# Rekonstruktion extremer Küstenformungsprozesse in der Region Galway (West-Irland)

Inaugural-Dissertation

zur
Erlangung des Doktorgrades
der Mathematisch-Naturwissenschaftlichen Fakultät
der Universität zu Köln

vorgelegt von

Wibke Erdmann
aus Castrop-Rauxel

Köln 2020

| | |
|---|---|
| Berichterstatter: | Prof. Dr. Frank Schäbitz<br>Prof. Dr. Martin Melles |
| Tag der mündlichen Prüfung: | 30.06.2020 |

Kumulative Dissertation - gemäß der Promotionsordnung
vom 12. März 2020

Für Jano, Juli und Cleo

# Danksagung

Der DFG danke ich für die Unterstützung der Küstenforschungen in Irland durch Bewilligung von Reise- und Datierungsmitteln in den Jahren 2007-2009 (Ke 190/25 - 1) und 2015 - 2017 (Ke 190/28 – 1) und der Universität zu Köln für Mittel zur Erweiterung des Datierungsprogramms, welche durch private Mittel ergänzt wurden.

Herrn Prof. Dr. Frank Schäbitz danke ich von ganzem Herzen für seine Geduld und die Flexibilität für Vereinbarkeit von Familie, Beruf und Feldarbeiten, mit der ich meine Promotion unter seiner Leitung durchführen konnte. Ebenso möchte ich Herrn Prof. Dr. Martin Melles für die Übernahme des Zweitgutachtens danken.

Danken möchte ich vor allem meiner Familie, die mit viel Verständnis, emotionalem Support, Optimismus und logistischer Unterstützung im Gelände einen großen Anteil am Gelingen hat und dabei gleichzeitig eigene Eindrücke der großartigen Landschaft meines Forschungsgebietes mitnehmen konnte. Prof. Dr. Dieter Kelletat trug vor allem durch seine Felderfahrung mit dem Nachspüren vergangener Prozesse sowie durch unzählige Diskussionen über Befunde vor Ort ebenfalls zum Gelingen dieser Arbeit bei. Seine Erfahrung im Lesen von Landschaften durfte ich kumulativ gesehen in den letzten 20 Jahren 24 Wochen lang, in 12 Ländern auf insgesamt elf Reisen genießen. Danke!

Eine Promotion – zumal, wenn sie mit Geländearbeit verbunden ist – erfordert einen beträchtlichen Zeitaufwand. Familienzuwachs durch Tochter Cleo, aber auch das Warten auf die Verabschiedung einer neuen Promotionsordnung, bestimmten letztlich den Zeitpunkt ihrer Fertigstellung.

Wibke Erdmann, Castrop-Rauxel, den 21.04.2020

Die Autorin in ihrem Arbeitsgebiet auf Inishmore 2015

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# Vorwort

Die hier vorlegte Dissertation zum Thema

***Rekonstruktion extremer Küstenformungsprozesse in der Region Galway (West-Irland)***

ist dem Bereich „Küstenforschung" zuzuordnen, einem besonders komplexen Teilgebiet der Naturwissenschaften im engeren Sinne (Geo- und Biowissenschaften), weil sich darin Formen und Prozesse aus dem terrestrischen und marinen Umfeld im Gürtel des Litorals vielfältig gegenseitig beeinflussen bzw. bedingen. Mit mindestens 1 Mio km Länge sind die Meeresküsten das ausgedehnteste Landschaftselement unserer Erde und dennoch in geologischen Zeitskalen sehr jung. Ihre Position und wesentliche Gestalt erhielten sie mit der deutlichen Verlangsamung des spät- und postglazialen Meeresspiegelanstieges vor ca. 7.000 bis 6.000 Jahren. Die glazial-eustatische und glazial-isostatische Transgression über Land führte beim Erreichen eines Quasi-Stillstandes zur verstärkten Energieumsetzung entlang **eines** Niveaus, so dass die weitaus meisten Meeresküsten erosiv bzw. felsig sind.

Studien an Grobsedimenten im Küstenraum sind kaum 30 Jahre alt. Sie bezogen sich zu Beginn eher auf zufällige Funde (noch) unerklärlicher Landschaftszeugnisse wie außergewöhnlich große Blöcke auf dem Atoll Rangiroa, Tuamotus (Bourrouilh – Le Jan & Talandier, 1985) oder gemischte, offenbar holozäne Ablagerungen oberhalb der heutigen Brandungszone in Schottland, welche sich später als Tsunamirelikte der norwegischen Storegga Slide von ca. 8100 BP herausstellten (Bugge et al. 1987; Dawson et al. 1988). Erste Vergleiche zwischen den potentiellen Prozessen für Blockbewegungen im Küstenraum lieferten u.a. Nott (1997) und eine breite Dokumentation zu Tsunamiablagerungen schließlich Bryant (2001, 2. erweiterte Auflage 2008).
Die weitgehend fehlende Möglichkeit, Blockablagerungen mit Labormethoden zu untersuchen fordert heraus, mit makro- und mikromorphologischen Feldanalysen das ganze Spektrum landschaftsbezogener Unterschiede (Relief und Höhenlage, Exposition und Wassertiefe, Orientierung und Formation, relative Altersbeziehungen von Blöcken und Blockgruppen, Inspektion aktueller Vorgänge, archäologische Hinweise u.a.m.) zur Interpretation heranzuziehen. Positive und negative Belege (welche einige Vorgänge sicher ausschließen) sind dabei in gleicher Weise zu bewerten. In dieses Methodenspektrum ordnet sich meine Arbeit ein.

Basierend auf Felderfahrungen im Studium der Geographie und Biologie bei einschlägigen Exkursionen und der Beteiligung an Forschungsprojekten in den Hochanden von Peru und Ecuador und der südlichen Karibik (letztere mit Erleben eines Hurrikans der Kategorie 4) reizte mich die Feldarbeit in Irland im Rahmen eines DFG-Projektes (KE 190/28-1). Bei Voruntersuchungen 2014 im gesamten Arbeitsgebiet, die der *near-time-inspection* der Folge von 6 Hurrikan-Stürmen des vorangegangenen Winters gewidmet waren (Erdmann et al., 2015) und den Feldkampagnen 2015 und 2016 mit Kartierungen und Beprobungen von Teilgebieten wurden verschiedene Schwerpunkte verfolgt und in Publikationen vorgestellt (Erdmann et al., 2017, 2018 a, 2018 b, vgl. Kapitel 4).

Diese Dissertation umfasst außer den Kopien der bisher erschienenen vier Publikationen (jeweils mit Einführung und abschließender Zwischenbewertung der erzielten Erkenntnisse in Kapitel 4) eine Kurzdarstellung des Arbeitsgebietes (Kapitel 1), eine knappe Fassung der bisherigen Forschungsgeschichte des Raumes (Kapitel 2) und daraus resultierender offener Fragen (Kapitel 3), eine abschließende Bewertung der Forschungsergebnisse in regionaler und überregionaler Hinsicht als Ergänzung des Forschungsstandes (Kapitel 5) sowie letztlich – daraus abgeleitet – Hinweise auf offene Fragen und mögliche Lösungsansätze.

# 1 Einleitung

## 1.1 Transportmechanismen für Grobmaterial an Meeresküsten

Über 70 % der Meeresküsten sind felsig und somit erosiv geprägt (Kelletat, 2013, S. 91), doch lassen Lehrbücher zur Küstenmorphologie klar das nachgeordnete Interesse an Felsküsten gegenüber Sedimentküsten erkennen (Anthony 2009; Carter 1989; Davidson-Arnott 2010; Finkl 2004; Kelletat 1995, 2013; Masselink & Hughes 2003; Schwartz 2005; Woodroffe 2003). Die meisten Publikationen über Felsküsten widmen sich Kliffen, obwohl Kliffe nur einen geringen Teil der Felsküstenabschnitte ausmachen (Furlani et al. ,2014; Gomez-Pujol et al., 2014; Kennedy et al., 2014a; 2014b; Naylor et al., 2014; Sunamura 1992; Sunamura et al., 2014; Trenhaile, 2014).

Sedimentarchive liefern durch ihre Stratigraphie Hinweise auf frühere Prozesse und erlauben die Erarbeitung einer Chronologie von Einzelereignissen. Blockablagerungen sind jedoch selbst bei größerer Mächtigkeit kaum schichtweise organisiert. Fehlen diese internen Merkmale, entfallen viele Analysemethoden, welche zur Erforschung der Entwicklungsgeschichte hilfreich wären. An Felsküsten mit Blockmaterial kommen eher „altmodische“ geomorphologische Methoden wie Beobachtung, Vermessung, Vergleich und Differentialdiagnose aller Naturobjekte in allen Maßstäben zur Anwendung. Zur Beurteilung der Intensität und Dominanz von Prozessen sind Schlussfolgerungen daher durch ausgedehnte Erfahrung bei Feldarbeiten in möglichst vielen unterschiedlichen Landschaften der Erde äußerst nützlich.

Dawson & Stewart (2007, S. 180) lieferten mit ihrer Aussage *"that boulder complexes may represent the most promising area of scientific enquiry"* eine hervorragende Begründung für mein Arbeitsthema.

Eigentlich sollten Grobmaterialablagerungen an Küsten – soweit ihre Herkunft aus dem Meer unstrittig ist – keine besondere wissenschaftliche Herausforderung darstellen, doch das Gegenteil ist der Fall. Gerade an diesen Objekten haben sich heftige Debatten und Missverständnisse zwischen verschiedenen geomorphologischen „Schulen“ entwickelt und dauern weiter an. Dies weist darauf hin, dass für die Analyse mariner und litoraler Blockablagerungen bisher weder allgemein anerkannte Bearbeitungs- und Analysemethoden noch ein anerkannter wissenschaftlicher Kenntnisstand existiert. Dieser Zustand bietet zahlreiche

Herausforderungen und eröffnet ein weites Feld für Hypothesen und Theorien, vor allem für die Bewertung der Feldbefunde hinsichtlich Umwelt- und Klimaveränderungen und ihrer Auswirkungen.

Die zentrale Frage im Diskurs litoraler Blockablagerungen und ihrer Herkunft war und ist, in wieweit das Grobmaterial ausschließlich durch Sturmwellen landwärts transportiert wurde oder ob Tsunamis beteiligt waren oder gar dominiert haben. Die besten Beispiele zur Differenzierung beider Prozesse liefern Feldstudien aus Japan, wo häufig am selben Küstenabschnitt sowohl starke Stürme (Taifune) als auch starke Tsunamis (beispielsweise Meiwa 1771 und Sendai 2011) auftraten und sehr gut dokumentiert wurden (z.B. Nanayama et al., 2000).

Die Blockablagerungen an der zentralen Westküste von Irland (Galway Bay und Aran-Inseln) repräsentieren die spektakulärsten Belege für holozäne marine Verlagerung solcher Grobmaterialien auf das Land, welche bisher weltweit von Feldbeobachtungen erbracht wurden. Sie sind in vielerlei Hinsicht außergewöhnlich, u.a. in ihrer kilometerlangen Erstreckung als Blockwälle, ihrer Höhe über dem Meeresspiegel (bis + 35 m), ihrer Verbreitung landwärts (bis 300 m weit noch oberhalb von + 15 m) und auch in der Größe (bis > 10 m Länge) und Masse (> 200 t) einzelner gegen die Schwerkraft bewegter Blöcke (Erdmann et al., 2015). Dies sind höhere, weitere und größere Werte als sie von ähnlichen Erscheinungen im Südwesten Islands (Etienne & Paris, 2010), der Banneg-Halbinsel der Bretagne (Fichaut & Suanez, 2011), dem stärksten nachgewiesenen Taifun („Hayan“, Philippinen 2013, vgl. Engel et al., 2014; Kennedy et al., 2017, May et al., 2015) und anderen stark exponierten und stürmischen Küsten der Erde dokumentiert wurden. Auch die Blockgruppen und die Blockwälle auf den Shetland Inseln (Hall et al. 2006) haben geringere Masse, Transportweite und Höhenlage. Größere Einzelblöcke mit einigen 100 t Gewicht in lokalen Blockgruppen sind bislang ausschließlich von Eleuthera (Bahamas, vgl. Hearty, 1997; Hearty & Tormey, 2017; Viret 2008), Tonga (Frohlich et al., 2009), Rangiroa (Tuamotu Archipel, vgl. Bourrouilh-Le Jan & Talandier 1985) und Dirk Hartog Island, Westaustralien (Playford, 2014) bekannt. Die von (oft historisch bekannten) Tsunamis verlagerten Riesenblöcke auf den südwestjapanischen Inselgruppen finden sich in der Regel auf breiten Riffplattformen und damit nahe dem Meeresspiegel.

Die Region um die Aran-Inseln bietet nahezu perfekte Voraussetzungen für das Studium von Blockbewegungen durch marine Prozesse: gestufte und vertikale Kliffe mit maximaler Exposition zum offenen Atlantik, aber auch innerhalb der Galway Bay,

sind hier kombiniert mit gut geschichtetem und geklüftetem harten Kalkstein. Dies erlaubt den marinen Kräften, Blöcke jeder beliebigen Größe herauszubrechen. Die maximale Transportenergie der marinen Kräfte lässt sich jedoch nur dann erschließen, wenn unbeschränkt Material in verschiedener Blockgröße in einem Relief zur Verfügung steht, welches nach Höhe, Steilheit und Expositionsgrad sowie Wassertiefe jede Dimension von Überschwemmungsdistanzen und Wellen- oder Tsunami-Auflauf ermöglicht, so dass sich Verbreitungsgrenzen (*envelopes* unterschiedlich starker Einwirkung) in allen Kategorien deutlich in der Landschaft erkennen lassen. Genau dieses ist in der Galway Bay und auf den Aran-Inseln gegeben. In den meisten bisher untersuchten Regionen sind Aussagen über Blockverlagerung und –transport nur eingeschränkt möglich aufgrund von geologisch und/oder geomorphologisch begrenzten Gegebenheiten wie Relief, Höhe, Exposition oder Größe vorhandener Blöcke.

Obwohl bereits Kataloge über historische Tsunamis aus dem Mittelmeerraum publiziert waren (z.B. Papadopoulos & Chalkis 1984), erfolgten intensivere Feldnachweise aus diesem Gebiet erst mit Studien aus Zypern durch Kelletat & Schellmann (2001). Forschungen über Tsunamis und Paläotsunamis vor allem durch die verheerenden Ereignisse 2004 in der Andamanen-See, 2010 vor Chile und 2011 vor Japan hatten ihren Schwerpunkt auf feinkörnigen Sedimentarchiven, weil diese durch ihre stratigraphische Ordnung Vergleichsmöglichkeiten mit älteren Ablagerungen bieten. Mittlerweile sind einige duzend Publikationen zu Blockablagerungen erschienen. Diese lassen sich in drei unterschiedlichen Ansätzen differenzieren: Nachweis unbekannter Tsunamis, Blockbewegung durch schwere Sturmwellen, und ergebnisoffene Untersuchungen mit dem Ziel der Erkenntnis- und Differenzierungsmöglichkeiten für alle Prozesse, die Blockbewegungen gegen die Schwerkraft leisten können. Der letztgenannten Kategorie sind die hier vorgestellten Studien zuzuordnen.

## 1.2 Vorstellung des Arbeitsgebietes

Die folgenden kurzen Kapitel beschränken sich auf die wesentlichsten für die Küstenentwicklung und den Materialtransport im Arbeitsgebiet wichtigen Aspekte. Alle publizierten Beiträge enthalten in ihren Einführungen weitere Hinweise.

### 1.2.1 Prä-holozäne Landschaftsgeschichte

An der zentralen Westküste Irlands greift die Bucht von Galway mit etwa 200 km Küstenlänge (im Naturmaßstab) fast 60 km tief ins Land ein (Abb. 1). Vor ihrem westlichen Ausgang zum offenen Atlantik erstreckt sich die Kette der Aran-Inseln (Inishmore, Inishmaan und Inisheer sowie die kleine Gruppe der Brannock-Inseln und Rock Island westlich von Inishmore) über etwa 26 km Länge. Durch die im Norden gelegene fast 10 km breite Buchtöffnung, den North Sound, können aus westlicher Richtung kommende Wellen und Dünung in die Galway Bay eindringen, während sich der South Sound zwischen Inisheer und dem Festland den Wellen und der Dünung von Süden öffnet. Die beiden Bereiche zwischen den drei Aran-Inseln, der Gregory Sound und der Foul Sound, sind mit unter 2 km zu schmal für ungehinderte Passagen sehr großer Wellen.

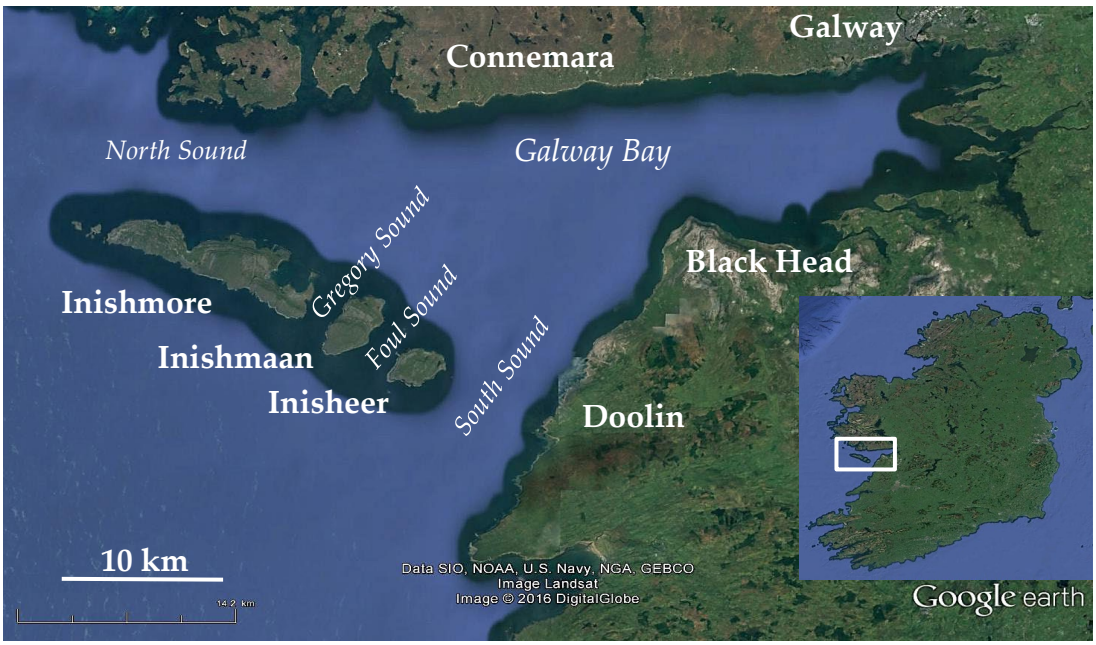



Abb. 1: Galway Bay mit den Aran-Inseln an der zentralen Westküste von Irland. Die engeren (kartierten und beprobten) Arbeitsgebiete umfassen die Aran-Inseln und den Abschnitt zwischen Doolin und Black Head innerhalb der Galway Bay (Quelle: Google Earth, 2016, ergänzt).

Zwei Strukturen sind auffallende Landschaftselemente: Zum einen ist es die geradlinige Nordbegrenzung der Galway Bay, welche die Granite von Connemara

und Galway von den Karbonkalken der Aran-Inseln und der südöstlichen Buchtflanken trennt (Fehmann, 1999; McNamara & Hennessey, 2010; Mc Sharry et al., 1999), und zum anderen die auffällige Richtung der Inselreihe mit einer nahezu geraden Kliffreihe zum Atlantik hin. Auch diese dürfte strukturell angelegt sein. Der Karbonkalk der Inseln fällt schwach nach SSW ein und formt eine Schichtstufe gegen die Galway Bay. Hier bilden Schichtköpfe des Stufenbildners Steilwände unterschiedlicher Höhe, die an besonders mächtige Kalkbänke gebunden sind. Entlang der untertauchenden Schichten in Richtung SSW verläuft eine Achterstufe, welche im jüngeren Holozän zum aktiven Kliff umgestaltet wurde. Sie trennt die Erhebungen der Inseln von einer sehr weiten und kaum gegliederten submarinen Ebene zum offenen Ozean hin, deren Gefälle auf etwa 5 km nicht einmal 10 m beträgt (Chart 3339, British Admiralty, 2005). Der Meeresboden befindet sich heute dort bei > 50 bis > 60 m Wassertiefe und lag nach Eisrückzug des LGM und vor dem letzten Anstieg des holozänen Meeresspiegels als offene Fastebene trocken.

Die gesamte Region Galway einschließlich der Aran-Inseln ist geomorphologisch geprägt durch mehrfache Vergletscherung mit deutlicher Glättung aller Oberflächen. Diese überspannen in der Karstlandschaft *The Burren* und auf den Aran-Inseln die weiten sehr flachen Falten des Kalkes und sind oft an dessen Anti- und Synklinalen adaptiert. Entlang der Granitküste von Connemara dominieren Rundhöcker geringer Größe und Höhe. Glaziale Sedimente sind in der Kalklandschaft durch eine Streu heller Granite sichtbar. Im Gegensatz zu vielen älteren Abbildungen der pleistozänen Eisgrenzen ist heute nachgewiesen, dass Irland bis fast an die Nordküste von Cornwall in England im LGM vollständig eisbedeckt war (Dunlop et al., 2010; O`Cofaigh et al., 2012; Simms, 2004, 2005). Für die Region der Westküste kartierten u.a. Sacchetti et al. 2011 die Galway-Endmoränen ca. 100 km westlich der Aran-Inseln in heute > 200 m Wassertiefe (Abb. 2), und bis in über 400 m Wassertiefe sind auf dem Schelf um den Rockall Trough (3000 m tiefes Seebecken westlich von Irland) zahlreiche Spuren von Eisberg-Kielen kartiert worden.

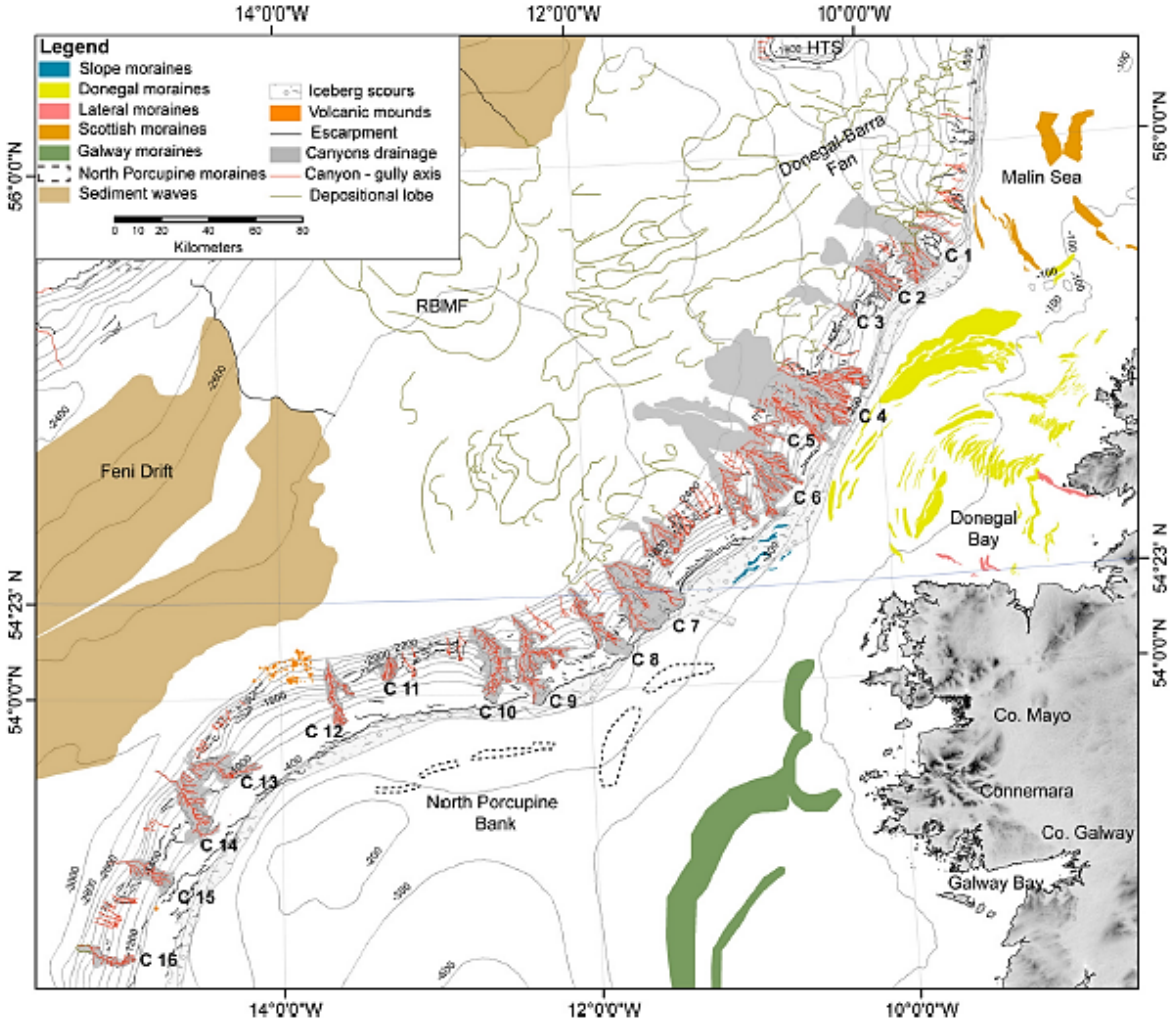



Abb. 2: Kartierung der Formen des Meeresbodens westlich von Irland mit besonderer Betonung der glazialen Relikte (aus Sacchetti et al., 2011)

Die Arbeitsgebiete wurden zwischen 17.000 und 16.000 BP eisfrei (Clark et al., 2012; Diefendorf et al., 2006; Van Asch et al., 2012, vgl. Abb. 3) und ab diesem Zeitraum dürften Schmelzwasserströme die breiten und schmalen Durchlässe in der Inselbarriere weiter ausgeformt haben. Wie durch Sondierungen von INFOMAR (2006) bekannt ist, besteht der Meeresboden in den breiten Sounds aus Kalkgestein ohne Sedimente, welche möglicherweise unter Mitwirkung der Gezeitenströmungen (bei > 4 m Springtidenhub) und Grundberührung durch sehr hohe Wellen beseitigt wurden. Die Wassertiefe liegt dort zwischen 50 und 55 m. Bekannt ist demnach, dass ab dem frühen Spätglazial die Region Galway/Aran wieder terrestrischen geomorphologischen Prozessen (vor allem periglazialen auf Permafrost über viele 1.000 Jahre und - wie bereits in einigen Interglazialen - Verkarstung) ausgesetzt war. Küstenformung setzte jedoch in einem deutlich tieferen Niveau als heute erst ein, nachdem der Meeresspiegel wieder die Inselkette erreicht hatte, was um ca. 10.000 BP der Fall gewesen ist.

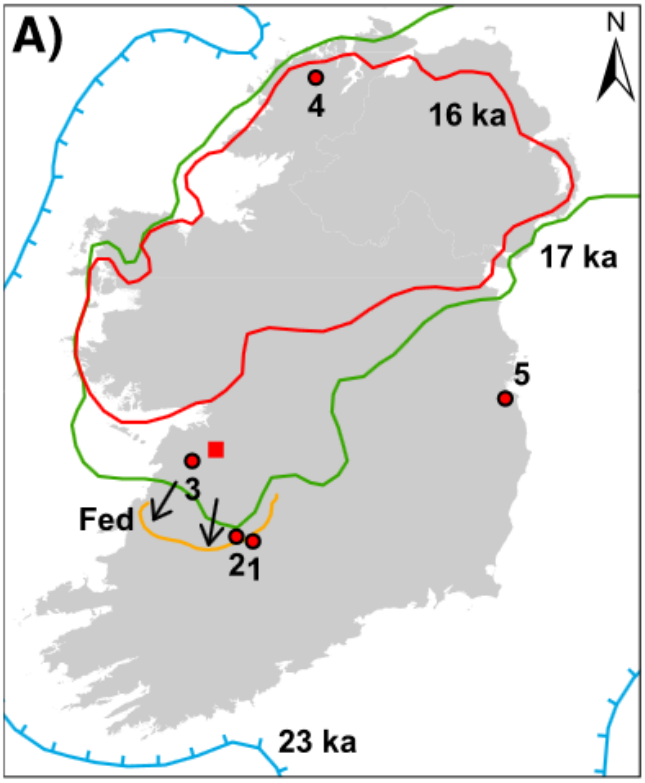



Abb. 3: Lage der Eisgrenzen in Irland zum Ende des LGM, datiert mit Expositionsaltern der Felsoberfläche mittels kosmogener Nuklide (aus Clark et al., 2012).

### 1.2.2 Küstenentwicklung und Meeresspiegelschwankungen

In der Literatur herrscht Einigkeit darüber, dass der Meeresspiegel in der Region Galway im Holozän niemals höher lag als heute (Carter et al. ,1989; Lambeck et al., 2014; O`Carra et al., 2014). Das Wasser umspülte um 9.000 BP das erste Mal die Inseln vollständig. Williams und Doyle (2014) publizierten Funde von unter Süßwassertorf verwurzelten Bäumen (heute nahe des mittleren Niedrigwassers) mit Altern von 7.400 bis 5.500 BP aus dem inneren Teil der Galway Bucht und schlossen daraus auf einen Meeresspiegel um – 5 m (+/- 1 m) zum Zeitpunkt dieser Waldverbreitung. Aus Süßwassertorf durch Stürme exhumierten Geweihstangen von Hirschen ließ sich ein Meeresspiegel um -1.5 m gegenüber heute für das frühe Mittelalter (500 AD) errechnen. Die innere Galway Bucht war demnach zu jener Zeit ein Süßwassersumpf und die Küste verlief etwa von Black Head im Süden nach Spiddal im Norden. Einen ähnlichen Meeresspiegelstand und -verlauf rekonstruierten Holmes et al. (2007) mit Hilfe von Ostrakoden aus den Ablagerungen des (heute 23m tiefen) Karstsees An Loch Mór im Nordosten der Aran-Insel Inisheer. Hinreichend exakte Kenntnis der holozänen Meeresspiegelstände ist unerlässlich zur Beurteilung der Transportleistungen mariner Kräfte landwärts und aufwärts. Dieses Forschungsprojekt konnte den oben skizzierten Kenntnisstand bestätigen und mit

weiteren Argumenten aus Feldbeobachtungen und Datierungen ergänzen (vgl. Erdmann et al., 2018 b, Fig. 1).

Bis auf die innersten flachen Abschnitte der Galway Bucht mit einigen kleinen Marschgebieten unterliegen alle Küsten des Arbeitsgebietes einschließlich aller Inselseiten der Abtragung. Dies ist sogar bei gut geschützten Strandabschnitten und heute inaktiven Dünenkomplexen der Fall. Ihre seeseitige Begrenzung sind niedrige aktive Kliffe. Die längsten Sektionen in der Galway Bay und um die Aran-Inseln weisen vertikale Kliffe verschiedener Höhen auf, angelehnt an das Kluftmuster des dortigen Kalkgesteins. Dieses ist zumeist bereits durch Lösung geweitet und kann somit leichter durch heftigen Wellenschlag geschwächt werden. Das Ausbrechen von Einzelfragmenten bis zu > 100 t Gewicht ist die Folge. Geschieht dieses bei extremen Sturmwellen, so können sogar Blöcke dieser Größe gegen die Schwerkraft auf Kliffplattformen bewegt werden. Die Kliffprofile sind oft treppenartig gestuft. Sehr deutliche Kliffstufen mit mehreren Metern Höhe werden meist veranlasst durch dünne Lagen von Tongesteinen und Tonschiefern (*shales, siltstones*) innerhalb der Kalkserien, an welchen sich Sickerwasser staut und in Form zahlreicher kleiner Quellen austritt. Wellen spülen dieses Material (sogar ohne Brandungswaffen) aus und lassen tiefe Einkerbungen mit hangendem Fels entstehen (Abb. 4).

Abb. 4: 50 m hohes Kliff im Südwesten der Insel Inishmore. Tiefe Unterhöhlungen sind entlang von wasserundurchlässigen Schichten (*shales*) im Bereich der Sturmbrandung angelegt.

Die höchsten vertikalen Kliffe sind an der SSW-Küste der Insel Inishmore unterhalb der bronzezeitlichen Festung *Dun Aonghasa* mit mindestens 70 m ausgebildet, an der Westküste der Insel Inishmaan werden maximal 32 m über der mittleren Hochwasserlinie erreicht, ähnlich hoch sind die Kliffe auch noch innerhalb der Galway Bucht an der SE-Küste bei Lackglass, während die Insel Inisheer meist flach eintauchende Felsküsten aufweist. An steilen Abschnitten verläuft die Küstenerosion zumeist durch Kollaps ganzer Wände. Dadurch entstehen Halden aus Grobmaterial am Fuß der Kliffe (Abb. 5). Küstenrückgang gerade an den steilsten und höchsten Abschnitten ist ein schrittweiser Prozess mit plötzlichen Abbrüchen und langen Stabilitätsphasen.

Abb. 5: Abbruch eines 22 m hohen Kliffs westlich des *Black Fort* an der SW-Küste von Inishmore. Der helle Blockbereich stammt von einem Kollaps im Jahre 2000, die sehr großen Blöcke sind wesentlich älter (Aufnahme: Scheffers 2007).

Küstensedimente finden sich in kleinen *pocket beaches* als grobe Sande und Kiese und in offener Lage auch als Schotter- und Blockstrände – letztere häufig als Strandwälle ausgebildet – mit meist sehr guter Rundung der Einzelfragmente.

Am auffälligsten sind jedoch Blockablagerungen oberhalb der Hochwasserlinie und weiter landeinwärts – auf der Insel Inishmaan bis zu 300 m und bis +35 m MHW (= 35 m über mittlerem Hochwasser). Die großen Blöcke sind geradezu

landschaftsbestimmend (Abb. 6), auch noch auf Kliffplattformen bis über 20 m Höhe und in langgestreckten und bis 6 m hohen Blockwällen angehäuft. Nahe am Meer liegen an diversen Stellen oft mehrere Blöcke in *imbrication* (Abb. 7), gelegentlich mit Einzelfragmenten bis über 20 t an Masse.

Abb. 6: Großer, unregelmäßig geformter Block innerhalb der Galway Bucht, südlich von Cancapple. Dieser liegt auf einer Kliffstufe von ca. 15 m Höhe, entstammt aus der Basisschicht und wiegt etwa 70-80 t.

Abb. 7: *Imbrication* (dachziegelartige Lagerung) sehr großer Blöcke. Alle Beispiele liegen auf dem Festland innerhalb der Galway Bucht.

### 1.2.3 Aktuelle Küstenformungsprozesse

Neben den Gezeiten (Springtidenhub an den Aran Inseln etwa 4 m, in Inneren der Galway Bucht 5 m) tragen vor allem Starkwellen am meisten zur Küstenformung bei. Sie kommen entweder als Windwellen oder als Dünung aus dem Atlantik, vor allem aus den höheren geographischen Breiten infolge der Rechtsablenkung durch die Corioliswirkung. Bei Stürmen, deren Zentrum nahe der Galway Bucht vorbeizieht, kann ein niedriger Luftdruck zu *storm surges* führen (1 cm Meeresspiegelerhöhung pro 1 hPa Luftdrucksenkung). Hinzu kommt Windstau.

Im Februar 2014 führten Winterstürme der Hurrikan-Kategorien 3+ und 4 dazu, dass in der mittelalterlichen Altstadt von Galway City 1,5 m Hochwasser stand. Dies war der höchste sicher bekannte Flutstand seit dortigen Aufzeichnungen. Der Winter 2013/14 hatte allerdings außergewöhnlich starke Stürme nach Anzahl, Luftdruck (5 Mal unter 950 hPa, Abb. 8) und Windgeschwindigkeiten. Sie wurden von den Küstenbewohnern und den meteorologischen Diensten Irlands als die stärksten „*in living memory*“ beschrieben. Die Wellenhöhe erreichte an der nächstgelegenen Messboje, etwa 90 km westlich der Aran Inseln, annähernd 30 m und Wellen um etwa 20 m Höhe wurden an den exponiertesten Küstenabschnitten der Region mit Tiefwasser beobachtet.

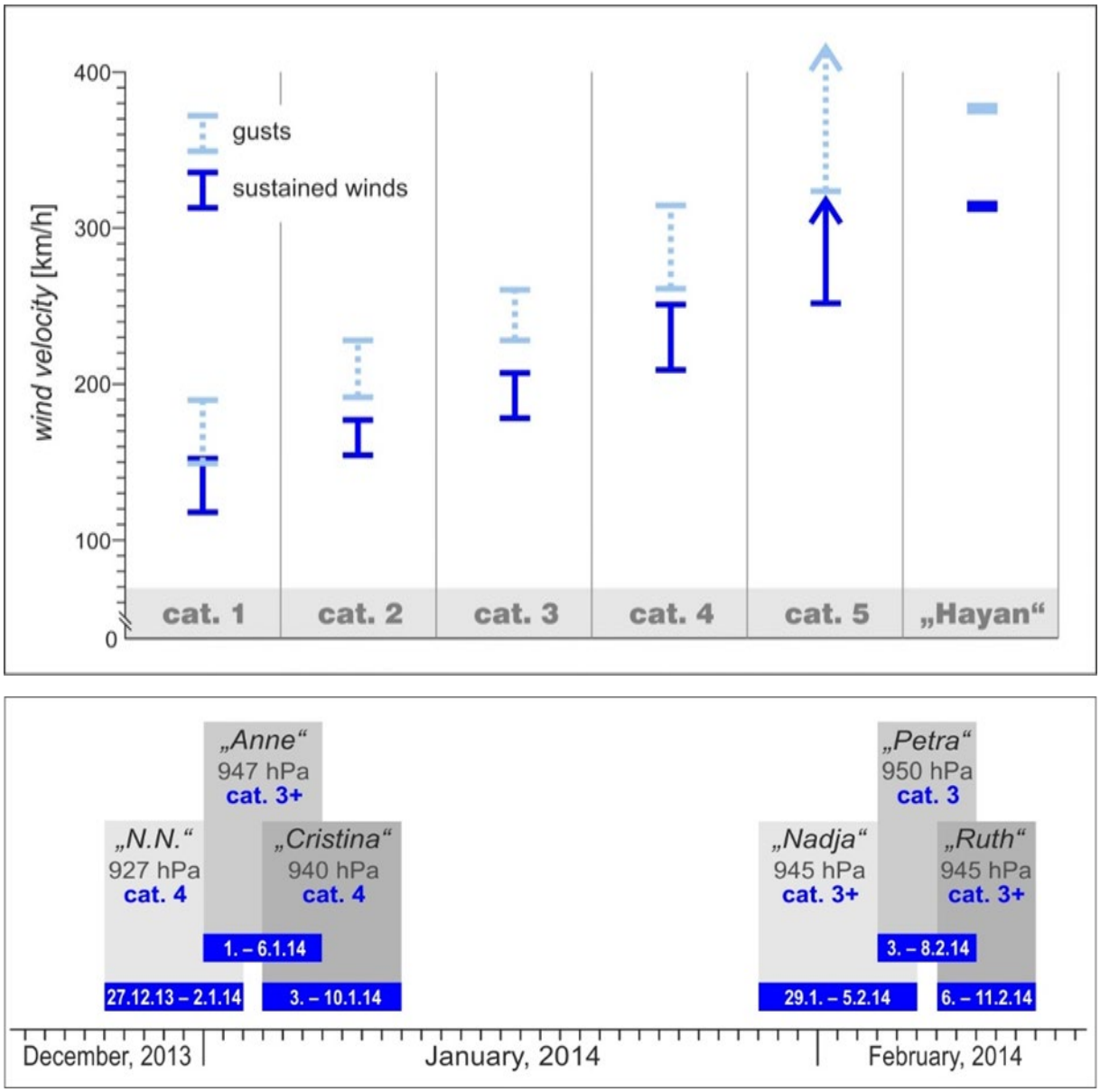



Abb. 8: Starke Stürme an der Westküste Irlands im Winter 2013/14, verglichen mit dem Super-Taifun Hayan (lokal: Yolanda), der im November 2013 auf die Philippinen traf. Sein niedrigster Luftdruck betrug 895 hPa (May et al., 2015). (aus Erdmann et al., 2015, Figs. 1.2 a und b)

Aufzeichnungen über Wellenhöhen im Arbeitsgebiet finden sich bei Draper (1972, 1991), Aqua-Fact International (2002) und MET ÈIRANN (monatliche und jährliche Berichte, z.B. 2007). Die Geschichte vergangener Sturmereignisse und ihre Auswirkungen beschreiben u.a. Brayne (2003), Burt (2006), Hickey (2001), Lamb (1991), MacClenaghan et al. (2001), O`Brian et al. (2013) und Shields & Fitzgerald (1989), sowie Erdmann et al. (2015) und Masselink et al. (2016) für den Winter 2013/14.

# 2 Abriss der Forschungsgeschichte zur Küstenformung in der Region Galway Bay

Zum Verständnis der für die eigenen Publikationen gewählten Schwerpunkte ist ein kurzer Abriss der Forschungsgeschichte zur Küstenformung in der Region Galway Bay notwendig. Ein besonderes Gewicht haben dabei die Publikationen einer Arbeitsgruppe um Rónadh Cox, USA und die eigenen Arbeiten in der Nachfolge der Arbeitsgruppe um Anja Scheffers, Australien.

Es ist anzumerken, dass es sich im Folgenden um eine sehr kondensierte Darstellung handelt, um Wiederholungen zu den vorgelegten eigenen Publikationen zu vermeiden. Alle Beiträge – vor allem die frühen – liefern wertvolle Beobachtungen zu den Gegebenheiten, beschränken sich jedoch räumlich auf die Inseln Inishmore und Inishmaan und dort auf die Küstenabschnitte mit hohen Kliffen und sehr großen Blöcken (*Cliff Top Mega Clasts*). Zudem bestand die These um etwa 2004 und früher, dass andere Prozesse als Sturmwellen für Blockverlagerungen im Westen Irlands für höchst unwahrscheinlich resp. ausgeschlossen werden müssen. Diese Grundüberzeugung hat das Spektrum von Schlussfolgerungen und sogar die spontane Einschätzung von Fakten im Gelände eingeengt.

## 2.1 Der Anfang

In Kenntnis der archäologischen und historischen sowie der aktuellen marin/meteorologischen Gegebenheiten im Westen Irlands hat der Geologe D. M. Williams (Universität Galway) eine aktual-geologische Frage mit einem laufenden Disput über Ursprung, Zweck und Lage eisenzeitlicher Festungen verknüpft:

> Williams, D.M. (2004): Marine erosion and archaeological landscapes: A case study of stone forts at cliff-top locations in the Aran Islands, Ireland. - Geoarchaeology 19(2):167 – 175

In dieser Publikation geht es darum, ob *Promontory Forts*, Festungen aus der Eisenzeit, die Kliffsporne als Schutz- und Rückzugsgebiete mit zusätzlichen Wehranlagen wie Gräben, Wälle, später auch Mauern in unruhigen Zeiten nutzten, tatsächlich auf den Kliffspornen angelegt wurden oder ob es sich um ursprünglich ovale, runde oder halbkreisförmige Festungen im Land handelte, die durch erheblichen Kliffrückgang beschädigt wurden, heute direkt an Kliffen liegen und nur noch rudimentär vorhanden sind. Williams beschreibt dies anhand von *Black Fort* (Dún Dúchathair) an

der Südküste der Insel Inishmore, eine eisenzeitliche Anlage aus der Zeit zwischen 2500 – 2000 BP (Abb. 9 und 10).

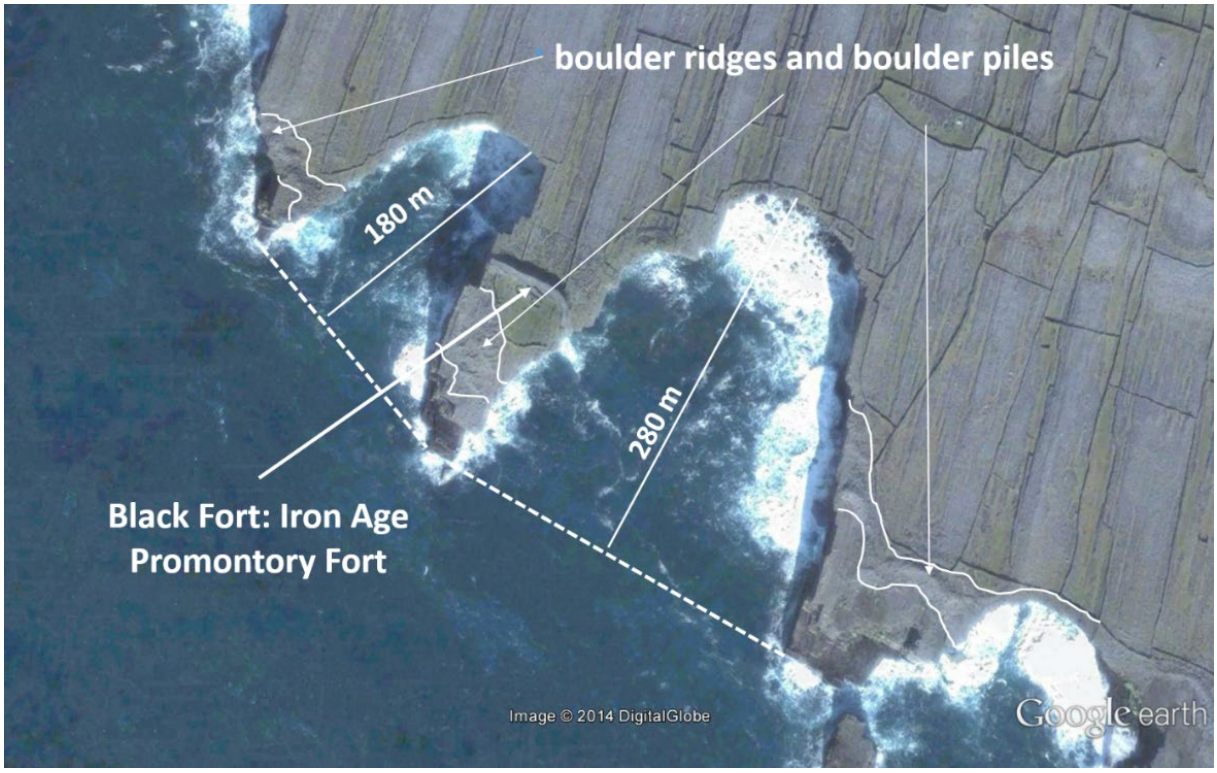



Abb. 9: Lage des *Black Fort* (Dún Dúchathair) auf Inishmore. Deutlich zu erkennen die zum Land hin geschützte Lage auf einem über 20 m hohen Kliffsporn. Gekennzeichnet sind die begleitenden Formen und Ablagerungen, auf welche Williams (2004) seine Argumente stützt. (Quelle: Google Earth 2005, verändert)

Abb. 10: Etwa 500 m breiter Ausschnitt aus einer topographischen Aufnahme von 1839 des National Survey (Maßstab ca. 1: 28.000) zeigt die Buchten und Kliffsporne um das *Black Fort* in gleicher Form wie das Satellitenbild 165 Jahre später: Die Klifferosion ist (zumindest) seit 1839 äußerst gering. Auch O`Donovan (1839) gibt in seinen Notizen zur topographischen Aufnahme keine Hinweise auf starke Erosion um das *Black Fort*.

Williams kannte die häufigen starken Stürme der Region und ihre Fähigkeit, gelegentlich größere Blöcke oberhalb der Kliffe abzulagern. Er berichtet über *cliff-top storm deposits* auf der Spitze des Sporns des Black Fort und auf beiden benachbarten Kliffspornen, die vom *Black Fort* durch Einbuchtungen von etwa 180 m und 280 m getrennt sind (Abb. 9). Seine Schlussfolgerung ist, dass diese Ablagerungen ehemals einen durchgehenden Wall auf einem durchgehenden Kliff geformt haben und in jüngerer Zeit – lange nach dem Verlassen des *Black Fort* – durch einen starken Sturm getrennt wurden. Als Zeitpunkt dieses Sturmes benennt er 1839, das Jahr mit der „*Night of the Big Wind*" (vgl. Shields & Fitzgerald, 1989; MacClenaghan et al., 2001; Burt 2006). Im selben Jahr 1839 wurde durch den Ordnance Survey erstmals eine detaillierte topographische Karte der Aran-Inseln angefertigt (publiziert 1841), auf welcher die Einbuchtungen in ihrem heutigen Erscheinungsbild gezeichnet sind.
Vergleiche der Eingriff-Tiefe der Buchten zum Zeitpunkt des Sturmes ergeben eine durchschnittliche Klifferosion von etwa 1 m /Jahr, Williams beziffert sie als langjährigen Mittelwert mit 0,2 – 0,4 m/Jahr.
Diese Überlegungen klingen schlüssig, jedoch beruhen sie auf mindestens drei unbewiesenen Annahmen:

1. 1839 erfolgte eine extreme Klifferosion.
2. Die Blockhaufen auf den Kliffspornen sind Teil eines ehemals durchgehenden Walles.
3. Die *Promontory Forts* sind völlig anders gestaltete Anlagen im Inland gewesen.

Wie zu sehen ist, bedingen sich die Annahmen gegenseitig, es handelt sich dabei um einen oder mehrere Zirkelschlüsse. Allein 172 *Promontory Forts* aus der Eisenzeit und sogar zurück bis ins ausgehende Neolithikum sind noch heute entlang der Westküste Irlands zu finden (vgl. Abb. 11), ihre Konstruktion und ihr Zweck sind offensichtlich. Zudem ist davon auszugehen, dass bei einem so gewaltigen Kliffrückgang große Mengen an abgestürzten Blöcken innerhalb der beiden Buchten bis über die Hochwasserlinie erhalten geblieben und bei der topographischen Aufnahme einige Monate später aufgenommen worden wären.

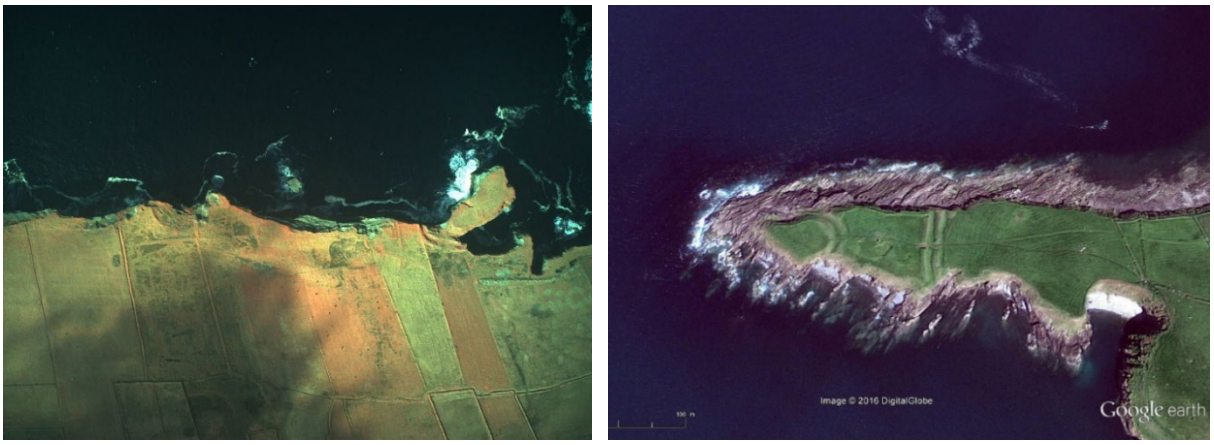



Abb. 11: Beispiele für *Promontory Forts* – manche zurückgehend bis auf das Späte Neolithikum – aus dem County Clare südlich der Galway Bay. Sie liegen in sehr exponierter Lage auf Kliffen, sind jedoch trotz des hohen Alters noch in ihrer Funktion zu erkennen (Quellen: links: National Coastline Survey of Ireland, 2000; rechts: Google Earth, 2016)

Die hohe Quote für den durchschnittlichen Kliffrückgang in der Region Galway wurde von nachfolgenden Autoren (Hall et al., 2006, 2010; Hansom & Hall, 2008, 2009; Cox et al., 2012) übernommen. Daraus ergaben sich weitere Fehleinschätzungen, u.a. in Bezug auf das Alter und die Intensität der landwärtigen Verschiebung von Blockwällen auf Kliffen und damit eine hohe Dynamik der Umgestaltung der Felsküsten. Diese Annahmen sind mehrfach, auch mit Altersdatierungen der Blockablagerungen und konkreten Beispielen der Küstenveränderung mit Hilfe archäologischer und historischer Zeugnisse widerlegt resp. relativiert worden (Scheffers et al., 2009, 2010 a und b, Erdmann et al., 2015, 2017, 2018 a, 2018 b).

Vor dem Hintergrund der Annahmen Williams` (2004) erschien im selben Jahr eine Publikation mit dem Schwerpunkt Blockablagerungen, vor allem in *cliff-top position:*

> Williams D. M., & Hall, A. M. (2004): Cliff-top megaclast deposits of Ireland, a record of extreme waves in the North Atlantic — storms or tsunamis? Marine Geology 206:101–117.

In dieser Publikation wird ein Irrtum begründet, welcher in nahezu allen folgenden Publikationen übernommen wird: Es ist die Höhe von Sturmablagerungen bis zu 50 m über dem Meer (angeblich die höchsten weltweit von rezenten Stürmen) mit einem Block von noch 2,9 t (Williams & Hall, 2004, Fig. 5) Die Abbildung zeigt die senkrechten Kliffe 400 m nördlich der Lokalität Crummel an der Westküste von Inishmaan (vgl. Erdmann et al., 2018 b). Dass diese Höhe bei Weitem übertrieben ist, wurde durch eigene Messungen mit Bandmaß und Triangulation bestätigt: Der Wert beträgt exakt 30 m bis zur mittleren Hochwasserlinie. Williams & Hall (2004, Fig. 5

und S. 107) beschreiben für diesen Ort auch eine Folge von kürzeren Blockwällen, die parallel zur Küste und jeweils von schuttfreien Streifen getrennt liegen, die landwärtigen älter als die seewärtigen. Auch dies ist sachlich falsch: Die kurzen Wälle verlaufen eher senkrecht zum Kliff, gehen meist nahezu ineinander über und sind gleich alt.

Die Publikation von Williams & Hall (2004) steht am Anfang der Forschungsgeschichte zu den auffälligen Großblockablagerungen der Aran-Inseln. Im Gegensatz zu späteren Veröffentlichungen zeichnet sie sich durch zahlreiche präzise Beobachtungen aus, wenn auch die daraus gezogenen Schlussfolgerungen nicht immer folgerichtig sind. So wird beispielsweise der Unterschied in deutlicher *imbrication* zwischen den seewärtigen Hängen der Blockwälle und der eher chaotischen Lagerung in landwärtiger Richtung erkannt, aber eine Gesamtbildung dieser Strukturen wird erst ab 1839 für möglich gehalten, mit Bezug auf die „*Night of the Big Wind*“ 1839.
Gestützt wird das relativ junge Alter durch „Recent emplacement and reworking […] evidenced by trapped plastic detritus within the deposits” und “eyewitness accounts of large storms during which clasts have been emplaced” (Williams & Hall, 2004, S. 105). Die zweite Aussage bezieht sich auf einen Block von etwa 78 t, der – so die Annahme der Autoren – auf Inishmaan in 12-14 m Höhe und > 100 m vom Kliff entfernt ausgebrochen und auf den Blockwall transportiert wurde.
An vielen Küsten der Erde finden sich Kunststoffteile als Küstenverschmutzung oftmals eingeklemmt zwischen alten Blockablagerungen, doch die Vorstellung, es habe dort gelegen und Blöcke wurden darauf gelegt, ist sicher falsch: die Kunststoffreste werden durch Wellen und Boren in kleinste Fugen eingepresst und erscheinen nun als innere Teile von Grobsedimenten. Der Großblock von Inishmaan muss nicht deshalb im Jahre 1991 verlagert worden sein, weil ihn ein Inselbewohner damals zum ersten Mal sah. Möglich ist auch, dass dieser bereits vorhanden gewesen und durch die Abtragung der seeseitigen Blockwallhänge entblößt und damit zum ersten Mal sichtbar geworden ist, ein Vorgang, welcher bei Erdmann et al. (2015, 2017, 2018 b) beschrieben und durch Beobachtungen belegt wird.

Das Alter der Blockwälle wird als eher rezent und ggf. zurück bis 1839 angenommen, und für diesen Zeitabschnitt wird betont, dass keine Tsunamis vorgekommen sind und man diesen Prozess deshalb ausschließen möchte. Doch konnten bereits vor einigen Jahren Scheffers et al. (2010 a) und Erdmann et al. (2017, 2018 b) durch zahlreiche Altersdaten eine Geschichte der Blockablagerungen nachweisen, welche

mehr als 6.000 Jahre zurückreicht. Für einen so langen Zeitraum Tsunamis irgendwo auf der Erde auszuschließen ist zumindest gewagt, und der positive Nachweis von Palaeotsunamis immer eine Herausforderung.

In Williams & Hall (2004) wird die Idee geäußert, dass vorwärts schießende Boren auf Kliffplattformen das 2,4 -fache der Wellengeschwindigkeit erreichen können. Hansom et al. (2008) entwickeln den Gedanken später weiter mit Vorstellungen, die physikalischen Gesetzen widersprechen (siehe Kurzbesprechung unten).

Williams & Hall (2004, S. 105 und 106) liefern jedoch auch Hinweise auf offene Fragen, z B. *„that older ridges* (d.h. landwärtig des Hauptwalles gelegene) *represent the results of older and more extreme events formed in more distal locations when the cliff edge was further than the present day*", und dass bei schweren Stürmen auf den Shetland-Inseln 1992 und 1993 nur kleine Blöcke in Richtung der *ridge fronts* bewegt wurden und deshalb frühere Stürme *„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 interventials of millenia*". Genau diese Widersprüche (und Zweifel) waren Gründe für dieses DFG-Projekt in der Galway-Region.

## 2.2 Unterstützung und Ausweitung der Sturm-Hypothese

2006 und 2009 erschienen Publikationen von Hall und Hansom (Hall et al., 2006; Hansom & Hall, 2009) mit ähnlichem Inhalt und Bearbeitung von *Cliff Top Storm Deposits* der Aran-Inseln und von der Hauptinsel Shetlands, auf welcher sich am *Geo*, ein schmaler kluftbedingter Kliffeinschnitt, *Grind of the Navir* ein hoher und rezent im seewärtigen Teil aktivierter Blockwall aus Ignimbriten befindet.

> Hall A. M., Hansom, J. D., Williams D. M. und Jarvis J. (2006): Distribution, geomorphology and lithofacies of cliff-top storm deposits: examples from the high energy coasts of Scotland and Ireland. Marine Geology 232: 131–155.

Das Beispiel der Region Galway ist hervorzuheben: Erneut findet sich das Altersargument mit eingetragenem anthropogenen Material wie Plastikteilen, jedoch auch die Bemerkung (S. 132), dass *„angularity, lack of sorting and large size of boulders …are not features commonly associated with modern storm beaches"*. Zudem ermittelten die Autoren für *Grind of the Navir* einen Kliffrückgang von jährlich 5-6 mm, eine Größenordnung, die im Gegensatz zu jener von Williams (2004) steht, aber in völliger Übereinstimmung mit eigenen Schlussfolgerungen für die Aran-Inseln und Teile der exponierten Galway Bucht.

Hansom J. D., & Hall A. M. (2009): Magnitude and frequency of extra-tropical North Atlantic cyclones: a chronology from cliff-top storm deposits. Quaternary International 195:42–52.

Die größten Widersprüche zu den Erkenntnissen der Arbeitsgruppen Scheffers & Kelletat und Erdmann & Kelletat besteht in der Heranziehung von Plastikteilen als Altersargument und damit einer kurzen Entwicklungsgeschichte der Grobsedimente sowie der Argumentation mit dem *North-Atlantic Sea Salt Record* aus grönländischen Eisbohrkernen, mit welchem keine Sturmgeschichte weit westlich davon verbunden werden kann (vgl. Scheffers et al., 2009, 2010a).

Hansom J.D., Barltrop N.D.P. und Hall A.M. (2008): Modelling the processes of cliff-top erosion and deposition under extreme storm waves. Marine Geology 253(1–2):36–50.

Die Publikation von Hansom et al. (2008) widmet sich laut Titel zwar dem Modellieren von Abtragungsprozessen am Klifftop und auf der Kliffplattform sowie dem Charakter der landwärts schießenden Bore, dient jedoch nach dem gesamten Kontext ausschließlich dem Beleg außergewöhnlicher Transportvorgänge aus Sturmwellen, um die vorhandenen Blockablagerungen auch nur durch Sturmwellen zu erklären. Der Schlusssatz des Abstracts („*The modelling results show, that extreme storm waves are capable of quarrying, transporting and depositing large blocks at altitude and significant distances inland and so present serious questions about the use of such deposits as diagnostic of paleo-tsunami")* möchte zudem suggerieren, dass andere Autoren alle irgendwie großen Blöcke ausschließlich als Tsunamibeleg interpretieren, was so nicht richtig ist.

Nach eigenen Beobachtungen bei starken Stürmen (Hurrikan Ivan 2004 auf Bonaire, Winterstürme an der Galway Bucht im Februar 2014, Herbststürme auf den Aran-Inseln im September 2016) ist die Beziehung zwischen Kliffhöhe und Wellenhöhe nicht so einfach wie dargestellt. Auch bei Wellen, die mehrere Meter höher sind als die obere Kliffkante, entstehen durch Reflexion vorhergehender Wellen, das Zusammenbrechen des vertikalen *jets* am Kliff und die Reibung an der Kliffoberkante und auf der Kliffplattform zumeist *white water bores*, die eine viel geringere Dichte und damit viel geringere Energieübertragung als *green water bores* haben.

Wahrscheinlich liegt bei Hansom & Hall (2009) ein Missverständnis in der Auswertung der Literatur vor: Nach den Tests von Ryu et al. (2007) kann ein vertikal aufsteigender *jet* (=Strahl) am Kliff eine Geschwindigkeit bis zum 2,4fachen der Wellengeschwindigkeit erreichen, eine Bore (auf dem Kliff) das maximal 1,5fache. Die

zitierte *„High flow velocities rapidly accelerate and transport blocks inland until the flow attenuation results in deposition of blocks at the limit of run-up"*, also Akzeleration an jeder Geländestufe um das 2,4fache, widerspricht allen Gesetzen der Physik: Die Bore würde nach drei Stufen – ein häufig auftretendes Szenario auf den Kliffplattformen der Aran Inseln – bei zunächst 6 m/s Wellengeschwindigkeit auf nahezu 300 km/h beschleunigen! Im Assessment Manual EuroTop (2007) wird die maximale Geschwindigkeit eines *overtopping flow* entlang der Nordseeküste wie Überströmung eines Deiches mit 5-6 m/s (entspricht max. 21,6 km/h) angegeben.

Zudem kann die Modellvorstellung bezweifelt werden, dass die Oberkante eines Kliffes wegen der herrschenden Kräfteverteilung am stärksten abgetragen wird. Dagegen sprechen die vielen vertikalen und bis zu 20 m überhängenden Kliffe der Aran-Inseln im gut geschichteten Kalkstein. In erster Linie ist es nicht die *impact pressure* einer Welle, welche den Gesteinsausbruch ermöglicht, sondern die Tatsache, dass interne Kalklösung entlang der Schichtfugen und Klüfte bereits nahezu lose liegende Fragmente für einen Transport bereitgestellt haben.

Die Vorstellung, dass *„the flow attenuation results in deposition of blocks at the limit of the run up"* ist sicherlich nicht schlüssig: *"Blocks"* oder auch nur kleine *"boulders"* werden sicherlich unterhalb resp. seewärts der *„limit of run up"* bereits ausfallen, während das Wasser (ggf. mit *gravels* und feinerem Material) sich noch abhängig von der Neigung und der Rauigkeit des Reliefs weiterbewegt.
Schließlich ist es nicht möglich von einer *„continued modification of ridges during major storms"* zu sprechen. Wäre dies der Fall, so müssten die wenig jenseits der seewärtigen Blockwälle liegenden viel älteren und niedrigeren (auf einige tausend Jahre datierten) Wälle längst erreicht und überschüttet worden sein, aber auch dieses ist nicht der Fall (vgl. Erdmann et al., 2017).

> Zentner D. (2009): Geospatial, hydrodynamic, and field evidence for the storm-wave emplacement of boulder ridges on the Aran Islands, Ireland. Williamstown, MA, Williams College, Thesis, 190 p.

Die Arbeit von Zentner (2009) stützt sich auf die erwähnten Publikationen, übernimmt deren Schlussfolgerungen für die Prozessgeschichte (=*storm only*) und erarbeitet zumeist quantitatives Datenmaterial durch Ausmessung von Querprofilen der Blockwälle und mittlerer Korngrößen in den Blockwällen. Diese Methode richtete sich nach zuvor gesetzten Geländepunkten mit einem strikten Netz, nicht jedoch nach Unterschieden oder Hinweisen aus der Naturlandschaft selbst. So erscheinen die Ergebnisse zwar als statistisch korrekt, lassen jedoch kaum erkennen, in welchen

Milieus sie aufgenommen wurden. Beispielsweise wird beschrieben, dass die mittlere Längsachse der Fragmente in den Blockwällen 3,9 cm beträgt. Dieser Wert ist unbrauchbar, da so kleine Klasten in den Blockwällen nicht vorkommen. Durch solche Statistiken ist es nicht möglich, den Charakter der gewaltigen Blockablagerungen auch nur annähernd zu beschreiben.

## 2.3 Widerspruch und Disput

Scheffers et al. (2009) publizierten Ergebnisse ihrer Feldforschung entlang der Küsten der Shetland und Orkney Inseln und der Äußeren Hebriden in Schottland sowie der irischen Westküste mit Schwerpunkt in der Region Galway einschließlich eines ersten Austausches von Pro- und Kontra-Argumenten bzgl. Sturm und/oder Tsunami.

> Scheffers, A.; Scheffers, S.; Kelletat, D., and Browne, T., 2009. Wave-emplaced coarse debris and megaclasts in Ireland and Scotland: Boulder transport in a high energy littoral environment. Journal of Geology, 117, 553–573.

Der Ansatz bestand darin, induktiv Fakten aus der Natur zu sammeln und deren gesamte Fülle differentialdiagnostisch zu bewerten, ohne zuvor einen Prozess auszuschließen. Im Gegensatz zu den bisher aufgeführten Autoren wurden auch Blockablagerungen an geschützten Küstenabschnitten und an weiten Flachwasserabschnitten untersucht, welche nicht von rezenten Prozessen vergangener Jahrzehnte aktiviert wurden. Somit mussten neben Sturmwellenaktivität auch (frühere) Tsunamis als Formungskraft in Betracht gezogen werden. Zudem erlaubten archäologische Altersbefunde wie neolithische *middens*, bronze- bis eisenzeitliche *Promontory Forts*, Wikinger- Bootshäuser in unmittelbarer Küstenlage und Datierungen von Blockablagerungen in Klifftop-Lage mit Altern bis zu 3.500 BP (vgl. Scheffers et al., 2010a) nur den Schluss, dass viele Küstenabschnitte nur wenig zurückgewichen sind. Somit können auch die Blockwälle nicht seit Jahrtausenden in ständiger landwärtiger Bewegung sein. Weitere Hinweise liefern die gürtelartig angeordneten Kleinformen der Bioerosion auf Kalk und deren Bildungsgeschwindigkeit. Diese Argumente wurden in früheren Arbeiten anderer Autoren nicht beachtet, da das Interesse nahezu ausschließlich auf die größten Blöcke in extrem offener Exposition gerichtet war.

> Hall, A.M.; Hansom, J.D., and Williams, D.M., 2010. Wave-emplaced coarse debris and megaclasts in Ireland and Scotland: Boulder transport in a high-energy littoral environment - A discussion. Journal of Geology, 118, 699–704.

Diese Kritik enthält bereits im Abstract eine falsche Aussagenzuweisung („*Scheffers et al, 2009 state, that no evidence exists for storm wave dislocation of large boulders […] at cliff*

*top locations…")* und wiederholt ansonsten die früheren Auffassungen der Autoren ohne weitere Auseinandersetzung mit neuen Argumenten. Zur Verstärkung der Argumente der Autoren steigen die Gewichtsangaben der ausschließlich von Stürmen bewegten Blöcken weiter (hier auf > 1000 t), ohne die Dislozierung gegen die Schwerkraft zu nennen. Bewegungen der Schwerkraft folgend finden unentwegt in allen geomorphologischen Prozessen der Erde statt, diese sind somit für die Begründung eines bestimmten Prozesses unbrauchbar. In den Conclusions findet sich eine weitere falsche Aussage: "*This leads us to seriously question the reliability of the Scheffers et al. (2009) approach and of their criteria when applied to any rock coast that is exposed to major storms. We caution those who dogmatically contend that any mega-block transport by waves must require a tsunami...":*

> Scheffers, A.; Kelletat, D., and Scheffers, S., 2010 b. Wave-emplaced coarse debris and megaclasts in Ireland and Scotland: Boulder transport in a high-energy littoral environment: A reply. Journal of Geology, 118, 705–709.

In der Erwiderung von Scheffers und Kelletat (Scheffers et al., 2010 b, erneut im Journal of Geology) erfolgten Klarstellungen der Fehlinterpretationen und Wiederholungen der wichtigsten Argumente. So sinnvoll solche Dispute sind, vor allem wenn sie die Leser in der gleichen Quelle und relativ zeitnah verfolgen können, erfüllen sie nur den Zweck des Austausches von Argumenten und Schärfung der Schlussfolgerungen, wenn sie auf einer ähnlichen Erfahrungsbasis beruhen und damit gegenseitig verständlich bleiben. Das war zu jenem Zeitpunkt (2009/2010) nicht der Fall.

> Williams, D.M., 2010. Mechanisms of wave transport of megaclasts on elevated cliff-top platforms: Examples from western Ireland relevant to the storm wave versus tsunami controversy. Irish Journal of Earth Sciences, 28, 13–23.

Williams lieferte selbst noch einmal seine Einschätzung über den wichtigsten Prozess des Transportes großer Blöcke auf hohen Kliffen. (Williams, 2010) beruht auf Hansom et al. (2008), mit dem Argument einer stetig beschleunigten Bore an strukturellen Stufen auf Kliffplattformen. Diese ist wegen seiner Negierung einfacher physikalischer Gesetze (Energieverlust durch Reibung und Energieverlust bei Bewegung gegen die Schwerkraft) nicht haltbar.

> Williams, D.M., 2011. Discussion of megaclast transport and erosion of rocky shorelines: A reply to Knight J. Irish Journal of Earth Sciences, 29, 25–26.

In einer weiteren Publikation gibt Williams (2011, S. 26) eine Einschätzung ab, welche Bedeutung Bohrmuscheln für Datierung von Grobsedimenten haben: „*...taking shell to*

*establish a chronology of events for megaclast ridges is […] scientifically unsound and the results with their wide variation of ages are best explained as a periodic sampling by extreme waves of natural shell populations from offshore environments in western Ireland".* Dieser Hinweis mahnt zur Vorsicht, muss jedoch für geschichtete feinere Sedimente im Zusammenhang mit Blockwällen nicht gelten, und gilt sicher nicht für die Alterseinstufungen, die mit Hilfe von Bohrmuscheln in Blöcken gewonnen wurden (vgl. Scheffers et al., 2010a, Erdmann et al., 2015, Erdmann et al., 2017, 2018 b).

Außerhalb der Diskussion um die Gegebenheiten in der Region Galway publizierten Paris et al. (2011) eine Art Zusammenfassung zum aktuellen Sachstand von Blockbewegung an Kliffen, jedoch, wie sie schreiben (S. 2: *„it is a focused rather than an exhaustive review…")* also selektiv und mit einigen Tatsachenfeststellungen, welche durch Naturbelege (noch) nicht gesichert sind, beispielsweise:

S. 6:" …fundamental difference between tsunamis and storms, the first do not form ridges and boulder beaches… (ridges and boulder beaches) need repeated reworking by waves and not a single impact of a tsunami wave."
"When the platform is bounded by a cliff, the largest boulders are concentrated at the cliff foot which acts as a sediment trap" Dies gilt sicher nicht für den Raum Galway.
"…cliff top boulders [...] boulder ridges located no more than 120 meters inland from the cliff..." Im Raum Galway reichen Boulder Ridges bis 300 m landein, zudem noch in >15 m MHW.

S. 7:" …The organization of coarse clasts into supra-tidal ridges requires repeated reworking by waves rather than the single impact of a tsunami wave…"

S. 8: "The spatial scale of existing studies is typically limited to one location… There is a need to examine contemporary boulder morphodynamics at multiple sites…"
Dies ist bedeutsam, da der Vergleich innerhalb eines größeren Radius, in verschiedenen Relieftypen und Expositionen und möglichst weltweit sein sollte und dadurch eine der wichtigsten Möglichkeiten für Schlussfolgerungen ist.

Hierzu lässt sich eine interessante Publikation von Goto et al. (2010) anführen: Die Autoren konnten in einem Gebiet mit häufigen starken Tsunamis und tropischen Zyklonen (Taifunen) im Süden Japans Blöcke des großen Meiwa-Tsunami von 1771 deutlich von Blockverlagerung durch Taifune unterscheiden. Letztere sind nicht nur kleiner, sondern auch auf den Raum maximal 300 m von der Riffkante beschränkt.

Einige hundert schwere Stürme seit dem Meiwa-Tsunami haben dessen Blöcke nicht bewegt.

## 2.4 Verteidigung der storm-only-Hypothese

Eine ausführliche und mit vielen Abbildungen versehene Publikation begründete einen neuen Abschnitt in der Forschungsgeschichte der Aran-Inseln:

> Cox, R., Zentner, D. B., Kirchner, B. J., und Cook, M.S. (2012): Boulder Ridges on the Aran Islands (Ireland): Recent Movements Caused by Storm Waves, Not Tsunamis. Journal of Geology 120: 249–272.

Es folgen einige Zitate, welche den (deduktiven) Ansatz deutlich erkennen lassen:

S. 249/250: „No tsunamis have affected this region in recent centuries, so if these deposits are forming or migrating at the present time, they must be storm activated."

"…shells of Hiatella arctica (subtidal rock-boring bivalves preserved in life position within ridge boulders) yield radiocarbon ages from ≈ 200 AD to modern (post-1950 AD)."

"…there is abundant evidence for ridge activity since the 1839 mapping, and as there have been no tsunamis in the northeastern Atlantic during that time period, we conclude that the Aran Islands boulder ridges are built and moved by storm waves."

"These observations indicate that the ridges migrate progressively landward. Mass was also added to the deposits […] boulders are […] in trans-ridge movement."

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."

"[...] if they are active in recent decades and centuries, then – no matter how long their history and no matter whether tsunamis of the past have contributed to them – storms must build and move them."

p. 251: "[…] if data from marine shells are from ages before 18$^{th}$ century, some workers (Kelletat 2008, Scheffers et al., 2009, 2010 a) argue that the boulder ridges must be uniformly old".

p. 261: "The new radiocarbon data thus confirm that the ridges are gaining mass at the present day".

"The tendency, therefore, for the boulder piles to get higher and wider over time as their leading edges advance landward".

Weder die Beobachtungen noch die Schlussfolgerungen können bestätigt werden: Wie in Erdmann et al. (2015, S. 102 und Fig. 5.1) dargelegt, verlieren die *ridges* seit langer Zeit an Masse, ihr seewärtiges Profil wird zurückgeschnitten und konkav umgestaltet. Die Aktivierung bezieht sich ganz überwiegend auf die Bewegung existierender Fragmente in den Blockwällen, von denen viele meerwärts verschwinden, und die Menge der bewegten Teile steht in keinem Verhältnis zum relativen Mangel oder gar dem Fehlen von Ausbruchspuren am Kliff und auf der Kliffplattform oder dem von den Autoren selbst angenommen starken Kliffrückgang. Eine ständige Ernährung und ein Wachsen der *boulder ridges* sowie ihre landwärtige Wanderung können durch zahlreiche Belege und Datierungen ausgeschlossen werden. Außerdem sagt eine gegenwärtige Aktivierung der Blockwälle nichts darüber aus, was sie in 6.000 Jahren geschaffen oder verändert hat.

p. 269: "[…] tsunamis may be generate block movements on western European cliff tops in earlier times […] but tsunamis alone cannot be the cause of these ridges".

Niemand hat bisher Tsunamis allein für die Blockwälle verantwortlich gemacht. Stürme mögen heute an den r*idges* etwas verändern, aber Tsunamis in älterer Zeit sind ebenfalls bedeutsam für ihre Bildung gewesen. In Erdmann et al. (2017) finden sich über die Blockargumente hinaus geomorphologische und sedimentologische Belege für Tsunamiwirkung bis mindestens 20 km in die Galway Bay hinein.

