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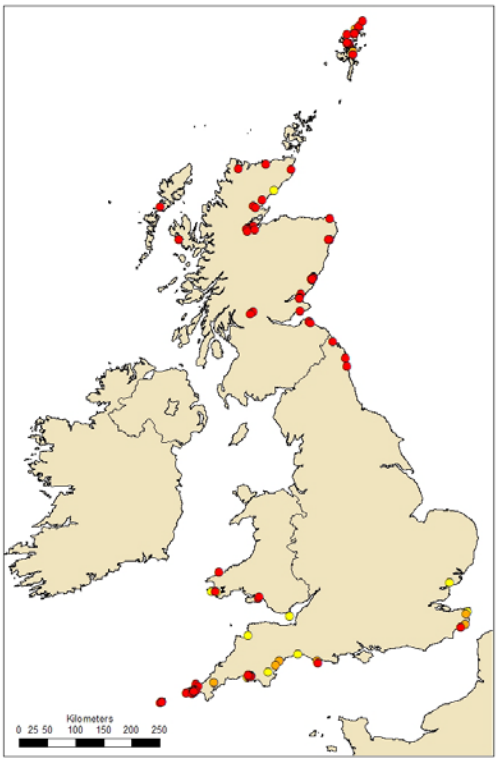
A catalogue of tsunamis reported in the UK

Energy and Marine Geosciences Programme

Internal Report IR/15/043



BRITISH GEOLOGICAL SURVEY

ENERGY AND MARINE GEOSCIENCES PROGRAMME

INTERNAL REPORT IR/15/043

A catalogue of tsunamis reported in the UK

D Long

Keywords

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Front cover

Sites of reported tsunami events in the UK. Red circles = good evidence for tsunami. Orange circles = tsunami event uncertain. Yellow circles = non-tsunamis previously attributed.

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
www.bgs.ac.uk
Shop online at: www.geologyshop.com

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☎ 020-7942 5344/45 email: bgslondon@bgs.ac.uk

Forde House, Park Five Business Centre, Harrier Way, Sowton, Exeter, Devon EX2 7HU

☎ 01392-445271 Fax 01392-445371

Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9038 8461

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345

Columbus House, Greenmeadow Springs, Tongwynlais, Cardiff, CF15 7NE

☎ 029–2052 1962 Fax 029–2052 1963

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

Foreword

The first catalogue was produced as a contribution to EU Framework 6 STREP project TRANSFER Work Package 1 in 2007 (Long and Wilson, 2007). TRANSFER (Tsunami Risk and Strategies for the European Region) was a project examining the tsunami processes in the European area to assess the tsunami hazard, vulnerability and risk assessment, and to identifying how the best strategies to reduce tsunami risk can be delivered to local communities and civil defence agencies. The catalogue attempted to list tsunami events and events previously reported as possible tsunamis detected around the coast of the UK during the Holocene.

This report comprises an update to that catalogue listing additional sites and events as a contribution to NERC's Arctic landslides project to assess the tsunami risk to the UK. It includes events detected by their geological evidence, human observations or by measurements recorded by tidal gauges.

Acknowledgements

Comments on the initial listing were received from the following:

Prof A.G. Dawson, Aberdeen University

Dr R.M.W. Musson, British Geological Survey,

Prof D.E. Smith, Oxford University,

Dr P. Woodworth, Proudman Oceanographic Laboratory

Comments on this update have been made by Prof D. Tappin, British Geological Survey and Dr S. Dawson, University of Dundee.

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Summary

Over the years many events around the coasts of the UK have been described as tsunamis or tidal waves. Evaluation of the data indicates only a few of these events are definitely tsunamis. The data types vary from sedimentary deposits, primarily of pre-historic events, through recorded observations, particularly reports in 19th and 20th century newspapers, to tide gauge records mainly from the latter half of the 20th century.

The major tsunami events within the UK include the Storegga tsunami which struck coasts in the northern half of the country about 8150BP, and the tsunami triggered by the 1755 Lisbon earthquake. Lesser events are primarily associated with earthquakes with epicentres offshore Portugal, but others are local events triggered by coastal cliff falls. These lesser events are often only noted on tide gauge records.

Most reported events are probably not tsunamis. Many are likely to have been weather related events known as meteotsunamis. These are large amplitude, long wavelength seiches caused by rapid changes in air pressure. They occur predominantly along on the south coast of England and have over the years caused fatalities and damage to structures. Some are uncertain events where the triggering mechanism is not clear. These include sediment layers found in Shetland resembling tsunami deposits but it is uncertain if the sediment is deposited by waves or are aeolian or through downslope processes.

1 Introduction

1.1 TSUNAMIS ON THE UK

It is often thought that as the British Isles are located on a passive continental margin they are not subjected to geohazards usually associated with active margins. One of the most dramatic and unpredictable of marine geohazards is tsunamis. They are translational waves that travel at great speed in deepwater but as they approach the coastline and enter shallow water the wave slows down but increases dramatically in height. When they strike the coast they can be very destructive, both in their initial impact and as they withdraw sucking any loose material out to sea.

This catalogue of tsunamis in the British Isles has been created by searches of published papers and examination of existing databases. Existing databases include the large global US National Geophysical Data Center NOAA/WDC Historical Tsunami database (http://www.ngdc.noaa.gov/seg/hazard/tsu_db.shtml), BRGM maintain a database of tsunamis reported for French territory (www.tsunamis.fr), which provides useful information on events in the English Channel. Reports within the Tsunami Runup data base that are known to be reports of seiches have been excluded. Also some reports of tsunami run-ups have been mis-positioned e.g. the event of 31st March 1761 at Carrick in County Wexford, Ireland has been mis-recorded as occurring at Carrickfergus, UK. At a regional level several catalogues have been produced since the GITEC project to the most recent integrating the results from several EU projects (Maramai et al 2014). These are available online at: http://roma2.rm.ingv.it/en/facilities/data_bases/52/catalogue_of_the_euromediterranean_tsunamis. The events in these catalogues have also been examined and reports with great uncertainty have been ignored. Where there has been some uncertainty then they are listed but event date in Chapter 3.

1.2 TYPES OF TSUNAMI

Any tsunami starts with the rapid displacement of water volume. Therefore, for a tsunami to occur, some source is required that causes such a displacement. This can be one of three things:

- A sudden vertical movement of the sea floor as the result of faulting;
- Sudden movement of a large amount of material underwater, as in an underwater landslide;
- A large amount of material entering the sea rapidly.

The first case is mostly restricted to earthquakes that cause fault rupture (vertical or with a vertical component) extending to the sea bed. It is also possible for blind thrust faulting to create folds or ridges at the free surface, even when the fault itself does not extend to the surface, and this could have a similar effect. In the context of tsunami threat to the UK it is earthquake triggered events on the European / African plate boundary west of the straits of Gibraltar that is of most concern.

In the second case, underwater landslides may be triggered by earthquakes; even by moderate earthquakes if the slope is sufficiently unstable. However it is possible that they may be triggered by other events such as the dissociation of gas hydrates (Kvenvolden, 1988), or underwater volcanic eruptions where the material could be quite variable e.g. lava, hot waters or gas. In the context of tsunami threat to the UK the continental margins with the thickest deposits of unconsolidated material that may be involved in submarine landslides are generally to the north of the UK within the Norwegian Sea. The example is the Storegga Slide offshore mid-Norway. Even modelling events in the Arctic suggest a submarine landslide induced tsunami could reach the UK (Berndt et al., 2009).

In the third case, the most probable circumstance is a large terrestrial landslide that enters the sea (volcanic slope collapse, Coastal landslide or cliff fall being a possible cause). An alternative cause would be the impact of a large asteroid, but asteroid impacts of sufficient magnitude are extremely rare even on a geological time scale. The potential sources of such tsunami are more widely distributed varying from suggested volcanic island collapse in the Canary Islands (Ward and Day, 2001) to coastal landslides in Scottish sea lochs. Most coastal landslide triggered tsunamis are very local in extent as the wave attenuated rapidly away from the slump area. Within the UK some coastlines are regularly subjected to cliff falls and these can trigger a tsunami impacting nearby coasts, e.g. Folkestone 1911. Therefore the threat of tsunamis increases the area at risk when considering coastal rockfalls.

Tsunamis should not be confused with seiches that are the watery manifestation of the ground wave of an earthquake.

Tsunami-like effects can be created by certain meteorological conditions that are sometimes referred to as meteotsunami. These have been reported in the UK and some claimed tsunamis are more likely to be meteotsunamis. Although they are not the subject of this catalogue details of some events are given in chapter 4 as well as sources of data.

1.3 THE IMPACT OF TSUNAMIS ON THE UK

A study of tsunamis and the UK for the Department for Environment Food and Rural Affairs (DEFRA), following the Indian Ocean tsunami of 2004 (Kerridge et al., 2005), showed that although the risks of a tsunami striking the coasts of the UK are very low, they cannot be ignored. Even if the likely wave heights are comparable to those of typical storm surges and therefore covered in many places by flood defence infrastructures, a tsunami wave could occur on top of a storm surge and therefore have the potential to exceed defences. Also, if a tsunami struck when conditions were calm communities would not be as prepared as they are when a storm had been building up.

The most significant tsunami to strike Europe in modern times occurred in 1755 when the wave caused much devastation to the coasts of Portugal, Spain and Morocco. The wave also struck the southwestern parts of the British Isles with local maximum run-ups of 2-3m in the Scilly Isles and in Cornwall. Tsunamis generated by earthquakes in the same area west of the Straits of Gibraltar of a lesser magnitude have caused much smaller run ups in the UK. The extensive continental shelf south west of the UK and Ireland slows down such waves. Studies in SW Iberia indicate that similar events occur with a frequency of 1000-2000 years (Luque et al., 2001). Therefore there is a possibility that a prehistoric tsunami could have struck the southwestern part of the UK and the southern part of Ireland. This area is the most likely source area for future tsunami waves to strike the British Isles.

About 8200 years ago the UK was affected by a tsunami generated by a massive submarine landslide off the coast of Norway. Run-ups varied from a few metres in southeast Scotland to more than 20m in Shetland. Studies have shown that this slide, the Storegga Slide, is just the latest of several megaslides to have affected the continental margin over the last half million years. The geological model indicates that another glacial period will be required to allow the build out of the volume of sediment needed for failure again in the Storegga area (Solheim et al., 2005). Although the size of a potential tsunami striking the British Isles from this area is greater than that offshore Portugal its frequency is considerable less.

2 Evidence for tsunamis

2.1 TSUNAMI DEPOSITS

When a tsunami wave strikes a coastline it is often heavily laden with sediment entrained from the seafloor. Tsunami waves typically disturb the seafloor at greater water depths than storm waves and their energy will move material into suspension that is not normally disturbed. When the wave strikes the coast and subsequently withdraws it often leaves behind a layer of the entrained sediment.

Sediments have been identified associated with the Holocene Storegga Slide tsunami along the coasts of northern UK and the 1755 Lisbon earthquake tsunami in the Scilly Isles (Dawson et al., 1991; Foster et al., 1991). These can often be recognized as a thin landward tapering horizon that includes marine material (e.g. marine microfossils) within sediments deposited above sealevel, such as lacustrine or peat units. The horizon may include ripped-up clasts of the surrounding material and boulders possibly source from offshore.

Physical evidence of a tsunami event provides an opportunity to date events. The Holocene Storegga Slide tsunami has been dated by radiocarbon dating of sediments that bracket the event (Smith et al., 2004) or of transported material contained in the deposit. In the latter case, dating moss still containing chlorophyll provides good evidence for an age of material alive when the tsunami struck (Bondevik, 2002). Examination of entrained material has even suggested the season of the event (Dawson and Smith, 2000; Bondevik et al., 1997). Deposits of the Lisbon tsunami in the Scilly Isles have been dated by OSL methods supporting the historic age of the deposit (Banergee et al., 2001).

Deposits also provide an opportunity to measure the extent and other characteristics of a tsunami event not observed or reported in historical documents, e.g. using particle size analysis to estimate velocity and extent of individual waves within the tsunami.

2.2 HISTORICAL OBSERVATIONS

There are many reports of unusual movements of the sea. Some were documented soon after the event such as the 1755 Lisbon earthquake and tsunami when the Royal Society gathered together numerous reports throughout the UK. Others may have been written down some time later reporting second hand events. However even as recently as Victorian times there was often uncertainty in phenomena and their correlation or not, including earthquakes, atmospheric changes and storms (Melville, 1996). It should be noted that place-names may well have changed over the years and positioning observations can be difficult. Also in the past, dates and times were not consistent across the country but reflected local conventions.

2.3 TIDE GAUGES

Tide gauges provide a record of changes in sea level around the coast, often located on piers. Some sites around the UK have records extending back continuously more than 100 years. The stations were established and are operated to record low-frequency processes such as tides and storm surges. However, tide gauges can record tsunami events that are smaller in amplitude than that likely to be noted by human observations. Since the first part of the 18th century tide gauge records were in the form of paper charts providing a continuous record, which should have, in principle, provided a good source of tsunami information. However, in many places, once the charts had been digitised for their tidal information (usually digitised with hourly sampling which is too low a frequency to resolve tsunami events), they were often destroyed or allowed to decay.

Since the 1970s charts have been replaced by electronic sampling at most UK sites, averaging 15 minutes between measurements, although there are plans to reduce the period averaged to 5 minutes. The data can be obtained in real-time / near real-time at: http://www.ntslf.org/data/uk-network-real-time . There are also plans for separate high frequency (1Hz) pressure sensors at 4 UK sites as part of a study for DEFRA and this would feed into international projects such as TRANSFER, and IOC NEAMTWS. The proposed sites are Newlyn, Cromer, Holyhead and Lerwick (P.Woodworth, POL, *pers comm.*).

Currently (2015) there are nine tide gauge locations around the UK from where high frequency data is available on-line (Table 1). Such information will greatly assist assessment of future possible tsunamis.

Table 1 High frequency tide gauge stations around the UK. Data taken from http://www.ioc-sealevelmonitoring.org/list.php on 19/8/15

Location	Code	Contact	Latitude	Longitude	Sampling rate	Frequency (Hz)
Deal Pier	dlpr	Channel Coastal Observatory	51.22379	1.40926	10s	0.1
Herne Bay	hbay	Channel Coastal Observatory	51.38211	1.11521	10s	0.1
Lerwick	lerw	National Oceanography Centre	60.15532	-1.14519	10s	0.1
Lymington	lymg	Channel Coastal Observatory	50.74031	-1.50708	10s	0.1
Port Issac	ptis	Channel Coastal Observatory	50.59417	-4.83441	10s	0.1
Sandown Pier	sdpr	Channel Coastal Observatory	50.65111	-1.15316	10s	0.1
Second Severn Crossing	sscr	Channel Coastal Observatory	51.57012	-2.70001	10s	0.1
Swanage Pier	swpr	Channel Coastal Observatory	50.60933	-1.94918	10s	0.1
West Bay Harbour	wbhr	Channel Coastal Observatory	50.71017	-2.76398	10s	0.1

3 Events

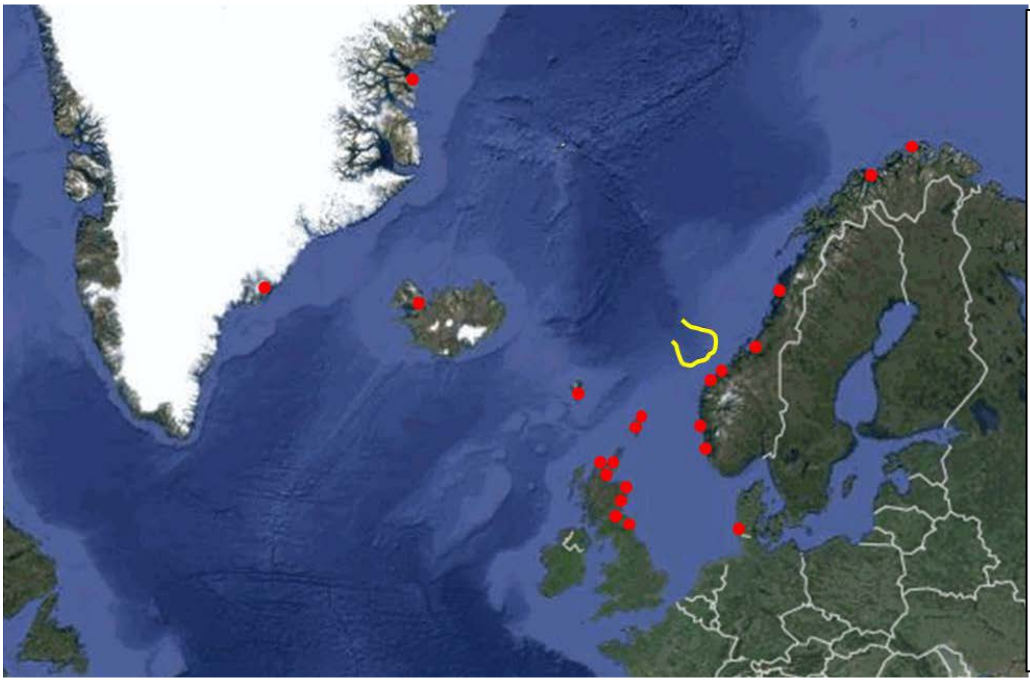
A range of events has been reported at various sites around the UK within the Holocene record and attributed to being a tsunami. For some events there is a strong link between the UK coastal evidence and the source of the tsunami so there is a high confidence that the event was a tsunami. For some it can be shown that the linkage is impossible and therefore the event has been wrongly termed a tsunami and can be explained by other causes. For some events there is no obvious source of a tsunami and these are classified as uncertain.

These events have been dated either into years BP (before present, referenced to 1950 AD) where an age has been determined from radiocarbon dating and then extrapolated into calendar years, which have a level of uncertainty in the region of ±200 years, or as calendar years where historical records allow the determination of the actual date.

3.1 ~8150 BP

UK tsunami catalogue event 1

Along the eastern and northern coasts of Scotland numerous sites have been identified as containing a thin continuous layer of marine sediments (Smith et al., 1985; 2004) often with intertidal, lacustrine and terrestrial deposits, with a few similar sites located in northeast England (Figure 2). A similar horizon has been detected along much of the western coast of Norway (Bondevik et al., 1997), and at sites in Denmark (Fruergaard et al., 2015), the Faroes (Grauert et al., 2001), Iceland (Hansom and Briggs, 1991) and Greenland (Wagner et al., 2007; Long et al., 2008) (Figure 1). This event is attributed to the failure of 3500km^3 of sediments on the mid-Norwegian margin known as the Holocene Storegga Slide (Dawson et al., 1988; Long et al., 1989) (Figure 1). For a comprehensive analysis of the slide and its dating see Bryn et al., (2005); Haflidiason et al., (2005) and Solheim et al., (2005).



