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Wibke Erdmann
Dieter Kelletat
Anja Scheffers
Simon K. Haslett

Origin and Formation of Coastal Boulder Deposits at Galway Bay and the Aran Islands, Western Ireland

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Wibke Erdmann
Seminar for Geography and Education
University of Cologne
Cologne
Germany

Dieter Kelletat
Seminar for Geography and Education
University of Cologne
Cologne
Germany

Anja Scheffers
Southern Cross GeoScience
Southern Cross University
Lismore, NSW
Australia

Simon K. Haslett
Coastal and Marine Research Group
University of Wales
Cardiff
UK

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Preface

The most extended geomorphological feature on Earth is the coastline, being more than one Mio km long in total. They all are very young in geological timescales and started their evolution about 6000–7000 years ago, when sea-level again reached modern values after the −120 m low-stand of the last ice age. Coastal forms and sediments normally are comparably easy to detect because of their open exposure and only limited thickness, and the methods to analyse the deposits are well developed. Nevertheless, some important questions on coastal evolution are rather embryonic in the geosciences, such as research on the importance of extreme events (for landforms and sediments) like tropical and extra-tropical storms (*paleotempestology*), or *paleo-tsunami research*. Until today, for most coastlines, it is unknown whether the continuous forming under "normal" conditions of wave and tide impacts, or extraordinarily strong but rare events contribute more to coastal evolution, but during the past two decades significant advances have been made.

It is surprising that a rather simple problem also remains unsolved, which is the process and energy required to move large fragments from sea to land, or, in other words, which forces have deposited large boulders onshore: storm waves or tsunami flow? Identifying transport modes of tsunami flow is difficult because of the rareness of the processes involved, but storm wave modes certainly have been observed and even registered, numerically measured, and modelled many thousand times. However, if a publication on coastal boulder deposits by storm waves is presented, critics might favour of a tsunamigenic transport, and vice versa.

As the central west coast of Ireland is not only strongly exposed to winter storm waves but also exhibits one of the most spectacular coastal boulder deposits of the World regarding size of clasts, position inland and above sea-level, the documentation of the wide spectrum of natural features from this region may help to develop the general discussion on coastal boulder transport processes. We present material which has been gained from the Galway Bay and Aran Island area through our own fieldwork since the year 2006 (as well as from other coastal regions of the world under extreme conditions by own research and from the literature) in an extensive documentation with the main emphasis on quantitative field data, based also on recent investigations on the result of six extraordinary winter storms of the season

2013/2014 in the NE Atlantic Ocean. In comparison to observations from other coastal sections of the World under extreme forming processes we will conclude on the main processes involved and, therefore, to promote the knowledge of coastal evolution under strong geomorphological and sedimentological impacts.

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Cologne, December 2014 Wibke Erdmann
Dieter Kelletat
Mullumbimby Anja Scheffers
Cardiff Simon K. Haslett

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Chapter 1
Introduction

Abstract Western Ireland has one of the most exposed coastlines of the world. Its large coastal boulder deposits challenge researchers to solve the question of transport: by extreme storm waves, or by tsunamis? This chapter presents the state of the discussion, based on the storm history of the region and in particular on recent field inspections of the transport energy of six extraordinary winter storms of the season 2013/14. To build a base for conclusions from Ireland on similar boulder deposits worldwide, references on other regions and in particular from near-time inspections of storm effects are presented. The challenges to solve this imply how precise wave heights measured in the open ocean are significant for their energies at the coastline, and how the transport process by storm waves at near vertical cliff faces in fact works. As all the deposits derive from a high sea-level of the Recent Holocene, any variations in sea-level over the last >6000 years have also to be considered.

Keywords Coastal boulders · Storm waves · Tsunamis · Western Ireland · Recent winter storms · Wave transport modes

The central west coast of Ireland around the Aran Islands belongs to the most exposed European coastlines, open to storms from the NE Atlantic with very high waves approaching over deep waters. Their geological setting with old (Carboniferous) and well stratified limestone (Fig. 1.1) allows waves to liberate platy and angular boulders of sizes from small boulders to blocks >10 m long and a mass of >100 tons, which now can be found high above the high water tide level. Their dislocation to inland and against gravitation is acknowledged from all researchers working on questions of coastal boulder transport in the area. Our documentation intends to sum up the objective evidence from nature, added to by a discussion on arguments published, and our additional and new conclusions.

Storm wave movement and emplacement of large boulders and blocks, from near the coastline, at cliff top position, or more than 200 m to inland, have been observed (in only very few cases during the dislocation, mostly shortly after the events) and published in a rising number during the last 10 years from different regions of the

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Fig. 1.1 A typical aspect of a cliff coast or a stepped cliff of the Aran Islands. Undermining occurs along shale strata, where freshwater springs may seep out. Boulder ridges in cliff top position, here at about +15 m MHW. Photo shows an aspect from Inishmore's SW coast (Image credit: D. Kelletat)

World, either from tropical cyclones, or from winter storms: Noormets et al. (2004), from Hawaii, Williams and Hall (2004) from western Ireland, Scheffers and Scheffers (2006) from Bonaire, southern Caribbean, Hall et al. (2006) from Ireland and Scotland, Fichaut and Suanez (2008) from Banneg Island, Britanny, France, Goto et al. (2009) from Japan, Hansom and Hall (2009) from the NE Atlantic Ocean, Knight et al. (2009)from NW Ireland, Scheffers et al. (2009) from western Ireland, Suanez et al. (2009) from Banneg Island, Britanny, France, Zentner et al. (2009) from the Aran Islands, central west coast of Ireland, Terry and Etienne (2010) from tropical islands of the Pacific Ocean, Etienne and Paris (2010) from Reykjanes peninsula, SW Iceland, Goto et al. (2010a, b, c), from Okinawa, southern Japan, Hall (2010) from Scotland, Scheffers et al. (2010a, b) from Ireland and Scotland, Khan et al. (2010) from Jamaika, Williams (2010, 2011) from the west coast of Ireland, Fichaut and Suanez (2011) from the Banneg Island and Briggs (2007) from Bair d'Audierne, Britanny, France, Paris et al. (2011) in a general reflection on storm boulders, Cox et al. (2012) on western Ireland, Terry et al. (2013) from the tropical Pacific, or Annie Lau et al. (2014) from French Polynesia.

As a general result we can conclude, that boulders moved by recent storms may be large (a few tons and over 20 tons in singular cases), but their lifting against gravitation often is reduced to a few metres, and their horizontal transportation to some metres up to around 100 m, depending on the slope, roughness and friction, boulder forms and wave approach as well as bathymetry, where the largest boulders have been moved for the shorter distances and up lower elevations against gravitation.

Another group of publications is devoted to the problem, whether the boulders in a coastal environment have been dislocated by storm waves or by tsunami impacts with their much longer water flow. Often the authors keep interpretations open and give their observations and conclusions to fellow scientists for discussion. Recent papers are—among others—Scheffers (2002, 2005) for islands in the southern Caribbean, Goff et al. (2004) for New Zealand, Whelan and Kelletat (2005) for the Lisbon region (Portugal), Barbano et al. (2010) for Sicily (Italy), Switzer and Burston (2010) for SE Australia, Goto et al. (2010d) for the Ryukyu Islands of southern Japan, Lorang (2011) in a general discourse, Richmond et al. (2011) for the south coast of Hawaii, or Weiss (2012) again in a general discussion.

Some authors as Bourrouilh-Le Jan and Talandier (1985) for Tuamotu, (SE Pacific), or Frohlich et al. (2009) for Tonga tend to a tsunamigenic source of the dislocation of giant blocks (>1,000 tons), but do not exclude exceptional waves from tropical cyclones (category 5).

Aware of the uncertainties of interpretations concerning the transport mode and process, several authors and teams worked on simulations of transport processes, either by tests in a lab or wave channel/tank, by physical calculations of a wide combination of boulder settings and characters, or by modelling (only sometimes on the base of observations and data from nature). Among these are e.g. Nott (2003a, b) discussing the boulder transport according to the origin of boulders from the three principally different settings at a rocky shoreline as submerged, subaerial, or joint bounded, Ryu et al. (2007) modelling green water or bore velocity after wave breaking, Hansom et al. (2008) modelling cliff top erosion by boulder dislocation, Benner et al. (2010) in finding the threshold size of boulders moved either from storms or from tsunamis, and Nandesana et al. (2011) or Nandesana and Tanaka (2013) with interesting test results from a wave and flow channel.

As our contribution to the boulder movement problem along rocky shorelines of the world in this chapter is restricted to the central west coast of Ireland and additional arguments from the winter storm season of mid-December 2013 to mid-February 2014, we should present some data on former strong storms in this wider area for a better judgement on the strength of wave forces during this period and region. For recent decades, measurements of air pressure and winds are available from several stations, but a good base for the reconstruction of earlier conditions is possible, at least for the "Night of the Big Wind" in 1839 AD. According to Shields and Fitzgerald (1989) and Burt (2006), a central pressure of only 918 hPa to 922 hPa in the core of this depression near the Shetland Islands of northern Scotland put this event to be equal to a category 5 hurricane, where one minute sustained winds may reach more than 250 km/h. Lamb (1991) considered it the most severe storm to affect Ireland within the last 500 years and one of the deepest depressions ever recorded in the immediate vicinity of the British Isles.

For the Aran Islands of western Ireland, the study sites of this paper, a central pressure of a little less than 970 hPa has been reconstructed for the same event (Shields and Fitzgerald 1989), with wind gusts up to 167 km/h. Byrne (2003) give details for the 1703 AD storm over Great Britain, and Hickey et al. (2001) for the 1953 winter storm in Scotland, a depression which brought a flood catastrophe to the Netherlands with hundreds of fatalities.

Following hurricane Debbie, in 1961 sustainable winds of 124 km/h and gusts up to 172 km/h occurred in northern Ireland (MacClenaghan et al. 2001), and for the last half of the 20th century in northern Ireland sustained winds (10 min) of 126 km/h and gusts in excess of 200 km/h are plausible for the same region (Williams and Hall 2004).

On February 9th, 1988, central pressure of a cyclone was 943 hPa (a category 3+ hurricane) with gusts of 185 km/h at 57 °N, in 1991 at the Aran Islands central pressure was measured to be 946 hPa with winds in excess of 150 km/h (MacClenaghan et al. 2001), on January 8th, 1993, at the Shetland Islands, pressure was down to 916 hPa (similar to a category 5 hurricane), and winds reached more than 170 km/h at the Irish Donegal coast in 1998 (Turton and Fenna 2008). At the open water buoy M1, which is anchored 95 km west of the Aran Islands, during the strongest storm in 2007 a central pressure of 966 hPa with 130 km/h sustainable winds (10 min) has been registered (Turton and Fenna 2008).

In these storm events with exceptional force, the six winter storms of the season 2013/14 (Fig. 1.2a) fit very well, and their categorizing as very extreme events even for the stormy coastlines of the NE Atlantic Ocean by coastal people, with waves higher than ever in their live or memory, seems a reasonable judgement.

The lowest central pressure of Ireland's winter storms 2013–2014 has been:

- end of year 2013/14: 927 hPa
- "Anne", January 1–6, 2014: 947 hPa
- "Cristina", January 3–10, 2014: 940 hPa
- "Nadja", January 29–February 5, 2014: 945 hPa
- "Petra", February 3–8, 2014: 950 hPa
- "Ruth", February 6–11, 2014: 945 hPa

A central pressure of 945–964 hPa equals a category 3 hurricane, and 944–920 hPa is a category 4 hurricane which means, that from these six storms within only 8 weeks, four had a hurricane 3 wind force (1 min sustained winds of 178–208 km/h), and two a hurricane 4 wind force (209–251 km/h 1 min sustained winds) (Fig. 1.2b). Except of (most probably) the 1839 AD "Night of the Big Wind" (just category 5), the winter storms of the season 2013/14 therefore, belong to the strongest for the last nearly 200 years (and maybe a much longer period back).

Fortunately, some wave data are available for strong storms in the vicinity of western Ireland (Draper 1972, 1991; Aqua Fact 2002; Met Éireann 2007; Turton and Fenna 2008, or O'Brien et al. 2013), although not for the direct coastline situations. The highest wave so far recorded from a research vessel in the Rockall Area of the NE Atlantic, which is about 400 km NW of the Aran Islands, was 29.1 m in 2000 AD, whereas at the M1 buoy 95 km west of the Aran group (Fig. 1.3) waves have been measured to 18.2 m, the highest ever recorded in these waters from an anchored device (Zentner 2009). For comparison, the highest

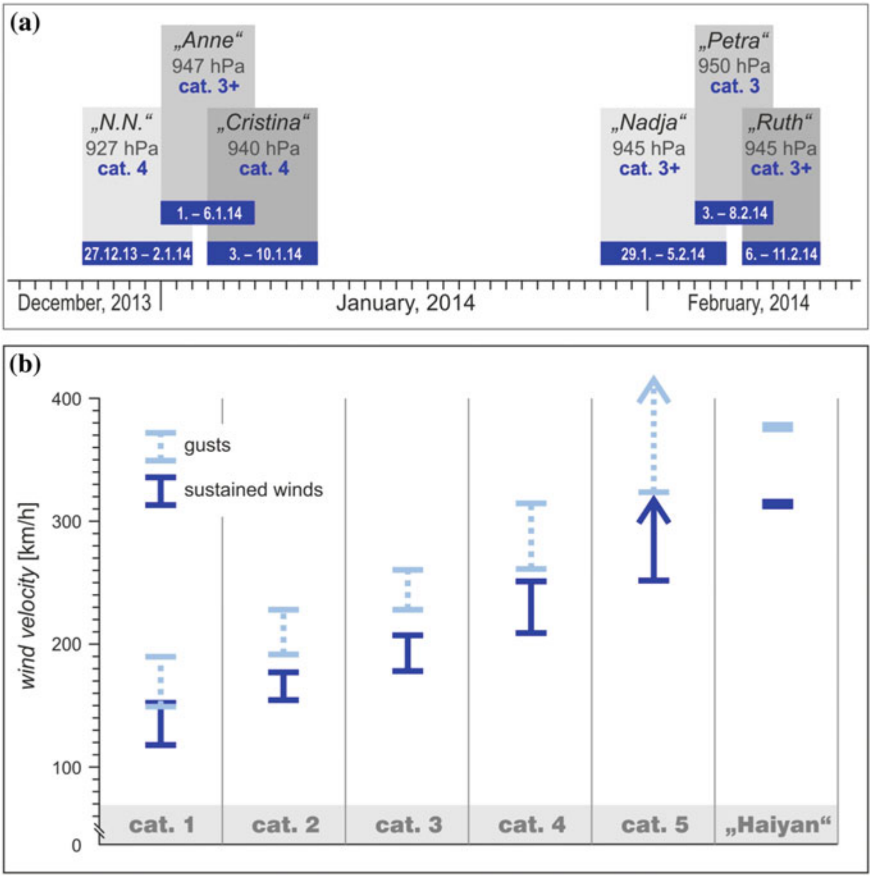

Fig. 1.2 **a** Temporal distribution, central pressure and hurricane categories of six extreme winter storms west of Ireland in the season 2013/14. **b** Velocity of sustained winds (1 min) and gusts of hurricane categories 1–5 and super-typhoon "Haiyan" (Philippines, Nov. 2013), according to the Saffir-Simpson-Hurricane Scale (Image credit: Anne Hager)

recorded wave in the Gulf of Mexico from a buoy was 27.7 m during hurricane Ivan (category 5) in 2004. The same hurricane, although 200 km passing to the north, brought waves at least 12 m high directly at the 5 m high cliffs of Bonaire's east coast (Scheffers and Scheffers 2006). As boulders of around two tons have been broken from the cliff top of Inishmaan (the middle of the Aran Islands) and have been dislocated for a few metres about 24 m above MHW level (see Chap. 4: Results), waves may have had a height of around 15 m along the deep water coasts in open exposure to the Atlantic Ocean. As a consequence we can assume, that these winter storms represented very strong wave power and transport capacity for boulder movements onshore, in particular because of thousands of energy inputs during the six consecutive hurricane conditions. Observations of boulder dislocation from these events therefore may document the upper values for their deposits (size of fragments moved, distances to landward and against gravitation) possible in this area, and give a new base for conclusions of the genesis of cliff top boulder ridges in western Ireland (Fig. 1.3).

Text documents and photographs on the boulder deposits of the exposed sides of the Aran Islands can also be found in Williams (2004), Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al. (2008), Hansom and Hall (2009), Zentner (2009), Scheffers et al. (2009, 2010a, b), Hall (2010), Williams (2010, 2011), and Cox et al. (2012). Beside the strong exposure to deep water waves, the petrographic disposition supports boulder quarrying and plucking: near horizontal bedding planes (Fig. 1.1) and patterns of fractures/joints (often crossing in about 90°) give way to weathering, in particular by limestone solution. Fragments are often still joint bounded, but more or less as loose boulders waiting for dislocation by waves, either down into the sea, upwards on a cliff top, or to landwards. Their size is strongly dependent on the separation distance of main joints and the thickness of the limestone strata: most of the boulders are less than one m thick, often even less than 0.5 m, but maybe very long. As a result of the petrographic conditions, the size of the dislocated boulders may not represent the storm wave forces or other processes that would be required to transport them. This is an important point when comparing coastal boulder size around the world to judge required transport power: only if all sizes of boulders (up to giant blocks) are available, a logic conclusion on maximum transport power active at the different sites is possible.

Several authors have delivered a large number of boulder and ridge measurements as a statistical basis. Zentner (2009) measured 2688 boulders with all three

Fig. 1.3 Position of anchored buoys west of Ireland. M6 lies nearly 400 km, M1 about 95 km west of the Aran Islands (Image credit: © Google earth 2012, modified)

axes, but evidently not incorporating really large ones: only 102 (3.8 %) had longest axes between 1–2 m, and 10 (0.37 %) longest axes of 2–3 m, not a single boulder had a volume of four m^3 or higher or a mass of 10 tons or more. This is not representative for most of the boulder deposits as can be seen in the documents of this paper. Cox et al. (2012) inspected 114 transects of ridges and measured the 5 largest clasts in each transect which sums up to 570 individual boulders measured.

Within the last decade, several publications have been devoted to the coastal boulder deposits in the Galway and Aran landscapes (in chronological order, bold letters from the authors of this paper):

The first and substantial paper on the problem (Williams and Hall 2004) is based on many interesting observations. It comes up with the conclusion, that storm waves are responsible for the organization of the boulder ridges.

The following papers of Hall et al. (2006), Hansom et al. (2008), and Hansom and Hall (2009) as well argue for a storm wave origin, as does Zentner (2009) in her thesis, and Hansom et al. (2008). Scheffers et al. (2009, 2010a) argue for tsunami processes for the initial and significant dislocation of the largest group of old boulders based on comparison with other own observations along different high energy coastlines of the world, and present again their arguments in a reply to Hall et al. (2010) in Scheffers et al. (2010b).

Williams (2010) updated his arguments with the hypothesis of wave forces changed into bore flow of high velocities and again prefers storm wave dislocation. Cox et al. (2012) sum up arguments from the papers mentioned above and discount any tsunami contribution to boulder ridge forming. They do not, however, include arguments found along the sheltered sides of the Aran Islands or from the Galway Bay east coast. Therefore, we will examine them (and others published) again in this contribution, added by impressions from our study of the transport energy and boulder emplacement in the region from six extreme winter storms of the season 2013/14.

There is no doubt, that storms with hurricane wind forces and significant highest waves in the order of 15–18 m in the open Atlantic Ocean west of Ireland occur, and a 29.1 m high wave has been measured in 2000 AD by a research vessel in the Rockall region (about 400 km west of the Aran Islands, see Zentner 2009). These wave heights, however, cannot be used for any calculation of transport energies at the rocky and cliff coasts of the Aran Islands, and in particular not for their bayward shores or those from inside Galway Bay, which also exhibit large coastal boulders in clusters and ridges.

As the wave height is given as the vertical distance from the crest to the trough, even a 20 m wave in deep water at the cliff coast (in our views most probably beyond reality) will only produce a *green water bore* at cliffs lower than 10 m. Higher cliffs (which are present along most of the exposed cliff lines of the Aran Islands) may just exhibit *white water bores* with a lot of turbulences and therefore loosing energy for boulder transport on cliff top platforms compared to green water bores.

Another point, presented with different data in the literature, is the velocity of "*green water*" bores on cliff top platforms as transformation of the rising high wave at a steep cliff and immediately at the cliff top. Williams and Hall (2004) as well as Hansom et al. (2008, based on Cox and Ortega 2002), Williams (2010), and Zentner (2009:44) …*The acceleration inland of overtopping bores explains why wider ridge systems are found farther inland, independent of cliff height”),* argue with exceptional velocities experienced over the cliff-top platform under bore flow conditions to move large clasts and assume, that green-water overtopping of a cliff-top platform results in wave collapse onto the deck and the development of a bore whose velocity may be up to 2.4 times that of the original wave. As the cliff top platform often has several steps (which might produce several bore flows), they additionally argue, that in the case of the platforms of the Aran Islands forward wave velocities will increase progressively by crossing platform margins (steps) thus enhancing the waves' capabilities for clast transport at progressively higher levels (or, in other words: the bore flow velocity will rise from step to step, maybe with the factor of 2.4 each time! Williams and Hall (2004:115) *“In the case of the platforms of the Aran Islands forward wave velocities will be increased progressively by crossing platform margins thus enhancing the waves' capabilities for clast transport at progressively higher levels”*). This, however, means, that although the movement has to overcome friction and gravitation on a rising slope as well as transport of fragments, it will not loose but gain energy—an idea which is in contrast to all the physical laws we know. If we take the results from Ryu et al. (2007) there may be a general misunderstanding: Ryu et al. (2007) found the maximum horizontal velocity on a (horizontal?) platform to be 1.15 times that of the wave phase. But the rising splash at a vertical cliff could be 2.9 times the wave's velocity (which resembles 2.6 times the maximum bore velocity). The splash velocity maybe important to break fragments out of the cliff top, but for their dislocation to inland on the cliff top platform, a strong flow is needed, which, according to Ryu et al. (2007), is not too much different from the wave velocity and, therefore, not a multiplication of the wave's energy by transforming into bore flow.

Multiple calculations and equations for boulder transport from different initial scenarios and of different form and mass exist, differing in methods, mathematics and therefore results, not always close to natural conditions. We prefer to support our arguments with field observations and measurements, and in a second step in comparison these natural and objective data with those from similar settings around the coastlines of the world. This is in particular the case regarding boulder transport by storm waves (including those from tropical cyclones with high surges). Additionally, we combine these data with observations on the extension, altitude, distance to the shoreline and mass of single boulders and whole boulder ridges, together with age indicators for their activity. Again—as we do not have observations from processes a long time ago—we have to compare the observations with published data from other coastal regions of the world, in particular those affected by other strong forces, which might be tsunami flow. We will do this without any prejudice and will avoid such conclusions as found in Cox et al. (2012, p. 251): *“…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"*. We are convinced, that even if boulder movement of significant size and distance has taken place during recent storms, the construction of the ridges and their old history does not exclude other forces than storm waves, which are tsunamis. This is in particular the case, as the extreme powerful six winter storms of the season 2012/14 along the Irish west coast have not been able to dislocate boulders of the highest class into the higher elevations and distances from the cliffs as can be observed in the old ridges.

Discussing coastal deposits far and high on land which have been dated up to 4,000 years BP has to include the question on the sea-level history for the Recent Holocene: was it ever higher than today, and are some of the exceptional deposits the result of a higher sea-level which allowed boulder transport further inland and to higher elevations? As Galway Bay and the Aran Islands have been covered by several 100 m of ice during the last glaciation we might expect a glacio-isostaic rebound and uplift of the coastal region which has lifted the deposits under debate into higher elevations than marine forces may have the power today. As a result of several studies and modelling the glacio-isostasy, the central west coast of Ireland is situated outside an uplift area and shows sea-levels between −2 and −4 m about 6000 years ago (Brooks et al. 2008; Bradley et al. 2011). This also excludes signatures of higher Holocene sea-levels by eustatic reasons in Galway Bay and the Aran Islands. What we see today in the coastal boulder deposits therefore, must be the result of marine transport power during sea-levels lower or in the same elevation as today, but—due to coastal erosion over time—certainly working farther apart from the modern surf belt to seawards.

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Chapter 2
Study Sites, Methods and Aim

Abstract Rocky shorelines within southeastern Galway Bay and on the Aran Islands exhibit stepped platforms as well as steep cliffs with heights up to more than 20 m. Here field research on recent boulder movement by six exceptional strong winter storms of the season 2013/14 has been made. Quantitative data on boulder location, size, distances moved horizontally and vertically, and source of the boulders have been collected, as well as observations and documentation on signatures of the transport process on the rock platforms and on boulders themselves. The results are compared with the size of existing (old) boulders and their potential transport data. During fieldwork special emphasis was given on the morphologic aspects of boulder deposits and their internal architecture, and to imply sites of different intensity of exposure and bathymetry. The investigations should contribute to the question of boulder ridge genesis, with an extended documentation from field impressions in figures and photos as a base for later conclusions.

Keywords Study sites · Impact marks · Quantitative boulder data · Bulk density · Coastal erosion · Morphologies of deposits

In this chapter, we concentrate on the boulder clusters and boulder ridges deposited at the coastlines of the three Aran Islands as well as at the south-eastern coast of Galway Bay (Figs. 2.1, 2.2, 2.3 and 2.4).

In 2006, 2007 and 2008, we inspected and documented all the coastlines of Inisheer, Inishmaan and Inishmore as well as the 20 km long coastal section between Black Head and Doolin at the mainland (see Scheffers et al. 2009, 2010a, b). In June, 2014, we visited the area again to document the consequences of six extreme winter storms of the season 2013/14. Beside measurements of boulder axes lengths, volume, density and mass, we collected data on (potential) horizontal and vertical transport distances (if source areas could be identified), and took samples for numerical dating from boring bivalves (*Hiatella arctica*) out of large dislocated boulders. We also observed other signatures of dislocation and relative age like lichen cover or biogenic hints like calcareous algae, *Patella* resting places, sea urchin resting places, and bioerosive rock pools, all from the supra-tidal to sub-tidal region, as well

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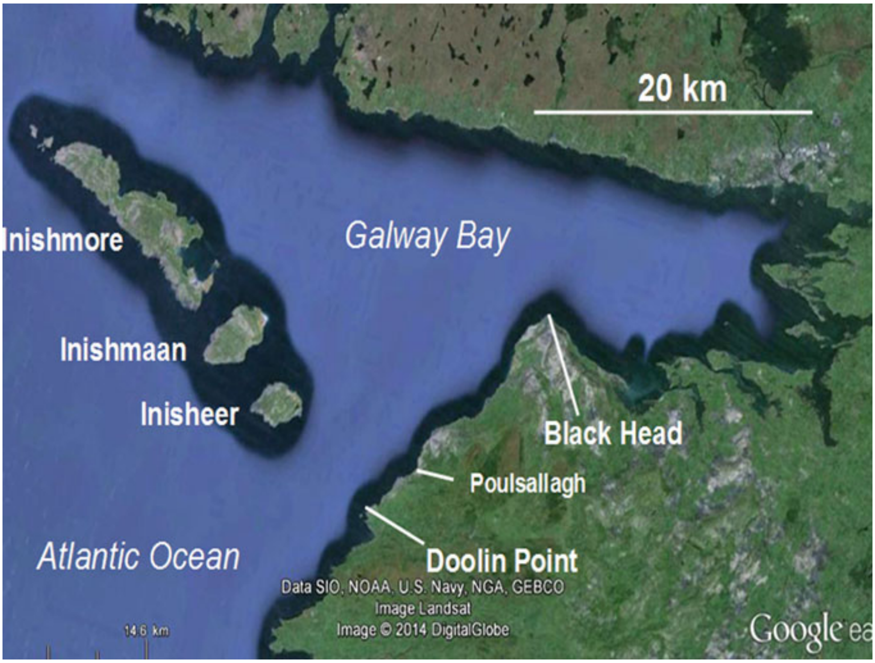

Fig. 2.1 Study area at the central west coast of Ireland: the three Aran Islands Inishmore, Inishmaan and Inisheer, and the SE coast of Galway Bay from Doolin to Black Head (*Image credit* © Google earth 2012, modified)

as the intensity (if given) of terrestrial limestone solution on rock and boulders. The setting of the boulders and the internal architecture of large deposits have been described, as well, either deriving from an original settling, or from later movements within boulder ridges.

One of our main objectives, however, was the reception of the total environmental parameters of these coarse coastal deposits in the Galway and Aran region, including

- degree of exposure;
- bathymetry (from Chart 3339, edition 2005, and new sounding of INFOMAR);
- potential sea level changes since the Recent Holocene;
- morphologies of the deposits like ridges, clusters, imbrication and imbrication trains, and parallel ridges, ripple-like ridges, or boulder piles;
- signatures of old and fresh impacts, such as striations or shatter marks;
- soil development and erosion of terrestrial deposits at or near the boulder deposits;
- the question of coastal erosion in exposed and sheltered as well as steep (vertical, overhanging) and stepped cliff profiles or rocky coastal slopes, and boulder and cobble beaches;
- the intensity of biogenous processes in the tidal realm forming, for example, rock pools or barnacle carpets.

