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Extreme wave events in Ireland: 14 680 BP–2012

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Abstract. The island of Ireland is battered by waves from all sides, most ferociously on the west coast as the first port of call for waves travelling across the Atlantic Ocean. However, when discussing ocean events relevant to the nation of Ireland, one must actually consider its significantly larger designated continental shelf, which is one of the largest seabed territories in Europe. With this expanded definition, it is not surprising that Ireland has been subject to many oceanic events which could be designated as "extreme"; in this paper we present what we believe to be the first catalogue of such events, dating as far back as the turn of the last ice age.

1 Introduction

The study of extreme wave events on the ocean is a rapidly expanding area of research worldwide that links together sailors, marine officers, oceanographers, physicists and mathematicians around a common aim of understanding the formation and dynamics of large ocean waves and currents. Although much work in this area is based on modelling and experiments in controlled wave tanks, the starting point of all studies in this field is of course observation in the natural world. To this end, several reviews of observational ocean events which could be classed as extreme have appeared in the literature (Kharif and Pelinovsky, 2003; Tinti et al., 2004; Ambraseys and Synolakis, 2010; Nikolkina and Didenkulova, 2011), but there is clearly the need for as much detailed cataloguing as possible. The purpose of this paper is to present such an overview for the nation of Ireland.

Ireland of course refers to the well-known island situated on the western edge of Europe, which we consider here in its entirety including both the Republic of Ireland and Northern Ireland. From an oceanographic perspective, however, it is necessary to consider the full designated continental shelf of Ireland, which is of course very much bigger and which indeed is one of the largest seabed territories in Europe, as shown in Fig. 1.

But even when it is possible to delimit a geographical area, a problem that arises immediately when attempting to prepare a catalogue of events is that of the particular time frame of interest, and the differing fidelity of the observations. In the interest of completeness, we have tried to include as many events as we have been able to document, albeit that sometimes we summarise observations from the distant past and from testimonials where the reliability of the observations cannot be verified. But when viewed as a whole, it is clear that there is a great deal of evidence supporting a long history of large ocean waves and currents on the oceans surrounding Ireland as well as on its coast. This said, of course such a study cannot be exhaustive, but we have attempted to be as complete as possible at the time of preparation. In fact, our desire to be comprehensive has encouraged us to include in this overview a short section including results from legend, and whilst the scientific basis of such events is less certain than the other results we present, we believe that such results are complementary to the more reliable observations described in the rest of this paper.

This paper is organised as follows. In Sect. 2, we first clarify our use of terminology to describe different categories of "wave" events as storm waves, tsunamis and rogue waves. In Sect. 3, we present the main catalogue of documented wave events in Ireland listed under these three categories, whilst Sect. 4 presents additional related descriptions, including those from legend. Section 5 presents a discussion of how these wave events may relate to boulder deposits in Ireland, which are of particular relevance to cliff-top deposits on the west coast. Finally in Sect. 6 we present an overall conclusion and make suggestions for further directions of research.

2 Categories of ocean waves

We consider "extreme wave" events in Ireland in three broad categories that we discuss in more detail below: storm waves, tsunamis, and rogue waves. In the context of quoting from various sources as we do in the following section, it must be recognized that the descriptions used by the public and media do not always follow precise scientific definitions, but we attempt to – wherever possible – refer back to the definitions in this section when commenting on the results in the catalogue below.

Storms are very common in Ireland (driven by the strong winds on the west coast in particular), but tsunamis are not common due to the location of Ireland relative to the tectonic plate boundaries. In fact, the number of earthquakes documented in Ireland since 1760 is just over 100, and the largest of these has a magnitude of only 4.4. However, earthquakes and landslides very far from Ireland itself can still generate tsunamis that travel great distances without losing much energy, and events like this have affected Ireland in the past.

There are two historical submarine mass movement events of particular interest: the first occurred in the Barra Fan, offshore north-west of Ireland (Owen et al., 2010), and the second in the Porcupine Basin, offshore south-west of Ireland (Huvenne et al., 2002). Both of these locations are indicated in Fig. 1. Furthermore, a phenomenon referred to as "meteo-tsunami" (a meteo-tsunami is an atmospherically induced destructive ocean wave in the tsunami frequency band) could also pose a threat to Ireland, and since this has been documented in England (Haslett et al., 2009), it is reasonable to assume that meteo-tsunamis may also have impacted Irish shores in the past and pose a threat for the future. Rogue waves or freak waves refer to a particular class of wave events that has only recently been accepted as a distinct wave class (Nikolkina and Didenkulova, 2011). However, as we describe here, it is possible that many fatalities in Ireland may well have arisen from events that could be considered as rogue waves.

The vast majority of waves on the ocean are surface gravity waves generated by the wind blowing over a large stretch of water surface. After the (wind sea) phase of generation by local winds, the propagation of surface waves away from the generation area yields ocean swell. In general, surface waves at any particular point on the ocean are a combination of locally generated waves from a local wind sea and swell generated remotely (mixed sea states). Extreme sea levels occur when particular wave generation or propagation dynamics yield surface elevations that are larger than expected for the particular area considered.

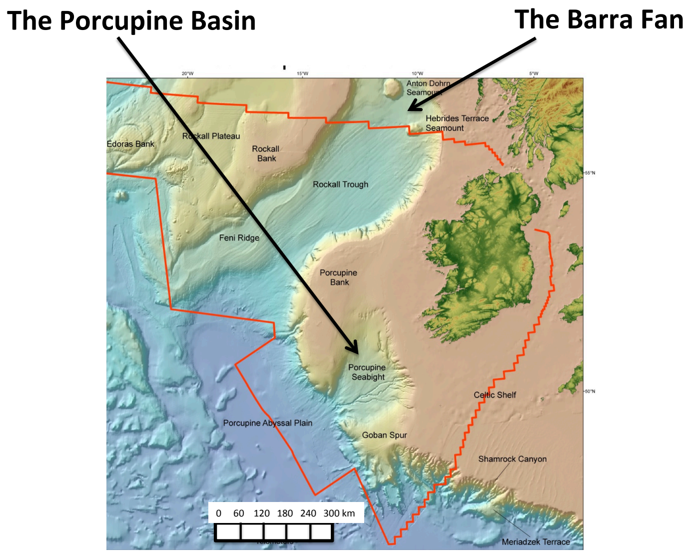

Fig. 1. A snapshot from The Real Map of Ireland from the Irish Marine Institute, www.marine.ie, with the locations of the Barra Fan and the Porcupine Basin overlaid. The red line indicates the current designated Irish continental shelf, which is one of the largest seabed territories in Europe.

2.1 Storm waves

Storm waves are wind surface waves that reach unusually large amplitude due to forcing by strong winds. For example, gale to hurricane force winds ranging from 8 to 12 on the Beaufort scale can produce maximum wave heights from 7.5 m to $\geq$ 16 m (Metoffice.gov.uk, 2012).

The climate in Ireland is dominated by the Atlantic Ocean, and its associated wind patterns are responsible for the generation of a large population of storm waves. The polar front (transition between warm dense air moving north and cold dry air moving south) is a feature that plays an important role in Irish weather, and winds generally blow from the south and west. The Atlantic low-pressure systems move eastwards across Ireland in December and January bringing strong winds. Occasionally, in late summer and early autumn tropical depressions mixing with North Atlantic depressions can produce severe storms such as the one that occurred during the Fastnet race in August 1979. From 1961 to 1990 the mean number of days per year with gales at Malin Head, Co. Donegal, was 66 (met.ie, 2012). This highlights just how prevalent strong winds are in Ireland, and motivates our consideration of storm waves as an important category of extreme ocean events in this catalogue.

Even though storm surges are obviously associated with storms, we prefer to include them in the next section on tsunamis, the reason being that storm surges can be considered as long-period waves with a typical wavelength of several tens of kilometers like tsunamis.

2.2 Tsunamis

Tsunami waves are one of the most catastrophic events that can naturally occur. They have devastated countries at severe human cost, wiping out miles of coastline, towns and villages on a path of destruction. The recent events in Japan in 2011 and Indonesia in 2004 are a stark reminder of their destructive power (Synolakis and Bernard, 2006).

Tsunamis are generated from a sudden impact on the ocean caused by earthquakes, landslides or volcanoes displacing large volumes of water. We note that although the geological origin of tsunamis is that most often cited, the effects of landslides and volcanoes can be as equally destructive (Okal and Synolakis, 2003). In the open ocean a tsunami is usually only a few tens of centimeters high, travels at around 800 km h^{-1}, the speed of a commercial jet airplane, with a wavelength of the order of 100 km. The basic physics of tsunamis on the open ocean follows that of a linear shallow water wave.

Tsunamis conserve energy well until reaching the shore where they are compressed because of shoreline bathymetry and they drastically grow in height as they slow down. It is common that the first sign of a tsunami is an extreme withdrawal of the sea followed by a wave that seems small in the distance, but which grows rapidly and which can be followed by successive waves sometime after. The first wave is not always the largest (Stefanakis et al., 2011). Without the proper infrastructure and education on the warning signs and evacuation methods, tsunamis can have deadly effects on coastal communities.

2.2.1 Storm surges and meteo-tsunamis

A storm surge is an increase in the level of sea surface associated with low atmospheric pressure, and as such is a long-period wave. Storm surges can have particularly destructive effects in coastal areas where there is a significant difference between low tide and high tide. A meteo-tsunami is also a long-period wave that possesses tsunami like properties but is meteorological in origin. The meteo-tsunami phenomenon has much in common with storm surges (Levin and Nosov, 2009). The period of storm surges can range from several minutes up to several days. It is important to emphasize that even though storm surges and locally generated wind waves can be present together, we consider them separately, since wind waves and choppy seas are characterised by periods smaller than a minute. The only formal difference between a storm surge and a meteo-tsunami consists in the difference between their maximum periods. The maximum period for a tsunami does not exceed several hours, while storm surges may last several days.

In recent years more attention has been paid to tsunamis of meteorological origin (Rabinovich et al., 2009). Extreme wave formation in coastal waters may be considered as a meteo-tsunami if it takes on long-period tsunami like characteristics. Meteo-tsunamis are very sensitive to resonance generated by local coastal geometry and topography which can cause large seiches, for example inlets, bays, and harbours (Haslett and Bryant, 2009). Multiple events have been analysed along the coast of southern Britain, in particular by Haslett and Bryant (2009). Also, Dawson et al. (2000) have documented abnormal sea-surface fluctuations in South West England.

On 27 June 2011, a 0.5–0.8 m high tsunami struck approximately 200 miles of coastline on the south-west of England. Eyewitness reports said that the weather was extremely warm and humid at the time and the sea was "as calm as a mill pond." Then the sea retreated and suddenly rushed back in. Also there was a feeling of static in the air and people's "hair was standing on end" (*The Guardian*, 29 June 11). Based on the range of impact and lack of height variation, the British Geological Survey (BGS) indicated that it was likely to have been a meteo-tsunami caused by a squall, or several squalls, that developed during a summer storm. If meteo-tsunamis can explain some large wave events in England, then maybe similar events in Ireland can be linked to meteo-tsunamis.

Mecking et al. (2009) carried out numerical simulations of Tropical Storm Helene (2000) driven by atmospheric pressure and surface winds. They were able to capture the observed response of unexpected "rapid tides" along the coast of Newfoundland during this storm. This rapid rise in tide can be compared to a tsunami and so could be categorized as a meteo-tsunami. This study highlights the importance of capturing the atmospheric pressure effects when modelling the sea level response to a storm and may be a first step towards modelling meteo-tsunamis.

2.3 Rogue waves

Rogue or freak waves are large, unpredictable and highly powerful waves that have the potential to cause huge damage (Kharif and Pelinovsky, 2003). They seem to appear from nowhere with a height 2–3 times that of the surrounding sea state, exist for a short time and then disappear.

