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Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and coastal lakes, western Norway

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ABSTRACT

Sedimentary successions in small coastal lakes situated from 0 to 11 m above the 7000 year BP shoreline along the western coast of Norway, contain a distinctive deposit, very different from the sediments above and below. The deposit is interpreted to be the result of a tsunami inundating the coastal lakes. An erosional unconformity underlies the tsunami facies and is traced throughout the basins, with most erosion found at the seaward portion of the lakes. The lowermost tsunami facies is a graded or massive sand that locally contains marine fossils. The sand thins and decreases in grain size in a landward direction. Above follows coarse organic detritus with rip-up clasts, here termed 'organic conglomerate', and finer organic detritus. The tsunami unit generally fines and thins upwards. The higher basins (6–11 m above the 7000 year shoreline) show one sand bed, whereas basins closer to the sea level 7000 years ago, may show several sand beds separated by organic detritus. These alternations in the lower basins may reflect repeated waves of sea water entering the lakes. In basins that were some few metres below sea level at 7000 years BP, the tsunami deposit is more minerogenic and commonly present as graded sand beds, but also in some of these shallow marine basins organic-rich facies occur between the sand beds. The total thickness of the tsunami deposit is 20–100 cm in most studied sites. An erosional and depositional model of the tsunami facies is developed.

INTRODUCTION

Tsunamis are large sea waves caused by dislocation of the sea floor during earthquakes (faulting), submarine slides or volcanic eruptions. Asteroids and comets hitting the ocean will also generate tsunamis. A clastic unit within mudstone at the Cretaceous-Tertiary boundary in Texas has been interpreted as the product of a megatsunami generated by such an impact (Bourgeois *et al*., 1988; Smit *et al*., 1992). Tsunamis have long wavelengths, often 100–200 km, and travel across oceans with high velocities. In a water depth of 4000 m the velocity is about 700 km h^{-1}. In the deep ocean the wave height is low, but when reaching shallow water the wave height is greatly amplified. Thus, when tsunamis hit the shore they frequently represent catastrophic events. From September 1992 to July 1993, 1500 people were killed by three tsunamis, hitting the coasts of Nicaragua, Flores Island (Indonesia) and Japan (Satake, 1994).

From a geological point of view, a tsunami represents a shortlived, but extremely powerful agent. Recent tsunamis show a very complex pattern of erosion and deposition (Yeh *et al*., 1993; Synolakis *et al*., 1995) and large volumes of sediments may be eroded and transported both landwards and seawards. Sedimentological studies of inferred tsunami deposits are known from shallow marine areas (Bourgeois *et al*., 1988), lakes (Minoura & Nakaya, 1991) and coastal sequences on land (Darienzo & Peterson, 1990; Atwater & Moore, 1992; Dawson *et al*., 1993; Minoura *et al*., 1996), but in general the sedimentological process associated with an inundating tsunami and the tsunami deposits themselves, have been little studied (Dawson *et al.*, 1993).

Dawson *et al.* (1988, 1993) have given convincing arguments that a tsunami struck the coast of Scotland around 7000 years BP and proposed (Dawson *et al.*, 1988) that this tsunami was triggered by the so-called Second Storegga slide on the continental slope off western Norway (Bugge *et al.*, 1987; Jansen *et al.*, 1987). According to numerical modelling of the slide (Harbitz, 1992), the coast of western Norway, situated close to the slide area (Fig. 1), should have been struck more violently by this tsunami than any other coastal area around the Norwegian Sea. We have searched for evidence of the Storegga tsunami by coring many lake basins above and below the 7000 year BP shoreline along the western coast of Norway. Such nearshore depressions or small basins are considered well-suited sites to search for tsunami deposits because they are efficient sediment traps, and sediments deposited in such closed basins have a high preservation potential. We have found a particular deposit inferred to be the result of the Storegga tsunami invading such basins. The sedimentology of this tsunami deposit is the focus of the present paper. More than 40 radiocarbon dates of this deposit from different basins suggest an age of between 7000 and 7200 years BP. Based on the spatial variation and facies relationships, an erosional and depositional model for tsunami sedimentation is presented, as well as sedimentological criterias to identify tsunami events in shallow basin sedimentary sequences. In a parallel paper (Bondevik *et al.*, 1997) we have

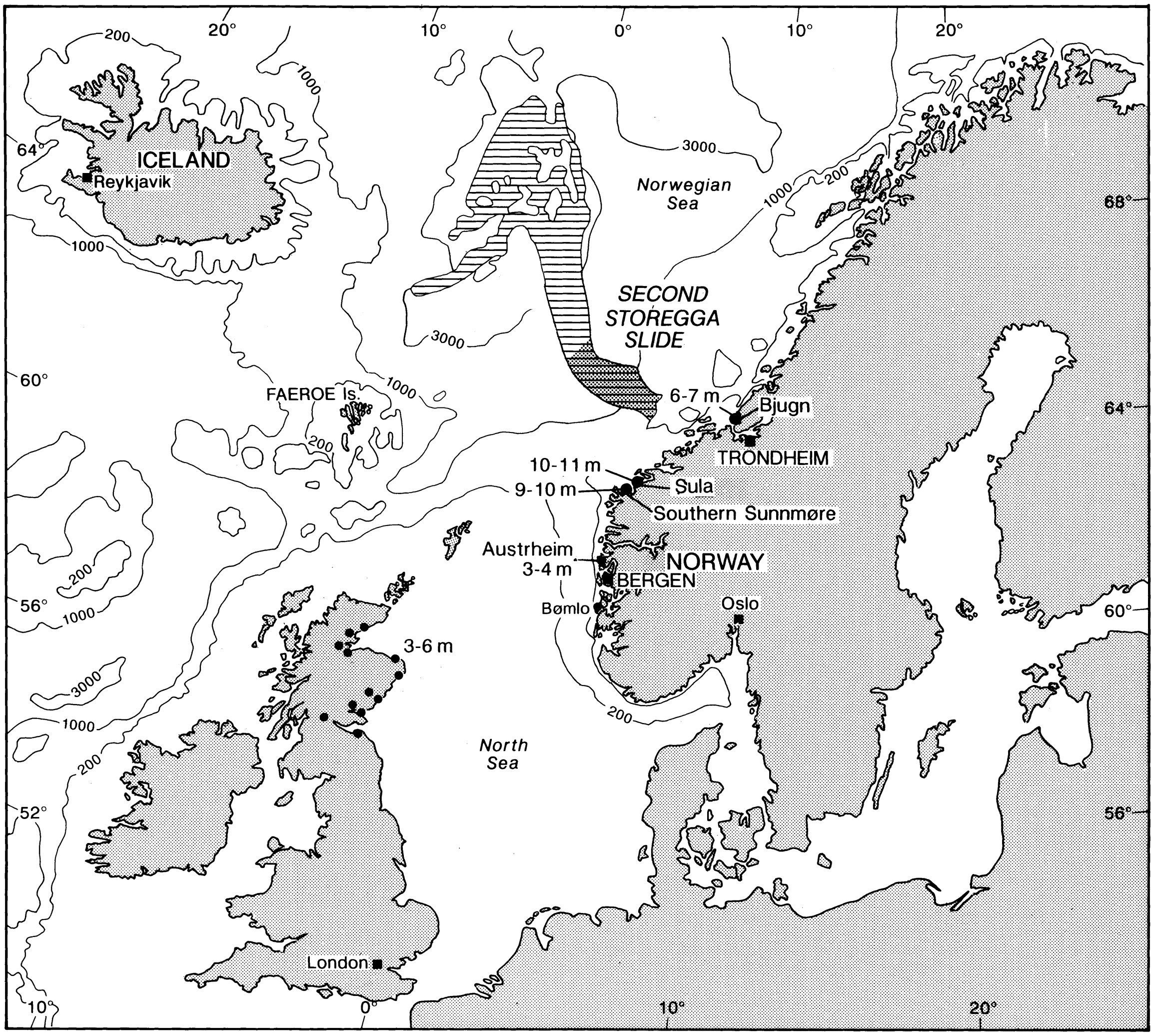


Fig. 1. Bathymetric map of the Norwegian Sea and North Sea showing the areal extent of the Second Storegga submarine slide. The erosional area is shaded (after Bugge *et al.* (1987)). Dots in Scotland represent locations with tsunami deposits (from Dawson *et al.* (1993)). Along the Norwegian coast tsunami deposits are reported here from Bjugn, Sula and southern Sunnmøre. Reconstructed runup-heights are from Bondevik *et al.* (1997).