Fig. 2.2 Typical aspect of the coastal landscape along the exposed coastlines of the Aran Islands (here: Inishmore): steep cliffs in slightly seaward dipping Carboniferous limestone along the main body of the islands, which are smoothed by ice age glaciers. Galway Bay in the background (*Image credit* Anja Scheffers)

Fig. 2.3 Quarrying of boulders along the well stratified limestone coast of eastern Galway Bay. The pattern of joints opened by terrestrial karstification can be seen inland among the drystone walls (*Image credit* Anja Scheffers)

Fig. 2.4 Extremely steep or even overhanging cliffs along the Aran Islands coastlines exposed to the open Atlantic Ocean (*Image credit* D. Kelletat)

Location was assigned from satellite images (by Google Earth Pro, covering at least the years 2000 to 2012) and our own oblique aerial photographs of 2007 as well as from the Helicopter flight documentation of the National Coastline Survey, Marine Institute, Dublin (Ireland 2000), also using DGPS and simple levelling where possible. The altitudes have been related to MHW, controlled by the upper barnacle and *Fucus vesiculosus* belt where possible. Bulk density of several limestone samples has been measured by the Archimedean principle to be from 2.543 g/cm^3 to 2.738 g/cm^3 with a mean of 2.64 g/cm^3. For simplification and to avoid over-scaling of the figures we calculated the volume (from multiplying the *mean* length of a-, b-, and c-axes of boulders) with 2.5 to get the mass of single fragments.

We also feel that it is important not only to concentrate on the very exposed cliff top deposits on the highest elevations with the largest boulders and most perfect ridges, but in particular to check the sheltered coastlines of the Aran Islands to their bay-ward sides, and along coastal sections within Galway Bay. These areas have not been inspected by other authors, but they may hold the key for improving our understanding on the energy and kind of coastal processes (storm waves or tsunamis), at least responsible for some of the movements and forms. The same is true regarding some forms combined with the main ridges like older ridges at their landward side (mentioned but not discussed in terms of their genesis by Williams and Hall (2004), or Zentner (2009)), piles of boulders, or ripple-like features within ridges. Our aim is to document the objective natural appearance as accurately as possible as a base for the interpretation of recent and old processes. This requires the collection of all geomorphologic arguments to establish the story of the Aran and Galway coastal boulder ridge genesis during the Recent Holocene, also to compare these features with similar ones around the World's coastlines.

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Chapter 3
Results from Field Work

Abstract This chapter documents the distribution of very large single coastal boulders from recent storm waves along the most exposed shorelines of Inishmore and Inishmaan as well as from the more protected coast of inner Galway Bay, as well as signatures of the movement process in the form of striations or impact marks on rock and boulders. A comparison of the size and transport distances of freshly moved boulders, old boulders moved recently, and the minimum size of old boulders not recently moved although within the surf belt allows to find a threshold for storm wave power on boulder dislocation. For an objective judgement, field documents from other exposed rocky coastlines of the world are also presented.

Keywords Boulder size · Recent movements · Signatures of movement · Inishmore · Inishmaan · Galway Bay · Worldwide comparison

3.1 Observation on Recent Storm Wave Movement of Coastal Boulders on the Aran Islands and in Galway Bay

3.1.1 Size of Dislocated Boulders

The first aspect from the boulder deposits in Galway Bay and on the Aran Islands is the impressive size of their fragments (Figs. 3.1, 3.2 and 3.3), which may hold the key for a first approximation to the moving forces. Very large boulders occur single, as small clusters, incorporated in high and long ridges, as well as flat lying, leaning against rocky or boulder obstacles or forming perfect imbrication, even in longer imbrication trains. Small boulders and cobble size fragments often fill the gaps between large boulders, but the "pores" between them also maybe open, so that many boulders are balancing or just rest on a few points as basement (as in Fig. 3.3d).

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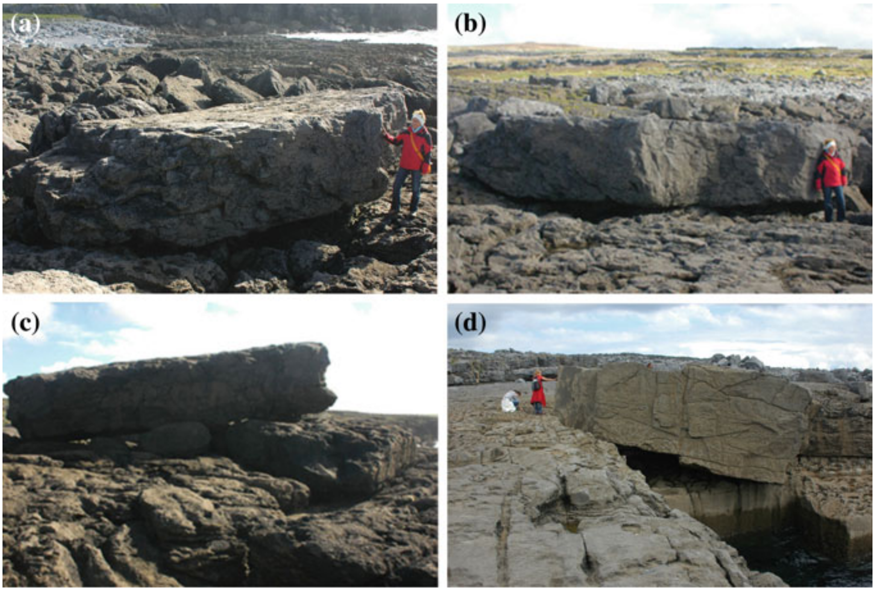

Fig. 3.1 Very large single dislocated coastal boulders from the Galway area. **a**, **b** Galway Bay (>80 tons) same boulder. **c** Galway Bay (>50 tons). **d** Inishmore, west of wormhole (>200 tons) (*Image credit* D. Kelletat)

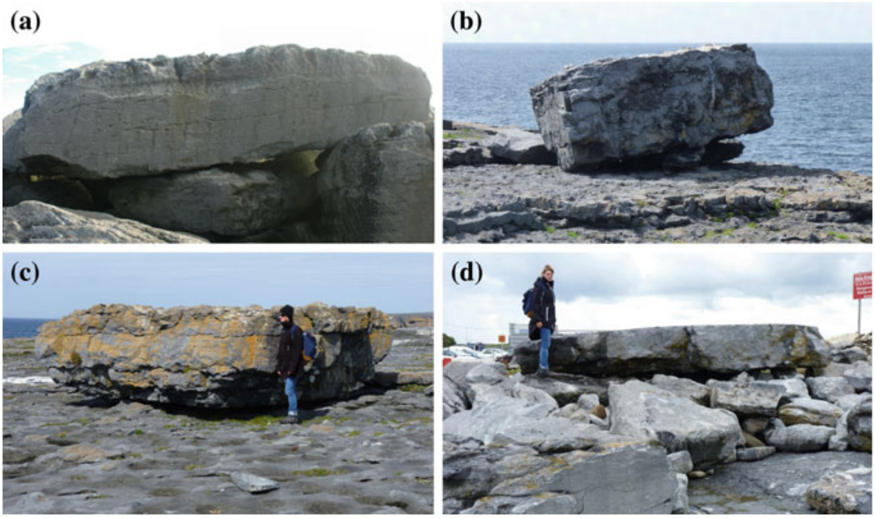

Fig. 3.2 Large coastal boulders on rock platforms or in boulder clusters. **a** Poulsallagh, Galway Bay (~40 tons). **b** Inishmore SW coast (>20 tons). **c** Inishmore, SW coast at +10 m (>40 tons). **d** Doolin SE (>30 tons) (*Image credit* D. Kelletat)

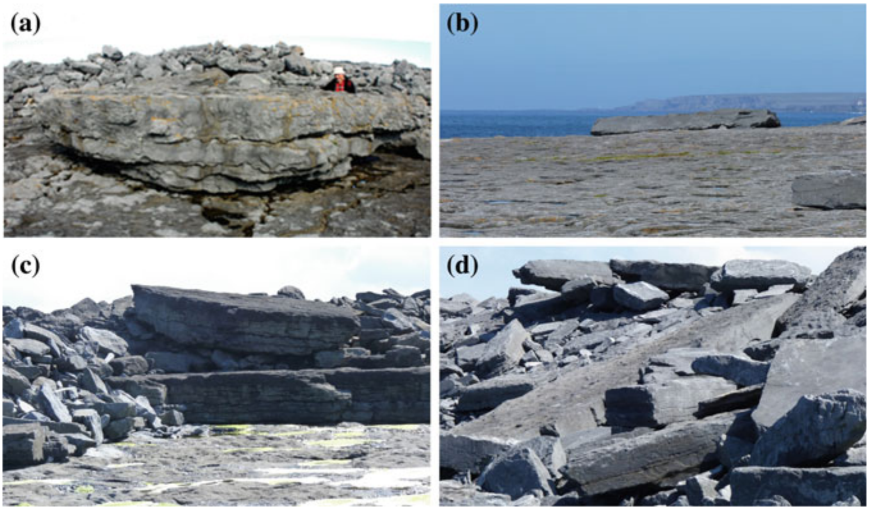

Fig. 3.3 Boulders may occur isolated or in ridges, sometimes in delicate balancing setting up to ridge crests. Their longest axe often is oriented perpendicular to the coastline, in direction of movement (as in (**d**)) is a rare setting. **a** Inishmore SW, +11 m MHW (50 tons). **b** Inishmaan, +9 m MHW (>25 tons). **c** Inishmaan, +13 m (42 tons). **d** Inishmaan, +14, 11.7 m long (75 tons) (*Image credit* D. Kelletat)

3.1.2 Observations on Recent Storm Wave Boulder Movement on Inishmore Island

Inishmore (Fig. 3.4) is the largest and longest (14 km) island of the Aran group, separated from Connemara mainland in the north by the 8.6 km wide and more than 60 m deep north entrance channel into Galway Bay, and from Inishmaan in the southeast by 1.8 km of water with a maximum depth of about 50 m. The island is asymmetrical in that sense, that the north-eastern coastline is low, whereas the south-western one exhibits cliffs (often vertical or even overhanging, but mostly stepped) up to 85 m high. On those lower than about +30 m MHW, one main and a few short boulder ridges can be observed, the latter one behind the main and evidently younger one. Our inspection in June, 2014, was restricted to the west end of the island (Figs. 3.4, 3.5 and 3.6) as well as to the eastern part of the southwest coast and concentrated on fresh boulder movements from the winter storms December, 2013, to February, 2014. Earlier studies have been dedicated to all of the island's shorelines (Scheffers et al. 2009, 2010a, b), and additional and well documented information can be found in Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al. (2008), Zentner (2009), and Cox et al. (2012).

The west end of Inishmore is a special site, even if only less than 1 km long. It exhibits clusters and ridges of huge boulders (up to more than 50 tons), often in a perfect imbrication, and a cobble beach also including small boulders, about 400 m

Fig. 3.4 Inspection sites of 2014 on Inishmore Island (*Image credit* © Google earth 2012, modified)

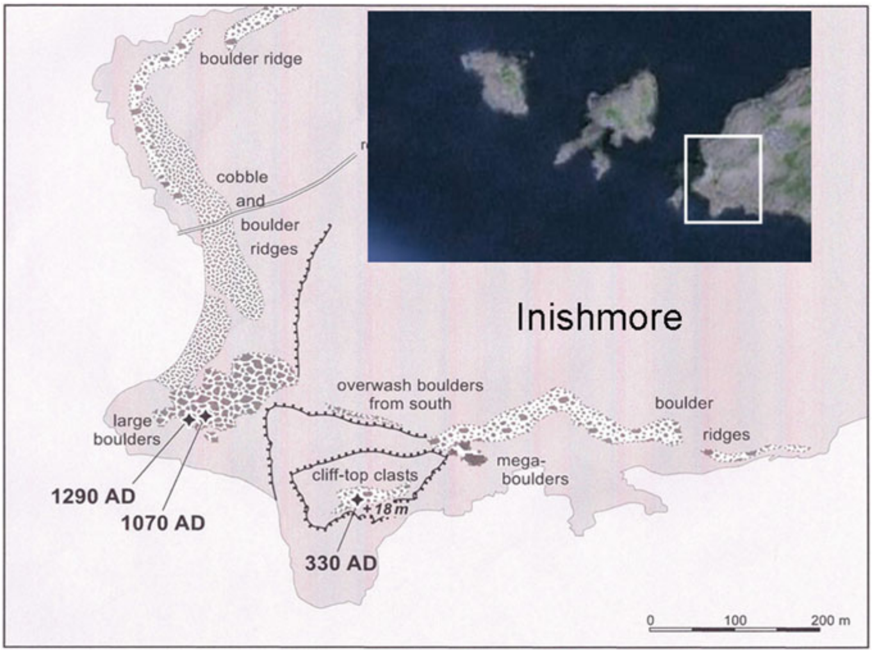

Fig. 3.5 Scetch map (from Scheffers et al. 2010a) of boulder deposits on the western part of Inishmore Island. *Insert* Brannock Islands west of Inishmore. Water depth here is less than 10 m, partly less than 5 m

Fig. 3.6 Oblique aerial view (same as in the map Fig. 3.5, looking north) of the west end of Inishmore. Apart from the light coloured boulder and cobble beach in the centre, at the southern and northern headlands large boulders from older events are deposited often in perfect imbrication, and fresh and smaller ones dislocated, as well (*Image credit* Anja Scheffers)

long, up to 50 m wide and with a crest at a maximum of more than +4 m MHW, the only longer "beach" at an exposed side of Inishmore. The kind of exposure, however, differs from the long SW coastlines with higher cliffs, because the group of the low Brannock islands to the west give shelter from high waves and swell, and the waters are shallow with depths of less than 10–less than 5 m. Therefore, waves during storms break apart from the shorelines in deeper water, and wave refraction determines the approach angle of large waves to this section of the coast, in particular in the northern part.

At the west end of Inishmore Island, three rocky headlands (Figs. 3.4 and 3.5) dominate the topography. Those to the west are low, that to the south as a small table mountain up to +18 m MHW. All these headlands exhibit boulders from the intertidal, subtidal, and supratidal, partly with borings of the bivalve *Hiatella arctica*. The huge blocks southwards of the table mountain (Fig. 3.2, lower right part) with hundreds of tons in weight may have been broken by wave impacts, but their dislocation to the shoreline may well be the result of cliff break down and its kinetic energy. Therefore we do not classify them as "coastal" boulders.

On the southern headland to the west, boulders up to >50 tons occur at a few metres above MHW, all dislocated and many of them in a perfect imbrication or imbrication trains (Fig. 3.7).

Fig. 3.7 Imbrication train at about +5 m MHW from the southern flat headland on westernmost Inishmore. This image from summer 2007 shows a younger boulder in the centre with a weight of about 9 tons, most probably emplaced by the storm earlier that year. It now has been displaced to the gap between the boulders to the left (*Image credit* D. Kelletat)

Signatures of freshly moved boulders in this southern part of Inishmore's west end can be seen at many places, either in the form of freshly polished small basins, larger white patches where sand and gravel has been dislocated by vortex movements, impact marks on the rocky ground or at large stable boulders, fresh polishing along existing older boulders, or dislocation of fragments of significant size (Figs. 3.7, 3.8, 3.9, 3.10, 3.11, 3.12 and 3.13).

The nearly 400 m long and >50 m wide cobble beach in the centre of Inishmore's west coast has been overwashed partly, but a mixed remnant of sediment with sand, soil and vegetation has not eroded by the strong storms, maybe because wave power in this part of the coast opposite of the small Brannock Island was limited because of shallow water conditions and strong refraction (Fig. 3.14).

On the northern headland of Inishmore's west end, cliffs rise to 4–5 m above MHW curving around from W to N exposure, lying partly protected from direct wave approach trough the 8.6 km wide northern entrance into Galway Bay in the refraction zone from the northern Brannock Island shores (see Fig. 3.6).

Again, here on cliff tops, large well imbricated platy boulders can be found in a stable setting, weighing up to nearly 50 tons. They form a kind of ridge or elongated cluster parallel to the northern cliff line, leaving a bare rocky platform 15–20 m wide in general. Fresh boulders have been broken from the edge of the cliff, tumbled into the old boulder cluster, impacted the larger old boulders and

Fig. 3.8 Inishmore Westend: comparing boulder sizes: old (48.1 and 43.8 tons) and fresh (<1 t). Scale is 1 m. Around the fresh boulder, the rocky surface has been impacted with fresh marks, evidently from the tumbling of the small boulder (and other particles) (*Image credit* D. Kelletat)

sometimes came to rest within their gaps or even further inland (Figs. 3.15, 3.16, 3.17 and 3.18). In rare cases large boulders have been lifted for some centimetres and turned their axe direction to a maximum of a few decimetres (Fig. 3.19). In general, however, the amount and size of freshly moved boulders remains small compared to the existing ones moved by older extreme events (Fig. 3.20).

Inishmore exhibits continuous boulder ridges for about 6 km of length from the headland west of Black Fort to the puffing hole sites at the south-eastern end of the island, i.e. from about +28 m MHW to mostly above +10 m MHW as the lowest. The old ridges, described by Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al. (2008), Zentner (2009), Scheffers et al. (2009, 2010a, b), and Cox et al. (2012), are situated on an upper limestone platform with a very low inclination to seaward usually bare of fragments. The boulders in the ridges are often rectangular and platy, only small ones maybe rounded a little bit. The sharp edges of large ones derive from the cliff, cliff top or steps in the high platforms, but we also found one of 8.7 tons in weight at +17.4 m above MHW (at 53°06′55″N and 09°46′25″W), exhibiting old bivalve borings as a document for its source in the inter- or sub-tidal zone and a very wide transport against gravitation (20 m or more) and to landward (60 m or more). Lower platforms in the form of a stepped cliff occur at several sites. In particular in both embayments NW and SE of the Black Fort promontory, cliffs

Fig. 3.9 At the eastern side of the large and old imbricated boulder (48 tons) of Fig. 3.8, another fresh emplaced one (overturned, transported 20 and 0.9 m against gravitation, flat lying, 3.1 tons) can be seen (*Image credit* D. Kelletat)

Fig. 3.10 Panorama of very large (up to 50 tons) imbricated boulders at the southern section of Inishmore's west end. Transport distance is mostly more than 40 m, and uplift against gravitation was a few meters. This imbrication is a very stable setting, in particular at this site, where backwash is not possible (*Image credit* D. Kelletat)

Fig. 3.11 Bare and freshly polished rock surface among old boulders at Inishmore's southern west end (*Image credit* D. Kelletat)

are overhanging for 10 m and more, and on their top no old or fresh boulders have been deposited.

We will now document a collection of fresh emplaced large boulders and their environment along this coastal section (Figs. 3.21 and 3.22 as well as 3.25 and 3.26). The first signatures of strong young impacts can be found at about +25 m MHW within the Black Fort promontory as destroyed patches of soils with grass, and less than a handful of small boulders (some flat and overturned, moved up to 2 m horizontally) of about 0.02 t of mass. From directly SE of Black Fort, a few striations occur on the upper cliff top platform and rise in number and density to lower elevations in south-eastern direction. They are in particular significant just in front of the old ridges and at those sites, where a refreshing of their seaward slope has taken place evidently by young wave wash over.

It is significant, that most of the boulders moved are not emplaced freshly from the cliff or edges of the platforms, but taken from the old deposits and moved many times tumbling on their slope. From this movement, the frontal slopes locally are steepened or set-back for 1 m or so. Dense striations up to a continuous polishing may appear at the most landward strip of the platform at the base of the ridges. Many fragments also have been washed into the sea, so that the amount of coarse

Fig. 3.12 Intensive polishing by pebbles and sand, moved during the winter storms 2013/14 in a depression of old boulders in the southern section of Inishmore's west end (*Image credit* D. Kelletat)

material left after the series of the six extreme winter storms of the season 2013/14 is less than before.

The largest boulder found freshly pulled from the rock at a cliff top at +22 m MHW is 4.2 tons, its dislocation was 8 m horizontally and 0.9 m against gravitation (Fig. 3.21). At other cliff top sites more boulders have been washed down and into the sea than have been emplaced on the cliff top (Fig. 3.22). The rock pool belt in lower elevation—although very much exposed—seems to be less affected (Fig. 3.23). Striations occur in dense patterns from an elevation of about +20 m and lower on the uppermost platform (Fig. 3.24). The boulder of about 7 tons on the seaward ridge slope +16 m above MHW is exceptionally large for this elevation (Fig. 3.25), mostly here and lower old boulders dominate an old ridge (Fig. 3.26). Even if the seaward ridge slope seem to be covered by fresh boulders (e.g. as in Fig. 3.25 above the large boulder), the lack of related out-breaks and the concave shape of the ridge front suggest that most of them derive from the older ridge itself and have been just moved during the winter storm season of 2013/14. Only at places where the old ridge crest shows a saddle, fragments (refreshed by movement and collision with others) of up to 0.3 tons can be found locally near the crest or even a little bit down on the landward slope, if elevation is less than about 15 m MHW in full exposure. The largest fresh moved boulders have only up to 10 % of

Fig. 3.13 Old stable boulders partly with lichens in a wide boulder cluster of Inishmore's west end. Many of them show striations (*straight* or *curving*) from the movement of smaller boulders during the winter storms of 2013/14, which evidently have saltated over this rough surface (*Image credit* D. Kelletat)

mass compared to old ones at the same environment. They are situated in a lower position and clearly have been moved less horizontally and vertically. This evidence from the south-eastern section of Inishmore is in strict agreement with those found at the western end of the island.

3.1.3 Observations on Inishmaan Island

Inishmaan (Fig. 3.27) is the central island of the Aran group, separated from Inishmore in the west by a 1.8 km wide channel, and to Inisheer Island in the east by 2.2 km of water, both between 50 and 30 m deep, diminishing quickly into Galway Bay. The most exposed west and southwest coast of Inishmaan exhibits vertical cliffs in the northern section up to +28 m above MHW, whereas to the SW corner of the islands stepped cliffs dominate, separated by wide ramps with angles between about 7°–15°. The old boulder ridge crest has an elevation of close to +30 m MHW in the north and 4.5 m MHW at the south coast. Our inspection in 2014 was restricted to both areas marked in Fig. 3.27. An extended field survey has

Fig. 3.14 Overwash of the cobble ridge of Inishmore's west end, where a remnant of older sediments has been left on the crest (*Image credit* D. Kelletat)

Fig. 3.15 Striations of boulder movement with constant ground contact (i.e. shifting/gliding with many wave impulses), seen from both sides. Mass of the boulder is around 200 kg, distance moved about 50 m at +5 m MHW (*Image credit* D. Kelletat)

been made earlier in 2006 and 2007, and published data from this region can be found also in Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al. (2008), Zentner (2009), Scheffers et al. (2009, 2010a, b), and Cox et al. (2012).

Fig. 3.16 Fresh boulder of about 0.4 tons, found overturned on old soil and vegetation about 160 m inland from its source (*Image credit* D. Kelletat)

Fig. 3.17 A former front of the boulder ridge has been pushed to inland, leaving a belt of rock without endolithic *cyanophyceae* and therefore, a light and fresh colour. Moved boulders are either imbricated at the slope, or tumbled in between the old boulder clusters with a lot of fresh impact marks (*Image credit* D. Kelletat)

So far as we know, the northwestern part of Inishmaan has not previously been inspected for old or fresh boulder dislocation, but large fields of boulders can be seen from a distance and even from Google earth satellite images. We made a

Fig. 3.18 Sites of fresh break out at the cliff top +4.5 m above MHW. From here a fresh boulder of 3.5 tons has been steeply imbricated against old boulders, with a horizontal movement of more than 15 m (*Image credit* D. Kelletat)

detailed study of the section close to the structural step of limestone, in fact a cuesta. A high (>6 m above MHW) boulder ridge starts from the structural cliff to the north, diminishing in elevation and becoming broader to landward. The base is an undulating limestone area several metres above MHW, strongly karstified with deep karren of different forms including shallow basins. In between these features on the flat segments of bare limestone, well rounded boulders from 100 kg to 1–2 tons are scattered up to 200 m to inland (Fig. 3.28). Most of them derive from the immediate inter-tidal and sub-tidal, which along this coastline is shallow and therefore, a good place for collecting boulders and fine deposits over a longer time. This can be seen by borings from *Hiatella arctica* (Fig. 3.29), often with shells preserved. To the sea and about 50–80 m from MHW, large boulders of many tons (up to >20 tons) are organized in a ridge. Again, many of these boulders contain *Hiatella* borings or the resting places of sea urchins. Most of the boulders are well rounded, which is proof for their long time of movement within the surf belt. As they carry the tiny borings on their rounded surface, their movement within the surf belt must have been interrupted by quiet phases. Extreme event impacts finally moved the large boulders to inland and on the limestone pavement many metres above MHW. Imbrication is less developed (because of unsuitable boulder forms), but exists. The largest boulder measured is leaning against two other ones in front

Fig. 3.19 This old boulder of about 12.3 tons has been pushed aside for about 0.5 m at +4.5 m MHW (see white exposed belt in front of it), and lifted for some centimetres at its front site (*left*). Largest Brannock Island in the distance (*Image credit* D. Kelletat)

of the main boulder ridge. It is overturned, well rounded as well, and has a mass close to 20 tons (Fig. 3.30).

In this coastal environment, striations, freshly polished basins made by former terrestrial karstification, and freshly emplaced boulders can be found. Impact marks of their dislocation and saltation on top of the main ridge and among the old boulders can easily be detected (Fig. 3.31). The largest freshly moved boulders are in the order of >5 tons at around +4–5 m MHW and 40–70 m from the high water level (Fig. 3.32), smaller ones are dislocated up to at least 150 m from the MHW line.

The Inishmaan west and southwest coasts exhibit an extraordinary boulder ridge regarding continuous development, altitude, width and containing very large boulders and blocks. The ridge starts in the north at Crummel locality >28 m MHW with a series of boulder piles and short ridge segments running nearly perpendicular to the vertical cliff. Here no fresh signatures from the 2013/14 winter storms have been observed. Close to +20 m elevation MHW, a single and small boulder on the old and weathered cliff platform occurs (Fig. 3.33), and a little bit lower and further south a few striations appear. Around +14 m MHW, the first large boulder (2.5 tons) could be found (Fig. 3.34). Around this location, first disturbed small boulders at the ridge front have been refreshed by wave impacts, with a light colour

Fig. 3.20 A fresh boulder of 0.3 tons among older ones, resting higher, moved wider to inland and having up to 20 times that weight (*Image credit* D. Kelletat)

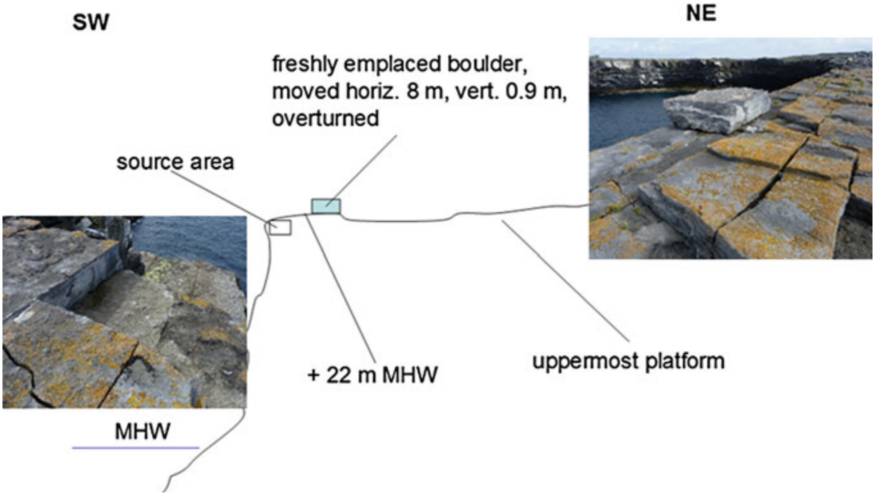

Fig. 3.21 Scenario for a fresh boulder emplacement of 4.2 tons on the bastion of the promontory just east of Black Fort at +22 m MHW. Lichen cover documents that this cliff top has been rarely affected. The site is at 53°06′08.99″N and 09°41′04.59″W (*Image credit* D. Kelletat)

Fig. 3.22 Break out sites of the cliff top edge around +20 m above MHW: only a few boulders have been displaced on the platform, most of them have been washed into the sea (*Image credit* D. Kelletat)

Fig. 3.23 The small rocky island and lower rock platform with bioerosive rock pools south of Black Fort shows only a few sites with destruction/erosion by winter storms of the season 2013/14. No boulders have been deposited here (*Image credit* D. Kelletat)

Fig. 3.24 Below the elevation of +20 m MHW, striations and small impact marks may decorate the uppermost cliff platform (here at +14 m MHW) (*Image credit* D. Kelletat)

Fig. 3.25 At about +16 m MHW, a boulder with the mass of about 7 tons has been ruptured from the higher platform, and smaller ones are washed out of the old ridge and tumbled around on its seaward slope (scale on boulder is 0.5 m) (*Image credit* D. Kelletat)

and tiny impact marks. They have been tumbled many times, so that single striations cannot be identified. As in the wider environment, no sources for these boulders could be detected, they evidently must derive from the ridge front itself. A limited wave power of 2013/14 winter storms is also documented by two boulders

Fig. 3.26 Single overturned boulders among older ones, leaned against steps on the rock platform, and tumbled up to the old ridge front slope. The large dark (old) rectangular boulder has a mass of about 3 tons and is only 0.4 m thick (*Image credit* D. Kelletat)

of 1 and 1.6 t (Fig. 3.35), which have been broken directly from the cliff top around +12 m MHW, but have been deposited immediately beside on the cliff top.

