in the center of the 2008 image weighs about 1.5 t (table A4). It is missing from the top-right 2010 image. The lowermost photo shows the new resting place of this block, a horizontal distance of 9 m from its original location and 105 cm higher up. The white marks on the ramp are scratches made by the boulder as it moved, showing that it was pushed up the initial ledge and then slid along the bedding-plane surface.

from the eastern end of Inishmore, where "a block 15 × 14 × 4 feet"—that is, 53 t—"seems to have been moved 20 yards and left on a step 10 feet higher than its original site," and from southwest Inishmaan, where "a block 20 × 5 × 1 has been raised 20 feet and moved 31 yards from its natural site. A little south of this, near Aillyhaloo, a block 19 × 8 × 3 was raised 5 feet and moved 8 yards; and another 27 × 9 × 4 was raised 4 feet and carried 9 yards" (p. 33). The Inishmaan block measurements (which are in feet) correspond to masses of about 7, 33, and 72 t, respectively.

A particularly large storm on January 6–7, 1839—remembered in Ireland as the "Night of the Big Wind"—caused extensive coastal damage and initiated boulder movement on the Aran Islands cliffs.

Barometric pressures as low as 918–922 mb were measured (Shields and Fitzgerald 1989; Lamb and Frydendahl 2005); analysis and recalibration of the original data yields a mean-sea-level pressure equivalent of 930 mb (Burt 2006), corresponding to a category 4 hurricane. Prehistoric structures at Dún Duchathair on Inishmore (on top of cliffs that are 23 m AHWM) were described later that year by O'Donovan (1839), who reported that they "seem to have suffered in a special manner from the late memorable storm, which hurled the waves in mountains over those high cliffs, [and] cast rocks of amazing sizes over the lower ones to the east of them" (p. 118).

Movement of 1–10-t Blocks, 2006–2011. Hurricane-force winds are not required to move large boulders in the ridge system. Our observations show that blocks orders of magnitude above the median size of ridge boulders, with masses about the median of the largest five clasts in any given transect (table A5), are currently being moved in the Aran Islands ridge systems. The post-1950 clast, litho 2 (table A3), sits partially buried at the ridge base within transect IM13 (table A2), along the southern shore of Inishmaan. This boulder—subtidal when the Hiatella bivalves were living—is emplaced 4 m AHWM and 46 m inland. Other boulders scattered on the ramp and on the front sides of the ridges bear evidence of even more recent emplacement, as they preserve nonburrowing, delicate organisms (barnacles with their inner valves intact, articulated mussels still attached by byssus threads, and even coralline red algae, defleshed but still articulated). These boulders, observed in 2010 and which by the freshness of the encrusting fauna cannot be more than a couple of years old, include several with masses of ≈0.8 t at a few meters AHWM and around 150 m inland, as well as a few larger ones—for example, 1.2 t at 5 m AHWM and 150 m inland and 1.4 t at 5 m AHWM and 220 m inland. The fauna indicate that all of these are intertidal or subtidal blocks, so their subaerial resting places represent minimum horizontal and vertical transport distances. One such boulder, 0.74 t, sat 7 m AHWM and 221 m inland on southwestern Inishmaan in June 2010, covered in freshly dead mussels and coralweed. In June 2011, the block had disappeared from its 2010 location, but we found it 59 m farther inland (280 m from HW), having lost its coating of mussels and most of the coralweed but having gained an additional 3.6 vertical m (total of 10.6 m AHWM). Clearly, regular storm waves are capable of moving blocks of 1.5 t several meters vertically and up to quarter of a kilometer inland.

Photo pairs (dated before-and-after shots) show movement of numerous blocks in the 1–2.5-t range, and we provide a few examples here. On Inishmore, a 1.5-t boulder, originally at 5 m above and 20 m inland from the HW mark, moved 9 m horizontally and 1 m vertically sometime between 2008 and 2010 (fig. 10; table A4). On Inishmaan, similarly, several blocks (masses range from about 1 to 2.5 t) present in a 2010 photo are clearly not present in the 2006 picture (fig. 11). The figure 11 location is transect IM32 (table A2), so these blocks were emplaced sometime between 2006 and 2010 at 11 m AHWM and at 118 m inland.