Wie weit sich Hypothesen, Theorien und Modelle mittlerweile von der Realität in der Natur entfernt haben, belegt die Publikation von Weiß (2012) über *"The mystery of boulders moved by tsunamis and storms"* und die darauf aufbauende von Weiß & Diplas (2015). Die Autoren diskutierten die Bewegungsprozesse eines kugelförmigen Blocks, und die Schlussfolgerungen wurden umgehend von Terry et al. (2013) aufgegriffen. Weiß & Diplas (2015) schließen, dass *„sliding"* der wichtigste Bewegungsprozess ist und infolgedessen Reibung die wichtigste physikalische Größe. Wenn die Rauigkeit größer sei als 30% des Blockradius (oder 15% des Blockdurchmessers) kann ein Block

nicht mehr transportiert werden. Das bedeutet, dass ein runder Block mit 2 m Durchmesser (einem Volumen von ca. 4,2 m³ und einer Masse von ca. 10 t bei 0,3 m Rauigkeit des Untergrundes) unbewegt bleiben muss und ein solcher mit 1 m Durchmesser (= ca. 0,52 m³ Volumen und 1,3 t Masse) bei 15 cm Rauigkeit/Mikrorelief ebenfalls. Für Kalksteinküsten wie in der Galway Bay und auf den Aran-Inseln bedeutet dies, dass solche kugelförmigen Blöcke niemals über die Zone der supralitoralen Bioerosion mit ihren *rock pools* landwärts gelangen können, denn diese sind in der Regel tiefer als 0,3 m und nahezu immer tiefer als 0,15 m. In Konsequenz müssten sich diese Blöcke in *rock pools* als Sedimentfallen ansammeln. In Wirklichkeit aber sind die Gürtel mit *rock pools* vollständig sedimentfrei, und weitaus größere Blöcke finden sich landwärts davon.

Auf dem Kalkgestein des Untersuchungsgebiets sind die Bewegungsspuren nahezu aller schweren Fragmente durch linienhafte Kratzer eingraviert und für mindestens 2-3 Jahre konserviert. Ihre Muster (Abb. 12) erlauben eine Differenzierung verschiedener Bewegungsprozesse wie Schleifen/Schieben (*sliding*), Rollen (*rotation*), oder Springen (*saltation*). Die Rauigkeit des Untergrundes spielt für größere Fragmente überhaupt keine Rolle, sondern allenfalls der Abstand der kleinen Erhebungen im Mikrorelief, den sie aufgrund ihres großen Durchmessers berühren (können), während Vertiefungen beliebig dimensioniert und geformt sein könnten ohne die Dislokation selbst sehr schwerer Blöcke zu behindern oder zu verhindern.

Abb. 12: Kratzspuren (*striations, striae*) als Dokumente für Blockbewegung auf Kalkstein. Sie bleiben einige Jahre sichtbar und können sogar Hinweise auf den Bewegungsmechanismus (*sliding, rotation, saltation*) geben.

Weitere Arbeitsschritte der Arbeitsgruppe um Rónadh Cox wurden auf internationalen Meetings präsentiert. Hier wird ausschließlich von „*moved boulders*" gesprochen und Stürme als alleiniges Wirkungs-Agens verteidigt, obwohl ein Transport sehr großer Blöcke gegen die Schwerkraft – unbestreitbares Erfordernis für landwärtige Blockansammlungen – nicht belegt wird:

> Cox, R., Watkins, O., Tellez, K., Stamp, L.K., Irvine, S.W., Castro, J.A., Atwood, C.E., and Adamson, K.P. (2014): Measuring the Effects of Winter Storms (2013-2014) on Boulder and Megagravel Accumulations in Western Ireland. – Presentation at 2014 Geological Society of America Annual Meeting, Vancouver, BC, Canada.
>
> Cox, R., and Watkins, O. (2015): Storm-Wave Movement of Megagravel in Western Ireland: Implications for Understanding Both Storms and Tsunamis. - Geological Society of America - 2015 Annual Meeting in Baltimore, Maryland, USA, Paper No. 197-13.

Diese Arbeiten bemühen sich, die *storm-only-These* zu stützen (Cox et al., 2014, 2015, 2016 a, b). Auf bereits erschienen Publikationen (z.B. Erdmann et al., 2015) wird nicht Bezug genommen. Argumentiert wird ausschließlich mit Hilfe von Fotovergleichen unbestritten frisch bewegter Blöcke ohne Erläuterung, woher und wie die größeren, höheren und weiter landeinwärts liegenden Blöcke gegen die Schwerkraft bewegt

wurden, und wie weitere Formen (z.B. rhythmische Querwälle und zungenartige *washover*-Loben) in die *storm-only-Hypothese* eingebaut werden können. Es ist davon auszugehen, dass diese geomorphologischen Hinweise auf extrem starke Strömungen in Höhen bis über 30 m von der Arbeitsgruppe entweder nicht gesehen wurden oder sie sollen bewusst aus der Diskussion herausgehalten werden, weil sie nicht in eine *storm-only*-Vorstellung hineinpassen. Die Arbeiten werden von Pressemitteilungen und Interviews begleitet, in welchen behauptet wird, nur ihre Arbeitsgruppen verfügen über vergleichende (vorher - nachher) Fotodokumente, v.a. in Bezug auf Blockverlagerung durch die außerordentlichen Winterstürme 2013/14 in der Region Galway. Auch dieses ist nicht korrekt (siehe u.a. Erdmann et al., 2015).

In Erdmann et al. (2015) finden sich ausführliche Dokumentationen von Blockverlagerungen durch die Hurrikan-Stürme der Saison 2013/14 in einer erheblich größeren Region als sie von Cox et al. untersucht wurden. Zudem werden in Erdmann et al. (2015) die quantitativen Befunde mit denjenigen in anderen Regionen der Erde verglichen, was allein eine Bewertung ihrer Besonderheit erlaubt.

# 3 Ausgangssituation für die eigenen Arbeiten, Ziele und Methoden

Die Ziele dieser Arbeit haben sich aus der seit 2004 (Williams & Hall 2004) andauernden und seit 2012 (Cox et al., 2012) verstärkten Diskussion um die Genese und die Zeitstellung der Blockablagerungen auf den Aran-Inseln entwickelt. Die Arbeitsgruppe Scheffers/Kelletat hatte in einem DFG-Projekt (Ke 190/25-1) zur

„Paläo-Tempestologie des jüngeren Holozäns im Westen Großbritanniens (Irland und Äußere Hebriden, Orkney-Inseln und Shetland–Inseln Schottlands) gestützt auf geomorphologisch-pedologische und archäologische Indizien“

zwischen 2006 und 2008 entlang der am stärksten exponierten Küsten Europas vor allem den Sedimentcharakter an geschützten Küstenabschnitten mit flachem *fore-shore* im Fokus gehabt und in allen Arbeitsgebieten alte, jetzt inaktive Blockablagerungen außerhalb der Reichweite gegenwärtiger Sturmbrandung nachgewiesen (Scheffers et al., 2009, 2010 a, b). Diese Befunde standen und stehen im starken Gegensatz zu der *storm-only*-Hypothese, wie sie seit 2004 (Williams, Williams & Hall) bis heute vehement vor allem von der Arbeitsgruppe um R. Cox publiziert (Cox et al., 2012, 2014, 2015, 2016 a, b) wird. Die Autoren arbeiten vor allem mit quantitativen Daten zu Blockgrößen und dem Vergleich von Bildmaterial von Blockpositionen über mehrere Jahre. Publiziert sind bisher nur Dokumente von den am stärksten exponierten SSW-orientierten Kliff-Küsten der Aran-Inseln, vor allem von Inishmore und Inishmaan. Berücksichtigt wurden (und werden offenbar) nur Bewegungen von frischen groben Fragmenten, wobei nicht immer deutlich ist, wie deren Masse, Transportwege und Transportmechanismen ermittelt wurden. Die Existenz unbewegt gebliebener Blöcke und deren Ablagerungsmechanismen werden nicht geprüft, und vor allem wenig exponierte Küstenabschnitte, solche vom nahen Festland innerhalb der Galway Bay oder feinere Sedimente und deren Beziehung zu den großen Blöcken werden nicht thematisiert. Damit ist nur ein sehr kleiner räumlicher und thematischer Ausschnitt aus den zur Verfügung stehenden Naturdokumenten der Region Galway Bay und Aran-Inseln für Schlussfolgerungen genutzt worden. Einige Prozesse (z.B. Tsunamis) werden von vornherein ausgeschlossen, andere werden als sicher dargestellt (z.B. die landwärtige ständige Verschiebung von Blockwällen bei Winterstürmen), doch wurden dafür positive Indizien nicht beigebracht.

Da tiefere Geoarchive mit Feinmaterial auf den Aran-Inseln und in der äußeren Hälfte der Galway Bay fehlen, aus denen eine detaillierte Prozessgeschichte an wenigen Stellen hätte erarbeitet und dann an der gesamten Landschaft überprüften werden können, war ein strikt induktiver Weg einer Aufnahme aller Formen und Ablagerungen notwendig, die auch nur im Entferntesten Hinweise auf marine/litorale Vorgänge geben könnten. Für eine möglichst flächendeckende Bearbeitung des Arbeitsgebietes standen dafür Satellitenbilder in ausreichender Qualität von Google Earth (Auflösung ca. 2 m für ca. 70% der Arbeitsgebiete) und eine Helikopter-Befliegung des *National Coastline Survey* Irlands in Infrarot-Falschfarben (1999/2000) für alle Küstenabschnitte im Maßstab von ca. 1:4.000 und einer Auflösung von < 1 m zur Verfügung. Dieses war insofern nützlich, weil nur für die Aran-Inseln eine topographische Karte 1:25.000 erschienen ist, für die Küsten der Galway Bucht lediglich 1:50.000 (*Ordnance Survey of Ireland*).

Die Sammlung von Fakten aus der Landschaft in allen Expositionen und Reliefeinheiten resultiert zwangsläufig in einer großen Fülle von Eindrücken und Dokumenten. Sie impliziert aber gleichzeitig Vorsicht vor zu sehr begrenzten oder einseitigen Hypothesen: was für einen sehr exponierten Kliff-Abschnitt als wichtiger Prozess angenommen wird (z.B. extreme Sturmwellenwirkung oder Tsunamis) muss modifiziert auch in nahegelegenen geschützten Bereichen gewirkt haben, auch wenn dort Spuren gelegentlich schwer zu finden sind. Ein über lange Zeit wirksamer massiver Küstenrückgang würde die Bewahrung alter Formen und Ablagerungen erschweren oder unmöglich machen. Altersdatierungen werden allerdings in einer recht breiten räumlichen Verteilung benötigt, um die vielen erkennbaren Phänomene relativer Altersunterschiede aus dem marinen, litoralen und terrestrischen Bereich nach ihrer wirklichen Größenordnung beurteilen zu können. Das gilt vor allem für Oberflächen auf Festgestein und Blockwerk in Kalklandschaften. Dabei war hilfreich, dass mit dem Eisfreiwerden vor 17.000 bis 16.000 Jahren ein maximaler Rahmen gegeben ist und durch die gut belegte Meeresspiegelkurve diese Zeitspanne für marin-litorale Hinweise noch einmal unterteilt ist. Je stärker allerdings Prozesse an der Küste auftreten, umso weiträumiger ist ihre laterale Prägung. Im Arbeitsgebiet muss selbst im geneigten Felsgebiet mit vielen 100 m Reichweite landwärts mit starken Stürmen gerechnet werden.

Hauptziel der Forschungen im Westen Irlands war und ist die Klärung der wichtigsten und prägenden Prozessabläufe für die Küstengestaltung seit einem bereits hohen Meeresspiegelstand, unter besonderer Berücksichtigung der außerordentlichen

Blockvorkommen und in einem Zeitrahmen von mindestens 7.000, vielleicht sogar 9.000 Jahren zurück. Dabei ist kein möglicher Prozess auszuschließen (Sturmwellen, *Freak Waves*, Tsunamis, *Infragravity Waves),* doch ist es bisher nicht möglich gewesen, die Beteiligung lange zurück liegender *Freak Waves* und *Infragravity Waves* an der Küstenformung zu identifizieren und zu quantifizieren.

Die Kartierung und damit Erfassung des räumlichen Bezugs von Formen und Ablagerungen einschließlich der Erhebung von Transportwegen landwärts und gegen die Schwerkraft, Bestimmung von Blockvolumen und –massen, Organisationsformen resp. Lage von Blöcken (z.B. *imbrication* oder rhythmische Lagerungen) und alle Indizien für relative Altersunterschiede (u.a. mikromorphologische Merkmale wie Verkarstungsintensitäten im terrestrischen Milieu und Bioerosionsintensitäten im litoralen Umfeld) stehen im Mittelpunkt. Feinere Sedimente (meist Grobsand mit *granules* und Bruchschill, Abb. 13) wurden nach Korngrößen, Gehalt an organischem Kohlenstoff und anderen Elementen sowie dem Formcharakter der Einzelkörner analysiert. Alle Proben wurden zudem auf besondere Merkmale mikroskopisch untersucht, doch erbrachten diese Analysen wegen des groben Korngefüges weniger Erkenntnisse als die Beurteilung der Sedimente am Aufschluss selbst, denn Leithorizonte, Verknüpfung mit Torfen und andere Hinweise sind im Arbeitsgebiet nicht entwickelt. In geschichteten Sedimenten, aber auch in chaotischen wurden möglichst jeweils mehrere Horizonte mit Hilfe von Fragmenten von Mollusken datiert, das Verlagerungsalter von Blöcken ausschließlich durch Altersbestimmung der Bohrmuschel *Hiatella arctica.* Die Altersbestimmung erfolgte durch Beta Analytic (Florida, USA) mit dem AMS-Verfahren unter Anwendung des regionalen MRE von Omey Island, einer kleinen Insel 45 km nördlich der Galway Bucht. (-142 +/-16 Jahre, Ascough et al., 2006, 2009),

Abb. 13: Feinere Sedimente (Schotter bis Schluffe) sind oft in terrassenartigen Resten landwärts der groben Blockwälle anzutreffen (a und b), gelegentlich auch mehr als 20 m ü. MHW auf Kliffplattformen (c).

# 4 Abgeschlossene Publikationen

Die folgende kurze Übersicht beschreibt die Abfolge der wissenschaftlichen Arbeiten im Promotionsprojekt aufgrund der in den einzelnen Feldarbeiten jeweils erreichten Erkenntnisse bzw. neuen Fragen. Die Präsentation der Publikationen als Kopien der Originale wird begleitet von einer kurzen Charakterisierung, einer Zusammenfassung und einem abschließenden Fazit.
Der Titel des bewilligten DFG-Projektes (Ke 190/28-1) lautete:

> „Blockwälle und Overwash-Sedimente in der Galway Bay West-Irlands. Genese und Chronologie extremer Wellenereignisse im Jüngeren Holozän".

Diesem Antrag ging ein DGF-Projekt „Paläo-Tempestologie des Jüngeren Holozäns im Westen Großbritanniens (Irland und Äußere Hebriden, Orkneys und Shetland-Inseln Schottlands) gestützt auf geomorphologisch-pedologisch und archäologische Indizien" (KE 190/25-1) voraus, bearbeitet von Kelletat und Scheffers 2006-2008. Die Ergebnisse dieser Arbeiten sind publiziert (vgl. Scheffers, 2008, Scheffers et al. 2009, 2010 a, 2010 b) und bilden eine bedeutende Arbeitsgrundlage meines Promotionsvorhabens.

Im Juni 2014 erfolgte als Initial-Projekt eine *near-time-inspection* der geomorphologischen und sedimentologischen Auswirkungen von sechs außerordentlichen Sturmereignissen. Drei Sturmereignisse wurden mit Hurrikanstärke 3 registriert, weitere drei mit Hurrikanstärke 4, den stärksten der letzten 60 Jahre (und wahrscheinlich der letzten Jahrhunderte) zwischen Ende Dezember 2013 und Mitte Februar 2014 an der zentralen Westküste Irlands (vor allem Galway Bay und Aran Islands). Zum Vergleich konnten die Dokumente des oben erwähnten Projektes von Scheffers und Kelletat herangezogen werden. Im Sommer 2015 wurde der gestellte DFG-Antrag bewilligt, im September 2015 und 2016 erfolgten weitere Feldarbeiten.

Die Ergebnisse der *near time inspection* wurden, eingebettet in den Forschungsstand von 2014 und mit breiter Dokumentation aller geomorphologischen Einheiten des weiteren Arbeitsgebietes (142 Abbildungen und 4 Tabellen) in der Springer-Serie „Springer Briefs in Geography" (*peer-reviewed*) publiziert als

> (1.) Erdmann, W.; Kelletat, D.; Scheffers, A., und Haslett, S.K., 2015. Origin and Formation of Coastal Boulder Deposits in Galway Bay and on the Aran Islands, Western Ireland. Springer Briefs in Geography, Dordrecht, The Netherlands, 125 p.

Bei der Feldkampagne 2015 wurde erstmals der Abschnitt entlang der SE-Küste innerhalb der Galway Bay vollständig kartiert und eine erste Chronologie der Blockablagerungen sowie der punktförmig verteilten feineren Küstensedimente mit AMS-Altern anhand von Mollusken erarbeitet. Dabei konnte gezeigt werden, dass in einem etwa 100 m breiten Saum grobsandige und Blocksedimente in verschiedenen Archiven das gesamte Jüngere Holzän repräsentieren. Für Sturmablagerungen bislang noch nie beschriebene *washover*-Formen nährten Zweifel an einer *storm-only*-Hypothese für alle Blocklagerungen der Region. Die Ergebnisse dieses Arbeitsabschnittes sind ebenfalls publiziert:

> (2.) Erdmann, W.; Kelletat, D., und Kuckuck, M. (2017): Boulder ridges and washover features in Galway Bay, western Ireland. Journal of Coastal Research, 33(5), 997 – 1021.

Durch diese Arbeiten konnte nachgewiesen werden, dass die Region Galway mit den Aran-Inseln aufgrund der ausgedehnten Blockablagerungen, der Größe und Masse einzelner Blöcke, der landwärtigen Position von Blockwällen und der Bewegung sehr großer Blöcke signifikant gegen die Schwerkraft eine Sonderstellung in Europa einnimmt. Darüber hinaus kann dieses Gebiet als hervorragende natürliche Testregion für Forschungen zum Blocktransport durch mögliche marine und litorale Prozesse dienen. Quantitative Daten und Felddokumente zur Mobilität und Immobilität von Blöcken durch die außerordentlich starken Stürme der Wintersaison 2013/14 wurden daher als eine gesonderte Publikation in die allgemeine Diskussion zum Blocktransport an Küsten eingebracht:

> (3.) Erdmann, W.: Kelletat, D., und Scheffers, A. (2018): Boulder transport by storms – Extreme-waves in the coastal zone of the Irish west coast. Marine Geology, 399: 1-13

Zur Ergänzung der Entwicklungsgeschichte von Küstenablagerungen in den Arbeitsgebieten und der Vervollständigung einer Chronologie der Ereignisse in sehr groben und feineren Geoarchiven wurden im September 2016 auf den Aran-Inseln Inishmore und Inishmaan Kartierungen und Beprobungen durchgeführt, um für diesen Abschnitt eine ähnliche Datengrundlage wie für die Galway Bay zu erhalten und einen Vergleich beider unterschiedlich exponierter Gebiete zu ermöglichen. Die Altersdatierungen für diesen Zeitabschnitt wurden durch die Universität zu Köln und eigene Mittel ermöglicht, sie wurden ebenfalls publiziert:

> (4.) Erdmann, W.; Scheffers, A. M. und Kelletat, D. H. (2018): Holocene Coastal Sedimentation in a Rocky Environment: Geomorphological Evidence from the

Aran Islands and Galway Bay (Western Ireland). Journal of Coastal research. Volume 34, Issue 4: pp. 772 – 792.

## 4.1 Potential des Arbeitsgebietes im weltweiten Vergleich und *near-time-inspection* von Extremstürmen der Saison 2013/14 (Erdmann et al., 2015)

Ins Deutsche übertragene Abstracts sind jedem Teil dieser kumulativen Dissertation vorangestellt. Bei Erdmann et al. (2015) handelt es sich um fünf Abstracts, da die Publikation ebenfalls als E-Book erschien und fünf einzelne Abschnitte jeweils ein Abstract und ein Literaturverzeichnis beinhalten. Für diese Publikation wurde eine gemeinsame Zusammenfassung für alle fünf Kapitel erstellt.

Erdmann, W.; Kelletat, D.; Scheffers, A., und Haslett, S.K., 2015. Origin and Formation of Coastal Boulder Deposits in Galway Bay and on the Aran Islands, Western Ireland. Springer Briefs in Geography, Dordrecht, The Netherlands, 125 p.

**Zusammenfassung**

Im Westen Irlands liegt eine der am stärksten exponierten Küste der Erde. Ihre ausgedehnten Blockablagerungen haben Wissenschaftler zu Überlegungen über deren Transportbedingungen veranlasst, i.w. zu der Frage, ob Sturmwellen dazu ausreichen oder Tsunamis am Transport beteiligt gewesen sind. Die Einführung stellt zunächst den gegenwärtigen Forschungsstand dar, gestützt auf die Geschichte der Stürme in der Region und in besonderer Weise auf die Transportenergie der außerordentlich starken Stürme (vergleichbar mit Hurrikanen) in der Wintersaison 2013/14. Als Beurteilungskriterien für deren Stärke und Wirkung in Irland werden Vergleiche mit anderen Küstenregionen der Erde angestellt, von denen ebenfalls *near-time-inspections* extremer Sturmwirkung vorliegen. Bei diesen Vergleichen muss u.a. geklärt werden, ob (und wie) im offenen Ozean gemessene Wellenhöhen ihre Energie an der Küste entfalten, und wie Transportprozesse an vertikalen Kliffküsten tatsächlich ablaufen. Da alle Ablagerungen innerhalb des Jüngeren Holozäns erfolgten, muss die Geschichte der Meeresspiegelschwankungen für die letzten 6.000 Jahre mit einbezogen werden.

Im engeren Untersuchungsgebiet der südöstlichen Galway Bay und der Aran-Inseln treten strukturell gestufte und vertikale Kliffe bis weit über 30 m Höhe auf. An diesen Abschnitten wurden Felduntersuchungen zu Blockbewegungen nach den außerordentlich starken Winterstürmen 2013/14 durchgeführt und dabei quantitative Daten zur Lokalität, Größe, horizontaler und vertikaler Bewegung und dem

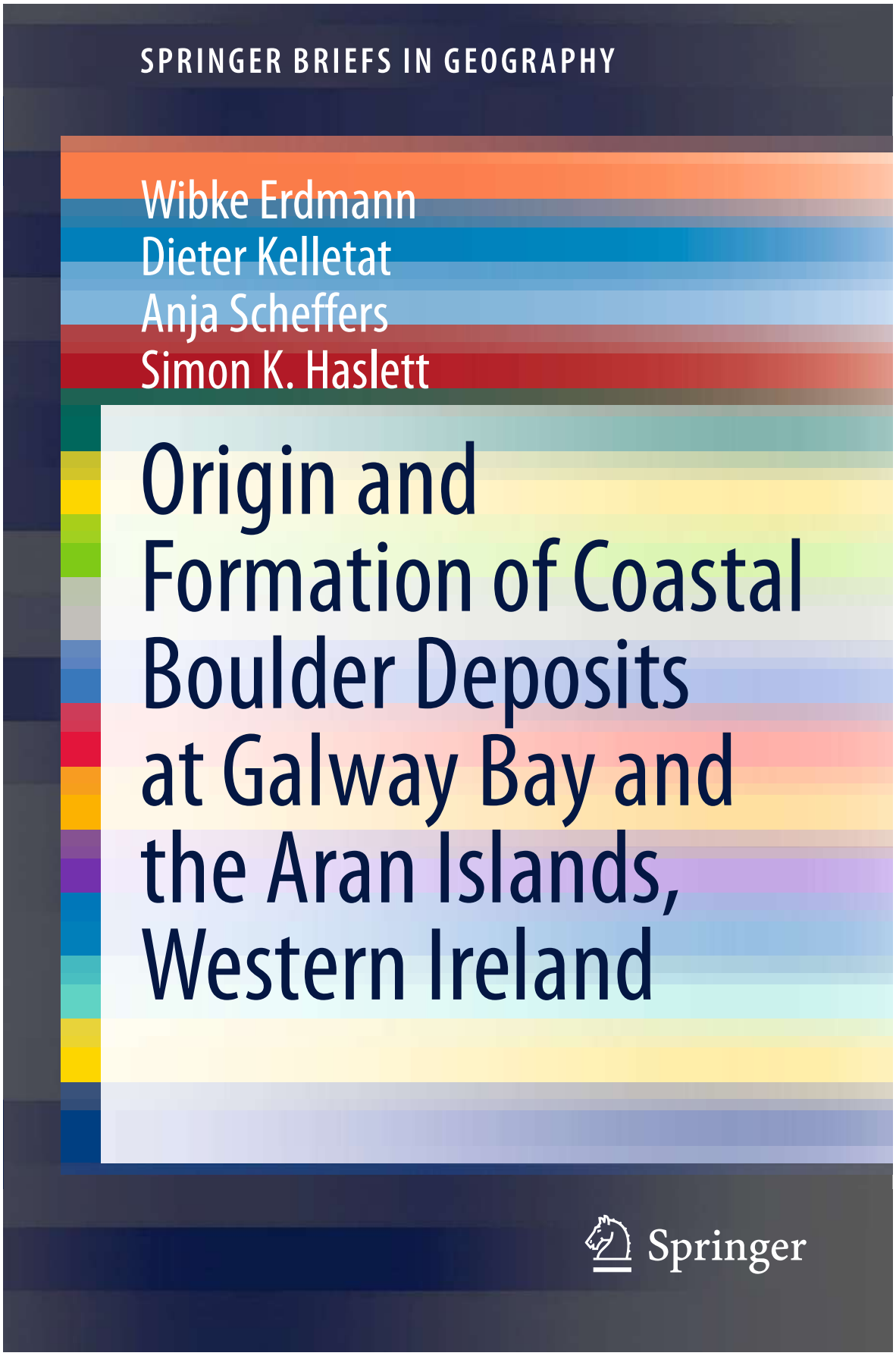
Ursprungsgebiet der Blöcke erhoben, gemeinsam mit Dokumenten über einzelne Transportprozesse, welche durch Kratzspuren auf den Felsplattformen und an den Blöcken selbst abgelesen werden können. Die Ergebnisse werden mit ähnlichen Daten von Blöcken verglichen, welche bei diesen jungen Stürmen unbewegt blieben. Besondere Aufmerksamkeit wird der Morphologie der Blockablagerungen und ihrem inneren Gefüge gewidmet, vor allem im Vergleich von stark und wenig exponierten Lokalitäten und solchen mit unterschiedlicher Wassertiefe im *foreshore*-Bereich. Zudem wurden erste Proben für Altersdatierungen aus allen Sedimenteinheiten genommen. Diese Studien sollen dazu beitragen, die Genese und die Geschichte der weit verbreiteten Blockwälle zu beleuchten. Als Grundlage für spätere Schlussfolgerungen werden daher zahlreiche Feldbelege in Form von Fotos und Graphiken vorgelegt.

Neben Größe, Masse, Gestalt, Höhenlage, Exposition und Vergesellschaftung sehr großer Blöcke wurden auch Spuren von ihren Bewegungsprozessen aufgenommen, welche als *striations* und *impact marks* auf Felsplattformen oder den Blöcken selbst von den Extremstürmen 2013/14 erhalten sind. Der Vergleich frisch bewegter und unbewegter Blöcke und deren räumliche Beziehung erlaubt die Abgrenzung eines Bereichs sicher sturmbedingter Verlagerung von höheren und weiter landwärts gelegenen Abschnitten, die gegenwärtig von Hurrikan-Sturmwellen nicht erreicht werden, aber dennoch ausgedehnte sehr grobe Blockablagerungen aufweisen, welche bei einem deutlich tieferen Meeresspiegel an Land gebracht wurden. Um zu einem objektiven Ergebnis zu gelangen, werden diese Erkenntnisse mit Geländedaten von anderen exponierten Küstenbereichen der Erde verglichen.

Die Organisationsformen von Ablagerungen großer Blöcke auf den Aran-Inseln und in der Bucht von Galway sind sehr verschieden: Einzelblöcke können flach oder steil an strukturellen Felsstufen der oberen Kliffplattform lehnen oder dachziegelartig an allen Seiten von Hindernissen, oder auch sogenannten *imbrication trains* bilden, selbst wenn die einzelnen plattigen Blöcke mehrere Zehner Tonnen wiegen. Einige Blöcke entstammen der oberen Kliffkante, andere von den Strukturstufen oberhalb der Kliffe, manchmal auch aus der Gezeitenzone oder aus dem Supratidal am Fuß der Kliffe. Die allermeisten frisch bewegten Blöcke finden sich allerdings an den seeseitigen Böschungen alter Blockwälle, wo sie nicht neu angeliefert, sondern lediglich aktiviert wurden. Die auffälligste Form von Blockansammlungen sind mehrere Kilometer lange und etwa 30-80 m breite Wälle mit einer Mächtigkeit von einigen Metern. Ihre Querprofile sind asymmetrisch, mit den steilen Hängen zur Seeseite. Landwärts und

abgesetzt von ihnen können noch niedrige und schmale Blockwälle liegen. Auf steilen Küstenvorsprüngen bis über 25 m MHW können mehrere kleine Blockwälle und Blockgruppen ausgebildet sein, welche lange nicht mehr aktiviert wurden. Weitere und so bislang nicht beschriebene Erscheinungen sind auf Wallrücken balancierende Blöcke bis mindestens 10 t, noch 15 m oder mehr über dem Hochwasserniveau. Zudem treten Rippelmuster zwei unterschiedlicher Größen auf: die einen kleindimensioniert parallel zum Wallrücken auf der landseitigen Böschung, die anderen auf Blockwallsegmenten quer zum Hauptwall. Zudem finden sich über 100 m lange, im Längs- und Querprofil konvexe Blockzungen aus mittelgroßen und meist gerundeten kleineren Blöcken, deren Gesamtmasse zwischen 10.000 und 45.000 t beträgt.

Aufgrund der Beobachtungen und ausführlichen Dokumentation der Feldbefunde werden die Organisationsformen der Blockgruppen diskutiert. Für lange *imbrication trains* werden *Van Karman-Vortices* angenommen, während balancierende Blöcke auf den Wallrücken durch Unterminierung der seewärtigen Böschung bei starken Stürmen vorrübergehend in diese delikate Lage geraten und danach zur Leeseite – also in ihre Herkunftsrichtung – abwärts gleiten oder gespült werden. Die Asymmetrie der Blockwallquerschnitte deutet auf langanhaltende erosive und versteilende Prozesse durch Sturmwellen und -boren hin. Durch diesen Prozess werden die alten, offensichtlich mit erheblich größeren Energien als von rezenten Extremstürmen gelieferten und geformten Blockwälle allmählich aufgezehrt. Relative Altersabschätzungen konnten aufgrund des Flechtenbewuchses und des Verwitterungsgrades – insbesondere der Verkarstungsintensität des Karbonkalks – gewonnen werden, während durch 23 AMS-Altersdatierungen aus den Blockwällen belegt wird, dass diese mehrere Tausend Jahre alt sein können. Die Ausbildung der Blockwälle entlang der SE-Küste der Galway Bay wird vor allem unter Berücksichtigung der relativen Schutzlage und geringen Wassertiefe beleuchtet. Die Geschwindigkeit des Kliffrückganges und insbesondere eine mögliche Verschiebung der Blockwälle landwärts sind weitere wesentliche Aspekte. In der Zusammenfassung wird der tsunamigene Ursprung der alten und massiven Blockwälle wiederum zur Diskussion gestellt.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Wibke Erdmann · Dieter Kelletat
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# Origin and Formation of Coastal Boulder Deposits at Galway Bay and the Aran Islands, Western Ireland

Springer

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

ISSN 2211-4165 ISSN 2211-4173 (electronic)
SpringerBriefs in Geography
ISBN 978-3-319-16332-1 ISBN 978-3-319-16333-8 (eBook)
DOI 10.1007/978-3-319-16333-8

Library of Congress Control Number: 2015935608

Springer Cham Heidelberg New York Dordrecht London
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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.

We thank Petra van Steenbergen and Hermine Vloemans from Springer (Dordrecht, The Netherlands) for their advice and assistance to publish this documentation in a wide format, and we are indebted to Anne Hager, Gudrun Reichert and Frank Schmidt-Kelletat for their patience and practical support during the development of this publication.

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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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_1

**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

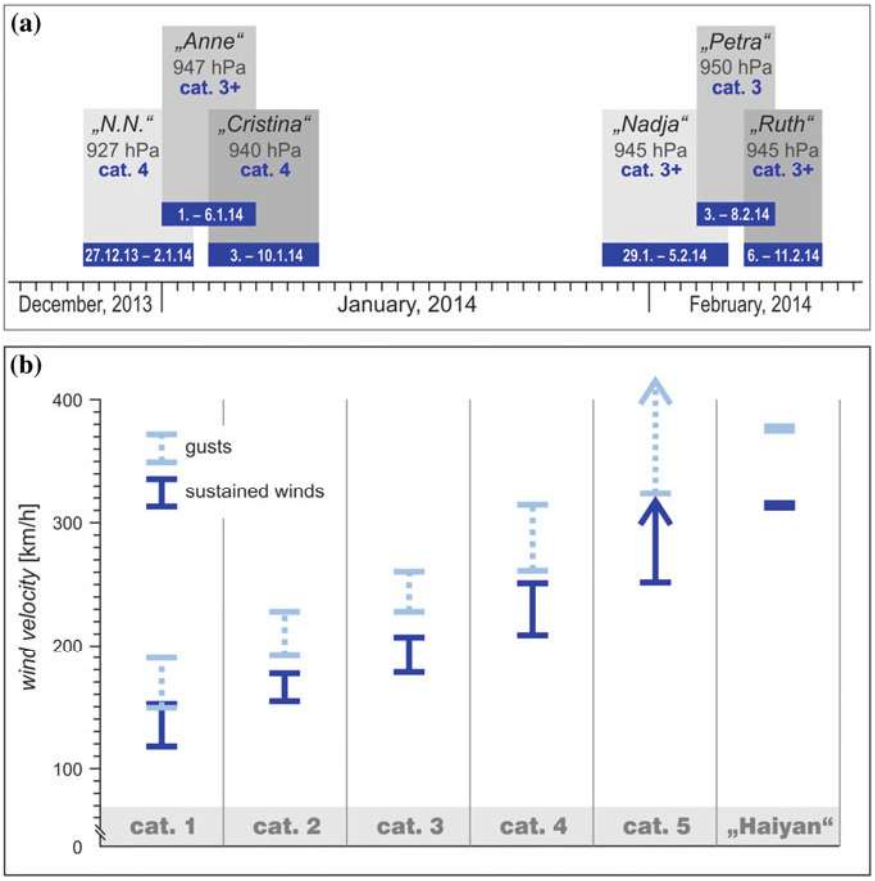


**Fig. 1.2** **a** Temporal distribution, central pressure and hurricane categories of six extreme winter storms west of Ireland in the season 2013/14. **b** Velocity of sustained winds (1 min) and gusts of hurricane categories 1–5 and super-typhoon “Haiyan” (Philippines, Nov. 2013), according to the 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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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_2

**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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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_3

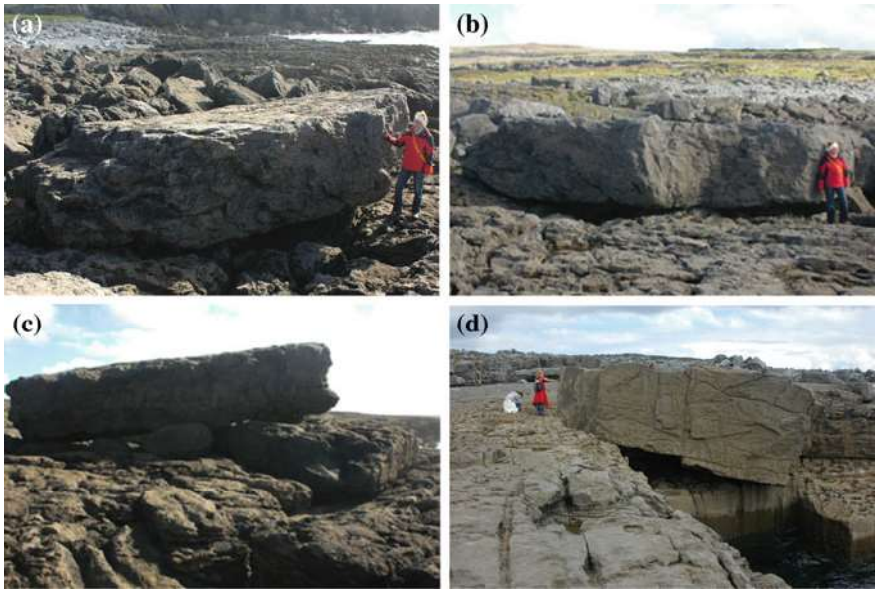


**Fig. 3.1** Very large single dislocated coastal boulders from the Galway area. **a**, **b** Galway Bay (>80 tons) same boulder. **c** Galway Bay (>50 tons). **d** Inishmore, west of wormhole (>200 tons) (*Image credit* D. Kelletat)

**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)

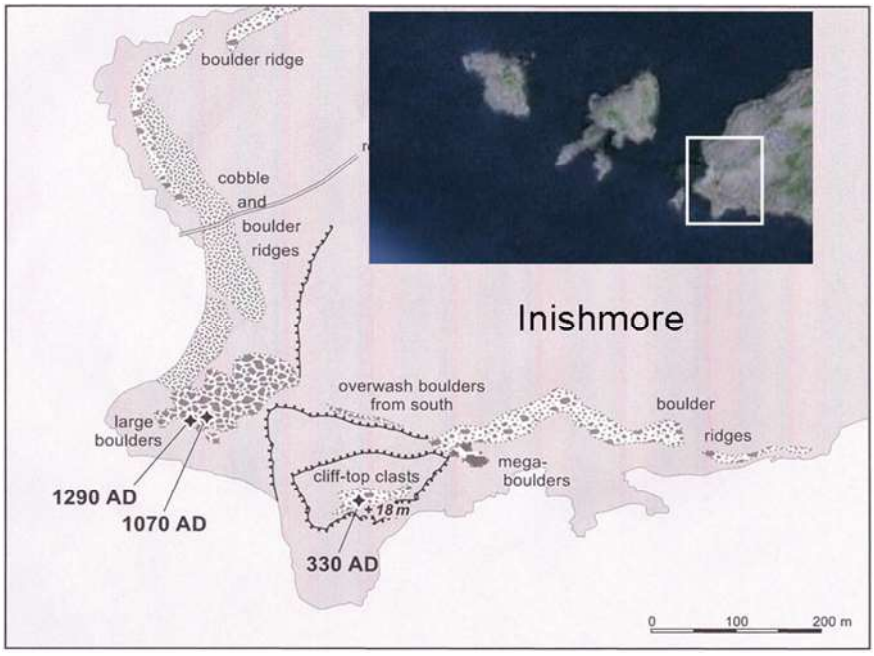


**Fig. 3.5** Scetch map (from Scheffers et al. 2010a) of boulder deposits on the western part of Inishmore Island. *Insert* Brannock Islands west of Inishmore. Water depth here is less than 10 m, partly less than 5 m

**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)

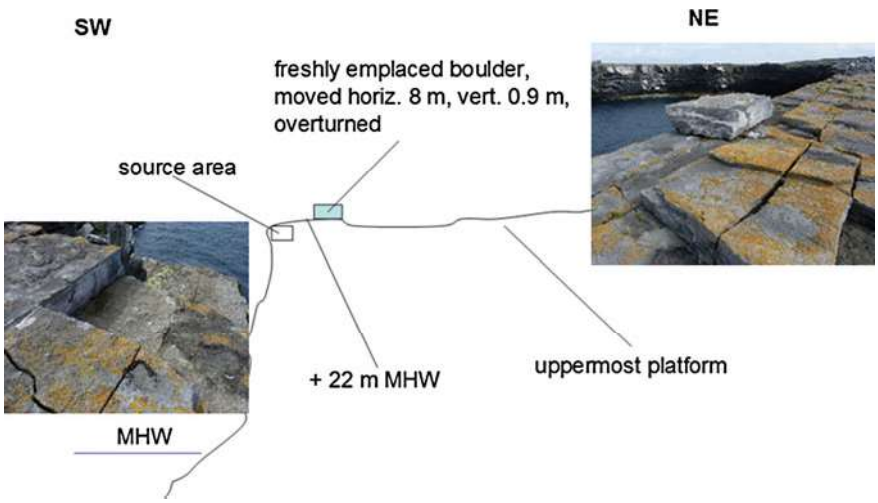


**Fig. 3.21** Scenario for a fresh boulder emplacement of 4.2 tons on the bastion of the promontory just east of Black Fort at +22 m MHW. Lichen cover documents that this cliff top has been rarely affected. The site is at 53°06′08.99″N and 09°41′04.59″W (*Image credit* D. Kelletat)

**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)

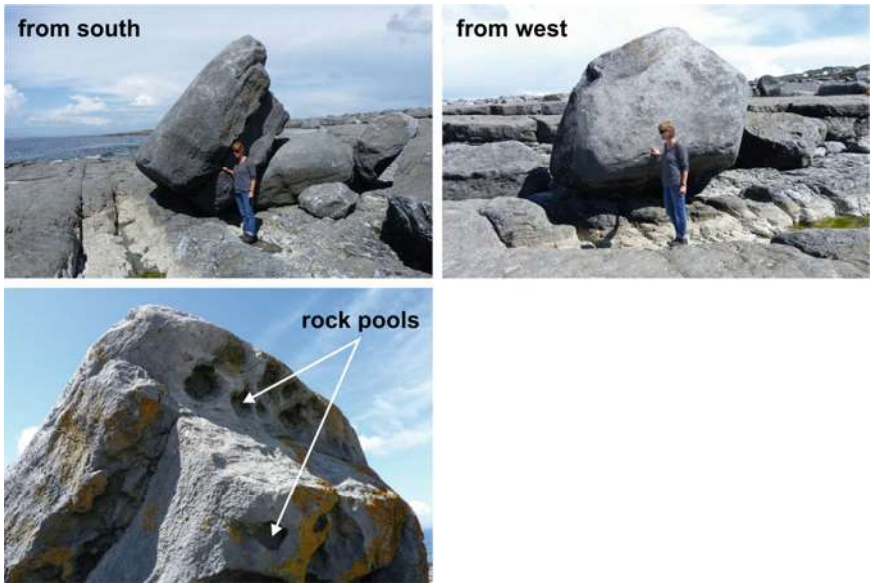


**Fig. 3.30** Largest single boulder (7.6 $m^3$ = 20 tons) in front of the seaward ridge, with rock pools from its former supra-tidal position. Light-coloured basins in the rock are freshly polished sites from strong surf action in winter 2013/14 (*Image credit* D. Kelletat)

**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)

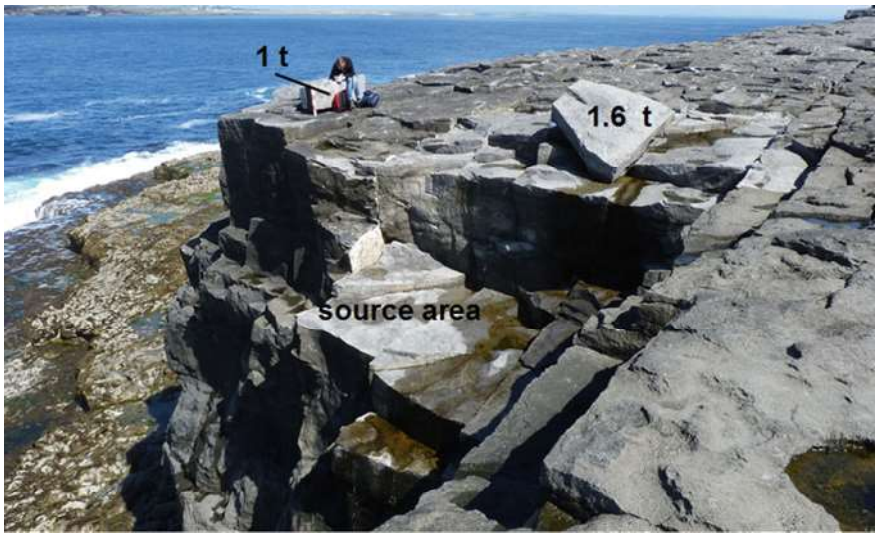


**Fig. 3.35** Inishmaan W: two fresh boulders at +12 m MHW, 1 ton at cliff edge (with sitting person), and a tilted one of 1.6 t, with source area of both. Site is at 53°04′40″N and 09°36′56″W (*Image credit* D. Kelletat)

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),

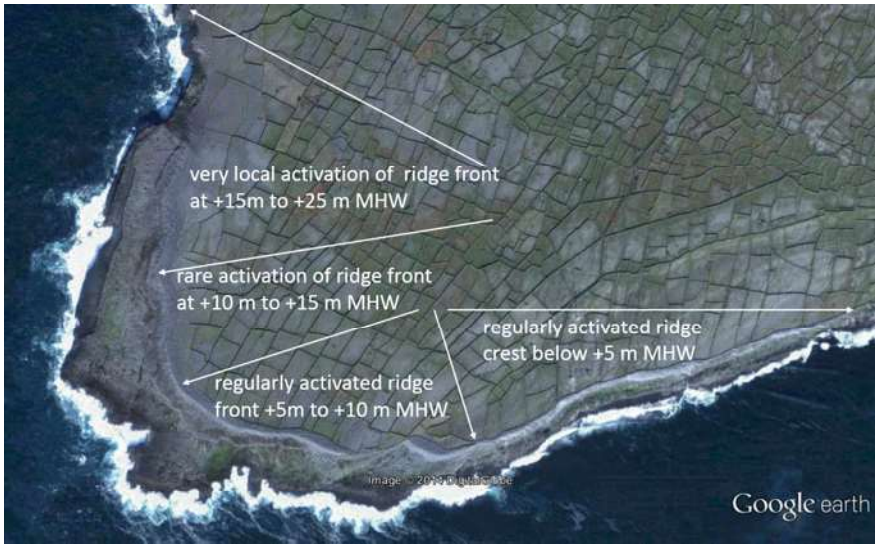


**Fig. 3.41** The intensity of boulder ridge activation (by winter storms of 2013/14, but also back to 2005 AD—date of this satellite image) is clearly depending on the elevation of the ridge and the cliff platform in front (W to S) of it and seen by this satellite image in the different colours of the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

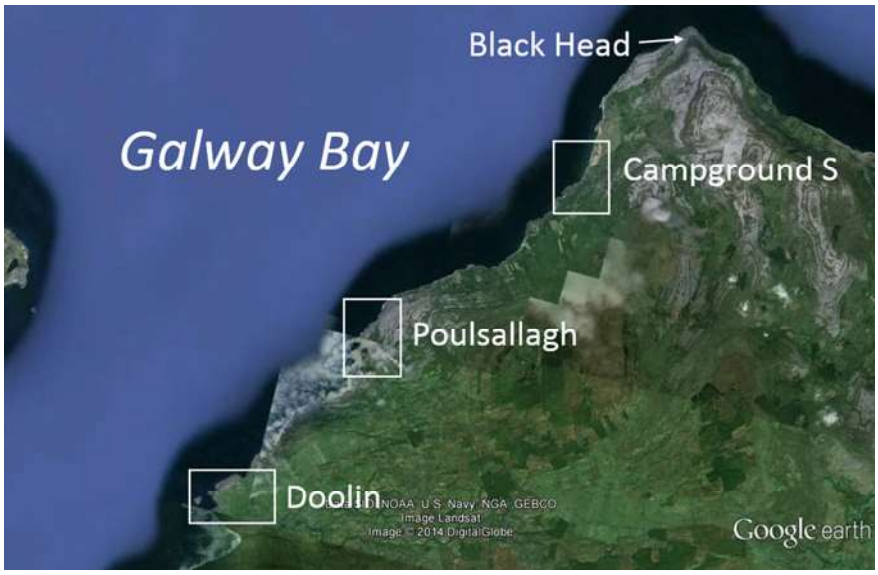


**Fig. 3.42** Inspection sites 2014 along the SE coast of Galway Bay (*Image credit* © Google earth 2012, modified)

**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)

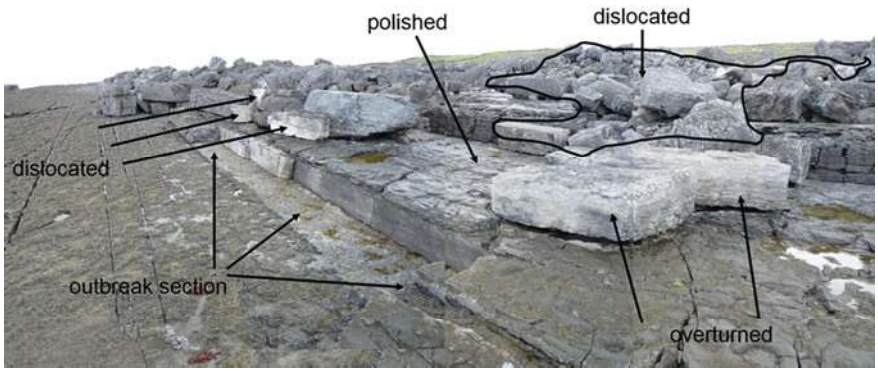


**Fig. 3.45** Open fractures and joints in well stratified limestone give good places for strong wave attack and boulder dislocation (*Image credit* D. Kelletat)

**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)

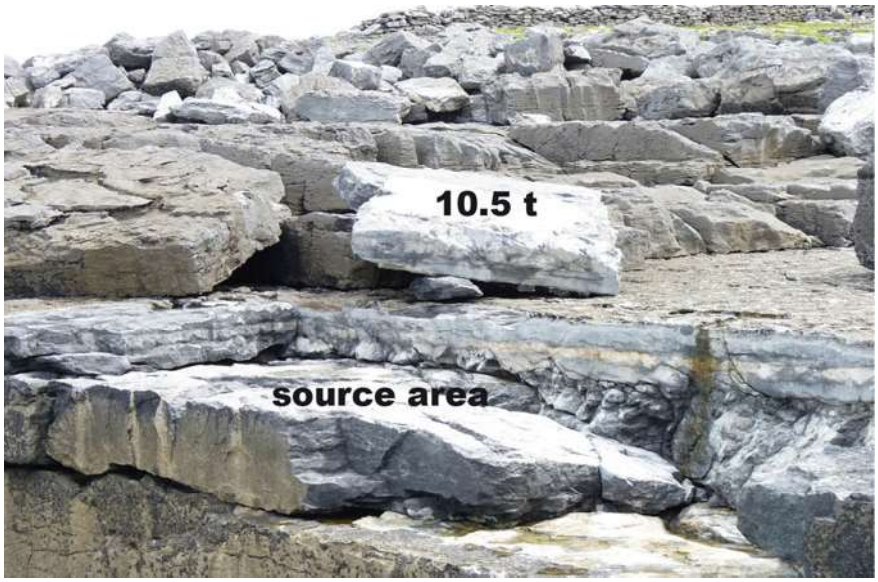


**Fig. 3.54** Overturned platy boulder of several tons at about +5 m MHW just north of Doolin Point, and its white place of origin nearby. The boulder has been dislocated for 4 m horizontally and 1.5 m against gravitation (from +3.5 to +5 m MHW). Site is at 53°01′N and 09°24′31″W (*Image credit* D. Kelletat)

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)

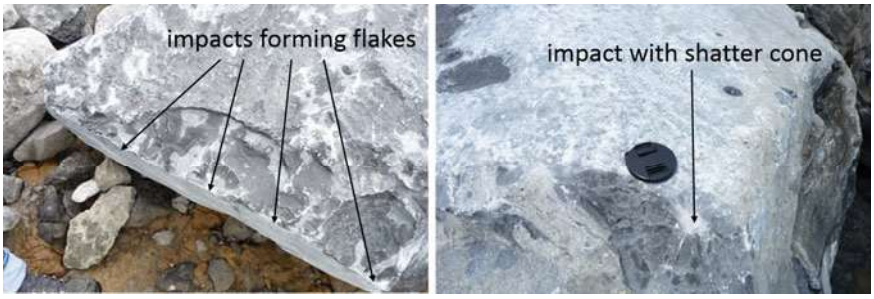


**Fig. 3.58** Typical signatures of strong impacts during the collision of boulders. *Left* Break out of flakes along the boulder edges, *right* fresh collision mark forming a shatter cone on a rounded boulder (*Image credit* D. Kelletat)

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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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_4

**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)

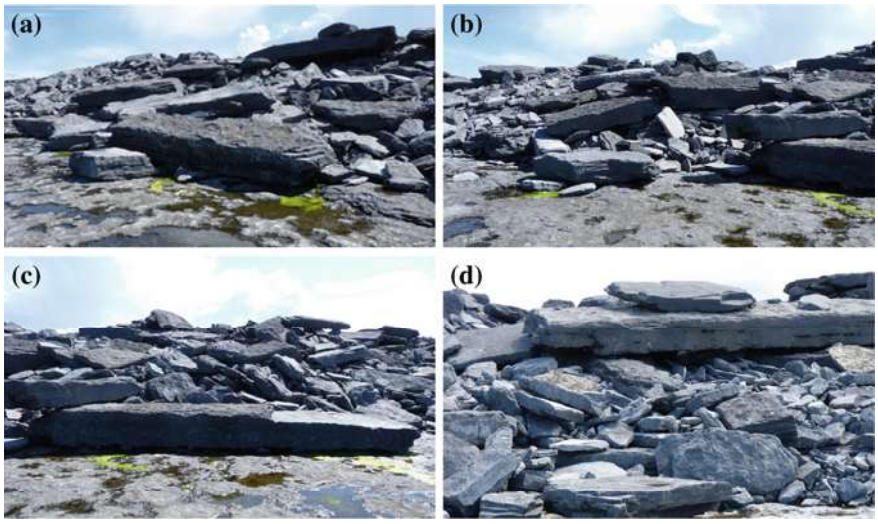


**Fig. 4.12** Undermining maybe the most important process to make formerly stable boulders in higher ridge sections unstable. All images are from the seaward slope of the Inishmaan ridge around +13–16 m MHW. **a** large clasts piled up at around +15 m MHW. **b** Some activation around the ridge base. **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).

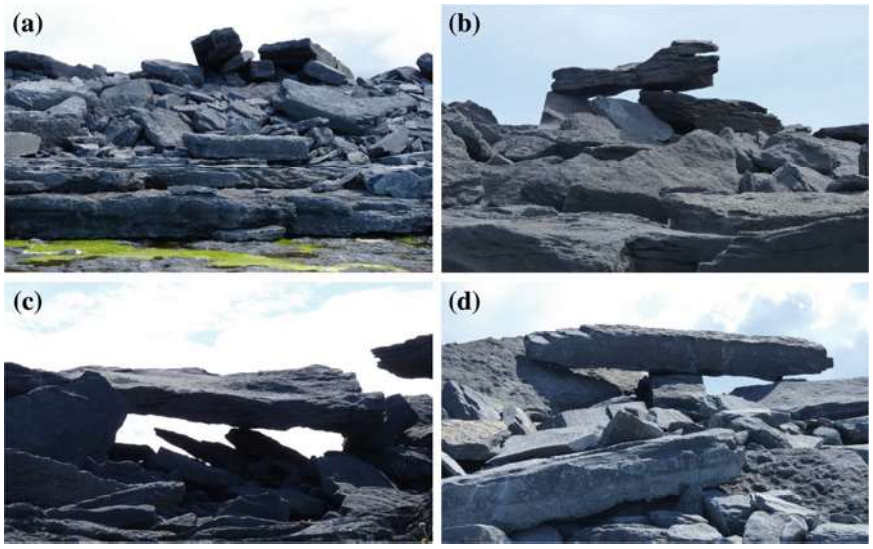


**Fig. 4.14** These delicate positioned boulders are really large, mostly with longest axes around and over 4 m. All examples are from the west coast of Inishmaan at more than +12 m MHW and 140–240 m from the surf belt (*Image credit* D. Kelletat)

## 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)

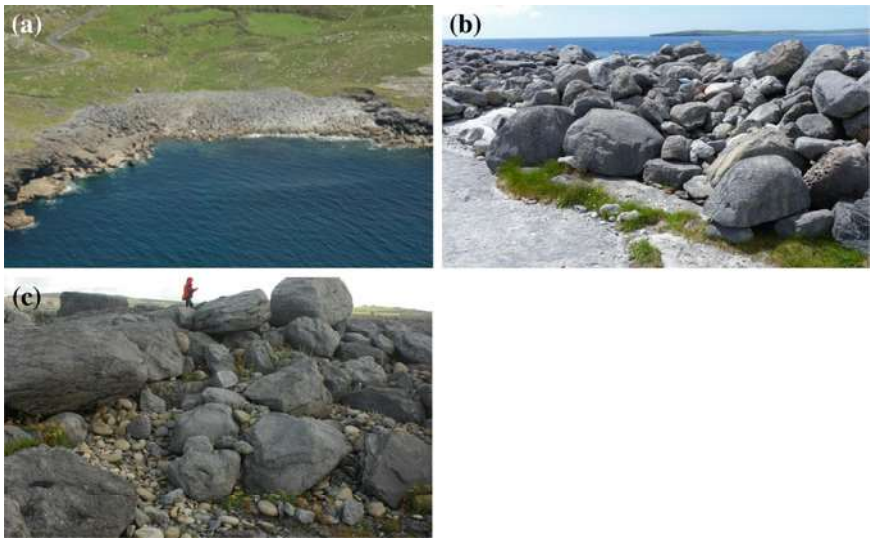


**Fig. 4.24** Types of boulder ridges with mixed coarse and small fragments, or well-rounded boulders up to a few tons, is rather rare in the Galway-Aran region. **a** Up to 7 m high boulder ridge at Poulsallagh, SE coast of Galway Bay (*Image credit* A. Scheffers). **b** Well rounded boulders up to 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)

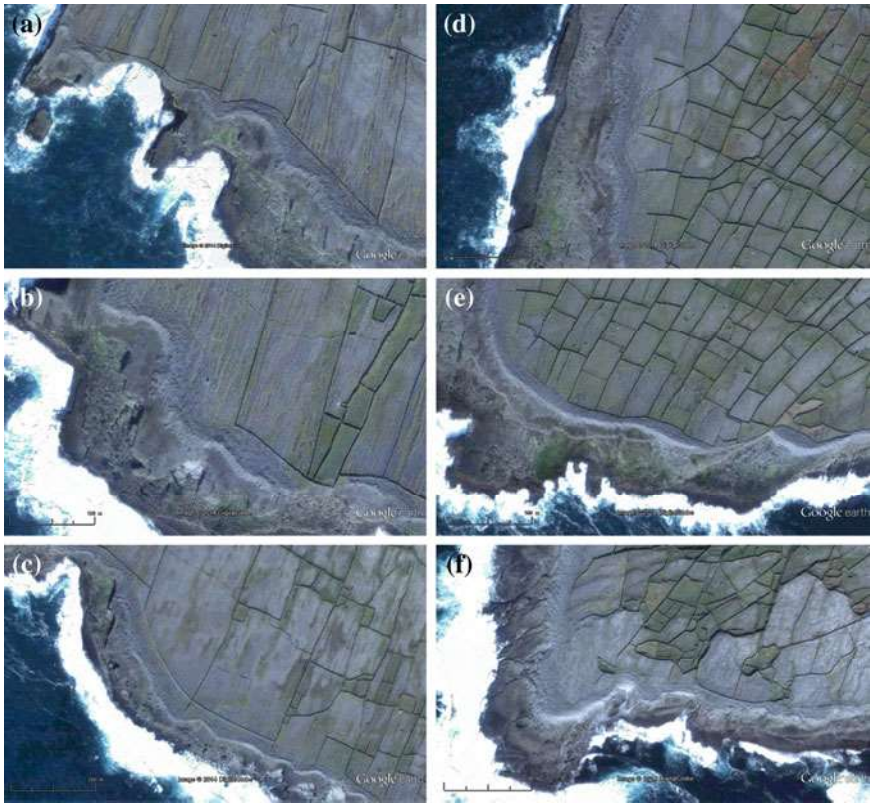


**Fig. 4.25** Well organized and long boulder ridges are significant for the cliff coastlines of the exposed W and S coasts of the three Aran Islands even in elevation up to more than +20 m MHW. Their curvature may or may not be adapted to the coastlines. **a–c** from Inishmore SW, **d**, **e** from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

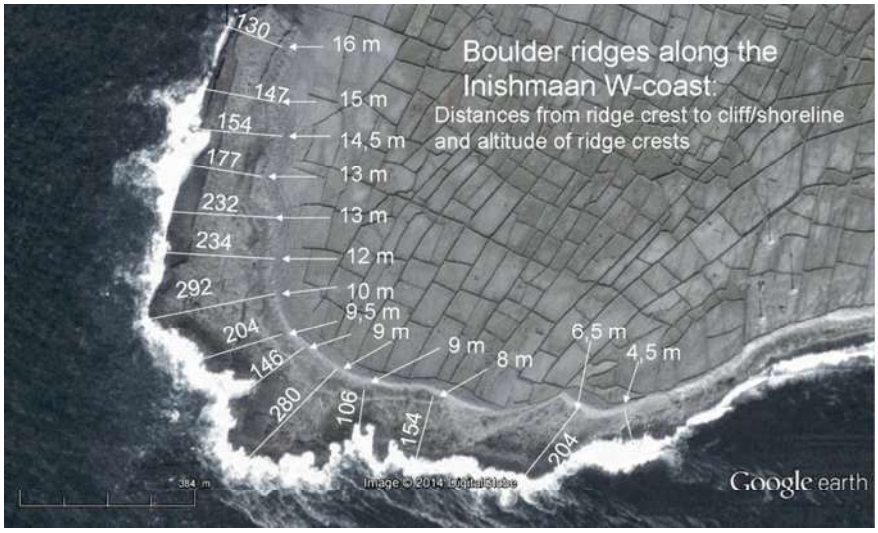


**Fig. 4.28** The distance of the boulder ridges to the cliff line, as shown here from SW Inishmaan, is very large compared to data from the literature, and in higher elevations, as well. The more narrow relation of the two is significant for the higher sections (to the north), but also for low sections (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

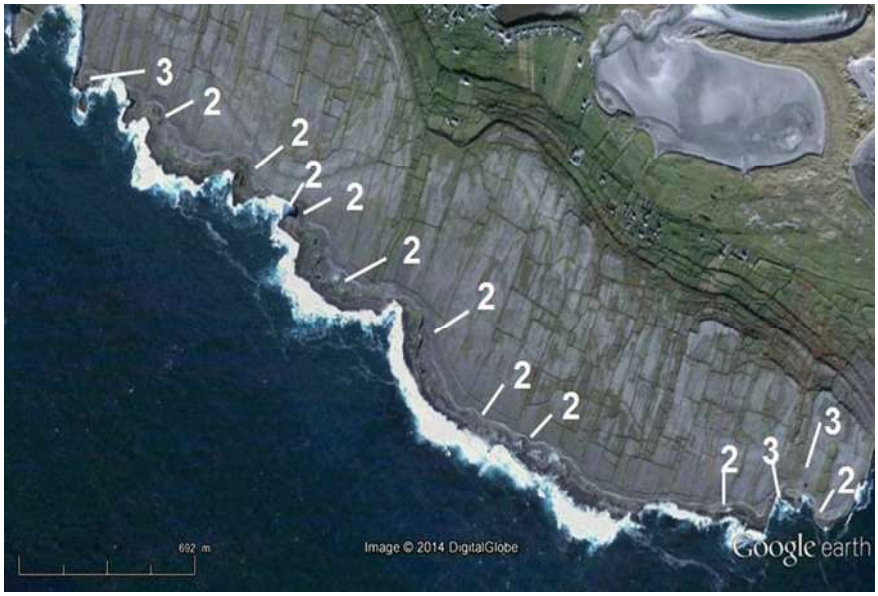


**Fig. 4.30** Southeastern section of Inishmore's exposed Atlantic coastline with cliffs general between +25 and +10 m MHW (lowering to the east) mostly show two ridges (the main one and another one close by to landward), and only on the promontory tips around the Black Fort in NW, and around the puffing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

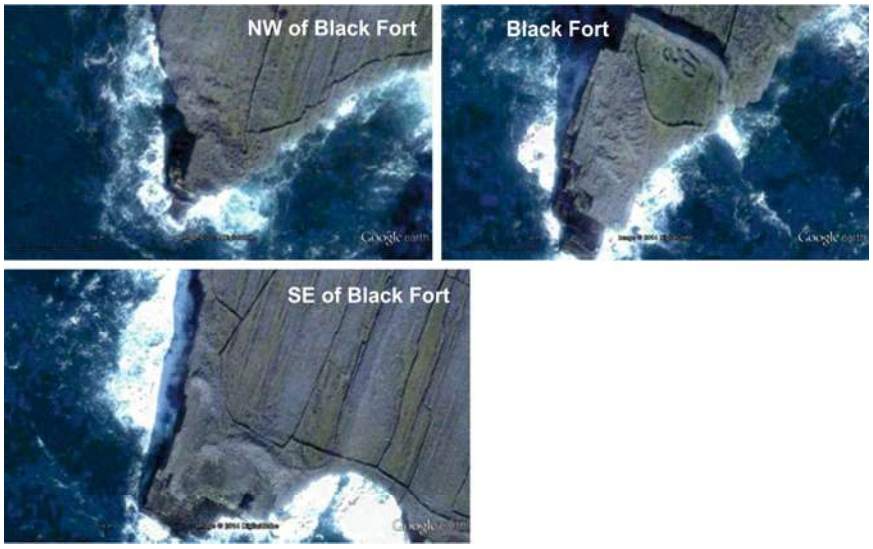


**Fig. 4.32** A larger view on the three promontories around the Iron Age Black Fort (*Image credit* ©Google earth 2005)

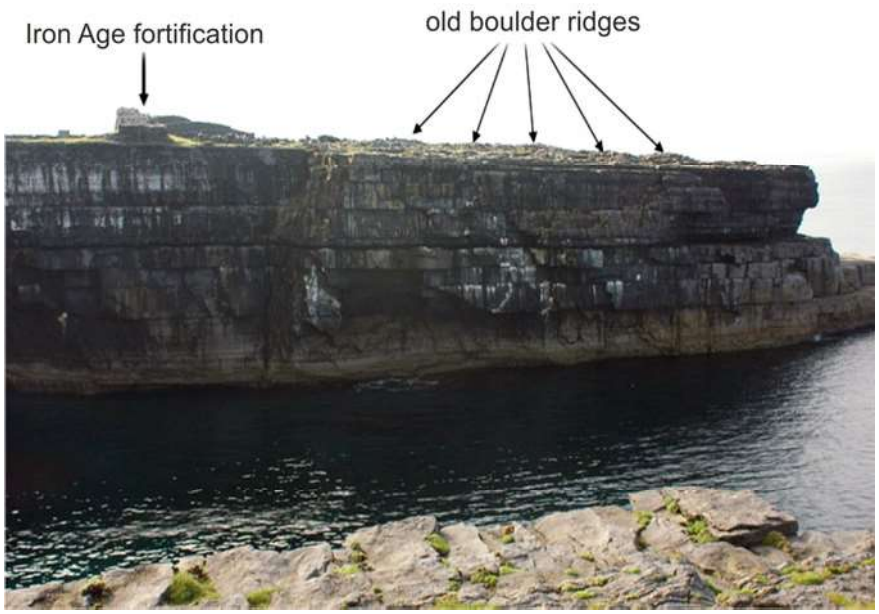


**Fig. 4.33** View from the NW of Black Fort to the promontory with the thick Iron Age wall (built between 2000 and 2500 BP). Five different boulder elevations can be identified at +23 to +26 m above MHW (*Image credit* D. Kelletat)

**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

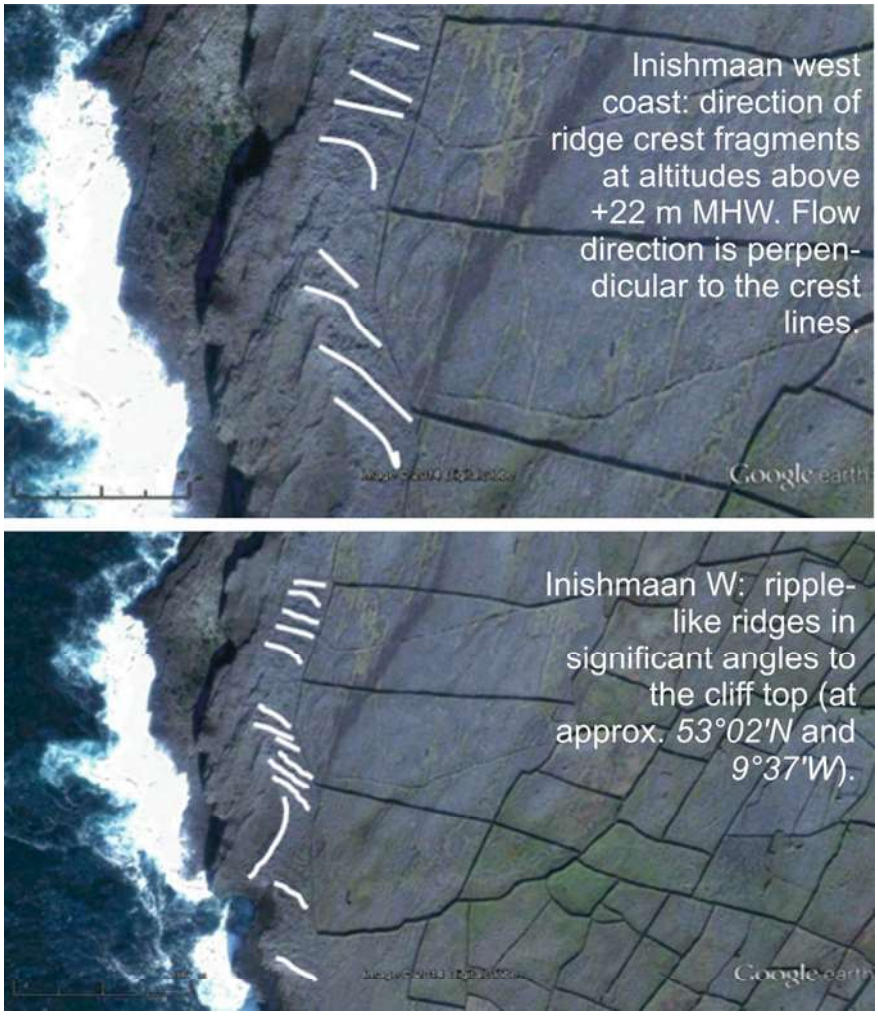


**Fig. 4.36** Many short ridge sections south of Crummel more than 20 m above MHW are developed. They tend to an overall ripple-like aspect from one event, and not to a series of deposits formed over a longer time and in time laps of longer duration (see also Figs. 4.35 and 4.37) (*Image credit* ©Google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

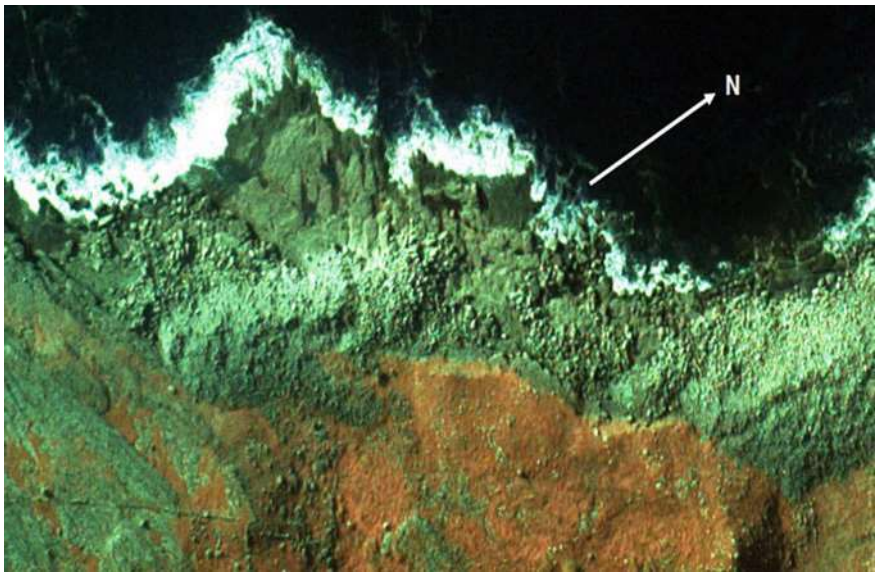


**Fig. 4.40** Boulder ridges within Galway Bay (southern east coast) are organized less than those on the Aran Islands, closer to the shoreline and mostly in low elevations. Single boulders incorporated, however, may show the same mass. Picture shows a section 5 km NNE of Doolin Point, scene is 100 m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

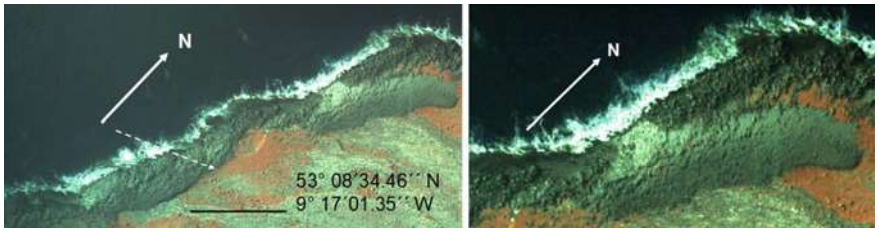


**Fig. 4.41** As on the Aran Islands, within Galway Bay boulder ridges also may appear as more than one deposit. In this case close to Black Head, the inner wide ridge seems to be deposited from the south as a broad overwash feature 200 m long. Scale is 100 m (overview and detail) (*Image credit* National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

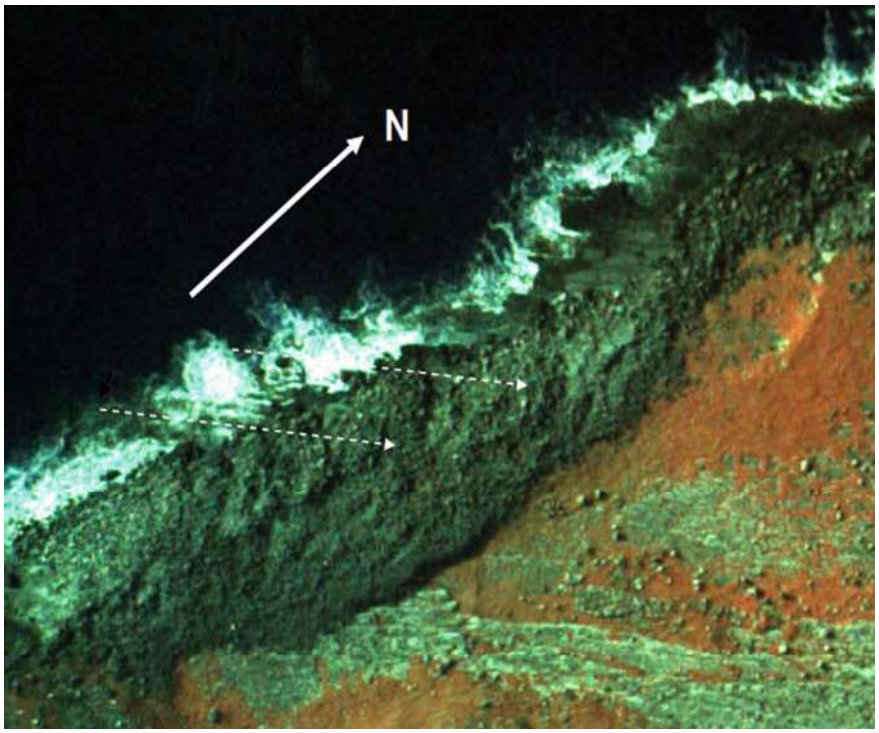


**Fig. 4.42** Another similarity to Aran ridges are integrated ripple-like features, organized by impacts arriving in a tight angle with regard to the coastline. Picture shows a 250 m long section of a boulder ridge 2 km SW of Black Head within Galway Bay. *Thin arrows* indicate flow direction to form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