reconstructed the runup from this tsunami along the Norwegian coast (Fig. 1) by coring a staircase of basins above the 7000 year shoreline.

GEOLOGICAL SETTING

The numerous small lakes and bogs in rock basins along the coast of Norway were excavated by glacial erosion (Figs 2 and 3). After the last glaciation, Scandinavia was still glacio-isostatically depressed, and consequently relative sea level was higher than at present. Marine sediments are therefore found in the lower part of sedimentary sequences in lake basins situated below the highest postglacial shoreline. Due to glacio-isostatic uplift the basins subsequently emerged from the sea and turned into fresh-water lakes and bogs. This is recorded as a sequence of marine sediments followed by brackish to fresh-water sediments. Brackish water sediments accumulated when sea level was close to the threshold of the basin. Once the threshold of the basin emerged above high tide level, lacustrine sedimentation commenced.

The boundary between marine and lacustrine sediments in such basins has been radiocarbon dated at many localities and used to reconstruct postglacial sea-level changes. In this way a number of well-documented sea-level curves from western Norway have been constructed, and the shoreline geometry is considered to be relatively well-known (Kaland, 1984; Anundsen, 1985; Svendsen & Mangerud, 1987). All shorelines are tilted towards the coast because of larger glacio-isostatic uplift in the inland, where the ice-sheet was thickest. If a tsunami struck the coast while the threshold of a basin still was below sea level, tsunami deposits should be expected within the marine sequence. If the basin was above sea level, the tsunami deposits should be found in the lower part of the lacustrine sequence.

A total of 18 basins with inferred tsunami deposits have been studied along the Norwegian coast (Bondevik *et al.*, 1997). These form the basis for the erosional and depositional model of tsunami sedimentation in shallow basins presented at the end of the paper. The basins, presently lakes or bogs (palaeolakes) are typically 50–100 m wide, 100–400 m long and 10–15 m deep (Figs 2 and 3). The topography around the lakes is an undulating rock surface with a thin and discontinuous sediment cover.

To visualise the relationships and geometry of the tsunami deposits we will describe the sediments in three basins at Bjugn (Figs 1 and 2). According to a local sea-level curve for the area constructed by Kjemperud (1982), Gorrtjønna (42 m a.s.l.) and Kvennavatnet (37 m a.s.l.) were situated above sea level whereas Audalsvatnet (33·5 m a.s.l.) was slightly below sea level 7000 years ago (Fig. 2). These conclusions were confirmed during our study.

METHODS

Sediments have been mapped across each basin using a Russian peat sampler. Samples for laboratory investigations were collected with a 110 mm diameter piston corer, which provided up to 2 m-long core sections.

In the laboratory the cores were first split lengthwise, photographed, described in detail and then subsampled for further analysis. Grain size data were derived by wet sieving. The organic content of the sediments was determined by the weight loss on ignition (LOI). Samples were dried at 105 °C for 24 h and ignited at 550 °C for 1 h. Weight loss was calculated as a percentage of the dried sample weight. In this type of sediment organic carbon is about 50% of the loss on ignition. Microfossils (foraminifera and diatoms) from certain critical levels were analysed as an aid to interpreting the sedimentary environment. Radiocarbon dating was carried out at the Radiological Dating Laboratory in Trondheim, Norway. Bondevik *et al.* (1997) give further details about the radiocarbon dates of the tsunami deposits.

LITHOFACIES

The sediments are classified into nine facies on the basis of lithology and structure. For convenience these facies are divided into two groups. The group A facies have previously been described from many lakes and bogs along the coast of Scandinavia and are related to normal sea-level changes. Group B facies, however, have in contrast been little studied; it is these that we interpret as tsunami deposits.

Group A facies, enclosing sediments to the tsunami deposits

The facies in group A are important as the enclosing sediment of group B facies (tsunami deposits) and for reconstruction of local sea level at the time the tsunami struck the coast.