The comparison of old and freshly displaced boulders gives a good hint to the capability of the winter storm waves of 2013/14 (Figs. 3.36, 3.37 and 3.38). A recent displacement of fragments is not always a signature of active moving by storm waves, as Figs. 3.37 and 3.38 may show: waves washing up on the seaward ridge slope move smaller boulders often downwards and even across the cliff platform and into the sea, and by this erosion process large boulders and blocks can be undermined and consequently move downwards. If undermining is no longer possible as at the base of the ridge front, large boulders may accumulate with their longest axe parallel to the ridge extension (Figs. 3.38 and 3.39).

The lower the ridge, the more chance to activate its deposits by storm waves (Fig. 3.40). This can clearly be identified by recent observations (from June, 2014, regarding the six exceptional winter storms 2013/14), but also by older satellite images, at least back to 2005 (Fig. 3.41), but most probably—because this seems to be an ongoing process—on images several decades old. The landward slope of the ridges, however, with their darker surface colour, indicate a much less or even missing recent activation (Fig. 3.41).

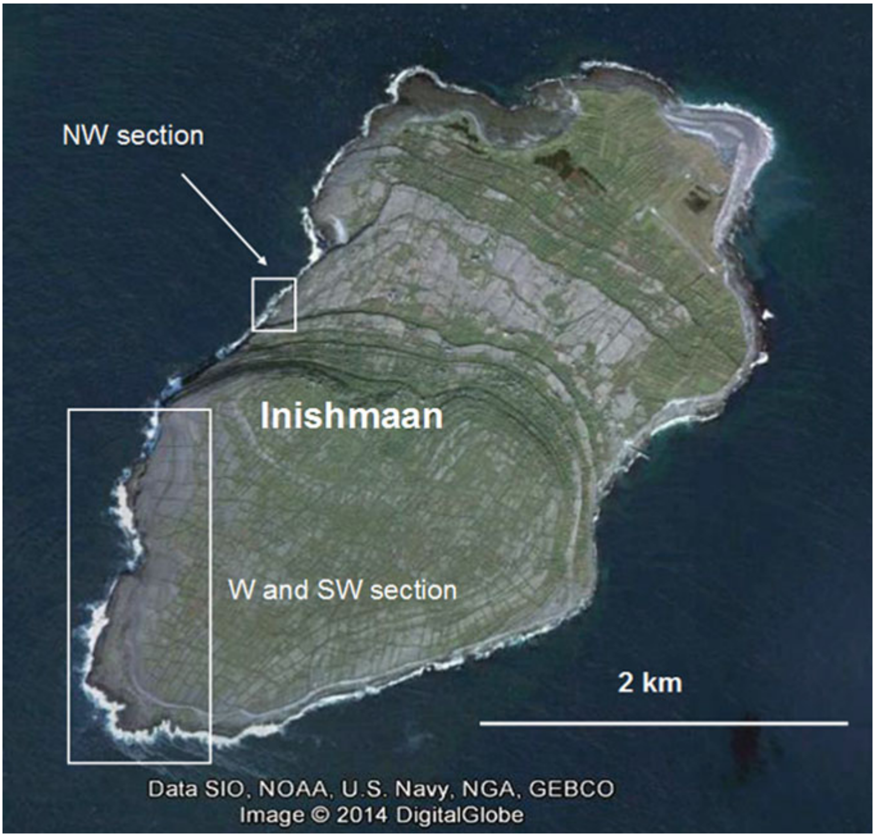

Fig. 3.27 Inspection sites (June 2014) on Inishmaan Island (*Image credit* © Google earth 2012, modified)

3.1.4 Observations Along the SE Coast of Galway Bay (Doolin to Black Head)

Doolin is located east of the SE entrance to Galway Bay just opposite of Inisheer Island of the Aran group and in sight of the Burren and the cliffs of Moher, two famous landscapes of western Ireland. The distance of Doolin Point to Inisheer is 7.4 km with a max. water depth of about 60 m. Little Crab Island, within the 10 m water depth contour around Doolin, is situated only 250 m from Doolin Point (NE of the island), 350 m from the flat rocky point south of Doolin ferry pier (SE of the island), and 500 m from the boulder beach between both of these promontories. Crab island is only 180 m long (N to S) and 120 m wide (W to E), but it still has a rest of drift deposit from the last ice age on its centre and top at +8 m MHW, although large boulders broken from the cliffs all around point to strong wave attacks.

Fig. 3.28 Scattered boulder clusters and the main ridge to seaward. Looking to Inishmore Island (*Image credit* D. Kelletat)

Fig. 3.29 Boulders of sizes up to many tons exhibit bivalve borings (*Image credit* D. Kelletat)

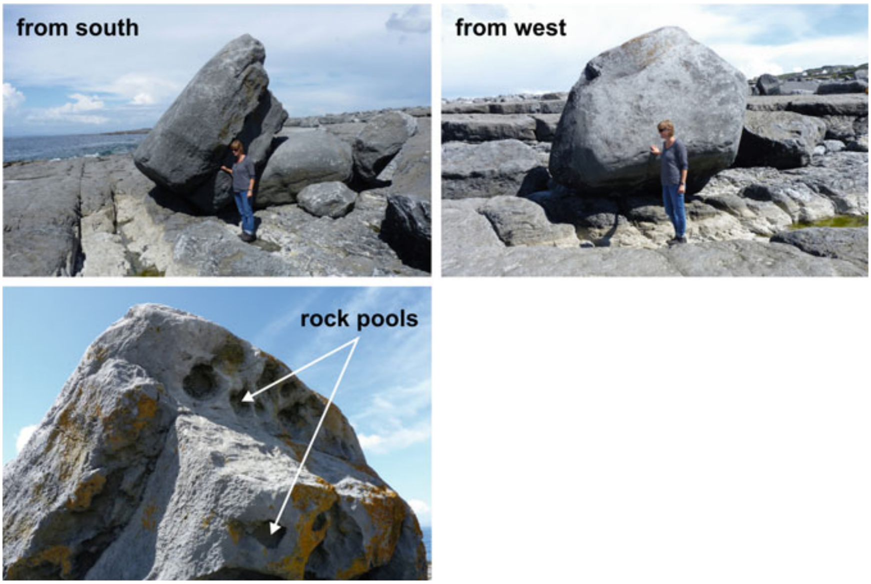

Fig. 3.30 Largest single boulder (7.6 m^3 = 20 tons) in front of the seaward ridge, with rock pools from its former supra-tidal position. Light-coloured basins in the rock are freshly polished sites from strong surf action in winter 2013/14 (*Image credit* D. Kelletat)

Fig. 3.31 Fresh impact mark from boulder saltation at a >20 ton boulder (*Image credit* D. Kelletat)

Fig. 3.32 Large old boulders with a smaller fresh one on top, looking south (*Image credit* D. Kelletat)

Fig. 3.33 Single fresh boulder nearly 20 m from the cliff top in an environment lacking fresh striations. Site is at 53°04′38″N and 09°36′54″W and +20 m MHW (*Image credit* D. Kelletat)

Fig. 3.34 Fresh boulder of 2.5 tons, tracked from a higher step of the main cliff top platform to seaward, now resting at +14 m above MHW (*left* looking seaward, *right* looking to the main old ridge). Scale is 0.5 m, and site at 53°04′42″N, 09°36′55″W (*Image credit* D. Kelletat)

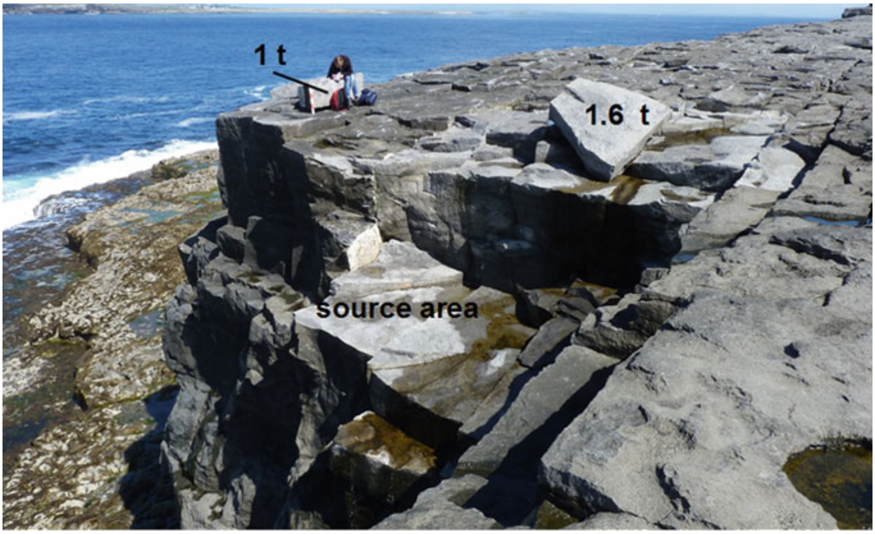

Fig. 3.35 Inishmaan W: two fresh boulders at +12 m MHW, 1 ton at cliff edge (with sitting person), and a tilted one of 1.6 t, with source area of both. Site is at 53°04′40″N and 09°36′56″W (*Image credit* D. Kelletat)

We earlier investigated the nearly 20 km long coastline from Doolin to Black Head, but our inspection in June 2014 for the recent winter storm impacts was restricted to the closer Doolin region, a section on both sides of Poulsallagh and its high boulder ridge, as well as a 2 km long part south of the campground in the north (Fig. 3.42).

All three coastal sections, although partly within Galway Bay and in the shelter of the chain of the Aran and Brannock islands, exhibit exceptional large boulders single, in irregular clusters, in imbrication trains, or in boulder ridges. The largest reach >100 tons at about +5 m MHW and >50 m from the surf belt at the northern

Fig. 3.36 Another aspect of a cliff top platform at the west coast of Inishmaan at +12 m MHW: large old boulder not moved freshly, and two freshly emplaced ones from a cliff top outbreak. The smaller one is overturned (*Image credit* D. Kelletat)

Fig. 3.37 Examples of freshly moved boulders and partly activated ridge front at elevations of +12 to +15 m above MHW (*Image credit* D. Kelletat)

Fig. 3.38 Undermining of old platy boulders and their dislocation to downwards (around +13 to +16 m MHW). For most of the fresh fragments their source cannot be found at the cliff, at cliff steps or at the cliff top: they derive from the seaward old ridge slope (*Image credit* D. Kelletat)

and more protected part. The rocky shorelines exhibit stepped cliffs (e.g. Doolin Point), rocky platforms dipping to the sea, boulder beaches as around Poulsallagh, but also perpendicular cliffs about 15 m high as south of Poulsallagh.

West of the Doolin boulder beach (N of the ferry pier), from a more protected place to exposed ones with regard to the wide entrance to Galway Bay, clusters of boulders freshly displaced from the intertidal, or broken from the cliff face or structural steps along the rocky coast can be found, with weights of single fragments up to around 3 tons (Figs. 3.43 and 3.44). In between, however, parts of the coast seem largely unaffected and covered with lichen, apart from places with fresh striations or more isolated patches of fresh boulders, sometimes restricted to a higher elevation (Fig. 3.45). Some structural steps on the coastal slope contain boulders in a joint bound situation, but no longer fixed at the main rock but separated by tiny fractures and joints. These places evidently can be easily transformed by strong waves with significant boulder transport against gravitation (Fig. 3.45).

In this setting, isolated groups of large boulders may occur, dislocated from a lower platform (just above MHW) from a 35 m^2 large area (Fig. 3.46), broken into several pieces (the largest of 6.1, 7 and 20.3 tons), and emplaced from a step just above the source platform to the front of the next higher step, there steeply

Fig. 3.39 Very large old boulders in a ridge section of Inishmaan at around +11–12 m MHW, and some smaller cube-like ones in the left corner of the picture. Undermining by recent storm waves may move the large boulders following gravitation to downwards (*Image credit* D. Kelletat)

inclining, and even on this higher platform, again without overturning deposited horizontally (Figs. 3.47, 3.48 and 3.49). Interestingly, the storm waves responsible for this destruction, dislocation and emplacement approached with an angle of about 35° to the coastline, evidently refracted from the open waters by shallow ground. We assume that this scene has been formed by a single wave (or waves combined by refraction and directed to a single point). As can be seen of the boulders, they have been liberated in their joint bound scenario, with the frontal thickness of the plates being less than 0.5 m. As the largest and lowermost dislocated boulder has only been lifted less than 1 m, and shifted for a few metres to sideward, it must have been displaced by an under-pressure situation on its top (and the top of all other boulders from this source as in Figs. 3.46) when the flow crossed the lower platform. This situation is physically similar to that of the lift of an airplane from above of the wings. The uppermost boulder on the higher platform may have been moved similarly but for a greater distance and a wider step upwards, because it rests in the same position (not turned over), and its surface does not show significant impacts from collision.

Close to Doolin Point, sections with bare platforms (but striations in different directions, Fig. 3.50, foreground), and those where fresh medium sized boulders (less than 2 tons) covering higher structural steps and form a kind of a ridge

Fig. 3.40 Crest of the main Inishmaan ridge at the western section of the south coast, here about +5 m MHW. Activated seaward slope and a light coloured (i.e. freshly polished) belt on the rock platform in front of it. Boulders in the foreground have not been affected by recent storms even below +6 m MHW (*Image credit* D. Kelletat)

(Fig. 3.51, 3.52 and 3.53) are typical, as well as local outbreaks from platform faces (Fig. 3.52). The largest boulders which have been moved against gravitation and to inland by the winter storms 2013/14 are in the order of several tons in mass, where 10 tons seems to be the upper point of the scale for these events (Fig. 3.54).

East of the ferry harbour of Doolin (now changed by a wide construction area) a lower coastline with a rocky platform inclining to the sea (southwards, to shallow water) and boulder accumulations with cobbles and pebbles incorporated extend for a few hundred metres into the bay between the Doolin area and the cliffs of Moher. Many of the larger boulders (i.e. more than a few tons up to >30 tons in weight) have been tracked from a well-developed terrestrial karst terrain during the ongoing transgression to landwards. They mostly settle on other large boulders, but the accumulation pattern is more one of a boulder field and not a real ridge with a significant crest. The seaward part of the rocky base around MHW exhibits a perfectly developed bioerosive rock pool zone (Fig. 3.55), bare of fragments but with intense polishing in the upper parts. Ongoing transgression of the boulder fringe on land can be seen by fresh crossing of old soil (Fig. 3.56), and at many places, in particular within existing rock depressions, the work of polishing by small fragments (pebbles, sand) during the recent storms can be seen (Fig. 3.57),

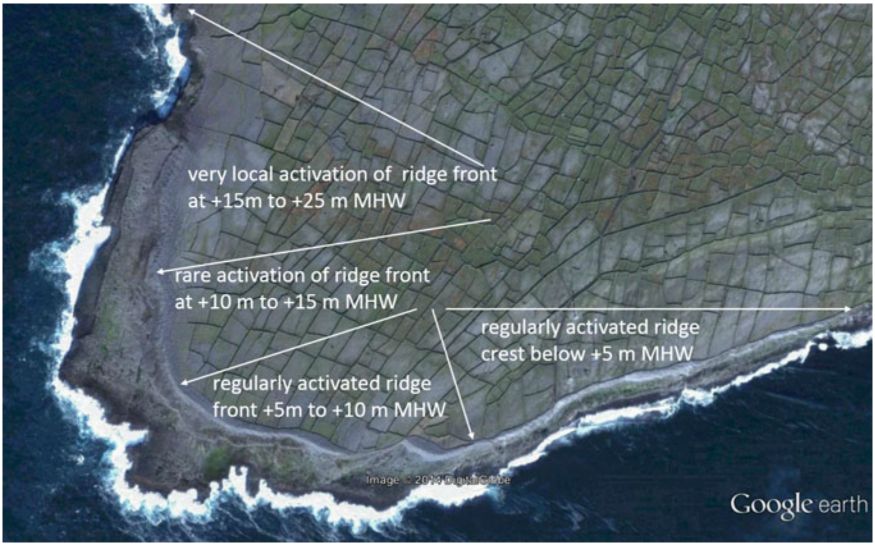

Fig. 3.41 The intensity of boulder ridge activation (by winter storms of 2013/14, but also back to 2005 AD—date of this satellite image) is clearly depending on the elevation of the ridge and the cliff platform in front (W to S) of it and seen by this satellite image in the different colours of the front and back slopes. Compare also the difference between ridge contour and cliff contours (*Image credit* © Google earth 2012)

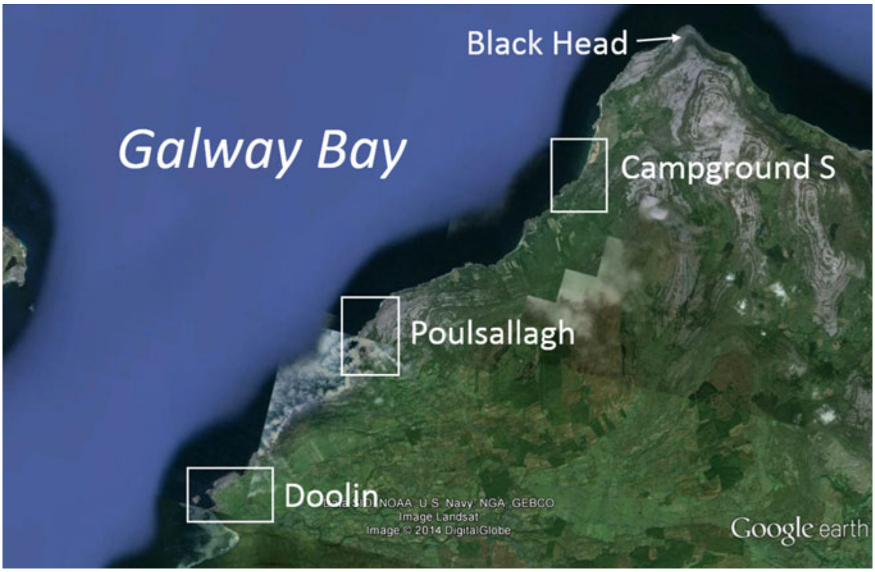

Fig. 3.42 Inspection sites 2014 along the SE coast of Galway Bay (*Image credit* © Google earth 2012, modified)

Fig. 3.43 Close to the small boulder beach of Doolin, boulders of up to 3 tons have been dislocated from the surf belt (where they have been partly well rounded) to a few metres above MHW. The rocky coast in the wave shadow of Crab Island and along water depths of only around 5 m as a maximum, is not regularly affected by storm waves (*Image credit* D. Kelletat)

Fig. 3.44 Isolated site with a fresh boulder deposit and dislocation close to Doolin Point (*Image credit* D. Kelletat)

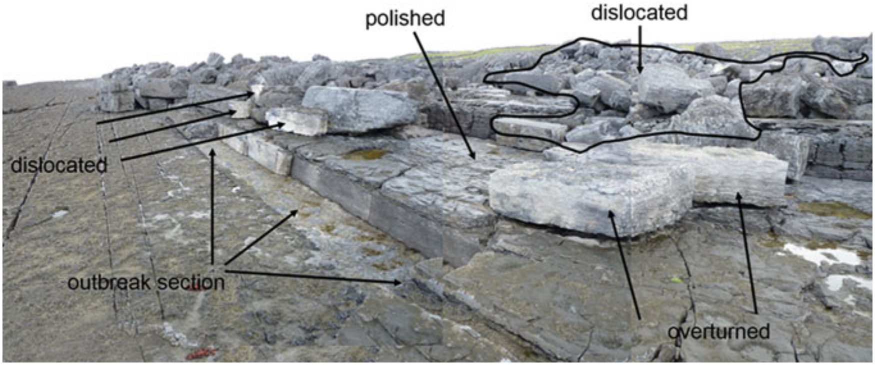

Fig. 3.45 Open fractures and joints in well stratified limestone give good places for strong wave attack and boulder dislocation (*Image credit* D. Kelletat)

Fig. 3.46 Freshly exposed rock with a 35 m^2 large source area for the platy boulders in Figs. 3.47, 3.48 and 3.49 (*Image credit* D. Kelletat)

although these finer sediments are lost into the sea and only a small amount seems to be added to the boulder belt. At large boulders, collision marks with strong impacts and outbreak of flakes along the boulder edges are further evidence for the movement of large and heavy clasts by recent storms (Fig. 3.58). Interestingly, even large older boulders have been lifted through buoyancy for a decimetre or so, and now rest upon cobbles (Fig. 3.59).

Fig. 3.47 Beside nearly unaffected sections of the cliff coast near Doolin Point and still east of it, significant fresh break outs of large boulders can be seen, like this boulder set with masses of 6.1 tons (with person sitting), 7 tons (steep inclining), and 20.3 tons (in the foreground) as the three largest ones. They represent about 33 tons from a source area nearby, which delivered about 41 tons from an area of 35 m^2. The difference of 8 tons can be found in the smaller platy boulders below the person in this image (*Image credit* D. Kelletat)

Fig. 3.48 Looking down from the steeply inclining and overturned 7 ton boulder to the flat lying 20.3 ton boulder and the source area (light coloured place behind of it, see Fig. 3.46) (*Image credit* D. Kelletat)

Fig. 3.49 Lowest boulder (20.3 tons), dislocated from the *right side* less than 1 m against gravitation and 5 m apart from its source (Fig. 3.46). During settling down (or by buoyancy of later waves?) it has been split in the *middle*. Scale on the boulder is 2 m long. Crab Island at right horizon, and cliffs of Moher in the distance at *left* (*Image credit* D. Kelletat)

Fig. 3.50 Except of some striations, wide parts of the stepped cliff near Doolin Point maybe without any signature of recent storm impacts (*Image credit* D. Kelletat)

Fig. 3.51 Strong waves of the winter season 2013/14 have dislocated boulders of medium size (around 1 ton as the maximum) in higher elevation, but really large boulders close to the surf belt have not been moved (*Image credit* D. Kelletat)

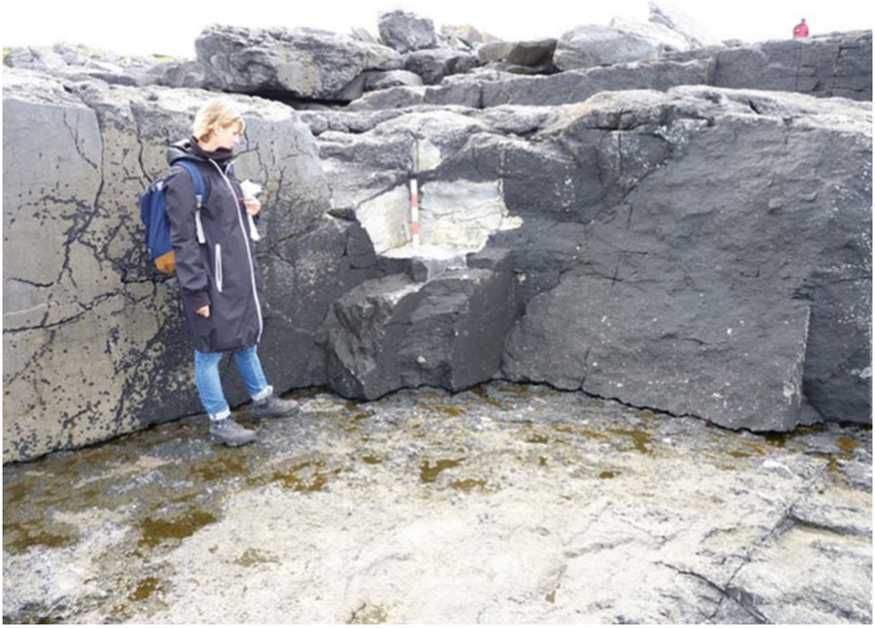

Fig. 3.52 As east of Doolin Point, cliffs north of it and in an open exposure to waves passing the wide south entrance to Galway Bay often show only local fresh break outs at weathered cliffs covered with a carpet of endolithic *cyanophyceae*, which give the black colour on the cliff faces (sometimes in association with the black lichen *Verrucaria maura*, in particular close to MHW). Scale is 0.5 m (*Image credit* D. Kelletat)

Fig. 3.53 Even where many medium sized boulders have been freshly accumulated as a large cluster or ridge, in the way of the winter storm waves 2013/14, old boulders with masses of 10 tons or more left unaffected even in low position (*left image* looking from E, *right image* looking from W) (*Image credit* D. Kelletat)

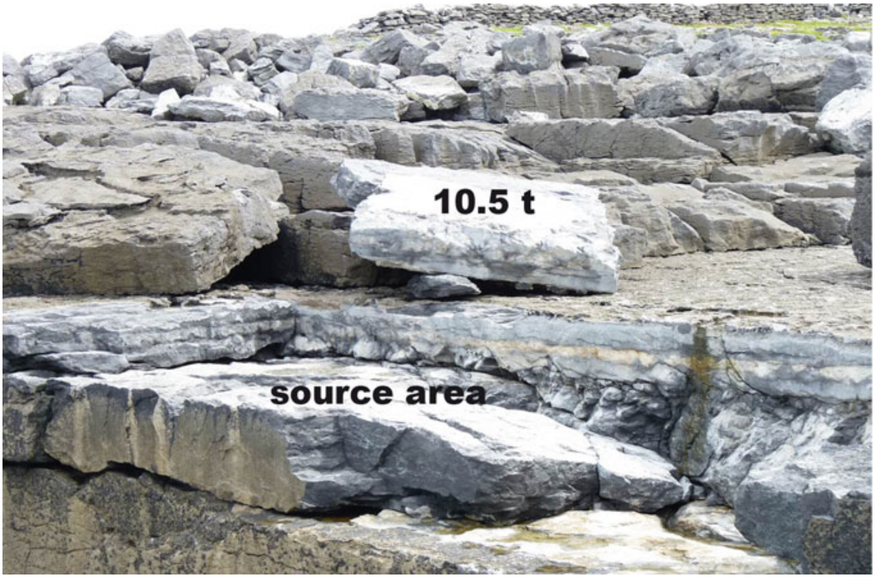

Fig. 3.54 Overturned platy boulder of several tons at about +5 m MHW just north of Doolin Point, and its white place of origin nearby. The boulder has been dislocated for 4 m horizontally and 1.5 m against gravitation (from +3.5 to +5 m MHW). Site is at 53°01′N and 09°24′31″W (*Image credit* D. Kelletat)

About 5 km north of Doolin Point and close to the promontory of Poulsallagh, a nearly 7 m high boulder beach ridge is an old deposit but over-washed also by younger storms. Its crest, however, exhibits a remnant of an old cover of well stratified sand with pebbles and shell debris. This points to a longer (several centuries, at least) time of conservation without complete over-washing. From this

Fig. 3.55 A well developed supra-tidal belt of bioerosive rock pools only slightly affected by fresh polishing (east of Doolin's ferry harbour) (*Image credit* D. Kelletat)

Fig. 3.56 Although along shallow water (less than −5 m), at the western part of the boulder beach just east of Doolin's ferry harbour, active erosion and transgression over old soil is exposed as a result of the winter storms of 2013/14 (*Image credit* D. Kelletat)

Fig. 3.57 In basins of the supra-tidal rock platforms (east of Doolin harbour) fresh polishing by sand and pebbles have lightened the rock where basin-like forms are present. Small particles (the tools for abrasion) have been washed out (*Image credit* D. Kelletat)

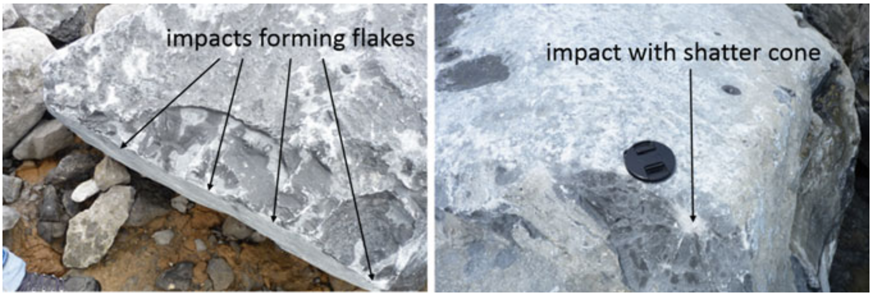

Fig. 3.58 Typical signatures of strong impacts during the collision of boulders. *Left* Break out of flakes along the boulder edges, *right* fresh collision mark forming a shatter cone on a rounded boulder (*Image credit* D. Kelletat)

ridge we took some samples of boring bivalves in boulders from the southern crest area, which gave ages within high Medieval times (Scheffers et al. 2010a). The dislocation of large boulders of several tons can be identified in the vicinity, now resting on cliff steps and intermediate platform several metres above MHW. The largest of these boulders with a weight of 12.1 tons (Fig. 3.60) is situated isolated

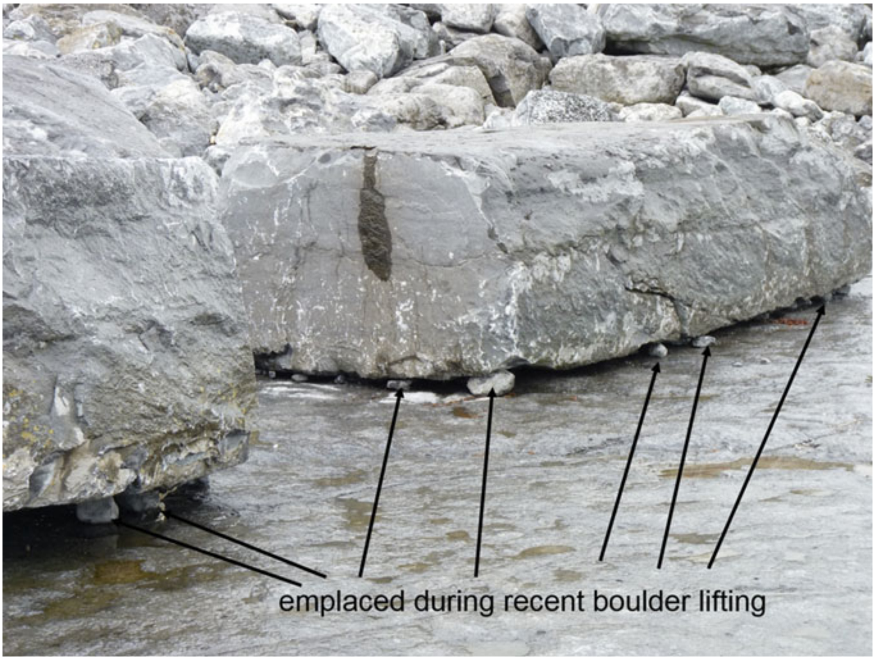

Fig. 3.59 Through the lifting of large old boulders, cobbles have been placed under them as a new basement (*Image credit* D. Kelletat)