There is no universal definition of a rogue wave, but one often used is that of a wave which is at least twice as high (trough to crest) as the significant wave height (four times the standard deviation of the surface elevation) of the surrounding waves. Until recently, stories of rogue waves were thought to be folklore or exaggerated because they could not be explained scientifically, but there is now acceptance that they constitute an important class of wave, although there is unlikely to be only one unique generation mechanism. Rogue waves occur in both deep and shallow waters, and may act as a single wave or a group of waves. It is almost certainly the case that different mechanisms may contribute to the formation of rogue waves, including both linear and nonlinear processes influencing waves both in the local vicinity of a wind sea, as well as propagating swell. For example, linear superposition and directional focussing

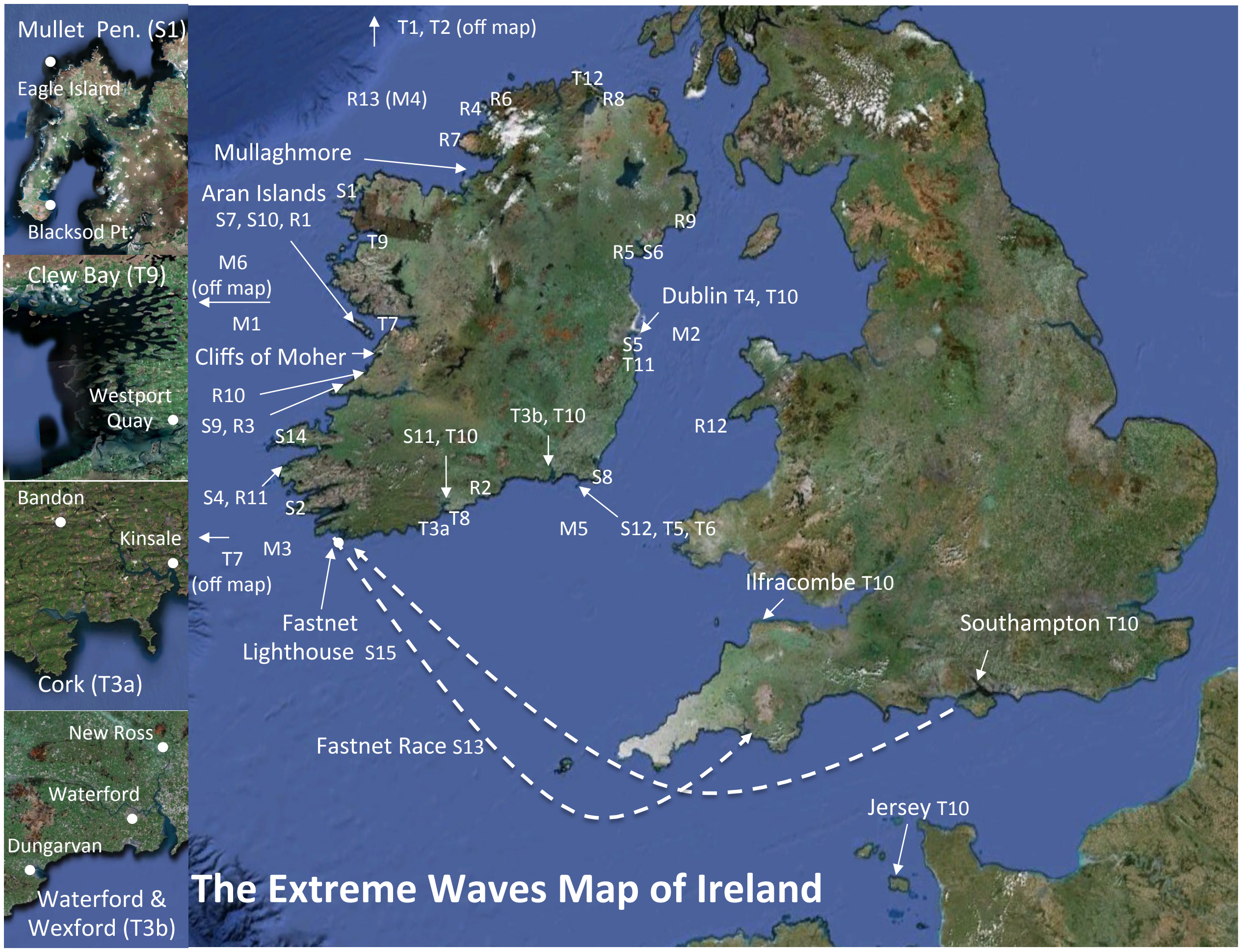

Fig. 2. Location of extreme wave events in Ireland (see Table 1).

effects could readily increase local wave height in the presence of local wind, whilst nonlinear instabilities could increase local wave group amplitude for a propagating swell. To our knowledge, the first plausible explanation of how an extraordinary (abnormal) wave condition can be realized in the ocean was provided through analyses of the Suwa-Maru incident on 23 June 2008 (Tamura et al., 2009). Crossing sea conditions were a precursor to the development of a narrow spectrum. When the resulting unimodal wave spectrum is sufficiently narrow and nonlinear, a freak wave might occur due to modulational instability.

It is important to state that rogue waves are intrinsically random in nature, and thus deterministic ocean processes such as tsunami and storm surge should probably not be included in the category of rogue waves. In the context of nonlinear wave theories which are currently being considered in great detail, it is interesting to remark that many of the theoretical ideas underlying nonlinear water wave formation have not actually been confirmed in the hydrodynamic environment. However, recent work using analogies between ocean deep water waves and light propagation has indeed been able to confirm many predictions (Peregrine, 1983) of nonlinear deep water wave growth and decay in an optical environment (Kibler et al., 2010, 2012). This work has since motivated direct observation of nonlinear waves in water tanks, and thus it seems likely that a more complete picture of the role of nonlinearity in water wave growth and shaping will soon emerge (Chabchoub et al., 2011, 2012).

3 Events

We use the Before Present (BP) timescale, as is common in archaeology and geology, to specify when events in the past occurred, and we adopt the standard practice to use 1 January 1950 as the origin of the age scale.

In this section extreme wave events in Ireland are catalogued in terms of the three categories described above: storm waves, tsunamis, and rogue waves. This categorization is made based on an overall assessment of the available

Fig. 3. Eagle Island (picture from National Geographic, travel.nationalgeographic.com/travel/countries/ireland-photos/).

descriptions, although of course there is uncertainty when the wave descriptions are based on eyewitness accounts. There could well be some overlap between our categorizations, and in cases where there may be more than one possibility, it is noted. However, our aim is to provide an important first step in developing as complete a catalogue as possible for extreme wave events in Ireland.

Two of the events we describe – the Peach Slide in 14 680 BP and the Storegga Slide in 8200 BP – occurred around the end of the last glacial period. These are both large-scale submarine landslides, and it is speculated that tsunamis generated by the slides may have reached Ireland. All other events date from 1755 until present day and are backed by documented eyewitness accounts, newspaper reports, published papers or tsunami databases. The two tsunami databases used are the Russian Academy of Sciences' Tsunami Laboratory Historical Tsunami Database (RAS, 2012) and the US National Oceanic and Atmospheric Administration's National Geophysical Data Center Tsunami Event Database (NOAA, 2012). The catalogue describes 22 storm wave events, 15 tsunamis and 13 rogue wave events, with Fig. 2 giving their locations.

3.1 Storm waves

3.1.1 1837, 1861, 1894, 1935, 1987, 1988, 1989: the Mullet Peninsula, Co. Mayo [S1]

The Eagle Island and Blacksod Point lighthouses on the Mullet Peninsula in Co. Mayo (see first inset of Fig. 2 for map location and Fig. 3 for a picture of Eagle Island) have been hit by extreme waves on multiple occasions. Eagle Island lies just off the Mullet peninsula close to the continental shelf. The light is 67 m above sea level. Built in 1835, the lighthouse originally had two towers but only one remains today.

In 1837 there is an account of a huge wave: "An ocean wave (there being no hurricane at the time)... swept over the island, the lightkeepers with their families taking refuge in the tower, just in time to save their lives, when the roofs of the dwelling homes were carried away" (*The Irish Times*, 15 October 1869).

On 11 March 1861 another huge wave did considerable damage. The Commissioners of Irish Lights (CIL, 2012) describe the event: "On the 11 March 1861 at midday the light room of the East tower was struck by the sea smashing 23 panes, washing some of the lamps down the stairs, and damaging the reflectors with broken glass beyond repair. It must have been an incredible wave to have come up 133 feet [40.5 m] of rock and then a further 87 feet [26.5 m] of lighthouse tower to cause so much damage."

On 29 December 1894 a storm "damaged the dwellings of the East station beyond repair and also broke the lantern glass, put out the light and damaged the protecting wall" (CIL, 2012). In a letter written by one of the inhabitants of Eagle Island, Polly Ryan describes to her sister Kate the horror of what happened that night (Ryan, 1895). She and the others in her house were woken "at half past two to jump out of bed into water." She tells how a terrible gale was blowing all night and how the "Green Seas were going over our houses." The door to their room was broken down, and all the rooms "filled with the sea." The sea was raging outside, the "window frames, roofs and all the house was going to pieces" and the "slates were being lifted off like flies." At a neighbouring house the sea "ran over the house smashing the door in the hall, filling to rooms" and was coming in the chimney putting the fire out. The house "got all broken down, up-stairs got knocked into one. The windows all broken in, the staircase carried away." As for the lighthouse tower the "lights were put out several times, all the panes in the tower windows were put in." The store houses "were levelled to the ground, pantries and everything smashed." She also describes paving stones (flags) being transported: "Flags were torn up and tossed around like marbles." She finishes by saying "the Lower station is a complete wreck." On 25 January 1935 another storm struck the light putting it out of action (CIL, 2012). In January of 1987 and February of 1988, "substantial damage was again done by storms" (CIL, 2012).

Lighthouse photographer John Eagle (Eagle, 2012) describes some of the damage that has been done at Eagle Island: "On one occasion a rock was thrown up the high cliffs by a severe storm, it smashed the glass and then the tower filled up with water.... The door had to be drilled to let the water before it could be opened."

Given the description, this was most likely during the 1861 or 1894 event.

Although we have included these events here as storm waves, a wave height of 67 m is extraordinary. It is likely that such a wave height represents the water height after projection at the base of the lighthouse. But even if this was the

Table 1. Legend corresponding to Fig. 2.

Label	Event	Notes
S1	1837, 1861, 1894, 1935, 1987, 1988 and 1989: the Mullet Peninsula, Co. Mayo	See inset
S2	1869 and 1881: Calf Rock, Co. Cork	
S3	1839: Night of the Big Wind	Not shown (whole country)
S4	1864: Valentia, Co. Kerry	
S5	1877: Railway Lines, Co. Dublin and Co. Wicklow	
S6	1899: Greenore, Carlingford Lough, Co. Louth	
S7	1941: Inisheer Lighthouse, the Aran Islands	
S8	1945: Rosslare, Co. Wexford	
S9	1951: Kilkee, Co. Clare	
S10	1953: the Aran Islands	
S11	1962: Co. Cork	
S12	1974: Kilmore, Co. Wexford	
S13	1979: Fastnet Race	
S14	1982: Ventry, Co. Kerry	
S15	1985: Fastnet Rock Lighthouse	
T1	14 680 BP: the Barra Fan, Peach Slide	Off map, see Fig. 1
T2	8200 BP: Storegga Slide	Off map, see Fig. 8
T3	1755, 1761, 1941 and 1975: the Lisbon, Portugal, tsunamis	See insets
T4	1767: The River Liffey, Dublin	
T5	1841: Kilmore, Co. Wexford	
T6	1854: Kilmore, Co. Wexford	
T7	1894: Galway Bay & the Atlantic (*Festina Lente* and *Manhattan*, off map)	Locations off map: (50°12′ N, −35°23′ W), (51°26′ N, −27°31′ W)
T8	1922: Ballycotton, Co. Cork	
T9	1909: Westport Quay, Co. Mayo	See inset
T10	1910: Cork, Waterford, Southampton, Jersey, Dublin and Ilfracombe	
T11	1912: Bray, Co. Wicklow	
T12	1932: Inishowen, Co. Donegal	
R1	1852: Inis Mór, the Aran Islands	
R2	1883: Youghal , Co. Cork	
R3	1899: Kilkee, Co. Clare	
R4	1914: Iniskeeragh, off Donegal	
R5	1936: Dundalk, Co. Louth	
R6	1972: Mullaghderg, Donegal	
R7	2004: L.E. *Róisín*, off Donegal coast	
R8	2006: off Portrush, Co. Antrim	
R9	2006: Ardglass, Co. Down	
R10	2007: Doonbeg, Co. Clare	
R11	2007: Valentia Island, Co. Kerry	
R12	2011: *Swanland*, off Bardsey Island, the Irish Sea	
R13	2011: Largest wave recorded in Ireland	M4 data buoy
M1–M6	Locations of data buoys	

case or if the damage was induced by projected rocks, these would remain remarkable events.