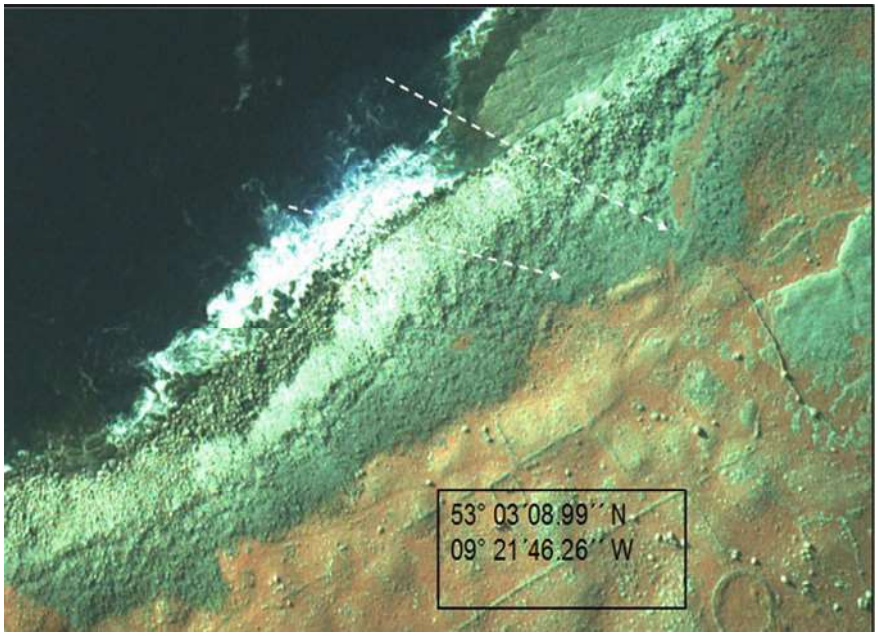


**Fig. 4.43** Ripple features in broad boulder ridges may be well organized regarding their size and distance. Scene is from Galway Bay near Poulsallagh and 200 m wide. *Thin arrows* indicate flow direction (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

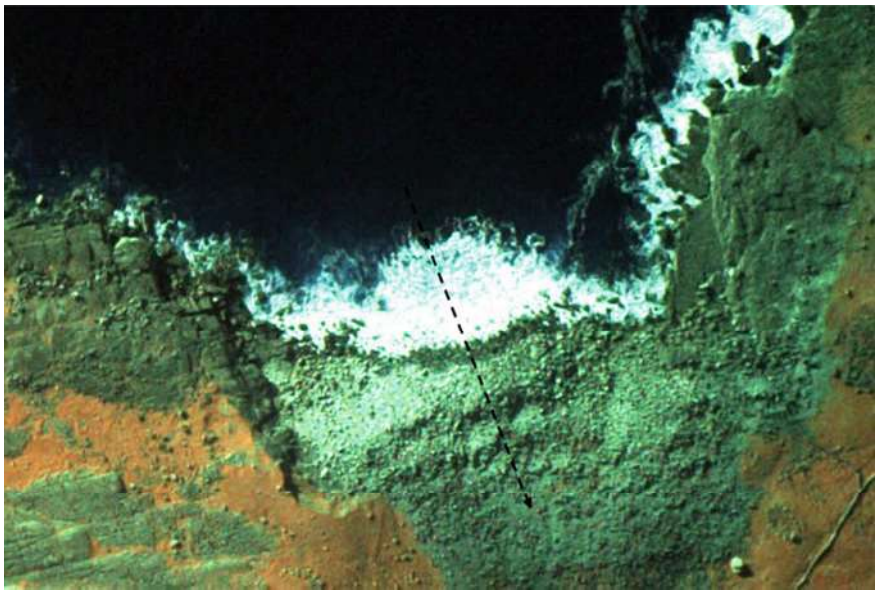

**Fig. 4.44** Within high and broad ridges, patterns of parallel low crests, diminishing in elevation, relative height and extension occur, allowing to reconstruct the direction of incoming impacts. Image shows the 7 m high and 150 m long ridge SW of Poulsallagh (*Image credit* National Coastline Survey,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

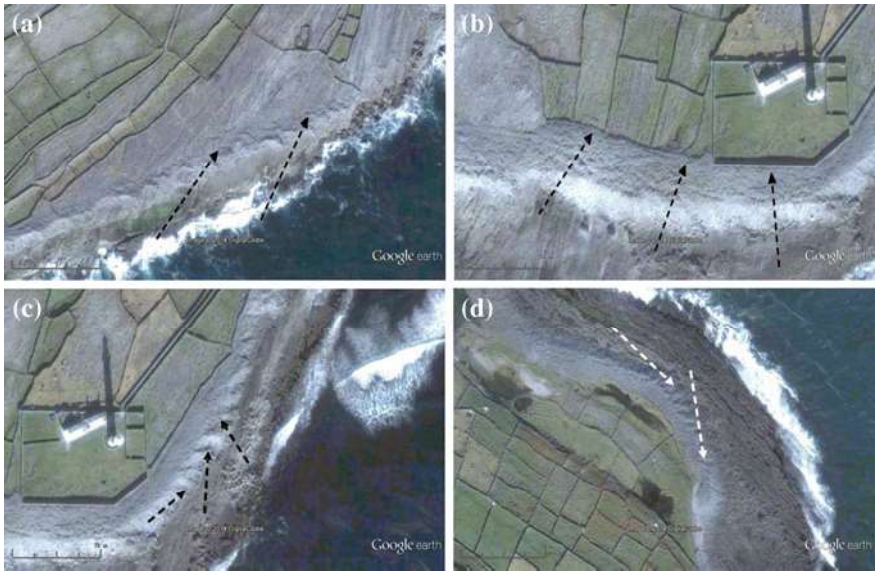


**Fig. 4.45** On all three Aran Islands two different ripple features may occur: **a** Inishmaan SE coast. **b** Inisheer south coast (ripples more or less parallel to the main crest general direction). **c** Inisheer SE coast (see enlargement in Fig. 4.46). **d** Inishmore north coast. Series of curving 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)

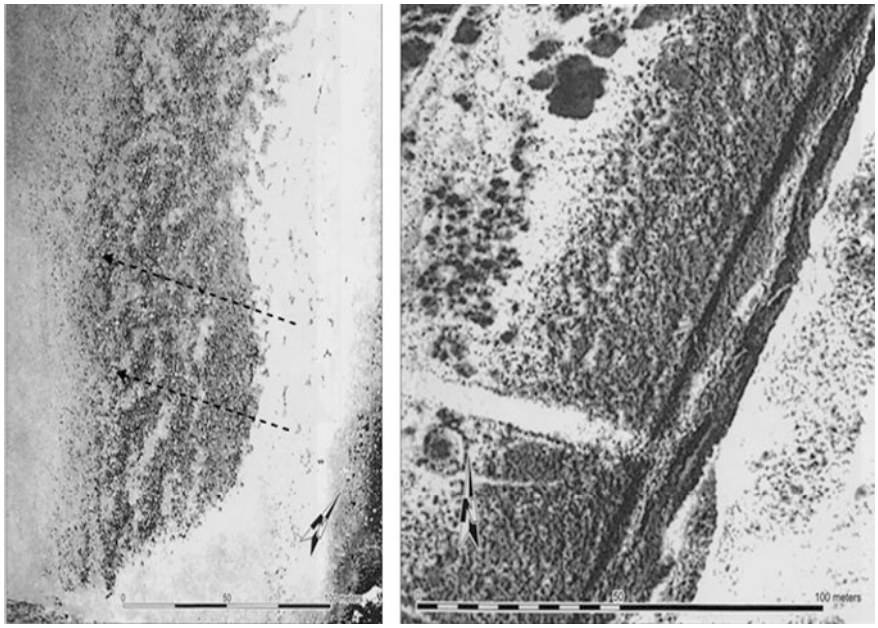


**Fig. 4.47** Ripple structures on old and coarse tsunami deposits at the east coast of Bonaire Island, southern Caribbean (from Scheffers 2006). *Thin arrows* indicate flow direction. Scale is 100 m

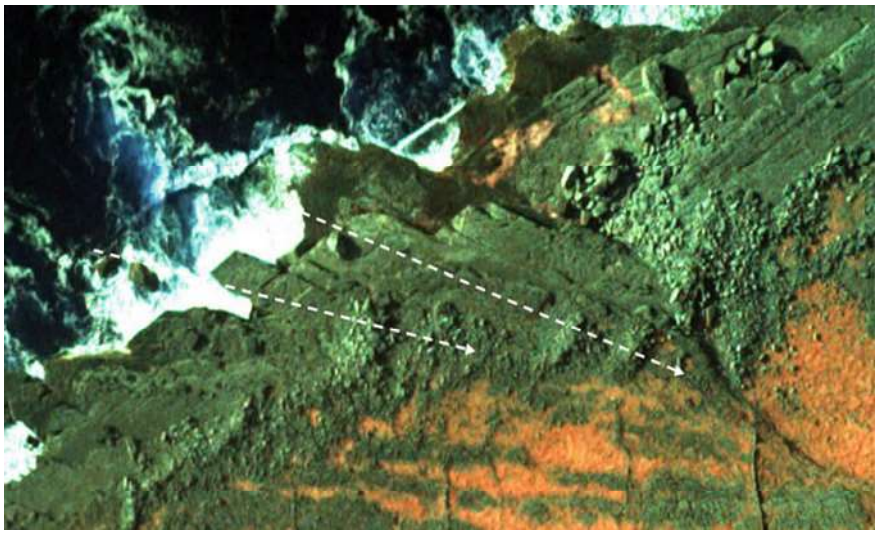

**Fig. 4.48** Although these ripple-features are rather wide spaces and on the first glance may document individual deposits over a longer span of events in time, they most probably belong to the same process and show a pattern formed by the same forces and in the same time frame. Scene is NE of Doolin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

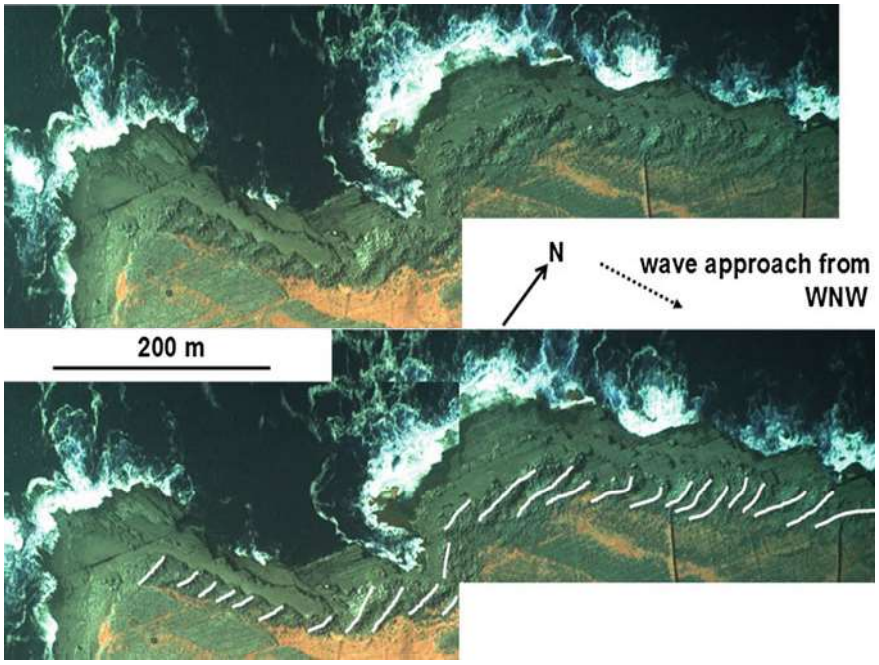


**Fig. 4.49** The closer the deposit sites are to the entrances into Galway Bay and the open Ocean, the better and clearer internal features within the main ridges are organized. Example is close to Doolin Point (*Image credit* National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

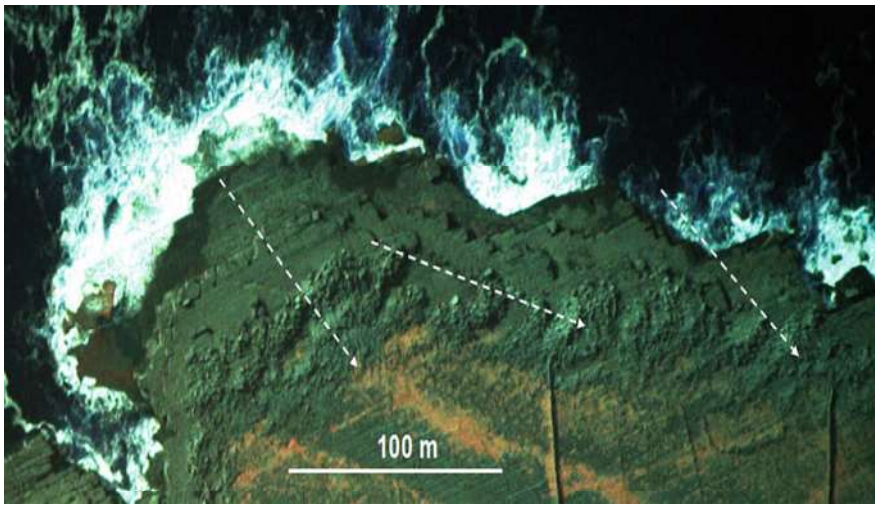


**Fig. 4.50** Detail from Fig. 4.49 documenting that the exposure of the slightly curving internal ripples and their change in direction is not triggered by modern cliff contours. Site is NW of Doolin. *Arrows* indicate flow direction (*Image credit* National Coastline Survey, Marine Institute, Dublin,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

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W. Erdmann et al., *Origin and Formation of Coastal Boulder Deposits at Galway Bay and the Aran Islands, Western Ireland*,
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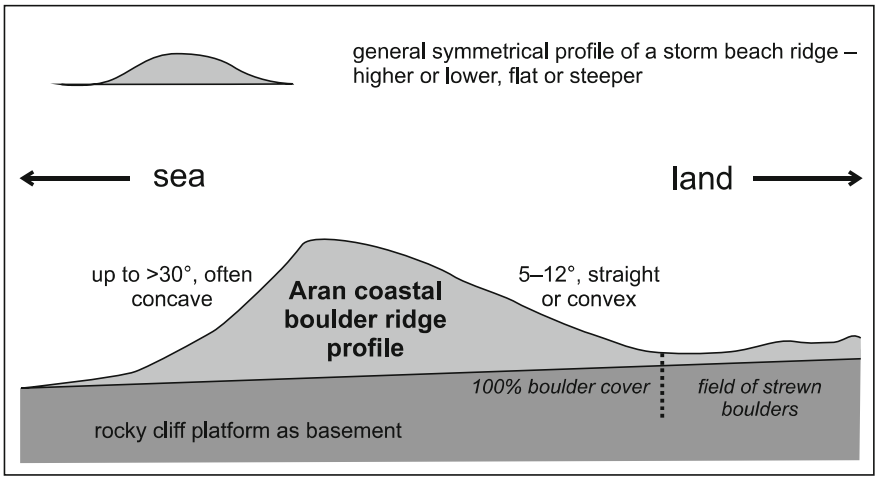


**Fig. 5.1** Comparison of profiles of "normal" beach ridges (sandy and coarse once), and the main boulder ridges in the Galway and Aran area. The latter may well be the remnant of a wider deposit, eroded from the sea by multiple storm impacts during a long time of the Recent Holocene (*Image credit*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

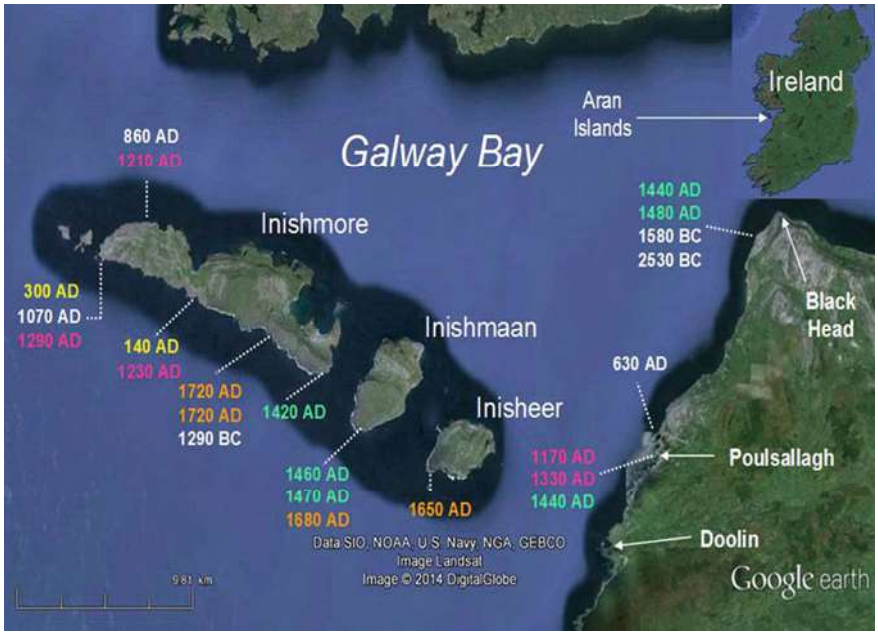


**Fig. 5.6** Twenty three calibrated AMS data (Scheffers et al. 2010) from coastal boulder deposits at the Aran Islands and inside Galway Bay form age clusters and span a time frame of more than 4,000 years. *Same colour* indicates same age cluster. *White colour* means single age (*Image credit* ©Google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

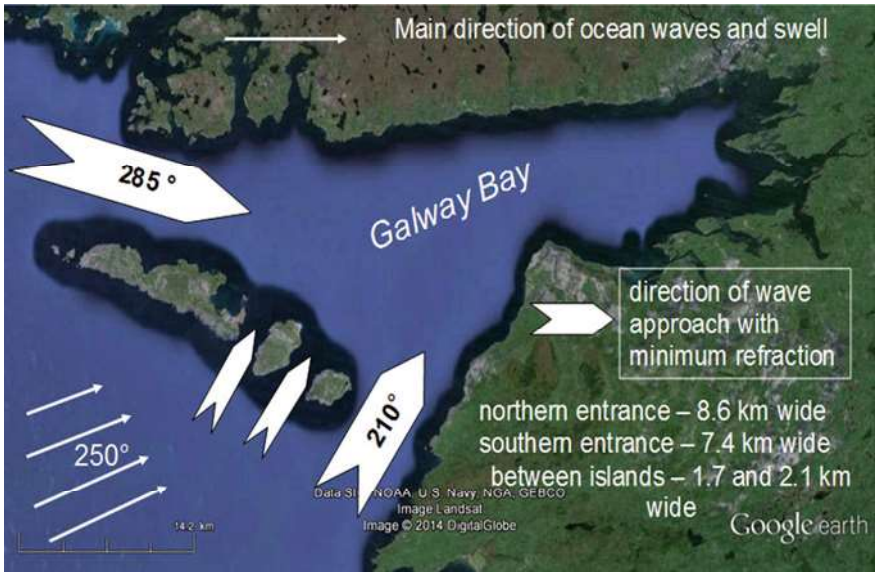


**Fig. 5.7** Main approach of open ocean waves and swell in all seasons is from SSW (250°), but by the topography and bathymetry at the entrance of Galway Bay, refraction must occur. Additionally, water becomes shallower to inside the bay, diminishing wave energy (*Image credit* ©Google earth 2014 and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

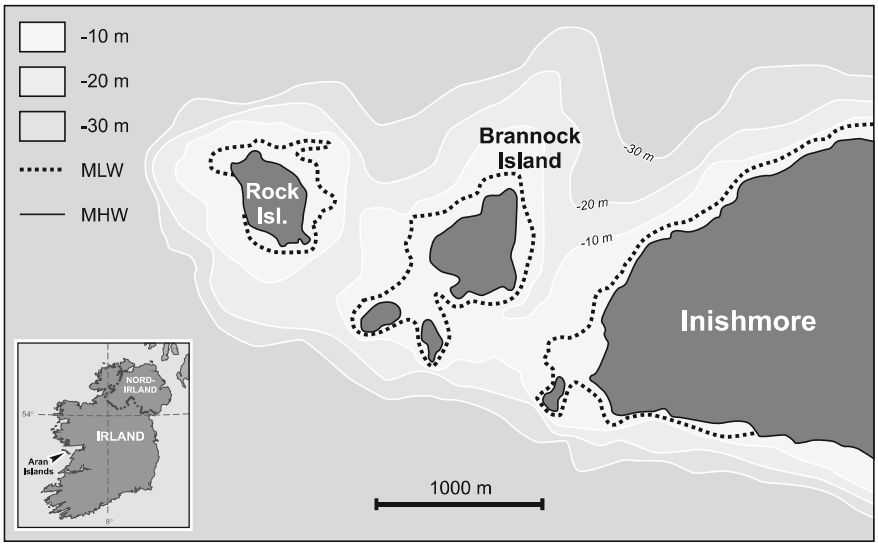


**Fig. 5.8** Bathymetric situation around Brannock and Rock Island at the west end of Inishmore Island: an inter-tidal up to 200 m wide is fringed by shallow water with influence on wave breaking and wave energy to dislocate boulders (*Source* Irish Chart 3339: Approaches to Galway Bay Including the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

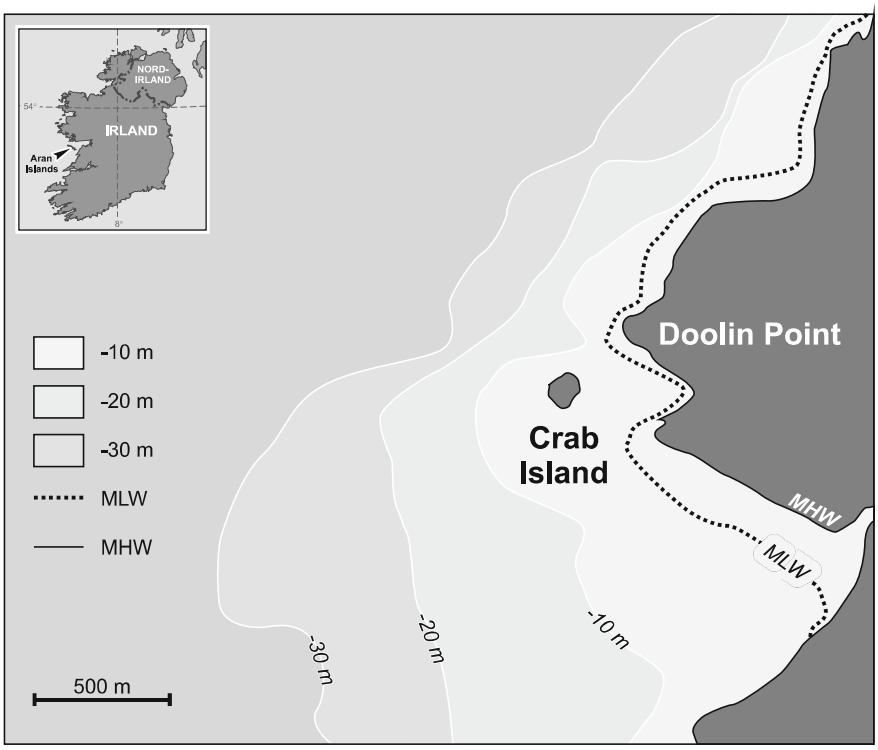


**Fig. 5.9** Bathymetry near Doolin Point and Crab Island at the SE entrance to Galway Bay. Water depths of 10 m encircles Crab Island (*Source* Irish Chart 3339: Approaches to Galway Bay Including the Aran Islands (1981) 1:50.000, edition 2005, *graphics* A. Hager)

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

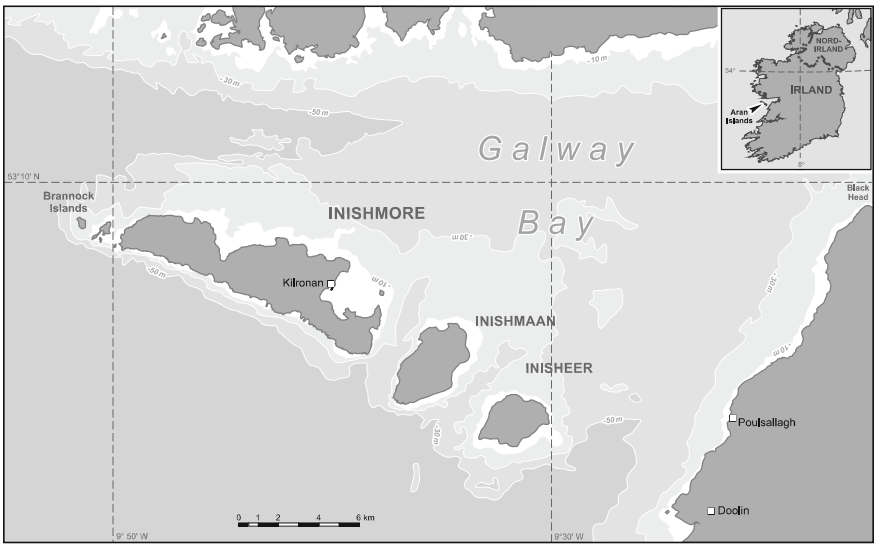


**Fig. 5.10** Bathymetry of the Galway Bay and around the Aran Islands. Depths of 50, 30 and 10 m are indicated (*Source* Irish Chart 3339: Approaches to Galway Bay Including the Aran Islands (1981) 1:50.000, edition 2005, *graphics* G. Reichert)

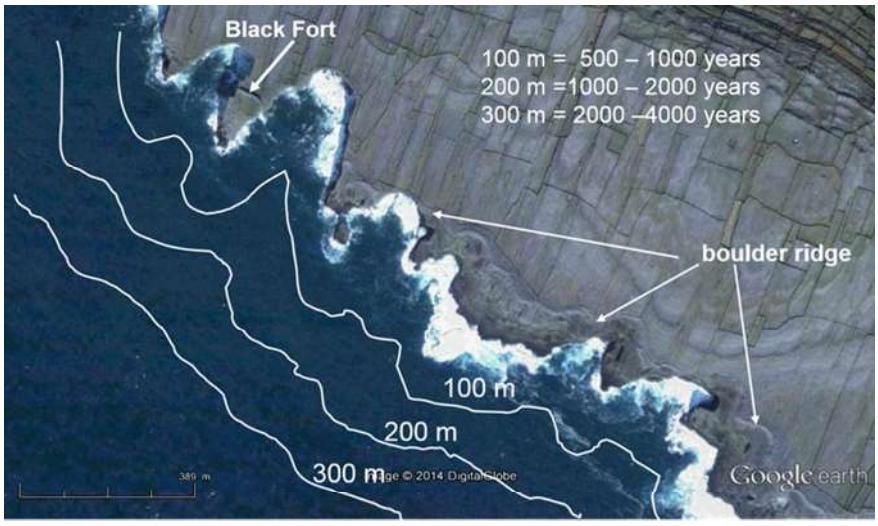


**Fig. 5.11** Model of former coastline position (of 100, 200 and 300 m) at the southwest coast of Inishmore near Black Fort, assuming a cliff erosion of 0.1–0.2 m/year. According to Williams (2010), this is at the lower range. Williams (2004) and Williams and Hall (2004) interpreted the short ridge 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 megaclasts, 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

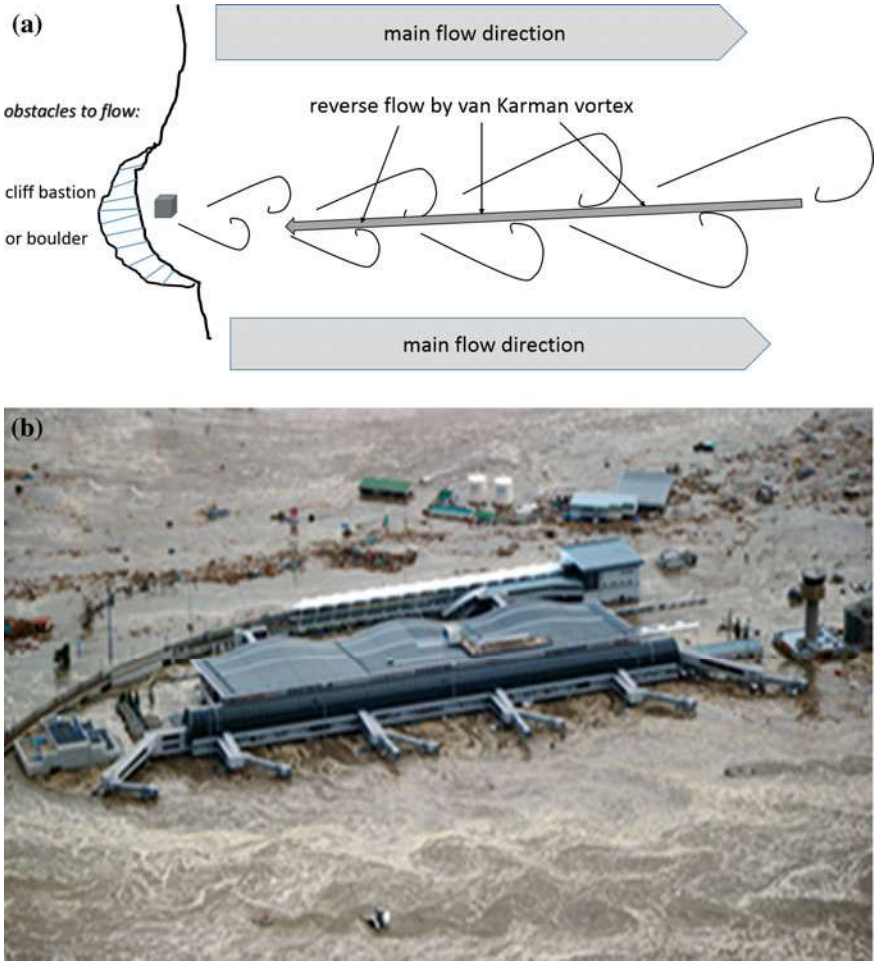


**Fig. 5.14** Van Karman vortex: **a** model of cylinders in a van Karman vortex, forming behind an obstacle during steady flow. This flow is concentrated along a single line from both rows of cylinders, and within this central line, movement is directed against the general flow which allows, if strong 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

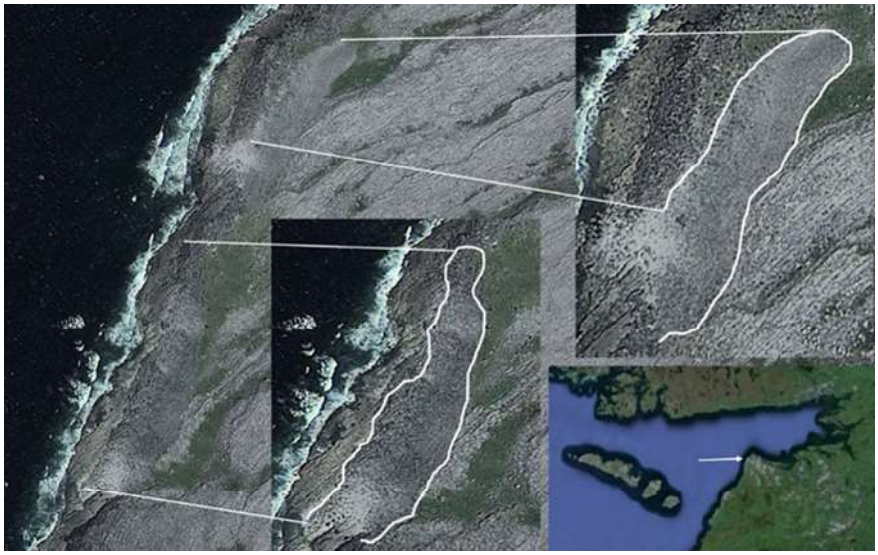

**Fig. 5.15** Two wash-over features from SSW, 1.6–2 km SW of Black Head (*insert* shows position within Galway Bay). The southern feature is 176 m long and max. 47 m wide, the northern one 164 m long and max. 37 m wide (and behind a seaward boulder ridge, see also Fig. 5.17). Both deposits contain of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

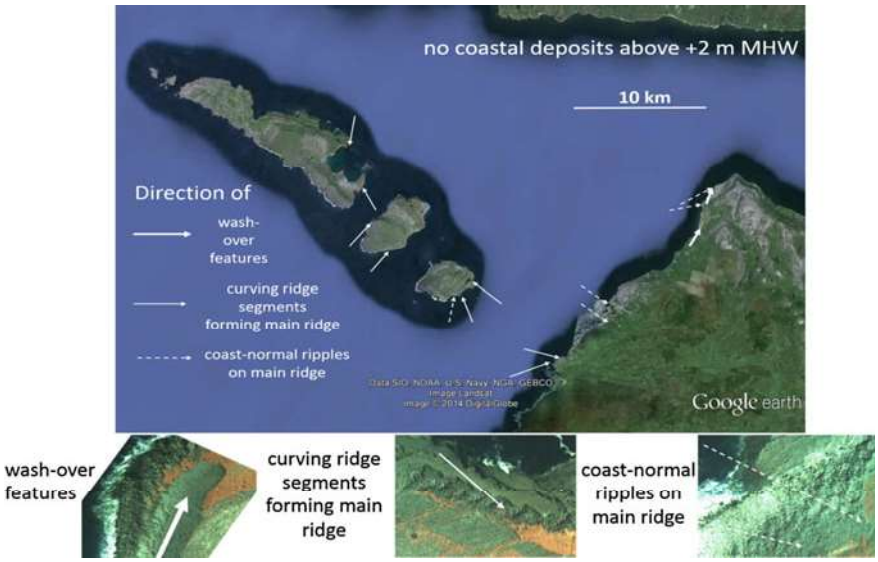


**Fig. 5.17** Three different geomorphological signatures of strong wash-over processes on the Aran Islands and within Galway Bay (*Image credits* ©Google earth 2014, and National Coastline Survey, Marine Institute, Dublin, Ireland, 2000)

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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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_6

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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**Fazit**

Gelegentlich kommt beim Lösen von Problemen der Zufall zur Hilfe: Von Ende Dezember 2013 bis Mitte Februar 2014 trafen sechs starke Stürme auf die Westküste Irlands, vier davon als Kategorie 3-Hurrikane, zwei als Kategorie 4-Hurrikane (Abb. 9). Nach dem Eindruck der Küstenbewohner und den Registrierungen der meteorologischen Dienste waren es die extremsten Stürme *„in living memory“*, d.h. seit mindestens 60 Jahren. Das gilt erstaunlicherweise weniger für morphologische Veränderungen der Küstenformen, (an welchen diese Stürme heute nicht mehr erkennbar sind), als vielmehr für die Verlagerung frischer Blöcke gegen die Schwerkraft und landeinwärts. Diese Ereignisse waren Anlass genug, zeitnah im Juni 2014 im Gelände die Spuren dieser Stürme aufzunehmen. Zudem bestand die Möglichkeit zu einer breiten Darlegung und Dokumentation der Befunde in der Reihe *„Springer Briefs in Geography“*.

Um Signaturen von starken Stürmen in einer Küstenlandschaft nachzuweisen gibt es keine generelle Vorgehensweise. Neben den Küstenformen ist es vor allem der Gesteinstyp, der Veränderungen aufnimmt und gegebenenfalls für eine gewisse Zeitspanne bewahren kann. Im Kalkgestein, wie es in der Region Galway vorherrscht, erfolgt dieses durch Abrieb an allen Kontaktstellen mit Nachbarfragmenten oder dem Untergrund. Kleinere Korngrößen wie Kiese oder kleinere Blöcke werden schnell aufgehellt, große und sehr große Blöcke wegen ihrer geringeren Bewegungsmöglichkeit oft nur punktuell, während auf dem Untergrund alle Kontakte durch gepunktete Linien, Striche oder Streifen heller Oberflächen entlang des Brandungssaumes dokumentiert sind. Stellen mit sehr harter Kollision (abhängig von der individuellen Masse der beteiligten Blöcke) haben *impact-marks* mit einem zentralen Auftreffpunkt, von welchem strahlenförmig feine Linien über die Ausbruchstelle verlaufen. Die Ausbrüche selbst sind *chips* unterschiedlicher Größe, von etwa handgroß bis zur Länge von 1 m, gewöhnlich flach und lanzettartig. Gelegentlich sind sie im Blockgemisch zu identifizieren, werden jedoch wegen ihrer geringen Größe leicht ins Meer zurückgespült.

An stets durch Wellen aktiven Küstenabschnitten wie Stränden aus Kies, Schottern und kleineren Blöcken (letztere meist bereits als Wälle ausgebildet) sind Sturmeinflüsse nicht besonders auffällig. Diese Abschnitte weisen wegen der Aktivität keine Farbveränderungen (durch Verwitterung, Flechtenbedeckung oder Besiedlung mit epi- und endolithischen Algen und/oder Cyanobakterien) auf und zeigen sich in den hellen Grundfarben des Kalksteins. Je gröber die Fragmente, je höher im Gelände

und je weiter weg vom Brandungssaum, desto auffälliger und seltener werden die einzelnen Spuren der Aktivierung bei Stürmen. Sie sind erkennbar als aufgehellte Stellen durch frischen Ausbruch neuer Fragmente (am Kliff, an Kliffstufen, auf Kliffplattformen). Das gilt vor allem für kleinere Blöcke an den seeseitigen Böschungen existierender (auch sehr alter) Blockwälle, an welchen Sturmwellen infolge der Steilheit auflaufen und an diesem Hindernis endgültig ihre Energie verlieren. Dabei ist dieser Prozess nicht allein von der Höhenlage und Entfernung vom Meeresspiegel abhängig, sondern erscheint in seiner Verteilung eher durch lokale Faktoren, vor allem die Konfiguration der Kliffe, welche die räumliche Verteilung des Wellenauflaufes bestimmen, gesteuert zu sein. Daher liegen aktivierte und nicht aktivierte Blockwallabschnitte oft in gleicher Höhe und Exposition, sind aber insgesamt unregelmäßig verteilt. Eine Ausnahme bilden hohe geschlossene Blockwälle in geringer Meereshöhe und relativ nahe am Brandungssaum wie an Abschnitten der Südküste von Inishmaan. Dort finden sich Blockwallabschnitte, die geschlossen bis zur Kronenhöhe und dann unregelmäßig auf der landseitigen Böschung aktiviert wurden, zuletzt im Winter 2013/14. Eine Blockverlagerung bis auf vegetationsbedeckte Oberflächen war nicht auszumachen.

Mit der Identifizierung der Lage und Masse frisch bewegter Blöcke lassen sich etliche quantitative Daten für Blocktransport durch Starkwellen zusammentragen. Dieses ist auch die von Cox et al. in verschiedenen Präsentationen (2014, 2015, 2016 a, b) und einer Publikation (Cox et al., 2012) angewandte Methode, ergänzt durch Bildvergleich mit Gegebenheiten aus vergangenen Jahren. Wenn man alle Expositionen, Höhenlagen und Relieftypen sowie geologischen Voraussetzungen (z.B. ursprüngliche Schichtmächtigkeit) in einem größeren Raum beachtet, kann die maximale/optimale Umgestaltungskraft für das Küstenrelief und die Küstensedimente ermittelt werden. Bei Beschränkung auf ausgesuchte (z.B. nur extrem exponierte) Lagen wird das allerdings nicht gelingen. Zudem ist die Betrachtung nur frisch verlagerter Fragmente ein zu kleiner Ausschnitt der von der Natur bereitgehaltenen Informationen. Weitere Erkenntnisse können erlangt werden, indem auch geprüft und quantitativ erfasst wird, welche bereits vorhandenen Fragmente bei den Starkereignissen **nicht** bewegt wurden. Das Schicksal beider Dispositionen (frischer und älterer Fragmente) sollte zudem nicht nur für lokale, sondern überregionale und ggf. weltweite Vergleiche herangezogen werden (vgl. Erdmann et al., 2015: 60-67). Nur wenn die unterschiedlichen Reliefverhältnisse, Geologie, Exposition, Wassertiefe, Blockformen und Blockdichten bekannt sind lässt

sich beurteilen, inwieweit Stürme allein für alle weltweiten Blockverlagerungen verantwortlich sind oder andere Kräfte zusätzlich diskutiert werden müssen.

Ein weiterer Aspekt ist bedeutsam, nämlich die potentielle Herkunft der Blöcke, welche nun an Land in langen hohen Wällen aufgetürmt sind (Erdmann et al., 2015: 76-82). Sie lässt sich gelegentlich durch die Passform an einer nahen Kliffstufe verorten, und kurz nach Stürmen sind auch die Ausbruchstellen noch gut erkennbar. Andere Blöcke belegen ihre Herkunft aus der Brandungszone durch eine gute oder zumindest partielle Zurundung. Sichere Hinweise auf ihren Ursprung geben vor allem Spuren von Lebewesen wie Anhaftungen von Kalkalgen und Balaniden (Herkunft: oberstes Subtidal bis unterstes Supratidal), *Patella*-Wohnplätze (Herkunft: oberes Tidal), Bohrschwamm -Perforierungen (*Cliona* sp., Herkunft: unteres Tidal und oberes Subtidal), Seeigel-Wohnplätze (Herkunft: unterstes Tidal und Subtidal), sowie Bohrmuschellöcher (Herkunft: *Hiatella*, oberes Subtidal bis mittleres Tidal). Vor allem von *Littorina* angelegte *rock pools* kennzeichnen das untere Supralitoral.

Die Ausdehnung auf und Dokumentation für alle wichtigen Formgruppen der Blockablagerungen in der Region Galway war sinnvoll und lieferte Hinweise auf die Erscheinung doppelter Blockwälle in oft enger Nachbarschaft, wobei die landwärtigen niedriger und schmaler sind und von jüngeren Ereignissen nie verändert (d.h. nie mehr erreicht) wurden. Da diese Verhältnisse über einen längeren Zeitraum, bei steigendem Meeresspiegel und erosivem Küstenprofil typisch für das Arbeitsgebiet sind, ergaben sich wichtige Hinweise auf die mangelnde oder sogar fehlende Landwärtsbewegung der Blockwälle. Dieses steht in völligem Kontrast zu den Schlussfolgerungen bei Cox et al. (2012) auf eine stete Wanderung landwärts von Kliffen und Blockwällen.

Einen Schwerpunkt dieser Arbeit bildet die breite Dokumentation in Fotos und Graphiken. Sie liefert Hinweise zum Alter der Blockablagerungen, zur Geschwindigkeit der Klifferosion und zu großen *washover*-Loben als besonders signifikante Tsunamibelege, und zwar am Festlandsabschnitt im SE der Galway Bay, aber auch auf den Inseln Inishmaan und Inishmore. Solche *washover*-Zungen mit Augenblickstransport von weit über 10.000 t sind bislang weltweit noch nicht beschrieben.

Die *near-time inspection* 2014 brachte bei Doolin Point ein frisches Block-Setting zutage, welches die Erhebung einer ganzen Reihe exakter quantitativer Daten zur Bewegungsstrecke (auch gegen die Schwerkraft), Einfluss der Blockform, bewegende Kraft sowie Herkunft und Art der Bewegung ermöglichte. Es steht als ein typisches

Beispiel für sturmbewegte flache Blöcke jeder Größenordnung. Diese Daten ermöglichten, mit ihnen publizierte Hypothesen, Theorien und Modelle zur Blockbewegung durch marine Kräfte sowie Veröffentlichungen über lokale Ansammlungen großer Blöcke seit 2000 und weltweit zu vergleichen.

## 4.2 Kartierung und Beprobung in der Galway Bay (Erdmann et al., 2017)

Der Reichtum ganz verschiedener Ablagerungstypen innerhalb der Galway Bay, aber auch die vielen Hinweise auf extreme Blockbewegungen selbst in relativer Schutzlage mit flachen *fore-shore* Bedingungen erforderte geradezu die Vertiefung der Feldstudien an dem 25 km langen Abschnitt von Doolin bis Black Head mit einer Gesamtkartierung und dem Versuch der Erfassung des Zeitraumes, den diese sehr groben und feineren Sedimentarchive überdecken. Die Feldarbeiten dazu wurden im Herbst 2015 durchgeführt:

> Erdmann, W.; Kelletat, D., und Kuckuck, M., 2017. Boulder ridges and washover features in Galway Bay, western Ireland. Journal of Coastal Research, 33(5), 997–1021.

**Zusammenfassung**

Küstennahe Blockablagerungen auf einigen Abschnitten der Aran-Inseln werden seit über zehn Jahren untersucht und diskutiert, während ähnliche marine und litorale Sedimente innerhalb der Galway Bay bislang nur beiläufig erwähnt wurden. Ziel dieser Studie ist es daher, alle Küstensedimente entlang der äußeren Küste der Galway Bay entlang der 25 km langen Strecke zwischen der Öffnung des South Sound und der Lokalität Black Head in der Bucht zu kartieren und zu analysieren. Hier existieren vor allem lange Blockwälle mit *imbrication* parallel zur Brandungszone, während Blockablagerungen oberhalb der Kliffe eher chaotisch sind. Die Größe individueller Blöcke ist dagegen ähnlich wie jene an den extrem exponierten Seiten der Aran-Inseln. Landwärts der Blockwälle deuten lokal geschichtete feinere Ablagerungen auf gelegentlich Sedimentationsbedingungen durch *washover*-Prozesse, die meisten feineren Sedimentarchive sind aber ebenfalls chaotisch, die vertikalen Altersfolgen weisen Inversionen auf. Zwei weitere Ablagerungsformen konnten kartiert werden, die bisher (für Europa) noch nicht bekannt sind. Es handelt sich um quer zu den Hauptwällen verlaufende Wallstücke aus groben Blöcken, und zungenartige *Overwash*-Erscheinungen, beide sicher von gerichteten sehr starken Strömungen verursacht. Altersbestimmungen aus all diesen Sedimentgruppen erbrachten Daten zurück bis in das Mittelholozän und sogar darüber hinaus. Allerdings lag der

Meeresspiegel in dieser Region zu jener Zeit mehrere Meter tiefer als heute und die Küste damit deutlich weiter westlich. Der Transport sehr großer Blöcke erfolgte vor einigen 1.000 Jahren höher und weiter landwärts als selbst die stärksten heutigen Stürme Blockbewegungen verursachen können. Das und die Einbeziehung der Sonderformen erfordert neben starken Stürmen weitere Transportprozesse außerordentlicher Wirkung, und ihr Verhalten in exponierten und geschützten Lagen muss diskutiert werden.

| Journal of Coastal Research | 33 | 5 | 997–1021 | Coconut Creek, Florida | September 2017 |
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# Boulder Ridges and Washover Features in Galway Bay, Western Ireland

**Wibke Erdmann[†]*, Dieter Kelletat[†], and Miriam Kuckuck[‡]**

[†]Institute for Geography and Education
University of Cologne
Cologne 50931, Germany

[‡]Institute for Geography
University of Osnabrück
Osnabrück 49074, Germany

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**ABSTRACT**

Erdmann, W.; Kelletat, D., and Kuckuck, M., 2017. Boulder ridges and washover features in Galway Bay, Western Ireland. *Journal of Coastal Research,* 33(5), 997–1021. Coconut Creek (Florida), ISSN 0749-0208.

Boulder deposits of the Aran Islands in the Galway region (western Ireland) have been under investigation for more than 10 years, whereas marine and littoral deposits inside Galway Bay have only been mentioned cursorily. The aim of this study is to investigate all coastal deposits along the most exposed bay coasts from the opening of South Sound to Black Head 25 km inside Galway Bay. Long ridges with imbricated large boulders exist near the surf belt, whereas boulder deposits in clifftop positions are mostly chaotic. The size of individual boulders is similar to those on the exposed island sites of the Aran archipelago. Landward of boulder ridges, stratified fine sediments occur that point to quiet sedimentary conditions. Two more forms and deposits are mapped that are rarely mentioned for western Europe: boulder ridges with crossway secondary ridges and tonguelike washover deposits of medium boulders, both from extraordinary flow events. Dating of all units resulted in ages back to the first half of the Holocene and mid-Holocene times. During the older periods, sea level in the area was several meters lower than today and the coastline was farther west. Dislocation of very large boulders some thousands of years ago was higher and farther inland than by the strongest storms of recent times. This requires interpretation with respect to formation processes and their results in exposed and more sheltered littoral environments.

**ADDITIONAL INDEX WORDS:** *Coastal sediments, boulder movement, storms, tsunamis, sedimentology, extreme events, Holocene.*

## INTRODUCTION

Holocene coastal boulder deposits on the central west coast of Ireland (Galway Bay and Aran Islands) represent the most spectacular evidence of those features by marine forces yet described worldwide in a natural setting. In several respects, the Galway and Aran boulder deposits surpass all others known: extension for kilometers, elevation above sea level (up to 30 m), distribution to inland (up to 250 m), and the mass of single boulders exceeding 50 or even 70 tons with longest axes of more than 10 m (*e.g.*, Erdmann *et al.*, 2015). These are all larger, higher, or farther inland than similar deposits in SW Iceland (Etienne and Paris, 2010), Banneg Island (Brittany, France, according to Fichaut and Suanez, 2008, 2011; and Suanez, Fichaut, and Magne, 2009), or other exposed shorelines of the world. Boulder ridges and boulder clusters on the Shetland Islands, as described by Hall, Hansom, and Williams (2010), and Hall *et al.* (2006), also have less elevation and landward extension and smaller boulder sizes. Larger boulders or blocks (greater than 100 tons) are only known as single features (*e.g.*, Engel *et al.*, 2014, from the Philippines; Frohlich *et al.*, 2009, from Tonga; or Playford, 2014, from Western Australia).

The natural disposition of boulder movement by marine forces along the Aran Islands is close to an optimum; plunging cliffs are exposed to the fetch of the northern Atlantic Ocean combined with stratified limestone fractioned by joint patterns. This enables marine forces to break off fragments of platy form. However, even the largest fragments represent the maximum transport power of marine forces only if they meet the maximum size classes of individual joint-bound or loose boulders in a relief, which allows maximum inundation and wave run-up values. This is the case in the Galway-Aran region. In most natural settings, boulder size is limited, and one will never know which sizes of boulders would have been moved if present during the strongest impacts.

The 60-km W-E axis of Galway Bay separates a granite landscape in the north from an undulating Carboniferous limestone terrain in the southeast. The overall geomorphology derives from multiple glaciations that extended over the entire bay and the chain of the Aran Islands, disappearing from the area between 17,000 and 16,000 BP (Clark *et al.*, 2012; Diefendorf *et al.*, 2006; Van Asch *et al.*, 2012). The mapping of the sea floor by Sacchetti *et al.* (2011) exhibits end moraines of the last glaciation up to 100 km west of the Aran Islands. Meltwater deepened the sounds framing the Aran Islands (Figure 1) and 50 to 60 m of water is present today. Indications for a total ice cover, at least during the Last Glacial Maximum (LGM), are erratic boulders from Connemara and Galway granite that are present on all Aran Islands but rare between Doolin and Black Head.

Within Galway Bay, cliffs with a maximum of 30 m often exhibit stepped structural platforms down to the foreshore. Maximum cliff heights in the wider area (approximately 70 m) occur on the SW coast of Inishmore Island. The intensity of cliff retreat in the area is under debate: Cox *et al.* (2012), Williams

*DOI: 10.2112/JCOASTRES-D-16-00184.1 received 26 October 2016; accepted in revision 24 January 2017; corrected proofs received 23 March 2017; published pre-print online 8 June 2017.*
*Corresponding author: werdmann@uni-koeln.de
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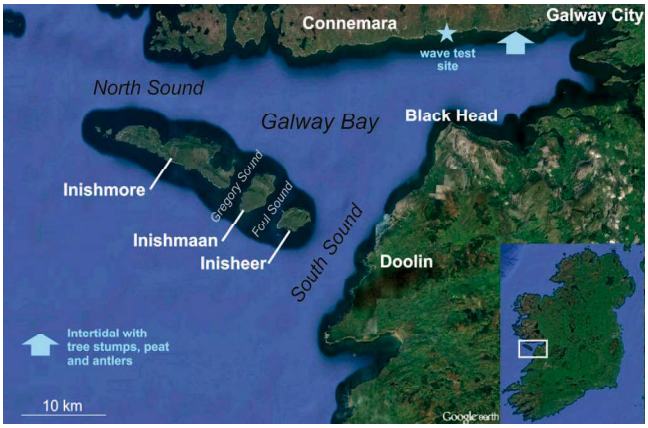


Figure 1. Galway Bay on the central west coast of Ireland. Field studies for this paper have been concentrated on the section from Black Head to Doolin (satellite image: Google Earth). At the Spiddal wave test site (23-m water depth), the maximum wave height during a 5-year period was approximately 3.5 m.

(2004), and Williams and Hall (2004) argue for rates of several decimeters per year (0.2–0.4 m/y, and at some places up to 0.8 m/y). Estimates are smaller and based on well-preserved glacial rock profiles on the east coast of Inishmore and the west coast of Inishmaan. These profiles allow only a maximum of 100-m cliff retreat, because the Holocene high sea level indicates a rate of marine erosion of a few centimeters per year on average (see also Carbone *et al.*, 2013; Devoy, 2008; Hall, Hansom, and Jarvis, 2008; McKenna, Carter, and Bartlett, 2009; Rosser *et al.*, 2005, 2010). This rate is less than that from data from the chalk cliffs of the English Channel (Recorbet *et al.*, 2010) and approximately half rates found in resistant rock by Earlie *et al.* (2015, 0.1 m/y), Lim *et al.* (2010, 2011), and Young *et al.* (2011, approximately 8 cm/y). More arguments for a slow cliff retreat come from karst features (karren or meander karren and rainwater pools) on cliff platforms. The topography indicates that Gregory and Foul Sounds (Figure 1) existed before and during the LGM. Scheffers *et al.* (2009) argued for a small rate of coastal retreat because of the existence of Neolithic to Iron Age middens, Iron Age promontory forts, Viking boat shelters, and medieval castles still close to the modern shoreline or on sheer cliffs. Scheffers *et al.* (2010) added arguments from the development of rock pool belts along the mean high water (MHW) level or from old photographs from distinctive morphological features such as the Wormhole (published by Fehman, 1999, p. 34).

When LGM ice receded from the Galway region from 17,000 to 16,000 BP, Galway Bay was a wide basin 30 to 60 m above sea level, fringed on the west by three main and three minor elongated elevations in the form of cuestas (now the Aran, Brannock, and Rock Islands) (Clark *et al.*, 2012; Diefendorf *et al.*, 2006; Van Asch *et al.*, 2012). Meltwater streams drained the basin through two wide openings in the north and south (North Sound and South Sound; Figure 1) and two smaller channels between Inishmore and Inishmaan and between Inishmaan and Inisheer.

Sea level in the Holocene was never higher than today on the central west coast of Ireland (Bradley *et al.*, 2011; Brooks *et al.*, 2007; Carter, Devoy, and Shaw, 1989; Fleming *et al.*, 1998; Holmes *et al.*, 2007; Lambeck *et al.*, 2014; O'Carra *et al.*, 2014; Orford, Murdy, and Freel, 2006; Peltier *et al.*, 2002; Schettler *et al.*, 2006; Shaw and Carter, 1994; Shennan and Horton, 2002; Shennan *et al.*, 2002; Shennan, Milne, and Bradley, 2012). In addition to geomorphological and sedimentological arguments and those from the modeling of glacioisostatic rebound, the lack or rareness of Mesolithic (7000–4000 BC) and Neolithic or Bronze Age (4000–600 BC) archeological remains in the immediate coastal environment also point to ongoing drowning (Driscoll, 2012; Gosling, 1993). Williams and Doyle (2014) published data for rooted trees (oak from 7200 and 6200 BP and pine from 7400 and 5750 BP) in the lower modern tidal realm in northern Galway Bay exposed by recent storms (compare with Figure 1) as evidence for a sea level 5 m (±1 m) below the present level during their growth periods. Because these tree stumps are covered by freshwater peat up to 2 m, it is assumed that inner Galway Bay was a swampy environment with a coastline farther toward the bay opening in the west. Holmes *et al.* (2007) identified a similar sea-level curve from the karst lake An Loch Mór on Inisheer Island of the Arans, and dating of inactive dunes at Fanore and the time of drowning of their source area resulted in similar data.

The westward opening of North Sound and the southward opening of South Sound allow waves and swell into Galway Bay, which is large enough to develop its own wave regimes during strong storms. Tides are another important factor, ranging from 1.8 m during neap tide to 4.2 m during spring tides at Kilronan (Inishmore) and up to 5.2 m near Galway city (according to Chart 3339, British Admiralty, 2005). Storm surges are a threat to the inner bay shorelines because of the funnel shape of the bay.

Stepped cliff profiles with platforms adapted to strata are characteristic between Doolin and Black Head. Marine indentations are controlled by small valleys or synclines in the rock structure. At Poulcraveen and Cancapple (for locations, see Figure 2), active cobble beaches occur, and sandy beaches occur in Fanore Bay. Dune fields (at Fanore and Doolin) are inactive and covered by dense vegetation. The most significant signature along the coastal section from Doolin to Black Head is boulder deposits up to many meters above the high water mark that consist of single large boulders of many tons in mass (Figures 3 and 4), boulder clusters, or boulder ridges (Figures 4, 5, 11, and 12), as described and documented in detail by Erdmann *et al.* (2015). Their maximum elevation along the SE section of Galway Bay is 23 m above MHW, their width generally is less than 100 m, and their maximum thickness is 5 to 6 m. In contrast to the open SW coasts of the Aran Islands, the foreshore along the section from Doolin to Black Head is mostly shallow; the 20-m isobath is 400 to 700 m from the cliffs. Rockfalls occur along more or less N-S trending joints opened by limestone dissolution and the constant hammering of high storm waves (Earlie *et al.*, 2015). Talus slopes with very large angular blocks may protect the foot section of cliffs. Over many decades of storm impact, these blocks have been tumbled and rounded and their mass has shrunk. The final stage is a near-

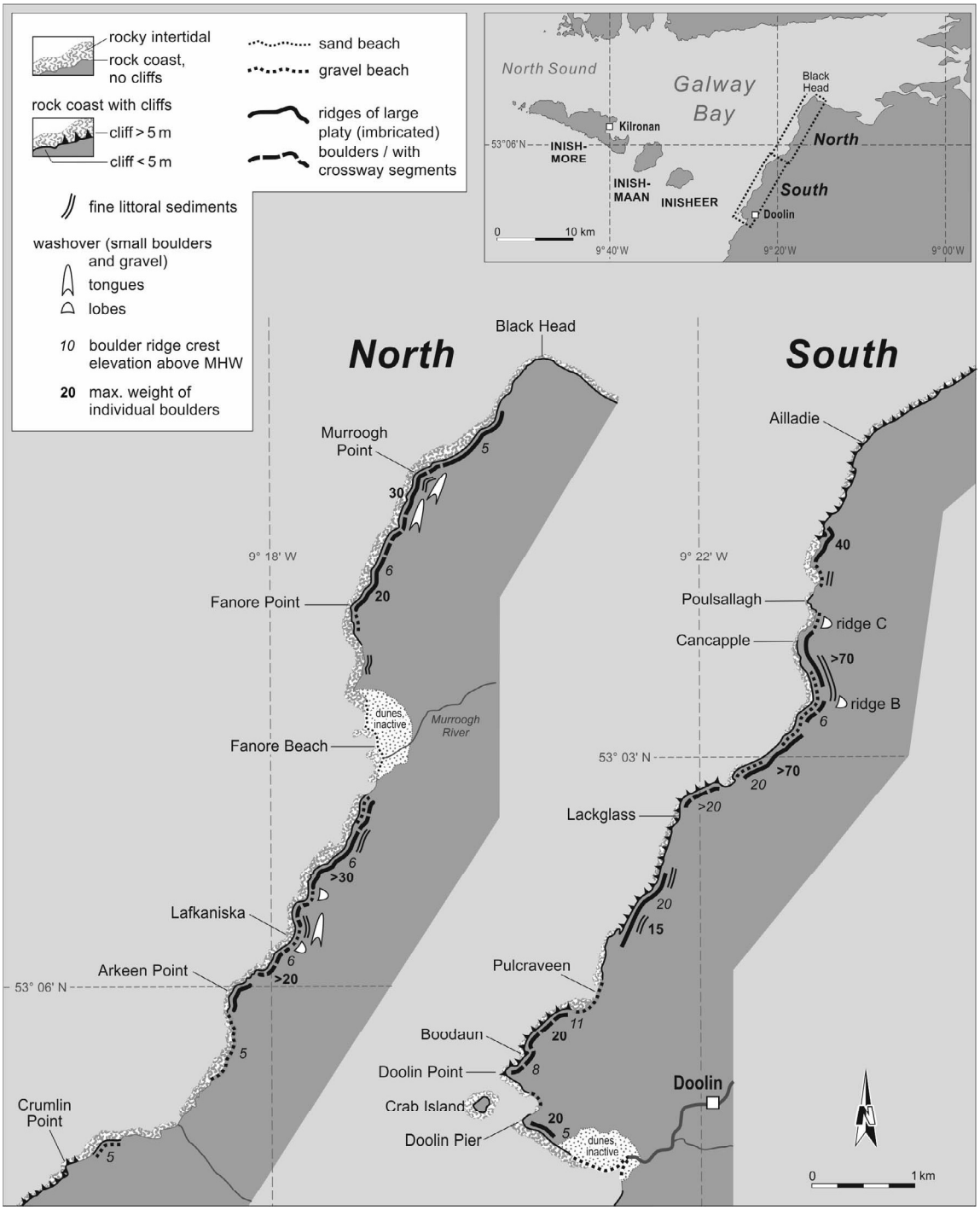


Figure 2. Mapping of the main geomorphological and sedimentological features in the more than 20-km-long study area between Black Head and Doolin, SE coast of Galway Bay, with locations mentioned in the text (cartography: Gudrun Reichert).

total reworking of rockfall products; cliffs may plunge again into deep water, which intensifies wave attack and may lead to the next rockfall. Recession of (vertical) cliffs is an episodic process, and the time frame for collapse and reworking of talus debris depends on exposure to storm waves and particularly on foreshore bathymetry, and it may well happen with temporal steps of centuries.

Wave height observations for the area are found in Aqua-Fact International (2002), Draper (1972, 1991), and Met Éireann (2007). Between January 4 and 6, 2014, offshore

Figure 3. Exceptionally large boulder in clifftop position inside Galway Bay near Lackglass 16 to 17 m above MHW, dislocated from its base layer upward. The longest axis is 6.5 m, the width is 4.1 m, the thickness is 3.4 m, the volume is more than 30 $m^2$, and the mass is more than 70 tons (people shown for scale).

waves were on the order of 30 m and those of approximately 21 m were visible from the coast. Six winter storms in 2013–14, all of hurricane categories 3 and 4, were the strongest during at least the last 60 years in western Ireland. The town center of Galway at Spanish Arch was flooded more than 1 m deep, and the Muirios graveyard's protection wall was knocked over by strong waves, which resulted in human remains being

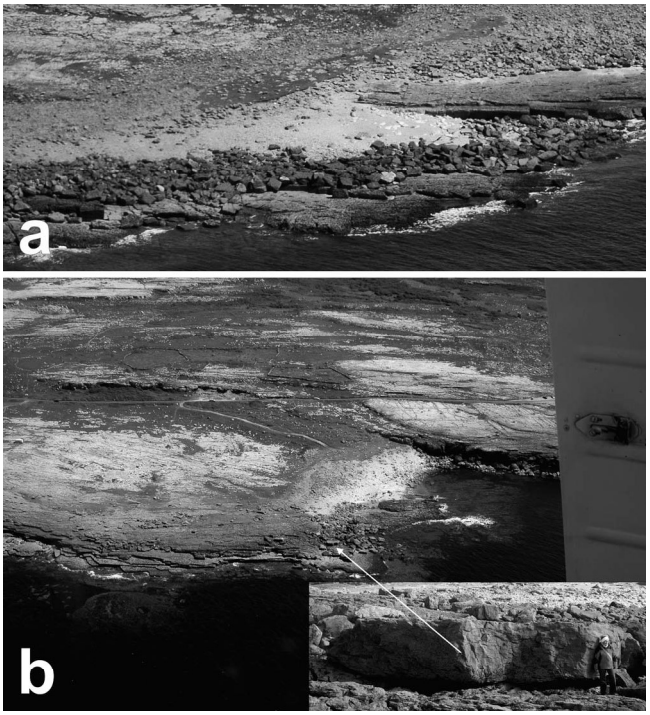


Figure 4. (a) Boulder ridge with platy fragments (2 to 20 tons) between Poulsallagh and Cancapple, separated from the intertidal zone by a belt of base rock. (b) Large boulder (>50 tons) at Poulsallagh, lifted from structural steps (seen from the west or the sea).

Figure 5. Clifftop boulder ridge approximately 1.5 km south of Lackglass and 15 to 18 m above MHW, spanning 178 m N-S and up to 58 m from the cliff edge (seen September 2015). Fragments were activated during the winter storms of 2013–14; fresh outbreaks from cliff steps are absent.

uncovered near the village of Baile na nAbhann. The storm history, with emphasis on exceptional events, is discussed in Brayne (2003); Burt (2006); Hickey (2001); Lamb and Frydendal (1991); MacClenahan *et al.* (2001); O'Brian, Dudley, and Dias (2013); and Shields and Fitzgerald (1989), as well as in Erdmann *et al.* (2015) for the winter season of 2013–14.

## METHODS

This study is based on fieldwork on the Aran Islands and at Galway Bay in 2005 and intensified in 2006 and 2007. In June 2014, a near-time inspection of the morphological and sedimentological results of six extraordinary winter storms of the season 2013–14 followed (Erdmann *et al.*, 2015). Another field survey in September 2015 on the SE coast of Galway Bay put the focus on discrimination of sedimentological units from marine and littoral processes, including sampling of datable material, to establish a first overview on their chronology during the Holocene. Aerial photographs from the National Coastline Survey of Ireland (scale approximately 1:4000; Marine Institute, 2000) and differential GPS were used. Fine sediments were analyzed for stratification, organic content, grain size, sorting, and mineralogy and were investigated by microphotography. Boulder settings were mapped (Erdmann *et*

Figure 6. Fresh angular boulders on a seaward clifftop ridge (most of them taken from the ridge itself) in a chaotic setting.

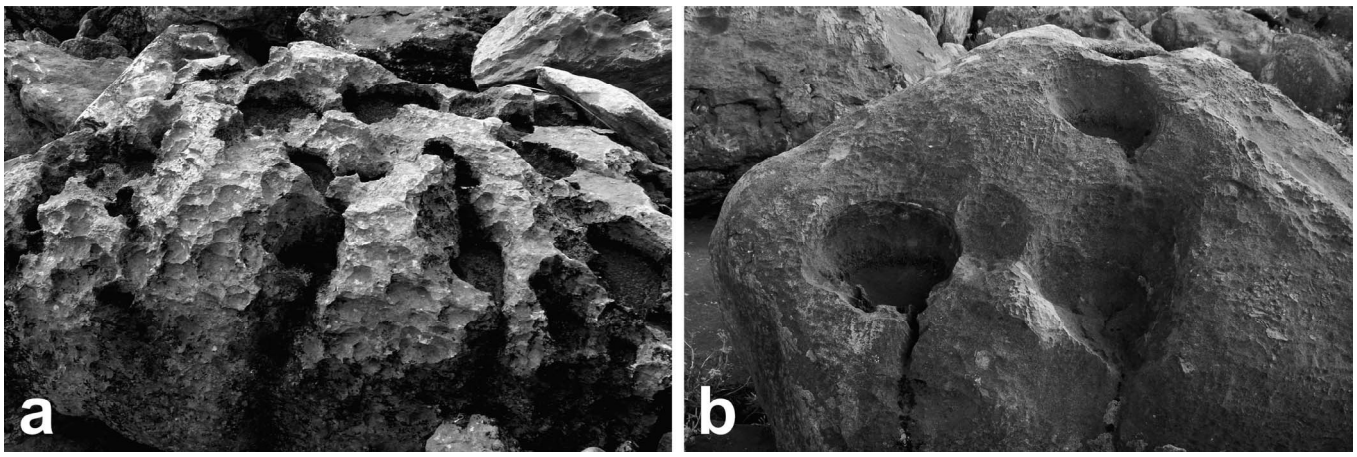


Figure 7. Biogenic flat-bottomed rock pools from the supratidal zone. Dislocation usually results in inclination, which leads to one point of overflow if filled with rainwater and karrenlike features if overflow rills form. Because freshwater dissolution is a slow process (roughly 0.01 m/y to a maximum of 0.1 m/y, according to the height of karst tables under glacial erratics nearby; compare with Godard *et al.*, 2015), boulder deposition without significant later movement points to several hundred to more than 2000 years of formation.

*al.*, 2015), and the organization of boulder clusters and boulder ridges was studied, as were the dimensions of single boulders. Transport processes (shifting, rolling, and saltation) were identified from striations on the limestone bedrock and boulders (Erdmann, Kelletat, and Scheffers, in review), and tests for density of the Carboniferous limestone (2.6 g/cm$^3$) were used to calculate boulder mass from freshly displaced and old boulders.

Several indicators for the relative age of boulder dislocation, such as lichen cover; typical small morphologies from intertidal or subtidal organisms such as sea urchins, limpets, boring bivalves, and *Cliona* borings; and rock pools formed by limestone bioerosion have been studied (Figures 7–10; compare Kelletat, 1986, 1988; Spencer, 1988; Trudgill, 1987; Trudgill and Crabtree, 1987; and Trudgill *et al.*, 1987). Numerical data were obtained from *Hiatella arctica* with its (articulate) shell still in the living position and from marine and terrestrial gastropods from related sediments. The numerical dating technique was radiocarbon accelerator mass spectrometry (AMS; Beta Analytic, Miami, Florida, U.S.A.).

Age data of marine carbonates have the disadvantage of a standard error in age; they are approximately 400 years older than terrestrial remains. In addition, a local or regional difference in age must be calculated (Reimer *et al.*, 2002, 2013; Reimer and Reimer, 2005). The nearest site where a comparison of marine and terrestrial samples has been investigated is from a Norse settlement of early medieval times (Ascough *et al.*, 2006; Ascough, Cook, and Dugmore, 2009) on Omey Island at 53°32′ N and 10°10′ W (50 km north of the North Sound entrance into Galway Bay). Four specimens of *Patella vulgata* and four samples of *Hordeum* sp. (barley) were dated using a marine reservoir error (MRE) for Omey Island of 252 ± 29 years. The Delta R value for the site (the difference from the worldwide standard error used in the calibration curves (*e.g.*, Reimer *et al.*, 2002, 2013; Reimer and Reimer, 2005) is –142 ± 16 years. This value is valid for the last several thousand years (Stern and Lisiecki, 2013) and is supported by a study by Butler *et al.* (2009) of 31 tests of *Arctica islandica*. Marine samples published by Scheffers *et al.* (2010) are corrected in Table 1 for Omey Island's MRE.

Dating deposits and establishing a chronology of events is a challenge in the study area. Geoarchives with fine sediments (silt and sand) are rare, shallow, and occasionally poorly stratified. Deposits of very large boulders in clusters and ridges resting on bedrock usually have no stratigraphic context. Washover lobes and tongues consist of medium boulders without an inner structure and without a stratigraphic relation. The only chance to obtain numerical data from these coarse deposits is from organic material. Because fresh boulders dislocated from the intertidal or subtidal zones often exhibit organic remnants in dense covers (Figure 9b), older boulders rarely show *Hiatella arctica* protected in their borings a few centimeters deep.

Figure 8. Significant dissolution forms on top of a 10-ton boulder from Lafkaniska, giving a tentative minimum age of deposition of more than 500 years (but probably up to approximately 2000 years).

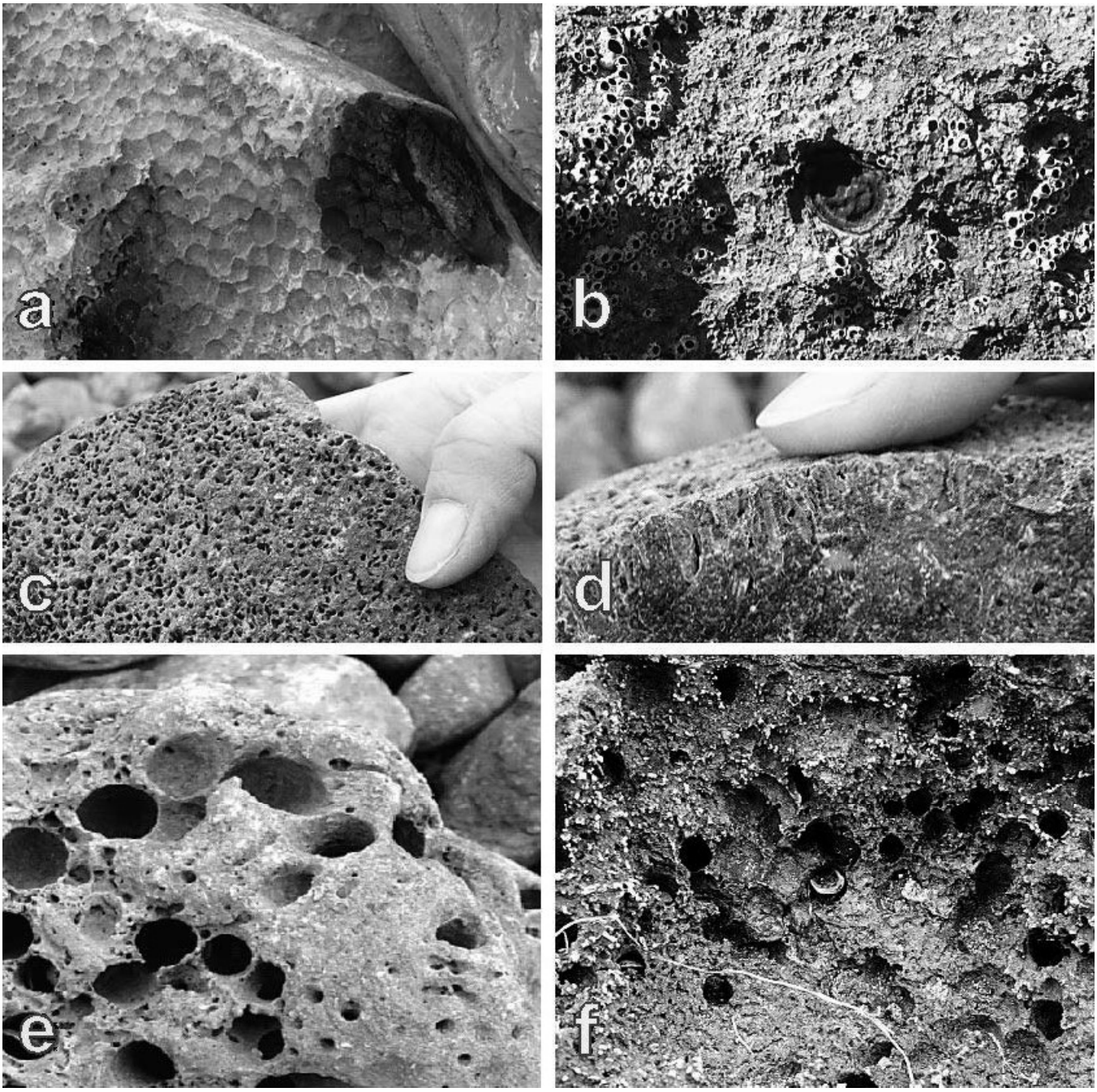


Figure 9. Biogenic signatures on limestone boulders indicating their level of origin: (a) sea urchin *(Paracentrotus lividus)* home places from the upper subtidal zone; (b) *Patella* home place from the intertidal to the lowermost supratidal zones; (c) and (d) sponge borings (*Cliona lampa,* two aspects) from the subtidal zone; and (e) and (f) *Hiatella arctica* borings from the lower intertidal and upper subtidal zones, some with shells in living position.

The data distribution of boulder deposits in the supratidal zone depends on the original distribution of *Hiatella* in its living environment, the dislocation of boulders with *Hiatella* by strong marine processes, the preservation of shells in a supratidal environment, and the visibility and detection of these shells from the uppermost layer of immobile boulders. Overrepresentation of younger dislocation events evidently is real.

Studies in the sedimentology of the coastlines along Galway Bay have been neglected in favor of boulder ridges from the coasts of the Aran Islands along the open Atlantic Ocean. Therefore, the focus of this study is to establish a chronology of coastal deposition along the most exposed sector of the Galway Bay coast from Doolin (at the entrance of South Sound) to Black Head (Figures 1 and 2). As a contribution to the genesis of relic

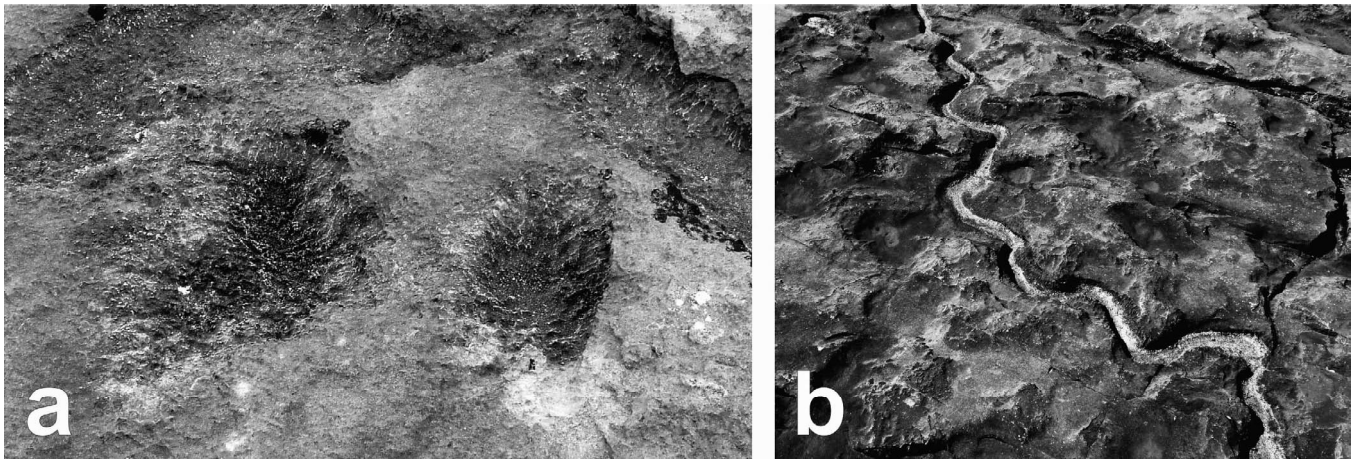


Figure 10. (a) Rainwater dissolution pools with radial microkarren on Carboniferous limestone. (b) Meander karren, 8 cm deep. The scene here is 2 m wide.

forms of earlier marine forces, field observations and dating from boulder ridges and washover deposits are presented. Only large boulders and their dislocation against gravitation, as well as washover features of different forms, are discussed, not their movement in general. The geomorphology of the coastal environment is at least as important for conclusions as sedimentology and numerical dating. Nonetheless, sediment samples are treated for their physical and chemical parameters and texture, structure, and soil development, as well as indicators for transport processes such as storm waves, bores, or (potential) tsunamis, according to the catalog of methods in Goto *et al*. (2015).