The largest single block that we have identified as having moved in the last few years is a 10.5-t boulder at the southwestern tip of Inisheer (table A4). This block shifted about 2.5 m laterally and about 1 m downward between 2010 and 2011 (fig. 12). Several other blocks have moved around in this ridge segment—for example, the 3.5-t block that was hoisted up onto the ridge, 5 m laterally and 1 m vertically (its 2010 position is not visible in fig. 12 but was determined from other photographs). The two large, flat-lying blocks that form a kerb between the ridge and platform at the bottom left of the photograph moved several meters laterally to arrive at their 2011 positions. The greatest significant wave height (SWH) between June 2010 and June 2011 was 13.3 m, recorded at the M6 buoy on November 8, 2010. The moved blocks are 3–5 m AHWM and 52–55 m inland from HW.

Megagravel Movement, Nineteenth Century to Recent. But 2–10-t boulders, impressive as they are, are much smaller than the megagravel blocks (>4 m; Blair and McPherson 1999) that make the ridges so stupendous (figs. 8, 11) and which Scheffers et al. (2009) designate as critical to establishing ridge-formation models. Can we constrain the time of movement of some of these large blocks? We think the answer is yes.

The largest block that we measured within a boulder ridge (table A5; fig. 8) weighs about 78 t and is one of a set of very large blocks that occur along the southwest coast of Inishmaan. Island resident Padraic Faherty directed us to these blocks, which he told us appeared in their present positions after a strong storm in January 1991. He was very specific in his description of the shape, attitude, and surroundings of the largest block and showed us its exact location on a map. We went to the location and found the block exactly as reported. We photographed it and a nearby 40-t block, and both Padraic Faherty and Teresa Faherty confirmed that the 80-t block was the one described and that the 40-t block had been emplaced in the same

Figure 11. Recent block movement on southwestern Inishmaan. *B* includes several blocks (indicated by stars) that are absent from *A*. The date of the photo in *A* was kindly given by Anja Scheffers (pers. comm.). The newly emplaced blocks in *B* have masses up to ≈2.5 t. The photo in *B* was taken at the site of transect IM32 (table A2, available in the online edition or from the *Journal of Geology* office). The clast with the seated person has a mass of ≈35 t, and the flat-lying block in the foreground is ≈14 t (clasts IM32-4 and IM32-1; table A5, available in the online edition or from the *Journal of Geology* office). The 35-t boulder sits at the approximate location of a nineteenth-century field wall (see fig. 6) and is about 120 m inland above high-water mark.

storm. Padraic Faherty told us that they were noticed immediately after the storm and that their size and abrupt appearance caused amazement among the people who saw them.

We have connected the narrative observations of the Inishmaan residents to a specific storm: a North Atlantic depression with a central pressure of 946 mb (equivalent to a category 3 hurricane) that occurred on January 5, 1991. It was classified as an extreme storm event (MacClenahan et al. 2001). Winds gusted in excess of 80 knots, with Belmullet (the weather station closest to the Aran Islands) recording 23 h of gale-force winds and sustained winds of 40 knots for 5 h. The waves forced by the storm winds built on swell previously developed by strong winds that had been blowing for a couple of weeks. At the height of the storm, the modeled SWH was 15 m, and individual waves off the west coast of Ireland had heights up to 30 m (Met Éireann 1991). We find the observations of the residents credible, especially given that their report is so specific with respect to time and corresponds to a significant storm event for which the sea state was meteorologically classified as "phenomenal" (Met Éireann 1991).

We recognize that the evidence for emplacement of the 78-t block during this storm is anecdotal but see no reason to discount the observations of the