At Blacksod Point Lighthouse, built in 1864, there was a huge wave during a storm in 1989 that caused serious damage to the lighthouse. This lighthouse is 13 m above sea level. A description is given by a school group who were given a tour of the lighthouse from the lightkeeper Vincent Sweeney: “When the storm came to the lighthouse it smashed everything in its path. It was so strong that it blew a barrel full of oil in the window down the hall and into the kitchen. The storm flooded the whole house.” The wave also knocked down a 4 m high granite wall.

3.1.2 1869 and 1881: Calf Rock, Co. Cork [S2]

On 27 November 1881 the lighthouse at Calf Rock, situated off the south-western tip of the Beara Peninsula in the west of Co. Cork (see Fig. 2), was destroyed in a violent storm. The tower was completely severed. The Commander of HMS *Salamis* reported that they had seen five men on the rock who had written in red on the remaining portion of the lighthouse “NO ONE HURT WANT TO LEAVE THE ROCK.” Due to the the severity of the weather, it was nearly two weeks before six men were rescued from the rock by HMS *Seahorse*. Calf Rock lighthouse was originally established in 1866. The lighthouse was 31 m high from ground level to the vane and was made from cast iron plates bolted together. It was hit by a storm on 30 January 1869 which washed away 2.4 m of the balcony (Costeloe, 2000) (see Fig. 4).

Strong currents from the north and south rush together at Calf Rock, producing a local region of highly agitated sea that makes it extremely dangerous to land on the rock (Harrington, 2000–2001).

Fig. 4. Calf Rock, off the coast of Cork (www.begleys.com/Boating%20album.htm).

3.1.3 1839: Oíche na Gaoithe Móire – The Night of the Big Wind [S3]

The night of 6–7 January 1839, now referred to as "The Night of the Big Wind", "probably caused more widespread damage in Ireland than any other storm in recent centuries. Winds reached hurricane force and between a fifth and a quarter of all houses in Dublin experienced some damage, ranging from broken windows to complete destruction" (see Met.ie/wind, 2012, in the list of References).

The sea played a big part in the damage caused that night, including 42 shipwrecks (Forsythe et al., 2000). Shields and Fitzgerald (1989) describe freak phenomena that were documented at the time or have survived through oral tradition. A rare sea bird was found 90 miles from the sea, herrings were found 6 miles inland and it was said that trees 12 miles inland were covered with salty brine. Sand banks at Ballyshannon Harbour, Co. Donegal, were eroded and "carts of sand could be gathered" nearly two miles inland.

Furthermore, three acres of bog in Cork between Newmarket and Kanturk were moved nearly a mile and across a rapid river (likely to be the River Dalua that flows between the two towns). Another account from Delaney (1996) recounts sea water being carried inland and pouring down the chimneys, the smell of salt which lingered in houses for weeks, seaweed carried inland great distances and fish found miles from the shore.

Bunbury (2005) describes the Night of the Big Wind, in particular the ferocity of the ocean: "[T]he waves actually broke over the tops of the Cliffs of Moher. . . the ocean tossed huge boulders onto the cliff tops of the Aran Islands." Note that boulders moved by waves have been identified on cliffs up to 50 m high on the Aran Islands (Williams, 2010).

A log book account of a ship that was thrown onto a reef states that "a dreaded squall came on them, the brig drove broad side on a reef of rocks. . . the sea threw her off her beam ends." They had a lucky escape two hours later when "a dreadful sea lifted the whole brig clear off the reef" (*The Galway Weekly Advertiser*, 19 January 1839).

3.1.4 1864: Valentia Harbour, Co. Kerry [S4]

On 26 November 1864, two lifeboats experienced a "great. . . wave" during a trial in Valentia Harbour, Co. Kerry. The weather was particularly bad at the time, with force 10 winds and a "tremendous sea was running and breaking wildly." The wave is described "gathering itself about a mile seaward", and as it met the lifeboat, "its crest towering 25 feet [8 m] above her, and overhanging" (*The Irish Times*, 12 December 1864).

Though this could be considered a rogue wave, judging from the description given, it is more likely to have been an overly animated description of what happened to a particularly small boat in a rough sea.

3.1.5 1877: railway lines, Co. Dublin–Co. Wicklow [S5]

In January 1877, the train line between Kingstown (Dún Laoghaire) and Bray was "considerably damaged by recent floods, rains and. . . waves" (*The Irish Times*, 25 January 1877).

3.1.6 1899: Greenore, Carlingford Lough, Co. Louth [S6]

In early January 1899, during a bad storm in Greenore, Carlingford Lough, Co. Louth, a boat trying to enter the harbour "was unable to do so, and in the severe storm that followed was lost sight of." The following day it was reported that the "waves in the Channel ran mountains high. . . a vessel had been wrecked off Holyhead" (*The Irish Times*, 3 January 1899 and 4 January 1899).

3.1.7 1941: Inisheer Lighthouse, the Aran Islands, Galway Bay [S7]

During a severe flooding in January 1941, the force of the sea rolled a giant rock, estimated to be 84 tonnes, up on the shelving flat rock beach south-west of the tower (Scanlan, 1993). The platform was 2 m above sea level and wave heights were sufficient to flood the lighthouse, ≥ 5 m above sea level (Williams and Hall, 2004).

3.1.8 1945: Rosslare, Co. Wexford [S8]

Gales and high tides were experienced in coastal towns around Ireland on 18 December 1945. A steamer was "severely battered before she reached shelter in Rosslare", Co. Wexford. Also an "exceptionally high tide" washed away part of the cliffs in Rosslare Bay (*The Irish Times*, 19 December 1945).

Fig. 5. Fastnet Rock (yachtpals.com/files/news/fastnet-rock-boat.jpg).

Fig. 6. Overturned yacht during 1979 race (www.gerry.odonoghue.com/images/fastnetNS.jpg).

3.1.9 1951: Kilkee, Co. Clare [S9]

Damage was caused by a "storm and… wave" in Kilkee, Co. Clare, in December 1951 (*The Irish Times*, 22 May 1952).

3.1.10 1953: the Aran Islands and the Irish Sea [S10]

A storm in 1953 halted the construction of the slipway at Gort Na gCapall on the Aran Islands and also sank the *Princess Victoria* in the Irish Sea when "the stern gates to the car deck were forced open in heavy seas", with the loss of 132 people (*The Irish Times*, 5 June 2003, and *BBC News*, 1 January 1953).

Williams and Hall (2004) document eyewitness accounts from Gort Na gCapall. The storm caused the total destruction of the construction machinery and a large number of megaclasts (up to 2 m in length and 15 m above sea level) were transported so that there was no longer access to the slipway for boat launching. Waves reached breaking heights of approximately 12 to 15 m.

3.1.11 1962: Co. Cork [S11]

In early March 1962, storms and flooding across the country were reported along with "a… wave which had flooded every sea port in the south-east of Ireland." Cork was worst affected because of its position (*The Irish Independent*, 9 March 1962, and *The Irish Times*, 9 March 1962). Two years later it was reported that "the Memorial Park in Youghal was almost washed away by a… wave… years ago." This may be referring to the 1962 incident (*The Irish Times*, 12 September 1964). This event could alternatively be classified as a storm surge.

3.1.12 1974: Kilmore, Co. Wexford [S12]

On 11 February 1974, storm waves at Kilmore Quay, Co. Wexford, "tore a 35-ft [10.7 m] gap in the new concrete pier and sea wall." The harbour had undergone improvements only 16 months previously. Local fishermen said the high tides were recurring because of constant strong winds, and the islands of Inishbofin, Inisturk and Inisturbot were cut off (*The Irish Times*, 12 February 1974).

3.1.13 1979: Fastnet Race [S13]

The Fastnet race is a famous offshore yacht race that takes place every second year in August over 4–5 days, starting near the Isle of Wight in England, rounding the Fastnet Rock off the south-west coast of Ireland and finishing at Plymouth in England (see the dashed line in Fig. 2). The 1979 race began on 11 August, a sunny day in calm waters, but stormy conditions put competitors into great difficulty, resulting in 15 deaths, 24 boats lost or abandoned, and a total of 194 out of 303 boats not finishing. Rescue workers picked up 140 survivors (see Figs. 5 and 6).

Matthew Sheaha, one of the competitors, said about the conditions "[a] lot has been made out about the strength of the wind… but it was the sea state that was the real issue. The waves were… 40–50 ft [$\sim$ 12–15 m] tall and very steep sided, but coming from all kinds of different angles and breaking. It was like being in the middle of multiple avalanches. Quite extraordinary" (*BBC Sport*, 9 August 2009). A report on the exceptional weather during the race from Met Éireann (Met.ie-Fastnet, unknown) contains records of force 10 winds in some areas with recorded wave heights of 7.5 m off the coast of Waterford, and a maximum of 14.5 m. The report also describes how the weather system originated from a depression near Newfoundland late on the 11th that moved eastward and started to deepen rapidly on the 13th. This turned north-eastwards coming in over the south-west of Ireland late on the 13th and centring over Wexford early on the 14th. It was during this period (13th–14th) that the worst damage occurred. Records of the wind at the Fastnet Lighthouse show that south-south-easterly gales

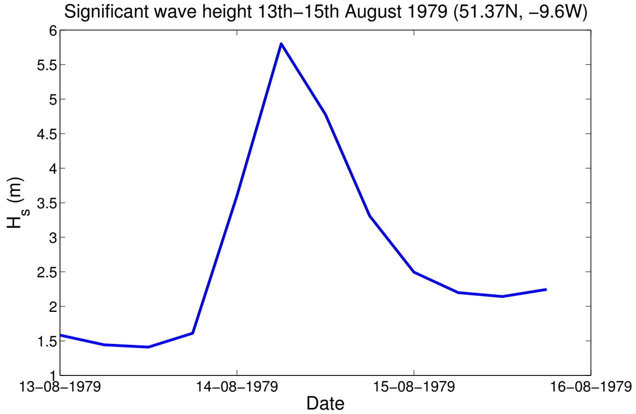

Fig. 7. ECMWF model data every 6 h from ERA-Interim reanalysis: significant wave height in the Irish Sea (51.37° N, −9.6° W) during the Fastnet Race 1979 disaster, 13–15 August.

were recorded ahead of the depression on the evening of the 13th, which became westerly storm force in the early hours of the 14th and developed into north-westerly gale force winds which eased during the afternoon.

Model data from the European Center for Medium-Range Weather Forecasts (ECMWF, 2012) by ERA-Interim reanalysis is shown in Fig. 7 (every 6 h) on 13, 14 and 15 August 1979. The data has been bilinearly interpolated to a latitude/longitude position of (51.37° N, −9.6° W), which lies approximately 2 km south of Fastnet Rock. The significant wave height peaks at 5.8 m on the morning of the 14th at 6 a.m. (local time). Reanalysis is a process by which a numerical model and observations of many different sorts are combined in an optimal way to produce a best estimate of the various atmospheric, wave and oceanographic parameters. The ERA-Interim reanalysis is the latest global atmospheric reanalysis produced by ECMWF.

Clearly, the driving force of this disaster was the storm that came in across the Atlantic, and so most of the waves encountered were large storm waves. However, rogue waves cannot be ruled out given the indications of the significant wave heights of 5.8–7.5 m (Met Éireann and ECMWF) and reports of maximum wave heights approximately twice as high 12–15 m (Met Éireann and Matthew Sheaha).

3.1.14 1982: Co. Kerry [S14]

In October of 1982 "huge waves…split open the wreck of the Spanish container ship, *Ranga*" off the cliffs near Coumeenole Beach, in Ventry, Co. Kerry (*The Irish Times*, 16 October 1982).

3.1.15 1985: Fastnet Rock lighthouse [S15]

In 1985, the Fastnet Rock lighthouse keeper at the time, Dick O'Driscoll, recalls a storm wave reaching as high as the light and crashing through the glass, sending the poisonous vat of mercury pouring down the stairs. The Fastnet light stands 49 m above mean sea level. He said that suddenly afterwards there was a great calmness (*The Economist*, 18 December 2008 and www.cil.ie).