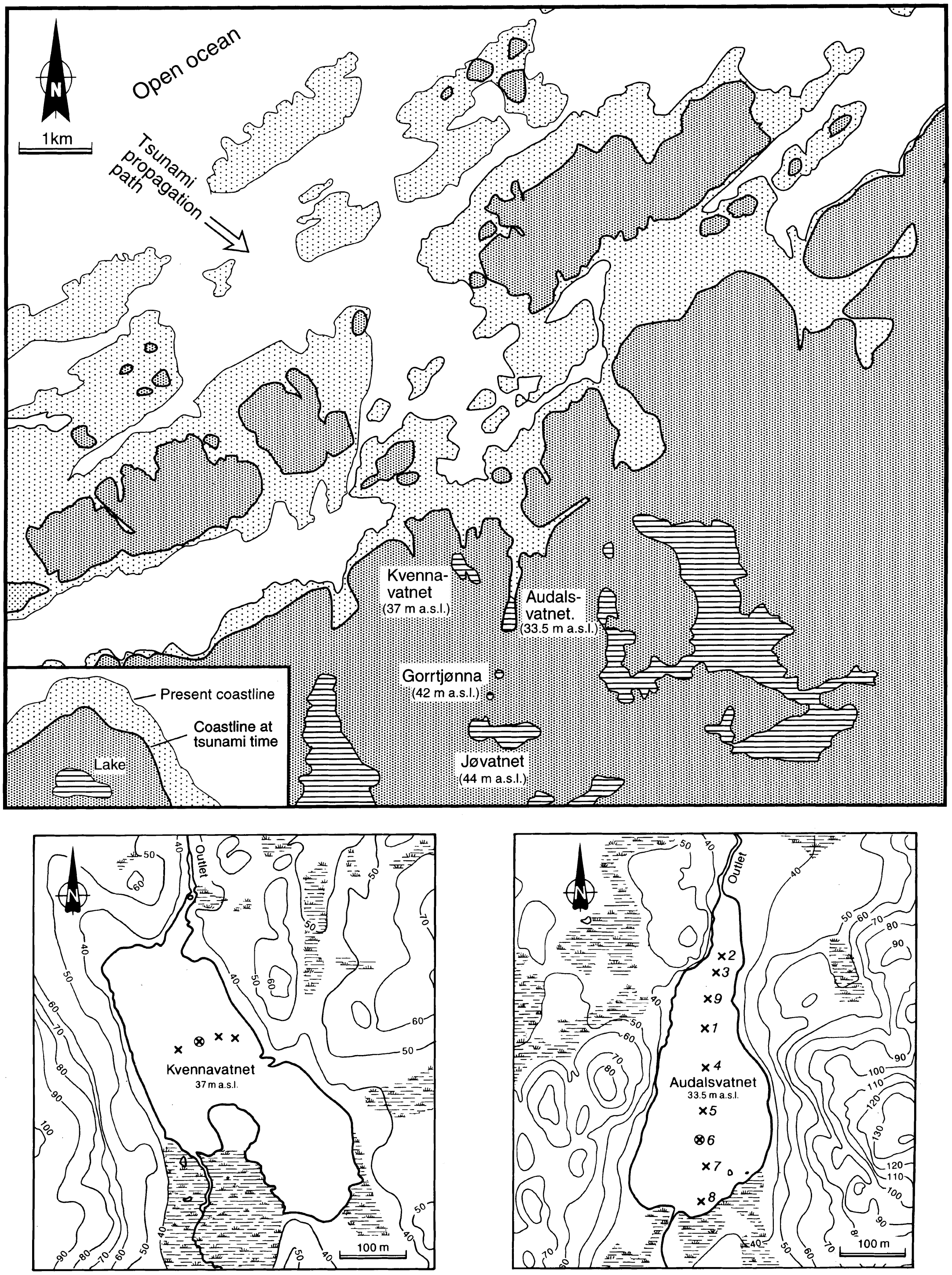


Fig. 2. Map showing the studied lake basins at Bjugn in relation to the coastline at tsunami time (*c.* 7000 years BP) and the present coastline. Tsunami deposits have been found in Audalsvatnet (below sea level of that time), Kvennavatnet and Gorrtjønna, but not in Jøvatnet. The lower maps show the two lake basins Kvennavatnet and Audalsvatnet with the location of cores. Encircled crosses indicate cores presented in Fig. 5 (Audalsvatnet) and Fig. 6 (Kvennavatnet).

Grey to brownish grey, massive, sandy silt (facies 1) was deposited when the basin was an overdeepened bay or inlet. Marine mud and microfossils were trapped in this overdeepened basin and protected from wave erosion during the subsequent emergence. This is followed by

Fig. 3. Photo of the northern part of Audalsvatnet and Kvennavatnet in Bjugn. View towards NNE. The sea is seen in the background. When the tsunami struck the coast 7000–7200 years ago, Audalsvatnet was a bay, whereas Kvennavatnet was just above sea level. Compare with Fig. 2.

facies 2, a finely laminated algea gyttja, normally 2–5 cm thick, showing a significant reduction in clastic mineral content. This brackish-water facies is common at the transition between marine and lacustrine sediments in emerged basins along the western coast of Norway (Lie *et al.*, 1983; Kaland, 1984; Kjemperud, 1986). The well-preserved lamination is most likely a result of anoxic bottom water that prevents bioturbation (Corner & Haugane, 1993). During the deposition of this facies, sea level was at or slightly below the basin threshold.

When sea level was below the threshold, the basin turned into a lake, and lacustrine brown gyttja accumulated. The facies succession 1–2–3 represents the emergence of the basin out of the sea.

Group B (tsunami facies)

This group consists of a mixture of different sediments resting on an erosional unconformity which typically can be traced throughout the basins. Both the description and naming of these facies has been difficult because of their large variability.

Graded sand (facies 4)

This is a graded bed, commonly rich in shell fragments. The lower part is coarse sand or, in some cases, fine gravel, grading upwards to medium sand (Figs 4–6). It has a clear erosive base (Fig. 4). The facies is commonly 4–6 cm thick but may reach a thickness of 20 cm. If present, it usually occurs at the base of group B.

Massive sand (facies 5)

Moderately to poorly sorted, fine gravel to fine sand with sharp boundaries. It usually contains foraminifera and shell fragments (Fig. 7). The bed is normally thinner than the graded sand (facies 4) and varies from 1 mm to 4–5 cm. It has no internal structures.

Organic conglomerate (facies 6)

This facies typically has a heterogeneous composition and may include different materials. The main characteristic is clasts of peat, gyttja and silt (Figs 4 and 7). The clasts normally have an irregular form and are commonly from 0·5–6 cm across, but may also be larger (at least 20 cm). The

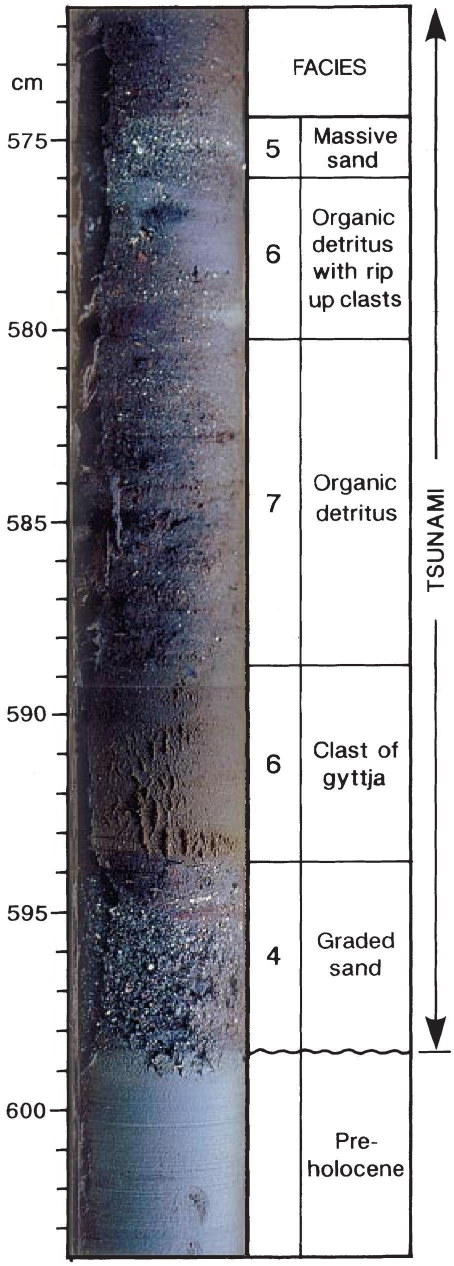


Fig. 4. Photo of facies 4, 6 and 7 of the lower part of group B facies (tsunami facies) in Kulturmyra, southern Sunnmøre.

clasts occur together with shell fragments, twigs, pieces of wood and plant fragments in a matrix of gyttja with silt and sand. The clasts are most frequent in the lower part. Lenses of sand may also be present. We introduce the term 'organic conglomerate' for this facies because it is characterized by clasts of organic sediments (although clasts of silt occur) in a matrix mainly of organic matter.