Red dots indicate sites of tsunami deposits (representative sites only in Scotland and Norway)

Yellow line indicates location of Storegga headwall

Figure 1 Sites with evidence of Storegga tsunami across the North Atlantic

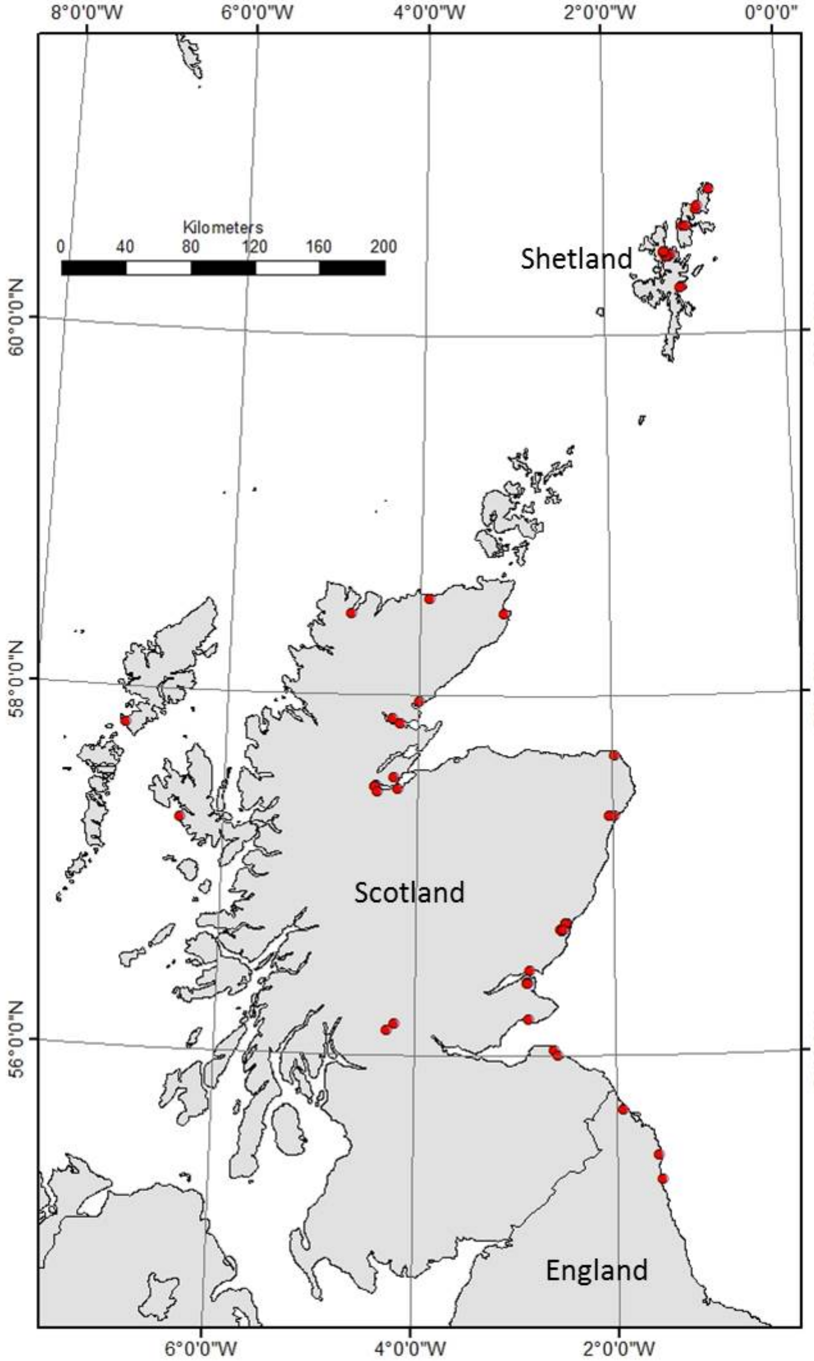


Figure 2 Sites containing geological evidence for the Storegga tsunami event in the United Kingdom

The Holocene Storegga Slide is dated offshore to 7250±250 ^{14}C yr BP (Haflidason et al., 2005) and its associated tsunami deposit is dated onshore to 7300±20 ^{14}C yr BP, 8120 – 8175 calendar years BP i.e. before AD1950 (Bondevik et al., 2012). This is approximately 8200 calendar years ago. Note this contrasts with previous dating results carried out during the 1980s on the Storegga Slide that concluded that there were three distinctive slide events (Bugge et al., 1987, and Jansen et al., 1987). The latest interpretations indicate that the Holocene Storegga Slide is just the most recent of a series of mega-slides (>2000 km^2) that have occurred offshore mid-Norway since the end of the Pliocene, with a frequency of roughly once every 100,000 years over the last 0.5 Myr (Bryn et al., 2003; Solheim et al., 2005).

Within the UK sedimentary deposits have been found at sites in Shetland and the east coast of Scotland and northeast England. Sites in western Scotland are less certain and reflect environmental changes attributed to tsunami impact. To date no sites have been found in the Orkneys, however it should be noted that sealevel was many metres below present and evidence may have been disturbed during the subsequent marine transgression.

The deposits generally consist of fine to medium grained sand, often showing a fining upwards sequence that can be repeated up to five times interpreted as sedimentation by individual waves within the train of waves that comprise the tsunami event. The tsunami deposit layer is generally less than 10cm in thickness but may be up to 70cm thick. The sands include microfossils that are indicative of shallow marine conditions. These fossils are often broken indicative of turbulent conditions. Where the layer has been deposited within coastal peats ripped clasts of peat can be seen (e.g. Maryton). At the Maggie Kettle’s Loch section it can be very clearly shown that the peat clasts are associated with the second wave, indicating that the coastal peats were eroded by the first wave, causing blocks of peat to be floating about when they became incorporated within the deposits associated with the second wave (Bondevik et al., 2003). The best examples of the sediment layer exposed in sections are in the coastal peat cliffs of Shetland (e.g. Whalefirth (Figure 3)).

Figure 3 coastal peat section at Whalefirth, Yell

There is a general decrease in run up heights from north to south. The highest sediment run ups occur in inlets, (~20m) at sites around Sullom Voe, a large north facing inlet (Bondevik et al., 2003) reducing to a few metres run up in the vicinity of the Firth of Forth. Lower values may exist further south but from Northumbria southwards the former shoreline is now offshore and any tsunami deposits from this event would have been vulnerable to erosion and reworking during the subsequent Holocene marine transgression. However as several of the sites in Shetland show, the layer can be preserved below the present day sealevel by subsequent sedimentation even with marine transgression. It has been suggested that the Storegga tsunami wiped out “Doggerland” (Weninger et al., 2008) through the drowning of Dogger Bank. This is not the case, as the former shoreline would have been about -31m below present and the bank would have still reach altitudes of at least 10m and terrestrial sediments post 8150BP have been found. However the impact of the wave on this extensive flat landscape may have been significant.

The extent of inundation and altitude can be difficult to estimate but by examining how the deposit occurs within lake basins, lake thresholds provide altitude control. In coastal sequences where the deposit transgresses from within intertidal muds into coastal peats such as at Fullerton (Smith et al., 1980) or Creich (Smith et al., 1992) the transgression provides a position for the high water mark on the day the wave struck (Long et al., 1989). The actual run up of the wave would have exceeded the extent of preserved sediments so these provide only a minimum inundation.

Two sites in the Minches suggest evidence of a change from freshwater conditions to brackish at about the time of Storegga. The inundation of a tsunami wave is likely to have reduced and reorganized beach barriers, as noted in the Algave (Andrade, 1992; Font et al, 2013), whereby backbeach lagoonal settings may have become brackish until beach barriers were restored (Selby and Smith, 2015).

Examination of clasts within the tsunami deposit can also indicate the season of the event as well as provide material for dating. The stage in the development of buds (Bondevik et al., 1997), fruit (Dawson and Smith, 2000) and moss (Rydgren and Bondevik, 2015) and also the size of fish bones (Bondevik et al., 1997) at sites in Norway and Scotland entrapped within the tsunami deposits suggest that the Storegga tsunami struck in late autumn. However sedimentological evidence from Finmark in northern Norway implies that it occurred when the ground was not frozen (Romundset and Bondevik, 2011) suggesting a time between April and October. Combining together all this information suggests that the tsunami struck about October time ~8150 cal years BP.

This is considered a tsunami event.

3.2 ~5500 BP

UK tsunami catalogue event 2

A thin horizon of marine sand has been found at two sites in Shetland (Garth Loch and Loch of Benston) less than half a kilometre apart and attributed to a tsunami event that has been termed the Garth Tsunami (Bondevik et al 2005). This tsunami deposit occurs above tsunami deposits from the ~8150 BP Storegga Tsunami event and is up to 65cm thick. Dating of a twig within the deposit in the Loch of Benston and from just below the deposit at Garth Loch revealed similar radiocarbon ages (4965±55 ^{14}Cyr BP and 4895±70 ^{14}Cyr BP respectively) extrapolated to ~5500 calendar years BP. According to the constructed sea level curve the run-up for this event was probably more than 10 m.

Other sand layers in the Mid-Yell area have been linked with this event (Costa et al., 2015). However these features have little lateral continuity and are located in areas of peat slides which may provide a mechanism for the formation of an intermittent sand layers within a peat sequence.

A possible tsunami deposit of similar age has been noted on the coast of mid-Norway near Bergsøy that may correlate with this ~5500 BP event (Bondevik et al., 2005). No source has been suggested for this event other than originating in the North / Norwegian Sea. It is worth noting that Halflidi and others (2005) reported several small slides on the northern flank of the Storegga Slide with ages about 5000 ^{14}Cyr BP, however it is considered that their volumes were too small to have created a tsunami sufficiently large enough to have struck the coast of Norway let alone Shetland more than 500 km away. Therefore a local source is required and to date no significant size landslide has been mapped in the coastal waters of Shetland that could provide such a source to create a tsunami event to strike all these sites on the eastern coast of Shetland.

This is considered an uncertain tsunami event.

3.3 ~1500 BP

UK tsunami catalogue event 3

A thin sand horizon (up to 5cm thick) has been found at two sites in Shetland, 40kms apart, Basta Voe and Dury Voe, extending to 5.5m and 5.6m above high tide respectively, and attributed to a late Holocene tsunami event (Bondevik et al., 2005) It was subsequently noted by Dawson and others (2006) to be found up to ~9m above OD. This has been termed the Dury Voe event.

At Basta Voe the sand layer is thin, only 1 to 2cm thick and can be found extending continuously 70 to 80m through peat cuttings (Figure 4). Sites with a similar sand layer have been found up to 2km up the valley away from the coast. The layer varies in thickness from a few millimetres to about 4cm maximum. It increases in altitude inland reaching a maximum altitude of about 9m.

Figure 4 Basta Voe, peat cutting showing thin sand layer

No source for the tsunami has been identified. Dawson et al. (2006) suggest a local submarine landslide off the eastern coast of Shetland. However, existing regional morphological seafloor information is not sufficiently detailed enough to test this hypothesis. In addition detailed multibeam surveys between Yell and Fetlar near the entrance of Basta Voe do not show any evidence of a submarine landslide (Dick, 2015). The areas where this feature is noted in Basta Voe, include areas of reported peat sliding (Flinn, 1994).

This is considered an uncertain tsunami event.

3.4 1014 AD

Haslett and Bryant (2007) describe four sites in north Wales of imbricated boulder trains. They consider that the boulders are of a size that would require storm heights in excess of currently modelled Irish Sea extreme storms and offer a tsunami event as an explanation for the formation of the boulder trains. The possible tsunami sources are given as an earthquake with an epicenter located approximately 15 km from the coast of the Lleyn Peninsula, around 4° 50’ W 52° 57’ N or a bollide impact, suggested by anomalous ammonia peak in ice-core samples dated to 1014 AD. Although North Wales has had several large earthquakes including a magnitude 5.4 M_L event in 1984 (Turbitt et al., 1985), they are below magnitudes considered tsunamigenic. Bollide impacts are difficult to confirm but it would be anticipated that impacts would have been more widely distributed and studies of the nearby coastal Malltraeth Marshes show no major inundation that might have been expected. The boulders are probably derived from coastal erosion of the glacial tills that comprise the rockhead covering at these localities.

There is no evidence that this was a tsunami event.

3.5 11TH NOVEMEBER 1099 AD

A tsunami event at St Michael’s Mount is listed in the GTSB for this date. This relates to a storm mentioned in the Saxon Chronicles as occurring on St Martin’s Festival and is linked with a great storm attributed in Cornish folklore for the loss of the land of Lyonesse.

> *This year also, on the festival of St. Martin, the sea-flood sprung up to such a height, and did so much harm, as no man remembered that it ever did before. And this was the first day of the new moon.* http://omacl.org/Anglo/part6.html

> ***The Lost Land of Lyonesse***
>
> *There are many legends of towns and countries submerged beneath the waves, but the legend of the lost land of Lyonesse is possibly the most famous. Lyonesse, we are told, was once a country beyond Land's End that boasted fine cities and 140 churches; then, on November 11th 1099 a great storm blew up and the marauding sea swept over it, drowning the luckless inhabitants and submerging the kingdom beneath the waves, until all that remained to view were the mountain peaks to the west, known to us now as the Isles of Scilly. Only one man survived. His name was Trevilian and he rode a white horse up to high ground at Perranuthnoe before the waves could overwhelm him.*

There is no evidence that this flooding was a tsunami event.

3.6 6TH APRIL 1580 AD

UK tsunami catalogue event 4

An earthquake affected southeast England and parts of the near continent on 6th April 1580. As many of the reports were from London, this event has been called the “London Earthquake” (Davison, 1924) although an assessment of the reports indicates that the epicentre was within the Straits of Dover (Neilson et al., 1984). Varley (1996) states that the earthquake “triggered a tsunami that inundated Dover, Boulogne and Calais, leading to hundreds of deaths”. Haslett and Bryant (2008) provide a large number of reports indicating loss of lives, ships and the collapse of a cliff at Dover. Neilson et al (1984) are more cautious, considering that due to uncertainty about the coincidence in time of inundation and earthquake, the flooding report may have had some other cause (presumably meteorological). Melville et al (1996) are dismissive of the idea of a tsunami from this event and suggest that that contemporary sources conflated descriptions of the earthquake with the effects of a storm that occurred very shortly afterwards. This is all the more likely since at this period it was not known that earthquakes were very short-lived phenomena, and to a 16th century writer it would have been natural to consider the seismic shock and a storm a day later as being part of the same occurrence. However Haslett and Bryant (2008) provide evidence that the weather was calm.

Undoubtedly the earthquake caused agitation of the water in harbours at Dover and Sandwich harbours (Neilson et al 1984). It is most likely that this movement was a seiche and not a tsunami as there is no evidence of any seabed displacement in the area and the strength of the earthquake (5.8 M_L (Musson, 1994)) was insufficient to cause a tsunami directly. The well surveyed bathymetry in the Channel shows no sign of or even the potential for a large underwater landslide. Recent modelling studies of this event (Roger and Gunnell, 2012) suggest that if the event was located within the Dover Strait and was of M_W 6.9 (considered the improbable maximum scenario), it could generate a tsunami locally in excess of 1m, but that a Mw 5.5 event is unlikely to have generated a coseisemic tsunami. These studies have also ruled out the possibility that a very large cliff fall (10^6 m^3) could generate a tsunami that would reach both sides of the channel, and an improbably large event 0.01km^3 would be needed (Roger et al., 2012). There is no historical evidence for such a large event. Therefore to explain the waves reported in harbours on both sides of the channel as tsunami triggered by cliff fall would require collapses of the chalk cliffs on both sides of the Straits of Dover. One of the reports refers to part of the castle walls at Dover collapsing into the sea along with the cliff underneath it, therefore cliff falls are a possible explanation of a tsunami event. More recent experience in Folkestone (December 1911) indicates that the effects of a cliff fall can be noticed at least 5km away.

This is considered an uncertain event.

3.7 30^TH JANUARY 1607 AD

UK tsunami catalogue event 5

At 9am on 30 January 1607, the lowlands surrounding the Bristol Channel suffered the worst coastal flooding on record. The floodwaters caused extensive damage to Bristol, many surrounding villages on the Somerset levels, and Barnstaple in North Devon. Flooding extended some 40km along both banks of the Bristol Channel to a depth of 2–3m and the erosion of all salt marshes in the area (Haslett and Bryant 2007). It has been claimed that a tsunami may have been responsible (Bryant and Haslett, 2002; Haslett and Bryant, 2004). The exceptional high tide (14.36m above chart datum) that occurred at 9am combined with the severe weather points to a storm surge as the more likely explanation. The most authoritative account says that a westerly gale blew for 16 hours although some records state that a strong south-west wind blew unbroken for three days (Horsburgh and Horritt, 2006).

Note that this event occurred when many places in the United Kingdom were using the Julian Calendar rather than the Gregorian Calendar now used and so is recorded as 20th January 1606.

It is unlikely that an earthquake could have caused a tsunami directly as seismic events with an epicentre around Britain are not expected to be large enough to generate significant surface rupture to cause a tsunami. Also there are no reports of damage to buildings to indicate a local earthquake. If it was a distant earthquake and its epicentre located further away than if it triggered a tsunami it could be expected that the wave would be been more wide ranging and not restricted to the Bristol Channel. If the origin of a tsunami is a submarine landslide, extensive bathymetric surveys on the shelf do not reveal any evidence of a slide within the Bristol Channel. Large landslides usually occur on the upper slopes of continental margin such as seen south of Ireland. A tsunami from such a source could be expected to have simultaneously struck the coasts of Ireland, UK and France, and therefore be more widely reported.

This is considered a non-tsunami event.