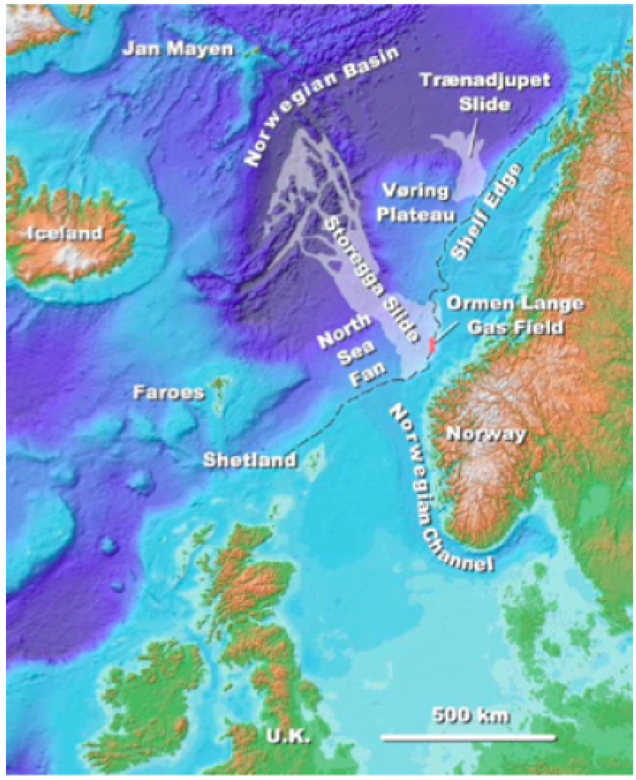

Fig. 8. Figure taken from Bryn et al. (2005) showing the location of the Storegga submarine slides on the mid-Norway margin.

3.2 Tsunamis

3.2.1 14 680 BP: the Barra Fan and Peach Slide, off north-west coast of Ireland [T1]

A large underwater landslide, called the Peach Slide, took place on the Barra Fan, about 250 km off the north-west coast of Ireland (see Fig. 1 for location). Holmes et al. (1998) suggest that four large-scale submarine landslides make up the Peach Slide.

Owen et al. (2010) sampled and analysed cores from the area. They concluded that the Peach 4 debrite, the most recent in a series of large-scale mass transport deposits, has a minimum age of 14 680 yr BP, was formed through a combination of blocky and muddy debris flows and affects an area of 700 km^2. This is about 3/4 the size of Dublin county.

A landslide of such proportion could very well have generated a large-scale tsunami that would have undoubtedly reached Irish shores given its location.

Fig. 9. Petrified forest, Bray, Co. Wicklow.

Fig. 10. Petrified forest, Bray, Co. Wicklow.

3.2.2 8200 BP (before 1950): Storegga Slide [T2]

The Storegga Slide is one of the world's largest known submarine landslides and occurred off the west coast of Norway generating a huge tsunami (see Fig. 8). Recent studies such as that from Bryn et al. (2005) estimate that the slide removed between 2500 and 3500 km^3 of sediment from the slide scar approximately 8200 yr BP. It is thought that inundation was as high as 30 m and reached Norway, Shetland, Scotland and the Faroes.

The length of the headwall of the slide scar is 290 km, and the slide travelled 300 km to the north-west down into the Norway Basin, and then more than 500 km beyond that in the form of a giant turbidity current (Bugge et al., 1988).

Rising sea level at the end of the last ice age cut Britain and Ireland off from the rest of Europe. Fossilised trees that once stood on dry land can been seen in Bray, Co. Wicklow, at low water (see Figs. 9 and 10). Numerous trigger mechanisms of the Storegga Slide related to the melting of the ice sheets have been proposed, including sediment overloading and earthquakes, while gas hydrate melting is likely to have influenced sliding locally (Bryn et al., 2005).

No reports of evidence of the tsunami reaching Irish shores have been found. However, given the location and size of the wave, it is possible that remnants of the wave reached Ireland, although Scotland would have sheltered Ireland somewhat.

3.2.3 1755, 1761, 1941 and 1975: the Lisbon, Portugal, tsunamis [T3]

On 1 November 1755 a magnitude 11 MMI (see Appendix A) earthquake struck Lisbon, Portugal, and created a tsunami that devastated Lisbon. The tsunami travelled to surrounding European and African countries but also reached countries as far as Canada and Cuba. In 1761 a magnitude 9 MMI (see Appendix A) earthquake struck Lisbon generating another tsunami. This event was not as devastating as the 1755 one, but the tsunami again travelled great distances, the furthest recorded being Barbados. Both tsunamis reached Irish shores (NOAA Tsunami Events Database).

An eyewitness account is given in Berninghausen (1968) from Kinsale, Co. Cork, on 1 November 1755: "Between 3 and 4 p.m., the water came over the quay with such violence as to throw many people down." In a letter from L. Nicola (on the same day) (Nicola, 1755–1756), Kinsale is described in more detail: "[A] large body of water suddenly poured into this harbour, with such rapidity that it broke the cables of two sloops, each moor'd with two anchors, and of several boats… carried up, then down, the harbour [...]. This was repeated several times [...]. The bottom of the harbour… was much altered… the perpendicular rise of the water… was five feet and a half [1.7 m]… and I am told it was much higher at the market-place, which it overflowed [...]. The successive risings and fallings of the water continued about ten minutes [...]. By different accounts received here the water was affected in the same manner along the coast, to the westward of this harbour, and it is reported, that, about nine o'clock in the morning a shock of an earthquake was felt at Cork."

Larkin (2010) relays the effects of the tsunami on Innishannon, Co. Cork. The wave rushed up the estuary of the Bandon River towards the town, the original bridge being completely destroyed. He says that the Bandon River was originally navigable from Kinsale up as far as Bandon town, but the tsunami permanently lowered the depth of the river (see third inset in Fig. 2). Larkin says that the course of the river allegedly changed through Innishannon Village, and the sand deposits at The Warren in Rosscarbery and the sand dunes at Long Strand at Castlefreke are a result of the tsunami.

Traditionally, the 1755 tsunami is thought to have separated the small island of Aughinish, on the southern shores of Galway Bay from Co. Clare, and the Norman castle of

Corranrue supposedly became victim of the same inundation (*The Irish Times*, 14 January 2005). Further south, the sand dunes at Barleycove in Co. Cork are believed to be a direct result of the tsunami (cork-guide.ie, 2012). Also, it is believed that the Spanish arch in Galway was damaged by the 1755 tsunami (galwaytourism.ie, 2012).

The 1761 tsunami occurred late on the 30th of March, and five run-up (the run-up is the tsunami amplitude when it hits the shoreline and is defined as the wave height above the mean high tide level) observations in Ireland at Kinsale, Waterford, Dungarvan and Newross are listed in NOAA Tsunami Events Database for the following day (see third and fourth insets of Fig. 2 to locate these places). In Kinsale, a run-up of 0.6 m was recorded: "[A]bout six o'clock p.m. near dead low water, the tide rose suddenly on the strand, about two feet [0.6 m] higher than it was, and went out again in the space of four minutes with great force, which was repeated several times; but the first was the greatest." In Waterford, Co. Waterford, "[t]he sea advanced 30 feet [9.1 m] on the shore." In Dungarvan, Co. Waterford, "five ebbings and flowings of the sea were observed between 4 and 9 p.m." At Ross, [Newross] Co. Wexford, "a violent agitation of the river there took place about 7 p.m." In Carrick, Co. Antrim, a run-up of 1.2 m was observed: "[T]he waters of the river Suir rose about 4 p.m. to extent of 4 feet [1.2 m] in the space of 5 min." Also in Cork City, Co. Cork, an earthquake was felt for less than a minute; "between the gates of the city it was more violent than that of November 1755" (Borlase, 1830).

More recently, in 1941 and 1975, there were earthquakes in the same area near Portugal and small tsunami waves were recorded by the tide gauge at Newlyn, located on the southwest corner of England. The tide gauge records from Dawson et al. (2000) are shown in Figs. 11 and 12.

3.2.4 1767: the River Liffey, Dublin [T4]

Run-up observations on the River Liffey, Dublin, on 5 September 1767 are listed both in the RAS Historical Tsunami Database (1.8 m) and in the NOAA Tsunami Events Database (1.5 m). There is no known cause for this, and it is listed as a questionable tsunami and very doubtful tsunami in each database, respectively. However, it is interesting to note that a run-up of 1.5 m is also listed on the NOAA Tsunami Database in Ostend, Belgium, on the same day.

3.2.5 1841: Kilmore, Co. Wexford [T5]

The RAS Historical Tsunami Database lists a questionable tsunami on 12 September 1841 at Kilmore, Co. Wexford. The cause is unknown.

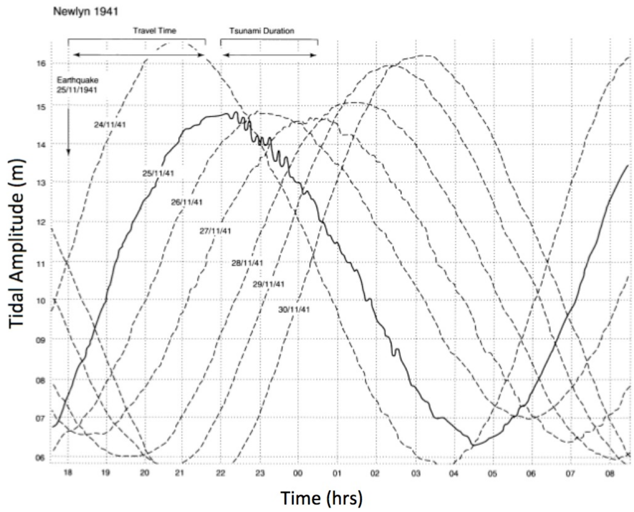

Fig. 11. Figure taken from Dawson et al. (2000). Hydrograph showing the arrival of the 1941 Portuguese tsunami at Newlyn, Cornwall (solid line), and the tide gauges on previous and subsequent days (dashed lines) (source: Proudman Oceanographic Institute).

3.2.6 1854: Kilmore, Co. Wexford [T6]

The RAS Historical Tsunami Database lists a questionable tsunami in Kilmore, Co. Wexford, on 16 September 1854 (currently listed as 1864 but to be corrected).

At the harbour in Kilmore, Mr. William Campbell gives an account of the "Phenomenon at Kilmore" as he saw it from his boat: "[O]n a sudden I heard a mighty rush of water against the back of a pier, and in a moment it came sweeping round the pier head, full three feet [1.5 m] high and abreast [...]. The inner dock was crowded with the small sailing craft of the place, and quite dry [...]. In less than five minutes every boat was afloat and we had high water. In five minutes more the water ebbed again to the lowest spring tide. This was repeated seven times in the course of two hours and a-half. St. Patrick's Bridge was alternately dry and covered to the extent of a mile. At the same time the sea was not by any means rough or heaving. . . two different currents running parallel and counter currents to these quite visible,. . . and the intervening colour of the original green hue, was stationary [...]. I can only compare the current to the opening of a sluice gate [...]. Had the occurrence taken place at the period of high water, the result would have been the complete overflow of the land in the district and consequent immense loss." The journalist interviewing Mr. Campbell concludes, "We have often heard old people of that place say that on the Sunday after Lisbon was destroyed by the earthquake of 1 November 1755, the day being remarkably fine, the sea at Kilmore suddenly rose and fell in like manner" (*Nation*, 30 September 1854).