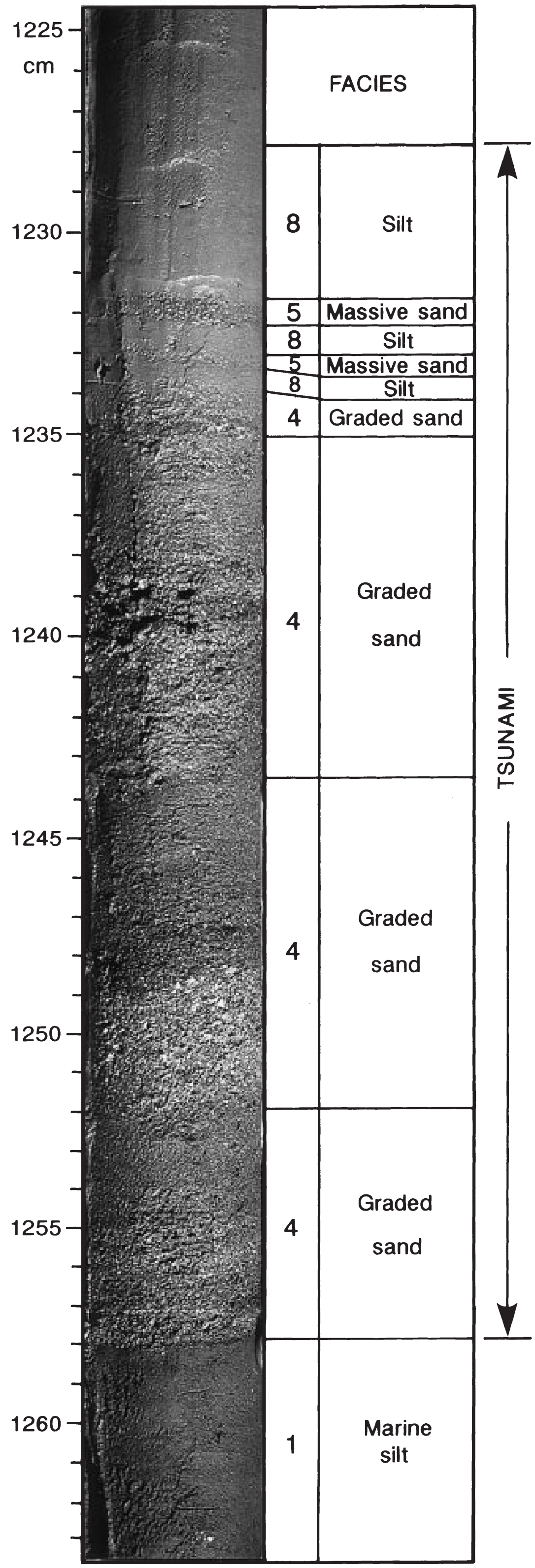


Fig. 5. Photo of the group B facies (tsunami facies) at core site 6 in Audalsvatnet (for location see Fig. 2) where six sand beds were identified. The sand beds thin upwards into laminae with silt in between.

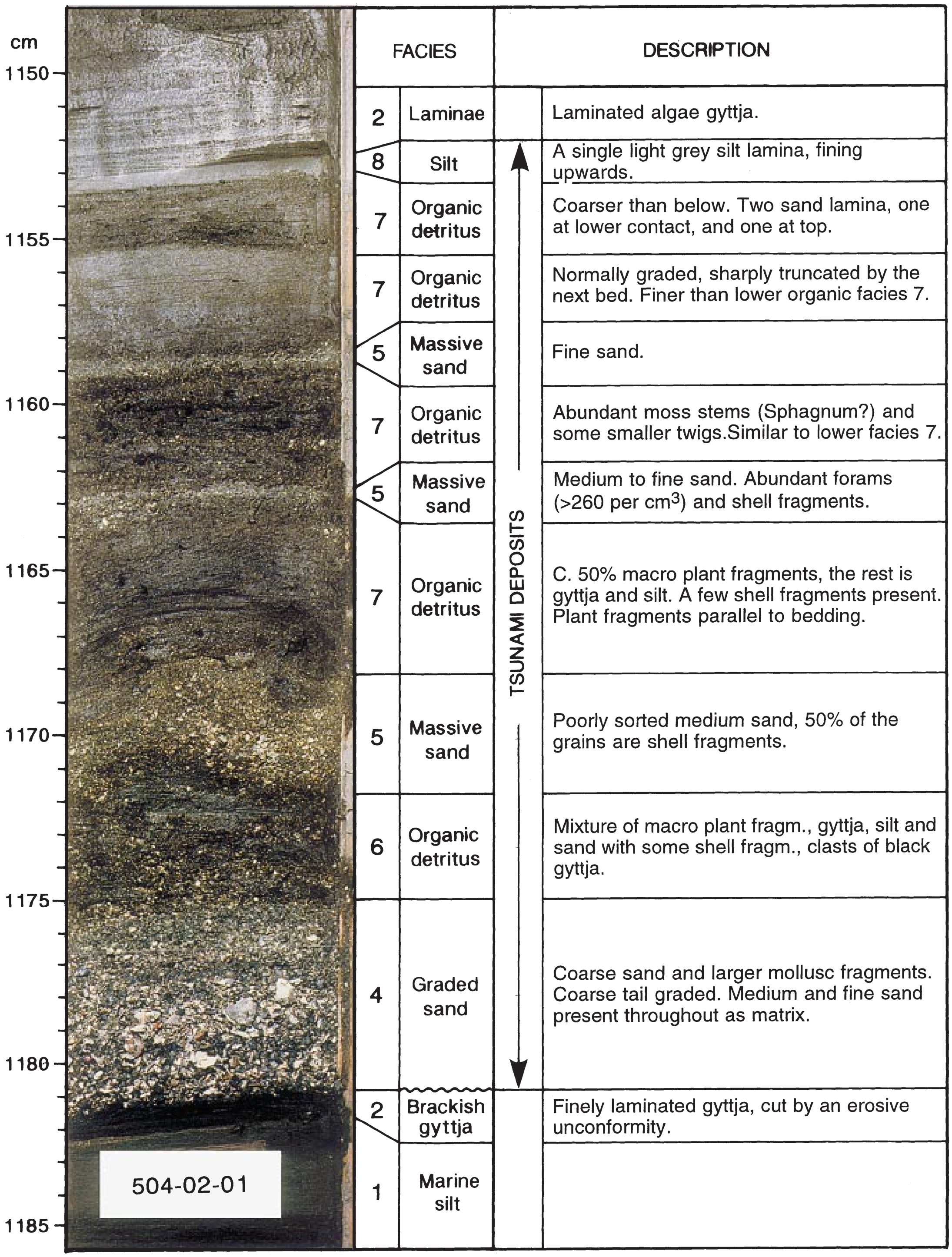


Fig. 6. The group B facies (tsunami facies) in core 504–02–01 in Kvennavatnet (for location see Fig. 2) consists of alternating sand and organic beds. On top a light grey suspension lamina of silt (facies 8) drapes the deposit.

Organic debris (facies 7)

Facies 7 resembles facies 6 and the boundaries between them are transitional. The main differences from facies 6 are the absence of clasts, lower content of sand and finer grained organic particles (plant fragments). The plant fragments are commonly orientated parallel to the bedding, in places giving a weak stratification to the facies

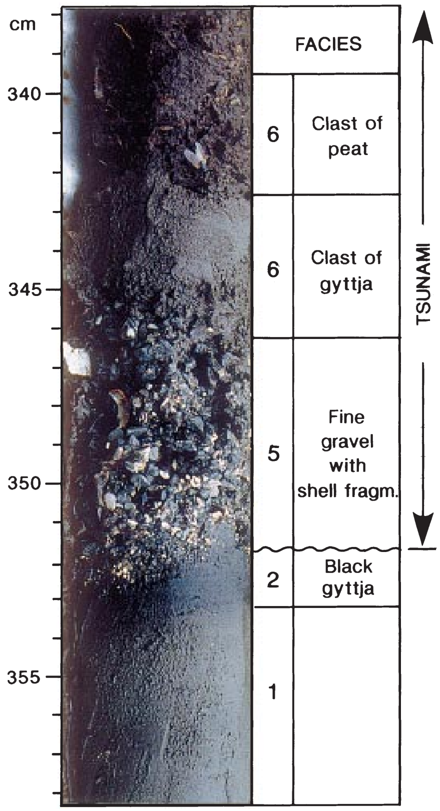


Fig. 7. The lower part of the group B facies (tsunami facies) in Gorrtjønna I close to the outlet (encircled core Fig. 9). At least 30 cm of lacustrine gyttja were eroded and facies 5, a fine gravel with abundant shell fragments, rests on the brackish-water gyttja (facies 2). Above facies 5, clasts respectively of peat and gyttja are seen (facies 6).