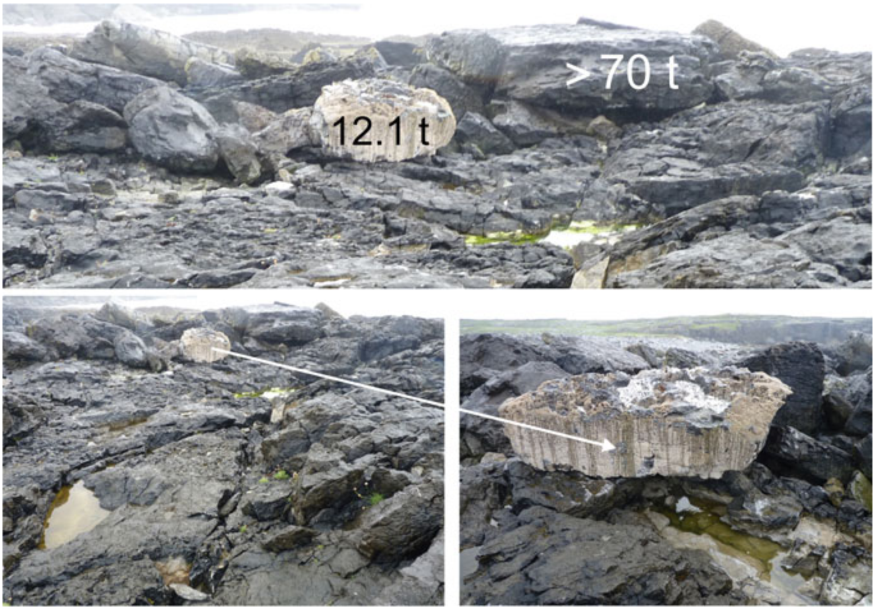

Fig. 3.60 Isolated large boulder of 12.1 tons north of Poulsallagh, now balancing on just 3 tiny points. It has been moved for 28 m (and 1.6 m against gravitation), most probably in one step. Directly *right* of it (in the *left image*), an old boulder of >70 tons has been dislocated earlier and at a higher place (*Image credit* D. Kelletat)

Fig. 3.61 Behind the high old boulder ridge (dark deposit at *left side* of image), a place of recent sand and pebble deposition and vegetation destruction occurs. Further inland, an old, wide and long overwash fan is preserved, though partly eroded at its seaward (western) fringe by a later storm. This event occurred a long time before the winter storm season of 2013/14 (*Image credit* D. Kelletat)

and evidently moved in one single step (without coming into contact with ground) for about 28 m over the lower seaward part of an old boulder ridge and 1.6 m against gravitation with its centre of mass. It derives from the inter-tidal zone, visible by the cover of rock pools on top, which themselves are decorated by a coating of calcareous algae, vermetids and barnacles. Just beside this fresh boulder, a much larger one (>70 tons) has been deposited earlier and a little bit further to

Fig. 3.62 A section south of the campground about 3.5 km SW of Black Head inside Galway Bay with very large (>40 tons) old boulders (rock pools on their surface indicate their source from the lower supra-tidal) on top of a barnacle-covered structural step, and a fresh boulder accumulation from the winter storms 2013/14 in the distance. Arrows indicate person for scale (*Image credit* D. Kelletat)

Fig. 3.63 Source and deposition places of two large boulders. *Left* Looking from seaward in direction of movement, *right* looking from above the old ridge (*Image credit* D. Kelletat)

Fig. 3.64 Large freshly dislocated boulders from winter storms 2013/14, deposited on the upper seaward slope of an old ridge containing much larger components further to inland and higher. Many of them exhibit lichen covers. The mass of the fresh boulder is around 4 tons each (*Image credit* D. Kelletat)

inland (Fig. 3.60, upper image, just right of the fresh boulder). Masses of more than just 10 tons are very rare in this section of the Galway Bay coast moved by recent storms (Figs. 3.63 and 3.64), and they are restricted to elevations of less than +5 m MHW. Many much larger ones, however, form boulder clusters and ridges up to at least +8 m MHW and northwards in direction to the inner Galway Bay close to

Black Head (e.g. Fig. 3.62). They can be found up to about 80 m to inland, now partly within soil and dense vegetation (Fig. 3.61a, b). Their organization and form clearly differs from glacial erratics, which also occur in this landscape.

Towards Black Head (south of the campground and relic dunes now partly under abrasion), the old boulder ridge has been filtered through by fresh sand and pebble, which can be found landward of it, combined with abrasion of vegetation and soil (Fig. 3.61). Freshly dislocated boulders often are isolated but large (Figs. 3.62, 3.63 and 3.64). Their transport distance horizontally is restricted to a maximum of about 15 m, and their lift vertically and against gravitation to a maximum of about 4 m. In the majority of cases, their source clearly can be identified along the MHW or lower supra-tidal, mostly from a rock pool zone.

Significant signatures from recent strong wave impacts are widespread along the inner Galway Bay, in particular striations in all directions, and polishing of the rock platforms in front of the old boulder ridge (Figs. 3.65 and 3.66). The movement of many small fragments in this narrow belt evidently is directed by the knick-point between the nearly flat supra-tidal and the steep and step-like rising of the first line of boulders. They also show a lot of small impact marks and striations. If the many finer fragments are not abraded totally during many hours (and dozens of hours within at least six strong storms 2013/14) of tumbling around, they must have

Fig. 3.65 Striations from fresh boulder movements in different direction can be found in high numbers on the supra-tidal rock platform, here crossing terrestrial karst features as these meander karren (*Image credit* D. Kelletat)

Fig. 3.66 A typical aspect at the seaward front of the old boulder ridge inside Galway Bay south of Black Head: polishing of the uppermost rock pool belt, but not severely affecting the barnacle cover a little bit lower and to seaward (*Image credit* D. Kelletat)

washed back into the sea, because in the ridge itself and between the large boulders a fresh sediment input is not significant, and the deposits landward of the ridge are not very extended and only thin and fragmentary.

3.2 Summary of Observations and Comparison of Storm Wave Moved Boulders in Western Ireland with Other Exposed Sections of the World's Coastline

As a result of our field work we present a summary of dislocation of large boulders in the Galway Bay area and on the Aran Islands. What mostly is missing in the literature (and leads to misunderstandings) is a correct definition of how the volume of a boulder has been determined: by multiplying the real length of a-, b- and c-axes, or finding the *mean* axe dimensions in the field and multiplying them. In our tables we give both values. A test may show, that in Table 3.1, the deviation of boulder volumes with the longest axes is between 118 and 265 % of the volume got from the mean axes values, with a mean value from 13 boulders of 164 %. In Table 3.2, the deviation is from 130 to 224 % with a mean of 147 %, and in

Table 3.1 Galway Bay and Aran Islands: freshly emplaced large boulders

Site	Altitude	Max. axes	Mean axes	Volume	Mass	Remarks
	m asl	m	m	m^3	t	
SE entrance to Galway Bay						
Doolin N	+4.3	1.4 × 0.73 × 0.59	1.18 × 0.67 × 0.51	0.4	1	Moved 10.3 m with vertical dislocation of 0.9 m, pushed/shifted
Doolin N	+3.1	6.9 × 3.55 × 0.57	5.2 × 3.33 × 0.47	8.1	20.3	Distance moved 7 m, vertical from +2.1 to +3.1 m
Doolin N	+4	3.9 × 1.95 × 0.50	2.8 × 1.95 × 0.45	2.46	6.1	Boulder has been overturned, lying flat, distance moved 17 m, vertical 1.7 m
Doolin N	+3.5	4.95 × 2.06 × 0.75	3.18 × 1.9 × 0.7	4.2	10.5	Distance moved 4 m, vertical 1.5 m (from +3.5 to +5 m)
Doolin N	+3.7	3.18 × 2.32 × 0.78	3.18 × 2.18 × 0.63	4.4	10.9	
Aran Islands						
Inishmore S	+23	3.08 × 1.55 × 0.6	2.16 × 1.52 × 0.52	1.7	4.2	Distance moved 7.5 and 0.78 m vertical
Inishmore W	+2.3	2.63 × 0.92 × 0.88	0.92 × 0.8 × 0.72	1.23	3.1	Distance moved 19, 0.9 m vertical dislocation, overturned boulder
In Galway Bay						
Poulsallagh	+1.6	4.47 × 2.29 × 1.05	3.22 × 1.67 × 0.9	4.8	12.1	Boulder dislocated without ground touching for 28 m and vertical 1.6 m

Table 3.3 the deviation is between 117 and 378 % with a mean of 202 % (or from all the 28 boulders mentioned in Tables 3.1, 3.2 and 3.3 the mean is +174 %). All these deviations are significant and will mislead to results on the power of moving processes for boulder dislocation.

Table 3.1 shows a selection of large boulders with their position above MHW, the maximum and mean length of axes (the latter to calculate their volume), and their mass in tons, calculated with a bulk density of 2.5 g/cm^3 m, which is below that found by tests using the Archimedean principle on dense Carboniferous limestone of the Galway and Aran region. The largest boulders freshly broken from a joint bound scenario and dislocated to upwards have a weight/mass of over 10 to just over 20 tons, and these large ones have been transported horizontally for 4–28 m and vertically for 0.78–1.6 m, starting at altitudes of 1.6–3.6 m above MHW. The maximum length of the a-axe of these boulders has been measured to be 6.9 m.

There are, however, larger old boulders dislocated, but their distance of movement horizontally and vertically is unknown because their original site before the winter storms cannot be reconstructed. Table 3.2 exhibits some examples: the largest of these old boulders set in motion again are close to 20 tons (18.4 and 20 t) close to MHW, but those with a mass of 1.7 and 2.5 tons are now resting at +13 and +16 m MHW. This size is not significantly larger than that of boulders freshly broken out of the coastal rocks, but the emplacement has taken place in a much higher altitude, and additionally further apart (up to 80 m) from the cliff line or the surf belt.

Our results concerning boulder mass movements by extreme winter storms compared to much larger old ones not moved is in congruence with Goto et al. (2010b) who clearly could discriminate storm boulders on the Ryukyu islands of Japan closer to the reef front and smaller as another group from historically known tsunamis, which shows, that even extreme storm waves (on the Ryukyu Islands by typhoons) are strictly limited in their maximum power. Based on measurements of 626 individual boulders, Goto et al. (2010a, b) found a group of storm dislocated boulders (max. size less than 47 tons) on a reef flat (i.e. dislocated horizontally) up to maximum 240 m from the reef edge, while those moved by the Meiwa Tsunami in 1771 AD with a maximum mass close to 216 tons are distributed from 390 to 1290 m from the reef edge.

Terry et al. (2013) inspected at Taveuni (Pacific Ocean atoll island) the transport capacity of cyclone waves during a category 5 typhoon (TC Tomas, 12–17 March 2010) with gusts up to 259 km/h. They found the largest boulder freshly moved was 4.85 tons on the reef flat, but much larger and older ones (up to 40 m^3 in size and at least around 75 tons) and 16 other large ones have not been mobilized during this exceptional strong typhoon. The authors also discuss, whether old carbonate clasts may have lost their mass by solution. For the Galway region, we can exclude this as a significant contribution to size reduction, adapted from missing related solution forms of any intensity on the boulders.

At the Reykjanes peninsula (Iceland), Etienne and Paris (2010) found the largest boulders in cliff top position (at about +9 m asl) to be 6.17 and 6.14 tons from a

Table 3.2 Galway Bay and Aran Islands: old boulders, dislocated

Site	Altitude	Max. axes	Mean axes	Volume	Mass	Remarks
	m asl	m	m	m^3	t	
Aran Islands						
Inismaan W	16	1.6 × 1.12 × 0.62	1.54 × 1.1 × 0.56	0.95	2.5	Boulder dislocated on seaward ridge slope
Inismaan W	13	2.3 × 1.12 × 0.59	1.4 × 0.6 × 0.48	0.4	1.0	
Inismaan W	13	2.24 × 1.6 × 0.37	1.6 × 1.32 × 0.3	0.64	1.7	Highest boulder dislocated to the landward slope of old ridge
Inishmaan NW	3.2	2.55 × 2.25 × 1.6	2.3 × 2 × 1.48	7.6	20	Dislocated from 1.5 m MHW to +2.8 m on distance 40 m, overturned to 120° and steep inclination
Inishmore W/S	3.3	3.6 × 3.42 × 0.56	3.2 × 2.92 × 0.44	4.1	10.3	Boulder shifted for nearly 2 m and axe direction turned 80°
Inishmore W/N	4.5	2.77 × 2.59 × 0.48	2 × 1.92 × 0.37	1.4	3.5	Distance moved >5 m, vertical from +2.9 to +4.5 m, shifted flat lying
In Galway Bay						
Camping S	0.9	5.2 × 3.3 × 0.75	4.8 × 2.74 × 0.56	7.3	18.4	

recent storm, but larger ones assumed to be moved by storms were emplaced further inland in former (unknown) times. They measure from 26 tons at +2 m MHW moved 15 m horizontally, to 70 tons at +6 m moved 65 m horizontally, the latter as one exceptional case. Hansom et al. (2008) modelled that a 12 m high wave (10 s period) may overtop a cliff 15 m high and lift and transport a boulder of 0.7 tons. They also argue, that during flow attenuation block deposition occurs at the limit of run-up, and that a wider platform allows the bore to develop from an impinging wave to achieve higher velocities (as on a smaller platform) with more and larger clasts being transported farther inland to build larger ridge systems. We disagree with these conclusions: the deposition of large boulders certainly stops before the maximum run-up, depending on the mass of the boulder, because maximum run-up elevation has only zero energy (but backwash potential), and the wider the platform, the more energy of the bore is lost and not magnified. Fichaut and Suanez (2008, 2011) studied boulders on Banneg Island, a very exposed spot at the southern entrance of the English Channel. The largest boulder moved by a storm in 2008 (with an exceptional high tide) measured 42 tons, but the median weight of 52 measured boulders was just 0.72 tons. The flow from inland rushing bores up a slope dislocated boulders of 0.3–1.4 tons between 50 and 90 m from the western cliff edge.

Etienne and Paris (2010), Richmond et al. (2011), or Paris et al. (2011) give the maximum dislocation of large boulders (i.e. of several tons in mass) to be around 100–120 m to landward, those further inland may derive from tsunami events.

It seems interesting to compare the data for freshly moved boulders with those which have been left stable within the reach of extreme storm waves (Table 3.3). Immobile old boulders are numerous in the ridges along the exposed coastlines of the Aran Islands, and also within Galway Bay, but only along the east coast, which is exposed most to incoming waves from the NW entrance of Galway Bay, and (with wave refraction), from its SE entrance. It is not surprising, that boulders with a mass of over 25–78 tons have been left stable, but more interesting is the fact, that even the lower category of common boulder size in the Galway and Aran region have not been moved (from 4.2 to 12.3 tons, i.e. in the size class of freshly displaced boulders). Additionally, these boulder sites are well exposed to strong wave and swell attack from the winter 2013/14 storms at only 4–5 m above MHW. The waves, however, have been in the order of about 12–15 m height directly at the rocky shorelines in the area, and water fountains with high velocity certainly have reached at least an altitude of 30 m. From these observations, we may be able to conclude on a certain threshold of boulder size/mass in relation to wave heights or storm intensities in the study area.

To test the objectivity of our observations, in Table 3.4 we compare the Galway and Aran boulders with young ones from other regions in the NE Atlantic Ocean (Reykjanes peninsula in SW Iceland as from Etienne and Paris (2010), Banneg Island in Britanny, France, by Fichaut and Suanez (2008, 2011), southern Caribbean by Scheffers and Scheffers (2006) from hurricane Ivan of category 4 in 2004, Hawaii (from young historical storms dated by the age of lavas at the base of boulders by Richmond et al. (2011)), and from Samar Island in the eastern

Table 3.3 Galway Bay and Aran Islands: old boulders, not moved

Site	Altitude	Max. axes	Mean axes	Volume	Mass	Remarks
	m asl	m	m	m^3	t	
SE entrance to Galway Bay						
Doolin N	4.3	3.3 × 1.25 × 0.80	2.27 × 1.2 × 0.74	2	5	
Doolin N	4.3	4 × 2.2 × 0.55	3.1 × 2.05 × 0.5	3.17	8	Boulder formerly overturned and imbricated 70°, rock pools at base
Doolin N	4.3	2 × 2 × 0.5	2 × 2 × 0.42	1.7	4.2	Boulder imbricated 35°
Doolin N	3	4.3 × 2.6 × 1.54	3.3 × 2.4 × 1.3	10.3	25.7	Boulder imbricated 50°
Doolin N	3	6.52 × 2.82 × 1.3	5.31 × 2.75 × 1.13	16.5	41.3	Boulder imbricated 15°
Doolin N	4.8	7.28 × 4 × 1.37	5 × 4 × 1.2	24	60	Boulder imbricated 9°
Aran Islands						
Inishmaan W	13	5.76 × 3.7 × 1.15	4.59 × 3.5 × 1.05	16.8	42.5	Boulder imbricated 12°
Inismore S	21	3.5 × 2.4 × 0.65	2.9 × 2 × 0.6	3.5	8-7	
Inishmore W/S	2.3	6.55 × 3.92 × 1.35	5.05 × 3 × 1.27	19.24	48.1	On boulder basement
Inishmore W/S	2.3	6.2 × 4.88 × 1.53	4.25 × 3.3 × 1.25	17.5	43.8	
Inishmore W/S	3.9	7.15 × 5.38 × 0.72	5.6 × 3.88 × 0.72	15.6	39.1	Based on other old boulders
Inishmore W/N	4.5	4.99 × 2.96 × 0.82	3.22 × 2.36 × 0.65	4.9	12.3	
In Galway Bay						
Poulsallagh	2.6	8.74 × 4.31 × 1.58	7 × 3.38 × 1.32	31.2	78	Based on other old boulders at ridge slope to seaward

Table 3.4 Boulders dislocated by waves from winter storms and tropical cyclones from the literature and personal observations (Reykjanes = SW Iceland—older winter storms, Banneg = Britanny/France—older winter storm, Bonaire = Netherlands Antilles—Hurricane Ivan 2004 [category 4], Philippines—Tropical cyclone Haiyan, Nov. 7th, 2013, a super-typhoon with sustained winds of 315 km/h and gusts up to 379 km/h)

Site	Altitude	Volume	Mass	Source
	m asl	m^3	t	
Reykjanes	2	9.73	26.83	Etienne and Paris (2010)
Reykjanes	2	14.8	38.47	Etienne and Paris (2010)
Reykjanes	2	22.46	53.51	Etienne and Paris (2010)
Reykjanes	6	26.04	70.31	Etienne and Paris (2010)
Banneg Island	9		32	Fichaut and Suanez (2008, 2011)
Hawaii			10	Richmond et al. (2011)
Bonaire	5		25	Scheffers and Scheffers (2006)
Bonaire	5		8	Scheffers and Scheffers (2006)
Bonaire	6		2.5	Scheffers and Scheffers (2006)
Aran Islands			3.5	Zentner (2009)
Aran Islands	25		5.8	Williams (2004)
Philippines	10		23	May, Pers. Comm. (2014)
Philippines	10		17	May, Pers. Comm. (2014)
Philippines	1		70	May, Pers. Comm. (2014)
Philippines	1	85	180	May, Pers. Comm. (2014)

Philippines by super-typhoon Haiyan, Nov. 7th, 2013, based on a personal communication from S.M. May, July 2014 (Table 3.4).

We can see, boulders in low elevation (2–9 m asl) and up to 70 tons have been found in SW Iceland and at the coast of Britanny, France, interpreted as storm deposits. They have not, however, combined with recent storms of known strength and wave heights. The direct observations from Bonaire during and after hurricane Ivan in 2004, with numerous waves at least 12 m high at a 5 m high cliff and significant water depth, just reached 2.5–25 tons as maximum boulder mass, so far as a horizontal movement of many metres has taken place. This leaves the question open, whether the largest boulders found at Reykjanes and Banneg may store signatures of other than storm energies, which is the same unsolved question for Galway and the Aran Islands.

Fortunately, we have some new observations (by personal communication from S.M. May after a visit to the Philippines in 2014) concerning the dislocation of very large boulders or blocks by super-typhoon Haiyan on Nov. 7th, 2013, at the east coast of Samar Island, eastern Philippines, where this typhoon took landfall. Here an uplift of boulders of 17 and 23 tons took place to +10 asl, and just above sea level dislocation for 30–40 m has been reconstructed from eyewitnesses and comparison of satellite images with boulders of 70 tons (overturned) and even 180 tons, in which the longest axe is 9 m.

These values are out of that energy class which so far has been found for winter storms or tropical cyclones of categories 3–5. We additionally have a concern, that the Haiyan waves first had to pass a fringing reef about 200 m wide before hitting and dislocating the boulders, which certainly has diminished wave height and energy. However, the winds of Haiyan with 314 km/h sustained, and 379 km/h in gusts, are extreme values even for the strongest TC category classified (Engel et al. 2014). A high surge additionally had formed a flow of many metres (up to 6 m at the boulder site?) which, if it lasted only about 1 min with constant energy, this is about 100 times the impact of a storm wave at a boulder (which is less than 1 s). This would put the Haiyan boulders at the Philippines in the same category of extraordinary events like freak waves, which may occur by chance and impact a coast, but certainly are not able to form long organized depositions like boulder ridges, and will not cross a wide fringing reef platform. The destruction left by super-typhoon Haiyan along the east coast of the Philippines is very similar to those left by the Indian Ocean Tsunami on Phuket Island, Thailand, Dec. 26th, 2004. Therefore we conclude that boulder masses of 20–30 tons (and about 20 m^3) transported for several metres horizontal and against gravitation are close to the threshold of boulder transport by storm waves worldwide. This is in the same order as found out by physical calculations by Benner et al. (2010).

In this discussion of boulder movement by storm waves and ridge formation, we are in opposition to Cox et al. (2012), in particular regarding the genesis of the ridges on the Aran Islands and their recent development, in several points: Cox et al. (2012: 251f) conclude, that the ridges gain mass through recent storms, but we found they lose mass because the storm waves took fragments from the seaward slope, wear them down by tumbling, and washes some of them into the sea. We also disagree that the ridges are moving to landward, because we did not find sites where this has been the result from the recent storm impacts (which did not reach the ridge crests or the landward slopes except of the very low ridges at the south coast of Inishmaan). The argument, that ridges may be activated in recent times and therefore, the wholesale ridges are made from recent storms (Cox et al. 2012: 252) “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” is not convincing, regarding in particular the age data we found in ridges, coming up to 4,500 years (Scheffers et al. 2009, 2010a, b).

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Chapter 4
Results: Organization and Architecture of Boulder Clusters and Boulder Ridges

Abstract The organization patterns of large coastal boulder deposits on the Aran Islands and within Galway Bay exhibit many different patterns: single platy boulders are leaning in low or steep inclination at structural steps on the upper cliff platform, but also show imbrication from different sides at an obstacle, or form imbrication trains even if the single clasts are many tens of tons in mass. Another setting is balancing on the crests of ridges, even if their mass is more than 10 tons and the crest is positioned at +15 m or more above MHW. The source for single boulders often is the cliff top front, or low structural steps on it, and only in rare cases in the tidal and supra-tidal zones. Most of freshly activated boulders, however, derive from older ridge fronts. The most significant form of deposition is a very long and 20–50 m wide ridge with a relative height of many metres. Cross sections of these ridges are asymmetrical with steep seaward faces. Lower ridges may occur to landward, separated from the main one, and at some promontories more than three ridges or boulder piles exist, all older than the main one. A special aspect are two different types of ripples: small ones parallel to the ridge crests at the landward slope, and wider diagonal and curved ones forming the main ridge in a longer row.

Keywords Imbrication · Imbrication trains · Balancing boulders · Boulder sources · Boulder ridges · Parallel ridges · Ripples · Ripple ridges

4.1 Imbrication and Imbrication Trains

Coastal boulders of the Aran Islands and within Galway Bay are in a high number tilting in different angles (up to nearly vertical positions with their main plane), mostly at the seaward slope of a ridge, or at structural steps on coastal slopes (Figs. 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6).

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Fig. 4.1 A 48 ton boulder at the west end of Inishmore. *Left* June, 2014, *right* June 2007. The two boulders beside the large one in the *left image* (flat lying platy of 3.1 tons, transported 20 m horizontally and 0.9 m against gravitation, and a smaller cubic one) have been freshly emplaced by extreme winter storms of the season 2013/14. Position is at about 4.5–5 m above MHW and >60 m from the surf belt (*Image credit* D. Kelletat)

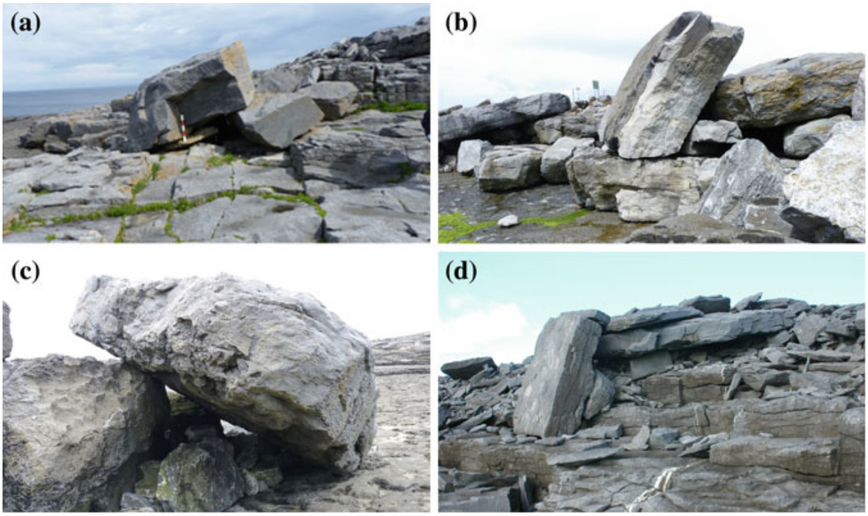

Fig. 4.2 Medium and steep inclination of large coastal boulders document a movement which includes an uplift at least of their frontal part **a** Doolin NW, largest boulder >20 tons, scale = 0.5 m. **b** Doolin Ferry east, steep boulder setting. **c** Inishmore west end, boulder >40 tons. **d** Inishmore SW, boulders 18–38 tons (*Image credit* D. Kelletat)

The platy form of the Aran and Galway boulders deriving from the well stratified limestone evidently enables imbrication of several boulders (Fig. 4.5).

The organization of boulders may also be rather complex, as in imbrication trains (Figs. 4.5, 4.6, 4.7, 4.8 and 4.9), and may even occur on ridge slopes or ridge crests (Fig. 4.10). In contrast to boulders leaning at structural steps, which may have moved downwards, those in imbrication patterns and imbrication trains on

Fig. 4.3 *Left* A 20 ton Inishmaan boulder has been dislocated from the intertidal zone, where it has been rounded for a longer time. At the landward side (in the shadow) rock pools also point to the intertidal or supra-tidal source area, i.e. the surf belt. *Right* On Inishmore's SW coast (*right image*), boulders leaning on structural steps can often be found. Their source stratum can easily be identified nearby (*Image credit* D. Kelletat)

Fig. 4.4 Old single boulders from the Doolin region. Aspect is from June, 2014, showing no refreshing or dislocation by the extreme winter storms of 2013/14 (*Image credit* D. Kelletat)

Fig. 4.5 Platy forms of the boulders are very suitable for a more complex imbrication pattern. This rock platform at the west end of Inishmore (partly freshly exposed) is at about +5 m MHW, largest boulders are about 50 tons in mass (*Image credit* D. Kelletat)

platforms must have been lifted against gravity. Their movement horizontally also generally is wider, because the next places of possible out-breaks often are tens of metres away. The possible genesis of imbrication of these very large boulders as well as boulder ridges will be discussed in the results section of this chapter.