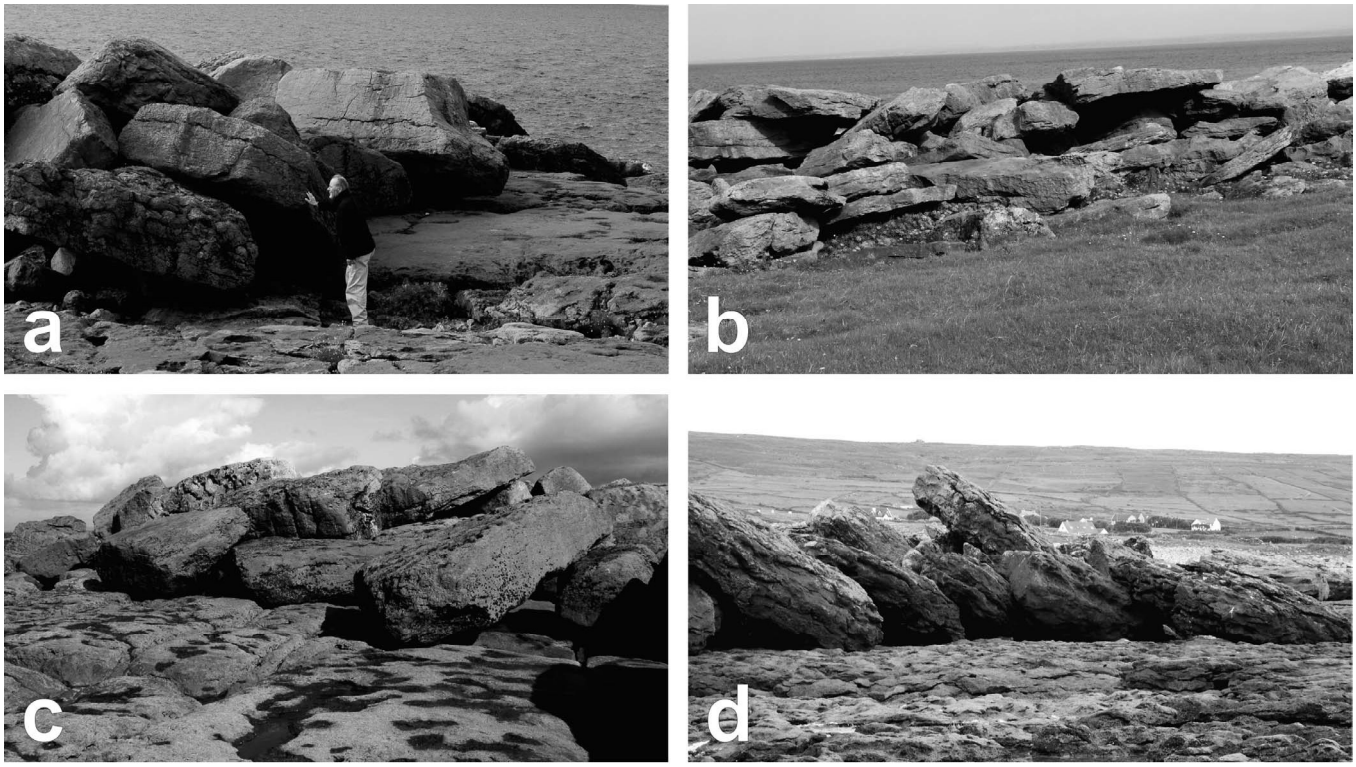


Figure 11. (a) and (b) Landward steep slopes of imbricated boulder ridges built by tabular fragments of many tons (up to 20 tons) in mass at Lafkaniska and Murroogh Point. (c) and (d) Imbrication with seaward dipping forms as stable structures against wave run-up (Poulsallagh area).

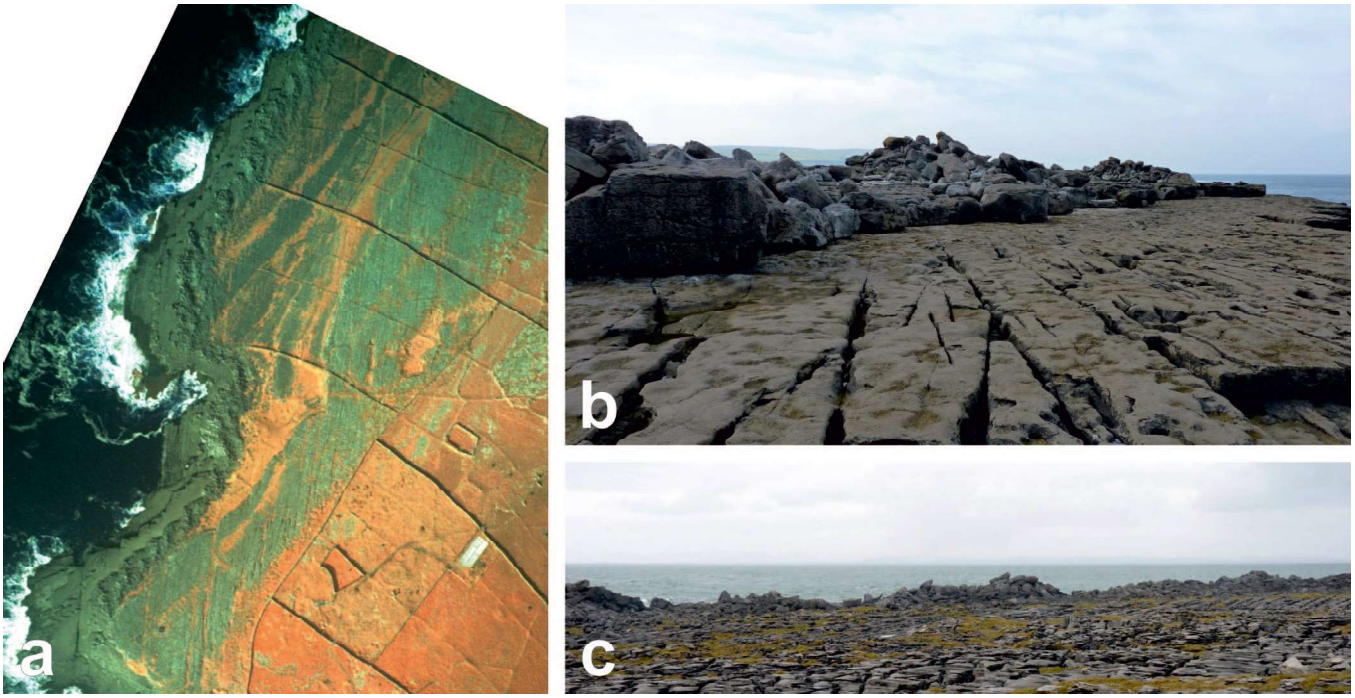


Figure 12. (a) Cliff platform and boulder ridge with individual curved ridge segments from Doolin Point to the north, 8 to 10 m above MHW. The scene is nearly 1 km wide (Marine Institute, 2000). (b) The same location: three secondary cross ridges. (c) Four secondary ridges across the main ridge north of Murroogh Point.

## RESULTS

Spectacular boulders and boulder ridges of the Galway area have been under discussion since 2004 (Cox *et al.*, 2012; Hall, 2010; Hall *et al.*, 2006; Hansom, Barltrop, and Hall, 2008; Hansom and Hall, 2009; Williams, 2004, 2010, 2011; Williams and Hall, 2004; Zentner, 2009) and have been interpreted as resulting from dislocation by (recent) storm waves. These authors exclusively investigated the exposed (W, SW, and S) coastlines of the three Aran Islands (Inishmore, Inishmaan, and Inisheer), but not the sheltered sides of these islands to Galway Bay or the coastlines within the bay. Observations from these settings have been presented by Erdmann *et al.* (2015) and by Scheffers and colleagues (Scheffers *et al.*, 2009; Scheffers, Kelletat, and Scheffers, 2010; Scheffers *et al.*, 2010) as near-time inspection and documentation of all geomorphological features. Because the transport energy of six extraordinary storms of the winter season of 2013/14 in this region (regarded as the most powerful in living memory) was limited compared with older deposits, discussion of the forming forces of boulder features of Galway Bay and the Aran Islands (storms and/or tsunamis) is ongoing.

### Boulders, Boulder Clusters, and Boulder Ridges

Along the Galway Bay coast from Doolin to Black Head, 5.5 km of the coast exhibit boulder ridges and boulder clusters (Figure 2) in which boulders of at least 2 m in length and 5 tons in weight (Figures 4, 5, and 11) are incorporated. Stratified limestone bedrock with bedding planes and joint patterns allows strong wave fracturing into platy boulders, deposited in ridges based above MHW and some distance from the surf belt

Table 1. *Numerical data of large boulders from the main seaward ridge from Galway Bay and Aran Islands. All data taken from the boring marine bivalve* Hiatella arctica *out of boulders.*

| Beta Lab No. | Location | Elevation (m + MHW) | δ13C | Conventional Age | 2σ cal BP† |
|---|---|---|---|---|---|
| 233799 | Inishmaan S | 5.0 | −2.1 | 610 | 450–380 |
| 428914 | Lafkaniska | 2.8 | +0.1 | 760 | 545–475 |
| 233793 | Inisheer SW | 2.0 | −1.5 | 670 | *610–440* |
| 233783 | Murroogh Point | 2.0 | +0.6 | 830 | *650–570* |
| 233797 | Inishmaan S | 3.0 | −0.3 | 850 | *660–570* |
| 233798 | Inishmaan S | 5.1 | −4.8 | 860 | *660–570* |
| 233784 | Murroogh Point | 2.4 | +0.4 | 900 | *690–610* |
| 233786 | Cancapple N | 6.0 | −0.7 | 910 | *700–610* |
| 233787 | Cancapple N | 4.5 | −10.0 | 1020 | *800–670* |
| 233795 | Inishmore W | 5.8 | −1.9 | 1110 | 860–760 |
| 233792 | Inishmore Wormhole | 6.1 | −0.2 | 1190 | 940–800 |
| 428913 | Lafkaniska | 2.6 | +0.8 | 1200 | 945–810 |
| 233790 | Inishmore N | 4.5 | −1.3 | 1210 | *980–810* |
| 233788 | Cancapple N | 5.0 | −1.6 | 1250 | *1030–840* |
| 233794 | Inishmore W | 5.0 | −1.4 | 1310 | *1070–900* |
| 428909 | Lafkaniska | 3.5 | +1.2 | 1400 | 1175–1030 |
| 233791 | Inishmore N | 4.5 | −0.9 | 1540 | *1320–1130* |
| 428908 | Lafkaniska | 3.5 | +0.1 | 1630 | 1370–1265 |
| 233796 | Inishmore W | 18.0 | −7.8 | 2070 | 1870–1680 |
| 233782 | Murroogh Point | 4.0 | −1.9 | 3620 | *3760–3570* |
| 428907 | Lafkaniska | 3.5 | +0.3 | 8060 | 8840–8825 |
| 428906 | Lafkaniska | 4.2 | +0.3 | 8540 | 9435–9280 |

†*Ages from a former publication (Scheffers* et al.*, 2010) are set in italics. All data are corrected to MRE from Omey Island (–142 ± 16; see Ascough* et al.*, 2006; Ascough, Cook, and Dugmore 2009).*

or more chaotically in the clifftop position. The large size of the boulders prevents transport except during extreme storm conditions.

Boulders are discriminated in three groups: according to their form, according to their origin, and corresponding to their age. More than 95% of the ridge boulders in the study area are Carboniferous limestone, which points to local sources. From their origin, they show two form types. Those broken from bedrock are platy from limestone strata with constant thickness. A group of smaller boulders (<1.5 m in diameter or length) is (partly) rounded, modeled by glacier transport and surf beat. They resemble glacial erratics posted on limestone plinths (karst tables). In some places, rounded sandstone cobbles mix with boulders.

The second group of boulders points to their origin from the supratidal zone, including structural steps and cliff tops where strong wave and bore impacts break off tabular boulders, or the intertidal to lower supratidal zone, where specific secondary forms on the boulders give hints to their former places. These can be differentiated in rock pools from lower supratidal or upper intertidal zones (Figure 7), round borrows by sea urchins from lower intertidal or higher subtidal zones (Figure 9a), limpet home places (Figure 9b), sponge borings (*Cliona* spp.; Figure 9c,d), and boring bivalves (*Hiatella arctica;* Figure 9e,f).

A third group of large boulders exhibits signatures of the age of dislocation. These signatures are weathering with (partial) rounding of edges; formation of karren and rainwater pools, particularly on flat-lying boulders; and a significant change in the shape of bioerosive forms. Other indicators are the presence or absence of organic crusts from calcareous algae, vermetids or barnacles, the preservation of bivalves in their borings, and a cover of lichen, particularly *Caloplaca* and *Xanthoria* spp.

It is possible to order boulders based on their setting before dislocation: submerged (those with organic crust or borings), subaerial (those with rainwater karren existing before dislocation and partly affected by or after transport), and joint bound (sharp-edged tabular boulders without biogenic formation). Their upper and lower planes may well exhibit dissolution forms, but their outer contours point to mechanical outbreak.

Boulders accumulated in ridges close to the sea often show perfect imbrication dipping to seaward (which is a westerly direction; Figure 11). Evidently, imbrication stabilizes the ridge construction, and strong waves may run up seaward boulder ridges and plunge down to the leeward side. This results in an asymmetrical ridge profile. In contrast, boulder ridges in a clifftop position exhibit only a few places with some imbrication and are more chaotically organized. Their seaward slope is steep, and the landward slope is rather flat.

According to numerical data (Table 1), the study site along the SE coast of Galway Bay has been an open rocky coastline with significant wave power for at least the last 6000 years. However, the modern situation is more suitable for boulder dislodgement than earlier Holocene periods simply because of coastal recession over several thousand years and today's higher sea level. Boulders in clusters and ridges on land that have been stable for a long time must have been moved by higher transport energies and stronger marine processes compared with a fresh boulder added with the same mass, elevation, and distance to the cliff in recent years. In their detailed field research, Williams and Hall (2004) stated that older ridges represent the results of more extreme events than those in modern times and that storms must have been stronger and may well have been so rare that they would occur only at intervals of millennia.

Based on near-time inspection after six exceptionally strong storms of the winter season 2013/14 (Erdmann, Kelletat, and Scheffers, in review; Erdmann *et al.*, 2015), the larger 80% of individual boulders in ridges have not been moved recently or within the last centuries; this was concluded from weathering, lichen cover, and numerical dating evidence. Based on forms and ages of boulder deposits in Galway Bay and along exposed and sheltered coasts of the three Aran Islands, tsunami impacts in this area are discussed during the Younger Holocene as a genetic factor, in addition to storms (Scheffers *et al.*, 2009, 2010; Scheffers, Kelletat, and Scheffers, 2010). This conclusion is supported by the strange geomorphology of boulder ridges with ripple marks on their landward slope (indicating strong overflow) and ridges constructed of curved single segments running crosswise to the general shore-parallel ridge direction (as in Figure 12).

In the field, it is evident that large boulder ridges span at least hundreds of years of deposition; however, numerical data are needed for more substantial conclusions and to include genetic problems. Cox *et al.* (2012) argued for storm wave dislocation (only) and that ridges gain mass over time (over approximately 2000 years). There is doubt that this is true. Dating from the inner bay ridges spans a time frame of more than 9000 years (Table 1), and additions of fragments during strong events, and in particular a loss by backwash into the sea, take place. More datable material is hidden in the boulder deposits, and more research is needed to identify their true history.

AMS data between 9400 and 8600 cal BP (Beta Analytic, Miami, Florida, U.S.A.) from boring bivalves in large boulders sounds strange; however, if these data are doubted, all other data from boring bivalves in limestone boulders have to be doubted. According to postglacial sea-level curves (*e.g.*, Fleming *et al.*, 1998), sea level around 9000 BP was 20 to 30 m below the present level, which in Galway Bay means a distance to the modern shoreline of 2.4 km for the 30-m isobaths, 1 km for the 20-m isobaths, and 500 m for the 10-m isobath (according to Chart 3339, British Admiralty, 2005, and INFOMAR, 2006, soundings). The potential transport distance for old boulders found today above MHW might be between 1 and 2 km and from 25 to 35 m against gravitation, but it is still not known whether this distance was accomplished by one movement (*e.g.*, by a strong tsunami) or by multiple movement steps (by tsunamis or storm waves or bores). However, it is unlikely that boulders with boring bivalves dislocated from their habitat have been broken from bedrock close by, because the *Hiatella arctica* habitat was 1 to 2 km from the site of deposition around 9000 BP. A strongly cemented deposit of mixed coarse sand, shells, and small boulders exists at the base of the old seaward ridge at Murroogh Point. Its age was dated for two samples of limpets to 4340–4130 and 4095–3910 cal BP. At that time, sea level in the area was more than 3 m lower than and more than 200 m seaward of the present level. A similar, but not

Figure 13. (a) and (b) Terracelike stratified washover deposits under strong lateral erosion. Examples are from south of Poulsallagh, 8 m above MHW and approximately 70 m inland of the MHW line. (c) Approximately 1.5 km south of Lackglass, stratified sand and silt are preserved 16 to 18 m above MHW and up to 50 m from a cliff top, with 0.3 m of silty sand at the base and 0.3 m of slightly stratified fine to medium sand with fine shell hash on top.

cemented, chaotic deposit was found at the base of the segmented large boulder ridge north of Doolin Point around 9 to 10 m above MHW. Data go back to nearly 6000 cal BP in boulders forming washover lobes nearby and landward of the main ridges (see "Lobate Washover Features").

## Finer Washover Sediments

Landward of the ridges of large boulders, washover deposits with silt, stratified coarse sand, shells, pebbles and cobbles exist (Figures 13, 17, and 18). Others are chaotic (Figures 14 and 15) and without stratification (either silty or a mixture of shell fragments and coarse sand and granules), which makes interpretation difficult. The material is aragonite from shell and calcite particles from limestone. These terracelike sediments that exist as a rather thin cover on structural or morphological steps all have a marine or littoral origin. Gastropods are mostly well preserved, and gastropod fragments are often rounded. These particles also occur singularly or in strata between sand layers within coastal indentation with modern gravel beaches. Sorting often is bad (Figures 14–17). Fourteen sites were studied, and 26 samples were taken from six of them for AMS dating (Table 2).

Geoarchives with finer sediments (silt, sand, granules, and pebbles) are local features and occur landward of high ridges of very large boulders and in clifftop positions up to at least 20 m above MHW in a few places. The most probable locations for sediment archives in the coastal landscape that are closed basins such as small karst depressions in reach of ocean waves and small dry valleys blocked by many meters-high coarse clast beach ridges constructed over several thousand years are tested. At these special sites, no stratified sediments, shells, shell debris, or peat layers exist, only silty or sandy structureless deposits approximately 0.5 to 1.3 m thick with dark brown soil over their total depth and covered by dense grassy vegetation. The lack of peat may be the result of good drainage on jointed limestone bedrock, and the lack of shell fragments may be a result of dissolution over time in brown soil.

Terracelike shallow deposits are under lateral erosion by storms and will probably disappear within the next few decades, because their elevation is only between 2.5 and 8 m above MHW. Those S and N of Lackglass and 18 and 21 m above MHW were also attacked by the storms of 2013/14, although they are positioned several decameters from cliff tops to inland. The deepest trench in these terraces, down to a layer of boulders, was 1.3 m (Figure 15) near ridge B of Cancapple. Slight changes in soil horizons Ah to B and Bt at that site point to more than one erosion process. Eight samples from the top to the base show inversions with a base age of nearly 6000 cal BP, a top base of 300–230 cal BP, five data samples between 2800 and 1800 cal BP, and one sample at 1100 cal BP (see also Table 2).

The oldest age found in these shallow sediments was 5990–5880 cal BP at Cancapple's ridge B and 4710–4530 cal BP 2 km south of Black Head; the youngest, between the Lafkaniska washover tongue and the seaward coarse boulder ridge, were 250–0, 265–70, and 315–245 cal BP. A small collection of juvenile gastropods (Figure 16c) from Murroogh had an age of 2730–2605 cal BP, corresponding to ages of 2850–2730 cal BP for the deepest profile of Cancapple ridge B from an

Figure 14. (a) Exposure of chaotic marine sediment at a storm cliff south of ridge C at Poulsallagh on reddish clay (81% silt and clay with granules of quartz and feldspar, and only 1% C, polymodal poorly sorted, symmetrically skewed, and platykurtic; a similar "red clay" at the base of the inactive Doolin dunes has been dated by Williams and Doyle, 2014, to 6636–6440 cal BP). The base is a thin layer of LGM ground moraine. (b) A closer look exhibits well-rounded cobbles, pebbles, granules, shell fragments (marked by circles), and a larger mud clast. The largest *Patella* shell (upper left) is dated to 2775–2695 cal BP.

approximately 60- to 70-cm depth and an age of 2775–2695 cal BP at a depth of 45 cm at ridge C (200 m to the north near Poulsallagh). Profile B also gave data for 2485–2305 and 2354–2255 cal BP between 85 and 110 cm below the surface; the latter data correspond to a 93-cm depth below the surface 30 m to the north in a profile with an age of 1730–1565 cal BP located 43 cm below the surface and two data samples of 1180–1040 and 1170–1000 cal BP located 33 to 36 cm below the surface. Murroogh Point had the only site where one could identify upward-graded bedding (Figure 19) in a shallow setting corresponding to ages of 2325–2150 cal BP located 34 cm, 1980–1825 cal BP located 20 cm, and 1095–940 cal BP located 10 cm below the surface.

Although ages between 1000 and 2000 cal BP correspond to sea levels significantly (2–5 m) below the present level and coastlines a few hundred meters to seaward, no further recent sedimentation has occurred at any site mentioned.

Williams (2011) argued that taking shells to establish a chronology of events for megaclast ridges is "scientifically unsound and the result with their wide variation of ages are best explained as periodic sampling by extreme waves of natural shell population from offshore environments in western Ireland" (Williams, 2011, p. 26). From field studies and datings, following this argument is not supported; *Hiatella arctica* is killed by the first movement of their home boulder, the dated age will preserve this moment, and the shell will not be replaced by younger specimens. Replacement is possible with the strong shells of littorinids (and other gastropods from offshore and the intertidal zone, such as *Natica* and *Nucella* spp.). Data mixing and data inversions are found only within less or nonstratified sandy deposits. The youngest age points to

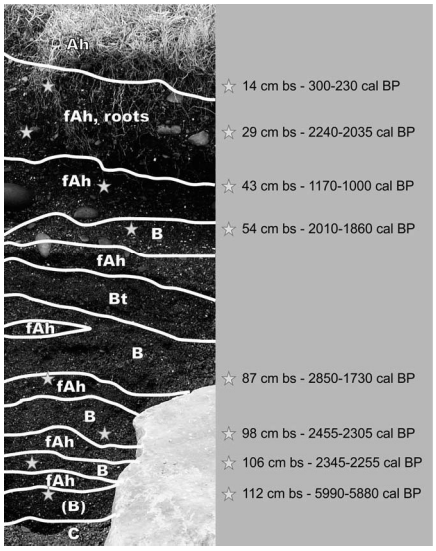


Figure 15. Section more than 1.2 m deep and 7 to 8 m above MHW 80 m from the MHW line south of Cancapple (ridge B). Oriented cobbles occur in the upper section, and granules with remnants of several soil horizons form the main deposit. The history of sedimentation is complex, showing data inversions, an old base datum, and a young top datum. A tentative interpretation may show at least four events: the oldest up to and around 5990–5880 cal BP; a younger one from 2345–2255 cal BP, taking deposits at least from 2850 cal BP on; another one at a maximum age of 1170 cal BP, moving sediments back to 2240 cal BP; and a last and young one between 300 and 230 cal BP. The difference in disturbed soil remnants between 54 and 87 cm below the surface supports this rough event history but does not fully tell the story.

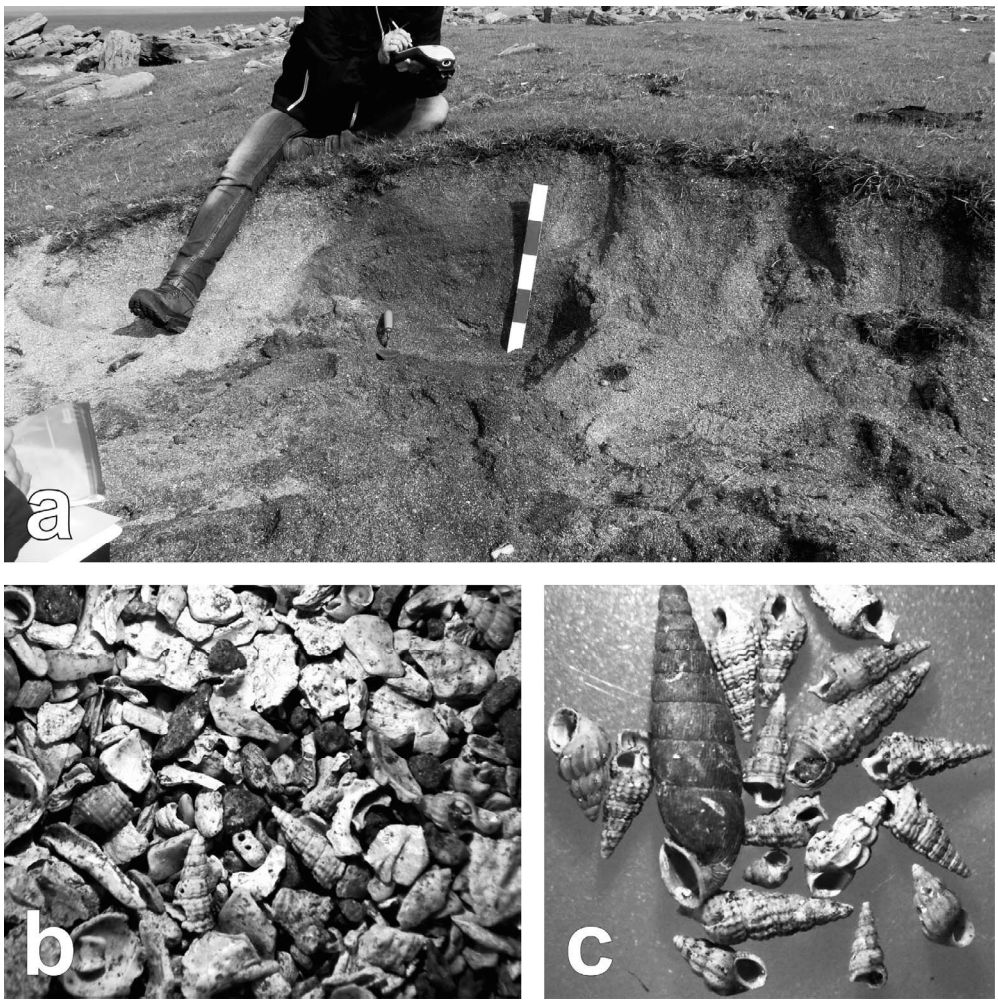


Figure 16. (a) Terracelike deposit south of Murroogh Point built by more than 80% of angular shell fragments (1–1.5 mm), juvenile gastropods, and less than 20% of granules and coarse sand, partly well rounded. The site is 4 m above MHW and 40 m from the MHW shoreline behind a ridge of large old boulders, and it exhibits no clear stratification. (b) Shell fragments dated 2130–1985 cal BP from 63 cm below the surface. (c) Juvenile marine gastropods (longest is 8 mm) from 75 cm below the surface, dated 2730–2605 cal BP.

the last dislocation event (not excluding several events of older age). In well-stratified sediments, all data show a clear history according to the stratigraphic principle. Where erosive contacts are not identified, new strata are identified by younger data, and several samples from the same stratum are in a similar time frame (as in Figure 18b).

## Lobate Washover Features

Washover features not yet described for Ireland or northern Europe exist along the SE coast of Galway Bay. These are lobes of small to medium boulders from intertidal and subtidal zones, documented by *Hiatella* borings. The lobes are more than 120 m long and more than 30 m wide and have a depth of several meters. In the region of Cancapple and Poulsallagh, as well as S and N of Lafkaniska, ridgelike lobes occur with their landward inactive slopes up to 100 m from MHW and elevations of 6 m. With a length of 50 to 100 m parallel to the coast, they contain 4000 to 10,000 $m^3$ of small to medium boulders. Tonguelike shapes dominate (Figure 2) at Lafkaniska and Murroogh Point (Figures 20–23). Their mass is larger than that of the ridgelike-shaped washover lobes: with a length of 140 m, a width of 42 m, and a thickness of more than 2.5 m, the Lafkaniska tongue (Figure 21) has a volume of approximately 15,000 $m^3$. With an estimated pore volume of 35% (during dislocation filled with water and fine sediments, overcoming internal friction), this amounts to a mass of approximately 25,000 tons dislocated in one step. The northern Murroogh Point tongue (Figure 22) is 120 m long with an average width of 30 m and an average thickness of nearly 3 m; this results in a volume of 10,000 $m^3$ and a mass of boulders (with reduction of 35% as pore volume in the tongue) of approximately 16,000 tons. The tongues are separated from the present shoreline by a high stable ridge of very large boulders and depressions with stratified sediments. All lobes and tongues are old deposits; the Lafkaniska lobe was not affected by the extraordinary winter storms of 2013/14. The

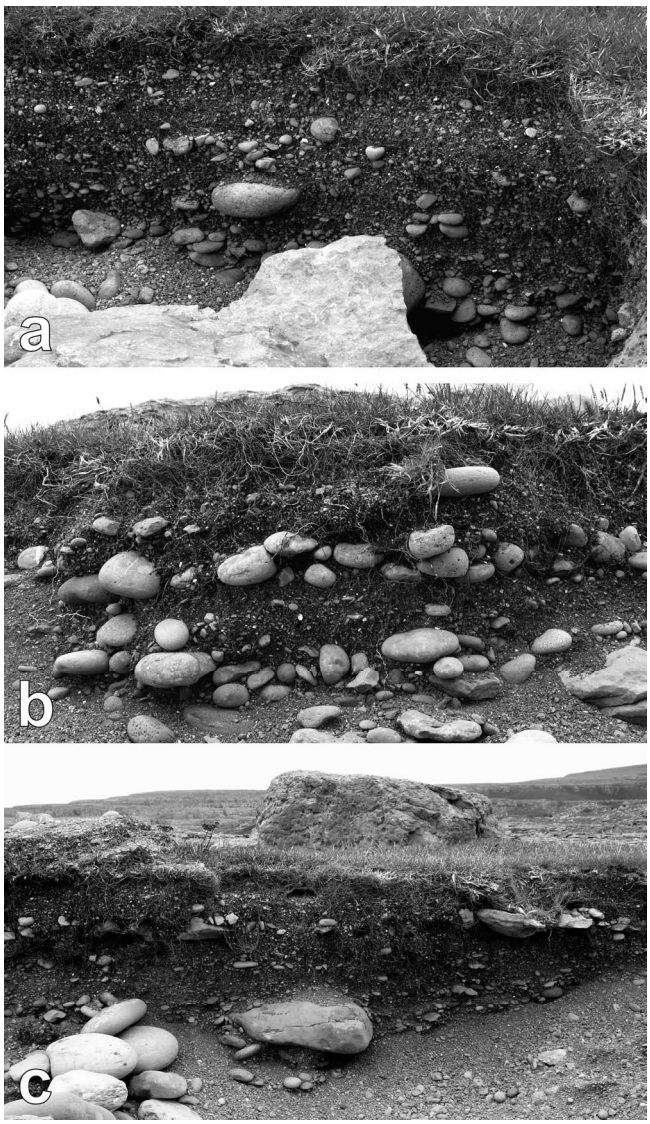


Figure 17. Stratified coarse sand, cobbles, and small boulders between Cancapple and Poulsallagh (compare Figures 1, 2, and 13). The geoarchives are 0.4 to 1.3 m deep and based on medium boulders, including those with *Hiatella* borings. Most pebbles and cobbles are clearly oriented, but stratification changes laterally within meters and sorting is generally bad. Samples of marine gastropods show consecutive data according to depth below the surface (bs):
33 cm bs = 1180–1040 cal BP
36 cm bs = 1170–1000 cal BP
43 cm bs = 1730–1565 cal BP
93 cm bs = 2345–2255 cal BP

Murroogh Point lobe shows activation of existing coarse gravel from the west at its seaward slope. The formation process of the lobes was from SSW to S. It is assumed that each of the lobes was formed by one extreme event that dislocated a huge mass of small and medium boulders at each site from a boulder beach and a sublittoral boulder deposit. The northern lobe of Lafkaniska was later cut by a long erosional scarp in the west.

Sharp contours around the lobes, steep and stable landward slopes, and masking of soil and vegetation along the eastern sides clearly show that the large washover forms are old features deposited from the SSW direction. Few numerical data were gained from the deposits, and they came exclusively from *Hiatella arctica* preserved in boulders. Ages of 5875–5690 and 5715–5580 cal BP were obtained from the thickest (southern) section of the Lafkaniska washover (Figures 23 and 24). The oldest age of the northern Murroogh tongue yet dated is 4980–4810 cal BP. Activation phases are documented from boulders with *Hiatella* shells; the southern Murroogh lobe gave ages of 665–555 and 425–280 cal BP and the northern Murroogh tongue gave five ages between 690–620 and 420–275 cal BP (Table 3).

## DISCUSSION

Based on regional data (Bradley *et al.*, 2011; Brooks *et al.*, 2007; Holmes *et al.*, 2007; Lambeck *et al.*, 2014; O'Carra *et al.*, 2014; Orford, Murdy, and Freel, 2006; Schettler *et al.*, 2006; Shennan, Milne, and Bradley, 2012; Williams and Doyle, 2014), a sea level 4 to 5 m lower 6000 years ago and approximately 2 to 3 m lower at 2000 BP is estimated, with the shoreline away from the modern one. This is significant for wave and bore processes at low-lying coastline sections, where bore inundation today reaches less than 100 m inland. It is not as significant for plunging cliffs, where boulder movement takes place up to approximately 20 m above MHW. However, one must keep in mind that foreshore conditions are not precisely known because of the lack of soundings.

The coastal section from Doolin to Black Head has significantly retreated for thousands of years along vertical cliffs and stepped rocky shorelines. Two areas with inactive dunes (at Doolin, with 0.25 $km^2$, and at Fanore, with 0.6 $km^2$; Figures 2 and 25, respectively) are cut by storm cliffs, and their former sand deposits have been drowned by several meters of water. This drowning also gives evidence for a significantly lower sea level (with the MHW shoreline at least 400 m from the modern one) at the dating times of gastropods (3300–3900 cal BP) within the dunes (Table 4).

Dunes at Fanore Beach and Doolin are colored brown down many meters from the surface because of iron mobilization (from mica) and infiltration in a humid climate. Organic content is extremely low (<1% in general). Two pairs of terrestrial gastropods (Figure 26c), each taken at a vertical distance of 1 m, gave ages of 3905–3820 to 3570–3445 and 3690–3660 to 3455–3365 cal BP, respectively, commensurate with the inactivity of the dunes over a long period. The calculation of age against sediment thickness results in sedimentation rates of less than 1 cm/y. Although coastal dunes in a humid climate quickly stabilize by vegetation, sedimentation rates are highly uncertain because many discordances occur in dune stratification. Thin bands of caliche point to quiescent periods with carbonate enrichment along silty layers (Figure 25).

Some coastal sediment units, even if 2000 years old or older, were partly activated during recent strong wave and bore impacts. This is particularly the case for beach ridges of small boulders, where fragments were tumbled on the seaward slopes and partly over the crest. Washover lobes formed by similar gravel but farther landward were activated partly at Murroogh

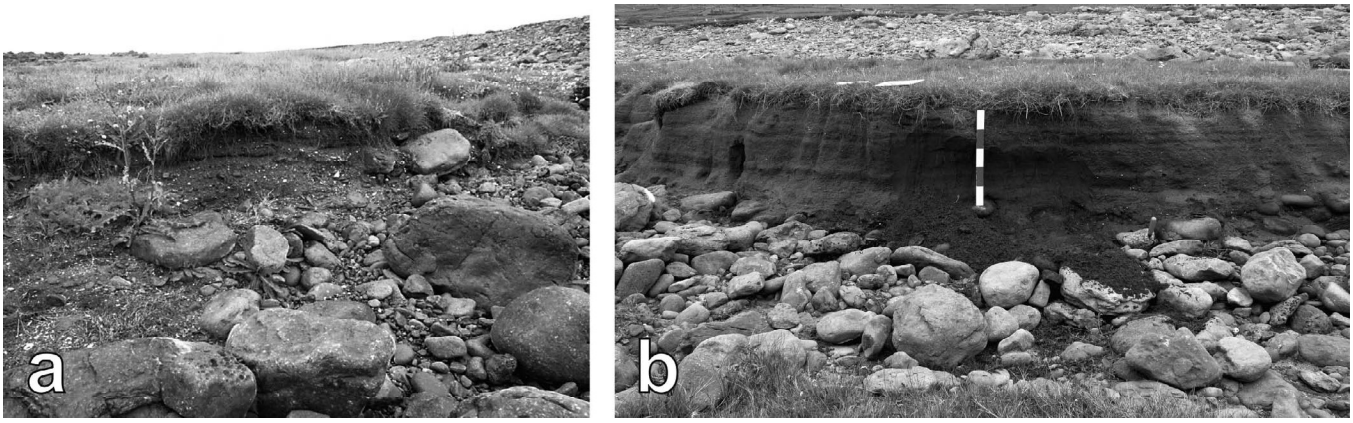


Figure 18. Two aspects of fine stratified sediments at Lafkaniska around 2.5 m above MHW and 30 to 40 m from the coastline based on rounded marine boulders. (a) Coarse sand with pebbles, shell hash, and preserved gastropods. (b) Stratified silt to medium sand with fine shell hash and single gastropods. This deposit has a maximum thickness of 0.9 m (scale of 0.5 m), contains 6% clay, and shows a brown soil over its vertical span. Gastropods from the same layer at 35 cm below the surface gave ages of 315–245, 265–70, and 250–0 cal BP.

Point, but not at Lafkaniska. The most recent impact occurred during the extraordinary 2013/14 winter storms of hurricane categories 3 and 4. In 2000, the year of publication of aerial photos of the Marine Institute's National Coastline Survey of Ireland, and at least in 2007, during early inspections, the surface of these ridges had a darker color with a patina of (epilithic and endolithic) cyanobacteria on or in the limestone.

Since the first detailed studies on the Aran boulders (Williams, 2004; Williams and Hall, 2004), the focus of explanation of the transport mechanisms of these extraordi-

Table 2. *Numerical data from more or less stratified finer marine sediments.*

| Beta Lab No. | Location | Material | Elevation (m + MHW) | δ13C | Conventional Age | 2σ cal BP[†] |
|---|---|---|---|---|---|---|
| 428910 | Lafkaniska | Marine gastropod | 1.2 | +1.9 | 370 | 250–0 |
| 428912 | Lafkaniska | Marine gastropod | 1.6 | +2.1 | 400 | 265–70 |
| 428920 | Cancapple N | Marine gastropod | 8.0 | +2.2 | 470 | 300–230 |
| 428911 | Lafkaniska | Marine gastropod | 1.4 | +1.3 | 490 | 315–245 |
| 428949 | Murroogh Point | *Patella* sp. | 3.4 | +1.7 | 550 | 420–275 |
| 428933 | Murroogh Point | *Hiatella arctica* | 3.3 | +0.9 | 550 | 420–275 |
| 236709 | Inishmore Black Fort | *Mytilus* sp. | 28.0 | −0.6 | 550 | *420–310* |
| 236711 | Inishmore | *Mytilus* sp. | 28.0 | 0.0 | 550 | *420–310* |
| 428915 | Fanore S | Marine gastropod | 3.7 | +2.0 | 670 | 500–410 |
| 428929 | Murroogh Point | Marine gastropod | 1.9 | +1.3 | 1000 | 740–645 |
| 236712 | Inishmore E | *Mytilus* sp. | 30.0 | −1.9 | 950 | *760–630* |
| 428928 | Murroogh Point | Marine gastropod | 1.9 | +1.5 | 1330 | 1095–940 |
| 428922 | Cancapple N | Marine gastropod | 7.75 | +3.1 | 1390 | 1170–1000 |
| 428919 | Cancapple N | Marine gastropod | 6.9 | +1.3 | 1390 | 1180–1040 |
| 428917 | Cancapple N | Marine gastropod | 6.7 | +0.4 | 1410 | 1200–1060 |
| 428918 | Cancapple N | Marine gastropod | 7.0 | +2.4 | 1940 | 1730–1565 |
| 428948 | Murroogh Point | Marine gastropod | 3.5 | +2.4 | 2150 | 1980–1825 |
| 236708 | Inishmore | *Mytilus* sp. | 18.0 | −0.2 | 2210 | *1990–1840* |
| 428923 | Cancapple N | Marine gastropod | 7.6 | +2.7 | 2180 | 2010–1860 |
| 428932 | Murroogh Point | Marine gastropod | 3.6 | +2.0 | 2270 | 2130–1965 |
| 428921 | Cancapple N | Marine gastropod | 7.9 | +3.0 | 2330 | 2240–2035 |
| 428950 | Murroogh Point | Marine gastropod | 3.3 | +1.5 | 2430 | 2325–2150 |
| 428926 | Cancapple N | Marine gastropod | 7.05 | −1.0 | 2470 | 2345–2255 |
| 428944 | Cancapple N | Marine gastropod | 6.4 | +2.5 | 2470 | 2345–2255 |
| 428925 | Cancapple N | Marine gastropod | 7.3 | +0.3 | 2540 | 2455–2305 |
| 428931 | Murroogh Point | Marine gastropod | 3.6 | +1.4 | 2740 | 2730–2605 |
| 428945 | Poulsallagh S | Marine gastropod | 6.1 | −0.4 | 2820 | 2775–2695 |
| 428924 | Cancapple N | Marine gastropod | 7.2 | +0.7 | 2880 | 2850–2730 |
| 236710 | Inishmore Black Fort | *Mytilus* sp. | 25.0 | +1.0 | 3370 | *3480–3280* |
| 428951 | Murroogh Point | *Patella* sp. | 2.6 | −0.9 | 3860 | 4095–3910 |
| 428938 | Murroogh Point | Marine gastropod | 2.8 | +0.5 | 4010 | 4340–4130 |
| 236707 | Murroogh Point | *Mytilus* sp. | 3.0 | +1.2 | 4340 | *4710–4530* |
| 428927 | Cancapple N | Marine gastropod | 7.0 | +2.4 | 5410 | 5990–5880 |

[†]*Ages from a former publication (Scheffers* et al.*, 2010) are set in italics. All data are corrected to MRE from Omey Island (–142 ± 16; see Ascough* et al.*, 2006; Ascough, Cook, and Dugmore 2009).*

Figure 19. Three fining upward sequences in coarse sand and granules at Murroogh Point behind the seaward boulder ridge. Numerical data (AMS) are ordered by their depth below the surface (bs) with a "normal" age sequence, although stratification is less developed:
10 cm bs = 1095–940 cal BP
20 cm bs = 1980–1825 cal BP
34 cm bs = 2325–2150 cal BP

nary large and high dislocated boulders was on storm waves, which are the main power of coastal transformation in the area. Combined with this focus, a hypothesis for a possible former environment of what is now promontory forts as inland ringforts was developed (Williams, 2004); the hypothesis includes a strong (0.2–0.8 m/y) cliff retreat. Nonetheless, and based on detailed observation, Williams and Hall (2004) found some evidence that would require millennium-scale extreme events for boulder dislocation, which points to some skepticism for the storm-only hypothesis.

More papers on the most exposed European shorelines in Scotland and Ireland that focused on clifftop storm deposits and implied storm waves as the only possible mechanism have been published (Hall, Hansom, and Jarvis, 2008; Hall *et al.*, 2006; Hansom, Barltrop, and Hall, 2008; Hansom and Hall, 2009). The first paper questioning a strong cliff retreat, the promontory fort hypothesis as earlier ringforts, and the exclusive contribution to boulder transport by storm waves, was Scheffers *et al.* (2009); it came under discussion by Hall, Hansom, and Williams (2010). An answer to these critics, that each large boulder on the coastlines of the world came from tsunami dislocation, was published in Scheffers, Kelletat, and Scheffers (2010). At the same time, a detailed study on Aran Island boulders and similar deposits within Galway Bay was published (Scheffers *et al.*, 2010). This was the first publication on the boulder problem of the area, with observations, arguments, and datings from the leeward (bayward) side of the Aran Islands and from coastlines inside Galway Bay; 23 numerical data samples were used, spanning more than 4000 years. Williams (2010, 2011) and Zentner (2009) again supported the storm hypothesis, using arguments from open ocean waves of extraordinary heights (25–30 m) measured by anchored buoys far west of Ireland.

Cox *et al.* (2012) again put the focus exclusively on sections of boulder ridges along the most exposed sides of the Aran Islands: "If data from marine shells are from ages before 18$^{th}$ century, some workers (Kelletat 2008, Scheffers *et al.,* 2009, 2010) argue that the boulder ridges must be uniformly old" (p. 251). This citation is wrong. It was never said that ridges are uniformly old; it was argued that in the history of boulder dislocation and ridge deposits, forces other than storms alone may be hidden and these forces could only be (as estimated from the sizes and placing of boulders) forces stronger than the strongest storms possible in that area, *i.e.* tsunamis.

The new results disagree with Cox *et al.* (2012, p. 251):

> If boulder ridges of the Aran Islands have been active in a recent (about 250 years) 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.
>
> If they are active in recent decades and centuries, then—no matter how long their history and no matter whether

Figure 20. (a) The landward flank of the southern washover feature at Murroogh Point, looking to the north. Vegetation and soil mantle of the lower parts document a lack of recent boulder sedimentation or landward movement. (b) Landward flank of the northern Murroogh Point boulder tongue, looking southward, with a sharp boundary with vegetation and soil (sitting people for scale).

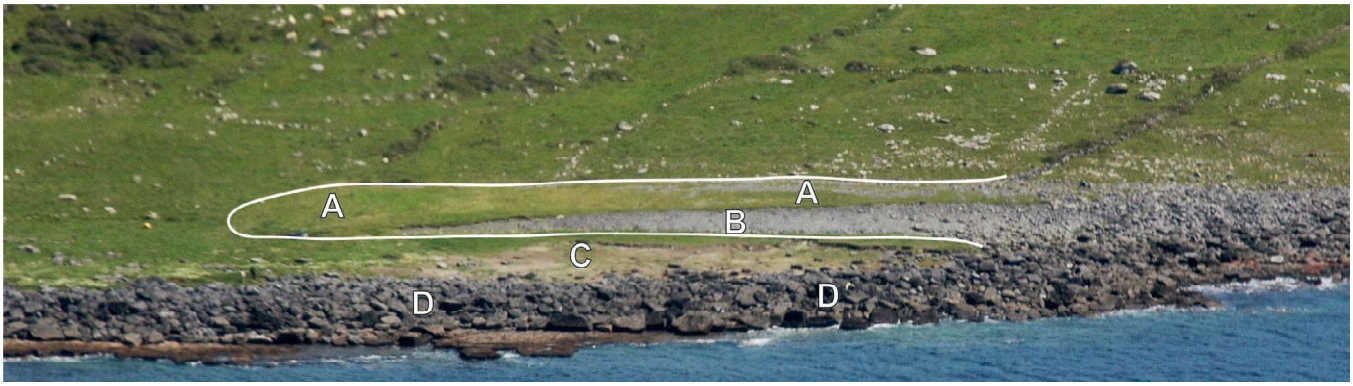


Figure 21. The Lafkaniska northern washover lobe seen from the west (oblique aerial photo). The nearshore is shallow, with a 20-m depth at a distance of 400 m from the modern MHW line and a 10-m depth at 200 m. A: Tongue of medium boulders, dislocated from the south (right). B: Sharply eroded western flank of the washover lobe. C: Stratified sand and silt with pebbles and shells under strong lateral erosion. D: Stable and well-imbricated ridge of large angular boulders (approximately 2 to 15 tons) on limestone base rock.

tsunamis of the past have contributed to them—storms must build and move them.

Cox *et al*. (2012, p. 252) also wrote that "if the Aran ridges are storm activated, then we can use the block sizes in those ridges to inform our understanding of coastal wave dynamics and the boulder-transport capabilities of storm waves." This is incorrect: storm wave activation of an existing boulder deposit does not mean that the boulders have been dislocated by storm waves to their place. Most of the larger boulders in the ridges have not moved within the last decades and centuries and probably have never moved since their first emplacement. Dating in the study presented here shows that ages may go back into the first half of the Holocene.

As in other regions of the world, not only the sizes of boulders that were recently moved are observed but also the sizes of boulders (and their setting, elevation, and distance to the coast) that were not moved by recent strong storms; documentation and comparison with reviews on the relevant literature can be found in Erdmann, Kelletat, and Scheffers (in review) and Erdmann *et al*. (2015). Whatever subject must be studied, a basic method has always been and is an open-minded inductive approach that does not exclude any process, hypothesis, or model, narrowing results and answers to open questions by as many observations as possible, including geomorphology, geology, sedimentology, sea-level history and other marine processes, and climate impacts, for a differential diagnosis of tentative conclusions and contributions to a current debate without a prejudice against other ideas, in particular not against evidence from nature.

The extremely large number and force of winter storms in the 2013/14 winter season allowed near-time inspection to judge the power of categories 3 and 4 hurricane force winds and waves. Inspections along the Aran Islands of Inishmore and Inishmaan, as well as the SE section of Galway Bay, 4 months after the storms found many boulders freshly emplaced and old boulders activated at the frontal parts of ridges (extended documentation is in Erdmann *et al*., 2015); however, not found are "ridges migrate progressively landward," "mass was also added to the deposits," and the "role of storms in growth and migration of supratidal boulder ridges," as presented in Cox *et al*. (2014) from their near-time inspection. In contrast, the mass of ridges was diminished by the activation of frontal slopes and backwash of small or medium boulders into the sea. There was no migration of ridges landward, because activation rarely reached the ridge crests, and at no place did it reach clifftop positions to their landward margins (Erdmann *et al*., 2015).

Cox and her team continue to work on the Aran Islands boulder deposits, in particular by comparing multitemporal photos of individual boulders to quantify their (potential) dislocation. These studies are accompanied by interviews and internet activities to support the storm-only hypothesis (see also the presentation of Cox and Watkins (2015) at the Geological Society of America annual meeting) by arguing that because the Galway area never had tsunami impacts, it is the ideal place to study storm-dominated coastal boulder deposits, including storm-made imbrication. By extending research activities from the Aran Islands into Galway Bay with more dating of all sedimentary units, including washover features, arguments and documents are added to this discussion. This dispute is particularly important because the respective boulder deposits are the most spectacular along the coasts of Europe and, probably (particularly regarding their extension and organization types), in the world.

The organization of large boulders in ridges exhibits two aspects: chaotic and imbricated. They are chaotic in freshly activated sections at clifftop positions, where a large number of fragments are moved (Figure 6; compare Hansom, Barltrop, and Hall, 2008; Hansom, Switzer, and Pile, 2015; and Scheffers *et al*., 2010). In this respect, the new observations differ from Cox *et al*. (2012). Older, unaffected boulder ridges in clifftop positions show rare imbrication except in assemblages of very large platy boulders. In contrast, old (lichen covered) boulder ridges close to the shoreline may be perfectly imbricated, including imbrication trains (Figure 11). This is typical for the Galway Bay section from Doolin to Black Head and for the

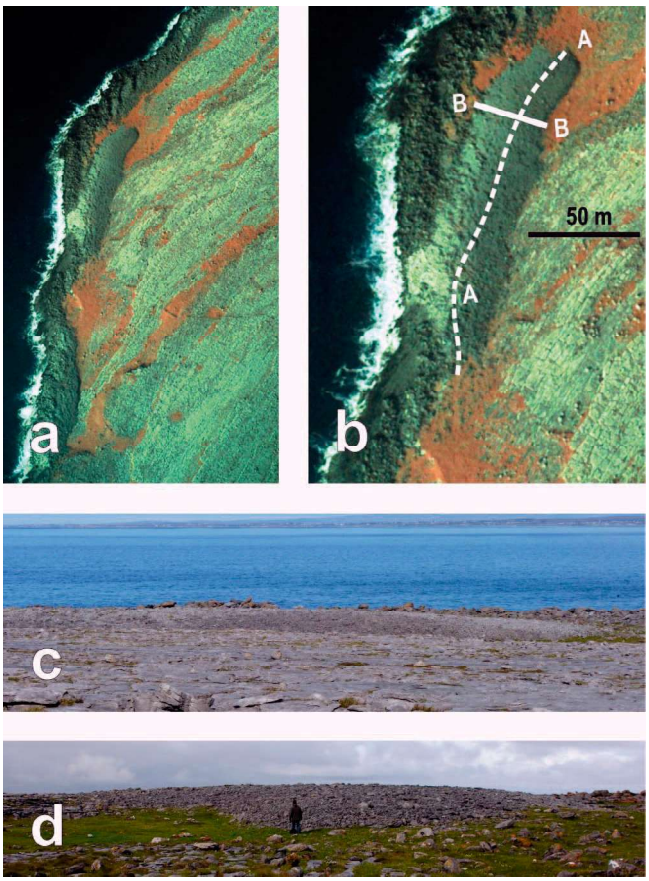


Figure 22. (a) Two washover lobes at Murroogh Point, with the northern as a boulder tongue and overforming by curving secondary ridges of large boulders (formed from the direction of 100°) at the southern lobe. The northern lobe exhibits activation in its SW part close to the sea (Marine Institute, 2000). The southern Murroogh Point washover has a total length of 170 m and a maximum width of 45 m; the main axis is to 21°. The form is fringed by a straight rock step at the inland slope. (b) Northern washover tongue at Murroogh Point with crestlines A and A′ and profiles B and B′ (Marine Institute, 2000). (c) Northern washover tongue (length of 120 m, highest elevation of 6.6 m above MHW, ending to the north or right 2.7 m above MHW) at Murroogh Point parallel to a ridge of very large imbricated boulders to seaward (seen September 2015, looking from the east). Seaward sections exhibit light colors from activation during storms of the season 2013–14. (d) Cross-sections B and B′ seen in 2007 from the north with a width of 32 m, a maximum elevation of 6.3 m over MHW, a base at left (east) 2.7 m above MHW and at right (west) 3.7 m above MHW.

western end of Inishmore Island or the low south coast of Inisheer Island.

The spatial and temporal relationships of boulder ridges and washover features are demonstrated by three profiles (Figure 26). With respect to coastal sediments, they are composed of different units:

(1) A seaward high ridge of very large and well-imbricated boulders (as high-energy deposits), with indicators of older age by weathering and lichen cover, supported by numerical dating (AMS) of boring bivalves (*Hiatella arctica*) still in living position.
(2) Horizontally stratified (or chaotic) finer sediments as geoarchives left by quiescent conditions.
(3) Washover lobes or tongues built by small and medium boulders in a chaotic setting in the profiles at Lafkaniska and Murroogh Point. These are the result of single extraordinary transport events, again with old ages when sea level was lower and the coastline farther distant. At Lafkaniska, no activation has occurred; at the Murroogh tongue, activation affected the seaward flank but did not disturb general contours.

The clear spatial order of forms and sedimentary units in the three profiles leads to the assumption that the landward ones are the oldest and the seaward ones are the youngest, but age dating complicates the picture. Oldest ages for the seaward large boulder ridge available for the Murroogh profile are 4300 and 4000 cal BP. On the Annagh peninsula in NW Ireland, a similar date (2100–2040 cal BC as a minimum) was found from peat on large boulders forming a high ridge in a sheltered environment up to 14 m above MHW (Scheffers *et al.*, 2009). At Lafkaniska ridge, the ages go back to 9300 and 8800 cal BP, with intermediate activation around 1300, 1100, and 900 cal BP and younger ones around 500 cal BP. Coarse gravel and boulder washover lobes and tongues at Lafkaniska date to 5650–5750 cal BP, and those at Murroogh Point date to at least 4900 cal BP, with younger activation between 600 and 300 cal BP. Stratified layers with fine sediments, often between the coarse deposits, gave ages from 5900 cal BP at the base of ridge B at Cancapple; several were between 2800 and 2300 to 1100 cal BP, and the youngest on top was close to 300 cal BP. These young ages also occur at Lafkaniska (300 to 200 cal BP), whereas at Murroogh Point, the oldest dates of fine sediments were around 2700 cal BP, followed by 2300 to 1900 cal BP, and the youngest were around 1000 cal BP (compare Tables 1 and 2).

Hansom and Hall (2009) investigated clifftop storm deposits from Shetland's main island and dated nine samples that sandwiched boulders: from peat and shell hash by 14C and from basal sand by optically stimulated luminescence (OSL). These samples were interpreted for the magnitude and frequency of extratropical North Atlantic cyclones to establish a chronology of stormy periods in comparison with Na+ from Greenland ice cores and the history of Icelandic lows. The authors found similarities in these data and mentioned 400–550, 700–1050, 1300–1400, and 1950–2005 AD as times with strong storms. Although a periodicity of similar storms in the Shetland and western Ireland region can be assumed, 65 data samples have not yet allowed the identification of changes in storminess for the North Atlantic (compare Tables 1–3). This is particularly the case for the probability of processes other than storms affecting boulder dislocation.

Even with 65 ages from three sedimentary units, clustering remains difficult. Age clusters are influenced by the preservation of *Hiatella* in boulders, which diminishes over time, and there are sampling difficulties within coarse ridges and at their bases. The group of very large boulders (>2 m long) derive from cliffs or structural steps at cliff tops, an environment without boring bivalves. Dating *Hiatella arctica* therefore has the disadvantage of missing ages for a boulder class that gives the

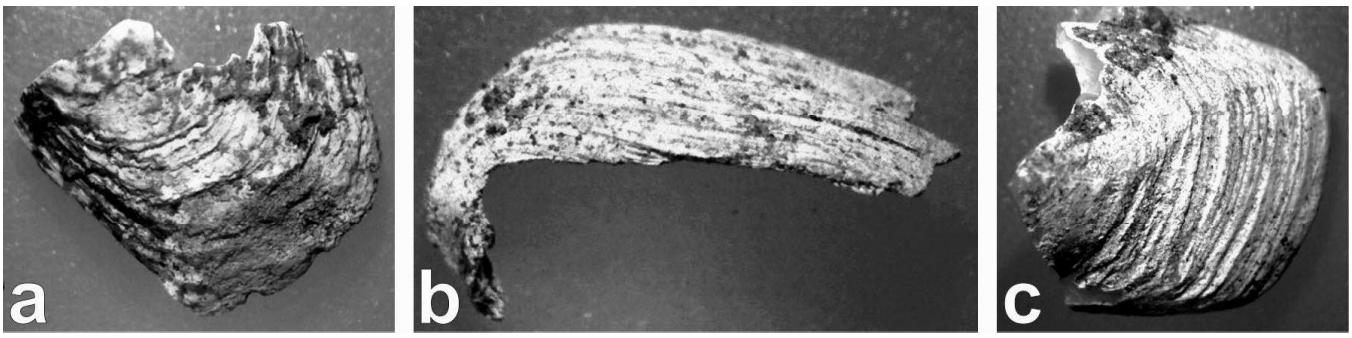


Figure 23. *Hiatella arctica* (>1 cm long) from washover lobes: (a) Lafkaniska dated 5715–5580 cal BP, (b) northern Murroogh tongue dated 4980–4810 cal BP, and (c) from younger activation of the Murroogh Point tongue dated 690–620 cal BP.

Aran and Galway ridges their significant aspect of extreme dislocation energies. Finally, activation of deposits during a rising sea level constantly adds younger material; therefore, the original or initial phase of boulder ridges is probably underrepresented in these data.

It is remarkable that sedimentary evidence of sea-level and coastline shift over more than 9000 years is all found within a belt of less than 100 m along the modern coastline. Younger data (from modern to approximately 1000 cal BP) are signatures for activation processes during strong storms or other marine processes such as tsunamis. Finding clusters in the data requires more vertical age determination in a systematic manner in very coarse deposits. An important fact is that the Lafkaniska and Murroogh boulder lobes (although several thousand years old) still show a gap of many decameters to the seaward ridge of large boulders. This documents a missing landward movement of the most exposed coarse deposits, perhaps supported by stabilizing imbrication.

As noted in "Methods," geomorphology is at least as important as numerical dating in reconstructing the evolution of the Holocene coastal environment and its driving forces. Therefore, features that are rarely mentioned for worldwide storm deposits are presented here (compare Erdmann *et al.* [2015] and Scheffers [2006]). These forms are best described as "ripples" (Allen, 1985; Amos and Friend, 2005). They appear from Doolin to Black Head and on the Aran Islands, and they exhibit two patterns. A smaller pattern consists of densely grouped shallow ridges with cord length and distances of several meters on the landward slopes of boulder ridges (Figure 27) that are easily visible on aerial photos but difficult to detect onsite. Deposits with these patterns are old (numerical data indicate 1000 years or more) and have not been transformed by washover from recent storms. The most landward extension of the ripple patterns from the modern MHW line in the case of ridge B south of Poulsallagh is 55 m and is 65 m in the case of ridge C (Figure 2). More sites in a similar position are found on the Aran Islands of Inishmore and Inishmaan. The ripple features are the result of a strong current downslope to inland and are probably formed simultaneously at each location.

More significantly, secondary crossway ridges appear along at least 10 sites on 5.5 km of ridges with very large boulders (Erdmann *et al.*, 2015). They occur either along the coastline, with their crests a few meters higher than MHW, or on clifftop positions 11 to 12 m above MHW. Sites are marked in Figure 28a (which indicates similar features on the Aran Islands), and two local examples are shown in Figure 28b,c.

Secondary ridges often slightly curve with the opening to the energy approach. Their direction differs from the main ridge direction by minima of 25 and 30° and maxima of 105, 70, and 68°; the average difference is 55 to 58°. The deviation is largest close to Black Head. The approach of energy is 90° to the left (open bay) from the direction of the secondary ridges, which is 270 to 295° in the northern section, with a mean of 252° (242–265°) for the southern section of Galway Bay's SE coast.

As the aerial images document, crossway ridges occur in groups. Their interpretation as temporally consecutive constructions (those NE are always older than those SW) is highly unlikely, because it would afford sequences of nearly the same energies and the same directions over a long time at the same distance from the modern shoreline, each time leaving only one ridge in front of an existing one. Instead, it is assumed that the cross-ridge patterns have been formed

Figure 24. A storm cliff in slightly consolidated dunes of Fanore showing a partly sigmoidal stratification with thin caliche bands of a former leeward exposure (to NW). Scale is 0.5 m. The sediment character is a unimodal, moderately well-sorted medium (59%) sand, symmetrically fine skewed and leptokurtic.

Table 3. *Numerical data from coarse washover lobes and tongues.*

| Beta Lab No. | Location | Material | Elevation (m + MHW) | δ13C | Conventional Age | 2σ cal BP† |
|---|---|---|---|---|---|---|
| 428916 | Fanore S | Marine gastropod | 3.8 | +0.9 | 550 | 420–275 |
| 428939 | Murroogh Point | Marine gastropod | 2.6 | +2.3 | 560 | **425–280** |
| 428947 | Murroogh Point | *Hiatella arctica* | 3.5 | +2.7 | 690 | **505–425** |
| 428946 | Murroogh Point | *Hiatella arctica* | 3.7 | +1.5 | 860 | **645–525** |
| 428937 | Murroogh Point | *Hiatella arctica* | 2.8 | +0.9 | 870 | **650–530** |
| 428930 | Murroogh Point | *Hiatella arctica* | 3.4 | +0.6 | 910 | **665–555** |
| 428936 | Murroogh Point | *Hiatella arctica* | 2.8 | +0.5 | 950 | **690–620** |
| 428935 | Murroogh Point | *Hiatella arctica* | 3.3 | −0.8 | 2280 | 2145–1985 |
| 428934 | Murroogh Point | *Hiatella arctica* | 3.3 | +0.4 | 4500 | **4940–4810** |
| 428903 | Lafkaniska | *Hiatella arctica* | 4.7 | +0.9 | 5150 | **5715–5580** |
| 428904 | Lafkaniska | *Hiatella arctica* | 4.7 | 0.0 | 5260 | **5875–5690** |

†*Ages from within Galway Bay (section Doolin to Black Head) show bold numbers. All data are corrected to MRE from Omey Island (–142 ± 16; see Ascough* et al.*, 2006, and Ascough, Cook, and Dugmore 2009).*

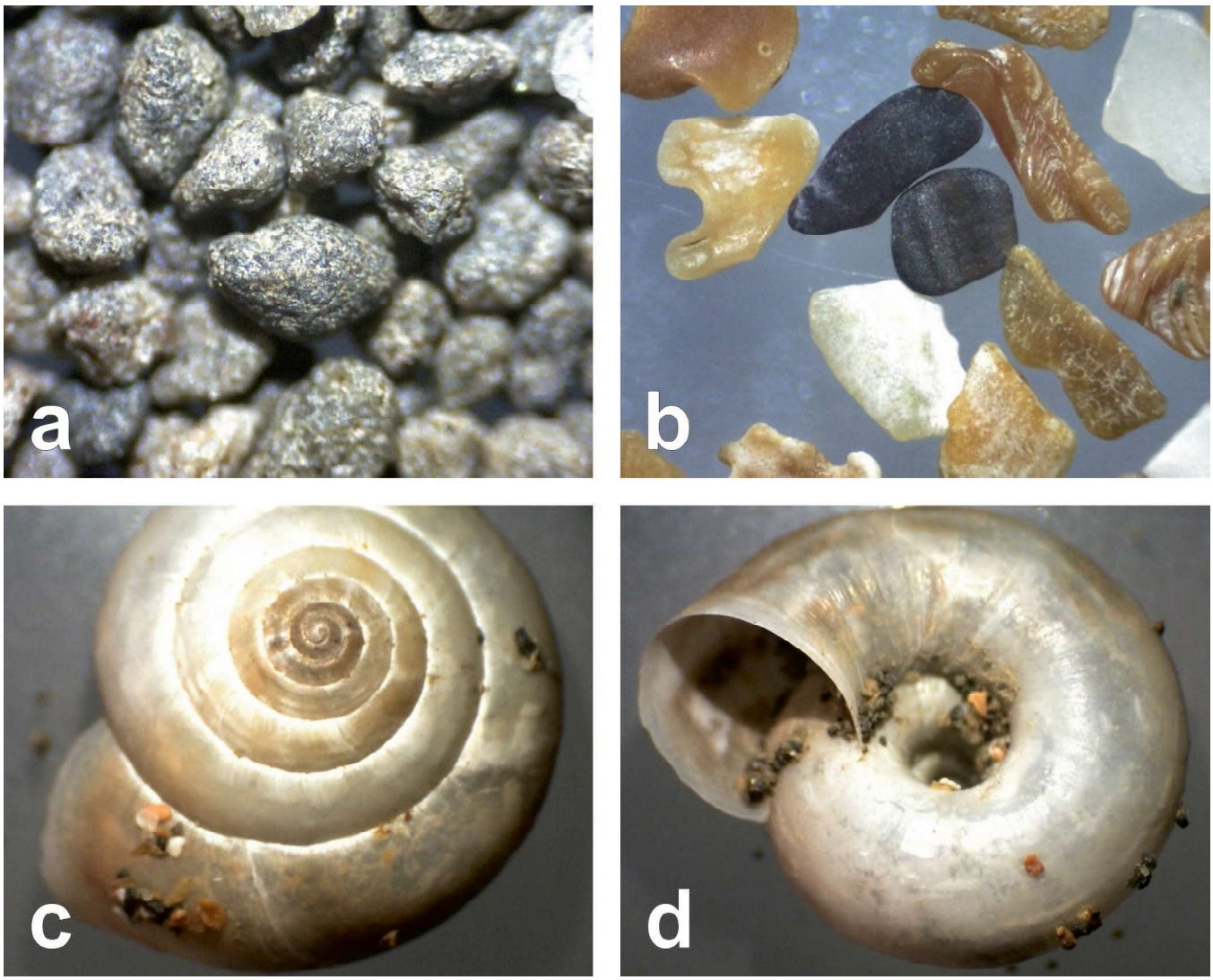


Figure 25. (a) Corroded surfaces of rounded quartz grains (0.2–0.5 m, 60×) from old Fanore dunes. Similar aspects are found in the Doolin dunes. (b) Modern beaches may exhibit rounded shell fragments and sand grains (here 1–2 mm). (c) and (d) Terrestrial gastropods *(Helicodonta obvolata*, size 1.5 cm) from the Fanore dunes, ages between 3905–3820 and 3455–3365 cal BP.

Table 4. *Numerical data of terrestrial gastropods in inactive dunes of Fanore.*

| Beta Lab No. | Location | Material | Elevation (m + MHW) | δ13C | Conventional Age | 2σ cal BP |
|---|---|---|---|---|---|---|
| 428941 | Fanore Beach | Terr. gastropod | 2.1 | −8.2 | 3270 | 3420–3410 |
| 428943 | Fanore Beach | Terr. gastropod | 2.4 | −7.6 | 3190 | 3455–3365 |
| 428942 | Fanore Beach | Terr. gastropod | 2.3 | −7.2 | 3370 | 3650–3560 |
| 428940 | Fanore Beach | Terr. gastropod | 2.0 | −7.2 | 3550 | 3795–3760 |

*Terr. = terrestrial.*

(originally as separate ridges or sculpted from an existing massive boulder ridge) contemporaneously by fast-moving flow over distances of at least 500 m, although containing boulders of at least 10 tons in clifftop positions up to 12 m above MHW in Galway Bay and up to 27 m above MHW on Inishmaan Island.

## CONCLUSION

Whereas boulder deposits on the three Aran Islands of Inishmore, Inishmaan, and Inisheer have been studied since 2004 (Williams, 2004; Williams and Hall, 2004), coastal sediments along the Galway Bay have only been mentioned cursorily, as in Erdmann, Kelletat, and Scheffers (in review),

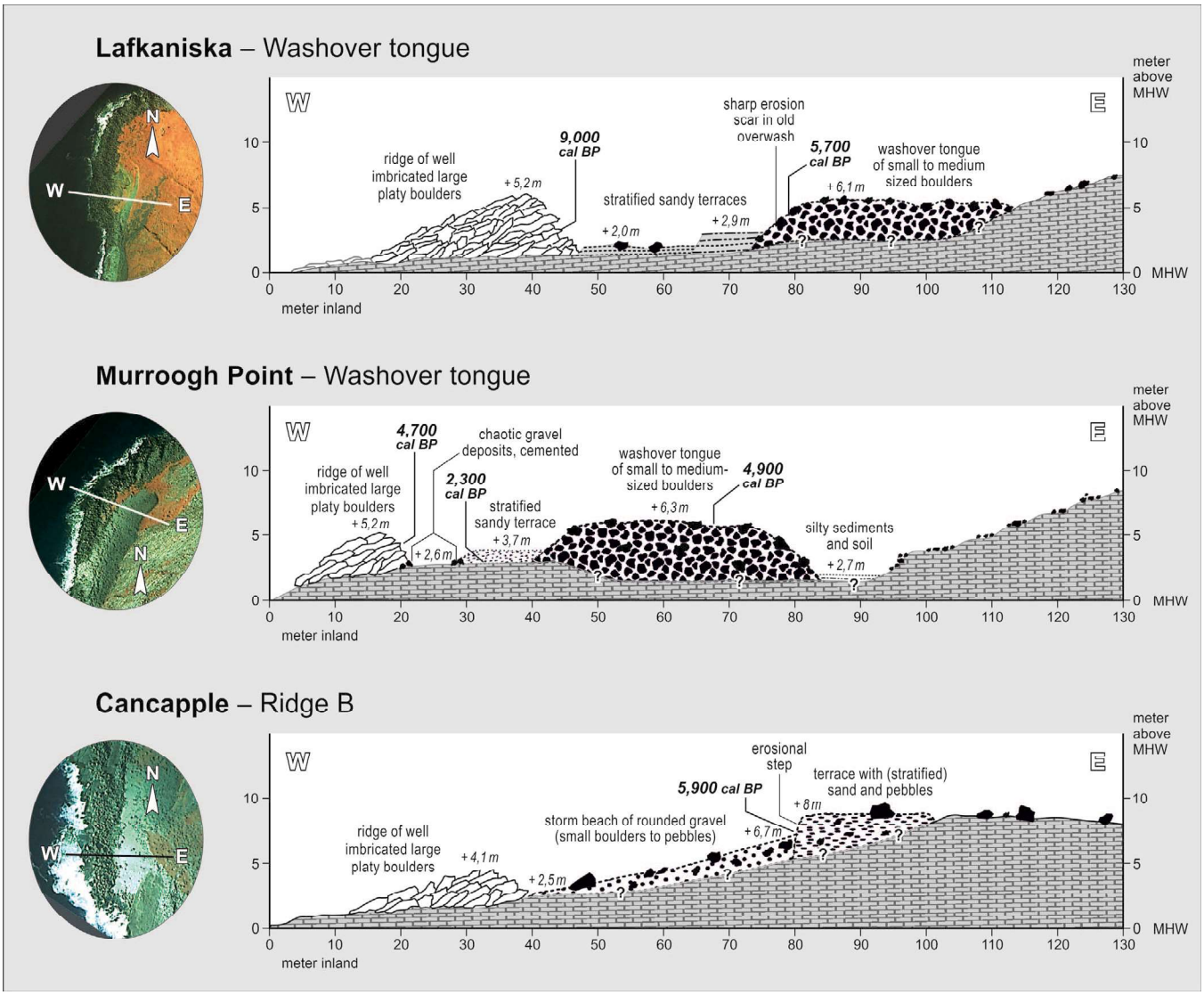


Figure 26. Three profiles over main sedimentary units along the Doolin–Black Head coastal section inside Galway Bay (infrared aerial photos: Marine Institute, 2000; graphics: Gudrun Reichert).

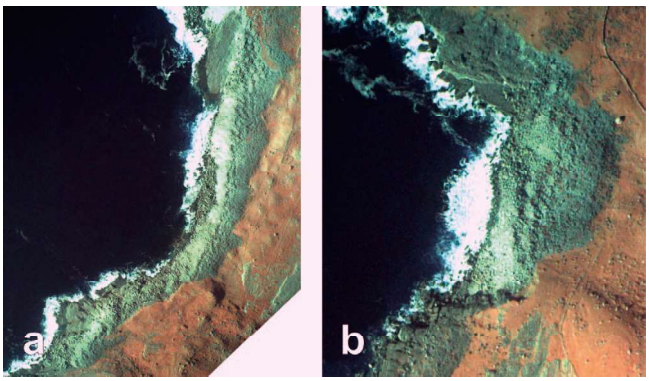


Figure 27. The widest beach ridges (washover features) of coarse gravel and boulders occur between Poulsallagh and Cancapple on the SE coast of Galway Bay. (a) The left ridge (ridge B) is 55 m wide, and (b) the right ridge (ridge C) is 65 m wide. Their darker-colored landward slopes exhibit ripplelike surface patterns from overflow with cord lengths and widths of several meters, whereas the relief between is approximately 0.5 to 0.8 m (Marine Institute, 2000).