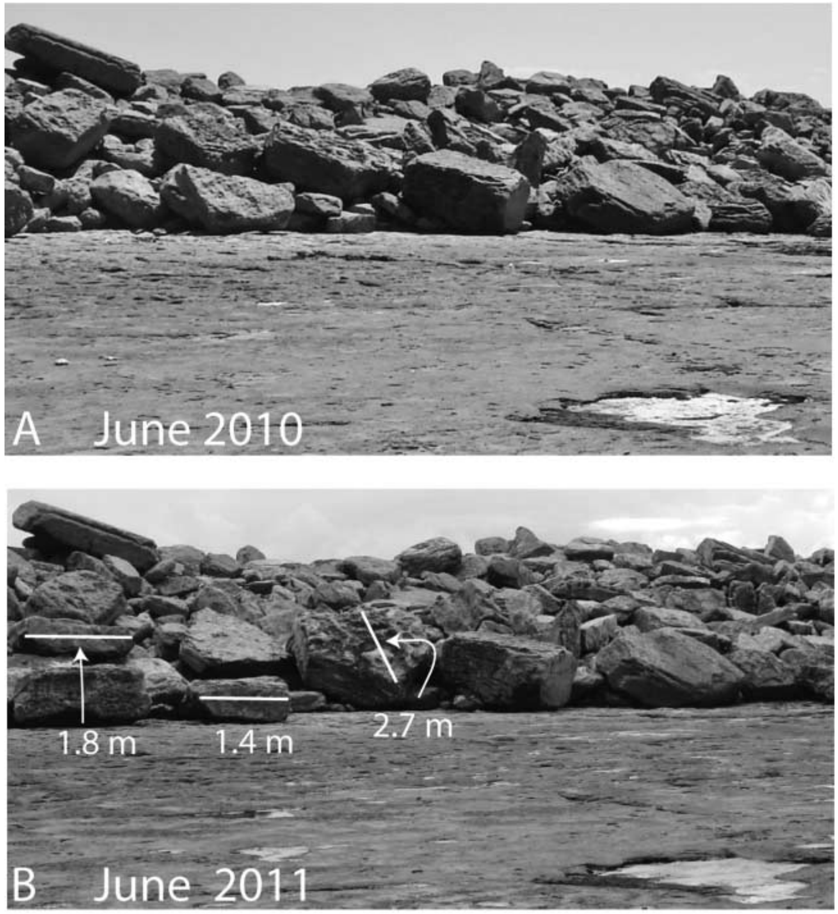

Figure 12. Photos of the boulder ridge at the southwestern tip of Inisheer (see fig. 1) taken 1 yr apart. Several differences can be seen, with some boulders having shifted within the ridge and others having been newly added. Scale bars highlight three of the moved blocks. The 1.8-m boulder (other dimensions, 1.2 m × 0.6 m) is ≈3.5 t in mass. The 1.4-m rock (other dimensions, 2.0 m × 0.6 m) is ≈4.4 t. The largest block observed to have moved is that indicated with a length of 2.7 m, which has a mass of ≈10.5 t (table A4, available in the online edition or from the *Journal of Geology* office).

local people who live and work on this coast, observing it on a daily basis. In the absence of a long-term program of scientific observations, we argue that it is reasonable to accept local reports of specific remarkable occurrences, especially if these can be verified by more than one observer.

But we do not have to rely on the short-term observations to demonstrate that the ridge megagravel has been moving on decadal and centennial timescales, thanks to the wonders of GIS (figs. 5, 6). The block on which the person is sitting in figure 11 weighs about 35 t, and the figure 8 block is about 78 t. Beneath them lies the approximate location of the nineteenth-century field wall, now buried under a 4–5-m thickness of ridge deposits (transect locations IM32–33: table A2). So whether or not one accepts the local residents' reports that the 78-t block was emplaced in 1991, the GIS analysis shows that it was certainly emplaced since the mid-nineteenth century. No tsunami events occurred during that period, so storm-wave emplacement of these giant blocks in a recent time frame seems an inescapable conclusion.

Discussion

Waves and Bathymetry. Boulder ridges occur at elevations up to 38 m AHWM, so it is necessary to consider the wave climate and near-coast bathymetry. The interaction between incident waves and the slope along which they shoal will play a crucial role in determining the behavior of incident waves (e.g., Brossard and Duperret 2004). Our understanding of the nonlinear dynamics of waves in steep coastal environments is limited, but the following discussion serves to illustrate that the study area has wave climate and bathymetric characteristics that can combine to produce large and energetic wave events at the coast.

Atlantic storms frequently generate wave spectra with SWHs in excess of 12 m, calculated as $4(M_0)^{0.5}$, where M_0 is variance about the mean of the sea-surface elevation (this equates approximately to the mean of the largest third of waves in a time series; for the M6 buoy data reported here, each time series is 1-h duration.) The M6 deepwater buoy off the west coast of Ireland has been operational since September 2006 (http://www.marine.ie/home/publicationsdata/data/buoys), and in the 56 months of record there are 35 instances of SWH >12.0 m, occurring during eight separate storms in ≈5 yr. Periods for these waves range from 11 to 14 s, corresponding to wavelengths ≈190–300 m. The largest SWH recorded (on December 9, 2007; Met Éireann 2007) was 17.2 m.

