Tsunami from the Storegga landslide

for the Encyclopedia of Complexity and System Science

Stein Bondevik

Faculty of Engineering and Science,

Western Norway University of Applied Sciences,

P.O. Box 133, N-6851 Sogndal, Norway

[9,000-12,000 words + figs. + tables: 15-16 pages of text with line spacing 2.

Format of figs: jpg, png and/or gif].

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0. Glossary

Sediment trap

A place where sediments accumulate and form deposits. Tsunamis are mainly erosive. Usually vegetation, soil and loose deposits are washed away and carried into the ocean. In order to find deposits left onshore there has to be some kind of a trap in which sediments carried by the tsunami are deposited and later protected from other processes, like running water, wind, burrowing animals and human activity. Coastal lakes, estuaries and bogs are such traps where Storegga tsunami deposits have been preserved.

Run-up

Maximum vertical height the tsunami runs up a slope. It is measured in meters from the sea level at the time the tsunami hits and up, vertically, to the maximum point of inundation. To reconstruct run up from ancient tsunamis is difficult for two reasons. First, you need to find the highest reaching tsunami deposit, second, you need to reconstruct the sea level when the tsunami hit. Run up reconstructed from tsunami deposits are usually minimum values and could be called sediment run up.

Retrogressive slide motion

A retrogressive slide starts in the lower area of the slope and retreats backwards, up the slope. A piece or block of deposits detaches and slides downslope. The missing piece causes loss of support to the deposits behind it (upslope) and another piece is released. This development continuous up the slope with the release of other pieces, one by one, until the last piece on top of the slope has failed. A retrogressive slide motion is a typical development in submarine slides and in quick clay slides onshore where the slope angle is low. Often such slides spread over long distances.

Mesolithic

Meso- means middle and -lithic means stone or rock; it is the middle period in the Stone Age. The Mesolithic began with the Holocene warming, around 11,500 years BP, and ended when farming was introduced - in Scandinavia around 6000 years BP. The Storegga Slide happened in the Mesolithic when humans were hunter-gatherers and moved seasonally, following animal migrations and plant changes. In Norway and Scotland numerous excavations have found Mesolithic settlements on or close to the former shores. They may have been affected by the Storegga tsunami.

Radiocarbon ages

A radiocarbon year varies in length relative to a calendar year. This is due to changes in the amount of radioactive carbon, ^{14}C, in the atmosphere over time. Best age estimate of the Storegga tsunami is 7320±20 radiocarbon years Before Present, BP. From counting back year by year on tree rings that have been systematically radiocarbon dated, this age corresponds to the tree rings that grew in the time interval 8120-8175 year BP. In the following text radiocarbon years are noted as ^{14}C yr BP.

1. Definition of the subject

The Storegga tsunami was generated by the Storegga landslide off the Norwegian coast about 8150 years ago. The tsunami deposits show that the coasts of Scotland, Norway, Shetland, Faroe Islands and possibly also Eastern Greenland and Denmark was inundated, and that the tsunami ran up to heights ranging from 3 to more than 20 meters above sea level of that time. The Storegga tsunami is important for two reasons: First, it shows that big tsunamis have happened along passive margins and outside of the Pacific Ocean. Second, it is the only slide-generated tsunami of a basin-wide range where the run-up has been mapped out in the field and the tsunami simulated with numerical models.

2. Introduction

When geologists first dug up deposits from the Storegga tsunami, they interpreted them as being the result of another process, a flood, a big storm surge or a sea level rise. The Norwegian Sea and North Sea have passive margins with small earthquakes, so to think of tsunami deposits in this part of the world was not in anyone's mind until the Storegga Slide was discovered in the 1980s. Also the layer was often overlooked when encountered in the field during sea level studies because it was just 'noise' in the overall picture – and in field notes was often mentioned as some kind of disturbance that complicated the stratigraphy.

Run-up pattern (Fig. 1) and radiocarbon dates point towards the Storegga Slide as the source for the tsunami. Sites closest to the slide, like western Norway, Shetland and Faroe Island show the largest run-up – about 8 to more than 20 m (Fig. 1). Sites farther away show run-up less than 5 m (Scotland, northern Norway). The most accurate date for the tsunami is 8150±30 years BP and comes from radiocarbon ages of moss, unexpectedly well preserved within the tsunami deposits (see chapter on age) that were killed during the tsunami event. The slide itself was dated from radiocarbon ages of calcareous foraminifera found within the first centimeters of sediments deposited on top of the slide material. Those foraminifera-ages fall within the time interval of 8100±250 years BP. Both the run-up pattern and age suggest that the tsunami was triggered by the Storegga Slide.

The Storegga tsunami deposits are preserved in different kinds of 'traps'; coastal lake basins, estuaries and bogs. All the different sites at present are listed in Table 1 together with references to the original publications, type of sediment traps, run-up (if reconstructed) and a short comment to the run-up estimates and/or deposits. In the following, I will present and discuss the findings from one location with lake- and marine basins (western Norway), one location from an estuary (Scotland) and one from a peat outcrop (Shetland). To find information about the other sites you will have to look up the publications in Table 1. First, I will tell you how the Storegga tsunami was discovered and then describe the slide that generated the tsunami.

3. How the Storegga tsunami was discovered

Storegga means the ‘big edge’. It is the name of about a 100 km long stretch of the back-wall (total ca. 300 km) of the Storegga slide in the Norwegian Sea (Figs. 1 and 2). Along this edge fishing can be very good because of strong upwelling, and men from western Norway have been fishing here for at least 300 years (Rødal, 1996). The anglers found a big change in depth – from the shallow shelf of about 200-300 m depth to 500-600 m depth across a very short distance; thus, they named the place *Stor-egga* (Fig. 3). Little did they know that their fishing place was along the back wall to what has been called the largest exposed submarine slide in the world (Bugge et al., 1987; Haflidason et al., 2005).

The slide itself was identified when the continental shelf of Norway was mapped in the 1970s (Bugge, 1983; Bugge et al., 1978). It was soon recognized as a very big slide complex consisting of three individual slide events (Bugge et al., 1987; Jansen et al., 1987). However, much more detailed data (e.g. multi-beam echo sounder, detailed high-resolution seismic lines and sediment cores) showed that the slide was not three individual events as initially believed, but was one major event consisting of different phases. The slide involved a volume of 2400-3200 km^3 (Table 2), and from a large number of cores the slide was radiocarbon dated to 8100 ± 250 years BP (Haflidason et al., 2005). In the early paper by Jansen et al., (1987) it was speculated that such a big slide could have caused a tsunami.

Deposits of the Storegga tsunami were first recognized in Norway and Scotland in the 1980s. John Inge Svendsen, a student at that time at the University of Bergen, Norway, cored coastal lakes on Sunnmøre (site h in Fig. 1) and in one of the basins he found a sand layer with brackish diatoms inter-bedded in fresh water lake mud. Alastair Dawson, at the University of Coventry, UK, knew of a wide spread sand layer in estuarine mud in North East Scotland previously interpreted as a result of a storm surge (see below). Both suggested, independently, that these deposits were laid down by a tsunami generated from the Storegga Slide (Dawson et al., 1988; Long et al., 1989b; Svendsen, 1985; Svendsen and Mangerud, 1990). Their interpretation was motivated by the discovery of the Storegga Slide; Dawson read the paper by Jansen et al. (1987) in Marine Geology about the Storegga Slide and Svendsen heard first about the Storegga Slide from colleagues and fellow students studying the Storegga Slide at the same department (Befring, 1984; Edvin, 1984).