Erdmann *et al.* (2015), and Scheffers *et al.* (2010). This paper focuses on a 25-km-long coastal section within Galway Bay from Doolin to Black Head and includes observations and dating from all coastal sediment units. Inside Galway Bay, marine forming processes are reduced by shelter from the Aran Islands and diminishing water depth. Nonetheless, evidence of extraordinary transport processes dominates the coastal section to Black Head. Although geoarchives with fine and stratified marine or littoral sediments are shallow, they give insight into more than 5000 years of deposition, and in the very coarse boulder ridges, data reach back into the first half of the Holocene (>9000 years cal BP). Interpretation is difficult because of the close neighborhood of extreme energy deposits, such as boulders, blocks, and fine sediments from quiescent overflow processes. In addition, washover lobes and tongues of coarse gravel document single events of enormous transport energy from flows approximately 5000 years ago, with a wider inundation than is observed during modern extraordinary winter storms. The high transport energy events are from periods of a significantly lower (4–5 m) sea level in mid-Holocene times, which implies a coastline position farther to seaward by dimensions of several hundred meters. Based on near-time inspections after the strongest recorded storms and in the living memory of the locals in 2013/14 (Erdmann *et al.*, 2015), the question arises whether the largest category of boulders and blocks might have been dislocated onshore by waves with bores or by tsunamis (compare Bryant and Haslett, 2003, 2007, and Haslett and Bryant, 2005, 2007). The position inland, the elevation, and the size of individual boulders are clearly beyond the energy available from known storms. Storms modify coastal deposits; however, the shape and position of boulder ridges and washover lobes has been unchanged for centuries to millennia. In addition to rare fining upward sequences and mud clasts in finer sediments and their chaotic aspect with age inversions, boulder lobes, ripples on old beach ridges, and

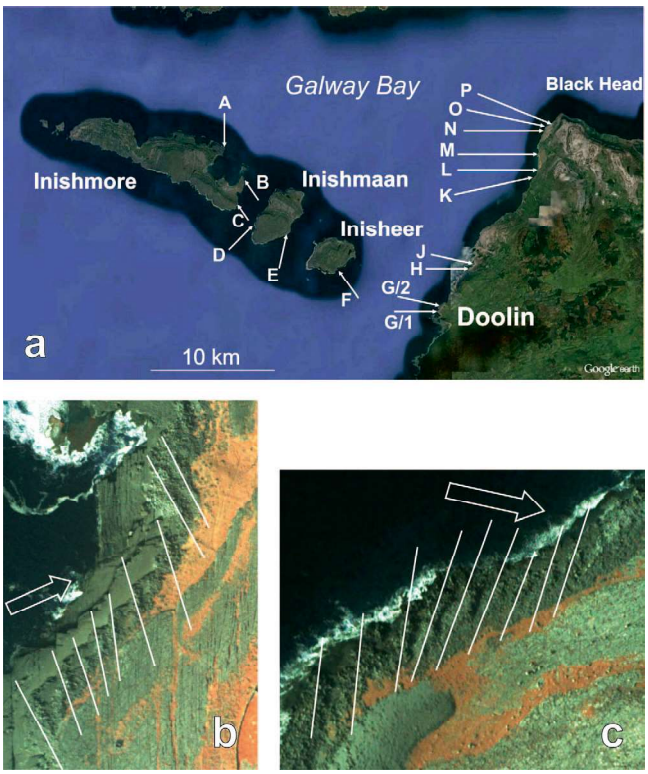


Figure 28. (a) Sites, where main ridges of large boulders are dominated by secondary cross-running ridges. Arrows (A–P) indicate direction of energy approach (from WSW to WNW between Doolin and Galway Bay) (Google Earth, modified). (b) Example of a coarse boulder clifftop ridge (point G1 in a) is 8 to 12 m above MHW, running north from Doolin Point, with nine cross-running secondary and slightly curved ridges (marked by thin white lines) along a section 450 m long. The energy approach to form these secondary ripples by a strong current is marked by an arrow (Marine Institute, 2000, modified). (c) Secondary cross-running ridges (marked by thin white lines), forming the main large boulder ridge at Murroogh Point (point O in a) close to MHW level. The section shown is about 250 m long. The energy approach of a strong current to form these secondary ridges is marked by an arrow (Marine Institute, 2000, modified).

secondary ridges crossing main boulder ridges close to MHW and on cliff tops point to strong currents among formation processes in the Holocene. These currents must have moved over distances of hundreds of meters. To form crossway ridges with boulders up to 15 tons in a main ridge (Figure 12), up to a minimum of 12 m above MHW, and with a surface roughness of more than 1 m, flow velocities on the order of 15 m/s or more are needed, which, as far as is known, are only possible in strong tsunamis. Infragravity waves rarely affect more than 100 km of coastline in different exposures in the same manner (Figure 29). According to an assessment manual for coastal engineers (EurOtop, 2007), the maximum overflow velocity from storm waves or bores on constructions similar to cliff tops in the North Sea is 8 m/s. The most probable potential sources for Holocene tsunamis are mass wasting on the submarine slopes with a submarine relief of more than 2000 m into Rockall Trough and the Porcupine Basin 200 to 400 km W and SW of the study area

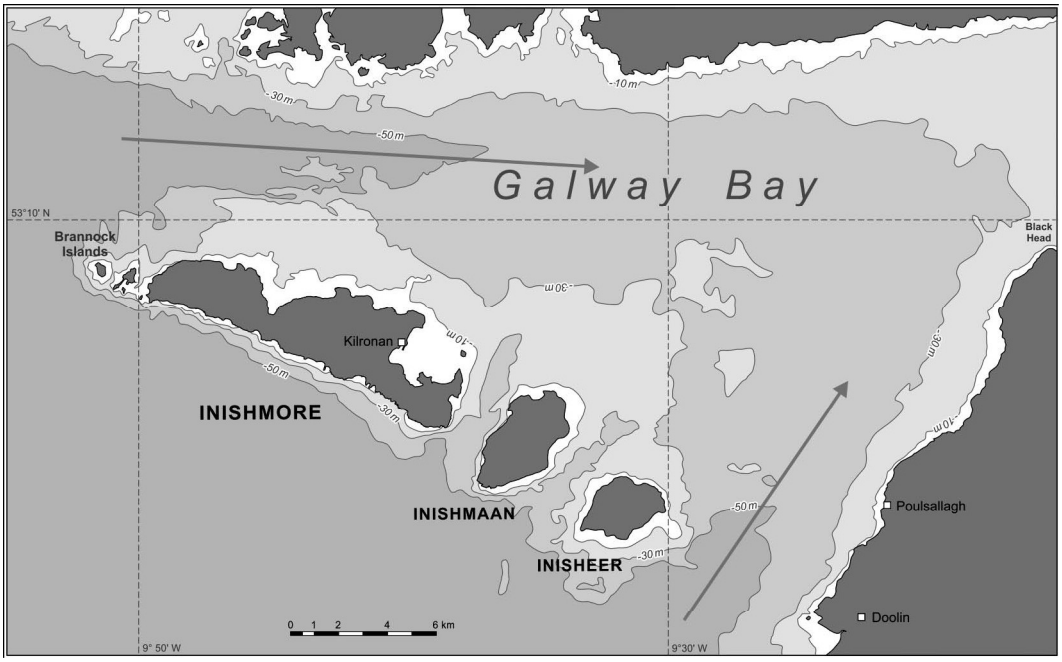


Figure 29. Bathymetry around the Aran Islands and in Galway Bay. Extreme flow processes (*e.g.*, tsunamis, blue arrows) may move through North Sound from a direction of 273° and through South Sound from a direction of 210° (bathymetry: British Admiralty, 2005). Because driving forces to organize the crossway ridges on large boulders came from WNW to WSW, flows crossing both sounds (with a slight refraction to the right) may have necessary effects on the Doolin–Black Head section (cartography: Gudrun Reichert).

(Georgiopoulou *et al.*, 2012, 2014; Owen *et al.*, 2010; Sacchetti *et al.*, 2011; Shannon *et al.*, 2001). These authors identified submarine mass failures (slides and slumps) by multibeam sonar data that may have occurred well within the last 10,000 years as a threat to human life and nearshore engineering structures.

Theoretically, long time gaps in the data (Tables 1–3) may point to sea-level fluctuations (regression phases), low sediment supply, lack of strong storms or extreme events, or climate shifts, and more consecutive data from approximately 1000 cal BP may represent good preservation of *Hiatella* and other marine organisms.

The possibility that the oldest data have given wrong ages or came from fragments that rested onshore in another deposit and were dislocated later into ridges and washover lobes should be excluded. Also excluded are that the history of seas being several meters below modern levels in mid-Holocene times and still significantly lower in early medieval periods is inaccurate and that local crustal or isostatic movements influenced a special sea-level history in the study area. What is also doubted is that in prehistoric times, storms with waves and bore flows several times stronger than in today's hurricane category 3 and 4 events occurred that were able to form the long and high ridges. Skepticism exists of the simple conclusion that storms form organized deposits (such as imbricated ridges) and tsunamis leave chaotic patterns (as argued in Paris, Naylor, and Stephenson, 2011, p. 6). No significant imbrication remained from recent extraordinary storms in the area. Forming long imbrication trains by one wave or many waves in one storm does not fit reality, in particular to constantly obtain new large fragments from the same spot and lift them upward at their front to be added to an existing imbrication pattern (see discussions in Erdmann *et al.* [2015] and Scheffers and Kinis [2014]). Finally, more observations on strange ripple features in large boulder ridges, the mechanics of their origin, and the processes involved are needed. Some of these hypotheses will be answered by more research and more data from this area, and others can be eliminated by positive evidence in the future.

Steps forward in answering open questions, particularly concerning the nature of extreme events on the Aran Islands and within Galway Bay (as well as along the entire west coast of Ireland and beyond) require age dating of submarine slides west of Ireland and detailed stratigraphic research on marsh sediments along the innermost Galway Bay. In addition, more numerical data are needed from the Galway and Aran coastal boulders; they are best based on methods beyond the rare findings of shells bored into very old boulders, such as surface exposure dating with cosmogenic nuclides, OSL, and others to be developed.

## ACKNOWLEDGMENTS

This study was supported by a grant from Deutsche Forschungsgemeinschaft (German Research Foundation; Ke190/28-1). We thank Jens Erdmann and Frank Schmidt-Kelletat for assistance during field work and logistics and Gudrun Reichert for cartography.

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**Fazit**

Es lassen sich entlang der Festlandsküste zwischen Doolin und Black Head i.w. drei Formeinheiten ausweisen, die gleichzeitig sowohl unterschiedliche wie auch unterschiedlich gelegene Sedimentarchive bilden. Es ist zunächst meerwärts (außerhalb von hohen Kliffen sowie aktiven *cobble beaches* und *boulder beaches*) ein Blockwall mit Fragmenten von einigen t bis zu etwa 20 t. Diese sind gewöhnlich Platten, herausgebrochen aus dem Intertidal und Supratidal entlang von strukturellen Stufen im Kalkstein. Sie sind meist zu einer ausgesprochen stabilen *imbrication* geschichtet und steigen an der Seeseite flach auf, während sie zum Land hin abrupt und steil enden. Damit ist ihr Profil den vom Kliffrand oberhalb sedimentfreier Plattformen (bis max. +23 m MHW) zurückgesetzten chaotischen Blockwällen geradezu entgegengesetzt. Die meernahen sehr groben Blockwälle finden sich an mindestens 5,5 km der um 25 km langen Küstenstrecke von Doolin bis Black Head.

Landwärts der Blockwälle gibt es an 12 Stellen Reste von Sedimentterrassen aus sehr gut gerundeten Schottern und Kiesen, horizontal und vertikal wechselnd mit wenig gerundeten groben Sanden und Bruchschill, aus welchen zum Teil Proben entnommen wurden. Die feinsten Korngrößen sind Schluffe. Diese Geoarchive sind meist weniger als 1 m mächtig, maximale Mächtigkeiten konnten mit 1,3 – 1,4 m ermittelt werden, und sie ruhen – soweit feststellbar – auf dünnen Lagen mittelgroßer und angerundeter Blöcke auf dem anstehenden Kalk. Sie kommen mit den feinsten Fraktionen auch bis fast +20 m MHW auf Kliffplattformen vor. All diese „feineren" Sedimente weisen Böden und dichte Vegetation (zumeist Süßgräser) auf. Bodenreste (fAh, B, auch Pseudogley in den Schluffen) sind häufig, aber gestört. Aufgrund des groben Korns lieferten diese Aufschlüsse keine Sedimente, die mit Hilfe fortschrittlicher Laboranalysen weitere Ergebnisse hätten erbringen können. Korngemisch und Kornformen sowie Makroreste von marinen Organismen wurden mikroskopisch erfasst.

Innerhalb der geschichteten und oft auch chaotischen „feineren" Sedimente gibt es einige Signaturen, die als tsunamigen bezeichnet werden können (vgl. z.B. Goto et al., 2015). Es sind *mud clasts* zwischen Schottern und Kiesen, unscharfe *unconformities* an erkennbaren Faziesgrenzen, und *upward grading.* Alte Bodenhorizonte erscheinen meist in Linsen und Fetzen, auch völlig strukturlose Sedimente kommen vor.

Die Terrassenreste als Dokumente für Phasen oder Lokalitäten mit einem eher ruhigen Ablagerungsmilieu befinden sich in einem fortgeschrittenen Stadium der Seitenerosion durch Sturmbrandung, auch jene über den hohen Kliffen, und werden in spätestens wenigen Jahrzehnten verschwunden sein. Möglicherweise bleibt noch eine Schotterstreu länger sichtbar. Am weitesten reichen die Terrassenreste im

Abschnitt um Cancapple und Poulsallagh (etwa halbwegs zwischen Doolin und Black Head) bis 80 m landwärts, dort zwischen +7 - 8 m MHW.

Neben lokalen Resten inaktiver Dünen tritt noch eine dritte Formen- und Sedimenteinheit auf: Es handelt sich dabei um *washover* von zungenartiger Gestalt, bis mindestens 120 m lang, 30-40 m breit und entlang der Längsachse bis über 3 m mächtig, bestehend aus kleineren bis mittelgroßen Blöcken mit mehr oder weniger deutlicher Zurundung. Offenbar stammen sie aus dem Brandungsbereich und vom oberen Subtidal (nach Ausweis von Bohrmuschellöchern). Sie repräsentieren – gerechnet bei 30% Porenvolumen – jeweils eine Masse zwischen 10.000 und 20.000 t. Drei dieser länglichen zungenartigen *washover* sind ausgeprägt (zwei bei Murroogh Point im Norden, eine durch Vegetation verdeckt und deshalb weniger auffallend südlich von Fanore bei Lafkaniska), alle aus SSW angeliefert, nahezu küstenparallel in der Längserstreckung und landwärts des seeseitigen Blockwalles. Schwieriger zu erkennen sind im rechten Winkel zum Verlauf aktiver Strandwälle (d.h. landwärts) gerichtete plumpe und kleinere Blockzungen, offenbar älter als die deckenden ständig aktivierten Brandungsschotter.

Die räumliche Nähe von drei völlig verschiedenen Sedimenteinheiten auf einem Küstenstreifen von maximal 100 m Breite mit Altershinweisen über mehr als 9.000 Jahre ist deshalb besonders bemerkenswert, weil während dieser Zeitspanne der Meeresspiegel um nahezu 30 m angestiegen ist (seit etwa 7.000 cal BP noch um ca. 5 m). Für den Abschnitt entlang der Galway Bay mit relativ flachem *fore-shore* bedeutet dieses gleichzeitig eine horizontale Verschiebung der Küstenlinie um mehrere 100 m ostwärts allein durch den Transgressionsvorgang, auch ohne Annahme von Küstenerosion. Die relativ stabile Lage der Formen und Sedimenteinheiten wird dadurch bestätigt, dass der seewärtige massive Blockwall mit *imbrication* trotz Altersindizien von vielen tausend Jahren die etwa 5.000 Jahre alten *washover*-Zungen nicht erreicht, zerstört oder überfahren hat.

Ein wichtiges und nahezu flächenhaft anzuwendendes Instrumentarium für relative Altersunterschiede steht im Kalkstein zur Verfügung. Hier ist zunächst zu unterscheiden die Abtragungsintensität im (terrestrischen) Regenwassermilieu (chemische Lösung) bzw. im Salzwassermilieu (biologisch-erosiv). Letztere ist zwischen 10- und 100-mal so intensiv und formprägend wie Lösung durch Regenwasser. Während ausgeprägte *rock pool*–Bereiche mit einem Kleinrelief von Dezimetern bis zu Metern in einigen Jahrhunderten entstehen, benötigt die Lösung

eines Mikroreliefs von 10 cm durch Niederschlag weit über 1.000 Jahre – bei beiden vorausgesetzt, dass lediglich die erste Generation von entsprechenden Formen sichtbar ist. Die Bedeckung frisch aus dem Intertidal und Subtidal entfernter Blöcke mit Kalkalgen, Vermetiden und Balaniden verschwindet nach vielen Jahren oder wenigen Jahrzehnten vollständig. Für eine Besiedlung von Blöcken zu etwa 50% durch häufige Flechten (*Caloplaca marina, Xanthoria* sp.) werden 70 Jahre oder mehr benötigt. Ein dunklerer Überzug aus epi- und vor allem endolithischen Cyanobakterien auf Kalk bildet sich bereits in wenigen Jahren, *striations* oder Exposition frischer Blockflanken sind dann kaum noch auszumachen. Schlagmarken durch Kollision größerer Fragmente sind jedoch mindestens viele Jahrzehnte lang zu erkennen, jedoch in ihrem Alter sehr schwer abzuschätzen. Die Intensität der Bodenbildung im ständig feuchten und relativ warmen Klima West-Irlands heranzuziehen erschien zu gewagt. Sehr weit entwickelte Bodenprofile (z.B. Podsole) waren im Arbeitsgebiet nicht auffindbar, ebenso wenig wie Torfe. Auf die Nutzung archäologischer Hinweise für Alter und vor allem Küstenerosion wird in der Publikation 4 noch näher eingegangen.

## 4.3 Neue Ergebnisse zum Blocktransport an Felsküsten (Erdmann et al., 2018 a)

Die Kernfrage des andauernden Disputes über an Küsten dislozierte große Blöcke ist nach wie vor, ob Stürme und Boren allein dafür verantwortlich sind, oder ob potentiell noch stärkere Prozesse (wie Tsunamis) mitgewirkt haben. Aufgrund des Überblicks an ca. 100 km Küstenlänge um die drei Aran-Inseln und an beiden Flanken der Galway Bay während der Feldarbeiten 2014, 2015 und 2016 wurde eine Dokumentation zum Ausmaß und Ablagerungsgefüge großer Blöcke entwickelt, die sicher den jungen und schwersten Stürmen im Arbeitsgebiet seit Registrierung zugeordnet werden konnten. So entstand eine der wenigen bisher existierenden qualitativ und vor allem quantitativ ausgerichteten *near-time-inspection* als Ergänzung etlicher existierender Tests in Wellenkanälen oder Modellierungen, meist auf der Basis stark vereinfachter Annahmen. Insgesamt 84 numerische Altersdaten betreffen alle Ablagerungsformen und Sedimenttypen des Arbeitsgebietes. Exakte Daten zur Herkunft, Transportweg, zu horizontalen und vertikalen Distanzen, Blockmaßen, Form und Masse und vor allem dem Bewegungscharakter konnten gewonnen werden, wobei die Schleif- und Kratzspuren sowie *impact-marks* an Kalksteinblöcken und dem Kalkuntergrund wichtige Hinweise lieferten. Die Ergebnisse werden mit publizierten *near-time-inspections* und theoretischen Ableitungen verglichen, wobei sich deutliche Diskrepanzen zu früheren Aussagen ergaben:

> Erdmann, W., Kelletat, D., und Scheffers, A. (2018 a). Boulder transport by storms – Extreme-waves in the coastal zone of the Irish west coast. Marine Geology, 399: 1-13

**Zusammenfassung**

Diese Studie behandelt große Blöcke, welche in höheren geographischen Breiten an exponierten Küsten durch Winterstürme landwärts und deutlich gegen die Schwerkraft bewegt wurden. Um die zugehörigen Transportprozesse zu klären, wären direkte Beobachtungen während der stärksten gegenwärtigen Stürme notwendig, oder wenigstens Feldanalysen zeitnah nach solchen Sturmereignissen. Da aber beide Möglichkeiten noch selten aufgegriffen wurden, existiert eine große Zahl von offenen Fragen und Widersprüchen in Bezug auf die verantwortlichen Transportprozesse. Obwohl hinreichende Analysemethoden, wie sie für Feinsedimente in Laboratorien zur Verfügung stehen, für Blöcke weitestgehend fehlen, können Ergebnisse aus den geomorphologischen Befunden in verschiedenen Dimensionen in der Landschaft selbst gewonnen werden, wovon Beispiele in dieser Arbeit Zeugnis ablegen. Um das Verständnis für Blocktransport an Felsküsten weiter

zu entwickeln, wurden qualitative und quantitative Daten während einer *near-time inspection* nach den außerordentlichen Winterstürmen 2013/14 in der Region Galway und den Aran-Inseln gewonnen, deren Fokus u.a. auf eine spezielle Lokalität in der Nähe des Doolin Point am Eingang zur Galway Bay gerichtet war. Ein Vergleich dieser Befunde mit bereits publizierten Ergebnissen zur Blockbewegung an Küsten resultiert in Übereinstimmungen und Widersprüchen, beispielsweise zur Rolle von Blockformen, der Art des Transportes oder dem Unterschied des Transportes durch Wellen oder Boren. Diese werden hier dokumentiert und diskutiert.

Marine Geology 399 (2018) 1–13

Contents lists available at ScienceDirect

Marine Geology

journal homepage: www.elsevier.com/locate/margo

# Boulder transport by storms – Extreme-waves in the coastal zone of the Irish west coast

Wibke Erdmann[a], Dieter Kelletat[b,*], Anja Scheffers[c]

[a] Institut für Geographiedidaktik, Universität zu Köln, Gronewaldstraße 2, D-50931 Köln, Germany
[b] Dieter Kelletat, Institut für Geographiedidaktik, Universität zu Köln, Gronewaldstraße 2, D-50931 Köln, Germany
[c] Southern Cross Geoscience, Southern Cross University, Lismore Campus, Lismore, NSW 2480, Australia

ARTICLE INFO

Editor: E. Anthony

*Keywords:*
Coastal boulders
Storm waves
Near time inspection
Galway
Ireland

ABSTRACT

This study is concerned with large boulders located along exposed shorelines in higher latitudes, which have become dislocated onshore by winter storms and have moved against gravity. To identify the transportation processes that these boulders have undergone in detail, their direct investigation during storm wave conditions is necessary, or at least near time inspections after extraordinary wave events. As both methods are rare, a wide range of questions and contradictions with regards to the processes that have acted on these boulders, remains. Despite a lack of applicable methods as for fine sediments, the depositional environment and processes of boulder movement can be determined from geomorphologic evidence in the landscape itself. Examples are presented in this paper. To progress understanding of boulders in rocky coastal environments, qualitative and quantitative data are acquired during a near time inspection following extreme storms in winter 2013/14 with special focus on an extraordinary boulder site near Doolin at the entrance to Galway Bay (central west coast of Ireland). The comparison of these data to previously published research on coastal boulder movement results in agreements and discrepancies (e.g. on boulder forms and mode of transport, difference in wave and bore transport) which are discussed.

## 1. Introduction

Land based boulder deposits dislocated by marine forces exist on all continents and in all latitudes, and are most frequently found along exposed rocky shorelines. Previous research have predominantly attributed storm waves as the only important mechanism in these boulders deposition (e.g. Cox et al., 2012; Etienne and Paris, 2010; Fichaut and Suanez, 2008, 2011; Hall, 2010; Hall et al., 2006, 2010; Hansom et al., 2008; Lau et al., 2014; Noormets et al., 2004; Paris et al., 2011; Suanez et al., 2009; Terry and Etienne, 2010; Terry et al., 2013; Williams, 2004, 2011; Williams and Hall, 2004). Relatively few papers have focused on near time inspections of strong impacts on coastlines, and the majority of them with storm waves (e.g. Bartel and Kelletat, 2003; Engel et al., 2014; Erdmann et al., 2015; Goto et al., 2009, 2010; Kennedy et al., 2017; Khan et al., 2010; May et al., 2015; Saintillan and Rogers, 2005; Scheffers and Scheffers, 2006). A number of papers have focused on natural settings where boulders are moved on a planar surface and not against gravity, in particular on reef platforms. These settings offer comparable simple conditions, but irregular boulder forms (as from coral reefs) and roughness of the platforms are complicating factors.

Evaluating published documents for physical calculations, modelling or wave tank experiments, significant discrepancies are found in the mode of movement between waves and bores, in particular regarding the energy for a specific transport process (sliding, overturning/rotation, saltation), and the importance of transport parameters involved (e.g. wave height, flow velocity, boulder forms, bed roughness). Some examples are given at the end of this introduction.

Size, form and origin of boulders, organization of boulder deposits (single, in clusters, imbricated, in ridges etc.), bathymetry, and wave regimes are among the parameters that inhibit the transfer of the environments into models or physical tests on a smaller scale. In particular, theories and models work with simplified conditions, which focus on specific processes. The development of such models are further complicated if the deposits represent a longer history in which changes of climate, wave regimes, bathymetry, sea level or processes in the coastal landscape, with positive or negative impacts on preservation, influence the picture that is trying to be analyzed. The local relief points at which a wave breaks and friction affects wave velocity and transport competence. Wave impact may set a boulder in motion, but bore flow is

* Corresponding author.
*E-mail addresses:* werdmann@uni-koeln.de (W. Erdmann), dieter.kelletat@t-online.de (D. Kelletat), anja.scheffers@scu.edu.au (A. Scheffers).

https://doi.org/10.1016/j.margeo.2018.02.003
Received 8 September 2017; Received in revised form 29 November 2017; Accepted 8 February 2018
Available online 09 February 2018
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necessary to keep it in motion and dislocate it significantly (Benner et al., 2010).

For boulder dislodgement to occur strong forces have to act on the rock from which it originates. Although the direct observation of the dislocation process during a storm is difficult, in some areas with carbonate rocks boulder movements scrape the bedrock or neighboring fragments, and these signatures can be observed for some time (up to years in some cases) after an event. These marks enable the collection of quantitative data on mass, distance, direction and the kind of movement the boulders have undergone, and may enable clarification of physical processes of boulder transport (e.g. continuous lines by sliding/shifting, interrupted lines by jumping or – if shown as series of similar marks, points or short lines – by rolling of an angular fragment). Despite such data, there are still more questions to be answered than a general agreement with regards to dislocation processes of boulders and the most important parameters at work in these processes.

Nott (2003) distinguished boulders of different forms (cubic or platy), and identified three pre-transport settings (submerged, subaerial and joint bounded). He concluded, that the form of a boulder is much more important than its mass, and a cube is transported more easily than a plate form. Conversely, Nakamura et al. (2014) found that the flatter the boulder the lower the velocity needed to move it. Imamura et al. (2008), Goto et al. (2009), Nandesana and Tanaka (2013), and Nakamura et al. (2014) found that boulders need relatively low wave and bore velocities (3–3.5 m/s) for sliding, whilst higher velocities are needed for rotation, and even higher velocities for saltation. However, centrifugal forces and interaction/collision of fragments may lead to a greater range of transport from rotation and saltation compared to sliding.

Sliding is the process of boulder movement that exhibits the greatest friction. Weiss (2012) and Weiss and Diplas (2015) exclude the sliding process if bed roughness is 30% or more of a (spherical) boulder's radius. During rotation or saltation, however, bed roughness/friction are nearly insignificant. A longer transport distance needs bore flow, which, according to Ryu et al. (2007), may reach a maximum horizontal velocity 1.5 times the phase speed of a wave. Hansom et al. (2008) modelled green water bore flows which, however, accelerate with the factor of 2.4 at each (structural) step on a cliff-top.

With regards to boulder settings before movement, Nott (2003) argued that a submerged boulder requires the smallest waves for transportation, in contrast to subaerial or joint bound scenarios. However, a submerged boulder needs the highest lift against gravity to reach a new position on land, and may be exposed to a subaerial position just before a large wave hits, as water recedes strongly in front of breaking waves.

As all theories and models are based on simplifications of natural conditions, field data on the size of boulders and distance moved against gravity are valuable for validation of such models.

Richmond et al. (2011) support the idea that storm boulders of medium size cannot be found further than an average of 50 m to 100 inland. Terry et al. (2013) found a significant difference between the large mass (> 40 $m^3$) of existing boulders, mostly unaffected by a TC (Tropical Cyclone) of cat. 4–5, and those moved by a storm of this energy with a maximum boulder size < 5 tons. May et al. (2015) quantified the dislocation of the largest boulder observed during a storm on Samar Island, eastern Philippines, from TC Haiyan in 2013 (the strongest ever on record, with sustained winds of 315 km/h and gusts up to 375 km/h). The authors used multi-temporal satellite imagery, direct observation of the event, and eyewitness accounts including videos. The location is a boulder of coral rock with a mass of 180 tons, which has been moved around 40 m along the coastline, not against gravity. The authors argue that a rare combination of storm waves, surge and infra-gravity waves resulted in this extreme block movement. Kennedy et al. (2017) used field data from Typhoon Haiyan to discriminate the suitability of boulder forms (rectangular and non-rectangular cross sections), mass (up to > 100 tons) and elevation (max. 15 m MSL) for different kinds of movement.

It can be found that at many exposed sites around the world's coastline coastal boulders exist in individual dimensions and distances (vertical and horizontal) to the actual shorelines which needed significantly more energy as is offered from modern extraordinary winter storm waves or waves from strong tropical cyclones. In particular because of different sources of information (fieldwork, wave tank experiments, theories on wave motion, calculations on wave transport energies, bore flow physics, models of boulder transport etc.), a balanced review of all coastal boulder transport processes is not possible in a paper with limited length.

The discussion on boulder movement onshore remains difficult if information on important facts are missing, e.g.

- methods of identifying boulder forms, volumes and boulder mass, or source area,
- distance of boulder movement (from its source, from the shoreline, at which elevation, how far against gravitation),
- friction/bed roughness,
- mode of movement (single or with other fragments, in one or many steps, by one or many events),
- kind of movement (sliding, rotation, saltation, no surface contact between start and place of final deposition),
- process of movement (waves, bores, tsunamis, infra-gravity waves, freak waves),
- age since deposition (with relative or numerical methods).

## 2. Study area and methods

Conclusions from local and regional studies are most valid for these specific sites and regions. The same is true for theories, tests and models, due to their focus on specific parameters. To undertake an overall validation more investigations into the phenomenon of coastal boulder dislocation is needed. Consequently, we will concentrate on an area of an exceptional variety of boulder settings (single blocks, boulder clusters, imbrication trains, kilometres long ridges on high cliff tops) from the Aran Islands and the SE-coast of Galway Bay, on the central west coast of Ireland (Fig. 1).

The 60 km W-E axis of Galway Bay separates a granite landscape in the north from a Carboniferous limestone terrain in the southeast (Fehman, 1999; McNamara and Hennessy, 2010). In a landscape with very variable topographies, exposure and water depth, bedding and jointing deliver all sizes of boulders and blocks in elevations from sea level to > 50 m asl. The results is, that marine transport forces can act upon a diverse range of material available for dislocation and for each storm or other extreme process, an “envelope” for dislocated material can be identified. The same is true for the younger Holocene and for different sea levels, so far as a matrix of numerical ages are established. This all positions the Aran Islands and parts of Galway Bay as a perfect natural test area for the topic of coastal boulder movements.

The storm history with emphasis on exceptional events is discussed in Brayne (2003), Burt (2006), Erdmann et al. (2015), Hickey (2001), Lamb and Frydendal (1991), MacClenahan et al. (2001), and O'Brian et al. (2013), Shields and Fitzgerald (1989), as well as in Erdmann et al. (2015) and Masselink et al. (2016) for the winter season of 2013/14.

Several indicators for the relative age of boulder dislocation such as small morphologies from intertidal/subtidal organisms like sea urchins, limpets, boring bivalves, and *Cliona* borings, and rock pools formed by bio-erosion have been studied (compare also Kelletat, 1986, 1988; Spencer, 1988; Trudgill, 1987; Trudgill and Crabtree, 1987; Trudgill et al., 1987). Their intensity is compared with terrestrial limestone dissolution on boulders (e.g. using the height of pedestals under glacial erratics in the study area, and data from Pfeffer (2010)).

Text documents and photographs on the boulder deposits of the exposed sides of the Aran Islands are found (chronologically) in Williams and Hall (2004), Hall et al. (2006, 2010), Hansom et al.

**Fig. 1.** Galway Bay and the line of the three Aran Islands. Large boulders and blocks moved by storms of the winter season 2013/14 occur along the cliffed island coastlines of Inishmore, Inishmaan and Inisheer (all strongly exposed to the open Atlantic Ocean), and at the section Doolin to Black Head within Galway Bay (Credit: Google Earth, modified).

(2008), Hansom et al. (2008), Zentner (2009), Scheffers et al. (2010), Hall (2010), Williams (2011), and Cox et al. (2012), but all without detailed knowledge of the age of emplacement.

Several authors have delivered a large number of boulder measurements from the area as a statistical basis. Zentner (2009) measured 2688 boulders with all three axes, but not incorporating very large ones: only 0.37% had longest axes of 2–3 m, not a single boulder had a volume of 4 $m^3$ or higher or a mass of 10 tons or more. 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. Later, Cox et al. (2014, 2016) investigated the dislocation of large boulders by the 2013/14 hurricane-force storms but – in contrast to this study – not restricted to those moved significantly against gravity. More documents and qualitative and quantitative data on the 2013/14 boulder dislocations can be found in Erdmann et al. (2015, 2017, 2018).

The Aran Islands and the south-eastern section of Galway Bay at the central Irish west coast certainly are one of the best natural laboratories to study coastal boulder deposits. The natural setting is unique because it offers – with the same rock type (very dense and resistant Carboniferous limestones) – a broad range of parameters to identify marine impacts over at least the second half of the Holocene. These diverse parameters include differences in exposure, coastal relief, elevation and nearshore water depths, as well as characteristics of the limestone bedrock (strata thickness of a few centimetres up to many meters, narrow and wide spacing of joint pattern) which determine the size of boulders in joint bound scenarios from a few kilograms to hundreds of tons.

Due to the unique natural setting, the impact and transport capability of marine processes can clearly be identified in the field. These resulted (in the Galway-Aran area) in Holocene coastal boulders up to > 200 tons, with the highest location of some of the boulders above MHW-level (Mean High Water level) worldwide (up to > 30 m) and their furthest distance to the modern shoreline (up to 280 m in elevations of > 10 m MHW).

To evaluate possible transport processes, strongly exposed and more sheltered rocky coastlines along the Aran Islands and the SE coast of Galway Bay with altogether 60 km in length have been inspected, mapped and measured in June 2014 (with additions in September 2015, February 2016, and September 2016). These observations have been compared with our own photographic documents from 2005 to 2008, a full set of false-color infrared aerial photographs from the National Coastline Survey (Marine Institute of Ireland, Dublin, 2000), and satellite images from Google Earth of the last > 20 years. The geomorphology of organization forms of large boulders like ridges, clusters and imbrication and their relation to other units of marine sediments (chaotic and (rarely) stratified sands and pebbles and washover tongues of medium-sized boulders) have been investigated. Micro-morphological signatures on limestone from the intertidal (biogenic rock pools, home-places of sea urchins and *Patella*, borings of *Cliona* and *Hiatella arctica*) have been compared with the intensity of terrestrial limestone dissolution (karst tables under glacial erratics, micro-karren) for relative age estimations of boulder dislocation. Over 80 numerical data of organic remains at and in boulders (in particular the boring bivalve *Hiatella arctica*) gave an impression of the age of boulder deposits in the study area covering the younger half of the Holocene (compare Scheffers et al., 2010, and Erdmann et al., 2015, 2017). Previous documentation on the marine boulder landscapes of the Galway and Aran region can also be found in Erdmann et al. (2015, 2017), in which all relevant publications since the fundamental paper of Williams and Hall (2004) are discussed. Quantitative data concerning movement of fresh boulders (from the winter-storm period 2013/14) are presented in Cox and Watkins (2015) and Cox et al. (2014, 2016).

## 3. Results: qualitative and quantitative data on recent boulder movements during extreme storm events from western Ireland

### 3.1. Overview

Many of the field observations and most of the models mentioned in the introduction referred to situations with low relief and reef platforms. Here, we present observations from complex topographies, including cliff landscapes, using near time inspection of boulder transport resulting from extreme storm waves and bores in the Galway area (see also Erdmann et al., 2015). These storms were a rare succession of six events which occurred from December 2013, to February 2014 (compare Erdmann et al., 2015, p.4–5). Three of these storms were of hurricane category 3 (central pressure of 945 hPa (hectopascal) and winds around 200 km/h), and three of hurricane category 4 (central pressure below 940 hPa and winds > 200 km/h). The local population considered the wave heights, storm winds and gusts to be the strongest in living memory, identified as the most energetic in the last 67 years (1948–2015) by Masselink et al. (2016).

The wave and bore moved boulders during these storms were first mapped in June 2014. The boulder forms identified in the study area are simple (plates, cubes, cuboids, but see differences in Fig. 2) and measuring their volume in the field using scales was simple. To estimate bulk density of Carboniferous limestone in the Aran Islands and eastern Galway Bay, randomly sampled rock fragments (n = 30) from different strata were measured following the Archimedean Principle, resulting in a mean density of 2.64 g/cm$^3$. Bulk density in this paper was calculated as 2.5 (gr/cm$^3$), as densities of all boulders mentioned were not measured.

The following figures provide examples of boulder dislocation nearshore and at cliff-top positions (Figs. 3–7). The majority of the boulders shown were moved without significant ground contact and minimum of collision with neighboring fragments. Their movement mainly occurred within one step from the source to the boulder's new location, and friction was of nearly no concern. On less inclined slopes the contact on the rock surface was often marked by striations (Figs. 8 and 9), which resemble cray lines, and rarely left incisions in the bedrock. These signatures indicate bed roughness, form of moved boulders (and their contact points deriving from this form), and kind of movement, in particular sliding and rotation.

As well as the dislocation of fresh large boulders that were transported to inland locations against gravity, small and medium-sized boulders (0.2 to max. 2 t) were transported along the seaward slope of existing boulder ridges on the Aran Islands of Inisheer, Inishmaan and Inishmore. There were a large number of these boulders (up to many hundred at one site), but fresh outbreaks at the cliffs or structural steps were rare (general documentation in Erdmann et al., 2015). The activation of boulder ridges is not considered to be the result of an addition of boulders (as Cox et al. (2012) argue) but mostly a repeated movement of existing ones on the seaward ridge slopes, including a loss of boulders by backwash into the sea. This process is restricted to ridges in lower elevation (< 15 m MHW), in particular along the most exposed sections of the Aran Island cliffs (of Inishmore and Inishmaan). At elevations higher than +15 m MHW, ridges are less affected, whilst on ridges higher than +20 m MHW only single small fragments freshly broken occur. At elevations of +25 m MHW, ridges were left unaffected and may contain old boulders with 10 tons or more in mass even if their deposition is > 100 m from the modern cliff edge.

In addition to fresh boulders, existing (old) boulders were moved by waves and bores during the extraordinary 2013/14 winter storms. Some of these older boulders, in particular of smaller size (< 5 tons), were displaced from their original location by decimetres to meters, but rarely against gravity. The most interesting result was that, whilst a larger class of fresh boulders had been moved to a landward or higher elevation (in particular pushed upwards from structural steps by breaking wave impacts), a smaller class of existing old boulders were left in their place (Fig. 10). More data on this phenomenon can be found in Erdmann et al. (2015).

### 3.2. A case study from Doolin, Co. Clare (western Ireland)

On cliff tops or slopes inland of the surf belt, waves are transformed into bores, and these bores rush uphill and may transport fragments from subaerial or joint bound settings. This was the case 200–250 m ESE of Doolin Point (Fig. 11), where dislocation of large limestone boulders enabled the collection of quantitative data on boulder size, mass, transport distances (horizontal and vertical), and type of transport. The situation is shown on the sketch map and in a profile (Figs. 11 a-c) as well as in Figs. 12 and 13, with additional quantitative data in Table 1. These data may be used for models on wave and bore transport competence, and the model results may be compared to the real natural processes during the storm.

Boulders (total mass about 44 tons) were moved early in February 2014, from a horizontal source area of 35 m$^2$ at +2.4 m MHW and 30 m from MHW from a joint bound scenario (partly separated from their base by internal karst solution, but broken from rock along > 13 m in plates 0.5 m thick). All figures given are minimum values. Direction of wave and bore approach was from 284°, crossing shallow water (−10 m) 300 m from the source area, and MLW (Mean Low Water) line 200 m from the source area.

Although the conditions for boulder transport in the Galway area are special with regards to the steep and cliffed coastlines and platy boulders from a joint bound scenario, several general aspects of the transport and deposition processes of these boulders can be gained from the evidences presented above:

1. Dislocation of the largest boulder (boulder A, 17.5 m$^2$ and > 21 tons) took place during the last extreme winter storm of the season 2013/14, which was "Storm Ruth", February 6–11, 2014, with a lowest central pressure of 945 hPa, a category 3 hurricane. It is concluded that all boulders A-D were dislocated during this event. Assuming that the dislocation of the joint bound boulders occurred during the peak of the storm, the maximum unbroken wave height approaching the coast at the −10 m line is calculated to 11–12 m.
2. Waves responsible for dislocation approached the supratidal rock platform as a green water bore, which transformed into a white water bore as it crossed rocky steps. These bores travelled > 100 m to the source area of the boulders. Wave and bore height and velocity diminished due to turbulence and friction caused by 0.3–1.3 m structural steps and the rough surface of the supratidal

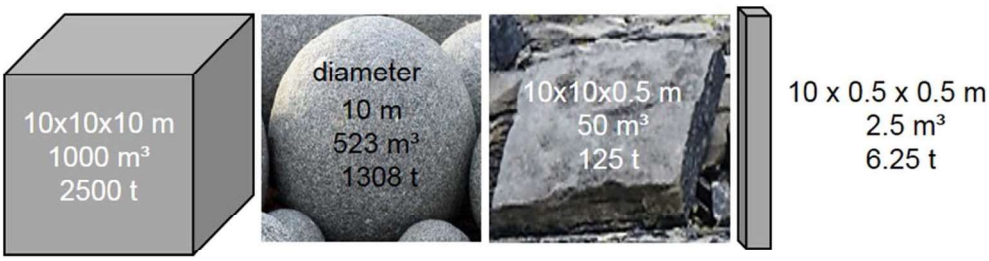


**Fig. 2.** Boulders are classified according to the dimensions of their longest axis, but with the same axis length they may vary in their volume and mass. The relations in percentage are: cube = 100/sphere = 52.3/plate = 5/column = 0.25, which results in a difference of one to several hundred. Additionally, the interrelation of volume and mass with waves, bores, topography and surface roughness result in an infinitely large number of natural scenarios for boulder movement conditions.

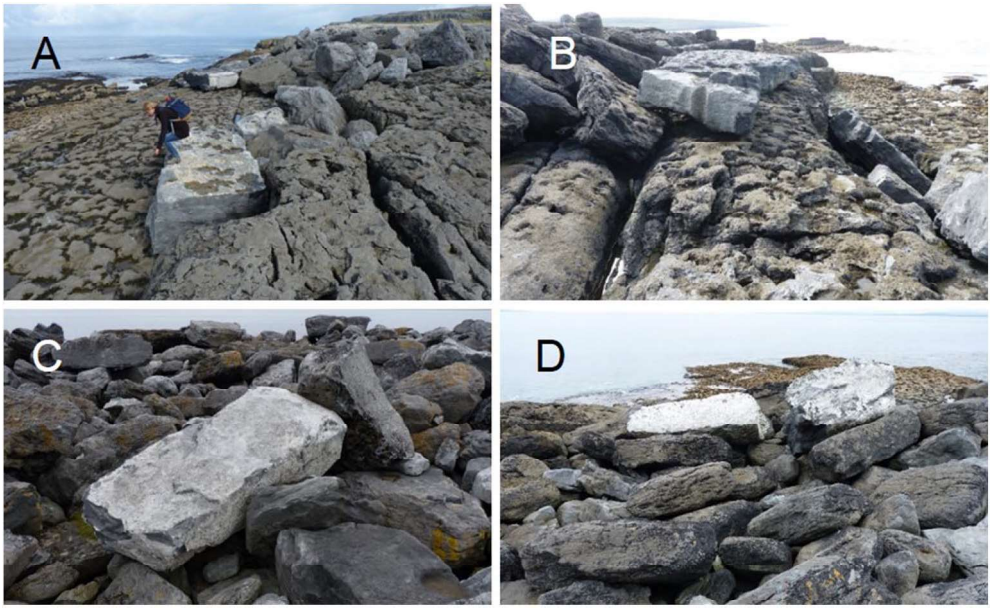


**Fig. 3.** Examples of boulders quarried by waves and bores during winter storms 2013/14 along the SE coast of Galway Bay (Doolin to Black Head), dislocated 3–6 m against gravity. Their mass is from 2 and 3.5 tons (D) up to 11 tons (A and B), highest elevation of fresh boulder deposits shown is +9 m MHW. Boulders in (C) to (D) are found between and on old boulders (masses up to > 20 tons in elevations up to +19 m MHW) not moved for (at least) many centuries deduced from the intensity of limestone solution by rain water. At the imbricated boulders of (D), *Hiatella arctica* in borings gave ages for dislocation from the intertidal of 5800 cal BP (Erdmann et al., 2017).

platforms. The maximum estimated height of the (white water) bore was 5–6 m when reaching the source area, which has a base height of +2.4 m MHW.

3. When the bore hit, the rocky plate was still joint bound and fixed along 13 m with its eastern section comprised of strong rock (but more or less opened by internal karst solution at its entire base) with a front perpendicular to wave direction, nearly 8 m long and 0.5–0.55 m high, i.e. on about 4 $m^2$ but had to move/lift a mass of rock in the order of 44 tons. This seems physically to be impossible, as a rock barrier exists at the platform's leeward side.
4. If wave height in open water SW of Doolin Point was 11–12 m, its velocity would have been around 13 m/s. A bore from this wave may have had an initial velocity 1.5 times that of wave velocity (Ryu et al., 2007, for green water bores) which is therefore about 18 m/s. Turbulence, which occurred during breaking and friction on several steps with a combined height of 5–7 m, and friction on the rock platforms, may have dampened bore velocity after > 100 m above MHWS (Mean High Water Springs) to an unknown value (with an approximate probable maximum velocity of the order of < 12 m/s).
5. As the bore moved along the cliff eastward to the boulder site, there was no backflow, which would have increased the mass of incoming water or the height of an incoming wave.

As the data presented on boulder dislocation at the Doolin Point scenario, and additional evidence of boulder movement at other sites in the Galway area, shows, platy boulders commonly move without significant ground contact or impact on the bedrock. Instead, these boulders were lifted vertically and then transported almost horizontally above the surface before deposition. The contours of these boulders are sharp, as are the contours of outbreaks. Similar results were observed from hurricane "Ivan" on Bonaire Island in the Caribbean in 2004 (Scheffers and Scheffers, 2006). For example, boulder A from the Doolin Point scenario, was transported by a bore over a flat surface, which was able to lift > 1 t/$m^2$ (> 21 tons with a surface of 17.5 $m^2$). As steps in the topography were overcome during this movement and no contact points on the surface are left, the dislocation was evidently performed in one step. The mechanism of this scenario is only possible if the flow produces a low pressure at the surface of boulders (the same physical law which makes airplanes fly) and lifts heavy masses before they were entrained in the flow and transported in the flow direction. A partly older and – regarding transport processes and results – similar boulder cluster was found at high elevation and far from the modern cliff edge at the west coast of Inishmaan (Fig. 14). Break out and dislodgement of platy boulders in coastal environments seem to be an effective process, especially in sedimentary rocks.

## 4. Discussion

The comparison of field data and models in addition to laboratory wave and flow tests have documented a number of unexplained features and processes in coastal boulder dislocation, due to the difficulty in transferring the complex combination of all parameters found in natural settings into laboratory tests or models. The parameters most difficult to reproduce are friction, coastal sloping, and nearshore bathymetry. Therefore, we are sceptical that boulder dislocation can be explained "*with simple theories*" (Weiss and Diplas, 2015). An additional challenge in data collection is which techniques were used to detect boulder mass (i.e. volume and density) in the case of waves or bores, or how

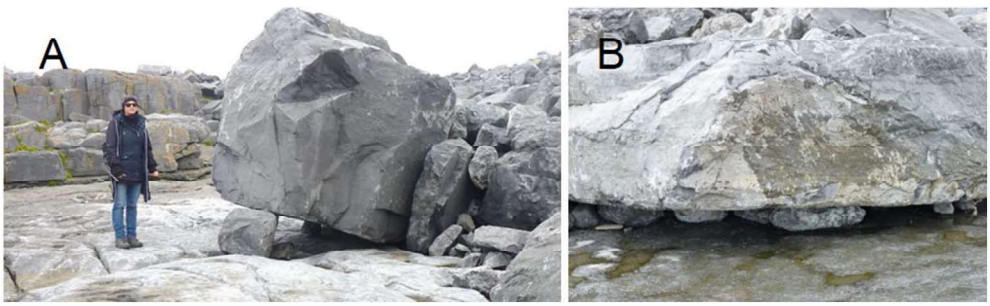


**Fig. 4.** By buoyance during storms in winter 2013/14, existing large boulders were vertically lifted and now are supported by small fragments that have formed pillars.

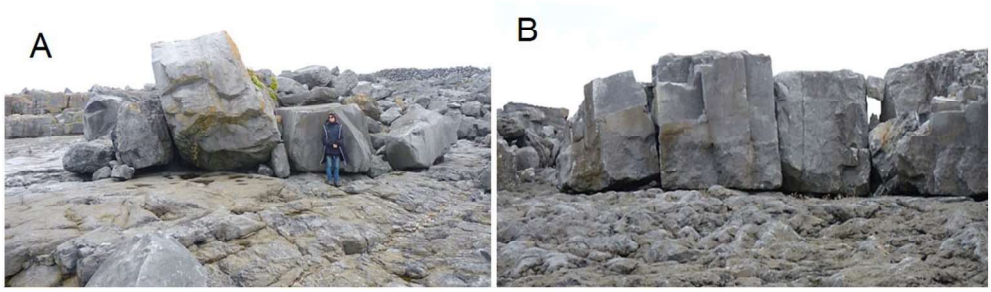


**Fig. 5.** Old boulders (up to 40 tons in mass) partially covered with lichen were moved for some decimetres during the 2013/14 storms at +6 to +7 m MHW east of the Wormhole, south coast of Inishmore.

nearshore bathymetry has transformed wave heights and wave forms from open ocean waves. The largest uncertainties (also shown in Kennedy et al. (2017) for the Haiyan Typhoon at the Philippines) are whether a boulder was transported by a recent or (unknown) older event, how far it was transported (and in how many steps) and how much of this process was against gravity, or where the source of the fragment was. This all is necessary for the evaluation of the processes that have acted on a boulder, and whether a certain setting can be used for generalization, or only represents a local case.

In the coastal limestone landscape along Galway Bay and the Aran Islands, the test site enables the identification of parameters involved in boulder dislocation and transport through signatures on the ground left during movements (impact marks and striations). These features also provide information about the influence of friction and can be identified during near time inspections but disappear after a maximum of a few years following the event in which the boulders were transported.

From the pattern of striations on the bedrock we can detect several important facts (see also Figs. 8 and 9):

a) Through observation of fresh boulders at the end of striations it is observed that boulder contact with the bedrock surface is generally much smaller than the base of the moved boulder. Generally, narrow striations occur even if a boulder with a surface of many square meters is moved. The question of how one can calculate friction parameters for modelling therefore arises.
b) Striations display the transport direction, even if they show an interrupted pathway, and even if the boulder pathway is straight or curved. A curving line most probably indicates boulder transport has occurred in one movement (from a wave or bore transport). In places with many striations the striations often occur in different directions, e.g. to landward from incoming waves and bores in different angles, or from refracted waves and backflow, or from tumbling around of fragments along structural steps or ridge slopes. In the latter case a white-colored belt of freshly abraded rock appears. Parallel to this belt, fragments on the ridge slopes have often lost sharp edges, which are typical for single boulders that have been freshly transported.
c) Most striations are not continuous lines, but include interruptions. These may derive from irregularities on the bedrock, or due to the character of the transport/movement of a boulder: Interruptions (in particular if they are regularly spaced) may suggest a step-by-step transport process involving a series of consecutive waves or bores of similar energy. Groups of similar contact points that occur along the same line suggest rotation of an angular fragment. Irregular spacing of contacts along one line are most probably derived from saltation, although whether this is triggered by one or several waves or bores is difficult to determine. Saltation contact marks also differ in size or intensity of color compared to those from rotation or sliding.

On coastal reliefs with accentuated topography, a high number of parameters affect boulder movement (Shanmugam, 2012), and cliff sections present additional challenges in the evaluation of physical processes. Because of the relief of cliff landscapes, even high waves will meet nearshore obstacles and are transformed into bores, whereas on a reef platform a wave may travel a greater distance before being transformed into a bore, if water depth is sufficient. Another difference important for boulder dislocation and transport is the possible effect of backwash; whilst this is minimal or missing on a platform (a reef), higher topographies enables this process to occur.

Although multiple models and hypotheses based on physical laws have been developed, we are far from a complete simulation of natural processes in theoretical approximations. The main reason is over-simplification of complex conditions, e.g.: is the boulder bound within a horizontal platform close to surf level, or in a rocky slope rising to landward (straight, concave, convex), bound in a cliff face, directly at cliff-top, or in the landward direction of the cliff-top (horizontal platform, rocky slope (straight, concave, convex), on a stepped profile (plain, with micro-relief))? Is the boulder hit by an open water wave, a translational wave, a steep surf wave after breaking with high air content, by a green water bore, a white water bore? Does the wave approach perpendicular to the coast or in an angle? Similar questions concern for all possible boulder settings (submerged, subaerial, joint bound).

As Scheffers and Kinis (2014) discussed, it is highly debatable whether a submerged boulder scenario generally requires smaller waves when compared to subaerial or joint bound situations because of buoyancy. We need to consider the exact submerged position of a boulder first. Is it that the submerged situation also occur during wave

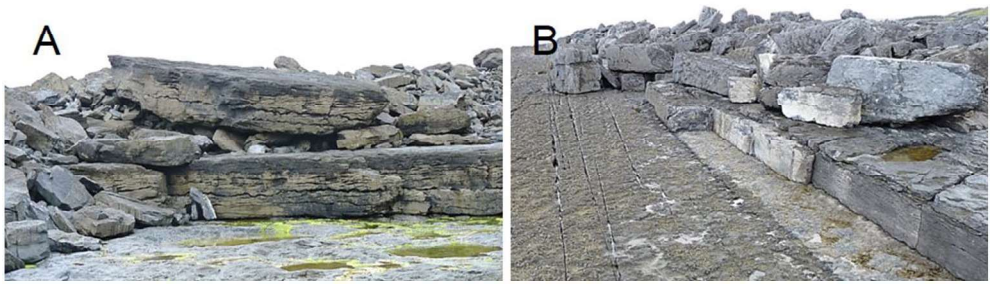


**Fig. 6.** The source of boulders can be identified either by their texture and internal signatures (old boulder dislocation in A), or by fitting to their original places (fresh dislocation in B).

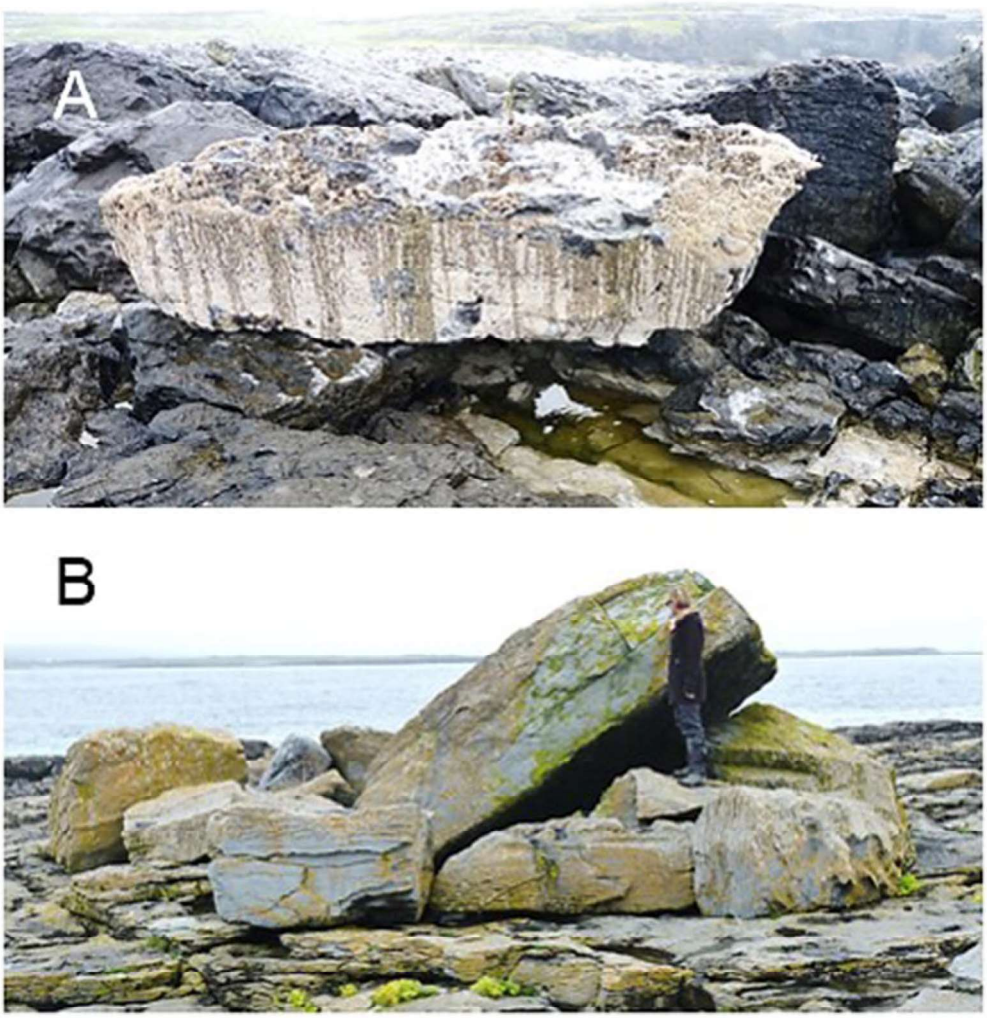


**Fig. 7.** Whereas fresh boulders (A: 12 t, dislocated horizontal for 28 m and vertical for 1.6 m) have been moved onto old boulder ridges (16 km inside Galway Bay, SE coast), old boulder clusters (B, central boulder about 25 t at Inishmaan's NW coast) remained unaffected by storm waves and bores in the 2013/14 season.

contact? This situation needs a deep submergence during still water conditions. If a boulder is only shallowly submerged, the scenario is transformed into a subaerial one during wave impact, because water strongly recedes in front of high waves. If the boulder is still submerged during impact of a high wave, its position is a) more seaward/distant from land, b) at a lower level, and c) placed in the seaward-directed orbital tracks of water particles. At least, these three facts do not support the placement of a formerly "submerged" boulder in a landward direction and against gravity.

Another important factor is friction. Is friction the same as bed roughness? They certainly depend on each other. Bed roughness is important for the physics of a wave or bore, but can almost be disregarded for a boulder transported through rotation or saltation, or one that is lifted vertical by buoyancy, as in the examples presented in Fig. 4.

A boulder in motion has a specific kinetic energy to be transported further, although bore energy diminishes inland and may be not sufficient to pick up a boulder of the same mass. Field observations confirm this; in a near time inspection it is generally found that relatively large fresh boulders were transported farther inland or to higher locations when compared to existing (old) and even smaller boulders closer to the sea (Fig. 9).

Another question that arises is related to the height at which a wave impacts a vertical cliff; a translational wave is higher compared to an open water wave in the same wave train, and again higher if transformed into a breaker. This transformation is dependent on water depth. However, nearshore bathymetry is predominantly unknown. Wave height is also important for bore development; a green water bore can only occur if a wave crest is higher than the cliff top, and the water mass of the upper part of the wave travels forward over a cliff-top platform. If the wave crest does not reach cliff height, a white water bore will form from a water jet rising vertically up the cliff front. A white water bore contains a lot of air and has a much lesser density and therefore much lesser energy (assuming the same velocity) compared to a green water bore.

As in other landscapes, the importance of one extreme event depends on the energy of former events and the time span between events: coastal or cliff retreat by storm waves maybe extreme if weathering has weakened rock structure and texture. If this material is dislocated, the next events (even if much stronger) will be less effective. Good examples for these conditions are rock falls at cliffs. Rock falls produce talus deposits (if nearshore bathymetry offers shallow conditions), which often include large boulders and blocks that protect the cliff foot and part of the cliff face. A sudden cliff retreat may follow decades or even centuries of stable conditions at cliff faces and cliff tops, before the talus is worn away by marine forces.

## 5. Conclusions

The argument that in the geologic past storms and associated waves

**Fig. 8.** Striations (scratch marks) in different directions document contact of bore-moved limestone boulders with limestone bedrock. Bed roughness reduces this contact to a minimal number of lines and rows of contact points (scene is 4.5 m wide, photo of June 2014).

and bores may have been multiple times stronger than during the time period since the instrumental record is consistently cited in the younger literature (as an example see Hearty and Tormey, 2017) and the discussion in the Washington Post (2015). Yet, wind and waves are subjected to the physical laws of atmospheric and oceanic conditions and additionally by local and regional environmental factors as for example topography or bathymetry.

These observations (and conclusions) can be found also in more recent publications, e.g. in Cox and Watkins (2015), or Hearty and Tormey (2017) with the suggestion of "superstorms" in warmer climates of the past and probably by climate change in the future. 'Superstorms' with magnitudes several times larger compared to modern category 5 Tropical Cyclones (TCs), however, are sheer speculation. Atmospheric physical laws dictate that they will collapse by internal and external friction. Observations, registrations and physical laws so far do not allow to speculate beyond the principle of uniformitarianism. Wind velocities of 400 km/h and more only occur on planet Earth for a very short time in tornadoes, which are spatially and temporally much too small to induce wave heights above strong tropical and extra-tropical storms.

The winter season 2013/14 at the west coast of Ireland provided an excellent opportunity to survey changes in the coastal landscape after a series of six winter storms of hurricane categories 3 and 4. These events have been the strongest in (subjective) living memory of the local

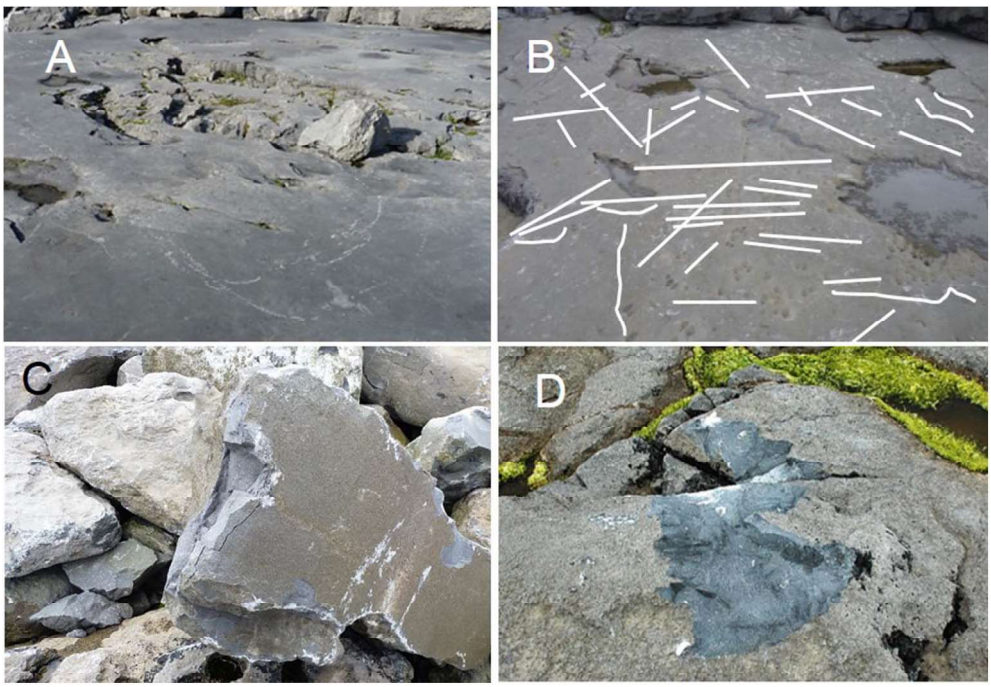


**Fig. 9.** Striations and impact marks in limestone rock of the Doolin - Aran region. (A): curving striation from a single and continuous bore transport. (B): "Mapping" of striation directions. Their short extension suggests transport of many boulders with very limited contact with the bedrock surface. (C) and (D): Hard collision with large fragments produce irregular boulder forms.

**Fig. 10.** Light colors on small boulders along the seaward slope of the main boulder ridge, on the south coast of Inishmore, are the result of activation during the 2013/14 winter storms. Old boulders (5–12 t, marked by arrows) on a cliff top platform at +8 to +9 m MHW remained stable, despite being hit by the full energy of collapsing storm waves during the same events.

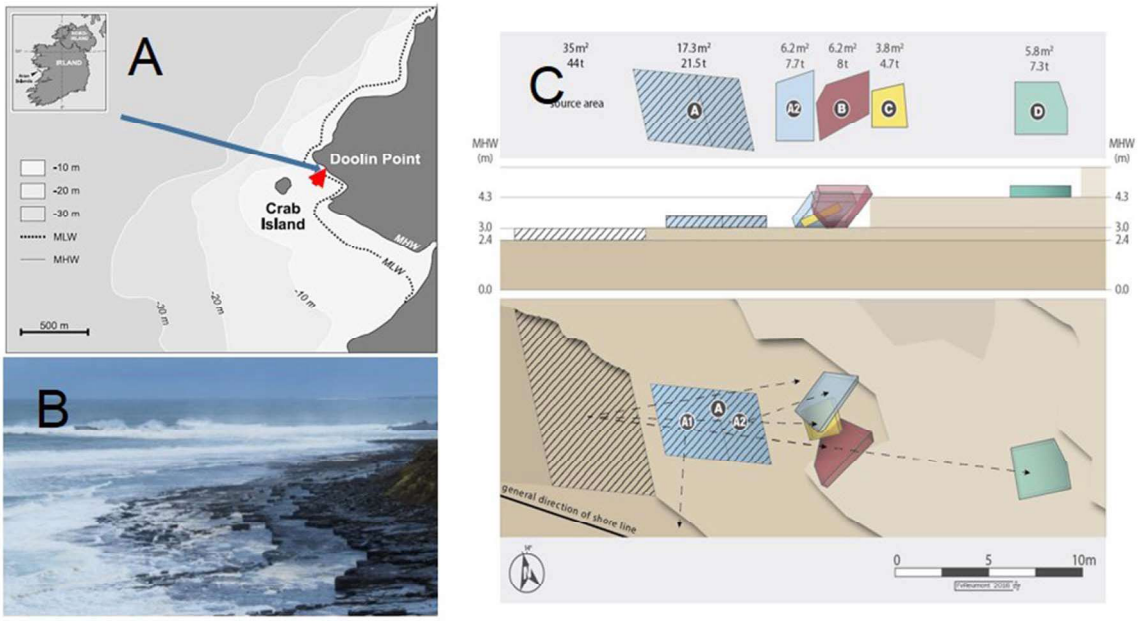


**Fig. 11.** (A): Position of the Doolin Point boulder setting (red arrow), formed by a storm with bores from WNW in early February 2014 (blue arrow). Extension of the intertidal and nearshore bathymetry is also shown. (B): Photo shows 6 m – waves breaking along the −10 m line around Doonnagore Bay. (C): Map and profile of boulder dislocation and settling of early February 2014, 200–250 m ESE of Doolin Point. All boulders were moved from the source area in the west at +2.4 m MHW. Boulders B and C have been overturned > 90°, boulder D is totally overturned, resting now at +4.3 m MHW. Boulder A is split during the first settling and was dislocated again in winter 2014/15: the western part (A1) disappeared into the sea, the eastern part (A2) was added to the central boulder cluster. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

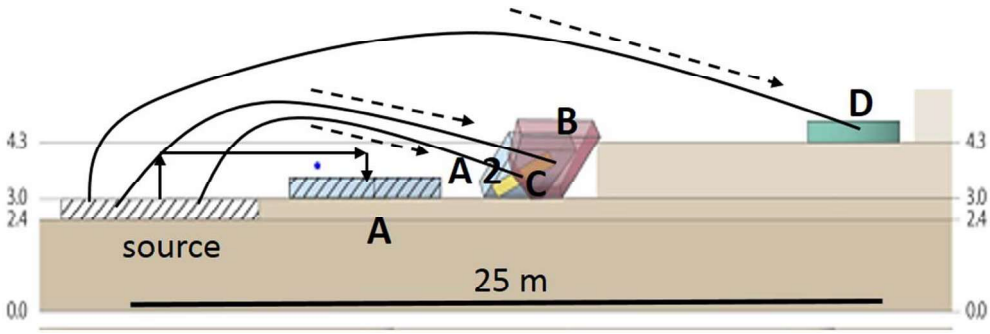


**Fig. 12.** Enlargement of the profile in Fig. 11(C): Movement of platy boulders early in February 2014, east of Doolin Point, on a stepped rock platform 2.4 m to 4.3 m above MHW. From the 35 m² large source area, Boulder A was lifted vertically, dislocated without ground contact for 7 m and settled softly, resulting in one crack 1.5 cm wide. Boulder D moved 24 m wide and 1.9 m against gravity and was overturned, whilst boulders B and C moved 12–13 m resting > 90° against a rock ledge and each other. Boulder A2 (as part of A) was added to the central boulder group during a storm early in 2015.

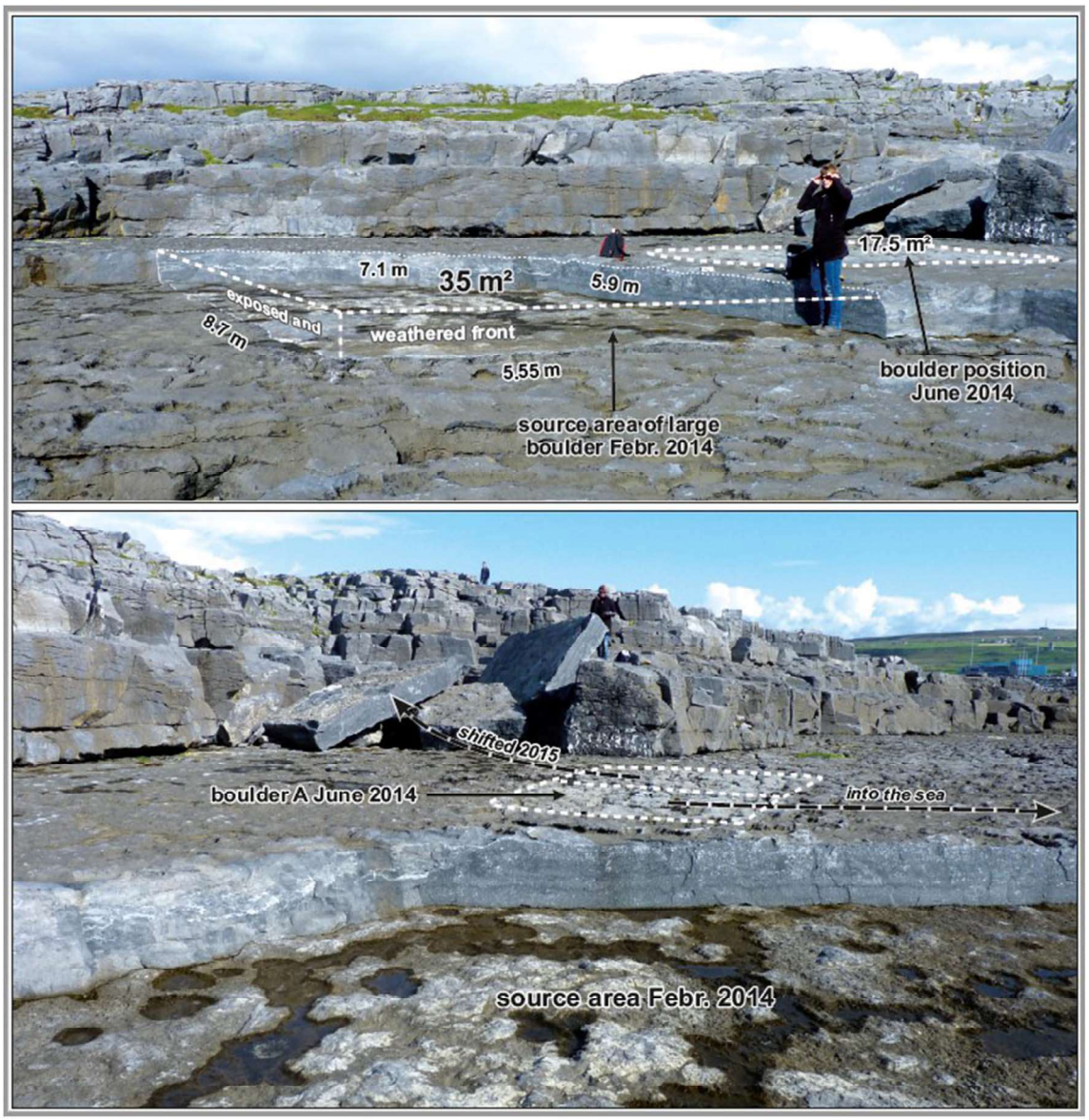


**Fig. 13.** Two aspects of the Doolin Point boulder setting; above: source area dimensions; below: central boulder cluster and the former position of boulder A.

**Table 1**
Quantitative data of the Doolin Point boulder setting.
All figures given are minimum values. Direction of wave and bore approach was from 284°, crossing shallow water (−10 m) 300 m from the source area, and MLW line 200 m from the source area.

| Boulder | Size [m²] | Volume [m³] | Mass [t] | Distance moved [m] | | Type of movement/scenario |
|---|---|---|---|---|---|---|
| | | | | Horizontal | Vertical | |
| A | 17.5 | 8.6 | 21.5 | 7.0 | 0.7 | Lifted and deposited without ground contact |
| B | 6.4 | 3.2 | 8.0 | 13.5 | 1.5 | Lifted, no ground contact, overturned 110° |
| C | 3.8 | 1.9 | 4.7 | 13.0 | 1.1 | Lifted, no ground contact |
| D | 5.8 | 2.9 | 7.3 | 24.0 | 2.5 | Lifted, no ground contact, overturned 180° |
| Activity in winter 2014/15 | | | | | | |
| A1 | 11.0 | 5.5 | 13.2 | | | Washed into the sea |
| A2 | 6.2 | 3.1 | 7.7 | 8.0 | 0.9 | Added to central boulder cluster |
| Activity in winter 2015/16 | | | | | | |
| D | 5.8 | 2.9 | 7.3 | 4.0 | | Moved to E |

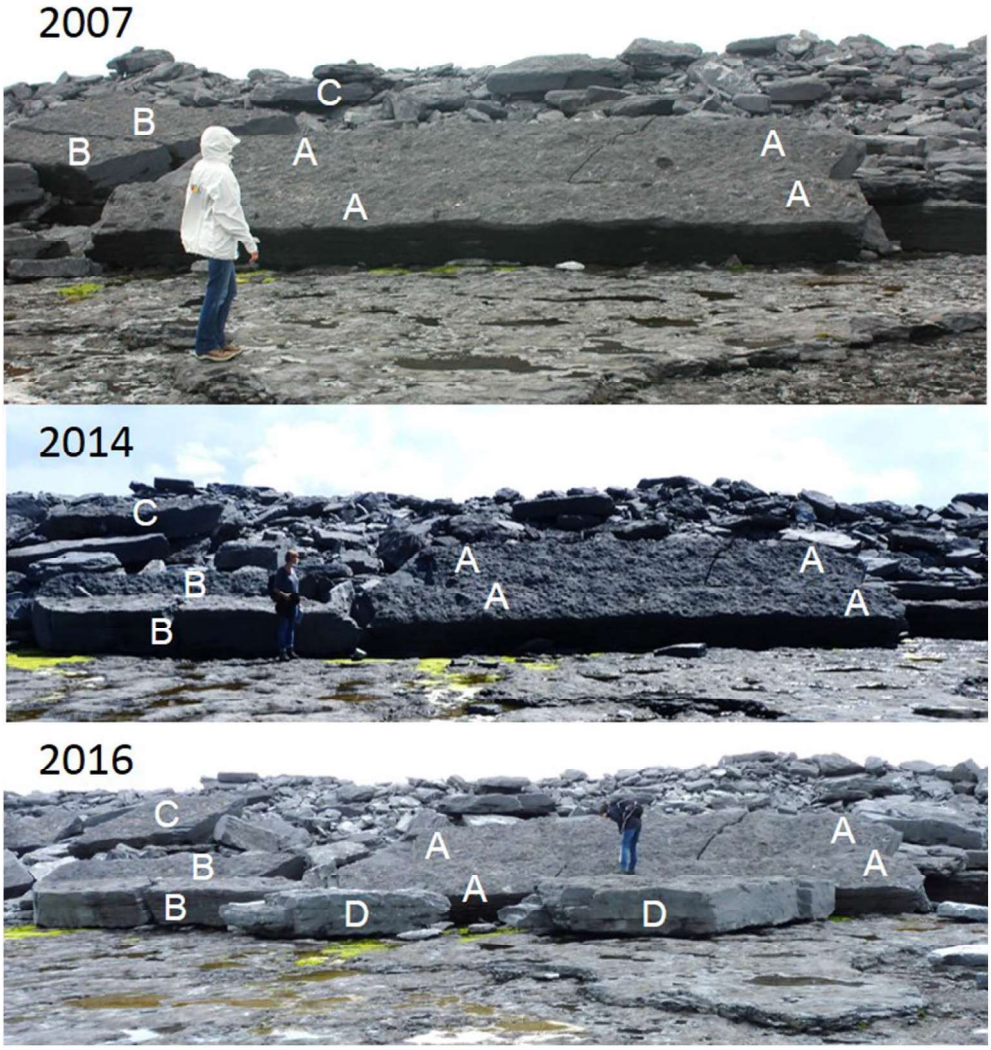


**Fig. 14.** Site and history of a boulder cluster at Inishmaan's west coast (53°04′09.04"N and 09°36′59.70"W) 11 m above MHW and 220 m from the modern cliff edge. One large boulder was dislocated from a structural step on the cliff platform at +9 m MH, moved in one plate (mean axes 14.1 m × 2.6 m × 0.7 m = 25.6 $m^3$ and a mass of 64 tons) and evidently in one short moment 35 m horizontal and 4 m vertical, overturning about 150°. This boulder was deposited at the seaward front of a 4 m high boulder ridge and broken into 4 pieces (double boulders A and B), getting minor fractures during further impacts and movements. Double boulders B moved downwards to the base of the boulder ridge between 2007 and 2014 (most probably during the hurricane-force winter storms 2013/14). Plate C moved downwards between 2014 and 2016. Fresh boulders D (not overturned) are broken from a cliff top platform in the season 2013/14, moved close to the setting early in 2015, reaching the boulder pair A in a winter storm early in 2016.