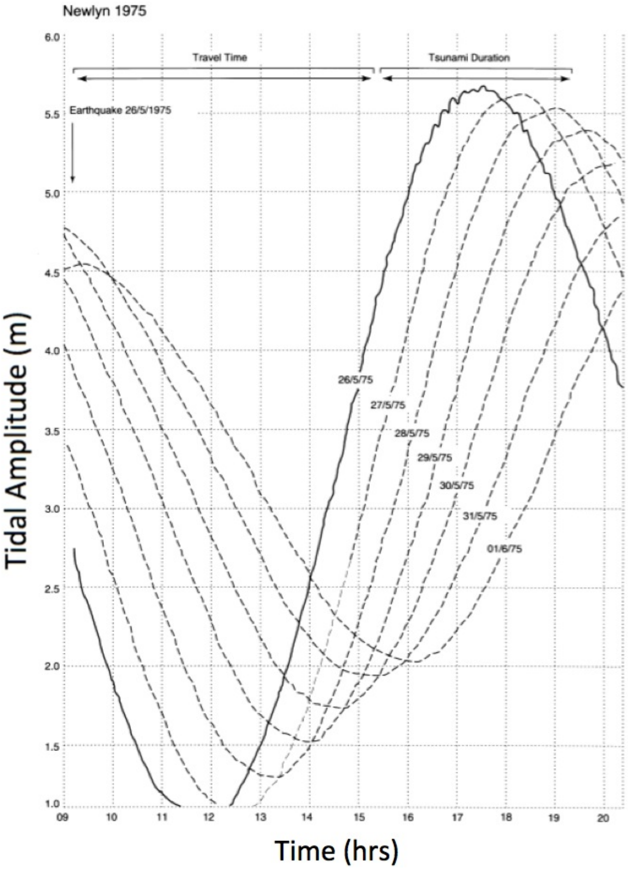

Fig. 12. Figure taken from Dawson et al. (2000). Hydrograph showing the arrival of the 1975 Portuguese tsunami at Newlyn, Cornwall (solid line), and the tide gauges on subsequent days (dashed lines) (source: Proudman Oceanographic Institute).

3.2.7 1894: Galway Bay [T7]

On 21 November 1894, a 12 m wave hit Galway Bay. It is listed as a probable tsunami caused by a volcano in the middle of the North Atlantic on the NOAA Tsunami Events Database (this is why we list it in this section), but we have not found any evidence for the presence of this volcano. An eyewitness account reads "the ship 'S.S. *Diamond*' lying-to awaiting daylight to enter port, reported that the wave was heard some time before it was seen and then seemed to be about 40 feet [$\sim$ 12 m] high. The vessel never rose to it but was literally submerged for a time" (Berninghausen, 1968).

A newspaper report described the incident as follows: "During a gale…the S.S. *Diamond* was attacked by a tremendous sea, which carried away her davits and boats, also the upper bridge, and smashed the lower bridge, broke the funnel, and carried away the mizzen mast. The cargo shifted, and the vessel was thrown on her beam ends. One of the sea men was washed overboard, but was thrown back on deck by a wave. The captain was thrown down." Also, another steamer that was coming in at the same time went missing. "She was seen by the crew of the S.S. *Diamond* before the wave struck the latter, but not afterwards. It is feared she has gone down with all hands" (*The Irish Times*, 24 November 1894).

Initial.	Ship's name.	Local time.	Date.	Latitude. North.		Longitude. West.		Speed.	Ship's course.	Wave's course.
				°	′	°	′	Knots.		
F	*Faraday* … …	6 45 a.m.	14/2/84	46	11	27	53	6	N. 72° E.	Port beam.
W	*Westernland* …	2.45 a.m.	27/11/86	47	59	43	57	7	S. 60° W.	Bow.
G	*Germanic* … …	9.40 a.m.	5/5/87	50	36	22	8	4	N. 68° W.	Bow.
U	*Umbria* … …	4.40 a.m.	26/7/87	50	50	27	8	16	S. nearly W.	3 points on starboard bow.
	H.M.S. *Orontes*..	5 p.m.	18/2/91	36	12	32	50	9	?	Bow.
L	*Festina Lente* …	noon.	16/11/94	50	12	35	23	?	S.E. by S.	?
M	*Manhattan* … …	2 a.m.	17/11/94	51	26	27	31	?	S. 86° W.	N.W.
D	*Diamond* … …	10 p.m.	21/11/94	53	9	9	52	Lying to	W.N.W.	W.N.W.

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Fig. 13. Table taken from Stromeyer (1895).

Stromeyer (1895) gives information about the wave encountered by the S.S. *Diamond* and waves encountered by two other ships, the *Festina Lente* and the *Manhattan*, in the North Atlantic within a few days of each other (see Fig. 13). The *Festina Lente* encounter is described as follows: "A steep sea fell on board from both sides." For the *Manhattan*, "[t]he sea was high, but fairly true until a mountainous wave broke on board from N. W."

The locations of the three ships and the volcano are shown in Fig. 14. Using the locations and times of the three events, an estimate of the period of waves travelling between the ships was calculated using deep water wave theory. If the wave was a tsunami, we should use the shallow water wave theory, but the results obtained below with deep water wave theory are quite realistic. The difference in distance dx and time dt is deduced from Fig. 13. The group velocity of the wave is then taken as $c_g = dx/dt$, and the period is given by $T = (4\pi/g)c_g$.

A wave travelling between the *Festina Lente* and the *Manhattan* would have a period of approximately 15 s, which is characteristic of a storm wave. However a wave travelling between these two ships and the S.S. *Diamond* in Galway Bay would need to have a period of 4–5 s. Therefore, it is probable that the *Festina Lente* and the *Manhattan* encountered the same wave system generated by a storm, but the S.S. *Diamond* encountered a different wave. We discard the possibility of a tsunami generated by the volcanic eruption for at least two reasons: (i) we found no evidence for the volcanic eruption, and (ii) a tsunami is barely felt in the middle of the ocean.

3.2.8 1922: Ballycotton, Co. Cork [T8]

A large wave caught out a farmer and two labourers as they were planting potatoes 250 yards from the shore near Ballycotton, Co. Cork, in early May 1922: "[A] huge…wave suddenly came on them, overwhelming the farmer, and making it a narrow escape for the others. The wave receded as quickly

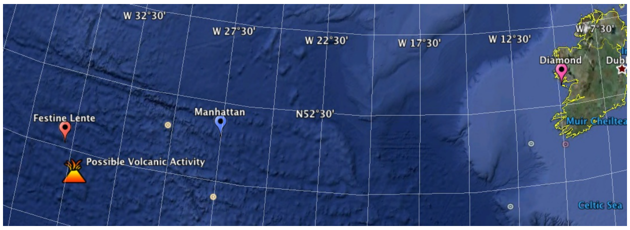

Fig. 14. Map from Google Earth showing locations of the three ships for the 1894 events and the volcano. The coordinates of the ships are: *Festina Lente* (50°12′00″ N, 35°23′00″ W), *Manhattan* (51°26′00″ N, 27°31′00″ W), and S.S. *Diamond* (53°09′00″ N, 09°52′00″ W). The volcano activity is in the vicinity of 49° N, 34.5° W.

as it came, leaving the men in a state of wonder" (*The Irish Times*, 3 May 1922).

Interestingly, an earthquake in Puerto Rico is documented on NOAA Tsunami Events Database at 8:24 p.m. (GMT −4) on 2 May 1922. A questionable tsunami due to an earthquake is logged with two documented run-up observations. The first is an eyewitness report of a train of three waves with a period of 45 min at Vieques Island, Puerto Rico, followed eight hours later by a similar train of smaller waves. The second was a water height of 0.64 m from a tide gauge in Texas over 3000 km away. Maybe this was the source of the wave in Cork. Using ETOPO1 bathymetry data, the average water depth along the line connecting Puerto Rico and Ballycotton was calculated as 3.553 km using 100 points. Assuming that the wave travelled across the Atlantic over this depth, it would have an average speed of $\sqrt{gh} = 186.6\,\mathrm{m\,s^{-1}}$ according to shallow water theory. Given that the distance from Puerto Rico to Ballycotton is approximately 6217 km, the tsunami would have reached Ballycotton after about 9 h and 15 min, so at approximately 09:40 the following morning.

3.2.9 Meteo-tsunamis and storm surges

1909: Westport Quay, Co. Mayo [T9]

In November 1909 an unusual wave and flooding occurred in Westport Quay. Eyewitness Lyons (1993) describes how he and his brother and father were travelling by horse and cart when they heard a "loud rumbling noise like thunder." The road flooded, splitting the wall, and the sea was "throwing these concrete blocks as if they were pebbles." They later learned that "the entire road all the way to Rosbeg was strewn with large pieces of broken sea-wall." About a hundred yards down the road they were ploughing "through four feet [1.2 m] of water which had now reached the body of the cart." Further down the road "there was a sudden surge of water" that lifted them in the air and threw them against the wall. Afterwards the road was covered with pieces of broken sea wall, timber and the contents of the local hotel. Boats also lay on the road and thousands of tons of sugar and treacle were destroyed along with many other food and clothing supplies. He notes that there was a dead calm everywhere and unusually the "telegraph wires leading towards the town were making a peculiar kind of high, screaming noise." This description could imply that the source of the wave was atmospheric, like that of the 2011 tsunami on the south-west coast of England when people described there being a dead calm, and their hair standing on end.

Another interesting feature of the location of this event is that it occurred in Clew Bay. A multitude of sunken drumlins (glacial landforms) are a distinctive characteristic of this area. This may have funnelled and amplified the wave that inundated Westport Quay in 1909. See the second inset of Fig. 2 for a satellite view of Clew Bay.

1910: Cork and Waterford [T10]

In mid-December of 1910 a "Tragedy at Sea" occurred resulting in the loss of five vessels. The ships that left Waterford and Cork on 15 December 1910 were reported as lost. They were headed to Jersey, Dublin and Southampton. It was suggested that they had been "enveloped by a... wave off the South-West coast" after a message was sent to Dublin that "a... wave had been observed by the people at the Tuskar Lighthouse, Wexford on the night of the 15 December." On the 16th "a gale raged with exceptional fury" off the south coast of Ireland (*The Irish Times*, 25 February 1911).

Haslett and Bryant (2009) give details of the major storm that occurred on 16 December 1910, accompanied by a unique large wave that struck Ilfracombe in North Devon. They claim that the wave possessed tsunami characteristics and could possibly have been a meteo-tsunami related to the excitation of large-amplitude seiches in a semi-enclosed water body, such as the Bristol Channel. The locations of the origins (Waterford and Cork) and the supposed destinations of the 5 vessels in December 1910 (Dublin, Jersey and Southampton) are shown in Fig. 2. Ilfracombe, Devon, where an unusually large wave struck, is also indicated.

1912: Bray, Co. Wicklow [T11]

Local residents in Bray, Co. Wicklow, believed they experienced a tsunami on 6 March 1912. They reported that the sea rose, flooding the esplanade 6 feet (1.8 m), and the weather was not stormy at the time. They also mention feeling a shock like an earthquake, which some attributed to the force of the waves against the sea wall. Also, it was said that along Bray Head "a huge mass of large paving stones was lifted up and carried on the walk to a height of three or four feet [1.1–1.5 m]" (*The Irish Times*, 20 March 1912 and 22 March 1912). However, a report a few days later (*The Irish Times*, 25 March 1912) put the event down to "an extraordinarily high tide", and although the heavy seas flooded the road, it said "[n]one of the cottages was flooded and the biggest paving-stone that was shifted by the seas was not heavier than 5lb weight." It also reported that the fishermen "attributed the flood to the high spring tide", although a telegram from respected seismologist Rev. Wm. O'Leary of Mungret College, Limerick is relayed in the same article indicating that an earthquake did in fact occur: "One small earthquake at 24 p.m. [midnight], 7th. Tremor. Storm experienced [between the] 5th to 8th would equally mask small disturbance." This indicates that there was an earthquake around the time of the flooding which may suggest a tsunami, but there is also evidence of a strong storm which could have caused a storm surge (*The Irish Times*, 25 March 1912). Furthermore, there is no record of any seismic activity around this time on Dublin Institute of Advance Studies earthquake listings (DIAS, 2012). Finally, we emphasize that there is no tide data available for Bray in 1912!

This event could be an example of an interaction between a tsunami and a storm surge.

3.2.10 1932: Inishowen, Co. Donegal, and Strabrega Bay [T12]

Multiple incidents occurred during "Violent Gales" across the country in January 1932. In particular Inishowen, Co. Donegal, experienced a "tremendous storm of wind and rain [...]; the tide... rose to a height not seen for very many years." In Strabrega Bay the tide was like a "tidal wave which ran inland high up the surrounding fields, into the farm yards, and even into the farm houses." Then the wind dropped suddenly, and within 45 min it was calm (*The Irish Times*, 15 January 1932).

3.3 Rogue waves

3.3.1 1852: Inis Mór, the Aran Islands [R1]

On 16 August 1852 a "Melancholy Accident" occurred at the Glasson Rocks on Inis Mór resulting in the loss of fifteen lives. A group were fishing on the cliffs when " a sudden swell of the Atlantic swept them off, when they perished before the slightest assistance could be rendered" (*The Galway Vindicator*, 18 August 1852).