Many researchers had encountered the Storegga tsunami deposits earlier, but without knowing about the Storegga Slide they explained the deposits as something else. The first scientist to core lake basins in western Norway, Knut Fægri, probably saw traces of the Storegga tsunami, but interpreted them as representing a sea level fluctuation (Fægri, 1944). Sissons and Smith (1965) were the first to study the layer in Scotland, where they found a persistent 5-cm thick sand layer in estuarine mud and peat, which they thought was deposited from a local flood of a river (Smith et al., 2004). Later, after discovering a similar layer at other sites in eastern Scotland, Smith et al. (1985) suggested it was caused by a "storm surge of unusual magnitude". In Norway the coarse grained layer found in lake mud was often interpreted to represent the peak of the mid-Holocene transgression (called the Tapes transgression in Norway) that happened about the same time, (Aksdal, 1986; Corner and Haugane, 1993; Kaland, 1984; Svendsen and Mangerud, 1987; Tjemsland, 1983) and that the layer was the result of strong currents running through the basins as they became submerged during this marine transgression (Kaland, 1984).

The deposit was soon mapped and studied along the eastern coast of Scotland (Dawson et al., 1988; Long et al., 1989b; Smith et al., 2004), in western Norway (Bondevik et al., 1997a; Bondevik et al., 1997b), the Faeroe Islands (Grauert et al., 2001) and Shetland (Bondevik et al., 2003; Bondevik et al., 2005b; Smith et al., 2004). During the earliest studies the authors tried to answer the question whether this deposit could be the Storegga tsunami deposit and focused on the layer's age and stratigraphical context (Dawson et al., 1988; Long et al., 1989b; Svendsen and Mangerud, 1990). Later studies focused on the sedimentology of the deposits (Bondevik et al., 1997b; Dawson et al., 1991; Dawson and Smith, 2000; Shi, 1995), run-up (Bondevik et al., 1997a; Smith et al., 2004) and numerical modeling of the tsunami waves (Bondevik et al., 2005a; Harbitz, 1992; Hill et al., 2014).

4. The slide that triggered the tsunami

The Storegga Slide is big (Table 2). It covers an area of 95,000 km^2 – the size of a European country like Portugal (92,391 km^2) – and involved a total volume of 2400-3200 km^3 (Haflidason et al., 2005). You could almost fit Belgium (30, 528 km^2) in the slide scar (Table 2, Fig. 3a). The volume is so big it is hard to imagine, but if you distribute the volume across the USA (9 834 000 km^2), it will cover the land with a 30 cm thick layer! The back wall has a length of 310 km and the total run-out length, including the distal turbidites – is 810 km (Fig. 2). Much of the slope of the slide is only between 0.3°-2° (Fig. 3b), and a big question is: How can anything fail on such a low angle slope and subsequently develop into a gigantic slide?

We learned much about the Storegga Slide in the Ormen Lange project – a project for the safe development of a deep water gas field within the Storegga Slide complex (Solheim et al., 2005b). The "Ormen Lange" gas field – named after a Viking ship from its lookalike in map view (Figs. 2, 3a) – is located just beneath the major headwall 1,900 m below the sea floor in a water depth of between 600 and 1,200 m (Bryn et al., 2007). Major questions for the project to solve were whether a new tsunami-generating-slide could occur in the area and if the planned activities and field installations to develop the gas field could trigger a new slide. To solve these questions a lot of data were gathered in the 1990s and the early 2000s; high resolution bathymetric- and seismic data, drillings, numerical models of the slide dynamics and trigger mechanism. The short answer to these questions from the Ormen Lange project was that there is a very low risk for a new slide to happen today or in the near future at Storegga (Bryn et al., 2005a). The gas field was set in production in 2007.

The material that failed in the Storegga Slide were glacial deposits and contourites of Quaternary age (Fig. 2). During periods of peak glaciation the Scandinavian ice sheet would reach the shelf break and deposit till on the shelf and debris flows on the upper continental slope. This material deposited from the glacier consist of about equal amounts of clay, silt and sand, has low water content (10-20 %) and high density. When the ice front was in a retreated position, during deglaciation and in interglacials and interstadials, silty clay with high water content (25-35 %) and lower density would be deposited (Berg et al., 2005). This silty clay was/is deposited underneath the North Atlantic current that runs along the continental slope and is called contourites named from 'contour' lines. Thus, the stratigraphy in the upper part of the Storegga area is a result of the climate cycles in the Quaternary and consist of alternating layers of glacial deposits and hemipelagic silty clay (Bryn et al., 2005b).

The slip planes or failure zones are all found within the contourites, the fine-grained hemipelagic silty clay. These sediments have different geotechnical behavior than the glacial deposits. Upon triaxial testing they develop clear shear planes, reach peak strength, and when further deformed their strength is substantially reduced, a process called strain softening or brittle deformation (Berg et al., 2005). The scarps or minor headwalls in the Storegga Slide (Figs. 2 and 3) indicate a glide plane jump to a higher stratigraphic level of a younger contourite. In the northern and southern part of the slide scar the slide is less than 100 m thick and slid along the O3 unit – a contourite formed during isotope stages 3-5. In the central part of the slide scar the slip has followed deeper contourite layers; the R2 and S2 layers (Figs. 2, 3 and 4).

It is difficult to explain how the Storegga slide could happen because of the very low slope gradient (Fig. 3b). Seismic profiles and detailed bathymetry show it must have developed retrogressively (Haflidason et al., 2004). This means that the slide started somewhere in the lower part of the slope and retreated up slope. Big pieces of slope material were released one at a time and the headwall would gradually retreat upslope during the slide process. Because of the low slope gradient, the blocks must have slid on a very weak and soft layer without much shear strength (Kvalstad et al., 2005b).

The clay layers that developed into failure planes lost their strength through strain-softening. The unloading of the toe or lower headwall caused expansion of the slope material and large strain developed in the softer clay – contourites - below the denser glacial material. The strain caused so-called strain softening of the contourite layer – a process where the strength of the material drops as the stress increases. Modelling has shown that such a process is possible where unloading of the headwall causes strain concentrations and strength loss in the failure layer sufficient to reduce the factor of safety below 1 and thus initiate a retrogressive slide process (Kvalstad et al., 2005a).

The retrogressive failure mechanism requires the triggering of the first slide in the toe area. Factors that would lead to an increase in pore pressure and thus reduce the shear strength have been considered, and the most probable triggers are high sedimentation during peak glaciation, gas hydrate melting and/or an earthquake (Bryn et al., 2005a). Rapid loading of glacial debris with low permeability may cause development of excess pore pressure. However, the sedimentation rate at the lower part of the Storegga slope is low. One mechanism that could lead to instability would be migrating pore water from the North Sea fan into the toe area – estimated to be about 160 km downslope of the major headwall (Fig. 2). The North Sea fan was a major depo-center during the glacial maximum and one idea is that pore water from this fan could be pushed into the lower part of the Storegga area and increased the pore pressure in this part of the slope and in that way reduced the shear strength.

5. Storegga tsunami deposits and run-up

Tsunami deposits are only rarely preserved and traces of ancient tsunamis can be hard to find. A prerequisite is that there is some kind of a sediment trap where the sediments could be left by the tsunami and is further protected from wind, burrowing animals, running water and human activity. The traps where Storegga tsunami deposits have been found are lakes and shallow marine basins near the coast, estuaries, or low areas where peat is accumulated - bogs. The difference between the dark organic lake gyttja, estuarine mud or dark peat and the light-colored tsunami sand has helped to distinguish and trace the tsunami deposits.

In order to reconstruct run-up heights the sea level at Storegga time had to be determined for each site (Table 1). For the coasts of Norway, Scotland and Greenland, the shoreline 8150 years ago is located above present day sea level. How much the 8150-year shoreline is above the present day shoreline depends on the rate of isostatic uplift the site has experienced since deglaciation. The opposite is the case for the Faeroe- and Shetland Islands where the sea level has risen more than land since the deglaciation, and sea level at Storegga time was about 10-15 m below the shoreline of today. The accuracy of the run-up estimates depends on tracing the tsunami deposits to its highest elevation and determine the sea level at Storegga time correctly. It is also important to remember that the up slope limit of a tsunami deposit usually would be lower than the actual limit of the tsunami (e.g. Smith et al., 2007). The true run-up could be several meters higher than the height of the tsunami deposits (see chapter on the numerical simulation).