3.8 2ND JULY 1749 AD

UK tsunami catalogue event 6

The Scots Magazine of 9th July 1749 reports an agitation of the sea at Dale in Milford Haven, Pembrokeshire where several waves were observed disrupting boats at their moorings:

> *"A letter from Milford Haven bears that on 2nd of July, about eleven o'clock, being near the time of low water, the sea exceedingly smooth, and the weather serene and fair, the inhabitants of Dale, in the said Haven, were alarmed by a sudden hideous rumbling of the water, and to the great amazement of a multitude of spectators, the tide was observed to run up, in the space of one minute, to high water mark, and with the same rapidity to retreat again. This phenomenon was repeated seven times in about three quarters of an hour. The violence of the torrent was so prodigious, that boats were forced from their moorings, and turned over and over. Many people were in danger of being swallowed up, but providentially no lives were lost."*

There are no other observations and no known sources for this to be a tsunami event. It is considered a non-tsunami event.

3.9 1ST NOVEMBER 1755 AD

UK tsunami catalogue event 7

The largest seismic event to have struck Europe in last few hundred years was noted from Scotland to Austria and north Africa, either felt as ground motion or seen as seiches in baths, lakes and enclosed harbours. However the greatest damage occurred in western Iberia and northwest Africa, where the effects of a tsunami added to the devastation caused by the earthquake.

The earthquake is estimated to have had a magnitude 8.5 Ms and probably centred on the Azores-Gibraltar boundary between the African and Eurasian plates. The earthquake struck at 9:50am (local time) destroying many buildings in Lisbon, Cadiz and Morocco, however it was followed by a tsunami 20 minutes later at Lisbon. The event is often referred to as the Lisbon Earthquake. The tsunami was observed along the western Iberian coast and Morocco and in the UK and Ireland and even across the Atlantic in the Caribbean and South America. The earthquake and tsunami killed between 60,000 and 100,000 people.

Reports of the event in Britain were gathered together by the Royal Society in London and provide a useful record. The reports are predominantly of the seiche noted about 11 o'clock in the morning in various harbours around the UK as well as in many lakes and ponds. However there were several reports from the coast of south west of England and Wales in the afternoon and evening when a series of waves were noted (Figure 5).

The observations describe dramatic movements of the water. Borlase (1755) described the arrival of the waves in Mount's Bay:

> *"…the first and second refluxes were not so violent as the third and fourth waves at which time the sea was as rapid as that of a mill-stream descending to an undershot wheel, and the rebounds of the sea continued in their full-fury for fully 2 hours … alternatively rising and falling, each retreat and advance nearly of the space of 10 minutes, till five and a half hours after it began".*

Further along the coast Huxham (1755) described events at Plymouth:

> *"…the tide had made a very extraordinary out (or recess) almost immediately after high water (about 4pm) left both the passage-boats, with some horses, and several persons, at once quite dry in the mud, though the minute or two before, in four or five feet water: in less than eight minutes the tide returned with the utmost rapidity, and floated both the*

boats again, so that they had near five feet water, The sea sunk and swelled, though in a much less degree, for near half an hour longer."

Sedimentation attributed to this tsunami event has been reported (Foster et al., 1991; 1993) from a series of cores taken at Big Pool on St Agnes in the Isles of Scilly. The particle size analysis of the main sand unit which exceeds one metre thick in places, suggests a high magnitude, low frequency depositional sequence, with a number of large waves spread over a period of several hours in order to produce the fining upward sequences observed. Radiocarbon dating suggests a mid-18th Century age (Foster et al., 1993) with a similar age estimate from optically stimulated luminescence dating for the deposits (Banerjee et al., 2001) and based on the morphology of the deposit it is attributed to the 1755 tsunami rather than a storm event.

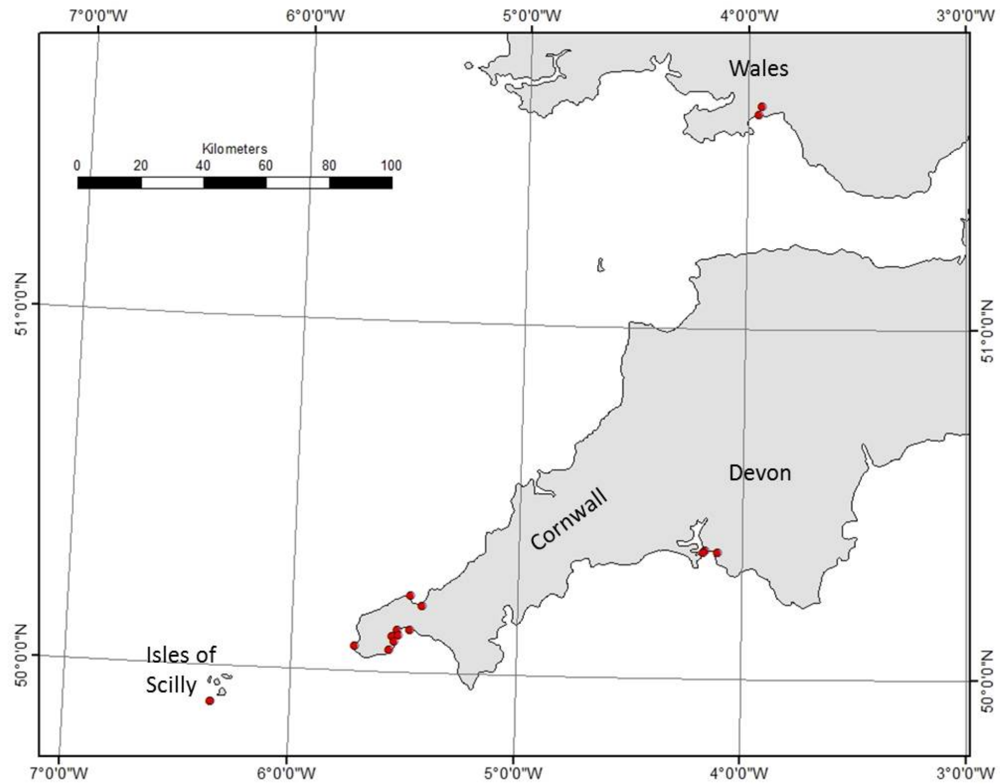


Figure 5 Sites in southwest Wales and England where the 1st November 1755 tsunami was observed

Observational evidence of sediment erosion and re-deposition is implied by the observations of Huxham (1755) in Stonehouse Creek, Plymouth who described the

"…tearing up of mud and sand banks in a very alarming mannar".

The impact on the southern coast of Ireland, at this time part of the United Kingdom, was just as dramatic, as reported by Nicola (1755) from Kinsale.

"On the first of November, between the hours of two and three afternoon, the weather being very calm, and the tide near full, 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.……"

"The Reverend Mr. Keef says, the perpendicular rise of the water at his quay was five feet and a half, as he measured it, and I am told it much higher at the market-quay, which it overflowed, and poured into the market-place……"

"…….it came with such rapidity, that some men, who were on the quay immediately, on the first rise of the water, ran off, but could not do it with expedition enough to prevent their being overtaken, and up to the knees."

Erosion and deposition by the wave was also noted:

"The bottom of the harbour, which is all a slab, was much altered, the mud being washed from some places, and deposited in others."

In south Wales there are reports at Swansea and at the White Rock copper works a short distance inland on the River Tawe (Blair, 1755). Edmonds (1862) quotes: *" a great head of water rushed up with a great noise, floated two large vessels, the least above two hundred tons (one whereof was almost dry before), broke their moorings and hove them across the river."*

This is considered a tsunami event.

3.10 31ST MAY 1759 AD

UK tsunami catalogue event 8

Dawson et al., (2000) quote Perrey (1849) as saying that an unusual coastal flood took place at Lyme Regis on 31st May 1759 where the sea "…*flowed in and out three times during an hour*…". However no other account have been found to corroborate this report in neighbouring areas, nor is any earthquake noted for this date.

This is first of a set of extreme marine floods events have been identified by Dawson et al (2000) who conducted extensive searches in SW England, only some of which have been attributed by them to past tsunamis.

This event is considered a non-tsunami event.

3.11 31ST MARCH 1761 AD

UK tsunami catalogue event 9

A similar suite of reports to that of the 1755 event was noted in south west Cornwall on 31st March 1761 (Borlase, 1762). He states that:

"On the Tuesday, the 31st of March 1761, about five o'clock in the afternoon, there was a very uncommon motion of the tide in Mount's-bay, Cornwall. […] After the tide has ebbed about four hours and half, (for the time is not determined with precision) instead of continuing to retreat gradually, as usual, till it had completed the six hours ebb, on a sudden it advanced as it is usually at the time of the Moon, at an hour and half high-water. It then retreated nigh to the point of low-water, then it advanced again, and retreated, making five advances, and as many recesses, in the space of one hour; viz. from about five to six o'clock; which was the whole time, that these uncommon stretches of the tide continued. But the first motion was most considerable, the sea advancing the first time to a quarter ebb; but the second advance was but as far as the sea reaches at half ebb. A small sloop of 30 tons burthen, at that time laden and dry in Penzance pier, by the first surge, was fleeted; by which it appears, that the waters rose at this place six feet perpendicular, that sloop requiring six feet of water to fleet it. At the pier of St Michael's mount, three miles to the east of Penzance the tide was observed, at the same

time, to rise and fall about four feet. At Newlyn, (a mile west of Penzance) the tide rose to the same height nearly, as at Penzance. At Moushole pier, (three miles SW of Penzance) it was only observed, that the sea was in great agitation, and the fishing boats in danger. At the islands of Scilly, the sea was judged to raise about four feet; but the agitation to have continued longer than in Mount's-bay, viz. more than two hours".

Similar waves were reported at several sites along the southern coast of Ireland, up to 1.2m in height and consisting of up to five waves. A letter from Kinsale, published by The London Chronicle on its 11th April 1761 issue and also reproduced in the Annual Register (1761):

"[…] it was about six o'clock in the evening; near dead low-water the tide rose suddenly in our Strand, about two feet higher that it was, and went out again in the space of four minutes with great force, which repeated several times, but the first was the greatest."

This event coincides with reports of a tsunami in Portugal with waves up to 2.4m in height at Lisbon, following a 7.5Ms earthquake with an epicentre at 34.5°N 13°W at 12:01 (Baptista et al., 2006). This tsunami was also observed across the Atlantic in the Caribbean.

This is considered a tsunami event.

3.12 9TH OR 10TH AUGUST 1802 AD

UK tsunami catalogue event 10

There are several reports in south west England indicating turbulent waters for either 9th or 10th August 1802 that was originally suggested as being due to a distant earthquake. With rises and falls of 35cm at Weymouth and 60cm at Teignmouth in a very short period of time (Dawson et al., 2000). A similar event is noted in Jersey in the Channel Islands by the Hampshire Chronicle 30th August 1802 indicating the water rose 1.2m in just eight minutes and retreated, being repeated three times but the date of this event is not clear.

The Exeter Flying post Thursday 19th August 1802 states:-

"On Monday morning last (9th) *a phenomenon happened here; between six and seven o'clock, the tide rose suddenly fourteen or fifteen inches* (~35cm), *ebbed again in the same manner, and repeated to doing three times within an hour! This very much alarmed many ladies who were at the time in machines bathing, for the floors of the machine, more than a foot* (30cm) *from the water, being instantaneously overflowed, consequently caused alarm. We are yet at a lost to account for this phenomenon."*

The Royal Cornwall Gazette of 21st August 1802 states:-

"On Tuesday (10th) *morning, at eight o'clock, a very singular circumstance occurred at Teignmouth. The sea at low water, instantaneously rose and fell nearly two feet* (60cm), *several times in the space of ten minutes, and the fishing-smacks at sea experienced such a violent commotion that they were in danger of being lost. The same phenomenon has been observed at Exmouth, Weymouth and several places along the coast."*

This reporter compared the event with phenomena associated with earthquakes in Italy and the destruction of Lisbon.

There are no reports of seismicity associated with this time.

This is considered an uncertain tsunami event.

3.13 31ST MAY 1811 AD

UK tsunami catalogue event 11

Dawson et al., (2000) note reports from Plymouth recording sudden rises and falls with an amplitude of 4 to 8 feet (1.2 to 2.4m) over a period of four hours from 3am, with further affects at 9am. Whereas Edmonds (1862) states:

> *"the sea rose on all the southern coasts of Cornwall as well as in Plymouth, from four to eight feet perpendicularly as mentioned in the Royal Cornwall Gazette published seven days afterwards; and Mr. Luke Howard states that at Plymouth it began at 3 a.m., and continued until 10 – that at 6 45 the sea rose eleven feet*."

Milne (1844) notes that the event coincided with a period of gales and low pressure. Therefore the event is likely to have been storm induced.

This is considered a non-tsunami event.

3.14 13TH SEPTEMBER 1821 AD

UK tsunami catalogue event 12

A report of sudden movements of water at Plymouth and Truro were reported in The Windsor and Eton Express on Sunday 16th September and in the Morning Post on 18th September:-

> *"On Thursday last about two o'clock, p.m. an extraordinary phenomenon, called a sea-boar, was observed at Plymouth and along the adjacent coast. The tide suddenly rose upwards of four feet, and almost instantly retired. One brig, and several boats broke adrift in Sutton pool, but no considerable damage took place. A similar occurrence took place at Truro about the same time."*

The database of tsunamis observed in France (www.tsunamis.brgm.fr) indicates that the event was also noted in Cherbourg where the wave was described as being 1m high. There are no known reports of seismic activity coincident with this event.

The report in the Morning Post also makes mention of a similar event being noted at Arundel on Friday 7th September 1821. There are no indications as to the weather on either occasion so the possibility of them being meteotsunamis cannot be excluded.

This is considered an uncertain tsunami event.

3.15 5TH JULY 1843 AD

UK tsunami catalogue event 13

Dawson et al., (2000) mention oscillations of the sea around the south west had been reported, including Penzance and Plymouth, where it consisted of rises and falls for two to three hours (Edmonds, 1845). The Exeter and Plymouth Gazette described the event:

> "*On Wednesday the 5th instant, there was an unusual movement of the sea in the Mount's Bay, which lasted about three hours; and it is said to have greatly resembled that which was produced in the Bay by the great earthquake of Lisbon. At Newlyn about the middle of the day, about an hour after the sea had begun to ebb, it suddenly retired to the depth of 3 or 4 feet, rushing outwards with a great eddy towards the south along the western arm of the bay, to the distance of at least half a mile, in a current of about quarter mile broad. It then returned in the same state of agitation to its former level. The time occupied in each of these movements was about 10 or 15 minutes. This ebbing and flowing was observed four times, the duration of each movement being nearly the same as at first."*

Edmonds later (1862) describes agitation of the sea at Newlyn, Mousehole, Porthleven, Marazion, Falmouth as well as Plymouth. Flooding was reported in several places but there is no known earthquake associated with it and it coincides with a widespread storm (Milne 1844). In addition there are extensive reports of agitated seas around Scotland and also at Bristol and Tynemouth (Milne, 1844). Reports gathered by Edmonds and described in the Royal Cornwall Gazette on 21st July 1843 note unusual thunder storms suggesting that this was a meteotsunami.

This is considered a non-tsunami event.

3.16 23RD MAY 1847 AD

UK tsunami catalogue event 14

Edmonds (1869) noted that in Mount's Bay rises and falls of 3 to 5 feet (0.9-1.5m) occurred all day and similar effects at Plymouth in the evening. This has been linked with reports of a slight tremor felt in the Scilly Isles, Penzance and Mount's Bay in the night before. Musson (1989) suggested that a large offshore earthquake occurred and the abnormal waves are associated with it. However locating an epicentre for the earthquake is not possible, nor is determining how such an earthquake induced the size of the tsunami wave reported. Also it is difficult to explain the time delay for a wave reaching west Cornwall and Plymouth in the evening to have come from come from an earthquake close enough to west Cornwall to be felt the night before.

A letter from Robert Blight of Penzance dated 24th May and published in the Cornwall Royal Gazette on Friday May 28th suggests the waves were only observed in the evening although sudden changes in the weather were noted during the day:

> *Whilst standing on the beach at Newlyn, on Sunday evening last, about half-past five o'clock, I was surprised at observing a sudden rush of the sea, towards the shore, and also its immediate return. Judging by a boat which lay aground near the beach, the rise was about 18 inches. The water became foul in an instant, owing to the nature of the beach. There was no appearance of a large wave, but a ripple near the shore, and a rushing noise at the time. It was then about low water, wind westerly, sky clouds, threatening rain. There are a few instances on record of a similar occurrence, but the most extraordinary one happened at the time when Lisbon suffered so much by an earthquake. Many persons witnessed this irregular motion of the sea on Sunday, and I have since been informed by a Mousehole fisherman that the sea continued to flow and ebb alternately until near nine o'clock, and that it sometimes rose as much as eight feet. The changes in the atmosphere during the day were very remarkable. In the morning, about six o'clock, we had a breeze from the south east; by eight, it was a perfect calm; between ten o'clock and two, the mercury sunk several degrees; about three in the afternoon a breeze sprung up suddenly from the west, and the sky, as suddenly, became overcast; by eight o'clock it was again calm; but at eleven, the wind again rose suddenly and whistled along as it does in November. It is very probable that all these changes, and even the agitation of the sea, were produced by electricity; for if we suppose that the irregular motion of the water was occasioned by a distant earthquake, which might have occurred about that time, still the electric field might have been the most potent agent; for no natural power seems equal to it; in fact it acknowledges no bounds, neither any sensible transition of time.*

This suggests that Edmonds (1869) has confused the timing of the events. The information on the weather conditions suggests the events resemble meteotsunamis that have been reported previously on this coast.

In the same Cornwall Royal Gazette article another correspondent under the name of "West of England Conservative" describes the event at Anderton, located on the west side of the Tamar near Plymouth:

> *"One of those remarkable tidal phenomena known as "the bore," was experienced in thi neighbourhood on Sunday. We have been informed that the wave that ran up Anderton Lake was near four feet high, and did considerable mischief by breaking on the shore at various points. At Anderton, several boats were injured and other damage done by the extraordinary force and height of the water."*

This event is considered a non-tsunami event and is probably a meteotsunami.

3.17 5TH JUNE 1858 AD

UK tsunami catalogue event 15

Newig and Kelletat (2011) report a tsunami event in the English Channel and the southern part of the North Sea. They show evidence from the UK, France, Belgium, The Netherlands, Germany and Denmark with a suggested run-up in the latter of 6m. In the UK they give reports for Margate, Ramsgate, Dover and Folkestone and quote Edmonds (1862) description for the Dover Straits / English Channel: ''… *the sea on the French and English coasts first retiring suddenly and then returning with great violence to a much higher level."*, and who refers to a letter in Illustrated London News of 12th June 1858, p575.