Fig. 4.6 Imbrication maybe from several sides, but most probably—at least with very large boulders—it is typical for the seaward face of ridges and obstacles. *Left image* is from SE of Doolin (person as scale), *right image* is from the west end of Inishmore. See fresh small outbreaks and impact marks from winter 2013/14 (*Image credit* D. Kelletat)

Fig. 4.7 Imbrication trains: *left* irregular/chaotic (from SE Inishmore with boulder mass up to 22 tons, +11 m MHW), *right* well organized, from inside Galway Bay SW of Black Head, boulder weights here are 4–10 tons at +4.5 m MHW (*Image credit* D. Kelletat)

Fig. 4.8 In imbrication trains, boulders may base all on the same level (*left image* from SW Black Head in Galway Bay just above MHW), or be stapled (*right image* Galway Bay, SW of Poulsallagh, at 3.5 m MHW) (*Image credit* D. Kelletat)

Fig. 4.9 Imbrication train (with boulders up to 50 tons) at the southern section of Inishmore's west end, unchanged from 2007 (*left*) to 2014 (*right*), but showing some freshly emplaced smaller boulders in both years (*person in image* of 2014 as scale) (*Image credit* D. Kelletat)

Fig. 4.10 Imbrication can also be found high on the seaward slope and even up to the crest of main ridges, sometimes more than 200 m from the shoreline (Inishmaan west coast). Ridge crest is at about +14 m MHW and >100 m from the cliff. While the largest boulders have not been moved in 2013/14 (*dark surfaces*), smaller ones at the seaward face of the ridge up to the crest have been refreshed with *light surface* colours (*Image credit* D. Kelletat)

4.2 Delicate Setting and Balancing Boulders

Beside imbrication, delicate setting of boulders balancing on others with only a few small points as a base, and in particular balancing on top of the ridge crest, can be found at all sites with boulder ridges in the Galway and Aran area (Scheffers et al. 2009, 2010 and Figs. 4.11, 4.12, 4.13 and 4.14). Cox et al. (2012) described these boulders as "in trans-ridge movement", which seems reasonable and they certainly are. But this implies, that they just are left up there by a recent strong storm, and will be moved down slope to landward by the next strong storm. This evidently is not the case: no one of these balancing boulders have been affected by the six strong winter storms of the season 2013/14, because the storm waves did not reach the ridge crest at these locations. Also, as these boulders are weathered and evidently old, they rest on ridge crests for a long time, at least for centuries. Within this time frame, however—if their dislocation is the result of storms—a storm much weaker than that which emplaced the boulder on the ridge crest will have occurred to push the balancing boulder downslope in the direction of gravity, which also has not happened (see also

Fig. 4.11 Seaward slope of the Inishmaan Ridge around +14 m MHW with the largest coastal boulder found on this island (approximately 75 tons), and a series of balancing boulders on the ridge crest. Their overhanging to seaward is the result of an undermining by backwash from smaller fragments out of the ridge front. By this dislocation (with backwash of smaller boulders into the sea), boulders appearing at the surface may be recorded as freshly emplaced from below (*Image credit* D. Kelletat)

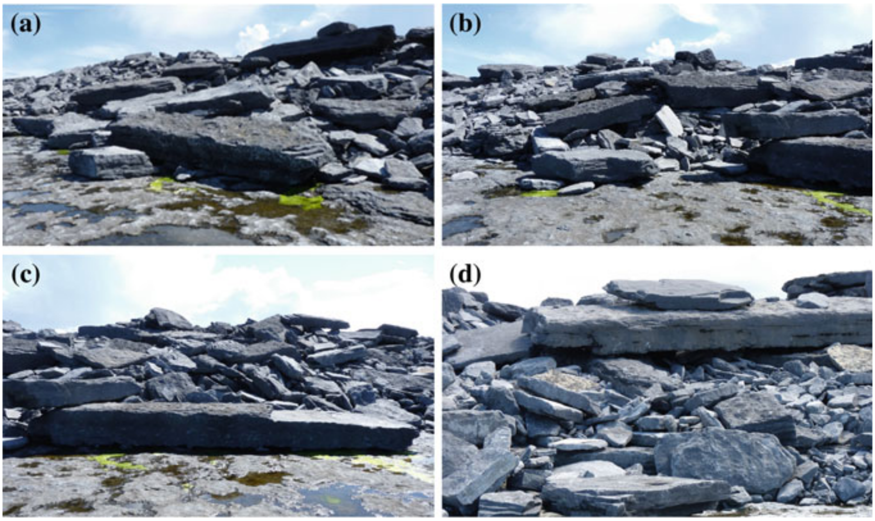

Fig. 4.12 Undermining maybe the most important process to make formerly stable boulders in higher ridge sections unstable. All images are from the seaward slope of the Inishmaan ridge around +13–16 m MHW. **a** large clasts piled up at around +15 m MHW. **b** Some activation around the ridge base. **c** Boulder at base of ridge is 8.32 m long, largest on ridge crest is 4.28 m long. **d** Recent boulder movements (mostly downwards) by undermining. Direction of boulder longest axe may also change by this process (*Image credit* D. Kelletat)

Fig. 4.13 The most impressive balancing boulders in ridge crest position can be found on Inishmaan Island in elevations of far more than +10 m MHW, largest in this section (*left image*) has a weight of at least 20 tons (*Image credit* D. Kelletat)

Scheffers and Kinis 2014). These observations lead to the conclusion, that we need other (or additional) forces and processes than storm waves for the architecture and organization of the main boulder clusters and boulder ridges of the Aran and Galway area (see Chap. 5, Discussion).

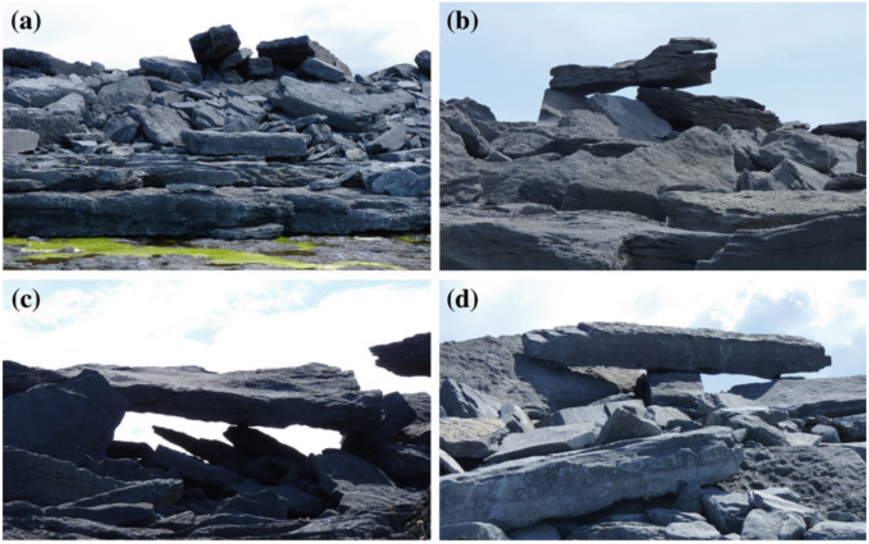

Fig. 4.14 These delicate positioned boulders are really large, mostly with longest axes around and over 4 m. All examples are from the west coast of Inishmaan at more than +12 m MHW and 140–240 m from the surf belt (*Image credit* D. Kelletat)

4.3 Source of Coastal Boulders

An important question to calculate transport energy to dislocate a boulder is the knowledge of its former source, e.g. joint bound in a rock platform or at a cliff face and cliff edge. Although we do not know in all the cases, whether a boulder has been dislocated during one event, at least its total transport distance as a maximum for energy calculation can be determined. There are several indicators—beside the petrographic character by comparing facies (Fig. 4.15).

The best and easiest to detect are those with characteristic smaller morphological decoration at the boulders. These may derive from terrestrial karstification, the rock pool belt of the lower supra-tidal (Figs. 4.16, 4.17 and 4.20), or from the inter-tidal and sub-tidal, where the living zones of boring bivalves (*Hiatella arctica*, Fig. 4.18), that of limpets (*Patella* sp.), and of sea urchins occur (Fig. 4.19).

In general, 99 % of the ridge material derives from the base rock (Carboniferous limestone), but in rare cases granite boulders can be found (Figs. 4.21, 4.22 and 4.23). Their position in ridges or—as in these images—directly at the seaward front needs some explanation or better speculation. Evidently the boulders with their characteristic rounded forms are classical erratics from the Pleistocene (last) Ice Age and derive from the crystalline rocks from around the city of Galway at the inner part of Galway Bay, or from Connemara in the north of the Aran Islands. Their position at the seaward front of recent Holocene beach ridges is enigmatic:

Fig. 4.15 Two boulder settings from the landward face of the main boulder ridge of Inishmaan's west coast at about +15 m MHW. *Left* Columnar old boulders (up to about 10 m in length) oriented nearly perpendicular to the coastline and possible flow direction. *Right* Landward slope of the main boulder ridge as seen from the crest. Very wide field of strewn boulders up to about 500 m from the shoreline at >+16 m MHW (*Image credit* D. Kelletat)

Fig. 4.16 Indicators for the source of the boulders: *left one* with rock pools from the upper intertidal to lower supratidal (50 ton, inside Galway Bay, person as scale), *right one* (about 18 tons) with features from terrestrial karst solution (Galway Bay, SW of Black Head, landward slope of ridge, about +4 m MHW and 90 m from shoreline) (*Image credit* D. Kelletat)

either they have been moved constantly from a landscape now eroded by the sea and shifted with other fragments to inland, meaning that they always or for a longer time have been close to the ridge, or they are overridden by a landward moving ridge, and more single granite boulder distributed on the fields of the islands may be incorporated and overridden in the distant future (Fig. 4.23). The latter hypothesis, however, has the disadvantage, that the granite boulders are smaller than other fragments in the ridge, though most probably would not have been emplaced while strong storms shifted a limestone boulder ridge to landward.

Fig. 4.17 Several boulders exhibit bioerosive rock pools on one side (former upper plain), often partly abraded by transport processes (Scene from inside Galway Bay, SE coast) (*Image credit* D. Kelletat)

4.4 Main Boulder Ridges in the Aran and Galway Region

The most interesting feature in the Galway and Aran area and—so far as we know, unique in coastal landscapes of the world—is the wide extension and perfect form of very long cliff top boulder ridges (Figs. 4.24, 4.25, 4.26, 4.27 and 4.28). They extend for nearly 20 km along all three Aran Islands at the exposed west to south and partly east coasts, and along the western facing coast of inner Galway Bay between Black Head in the north and Doolin in the south, although here more in separate sections, interrupted by boulder clusters, a few sandy beaches and higher cliff section without significant boulder deposits. As the transport of boulders depends on their size, and the energy of the impacting waves (or other forces from the ocean) depend on coastline forms and elevations, it seems reasonable, that the boulder deposits and in particular the ridges are adapted to these features, besides depending on the degree of exposure and water depth. Cliff lines, coastal slopes and

Fig. 4.18 Borings from the bivalve *Hiatella arctica* (lower inter-tidal to upper sub-tidal) are very significant. We found shell in them up to at least 3,000 years after dislocation, but most of the borings are empty. Scene is from Inishmaan NW coast at about +5 m MHW and 100 m from the shoreline. Boulder size shown is around 20 tons. See striations from recent boulder impacts of the winter storms 2013/14 on *right part* of image (*Image credit* D. Kelletat)

their conjuration and elevation are interrelated determine the wave transformation and transport distances of boulders inland and against gravity. As we can see in the satellite images (Figs. 4.25, 4.27 and 4.28), in the Galway and Aran region this relationship seems to be complicated or counter-intuitive: ridge distance and directions are much more smoothly running than the refraction-determining cliff and coastline contours. The relationship is stronger at higher elevations as at the SW coast of Inishmore (Fig. 4.25a, b) and the south coast of Inisheer (Fig. 4.25f), and an explanation involving only wave deformation seems not to be adequate.

Within the ridges, the large clasts are most significant, but they also contain a high number of small fragments and well-rounded ones in cobble and pebble size (Fig. 4.24). Therefore statistics based on a very high number of measured fragments irrespective to their size (e.g. Zentner 2009) will not reflect the sedimentologic character of the ridges, because although the number of small fragments is

Fig. 4.19 Sea urchin resting places (diametres 6–10 cm) from the upper subtidal as the source area of large boulders from Inishmaan's NW coast (*Image credit* D. Kelletat)

overwhelming, they do not determine the mass of rock which is stored in a ridge cross profile.

The cross profile of most beach ridges and beach ridge sequences worldwide are symmetrical and convex (e.g. Scheffers et al. 2011, 2012) but those from the Galway and Aran region are different: as recognized by all authors, the seaward slope general is steeper (up to 35°) and shorter, the crest well defined, and the landward slope has a smaller inclination (5°–12°, Cox et al. 2012) and is wider (Figs. 4.25, 4.27, 4.28 and 4.29), sometimes leading to strewn boulder fields and lastly individual medium-sized boulders within soil and vegetation (Fig. 4.29). While the crest in many cases (in particular at the highest elevations at the Inishmaan west coast) maybe many metres wide and convex, and the landward slope straight to concave, the seaward slope may be straight or concave, in particular if large boulders are present in the upper section. Shortly after the strong winter storms of 2013/14, we could see an activation of the seaward slope with diminishing of material which has been washed out into the sea even over wide cliff top platforms. This impact transforms the seaward slopes and steepen them. As a result, the ridges seem not to gain material by recent storms (Cox et al. 2012), but loose some of it.

Fig. 4.20 This 12.1 ton boulder dislocated 28 m to inland (and 1.6 m against gravitation) on a ridge inside Galway Bay exhibits several indicators of its origin from the upper intertidal: bioerosive rock pools, calcareous algae and vermetids (*white colour*), and barnacle carpets. The organisms will disappear after some time, but the rock pools will survive for many 1,000 years, which also gives a good hint to the very low rate of limestone solution in a terrestrial environment

In general, there is a strict difference in surface aspect of the boulders: at the seaward face they generally are sharp edged and have broken surfaces (Zentner 2009), but are larger on the landward slope. Those on the crest, on the landward slope and in particular scattered to inland are significantly weathered, their surface is rough, and straight edges and plain surfaces are rare. This gives an aspect of general older ages from seaward to landward.

The organization of perfect formed ridges is controversial. Morton et al. (2008) argue, that ridges only can be formed by storm waves, because tsunami events, with their lower frequency, are more likely to leave fields of isolated boulders. If this is correct, all very large boulders within ridges up to their crest also can only be moved by storm waves, which in the case of Galway and Aran is not the case, based on near-time inspections of the transport energy of extreme winter storm waves in 2013/14. Large boulders in well-ordered settings also occur in regions of less wave energy as on Mallorca Island of Spain (Kelletat et al. 2005), Algeria (Maouche et al. 2009), Apulia (Mastronuzzi and Sanso 2000), or the Peloponnese of Greece (Scheffers et al. 2008), and in general as Scheffers and Kinis (2014) have documented.

Fig. 4.21 One of a few ice age granite boulders of significant size (here about 2 tons), found at the seaward front of the main boulder ridge SW of Black Head within Galway Bay (*Image credit* D. Kelletat)

The distance of boulder ridges to the recent coastline, although in high elevations, also is much more than the 100 m or so (Fig. 4.28) mentioned as a maximum by Richmond et al. (2011).

4.5 Double and Multiple Boulder Ridges and Boulder Piles

As Williams and Hall (2004) have observed, at several localities of the Aran Islands, behind the main high ridges lower ones of a shorter extension are formed (Figs. 4.30, 4.31, 4.32, 4.33, 4.34, 4.35, 4.36, 4.37, 4.38 and 4.39). Their elevation is less than one m up to 1.5 m as a maximum, their length less than 100 m in any case, and their width mostly less than 30 m. They normally are separated from each other by swales, sometimes with soil and vegetation. In general, only one older ridge can be found, with the exception of the tips of high promontories (Figs. 4.31, 4.32, 4.33 and 4.34). Some of these ridge-like features can better be described as boulder piles (Figs. 4.31, 4.32, 4.33 and 4.34), because they lack a longer extension. Better developed are the older ridges on top of the highest cliffs as near Crummel on the west coast of Inishmaan (from +26 to +28 m MHW, see Figs. 4.35, 4.36 and 4.37) as well as those around the main puffing hole in the eastern part of Inishmore Island (Figs. 4.38 and 4.39). In this section it seems, that the older landward and

Fig. 4.22 Examples of granite boulders (all around one ton in mass) from the southern east coast of Inishmore, positioned directly in front of the main boulder ridge (*Image credit* D. Kelletat)

higher ridges have been deposited before the puffing hole has formed as a collapse of a surf cave's ceiling. In any case, they are older than the main high ridge closest to the modern cliff. Zentner (2009) describe these secondary ridges as developing from "blow outs" of waves overriding the main ridge, but their extension and form as seen in the figures, do not support this genesis. At Inishmaan's Crummel site, the direction of the ridges and their curving nature gives hints to whether they have been formed with the most northerly first and the next to the south in a consecutive time-line, or—as the chapter on ripple-like features in ridges will demonstrate—simultaneously. This will be discussed more in the next chapter.

Fig. 4.23 Several granite boulders as glacial erratics distributed in the field behind the main coastal boulder ridge from Inishmaan, central west coast region (*Image credit* D. Kelletat)

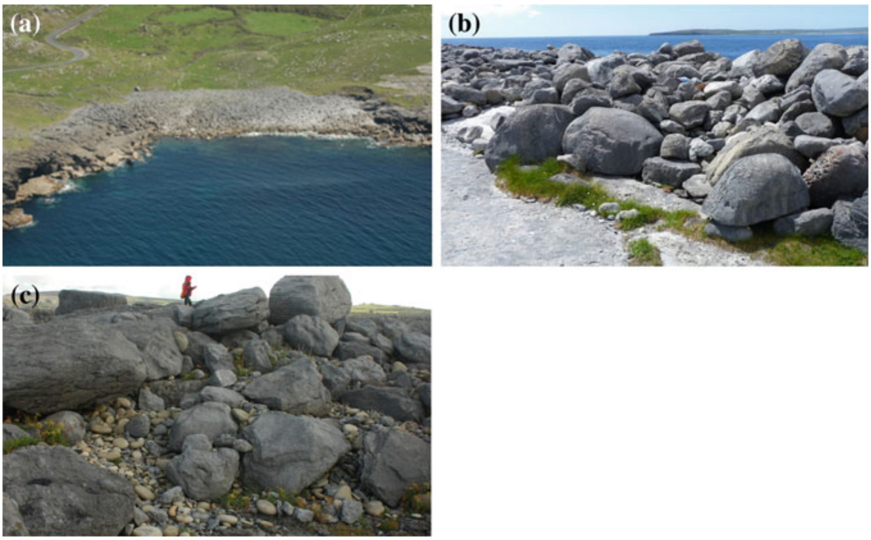

Fig. 4.24 Types of boulder ridges with mixed coarse and small fragments, or well-rounded boulders up to a few tons, is rather rare in the Galway-Aran region. **a** Up to 7 m high boulder ridge at Poulsallagh, SE coast of Galway Bay (*Image credit* A. Scheffers). **b** Well rounded boulders up to several tons in weight from a wide ridge at the NW coast of Inishmaan (looking to Inishmore). **c** Galway Bay SW of Black Head: well rounded sandstone cobbles in large old limestone boulder ridge (*Image credit* D. Kelletat)

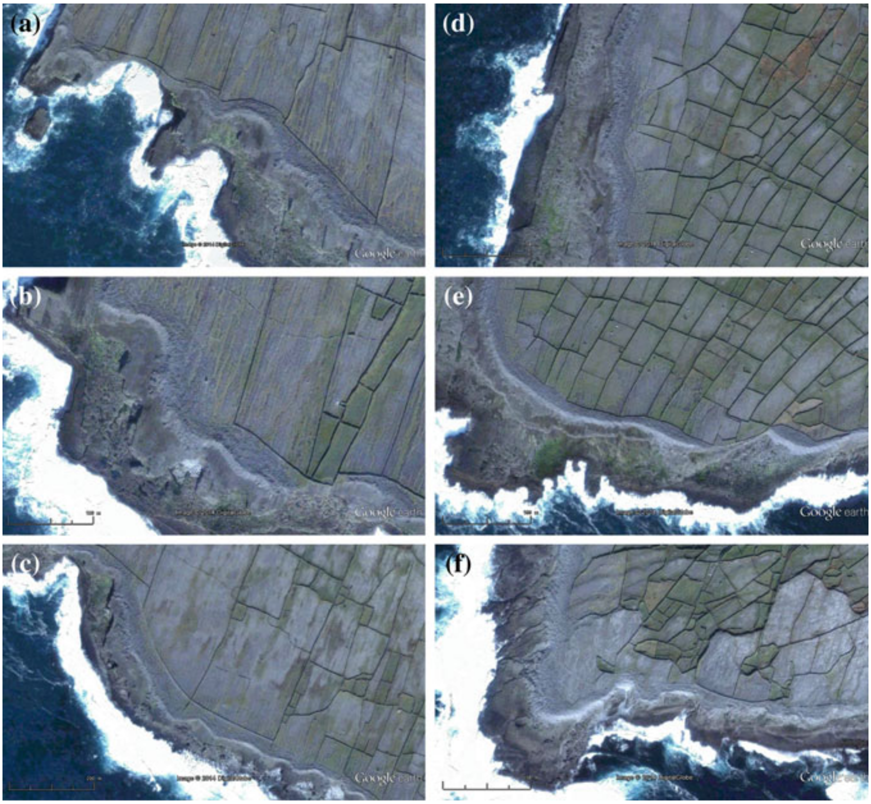

Fig. 4.25 Well organized and long boulder ridges are significant for the cliff coastlines of the exposed W and S coasts of the three Aran Islands even in elevation up to more than +20 m MHW. Their curvature may or may not be adapted to the coastlines. **a**–**c** from Inishmore SW, **d**, **e** from Inishmaan, **f** from Inisheer SW (*Image credits* ©Google earth 2012)

4.6 Ripple Features in Coastal Boulder Ridges

So far undescribed features combined with boulder ridges of the Aran Islands and deposits within Galway Bay are two different patterns in and on the coarse deposits. A first group looks like ripple marks more or less parallel to the ridge contour or its crest, diminishing in elevation, relative height and width to landward (Figs. 4.40, 4.41, 4.42, 4.43, 4.44 and 4.45). They are the result of strong flow (concerning the boulder character of the deposits) crossing the main ridges to landward. According to our observations, they have been inactive over a protracted period, and are not the result of repeated activation.

The second group of features, superimposed on the main ridges, are different: their forms are more like individual ridges of small elevation and extension, parallel

Fig. 4.26 Although the general approach of storm waves and swell during all seasons is dominant from SSW (250°), exactly this exposure of the Inishmaan ridge (9–10 m above MHW, with a maximum distance to the coastline of 290 m) is not adapted to the cliff line and its configuration. Section is at the SW-corner of Inishmaan. Compare also Fig. 4.25e (*Image credit* A. Scheffers)

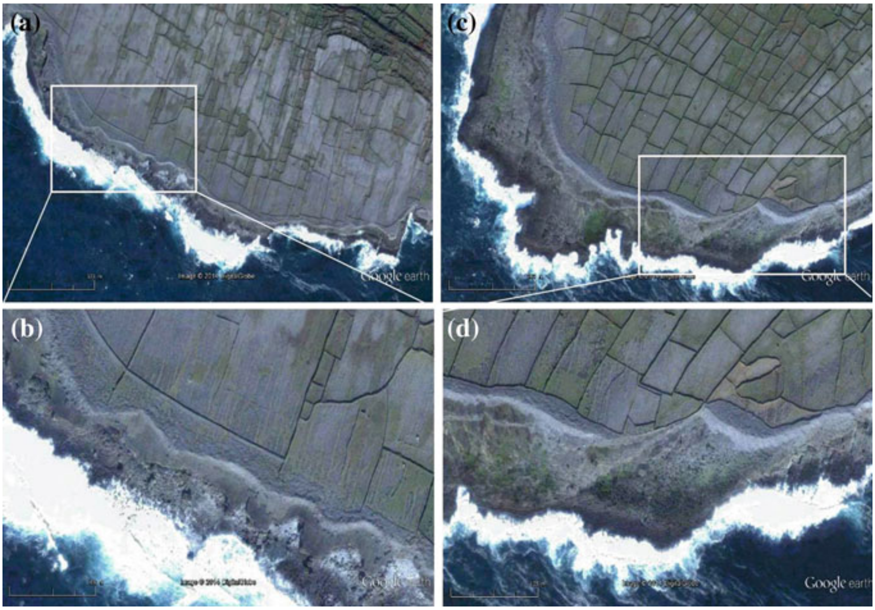

Fig. 4.27 Ridges are generally more adapted to the cliff line in higher elevations as in lower ones. **a** From +11 m MHW in the west to +5 m MHW to the east on Inishmore SE. **b** Detail from (**a**). **c** From +14 m MHW to +4 m MHW at Inishmaan SW. **d** Detail of (**c**). In lower elevations they show a very significant difference in colour: the seaward slopes are light in colour by rather constant refreshment and abrading during recent storms. Landward slopes are always less steep and dark which means inactive for decades, at least (*Image credits* ©Google earth 2005)

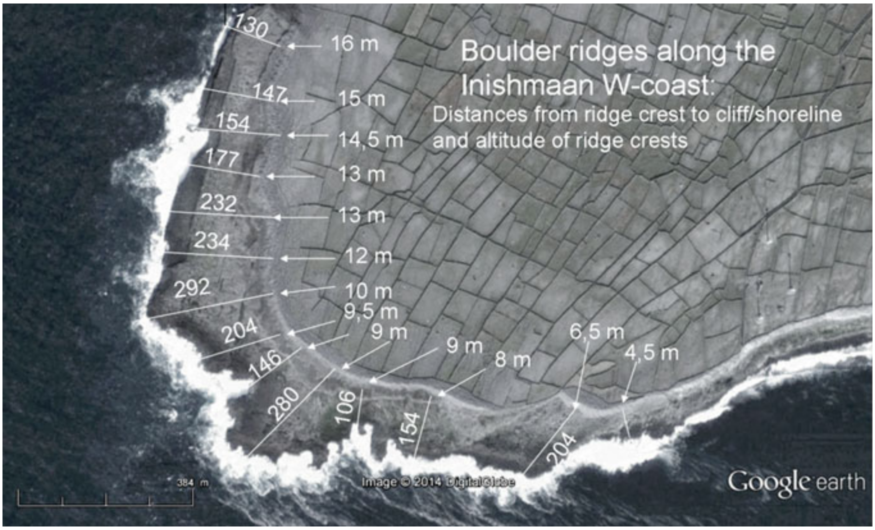

Fig. 4.28 The distance of the boulder ridges to the cliff line, as shown here from SW Inishmaan, is very large compared to data from the literature, and in higher elevations, as well. The more narrow relation of the two is significant for the higher sections (to the north), but also for low sections (to the east), here evidently because main strong wave approach is from SSW. Width of the main ridge mostly is between 28 and 49 m (*Image credits* ©Google earth 2005, modified)

Fig. 4.29 Two aspects from the landward/leeward slopes of the coastal boulder ridges of Inishmaan in a medium elevation around +15 m MHW: large boulders maybe present, partly dipping to landward, but the most significant feature is the wide low slope with strewn boulders, disappearing under soil and vegetation (*Image credit* D. Kelletat)

and often curving in an angle to the direction of the main ridge. Their exposure to the forming forces from the sea, reconstructable due to their similar alignment to incoming processes, can clearly be identified. They are similar to the landward ridges e.g. from Inishmaan (Crummel site), and like these, they seem to be formed simultaneously. Their combination in a certain direction lastly forms a wide main ridge (Figs. 4.42, 4.45b–d, 4.46, 4.48, 4.49 and 4.50). We assume that their form is

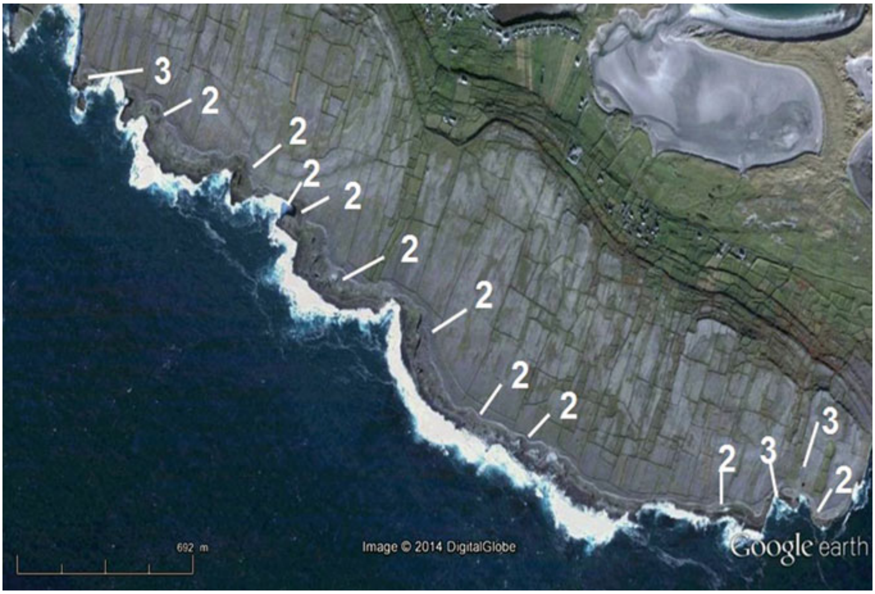

Fig. 4.30 Southeastern section of Inishmore's exposed Atlantic coastline with cliffs general between +25 and +10 m MHW (lowering to the east) mostly show two ridges (the main one and another one close by to landward), and only on the promontory tips around the Black Fort in NW, and around the puffing holes to the SE, more than two exist (*Image credit* ©Google earth 2005, modified)

Fig. 4.31 Short ridge sections or boulder piles at the Black Fort promontory in the centre of the image, as well as on both neighbouring promontories, all between +25 and +23 m MHW (*Image credit* ©Google earth 2005, modified)