5A. Coastal lakes in Norway

The tsunami traps in Norway, Greenland and the Faeroe Islands (Fig. 1) are lake basins close to sea level (Figs. 6 & 7; Table 1). These basins, most of them in bedrock, were excavated by glacial ice during the ice ages, and have accumulated sediments since the last deglaciation. Because they are over-deepened, the lake floor deposits are usually protected from later erosion and removal. The outer coast of Norway has many such basins (*e.g.* Fig. 9). In Norway, also basins below sea level at Storegga time collected tsunami deposits from the backwash that carried material from land into the sea (Figs. 7 & 22; Table 1).

Lake basins at the coast – if located below the marine limit – would hold a sedimentary record of sea level changes. In fact, accurate sea level curves have been reconstructed from the deposits in such basins in Scandinavia (*e.g.* Svendsen and Mangerud (1987)). When the threshold (Fig. 7) of the basin is below sea level, marine deposits would accumulate in the basin. When the threshold is close to sea level, brackish deposits would accumulate, and, when the threshold is above the spring tide level, lacustrine deposits would accumulate. By levelling the height of the threshold above the present day high tide and radiocarbon date the transition from brackish gyttja (organic mud) to lacustrine gyttja in the lake deposits, a point on a sea level curve is obtained. Through such sea level studies, geologists in Norway encountered the Storegga tsunami deposits in lake basins at the coast, and in the beginning, they did not understand what they were (see chapter 3).

The tsunami deposits form a distinct group of facies (Fig. 8) that are very different from the other sediments in the lakes (Figs. 8, 10-11). The tsunami deposits rest on an erosional unconformity that usually could be traced throughout the basins. Typically, we found more erosion at that end of the basin that faces towards the sea (Fig. 12b). The deposits can be divided into six different facies (Fig. 8). In some cores we found all the six different facies (Fig. 11 has five of them), other places only one or two of them is represented (Fig 12).

Graded sand. Usually, the first sediment to be deposited on the erosive surface is a graded sand bed (Figs. 8; 10-11). The lower part is coarse sand, in some cases fine gravel, grading upwards to medium sand. It is commonly rich in shell fragments. Normally 4-8 cm thick, but it may reach a thickness of about 20 cm.

Massive sand. No internal structures, poorly to well sorted, from fine gravel to fine sand. It may contain shell fragments. The massive sand bed is normally thinner than the graded sand and varies from 1 mm (one-grain-size thick) (Fig. 12c) to 4-5 cm (Figs. 10, 11).

Rip-up clasts in matrix. We introduced the term organic conglomerate for this facies in Bondevik et al., 1997b because it resembled a conglomerate of clasts of organic material distributed in a matrix of lake mud, organic detritus and sand. The clasts have an irregular form, 0.5-6 cm across (Fig. 11), but may also be larger (Fig. 12b).

Organic detritus. A mixture of lake mud, plant fragments and sand without rip-up clasts. It also, usually, is graded, especially if it is present at the top of the tsunami deposits (Fig. 11).

Silt. Some of the tsunami deposits are draped with a distinct laminae, 2-3 mm thick, of silt (Fig. 11). The silt fines upwards from very fine sand or coarse silt to silt. Sometimes the silt can be thicker, 1-2 cm.

Fine laminations. A few times we have seen 2-3 laminations in the organic lake mud on top of the tsunami deposits. We think they represent a period of saline bottom water caught in the lake basin in the few years after the tsunami event. This bottom water would prevent bioturbation.

The main arguments that these facies were deposited by a tsunami were listed in Bondevik et al. (1997b) and are repeated here:

1) The geometry of the bed with seaward erosion and landward fining (Fig. 12a, b) and the content of marine fossils clearly indicate a marine related process for its formation.

2) Radiocarbon dates show the same age in all areas, independent of the elevation of the basin above sea level (Figs. 11, 12d).

3) These facies are also found in basins that were below sea level at Storegga time (Figs. 10, 22). That shows that the backwash brought terrestrial material (rip-up clasts and terrestrial vegetation) into the sea.

4) Many of the characteristics of these deposits are also reported from known modern tsunami deposits; extensive erosion, rip-up clasts, decrease in thickness and grain size landwards, alternation between finer- and coarser- grained beds and as a whole, the deposit generally fines upwards.

We think the different sand layers in the tsunami deposits may represent the incoming tsunami waves. In the lower basins, less than 3 m above the sea level at Storegga time, there may be several sand beds interbedded with organic detritus (Figs. 10 & 11), whereas in the higher basins, 5-10 m above contemporary sea level, only one sand bed is usually found (Fig. 12). The individual sand layers may be deposited by the incoming waves and the organic muddy material in between (Fig. 11) settled out during slack water, the period between the waves. However, we cannot rule out that material deposited in the first inundating waves could have been later eroded by the subsequent tsunami waves inundating the basins.

To determine the run-up at a location, we (e.g. Bondevik et al. (1997a); Romundset and Bondevik (2011)) cored lake basins at different elevations and traced the tsunami deposits to the highest lake. The precision of these measurements depend on how close the lakes where to the true run-up heights and how accurate the sea level at Storegga time had been reconstructed in that area. If a tsunami deposit is found in a lake basin it means that the tsunami had to flow over the outlet threshold of the lake (Fig. 7). A minimum estimate of the height of the tsunami would then be the altitude of the threshold of the basin relative to the local sea level at Storegga time. The tsunami deposits where then traced successively to lakes at higher elevations. The first lake without any indication of inundation was interpreted to not have been reached by the tsunami.

For example, at site e (Fig. 1), in Bjugn, the run-up was reconstructed based on the deposits in five lake basins (Fig. 9) and I will here use this site as an example of how run-up has been reconstructed along the Norwegian coast (explained in more detail in Bondevik et al. (1997a). When the Storegga tsunami happened sea level was well above lake Audalsvatnet at 33.6 m a.s.l. because the tsunami deposits are found within marine sediments (Figs. 9 & 10). In the deposits in Kvennavatnet (37.1 m a.s.l.) diatoms show a change from marine to brackish sediments just underneath the tsunami deposits, but in the gyttja above the tsunami deposits the diatoms are solely freshwater species (Fig. 9 in Bondevik et al. (1997a)). A moss stem from the brackish gyttja just below the tsunami deposits was dated to 7350+/-80 ^{14}C years (Fig. 11) – close to the time of the Storegga event. This indicates that Kvennavatnet was very close to the sea level – and had probably just emerged from the sea at Storegga time. We estimated that 36 m a.s.l. was a reasonable estimate for the local sea level at Bjugn at Storegga time.

The next two lakes higher up is Gorrtjønna I and Gorrtjønna II – both with tsunami deposits – and a threshold at 42 m a.s.l. The two small lakes are today separated by peat growth (Fig. 9) – at Storegga time they were likely one open lake basin. The stratigraphy in Gorrtjønna I show an episode of deep erosion, most erosion towards the threshold, and deposition of many rip-up clasts, and gravel and sand that is finer grained towards land, away from the sea (Fig. 12a). In Gorrtjønna II we found a 1-2 cm fine sand to silt laminae, in few of the cores also with plant fragments, and I now interpret this to be the distal deposits of the Storegga tsunami. A detailed coring program at the outlet area of Jøvatnet (44 m a.s.l.) - were we should expect the inflow of the tsunami - with 13 cores (Fig. 9), did not reveal any candidate for a tsunami layer.

At this site run-up of sediments is more than 6 m and less than 8 m. The Storegga tsunami clearly inundated Gorrtjønna I at 42 m a.s.l but not Jøvatnet at 44 m a.s.l. The local sea level was estimated to 36 m a.s.l. Thus a minimum estimate is 42 m a.s.l. -36 m a.s.l. = 6 m, and a maximum estimate is 44 m a.s.l. – 36 m a.s.l. = 8 m. The inundation limit, from the 36 m contour line at Audalsvatnet to Gorrtjønna II is 900 m (Fig. 9).