The offshore bathymetry (shown by the location of the 30-m bathymetric contour in fig. 2) reflects the variety in onshore topography described earlier (in "Setting"). The subdued topography of Inisheer continues offshore as a gradual deepening: the submarine slope near Inisheer is about 2°, with the 30 m contour (GUNIO 2007) about 900 m from the coast, on average. Inishmore is steeper: the 30 m contour is generally less than 500 m from shore (3.5° average slope) and approaches to within 100 m in a few places (i.e., local slope of 17°). Southwestern Inishmaan projects out into the Atlantic and is the most exposed part of the Aran Islands. Its bathymetry is also the most dramatic: the 30-m contour is less than 200 m offshore on average (9° average slope) and comes as close as 50 m to Inishmaan's western coast (local slope of >30°). We speculate—but cannot prove—that these bathymetric characteristics may explain why the highest-elevation boulder ridges are found on Inishmaan.

Deep water so close offshore means that large ocean waves can approach unmodified to within a wavelength or two of the coast and that they do not break until they are very close to shore. The water depth at which waves break depends on both the size of the wave and the bottom slope. For 12-m waves with an 11-s period, the breaking depth is 15 m for a 2° slope and 11 m if the slope is 30° (calculations use equations in Smith 2003). A 17-m wave with a 14-s period will break in 20-m water at 2°, but if the slope is 30° it will break in water as shallow as 14 m. In the latter case, the breaking depth is only 30 m from the shoreline (based on equations in Dean and Dalrymple 1991; the calculations are based on waves approaching approximately normal to the coastline, which is commonly the case for the Aran Islands [Williams and Hall 2004]). These back-of-the-envelope calculations show that waves of the magnitude recorded in the last few years can approach to within a few tens of meters of the Aran Islands coast without breaking.

The closer the unbroken waves can approach, the more they are liable to interfere with earlier waves reflected back from the steep coastline, which can impede breaking and increase wave height. Brossard and Duperret (2004) have shown that for smooth, sediment-free ramps in front of vertical faces (as characterize much of the Aran Islands), wave-reflection coefficients can be as large as 0.8–0.9—that is, the reflected waves are 80%–90% as high as the incident waves. Interference between the incident and reflected waves can act to amplify wave heights, with the potential for (rare but probable) increase up to almost twice the original wave height. Consequently, the Aran Islands near-shore environment is subject to magnified wave heights and strongly nonlinear wave behavior.

Finally, we point out that the reported wave data from the buoy records are SWHs, not individual wave heights. Because the SWH measures the average of the largest third of waves, seas characterized by a given SWH will include waves that may be more than two times SWH. Thus, a 17.2-m SWH might incorporate waves ≈35 m high. The combination of large waves and constructive interference driven by wave reflection is likely to produce cliff overtopping. We also note that there exists less than 5 yr of record for open-ocean wave heights in this area; it therefore seems likely that we have not yet recorded the largest waves in this system. And it is important to remember that emplacement of the megagravel in the Aran Islands ridges would require only a few exceptionally large wave events per century.

Building Ridges versus Moving Individual Blocks: Repetitive Wave Action versus Tsunami Events. A fundamental trait of the boulder ridges is their organization: sharp-crested, sorted, and imbricated. Williams and Hall (2004) have argued that the pronounced boulder imbrication suggests the importance of repeat wave action in forming the ridges, and they also point to the relationship between ridge elevation and imbrication: higher-elevation ridges show poorer imbrication than do ridges near sea level. As ridges at lower elevation would experience more frequent wave reworking, one would expect them to be more organized in consequence.

Storm events—with their shorter recurrence intervals and higher wave frequency—are better candidates for building well-structured ridges. Tsunami events, with their much lower wave frequency, are more likely to leave fields of isolated boulders (Morton et al. 2008). Sedimentology is increasingly recognized as important in distinguishing storm from tsunami deposits. Boulder fields on Ishigaki Island, Japan, segregate into two groups: the population that fines exponentially landward has been attributed to storm-wave transport, whereas the group with no distance-size relationship was probably deposited by a tsunami (Goto et al. 2010*b*). Etienne et al. (2011) and Etienne and Paris (2010) also point out that no modern tsunami has produced ridges.