> *"Extraordinary Phenomenon at Boulogne. A letter from Boulogne-sur-mer on Saturday last says: - "An Extraordinary Phenomenon, considered volcanic, occurred here this morning at 8 o'clock. The tide which was receding, suddenly fell and left the harbour dry, but returned in five minutes with great force eight feet higher, accompanied with a perfect tornado of wind, and the sky densely obscured. The whole did not last more than ten minutes, but what was most strange, was, that there existed the brightest sunshine immediately before and after. P.S. The passengers of the Folkestone boat, who have just come in (half-past five p.m.), report that a similar occurrence took place there and at other places on the English coast at the same time as here."*

This event is reported in the NGDC list of tsunamis for June 5, 1858, a tsunami in the Dover Straits, England, with a maximum of water level of 2.4 m, and gives the source of the tsunami as unknown. These UK events and the equivalent reports in France are catalogued as a false or doubtful tsunami in the catalogue of tsunamis maintained by BRGM at www.tsunamis.fr.

The report from Boulogne mentions a sudden change in the weather. It seems as though this event occurred at a time when reports of sudden intense thunderstorms including hail were noted both on the coast and inland.

For example the Folkestone Chronicle stated:

> *"During the heavy tempest which broke over our town about seven this morning, and which was one of the most terrific we have witnessed for some years past, a very extraordinary phenomenon occurred in the harbour. About eight o'clock the storm had reached its height; the thunder keeping up a continuous roll, interrupted only by the heavy peals which followed the most vivid lightning; the rain falling in torrents for half an hour, accompanied by hail. The wind at this time being E.N.E. suddenly veered round to W.N.W., and the tide which had ebbed sufficiently for the steamers to ground suddenly returned, and rushed into the harbour at the rate of ten knots an hour, and with such force as instantly to fleet the steamers, rising at least three feet, snapping their hawsers like packthread, and causing such commotion among the vessels and boats as to create great*

alarm. The Princess Mary carried away her bowsprit and figurehead in fouling the Princess Helena, which was thrown almost on her beam ends; a number of large fishing boats were cast adrift, one being capsized, and drawn out to sea, where it sunk by the reflux, which was as sudden and almost as strong as the influx, and as dangerous to the shipping, great fears being entertained of the drift vessels being carried out to sea. The phenomena was several times repeated, but each time with less force; the most singular feature was, that outside the harbour was a dead calm. An occurrence of this nature is beyond the memory of the oldest seaman."

Reports from Pegwell Bay indicate that people were caught unaware by this event:

"A gentleman of Pegwell, near Ramsgate, states that during the severe thunderstorms of Saturday morning, about 9.15 a.m., the water in the bay, the tide being nearly two hours past flood, suddenly receded about 200 yards and returned to its former position with the space of about 20 minutes. The shrimpers, many of them elderly men, and others in the neighbourhood, never before experienced such a surprising phenomenon. The feathered tribe, such as gulls, &., peculiar to that part of the coast of Kent, were very numerous at the time."

This is most likely a meteotsunami and therefore is considered a non-tsunami event.

3.18 4TH OCTOBER 1859 AD

Dawson et al., (2000) plot localities where agitation of waves were reported on both the southern and northern coasts of Cornwall and Devon, and also further afield in the Bristol Channel (Swansea and Bridgewater) where events were recorded by Edmonds (1860, 1862). These rises and falls were noted over several hours. Edmonds also notes that a thunderstorm did occur and so it possible that this may be a meteotsunami.

This is considered a non-tsunami event.

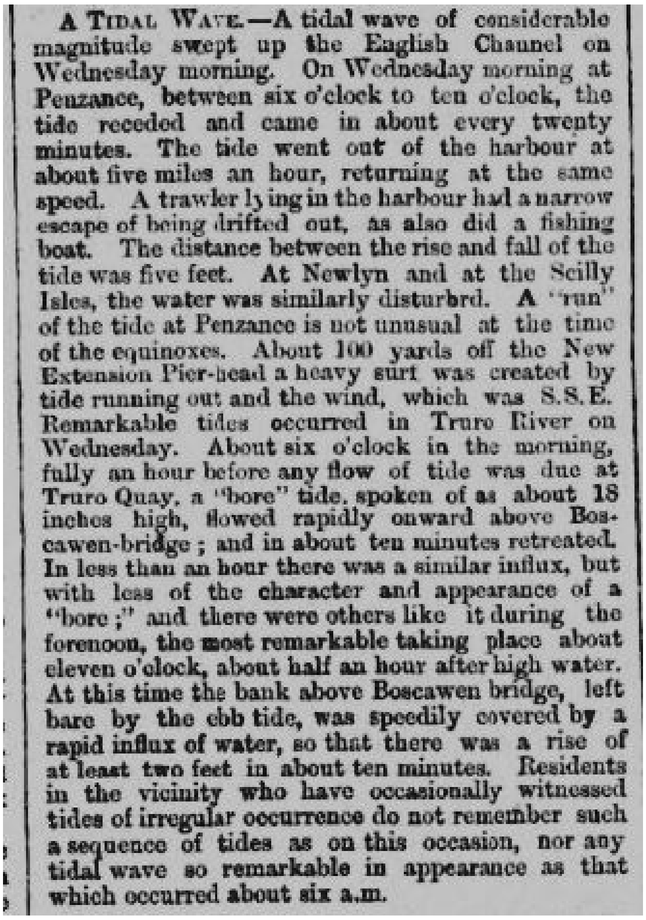
3.19 29TH SEPT 1869 AD

UK tsunami catalogue event 16

Dawson et al., (2000) report that Perrey (1872) records a series of waves seen in the Isles of Scilly, Newlyn, Penzance and Truro over a period of 4 – 5hrs. Examination of newspapers (Figure 6) of this time reveals the event was also observed in Plymouth, Totnes, Exmouth and Bideford. A few of the reports given times for when the event began (6am in Penzance and Truro to 10am in Exmouth) and this suggests a progression eastwards. Waves up to 0.9m are noted.

There was expectation of particularly large high tides on 6th October but would seem that the events of a week earlier were a surprise. The fact that the events were recorded both the English Channel and in the Bristol Channel and that that the first observation was frequently the sea receding make it less likely it was a meteotsunami. However the difference in the time the event was observed from west to east imply that it could not be a tsunami and that a meteotsunami is a more likely explanation. There are no earthquakes noted that could be associated with this event.

This is considered a non-tsunami event.



A TIDAL WAVE.—A tidal wave of considerable magnitude swept up the English Channel on Wednesday morning. On Wednesday morning at Penzance, between six o'clock to ten o'clock, the tide receded and came in about every twenty minutes. The tide went out of the harbour at about five miles an hour, returning at the same speed. A trawler lying in the harbour had a narrow escape of being drifted out, as also did a fishing boat. The distance between the rise and fall of the tide was five feet. At Newlyn and at the Scilly Isles, the water was similarly disturbrd. A "run" of the tide at Penzance is not unusual at the time of the equinoxes. About 100 yards off the New Extension Pier-head a heavy surf was created by tide running out and the wind, which was S.S.E. Remarkable tides occurred in Truro River on Wednesday. About six o'clock in the morning, fully an hour before any flow of tide was due at Truro Quay, a "bore" tide, spoken of as about 18 inches high, flowed rapidly onward above Boscawen-bridge; and in about ten minutes retreated. In less than an hour there was a similar influx, but with less of the character and appearance of a "bore;" and there were others like it during the forenoon, the most remarkable taking place about eleven o'clock, about half an hour after high water. At this time the bank above Boscawen bridge, left bare by the ebb tide, was speedily covered by a rapid influx of water, so that there was a rise of at least two feet in about ten minutes. Residents in the vicinity who have occasionally witnessed tides of irregular occurrence do not remember such a sequence of tides as on this occasion, nor any tidal wave so remarkable in appearance as that which occurred about six a.m.

Figure 6 A detailed account in the Cornubian and Redruth Times of 1st October 1869 describing an event on Wednesday 29th September 1869

3.20 28TH AUGUST 1883 AD

UK tsunami catalogue event 17

Berninghausen (1968) reports that waves from the tsunami initiated by the explosive eruption of Krakatoa, in Indonesia, on 27th August 1883 were detected at Devonport and Portland on tide gauges, as well as at other ports in Europe. The disturbance began at 0620hrs at Devonport, while the first large wave at Portland was detected at 1015hrs, where the maximum wave height was 2.5cm and at 1045hrs at Devonport where the maximum wave height was 10cm, some 30hrs after the first major eruption of Krakatoa. The time interval from the tsunami source are comparable to that associated with the 2004 Indian Ocean tsunami reaching the UK (see section 3.27), however the times given for observation suggest a movement along the English Channel from east to west, the opposite direction to that expected for a tsunami wave originating at Krakatoa. However, prior to the 2004 Indian Ocean tsunami (Press, 1956; Pararas-Carayannis, 2003) suggested that the waves recorded on tide gauges occurred too soon to be remnants of the initial tsunamis, and may have been caused by concussive air waves from the eruption (Press, 1956; Pararas-Carayannis, 2003). These air waves circled the globe several times and were still detectable using barographs five days later (Pararas-Carayannis, 2003).

This is considered a tsunami event.

3.21 22ND APRIL 1884 AD

UK tsunami catalogue event 18

One of the best studied earthquakes to strike southern England in historical times occurred at 0918 and is often referred to as the Colchester Earthquake as the greatest effects were noted in south east Essex (Musson et al., 1990). Although not large in magnitude ($4.6M_L$) but because of the earthquake's shallow depth (3km) its damage was severe (Musson 2007), though occasionally exaggerated (Musson, 1990).

Haslett and Bryant (2008) have suggested that there was an associated tsunami. There are several reports of boats at moorings being swayed violently. For example, the Chelmsford Chronicle of 25th April notes that:

> *"In the harbour the yachts and other vessels rocked considerably, and some men up the masts of one vessel were nearly thrown overboard by the unexpected vibrations."*

These observations may indicate seiching rather than a tsunami. The various newspapers provide very detailed descriptions of the effects of the earthquake in each village and town but don't mention any anomalous waves. A subsequent review of the event by Medola and White (1885) states that the absence of any distinct movement of the river Colne was generally confirmed.

There was however a single report in the Eastern Daily Press of 23rd April 1884 that states that:

> *"the sea is said to have rushed with restless force over the marshes* [of East Mersea Island], *receding some time afterwards, leaving thick deposits of sand behind, in some instances at incredible distances from the coast",*

which is similar to descriptions of a tsunami. This is used by Haslett and Bryant (2008) to suggest that the earthquake created a tsunami. The earthquake itself is too small to have generated a tsunami and there is no evidence that a landslide was triggered. However there were reports of groundwater escape in the same area that ceased after two and half hours and that this water was laden with sand so there may have been some mixing of reports.

It is considered that this is not a tsunami event.

3.22 18TH AUGUST 1892 AD

UK tsunami catalogue event 19

A tsunami event is listed in the global tsunami database for Pembrokeshire. This relates to an earthquake. Davison (1897) reported that:

> *The shock was felt by several persons in boats, the sensation being the usual one of having struck upon a rock. At Bulwell, on the southern shore of Milford Haven, two or three waves were seen to dash up the shore, the sea both before and after being absolutely still. The shock was also felt by the engineer of a steamboat on the river opposite Langwm. ' The water, although perfectly calm before, became suddenly swelled as with a heavy breeze. The boat seemed as if passing over a swell, and then another, and then another—three distinct waves, after which the water was troubled for a few seconds; then it became perfectly calm as before.' The waves lasted from 15 to 20 seconds, and crossed the river from north-west to south-east. I am indebted to the Rev. W. M. Morris for this* ***account.***
>
> *Some hours after the earthquake, one or more so-called tidal waves were observed at various places along the shore of the English Channel, and were generally regarded as an effect of the earthquake. The places from which I have obtained accounts of such waves are (from west to east): Scillv Isles, Porthpean (near St. Austell), Lostwithiel, River Yealm, River Dart, estuary of the Exe at Exmouth and Topsham, Weymouth, Portsmouth, and Bosham (in Sussex). It is unnecessary to enter into any detailed description of the waves,*

since, whatever their origin may have been, it is difficult for the following reasons to connect them with the Pembroke earthquake :--(1) All the places are situated along the English Channel. (2) The accounts obviously refer to several different waves, but, so far as one wave in particular can be traced, it advanced from east to west. (3) Similar waves were observed on the two days preceding that of the earthquake.

It is likely that the waves noted in Milford Haven relate to a seiche from the earthquake event whereas those waves noted in the English Channel have no connection with the earthquake for the reasons offered by Davison (1897) above. Haslett and Bryant (2009) include the English Channel events in their catalogue of meteotsunamis.

This is considered to be a non-tsunami as the earthquake was too small to generate a tsunami directly.

3.23 31ST DECEMBER 1911 AD

UK tsunami catalogue event 20

A very large landslide at Abbot's Cliff east of Folkestone caused a wave in Folkestone Harbour that was most notable in the shallow areas. Ropes and stanchions were damages as hawsers snapped. The event was described in the Folkestone, Hythe, Sandgate and Cheriton Herald of Saturday 6th January 1912 by a seaman (Charles Harrison) who was standing on the harbour as:-

"The great rush of water swept up towards the harbour from the east without the slightest warning. I have never witnessed anything like it. The sea was choppy, but not rough, previously. All at once there seemed to be a long heaving, lifting motion, as if the Channel were being raised in the air. The vessels in sight 'danced' violently, the colliers were tossed pell mell, and the crews on various steamers lying around shouted at the tremendous shock. It was an exciting moment – for it passed in a moment – and left us all wondering".

The newspaper article notes vessels were lifted two to three feet (0.6 -0.9m) by the wave. The effects in the outer (deeper) harbour were minimal.

As this event occurred in the evening it was a while before the waves were correlated with a large cliff fall is located approximately five kilometres northeast of Folkestone harbour that had occurred at Abbot's Cliff (Figure 7). This comprised a very large volume of chalk, figures of 800,000 tons were quoted. The cliff fall was reported in the Whitstable Times and Herne Bay Herald Saturday 6th January 1912

From the nearest coastguard station the noise made, as the avalanche of chalk swept down from the face of the cliff into the sea, is described as sounding like heavy guns booming. An examination on Monday showed that the chalk extended like a causeway some 400 yards to sea. It is about 200 yards wide, and at some places 30ft deep. The displacement of water caused by this immense mass entering the sea set up conditions similar to a tidal wave at Folkestone. The water rose several feet, and several colliers broke their cables and ran adrift, causing great alarm in the outer harbour. Fishing smacks danced like corks. The noise of the approaching wave was heard a mile distant, and not within living memory has such a one been seen.

The cliff fall consisted of just the middle and upper parts of the chalk. It was speculated that heavy rains over the preceding months had weakened the cliff, causing the rockfall leaving the debris at the foot of the cliff (Figures 8 and 9). The cliff was previously 348ft high here (McDakin, 1912). Hutchinson (2002) gives a volume of 500,000m^3 for this fall.

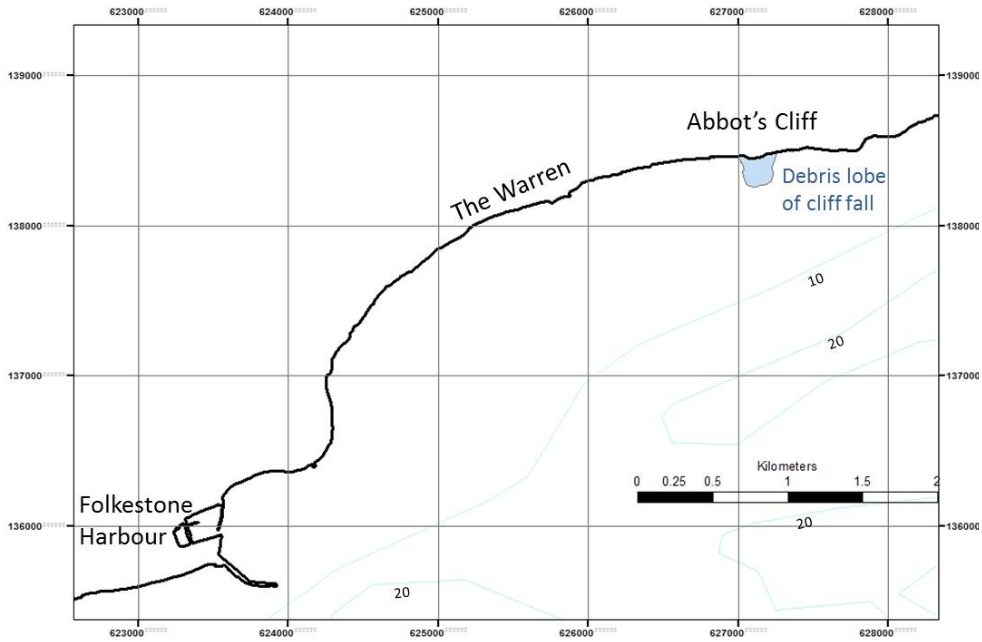


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Figure 7 Location of cliff fall and Folkestone harbour

The outline of the debris lobe is derived from the difference between OS maps before and after the events.

This landslide is unlike at the nearby landslides in the Warren which consist of rotational slides on the Gault. The extensive volume of fallen rock has remained at the foot of the cliff extending into the sea (Figure 10). The sea between Abbot’s Cliff and Folkestone harbour is shallow, less than 10m (Figure 7), so the wave would have moved relatively slowly.