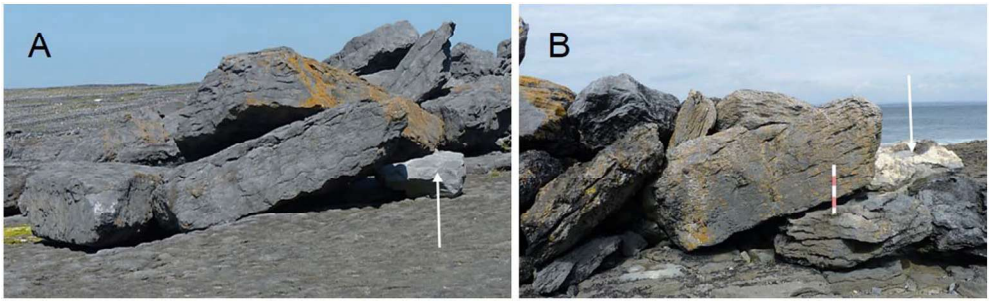


**Fig. 15.** Contrast of old and long-term stable, partly imbricated, large boulders (> 10 tons in mass), and much smaller fragments (indicated by arrows) from recent extreme storm wave events (A) from the south coast of Inishmore at about +11 m MHW, (B) from 20 km inside Galway Bay at +6 m MHW).

residents and based on (objective) meteorological and oceanographic data provided by Masselink et al. (2016) for the past 67 years, at least. Their impact on the rocky coastline and its sediments provides a rare insight into the transport capacity of these strong storms for coastal boulder deposits, and their power was significantly limited in comparison to elevation, distance and size of older boulders deposited in the Aran-Galway region.

During fieldwork along the central west coast of Ireland, including near time inspections shortly after these storms, a high number of freshly dislocated boulders were identified, some with masses around and over 10 tons. Old boulders up to 20–30 tons, several meters above MHW and up to 80 m apart from the sea, were also shifted or lifted by these storms, but were not moved significantly against gravitational forces. In these landscapes much larger coastal boulders also exist (50–230 tons), which were not affected by recent storms and remain in their original depositional location (Figs. 15 and 16; same observations by Terry et al. (2013) for Pacific islands). Weathering status and dating of dead boring bivalves in these boulders (Erdmann et al., 2017) identified that the dislocation and transport of these boulders to elevations > 20 m MHW, 5–10 m against gravity and up to 200 m from the shoreline or cliff was previously possible (back to the Mid-Holocene), when sea level in the Galway area was several meters deeper and the coastline seaward of the modern one (Holmes et al., 2007; Williams and Doyle, 2014; discussion in Erdmann et al., 2017). It is highly

**Fig. 16.** Very large old boulders (A: > 50 tons on clifftop + 10 m at 53°05′31.95″N and 09°39′45.71″W; B: 230 tons lifted for 5 m from MHW near Wormhole at 53°07′14.55″N and 09°45′W), both on Inishmore Island.

questionable that solely storm waves and their bores were responsible for the transport of these boulders against gravity onshore at the exposed cliff locations of the Aran Islands, as well as up to 25 km inside Galway Bay, as these storms had to have energy levels far above TC categories 5 and wave heights and wave velocities never registered worldwide. For the strongest storm event on registration (TC Haiyan on the Philippines in 2013), Kennedy et al. (2017) found a clear mass-elevation envelope outside of which no transport was observed. This is similar to the situation (and dimensions) in the Galway/Aran area, fitting for the winter storm processes 2013/14 as well as for all Holocene boulders in that region.

The discussion shows that more direct observations before, during and after strong events are needed to reach a general agreement on the parameters of boulder movement. Measuring waves in the open sea by buoys is the most appropriate way in which to monitor wave parameters, but the special character of waves at the point at which they come into contact with coastal slopes or cliffs cannot be documented using this method. Consequently, in situ estimations of energy transfer for boulder dislocation are still needed. The exact change from a wave impulse to a bore flow at a given site cannot be identified after the event because it depends on, among other parameters, difference in wave height, wave form, angle of approach, cliff form, or cliff face roughness. In many cases we are able to detect the most probable kind of movement of a boulder (e.g. sliding, rotation, saltation), but we do not know the extent to which it rotates, or how far it is lifted during saltation steps. We also cannot calculate the transport distance horizontally and vertically if we do not know the exact source of a dislocated fragment.

Basic knowledge on coastal energy impacts, including boulder transport, is inhibited by a lack of detailed information on the nearshore bathymetry and seabed configuration, which is responsible for the height, form and energy of approaching waves. Generally, water depths of < 10 m soundings in coastal locations are scarce, and the situation may change rapidly by strong events. Even in the INFOMAR Seabed Mapping Programme (Geological Survey of Ireland, Marine Institute, National Development Plan 2001–2013, published 2006) for Galway Bay, nearshore bathymetry has not been included.

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**Fazit**

Im Zuge der *near time inspection* 2014 zeigte sich bei Doolin Point ein frisches Block-Setting, welches die Erhebung einer ganzen Reihe exakter quantitativer Daten zur Bewegungsstrecke (auch gegen die Schwerkraft), Einfluss der Blockform, bewegende Kraft sowie Herkunft und Art der Bewegung ermöglichte. Es steht als ein typisches Beispiel für sturmbewegte flache Blöcke jeder Größenordnung. Daher waren diese Daten Anlass, bereits publizierte Theorien, Hypothesen und Modelle zur Blockbewegung durch marine Kräfte sowie Veröffentlichungen über lokale Ansammlungen großer Blöcke seit 2000 und weltweit vergleichend zu diskutieren.
Eine abschließende vergleichende Bewertung trifft in diesem Themenfeld auf etliche Probleme. Oft fehlen Angaben über die Ermittlung einfacher Größen wie Blockdimensionen, Blockformen, Dichte, exakte Lage, Transportwege, Bewegung gegen die Schwerkraft, durch Wellen oder Boren usw. Ein weiteres Problem bei theoretischen Überlegungen ist die große Vereinfachung und Reduzierung auf wenige Parameter, auch als Basis für endgültige Schlussfolgerungen auf die wirklich verantwortlichen Naturprozesse. Der Eindruck entsteht, dass etliche Autoren bisher entweder zu wenig Kenntnis von Vorgängen in der Natur gewinnen konnten, oder mit einer vorgefassten Vorstellung beobachtet haben.

Die Widersprüche, welche im Vergleich von Theorien, Hypothesen, Modellen und lokalen Studien in anderen Erdregionen zu den Gegebenheiten um Galway auffielen, sind der Hauptgegenstand dieser Publikation. Sie enthält aber auch mit dem *„Doolin-Boulder-Setting“* eine der ganz wenigen Kartierungen bzw. Fallstudien. Ihre Interpretierbarkeit wird wesentlich dadurch unterstützt, dass im Kalkgestein viele Prozesse geradezu aufgezeichnet sind und eine Weile sichtbar bleiben und gelesen werden können.

## 4.4 Kartierung und Beprobung der Aran-Inseln und Vergleich mit Daten aus der Galway Bay (Erdmann et al., 2018 b)

Im Hinblick auf die Aufgabe, nicht nur einen größeren und hinsichtlich Relief, Exposition und Sedimenten heterogenen Raum zu kartieren, sondern einen Überblick über die geomorphologische Entwicklung zu erstellen, fehlten bisher Altersdaten von den Aran-Inseln, welche zumindest ein chronologisches Raster über den Zeitabschnitt eines hohen holozänen Meeresspiegelstandes erlauben würden. Dies ist umso notwendiger, als die Aran-Inseln und ihre marinen Grobsedimente in der Forschungsgeschichte der Westküste Irlands bisher die größte Rolle gespielt haben. Daher wurden während der Feldarbeiten im Herbst 2016 neben ergänzenden Studien und quantitativen Messungen an den Blockmustern auch die wenigen flachen Archive mit feineren Sedimenten erschlossen und beprobt, so dass nun 84 Altersdaten aus dem gesamten Raum zur Verfügung stehen. Damit lassen sich vor allem Vergleiche zwischen den extrem exponierten Atlantikküsten der Aran-Inseln und dem hinter ihnen eher geschützten Abschnitt der Galway Bay vornehmen. Da – wie in den früheren Arbeiten von Scheffers et al. (2009, 2010 a, 2010 b) bereits geschlossen – eine Mitwirkung von Tsunamis am Aufbau und dem Charakter der Blockablagerungen in den Arbeitsgebieten stets wahrscheinlicher wurde, konnte nur eine hinreichende Zahl von Altersdaten aus verschiedenen Expositionen und Höhenlagen helfen, gewisse Datencluster aufzufinden. Hierbei können nun erste Ergebnisse vorgelegt werden. Sie sind außerordentlich wichtig für einen wünschenswerten Abgleich mit Altern von submarinen *mass-wasting-Prozessen* im steilen und 3.000 m tiefen *Rockall Trough* westlich von Irland, in dem Tsunami-auslösende Vorgänge für das Spätglazial und hinein in das Postglazial bereits von Ozeanographen ermittelt wurden.

Erdmann, W., Scheffers, A.M., und Kelletat, D.H., 2018 b. Holocene Coastal Sedimentation in a Rocky Environment: Geomorphological Evidence from the Aran Islands and Galway Bay (Western Ireland). Journal of Coastal Research, 34: 772 - 793

**Zusammenfassung**

Felsküsten, die überwiegend Grobsedimente und Blöcke aufweisen, sind in der Forschung stark vernachlässigt, vor allem, weil zu ihrer Analyse geeignete Labormethoden fehlen. Diese Arbeit befasst sich mit der Geomorphologie und den Ablagerungen außerordentlich großer Blöcke oberhalb von steilen Kliffen auf den Aran-Inseln Inishmore, Inishmaan und Inisheer. Diese Grobsedimente werden mit den Ablagerungsbedingungen isolierter und räumlich beschränkter feinerer Geoarchive und zungenartigen Formen aus kleineren Blöcken verglichen. Mikromorphologische Hinweise durch Lösungsformen auf Kalkstein im terrestrischen Milieu und bioerosive Formen auf dem gleichen Gestein im Litoral wurden darüber hinaus zur Abschätzung des (relativen) Verlagerungsalters herangezogen, wobei die Umlagerungsprozesse oder ihr Fehlen im Verlauf der extremen Stürme der Wintersaison 2013/14 wichtige Hinweise gaben. Die Zahl der Altersbestimmungen wurde auf nunmehr insgesamt 84 aus den Arbeitsgebieten Galway Bay und Aran-Inseln erhöht, woraus sich erste Hinweise auf die Häufigkeit und Chronologie extremer Wellenereignisse ableiten lassen. Außerdem diskutiert diese Arbeit vergleichend die Intensität des Kliffrückganges an harten Gesteinen und enthält eine Bewertung der Argumente der *storm-only*-Hypothese und der Mitwirkung von Tsunamis bei der Blockbewegung.

| Journal of Coastal Research | 34 | 4 | 772–792 | Coconut Creek, Florida | July 2018 |
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# Holocene Coastal Sedimentation in a Rocky Environment: Geomorphological Evidence from the Aran Islands and Galway Bay (Western Ireland)

**Wibke Erdmann[†], Anja M. Scheffers[‡], and Dieter H. Kelletat[‡]***

[†]Institute of Geography and Education
University of Cologne
Cologne, Germany

[‡]Southern Cross Geoscience
Southern Cross University
Lismore Campus, NSW, Australia

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**ABSTRACT**

Erdmann, W.; Scheffers, A.M., and Kelletat, D.H., 2018. Holocene coastal sedimentation in a rocky environment: Geomorphological evidence from the Aran Islands and Galway Bay (western Ireland). *Journal of Coastal Research,* 34(4), 772–792. Coconut Creek (Florida), ISSN 0749-0208.

Rocky shores predominantly comprising coarse gravel and boulders are a neglected area of research, in part because of the difficulty in undertaking laboratory analyses on such environments. This paper is concerned with the geomorphology of the deposition of exceptional large boulders in cliff-top positions along the Aran Islands' Inishmaan, Inishmore, and Inisheer coast. These deposits are compared with other depositional units such as isolated finer sediment archives and tonguelike washover features associated with small to medium-sized boulders. Micromorphological signatures from limestone dissolution onshore and bioerosive patterns from the tidal frame were also investigated, with particular consideration of the relative age of boulder movement. Field studies included near-time inspection of the transport power during the strongest storms in living memory in winter 2013–14. To explore spatial and temporal variation in boulder deposition, numerical data for event chronologies are included. The paper also discusses rates of cliff retreat and movement of boulder ridges and contains an evaluation of the storm-only hypothesis *vs.* contribution of tsunamis to boulder movement.

**ADDITIONAL INDEX WORDS:** *Coastal boulders, washover tongues, cliff retreat rate, micromorphology of limestone, AMS dating.*

## INTRODUCTION

The Aran Islands are located on the central west coast of Ireland and obstruct the entrance to 60 km-long-Galway Bay (Figure 1). The region predominantly comprises well-stratified, gently folded, and karstified Carboniferous limestone, with the exception of the northern shore of the bay in the Connemara region, which contains outcrops of granite (Fehman, 1999; McNamara and Hennessey, 2010; McSharry, Philips, and Densmore, 1999). The general geomorphology of the regions suggests intensive sculpting of the landscape that occurred in a previous glacial period (Dunlop *et al.,* 2010; O'Cofaigh, Dunlop, and Benetti, 2012; Simms, 2004, 2005), which ceased at around 17,000 to 16,000 BP (Clark *et al.*, 2012; Diefendorf *et al.,* 2006; Van Asch *et al.,* 2012). The limit of the Last Glacial Maximum has been located at around 170–250 km west of the Aran Islands on the continental shelf, with terminal moraines with a relative height of around 25 m (Sacchetti *et al.*, 2011, 2012, 2013).

The coastlines in the region are predominantly rocky with low, stepped profiles and vertical cliffs up to 70 m high on Inishmore, and up to 30 m on Inishmaan and in the southeast of Galway Bay. Marine sediments along the shorelines comprise large boulders, with individual masses of over 50 tons (Erdmann *et al.,* 2015, p. 20), and often form ridges of the order of a few meters high and decameters wide. These ridges are found in clifftop positions and are located up to more than 200 m away from the current cliff line (Erdmann *et al.,* 2015, p. 87). Fine sediments are patchy and only 0.5 to 1.5 m deep, mainly located behind seaward boulder ridges and on cliff platforms. Inactive dune fields in Doolin and Fanore, mainland County Claire, Ireland, and the NE section of Inishmore have, and are, undergoing erosion by waves, with the source of sand to these features restricted because of sea-level rise since the Late Holocene. Holocene sea level in the central west coast of Ireland did not exceed current sea level (Bradley *et al.*, 2011; Brooks *et al.*, 2007; Carter, Devoy, and Shaw, 1989; Fleming *et al.*, 1998; Holmes *et al.*, 2007; Lambeck *et al.*, 2014; O'Carra *et al.*, 2014; Orford, Murdy, and Freel, 2006; Peltier *et al.*, 2002; Schettler *et al.*, 2006; Shennan and Horton, 2002; Shennan, Milne, and Bradle, 2012; Shennan *et al.*, 2002). Drowning of Mesolithic remains (Driscoll, 2012; Gosling, 1993), dating of rooted trees under freshwater peat (Williams and Doyle, 2014) and the stratigraphy in karst lake An Loch Mór on Inisheer (Holmes *et al.*, 2007) suggest that relative sea level from about 7500 to 5000 BP was around 5 m lower than today, with an increase of 1.5–2 m since AD 500.

Marine forces are strong winter storms with maximum waves around 15 m high at exposed deep-water coastal sections and a spring tide range of 4 m on the Atlantic side of the islands, rising to >5 m in the inner bay. Water depth is around 50 m at the four sounds that lead into Galway Bay.

Cliff retreat and boulder movement were the focus of the first research undertaken in the area (Williams, 2004; Williams and Hall, 2004). The majority of authors argued that boulder

*DOI: 10.2112/JCOASTRES-D-17-00175.1 received 7 October 2017; accepted in revision 1 January 2018; corrected proofs received 25 January 2018; published pre-print online 1 March 2018.*
*Corresponding author: dieter.kelletat@t-online.de
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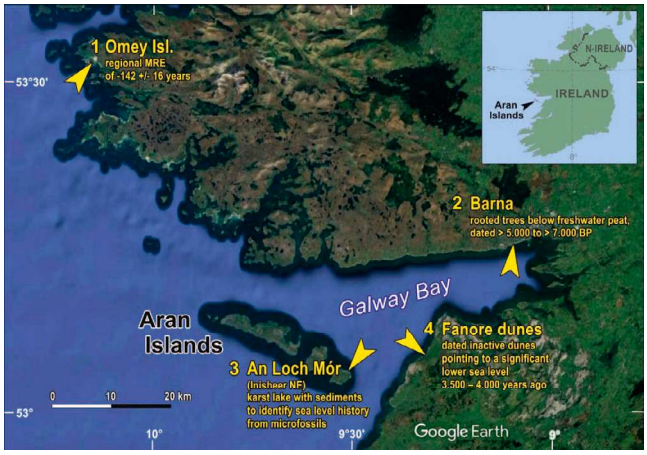


Figure 1. Galway Bay with the Aran Islands. The wide openings are North Sound and South Sound. Numbers 1 to 4 identify important sites for sea level history and dating: MRE from (1) Ascough *et al.* (2006) and Ascough, Cook, and Dugmore (2009); (2) Williams and Doyle (2014); (3) Holmes *et al.* (2007); (4) Erdmann, Kelletat, and Kuckuck (2017). (Credit: Google Earth December 2016, modified)

emplacement occurred by recent wave conditions, including movement of the largest boulders into the highest positions far away from the shoreline (Cox *et al.*, 2012, 2014, 2015; Cox, Jahn, and Watkins, 2016; Hall *et al.*, 2006; Hansom, Barltrop, and Hall, 2008; Hansom and Hall, 2009; Williams, 2010, 2011; Zentner, 2009). In contrast, Erdmann, Kelletat, and Scheffers (2017), Erdmann *et al.* (2015), and Scheffers *et al.* (2009, 2010) suggested that past tsunamigenic processes may have also transported boulders, back to at least Mid-Holocene times.

## METHODS

Coastal research on the Aran Islands has previously been focused on boulder transport and deposition mechanics and rates of cliff retreat. Study locations were confined to the most exposed sections of Inishmore (eastern part of the south coast from Black Fort to Puffing Holes) and Inishmaan (SW and W coast). However, since 2014, research has included sedimentary units at a wider variety of exposures, with particular focus on the relationship between boulder ridges, washover tongues, and finer sediment archives and the effect of a series of extraordinary winter storms in 2013–14, observed through near-time inspection (Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al.*, 2015; Erdmann, Kelletat, and Scheffers, 2017). Studies include identifying timing of boulder dislocation by relative age indicators, such as preserved biogenetic micromorphologies and limestone dissolution. Numerical accelerator mass spectrometry (AMS) dating has been undertaken for the region to develop a chronology of extreme marine events on the mainland and the islands and within the different sedimentary units. The history of coastal evolution and cliff retreat rates has also been identified, including changes in sea level, which were at least 5 m lower in the mid-Holocene, and rose, mostly likely in steps, to present day levels.

The history of boulder transport and terrestrial and littoral limestone erosion using age indicators and archaeological sites for identifying coastline and cliff retreat have been investigated, and sources of boulders through the use of biogenic micromorphologies have been determined. Additionally, marine deposits such as coarse sand with pebbles and washover lobes built by small and medium-sized boulders are mapped and dated. These sedimentary units were initially focused on in fieldwork undertaken by Erdmann, Kelletat, and Kuckuck (2017), Erdmann *et al.* (2015), and Erdmann, Kelletat, and Scheffers (2017), that also considered boulder ridges, with particular focus on their organization (imbrication trains, older ridges to landward, ripple features, and rhythmic organized crossway ridge segments [see Erdmann *et al.*, 2015, pp. 24, 72–73]. When considering boulder dislocation, only those are considered, which clearly are moved against gravity by getting a new position on a higher elevation than their former placement.

Because boulder forms are simple (cuboids, plates, columns), measuring their volume is straightforward and was done by measuring mean axis lengths. Tests ($n = 30$) from different limestone layers resulted in a mean density of 2.63 g/cm$^3$. Volumes were subsequently multiplied by 2.5 to estimate mass of these boulders.

To establish a timeline of coastal evolution material, numerical age dating (AMS) was collected (marine bivalves and gastropods). Boring bivalve *Hiatella arctica* remaining in boulders ashore and shell near the base of boulder ridges were used for dating features. The latter may be critical in interpretation, as three scenarios are possible: a deposit with shell and shell debris older than the boulder emplacement (most probably with some erosion of the shell bed), a contemporaneous deposition, and even deposit of some shell debris under existing boulders by strong wave pressure. The highest possibility is assumed for the age of the boulder emplacement close to the shell date or younger.

A number of these data have been published in Erdmann, Kelletat, and Kuckuck (2017) and Scheffers *et al.* (2010) and are calculated with the Omey Island Marine Reservoir Error (MRE) of –142 ± 16 years (with two sigma cal BP; compare Ascough *et al.*, 2006; Ascough, Cook, and Dugmore, 2009). If boulders contained rock pools from bioerosion of littorinids, their transformation was dated using terrestrial limestone dissolution, which can provide estimates of the timing of boulder dislocation and transport from one environment to another (Figure 2) using the difference in limestone erosion intensity between biogenic/littoral to chemical/terrestrial, which is around 20–50:1 (Godard *et al.*, 2015; Kelletat, 1988; Pfeffer, 2010).

The main aim of this study was to compare the character of marine and littoral deposits of sheltered coasts within Galway Bay with those from exposed sections of the Aran archipelago. Morphologies, ages, and extreme events (also studied by near-time inspection) were used to identify the contribution of the strongest marine processes, which are storm and tsunami effects on boulder transportation.

## RESULTS

This study is focused on coastal forms and deposits on the Aran Islands Inishmaan and Inishmore. Observations of large boulders on both islands, have previously been presented by

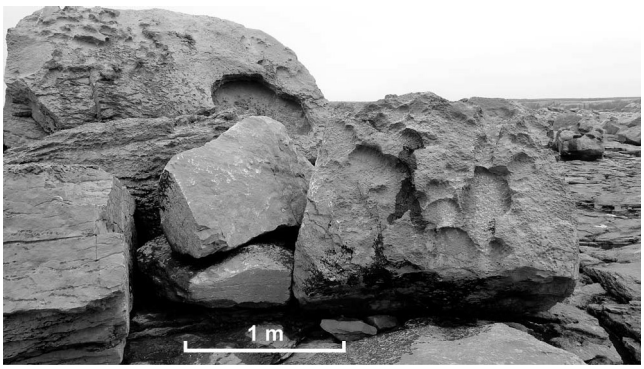


Figure 2. Boulders in the NNW of Inishmaan (up to >20 tons in weight) exhibit remnants of biogenic rock pools from their former near-tidal position. Since dislocation, terrestrial limestone dissolution has opened outflows of significant dimensions, which suggests deposition of these boulders in their current position occurred over 1000 y ago.

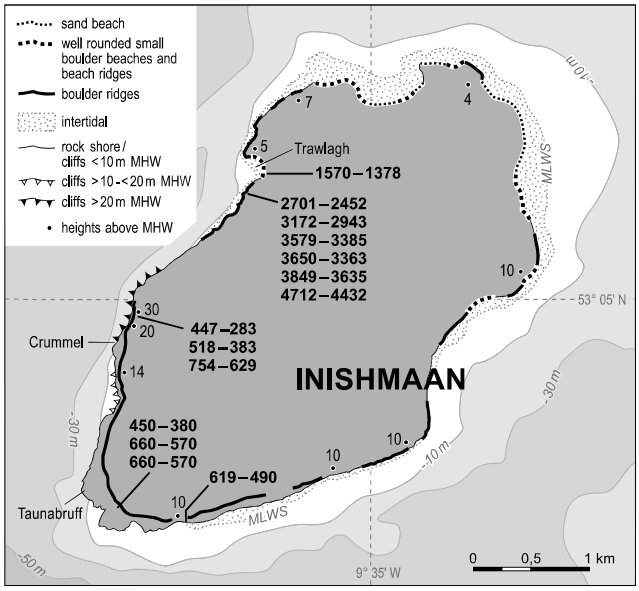


Figure 3. The main coastal forms and deposits on Inishmaan Island (cartography by Gudrun Reichert). AMS radiocarbon data are indicated (Beta Analytic, Florida); see also Table 4.

Cox *et al*. (2012, 2014, 2015); Cox, Jahn, and Watkins (2016), Cox and Watkins (2015), Hall *et al*. (2006), Hansom, Barltrop, and Hall (2008), Hansom and Hall (2009), Williams (2004, 2010, 2011), Williams and Hall (2004), and Zentner (2009). These authors argue that the boulders were dislocated by (winter) storms, with no contribution by tsunami events. However, these studies did not investigate marine deposits beside large boulders and only studied ridges and imbrication, and never deposits along sheltered coastal sections. Consequently, the conclusions of these studies can only be applied to a limited proportion of the coastal landscape.

## Inishmaan

Inishmaan (*Inis Meáin* in Gaelic; Figures 1–3) is an oval island 5.4 km long and 2.7 km wide, with a maximum elevation of 75 m above sea level (asl). It is part of the limestone cuesta, of which all Aran Islands are formed, which has subsequently been smoothed by glacial erosion.

The most prominent coastal deposits are boulder ridges up to >250 m inland of the shoreline, which have a mean length of 6 km (>1.4 km in clifftop position) and are several decameters wide. The ridges have an asymmetric cross-sectional shape (Erdmann *et al*., 2015, p. 102), with a steeper slope on the seaward side and a wide, shallower slope to the landward side. The ridges lead to a field strewn with boulders (Figure 4). Movement of sediment on the ridges varies with elevation. At elevations below 23 m above mean high water (MHW), activation primarily occurred along the seaward slope of the boulder ridges following extraordinary winter storms in 2013–14 (Erdmann *et al*., 2015). On the southern exposure, around 80–120 m from the modern shoreline, activation reached the crest of the ridges at elevations up to +8 m MHW, as well as partly down the leeward slopes. At elevations above 12–13 m MHW, refreshment of the boulder ridges has been restricted to confined locations on their seaward slopes, and to single small boulders above +20 m MHW.

The wide boulder ridges on the Aran Islands are chaotically organized. Their internal organization has been identified by the orientation of longest axis of very long boulders (Figure 4). These boulders originated from the clifftop platform along structural steps that have a primarily S–N joint orientation. The orientation of boulders in the direction of bore flow (W to E) may be the result of bore transport, as shown by tests in a wave channel undertaken by Nandasena and Tanaka (2013).

A number of boulders up to >4 m long are found to "balance" on the ridge crests (Figure 5; see also Scheffers and Kinis, 2014). Cox *et al*. (2012, p. 258) describe them as "in trans-ridge movement" and therefore that the "ridges gain mass over time" (Cox *et al*. 2012, p. 261) and may shift in a landward direction. Hence, if a wave is strong enough to push a boulder against gravity on the ridge crest, a much weaker one will cause it to fall down with gravity. It is highly unlikely that a boulder would remain in such a delicate position during and after a storm (Erdmann *et al*., 2015). These boulders are part of an old ridge of unknown origin, and have reached their "balanced" setting by seaward erosion of these ridges during more recent storms. Ridges lose mass over time and these "balancing" boulders will be undermined by erosion and will subsequently be transported down the seaward slope of the ridges.

A feature rarely mentioned in research that focuses on boulder ridges globally (but see Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al*., 2015; Erdmann, Kelletat, and Scheffers, 2017) is a rhythmic pattern of crossway-running ridge segments with similar distances, relative elevations, and widths (as shown in Figure 6). A series of such features are located north of Crummel, as at 50 m asl, mentioned by Williams and Hall (2004). In fact, the vertical cliff ends at only +31 m MHW. About 30 crossway ridges occur along 800 m of coastline (A1 and A2, Figure 6), rising from a crest height of about 16 m MHW to about 33 m MHW from S to N. In contrast

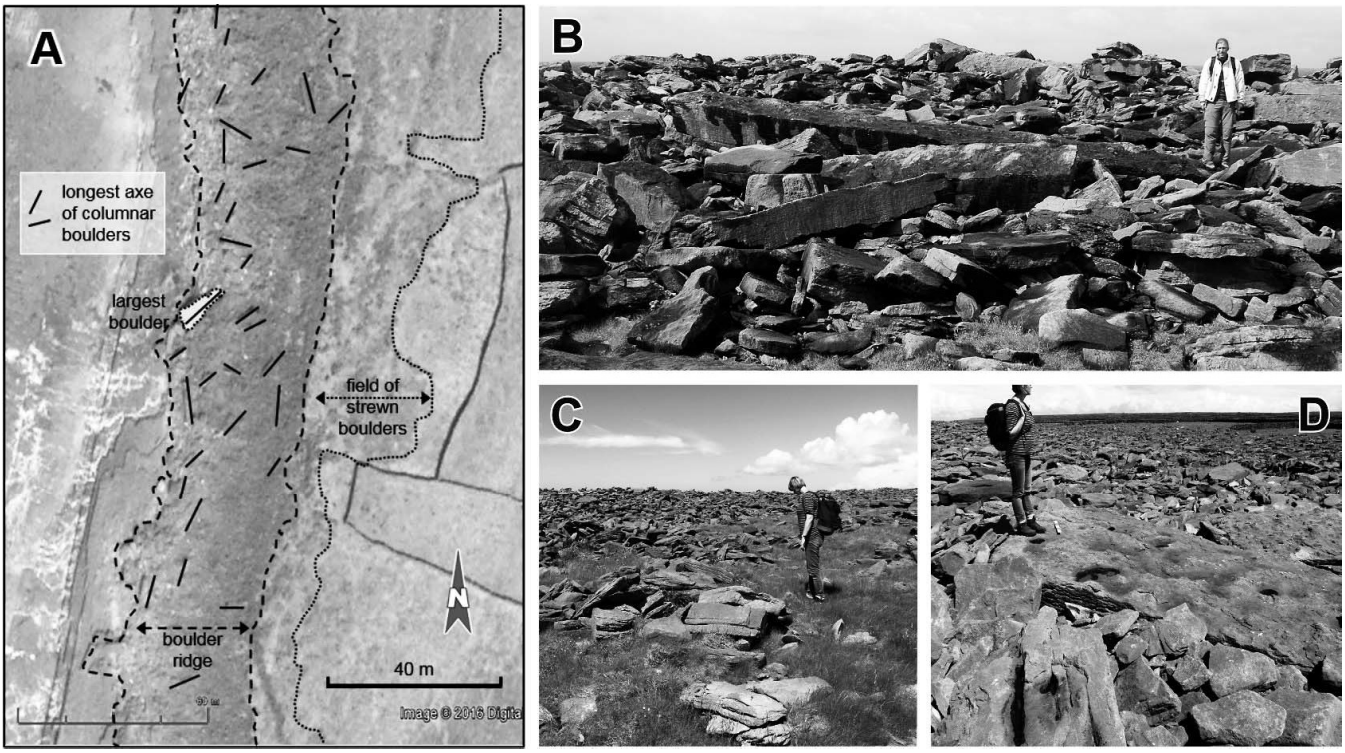


Figure 4. Inishmaan west coast: orientation of longest axes of large columnar boulders in main boulder ridge based at +13 m MHW and 150–190 m from cliff edge (A). The largest boulder (11.5 m long) is indicated. (Credit: Google Earth, 2005, modified). Terrestrial photographs (B–D) show areas of the landward section of the ridge, with old and very large boulders chaotically arranged and karstified.

to the cross-profile of the main ridge, which is steep to the seaward side and flat on the landward side, the shorter crossway ridges (B1–3, Figure 6) exhibit a flatter seaward (SW) and a steeper leeward (N–NE) slope.

The patterns of these crossway ridges do not represent an age sequence, but all are of a similar age. Whether these features were in the form they are observed today or were sculpted out of an existing continuous boulder ridge is not known. Both processes are only possible with a very strong flow from S–SSW to N–NNE up to an elevation of >30 m and with enough energy to cause boulders with a mass of a few tons to be incorporated into these features. A similar pattern occurs close to the shoreline on the east of Inishmaan's south coast, which is 500 m long and comprises around 25 individual segments with elevation up to around +6 m MHW. On Inisheer Island, a similar distinct sequence (250 m long) appears directly east of the lighthouse, formed by strong flow from a S to SSE direction (compare also Table 1).

Within >4 km of continuous boulder ridges along the south and (southern) west coast of Inishmaan, boulders with lengths of >4 m and masses of >20 tons are numerous. The largest identified thus far is 11.2 m long with a mass of approximately 75 tons and is located at a site around +14 m MHW on a seaward slope. Local people had not observed the boulder in its current location before a storm in 1991 (Cox *et al.*, 2012). However, the boulder may have become visible because of erosion of the ridge during the 1991 storm and could have been deposited earlier. Winter storms of the 2013–14 season did not transform the ridge crest along the sections shown in Figure 6 and did not move fragments greater than 5 tons at this elevation (+13–16 m MHW and >120 m from the cliff edge) against gravity (Erdmann *et al.*, 2015).

Several very large boulders (with a mass of around 50 tons) are found along the base of the seaward slope of Inishmaan's boulder ridge at the S and SW exposure (Erdmann *et al.*, 2015, p. 39). These boulders were derived from rock platforms in joint-bound scenarios where limestone dissolution widened bedding planes and joints. The boulders have been transported 10–30 m and around 2–3 m against gravity through vertical lifting by overflow of a bore, dislodgement to the ridge base, and in some cases turning over, with some breakage (Figure 7).

The surfaces of the boulders along Inishmaan's west coast do not contain organic remains from the tidal belt, which would enable them to be dated. However, in joints north of Crummel at +31–32 m above MHW, shell fragments and shell of *Patella*, littorinids, and *Mytilus* have been preserved from washover and dated to 754–629 cal BP, 518–383 cal BP, and 447–283 cal BP, respectively.

In front of the recently activated boulder ridge on the south coast of Inishmaan, single boulders with a mass of between 10 to 20 tons on the bare platform have not been transported for at least a century, as determined by their dense cover of lichen along their leeward sides and ages from *Hiatella arctica* of 619–490 cal BP. Previous sea urchin location marks and *Hiatella*

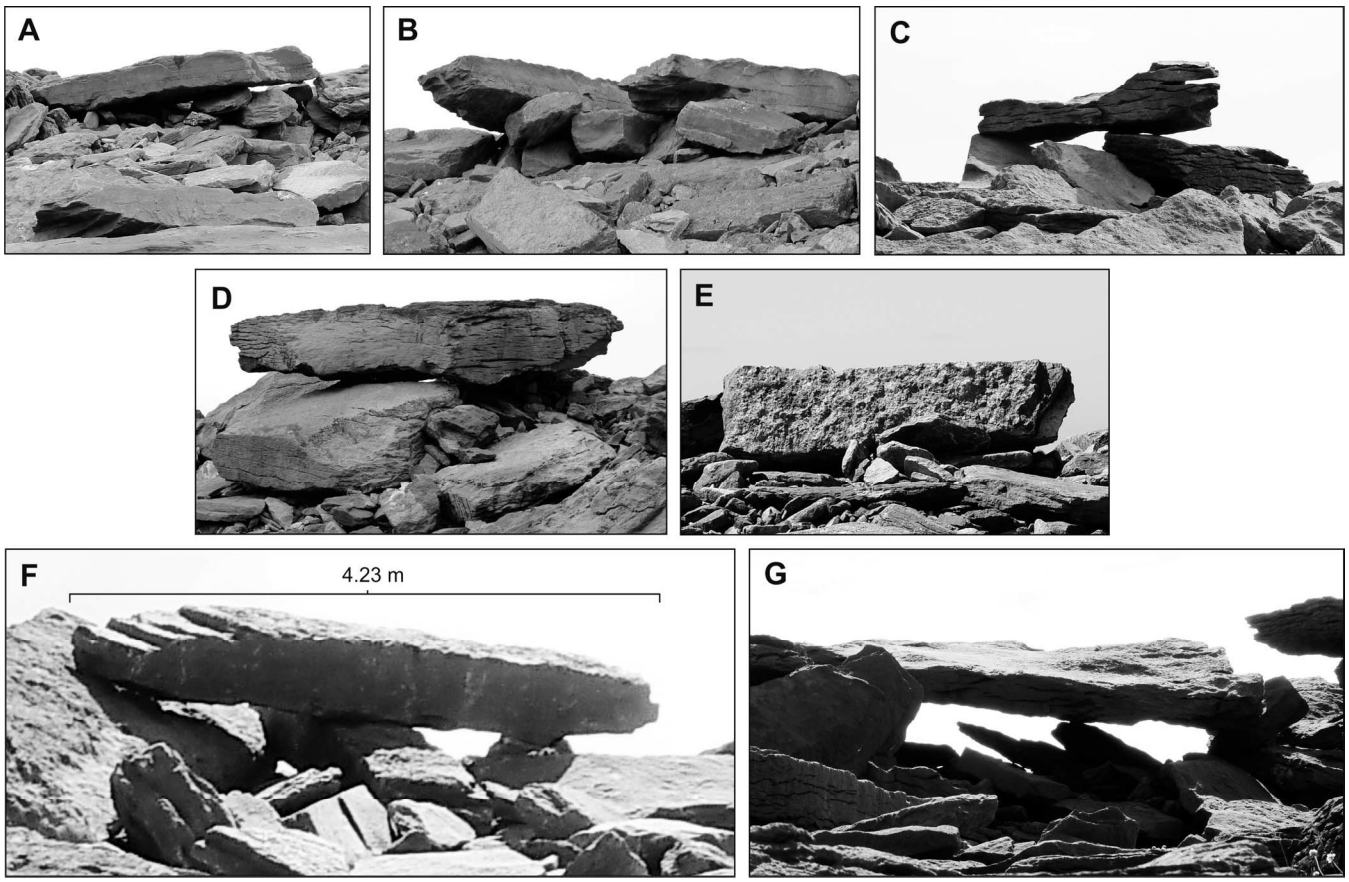


Figure 5. A selection of "balancing" boulders on the crest of the main Inishmore and Inishmaan boulder ridges, 50–220 m from MHW at +8 to +17 m MHW (A–G). The maximum lengths of the longest boulder axes are between 2.43 and 4.23 m (F), and these boulders have a mass of between around 3 to at least 10 tons. All are shown from the seaward side.

borings are preserved. The *Hiatella* borings in boulders from the ridge were dated to around 450–380 and twice 660–570 cal BP, respectively, and around 610–440 cal BP on the SW coast of Inisheer (Scheffers *et al*., 2010).

Along the NW coast of Inishmaan, north of Crummel to Trawlagh Bay, single boulders with a mass of up to at least 20 tons were found in a wide and 700-m-long boulder ridge on a rocky step. The majority of the boulders were well rounded, which suggests their source was in the surf belt. Many of them exhibit *Hiatella* borings, some with shells preserved. The ridge certainly is a multitemporal feature.

Fine marine sediments in boulder ridges are rare on the Aran Islands, which is similar to the mainland section of SE Galway Bay between Doolin and Black Head (for location see Figure 20), as described by Erdmann, Kelletat, and Kuckuck (2017). A shallow geoarchive (coarse sand, shell hash, shells, and small stones) was found on the landward side of the boulder ridge of Leic na Mantaí south of Trawlagh Bay, on a boulder bed and base rock. Three meters from the landward side of the boulder ridge, strata lie horizontal, with at least seven units observed, all undisturbed (Figure 8).

In shallow Trawlagh Bay, where the –10 m line is about 500 m from the shore, a beach ridge around 50 m wide and up to 6 m high is located on a rock platform, which is activated during strong storms along its entire width (Figure 9). The ridge is located on top of two relict washover tongues composed of rounded small boulders (0.2–0.6 m in diameter), deposited on the landward side of the ridge with their end around 170 m from the modern MHW line. The emplacement process for these boulders differs from storm wave events because of the direction and energy needed for their transportation. In contrast to the main boulder ridges along Galway Bay and on the Aran Islands, these washover tongues exhibit clear contours on their landward sides. A *H. arctica* on the southern boulder tongue was dated to an age of 1570–1378 cal BP.

## Inishmore

Inishmore (*Árainn* in Gaelic, meaning "large island") is the westerly and largest island of the Arans, 14 km long and between 1 and 3.4 km wide, with a maximum elevation of 123 m asl. The landscape morphology has been smoothed by glacial erosion. At the largest exposure to the open ocean, 7 km of

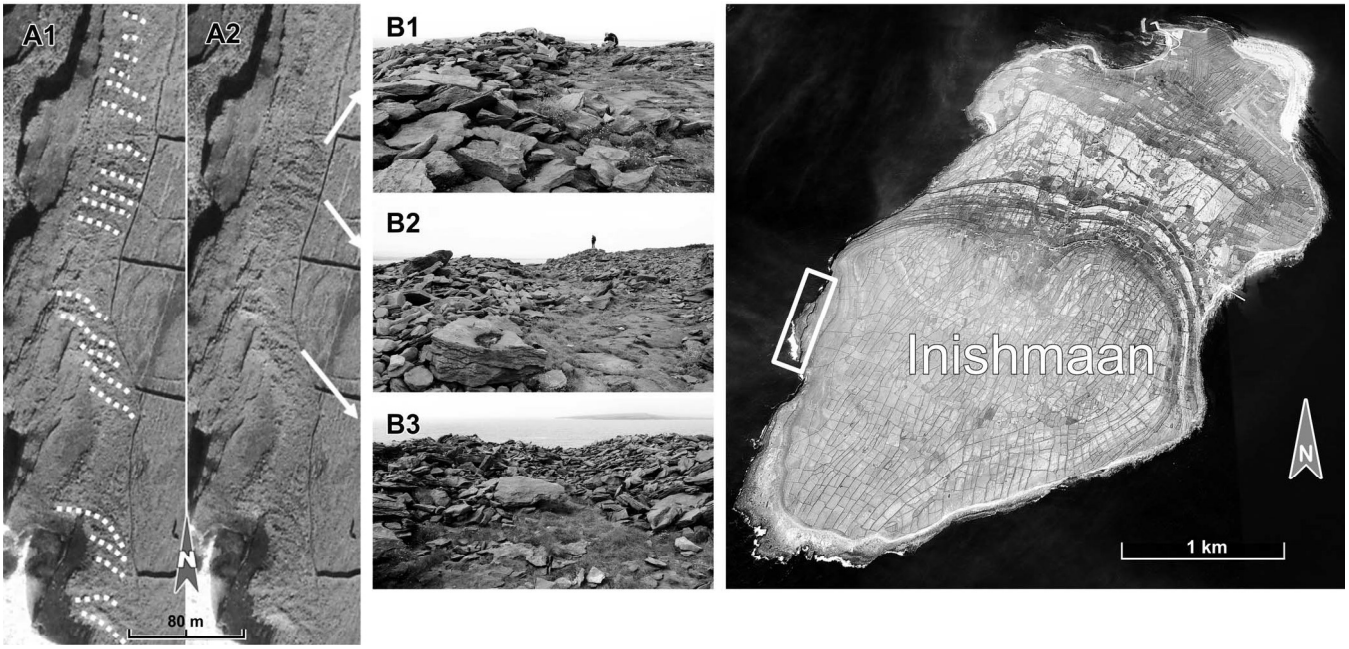


Figure 6. The pattern of crossway-running boulder ridge segments in clifftop positions along the west coast of Inishmaan between +17 and +32 m MHW (A1–A2). Photographs B1–B3 show details, and their position in A1 and A2 is indicated by arrows. (Credit: Google Earth November 2015, modified)

boulder ridges occur, most of them in clifftop positions, with an additional 3.6 km found along the more indented, sheltered, and shallower bayward side of the island (Figure 10). The SSW coastline exhibits vertical cliffs around 10 km in length, which are predominantly more than 20 m high. The clifftop boulder ridges closely follow cliff configuration. In several places, between one and three older, lower, and narrow ridges are preserved, located inland of the main seaward ridge.

Inland movement of a seaward ridge would result in contact with older ridges, and these younger ridges may override them or incorporate material from the older ridges. The older triple ridges of SE Inishmore (Figure 11) are thought to have formed before the large Puffing Hole (Poll Seideain) appeared by collapse of a water cave (Erdmann *et al.*, 2015, p. 92). Dissolution microforms on the boulders suggest ages of the order of at least a number of centuries.

Boulder ridges on cliff tops extend from the Puffing Hole area for about 6 km to "Black Fort" (Dún Dúchathair), an Iron Age (2500–2000 BP) promontory fort south of Kilronan village. Because the cliffs have a height of over 20 m, activation of these seaward ridge slopes is rare (documentation in Erdmann *et al.*, 2015). Around +24–25 m MHW, boulder piles occur at Black Fort and the two adjoining promontories with a basal age of 3480–3280 cal BP and hints to another washover dated two times at 420–340 cal BP (Scheffers *et al.,* 2010). No boulders and boulder ridges are found higher than +25 m MHW. As is the case on Inishmaan, the largest boulders exist at the base of the seaward ridge slope or in isolated locations in front of the

Table 1. *Position and dimensions of segmented boulder ridges with rhythmic crossway patterns (compare Figure 6).*

| No. | Location | Elevation above MHW (m) | Length of Section (m) | No. of Ridges | Internal Relief (m) | Direction of Energy Approach |
|---|---|---|---|---|---|---|
| On Aran Islands | | | | | | |
| Inishmore | | | | | | |
| 1 | N Kilronan | 4 | 140 | 12 | 1 | 340° |
| 2 | E coast | 5 | 150 | 11 | 1.3 | 155° |
| Inishmaan | | | | | | |
| 3 | Crummel | 15–31 | 660 | 30 | 0.5–1.8 | 193°–210° |
| 4 | SE coast | 6–8 | 500 | 19 | 0.6–1.2 | 205° |
| Inisheer | | | | | | |
| 5 | SE coast | 3–4 | 260 | 17 | 1 | 190°–165° |
| On Mainland within Galway Bay | | | | | | |
| Doolin Point (at entrance to South Sound) | | | | | | |
| 6 | S part | 8–9 | 220 | 11 | 3 | 260° |
| 7 | N part | 9–11 | 420 | 14 | 3 | 245° |
| South of Black Head | | | | | | |
| 8 | Murroogh Point | 4–5 | 310 | 15 | 1.5 | 280° |

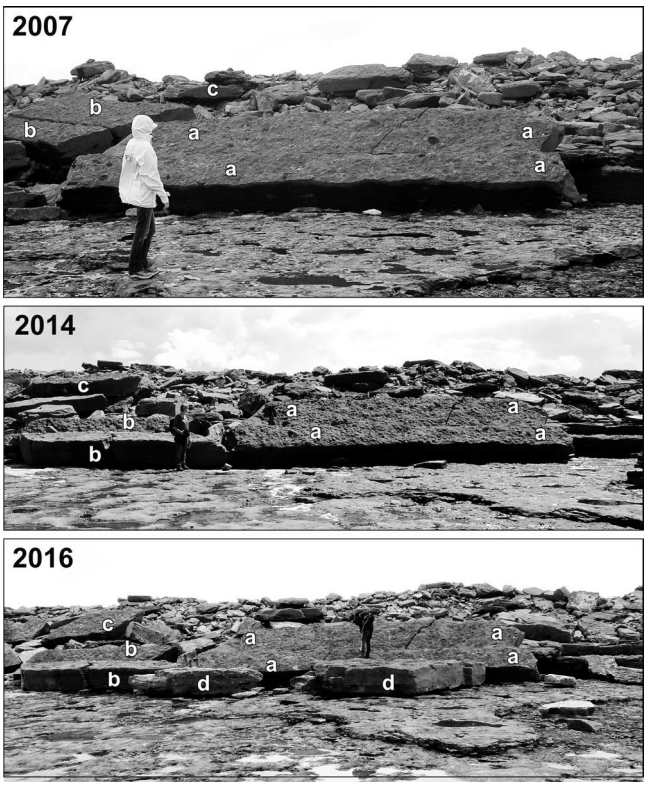


Figure 7. Site and history of dislocation for platy boulders on Inishmaan's west coast at 53°04′09.04″ N and 09°36′59.70″ W, 11 m above MHW and 220 m from the modern cliff. A large boulder was dislocated through lifting from a structural step on the cliff platform at +9 m MH and was moved in one large plate (mean axes $14.1 \times 2.6 \times 0.7$ m = 25.6 $m^3$ and a mass of 64 tons, *i.e.* lifting 1.75 t/$m^2$) over a distance of 35 m horizontally and 4 m vertically, overturned of the order of 150°. This boulder was deposited on the seaward front side of a 4-m-high boulder ridge and broken into 4 pieces (double boulders a and b). Double boulders b moved downward to the base of the boulder ridge between 2007 and 2014 (most probably during the hurricane-force winter storms of 2013–14). Plate c moved downward between 2014 and 2016. Fresh boulder d (not overturned) originated from a clifftop platform and moved close to the setting, reaching boulder pair a in a winter storm early in 2016 (from Erdmann, Kelletat, and Scheffers, 2017).

ridge on a rock platform. These boulders have undergone significant weathering and contain dissolution features and extensive lichen cover. These boulders have been lifted against gravity formerly, but have stayed isolated and immobile during young extreme storm events.

No clifftop boulders occur from Black Fort promontory close to the Bronze Age Fort of Dún Aonghasa, because the cliffs are too high. The cliffs are lower toward the isthmus at Blind Sound on both sides of the "Wormhole" (Poll na bPéist, meaning "Sea Serpent"), a rectangular (11 × 31 m) opening in a low cliff platform from the collapse of an underwater cave (Figure 12). Above the Wormhole, a cliff rises to +20 m MHW, undermined along a 1–1.3-m-thick stratum of shale with a spring line. Here, outwash occurs in addition to storm waves, and wide overhangs develop as a result of these processes. Two large boulders are located at this locations: a 55-ton boulder at 53°07′14.70″ N and 9°44′51.07″ W, 40 m from a low cliff at +5 m MHW, and a 230-ton boulder 300 m east of the Wormhole once lifted vertically by about 5 m (Figure 13). At clifftop position between +18 to +20 m MHW, shells have been dated at 1980–1840 and 1300–1120 cal BP (Scheffers *et al.,* 2010).

The Wormhole formed around 150–200 years ago, with no inclusion of the hole in local myths or legends suggesting it is older. The Wormhole ends abruptly at a vertical cliff, which means that cliff retreat was less than 1 cm/y, on average, at this site.

Dún Aonghasa, a location in sight of the Wormhole, is one of the largest Bronze Age structures in Europe, dated to 3100 BP, with three 5-m-thick and 6-m-high drystone walls centered around a natural rectangular rock platform and a wide belt of *chevaux de frise* dated to be from around 2800 BP (Figure 14). The *chevaux de frise* are sharp rock fragments, hammered into joints of the rock as protection against attacks of enemies. Similar artificial rockwork offers opportunities for relative dating of boulder dislocation, based on the amount of onshore limestone dissolution with karst features found on the boulders. The setting of the fort suggests minimal cliff retreat since its construction.

To the west of Dún Aonghasa the cliffs are lower at around +20 m MHW, and boulder ridges occur on these clifftop platforms. East of an 18-m-high small table mountain, where Scheffers *et al.* (2010) dated a ridge boulder to be from around 1870 to 1680 cal BP using *H. arctica*, a double-crested boulder ridge on a 5–7-m-high cliff platform exhibits a "window" between two crests, exposing a 0.6-m-thick loamy basal sediment with some evidence of soil formation and a base of frost-shattered limestone rock. This remnant of fine sediment has not been in contact with prior marine or littoral processes but is now strongly influenced by marine erosion. Small charcoal flitters in the loam were dated to be from 6753 to 6641 cal BP, similar to the terrestrial fine sediment dated by Williams and Doyle (2014) south of Doolin on the mainland coast under active storm boulders, in which charcoal was dated to an age of 6636–6440 cal BP.

The westernmost section of Inishmore is fringed by shallow water less than 10 m deep (UKHO, 2005; see also Figure 10). Within this area are several exceptional boulder deposits (Figure 15) that have not been described previously on this island but have been investigated on the mainland coast between Doolin and Black Head by Erdmann, Kelletat, and Kuckuck (2017). As well as blocks of >1000 tons deposited by cliff collapse, two washover tongues have been pushed into the rock basin, which contains Lake Amurvy. The light-colored tongue, which originates from a NNW (330°) direction, is formed of small, well rounded boulders, many of them with abraded borings of *Hiatella*. The tongue has a rock mass of approximately 25,000 tons. The washover feature that originates from the south is at least 2 m thick on average, but larger in length and width than the other tongue, containing >45,000 tons of rock (see also Table 2). In contrast to all other washover lobes in the Galway study area, this tongue comprises angular boulders up to 2 m long and has—as all other boulder tongues—a sharp and steep front. The stepped rock platform on the seaward side is considered to be the source area of the tongue, in which boulders may have been broken off during a short washover process or taken from an existing ridge deposit

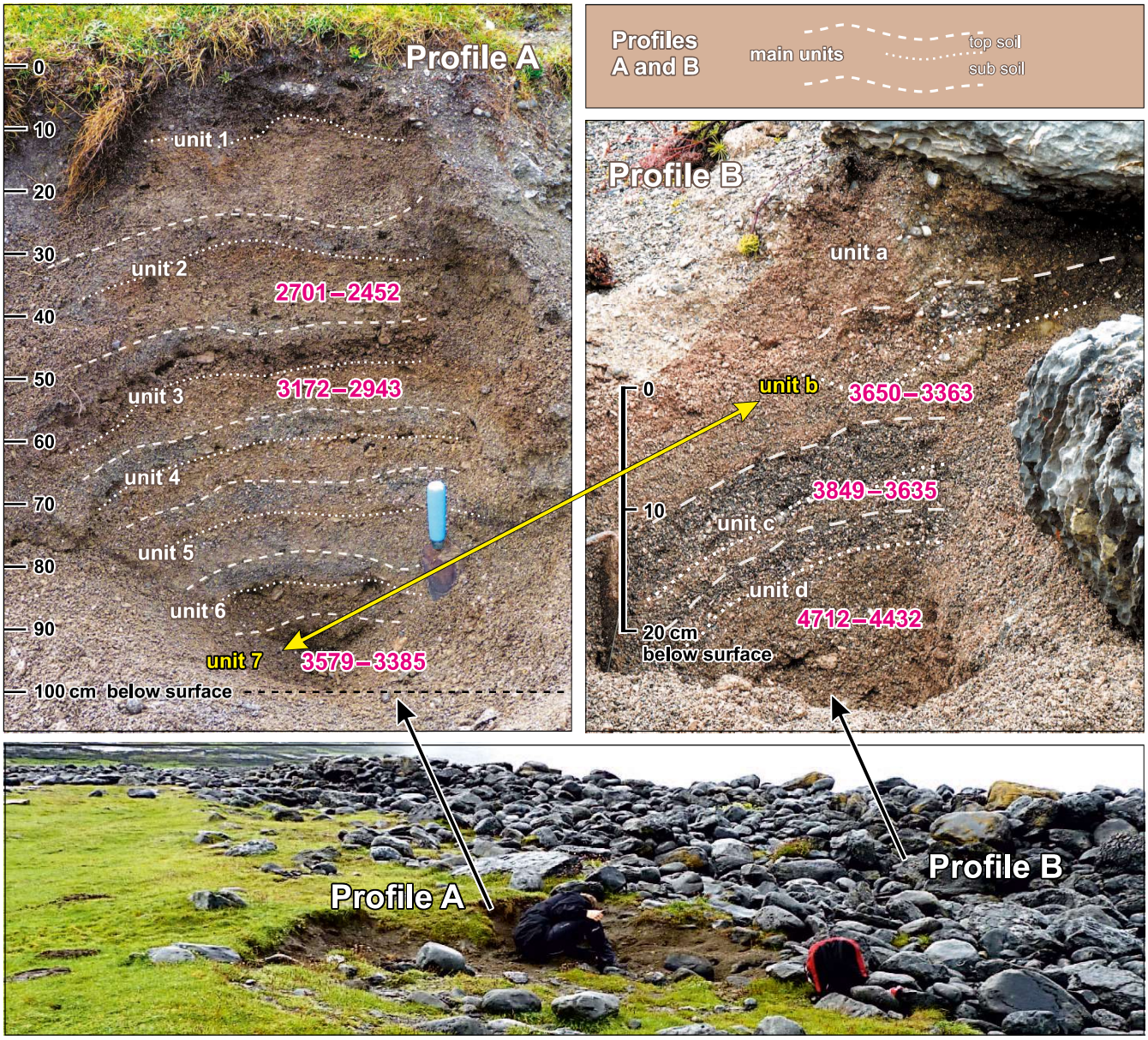


Figure 8. Shallow archives of coarse sand and shells behind the main boulder ridge on the seaward side in the NW of Inishmaan looking to the south. Up to seven undisturbed units with darker top soils and light-brown subsoils form a sequence interpreted as washover deposits. Unit 2 was dated to 2701–2452 cal BP, unit 3 to 3172–2943 cal BP, and unit 7 to 3579–3385 cal BP. Three meters east of this sequence, four soil remnants (a–d) are preserved in the stratigraphy. The age of unit b (3650–3363 cal BP) correlates with unit 7 in the eastern deposit; unit c delivered an age of 3849–3635 cal BP and the basal unit d an age of 4712–4432 cal BP. The positions of units a–d indicate the existence of (at least a part of) the boulder ridge before deposition of unit d close to 4700 cal BP, which gives an age for the boulder ridge of at least to the Mid-Holocene when sea level was about 5 m lower than in modern times.

onshore. *Hiatella arctica* along the frontal (most landward) part of this washover tongue gave ages of 526–416 and 916–748 cal BP. On the southern surface of the large washover lobe is an area of well-imbricated boulders, with imbrication trains formed by steep, inclining, platy boulders with a mass of the order of tens of tons (Erdmann *et al.,* 2015, p.72–73; Scheffers and Kinis, 2014). These features are in strong contrast to the chaotic appearance of the boulders within the lobe itself, and this imbrication is considered to have formed later, because of the lobe boulders acting as an obstacle to boulder transport. Boring bivalves found in the smaller boulders within the imbrication zone were dated by AMS to be from 1070 to 900, 940 to 800, and 860 to 760 cal BP. Boulder ridges also appear for many kilometers along the shallow northern and bayside shores, identified through mapping of the main coastal features of Inishmore Island (Figure 10). The boulders in these ridges

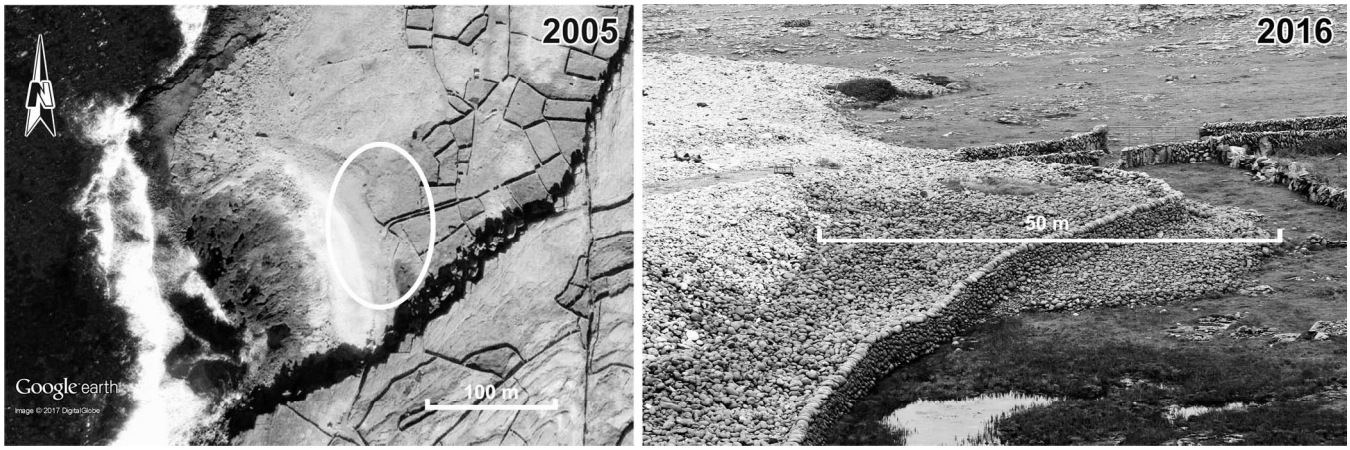


Figure 9. Storm beach ridge at NW Inishmaan Island (Trawlagh Bay), covering two old landward-extending washover tongues. A *Hiatella arctica* from a boulder of the larger tongue in front was dated to 1570–1378 cal BP. (Credit of left image: Google Earth 2005, modified)

predominantly have a mass of less than about 1–2 tons. From the high ridge separating "Red Lake" (Loch Dearg) from Galway Bay, two AMS data points from *Hiatella* were taken and dated to be from between 980 and 810 and between 1320 and 1130 cal BP.

On top of the wide western boulder beach ridge and the smaller washover tongue, remnants of a sediment (0.5–0.7 m thick) containing coarse sand, shell, shell fragments, and angular stones were found, fixed by vegetation, but having undergone notable erosion by storm waves. AMS dates from this sediment came out as 282–85 and 290–100 cal BP within the upper 25 cm, 424–270 cal BP at 40 cm below surface, and 1286–1136 cal BP close to the base and in contact with the boulder tongue surface at 65 cm below the surface. There was no visible stratification in these sediments, which are thought to have been derived from younger washover processes with lesser energy compared with the processes involved in forming the boulder tongues. Nevertheless, these features may give a minimum age for the washover boulder tongue deposition at their base.

## DISCUSSION

Boulders and boulder ridges on the Aran Islands have been studied originally by Williams and Hall (2004), and their genesis is still under debate (*e.g.*, Cox, Jahn, and Watkins, 2016; Cox *et al.*, 2012, 2014; Cox and Watkins, 2015; Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al.*, 2015; O'Boyle *et al.,* 2017). The discussion also reflects to the problem of

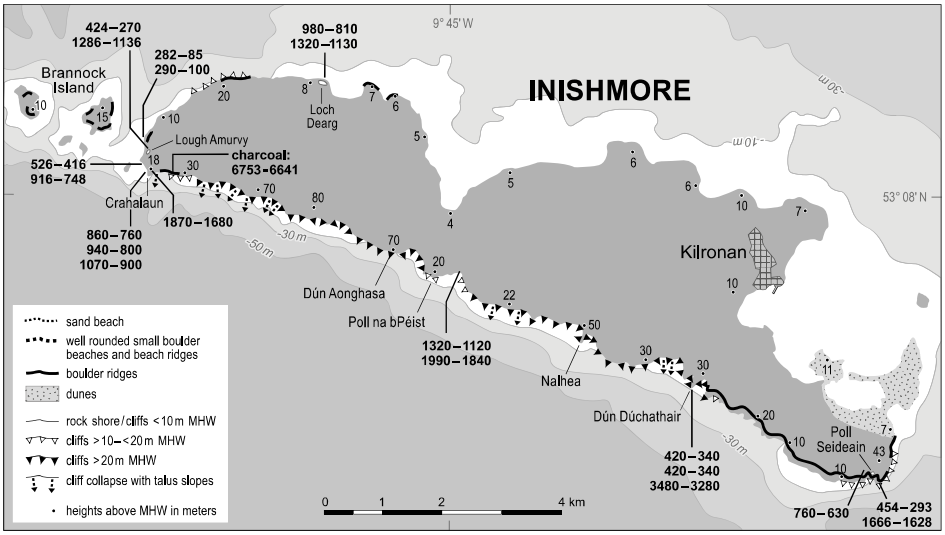


Figure 10. The main coastal forms and deposits on Inishmore Island (cartography by Gudrun Reichert). AMS radiocarbon data positions are indicated (Beta Analytic, Florida; see also Table 4).

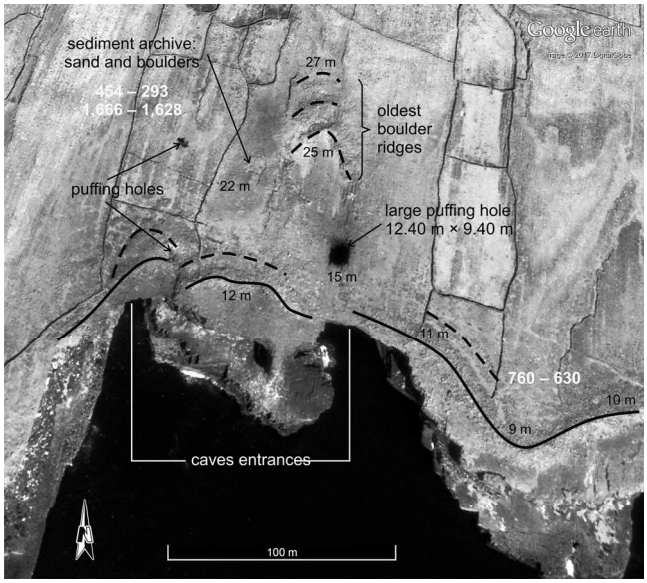


Figure 11. The forms and deposits in the Puffing Hole area (Poll Seideain) of SE Inishmore: the main clifftop boulder ridge at between +9 and +12 m MHW is accompanied by a series of lower and older ridge segments inland, with the easternmost ridge dated to at least 760–630 cal BP. Three curving ridge segments over 100 m inland are considered to be older and to predate the collapse of the largest puffing hole. In a shallow sediment archive, a marine shell was dated to 454–293 cal BP, and a terrestrial gastropod (*Helix*?) to 1666–1628 cal BP. Evidently, the complex situation of forms and sediments needs more numerical dating. (Credit: Google Earth December 2016, modified)

quantifying cliff retreat. Rates of 0.2 m/y or more are given by Williams (2004) and confirmed by Cox *et al.* (2012), assuming landward movement of boulder ridges by storms since the "Night of the Big Wind" in AD 1839. In this year, the Aran Islands were mapped by the Ordnance Survey of Ireland (published 1841, scale *ca.* 1:28,000). Evidence that ridge movement has occurred was published by Cox *et al.* (2012), who compared ridge contours and drystone walls on the 1839 map with satellite images of 2005 from Google Earth. The authors found one site in the SW of Inishmaan where they interpreted a shift of about 50 m, and another site in the eastern part of Inishmore which had moved by a lesser amount. However, archaeological remains from the Neolithic (Skara Brae, Orkney, U.K., and middens all along the Irish coast) over Bronze Age constructions (Dún Aonghasa), promontory forts (Neolithic to Iron Age; Figures 14 and 16), boat shelters from Viking times, or castles from Medieval periods still exist along the exposed coasts and suggest that a very low rate of cliff retreat has occurred (Scheffers *et al.,* 2009). Postglacial transformation of glacial profiles (as at Crummel on Inishmaan) through undermining by marine erosion also contributes to small amounts (maximum of about 150 m since Mid-Holocene times) of erosion.

Quantitative studies on cliff retreat in hard rock confirm low values of the order of a few centimeters per year or less (Carbone, 2013; Earlie *et al.,* 2015; Hall, Hansom, and Jarvis, 2008; Lim *et al.*, 2010, 2011; McKenna, Carter, and Bartlett, 2009; Rosser *et al.,* 2005, 2010; Young *et al.*, 2011). A similar environment exists at "Wormhole," where cliff retreat is thought to have been nonexistent for >100 years.

If the mass of ridges is growing through the addition of boulders, boulders move over the ridge crest, and the ridges move inland (Cox *et al.*, 2012), the mass of the ridge can be assumed to be equivalent to coastal retreat over the time of ridge formation (compare Table 3).

If cliffs erode fast, clifftop boulder ridges will either erode by wave inundation or shift landward. In general, movement of boulder ridges landward occurs over minimal distances, and dating of these environments suggests timelines of the order of a few thousands of years (see Erdmann, Kelletat, and Kuckuck, 2017), which suggests cliff retreat is minimal. Consequently, boulder ridges are not thought to move landward in any locations higher than about 10 m MHW, while their seaward fronts may well be cut back and boulders transported into the sea during strong storm wave events (Figures 17 and 18). As a result, ridges lose volume and mass over time. The forces that form the ridges and enable a larger mass of boulders to accumulate, as can be observed today, with a lower (and rising) sea level during the early Holocene is still poorly understood.

A limited number of sites with fresh boulder outbreaks have been found from the extraordinary 2013–14 winter storms (documentation in Erdmann *et al.*, 2015). Between the ridges and the cliffs, and up to >20 m above MHW, cliff platforms are bare of any fragments, regardless of whether platforms are at high elevations or close to sea level, and even if the platforms are over 100 m wide. Waves strong enough to hit the ridges may have taken fragments from their seaward slopes and, receiving energy from reflection at the ridge and a downward movement, may have dislocated and transported these fragments into the sea.

Observations of changes at boulder ridges and single boulders on Inishmaan, Inishmore, and Inisheer were made at 17 very exposed sites, with a total distance of 3810 m in the field and on the basis of Google Earth satellite images from 4 November 2005, and 22 April 2015 (9.5 y or 113 mo; examples in Figure 20) observed. Over this time span, several strong winter storm events occurred along the west coast of Ireland (based on the monthly data from Met Éireann [2014]):

Between November 2005 and April 2015, a greater number of stormy periods occurred than normal (*e.g.*, in winter 2007–08; December 2007 with lowest pressure 967.7 hPa and waves up to 17 m, January 2008 gusts up to 168 km/h, March 2008 pressure below 980 hPa and waves >13 m).

The strongest storm conditions occurred in winter 2013–14 with 12 storms, of which six reached hurricane categories 3 and 4 and open ocean wave heights of the order of >20 m (Masselink *et al.,* 2016). These storms produced the highest wave energy along the Irish west coast since the year 1948 (or longer).

In summary, dating of cliff retreat and ridge displacement using morphological and archaeological arguments came to similar conclusions of little change along the Galway-Aran coastlines, even with a sea-level rise of about 5 m since Mid-Holocene times (Holmes *et al.*, 2007; Williams and Doyle, 2014). On the mainland between Doolin and Black Head, washover tongues dated to 4000 and 5000 cal BP occur only 20 to 30 m

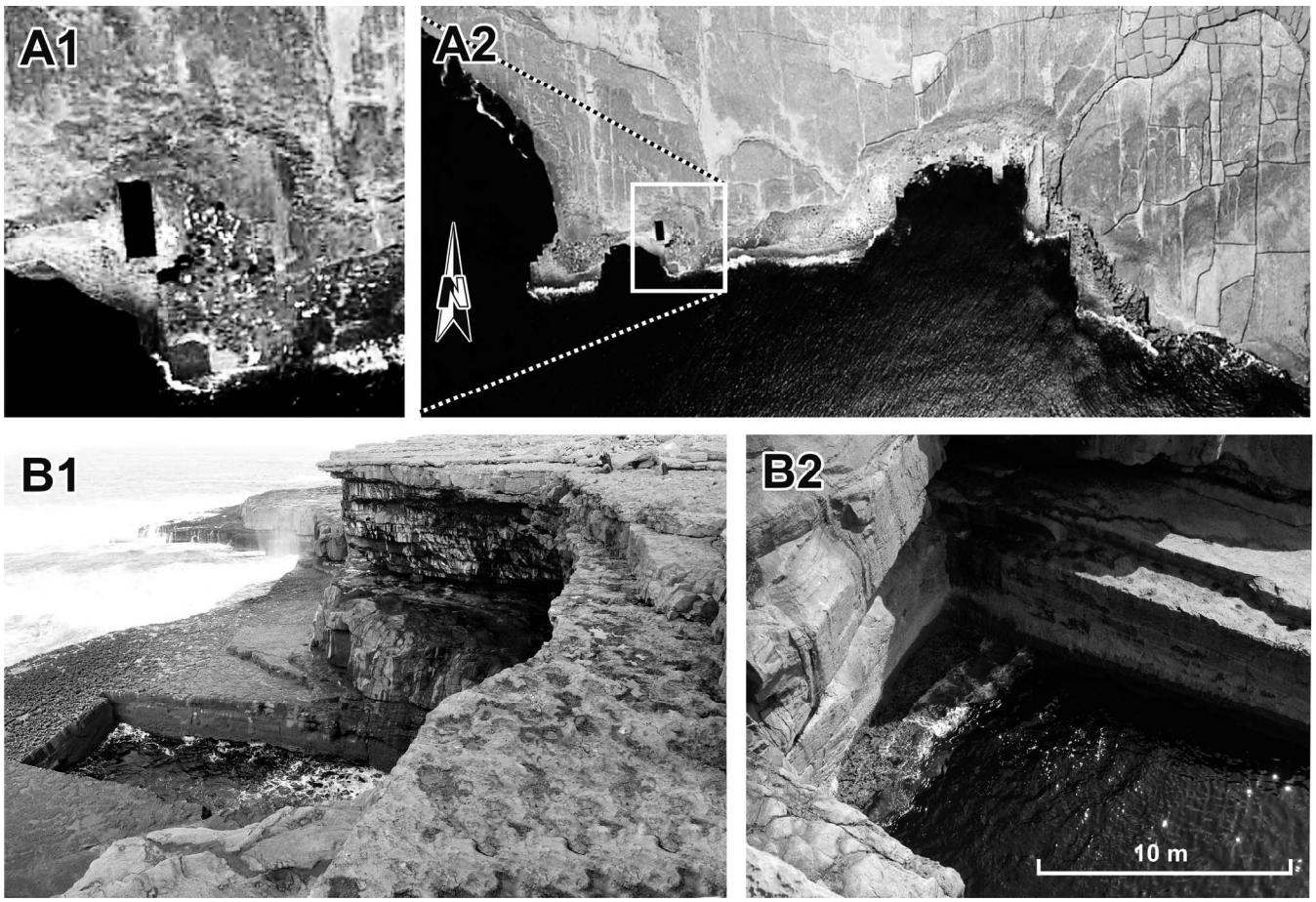


Figure 12. (A, B) Central south coast of Inishmore, east of Blind Sound, with rectangular "Wormhole" (Poll na bPéist, 11 × 31 m) immediately below a cliff +20 m MHW(see sitting person on top for scale in B1), in line with the main joint directions, and boulder ridges in the eastern section in A2. (Credit: National Coastline Survey, Marine Institute of Ireland, Dublin, 2000)

Figure 13. The largest boulder, which was lifted about 5 m vertically directly above MHW, at 53°07′14.55″ N and 09°44′51.07″ W (300 m east of "Wormhole"). Mean axis lengths are 7.0 × 4.6 × 2.9 m = >90 $m^3$ = about 230 t. Scale is 0.5 m.