Difficulties of Using Wave Equations to Draw Conclusions about Boulder Transport in Coastal Settings. Wave-transport equations (especially those of Nott 2003*a*, 2003*b*) have been used as a cornerstone of the argument that the Aran Islands boulders cannot be storm deposited. Scheffers et al. (2009, 2010*a*) posit an upper limit of 10–20 m^3 (26–52 t at 2.6 t/m^3) for storm-wave boulder movement, and although the vast bulk of the Aran Islands ridges are made of clasts well below that mass (table A2), the ridges contain many clasts that are much bigger (e.g., table A5). Therefore, argue Scheffers et al., the Aran Islands ridges must be tsunamigenic.

We disagree. The reasoning by Scheffers et al. (2009, 2010*a*) assumes that the Nott (2003*a*, 2003*b*) equations fully describe wave behavior at the coast, but this is not in fact the case. Morton et al. (2008) point out that although the Nott equations have been commonly used as evidence for tsunami emplacement of large clasts, "there is a clear need for evaluating the basic assumptions of the equations and applications of the results" (p. 636). The Nott equations—and recent updates by Nadesna et al. (2011)—are a valuable tool for thinking about wave dynamics and have helped us wrestle with the problems of block transport, but they represent a simple model of progressive wave motion. Important variables are not considered, including nonuniform coastal slopes and foreshore bathymetry (Kelletat 2008). It does not seem that the equations can be applied in the case of very steep, stepped, or cliffed coasts, such as those that prevail in the Aran Islands, and they do not account for wave-modifying effects, such as reflection and constructive interference.

The physical experiments of Hansom et al. (2008) show the complex behavior that results when wave trains impact a cliff wall. Because the cliff modifies the behavior of the leading wave and causes it to fall back and interact with the successive waves in the train, even waves that break below the cliff top can generate overtopping bores that inundate the cliff-top ramp with high-velocity flow. Hu et al. (2000) have pointed out that "wave overtopping is a complex phenomenon to model. It involves wave shoaling, wave breaking, wave reflection, turbulence and possibly wind effects on water spray. Because of wave reflection, the complex nature of random waves is an important factor in wave overtopping. Unsurprisingly therefore, the accurate numerical modeling of wave overtopping is a very difficult task" (p. 434).

An additional wrinkle in trying to model boulder transport comes from individual waves that can be much taller than the background wave spectrum. Such rogue waves—defined as having at least twice the local SWH (Kharif and Pelinovsky 2003)—have been studied mostly in the open ocean context, where bathymetry is not a variable. Recently, however, workers have begun to investigate the production of rogue waves in shallow-water coastal settings and to articulate the conditions under which exceptionally large and steep waves may form (e.g., Didenkulova and Anderson 2006; Soomere 2010; Didenkulova 2011). Compilation of data from Taiwan, where people are killed regularly by such "mad-dog" waves, has shown that they occur mostly along cliffed coasts or at breakwaters fronting waters >10 m deep, with steep offshore slopes (Tsai et al. 2004).

Modeling such waves—predicting their formation from the background wave spectrum and characterizing their heights—is beyond our current capabilities (e.g., Tsai et al. 2004; Soomere 2010), especially when combined with the additional complexities of wave-cliff interactions (Ryu et al. 2007; Hansom et al. 2008). New ideas and data are rapidly emerging, however, and recent modeling by Hansom et al. (2008) has expanded our understanding of excavation and transport of large blocks by large overtopping waves.

These relatively rare individual rogue wave events are likely to be key players in moving megagravel in coastal settings. To wit, the numerous megagravel blocks of the Aran Islands boulder ridges are impressive but numerically a minor constituent of the ridges (table A2); thus, their emplacement reflects infrequent, extra-high-energy wave events. Thus, the inadequacy of current numerical models is highlighted in two ways by the Aran Island deposits: the steep bathymetric setting precludes use of progressive-wave models to predict wave behavior at the coast, and movement of the largest clasts may be accomplished by waves that greatly exceed the SWH values for any given storm event.