3.3.2 1883: Youghal [R2]

In April 1883, "An Extraordinary Occurrence" occurred in Youghal Harbour, Co. Cork, when the water was "suddenly agitated in a most violent manner for about ten minutes... accompanied by a roaring sound." It was a localized event since some of the boats "appeared to have been struck by a furious hurricane", but others a few hundred yards away were not affected. Afterwards the water calmed down, and it was described by a sailor as "one of the most extraordinary things he has ever seen in the harbour [...]" (*The Irish Times*, 28 April 1883).

Fig. 15. L.E. *Róisín* (source: www.military.ie/naval-service/fleet/large-patrol-vessel/le-roisin-p-51).

3.3.3 1899: Kilkee, Co. Clare [R3]

In July 1899 a "Marvellous Escape From Drowning" occurred in Kilkee, Co. Clare, when a wave came out of nowhere. While a man was teaching his son how to swim, "an enormous... wave burst with extraordinary force over the adjoining rocks, completely submerging the two bathers in a cauldron of foaming water, and whirling them round for a considerable distance." Another man was also washed off the rock (*The Irish Times*, 22 July 1899).

3.3.4 1914: Iniskeeragh, off Donegal [R4]

In February 1914, the small island of Iniskeeragh, lying off Arranmore, off the Donegal coast, was hit by a huge wave. Reports said the island was "almost entirely submerged" and that the residents heard a roar of water before it arrived. There was severe loss of property (*The Irish Times*, 20 February 1914).

3.3.5 1936: Dundalk, Co. Louth [R5]

On 4 July 1936 two unusually large waves were observed in Dundalk, Co. Louth. Local fishermen first thought they saw "whales, approaching rapidly up the seaway", but it turned out to be "immense waves, which rushed at great speed" and made a "clean sweep on both banks" (*The Irish Times*, 6 July 1936).

3.3.6 1972: Donegal [R6]

On 13 July 1972, four schoolgirls were swept away by "a freak wave" at Mullaghderg Beach, near Kincaslagh, Donegal. A group of 200 school children had been swimming with their teachers at the beach which is "normally regarded locally as reasonably safe but subject to fast moving waters and dangerous undercurrents under certain tidal and wind conditions." The incident occurred when two of the teachers got into trouble and the children "formed a human chain" to try

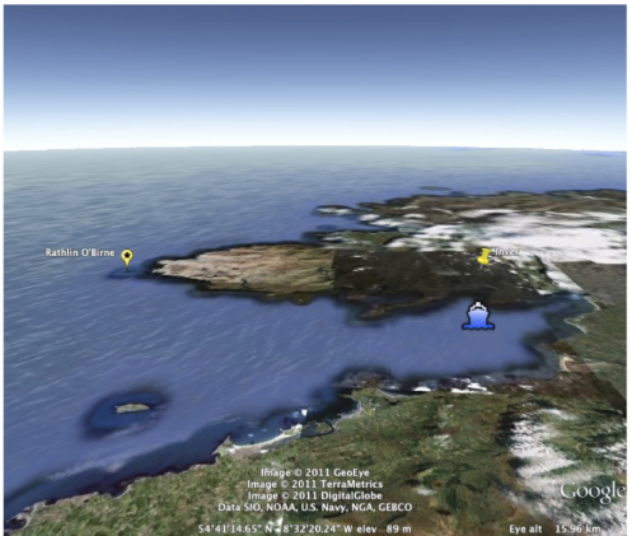

Fig. 16. The approximate location of L.E. *Róisín* (boat) when it received the pan-pan broadcast, and the location of Rathlin O’Birne Island close to where L.E. *Róisín* encountered the two waves.

Fig. 17. Rathlin O’Birne Island.

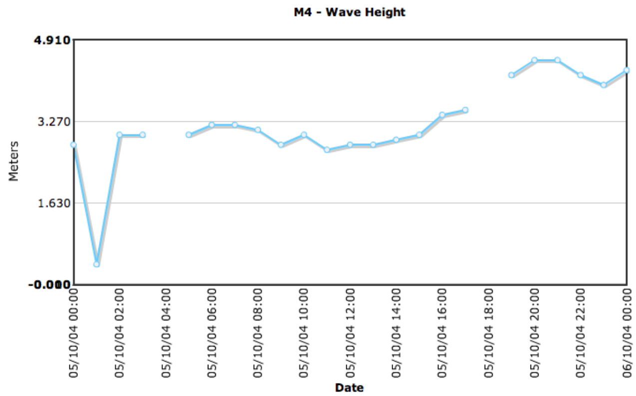

Fig. 18. M4 data buoy significant wave height readings on 5 October 2004 from www.marine.ie/home/publicationsdata/data/IMOS/IMOSDBObservations.htm.

to help them but the wave broke the chain and swept the four girls away (*The Irish Times*, 14 July 1972).[1]

3.3.7 2004: L.E. *Róisín*, off the coast of Donegal [R7]

On 5 October 2004, an Irish naval ship was hit by two rogue waves on its way to help a Canadian submarine, HMS *Chicoutimi*, that got into trouble when a serious fire broke out. L.E. *Róisín* (see Fig. 15) had taken shelter in Donegal Bay near Inver due to bad weather when it responded to a pan-pan broadcast. See Figs. 16 and 17 for location. Captain Lt. Cdr. Terence Ward gave an eyewitness account for the purpose of this research. There was a gale of about force 8 to 9 and a heavy swell with waves approximately 3 to 4 m. As they came around Rathlin O’Birne Island, the ship began to climb a very large wave, pivoted on the crest, then fell down the other side and plunged into a second large wave. About one third of the ship was submerged for a time, until the buoyancy pushed it back up through the wave. The two waves were approximately 10–12 m with a very short period. The windscreen wipers were all detached, the flare cracked and a piece of the deck broke away allowing water to get in. A decision was made to turn back for repairs.

Furthermore, an inquiry concluded that the fire on board the HMS *Chicoutimi* was caused by a wave, much higher than the four meter sea state, that overflowed the tower which was open during repairs (Murphy et al., 2004).

The M4 data buoy located about 75 km off the north-west coast of Ireland (see Fig. 2) recorded significant wave heights of ≤ 4.5 m and wind speeds ≤ 27 knots on the day of the incident (see Figs. 18 and 19). However, it also recorded maximum gusts of up to 47 knots (see Fig. 20).

The ECMWF global wave model (ECMWF, 2012) estimates a significant wave height of ≤ 3.6 m at Rathlin O’Birne Island (54.66° N, −8.8° W) on 5 October that year, which is in line with the sea state described by Lt. Cdr. Terence Ward. A 10–12 m wave definitely indicates a rogue wave in these circumstances. Possible causes may have been the strong gusts of wind or the tidal streams and bathymetry around Rathlin O’Birne Island (a possibility suggested by Lt. Cdr. Ward).

3.3.8 2006: off Portrush, Co. Antrim [R8]

On 21 May 2006 a 15 foot fishing boat “was capsized and totally destroyed by a freak wave” just off the coast of Portrush, Co. Antrim. The unpredicted wave overturned the boat, trapping the fisherman underneath it. Luckily he managed to free himself and was close enough to swim to the shore without injury (*The Belfast Telegraph*, 22 May 2006, and *Coleraine Times*, 25 May 2006).

[1] An anonymous referee suggested that the wave might have been created by a rip current.

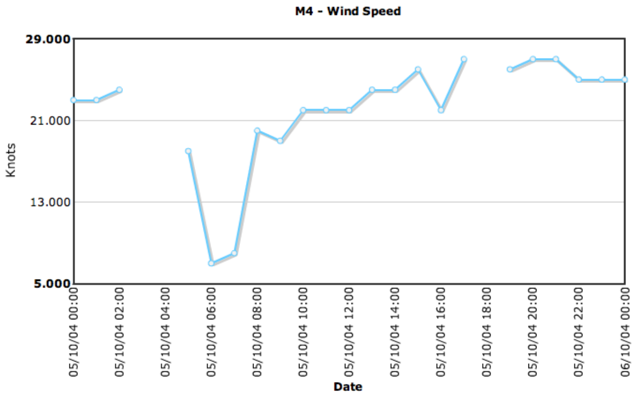

Fig. 19. M4 data buoy wind speed readings on 5 October 2004 from www.marine.ie/home/publicationsdata/data/IMOS/IMOSDBObservations.htm.

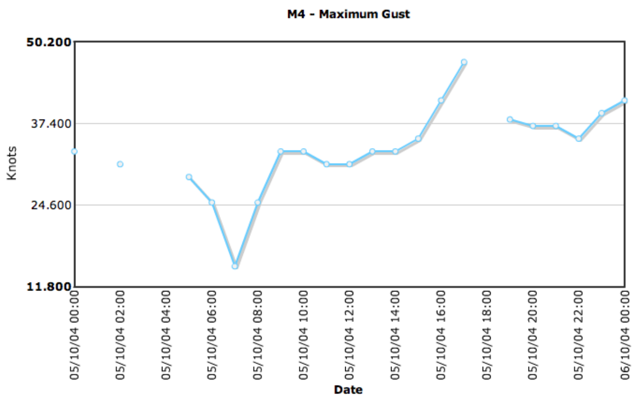

Fig. 20. M4 data buoy maximum gust readings on 5 October 2004 from www.marine.ie/home/publicationsdata/data/IMOS/IMOSDBObservations.htm.

The M2 data buoy located in the Irish Sea (see Fig. 2) recorded significant wave heights ≤ 1.5 m on 21 May 2006. Furthermore, the M2 recorded wind speeds of ≤ 22 knots with maximum gusts of ≤ 29 knots. This suggests that there were not gale force winds on the given day. However, it should be noted that Portrush lies at the more exposed north coast of Ireland and the M2 data buoy is in a more sheltered position in the Irish Sea. Additionally, the ECMWF global wave model (ECMWF, 2012) estimates the significant wave height that day to be ≤ 1.42 m using bilinear interpolation to a position off the coast of Portrush (55.38° N, −6.67° W). If the waves were approximately 1.5 m on the day of the incident, then a 3 to 4.5 m wave could be considered a rogue wave.

3.3.9 2006: Ardglass, Co. Down [R9]

A man was swept away by a wave as he leaned on a pier wall at the harbour talking to local men in Ardglass, Co. Down, on 2 December 2006. The wave "swept over the pier and dragged him into the waves." The wind was particularly bad at the time, blowing with gale force in Ardglass (*The Irish Independent*, 4 December 2006). Gusts of up to 64.8 knots and storms were reported across the country caused by a deep depression from the Atlantic (*The Irish Times*, 4 December 2006).

The ECMWF global wave model (ECMWF, 2012) estimates significant wave heights of ≤ 2.43 m using bilinear interpolation to a position on the coast off Ardglass (54.26° N, −5.6° W).

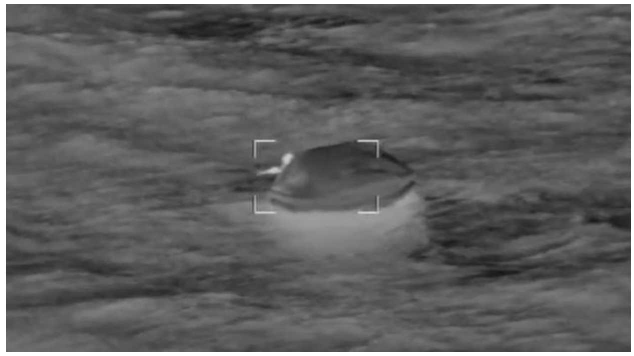

Fig. 21. *Swanland* rescue (image from BBC news, 11 December 2011 www.bbc.co.uk/news/uk-16055328).

3.3.10 2007: Doonbeg, Co. Clare [R10]

A Moldovan man died while fishing in the Blue Pool area of Doonbeg, Co. Clare, on 1 July 2007. It is thought that a wave swept him off the rocks. The coastguard said that weather conditions were bad at the time but that the area is "notorious for freak waves" (*RTE News*, 1 July 2007).

Information from the M3, M4 and M6 data buoys (see Fig. 2) show that the significant wave height that day was ≤ 4.7 m, with the largest value occurring at the M3. Also, the maximum recorded values for wind speed and maximum gusts at the three buoys considered occurred at M3 with values of 20 knots and 29 knots, respectively.