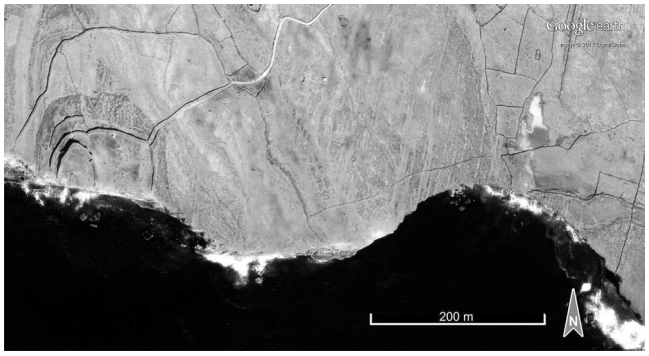


Figure 14. The position of the Bronze Age Fort Dún Aonghasa (3100 BP) on a 70-m-high vertical cliff on the south coast of Inishmore, with three drystone walls and a belt of *chevaux de frise* around. (Credit: National Coastline Survey, Marine Institute of Ireland, Dublin, 2000)

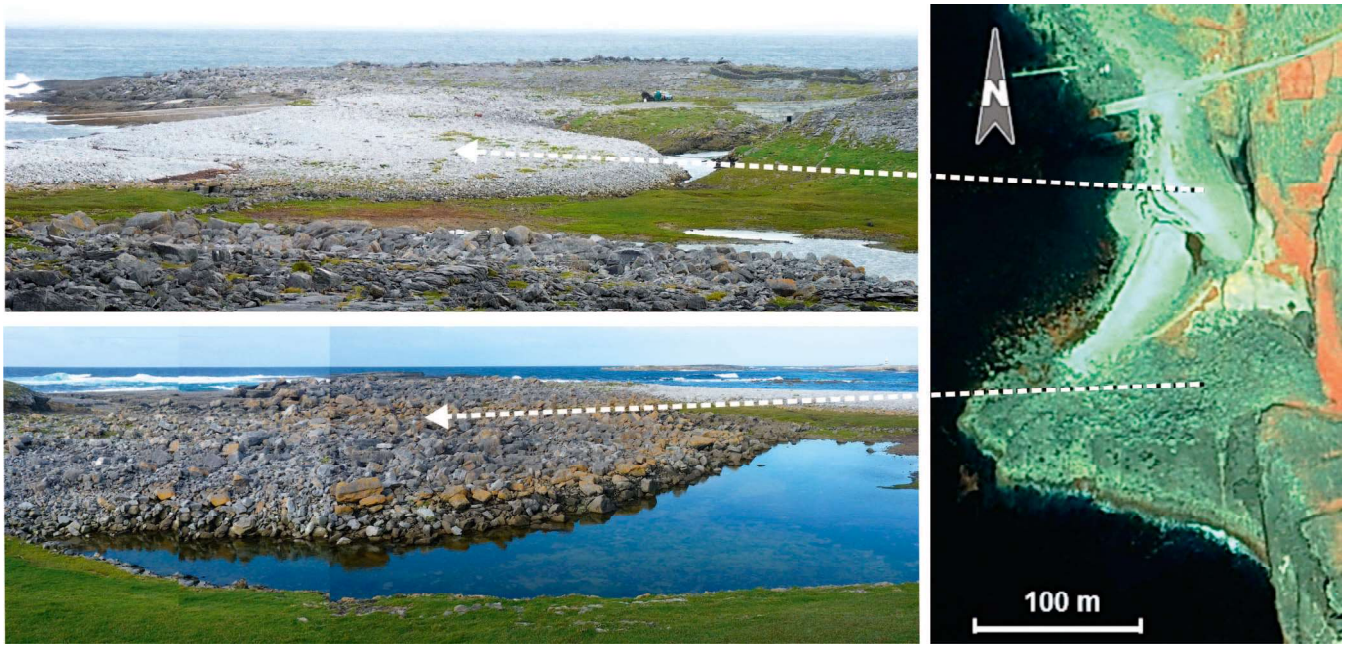


Figure 15. Two washover lobes (both >100 m long) at the westernmost end of Inishmore. The northern lobe looking from the south, the southern one looking from the north (aspects from September 2016). (Credit of aerial photograph: National Coastline Survey, Marine Institute, Dublin, 2000)

inland from the main boulder ridge along the seashore, and ridges have not reached these washover features (Erdmann, Kelletat, and Kuckuck, 2017).

The first research undertaken in the Galway-Aran region concluded that only strong storms dislocated the largest boulders and formed boulder ridge, and that these forms and depositions were recently deposited, because incorporated within them were nylon lines and plastic debris among the boulders (Cox *et al.,* 2012; Williams and Hall, 2004). However, Williams and Hall (2004, pp. 105–106) also recognized "that older ridges represent the results of older and more extreme events formed in more distal locations when the cliff edge was further than the present day," 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."

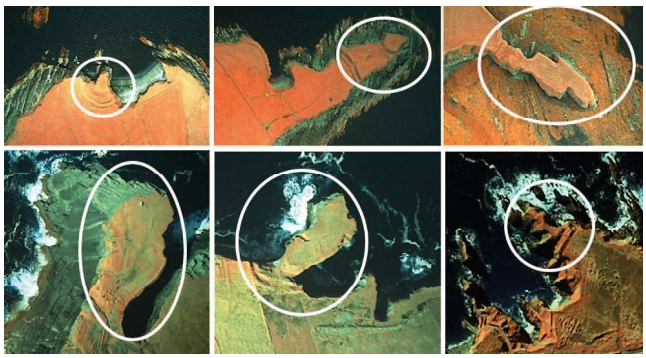

Figure 16. Six examples of promontory forts along the strongly exposed west coast of Ireland. Double trenches and ridges date back to Neolithic times, whereas promontory forts were in use until at least the Iron Age, some of them protected with high, thick drystone walls on the landward side. (Credits: National Coastline Survey, Marine Institute of Ireland, Dublin, 2000)

These observations (and conclusions) are presented also in more recent publications (*e.g.*, in Cox *et al.* [2015], or Hearty and Tormey [2017]) with the idea of "superstorms" in warmer climates of the past and probably because of climate change in the future. Superstorms with energies several times increased compared with modern category 5 tropical cyclones, however, are a fiction because they will collapse by internal and external friction. Observations, registrations, and physical laws so far do not allow to speculate beyond the principle of uniformitarianism. Wind velocities of 400 km/h and more only occur on planet Earth for a very short time in tornadoes, which are spatially and temporally much too small to induce wave heights above strong tropical and extratropical storms.

Besides additional field work, numerical dating of all sedimentary units in the Galway-Aran region and at other places along the Irish west coast are needed to identify extreme coastal events over at least the second half of the Holocene (compare data in Erdmann, Kelletat, and Kuckuck, 2017, as well as Table 4). Such dating would enable connections between onshore data and offshore data of young mass wasting processes in the near North Atlantic, and interpretation of potential tsunami impacts on formation of coasts.

Overall, 83 AMS data points are currently available for marine deposits located on the exposed Aran Islands and the

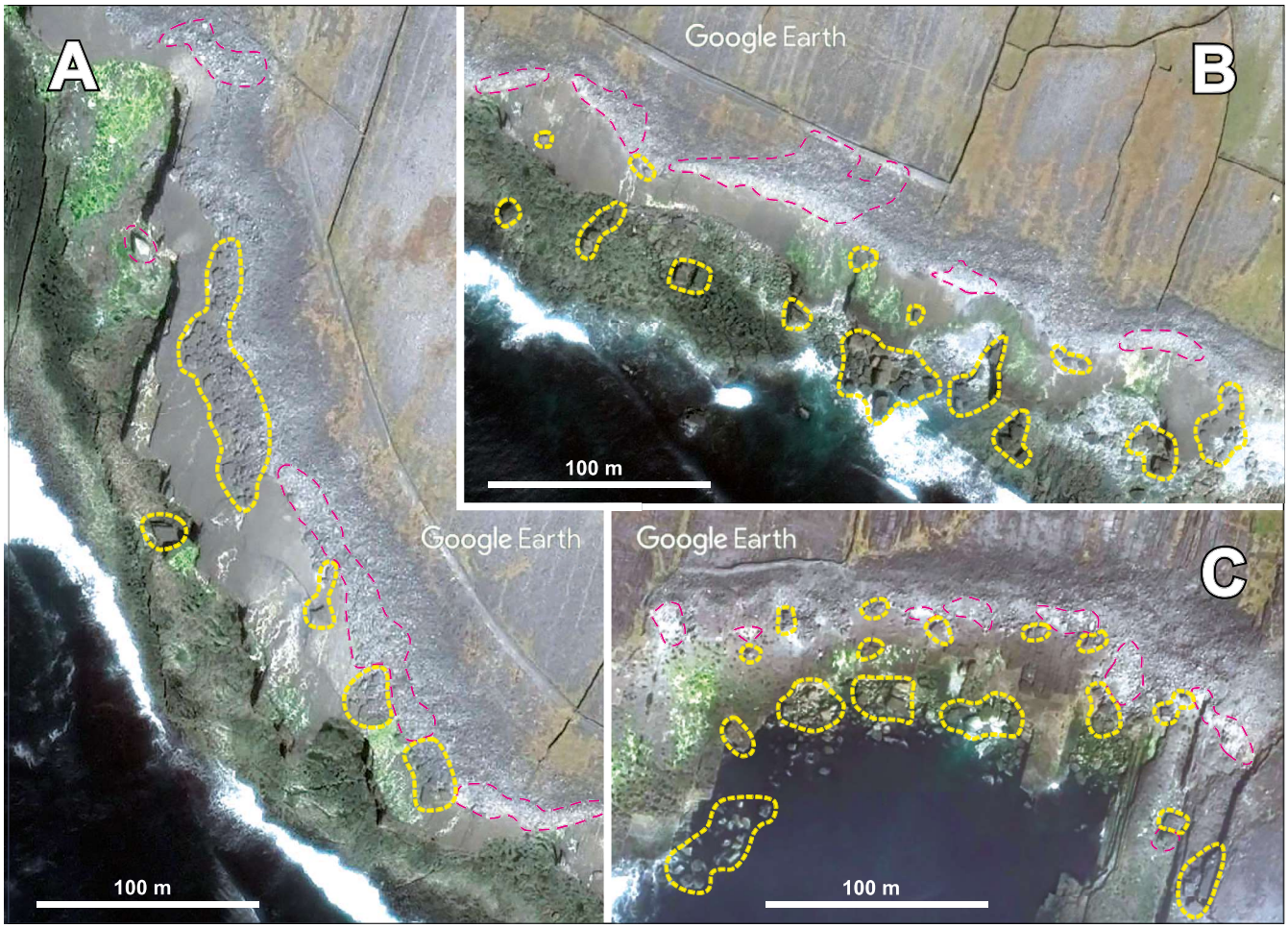


Figure 17. Examples of three (from 17) test sites for changes in boulder arrangements between 2005 and 2015 on Inishmore Island: (A, B) from the south coast, SE section, (C) from the central south coast near Wormhole. Red frames: modified or activated since 2005 (in particular during winter 2013–14), yellow frames: stable boulder arrangements since 2005 (or far longer back in time). (Credits: Google Earth April 2015, modified)

more sheltered SE coast of Galway Bay (Erdmann, Kelletat, and Kuckuck, 2017; Scheffers *et al.*, 2010; this study). Of these dates, 44% ($n = 37$) come from the boring bivalve *H. arctica* in boulders covering the last 9400 years of the Holocene (except for the period 6000–8800 BP), 56% ($n = 46$) from small gastropods (mostly littorinids) and the *Mytilus* sp. bivalves in shallow sediment archives. Younger shells may also be present in higher numbers, but geoarchives were reduced by marine erosion during Holocene sea-level rise in the study area, meaning it has been difficult to find statistically sound data clustering that indicates extreme events. In all data up to 9400 cal BP, three groups have been identified that are found with three to four times higher frequency compared with other clusters: 420–300, 650–500, and 1100–850 cal BP. These data clusters represent all the sedimentary units present (finer shallow archives, washover tongues of medium-sized boulders, clusters and ridges of very large boulders) in both regions (very exposed Aran islands and more sheltered Galway Bay coastlines) from low elevation up to >30 m above MHW. Table 5 shows a compilation of short time frames using several data sets that is likely to represent strong events for onshore sedimentation of all sediments up to large boulders. These interpretations, however, should be considered with caution, in particular in regards to the poor data clustering given in brackets for the older events, because only a few data have been collected so far, their preservation status is poor, and multiple displacements cannot be ruled out.

Studies with a focus on clifftop storm deposits have also been undertaken in the Shetland Islands, U.K. (Hall *et al.,* 2006; Scheffers *et al.,* 2009). Further to the north, studies on the Reykjanes peninsula of Iceland discussed similar widespread accumulations of large boulders (Etienne and Paris, 2010), whilst Suanez, Fichaut, and Magne (2009) and Fichaut and Suanez (2011) undertook similar studies on Banneg Island of Brittany, France, to the south. These authors found another interesting phenomenon similar to the Aran Islands: a negative budget for the boulder masses onshore from the winter storms 2013–14 (*e.g.*, accretion in boulder clusters of 50 $m^3$ and loss of

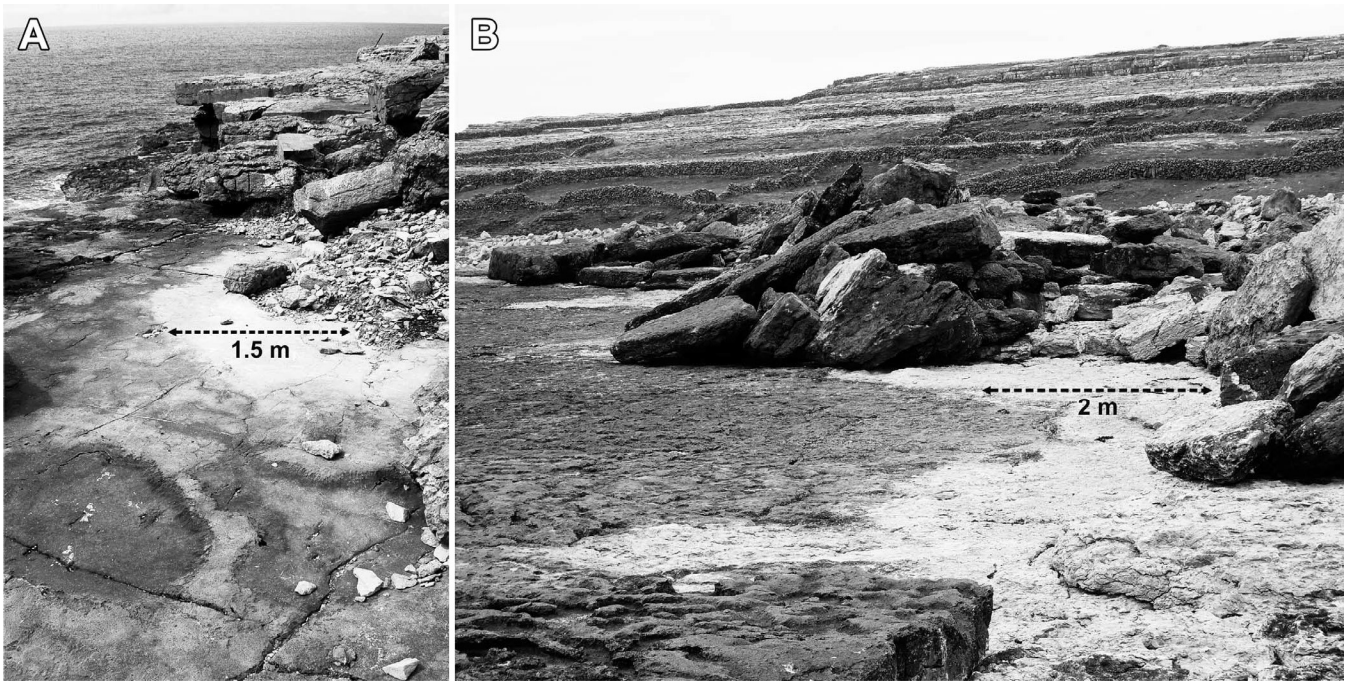


Figure 18. Strong storm wave impacts eroded existing boulder ridges (A) along their seaward side in sections with small boulders during winter 2013–14 (examples from Inishmore), resulting in an exposed limestone base rock (B). Sections with larger boulders in the ridges remained unaffected.

75 $m^3$, accretion of 10 $m^3$ and loss of 18 $m^3$). The data are results of comparison of pre- and post-2013–14 storm wave deposits. In the first case, freshly added and activated boulder mass was 50 $m^3$, but the total mass at this site was 75 $m^3$ less compared with the prestorm situation. In the second case, although the mass of fresh boulders was 10 $m^3$, the total mass after the storm was reduced by 18 $m^3$.

Autret *et al.* (2016) combined investigations of the Banneg Island boulders with measurements of hydrodynamic conditions over the 2013–14 winter period, the most energetic stormy period in 67 years (1948–2015), as identified by Masselink *et al.* (2016). Banneg Island is strongly exposed to storm wave approach from 240°–260°, with deep waters (–50 m) close to cliffs, similar to that of the Aran Islands. Consequently, a comparison of boulder dislocation between the two sites to test the storm-only hypothesis is reasonable.

Regnauld *et al.* (2010) argue that tsunamis have quarried large blocks on the Brittany Islands of Molène and Ouessant, including the Lisbon tsunami of AD 1755. However, Autret *et al.* (2016) found no evidence to prove the occurrence of tsunami waves in the Iroise Sea over the last centuries, including the period in which the Lisbon event of AD 1755 occurred.

In the discussion of extreme events along the central west coast of Ireland, the storm-only hypothesis (from Williams and Hall, 2004, to Cox, Jahn, and Watkins, 2016, and O'Boyle *et al.*, 2017) stands against a contribution of tsunami(s) in mass movements (Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al.*, 2015; Scheffers *et al.*, 2009, 2010; see also Table 6).

Regarding transport mechanisms (*e.g.*, storm waves and bores *vs.* tsunami flow), recently moved boulders are relatively small compared with old boulders (single, in clusters, or in ridges) and have not been affected by recent extraordinary storm events. The longest axis of the latter are over 10 m, with a volume of over 30 $m^3$ and a mass over 70 tons (and 230 tons in one case). These boulders are thought to have been transported over distances of the order of >20 m and several meters against gravity, with starting points at least +15 m MHW and at least 150 m from the shoreline. The time of dislocation may have occurred a few thousand years ago when sea level was several meters below present and the shoreline was located a few hundred meters away from its present location. Similar to Banneg Island of Brittany, on the Aran Islands' cliff platforms, double or triple ridges occur, but those in Ireland have not been affected by recent storms.

Physical data from marine boulders in the Galway-Aran region collected by Cox, Jahn, and Watkins (2016), Cox *et al.* (2012, 2014), Erdmann, Kelletat, and Kuckuck (2017), Erdmann *et al.* (2015), Erdmann, Kelletat, and Scheffers (2017), Scheffers *et al.* (2009, 2010), and Williams and Hall (2004), enables boulder distribution to be categorized with respect to size, inundation and run-up, elevation, and transport dimensions against gravity. Categorization is also possible for boulder dislocation during the extraordinary (hurricane category) storms of winter 2013–14 and existing boulders. A recent study that provided some of the necessary data for the same classifications was made by Kennedy *et al.* (2017) along a 4.5-km-long coastal section in eastern Samar, Philippines, related to Typhoon Haiyan (Super Typhoon Yolanda in the Philippines) of 2013. For both regions and events, extreme waves with maximum (potential) significant heights in the range of $H$

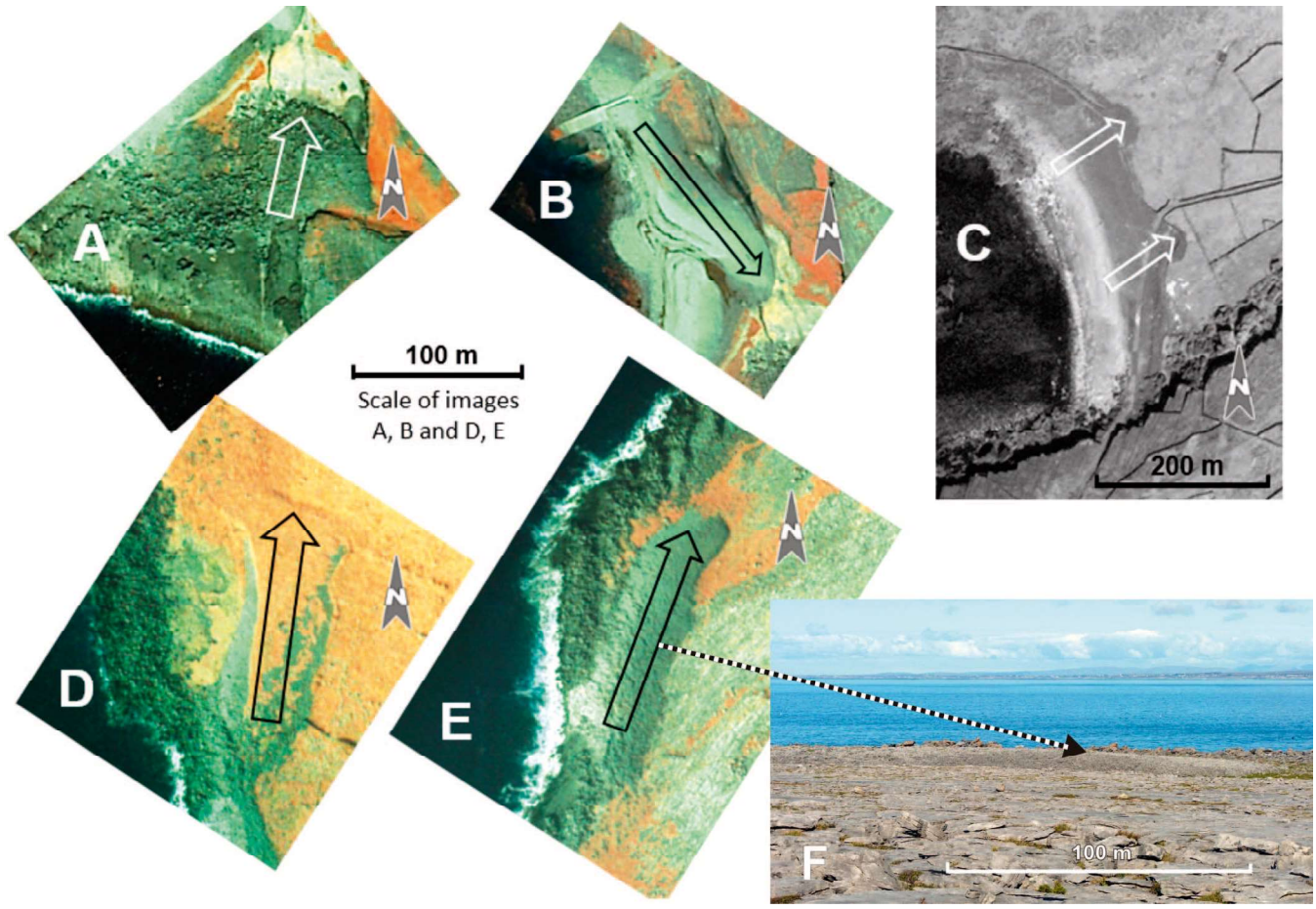


Figure 19. A compilation of washover lobes and tongues from the Galway-Aran region. All parts are in the same scale and north-oriented. (A) A broad lobe of large angular boulders in the westernmost region of Inishmore. (B) A tongue of small to medium-sized rounded boulders in the westernmost region of Inishmore. (C) The visible ends of two tongues of well-rounded medium-sized boulders in the northwest region of Inishmaan (Trawlagh Bay). (D) A vegetation-covered tongue of mostly rounded medium-sized boulders at Lafkaniska within Galway Bay, with a sharp erosional western scar from a later extreme event. (E) A well-defined tongue of medium-sized rounded boulders, at Murroogh Point, south of Black Head within Galway Bay. (F) Same as panel E, seen from east in September 2015. (Credits A, B, D, and E: National Coastline Survey, Marine Institute of Ireland, Dublin, 2000, modified; C: Google Earth April 2015, modified)

= 15–20 m and a deep-water coastal section and plunging cliffs are typical. On Samar, the elevation limit for boulder dislocation was 15 m above mean sea level and inundation width 280 m from Haiyan. On the Aran Islands and along the SE section of Galway Bay, the elevation envelope along >50 km of coastline is around +32 m at the mainland, +29 m on Inishmore, and about +34 m on Inishmaan, with inundation ranges of 110 m on the mainland, 200 m on Inishmore, and 310 m on Inishmaan. These values are for all Holocene boulder deposits, whereas data for the 2013–14 hurricane events, elevation ranges are significantly lower: +26 m on the mainland, +24 m on Inishmore, and +23 m on Inishmaan, with inundation ranges of 80 m on the mainland, 120 m on Inishmore, and 210 m on Inishmaan. In contrast to Kennedy *et al*. (2017), these data for the Galway-Aran area are confined exclusively to boulders with a transport against gravity. Another difference from the Samar study of Kennedy *et al*. (2017) is that on Aran, initial and final locations of boulders are known and identified in the landscape. Although some features and data are comparable between extreme winter storm events on Aran and Super Typhoon forces on the Philippines, discrepancies and errors also exist: in Kennedy *et al*. (2017, figure 12), the Aran boulder group lies outside of regions with large coastal boulders at elevations up to 50 m, a similar limitation to that found in Williams and Hall (2004) for a site on Inishmaan that in fact has an elevation of only 30 m (Erdmann, Kelletat, and Kuckuck, 2017).

Another point is the type of boulder movement (sliding, overturning, lifting), identified using a combination of field data and modeling (Kennedy *et al.,* 2017, figure 14). Sliding is found close to the area where no motion occurs, although surface roughness on Samar is extreme (0.5–1 m by strong karstification). Overturning is shown to require stronger velocities of waves, bores, and flow and lifting the strongest velocities, with at least double those for sliding, and rarely occurring along inclined coastal topographies. In contrast to

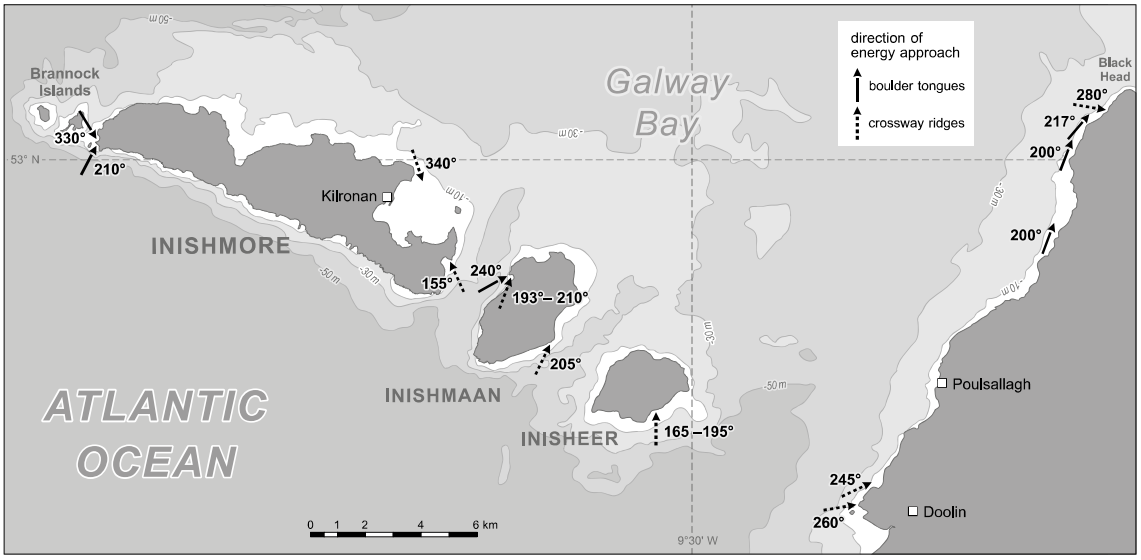


Figure 20. The distribution and direction of incoming energy for two groups of geomorphic and sedimentary features (boulder tongues and crossway ridges) as evidence for extreme flow events on the Aran Islands and along the SE coast of Galway Bay.

these Samar results, in the Aran and Galway area, sliding occurs with minimal ground contact and hovering after lifting, whereas lifting from a joint-bound scenario is by far the most common type of movement, because the large majority of platy boulders from sedimentary rock (limestone) are broken and lifted along structural steps on cliff platforms (compare the documentation in Erdmann *et al*., 2015, and Erdmann, Kelletat, and Scheffers, 2017). Lifting and overturning in the Irish study sites is most effective with rectangular boulders, whereas Kennedy *et al*. (2017) found that nonrectangular boulders aid overturning and lifting, in particular from joint-bound scenarios.

Finally, the question arises as to whether four phenomena observed in the Galway and Aran region, in combination with boulder deposits, are unique or exist in other parts of the world's rocky coastlines. The features in question are ripples on the leeward slopes of ridges from large boulders (Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al.,* 2015), balancing large boulders on ridge crests (Figure 5), rhythmic crossway ridges forming a main seaward ridge of large boulders (Figures 6 and 20), or massive tonguelike washover deposits of boulders (Figures 9, 15, 19, 20). All these features have not yet been considered in terms of storm wave or bore processes but may fit with the physics of strong tsunami flow.

## CONCLUSIONS

Near-time inspection after extreme (winter) storms (*e.g*., Autret *et al.,* 2016; Cox, Jahn, and Watkins, 2016; Cox *et al.,* 2014; Cox and Watkins, 2015; Erdmann *et al.,* 2015; Erdmann, Kelletat, and Scheffers, 2017; Kennedy *et al*., 2017) provide new information on potential forces of waves and bores needed to dislocate and transport boulders far away from the shoreline or cliff edge to higher elevations. A general comparison of boulder size, mass, dislocation, distance inland and against gravity, elevation above MHW, degree of exposure, and water depths for wave approach (compared with worldwide observations of coastal boulder deposits, see Erdmann, Kelletat, and Kuckuck, 2017; Erdmann *et al.,* 2015) suggest that the strongest storms in living memory had less transport power than previous marine events.

However, studies on large boulders alone will not lead to progression in the understanding of boulder movement while arguments remain that suggest storms were several times stronger previously or under different climatic conditions than

Table 2. *Washover lobe data (compare also Figure 19).*

| No. | Location | Length (m) | Width (m) | Thickness (m) | Material (m) | Mass (70%) (t) | From Direction |
|---|---|---|---|---|---|---|---|
| Tonguelike washover lobes on the Aran Islands | | | | | | | |
| 1 | Inishmore W | 150 | 45 | 2.2 | small boulders | >25,000 | 330° |
| 2 | Inishmore W | 128 | 110 | 2.0 | large boulders | >49,000 | 210° |
| 3 | Inishmaan NW, two parallel tongues of small, well-rounded boulders | 50 | 30 | 2.2 | small boulders | both >11,000 | 240° |
| Tonguelike washover lobes inside Galway Bay | | | | | | | |
| 4 | Lafkaniska at SE section of Galway Bay | 153 | 58 | 2.0 | small boulders | >30,000 | 200° |
| 5 | Murroogh Point, 20 km inside Galway Bay, southern washover lobe | 172 | 35 | 1.8 | medium boulders | >18,000 | 200° |
| 6 | Murroogh Point, 20 km inside Galway Bay, northern washover tongue | 136 | 36 | 2.0 | small boulders | >14,000 | 217° |

Table 3. *Calculation of cliff retreat on Inishmaan and Inishmore, based on the actual volume of boulder ridges, assuming the ridge cubature is equivalent to the cliff-rock platform erosion cubature over time of ridge existence. First example is from Cox* et al. *(2012, p.253, fig. 3); other examples are from own fieldwork. Total erosion for the time of ridge forming given as lateral erosion of cliff/vertical erosion of rock platform, or both.*

| Coordinates | Ridge Rock Volume ($m^3$)† | Distance (m MHW) | Elevation of Crest (m MHW) | Cliff Height (m) | Total Erosion (m) |
|---|---|---|---|---|---|
| 53°0774″ N 09°6150″ W | 40 | 70 | +22.3 | 20.0 | 2.0/— |
| 53°0358″ N 09°3636″ W | 46 | 128 | +9.0 | 5.0 | 9.2/0.36 |
| 53°0358″ N 09°3622″ W | 63 | 88 | +8.0 | 4.0 | 7.9/0.72 |
| 53°0546″ N 09°4006″ W | 35 | 102 | +10.0 | — | —/0.75 |
| 53°0606″ N 09°4048″ W | 36 | 63 | +16.0 | 6.0 | 6.0/0.75 |

†*At 1-m lateral width.*

today (compare Cox *et al.,* 2015, with Hearty and Tormey, 2017). Storms, as observed worldwide, are physically limited because of internal friction and self-destruction and collapse of the system.

In Erdmann, Kelletat, and Kuckuck (2017) and Erdmann *et al.* (2015), boulder tongues of significant size (>100 m long, containing far more than 10,000 tons of rock) formed and deposited from a single process in one moment, as well as sequences of crossway ridge segments forming a main ridge from a similar process, are documented for the first time. They are at least as significant for tsunamis as many of the signatures for fine sediment deposits mentioned in the younger literature (erosional base, mud caps, mud clasts, fining upward sequences, *etc.*). Historical data for paleotsunamis do not exist for the research area, except for the Lisbon event in AD 1755, when the old city of Galway was flooded and partly damaged. However, a myth of a flooding event in AD 799/804, killing 1010 people and splitting an island named Fita (or Fitha) into three parts, is mentioned by O'Brian, Dudley, and Dias (2013) in relation to the three Aran Islands. Geomorphic evidence from the glacial relief of the Aran Islands indicates that the two channels between them have existed since at least the last Ice Age. However, the separation of the little Brannock and Rock Island (Figure 20) from Inishmore in the west may well result from a early Holocene event.

The argument of Cox *et al.* (2012) and Hearty and Tormey (2017) that evidence of storm wave boulder movement and missing knowledge on historical tsunamis exclude the latter

Table 4. *Thirty-five AMS radiocarbon values from marine deposits on the three Aran islands (italics: data from Scheffers* et al.*, 2010; bold: new data from this study) in chronological order.*

| Beta Lab. No. | Location and Environment | Material† | Elevation [m + MHW] | δ13C | Two Sigma Cal BP‡ |
|---|---|---|---|---|---|
| **469384** | **Inishmore W, washover sand** | **mar. gastr.** | **5.2** | **+1.0** | **282–85** |
| **469385** | **Inishmore W, washover sand** | **mar. gastr.** | **5.1** | **+0.6** | **290–100** |
| *236711* | *Inishmore S, in boulder ridge* | *Mytilus sp.* | *24.0* | *0.0* | *420–340* |
| *236709* | *Inishmore S, in boulder ridge* | *Mytilus sp.* | *24.0* | *−1.9* | *420–340* |
| **471345** | **Inishmore W, washover sand** | **mar. gastr.** | **6.0** | **+2.9** | **424–270** |
| **472235** | **Inishmaan W, cliff top point** | **mar. gastr.** | **31.0** | **+1.4** | **447–283** |
| *233799* | *Inishmore S, in ridge boulder* | *Hiatella arctica* | *5.0* | *−2.1* | *450–380* |
| **471347** | **Inishmore E, marine sands** | **mar. bivalve** | **21.0** | **+0.4** | **454–293** |
| **471336** | **Inishmaan W, cliff top joint** | **mar. gastr.** | **31.0** | **+2.1** | **518–386** |
| **469382** | **Inishmore SW, washover tongue** | **Hiatella arctica** | **3.2** | **−0.1** | **526–416** |
| *233793* | *Inisheer SW, in ridge boulder* | *Hiatella arctica* | *2.0* | *−1.5* | *610–440* |
| **469374** | **Inishmaan S, in large boulder** | **Hiatella arctica** | **3.0** | **+1.4** | **619–490** |
| *233797* | *Inishmaan S, in ridge boulder* | *Hiatella arctica* | *3.0* | *−0.3* | *660–570* |
| 233798 | *Inishmaan S, in ridge boulder* | *Hiatella arctica* | *5.1* | *−4.8* | *660–570* |
| **469375** | **Inishmaan W, cliff top joint** | **Patella sp.** | **31.0** | **+2.1** | **754–629** |
| *236712* | *Inishmore E, in boulder ridge* | *Mytilus sp.* | *25.0* | *−1.9* | *760–630* |
| *233795* | *Inishmore E, in ridge boulder* | *Hiatella arctica* | *5.8* | *−1.9* | *860–760* |
| ***469381*** | ***Inishmore SW, washover tongue*** | **Hiatella arctica** | ***3.5*** | ***+0.8*** | ***916–748*** |
| *233792* | *Inishmore W, in ridge boulder* | *Hiatella arctica* | *6.1* | *−0.2* | *940–800* |
| *233790* | *Inishmore N, in ridge boulder* | *Hiatella arctica* | *4.5* | *−1.3* | *980–810* |
| *233794* | *Inishmore W, in ridge boulder* | *Hiatella arctica* | *5.0* | *−1.4* | *1070–900* |
| **471346** | **Inishmore W, washover sand** | **mar. gastr.** | **6.0** | **+0.2** | **1286–1136** |
| *233791* | *Inishmore W, in ridge boulder* | *Hiatella arctica* | *4.5* | *−0.9* | *1320–1130* |
| **469380** | **Inishmaan NW, washover tongue** | **Hiatella arctica** | **4.7** | **−0.8** | **1570–1378** |
| **472236** | **Inishmore E, washover sand** | **terr. gastr.** | **22.0** | **−5.3** | **1666–1628** |
| *233796* | *Inishmore W, in ridge boulder* | *Hiatella arctica* | *17.0* | *−7.8* | *1870–1680* |
| *236708* | *Inishmore S, in ridge boulder* | *Mytilus sp.* | *18.0* | *−0.2* | *1990–2452* |
| **469376** | **Inishmaan NW, washover sand** | **mar. bivalve** | **4.2** | **+2.0** | **2701–2452** |
| **471338** | **Inishmaan NW, washover sand** | **Hiatella arctica** | **3.0** | **+0.8** | **3172–2943** |
| *236710* | *Inishmore S, in boulder ridge* | *Mytilus sp.* | *25.0* | *+1.0* | *3480–3280* |
| **469337** | **Inishmaan NW, washover sand** | **Patella sp.** | **4.1** | **+0.3** | **3579–3385** |
| **471339** | **Inishmaan NW, washover sand** | **mar. gastr.** | **3.5** | **+1.6** | **3650–3363** |
| **469378** | **Inishmaan NW, washover sand** | **mar. gastr.** | **4.6** | **+2.7** | **3849–3635** |
| **471340** | **Inishmaan NW, washover sand** | **mar. gastr.** | **3.5** | **+0.6** | **4712–4432** |
| **471344** | **Inishmaan SW, terr. deposit** | **charcoal** | **6.5** | **−26.1** | **6753–6641** |

†*mar. gastr. = marine gastropod; mar. bivalve = marine bivalve; terr. gastr. = terrestrial gastropod*
‡*Two-sigma calendar-calibrated age range before the present.*

Table 5. *Clustering of potential events, based on 83 randomly taken AMS radiocarbon data along >60 km of shorelines of SE Galway Bay and the three Aran Islands, distributed over all sedimentary units (large boulder ridges, medium washover boulder tongues, coarse sand deposits). Data are taken from the central values within the two sigma range. Italic entries indicate a low probability because of few data and wide time spans.*

| Time (cal BP) | Span (y cal BP) | No. of Data Points |
|---|---|---|
| 318 | 1 | 3 |
| 347–371 | 23 | 6 (three of them in 365 cal BP) |
| 447–471 | 15 | 4 |
| 585–619 | 33 | 6 (two of them in 610 cal BP) |
| 650–655 | 4 | 3 (two of them in 655 cal BP) |
| 692–695 | 3 | 3 (two of them in 692 cal BP) |
| 870–895 | 24 | 3 |
| 1085–1130 | 44 | 4 |
| 1903–1935 | 32 | 3 |
| 2238–2380 | 141 | 4 (two of them in 2300 cal BP) |
| *(3482–3665* | *182* | *3)* |
| *(4772–4620* | *47* | *2)* |
| *(5648–5935* | *286* | *3)* |

from geomorphologic and sedimentologic contributions cannot be taken as convincing: recent extraordinary storm impacts have often not reached the existing envelopes of boulders deposited from old events and a lower sea level. The history of events during the Holocene for coarse deposits remains mostly unknown because of a lack of deposition data from most sites studied to far.

To understand the influence of tsunami events on the west coast of Ireland, potential source areas in the Atlantic Ocean need to be investigated. The events may be initiated (as far-field tsunamis) from the continental rise along the east coast of North America; the Puerto Rico structure; volcanic collapses at the Azores, Canaries, and Madeira; or the Gorringe Bank, which was the source of the Lisbon Earthquake and Tsunami in AD 1755. The steep flanks of the Rockall Trough is the closest source area to Ireland, where slope failure features from late glacial to Holocene times have been identified as a hazard for coastal populations and infrastructure (Georgiopoulou *et al.*, 2012, 2013, 2014; Övrebö *et al.,* 2005; Owen *et al.,* 2010; Salmanidou *et al.*, 2015). Sacchetti *et al.* (2011, 2012) mapped hundreds of individual scarps between 2 and 60 km long and 15 and 150 m high, with depositional lobes up to 40 km long and 50–60 m high along the western slope into Rockall Trough. According to Salmanidou *et al.* (2015), remobilized volumes estimated to be between 275 and 765 $km^3$ may have been transported during single events. Rafting blocks in these debris

Table 6. *Synopsis of arguments pro and con discussing marine forces responsible for boulder dislocation along the rocky coastlines of the Aran Islands at the entrance to Galway Bay, western Ireland.*

| Local State of the Art Important for Conclusions | |
|---|---|
| In 2004, when the fundamental paper of Williams and Hall (2004) was published, sea levels during the early Holocene were not known in detail. Holmes *et al.* (2007) reconstructed a sea level about 5 m deeper than the modern one in Mid-Holocene times, and about 1.5 m deeper around 500 BP, confirmed by Williams and Doyle (2014) and Erdmann, Kelletat, and Kuckuck (2017). | |
| Arguments for a *storm-only* hypothesis | Arguments for a contribution of *tsunamis* in boulder dislodgement |
| Related publications in chronological order: Williams and Hall (2004); Hall *et al.* (2006); Hansom, Barltrop, and Hall (2008); Hansom and Hall (2009); Zentner (2009); Williams (2010); Cox *et al.* (2012, 2014); Cox *et al.* (2015); Cox and Watkins (2015); Cox, Jahn, and Watkins (2016). | Related publications in chronological order: Scheffers *et al.* (2009, 2010); Erdmann *et al.* (2015); Erdmann, Kelletat, and Kuckuck (2017); this paper. |
| (1) investigated the most exposed deep-water cliff coastlines of the Aran Islands Inishmore and Inishmaan and their boulder deposits; | (1) investigated coastlines in all exposures on the Aran islands and within Galway Bay and their boulder deposits; |
| (2) low and sheltered coastal sections, nearshore water depth and former sea levels were not considered; | (2) investigated all topographic situations and concerned sea level history and nearshore bathymetry; |
| (3) "recent" processes and indicators (nylon lines, plastic bottles) in boulder clusters taken as proof for a young age of boulder ridges and clusters; | (3) established a framework of >80 AMS radiocarbon data points covering >6000 y from all sedimentary units of the Aran Islands and from inside Galway Bay; |
| (4) only storm-activated boulders considered, even if not dislocated against gravity; | (4) also considered immobile boulders that earlier were dislocated against gravity; |
| (5) based on a high rate of cliff retreat (since Williams, 2004: 0.2–0.8 m/y), continuous shift of boulder clusters to landward are assumed; | (5) overall longtime stability of boulder ridges and very small rates of cliff retreat in the second half of the Holocene found; |
| (6) no sediments beside large boulders considered; | (6) all sediment units (silt to blocks) considered; |
| (7) geomorphic indicators not typical for wave-bore transportation not found or discussed. | (7) all macro- and micromorphological signatures in the landscape and at boulders investigated, form and depositional units (rhythmic crossway ridge sediments, ripple marks in boulder field, large tongues of boulders, chaotic and bimodal sediments with mud clasts or fining upward sequences) investigated not typical for storm processes, and hints to the source area of tsunamis along the Rockall Trough west of Ireland, where submarine mass wasting processes have been found from late into postglacial times. |
| Important notice | |
| In the fundamental paper of Williams and Hall (2004, pp. 105–106), ideas are found for discrepancies between modern storm activation and the overall appearance of boulders on the Aran Islands: | |
| . . . 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" . . . and 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." | |

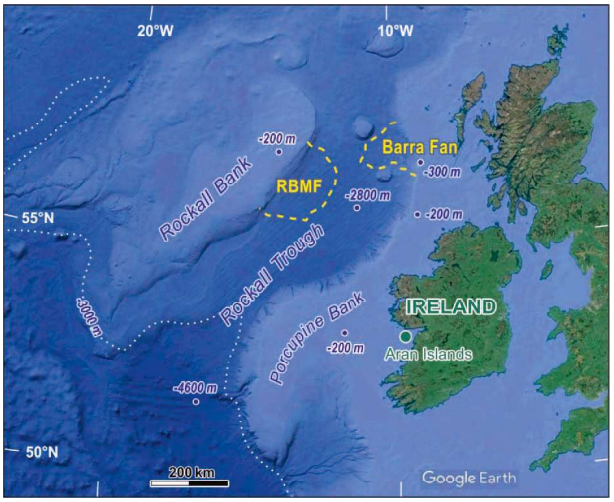


Figure 21. The spatial relation of the deep Rockall Trough as a potential tsunami source region for the Aran Islands. Two areas of late to postglacial submarine mass wasting processes (Barra Fan and Rockall Bank Mass Flow [RBMF]) are indicated. (Credit: Google Earth December 2016, modified)

flows measure 2 km in size (Unnithan *et al.,* 2000, p. 23, figure 3). Fruergaard *et al*. (2015) identified sediments from the Storegga Slide off Norway (about 8100 BP) in a paleolake on Römö (an island in southwesternmost Denmark) with a run up of 20 m after crossing >500 km of the North Sea shelf, with water depths of less than 100 m (compare also Weninger *et al*., 2008). Although the western slope of Rockall Trough is about 400 km from the Aran Islands, a tsunami from this region has an initial velocity of at least 550 km/h with a water depth of >2500 m, which would reduce to >200 km/h crossing the Porcupine Bank of 400 m and less.

To solve these unresolved questions, new methods (in dating cliff retreat rates and boulder emplacement or reactivation) with cosmogenic nuclides (in limestone with chlorine 36) are available but have not, to date, been applied along the Galway coastlines. It is not known whether the sedimentary coastlines of the innermost Galway Bay, which includes marshland and freshwater peat environments, may contribute to the chronology of extreme events in coastal formation during the Holocene, because sea level 7000 to 5000 years ago was 5 m lower and many kilometers away from the same area during Mid-Holocene times. Although it is highly likely that the Galway and Aran Island boulder deposits and their organization belong to the most spectacular of the world's coastlines, the answer to these unanswered questions may come from other locations along the west coast of Ireland. With the present research undertaken in mind, it is recommended that more research on rocky coasts and coarse marine deposits is undertaken in NW Europe and around the world, in combination with submarine process identification and dating, because these objects and their processual relation are strongly underrepresented in coastal research activities.

## ACKNOWLEDGMENTS

This project was supported by a grant from the German Research Foundation (Deutsche Forschungsgemeinschaft) and assistance with technical problems and logistics in the field by Jens Erdmann and Frank Schmidt-Kelletat. Graphics have been contributed by Gudrun Reichert.

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**Fazit**

Neben ergänzenden Kartierungen, Messungen und Beprobungen auf den Aran-Inseln wurde das insgesamt aus den Arbeitsgebieten zusammengetragene Material hinsichtlich sehr verschiedener Themen bewertet. Das betrifft u.a. Methoden zur relativen Altersabschätzung und Inaktivität bzw. Aktivität von Blöcken, vor allem hinsichtlich terrestrischer Kalklösung, welche charakteristische Formen aus dem Litoral nach Ablagerung modifiziert haben können, und einen Vergleich der Ablagerungsmuster und –gefüge zwischen exponierten (und hochliegenden) und weniger exponierten (und niedrigen) Standorten. Die am Karbonkalk durch geomorphologische und archäologische Indizien ablesbare Intensität des Kliffrückganges wird ebenso diskutiert wie die Erhaltung bzw. Veränderung der großen Blockwälle. Zusätzlich konnte für eine Reihe von geomorphologischen Merkmalen deren Existenz und Verbreitung auf den Inseln und am Festland erstmalig nachgewiesen werden. Es sind Rippelformen auf Blockwällen und zu einem weiten Muster segmentierter Blockwälle umgestaltete Hauptwälle und über 100 m lange Blockzungen als Vollformen, deren Blockmasse zwischen > 10.000 t und ca. 45.000 t beträgt und die höchstwahrscheinlich bei ganz kurzfristigen Tsunami-*washovers* angelegt wurden.

Aus Blöcken und auch aus feineren Archiven und deren Stratigraphie wurde mit Hilfe von 23 neuen AMS-Daten eine Sedimentationsgeschichte über mehr als 5.000 Jahre jetzt auch für die Aran-Inseln erkannt. In den insgesamt 84 Altersdaten aus den Arbeitsgebieten lassen sich vorläufig (und ohne abschließende Interpretation) etwa 10 Datencluster ablesen. Ob sie im einzelnen Sturmereignissen oder Tsunamis zugewiesen werden können ist solange offen, wie detaillierte Altersbestimmungen an den *mass – wastings* des *Rockall Trough* im Westen von Irland ausstehen.

# 5 Bewertung des Forschungsfortschrittes, regionale und überregionale Ergebnisse

Den (vorläufigen) Abschluss des Projektes bildet ein Vergleich wissenschaftlicher Fragestellungen und Herangehensweisen der Arbeitsgruppen, die von vornherein andere Prozesse als Stürme ausschließen, aber nur sehr kleine Küstensegmente überhaupt untersuchen, und ergebnisoffenen Arbeitsmethoden, welche alle Dimensionen und Variationen ausgedehnter Küstenlandschaften differential-diagnostisch einer Analyse zuführen möchten.

In diesem Kapitel sollen die wesentlichen methodischen Schritte der eigenen Publikationen nur kurz angerissen werden, da diese bereits im Original vorliegen. Ein größerer Fokus wird auf den Zusammenhang der Gedankenführung und der einzelnen Arbeitsschritte gelegt.

Es scheint so, als habe die Natur in der Region Galway Bay die ungelöste Frage nach dem Mechanismus des Blocktransportes einen Schritt vorwärtsbringen wollen: Von Ende Dezember 2013 bis Mitte Februar 2014 trafen sechs schwere Stürme auf die Westküste Irlands, vier davon als Kategorie 3 – Hurrikane, zwei als Kategorie 4 – Hurrikane. Nach dem Eindruck der Küstenbewohner und den Registrierungen der meteorologischen Dienste waren es die extremsten Stürme *„in living memory“*, d.h. seit mindestens 60 Jahren. Das gilt erstaunlicherweise weniger für morphologische Veränderungen der Küstenformen (an denen heute diese Stürme nicht mehr identifizierbar sind), als vielmehr für die Verlagerung frischer Blöcke gegen die Schwerkraft und landeinwärts. Diese Ereignisse waren Anlass genug, zeitnah (im Juni 2014) im Gelände die Spuren dieser Stürme zu verfolgen (vgl. Erdmann et al., 2015). Außerdem bot sich die Gelegenheit zu einer breiten Darlegung der Befunde in der Reihe *„Springer Briefs in Geography“* einschließlich der Dokumentation mit zahlreichen Fotos und Graphiken, so dass auch etliche offene Fragen zur Entwicklung von Formen und Sedimenten in der Galway Bay und auf den Aran Inseln einbezogen wurden.

Um Signaturen von starken Stürmen in einer Küstenlandschaft nachzuweisen gibt es kein generelles Vorgehen. Neben den Küstenformen ist es vor allem der Gesteinstyp, der Veränderungen aufnimmt und gegebenenfalls für eine Weile bewahren kann. Im Kalkgestein (wie im Arbeitsgebiet) erfolgt dieses durch Abrieb an allen Kontaktstellen mit Nachbarfragmenten.

Die Transportleistung ist nicht allein von der Höhenlage und Entfernung vom Meeresspiegel abhängig, sondern erscheint in ihrer Verteilung eher durch lokale Faktoren, vor allem die Konfiguration der Kliffe, welche die räumliche Verteilung des Wellenauflaufes bestimmen, gesteuert zu sein. Daher liegen aktivierte und nicht aktivierte Blockwallabschnitte oft in gleicher Höhe und Exposition, sind aber insgesamt unregelmäßig verteilt. Eine Ausnahme bilden hohe geschlossene Blockwälle in geringer Meereshöhe und relativ nahe am Brandungssaum wie an Abschnitten der Südküste von Inishmaan (Abb. 14). Dort finden sich Blockwallabschnitte, die geschlossen bis zur Kronenhöhe und dann unregelmäßig auf der landseitigen Böschung aktiviert wurden, letztmalig im Winter 2013/14. Eine frische Blockverlagerung bis auf vegetationsbedeckte Oberflächen gibt es im Arbeitsgebiet nicht.

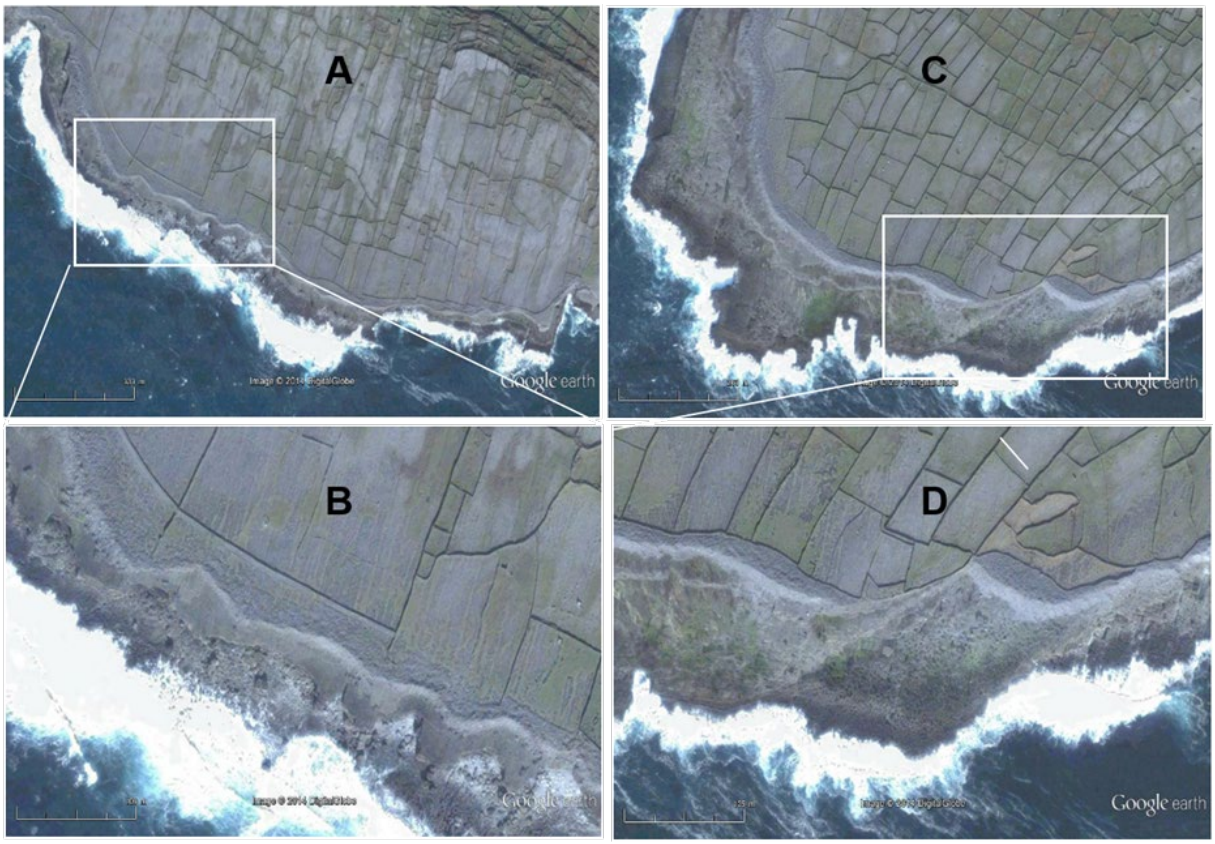


Abb. 14: Blockwälle an der Süd- und Südwestküste von Inishmore (A und B) und Inishmaan (C und D). Die Ausschnitte (B und D) zeigen jeweils ca. 600 m lange Wallabschnitte (Credit: Google Earth, 2005).

Zwei weitere Aspekte sind bedeutsam, welche im Bereich der Galway Bay und den Aran-Inseln sturmbedingt Veränderungen hervorrufen, welche den Landschaftseindruck bestimmen. Plattformen oberhalb der Kliffe haben seewärts absteigende Strukturstufen, und die Kalkschichten fallen nahezu überall ebenfalls

seewärts (nach SW) ein wenig ab (2-4°). Daher ist der *backwash* (verstärkt durch die Reflexion von den steilen Blockwällen) ausreichend stark, um kleinere Fragmente ins Meer zu spülen. Gröbere Teile werden - sofern sie den Blockwall erreichen - durch die Umkehr der Strömungsrichtung abgelagert. Die Folge ist eine oft (bis > 200 m) breite schwach geneigte Fläche zwischen Blockwällen und dem Kliff bzw. der Brandungszone, frei von Sedimenten jeder Korngröße. Damit wird eine Art „Tafel" angeboten, auf der die Blockbewegungen in Kalkstrichen „geschrieben" werden können. Der zweite Grund liegt in einer Eigenschaft der Bewegung von Fragmenten: sind das einzelne oder relativ wenige, gehorchen sie dem normalen Transport durch Wellen und *bore-flow.* Sind es viele, so dass sie miteinander kollidieren, wird die Bewegung der einzelnen Teile durch mehrfache Kollision stärker aktiviert, die einzelnen Objekte können sich schneller bewegen und insgesamt kann eine größere Zahl von Objekten und eine größere Masse bewegt werden. Grund ist die stärkere Turbulenz, wie Nandasena & Tanaka (2013) und Nandasena et al. (2011) mit Naturbeobachtungen und Tests im Wellenkanal belegten.

In den einschlägigen Publikationen zum Blocktransport im marin-litoralen Milieu finden sich zahlreiche Widersprüche (vgl. u.a. eine Dokumentation für den Zeitraum seit 2000 in Erdmann et al., 2017). Benner et al. (2010) lieferten eine kritische Übersicht mit dem Schwerpunkt auf direkter Wellenwirkung (d.h. ohne die Berücksichtigung von Boren) und die Bedeutung von lang dauernder Umströmung eines Blockes für seinen Transport. Messungen bei starker Brandung sind sehr schwierig, und die Übertragung der Ergebnisse wegen der nahezu unendlichen Menge an Faktorenverknüpfungen oft gewagt. *Near-time inspections* nach starken Wellenereignissen schaffen hier zwar keine Abhilfe, im Falle der „Aufzeichnung" von Einzelprozessen im Kalkgestein können sie jedoch wichtige Informationen liefern. Daher war es von Bedeutung, im Juni 2014 an möglichst vielen Stellen auf den Aran-Inseln und innerhalb der Galway Bay das Ergebnis des Blocktransportes durch die Winterstürme 2013/14 im Gelände detailliert aufzunehmen. Das geschah durch kontinuierliche Inspektion von insgesamt mehr als 60 km Küstenlinie in verschiedenen Expositionen und entlang flacher Küsten und sehr hoher Kliffabschnitte. Die neuen Verhältnisse konnten zudem in vielen Fällen mit eigenen Aufnahmen seit 2005 verglichen werden. Vorab muss gesagt werden, dass die Diskussion ausschließlich Blöcke thematisiert, die eindeutig gegen die Schwerkraft bewegt wurden. Daher bleiben die Maximalwerte der Blockmassen deutlich hinter jenen von Cox et al. (2014, 2015, 2016 a, b) zurück.

Mit der Identifizierung der Lage und Masse frisch bewegter Blöcke lassen sich etliche quantitative Daten für Blocktransport durch Starkwellen sammeln. Dieses ist auch die von Cox et al. (2012) angewandte Methode, ergänzt durch Bildvergleich mit Gegebenheiten aus früheren Jahren. Wenn alle Expositionen, Wassertiefen, Höhenlagen und Relieftypen sowie geologischen Voraussetzungen (z.B. ursprüngliche Schichtmächtigkeit) in einem größeren Raum Beachtung finden, kann die maximale Umgestaltungskraft für das Küstenrelief und die Küstensedimente in sogenannten *„envelopes"* (Kennedy et al., 2017) der räumlichen Verteilung ermittelt werden. Bei Beschränkung auf ausgesuchte (z.B. nur extrem exponierte) Lagen wird das allerdings nicht gelingen. Außerdem ist die Betrachtung nur frisch verlagerter Fragmente ein zu kleiner Ausschnitt der von der Natur bereitgehaltenen Informationen. Weitere Erkenntnisse bieten sich z.B. dadurch, dass auch geprüft und quantitativ erfasst wird, welche bereits vorhandenen Fragmente bei den Starkereignissen **nicht** bewegt wurden. Das Schicksal beider Dispositionen (frischer und älterer Fragmente) sollte zudem nicht nur für lokale, sondern überregionale und ggf. weltweite Vergleiche herangezogen werden (vgl. Erdmann et al., 2015: 60-67). Nur dann – und wenn die unterschiedlichen Reliefverhältnisse, Geologie, Exposition, Wassertiefe, Blockformen, Blockdichten, Ablagerungsalter u.v.a. bekannt sind - lässt sich beurteilen, inwieweit Stürme allein für alle weltweiten Blockverlagerungen verantwortlich sind, oder andere Kräfte zusätzlich diskutiert werden müssen. Außerdem ergeben sich dann bessere Grundlagen für eine Einschätzung wie wahrscheinlich es ist, dass in Irland oder woanders auf der Welt auch Superstürme im Abstand von 1.000 Jahren oder mehr gewaltet haben könnten oder in Zukunft zu erwarten sind.

Auf den Aran-Inseln gibt es Blöcke von über 50 t, die mehr als 200 m vom Meer entfernt und 12-14 m über der MHW-Linie liegen, aber seit langem nicht bewegt wurden.
Ein Block von 230 t wurde nahe der Brandung früher um ca. 5 m gehoben, aber blieb seit mindestens 2007 (nach Fotovergleich), wahrscheinblich aber seit vielen Jahrhunderten (beurteilt nach den Mikroformen der Kalklösung an seinen Flanken) unbewegt (vgl. Erdmann et al., 2018 b).

Neben der Blockverlagerung sind auch verschiedene Organisationsformen von Blöcken dokumentiert (Erdmann et al., 2015: 69-75) und zwar vor allem *imbrication* und *imbrication trains* und auf der Wallkrone balancierende Blöcke in sehr instabiler Position (Abb. 15). Perfekte *imbrication* zeigt sich vor allem in meernahen Blockwällen

und bei flachen Blöcken, während auf hohen Kliffplattformen die Organisation meist chaotisch ist, wenn auch an der Wallfront lokal *imbrication* vorkommt.

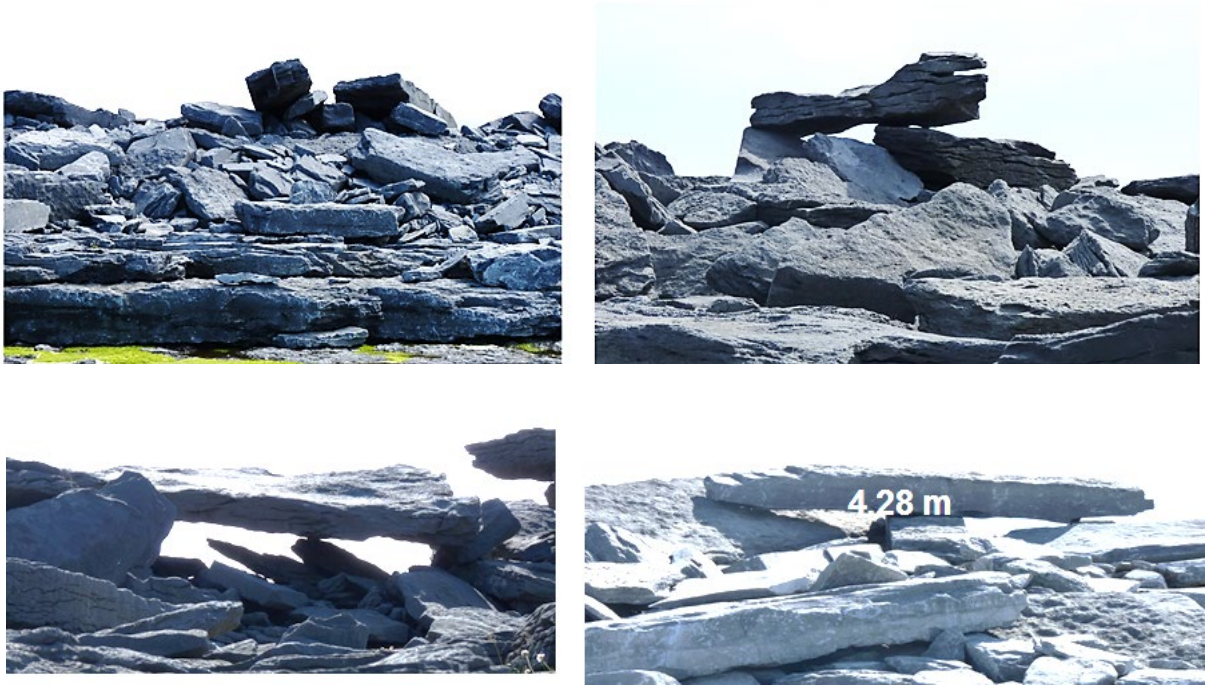


Abb. 15: Auf der Wallkrone „balancierende“ und fragil gelagerte große Blöcke auf der Insel Inishmaan (aus Erdmann et al., 2015, Fig. 4.14).

Eine einfache Antwort, wie sie Weiß (2012) gibt, dass Sturmwellen wegen ihrer großen Zahl *imbrication* anlegen, Tsunamiwellen wegen der Kürze der Einwirkung aber nicht, ist nicht überzeugend. Bei beiden Prozessen ist *imbrication* sicher möglich. Scheffers & Kinis (2014) lieferten Beispiele von flächen- und linienhafter *imbrication* (*imbrication trains*) vom Japan-Tsunami Tohoku 2011. Die Bildung von *imbrication trains*, wie sie als ältere Formen in der Galway Bay relativ häufig vorkommen, ist allerdings durch Stürme nur schwer vorzustellen. Sie benötigen mehr oder weniger gleichzeitig oder in Abständen das Aufnehmen ähnlich großer flacher Blöcke von der annähernd gleichen Stelle, einen Transport zu bereits vorhandenen geneigt angelehnten Blöcken, ihren *lift* an der Frontseite und die Anfügung seewärts an die vorhandene *imbrication*. In Erdmann et al. (2015, S. 117, Fig. 5.14) wird das Problem dargestellt und eine Lösung (*van Karman vortices*) vorgeschlagen.

Für auf der Wallkrone balancierende (meist alte, d.h. dort bereits lange liegende) Blöcke gibt es die Überlegung (Erdmann et al., 2015:74-76), dass sie in diese Höhe gegen die Schwerkraft transportiert worden sein müssen, aber von einer erheblich kleineren Welle leicht landwärts/abwärts gestoßen würden, also das häufige Ablegen ganz oben während eines starken Sturmes nur schwer vorstellbar ist. Diesen

Mechanismus bevorzugen jedoch Cox et al. (2012) mit der Aussage, dass sich diese Blöcke in *„trans-ridge movement“* befinden. Mit der Beobachtung, dass die jungen Stürme von 2013/14 Material von den seeseitigen Wallböschungen entfernt haben und nicht die Masse der Wälle vergrößerten, erklärt sich die balancierende Lage deutlicher: durch Unterminierung der Blockbasis werden sie mehr und mehr freigelegt, bis einige gerade noch in zur Seeseite überhängender Position verharren können (Abb. 15). Sie werden bei der ersten Wellenwirkung mit Materialbewegung auf dem Wallhang seewärts zurück bewegt in die Richtung, aus der sie einst gekommen sind, nämlich seewärts/abwärts.

Ein weiterer Aspekt ist von Bedeutung (Erdmann et al., 2015: 76-82), nämlich die potentielle Herkunft der Blöcke, welche nun an Land in langen hohen Wällen aufgetürmt sind. Sie lässt sich gelegentlich durch die Passform an einer nahen Kliffstufe verorten, und kurz nach Stürmen sind auch die Ausbruchstellen noch gut erkennbar. Andere Blöcke belegen ihre Herkunft aus der Brandungszone durch eine gute Zurundung oder wenigstens partielle Rundung. Sichere Hinweise auf ihren Ursprung geben vor allem Anhaftungen von Kalkalgen und Balaniden (oberstes Subtidal bis unterstes Supratidal), *Patella*-Wohnplätze (oberes Tidal), Bohrschwamm - Perforierungen (*Cliona*, unteres Tidal und oberes Subtidal), Seeigel-Wohnplätze (unterstes Tidal und Subtidal), sowie Bohrmuschellöcher (*Hiatella*, oberes Subtidal bis mittleres Tidal) (Abb. 16). Vor allem von Littorinen angelegte *rock pools* kennzeichnen das untere Supralitoral (Abb. 17).

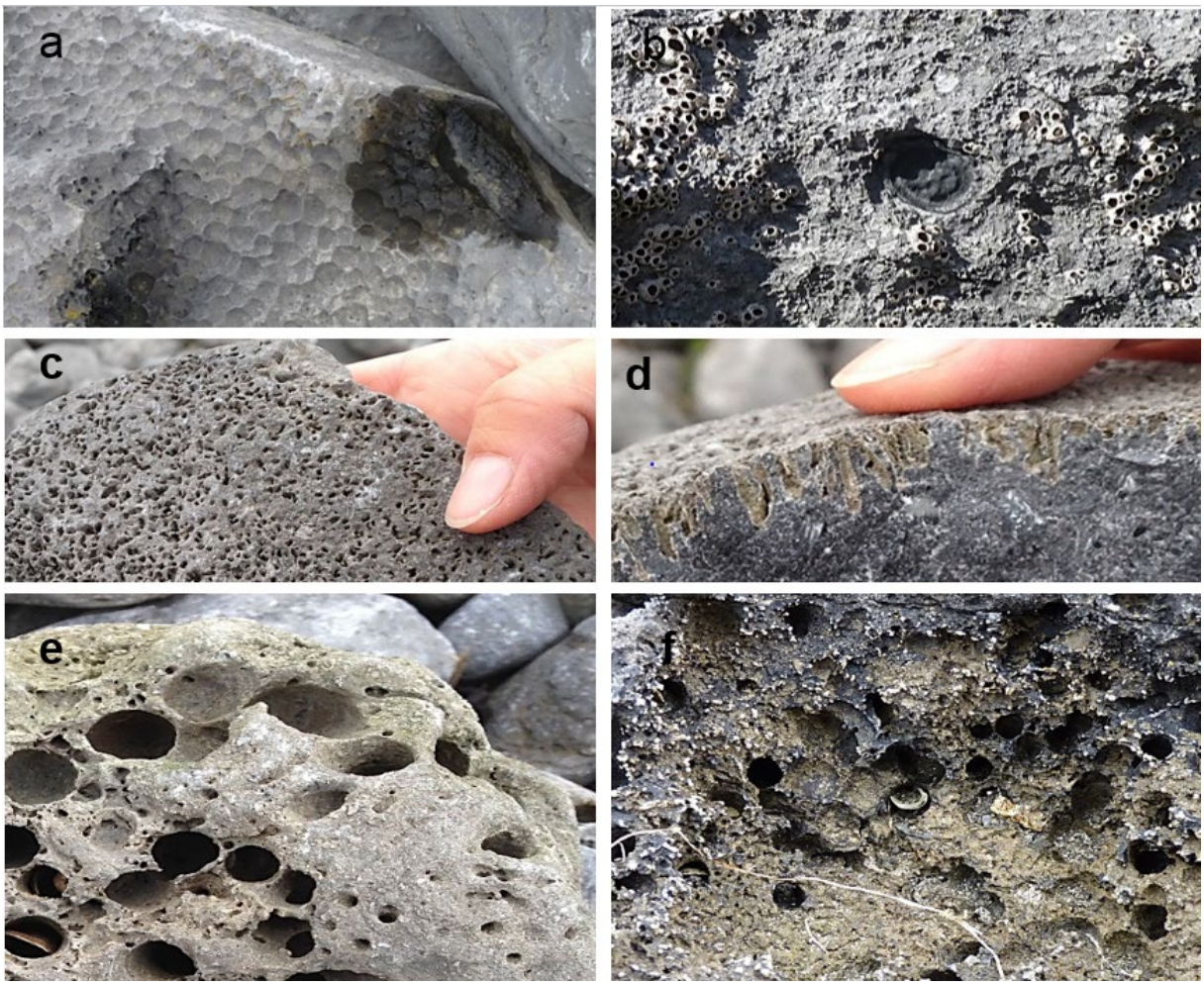


Abb. 16: Bioerosionsspuren als Herkunftsindizien von Blöcken: a: Seeigel-Wohnplätze; b: *Patella – home place*; c und d: Bohrschwamm-Spuren (*Cliona*); e und f: Bohrungen von *Hiatella arctica* (aus Erdmann et al., 2017, Fig. 9).

Abb. 17: Zwei Formtypen der biogenen *rock pools* im unteren Supratidal von Inishmore.

Eine Ausdehnung der Dokumentation auf alle wichtigen Erscheinungsformen der Blockablagerungen in der Region Galway erschien nötig, daher erhielt das Phänomen doppelter Blockwälle einen besonderen Fokus. Diese treten oft in enger Nachbarschaft zueinander auf, wobei die landwärtigen immer niedriger und schmaler sind und von jüngeren Ereignissen nie verändert (d.h. nie mehr erreicht) wurden. Da diese Verhältnisse über einen längeren Zeitraum, bei steigendem Meeresspiegel und erosivem Küstenprofil typisch für die Arbeitsgebiete sind, ergaben sich wichtige Hinweise auf die (mangelnde oder sogar fehlende) Landwärtsbewegung der Blockwälle, welche von Cox et al. (2012) besonders hervorgehoben wird.

An etlichen Stellen weisen die Hauptwälle eine rhythmische Gliederung der landwärtigen Böschung in Form mittelgroßer Rippeln auf, auch wenn das Material mit 0,2 - 1 m langen Achsen sehr grob ist. An anderen Stellen und erheblich ausgedehnter findet sich eine rhythmische Gestaltung der Hauptwälle in Form quer (mehr oder weniger senkrecht zum Kliff) laufender kurzer und etwas gebogener Blockwälle, die bis 35 m über dem Meer (auf Inishmaan) anzutreffen sind. Daran stellt sich die (derzeit noch ungelöste) Frage, ob sie gleichzeitig in diesem Muster entstanden sind, oder ob sie aus einem normalen/ typischen/gewöhnlich aufgebauten und durchgehenden Blockwall skulpturiert/ herausgearbeitet/geformt wurden. Für beide möglichen Szenarien kommen Sturmwellen nicht in Betracht, sondern nur eine sehr starke Strömung über eine gewisse Zeit und weite Distanz, die auch noch in Höhen bis

mindestens +35 m und küstenparallel verlaufen muss. Diese Formen lassen auf Tsunamis schließen (Erdmann et al., 2015: 115 ff.). Die vorgelegte Dokumentation wird vervollständigt durch Hinweise zum Alter der Blockablagerungen, zur Geschwindigkeit der Klifferosion und durch einige Dokumente zu großen *washover*-Loben als besonders signifikante Tsunamibelege, und zwar am Festlandsabschnitt im SE der Galway Bucht, und auch auf den Inseln Inishmaan und Inishmore. Solche *washover*-Zungen mit Augenblickstransport von weit über 10.000 t an Gesteinstrümmern sind bisher noch nicht beschrieben.

Im Zuge der *near-time inspection* 2014 zeigte sich bei Doolin Point ein frisches Block-Setting, welches die Erhebung einer ganzen Reihe exakter quantitativer Daten zur Bewegungsstrecke (auch gegen die Schwerkraft), Einfluss der Blockform, bewegende Kraft sowie Herkunft und Art der Bewegung ermöglicht. Es steht als ein typisches Beispiel für sturmbewegte flache Blöcke jeder Größenordnung. Diese Daten gaben Anlass, mit ihnen publizierte Theorien, Hypothesen und Modelle zur Blockbewegung durch marine Kräfte sowie Veröffentlichungen über lokale Ansammlungen großer Blöcke seit 2000 und weltweit zu vergleichen (Erdmann et al., 2018 a).

Ein Review zum *state-of-the-art* trifft in diesem Themenfeld auf etliche Probleme. Oft fehlen Angaben über die Ermittlung einfacher Größen wie Blockdimensionen, Blockformen, Dichte, genaue Lage, Transportwege, Bewegung gegen die Schwerkraft, bewegt durch Wellen oder *bores* u.a.m. Ein anderes Problem bei theoretischen Überlegungen ist die große Vereinfachung und Reduzierung auf ganz wenige Parameter, auch als Basis für endgültige Schlussfolgerungen auf die wirklich verantwortlichen Naturprozesse. Dadurch entsteht der Eindruck, dass etliche Autoren bisher entweder zu wenig Kenntnis von Vorgängen in der Natur gewinnen konnten oder mit einer vorgefassten Vorstellung beobachtet haben. Die Widersprüche, welche im Vergleich von Theorien, Hypothesen, Modellen und lokalen Studien in anderen Erdregionen zu den Gegebenheiten um Galway auffielen, sind der Hauptgegenstand der Publikation Erdmann et al. (2018 a). Sie enthält aber auch mit dem *„Doolin-Boulder-Setting“* eine der ganz wenigen Kartierungen bzw. Fallstudien. Ihre Interpretierbarkeit wird wesentlich dadurch unterstützt, dass im Kalkgestein viele Prozesse geradezu aufgezeichnet sind und eine Weile auch bleiben und gelesen werden können.