5B. Estuaries in Scotland

In Scotland the Storegga tsunami deposit (Fig. 1) is typically a wide spread sand layer in estuarine mud (Table 1). An estuary is a drowned valley with an open connection to the sea (Fig. 13). The water in this partly enclosed basin is brackish, because fresh water enters from the upland rivers and mixes with seawater coming in from the ocean. Fine-grained mud accumulates on the floor of the estuary (Fig. 13). Many of the estuaries were formed when glacially scoured valleys were flooded during the sea level rise after deglaciation. Therefore, it is usually peat underneath the estuarine mud deposits that accumulated when sea level was lower (Fig. 14).

Geologists have successfully used deposits in estuaries to reconstruct sea level changes. The change from peat to overlying mud documents a sea level rise, and a change from mud to overlying peat documents a sea level fall. As sea level rose the peat/mud boundary moved inland, when sea level fell, the same boundary moved seawards. By radiocarbon dating the peat just underneath or just above the estuarine mud, a time for when the sea level stood at this elevation is found. Usually the estuarine mudflats approximate the mean high water mark of spring tides (Smith et al., 2004). For instance at Dornoch Firth the modern estuarine mudflats lie 0.3-0.6 m above mean tide level (Smith et al., 1992). It was during studies of estuarine deposits to reconstruct sea level changes in Scotland that geologists encountered a wide spread sand layer that is now ascribed to the Storegga tsunami event (see chapter 3).

The Storegga sand layer extends for several hundred meters in the estuary deposits and some places continuous up-slope into peat. The layer varies in thickness. A few places it is more than 0.5 m thick, for example in the profile in Fig. 14 it is 1.56 m thick in a core ca. 235 m seaward of the limit of the sand. However, in most cores it is between 10 and 30 cm thick. Usually the sand layer tapers off inland and it also fines in grain size in this direction.

Grain size distribution through the Storegga sand layer, from bottom to top, show one or two fining-upward sequences. Most samples show a peak in the fine sand fraction, and all sites (except one) register one or two fining upward sequences (Smith et al., 2004). A few sites show more than two fining upward sequences (site o; a lagoon in Dawson and Smith (2000) and site q; Dawson et al. (1991). According to Smith et al. (2004) the more sheltered and inland boreholes would have one fining upward sequence, while more seaward boreholes could have multiple fining-upward sequences. This could mean that the sequences preserved reflect the number of waves inundating the site. Only the highest locations would be inundated by the largest wave and so exhibit one fining upward sequence.

The Storegga sand layer in estuarine settings show in general little evidence of erosion. Rip-up clasts, commonly found in the Norwegian lakes and in Shetland peats, are usually not present. Site n in Sutherland (site o, Fig. 1 and Table 1) has rip-up clasts, but according to its enclosing deposits it is not an estuary, but a lagoon (Dawson and Smith, 2000) and its deposits are similar to coastal lakes in Norway. The lower surface of the tsunami sand layer is usually sharp, but show little variation between boreholes that could be attributed to erosion.

Run-up of the Storegga sand layer out of the estuary and into former gullies or minor valleys near the head of the estuaries is between 2 and 5 m (Fig. 1). The run-up is measured from the highest altitude of the estuarine mud below the Storegga sand and up to the highest altitude of the Storegga sand layer (see example in Fig. 14). The run-up seems to decrease towards the south along the Scottish coast (Fig. 1).

5C. Peat outcrops on Shetland

Storegga tsunami deposits are only accessible through coring at most of the sites in Fig. 1, but natural outcrops, where the deposits are exposed in a larger section, have been found on the Shetland Islands (site m in Fig. 1; Fig. 16). In the Sullom Voe area there are a few natural outcrops in peat with Storegga tsunami deposits (Bondevik et al., 2003; Bondevik et al., 2005b; Smith et al., 2004). The outcrops are formed by erosion of storm waves along the shoreline, or rivers that cut through the peat surface. Natural outcrops with Storegga layers have not been reported from Norway - a digging machine was used at Harøy (site f) to expose peat with Storegga sand underneath a beach ridge (Bondevik, 2003). In Scotland, the only site that exposes Storegga layers is the cliff at Maryton (Fig. 15).

In this chapter, I will present a fascinating outcrop in Shetland, near Maggies Kettles Loch on the western side of Sullom Voe (Fig. 16), that gave us new understanding – in particular about run-up and deposition and formation of rip-up clasts. Below follows a clipping (text in italic) from the three paragraphs in Bondevik et al. (2003) that describes the deposits. (I have changed the figure number so it is correct with this paper.)

*Close to the present shore, the tsunami deposit is 30–40 cm thick and shows large rip-up clasts of peat embedded in the sand (*Figs. 17, 18a*). Many of the clasts are 10–30 cm in diameter with sharp edges. Also, pieces of wood and trunks were found in the sand. The sand, which is medium to very coarse, contains pebbles and cobbles; we even found a boulder as large as 25 cm in diameter* (Fig. 17)*. The sand thins and fines inland; also, the erosion of peat decreases in this direction (*Figs. 17, 18b*). Close to the sea, the sand is 30–40 cm thick. From about 18 m from the shore and inland, the sand thins from 10 cm to less than 1 cm at the maximum elevation* (Fig. 17)*.*

Between 0.8 and 4 m above high tide, the sand is normal graded, from very coarse sand with fine gravel particles at the bottom, to medium sand at the top. From 6 m above high tide and inland, the sand is massive—between 4 and 1 cm thick—and discontinuous, and it ends 9.2 m above high tide (Fig. 17)*.*

Rip-up peat clasts, typical for the section between 0 and 6 m, make up a bed within the sand, with a distinct lower boundary (Figs. 17 and 18a)*. We interpret this as a result of at least two waves inundating the land. The first wave eroded the peat surface and transported rip-up clasts of peat and sand. The backwash left the eroded clasts and other organic remains at the surface of the tsunami-*

laid sand. The following wave buried the clasts in sand. Storegga tsunami deposits inferred to show repeated waves are also known from coastal lakes in western Norway (Bondevik et al., 1997b).

It is difficult to estimate the run-up on Shetland because we do not know exactly how many meters the sea level at Storegga time was below present sea level. Hoppe (1965) radiocarbon dated peat found between 8.6 and 8.9 m below the high tide level to between 5990 and 7900 years BP; thus sea level at 6000–7000 years BP was at least 9 m below present sea level. Another point on the sea level curve comes from a marine basin 2 m below present high tide level that prior to 3500 years ago was a freshwater lake (Bondevik et al., 2005b). When the Storegga tsunami happened, relative sea level was clearly lower than 10 m below present sea level. A sea level curve constrained by the above-mentioned radiocarbon dates, show the sea level to be as low as somewhere between 15 m and 30 m below present day sea level at Storegga time (Bondevik et al., 2005b).

Shetland has the highest recorded run-up from field evidence. The sand bed in peat at the western shores of Sullom Voe (Fig. 16) was traced to 9.2 m above high tide (Fig. 17). We also traced it in hand cores to continue 2.4 m below high tide in peat underneath the present day beach gravel. Thus, we have measured a minimum runup of 11.6 m (Bondevik et al., 2003). In boreholes at Scatsta, on the eastern side of Sullom Voe (Fig. 16), the sand was traced even higher, to 11.8 m above spring tide (Smith et al., 2004). A conservative estimate of the relative sea level when the Storegga tsunami happened is 10–15 m below the present, giving a run-up of more than 20–25 m for the Sullom Voe area in Shetland. Such a high run-up is twice as high as the simulated run-up from the numerical tsunami models.

6. Numerical simulation of the Storegga tsunami

Numerical simulations of the Storegga tsunami show how the waves propagated into the North Sea and Norwegian Sea (Fig. 19; https://dx.doi.org/10.6084/m9.figshare.918635). The results from three different tsunami models (Bondevik et al., 2005a; Harbitz, 1992; Hill et al., 2014) are presented here, and they all model the slide as a box of material that is released at the top of the slope, accelerates over a certain length up to a maximum velocity, and then decelerates until it stops. Although we know the Storegga Slide developed retrogressively (see chapter 4), that it started in deeper water and moved piece by piece upslope, the different models of the slide moving as one piece or single box down the slope, return run-up heights in overall agreement with field observations (Bondevik et al., 2005a).