3.3.11 2007: Valentia Island, Co. Kerry [R11]

On 13 July 2007, internationally renowned rock climber Michael Reardon was swept away by a large wave as he stood on the ledge of an inlet around the bottom of Wireless Point merely 15 feet [4.6 m] above the Atlantic. After Reardon finished his two cliff climbs, his photographer who was with him at the time said he "was waiting on an algae-covered platform for the big swells to pass by so that he could walk back over to me on the opposite side of the inlet. A rogue wave came into the inlet and curved rightwards as it crashed into Mike. He tried to stabilize himself on the platform but the water was too powerful and sucked him in. The current pulled Mike out 150-plus meters in mere seconds" (*Los Angeles Times*, 19 July 2007).

Fig. 22. *Swanland* (image from BBC news).

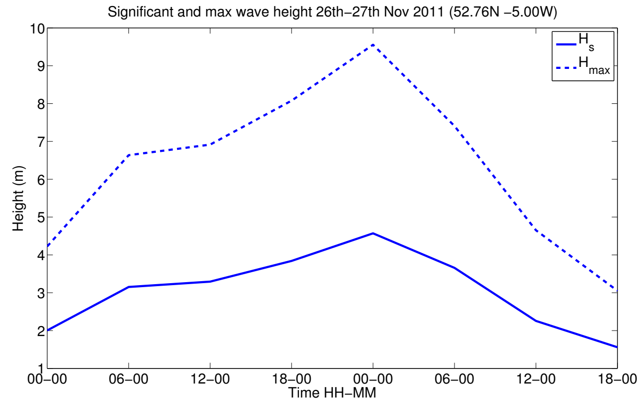

Fig. 23. ECMWF global wave model 6-hourly output of significant and maximum wave heights, H_s and H_{max}, respectively, bilinearly interpolated to a location in the region where the *Swanland* sank (52.76° N, −5.00° W) on 26–27 November 2011.

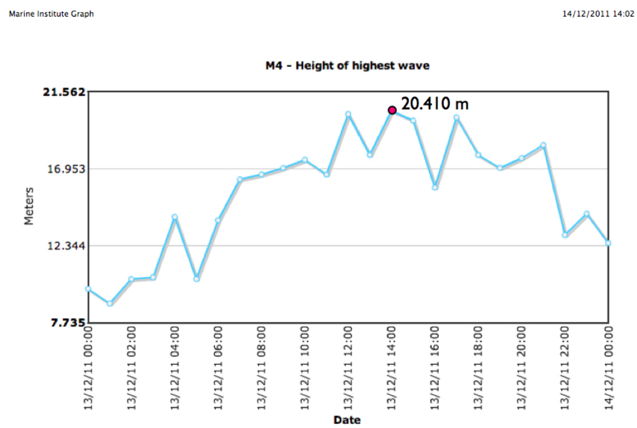

Fig. 24. Marine Institute's data for maximum wave height at M4 weather buoy on 13/12/11. Retrieved from www.marine.ie/home/publicationsdata/data/IMOS/IMOSDBObservations.htm.

The M3 data buoy (see Fig. 2) recorded significant wave heights ≤ 2.5 m on this day with wind speeds ≤ 18 knots and maximum gusts of up to 25 knots. Therefore, the waves were probably not very high at the time, so a 5 m wave could be considered a rogue wave.

3.3.12 2011: Cargo Ship, *Swanland*, the Irish Sea [R12]

On 27 November 2011, the 81 m cargo ship, *Swanland* loaded with 3000 tonnes of limestone sank in heavy seas in the Irish Sea after she was struck by "an enormous wave", rolled and broke her back (see Figs. 21 and 22). The *Swanland* sank off Bardsey Island about 16 km west of the Llŷn Peninsula, North Wales, at approximately 2:20 a.m. (*BBC News*, 27 November 11). The wave was reported to be 15 m (RAF, 2011). There are only two known survivors from the eight originally on board the ship.

The closest Irish data buoy to the *Swanland* when it was hit is the M2, which is positioned north-west (see Fig. 2) of the incident. It recorded significant wave heights of only ≤ 3.2 m over the 2–27 November 2011. The M5 data buoy, which lies south-west of the incident, recorded significant wave heights of ≤ 4.6 m over the same period. However, the M2 also recorded maximum wave heights (hourly), and the largest recorded was 4.8 m. It also recorded wind speeds and maximum gusts of ≤ 28.7 knots and ≤ 42.35 knots, respectively.

The ECMWF global wave model (ECMWF, 2012) estimates significant wave heights of ≤ 4.57 m over the 26–27 November 2011 when bilinearly interpolated to a position in the region where the *Swanland* sank (52.76° N, −5.00° W). However, the model also gives a maximum wave height output, and this gave values up to 9.55 m. The largest values of both significant and maximum wave heights occur at midnight on the 26th, and considering it is a 6-hourly output, this coincides well with the time the wave struck at approximately 2 a.m. on the 27th (see Fig. 23).

3.3.13 2011: largest wave ever recorded in Ireland [R13]

On 13 December 2011 the M4 weather buoy registered a 20.4 m wave (see Fig. 24) in a sea state with a significant wave height of 12.97 m. The M4 is located 75 km north of Belmullet on the north-west coast of Ireland (see Fig. 2). Since this is an hourly observation, we cannot tell exactly what happened leading up to this huge wave or afterwards. This information cannot be analysed until the full set of data is retrieved from the buoy which is only done twice a year. However, it could be useful in determining how the wave developed and whether or not it could be considered a rogue wave. Since the weather buoy network is relatively new (November 2000), it is likely that this is not the largest wave that has developed in Irish waters.

In fact, on 11 November 2010 the Belmullet wave buoy, owned by the Sustainable Energy Authority of Ireland, with access provided through the Marine Institute, recorded some

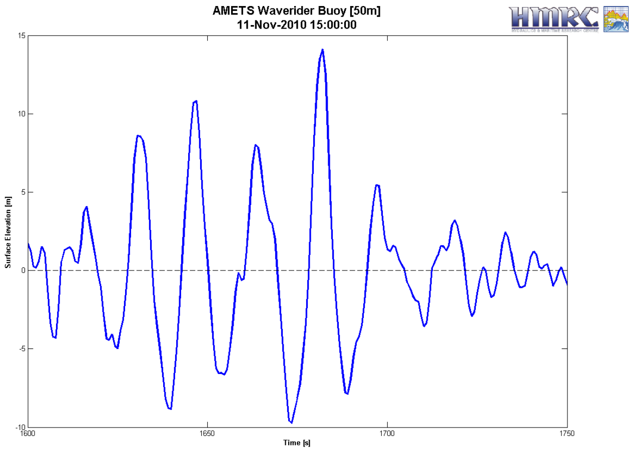

Fig. 25. Marine Institute's data for the free surface elevation at the Belmullet wave buoy on 11 November 2010. Retrieved from Brendan Cahill at HMRC, UCC. The time span of the data shown is 150 s. The surface elevation ranges from -10 m to $+15$ m.

extremely high maximum wave height values. Considering the zero down-crossing (trough–crest measurement) instead of the zero up-crossing (crest–trough, as the Marine Institute does), the extreme wave shown in Fig. 25 (B. Cahill, personal communication, 2012) can actually be considered to be 23.87 m (14.12 m–($-$9.75) m).

Note that wave buoys may actually be underestimating the crests of very large waves so it is likely that larger waves may actually have occurred in Ireland.

4 Other waves

4.1 Surf waves

As an island exposed on the west coast to the Atlantic, Ireland boasts some of the best big wave/tow-in surfing in Europe. Although surfing in Ireland is still a relatively recent development, it is attracting an international group of surfers. Some of the most famous big wave spots are listed below. Two of the most well known surf spots, Mullaghmore, Co. Sligo, and the Cliffs of Moher, Co. Clare, are shown in Fig. 2.

4.1.1 Aileen's Wave, off the Cliffs of Moher, Co. Clare

Aileen's Wave is named after "Aill na Serracht", meaning the "Leap of the Foals." This is Ireland's most famous big wave surf spot, located at the Cliffs of Moher, Co. Clare, and has been compared to world famous big waves such as Teahupoo in Tahiti, Jaws in Maui, and Belharra in France. Swells usually reach a height of about 8 m, but have been surfed up to 12 m. The wave is created by a submerged reef. The experience level given by yoSurfer (www.yosurfer.com) is "pros and nutters" (see Figs. 26 and 27 for images of the wave and its location).

Fig. 26. Aileen's Wave (from www.cliffsofmoher.ie).

Fig. 27. The Cliffs of Moher (from www.cliffsofmoher.ie).

4.1.2 Prowlers, off the coast of Mullaghmore, Co. Sligo

A surf spot deemed the "Prowlers" can be found about 3 km off the coast of Mullaghmore, Co. Sligo. Though the exact location has not been revealed by the group of surfers who first surfed the wave in 2009 (Neil Britton, Richie Fitzgerald, Mike Hamilton and Aaron Pierce), they describe the area as an underwater mountain that focuses the wave as it emerges from 40–50 m open ocean into approximately 2–3 m depths. However, because this area is usually affected by crossing swells, surfers must wait months at a time for good surfing conditions (www.northcore-europe.com/surf-videos.html).

See Figs. 28 and 29 for images of the wave and the surrounding area.

4.1.3 2011: Surf competitions

In February 2011, "Tow-in Surf Session", Ireland's first big wave invitational surf contest, was held in Mullghmore Co. Sligo. Wave heights reached 6–7 m (*Irish Independent*, 15 February 2011).

From 23 September to 2 October 2011, the European Surfing Championships were held in Ireland for the first time, in Bundoran, Co. Donegal.

4.1.4 2012 Big waves

Al Mennie and Andrew Cotton, two of the world's top big wave surfers, claim to have found two surf spots off Ireland that could produce 120 foot ($\approx$ 37 m) waves. One is off Donegal and the other off Antrim, both crashing down on

Fig. 28. Prowlers, off the coast of Mullaghmore, Co. Sligo (from http://blog.surf-prevention.com/2010/11/12/al-mennie-prowlers-irlande-surf-casque/).

Fig. 29. Mullaghmore, Co. Sligo.

rocky reefs at a depth as shallow as 5 feet (1.5 m). They say that 90 % of the waves are unridable, but they are waiting for perfect conditions which might only happen twice a year. Al Mennie said that he looked for the same characteristics in Ireland as that in the US and Hawaii, and now they have found waves in Ireland that are bigger and better and could be the biggest in the world. Unfortunately, they will not release the exact locations for safety reasons (*Irish Independent*, 9 January 2012).

4.2 Potential tsunami: Cumbre Vieja, La Palma, Canary Islands

Although no historical records exist of lateral collapses of island volcanoes, around the world evidence exists of this type of collapse in the form of scars on the seafloor. These types of events could pose a threat of catastrophic proportions because of the landslide and the subsequent tsunami that such collapses would generate. In particular, sea floor mapping around the Hawaiian Islands in the Pacific Ocean and the Canary Islands in the Atlantic Ocean have revealed these types of scars and landslide deposits. Research carried out by Stephen Ward (UC Santa Cruz) and Simon Day (UC London) suggests that Cumbre Vieja Volcano on the island of La Palma in the Canary Islands may experience a major volcanic slide along its western flank during a future eruption, potentially depositing 150–500 km^3 of rock into the sea.

The Cumbre Vieja has been the most active volcano in the Canary Islands for most of the past 125 000 yr; its peak lies 2 km above sea level and has average slopes of 15–20° (Ward and Day, 2001). Day et al. (1999) observe that the volcano has undergone major structural changes over the past several thousand years and argue that this is due to stress patterns associated with the growth of a detachment fault under the western flank. Ward and Day (2001) believe that a future eruption near the summit is likely to trigger a flank failure and conclude that the developing detachment underlies most if not all of the western flank of the volcano. They suggest that a wedge shaped slide block with dimensions (15–20 km) × (15–25 km) × (1–2 km) may break off and create a mega-tsunami that could propagate across the whole Atlantic basin.

They model the tsunami that could be generated by such a 500 km^3 slide block travelling at a maximum speed of 100 $m\,s^{-1}$, travelling 60 km out to sea over a period of 10 min, from the western flank of Cumbre Vieja. Run-up heights of the order of hundreds of meters are predicted around neighbouring Canary Islands within minutes of the slide. Waves 50–100 m in height are predicted to hit the African mainland within the first hour, while 5–7 m waves are expected to reach England and Spain within 3–6 h. La Palma Island blocks most of the radiation in this north-easterly direction. Along the coastlines of the Americas, waves up to 25 m are estimated approximately 6 h after the landslide occurs (see Fig. 30).