(Fig. 4). Facies 7 is typically graded, especially if it occurs near the top of group B, which it commonly does. In the upper part of facies 7, plant fragments >2 mm may be absent and the sediment is a coarse detritus gyttja with silt and fine sand.

Light grey silt (facies 8)

This facies is present either as a distinct lamina between 2 and 5 mm thick, or as a bed. In both cases the unit fines upwards. If present, it occurs on top of facies 5 or 7, and marks the top of group B (Figs 5 and 6).

Fine laminae in lacustrine gyttja (facies 9)

In some of the basins we have seen a few laminae in the lacustrine gyttja on top of group B. They are about 1–2 mm thick.

Description of group B facies in three basins at Bjugn

Audalsvatnet (2–3 m below the tsunami sea level)

Audalsvatnet (-vatn means lake) is about 500 m long and between 100 and 150 m wide with an outlet brook across a bedrock threshold at 33·5 m a.s.l. at the northern end. The water depth is on average 10 m and nine core sites were studied in the lake (Fig. 2).

The lake emerged from the sea 6000–6500 years BP (Kjemperud, 1982). A sequence with a transition from marine (facies 1) via brackish (facies 2) to lacustrine (facies 3) sediments is found. Within the marine facies (organic silt), 70–90 cm below the brackish facies, there is a distinct sequence of group B facies, 20–30 cm thick in the central part of the basin (Fig. 8). At core sites 5, 6 & 7 (Fig. 2) six separate sand beds are present, most of them graded (Fig. 5). About half of the sand grains are shell fragments. Between some of the beds a distinct erosion surface is evident. Close to the outlet the sand could not be penetrated (core sites 2 & 3) and at core site 9 (Fig. 2) the corer stopped in a loosely packed, fine gravel of shell fragments. Here, facies 4 is more than 35 cm thick.

The sand beds get finer and decrease in thickness upwards, from *c.* 10 cm (medium sand) in the lower part to 0·5 cm (fine and very fine sand) in the upper part (Fig. 5). The upper sand laminae are separated by silt, facies 8. Some of the sand beds contain plant fragments, including many moss stems (Fig. 5). One silt clast was also found in the sand. The sand sequence (facies 4 and 5) is overlain by 10–15 cm of silt of facies 8. This bed gets more fine-grained and organic-rich upwards, and grades into the marine facies across a boundary of *c.* 5 cm (Fig. 8).

Kvennavatnet (1–2 m above the tsunami sea level)

Kvennavatnet, about 450 m long and 200 m wide, has a bedrock threshold at its northern end at 37 m a.s.l. The core sites are located near the middle of the lake (Fig. 2).

Laminated gyttja (facies 2) is found both below and above the tsunami deposits (Fig. 6). Below the tsunami deposits facies 2 contains brackish-water species, whereas above, facies 2 is dominated by freshwater species, indicating that Kvennavatnet had just emerged above sea level at tsunami time, 7000–7200 years BP. All cores

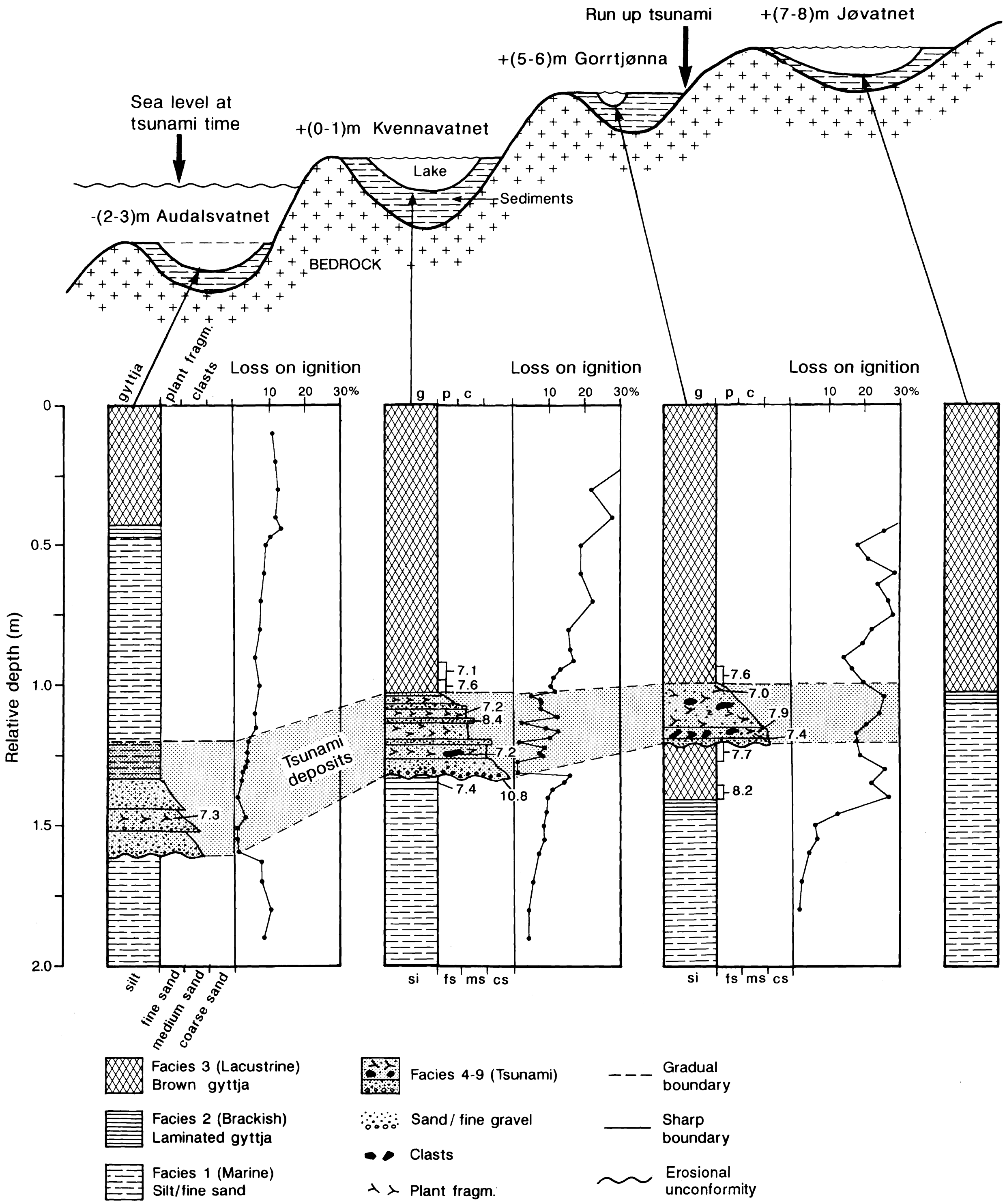


Fig. 8. The upper part shows a simplified cross-section of lake basins at Bjugn (Fig. 2) in relation to the sea level at tsunami time. Beneath each basin a core log and corresponding loss on ignition curve is shown. For the organic-rich facies the horizontal axis on top of the core is used to indicate grain sizes of plant fragments and clasts. The horizontal axis at the bottom is used for minerogenic facies. In Audalsvatnet the tsunami deposit is found in marine sediments, in Kvennavatnet in brackish sediments, and in Gorrtjønna I in lacustrine sediments. For location of cores: Audalsvatnet and Kvennavatnet, encircled crosses in Fig. 2; Gorrtjønna, encircled cross close to inlet, Fig. 9. Radiocarbon ages in thousands years BP are shown.