The modelled slide box has a dimension that tries to fit the reconstructed morphology in the source area of the slide. Harbitz (1992) and Hill et al. (2014) uses a slide box with a near uniform thickness of 144 m, width 85 km (Harbitz, 1992) and 175 km (Hill et al., 2014) and a length of 150 km – the corners of the box are smoothed to avoid numerical noise. The slide box in Bondevik et al., (2005a) represents the excavated area better as it varies in thickness according to the pre-slide bathymetry. This block has a maximum thickness of 400 m at the headwall and tapers off to zero at the end (length 150 km) with a total volume of 2400 km^3 – similar to the minimum volume estimate of the total Storegga Slide (Haflidason et al., 2005).

Maximum velocity of the slide is 35 m/s in the three different simulations. This velocity comes from two sources; the observations from the 1929 Grand Banks Slide and a numerical simulation of the slide movement itself. Telephone cables between Europe and America broke subsequently as the Grand Banks Slide propagated downslope. According to the different cable breaks the slide velocity was estimated to 28 m/s at about 150-200 km from the shelf edge (Heezen and Ewing, 1952). In a numerical simulation of the slide De Blasio et al., (2005) found that a maximum velocity of 60 m/s was needed to allow the Storegga Slide to propagate to its observed run-out length. A maximum velocity of 35 m/s for the slide block is reasonable and it generated tsunami waves that fitted rather well with the field observations of run-up (see below). Bondevik et al., (2005a) also simulated the tsunami using a lower maximum slide velocity of 20 m/s (Fig. 19).

In the simulations the slide box accelerates half the run-out distance (75 km) where it reaches a velocity of 35 m/s (after 56 minutes), and then immediately starts to decelerate for another 75 km until it stops at a run-out length of 150 km. The slide box moves for about 1.9 hours.

The run-out length of 150 km is close to where the real slide disintegrated from a debris flow into turbidity currents that ran farther downslope (Fig. 2).

In the numerical simulation the Norwegian Sea/North Sea with coastlines are divided into square boxes, called a grid, with a certain resolution (e.g. 500 X 500 m) and a set of equations that calculate the flow of water in and out of the grid cells (boxes). The equations are called linear shallow water equations and are derived from the assumptions of conservation of mass and conservation of linear momentum. If more water flows into a grid cell than flows out of the grid cell the water level in that cell must rise because water is not compressible (conservation of mass). The other equations are derived from Newton's 2nd law, written for fluid motion under the assumption that the momentum is conserved.

The simulations show that the tsunami propagates outwards in all directions from the slide area. A large depression of 5-8 m moves towards the Norwegian coast as the slide moves downslope, whereas a positive wave of about 3 m in height moves seawards towards Shetland, Iceland and Greenland – most of the energy is transferred in the same direction as the slide moves (Fig. 19). About 30 minutes after the slide was released the first and negative wave reaches the Norwegian coast. From 1.5 hour (Bondevik et al., 2005a) to 2 hours (Hill et al., 2014) after the slide started the first wave reached Shetland and the Faeroe Islands (Fig. 19).

The simulated waves compares rather well with the field observations of tsunami deposits at most of the locations. Tsunami deposits must be regarded as minimum estimates of the true run-up. Run-up could have been higher without leaving a traceable deposit in the field. For instance, in the Tohoku tsunami in Japan in 2011 some places had only 60 % of the inundated area covered with a sand deposit (Goto et al., 2012). Along the western coast of Norway the largest simulated wave height overestimates the sediment run-up by 20-40 % (Fig. 20) (Bondevik et al., 2005a; Hill et al., 2014). However, the run-up deduced from deposits on the Faeroe Islands and Shetland Islands is more than 50 % higher than the largest simulated waves (Fig. 20). Bondevik et al. (2005a) explain this discrepancy that the observations of deposits here are within fjords and sounds (Fig. 16), whereas the simulation is from the very coast (Fig. 20), and the larger observed run-up reflects amplification within a narrowing and shallowing fjord. The simulations of Hill et al. (2014) gave a slightly better fit to the sediment run-up in some areas probably because they used a more detailed bathymetry of the coastlines and a bathymetry that included changes in sea level since 8000 years ago.

Maximum wave height (ocean surface elevation) depends on the volume, initial acceleration and maximum velocity of the slide (Harbitz et al., 2006; Løvholt et al., 2005). It is important to remember that as the slide moves it forms a bulge on the sea surface in the slide direction and a depression at the rear – both propagates at a velocity of $c = \sqrt{gh}$, g is acceleration of gravity and h is water depth. For submarine slides the propagating tsunami waves move faster than the slide and that limits the build-up of the wave. Wave length of the generated tsunami depends on the length and width of the slide, while the maximum surface elevation depends on the thickness of the slide, the velocity and acceleration of the slide, and the propagating velocity of the tsunami waves (i.e. water depth). For landslides in the Storegga escarpment Løvholt et al. (2005) found that both the products of initial acceleration and volume, $a_0 \times V$ and maximum velocity and volume, $U_m \times V$ correlate well with the maximum surface elevation of the generated tsunami.

7. Dating the Storegga event

Tsunami deposits are often difficult to date accurately. The radiocarbon clock starts when an organism dies, and the challenge has been to find the remains of plants or animals that were actually killed in the tsunami and not just remains of already dead organisms that have been redeposited. Only radiocarbon ages of the true victims will return an accurate age when the tsunami happened. However, most of the organic material within a tsunami deposit is redeposited and much older than the tsunami event itself and comes from the heavy erosion by the tsunami of older deposits along the shores containing 'dead' organic material (e.g. Jankaew et al. 2008).

From the beginning the Storegga tsunami deposits were dated on samples of bulk organic material resting directly upon/or below the Storegga tsunami deposits. Smith et al. (2004) found an age of ca. 7000 radiocarbon years from over 50 such dates in Scotland and concluded that there might have been a time delay for the start of peat accumulation on top of the tsunami deposits because the ages were about 200-300 years younger than radiocarbon dates of better and other samples (see below). Another problem arises from the penetration of roots into the deeper layers of peat. Roots can transfer current atmospheric CO_2-carbon to deeper layers thus reducing the radiocarbon age of the peat. It is also likely that roots could grow through the tsunami sand layer and into the peat below. See radiocarbon ages in Fig. 14 that probably illustrates this.

Another and better way is to date individual fragments from the above-ground-parts of plants, like twigs, leaves, fruits and seeds washed out from the deposits. Based on a careful selection of such fragments, Bondevik et al. (1997a) proposed that Storegga tsunami dates to 7250-7350 radiocarbon years (see Fig. 11 with the ages of twigs) . In a comprehensive study of many of the radiocarbon ages (n = 127) of the Storegga tsunami, Weninger et al. (2008) concluded the event to have happened at 7300 ± 30 ^{14}C years BP, corresponding to the interval 8200–8000 years BP (2-σ range).

The best material found so far for radiocarbon dating is samples of green moss from within the Storegga tsunami deposits. Such moss fragments, still green, were found in backwash deposits at site d (Fig. 21) and c (Fig. 22) in northern Norway (Fig. 1 and Table 1).The mosses are still green colored because they contain small amounts of chlorophyll. A little of their chlorophyll survived because the tsunami buried the mosses in shell-rich sediments below a protecting layer of marine mud (Fig. 22). These sediments preserved the chlorophyll by keeping out light and oxygen, and by keeping the pH above 7. Because of their preserved green color we know the green mosses were buried alive and their radiocarbon clock started ticking within hours after the Storegga Slide had set off the tsunami (Bondevik et al., 2012).

The green moss species within the Storegga tsunami deposits were radiocarbon dated and weighted to a mean of 7300 ± 20 ^{14}C years BP, corresponding to about 8150 ± 30 years BP. This mean combines seven ages, each on a different piece of green moss, their ages range from 7231 ± 64 to 7387 ± 72 years BP. Through Bayesian analysis, also including radiocarbon ages of other samples from below and above the tsunami deposit, the calibrated age interval is narrowed to 8120-8175 (68.2% level) and to 8070-8180 (95.4% level) years BP, with 8150 as the most probable year for the Storegga event (for details see Bondevik et al.,2012).