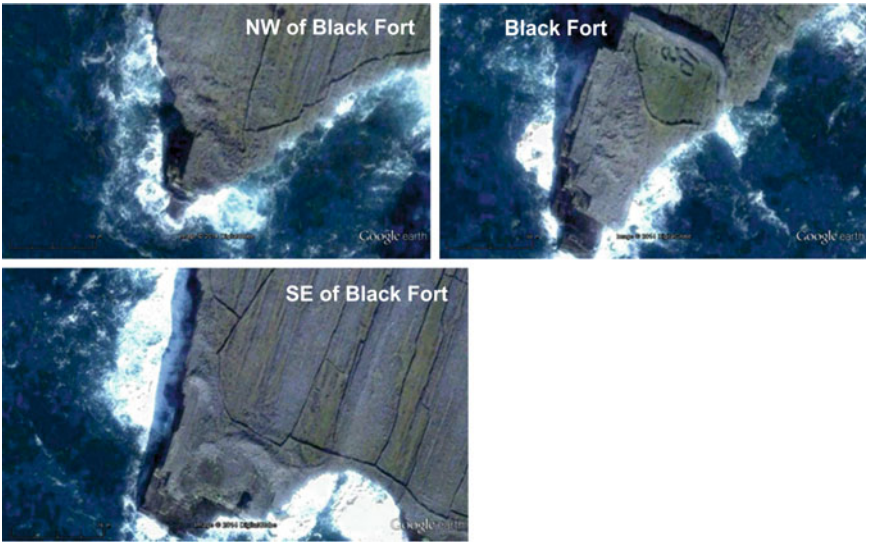

Fig. 4.32 A larger view on the three promontories around the Iron Age Black Fort (*Image credit* ©Google earth 2005)

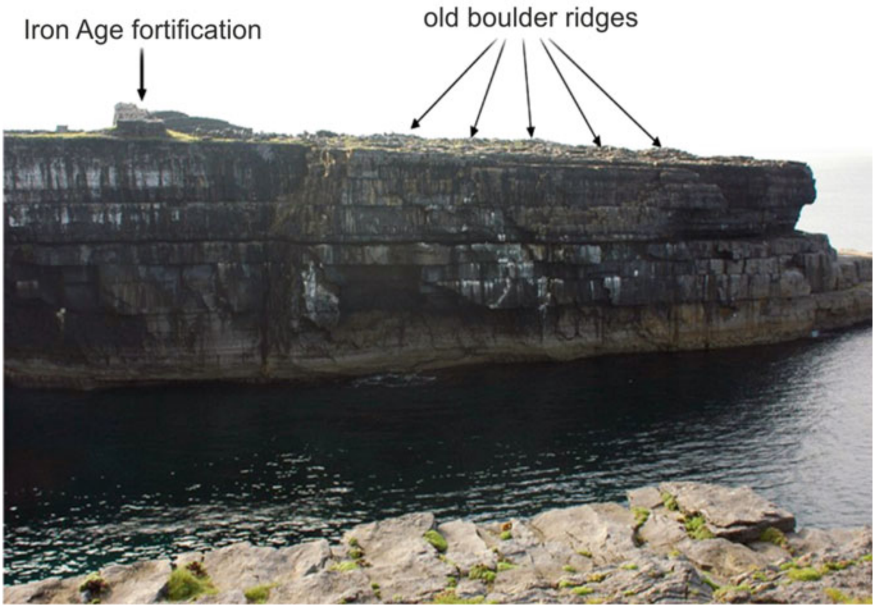

Fig. 4.33 View from the NW of Black Fort to the promontory with the thick Iron Age wall (built between 2000 and 2500 BP). Five different boulder elevations can be identified at +23 to +26 m above MHW (*Image credit* D. Kelletat)

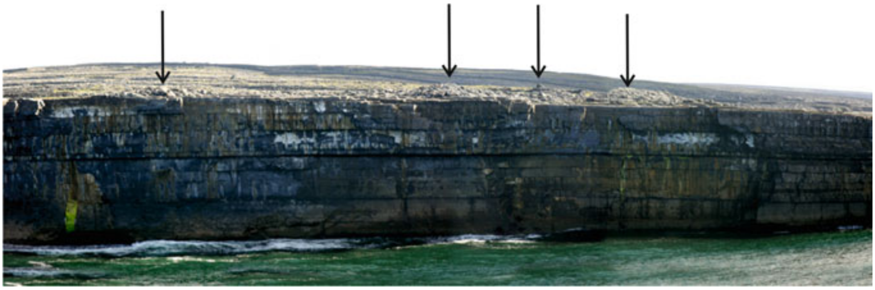

Fig. 4.34 Looking from the Black Fort to SE, at least 4 ridge sections or boulder piles can be seen. If elongated, their extension is perpendicular and not parallel to the cliff line (*Image credit* D. Kelletat)

Fig. 4.35 Short more or less parallel boulder ridges at Crummel on Inishmaan, nearly perpendicular to the cliff line at the highest and vertical cliff section of Inishmaan Island (+28 m above MHW, see also Fig. 3.39) (*Image credit* D. Kelletat)

older and not active in total, as no transformation or change occurred during the exceptional strong winter storms of 2013/14. Two general scenarios for these ripple-patterned ridges are possible: forming by wave refraction triggered by the finer coastal contours and leading to distinct wave trains for each small ridge feature, or the formation during one event (which may refresh from time to time) as in a strong

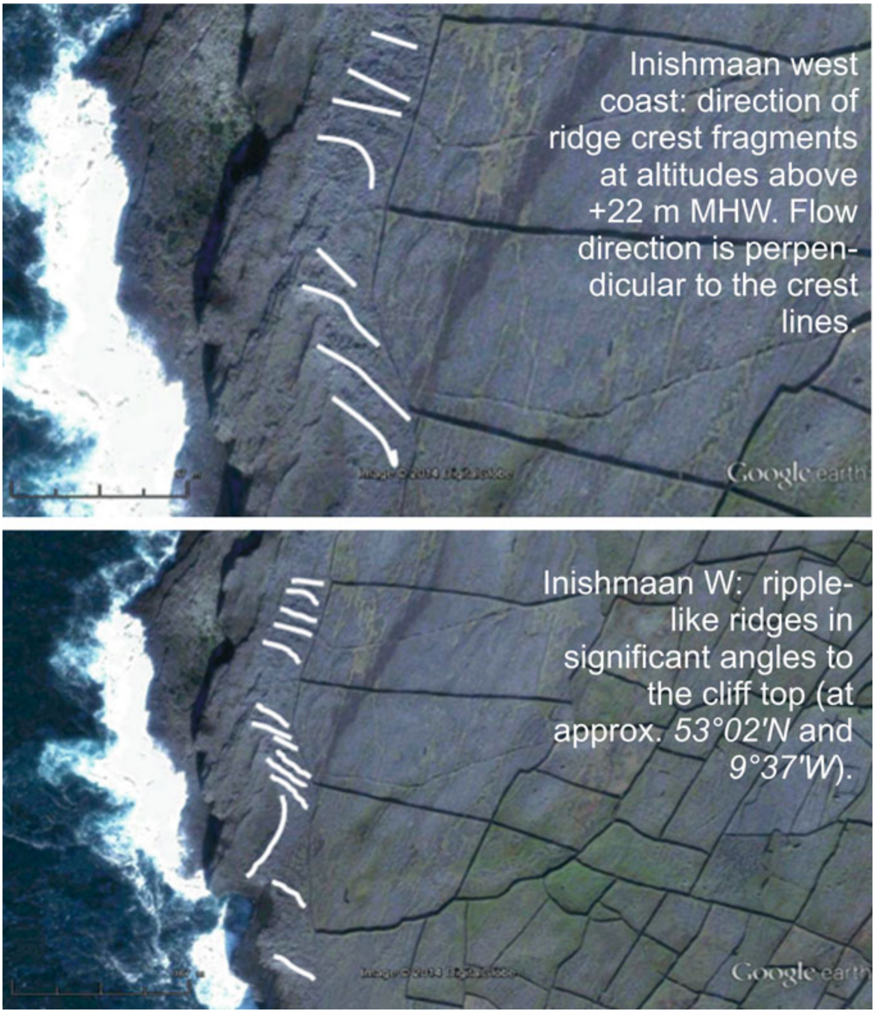

Fig. 4.36 Many short ridge sections south of Crummel more than 20 m above MHW are developed. They tend to an overall ripple-like aspect from one event, and not to a series of deposits formed over a longer time and in time laps of longer duration (see also Figs. 4.35 and 4.37) (*Image credit* ©Google earth 2005)

and wide flow. Their genesis compared with all the other forms will be evaluated in the Discussion part (Chap. 5) (Fig. 4.47).

The age or times of activity of the ridges are argued in the literature to be generally young because of fishing gear or plastic bottles etc. maybe trapped within them and even under very large boulders (Zentner 2009; Cox et al. 2012). Observations on many coastlines of the world lead us to another conclusion: waves

Fig. 4.37 The Crummel ridges of Inishmaan have a shape different from that of the main Aran ridges: their seaward (here: southward) slope is not as steep as the landward (northward, leeward) slope. These parts were not affected by the six extreme winter storms of 2013/14. A view on the swale between two of these features can be seen in Fig. 4.39, right image (*Image credit* D. Kelletat)

Fig. 4.38 Landward ridges in the puffing hole region of eastern Inishmore are ordered from land- to seaward, giving a clear age sequence. Figure shows elevations in m above MHW. Distance of the northernmost ridge at +29 m to the cliff is 136 m. The large puffing hole at +18 m has dimensions of 13.5 × 8 m and is situated 36.5 m from the modern cliff (*Image credit* ©Google earth 2005, modified)

(and even strong winds) may emplace these light debris into existing boulder deposits, and as the boulders move down by undermining during younger storms, even large old boulders may bury young rubbish. Therefore, we would not use these signatures for age conclusions of whole deposits.

Fig. 4.39 At the puffing holes of Inishmore (*left* up to +29 m MHW), and at Crummel (*right* Inishmaan, up to +27 m MHW, relative height about 1.5 m), old and short ridges inland and higher than the main one are well defined and partly separated by swales, where boulders from both sides have been buried under soil and vegetation. The boulders are weathered and not moved for a long time. Imbrication is less developed compared to the high main ridge to seaward (*Image credit* D. Kelletat)

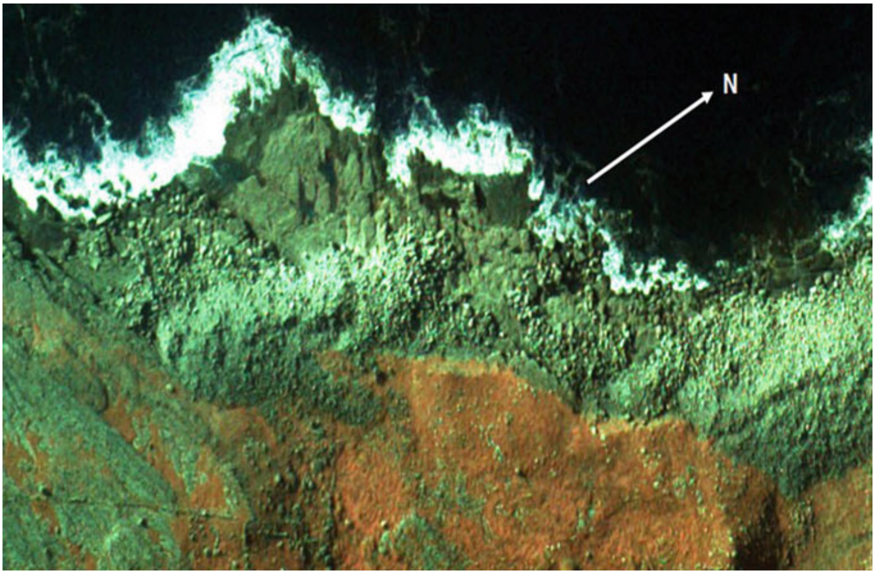

Fig. 4.40 Boulder ridges within Galway Bay (southern east coast) are organized less than those on the Aran Islands, closer to the shoreline and mostly in low elevations. Single boulders incorporated, however, may show the same mass. Picture shows a section 5 km NNE of Doolin Point, scene is 100 m wide (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

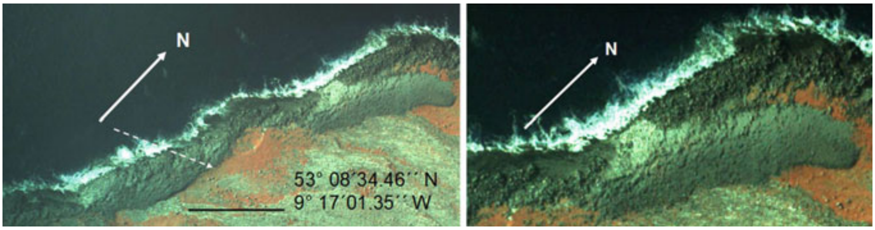

Fig. 4.41 As on the Aran Islands, within Galway Bay boulder ridges also may appear as more than one deposit. In this case close to Black Head, the inner wide ridge seems to be deposited from the south as a broad overwash feature 200 m long. Scale is 100 m (overview and detail) (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

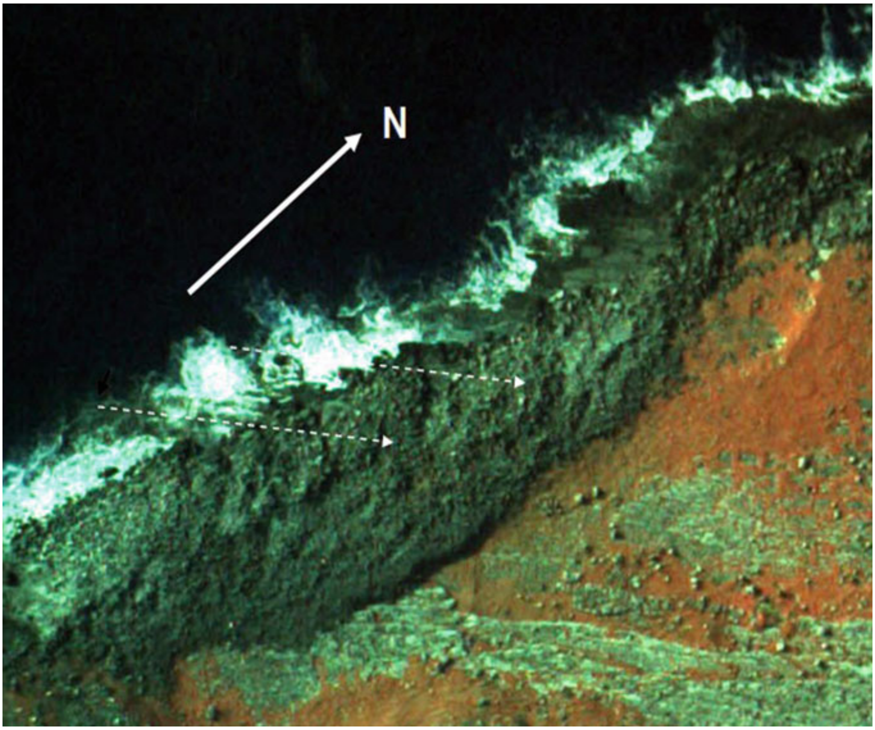

Fig. 4.42 Another similarity to Aran ridges are integrated ripple-like features, organized by impacts arriving in a tight angle with regard to the coastline. Picture shows a 250 m long section of a boulder ridge 2 km SW of Black Head within Galway Bay. *Thin arrows* indicate flow direction to form the "ripple" features on the main ridge (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

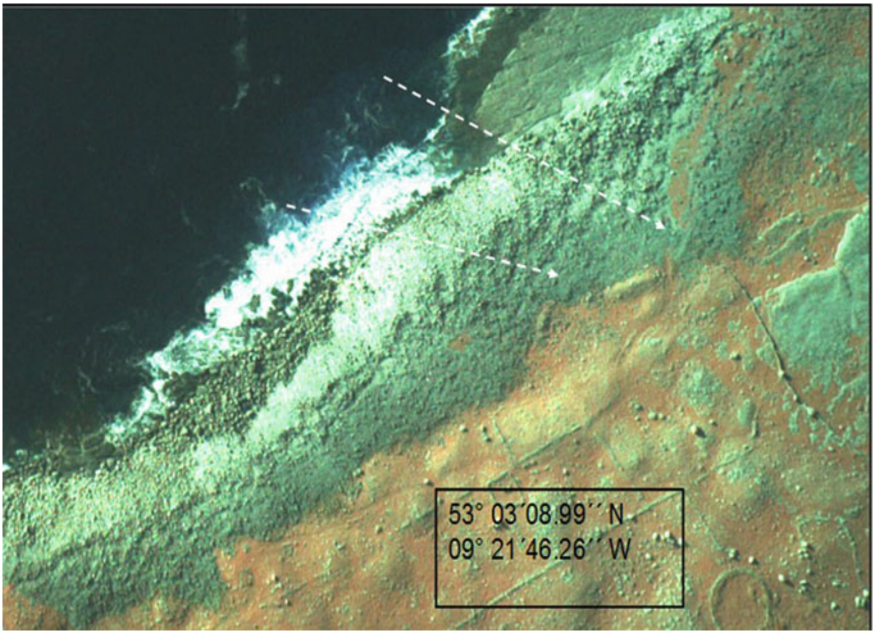

Fig. 4.43 Ripple features in broad boulder ridges may be well organized regarding their size and distance. Scene is from Galway Bay near Poulsallagh and 200 m wide. *Thin arrows* indicate flow direction (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

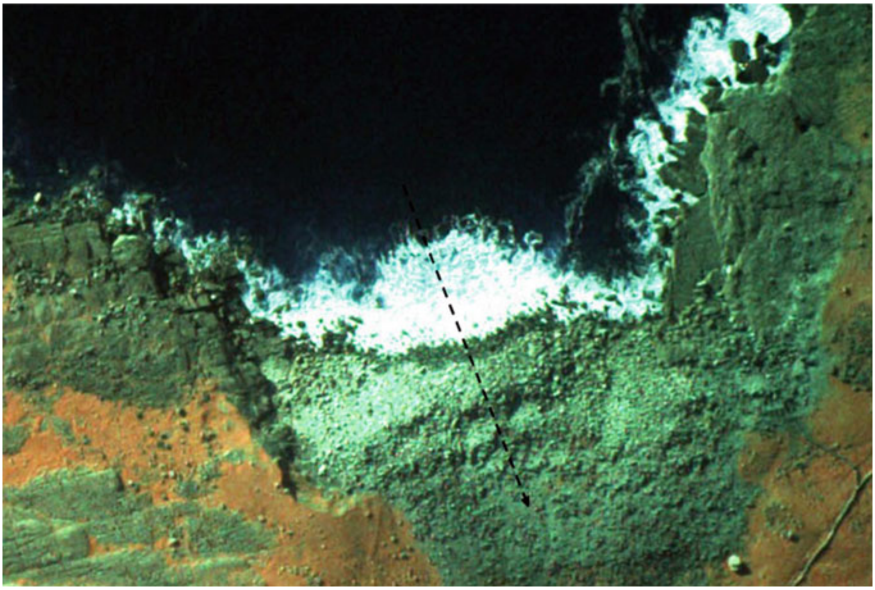

Fig. 4.44 Within high and broad ridges, patterns of parallel low crests, diminishing in elevation, relative height and extension occur, allowing to reconstruct the direction of incoming impacts. Image shows the 7 m high and 150 m long ridge SW of Poulsallagh (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

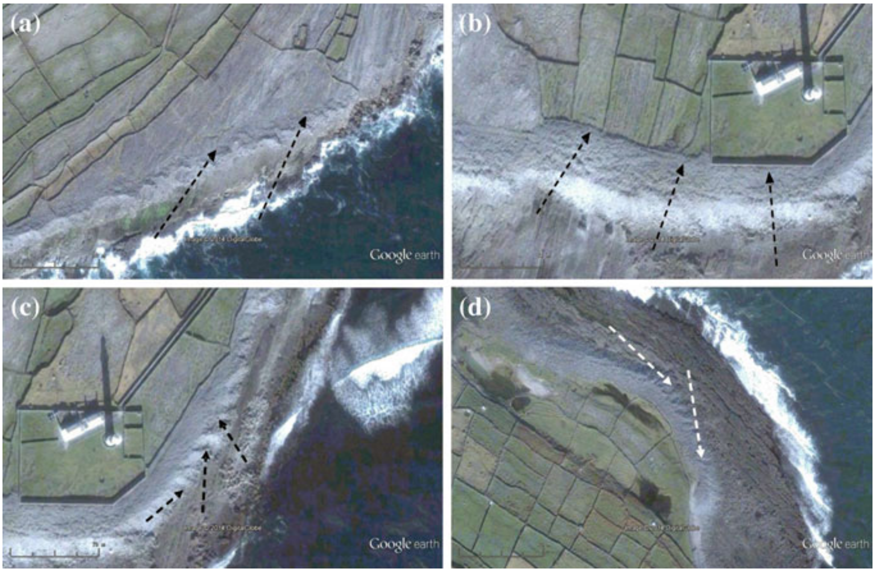

Fig. 4.45 On all three Aran Islands two different ripple features may occur: **a** Inishmaan SE coast. **b** Inisheer south coast (ripples more or less parallel to the main crest general direction). **c** Inisheer SE coast (see enlargement in Fig. 4.46). **d** Inishmore north coast. Series of curving ridges and boulder piles are formed in a significant angle to the coastline as in (**d**) built from NW curving to SSE, from a sheltered site of Inishmore north of the Kilronan Harbour (*Images credit* ©Google earth 2005)

Fig. 4.46 In contrast to the general approach of waves and swell from the open ocean, which is 250°, these features show a flow direction from 180° to 160° (*Image credit* ©Google earth 2014)

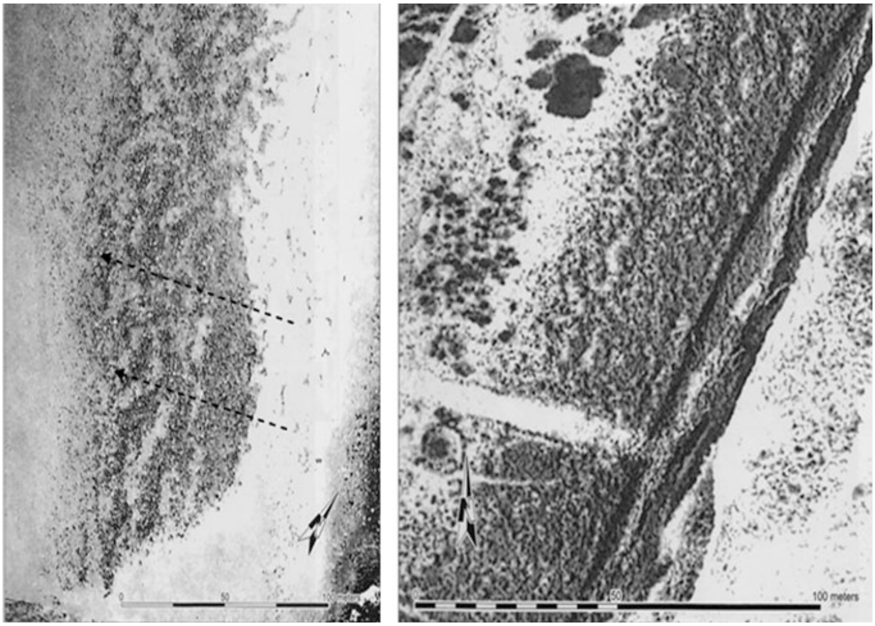

Fig. 4.47 Ripple structures on old and coarse tsunami deposits at the east coast of Bonaire Island, southern Caribbean (from Scheffers 2006). *Thin arrows* indicate flow direction. Scale is 100 m

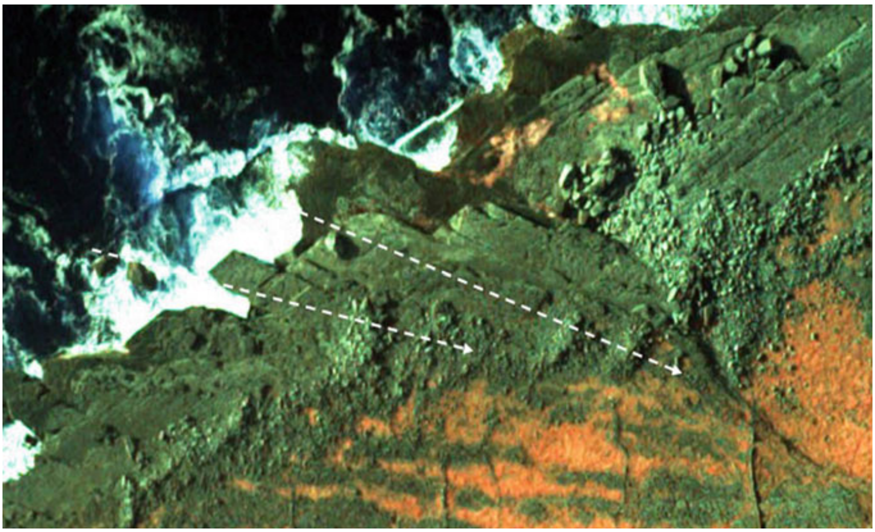

Fig. 4.48 Although these ripple-features are rather wide spaces and on the first glance may document individual deposits over a longer span of events in time, they most probably belong to the same process and show a pattern formed by the same forces and in the same time frame. Scene is NE of Doolin Point and 120 m wide (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

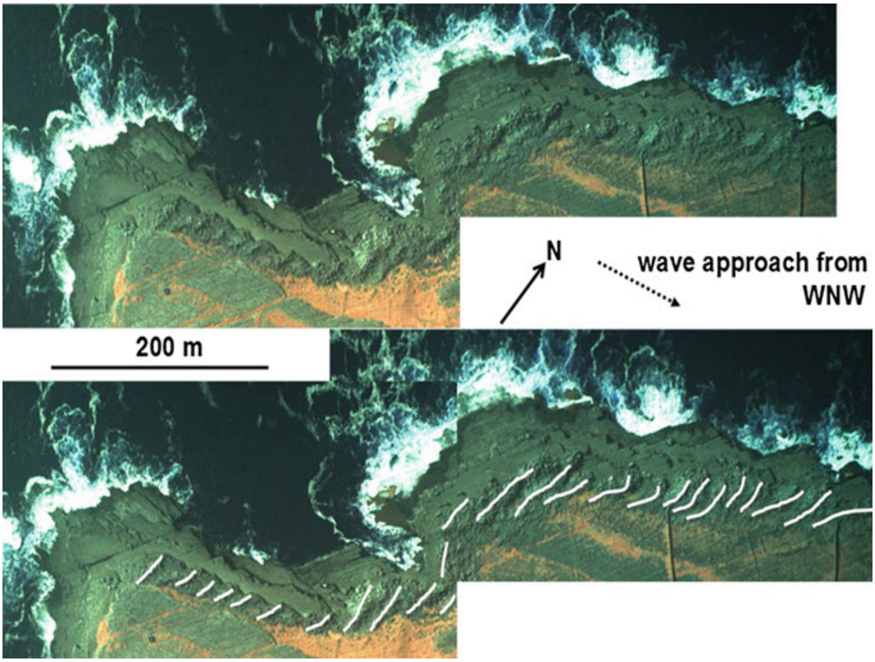

Fig. 4.49 The closer the deposit sites are to the entrances into Galway Bay and the open Ocean, the better and clearer internal features within the main ridges are organized. Example is close to Doolin Point (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

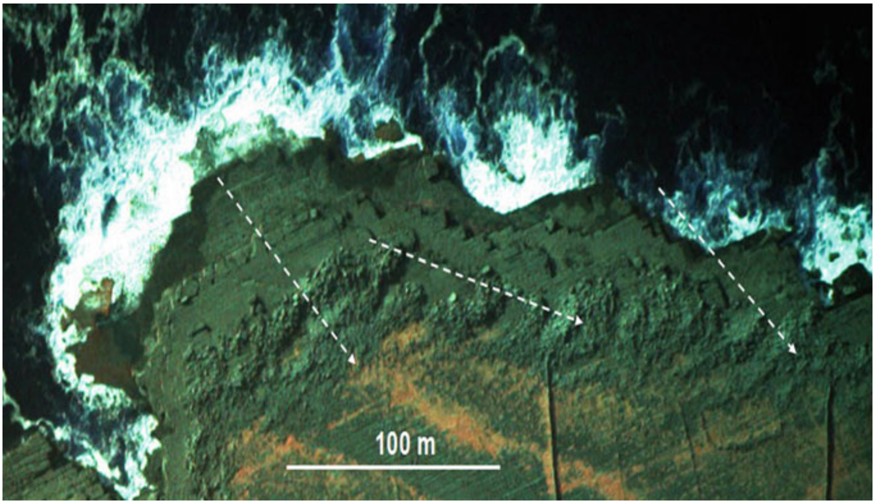

Fig. 4.50 Detail from Fig. 4.49 documenting that the exposure of the slightly curving internal ripples and their change in direction is not triggered by modern cliff contours. Site is NW of Doolin. *Arrows* indicate flow direction (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

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Chapter 5
Discussion

Abstract Based on the observations and wide documentation of field aspects, the formation of boulder clusters are discussed. For imbrication trains of very large clasts, a van Karman vortex is proposed. Balancing boulders often show this delicate position because of undermining of ridge faces by more recent storms. The asymmetry of the ridge cross-sections point to a longer erosive process by storm waves, reducing the mass of an older deposits formed under much higher energies than recent storm waves may offer. Relative ages have been concluded by lichen cover and general weathering, and 23 numerical data from boulder ridges are presented with ages going back for several 1,000 years. The formation of ridges along sheltered coastlines within Galway Bay are discussed concerning bathymetry and wave refraction. The velocity of cliff erosion and in particularly the shifting of whole ridges to landward is another point of discussion. In the conclusion, a tsunamigenic origin of the old and massive boulder ridge again is offered for discussion.

