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

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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
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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

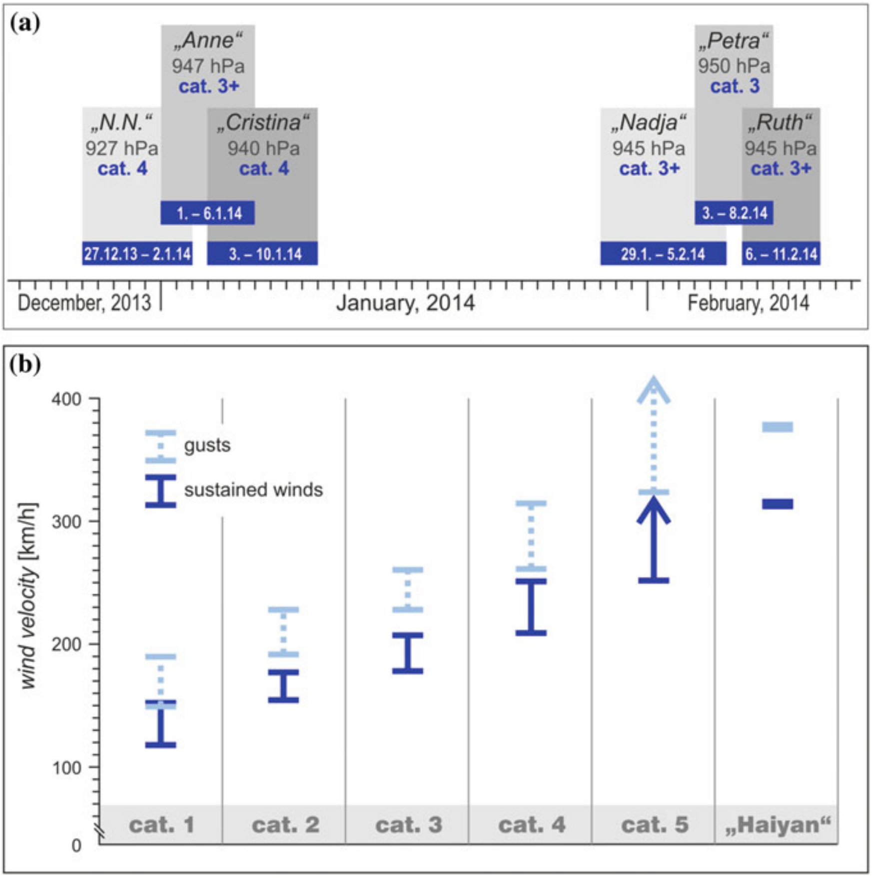

Fig. 1.2 **a** Temporal distribution, central pressure and hurricane categories of six extreme winter storms west of Ireland in the season 2013/14. **b** Velocity of sustained winds (1 min) and gusts of hurricane categories 1–5 and super-typhoon “Haiyan” (Philippines, Nov. 2013), according to the Saffir-Simpson-Hurricane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