It was also a challenge to obtain accurate ages of the Storegga slide itself. The slide cuts deep into older layers and the slide material is thus much older than the event itself (Figs. 2-4). Most dates come from radiocarbon ages of foraminifera that accumulated in mud on top of the slide deposits after the slide event. Those ages are thus younger than the event. Based on very many radiocarbon ages Haflidason et al. (2005) concluded that the age of the slide is 8200 ± 250 years BP – in agreement with the ages of the tsunami deposits.

The green mosses also told another story - that they were killed in the fall - possibly in October (Rydgren and Bondevik, 2015). One of the species of the green mosses was *Hylocomium splendens* that grows in a regular pattern. New segments on the moss, called daughters, branch off from the previous year's segments, called the mother segments (Fig. 23). The size ratio between the daughter and the mother segments indicate the time of the year. From measuring the size ratio between the daughter- and the mother segments of 19 samples of *Hylocomium splendens,* Rydgren & Bondevik (2015) were able to suggest that the Storegga mosses were killed in October-November (Fig. 23). The giant tsunami happened late in the fall – so late in the year that humans living along these coasts were most likely near their sea shore settlements preparing for the coming winter - and not in the mountains to hunt reindeer.

8. Storegga tsunami and Stone Age humans

Mesolithic humans occupied the coasts of Norway and Scotland and must have been hit by the Storegga tsunami. Remains of Mesolithic settlements are usually located on or near the former shores - thus their settlements would be very vulnerable to a tsunami. Rock carvings illustrate hunting and fishing from boats, and settlements on distant islands suggest that they had advanced maritime skills at that time (Bjerck, 2013). However, evidence that prove that humans or settlements were actually hit by the Storegga tsunami have not yet been discovered, although archaeologists have been aware of the Storegga tsunami for more than a decade. Sands of Storegga age cover two Mesolithic settlements, at Dysvikja in western Norway and Inverness in Scotland, but we do not know if humans still occupied these settlements when the Storegga tsunami hit, or if the humans had already left the sites for other reasons, like the rising sea level during the mid-Holocene transgression (Tapes transgression).

The same might be true for Doggerland (Coles, 1998), a low lying Island in the North Sea, occupied by humans in Late Paleolithic and Early Mesolithic. Hill et al. (2014) used ocean depths in their tsunami model that was corrected for changes in sea level that have occurred the last 8150 years, and at that time Doggerland was just above sea level by a few meters. In their simulation you can see how Doggerland is hit by the tsunami (https://dx.doi.org/10.6084/m9.figshare.918635), the largest wave is about 5 m. However, the question is whether Doggerland was still occupied at that time, or whether humans had already left the Island(s) because of the rising sea level (http://www.bbc.com/news/science-environment-27224243). The youngest radiocarbon ages of human remains and artifacts from Doggerland retrieved so far are all older than Storegga time (Weninger et al., 2008). This would suggest that Doggerland was probably already abandoned by the time of the Storegga tsunami.

At Dysvikja at Fjørtoft (a neighbor Island to site f in Fig. 1; Table 1) a Mesolithic settlement of Storegga age was discovered below 1.2 m of beach gravel. The site contained flint tools, hazel nuts, three fireplaces and birch bark and other materials possibly part of a building construction (Indrelid, 1973). The critical point is a sand layer, between 7-15 cm thick, found above the cultural beds (youngest dated to 7550±90 ^{14}C yr BP (Indrelid, 1974) and below the 1.2 m of overlying beach ridge (Tapes beach ridge). When discovered, the sand layer was interpreted as deposited from wind, but this interpretation was questioned by Bondevik (2003), who found a similar stratigraphy (without the archeological material) at site f (Fig. 1), where a sand layer in peat below the Tapes beach ridge was interpreted to be deposited from the Storegga tsunami.

Rydgren and Bondevik (2015) found that Storegga happened in October/November and speculate that the autumn must have been a difficult time for the Mesolithic humans to be hit by the tsunami. At that time of the year most of the hunter-gatherer groups adapted to the coastal environment were back at the coast from visits in the mountains to hunt reindeer and/or moose in late summer and early autumn (Bang-Andersen, 1996; Bjerck, 2008). A tsunami in late autumn, after the hunters returned to the coast, could have caused high mortality. For those who survived, the loss and destruction of dwellings, boats, clothing, equipment and food supplies would have made the following winter very difficult (Bjerck, 2008).

9. Future directions

The various slide models used in the numerical simulations of the tsunami are not realistic and should be improved. We know the slide developed retrogressively, but the models simulate the slide as a box released at the top that slides down the slope. A new slide model should be developed for the tsunami simulation that has an initial slide in the area around the lower headwall (Fig. 2) and develops retrogressively, backwards, towards the top of the slope. Such a movement of the slide must have had a big effect on the tsunami generation, although the existing simulations fit rather nicely with the field observations of run-up (Bondevik et al., 2005a; Hill et al., 2014). Løvholt et al. (2005) studied such a retrogressive movement in general and found that the time lag between the different released blocks is crucial. If the time lag is longer than about 1 minute between the release of the next block a tsunami would not form.

Did the Storegga tsunami hit Stone Age humans? At present we do not know. Most of the settlements were probably at the coast and they were most likely severally damaged by the tsunami, but direct evidence have not yet been found, although the archaeologists are well aware of the Storegga tsunami event and have looked for it. Mesolithic settlements along the coast that are unearthed through excavations should have a program to look carefully at this. The two sites Dysvikja and Inverness are covered by Storegga sand, but the sites could have been abandoned before the tsunami happened.

The Storegga tsunami deposit can be a useful stratigraphic marker because of its large extent, short duration, and extensive deposits recognizable in many different coastal settings. The green mosses date the Storegga event to 8120-8175 (1 σ) / 8070-8180 (2 σ) years BP (Bondevik et al., 2012), but a tree-ring date of the Storegga event would date the event to the nearest decade. A prerequisite is that we could find remains of an old tree with the outer bark preserved that was killed during the tsunami. Some of the lake basins or bogs must have trapped parts of fallen trees during the tsunami. If we could find samples of such trees with some decades of rings we might be able to wiggle match the radiocarbon ages and get a better date for the Storegga event.

Are there other tsunami events than the Storegga that have been generated in the Norwegian Sea/North Sea? The short answer is yes, but they are much smaller. On Shetland we found two younger tsunamis; at 5500 and 1500 years BP (Bondevik et al., 2005b), but we do not know what triggered these events or how wide spread they are. Another big slide north of Storegga is the Traenadjupet Slide that happened about 4500 years BP (Laberg and Vorren, 2000). Could that slide also have triggered a tsunami? So far we have not found evidence for that, but that could be because we have searched in wrong places. A numerical simulation of a possible tsunami generated by the Traenadjupet slide could help us to choose the area along the coast that would have the largest run-up. However, none of these events compares to the giant Storegga. If Storegga happened today it would have caused a big catastrophe – comparable to the 2004 Indian Ocean tsunami.

10. Acknowledgements

I am grateful to the MAREANO project at Norwegian Geological Survey (NGU) and the Norwegian Hydrographic Service that allowed me to use their detailed bathymetry for figures 4 and 5, which were put together by Terje Thorsnes at NGU. Finn Løvholt and Jon Hill answered questions about the numerical simulations; David Smith answered detailed questions about run-up measurements in Scotland, provided the photo from Maryton in Fig. 15 and suggested changes to the text that improved the paper. Alastair Dawson and John Inge Svendsen gave valuable comments to the chapter "How the Storegga tsunami was discovered"?