Note that for this simulation, the slide volume of 500 km^3 was a worst case estimate of how much material could potentially break away from the volcano, but the block velocity of 100 $m\,s^{-1}$ was not a worst case estimate and when this velocity is increased to 150 $m\,s^{-1}$ the maximum wave heights towards America double (Day, 2011).[2] For Ireland, the risk would be around the south and west coasts, and judging from Fig. 30, they would be of the same order as that of England (5–7 m). Since these type of events occur very rarely, approximately of the order of thousands of years, if Cumbre Vieja were to experience a major collapse it may not happen for a very long time. However, there is presently no way to accurately predict when it might happen.

4.3 Legends

Ireland has a rich literary tradition, and as might be expected, the ocean has played a central place in many of its myths and legends. Although there are clearly problems in making clear scientific associations between tales or legend and

[2] Recurrent debates take place in the tsunami community to discuss the validity of such high speeds.

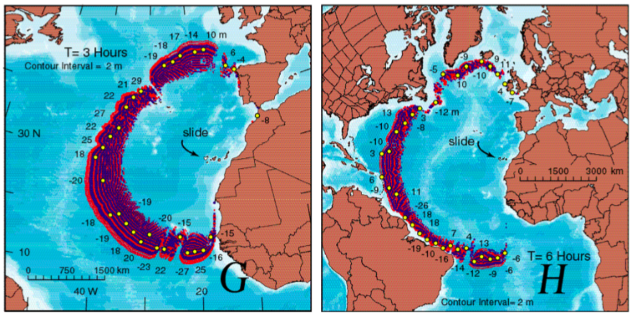

Fig. 30. Simulation of potential tsunami created by collapse of La Palma Island (snapshot of figure taken from Ward and Day (2001)).

specific wave classes, we include a short summary of legendary waves here for completeness.

4.3.1 The Creation of the Aran Islands

There is a tradition of the "bursting" of Galway Bay when the Aran Islands were joined to Clare by a sickle shaped peninsula. An area of flag and slate, like that of Moher, may have once extended towards Inisheer but was removed in early human times (*The Irish Times*, 18 July 1956). Irish annals record an incident between 799 and 804 AD: (i) "Violent thunder, accompanied by wind and fire, on the night before St. Patrick's Day, which destroyed many persons, i.e. one thousand and ten in Corcu Baiscinn; and the sea divided the island of Fita into three parts, and covered the land of Fita with sand, that is as much land as would support 12 cows" (U804.11, 2012). (ii) "There happened great wind, thunder, and lightning, on the day before the festival of Patrick of this year, so that one thousand and ten persons were killed in the territory of Corca Bhaiscinn, and the sea divided the island of Fitha into three parts" (M799.11, 2012).

4.3.2 The Buried City of Bannow

Legend has it that the island of Bannow, off the south coast of Wexford, appeared after the "Buried City of Bannow" had been engulfed by a wave in olden times (*The Irish Times*, 6 October 1951).

4.3.3 1014: The Battle of Clontarf

Legend has it that at "The War of the Gaedhil with the Gaill" one of Brian Boru's grandsons, Turlough, was killed when "the rushing... wave struck a blow against the weir of Cluaintairbh, and so he was drowned" (*The Irish Times*, 10 January 1961).

4.3.4 Kerry tsunami: "Bóthar na Scairte"

A folk tale related in Domahnall Ua Murchadha's story "Bóthar na Scairte" (Road of the Cataclysm) (Hayden, 2012) tells of the great hurler Clusach Ó'Fáilbhe, who was swept away "one fine summer's day" by a "terrible wave fifty feet [15.2 m] high." The legend says that he cried out as he was taken "there will be coals coming to Triagh Praisce ["beside Ballinaskelligs Island"] as long as I live in Gleann Smóil" and that half burnt sods of turf were washed up at Ballinaskelligs for fourteen years after. It is said that Skellig and Valentia were separated from the mainland after this event. Hayden (2012) describes how Domahnall Ua Murchadha justifies how "Bóthar na Scairte" was destroyed by an earthquake and tsunami.

4.3.5 >1670: Grafton St.

In a speech given in Georgian Dublin, a reference is made of a girl who was drowned "in a... wave at the foot of Grafton street" sometime after 1670 (*The Irish Times*, 21 February 1970).

5 Boulder deposits

Boulder deposits are of course not waves, but their presence provides impressive evidence for the impact of extreme wave events of some sort, and thus it is natural to include them in a catalogue of extreme waves, especially in an Irish context.

It is well accepted that boulders can be transported and deposited by the ocean and many examples can be found across the globe. However, the way in which this occurs is a controversial matter. Most research points to either storm waves or tsunamis as the source mechanism, though none of the research seems to consider rogue waves as a possibility. Bourgeois (2009), Dominey-Howes (2007) and Paris et al. (2009) give examples of boulder deposits documented all over the world. The standard mechanism for determining the initiation conditions of boulder transport is given by Massel and Done (1993) and Nott (1997, 2003). The basis of this condition relies on calculating the inertia, drag, lift and gravity forces acting on the boulder and determining when the clockwise torque is greater than the anticlockwise torque, thus initiating the boulder to turn.

In an Irish context, Hansom and Hall (2009) and Williams (2010) report accumulations of large boulders on cliff tops up to 50 m high on the deep water coasts. They attribute the emplacement of these megaclasts to extreme storm waves; in particular, Williams (2010) argues that there was no tsunami action involved. Hall et al. (2006) identify cliff-top storm deposits as ones that are typically located on exposed deep water coasts characterised by the presence of angular clasts > 1 m in diameter as boulder spreads or organised into cliff-top ridges. Cliff-top megaclast ridges on the west coast of Ireland demonstrate a pronounced imbrication on the seaward margins of the ridges. Williams (2010) attributes this organisation of boulders to the repetitive impact of large storm waves and suggests that storm waves are unlikely to transport such clasts more than a few tens of meters inland. Hall et al. (2006) characterise the waves that generate cliff-top boulder accumulations as ones that come from deep water offshore with full exposure to the storm and have limited onshore attenuation. Williams and Hall (2004) also point out that the waves impacting the cliff top where deposits are found in western Ireland have not been enhanced by constriction in bays and suggest that amplification of waves due to constructive interference of incoming waves with waves reflected from the cliffs may need to be considered. These effects have been demonstrated by Hu et al. (2000).

Despite the proven existence of extreme waves in the ocean greater than 35 m, none have been described as > 50 m, so an alternative mechanism of movement must be involved for the case of Ireland. Overtopping waves can be accelerated in a landward direction by high landward wind velocities. Kharif et al. (2008) showed that extreme wave events may be sustained longer by the air flow separation occurring on the leeward side of the crests. However, it has also been suggested that overtopping of waves on cliffs results in the formation of a landward moving high velocity bore which transports megaclasts (some tens of tonnes) across cliff-top platforms (Williams, 2010). Cox and Ortega (2002) demonstrated the downward collapse of overtopping waves onto a suspended platform experimentally and showed that the water column above the platform is transformed into a landward propagating turbulent bore with a velocity up to 2.4 times that of the initial wave velocity. Since turbulent bores may be likened to tsunamis in terms of their method of propagation, Williams (2010) believes it is this process that could explain the movement of boulders at such extreme heights above sea level. Furthermore, Hu et al. (2000) carried out numerical simulations of a wave surge crossing an underwater step, showing that the step increased the forward velocity of the surge by up to 40 % (Williams and Hall, 2004). Hall et al. (2006) propose that platforms and ramps on cliff tops are swept by wave-derived bores of water, parts of which can move up to $14\,\mathrm{m\,s^{-1}}$ (avg. $7\,\mathrm{m\,s^{-1}}$) while transporting boulders of up to $40\,\mathrm{m^3}$. Since megaclast ridges at 50 m on the north coast of Ireland are separated from the sea by a number of platforms, Williams and Hall (2004) believe that these may have accelerated incoming waves sufficiently to emplace clasts at this height.

Although there are those who believe that tsunamis are the most probable explanation of boulder ridges in these areas (Kelletat, 2008; Scheffers et al., 2009, 2010), a new study by Cox et al. (2012) concludes that boulders ridges on the Aran Islands have been caused by storm waves. They justify this through radiocarbon dating of shells indicating post-1950 emplacement, eyewitness accounts of boulders appearing after a storm on 5 January 1991, repeated photography of the area and comparison with Ordnance Survey maps from 1839. This evidence points to recent boulder movement activity, and due to the lack of significant tsunami evidence in the North Atlantic since the 1755 Lisbon event, they believe that storm waves are the only plausible cause.

6 Conclusions

The survey provided in this paper has attempted to cover the most well-known (or at least the most accessible) reports of extreme wave events in Ireland over the last 15 000 yr, but this list cannot, of course, be considered exhaustive. In fact, since this is the first such survey of its nature (to our knowledge), it may well be that we have missed a number of important events that have occurred in the past. This may be especially the case when records have been made and kept locally. One of the main objectives of this paper therefore is to stimulate others to search and add to the list of extreme events reported here. In this way, Ireland will establish an accurate database of its past ocean environment, which will be increasingly necessary in order to accurately inform the future development of this precious natural resource.

Our work leads us to draw a number of conclusions that will be important to bear in mind for future work in understanding the occurrence and risks of extreme wave events in Ireland. One initial point that is immediately apparent are the problems raised by the imprecise way in which wave events are understood and described by non-scientists. For example, the expression "tidal wave" has been used inaccurately in the past to describe all kinds of flooding, due not only to tsunamis but also due to storm surges. The tsunami risk for Ireland is of course very low, however, and we have concluded that the flooding often described as "tidal waves" has really been due to other mechanisms such as storm surges.

On the other hand, concerning unpredictable and destructive rogue waves, the relatively recent access to wave data in Ireland shows that the probability of occurrence of rogue waves is larger than expected, especially on the west coast of Ireland. It is indeed quite extraordinary that with only a handful of wave buoys over a few years one has been able to record the occurrence of rogue waves (those satisfying quantitative criteria), because rogue waves are by definition localized in space and the number of buoy sampling points are few. This points to further directions of study examining whether Irish wind patterns and/or factors such as currents and bathymetry may be favouring rogue wave formation off the Irish coast.

Concerning long term trends in the nature of waves around Ireland, at this stage and based on our data, it is not possible to conclude whether the number of extreme wave events in Ireland is increasing or decreasing. As discussed earlier, the data we used to establish this catalogue is sometimes from untrained observers, and thus it is dangerous to draw firm conclusions. Yet it is clear that the west coast is more vulnerable, and this already identifies a geographical area where future research efforts can be concentrated. However, this highlights how it is important to educate the public to describe accurately what they observe. Of course it is difficult to give quantitative measurements when one observes an extreme event, but a few important characteristics such as short vs long and widespread vs localized are essential to know.

Engaging the public in the observation of the behaviour of the marine environment will also bring many other benefits of course, increasing awareness of its vital planetary importance.

At the same time of course, developments in quantitative measuring devices such as buoys are to be encouraged and increased. It is only with accurate physical measurement that a more complete picture will emerge of the nature and frequency of wave events around Ireland. It is important to recall in this context how, despite centuries of anecdotal evidence, it was only after the quantitative wave record of the Draupner New Year's Wave was measured in 1995 that rogue waves were accepted as a genuinely separate class of waves meriting detailed study.

We also wish to stress the great potential of new developments in land-based observation of wave data. Specifically, ocean waves generate pressure changes at the sea bed which generate continuous background seismic noise or *microseisms*. These are associated with ocean wave activity and are generally stronger in coastal areas, although they are recorded on terrestrial seismic stations throughout the world. Background seismic noise levels increase during periods of increased ocean wave activity and, since Ireland is now equipped with an extensive seismic network, this represents an exciting opportunity to deploy a new set of instruments for understanding ocean wave phenomena (Moni et al., 2012).

Appendix A

Earthquake magnitude

- Modified Mercalli Intensity Scale of 1931 (NOAA)
  - 9: Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.
  - 11: Few, if any (masonry), structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

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