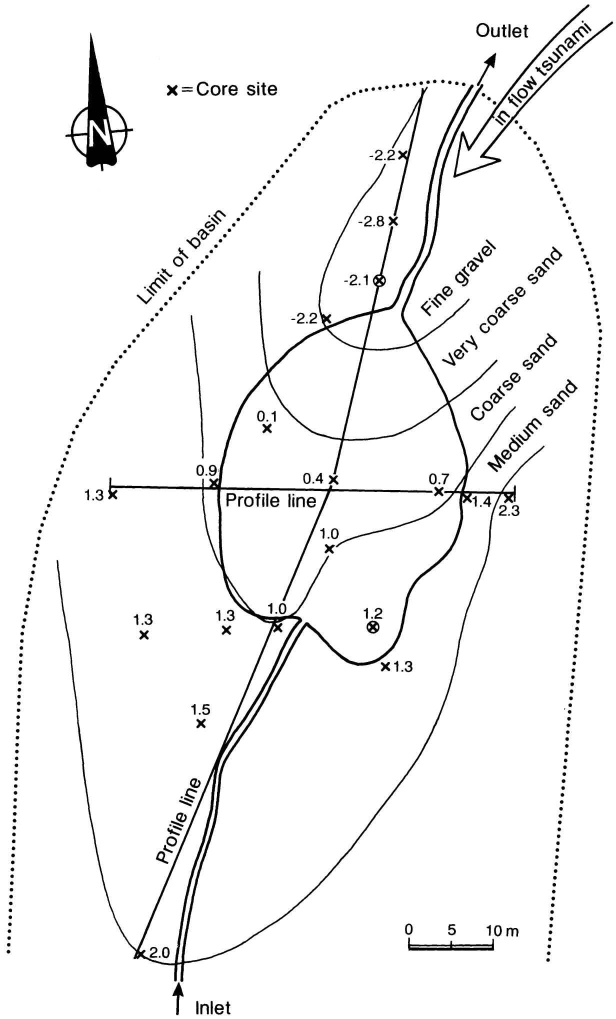


Fig. 9. Mean grain size distribution of the sand bed (in phi units) in Gorrtjønna I. The distribution pattern is inferred to reflect the inflow of the tsunami into the basin. The profile lines show the location of the cross sections in Fig. 10. The area between the lake (heavy line) and the limit of the basin was formerly part of the lake, but is presently a bog. Encircled cross close to the outlet locates the core presented in Fig. 7, encircled cross close to the inlet locates the core presented in Fig. 8.

show at least two sand beds (facies 4 and 5) with organic detritus (facies 7) in between. In this basin facies 8, a distinct light grey silt lamina 0·5 cm thick, is consistently found on top of the tsunami facies.

In the central part of the basin, the group B facies are thickest, *c.* 30 cm, and consist of 10 different beds (Fig. 6). There is a general fining upwards, as each subsequent sand bed is finer and thinner than the one below. The group B facies are described in more detail from core 504–02–01 in Fig. 6.

Gorrtjønna I (5–6 m above the tsunami sea level)

Gorrtjønna I is located just above Audalsvatnet (Fig. 2). The outlet of the small lake is across a bedrock threshold that has been artificially lowered by *c.* 1 m. Gorrtjønna I is presently 41 m a.s.l. and more than 20 sites from the basin were cored (Fig. 9).

The basin contains a typical emergence sequence with a gradual transition from marine via brackish to lacustrine sediments (Fig. 8). In the lower part of facies 3 (lacustrine gyttja) there is a well-defined erosional unconformity followed by a complicated pattern of group B facies. The erosional unconformity is easily traced because in places it cuts through both the lacustrine and brackish sediments (Fig. 10).

Across most of the basin a sand bed (facies 5), including shell fragments and foraminifera, rests on the unconformity. The sand is from 1 mm to 3–4 cm thick and is followed by facies 6 and 7. Facies 6 contains many clasts of the underlying brackish water gyttja, peat and lacustrine gyttja. Shell fragments, foraminifera and small bones of a marine fish (*Pollachius virens*) have been found by sieving the lower part of these facies. Facies 7 fines upwards and forms a gradual transition between group B and group A.

Three features in the overall geometry of the group B facies in Gorrtjønna I are important to understand the erosional and depositional process. First, the erosional unconformity at the base cuts deeper into the underlying sediments near the outlet and along the central axis of the basin (Fig. 10). Far from the outlet and towards the edges of the basin, there has been little or no erosion (Fig. 10). Second, the sand resting on the unconformity is thickest and coarsest near the outlet (Fig. 9). Away from the outlet and towards the edges of the basin the sand wedges out to a thin lamina and further out it disappears. Third, the group B facies is thickest in the deepest part of the basin, just inside the threshold.

Facies relationships and depositional mechanism of group B facies

In all basins group B facies rest on an erosional unconformity. In some of the basins the erosion has in places removed more than one metre of sediments, representing 2000–3000 years of accumulation. The erosion was largest near the outlet and diminishes away from the outlet and towards the edges of the basin (Fig. 10). The geometry of