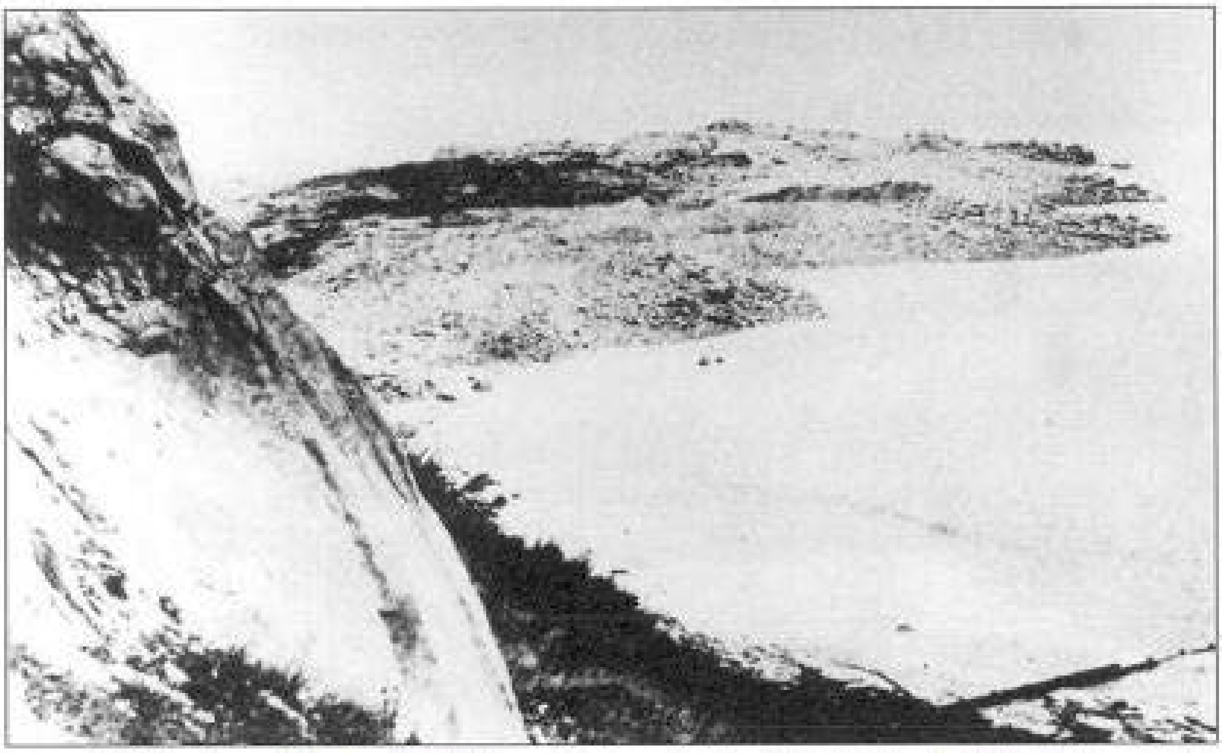

Figure 8 View from cliff top showing the debris from the 31st December 1911 cliff fall at Abbot’s Cliff near Folkestone, Kent

Figure 9 View from beach of the debris extending out to sea from the cliff fall of 31st December 1911 at Abbot’s Cliff, near Folkestone, Kent

Recent aerial images of Abbot’s Cliff taken from Bing maps and Google websites show the 1911 landslide and debris lobe remain evident.

The dashed line on the Bing maps image is the railway line that is located within a tunnel under the cliffs, entrance can be seen on the Google image

Figure 10 aerial views of Abbot's Cliff

Coastal landslips in this part of English Channel are a common occurrence (Hutchinson, 2002) with impact on local infrastructure (Birch and Warren, 2007). Some are slow moving such as the 1915 slide at the nearby Folkestone Warren but cliff falls of the chalk can be sudden and if they include a sufficient volume of material entering the sea they can trigger a tsunami, thereby extending the area at risk from that immediately adjacent to the cliff fall. Modelling of potential cliff falls to explain the 1580 event suggests that volumes of 10^6 m^3 could generate a tsunami (Roger et al., 2012).

This event is considered a tsunami

3.24 24TH JANUARY 1927 AD

UK tsunami catalogue event 21

A magnitude of 5.7 ML earthquake with an epicentre in the Viking Graben area was felt over much of Scotland and also along the coasts of Norway. The NGDC/WDS database attributes this earthquake to having caused a tsunami like event at Helmsdale in eastern Scotland. The earthquake had been extensively felt in Helmsdale between 5.17 to 5.20 a.m. however:

> *At the time of the shock the bar at the mouth of the Helmsdale River was calm, but at 5.30 a.m. great rollers began to come in from the south-east. Fishermen working 10 miles north-east of Helmsdale were alarmed by a change in the "draw" of the sea, and some of them made speed to get home before worse things happened*. (Tyrrell 1932)

Tyrrell's extensive review of the earthquake makes no other mention of associated movements of the sea. Ambraseys (1983) searched the available tide gauges, and found no trace of any fluctuation; however, his most northerly data set was at North Shields. The distance from the earthquake epicentre to Helmsdale is 400 km, so it seems inconceivable that waves originating in the Viking Graben could have reached Helmsdale in only 12 minutes (Kerridge et al., 2005).

This is considered a non-tsunami event.

3.25 25TH NOVEMBER 1941 AD

UK tsunami catalogue event 22

The tide gauge at Newlyn, Cornwall shows a tsunami occurred on 25th November 1941 following an earthquake west of Portugal, magnitude 8.2 Ms. The first waves begin at about 2200hrs approximately four hours after the earthquake. The wave was recorded at various tide gauges in Portugal and Morocco (Baptista and Miranda, 2009). The tsunami recorded at Newlyn consisted of seven waves with a maximum amplitude of about 20cm and lasted about four hours (Figure 11). Tide gauge records, from Le Havre, although of poor quality, suggest that the tsunami travelled up the English Channel (Dawson et al., 2000).

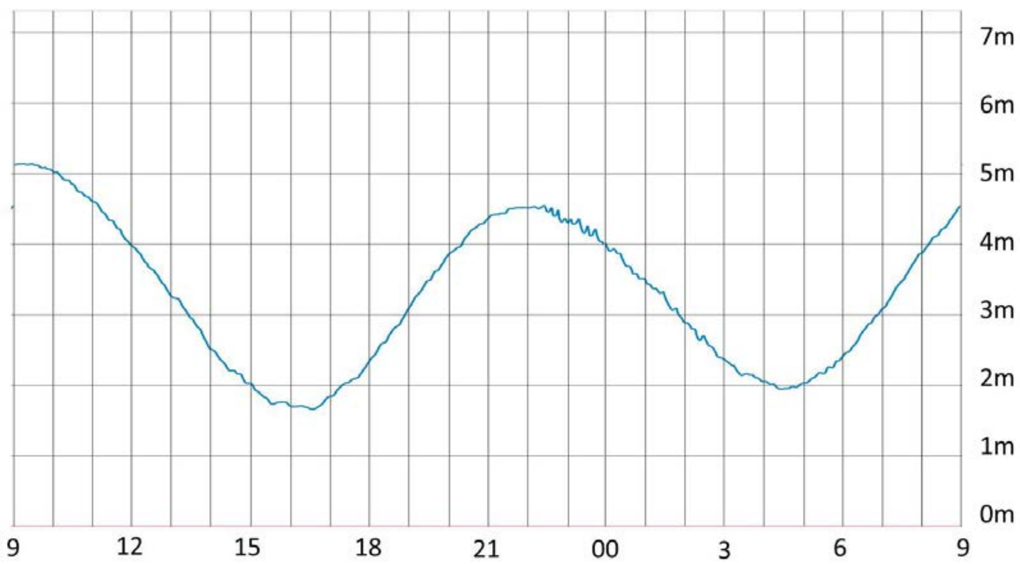

Figure 11 Tide gauge at Newlyn for 25th -26th November 1941

This is considered a tsunami event.

3.26 1ST FEBRUARY 1953 AD

The GTDB lists an event for Flanders and Norfolk for this date. This was a major storm flooding that began late on the 31st January 1953 when a northerly storm combined with spring tides to breach coastal defences leading to 1,835 people killed in the Netherlands, 307 killed in the United Kingdom and 28 killed in Belgium. A further 230 minimum are thought to have drowned at sea.

It was not a tsunami event.

3.27 23RD MAY 1960 AD

UK tsunami catalogue event 23

A tsunami was generated the by Chile earthquake of 22nd May 1960, at Magnitude 9.6 Mw the largest earthquake ever recorded. The tsunami, together with coastal subsidence and flooding, caused tremendous damage along the Chile coast, where about 2,000 people died. The waves spread outwards across the Pacific, 15 hours later the waves flooded Hilo, on the island of Hawaii, where they built up to thirty feet and caused 61 deaths along the waterfront. After 22 hours the waves flooded the coastline of Japan where 3m high waves caused 200 deaths. The waves also caused damage in other parts of the Pacific. Subsequent analysis of tidal gauges has shown the waves travelled around the world and were detected in the North Atlantic including Newlyn the day after the source earthquake (Van Dorn 1987). Van Dorn (1987) suggests that the wave had an amplitude of 2.5cm at Newlyn though difficult to read. The time taken for arrival at Newlyn suggests that the wave propagated around Cape Horn to arrive in the Atlantic.

This is considered a tsunami event.

3.28 28TH FEBRUARY 1969 AD

UK tsunami catalogue event 24

On 28 February 1969 at 0240, an earthquake west of Portugal (7.3 Ms) generated a tsunami that was recorded along the western coast of Spain and Portugal with a maximum amplitude (peak to trough) of almost 1m (Baptista et al., 1992). It is probable that this tsunami also reached SW England as Dawson and others (2000) note that the tide gauge record for Newlyn for this period reports heavy seiching on a day characterized by calm sea conditions. It can also be seen on the tide gauge record from St Marys in the Isles of Scilly where the waves had period of about 5 minutes with the third wave having the largest trough to crest amplitude of 0.25m (Figure 12) from about 0735 suggesting a five hour travel time from the source to reach the UK. A weak signal can be seen on the tide gauge at Fishguard beginning about two hours later with a maximum peak to trough of 0.1m, which may also be attributable to this event.

This is considered a tsunami event.

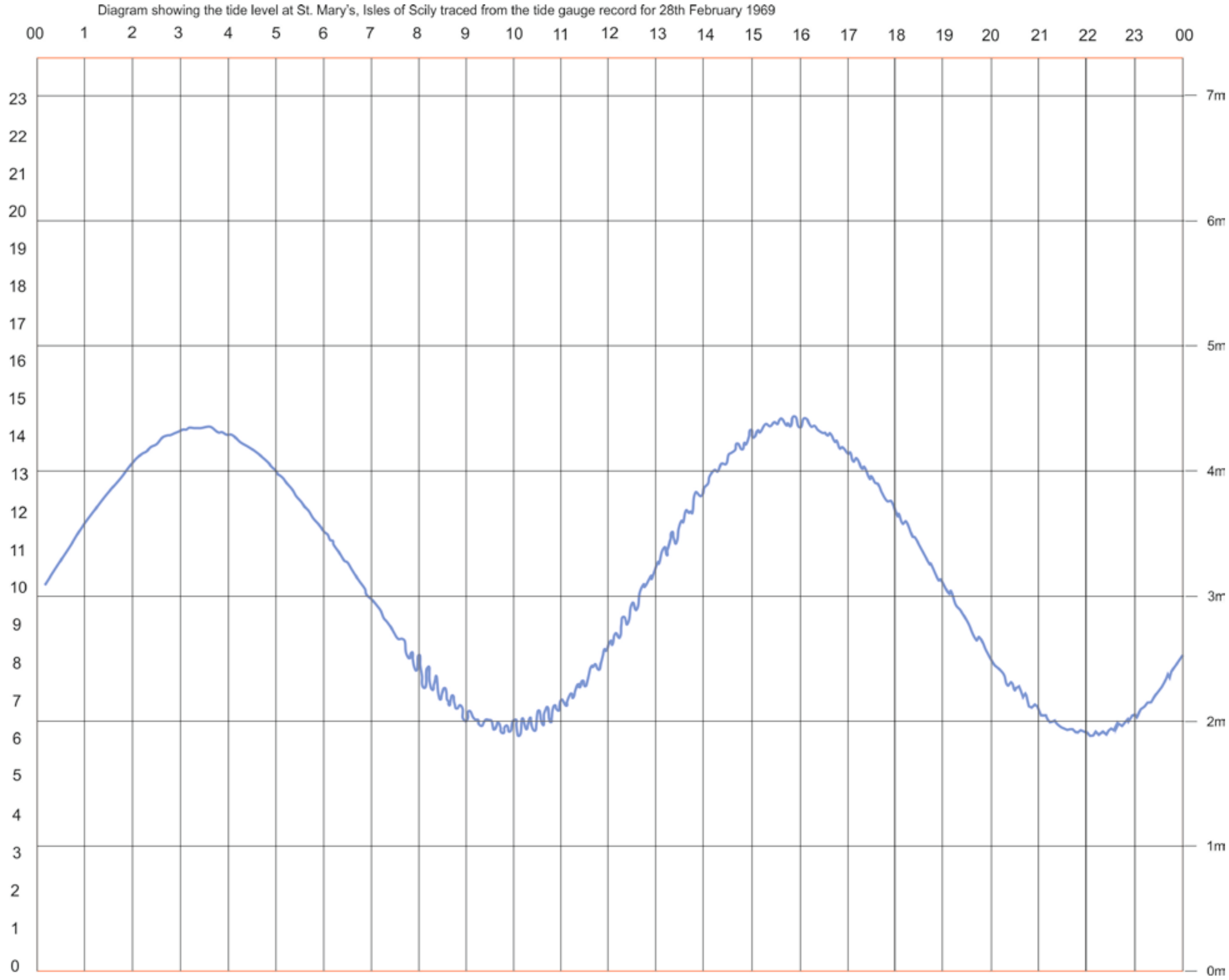

Figure 12 Tide gauge for St Mary's, Isles of Scilly, for 28th February 1969 showing arrival of tsunami wave at approximately 0735

3.29 26TH MAY 1975 AD

UK tsunami catalogue event 25

The tide gauge at Newlyn, Cornwall shows a tsunami occurred on 26th March 1975 following an earthquake west of Portugal, magnitude 7.9 Ms. The tsunami was clearly seen in the Azores, Portugal and Spain (Baptista et al., 1992). The tsunami that was measured at Newlyn UK consisted of eight waves with a maximum amplitude of about 6cm and lasted nearly four hours (Dawson et al., 2000). It was also detected at St Mary's in the Isles of Scilly from about 1430hrs just over five hours after the earthquake occurred (Figure 13). The tide gauge shows a maximum peak to trough amplitude of 0.16m with a period of about 9 minutes.

This is considered a tsunami event.

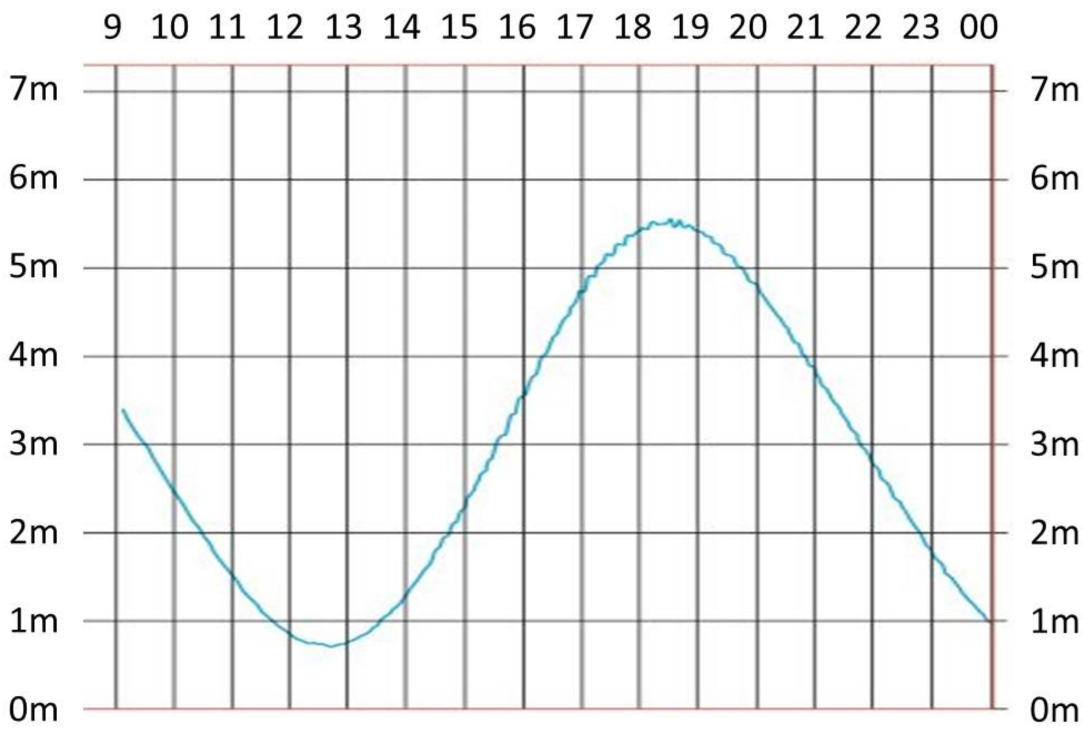

Figure 13 Tide gauge at St Mary's, Scilly for 26th May 1975 from 9am

3.30 27TH DECEMBER 2004 AD

UK tsunami catalogue event 26

The magnitude 9.3 Mw Sumatra earthquake of 26th December 2004 initiated a tsunami that caused upwards of 225,000 deaths in around the Indian Ocean. The tsunami was a global event (Titov et al 2005) travelling across the Indian Ocean and entering the Atlantic south of Africa. It was observed visually on the North American Atlantic coast (Rabinovich et al., 2006) and also on the West African coast (Joseph et al., 2006) but was restricted to recordings on the European Atlantic coastline as it reduced in energy. It was detected on tide gauges in the English Channel (UK and France) more than 30 hours after the triggering earthquake. It appears on the Newlyn record as a period of increased variability (Figure 14). The tsunami wave was possibly also recorded at Milford Haven although there was a moderate storm surge at the time, which may have created a confused signal (Woodworth et al., 2005).

This is considered a tsunami event.