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Table 1: Field observations of Storegga tsunami deposits and run-up estimates

Index on map	Area	Location	No. of sites	Reference(s)	Outcrop	Lake basin	Marine basin	Estuarine mud	Peat	Run-up (m)	Comments
a	East Greenland	Geographical Society Ø (Loon lake)	1	Wagner et al. (2007)			x			-	Sandy sequence with erosive base in marine silt interpreted as Storegga tsunami deposits. Dated to younger than 8500-8300 yr BP.
b	Northern Norway	Finnmark (Sørøya, Rolvsøya, Nordkinn)	5	Romundset and Bondevik (2011)		x				3-5	Coastal lakes along the outer coast of Finnmark show Storegga tsunami to propagate into the Barents Sea. Deposits in lakes 0-3 m above contemporary sea level. No traces in lake 5 m above contemporary sea level.
c	Northern Norway	Troms (Lyngen)	3	Rasmussen and Bondevik (2006) (Rasmussen et al.)		x	x			> 4.5-6	Storegga tsunami barely inundated lake at 25.2 m a.s.l. Sea level at 21 m a.s.l.
d	Northern Norway	Brønnøy (Hommelstø)	3	Bondevik et al. (2012) Rydgren and Bondevik (2015)			x			> 3	All basins investigated were below sea level at Storegga time, terrestrial plants and peat clasts within tsunami deposits indicate runup > 3 m.
e	Mid-Norway	Bjugn	3	Bondevik et al. (1997a)		x	x			6-8	Storegga tsunami overflowed lake at 42 m a.s.l., but not lake at 44 m a.s.l. Contemporary high tide sea level at 35-36 m a.s.l.
f	Western Norway	Sunnmøre (Harøy)	1	Bondevik (2003)	x				x	-	Sandlayer in peat below Tapes beach ridge; was traced in cores landwards of the beach ridge.
g	Western Norway	Sunnmøre (Sula)	6	Bondevik et al. (1997a)		x	x			10-12	Storegga tsunami barely inundated lake at 21.5 m a.s.l., but no traces of inundation in lake at 22 m a.s.l. Contemporary sea level at 10-11 m a.s.l.
h	Western Norway	Sunnmøre (Bergsøy, Leinøy)	4	Bondevik et al. (1997a)		x	x			9-13	A lake 8-9 m above contemporary sea level show large erosion from Storegga tsunami. Two lakes 12-13 m above contemporary sea level have no traces of inundation.
i	Western Norway	Nordfjord	2	Vasskog et al. (2013)		x				> 1-5	Two lakes at the head of the fjord "Nordfjord" – up to 3 m thick Storegga tsunami deposits. Lakes are 1-5 m above contemporary high tide sea level.
j	Western Norway	Florø	1	Aksdal (1986) Bondevik et al. (1997a)		x				-	A bed of gravel, sand and redeposited gyttja, draped with 2 mm silt, dated to 7360±110 ^{14}C years.
k	Western Norway	Hordaland (Austrheim)	5	Bondevik et al. (1997a)		x				3-5	A lake at 14 m a.s.l. was clearly inundate by the Storegga tsunami, but not a lake at 15 m a.s.l. Contemporay sea level at 10-11 m a.s.l.
l	Western Norway	Hordaland (Bømlo)	2	Bondevik et al. (1997a)		x				3-5	Storegga tsunami deposit in lake at 15 m a.s.l, but not in a bog at ca. 16 m a.s.l. Contemporary sea level at ca 12 m a.s.l.
m	Shetland	Unst, Sullom Voe	9	Bondevik et al. (2005b) Smith et al. (2004)	x	x			x	> 20	Storegga tsunami deposit found in 4 lakes located 0.5-3 m above present high tide level. Sand layer in peat outcrops

											traced to 9.2 m above high tide in the Sullom Voe area. Contemporary sea level 10-15 m below present sea level.
n	Faeroe Islands	Suderøy (Vagur)	1	Grauert et al. (2001)		x				> 14	Lake at 4 m a.s.l. at the head of 5 km long fjord with Storegga tsunami deposits. Contemporary sea level probably 10 m below present sea level.
o	Scotland	Sutherland, Caithness	2	Dawson and Smith (1997) Dawson and Smith (2000) site 7 & 8 in Smith et al. (2004)		x		x	x	4.6	In lower Wick River valley, Caithness, fine sand layer within peat. Tsunami deposits in filled-in lagoon at Strath Halladale in Sutherland.
p	Scotland	Loch Eriboll, Lochan Harvurn	1	Long et al. (2016)	x				x	-	Sand layer in a coastal cliff section of peat.
q	Scotland	Dornoch Firth	3	Site 9-11 in Smith et al. (2004) and references therein.				x		2	Widespread sand layer (Figs. 13 & 14).
r	Scotland	Inner Moray Firth	6	Smith et al. (2004) and references therein. Dawson et al. (1990)				x	x	3.3	Layer of fine sand of marine provenance in estuarine sediments; landwards it rises into peat. One of the sites is an archeological excavation at Inverness, “beach sand” resting upon a Mesolithic horizon with artefacts.
s	Scotland	North-East Scotland	3	Smith et al. (2004) and references therein.				x	x	3.3	Fine medium sand within peat landwards, seawards it continuous into estuarine mud.
t	Scotland	Tayside	6	Smith et al. (2004) and references therein. Dawson et al. (1988)	x			x	x	3.9	Fine sand layer in estuarine deposits around the Montrose basin, continuous into peat landwards. One site (Maryton) is in a cliff exposure (Fig. 15).
u	Scotland	Near St. Andrews (Silver Moss, Craigie)	2	Smith et al. (2004) Dawson et al. (1988)				x	x	2.9	Tapering layer of sand in estuarine deposits that pass into peat up-slope.
v	Scotland	Firth of Forth	2	Smith et al. (2004) and references therein.				x	x	1.4	Sand within estuarine mud, passes into peat at the valley side.
w	Scotland	Near Dunbar (east Lothian)	1	Smith et al. (2004) and references therein.					x	1.3	Sand in peat moss that contains marine and brackish diatoms. Radiocarbon dated to between 7590±60 and 7315±70 ^{14}C yr BP.
x	NE England	Broomhouse Farm	1	Shennan et al. (2000) Smith et al. (2004)					x	ca. 3	Sand horizon of marine provenance within coastal peat moss at Broomhouse Farm.
y	NE England	Howick, Northumberland	1	Boomer et al. (2007)				x		-	30 cm layer of coarse sands and pebbles dated to 8300 yr BP in marine clay/silt.
z	Denmark	Rømø	1	Fruergaard et al. (2015)		x				-	80 cm thick layer of sand and rip-up clasts of organic material.

Table 2: Storegga Slide numbers

Total volume	2400-3200 km^3
Total area, including depositional area	95,000 km^2
Area of slide scar	27,000 km^2
Length of upper headwall	310 km
Water depth at upper headwall	150-400 m
Run-out, including distal turbidites	810 km
Water depth at distalmost deposits	3800 m
Average slope gradient	< 1.0°
Steepest gradient in upper headwall	35°
Max vertical height of upper headwall	250 m
Ages of forams on top of slide deposits	7250±250 ^{14}C years (8150±250 calendar years) BP

(Data from Haflidason et al. (2005); Solheim et al. (2005a); Solheim et al. (2005b)

Figur text

Fig. 1: The Storegga slide in the Norwegian Sea is the largest exposed slide in the world. Red dots show locations of Storegga tsunami deposits. Run-up estimates, from deposits, to the right. Black column shows minimum estimate, grey columns is a maximum estimate of run-up. Letters correspond to the same sites described in Table 1.

Fig. 2: Outline and deposits of the Storegga Slide. Failure layers in the slide scar area, between the lower and upper headwall, are contourites deposited during interglacials and interstadials (S2, R2 and O3). Stippled lines show minor headwalls. The stratigraphy in the area belongs to the Naust formation (last 3 My) and is subdivided into five units; W, U, S, R and O (youngest) (Berg et al., 2005). To the left a table shows how the units refer to the marine isotope stages. Unit U is not exposed in the Storegga scar area. [Based on Fig. 1 in Haflidason et al. (2005) and Fig. 8 in Bryn et al. (2005a).]

Fig. 3: **a** Bathymetric image of the slide scar. The Ormen Lange gas field is located close to the upper headwall [redrawn from Fig. 2 in Kvalstad et al., 2005]. **b** Depth profile along the stippled line in **a**. The «wavy» line of the slope surface is because of the large blocks in the slide. Note the minor headwalls along the profile – this is a jump to a glide plane at a higher stratigraphic level. A large part of the slope is only 0.3° [redrawn from Fig. 3 in Kvalstad et al., 2005].