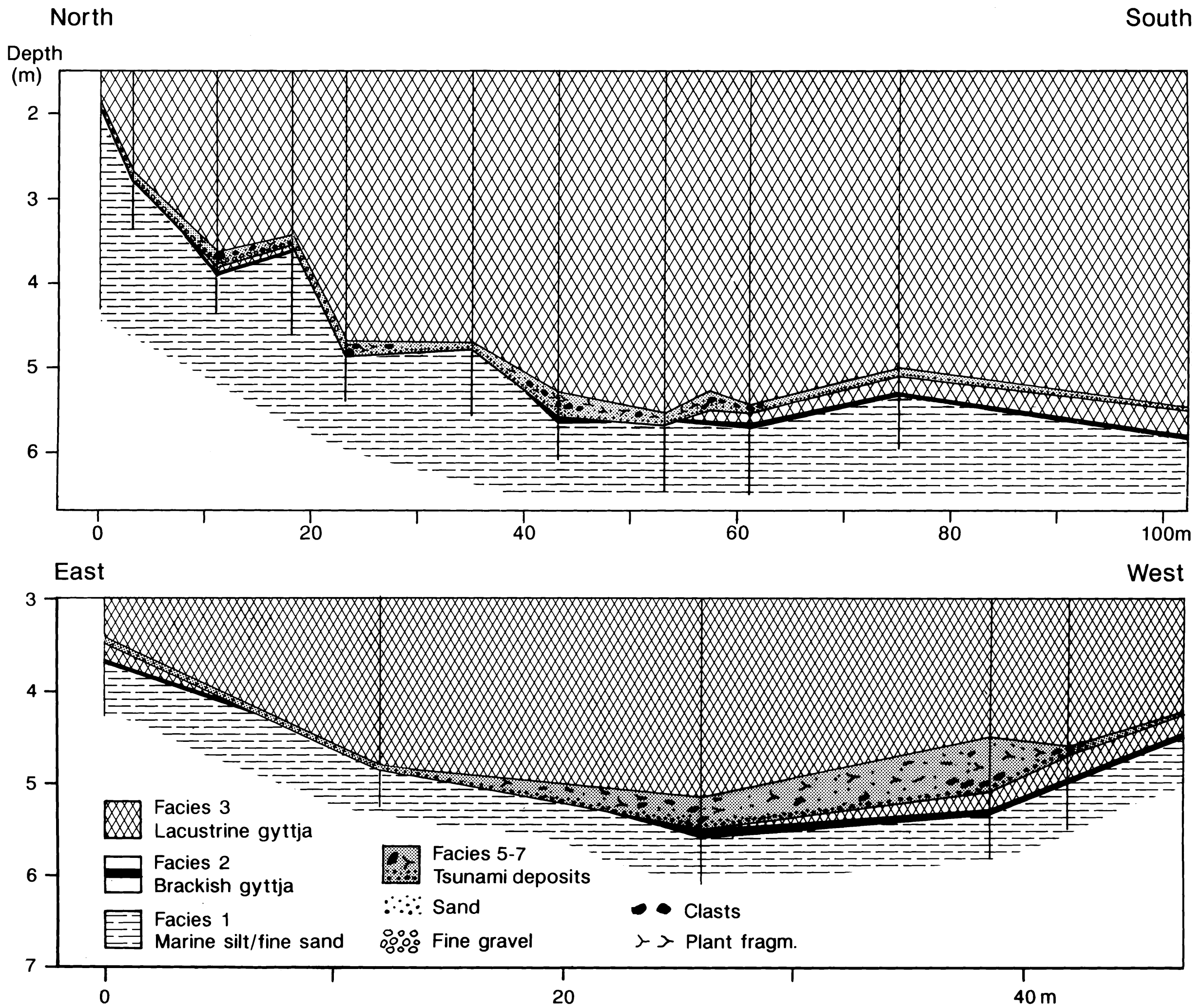


Fig. 10. Lithostratigraphic profiles across Gorrtjønna I (N-S and W-E). The core sites are marked by vertical lines. The erosional unconformity, thickness of the tsunami deposits and grain size diminishes to the south, away from the inflow area of the tsunami. In the southernmost core in the N-S profile, the tsunami deposit is a 2 mm thick lamina of fine sand. Note that the two profiles have different horizontal scales.

the erosional unconformity suggests that prior to deposition of group B facies there was a rapid flow into the basin from the seaward side with high shear velocities along the basin floor.

In all basins a sand bed rests on the erosional unconformity. Commonly this is a normally graded sand bed (facies 4) suggesting rapid deposition from suspension (Collinson & Thompson, 1989), but the basal layer can also be a massive sand to fine gravel (facies 5) including shell fragments (e.g. Gorrtjønna I, see above). The landward thinning and decreasing grain size of the sand (Fig. 9) demonstrates that the sand was deposited from the sea-side of the basin. The numerous marine fossils clearly suggest a marine origin of the sand, also where it is found in the lacustrine sediments.

The large rip-up clasts in facies 6 indicate erosion by a powerful current. Some of the clasts consist of coarse gyttja or peat, likely eroded from the rim of the lake. However, many clasts consist of fragments of deeper water facies from the basin floor, including lacustrine, brackish and even marine facies. The largest clasts are concentrated in the lower part of the group B facies. Facies 6 and 7 consist mainly of terrestrial/lacustrine material, but marine shell fragments and foraminifera may also be present in the lower part of these organic facies.

Basins that are situated more than *c.* 5 m above the 7000 year BP shoreline show a single thin sand bed (facies 5) and a thick bed of facies 6 and 7. Basins closer to, or below the 7000 year BP sea level are characterized by three to six sand beds

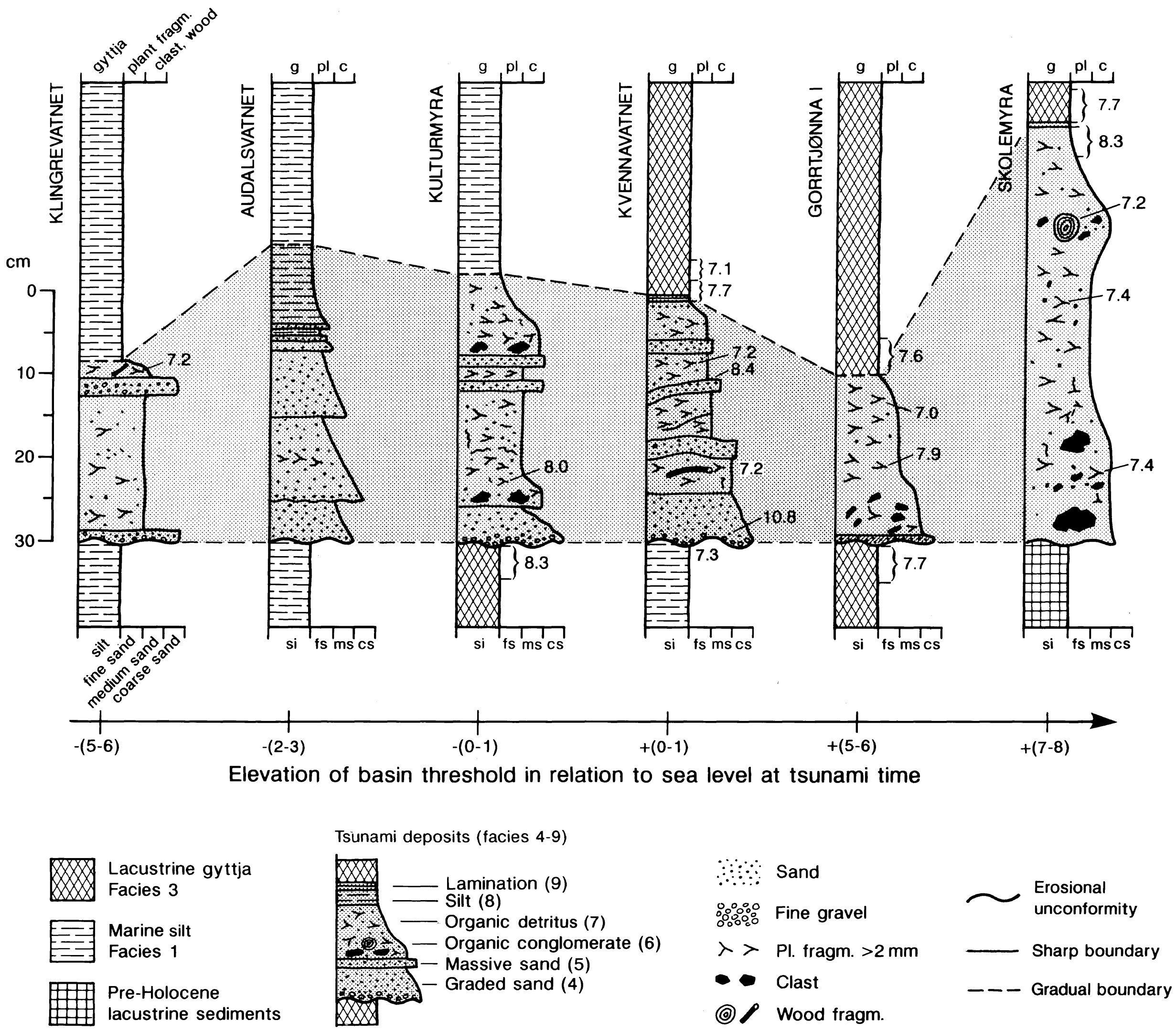


Fig. 11. Graphic logs of tsunami deposits organized from left to right with increasing elevations. Tsunami deposits in higher basins contain less sand and only one sand bed, in contrast to the lower basins where 3–6 sand beds may occur. Radiocarbon ages are shown in 1000 ^{14}C years BP. For the organic-rich facies the axis above the core is used for grain size. The axis below the core is used for minerogenic facies. Klingrevatn is located in Sula and Kulturmyra and Skolemyra in southern Sunnmøre (Fig. 1); the other lakes are at Bjugn (Figs 2 and 8).

separated by facies 6 or 7. This is the main sedimentological difference in group B facies relationships between the higher and lower basins (Fig. 11).