Als Ergebnis der *near-time-inspection* nach den Winterstürmen 2013/14, die auch entlang der bisher nie im Detail untersuchten Südostküste der Galway Bay bis Black Head ausgedehnt wurde, ergaben sich wichtige Beobachtungen an Formen und

Sedimenteinheiten, deren zeitliche Einordnung und Zuordnung zu einzelnen Ereignissen und Prozessen unbekannt war. Daher wurde im September 2015 dieser Küstenabschnitt detailliert kartiert, untersucht, beprobt und mit über 40 neuen Altern erfasst, um den Arbeiten an den extrem exponierten Atlantikküsten der Aran-Inseln solche im Schutze dieser Inselkette gegenüber zu stellen. Die Daten mit den zugehörigen Schlussfolgerungen sind Inhalt einer umfangreichen Veröffentlichung geworden (Erdmann et al., 2017).

Gesicherte Erkenntnisse geowissenschaftlicher Arbeiten geben einen guten Rahmen für Versuche zur chronologischen Abfolge der Ereignisse im Arbeitsgebiet. Dazu gehört das frühe Eisfreiwerden nach dem LGM weit draußen im Meer, ein Meeresspiegelstand ca. 5 m niedriger als heute vor etwa 7.000 Jahren und immer noch um 1.5 m tiefer vor 1.500 Jahren, und eine Korrektur des MRE für die Datierung an marinen Mollusken des Gebietes von -142 +/- 16 Jahren (Ascough et al., 2006, 2009).

Die räumliche Nähe von drei ganz verschiedenen Sedimenteinheiten auf einem Küstenstreifen von maximal 100 m Breite mit Altershinweisen über mehr als 9.000 Jahre ist deshalb besonders erstaunlich, weil während dieser Zeitspanne der Meeresspiegel um nahezu 30 m angestiegen ist (seit etwa 7.000 cal BP noch um ca. 5 m). Für den Abschnitt entlang der Galway Bay mit relativ flachem *fore-shore* bedeutet dieses gleichzeitig eine horizontale Verschiebung der Küstenlinie um mehrere 100 m ostwärts allein durch den Transgressionsvorgang auch ohne Annahme von Küstenerosion. Diese relativ stabile Lage der Formen und Sedimenteinheiten wird dadurch bestätigt, dass der seewärtige massive Blockwall mit *imbrication* trotz Altersindizien von vielen tausend Jahren die um 5.000 Jahre alten *washover*-Zungen nicht erreicht, zerstört oder überfahren hat.

Zwar geben die bisher 84 Altersdaten aus der Galway Bay und von den Aran-Inseln bereits einen guten Einblick in das (erstaunliche breite) Zeitfenster der heute entlang der Küsten befindlichen Formen und Sedimenteinheiten, doch reichen diese noch nicht aus, um hinreichende Informationen über den Zeitpunkt formungsrelevanter *extreme events* zu liefern. Das liegt vor allem daran, dass wegen der Nähe zur Küstenlinie und den häufig sehr starken Winterstürmen Auffrischungen (*activation)* existierender Komplexe vorkommen und dadurch junge Materialien (kleine Blöcke mit Bohrmuscheln, Molluskenschalen und –fragmente aus vorhandenen Depots) eingetragen werden können. Der zweite Grund ist die Schwierigkeit, für ältere Vorgänge ausreichend viele Daten zu erhalten. Diese dürften zumeist mehr oder

weniger unzugänglich nahe der Basis der Blockzungen und Blockwälle liegen, wo ein Aufschluss allenfalls mit Baumaschinen o.ä. möglich wäre. Proben aus nur ca. 1 m unter der Oberfläche in den leicht erreichbaren Basisschichten der feineren Ablagerungen ergaben bereits Alter von fast 6.000 Jahren cal BP.

Ein wichtiges und nahezu flächenhaft anzuwendendes Instrumentarium für relative Altersunterschiede steht jedoch im Kalkstein zur Verfügung (Abb. 18). Zunächst ist zu unterscheiden zwischen der Abtragungsintensität im (terrestrischen) Regenwassermilieu (chemische Lösung) und der im Salzwassermilieu (biologisch-erosive Lösung). Letztere ist zwischen 10 und 100-mal so intensiv und formprägend wie Lösung durch Niederschläge (Godard et al., 2015; Kelletat, 1988; Pfeffer, 2010; Spencer, 1988; Trudgill, 1987, Trudgill & Crabtree, 1987; Trudgill et al. 1987). Während ausgeprägte *rock pool*–Gürtel mit einem Kleinrelief von Dezimetern bis Metern in einigen Jahrhunderten entstehen, benötigt die Lösung eines Mikroreliefs von 10 cm durch Niederschlag mehr als 2.000 Jahre – bei beiden vorausgesetzt, dass lediglich die erste Generation von entsprechenden Formen zu sehen ist. Die Bedeckung frisch aus dem Intertidal und Subtidal entfernter Blöcke mit Kalkalgen, Vermetiden und Balaniden verschwindet nach vielen Jahren oder wenigen Jahrzehnten vollständig. Für eine Besiedlung von Blöcken zu etwa 50% durch häufige Flechten (*Caloplaca marina, Xanthoria* sp.) werden 70 Jahre oder mehr benötigt. Ein dunklerer Überzug aus epilithischen und vor allem endolithischen Cyanobakterien auf Kalk bildet sich bereits in wenigen Jahren, *striations* oder Exposition frischer Blockflanken sind dann kaum noch auszumachen. Schlagmarken durch Kollision größerer Fragmente sind jedoch mindestens viele Jahrzehnte lang zu erkennen, aber in ihrem Alter sehr schwer abzuschätzen. Die Intensität der Bodenbildung im ständig feuchten und relativ warmen Klima West-Irlands heranzuziehen erschien zu gewagt und wurde daher nicht durchgeführt.

Abb. 18: Erratika aus Granit (etwa 1,5 m Durchmesser) auf Kalk, mit einem 15-20 cm hohen Karsttisch. Da einige Dutzend Karsttische im Arbeitsgebiet ähnliche Höhen von 0,15 bis 0,35 cm aufweisen, ist davon auszugehen, dass die meisten eine Entwicklungszeit seit dem Eisfrei-Werden hatten, d.h. seit ca. 16.000 Jahren (und nicht zunächst länger durch Moränenschleier geschützt waren). Die Intensität der Lösung in diesem Milieu des terrestrischen Karstes läge demnach bei 0,01 bis 0,02 mm/a. Lösungsraten über alle Klimate hinweg werden in der Literatur für massiven Kalk mit langfristiger Größenordnung von 0,02 – 0,03 mm/a angegeben.

Bereits in der ersten und grundlegenden Bearbeitung der Blockablagerungen der Galway/Aran-Region wurde die entscheidende Frage erkannt und in den Titel aufgenommen: Williams & Hall, 2004: *Cliff-top megaclast deposits of Ireland, a record of extreme waves in the North Atlantic* — storms or tsunamis? Trotz einiger Zweifel entschieden sich die Autoren für die Sturmgenese. Als Scheffers et al. (2009, 2010 a, b) aufgrund räumlich ausgedehnterer Feldarbeiten in der Region Formen fanden, welche mit Sturmwirkung nicht erklärbar sind, gerieten Tsunamis mehr in den Fokus. Das führte zu deutlicher Kritik, obwohl die Befunde bis zu diesen ergänzenden Arbeiten von den Kritikern nie in Augenschein genommen wurden. Die geomorphologischen und sedimentologischen Tsunamibelege im Arbeitsgebiet sollen daher hier noch einmal kurz zusammengefasst vorgestellt werden:

1. Schräg zum Kliff verlaufende, rhythmisch, mit ähnlichen Längen (20-40 m), Breiten (10-20 m), Abständen der *crests* (25-30 m) und relativen Höhen (1-3 m) angeordnete Wallsegmente (Abb. 19 und 20), welche viele 100 m lange Abschnitte der Hauptwälle

vor allem in großer Höhe (auf Inishmore um 22-26 m, auf Inishmaan 14-35 m) bilden. Sie sind gewöhnlich 1-2 m hoch (bei Doolin Head im groben Blockwerk auch 3 m), die Fragmente viele Kilogramm bis zu wenigen Tonnen (Ausnahme in +8-10 m bei Doolin Head = bis zu 20 t), ihre Asymmetrie ist denen des Hauptwalles (Abb. 20, B) direkt entgegengesetzt: flache und längere Luvhänge (15-25°) und steile (25-40°) kürzere Leehänge. *Imbrication* ist erheblich besser ausgeprägt als im Hauptwall. Diese *cross-way ridges* weisen keine junge Aktivierung auf. Ihre Erscheinung entspricht Rippelmustern mittlerer bis großer Dimensionen, doch ist ihr Material erheblich gröber als von diesen beschrieben, mit Ausnahme derjenigen von Schmelzwasser-Seeausbrüchen der *channelled scablands* im NW der USA.

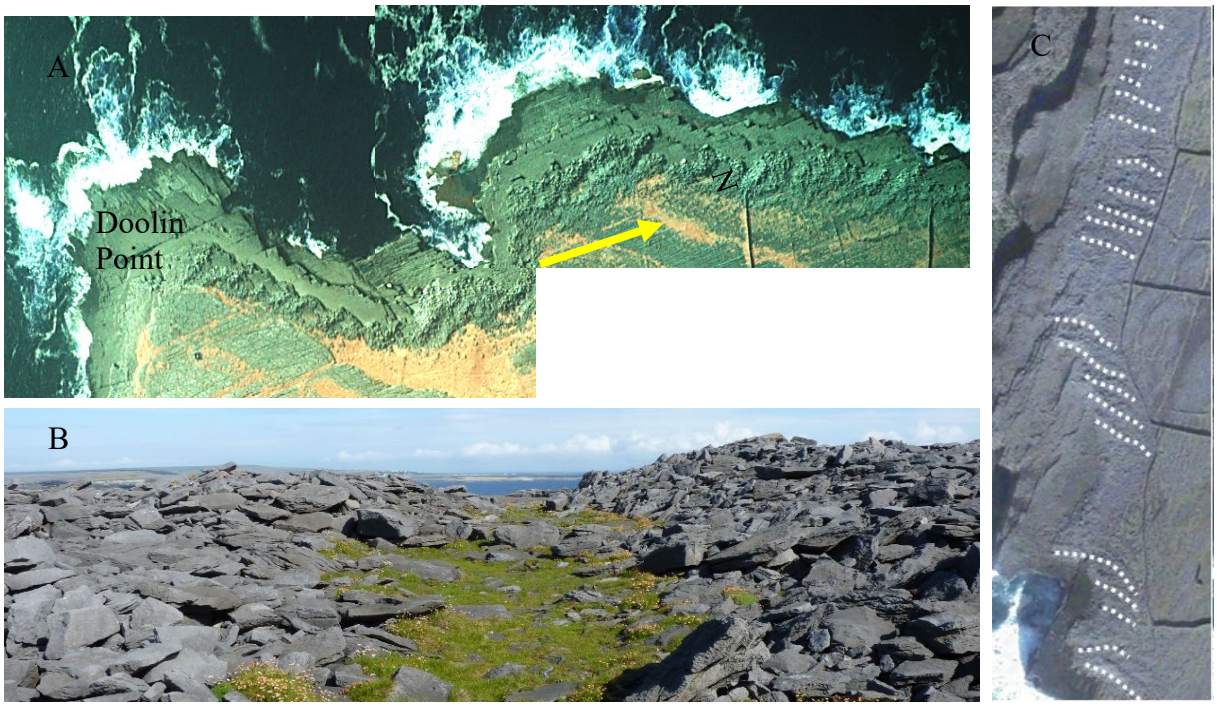


Abb. 19: Rhythmisch angeordnete Blockwallsegmente. A: 600 m langer Abschnitt nördlich Doolin Point auf dem Festland, 8-10 m über MHW; B und C: Inishmaan Westküste zwischen 14 und 35 m (in B bei 28 m) ü. MHW, die Formungskräfte kamen in B von links, C: > 700 m langer Abschnitt.

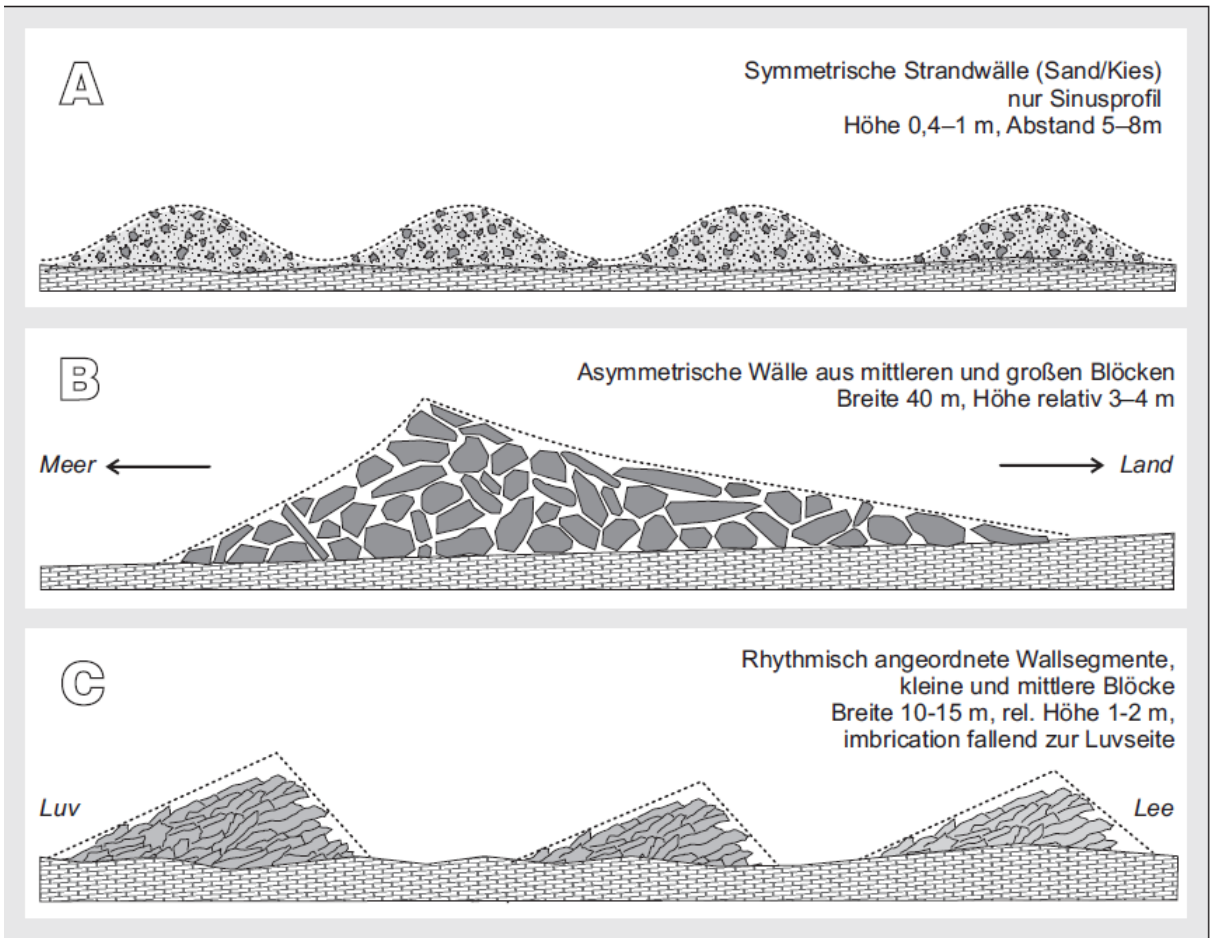


Abb. 20: Drei Haupttypen wallartiger Ablagerungen im Küstenbereich

Typ A: Normaltyp (als Strandwallsystem mit mehr oder weniger fortschreitender Anlagerung seewärts), oft aus Sand und Bruchschill bzw. Kies bestehend und eindeutig das Ergebnis von starken Stürmen. Typisch ist das recht gleichmäßige, symmetrische Querprofil. Typ B: Asymmetrische sehr grobe Blockwälle in Kliff-Top-Position auf den Aran Inseln. Die konkave seeseitige Böschung ist Abtragungsbereich, die Ursprungsform der Ablagerung ist nicht erhalten, ihre Genese umstritten (Sturm, oder i.w. Tsunamiwirkung). Typ C: Rhythmisch parallel zueinander angeordnete Wallsegmente aus kleineren und mittelgroßen Blöcken in großer bzw. maximaler Höhenlage (bis über +30 m MHW) und in Kliff-Top-Lage auf den Aran-Inseln. Die Längsachse der Wälle dieses Typs verläuft nicht parallel zur Küstenlinie (wie bei den Typen A und B), sondern annähernd senkrecht auf die Küste zu. Diese Wallsegmente sind durch nahezu küstenparallele starke Strömung gleichzeitig entstanden (vgl. Abb. 19 C) und weisen im Vergleich mit den großen Blockwällen ein entgegengesetztes Profil auf (flach zur Luv- und steil zur Leeseite und damit prinzipiell der perfekten *imbrication* der tiefliegenden Blockwälle innerhalb der Galway Bay gleichend, vgl. Abb. 7). Dieser Walltyp ist außerhalb der Galway Bay bisher nie beschrieben worden (Graphik: A. Hager).

2. Über 100 m lange und mindestens 30 m breite Blockzungen als Vollformen eines einzigen kurzen Transportprozesses (Abb. 21). Sie enthalten zwischen 10.000 t und 45.000 t Gestein. Wie die rhythmisch und schräg zum Küstenverlauf angeordneten Wallsegmente sind auch sie von eher küstenparallelen starken Strömungen aufgeschüttet. Im Arbeitsgebiet Galway Bay und den Aran-Inseln gibt es 7 solcher Blockzungen, davon 3 innerhalb der Galway Bay, dort mit ca. 4.000 bzw. 5.000 Jahre datiert (Bohrmuscheln in den Blöcken). Beide Formtypen sind bisher weltweit von Sturmablagerungen noch nicht beschrieben.

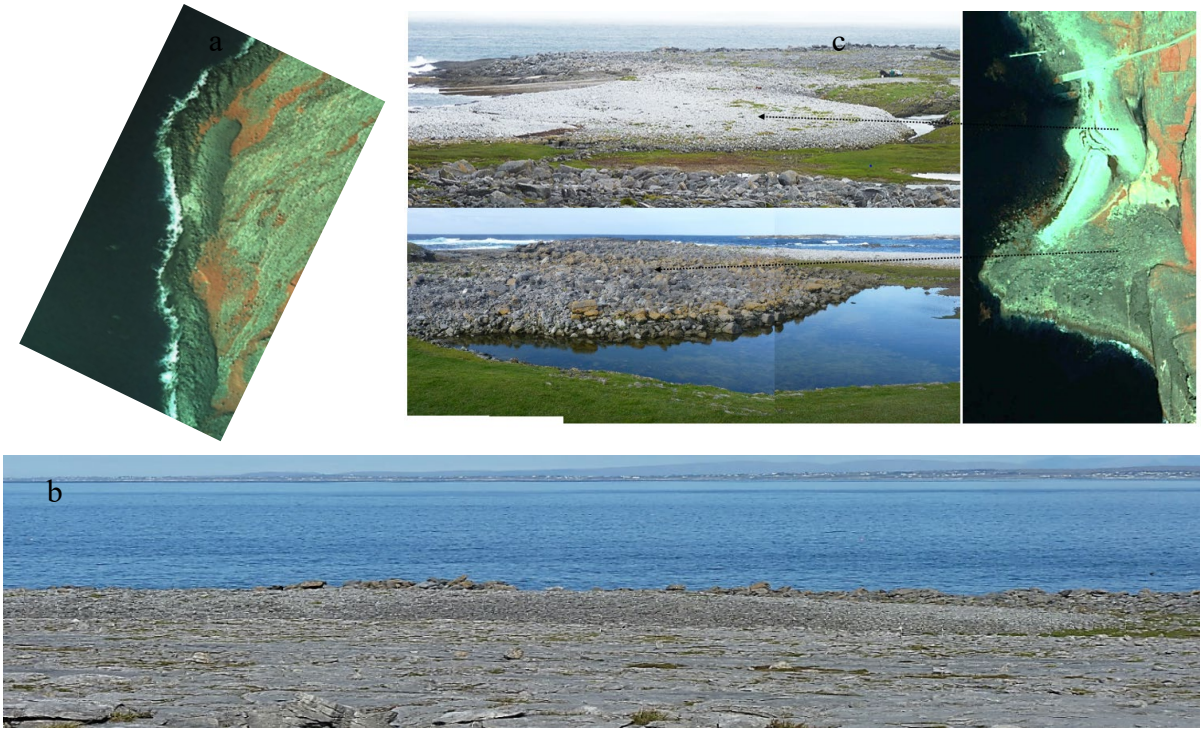


Abb. 21: Große Blockzungen. a und b: Murroogh Point, 20 km innerhalb der Galway Bay, c: westliches Ende von Inishmore.

Neben den ungewöhnlichen Akkumulationsformen aus Grobmaterial finden sich in den spärlichen feineren und sehr flachen Sedimentarchiven ebenfalls Hinweise auf Tsunamis, wie sie vielfach aus der Literatur beschrieben werden (Abb. 22).

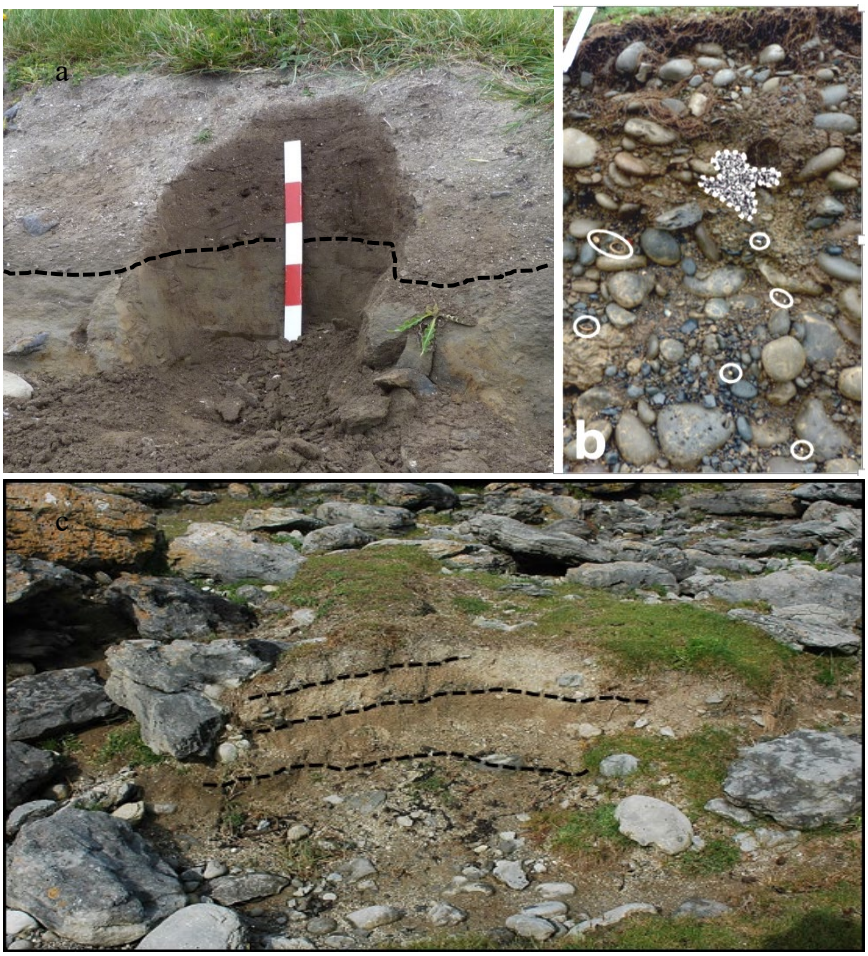


Abb. 22: Drei verschiedene Sedimenttypen aus der Galway Bay (SE-Küste). a: zwei strukturlose Sedimentpakete (liegend bimodal mit schluffigem Feinsand und Steinen, hangend Kies mit Muschelfragmenten und einigen Steinen, Maßstab 0.5 m); b: strukturlose Mischung aus gut gerundeten Schottern in feinerer Matrix, *mud clasts* (markiert) und Patella-Schalen (datiert auf 2.700 cal BP); c: 40 cm mächtiges Paket aus Grobsand und Bruchschill mit drei deutlichen Folgen von *upward grading* (untere datiert 2.325 – 2.150 cal BP, mittlere 1.980 – 1.825 cal BP, obere 1.095 – 940 cal BP).

Sedimente mit eher homogenen Schichten und klarer Stratigraphie sind im Arbeitsgebiet sehr selten. Das beste Beispiel (Abb. 23) ist eines im Westen von Inishmaan. Grobsande mit Bruchschill und feinen gut erhaltenen Gastropoden liegen hier in mindestens 9 Ereignis-Folgen vor, die einen Zeitraum von 2.000 Jahren überdecken. Jede Schicht weist mit der Abfolge von *sub-soil* und *top soil* einen Wechsel von Überschüttung und Ruhephase mit Bodenbildung auf, getrennt durch mehrere Jahrhunderte. Dieser Rhythmus ist mit Sturmwirkung am offenen Atlantik schwer zu erklären. Der seewärtige Blockwall mit (oft gerundeten) Blöcken bis 20 t an Masse deutet eher auf Tsunamiaktivität hin. Eine endgültige Klärung könnte durch flächenhafte Aufgrabung der landwärts anschließenden kleinen Ebene möglich werden, doch sind auch deren Sedimente weniger als 1 m mächtig.

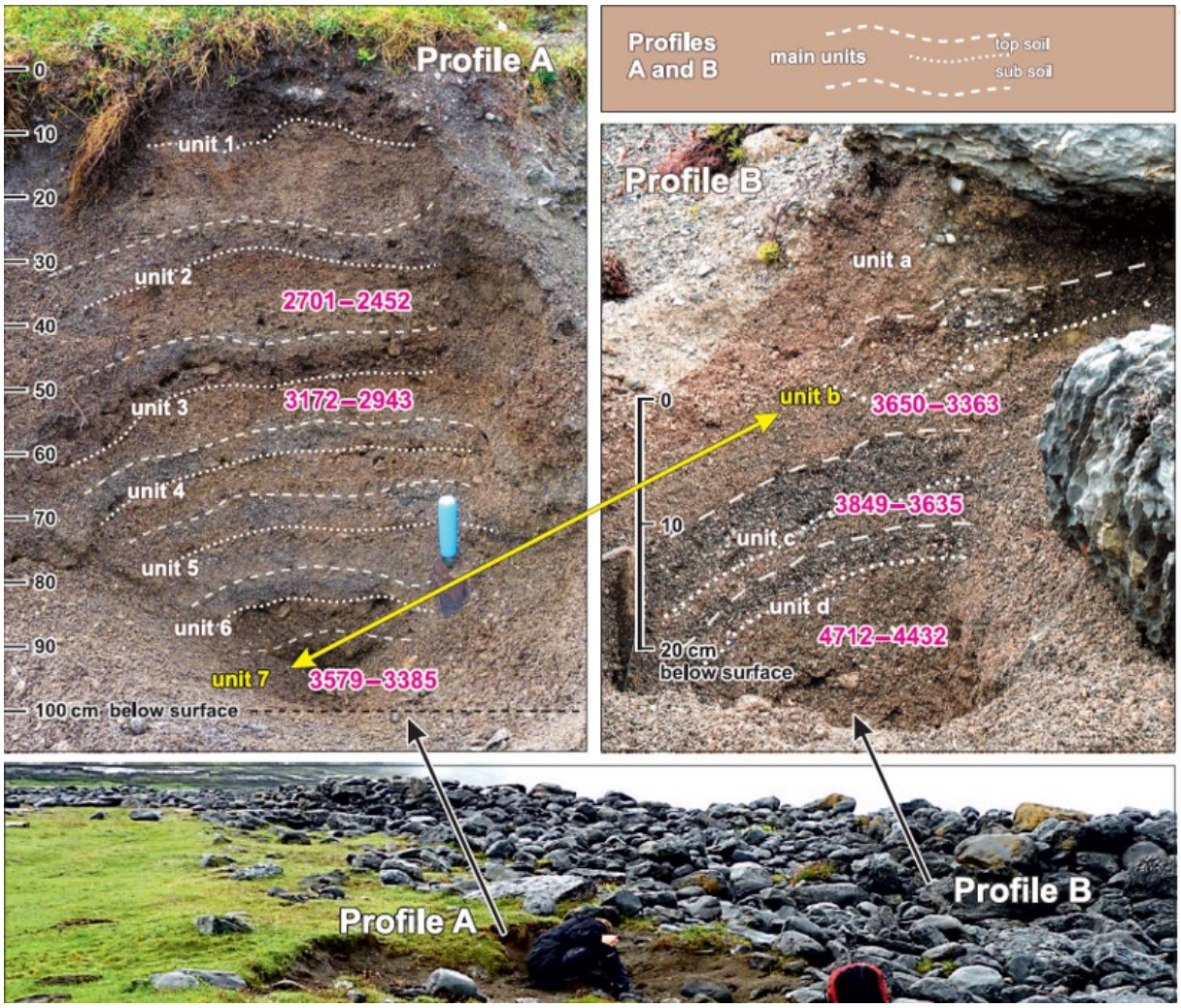


Abb. 23: Neunfache Abfolge von sehr ähnlichen feinkiesig-grobsandigen Sedimentlagen am landwärtigen Saum eines Blockwalles auf Inishmaan.

Die rhythmisch angeordneten rippel-ähnlichen Blockwallsegmente und die Blockzungen sind als eigene und nirgendwo aus Stürmen bekannte Formen hinreichende Belege für extreme Strömungen von großer Reichweite auch in Höhen von über 30 m, die nach bisherigem Forschungsstand nur von starken Tsunamis erzeugt werden können. Diese Ablagerungen und Formen aus einer Phase eines deutlich tieferen Meeresspiegels mit meerwärtigem Küstenverlauf benötigten eine erheblich größere Energie als die Leistungsfähigkeit der 6 Extremstürme des Winters 2013/14 beim höchsten Meeresspiegels des Holozäns in der Region und Wellen bis 20 m Höhe direkt an der Küste. Will man diese Ablagerungen und Formen nicht mysteriösen Superstürmen zuweisen, die nach Windgeschwindigkeit, Wellenhöhe und Reichweite der Boren jenseits physikalischer Möglichkeiten liegen dürften, so ist (bisher) allein aus der räumlichen Verbreitung dieser Grobsedimente-Muster weltweit kein anderer Prozess als Tsunamis bekannt.

## 5.1 Holozäne Meeresspiegelbewegungen

Die Forschung der letzten 25 Jahre zeigte, dass der relative Meeresspiegel (mittleres Hochwasser, MHW) an der zentralen Westküste Irlands im Holozän nie höher als heute lag (Bradley et al., 2011; Brooks et al., 2007; Carter et al., 1989; Fleming et al., 1998; Holmes et al., 2007; Lambeck et al., 2014; O´Carra et al., 2014; Orford et al., 2006; Peltier et al., 2002; Schettler et al., 2006; Shaw & Carter, 1994; Shennan & Horton, 2002; Shennan et al., 2002, 2012), weil dieser Abschnitt der irischen Westküste isostatisch absinkt, solange sich das ehemalige Eiszentrum des LGM im Westen Schottlands noch hebt. Die Modelle zur Glazialisostasie zeigen gleichermaßen, dass um 9.000 cal BP, dem Zeitraum der beiden ältesten Daten aus dem seewärtigen Blockwall, das Meeresniveau bei etwa -30 m verlief und damit die innere Galway Bay noch trocken lag. Eine fortlaufende Transgression lässt sich auch aus dem Fehlen mesolithischer und älter-neolithischer Funde ableiten (Driscoll et al., 2012; Gosling, 1993). Mit zwei Meter Süßwassertorf bedeckte noch verwurzelte Baumstämme wurden nahe Galway City an der Nordküste der Bucht im Intertidal entdeckt (*Quercus, Pinus, Betula*, vgl. Williams & Doyle, 2014) und zwischen 7.400 und 5.750 cal BP datiert. Williams & Doyle schätzen den Meeresspiegelstand zur Zeit der Wälder bei -5 m (+/- 1 m) und vermuten einen weiten Süßwassersumpf im Gebiet der heutigen östlichen Galway Bay.

Aufgrund völlig anderer Indizien und Methoden kamen Schettler et al. (2006) und Holmes et al. (2007) bereits zu einem ähnlichen Ergebnis. Sie erforschten die Geschichte des Karstsees An Loch Mór auf der östlichen Aran-Insel Inisheer. Die Wassertiefe beträgt maximal 23 m, die Bodensedimente sind 12 m mächtig, der See steht in zunehmend besserem Austausch durch kleine Karstgefäße mit dem Meer. Aus diesem Archiv und mit Hilfe von Mikroorganismen, welche die Zusammensetzung und Tiefe des Wassers anzeigen, wurde u.a. eine Meeresspiegelkurve für das Jüngere Holozän entwickelt. Einen beträchtlichen Teil (ca. 2 m) des späten Meeresspiegelanstieges legen Holmes et al. (2007) auf den Zeitabschnitt ab 500 AD. Ein Hochwasserstand bei -5 m um die Mitte des Holozäns und der zugehörigen Küstenverlauf ist gut vorstellbar: er ist nahezu identisch mit dem heutigen Springtide-Niedrigwasser, da der Springtidenhub in der mittleren Galway Bay bei nahe 5 m liegt.

Auf eine andauernde Transgression deuten auch heute inaktive und von Kliffen gesäumte Dünenfelder bei Doolin und Fanore hin. Ihre ehemaligen Auswehflächen (nach den Mineralbestandteilen von Gletscherschmelzwässern zusammengeführte Sande) sind längst ertrunken. Im Dünenkliff von Fanore wurden zwei Paare terrestrische Gastropoden (*Helix* sp., im vertikalen Abstand von je 1 m) zwischen 2.4

und 5 m unter der Oberfläche datiert. Der heute in Erosion befindliche Abschnitt des Dünenkörpers wurde demnach zwischen 3.905 und 3.365 cal BP aufgetragen (vgl. Erdmann et al., 2017, Tab. 4).

Im Westen von Inishmore ist der Rest einer terrestrischen steinigen Lehmlage mit Holzkohle, jedoch ohne jede Beimischung mariner Reste, unterhalb des aktiven Brandungssaums erhalten. Die Holzkohle wurde auf 6.400 cal BP datiert und ist im Alter identisch mit einem ähnlichen Sediment in exakt gleicher Lage bei Doolin auf dem Festland, veröffentlicht von Williams & Doyle (2014). Beide belegen, dass zu jener Zeit der Meeresspiegel deutlich tiefer und die Küstenlinie weiter entfernt von der heutigen lag. Direkt an der Festlandsküste in der Nähe des kleinen Flughafens in Connemara nördlich der Aran-Inseln ist ca. 80 m vom heutigen Kiesstrand und 1.5 m tiefer als dessen Strandwallkrone eine bronzezeitliche Grabstätte vollständig erhalten. Mit sehr unterschiedlichen materiellen Befunden kann somit über das gesamte Arbeitsgebiet das Ausmaß und die Zeitstellung des Meeresspiegels (mittleres Hochwasser) seit dem Mittel-Holozän sehr präzise rekonstruiert werden.

## 5.2 Intensität der Kliff-Erosion

Alle Küstenabschnitte in der Galway Bay und an den Aran-Inseln unterliegen heute der Erosion durch Wellenwirkung. Das ist nicht erstaunlich, da über das gesamte Holozän der Meeresspiegel bis heute ansteigt (und vielleicht dieser Anstieg sich derzeit beschleunigt). Dennoch gibt es wenige morphologische Hinweise auf eine signifikante Veränderung der Küstenkontur, so dass Rückschlüsse auf eine gleichartige und relativ gleichmäßige, insgesamt ähnliche und vor allem geringe Küstenerosion zulässig sind. Zu unterscheiden ist eine Verschiebung der Küstenlinie landwärts durch reinen Meeresspiegelanstieg, oder durch aktive Erosion. Tauchen flache Hänge unter, beträgt diese Verschiebung allein durch ca. 5 m Transgression seit dem Mittelholozän etliche 100 m, aber die Tendenz zu zusätzlicher Erosionswirkung mag gering sein, weil die Brandung frei auflaufen und dabei ihre Energie abgeben kann. Tauchen steile Kliffe in tiefes Wasser (*plunging cliffs*) verschiebt sich die Küstenlinie durch Transgression praktisch gar nicht, aber die Brandungsenergie trifft auf ein abruptes Hindernis und entfaltet an einem Horizont alle Energie über lange Zeit. Hier wären größere Erosionsbeträge eher möglich.

Die Intensität des Kliffrückganges hängt ab von einer Kombination zerstörender Faktoren (z.B. Wellenschlag/Brandung mit Höhe, Häufigkeit, Exposition, Wassertiefe, Sedimenten als „Brandungswaffen“) und bewahrender Parameter (z.B. Gesteinstyp

mit Dichte, Lagerung, Festigkeit u.a.). Man erwartet gewöhnlich an einem senkrechten Kliff die stärkste Energieentfaltung und nimmt diese Form als Ausdruck sichtbarer Zerstörung. Dieser Eindruck kann täuschen, denn vor allem bei Tiefwasserküsten (*plunging cliffs)* fehlt mit dem Sediment eine der stärksten Angriffswaffen des Meeres.

Viele Eigenschaften der Gesteine tragen zu völlig unterschiedlichen Ergebnissen bei der Formung bei. In den Arbeitsgebieten (östliche Galway Bay und Aran-Inseln) sind überall dichte widerstandsfähige Karbonkalke vorhanden. Stark wechselnde Schichtmächtigkeit (etwa 20 cm bis über 4 m) und (meist) rechtwinklige Klüftung bestimmen die oft gestuften Kliff-Formen. Dazu trägt auch bei, dass interne Lösung entlang der Schichtfugen und Klüfte bereits bis tief in das Gestein hinein Schwächelinien angelegt haben. Das Ergebnis sind Blöcke sehr verschiedener Größe aber sehr ähnlicher Form, nämlich flach-tafelförmig. Ob sie aus dem bereits gelockerten Gesteinsverband disloziert werden können, wird durch Kliffprofil, Kliffhöhe und Expositionsgrad sowie Masse der einzelnen Quader bestimmt.

Einen wesentlichen Faktor für die Stabilität der Kliffe stellen zwischengeschaltete Feinmateriallagen dar (*shales, silt stones*). An ihnen staut sich das Sickerwasser und tritt entlang von Quellhorizonten aus. Mit dem Quellwasser wird offenbar auch Feinmaterial ausgespült (*undermining*). Liegen diese Horizonte in Reichweite von Wellen, beschleunigt sich dort die Abtragung signifikant und tiefe Hohlkehlen bilden sich aus. Das hangende Gestein kann dennoch über sehr lange Zeit stabil bleiben, wie weite Überhänge belegen (Abb. 24).

Abb. 24: Ein 14 m hohes, stark unterhöhltes Kliff an der zentralen Westküste von Inishmaan, mit einem etwa 30 m vom Kliffrand zurückgesetzten Blockwall.

Kollaps von Kliffen ist der effektivste Abtragungsprozess mit großer Augenblicksleistung, doch folgt auf ihn jeweils eine Phase der Stabilität, solange die Blockmassen den Kliff-Fuß vor Wellenangriff schützen. Wegen der oft enormen Größe der abgestürzten Blöcke (einige 100 bis > 1.000 t kommen hier vor) dauert deren Aufbereitung zum Abtransport entsprechend lange.

Die maximale Höhe senkrechter Kliffe in der Galway Bay bei Lackglass erreicht 30 m, an den Aran-Inseln unterhalb des bronzezeitlichen Forts Dún Aonghasa auf Inishmore sogar 70 m. Seit Williams (2004) und seinem Argument, das heutige *Promontory Fort* Dun Duchathair (*Black Fort*) sei ehemals ein eisenzeitliches Ringfort weit im Inland gewesen, nehmen die meisten Autoren ein relativ starkes Zurückweichen der Kliffe um 0,2 bis 0,4m/Jahr an. Für die zweite Hälfte des Holozäns (die letzten mind. 6.000 Jahre) würde sich das summieren auf eine Küstenverschiebung zwischen 1,2 km und 2,4 km. Da die beiden sehr exponierten offenen und um und etwas über 50 m tiefen Wasserwege zwischen den drei Aran-Inseln nur weniger als 2 km breit sind, bezweifelten bereits Scheffers und Kelletat (Scheffers et al., 2010 a) diesen hohen Wert. Ein anderes Argument für eher sehr geringen Kliffrückgang lässt sich aus den gut erhaltenen glazialen Profilen der Hänge am Black Head an der zentralen Ostküste der Galway Bucht und im Westen der Insel Inishmaan ablesen (Abb. 25 und 26).

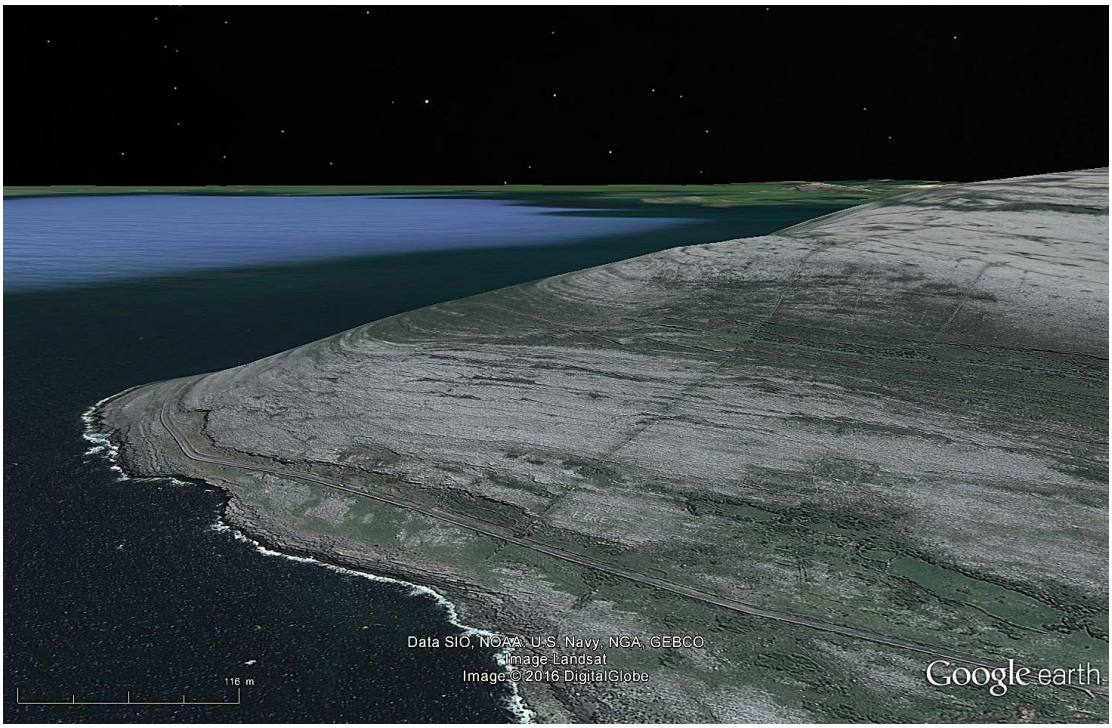

Abb. 25: Sehr gut erhaltene glaziale Felsskulptur am Black Head, 25 km innerhalb der Galway Bay, auf Karbonkalk (Blick von S). Ein Kliff von 3 - 4 m Höhe ist im Brandungsbereich angedeutet. Nur 1,5 km weiter südlich befinden sich Blockwälle aus Fragmenten von über 10 t und ein weit über 100 m langer *washover*-Lobus (Murroogh Point). (Credit: Google Earth, 2016).

Abb. 26: Glaziale Felsskulptur im Westen der Insel Inishmaan, Blick nach N. Maximale Höhe des senkrechten Kliffs liegt bei 32 m über MHW, das glaziale Profil kann insgesamt nicht mehr als ca. 100 m zurückgeschnitten worden sein. (Credit: Google Earth, 2016).

Umgerechnet ergeben Beträge der Küstenerosion an senkrechten Kliffen der Arbeitsgebiete maximal wenige cm/a und liegen damit in der Größenordnung, die auch von anderen Autoren in resistenten Gesteinen ermittelt wurden (Carbone, 2013; Earlie et al., 2015; Hall et al., 2008; Lim et al., 2010, 2011; McKenna et al., 2009; Rosser et al., 2005, 2010; Young et al., 2011). Scheffers et al. (2009, 2010 a) hatten mit der Existenz (bzw. dem "Überleben") archäologischer Altershinweise im unmittelbaren Küstenstreifen argumentiert. Diese überdecken einen Zeitraum von vielen tausend Jahren wie beispielsweise neolithische *middens* (Abb. 27), *Promontory Forts* aus der späten Bronzezeit und Eisenzeit, den neolithischen Küstensiedlungen Skara Brae auf den Orkney-Inseln (Abb. 28) und Jarlshof auf der Hauptinsel Shetland, wikingerzeitlichen Bootshäusern direkt oberhalb von Stränden oder mittelalterlichen Burgen direkt oberhalb senkrechter Kliffe (Abb. 29). Zudem bekräftigen sehr reif ausgebildete bioerosive Formen auf Kalkplattformen in Reichweite von Seewasser (*rock pools*) trotz Abtragungsgeschwindigkeiten durch Littorinen und Napfschnecken

(*Littorina, Patella*) in der Größenordnung von > 1 mm/a (vgl. Kelletat 1988; Spencer 1988; Trudgill 1987; Trudgill et al., 1987 a, b) ebenfalls geringen Kliffrückgang. Ihre perfekte Ausbildung und Vergesellschaftung erfordert einige 100 Jahre, doch sind sie im Arbeitsgebiet oft nahe am Kliff-Fuß zu finden.

Einen anderen Beleg liefert eine der großen Sehenswürdigkeiten auf der Insel Inishmore. Es ist das sog. *„Wormhole“ (*gälisch: *Poll na bPeist*) mit den Maßen 12 x 31 m. Es handelt sich um das eingestürzte Dach einer Unterwasserhöhle. Das Alter des Einsturzvorganges ist unbekannt. Da es jedoch keine Mythen und Sagen darüber gibt, ist davon auszugehen, dass das *Wormhole* erst einige Generationen lang existiert. Es wurde seit über 100 Jahren von Autoren aus dem nahe gelegenen Dorf Gort na gCapall erwähnt. Es grenzt unmittelbar an den Fuß des fast 20 m hohen Kliffes, so dass eine Abtragung seit dem Kollaps hier nicht mehr als insgesamt 1-2 m (d.h. wenige cm/a) betragen kann. Mit solch niedrigen Raten der Küstenerosion stehen auch die hohen Alter (> 2.000 bis > 9.000 Jahre) aller Typen von Küstensedimenten (Blockwälle, Feinmaterial-Terrassen, *wash-over*–Loben) im unmittelbaren Küstenstreifen im Einklang.

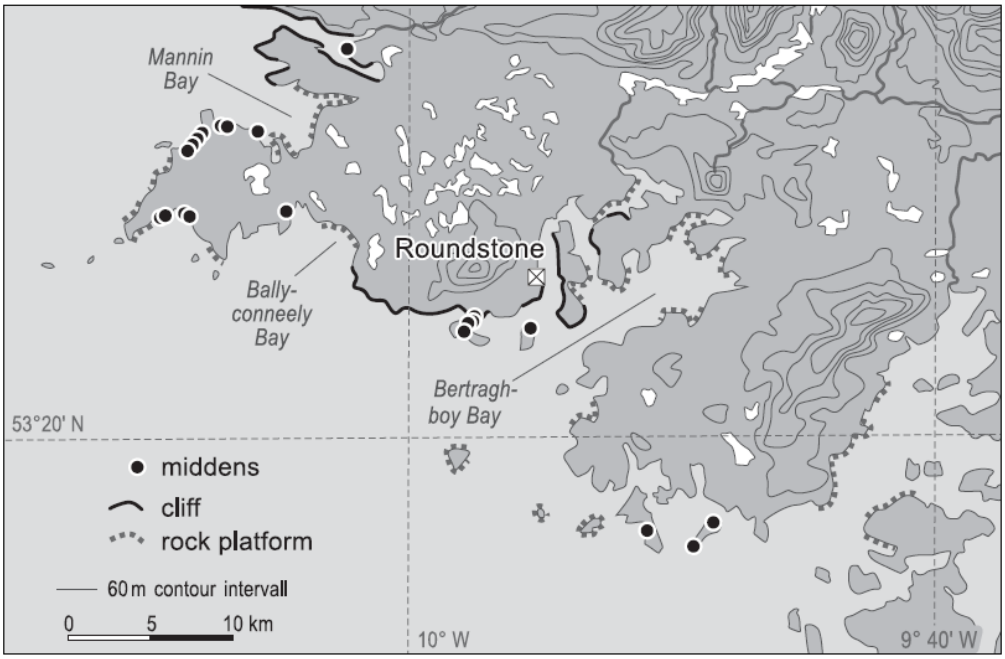


Abb. 27: Verbreitung von *shell middens* entlang der Granitküste von SW Connemara, nördlich der Aran Inseln (aus Scheffers et al., 2009, Detail).

Abb. 28: Skara Brae, eine neolithische Küstensiedlung (ca. 5.180 – 4.500 BP) auf den Orkney-Inseln (Schottland, vgl. Clarke & Maguire, 2000).

Abb. 29: Mittelalterliche Burganlage im Norden Irlands (E des Giant Causeway), gegründet auf ein sehr steiles Basaltkliff ohne signifikante Abtragung in den letzten 1.000 Jahren.

Zwar sind gerade die archäologischen Zeugnisse für eine sehr geringe Küstenerosion auch exponierter Abschnitte zahlreich und über viele Jahrtausende verteilt, doch wäre eine weitere und direktere Methode im Vergleich hilfreich. Dafür käme die Messung der Expositionsalter mit Hilfe von kosmogenen Nukliden (im Kalk: $^{36}Cl$) infrage, und zwar sowohl für das Alter bzw. die Entblößung neuer Kliffprofile wie auch für dislozierte Blöcke selbst. Zunächst müssten jedoch Tests am vorliegenden Karbonkalk, möglichst auch an verschiedenen Schichten und an Blöcken mit vielen Vergleichsmessungen aller Seiten durchgeführt werden. Der Aufwand, auf diese Weise verlässliche Altersspannen zu ermitteln, ist sicher groß, doch gibt es zahlreiche Stellen, an welchen Labormessungen kalibriert werden könnten, welche sich auf archäologische Vorkommen wie z.B. den *Cheveaux de frise* aus der frühen Eisenzeit beziehen könnten. Eine große Zahl frisch herausgebrochener Blöcke im Winter 2013/14 liefert die Grundlage für die Ermittlung eines Null-Alters.

## 5.3 Aktual-geologische Beobachtungen und Dokumentationen

Verglichen mit Jahrtausenden des Holozäns ist die potentiell mit (einigermaßen) zuverlässigen Quellen belegte Ereignisgeschichte in jedem Fall kurz. Inwieweit Sagen und Mythen Material liefern, ist meist schwer zu beurteilen. So gibt es (ohne präzise Quelle, erwähnt von O´Brian et al., 2013 für die Zeit 799/804 AD) die Sage, dass das Meer bei einer großen Flut 1.010 Menschenopfer forderte und die Insel Fita (oder Fitha) in drei Teile zerbrochen habe, die jetzt die Aran-Inseln sind. Wie geomorphologische Zeugnisse jedoch beweisen, waren die Inseln bereits vor dem letzten Hochglazial getrennt, und die Wasserwege zwischen ihnen dürften von Schmelzwässern im Spätglazial kräftig ausgeformt worden sein. Meereswirkung ist seit etwa 10.000 BP zu erwarten, als Gregory Sound und Foul Sound teilweise geflutet waren. Um 9.000 BP wurden Inishmore, Inishmaan und Inisheer (erneut) zu Inseln.

O´Brian et al. (2013) versuchten sich an der Geschichte von *extreme wave events* für den Zeitraum 14.680 BP bis 2012 AD. Beim ältesten (aber wohl kaum exakt datierten) Ereignis mit 14.680 BP handelt es sich um eine submarine Rutschung im Westen von Irland, deren Spuren jedoch heutige Küsten wegen des damals sehr triefen Meeresspiegelstandes nicht erreicht haben. Als zweites frühes Ereignis wird die *Storegga Slide* (8.100 BP, vgl. Bondevik et al., 2005; Bryn et al., 2005; Dawson et al., 1988;) vor SW-Norwegen erwähnt. Ihre Spuren reichen sicher von Island bis Dänemark und konnten auf den Färöern, Shetlands, Orkneys und dem schottischen Festland bis Nordengland gefunden werden, nicht jedoch (bisher) in Irland. Bei den übrigen *events* handelt es sich um jünger-historische Abläufe, oft basierend auf

Schiffskatastrophen. Sie werden klassifiziert nach Stürmen und Tsunamis, doch müssen einige Zuweisungen offenbleiben.

Lamb (1991) dokumentiert starke historische Stürme in der (nördlichen) Nordsee, vor allem auf der Grundlage von Wetteraufzeichnungen. MacClennaghan et al. (2001) legen eine Bewertung aufgrund von Windgeschwindigkeiten und Dauer der Stürme vor. Einer der stärksten Winterstürme der Neuzeit wurde im November 1703 AD erfasst als „*Britain´s night of destruction*", wie Brayne (2003) urteilt. Hickey (2001) behandelt den schweren Sturm von 1953, der ein extrem großes europäisches Gebiet betraf und weite Landstriche von Schottland bis (vor allem) in die Niederlande mit einer schweren Sturmflut und zahlreichen Menschenopfern heimsuchte. Für Irland gilt die „*Night of the Big Wind*" vom 6. auf 7. Januar 1839 als das extremste Ereignis (Shields & Fitzgerald, 1989), doch betrifft dieses eher die außerordentlichen Windgeschwindigkeiten (Hurrikan-Stärke 4 bis 4+, d.h. *sustained winds* von mindestens 1 Minute Dauer um 230 km/h), während von Schäden durch Wellenwirkung weniger bekannt ist. Burt (2006) hatte nach barometrischen Aufzeichnungen aller erreichbaren westeuropäischen Stationen auf einen Luftdruck im Kern des Tiefdruckgebietes wenig nördlich des schottischen Festlandes von 918 hPa geschlossen, für den Westen Irlands jedoch über 930 hPa und damit etwas mehr als der unbenannte Sturm vom 27.12 2013 bis 2.1 2014 mit 927 hPa. Nach Lamb (1991) dürfte 1839 der stärkste Sturm der letzten 500 Jahre (bis zum Jahre 1991) gewesen sein, doch ist seine unmittelbare Wellenwirkung auf die Untersuchungsgebiete nirgends genauer belegt.

Innerhalb der letzten 30 Jahre sind die Winterstürme von 1987, 1991, 1993 und 2007 als Extremereignisse registriert. Sie wurden jedoch im Winter 2013/14 – vor allem was die Wellenhöhe und Wellenwirkung betraf - von 6 Stürmen übertroffen (vgl. Abb. 8). Davon liegt eine große Zahl publizierter Fotos und Videos in allen Medien und im Internet vor. Seit 2006 arbeiten auch einige Messbojen im offenen Atlantik und registrieren (mit einigen Ausfallzeiten) u.a. die Wellenhöhen. Der höchste Wert (aus dem Februar 2014) wurde an der Boje M1 ca. 90 km westlich der Aran-Inseln mit 27,1 m gemessen.
Soweit die Recherchen ergaben, liegt nur ein Hinweis auf Tsunamis im Westen Irlands vor, und zwar vom großen Lissabon-Erdbeben und Tsunami 1755 AD (http://indigo.ie/~wildgees/images/sp-arch-galway.jpg). Dabei sollen Schäden im Altstadtzentrum von Galway um den *Spanish Arch* erfolgt sein. Bryant & Haslett (2007) und Haslett & Bryant (2007 a, b) rechnen jedoch auch die starken Überflutungen im

Bristol Channel und North Wales 1607 AD einem Tsunamigeschehen zu. Für die Region Galway fehlen allerdings ausreichende historische Hinweise auf Tsunamis, während außerordentlich starke Stürme mit zeitlichen Abständen zwischen einigen Jahrzehnten bis zu nur einigen Jahren für die letzten zwei bis drei Jahrhunderte als gut dokumentiert gelten können. Dabei scheint ihre Zahl und Intensität eher zuzunehmen. Unter Berücksichtigung des um ca. 5 m gestiegenen Meeresspiegels seit dem Mittelholozän sind für die längere Eventgeschichte (vor allem Zeitabschnitte älter als 2.000 Jahre) entlang des heutigen MHW-Niveaus Tsunamis als geomorphologisch und sedimentologisch wirksame *extreme events* wohl ebenso wahrscheinlich wie Winterstürme.

## 5.4 Alter der Küstensedimente und Ereignisgeschichte

In einem sedimentären Milieu mit weitgehend fehlender Stratigraphie sind Hinweise auf das Alter besonders wichtig. Von den relativen Indizien ist vor allem die Intensität der Kalklösung im terrestrischen und der biogenen Kalkabtragung im litoralen Milieu von Bedeutung, weil sie sich um mindestens eine Zehnerpotenz unterscheiden und eine größere Zeitspanne benötigen. Im terrestrischen Milieu sind das selbst bei Kleinformen einige Tausend Jahre. Wegen der unmittelbaren Nähe zur heutigen Brandungszone werden auch alte Ablagerungen gelegentlich modifiziert. Vor allem wird das bereits vorliegende Material bewegt, weitere Fragmente hinzugefügt bzw. durch *backwash* ins Meer verfrachtet.

Hinsichtlich der Altersbestimmung von Blockverlagerung kommen als zuverlässiges Material organische Reste an oder in Blöcken infrage, vor allem die in ihren selbst angelegten Bohrungen lange erhaltenen Schalen der *Hiatella arctica.* Sie kommen in Blöcken jeder Größenordnung vor. Einzige Voraussetzung ist längere Zeit ruhige Lage in der unteren Hälfte des Tidenhubs und im oberen Sublitoral. Damit lässt sich meist auch der Transportweg gut rekonstruieren. Eine mehrfache Umlagerung solcher angebohrten Blöcke mit erhaltenen Schalen ist weniger wahrscheinlich, weil alte Schalen leicht herausfallen, während die Schalen lebender Muscheln den Transport an Land zunächst überstehen. Ein Beleg für das hohe Risiko von Schalenverlust bei mehrfacher Verlagerung an Land ist ihre Seltenheit im Vergleich mit der Anzahl der Bohrlöcher (weit weniger als 0,1 %).

Obwohl mittlerweile 84 Daten aus den Arbeitsgebieten entlang der Galway Bay und den Aran-Inseln vorliegen (vgl. die Tabellen in Erdmann et al., 2017 und 2018 b, angegeben in 2 sigma cal BP mit einem regionalen MRE von -142 +/- 16 (Ascough et

al., 2006, 2009), ist eine zeitliche Festlegung von *extreme events* immer noch mit erheblichen Unsicherheiten belastet. 66 Daten stammen aus den drei marinen Sedimenteinheiten (sehr grobe Blockwälle entlang der Küstenlinie und auf hohen Kliffen, zungenartige *wash-over*-Loben, und geschichtete oder auch chaotische Archive mit feineren Sedimenten (Schluff, Sande, *granules*, bis zu *coarse gravel*)). Alter aus dem letzten Jahrtausend überwiegen (n = 32), zwischen 1.000 und 2.000 cal BP liegen 13, zwischen 2.000 und 3.000 cal BP noch 10 Daten, und älter als 5.000 cal BP noch 5, älter als 4.000 cal BP zusammen 9 Alter. Schwierige Zugänglichkeit der (sehr groben) Archive und Erhaltungszustand von organischen Resten spielen für die Altersverteilung der bisher ermittelten Daten sicher eine große Rolle. Allein die Hälfte der Alter stammt aus den kaum über 1 m tiefen Archiven mit feineren Korngrößen (bis zu *cobbles*). Immerhin liefern auch diese eine Geschichte, die lokal bis über 5.000 Jahre zurück reichen kann. Über das gesamte Untersuchungsgebiet am Festland wie auf den Aran-Inseln hat es sich als zuverlässig erwiesen, dass visuell ungegliederte/chaotische feinere Sedimente Altersinversionen aufweisen, erkennbar geschichtete aber konsequent abnehmende Alter von der Basis zum Top.

Prinzipiell bestünde die Möglichkeit, aus Feinmaterialarchiven OSL-Alter zum Vergleich mit den AMS-Ergebnissen zu gewinnen. Dies gilt jedoch nur eingeschränkt: nur wenige Sedimentarchive erscheinen dicht und abgeschlossen genug, um gute Proben zu erwarten. Viele sind sehr grob und damit auch durchgängig für die Verlagerung von feineren Körnern vertikal und horizontal. Dieses kann zu Problemen führen, zumal Altersunterschiede von 1.000 Jahren und mehr im Schichtabstand von 10 cm auftauchen. Sande und Schluffe sind außerdem oft Reste silikatischer Einschwemmungen aus alten Grundmoränen und Schmelzwässern und wahrscheinlich mehrfach umgelagert. Auch hier wären deshalb größere Testreihen zum Einstieg nötig.

# 6 Offene Fragen und mögliche Lösungsansätze

Nach 15 Jahren Forschungsgeschichte, 30 Publikationen und 84 Altersdaten, welche die Genese und Zeitstellung der umfangreichen Blockablagerungen im Küstenraum der Galway Bay und auf den Aran-Inseln im Fokus haben, sollten fundierte Aussagen möglich sein. Dem ist jedoch nur mit Einschränkungen zuzustimmen. Das liegt daran, dass die Mehrheit der Arbeiten anderer Forscher nur ein sehr begrenztes Spektrum an möglichen Hinweisen aus diesem Raum zum Gegenstand haben, und zwar die nahezu ausschließliche Betrachtung der außerordentlichen Blocksedimente (und darin möglichst der allergrößten Einzelblöcke und derjenigen, die eine junge Bewegung zeigen). Räumlich beschränkt sind diese Arbeiten auf die Aran-Inseln, und dort auf die östliche Südküste von Inishmore und die Westküste von Inishmaan, d.h. auf max. 5% des hier dargestellten Untersuchungsgebietes.

Eine weitere Beschränkung des Fortschrittes liegt – wie die Diskussion der Literatur belegt hat – darin, dass vorgetragene Befunde nicht objektiv geprüft wurden. Ein wissenschaftlicher Disput kann dann vorwärtsweisend sein, wenn die Bereitschaft zur Überprüfung nicht nur der fremden, sondern auch der eigenen Argumente besteht.
Ich hoffe, diesem Anspruch bisher gerecht geworden zu sein.

Auf eine Lücke in der Erkenntnisfindung haben wir bereits hingewiesen: es ist die ungleiche Verteilung der datierten Proben mit dem Schwerpunkt auf jüngere Zeitabschnitte. Inwieweit eine Beprobung der Blockwallbasis oder der Wurzelbereiche der langen *washover*-Zungen zielführender wäre ist schwer zu sagen. Das hängt in erster Linie davon ab, ob sich darin ausreichend viele und ausreichend gut erhaltene Bohrmuscheln befinden. Auf jeden Fall würden dafür erhebliche Mittel und schweres Gerät zum Aufschließen benötigt.

Ob es möglich ist, aus den Süßwassertorfen nahe Galway City, welche die alten Baumstümpfe im heutigen Intertidal begraben, eine Event-Geschichte zu erarbeiten, wäre zunächst durch ein systematisches Bohrmuster zu prüfen. Die kurze Beschreibung bei Williams & Doyle (2014) erwähnt zwei Sandlagen im Torf, die jedoch nicht weiter aufgeschlossen oder untersucht wurden. Bei geeigneten Wetterlagen ist der Bereich bis nahe der MNW-Linie, d.h. fast 5 m unter MHW, teilweise zugänglich.

Die ausgedehntesten und noch nicht untersuchten Abschnitte sind die Marschen im äußersten Osten der Galway Bay. Darunter könnten sich ehemalige geschlossene

flache Hohlformen (Lagunen) befinden, deren Position und Tiefe ggf. mit ERT erkennbar wird. Die Frage ist jedoch, ob hier tatsächlich überhaupt Event-Sedimente in früheren Phasen des Holozäns angeliefert wurden. Geht man wie z.B. Holmes et al. (2007) von einem Meeresspiegel 5 m unter dem heutigen im Mittelholozän aus und von einem noch deutlichen Anstieg innerhalb der letzten 1500 Jahre, so läge die Küstenlinie im Mittelholozän 5-10 km westlich der heutigen Marschen, und um 1500 BP noch ca. 1-2 km westlich. Zunächst müsste die Geschwindigkeit der Sedimentation (und ggf. Erosion) dieser Marschen über längere Zeitspannen durch Testbohrungen erfasst werden um zu beurteilen, ob gröbere Lagen von *storm surges* oder gar Tsunamis zu erwarten wären. Potentiell sollte 1755 AD als Leithorizont des Lissabon-Tsunamis dienen können, sofern die Berichte von der Flutung des Altstadtzentrums von Galway durch dieses Ereignis zutreffend sind.

Auf den Aran-Inseln ist bisher *An Loch Mór*, der tiefe Karstsee auf Inisheer, gut untersucht (Schettler et al., 2006, Holmes et al., 2007). Weitere Senken mit möglichen Archiven (auf Inishmore *Loch Amurvy* im Westen, mindestens teilweise auf Felsuntergrund, *Loch Dearg* Red Lake im Norden und sicher jüngere lagunenähnliche Senken im Dünengelände im Osten wie *Portcouragh Lough* und *Oghil Lough*) sind bisher nicht bearbeitet. Auf Inishmaan gibt es im Norden einige kleine Seen (*Loch Seasurrach*, *Loch Wirrabee* und *Sandhead Loch*) ebenfalls in Dünengelände und wahrscheinlich relativ jung, diese sind bislang ebenfalls unbearbeitet.

Ein anderer Ansatz wären ergänzende Arbeiten in potentiellen Herkunftsgebieten von Tsunamis im oder um den Nordatlantik. Wenn Tele-Tsunamis in Betracht gezogen werden, wie es einige Forscher für die amerikanische Ostküste erwägen, könnte dort nach Hinweisen gesucht werden. Einige *submarine slides* sind datiert, und mehrfach bearbeitet der Grand Banks Tsunami vor Neufundland 1929 AD (vgl. u.a. – chronologisch – Fine et al., 2005; Hornbach et al., 2007; Barkan et al., 2009; Grilli et al., 2009; Iacono et al., 2012, Leonard et al., 2012, oder Huvenne et al., 2016). Infrage kommt auch die erdbebenreiche Haiti-Puerto-Rico Kollisionsstruktur mit Tiefseegraben, der Raum Südnorwegen (Storegga, z.B. Bondevik et al., 2005; Bryn et al., 2005; Dawson et al., 1988; Fruergaard et al., 2015; Weninger et al., 2008), die Azoren am Kreuzungspunkt zweier großer Störungslinien, oder die Kanarengruppe mit möglichem Kollaps von Vulkanen.

Ein näherliegendes Gebiet mit Tsunamirisiken ist der *Rockall Trough* 200-400 km westlich von Irland, dessen submarine Formen durch Sondierungen u.a. von –

chronologisch - Unnithan et al. (2000), Shannon et al. (2001), Övrebö et al. (2005), Owen et al., (2010), Sacchetti et al. (2011, 2012, 2013), Georgiopoulou et al. (2012, 2013, 2014) und Salmanidou et al. (2015) gut erfasst sind. Dazu gehören auch der *Barra Fan* mit den *Peach Slides* oder der *Rockall Bank Mass Flow*. Bei einer Wassertiefe bis 3.000 m und relativ steilen Hängen sind zahlreiche Spuren von Massenbewegungen per Lidar durch das *Marine Institute of Ireland* erfasst. Einige Daten bzw. Zeitspannen für *submarine mass wastings* fallen ins Holozän, andere ins Spätglazial, in dem die Überlastung der Unterwasserböschungen durch Sedimentanfall aus den Schmelzwässern beim Eisrückgang besonders hoch war.

Die Existenz von Kaltwasserkorallen in 700 bis 1500 m Wassertiefe in der Region des *Rockall Trough*, die sogar (überwiegend im Holozän) *coral mounds* bis fast 200 m Höhe aufgebaut haben, könnte die Identifizierung von Störungen durch *mass wasting* erleichtern. Sie sind leichter zu datieren als die Abrissstellen von Rutschungen oder die Oberflächen zugehöriger *sediment lobes* auf dem tiefen Meeresboden, doch müsste ihr MRE zunächst gesichert werden. Damit bestünde die Chance, aus dem Altersvergleich von *onshore*-Ablagerungen der *extreme events* im Raum der Galway Bay, den Aran-Inseln und anderen Lokalitäten West-Irlands mit der Zeitstellung submariner Massenbewegungen im (nahen) Atlantik das Tsunamigeschehen weiter aufzuhellen. Bisher steht dafür nur der Nachweis der *Storegga Slides* aus dem Holozän im östlichen Atlantik zur Verfügung.

Sicher unverzichtbar ist eine regionale Ausweitung systematischer Untersuchungen entlang der Westküste Irlands auf Spuren besonders markanter Meereseinflüsse. Erste Schritte dazu einschließlich einiger weniger Altersbestimmungen (Mindestalter eines Blockwalles unter Torf 4.000 cal BP) liegen bereits vor, u.a. von Scheffers et al. (2009) von der Belmullet Halbinsel (*Annagh Head*) im Nordwesten von Irland. Die Verzahnung von Blockwällen mit Torfen bietet eine Disposition, die in den Arbeitsgebieten in der Region Galway nicht gegeben ist.

Die Region um Galway und die Aran-Inseln im Westen Irlands repräsentieren eine Küstenlandschaft mit vielfältiger Ausstattung zwischen Salzwassermarschen und Blockablagerungen ungewöhnlicher Ausdehnung und Einzelgröße auch im weltweiten Vergleich. Um ihre Entwicklungsgeschichte aufzudecken, ohne auf ausreichend tiefe und reiche Sedimentarchive zurückgreifen zu können, ist mindestens die gesamte Vielfalt der natürlichen Gegebenheiten wie beispielsweise das Küstenrelief, Expositionen, Bathymetrie, potentielle marine und terrestrische

Prozesse, archäologische Hinweise und relative Altersindizien zu berücksichtigen und in Schlussfolgerungen zu bewerten. Ich hoffe, auf dem Weg zu einer gut begründeten Interpretation ihrer Landschaftsgeschichte im Holozän einen kleinen wissenschaftlichen Fortschritt beigesteuert zu haben.

**Schlussbemerkung und Zusammenfassung**

Die Zunahme der Publikationen und Daten über extreme Wellenereignisse an der zentralen irischen Westküste hat bisher noch nicht zu einer Übereinstimmung bei den wichtigsten Arbeitsmethoden geführt. Der Grund liegt im Festhalten an vorgefassten Ansichten über die wirkenden Kräfte, ohne anders lautende publizierte Dokumente und Schlussfolgerungen sorgfältig auf ihre Tragfähigkeit zu prüfen.
Es ist zu hoffen, dass mit der Zahl von quantitativen Größen und Altersdatierungen das Gerüst der objektiven Fakten so überzeugend geworden ist, dass sich allmählich ein belastbarer *state of the art* entwickelt, der ein solides Fundament für weitere wissenschaftliche Fortschritte bildet. Dazu sollten möglichst die Feldstudien ausgedehnt werden auf die Sedimentationsräume der Marschen im Inneren der Galway Bucht, auf die kleinen Seebecken auf den Aran-Inseln und selbstverständlich auf weitere Küstenabschnitte in Irlands Westen mit unterschiedlicher Ausstattung von Relief, Gestein, Bathymetrie und Geschichte des Meeresspiegels im Jüngeren Holozän. Forschungen zur Genese von Blockablagerungen an anderen Küstenabschnitten der Erde werden hoffentlich ebenfalls dazu beitragen.
Dieses wird am ehesten gelingen, wenn den Belegen für *extreme events* an Land endlich vermehrt Untersuchungen der nahen Meeresgebiete – heute technisch weniger aufwändig – zur Seite gestellt würden, ebenfalls belegt mit (weiteren) Altersbestimmungen zu deren Geschichte. Damit könnten die oft bezweifelten Schlussfolgerungen auf eine Beteiligung von Tsunamis durch weitere unwiderlegbare Fakten gestärkt werden und ihren Platz in der Dynamik exponierter Felsküsten einnehmen. Nach dem bisherigen und nachprüfbaren Stand des Wissens ist dafür die zentrale Westküste Irlands das am besten geeignete Testgebiet.

**Summary**

The rising number of data and publications on extreme wave events at the central Irish west coast has not lead to a general accepted catalogue of related methods so far. Reasons are preconceived opinions on the working processes avoiding in-depth discussions of data from other published material. This blocks the progress of science regarding coarse coastal deposits and the forces, which dislocated them to onshore.

We hope that with a rising number of quantitative data (including relative age data) from the field and age dating from laboratories, a solid construction of facts becomes convincing enough to develop a state of the art as a starting point for more scientific progress. This should be supported by additional studies in the marsh sediments of innermost Galway Bay, the small lake basins on the Aran Islands and - very important - along other sections of the Irish west coast equipped with a similar richness in topographies, rock types and bathymetries but different Holocene sea level histories. Studies on the genesis of coastal boulder deposits at sites from other latitudes and climates around the world certainly will contribute to this aim.

To achieve this, more investigations on offshore conditions (forms and sediments, including age data for mass wasting processes) to compare their signatures for extreme events with known results onshore are needed urgently. By this, hints on definite (but often doubted) tsunami-triggering mass movements offshore will help to give this process its place in the dynamic of exposed rocky shorelines. Based on the present knowledge, the central Irish west coast with Galway Bay, the Aran Islands and the nearby Rockall Trough are a perfect test area.

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gemäß der Promotionsordnung vom 12. März 2020

„Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation selbstständig und ohne die Benutzung anderer als der angegebenen Hilfsmittel und Literatur angefertigt habe. Alle Stellen, die wörtlich oder sinngemäß aus veröffentlichten und nicht veröffentlichten Werken dem Wortlaut oder dem Sinn nach entnommen wurden, sind als solche kenntlich gemacht. Ich versichere an Eides statt, dass diese Dissertation noch keiner anderen Fakultät oder Universität zur Prüfung vorgelegen hat; dass sie - abgesehen von unten angegebenen Teilpublikationen und eingebundenen Artikeln und Manuskripten - noch nicht veröffentlicht worden ist sowie, dass ich eine Veröffentlichung der Dissertation vor Abschluss der Promotion nicht ohne Genehmigung des Promotionsausschusses vornehmen werde. Die Bestimmungen dieser Ordnung sind mir bekannt. Darüber hinaus erkläre ich hiermit, dass ich die Ordnung zur Sicherung guter wissenschaftlicher Praxis und zum Umgang mit wissenschaftlichem Fehlverhalten der Universität zu Köln gelesen und sie bei der Durchführung der Dissertation zugrundeliegenden Arbeiten und der schriftlich verfassten Dissertation beachtet habe und verpflichte mich hiermit, die dort genannten Vorgaben bei allen wissenschaftlichen Tätigkeiten zu beachten und umzusetzen. Ich versichere, dass die eingereichte elektronische Fassung der eingereichten Druckfassung vollständig entspricht."

**Teilpublikationen:**

1. Erdmann, W., Kelletat, D., Scheffers, A. und Haslett, S.K. (2015) Origin and Formation of Coastal Boulder Deposits in Galway Bay and on the Aran Islands, Western Ireland. Springer Briefs in Geography, 125 pp., 141 figs.
2. Erdmann, W.; Kelletat, D., und Kuckuck , M., (2017) Boulder Ridges and Washover Features in Galway Bay, Western Ireland. Journal of Coastal Research, 33 (5): 997 – 1021.
3. Erdmann, W.; Kelletat, D., und Scheffers, A., (2018 a) Boulder Dislocation by Storms, with Scenarios from the Irish West Coast. Marine Geology 399: 1-13.
4. Erdmann, W., Scheffers, A.M., und Kelletat, D.H. (2018 b) Holocene Coastal Sedimentation in a Rocky Environment: Geomorphological Evidence from the Aran Islands and Galway Bay (Western Ireland). Journal of Coastal Research 34: 772 – 793.

Castrop-Rauxel, 21.04.2020 _____

Wibke Erdmann