Our grasp of storm-wave dynamics is in its infancy, and no set of equations fully characterizes coastal wave behavior or wave-sediment hydraulics—yet. We argue, therefore, that the hypothesis of storm-wave emplacement does not stand or fall based on existing equations. The equations provide useful estimates for the energy required for boulder entrainment and can provide guidelines to the relationships between wave energy and block transport, but they cannot be used either to prove or disprove a transport and emplacement mechanism. That existing numerical recipes indicate that storm waves cannot move boulders that fieldwork and GIS analysis can prove have been moved by storm waves signifies that we do not yet understand the system well enough to model it quantitatively. Future work must therefore build on the existing equations and try to capture the nonlinear, possibly chaotic physics of coastal storm-wave behavior.

In Closing

Coastal boulder deposits record local extremes in clast transport energy and therefore provide anchor points for understanding wave transport and coastal erosion processes. The larger the clasts, the greater the force required to quarry and move them; and the higher the elevation above sea level, the bigger the waves involved. The question of whether storms or tsunami emplace these boulders is important, as shown by recent debate on the issue (Williams and Hall 2004; Scheffers et al. 2009, 2010*a*; Hall et al. 2010).

Why are there conflicting interpretations of these rocks? The bulk of the field evidence supports recent ridge activity, and the GIS analysis (figs. 5, 6) shows that whereas substantial lengths of ridge have remained stable in space, other large sections have moved wholesale since 1839, destroying walls and invading fields. But contradictory interpretations have been possible because existing equations appear to preclude storm-wave emplacement of the largest blocks measured in the Aran Islands boulder ridges.

There are, however, two reasons why these equations can be disregarded. First, proliferation of precise wave-height measurements has brought an enhanced appreciation for the frequency and magnitude of large ocean waves, especially those that are more than twice SWH (e.g., Turton and Fenna 2008). Second, existing wave equations do not include the effects of reflection from cliff and shoreline and the attendant wave amplification. Thus, nominal storm-wave heights and wave equations are not a good predictor of the absolute height or behavior of individual waves along a steep shoreline: larger waves than are represented by the SWH occur, and interaction with the coast and near-coast bathymetry can magnify those waves yet further.

We do not reject the hypothesis of tsunami involvement in ridge dynamics: a cliff-overtopping tsunami could certainly cause block dislodgement and motion, and prehistoric tsunamis may have contributed to ridge building. The ^{14}C data (table A3; fig. 4) demonstrate the long histories of the Aran Island ridges, and it is statistically probable that parts of these ridges—or their predecessors—were active before 2000 yr ago. In those distant times, it is possible that earthquakes or Storegga-slide-type continental slope collapse processes could have generated tsunamis that contributed to block movements on the western European cliff tops.

But tsunamis alone cannot be the cause of these ridges, and tsunamis cannot be implicated in any recent ridge activity. Hall et al. (2006, 2010) have pointed out that there is no written or geologic evidence for significant tsunami events affecting western Ireland in the historic past. And Scheffers et al. (2010*b*) have also stated that the maximum run-up height of any north Atlantic tsunami in the last 400 yr has been 6 m. Consequently, tsunamigenic boulder movements or ridge migration within the last few hundred years at elevations greater than 6 m is simply impossible. We must conclude that ridge activity in the modern and in the recent past is linked to storm activity.

To stand on the Inishmaan cliff tops when a swell is running is to know that the wave heights at the cliffs can be much greater than the equilibrium heights of the approaching deep-water waves. Waves steepen as they shoal, impact the coast, reflect back, and meet the advancing wave crests. The resulting mixture of constructive and destructive interference results in a very confused sea state, with intermittent production of very large individual waves. On days when fairly ordinary 5-m swells are running and wave watching from the cliff tops is only slightly perilous, it is common to observe individual waves shooting straight up the rock wall and collapsing on ramps 18 or 20 m above sea level. There are (as yet) no systematic observations of the highly complex coastal wave behaviors that must result during major storms where the SWH is >10 m. But if a 5-m SWH can inundate an 18-m-high ramp, we invite the reader—in the absence of direct observations of what it is like during strong storms—to combine imagination with the data showing recent large-block movement. We conclude that storm waves striking the Aran Islands cliffs and stepped coasts are indeed capable of erosion and transport of truly massive blocks and construction of organized, imbricated, sorted deposits.

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