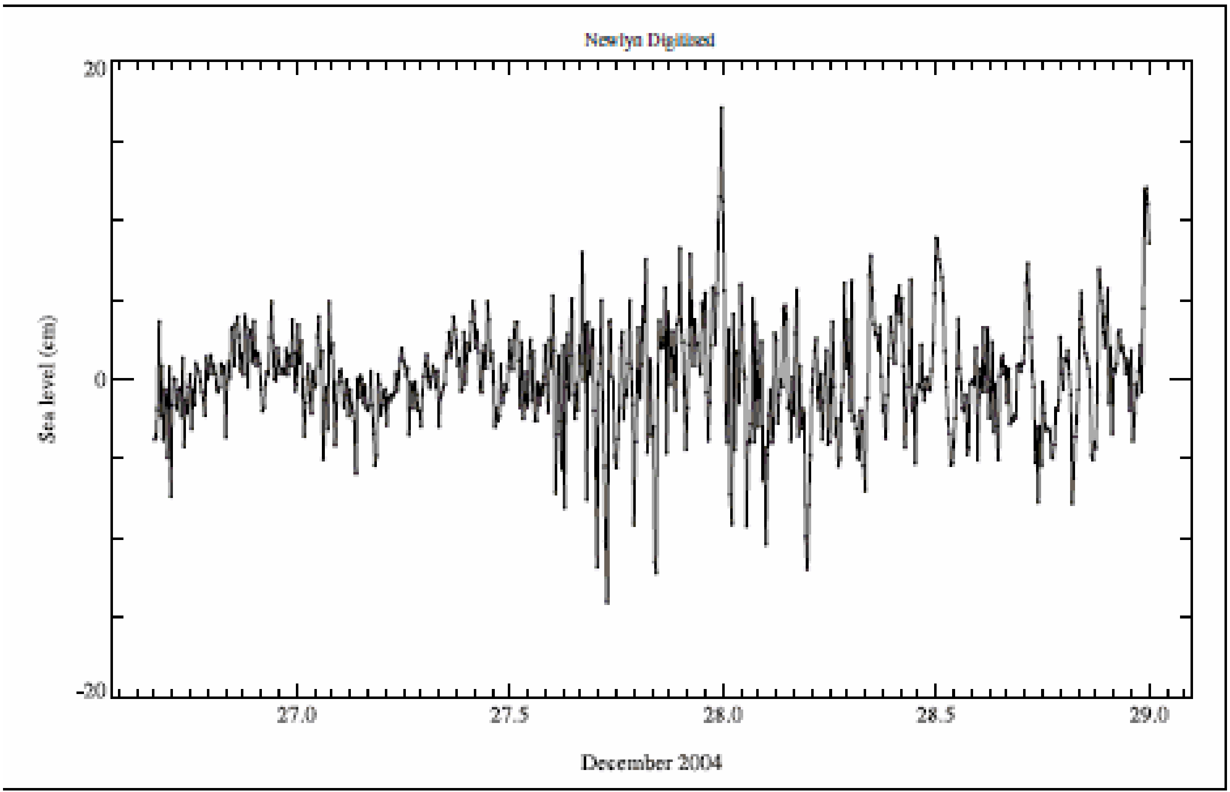

Figure 14 Sealevels at Newlyn derived from digitizing at 5 min intervals the trace of a chart recorder. The period of higher variability, the possible tsunami signal starts at 1400 UTC on 27 December 2004 (approximately day 27.6). From Woodworth *et al* 2005.

3.31 28TH MAY 2008 AD

A sudden draw down of the sea in Peterhead harbour followed by a very large wave about 10 minutes later was noted about 1230. A similar but smaller effect was noted in Fraserburgh. There was no seismicity associated with this event.

The same day, there was observed a withdrawal of 40 cm at Akrehamn at Karmøy close to Stavanger, Norway at 12 am local time (1hr ahead of UK time). In the area it was observed long periodic disturbances (ca. 6 hrs) with maximum amplitude of 40 cm registered at gauge at Stavanger, and Bergen 7-8 cm (Glimsdal et al., 2010).

Likewise Hvannasund in the Faroes, at 3 pm (local time, same as UK), registered wave heights up to 3 m with a wave period of 4-6 min. There were also several other observations at different locations in the north-eastern part of the Faroe Islands. However there is only one tide gauge in the Faroes, located at Gomlurætt, north of Kirkjubø, Strømø in the south west which did not register any anomalous waves.

Sudden changes in wind speed and direction over several oil platforms in the northern North Sea were also noted. This has led to the interpretation that the waves noted at Peterhead and Fraserburgh were caused by metrological conditions primarily a storm moving northwards in the North Sea (Sibley et al, in press).

This is considered to be a meteotsunami

4 Meteotsunami

Tsunami-like effects can be created by meteorological conditions such as cyclones, hurricanes and thunderstorms or more distinct events such as atmospheric pressure jumps and atmospheric gravity waves. These processes generate a wave with characteristics similar to tsunamis when the disturbance travels at the same speed as any surface wave it has generated thereby sustaining and adding to the wave (Monserrat et al., 2006).

Several such events have been recognized from historical records around the UK (Haslett and Bryant, 2009) and have been considered as an important potential coastal hazard having caused several fatalities (1929, 1932, 1964) (Haslett et al., 2009). These events are tabulated below (Table 2). Of note is the event on 20th July 1929 which lead to two deaths. It was observed at various locations along the eastern English Channel including Brighton, Worthing, Hastings and Folkestone. There was a single death reported at both the last two locations.

As such events have been recognized in recent times it must be assumed that similar events have occurred in historical times and may explain the origin of events reported around the British Isles and considered as tsunami for which no potential tsunami trigger has been identified. For example the 1858 event has been examined in detail (Newig and Kelletat, 2011) to suggest a tsunami source in the Atlantic although with anomalous waves occurring on both sides of the English Channel and extending into the North Sea as far as Denmark. These observations were reported at the same time as meteorological phenomena were noted, therefore a meteotsunami explanation seems more likely. A detailed review of the meteorological conditions accompanying the 27th June 2011 event in the English Channel illustrates how these events can develop (Tappin et al., 2013)

William Borlase who gathered reports of the 1755 and 1761 tsunamis reported to the Royal Society an agitation of the sea in Mount’s Bay in 1761 that has all the hallmarks of a meteotsunami.

Some of the tsunami-like events mentioned above may have a meteotsunami explanation particular where reference to accompanying thunderstorm or other meteorological phenomena such as the 4th October 1859 event discussed by Dawson et al., 2000.Although there are no mention of unusual weather conditions the times of the 29th September 1869 suggest a meteotsunami origin is the more likely explanation.

The fact that the frequency of these events is greater than tsunamis *sensu stricto* and that they have been known to cause fatalities means that these phenomena should be included in any risk assessment for the UK coastline.

Table 2 Probable meteotsunami events reported in the UK

Year	Date	Location	Data source
1761	July 28th	Mount’s Bay (Cornwall)	Borlase, 1762
1824	November 23rd	Chesil Beach (Dorset)	Haslett and Bryant, 2009
1858	June 5th	English Channel	Newig and Kelletat, 2011
1868	April 23rd	Burton Bradstock and Lyme Regis (Dorset)	Haslett and Bryant, 2009
1883	October 17th	Severn Estuary	Haslett and Bryant, 2009
1892	August 18th	Yealm (Devon), Fowey (Cornwall)	Haslett and Bryant, 2009; Haslett et al., 2009

1910	December 16th	Ilfracombe (Devon)	Haslett and Bryant, 2009
1929	July 20th	Folkestone (Kent), Brighton, (Sussex)	Haslett and Bryant, 2009; Haslett et al., 2009
1932	August 2nd	Aberavon (Glamorgan)	Haslett et al., 2009
1938	August 5th	Bridlington (Yorkshire)	Haslett et al., 2009
1939	July 4th	Milford Haven (Dyfed)	Haslett et al., 2009
1939	July 5th	Weymouth (Dorset)	Haslett et al., 2009
1957	July 6th	Bembridge (Isle of Wight)	Haslett et al., 2009
1964	May 17th	Arnside (Cumbria)	Haslett et al., 2009
1966	July 31st	Westward Ho! (Devon) and Pembrokeshire coast	Haslett and Bryant, 2009; Haslett et al., 2009
1979	February 13th	Bristol Channel and western part of English Channel	Haslett and Bryant, 2009
2008	May 28th	Peterhead and Fraserburgh (Aberdeenshire)	Sibley et al., in press
2011	June 27th	English Channel	Tappin et al., 2013
2015	July 1st	Stonehaven and Gourdon (Aberdeenshire)	Sibley et al., in press

5 Tsunami catalogue

This catalogue has been created by searches of published papers and examination of existing databases. Existing databases include the US National Geophysical Data Center NOAA/WDC Historical Tsunami database http://www.ngdc.noaa.gov/seg/hazard/tsu_db.shtml. Reports within the Tsunami Runup data base that are known to be reports of seiches have been excluded. Also some reports of tsunami run-ups have been mis-positioned e.g. the event of 31st March 1761 at Carrick in County Wexford, Ireland has been mis-recorded as occurring at Carrickfergus, UK. The catalogue produced for GITEC has also been examined and reports with great uncertainty have been ignored.

Positioning has been recorded to 0.1km accuracy using the British National Grid and subsequently converted to geographical co-ordinates using WGS84. This allows sites with several boreholes that have recovered a tsunami deposit or containing a coastal section to be noted as a single point. It also allows a general location for historical observations respecting that only a general area associated with a place name is available.

The evidence at each site/event is classified as deposits, observations or tidal measurements. The deposits are further subdivided into “S” where the deposits are seen in a section or “B” where they are buried but recognized in one or more boreholes.

The catalogue could be extended by listing additional attributes particularly for tsunami deposits by recording the height of deposit, thickness of deposit, its extent inland, what material is dated and any uncertainties of the dated material relates to tsunami deposit.

The data shows the events are concentrated in two areas, namely, along the southern coasts of England and Wales, and around the coast of Scotland and northeast England (Figure 15). The data types are similarly spatially divided with sedimentary evidence of tsunami events primarily in the north and with observations and tide gauge evidence located primarily in the south of the UK (Figure 16). Many sites have evidence of more than one type and from multiple events. Figure 16 displays the presence of tide gauge evidence on top of observation or sedimentary evidence.

Based on the comments given above in chapter 3 the reported tsunami events are subdivided into three groups with different levels of confidence in them being tsunamis. The categories are tsunami events, uncertain tsunami events and non-tsunami events. Their distribution is displayed in Figures 17-20.

6 Conclusions

Over the years many events around the coasts of the UK have been described as tsunamis or tidal waves. The terms have changed with time with the preferred term tsunami becoming widely used in the 21st century. Previously they were often described as tidal phenomena and compared with bores. The data types vary from sedimentary primarily of pre-historic events, through observations, particularly reports in 19th and 20th century newspapers, to tide gauge records. Evaluation of the data indicates only a few of the events are definitely tsunamis with most events deemed as non-tsunamis and a few designated as uncertain tsunami events.

The major tsunami events to have struck the UK include the Storegga tsunami which struck coasts in the northern half of the UK about 8150BP, and the tsunami triggered by the 1755 Lisbon earthquake. The Storegga tsunami was caused by a massive submarine landslide on the continental slope offshore mid-Norway. It struck coastlines in Norway, Denmark, the Faroes, Iceland and Greenland as well the UK. Evidence within the UK is primarily in Shetland and along the eastern coast of mainland Scotland and on the northernmost part of eastern England. The tsunami on 1st November 1755 was triggered by a magnitude 8.5 M_S earthquake striking the coasts of Morocco, Spain, Portugal, Ireland as well as the UK. It also crossed the Atlantic striking shores in the Caribbean and Brazil.

The lesser events are primarily associated with smaller earthquakes with epicentres offshore Portugal in similar areas as the epicentre of the 1755 event. Most of these events (1941, 1969 and 1975) were only noted on tide gauge records. An UK earthquake in 1580 may have initiated earth movements leading to tsunamis affecting coasts in the Straits of Dover. A coastal cliff fall on 31st December 1911 can be correlated with a tsunami event at Folkestone more than 5km away.

Most reported events are probably not tsunamis. Many are likely to have been weather related events known as meteotsunamis. These are large amplitude, long wavelength seiches caused by rapid changes in air pressure. They occur predominantly along on the south coast of England and have over the years caused fatalities and damage to structures.

Some reported events are classified as uncertain events where the triggering mechanism is not clear. These include sediment layers found in Shetland resembling tsunami deposits but it is uncertain if the sediment is deposited by waves or are aeolian or through downslope processes.

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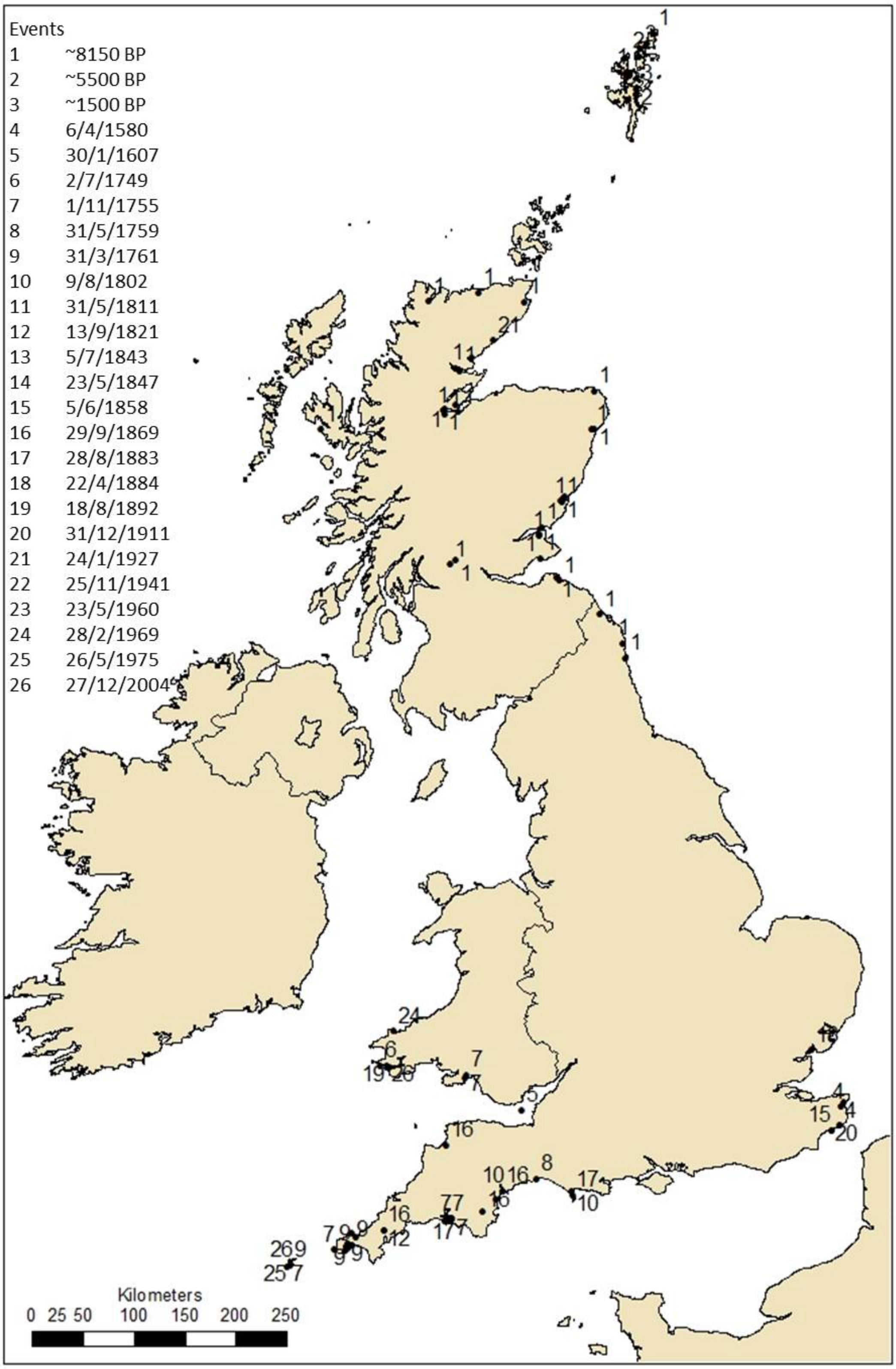

Figure 15 Map of locations of events considered in this catalogue

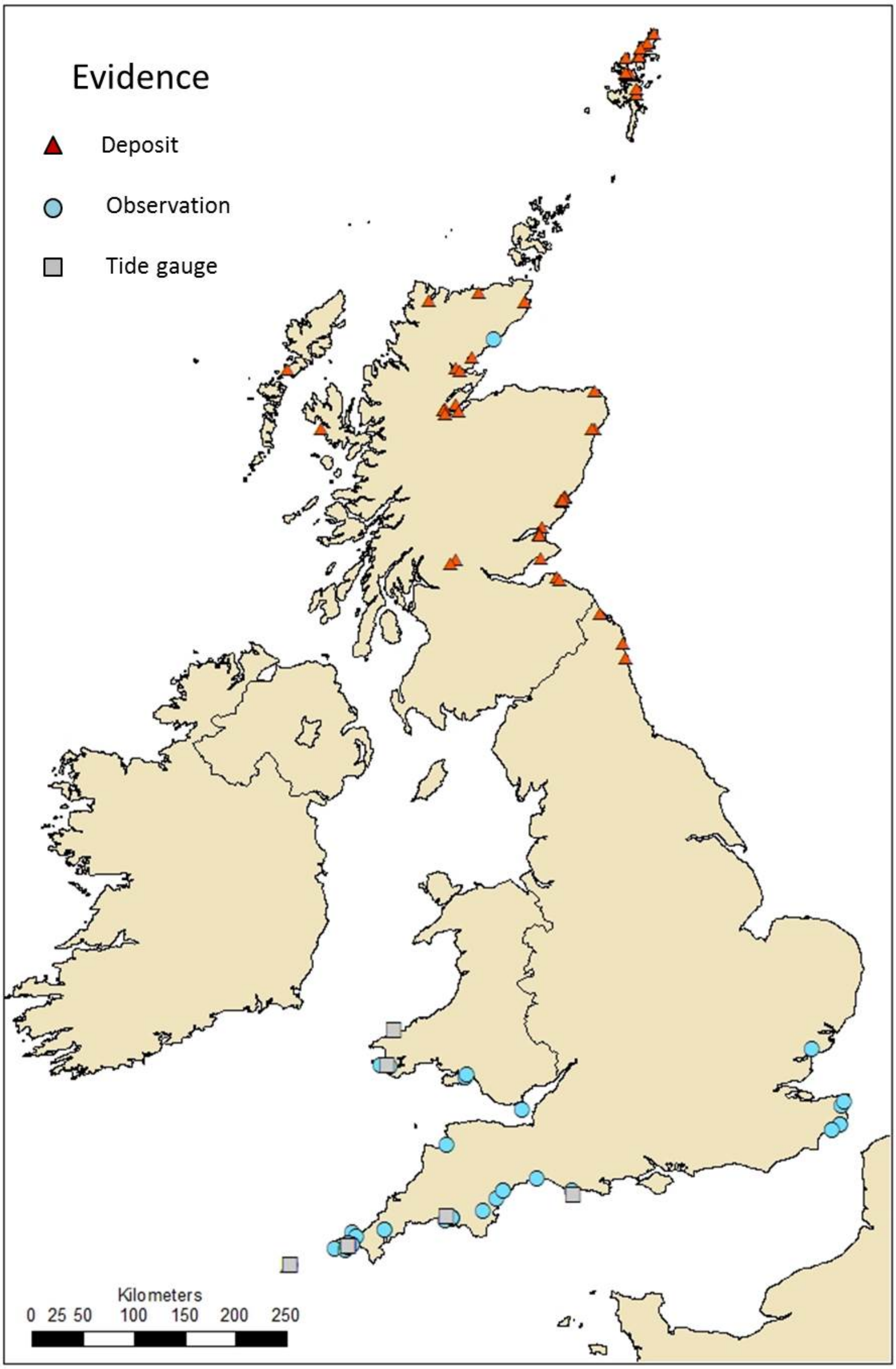

Figure 16 Map illustrating the type of evidence upon which previous claims of tsunami are based