Keywords Ridge origin · Recent activation · Relative ages · Numerical data · Granite erratics · Cliff erosion · Ridge movement · Van Karman vortex · Ridge genesis

To open the discussion, let us examine the geomorphology of ridges in the Galway Bay and Aran Islands region. As numerous published documents show, normally storm built ridges of coarse clasts show an overall convex form, higher/steeper, or only low and very wide (Fig. 5.1). Even ridge sequences formed by coarse fragments (either well-rounded pebbles to boulders, or irregular coral debris) from subarctic to tropical latitudes exhibit this general form, which is only steepened at the seaward front if erosion has occurred at an existing ridge (Scheffers et al. 2011, 2012 for the Abrolhos Islands, western Australia, and many others).

While the secondary ridges in western Ireland show a general convex forms (so far as this can be perfect by coarse irregular fragments), the main ridge is formed asymmetrical with the seaward and possible activated face 2–3 times as steep as the landward one and often concave. To landward, this kind of deposit leads over to a

W. Erdmann et al., *Origin and Formation of Coastal Boulder Deposits at Galway Bay and the Aran Islands, Western Ireland*,
SpringerBriefs in Geography, DOI 10.1007/978-3-319-16333-8_5

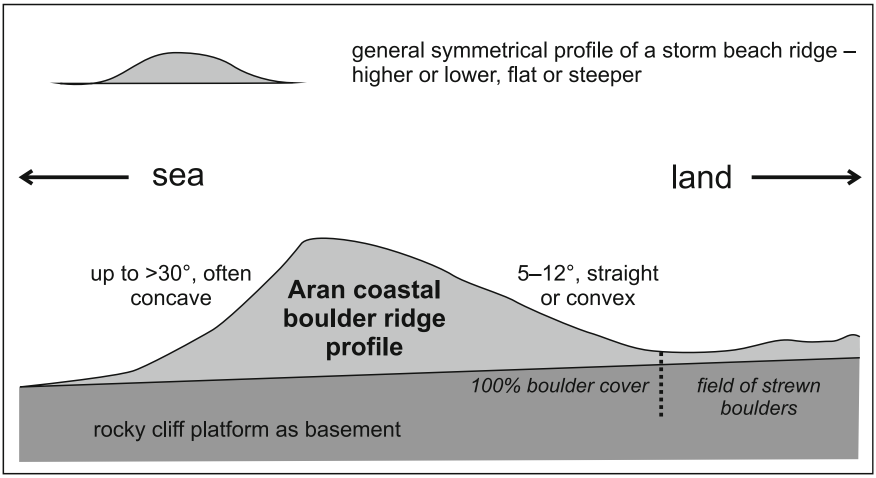

Fig. 5.1 Comparison of profiles of "normal" beach ridges (sandy and coarse once), and the main boulder ridges in the Galway and Aran area. The latter may well be the remnant of a wider deposit, eroded from the sea by multiple storm impacts during a long time of the Recent Holocene (*Image credit* D. Kelletat)

zone with 100 % of boulder cover on the ground, often flat or even rising on the general topography, and continue into fields of strewn boulders for some more decametres at many places. As shown in Fig. 5.1 its cubature is many times larger than all other kinds of coarse coastal deposits in that area. Agreeing that the frontal slope is under destruction by recent and ongoing activation, and that the main ridge deposits generally loose deposits and not gain some during strong storms, the process of initially constructing this deposit can be seen in another light: during the Recent Holocene, at least at one time a very large impact has accumulated a deposit in ridge form so high and massive, that later storms could not pass it but found it as a fixed barrier. Storm waves, however, run up on this deposit, re-activate it and could either add or erode particles. The overall asymmetric form shows, that erosion at the front face is dominant (Fig. 5.1). The process of depositing the huge mass of very coarse boulders, 10–50 times more in mass than that of all following storms in the ridge distance and elevation, must have been a tsunami (or more than one) as we may exclude storm intensity, which would require storm intensities and transport power far beyond all which has been observed worldwide in historical times. This conclusion is in strong contrast to that of Cox et al. (2012, p. 252), arguing for a steady and ongoing contribution of fragments to the boulder ridges: "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".

5.1 Recent Activation of Boulder Ridges Compared to Existing Deposits

As nearly all Irish and British authors during the last 10 years conclude that the boulder dislocation and, in particular, the boulder ridges are made by strong storm waves, it is important to add observations on processes and wave power of recent storms in the area. Therefore, we investigated exposed and sheltered shorelines again in June 2014 to better understand the transformation and activation of existing boulder deposits as from six extreme winter storms (hurricane categories 3 and 4) between mid-December 2013 and mid-February, 2014 with the highest waves (nearly continuously over weeks) local people ever have experienced in their lives or living memory. A clear finding emerged from these field studies: individual boulders up to 20 tons have experienced limited dislocation, locally out-breaks at cliff tops occurred and, in particular, lower ridge slopes to seaward below about +10 m MHW have been impacted by numerous waves. These waves have activated existing boulders on the slopes much more than delivered fresh material from the surf belt or the cliffs themselves. Medium-sized to smaller boulders have been freshly broken, striations and impact marks are left at many places in lower elevations, and certainly at a high number of sections the ridges have suffered from backwash of formerly existing material into the sea. The storm waves of winter 2013/14, however, only in rare cases reached the ridge crests or the landward slopes (nowhere higher than about +15 m MHW), where they did not leave any particular formation. As one result we can sum up, that most of the existing old boulders and ridges remained unaffected, boulders from more than 5 tons in weight and all of about 20 tons and more did not move from their location, all high ridge parts (>+15 m MHW) are totally unattached, and only singular boulders could be found on the cliff platform in front of the ridges. We therefore must conclude that the dislocation of the very large boulders, the transport of boulders far inland, and the construction of the high ridges, are the result either of storm waves of forces 20–100 times stronger than during the last winter season, or are the result from other forces. As freak waves can be excluded because they certainly are not able to form kilometres long ridges, the only conclusion reasonable is the existence of older tsunamis, which at least are responsible for the main boulder deposits in the Galway and Aran area.

The discussion on coastal boulder ridge genesis in the Aran and Galway region should be based on as much of objective and quantifiable field data as possible, including all sedimentologic and geomorphologic features. Therefore, we have presented a high number of images as a base for this discussion. The discussion also implies published conclusions from authors who have worked in the same area (Fig. 5.2).

We first will examine the relative and numerical ages of the boulder deposits and ridges, followed by a discussion on the velocity of cliff erosion and coastline recession in general. Based on this, a discussion on possible ridge shifting to

Fig. 5.2 Aspect of the main boulder ridge crest at the southern section of Inishmaan's west coast with very large boulders, here looking to south (June 2007). The large boulders mainly left unattached by the winter storms of 2013/14, but the chimney-like artificial landmark evidently has been destroyed, here in an elevation close to +16 m MHW and at least 150 m distant from the surf belt (*Image credit* D. Kelletat)

landward and its mechanism is considered. Finally, our conclusions on the genesis of the Aran and Galway coastal boulder ridges will close the debate.

Beside some indicators of terrestrial limestone solution, general weathering and the intensity of transformation of delicate forms from the tidal fringe (e.g. rock pools, borings, resting places of organisms, attached calcareous algae and vermetids), lichen cover on boulders may point to a certain time span of inactivity. The most common lichens along the rocky and boulder shorelines in Ireland are *Caloplaca* sp. (often *C. marina*), and *Xanthoria* sp., both with a vivid orange colour and easy to detect (Figs. 5.3 and 5.4). Zentner (2009) gives an age of >70 years to cover about 50 % of a boulder's exposed surface with *Caloplaca marina* lichen. Time-scales to calibrate the progression of lichen growth can be gained at cemeteries in the vicinity on grave monuments built from the same limestone and showing the year of construction. We find the data for boulder coverage a reasonable estimate. We should consider, however, that only positive evidence can be used for a careful calculation, and the absence of lichen does not mean that a boulder has been emplaced freshly. This can be seen on erratic limestone boulders from the last ice age and resting since deglaciation (i.e. for more than 10,000 years), now balancing on a rock pedestal which formed passively under the boulder protected from rain water solution, but often they do not show lichen cover.

Fig. 5.3 Examples of lichen covered boulders (*Caloplaca marina*) as relative age indicators on boulder ridges inside Galway Bay and around its SE opening at Doolin. Large boulder on the *lowest image* has a mass of approximately 29 tons (*Image credit* D. Kelletat)

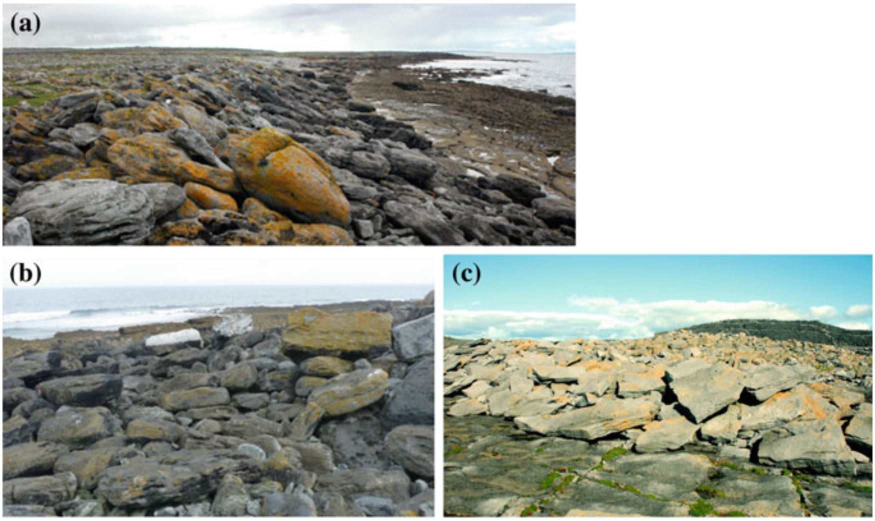

Fig. 5.4 Irregular distribution of lichen cover on ridge boulders. **a** Near Black Head (*Xanthoria* sp.). **b** SE coast of Galway Bay near the campground. **c** Inside Black Fort at Inishmore's south coast at +24 m MHW (*Image credit* D. Kelletat)

Other indicators for the stability or change of a certain coastal environment are small forms from the tidal zone, in particular rock pools (Fig. 5.5). They are formed by bio-erosion mostly from numerous littorinids, which graze on endolithic algae and rasp away the rock (Kelletat 1988). The velocity (roughly around 1 mm/year on dense limestone in the Irish latitudes) of this kind of bio-erosion is about 50 times that of terrestrial (rain water) limestone solution, which can be detected by the dimension of pedestals below erratics nearby (which come to heights of a few decimetres as a maximum for a time span of at least 10,000 years). Nevertheless, a rock pool of some size (0.2–1 m in diametre, and 0.1–0.4 m deep) needs centuries to form, and a dense belt of rock pools covering a certain elevation of the lower supra-tidal (Fig. 5.5) will need at least this time span. If coastal erosion is in the range of decimetres per year (0.2–0.3 on average, at some sites 0.8 m/year on average for the last 150 years, as concluded by Williams and Hall (2004) and Williams (2010), no climax belt of rock pools can be formed and shift with the rocky coastal system. From this evidence we conclude, that mean values of coastal erosion are much smaller than given in the literature.

This conclusion may be supported by numerical ages of shell deposits within coastal boulder ridges of the region, either as shell hash in a good stratigraphy immediately among or landward of boulder ridges, or (as 16 of 23 shown in

Fig. 5.5 Lower cliff platforms, decorated along the near supra-tidal with a dense belt of bioerosive rock pools (near Black Fort, south coast of Inishmore). Their size reach up to 0.5 m at least, and their depth generally 10–40 cm. Taking the intensity of bioerosion on dense limestone in these latitudes of less than 1 mm/year (Kelletat 1988), the time for a climax of these forms, always adapted to exposure and a certain belt parallel to the tidal levels, needs several 100 years, if we only assume that one generation of rock pools has been formed (*Image credit* D. Kelletat)

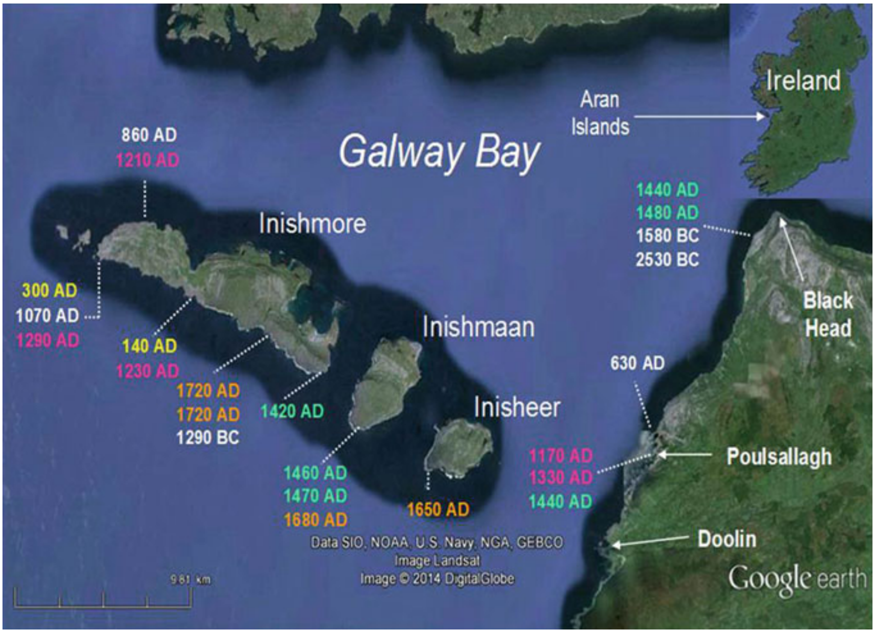

Fig. 5.6 Twenty three calibrated AMS data (Scheffers et al. 2010) from coastal boulder deposits at the Aran Islands and inside Galway Bay form age clusters and span a time frame of more than 4,000 years. *Same colour* indicates same age cluster. *White colour* means single age (*Image credit* ©Google earth 2014 and own graphics)

Fig. 5.6, from Scheffers et al. 2010) from shells of *Hiatella arctica* still present in the borings. Three of the data are BC (2530 BC, 1580 BC and 1290 BC), two fit in the first centuries AD (140 AD and 300 AD), five are high Medieval times (1170–1330 AD), six in late Medieval times (1420–1480 AD), and four in more recent centuries (1650–1720 AD). Some of these data are nearly identical from the Aran Islands and within Galway Bay. It is not clear whether these clusters represent the most extreme events, as they do not derive from the largest boulders but from medium-sized ones.

5.2 Genesis of Coastal Boulder Ridges in the Aran and Galway Area

The majority of authors point to extreme wave heights measured far apart from the coastlines as an argument for the wave power to transport mega-clasts. There is no doubt that in particular the SW coasts of the Aran Islands are situated in maximum exposure to NE Atlantic storm waves, but boulders of the largest size (>50 tons) also appear inside Galway Bay and close to shallow water conditions

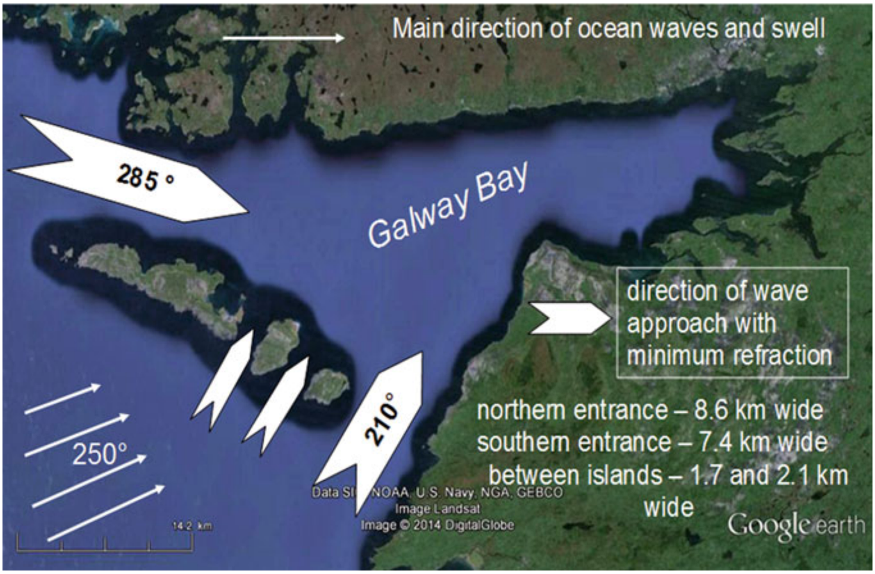

Fig. 5.7 Main approach of open ocean waves and swell in all seasons is from SSW (250°), but by the topography and bathymetry at the entrance of Galway Bay, refraction must occur. Additionally, water becomes shallower to inside the bay, diminishing wave energy (*Image credit* ©Google earth 2014 and own graphics)

(Figs. 5.7, 5.8, 5.9 and 5.10). This is in particular the case around the west end of Inishmore, where Rock Island, Brannock Island and some islets protect the main island's shorelines, and water depths between the islands and at Inishmore's west coast is partly less than 10 m, leading to a broad inter-tidal belt also with low inclination and related weakening of approaching waves. Nevertheless, the coastlines and the cliffs up to about +5 m MHW exhibit boulders around 50 tons, sometimes in perfect imbrication at 80 m from the MHW-line, and those on Inishmaan even >250 m from the coastline and at +15 m MHW. Waves or swell from the open Atlantic also loose energy by refraction passing the inlets to Galway Bay (Fig. 5.7) and the narrow passages between the Aran Islands. As friction of waves (that diminishes wave power) at the seabed will occur when water depth is significantly lower than half of the waves length, and wave length and wave heights are related to each other, all waves longer than about 200 m (which equals to a wave height of not more than 9 m) will begin to lose energy in Galway Bay waters of less than 30 m depth near the coastlines. Water depth along the outer coasts of the Aran Islands often is close to 50 m near the cliff base, and friction here is a minor component.

During our field studies on the effects of the extreme winter storms 2013/14 we observed, that cliff faces or low lying cliff steps seemed to be nearly unaffected although being close to the surf belt and the first-line attacked by incoming waves. Fresh fragments have been locally produced at the high cliff-top edges, in particular

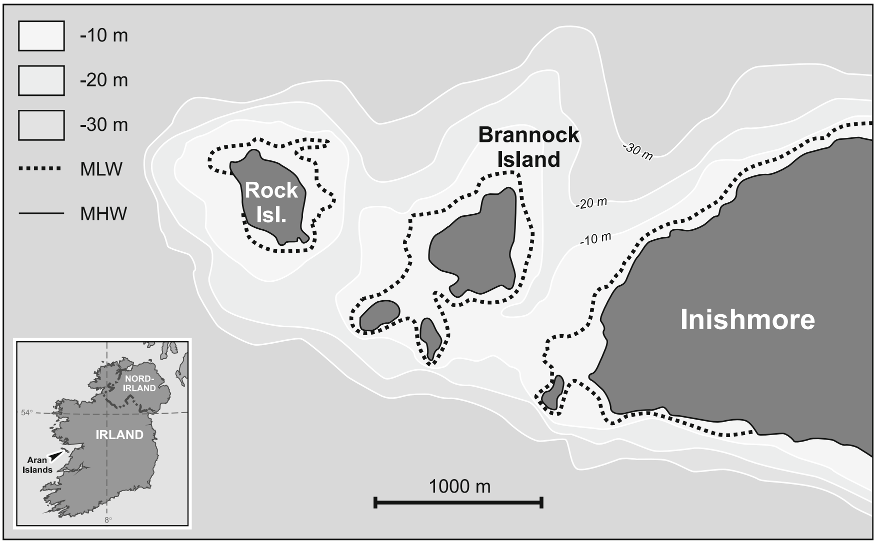

Fig. 5.8 Bathymetric situation around Brannock and Rock Island at the west end of Inishmore Island: an inter-tidal up to 200 m wide is fringed by shallow water with influence on wave breaking and wave energy to dislocate boulders (*Source* Irish Chart 3339: Approaches to Galway Bay Including the Aran Islands (1981) 1:50.000, edition 2005, *graphics* A. Hager)

where they protrude towards the sea, as well as at a few high platform steps where open fracture systems are well developed. Most of the freshly moved material, however, clearly was taken from the seaward ridge slope, eroded from these deposits being removed partly by backwash into the sea. The distribution of fresh impacts, outbreaks and boulder movements clearly was adapted to cliff and coast contours, directing strongest waves and surf as well as bore flow. Regarding the main boulder ridge, however, this is only adapted to coastline and cliff contours where the cliff top is high above MHW (significantly more than +15 m MHW). If the cliffs are lower (steep or stepped), the main ridge shows elegant swinging irrespective of the coastal contours or distance to the surf belt. This is exceptionally significant at the most exposed section of Inishmaan's SW coast. Compared to similar exposed coastal sites with large boulder deposits, the Aran ridges also show remarkable distances to the tidal region or shoreline in general: values of much more than 200 m occur, and landward boulder fields behind the ridge crests may reach about 350 m from the sea many metres above sea level and MHW. In the literature, distances from shore of boulder clusters and boulder ridges of 50–100 m are often mentioned as a maximum for storm wave transport of large boulders inland. Normally friction plays an increasing role and gets more important for boulder transport with distance along the transport path, which sounds reasonable and convincing. Examples of wide boulder fields of similar distance to the sea are the "ramparts" along the exposed east coasts of Curaçao and Bonaire in the southern Caribbean (Scheffers 2002, 2006; Scheffers et al. 2013), slightly set back

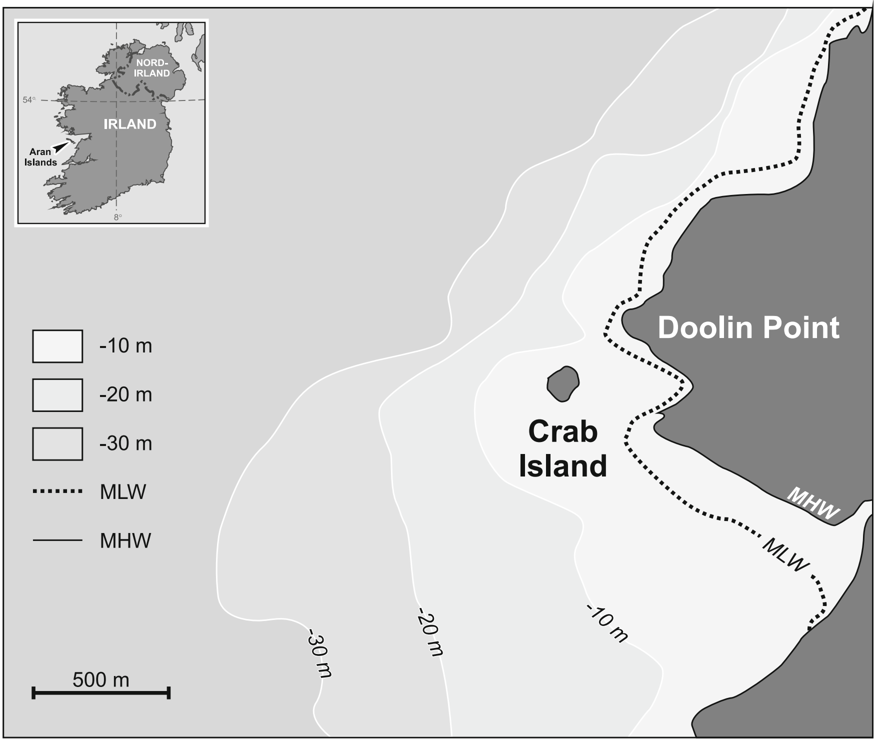

Fig. 5.9 Bathymetry near Doolin Point and Crab Island at the SE entrance to Galway Bay. Water depths of 10 m encircles Crab Island (*Source* Irish Chart 3339: Approaches to Galway Bay Including the Aran Islands (1981) 1:50.000, edition 2005, *graphics* A. Hager)

from the cliff tops as in the Galway region, and also superimposed with internal ripples. They have been found to be the result of several strong tsunamis during the last 6,500 years (Scheffers 2002, 2006).

The processes of cliff erosion and inland ridge movement certainly appear strongly related. Erosion of vertical cliffs in deep water has been calculated by Williams and Hall (2004), Zentner (2009), and Williams (2010) in the range of 0.2 m/year on average and at some localities up to 0.8 m/year. Figures 5.11 and 5.12 model the position of the cliff lines of SE Inishmore and SW Inishmaan under the assumption of cliff retreat rates of only 0.1–0.2 m m/year, which comes to values of 100 m in 500 years (using 0.2 m/year value). These calculations based on two assumptions (Fig. 5.13): one is the fact, that at the Black Fort promontory and those in NW and SE nearby, ridge fragments or boulder piles only occur at the tips of the promontories, but not in the embayments with overhanging cliffs cut into the island more than 100 m wide. It is assumed additionally, that during the “Night of the Big Wind” (a storm in 1839 AD), boulders were dislocated and deposited on hut relicts of the Iron Age promontory Fort (they did not disturb this part during winter

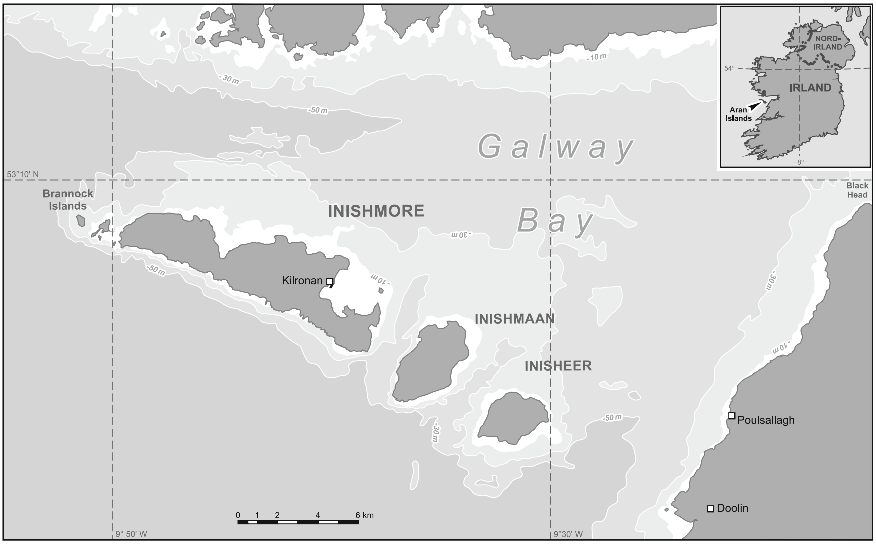

Fig. 5.10 Bathymetry of the Galway Bay and around the Aran Islands. Depths of 50, 30 and 10 m are indicated (*Source* Irish Chart 3339: Approaches to Galway Bay Including the Aran Islands (1981) 1:50.000, edition 2005, *graphics* G. Reichert)

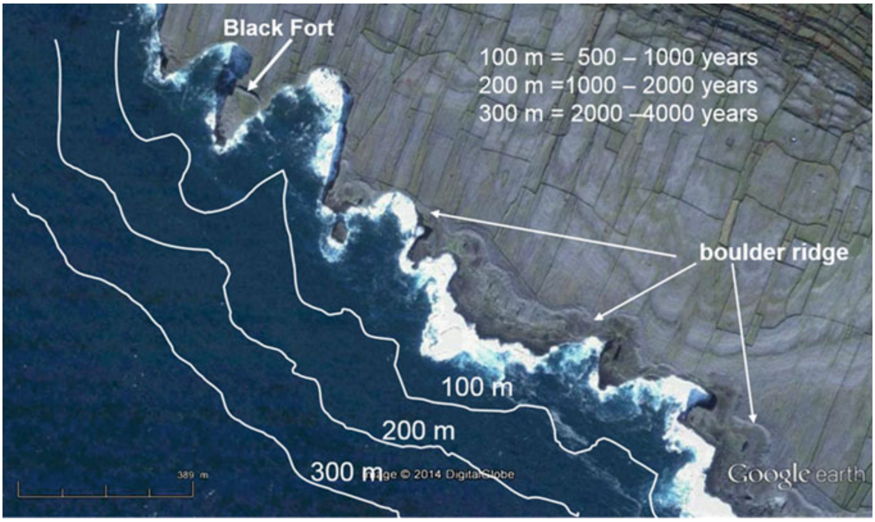

Fig. 5.11 Model of former coastline position (of 100, 200 and 300 m) at the southwest coast of Inishmore near Black Fort, assuming a cliff erosion of 0.1–0.2 m/year. According to Williams (2010), this is at the lower range. Williams (2004) and Williams and Hall (2004) interpreted the short ridge segments or boulder piles at the Black Fort promontory and both adjacent promontories as remnants of one continuous ridge later destroyed by strong cliff erosion to form both sharp embayments (*Image credit* ©Google earth 2014, modified)

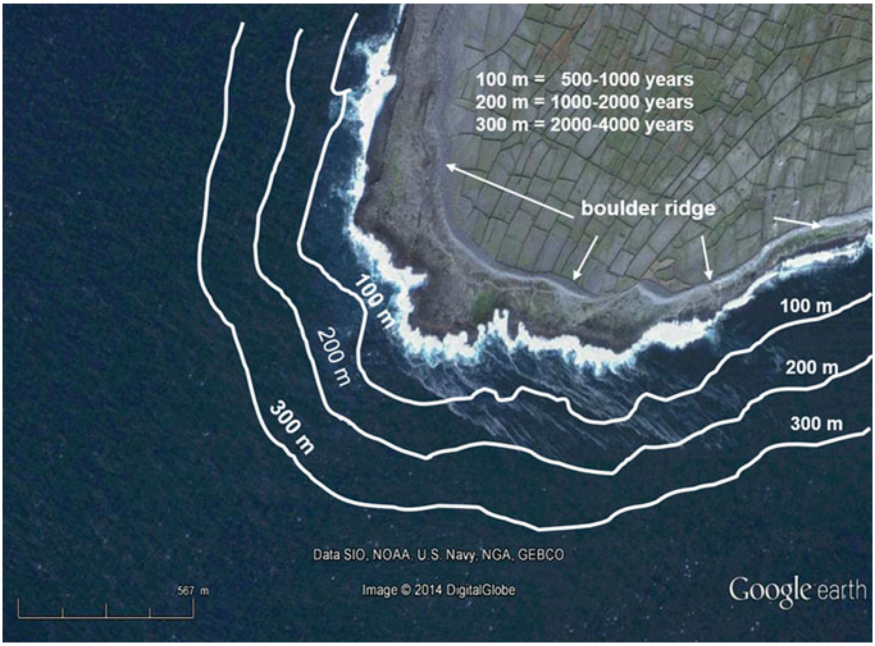

Fig. 5.12 Model of former coastline position in the southwest of Inishmaan with equidistances of 100, 200 and 300 m, assuming (according to Williams 2010) a cliff erosion of 0.1–0.2 m/year (*Image credit* ©Google earth 2014, modified)

storms of 2013/14). With regard to a second estimate, based on the assumption that the ridge fragments on the promontories are remnants of a formerly continuous ridge line running west to east where there are now deeply incised bays, an amount of cliff retreat around Black Fort may come to about 0.2 m–0.8 m/year (Williams 2004, 2010). As the inner parts of the embayments are positioned higher (>+27 m MHW) than the tips of the promontories, it also is plausible that the ridges never attained these elevations and the assumption is invalid. But based on the value of 0.2 m/year of cliff retreat, Williams (2004, 2010) additionally doubts that Black Fort has been constructed as a promontory fort exposed as it appears today but has been a round inland fort. Deriving from the Iron Age, 2,500–2,000 years ago, again using 0.2 m/year values, the coastline has to be placed at least 400 m to seaward for those distant times. These arguments may cast into doubt the existence of Iron Age promontory forts in general, which can be found in a similar delicate and well protected position at around 200 locations along the Irish west coast today. We consider this reasoning to be a somewhat circular argument.