Fig. 4: Bathymetric image of the central part of the slide scar, where the slide cut deepest into the deposits. Units O3, R2 and S2 acted as glide planes. Terrain data: MAREANO/NHS, 3D visualization: MAREANO/NGU (www.mareano.no).

Fig. 5: Focused image of the two "amphitheaters" along the upper headwall. For location see Fig. 4. Terrain data: MAREANO/NHS, 3D visualization: MAREANO/NGU (www.mareano.no).

Fig. 6: Coastal lake in Shetland, the Loch of Snarra Voe, on the Island Unst (Fig. 16). The lake is 0.6 m above the present high tide level, but was probably at least 10 m above sea level when Storegga happened. Here we found distinct Storegga tsunami deposits with gravel, sand, rounded rip-up clasts of over-consolidated silt and different types of marine shell fragments.

Most erosion was found in cores between the raft and the outlet of the lake (Bondevik et al., 2005b).

Fig. 7: A sedimentological model for erosion and deposition by a tsunami inundating a marine basin and a lake basin. The model is based on analysis of Storegga tsunami deposits in western Norway [redrawn from Fig. 12 in Bondevik et al., 1997b].

Fig. 8: Description of the Storegga tsunami deposits, given as an idealized, complete facies sequence of tsunami deposits in near shore lakes (yellow). The enclosing sediments are also shown. Note that if graded sand and massive sand occur in the same tsunami sequence they are normally separated by organic deposits (rip-up clasts, detritus or silt). [Based on Fig. 5 in Bondevik et al. (1997a)].

Fig. 9: Air photo of site e (Fig. 1, Table 1), Bjugn. Sea level at tsunami time in transparent blue – here shown as the surface below the 35 m-contour-line. Run-up is in transparent red – the surface between the 35 m contour line and up to ca. 42 m a.s.l. - drawn as a line between contour line 40 m and 45 m from 1:5000 maps. Cores as white dots. No tsunami deposits were found in Jøvatnet (44 m a.s.l). Audalsvatnet (33.6 m a.s.l.) was a few meters below sea level when the tsunami happened.

Fig. 10: **a** Photo of the Storegga deposits in Audalsvatnet, Bjugn (see location of core in Fig. 9). Ruler shows inches and cm. Below is a close-up of the upper boundary (**b**) and the lower boundary (**c**). The white spots in the sand are shell fragments. The four lowermost layers are graded sand, the other two sand layers above are massive sand separated by silt. Terrestrial moss stems were found in the sand layers – one was dated to 7315 ± 70 ^{14}C years BP (Bondevik et al., 1997a). The lower boundary is knife-sharp; the upper boundary is gradual, somewhere around 28 cm (12**28** cm below the lake surface) in grey silt.

Fig. 11: Tsunami deposits in Kvennavatnet, Bjugn (see location of core in Fig. 9). Depth is cm below lake level. To the right is description of deposits and radiocarbon ages (in ^{14}C years BP).

Fig. 12: Map, cross section, photograph and log from Gorrtjønna I, Bjugn (see location in Fig. 9; slightly modified from Fig. S3 in Bondevik et al., 2012). **a** Map with core locations (red crosses) and grain size in ϕ-units of tsunami- sand on the erosional boundary. **b** Cross section

along the stippled line in **a**. Note the big slab of peat in the tsunami deposits. According to the cores the peat slab must be inverted (upside down) because it is more humified at the top than at the bottom. **c** Photo shows the sand lamina on the erosional boundary in core 3-97 – only a few sand grains thick. **d** Radiocarbon ages from core 3-97. The core was chosen for radiocarbon dating because of the little erosion underneath the tsunami deposits.

Fig. 13: Esuary at Dornoch Firth in eastern Scotland. Boreholes at Creich and Dounie (site q in Fig. 1 and Table 1) show Storegga tsunami deposits in estuarine mud, see profile from Creich in Fig. 14. [Redrawn from figure 1 in Smith et al. (1992)].

Fig. 14: Profile at Creich, cores in grey lines, ages in radiocarbon years. Run-up is measured from highest recorded surface of estuarine mud beneath the tsunami deposit and to the upper reach of the tsunami layer, here measured to 2.3 m. [Redrawn from Long et al. (1989a) and Smith et al. (1992)].

Fig. 15: Outcrop at Maryton in the Montrose basin (site t in Fig. 1 and Table 1) show the Storegga tsunami as a 25 cm thick silty sand deposit between peat. The estuarine mud is laminated silt and clay (photo David Smith).

Fig. 16: Locations of Storegga tsunami deposits on the Shetland Islands. One of the outcrops, pointed to with an arrow, in Sullom Voe, is presented in more detail in text and in Figs. 17 and 18.

Fig. 17: The upper panel is a sketch of the Storegga tsunami layer in the 150-m-long peat outcrop on the western shore of Sullom Voe (Fig. 16) .The lower panel shows the first 16 m of the same outcrop. Between 0–6 m, large rip-up clasts of peat and pieces of wood embedded in the sand dominate the tsunami layer. Underneath the sand layer there is a profound erosional unconformity. Here the sand rests on till. From 9 m and inland, the sand is found in peat. Note that the sand layer thickens in the small depressions in the peat [redrawn from Fig. 2 in Bondevik et al. (2003)].

Fig. 18: **a** The first four meter of the outcrop (location indicated with a frame in Fig. 17) shows a large number of rip-up clasts embedded in the sand. Some of the clasts have sharp edges. The lower boundary of the peaty clasts forms a well-defined line in the sand. The red handle on the shovel is 9 cm long. **b** Photo showing the Storegga sand layer from about 12 m to 20 m in the peat outcrop (location indicated with a frame in Fig. 17). Note how the sand and gravel is thicker in the depressions in the peat. The shovel rests on hard till.

Fig. 19: Simulation of the Storegga tsunami 2 hours after the release of the slide. The wave front, ca. 3 m high, has just reached the Faeroe islands and Shetland. [Copy of fig. 8 in Bondevik et al. (2005a).]

Fig. 20: Simulated sea surface elevation at Bjugn, Shetland and Scotland during the Storegga tsunami. The locations are identical for both simulations, except Scotland where Hill et al. (2014) has the northernmost location. The two simulations differ slightly in arrival time of the tsunami because they use different bathymetry. Hill et al. (2014) has better resolution of the bathymetry near the coastline and the bathymetry is also corrected for changes in sea level the last 8000 years.

Fig. 21: Samples of green moss in Storegga tsunami deposits in Lyngen, Troms (site c, Fig. 1). To the left (**a**) is a photo of the core with tsunami backwash sediments. Terrestrial moss samples, washed out from a layer of shell fragments in the core, are placed clean on the core surface for display. The same moss samples to the right after being dried in the laboratory – the green color of the moss samples show much better off after drying.

Fig. 22: Storegga tsunami deposits from core site 5 at Djupmyra in Hommelstø (site d in Fig. 1). Uncorrected radiocarbon ages to the left. Weighted average of the green moss dates is 7320 ± 20 ^{14}C yr BP, calibrated to 8070-8180 years BP (Bondevik et al., 2012). Note that the tsunami deposits contain backwash deposits of peat- and soil clasts and terrestrial plants, preserved beneath a cover of marine mud. [Copy of Figure 2 in Rydgren and Bondevik, 2015.]

Fig. 23: **a** A well preserved sample of the moss *Hylocomium splendens* from Storegga tsunami deposits at Djupmyra, Hommelstø (Site d, Fig. 1, Fig. 22). The daughter segment is a little smaller than the mother segment. For this sample the daughter/mother size ratio is 0.63. **b** Plot of the size ratio between daughter and mother segments of *Hylocomium splendens* from modern samples (n = 20) collected in the months July, August, October, November and December. The size ratio of Storegga samples (n = 19) is somewhere between 4. October and 2. November. [From Fig. 4 in Rydgren & Bondevik, 2015.]