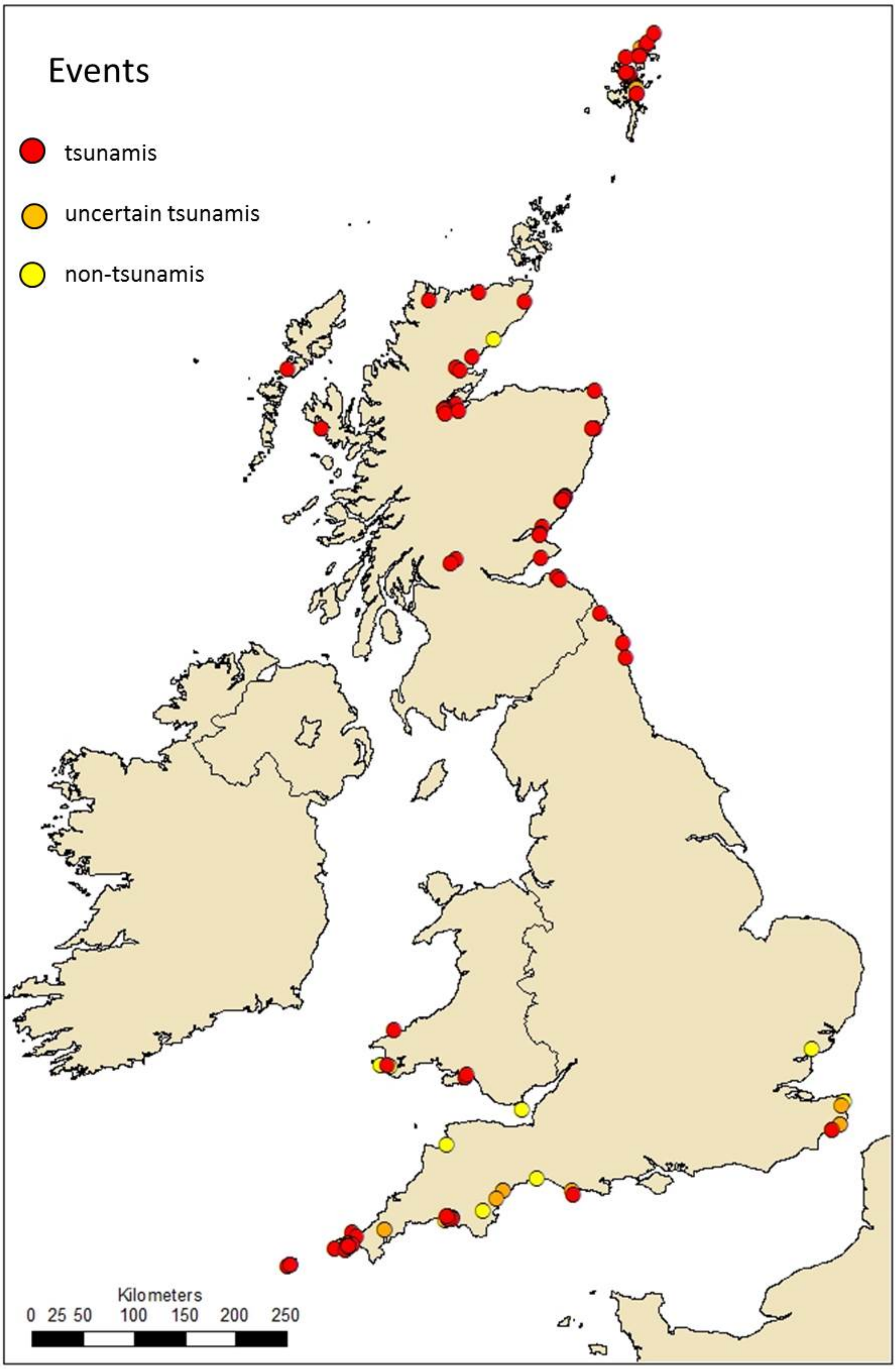

Figure 17 Location of all events considered as tsunamis in this catalogue showing confidence in interpretation

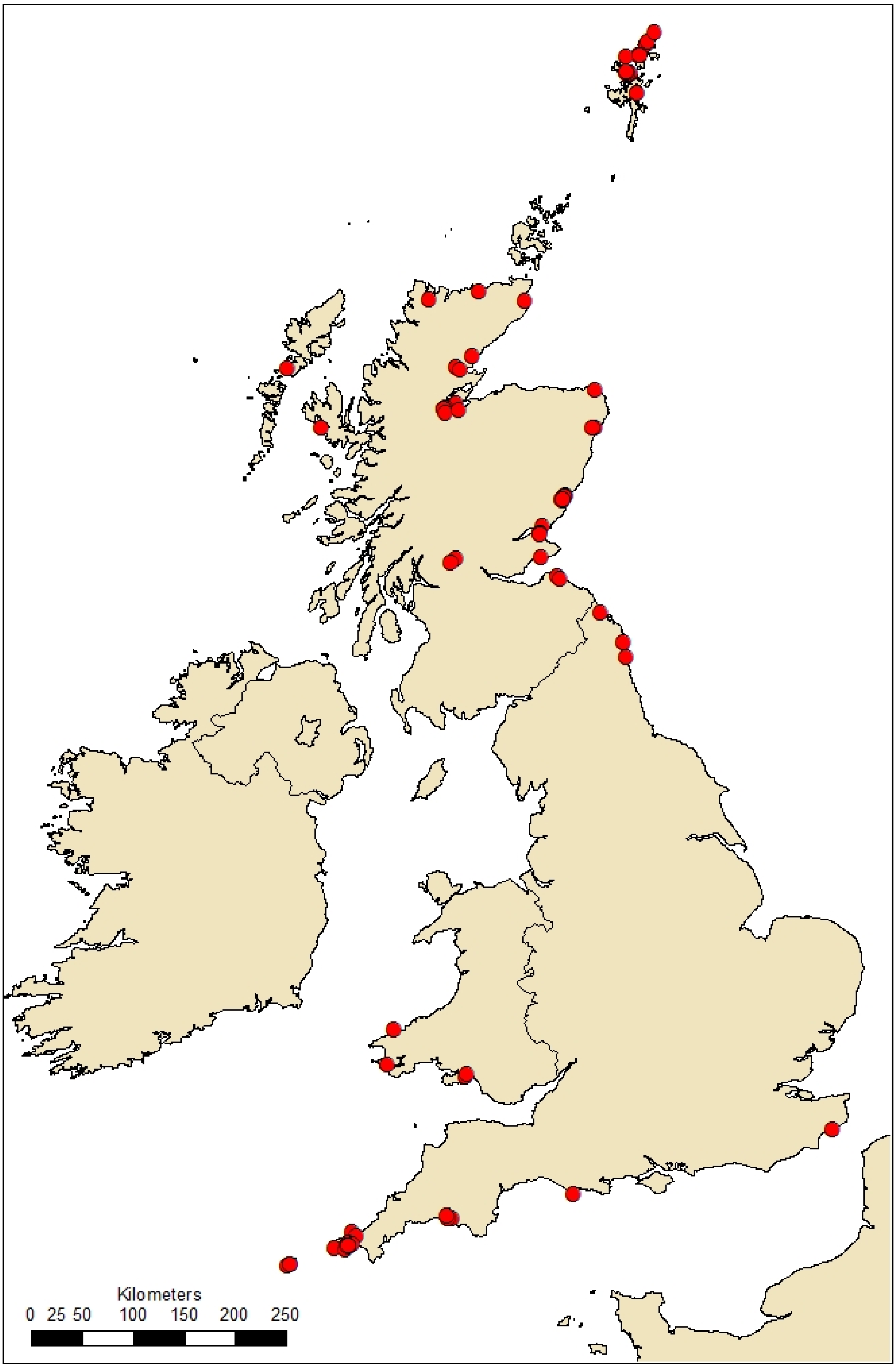

Figure 18 Map of events that are evaluated as being tsunami events

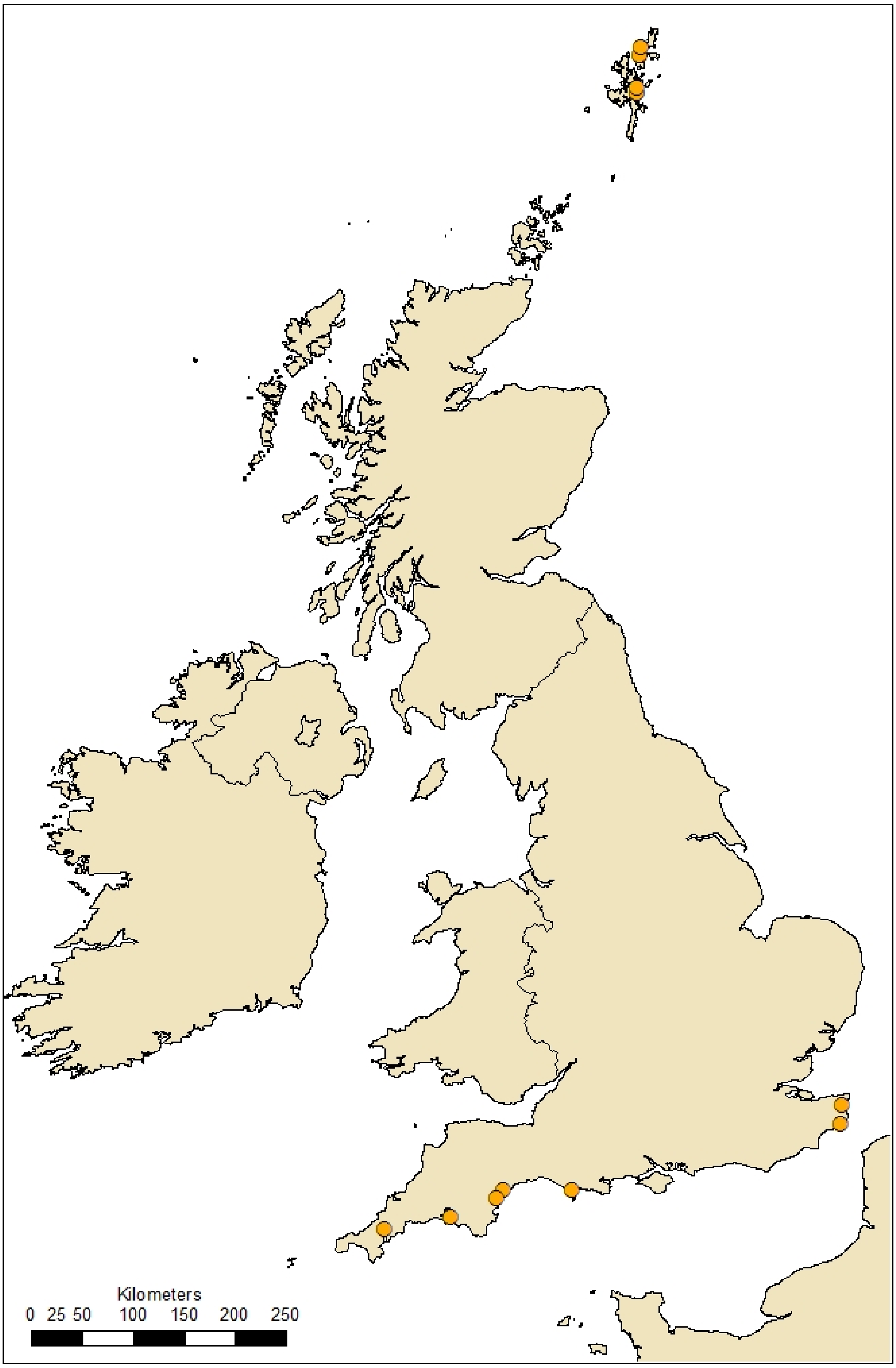

Figure 19 Location of uncertain tsunami events

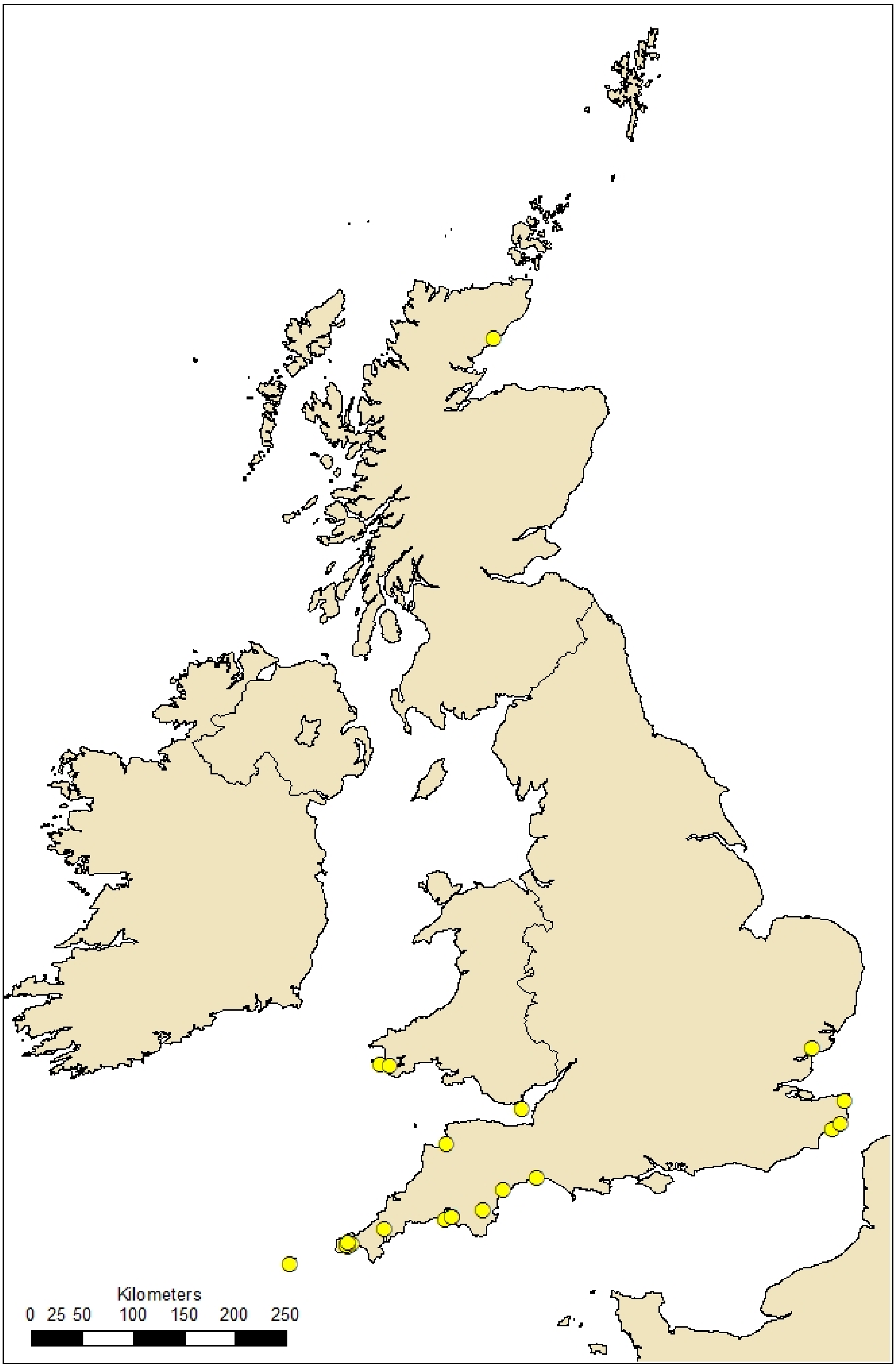

Figure 20 Location of non-tsunami events

7 Catalogue

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
1	1	tsunami	Snarravoe,	456900	1201400	-0.9579	60.6923	deposit	B	~8150yr BP				Bondevik et al 2005
2	1	tsunami	Burragarth	457300	1203800	-0.9499	60.7138	deposit	B	~8150yr BP				Smith 1993, Smith et al 2004
3	1	tsunami	Norwick	465100	1214100	-0.8035	60.8051	deposit	B	~8150yr BP				Smith 1993, Smith et al 2004
4	1	tsunami	Whalefirth	448350	1191600	-1.1193	60.6048	deposit	S	~8150yr BP			extensive layer in coastal peats at head of loch, easy access from road	Cascaldo et al *in press*
5	1	tsunami	Loch of Flugarth	436250	1190600	-1.3399	60.5972	deposit	B	~8150yr BP			Dated sand layer with marine diatoms within gyttja sequence	Bondevik et al 2002
6	1	tsunami	Mid Yell	450200	1191700	-1.0849	60.6056	deposit	S	~8150yr BP			sand layer at base of peats	Costa et al 2015
7	1	tsunami	Scatsta Voe	439600	1172700	-1.2805	60.4367	deposit	S	~8150yr BP			Run up probably >20m above palaeo sea level	Birnie 1981, Smith 1993, Smith et al 2004
8	1	tsunami	Garth’s Voe	440900	1174100	-1.2565	60.4492	deposit	S	~8150yr BP			Run up probably >20m above palaeo sea level	Birnie 1981, Smith 1993, Smith et al 2004
9	1	tsunami	Otter Loch	437600	1172700	-1.3168	60.4369	deposit	B	~8150yr BP			Run up probably >20m above palaeo sea level	Bondevik et al 2002
10	1	tsunami	The Houb, Sullom Voe	436500	1174700	-1.3364	60.4550	deposit	S	~8150yr BP			Run up probably >20m above palaeo sea level	Bondevik et al 2002; 2003
11	1	tsunami	Maggie Kettle's Loch	436700	1175600	-1.3326	60.4631	deposit	S	~8150yr BP			Sand layer with clasts of peat, run up probably >20m above palaeo sea level	Bondevik et al 2002; 2003
12	1	tsunami	Garth Loch	447000	1153800	-1.1504	60.2663	deposit	B	~8150yr BP				Bondevik et al 2005
13	1	tsunami	Loch of Benston	446500	1153600	-1.1595	60.2645	deposit	B	~8150yr BP				Bondevik et al 2005