Another argument for high coastal retreat values can be found in Cox et al. (2012), who reconstructed a shifting of the main boulder ridge to landward in a significant amount by comparing the 1841 Aran Island Maps (surveyed in 1839 AD from Ordnance Survey, showing ridges as well as artificial drystone walls very correctly) and their position on maps of the Ordnance Survey, Ireland's Trailmaster

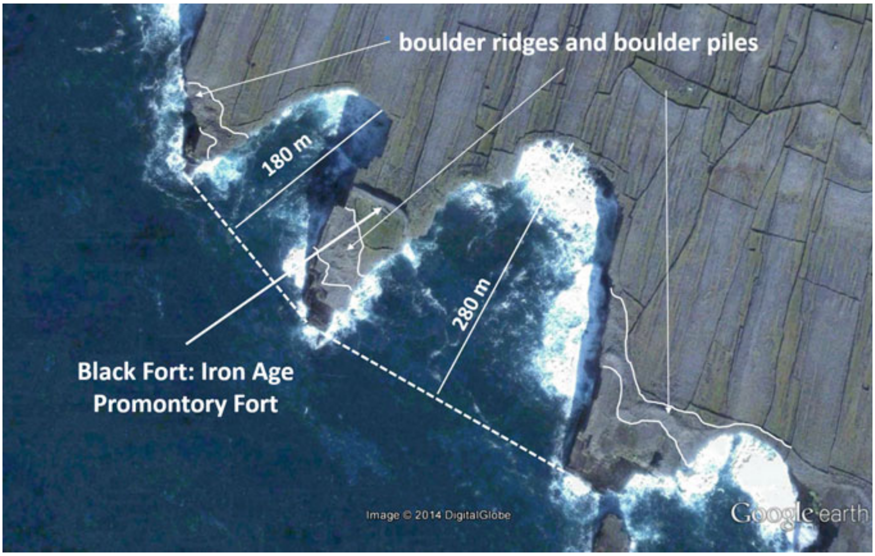

Fig. 5.13 The coastal configuration around Black Fort on Inishmore's SW coast offers two alternatives regarding the effect and velocity of cliff erosion: either this is low and the Black Fort has been constructed on an existing promontory in the Iron Age, and the lack of boulder deposits inside the bays is due to their higher elevation compared to the tips of the three promontories, or a continuous boulder ridge existed about 2500–2000 years BP, the Black Fort was an inland fortification, and the two flanking bays have been cut into the rock during the last 2000 years as a maximum time span. The difference in coastal erosive intensities from the first to the second assumption is in the order of 1:50/1:100! (*Image credit* © Google earth 2014)

Series 2006: 1:50,000, 2.5 m/pix. For the Inishmaan south coast values of up to 50 m during this time span of 166 years (from the Night of the Big Wind in 1839) have been measured using ArcMap and Orthophoto Maps 1:50,000. Apart from the fact, that this coastal sector is low (ridge crest not higher than +6 m MHW) and extremely exposed, the accuracy of this measuring method should be regarded with care. On a 1:50,000 map, one m is 0.02 mm wide, and 50 m just one mm, which comes very close to the accuracy of drawing the field maps. We doubt—even if destruction of drystone walls since the mapping of 1839 AD by the shifting of the boulder ridge can be verified by other methods, and there was no change in field borders by drystone walls since 1839 AD—that coastal retreat in general has been taken place in this exceptional amount. We will use as counter-arguments

(1) that within Galway Bay, e.g. south of Black Head, coastal retreat because of lesser wave energy in shallower water and after wave refraction will be much lesser as outside the islands. Nevertheless old dislocated boulders along the Black Head region also are in the order up to at least 50 tons (in an environment with BC-data from shell!), but should have been emplaced during times of a coastline farther out into the modern sea and not moved since (if we agree to a strong coastal retreat rate), and

(2) that at formerly plunging cliffs to deep water in SW exposure of the Aran Islands, a strong cliff retreat in the order of decametres, several 100 m or around 2 km (or more) since the beginning of the Younger Holocene high sea level about 6,000 years ago should have carved a coastal platform around the tidal level into the well stratified flat lying limestone, which is not existing. What we see maybe a partly transformation of steep cliffs into stepped cliffs with a general slope rising to landward.

Assuming high values of cliff retreat within the last centuries and millennia has the consequence, that the Aran Islands should have been separated not before the Younger Holocene, forming deep water channels (around 50 m deep, partly deeper) in between of them by ocean wave attack within the last 6,000 years. Even large ocean waves cannot scour the ocean bottom with significant energy in these depths. Additionally, glacial smoothing of the Islands on falling slopes to the inter-island channels document that openings existed since the last glaciation, at least. The channels may first be formed by melt water discharge during glacier recession from the island chain back to E and N. Within the wide channels at the NW and SE entrances to Galway Bay, recent sonar soundings by INFOMAR (***IN****tegrated Mapping* ***FO****r the Sustainable Development of Ireland's* ***MA****rine* ***R*** *esource* (*INFOMAR*) *programme, a joint venture between the Geological Survey of Ireland and the Marine Institute*) detected well preserved melt water stream beds in water depths down from −30 m leading into the open Atlantic Ocean. As a strong cliff recession and rock coast erosion also implies a strong landward shift of all coastal boulder deposits including the main boulder ridge we point to the fact, that numerical data from bivalve borings or shell hash well stratified in the ridge space have been found in temporal ranges of many 100 years and up to more than 4,500 years as near Black Head in Galway Bay, or more than 3,000 years as seaward of the Black Fort high wall on Inishmore. It is highly unlikely, that these shell and shell layers have been shifted with the ridge to landward with multiple dislocations over distances of a kilometre or more and over that long time span and still can be found in a good stratigraphic context. All these arguments and field evidence make it extremely difficult to rely on high values of coastal erosion in this environment.

Cox et al. (2012, p. 251) argue, that…"to reliably distinguish past tsunami events from those of high-energy storms and 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 size in those ridges to inform our understanding of coastal wave dynamics and the boulder transport capabilities of storm waves*"*. In general, we agree with this statement, but we do not agree that a storm activation will be the same as storm-generation. Also, we do not agree with the statement of Paris et al. (2011) that the organization of coarse clasts into supra-tidal ridges requires repeated reworking by waves rather than the single impact of tsunami waves.

Every old deposit, formed by a particular force, may be re-activated and transformed by later impacts of any kind.

We again point to the fact, that six exceptional winter storms 2013/14 have moved boulders of only a fraction of the size of existing ones, which also are positioned higher, further to inland and often dislocated by marine forces from a source at +15 m up to +25 m MHW to inland. We will not doubt the report of a local observer (referred to in Cox et al. 2012), that the 75 ton record boulder at the west coast of Inishmaan at about +15 m was emplaced during a strong storm in 1991, but, based on observations, that the storms of 2013/14 have washed back a lot of boulders from (lower lying) seaward ridge slopes and undermined large boulders, it also seems possible that this large boulder formerly was hidden under smaller objects, or at least not to be seen in its extreme position and, therefore, not previously registered as a memorable landmark.

Furthermore, we will add two more points to our catalogue of scepticism against a simple storm wave construction of the ridge features (and related forms, such as two forms of ripples patterns):

(1) A landward migrating ridge over time (for hundreds of metres, or more, during its existence according to the numerical data) will not move all of the mega-clasts, as not all storms are of sufficient energy to move all clasts. Therefore, the largest clasts will be left behind as the ridge migrates and will rest as isolated signatures of the power of the impact that originally emplaced them, which in the Aran and Galway area is not the case.
(2) The lower ridges, apart from the main one and landward of it, doubtlessly are older, but they still exist and have not been overridden or incorporated by the landward movement of the main ridge. Being older, which, again based on dating, must be in the order of 2,000 or even >4,000 years, and if produced by storm waves, they must have been established (on the Aran Islands and within Galway Bay) in distances of 0.5 km or more from an old coastline along low and extremely high cliffs shifting to landward, taken the erosion rates calculated (0.2 m/year or more). This, if real, is unique on Earth and needs special explanations or hypotheses.

The extreme winter storms of 2013/14, the strongest in living memory according to the local people in the Galway region, with extensive drowning/inundation in the old town's nucleus around Spanish Arch, but lacked the energy to transport the largest boulders or even to reach the highest sections of the existing ridges and, therefore, another force or process is required, which exceeds the highest and strongest storm waves of the NE Atlantic significantly.

A sound explanation of the forms and forming processes for the Galway and Aran boulder ridges should also include the genesis of minor forms on the ridges, or those combined to build a ridge. These are two types of ripples. The first are smaller ones that normally occur on the landward slopes of the main ridge, running more or less parallel to the crest of the main ridge. Their relative elevation is low (just decimetres), their cord length only around 10 m, becoming less to the base of the landward ridge slope. They are the result of water flow, here as an over-wash over the main ridge crest to landward. Because of the topography in which the ridges are situated, no backwash signatures can be found.

The second type of ripple-like features combined with boulder ridges are much larger, often curved, and parallel to each other in a row along the coast with deep swales in between. Their relative elevation may reach up to more than 1.5 m (depending on the size of the boulders), their crest distance to each other is approximately 15–30 m. Their general direction is at an angle to the coastline (up to 90°). As with compact main ridges, we can reconstruct the direction of formation of these smaller ripple-like ridges, being perpendicular to their alignment (and in curves as a radius to the curving). They evidently have not been formed at different times and step by step, but simultaneously, and then perhaps refreshed several times during their existence. Like the smaller type of "regular" ripples in boulder deposits, this larger type also is the product of a strong flow from one direction, in these cases more or less parallel to the shoreline at a low angle. A flow, which is able to form a dozen of wide boulder ripple-ridges at the same time on land and goes nearly parallel to the shoreline, cannot be a kind of bore of a large wave in elevations many metres above MHW. It needs a longer and constant strong flow as is characteristic of tsunamis.

Combined with the largest platy boulders, often imbrication or imbrication trains occur (see also Scheffers and Kinis 2014), and their organization must also fit in any explanation of the formational processes for the high boulder ridges and ripple-like ridges. Imbrication means that the front part of a boulder has to be lifted over an obstacle into a dipping orientation, and imbrication trains additionally need that this process takes place at exactly the same site either repeatedly, or in one step.

But how can an imbrication train of large boulders (5–50 tons) with a steep inclination (up to 70°) be organized by storms from different times, or different waves from the same storm? Where do these waves entrain new fragments? From the same site as the first, or from neighbouring (or those wider apart)? How can the large boulders not only be transported over a significant distance (metres to >100 m), but also against gravity? The impact of a storm wave on a boulder is far less than one second, and there is no time to put a boulder in this delicate position, and, what is much more difficult: several boulders (at the same time or one after the other), within seconds, or after hundreds of years?

A tsunami, however, lasts for a longer time (minutes to tens of minutes) compared to storm wave attack, establishing a constant flow, and—within a van Karman vortex organized behind any kind of obstacle—may organize a narrow line of ordered boulders collected from a wider part of the source area (which is necessary e.g. for the imbrication trains of Morocco (Mhammdi et al. 2008; and Algeria, Maouche et al. 2009) exhibiting rock pools from the supra-tidal zone allowing the reconstruction of their exact source area). A van Karman's vortex (plural vortices) may develop behind an obstacle in an unidirectional flow (of air or water). At a small angle of about 15–20° opening behind the obstacle, two lines of cylinders may form, both initiated by the friction at the obstacle and, therefore, with clockwise rotation along the left, and anti-clockwise rotation along the right fringe

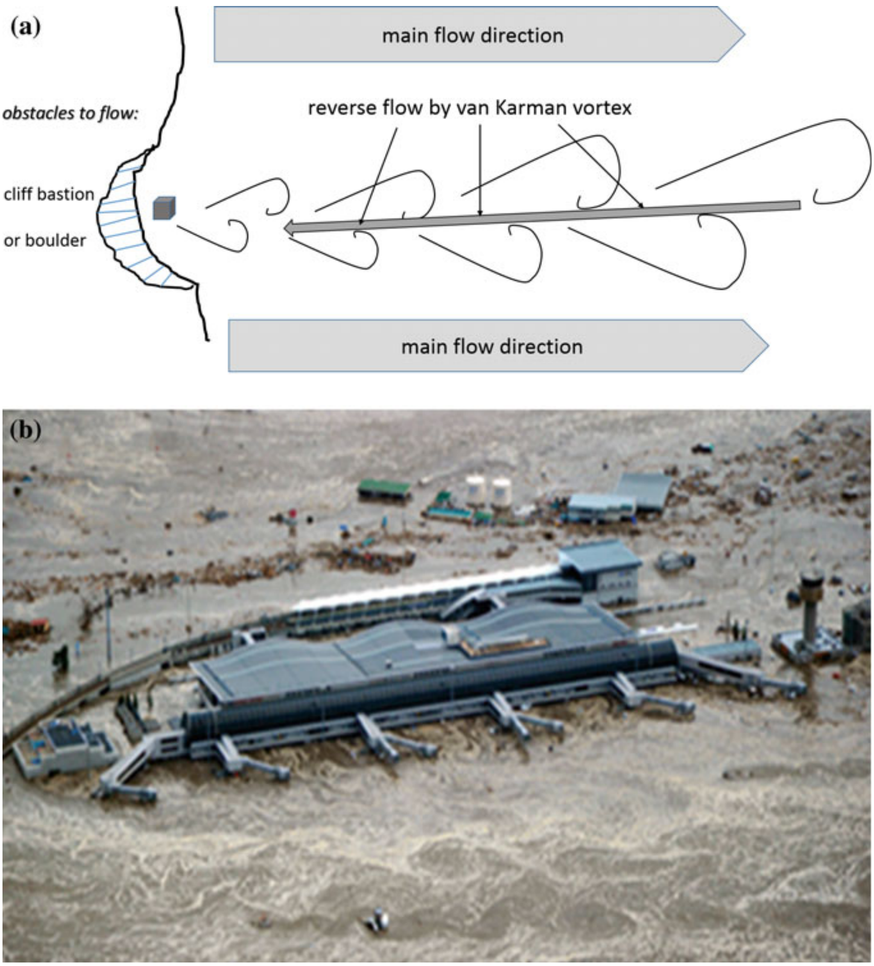

Fig. 5.14 Van Karman vortex: **a** model of cylinders in a van Karman vortex, forming behind an obstacle during steady flow. This flow is concentrated along a single line from both rows of cylinders, and within this central line, movement is directed against the general flow which allows, if strong enough, to lift the frontal parts of platy boulders for imbrication. **b** Van Karman Vortex on Sendai Airport, Japan, in a suspension flow (from *left*) during the March 11, 2011 Tsunami (see also Scheffers and Kinis 2014)

(Fig. 5.14). From this opening, the vortex loses energy, in particular along the inner sections of the cylinders, which are directed against the general flow.

Moreover, an imbrication train requires that the transporting force is able to take large boulders and order them in one row and lift all of them at the front to pack them together in an inclination often between 30° and 50°. Lifting means to move masses in the order of 10 to >50 tons 2–3 m against gravity, in the case of Aran and Galway often 100 m or more from the coastline and at elevations of many metres above MHW. This process in fact is unknown or rarely discussed so far, but—based on many observation in other environments of coarse clast dislocation—we discuss a scenario based on the principle of "van Karman vortex" being responsible for the formation (Fig. 5.14), that is the forming of rotating cylinders of water (or air) in two lines behind an obstacle in a constant and longer flow movement. The cylinder lines form an open angle to leeward, and the direction of movement within the cylinders (vortices) are directed from both sides to a central line behind the obstacle and back against general flow. This phenomenon can be observed looking from a bridge at the down-flow side and leeward of a pylon in the water. In fact, from the leeward side of the pylon in a river, a line of debris up to boulder size is deposited and organized, running straight in the flow direction and being well imbricated. In our examples of boulder imbrication trains at Galway and Aran, we need a very strong flow with a similar high energy for a longer distance inland, organizing boulder patterns several metres high and decametres long, taking all the large fragments from the same place, or organizing the train by pushing them in an exact line one after the other. This—from all the transport processes we know in coastal environments—only can be ascribed to tsunami flow.

We would like to point out, that for all the field evidence we attempt to explain, assumptions for moving forces are based on the present form and deposits. Formed some time ago, with a coastline in an erosional state, forces certainly had to be

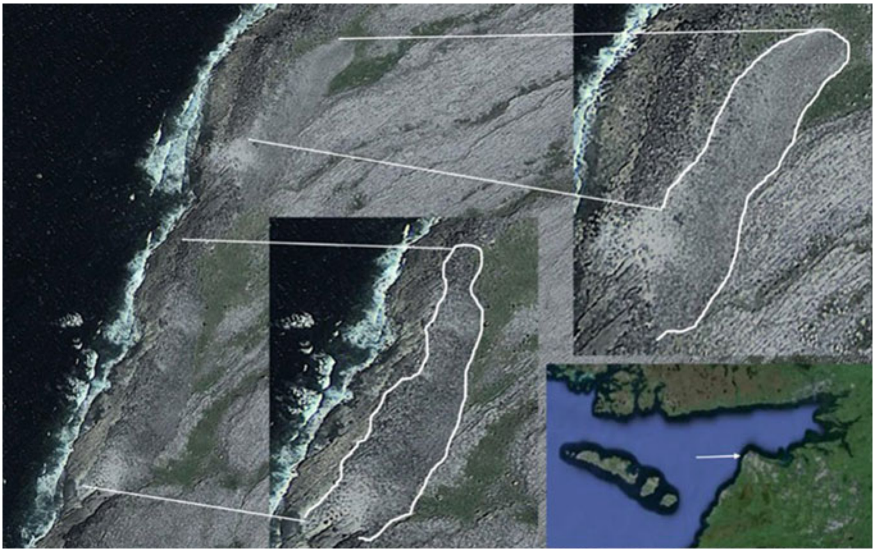

Fig. 5.15 Two wash-over features from SSW, 1.6–2 km SW of Black Head (*insert* shows position within Galway Bay). The southern feature is 176 m long and max. 47 m wide, the northern one 164 m long and max. 37 m wide (and behind a seaward boulder ridge, see also Fig. 5.17). Both deposits contain of coarse clasts (*Image credits* ©Google earth 2014)

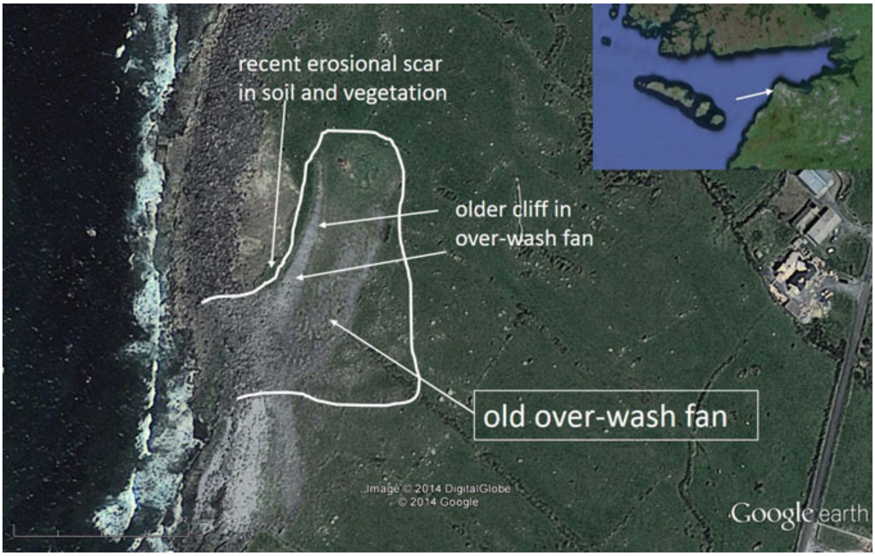

Fig. 5.16 Over-wash fan (with cobbles and small rounded boulders) from SSW behind the main boulder ridge, about 160 m long and eroded by two cliff-lines. The most recent cliff has been active again during the winter storms of 2013/14. Site is 5.9 km SW of Black Head, within Galway Bay (see *insert*) (*Image credit* ©Google earth 2014)

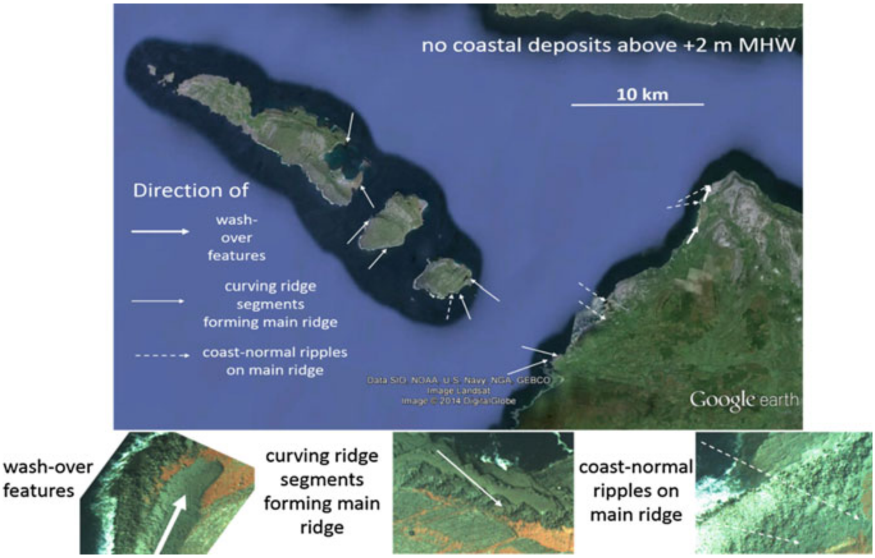

Fig. 5.17 Three different geomorphological signatures of strong wash-over processes on the Aran Islands and within Galway Bay (*Image credits* ©Google earth 2014, and National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

much stronger to establish these deposits in the form, and at sites, we find them in today. Another conclusion should imply, that all the older forms and patterns have been formed further to seaward and have been shifted without change to landward, mostly on rising slopes or crossing many structural steps upwards. We consider this assumption to be unrealistic.

Lastly, beside the dislocation of very large boulders high against gravity and some distance inland, and the two different kinds of ripple features on boulder ridges, or the construction of one single boulder ridge, inside Galway Bay i.e. in a more sheltered position, wash-over forms and deposits again point to processes of strong inland flow (Figs. 5.15, 5.16 and 5.17). A final answer on the transport and formational processes and their times of activity on the Aran Islands and within Galway Bay has to include all morphological and sedimentary evidence from the field.

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Chapter 6
Conclusions

To explain the field evidence of coastal boulder dislocation and forms of deposits combined, we need an explanation (or at least a hypothesis) which must incorporate

- the exceptional size of dislocated boulders;
- their exceptional distance deposited from the coastline in exceptionally high elevations (in a worldwide comparison);
- the ridge contours often not adapted to the coastal and cliff contours;
- the organization of imbrication and imbrication trains with boulders around 50 tons;
- over-wash features, also behind the main boulder ridge;
- the associated secondary forms of ripples and ripple-like ridge segments on the main ridge or forming the main ridge;
- the wide time span of data from boring bivalves in large boulders and from stratified shell hash in and immediately at the ridges;
- the existence of similar forms and boulder size along different exposures and bathymetries;
- a reasonable quote for shoreline and cliff recession in accordance to historical and/or archaeological facts, such as Iron Age Forts or drystone walls;
- and—if storm waves are regarded as the only impactors—how, how often and when storm waves far beyond a category 5 hurricane have occurred, and under which conditions super-storms in this region (much stronger than those in the "Night of the Big Wind" in 1839) are physically possible.

All these questions are left unanswered, as long as we do not agree that the only power stronger than the strongest storms may have attacked the Galway and Aran coastline during the Recent Holocene, i.e. tsunamis (see e.g. Scheffers et al. 2009, 2010). Cox et al. (2012) do not reject the hypothesis of tsunami involvement in ridge dynamics, but conclude from wave activation to favour storm wave genesis of the ridges (see also the interview of R. Cox on July 20th, 2014, by the University of Chicago (http://www.press.uchicago.edu/pressReleases/2012/April/JG_1204_Boulders.html [accessed Sept. 8th, 2014]). Problems persist in explaining all forms and deposits in

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the Galway and Aran area in terms of storm wave activity alone recognized by Williams and Hall (2004). On pages 105/106, Williams and Hall (2004) write 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* (underlining by the present authors). They also found (same pages), 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 and, that 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. As by physical laws (e.g. self-destruction by chaos), the energy of storms and waves on our planet have upper limits of strength, and storms more (or even multiple times) powerful than that of "perfect storms" or the "Night of the Big Wind" in 1839 AD can be excluded and, therefore, we should open our mind to the other major force sometimes occurring on the oceans, that of tsunami.

In the papers of Zentner (2009) or Cox et al. (2012) (as well as in interviews of Cox in Chicago/see various internet sources) it has been argued, that tsunamis can be excluded for the northern Atlantic ocean as impactors on the Galway and Aran region, because

- since the (weak) Lisbon event in 1755 AD, no tsunami has occurred
- the Storegga tsunami (in fact: tsunamis) are too old
- no possible tsunami sources or tsunami-triggering processes are known in the NE Atlantic.

The correct answer to these statements is simple: no systematic investigation of tsunamis or possible tsunami deposits along the coastlines of the northern Atlantic (except of the Caribbean/Gulf of Mexico, where a lot have been found and published) has been conducted so far. But we know e.g., that submarine slides are a threat (Great Banks tsunami off E Canada in 1929, others from the continental slope off Morocco, or from collapses of volcanic islands as the Azores, Madeira, or the Canaries, often not investigated systematically) are real.

Bryant and Haslett (2007) and Haslett and Bryant (2007) present historical and field evidence of tsunamis from historical and pre-historical times (as in Bristol Channel of 1607 AD, or at the coastlines of Wales).

As we are not experts in the archaeology of the east coast of North America, or the cosmology of the Maya and other early civilizations, we will not judge on the recent discussion on cosmic impacts in the North Atlantic by comets or meteors (probably in 539 and 1014 AD, and earlier around 2900 BC), but the discussion brought to light a lot of good arguments and cross checks from very different and distant sources, and it is just at the beginning (Abbott et al. 2010; Baillie 2007; Bryant et al. 2010).

As has been evident from many research projects on (possible) tsunami events within the time of a high Holocene sea level during the last 10–15 years and worldwide, most of the field inspections, identification, and dating still has to be made in the future to solve this important question.

To test this hypothesis, that one or more tsunami within the Recent Holocene have accumulated unusually high and wide deposits in a large and ridge-like form, much higher and wider than those of earlier storms (which can be found landward of the main deposits), the stratigraphy in back-ridge geo-archives as well as along the N and NE coast of Galway Bay by coring lagoons and marshlands could hold some clues to continue this discussion.

It is interesting to recognize, that earlier papers just discuss storms, as these could be observed easily and are registered in historical times. As soon as the idea of tsunamis had been published, replies and critics entered the discussion supporting the "storm waves only" hypothesis. But as this cannot explain all features and, in particular not the complex pattern of all geomorphologic and sedimentologic field evidence and rather old data, we have no choice as to re-open this discussion.

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