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
14	1	tsunami	Northton	99500	889900	-7.0596	57.7975	deposit	B	~8150yr BP			Sudden short incursion of marine sediments with freshwater sequence	Jordan et al 2010
15	1	tsunami	Talisker Bay	131500	830400	-6.4574	57.2850	deposit	B	~8150yr BP			inundation of brackish waters into freshwater site, possible erosion of beach barrier	Selby and Smith 2015
16	1	tsunami	Loch Eriboll	240000	954400	-4.7433	58.4485	deposit	S	~8150yr BP			dating suggests an erosion surface with sandy sediment cover	Long et al in prep
17	1	tsunami	Strath Halladale	289000	962600	-3.9069	58.5377	deposit	B	~8150yr BP			Intraclast suggests an autumn event	Dawson and Smith 1997; Dawson and Smith 2000
18	1	tsunami	Wick River	334200	952200	-3.1276	58.4535	deposit	B	~8150yr BP				Dawson and Smith 1997
19	1	tsunami	Smithy House	281100	899100	-4.0100	57.9656	deposit	B	~8150yr BP				Smith et al 1992
20	1	tsunami	Creich	264900	888800	-4.2777	57.8685	deposit	B	~8150yr BP				Smith et al 1992
21	1	tsunami	Dounie	269600	886100	-4.1971	57.8456	deposit	B	~8150yr BP				Smith et al 1992
22	1	tsunami	Munlochy Bay	264700	852900	-4.2609	57.5462	deposit	B	~8150yr BP				Firth 1984
23	1	tsunami	Bellevue	253700	848100	-4.4417	57.4997	deposit	B	~8150yr BP				Firth 1984
24	1	tsunami	Tomich	252500	847200	-4.4611	57.4912	deposit	B	~8150yr BP				Firth 1984
25	1	tsunami	Barnyards	252500	847000	-4.4610	57.4894	deposit	B	~8150yr BP			Minimum 2m run-up above palaeo high water mark	Haggart, 1982
26	1	tsunami	Moniack	254200	843900	-4.4308	57.4621	deposit	B	~8150yr BP			Minimum 4m run-up above palaeo high water mark	Haggart, 1982
27	1	tsunami	Castle St., Inverness	266800	845300	-4.2217	57.4786	deposit	B	~8150yr BP			Archaeological site "white sand" layer	Wordsworth, 1985, Dawson et al 1990
28	1	tsunami	Water of Philorth	401400	864100	-1.9765	57.6670	deposit	B	~8150yr BP				Smith et al., 1982
29	1	tsunami	Waterside	400700	826700	-1.9884	57.3310	deposit	B	~8150yr BP				Smith et al., 1983

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
30	1	tsunami	Tarty Burn	398200	827100	-2.0299	57.3346	deposit	B	~8150yr BP				Smith et al., 1999
31	1	tsunami	Dryleas	370600	760600	-2.4806	56.7363	deposit	B	~8150yr BP			Fine sand layer	Smith and Cullingford, 1985
32	1	tsunami	Dubton	370000	760200	-2.4904	56.7326	deposit	B	~8150yr BP			Fine sand layer	Smith and Cullingford, 1985
33	1	tsunami	Puggieston	369800	760300	-2.4937	56.7335	deposit	B	~8150yr BP				Smith and Cullingford, 1985
34	1	tsunami	Old Montrose	366700	756500	-2.5438	56.6992	deposit	B	~8150yr BP			Fine sand layer	Smith and Cullingford, 1985
35	1	tsunami	Fullerton	367500	756000	-2.5307	56.6947	deposit	B	~8150yr BP				Smith et al., 1980
36	1	tsunami	Maryton	368300	756600	-2.5177	56.7002	deposit	S	~8150yr BP			Sand layer with clasts of peat	Smith et al., 1980
37	1	tsunami	Broughty Ferry	347400	731300	-2.8539	56.4710	deposit	S	~8150yr BP			Archeological site of sand layer on Mesolithic - an exceptional flood	Hutcheson 1886; Lacaille, 1954, Smith et al 2004
38	1	tsunami	Craigie	345500	724200	-2.8833	56.4070	deposit	B	~8150yr BP				Haggart, 1978
39	1	tsunami	St Michael's Wood	345300	723900	-2.8864	56.4043	deposit	B	~8150yr BP				Haggart, 1978
40	1	tsunami	Silver Moss	345400	723500	-2.8847	56.4007	deposit	B	~8150yr BP				Chisholm, 1971
41	1	tsunami	Goodie Water	262400	700400	-4.2168	56.1764	deposit	B	~8150yr BP			Fine sand layer	Holloway, 2002
42	1	tsunami	Cocklemill Burn	346200	700900	-2.8672	56.1977	deposit	S	~8150yr BP				Tooley and Smith, 2005
43	1	tsunami	Over Easter Offerance	257700	696200	-4.2902	56.1373	deposit	B	~8150yr BP				Sissons and Smith, 1965
44	1	tsunami	Lochhouses	361600	682100	-2.6162	56.0303	deposit	B	~8150yr BP				Newey, 1965
45	1	tsunami	Hedderwick	364000	678700	-2.5773	55.9999	deposit	S	~8150yr BP			Fine sand and shell hash layer	D.E.Smith pers comm

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
46	1	tsunami	Broomhouse Farm	403700	645200	-1.9411	55.7003	deposit	B	~8150yr BP				Horton et al., 1999
47	1	tsunami	Howick	425800	616400	-1.5917	55.4406	deposit	B	~8150yr BP			Typical beach pebbles and cobbles in a coarse sand-silt matrix	Boomer et al., 2007
48	1	tsunami	Low Hauxley	428400	601800	-1.5542	55.3095	deposit	B	~8150yr BP			Archaeological site	Waddington 2014
49	2	uncertain	Loch of Benston	446500	1153600	-1.1595	60.2645	deposit	B	~5,500yr BP				Bondevik et al 2005
50	2	uncertain	Mid Yell	450200	1191700	-1.0849	60.6056	deposit	S	~5,500yr BP			sand layer within peats above prominent birch horizon	Costa et al 2015
51	2	uncertain	Garth Loch	447000	1153800	-1.1504	60.2663	deposit	B	~5,500yr BP				Bondevik et al 2005
52	3	uncertain	Basta Voe	451100	1198800	-1.0648	60.6698	deposit	S	~1500 BP				Dawson et al 2006, Toothill 1994
53	3	uncertain	Dury Voe	446100	1160100	-1.1653	60.3229	deposit	S	~1500 BP				Bondevik et al 2002; Bondevik et al 2005
54	4	uncertain	Sandwich	633600	159000	1.3501	51.2817	observation		6th Apr 1580			most likely a harbour seiche	Nielson et al 1984
55	4	uncertain	Dover	631700	140700	1.3111	51.1181	observation		6th Apr 1580			most likely a harbour seiche but may be due to associated cliff falls	Nielson et al 1984
56	5	non-tsunami	Bristol Channel	320000	160000	-3.1493	51.3335	observation		30 Jan 1607	900		extensive flooding	Bryant and Haslett 2002; 2004, Horsburgh and Horritt 2006
57	6	non-tsunami	Dale, Miford Haven	181200	205700	-5.1683	51.7075	observation		2nd July 1749	1100		sea runs up and down seven times in 45 minutes	Anon 1749
58	7	tsunami	Isles of Scilly, Big Pool	87800	8600	-6.3480	49.8954	deposit	B	0th Nov 1755				Banagee et al 2001; Dawson et al 1991, 2000; Foster et al 1993

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
59	7	tsunami	Stonehouse Creek, Plymouth	246100	54000	-4.1642	50.3651	observation		1st Nov 1755	1600			Huxham, 1755, Dawson et al 2000
60	7	tsunami	Creston, Plymouth	250000	53400	-4.1091	50.3608	observation		1st Nov 1755	1600		Sea withdraw 4-5 ft, sea returns in 8 mins.	Huxham 1755
61	7	tsunami	Crunhill, Plymouth	245400	53400	-4.1738	50.3596	observation		1st Nov 1755	1600		Sea withdraws and returns, breaks cable	Huxham 1755
62	7	tsunami	St Mount's Bay	151700	30000	-5.4738	50.1174	observation		1st Nov 1755	after1400		Sudden advance of the sea, retreat by 6 foot depth, took 5.5 hrs to settle	Borlase 1755
63	7	tsunami	Penzance	147800	30200	-5.5284	50.1176	observation		1st Nov 1755	1445		Sea rose 8ft	Borlase 1755
64	7	tsunami	Newlyn	146100	28300	-5.5509	50.0998	observation		1st Nov 1755			Sea rose 10ft	Borlase 1755
65	7	tsunami	Mousehole	146700	26500	-5.5413	50.0839	observation		1st Nov 1755			Similar to Newlyn	Borlase 1755
66	7	tsunami	Gwavas Lake	148000	28500	-5.5245	50.1024	observation		1st Nov 1755			The ketch Happy veer'd round estimate sea velocity at 7mph	Borlase 1755
67	7	tsunami	Lands End, Cornwall	134000	25400	-5.7177	50.0685	observation		1st Nov 1755			Agitation perceived	Borlase 1755
68	7	tsunami	Larmorna Cove, Cornwall	144900	24000	-5.5647	50.0607	observation		1st Nov 1755			Large blocks of granite deposited above high water	Edmonds 1845
69	7	tsunami	St Ives	152000	40900	-5.4767	50.2154	observation		1st Nov 1755			On north side sea rose 8-9ft	Borlase 1755
70	7	tsunami	Hayle	155800	37600	-5.4214	50.1874	observation		1st Nov 1755	after 1500		Surge 7 ft high	Borlase 1755
71	7	tsunami	Swansea	265100	192300	-3.9485	51.6129	observation		1st Nov 1755	1845		Agitation,	Borlase 1755
72	7	tsunami	Whiterock, Swansea	266300	194700	-3.9333	51.6352	observation		1st Nov 1755	1700-1900		Floating of beached vessels, vessels turned onto river bank	Borlase 1755
73	8	non-tsunami	Lyme Regis	334000	92000	-2.9351	50.7233	observation		31st May 1759			sea flowed in and out three times during an hour	Perrey 1849
74	9	tsunami	Penzance	147800	30200	-5.5284	50.1176	observation		31st Mar 1761			Sea rose 6 feet	Borlase 1761

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
75	9	tsunami	Mousehole	146700	26500	-5.5413	50.0839	observation		31st Mar 1761			great agitation	Borlase 1761
76	9	tsunami	Newlyn	146100	28300	-5.5509	50.0998	observation		31st Mar 1761			Sea rose almost as much as at Penzance	Borlase 1761
77	9	tsunami	St Michael's Mount	151700	30000	-5.4738	50.1174	observation		31st Mar 1761			Tide rose and fell 4ft at pier	Borlase 1761
78	9	tsunami	Isles of Scilly	90200	10900	-6.3165	49.9172	observation		31st Mar 1761			Sea rose 4 feet and agitation lasted 2 hours	Borlase 1761
79	10	uncertain	Weymouth	368000	79000	-2.4523	50.6093	observation		9th Aug 1802		0.35		Anon 1802a; Dawson et al 2000
80	10	uncertain	Exmouth	299700	80500	-3.4191	50.6156	observation		10th Aug 1802				Anon 1802a
81	10	uncertain	Teignmouth	294000	72500	-3.4961	50.5421	observation		10th Aug 1802		0.6		Anon 1802b; Dawson et al 2000
82	11	non-tsunami	Plymouth	250000	54000	-4.1094	50.3661	observation		31st May 1811		2.4	coincides with widespread gales	Dawson et al 2000
83	12	uncertain	Sutton Harbour, Plymouth	248400	54200	-4.1330	50.3682	observation		13th Sep 1821	1400	1.2	also noted in Cherbourg	Anon 1821
84	12	uncertain	Truro	183000	44000	-5.0446	50.2554	observation		13th Sep 1821				Anon 1821
85	13	non-tsunami	Penzance	147800	30200	-5.5284	50.1176	observation		5th July 1843				Anon 1843a; Edmonds 1845
86	13	non-tsunami	Plymouth	250000	54000	-4.1094	50.3661	observation		5th July 1843				Edmonds 1845
87	13	non-tsunami	Newlyn	146100	28300	-5.5509	50.0998	observation		5th July 1843		1	Four waves at 10 to 15 minute duration	Anon 1843b
88	14	non-tsunami	St Mount's Bay	151700	30000	-5.4738	50.1174	observation		23rd May 1847			Rises and fall 0.9-1.5m noted all day following slight tremor felt night before	Edmonds 1869
89	14	non-tsunami	Plymouth	250000	54000	-4.1094	50.3661	observation		23rd May 1847			Waves similar to St Mount's Bay noted in the evening	Edmonds 1869
90	14	non-tsunami	Newlyn	146100	28300	-5.5509	50.0998	observation		23rd May 1847	1730	0.6	sudden rush of the sea	Blight 1847
91	14	non-tsunami	Mousehole	146700	26500	-5.5413	50.0839	observation		23rd May 1847		1.2	waves continued until 9pm max amplitude 8ft	Blight 1847

site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
92	14	non-tsunami	Anderton	243000	52200	-4.2080	50.3487	observation		23rd May 1847		1.2	several boats damaged	Anon 1847
93	15	non-tsunami	Folkestone	623300	135900	1.1862	51.0788	observation		5th June 1858	0800	0.9	boats cast adrift and one capsized and sank	Newig and Kelletat 2011
94	15	non-tsunami	Dover	631700	140700	1.3111	51.1181	observation		5th June 1858				Newig and Kelletat 2011
95	15	non-tsunami	Pegwell Bay	636000	163000	1.3854	51.3171	observation		5th June 1858				Newig and Kelletat 2011
96	16	non-tsunami	Isles of Scilly	90200	10900	-6.3165	49.9172	observation		29th Sept 1869				Anon 1869a; Perrey 1872
97	16	non-tsunami	Newlyn	146100	28300	-5.5509	50.0998	observation		29th Sept 1869				Anon 1869a; Perrey 1872
98	16	non-tsunami	Penzance	147800	30200	-5.5284	50.1176	observation		29th Sep 1869	0600	0.75		Anon 1869b; Perrey 1872
99	16	non-tsunami	Truro	183000	44000	-5.0446	50.2554	observation		29th Sep 1869	0600	0.6		Anon 1869a; Perrey 1872
100	16	non-tsunami	Plymouth	250000	54000	-4.1094	50.3661	observation		29th Sep 1869		0.75		Anon 1869c
101	16	non-tsunami	Bideford	245500	126700	-4.2042	51.0189	observation		29th Sep 1869		0.9		Anon 1869d
102	16	non-tsunami	Totnes	280600	60300	-3.6825	50.4304	observation		29th Sep 1869				Anon 1869e
103	16	non-tsunami	Exmouth	299700	80500	-3.4191	50.6156	observation		29th Sep 1869	1000			Anon 1869f
104	17	tsunami	Portland	369000	76000	-2.4392	50.5831	tide gauge		28th Aug 1883	1015	0.025	May be seiching from air-waves due to eruption of Krakatau	Berninghausen 1968
105	17	tsunami	Devonport	244600	56000	-4.1872	50.3833	tide gauge		28th Aug 1883	1045	0.1	May be seiching from air-waves due to eruption of Krakatau	Berninghausen 1968
106	18	non-tsunami	East Mersea Island	605500	214500	0.9784	51.7914	observation		22nd Apr 1884			report in single newspaper following Colchester earthquake	Haslett and Bryant 2008
107	19	non-tsunami	Milford Haven	190200	203800	-5.0370	51.6936	observation		18th Aug 1892			waves noted coincident with Pembrokeshire earthquake	Davison 1897
108	20	tsunami	Folkestone	623300	135900	1.1862	51.0788	observation		31st Dec 1911	1830	0.9	ropes and stanchions damaged by wave following large cliff fall	Anon, 1912a,b

Site	event	confidence	name	National Grid easting	National Grid northing	Longitude WGS84	Latitude WGS84	evidence	type	age	time	wave height	comment	reference
109	21	non-tsunami	Helmsdale	302900	915200	-3.6483	58.1154	observation		24th Jan 1927			large rollers noted following an earthquake	Tyrell, 1932
110	22	tsunami	Newlyn	146800	28600	-5.5413	50.1028	tide gauge		25th Nov 1941	2200	0.2		Dawson et al 2000
111	23	tsunami	Newlyn	146800	28600	-5.5413	50.1028	tide gauge		23rd May 1960		0.025		Van Dorn 1987
112	24	tsunami	St Mary's, Isle of Scilly	90200	10900	-6.3165	49.9172	tide gauge		28th Feb 1969	735	0.12		BODC
113	24	tsunami	Newlyn	146800	28600	-5.5413	50.1028	tide gauge		28th Feb 1969				Dawson et al 2000
114	24	tsunami	Fishguard	195300	239200	-4.9837	52.0132	tide gauge		28th Feb 1969	1200	0.03		BODC
115	25	tsunami	Newlyn	146800	28600	-5.5413	50.1028	tide gauge		26th May 1975	1525	0.06		Dawson et al 2000
116	25	tsunami	St Mary's, Isle of Scilly	90200	10900	-6.3165	49.9172	tide gauge		26th May 1975	1420	0.05		BODC
117	26	tsunami	Newlyn	146800	28600	-5.5413	50.1028	tide gauge		27th Dec 2004	745	0.15		Woodworth et al 2005
118	26	tsunami	St Mary's, Isle of Scilly	90200	10900	-6.3165	49.9172	tide gauge		27th Dec 2004			less certain than at Newlyn	Woodworth et al 2005
119	26	tsunami	Milford Haven	188500	205000	-5.0613	51.7034	tide gauge		27th Dec 2004	938	0.16	may be confused by a storm surge	Woodworth et al 2005