In the lower basins the number of sand beds varies between core sites, likely due to erosion of a subsequent wave. The sequence of alternating sand and organic deposits indicates several pulses of erosion and re-deposition. However, the thickness of each sand bed and the grain size decreases upwards (Fig. 11) indicating that the velocity in each pulse decreased upwards.

In basins above the 7000 year BP shoreline, group B facies ends with the organic detritus facies (facies 7) that grades upwards into normal lacustrine sediments. However, in some basins the contact is sharp and marked by a colour difference and/or distinct laminae. In basins situated below the 7000 year BP shoreline a light grey silt (facies 8) fines upwards into the normal marine facies.

An assemblage of group B facies, that has an erosive base and is interbedded in finer, undisturbed sediments (marine silt or lacustrine gyttja) appears to be the result of a single erosional-depositional event. Radiocarbon dates of the group B facies show that it was deposited at the same time in all basins, around 7000–7200 years BP (Fig. 11), (Bondevik *et al.*, 1997). The alternating sand and organic facies suggests a pattern of episodic deposition. The sand facies 4 and 5 record high energy events and the organic facies 6 and 7 record intervals of deposition from suspension under calmer conditions.

DISCUSSION

We have considered several processes for the formation of the group B facies; flash floods into the basins, slumping within the basins, a normal sea-level rise (transgression), a storm surge or a tsunami.

The overall geometry of the group B facies described above excludes both local slumping from the sides of the basins and flash floods from the watershed. The abundant marine fossils and the geometry of the group B facies points towards a marine-related process. These facies have in fact been observed earlier but were then interpreted as the result of the sea entering basins during a sea-level rise, the Tapes Transgression, that took place between 8000 and 6000 years BP (Kaland, 1984; Aksdal, 1986; Svendsen & Mangerud, 1987). For several reasons we find this interpretation unlikely.

1 The group B facies are found in basins situated well above the maximum level of the transgression (Tapes beach ridge).

2 They are found in Bjugn where this transgression did not occur due to a higher rate of isostatic uplift (Kjemperud, 1986).

3 Group B facies are also intercalated in marine sediments.

4 The sedimentology of the group B facies is totally different from the marine sediments found in basins that were invaded by the Tapes Transgression.

5 If the group B facies was the result of a transgression, a gradual transition from marine via brackish to lacustrine sediments should be expected above the group B facies. Such a transitional zone is not found.

Storm surges generated by wind and atmospheric pressure may give maximum surges of 1–2 m above astronomical tides along the coast of Norway (Gjevik & Røed, 1976). Group B facies are found in basins situated as much as 10–11 m above contemporaneous high tide level. This far exceeds the calculated maximum storm surge amplitude. Storm surges are a high frequency phenomena, but the group B facies apparently represent an event that was likely unique during the entire Holocene in this area.

Known tsunami deposits possess many of the characteristics of the group B facies. Extensive erosion has been reported by eyewitnesses to many recent tsunamis. For instance in Lake Jusan, invaded by a Japan Sea tsunami in 1983, bottom sediments have been eroded to a depth of 30 cm (Minoura & Nakaya, 1991). Rip-up clasts, diagnostic for facies 6, are described from inferred tsunami deposits in shallow marine environments (Bourgeois *et al.*, 1988), in lakes (Kelsey *et al.*, 1995) and in uplifted coastal sequences (Dawson *et al.*, 1993).

The most commonly described tsunami deposit is a sheet of sand. Typically, as in facies 4, it is normally graded and shows a decrease in thickness and grain size landwards (Bourgeois *et al.*, 1988; Minoura & Nakaya, 1991; Atwater & Moore, 1992; Dawson *et al.*, 1993; Kelsey *et al.*, 1995; Minoura *et al.*, 1996). This trend is evident within individual basins (Fig. 9) and from lower to higher elevated basins in our study.

In basins closer to the 7000 year BP sea level, the group B facies consists of alternating sand and organic deposits. Such alternations between finer and coarser grained beds are reported from other studies of tsunami deposits in lake basins (Kelsey *et al.*, 1995), lagoonal sediments (Darienzo & Peterson, 1990) and estuaries (Reinhart & Bourgeois, 1995). In the tsunami deposit reported from Scottish estuaries, several successive normally graded sand beds, interpreted to be deposited by individual waves, are present (Dawson *et al.*, 1991). The same pattern is seen in Audalsvatnet (below the 7000 year BP shoreline); (Fig. 5). In these alternating beds the grain size and the bed thickness decreases upwards (Fig. 11). This general fining of the subsequent beds is also recognized by Darienzo & Peterson (1990).

We conclude that the only process that may have deposited the group B facies is a tsunami. This explains the erosion, marine sediments in basins above contemporaneous sea level, rip-up clasts, deposition from the sea side of the basin, alternation of sand and organic-rich beds, and the similar age of the deposit in all basins.

Erosion and depositional model for a tsunami inundating shallow marine basins and coastal lakes

Studies of recent tsunamis show a complex pattern of erosion and deposition (Yeh *et al.*, 1993; Shi, 1994; Synolakis *et al.*, 1995). Incoming waves may erode and transport material landwards, and the backwash carries material seawards (Minoura & Nakaya, 1991). In some of the basins we have investigated, the tsunami deposits (group B facies) are very complex, and in core holes only a metre apart the tsunami deposit may be markedly different. The reason must be the hydrodynamic response of the tsunami to local variations in bathymetry. Nevertheless, we present a generalized model for tsunamis inundating basins on the sea floor and basins above sea level (lakes) based on the interpretation of the group B facies (Fig. 12).

(a) Before inundation: normal sedimentation

The pre-tsunami reconstruction shows the situation before the tsunami impact; gyttja accumulates in the lake, peat along the rim of the lake, sand and gravel at the beach and marine silt and fine sand in the basin below sea level.

(b & c) Inundation: erosion of sediments and subsequent deposition of sand

When the wave raised above the lake threshold, saline debris-rich water flowed into the lake (Fig. 12b). The velocity increased across the threshold giving turbulence on the lee-side. Sediments on the basin floor were stirred into suspension, and in places ripped up into clasts. Erosion was largest where the tsunami entered.

A graded sand (facies 4), was deposited on the erosive surface (Fig. 12c). The landward thinning and fining demonstrate that the sand was deposited during inflow as the current velocity decreased. The shell fragments and forams show that a lot of sand was eroded at the sea-shore and carried into the lakes. Pieces of wood, plants and peat were eroded from the vegetated surroundings.

(d) Settling

After the traction transported sand was deposited, rip-up clasts, water logged wood fragments, sand and finer organic detritus settled out from suspension (facies 6 and 7); (Fig. 12d). Typically these organic facies are normally graded.

(e) Erosion and redeposition

Erosion and redeposition were also caused by the withdrawal of the tsunami from the basin. However, the velocity was less compared to the inflow phase, and thus erosion was not powerful enough to rework and redistribute all the deposited sediments. Often the estimated volume eroded during stage (b & c) was larger than the volume of the preserved tsunami facies. The reason must be that during withdrawal, the wave carried material out of the basin.

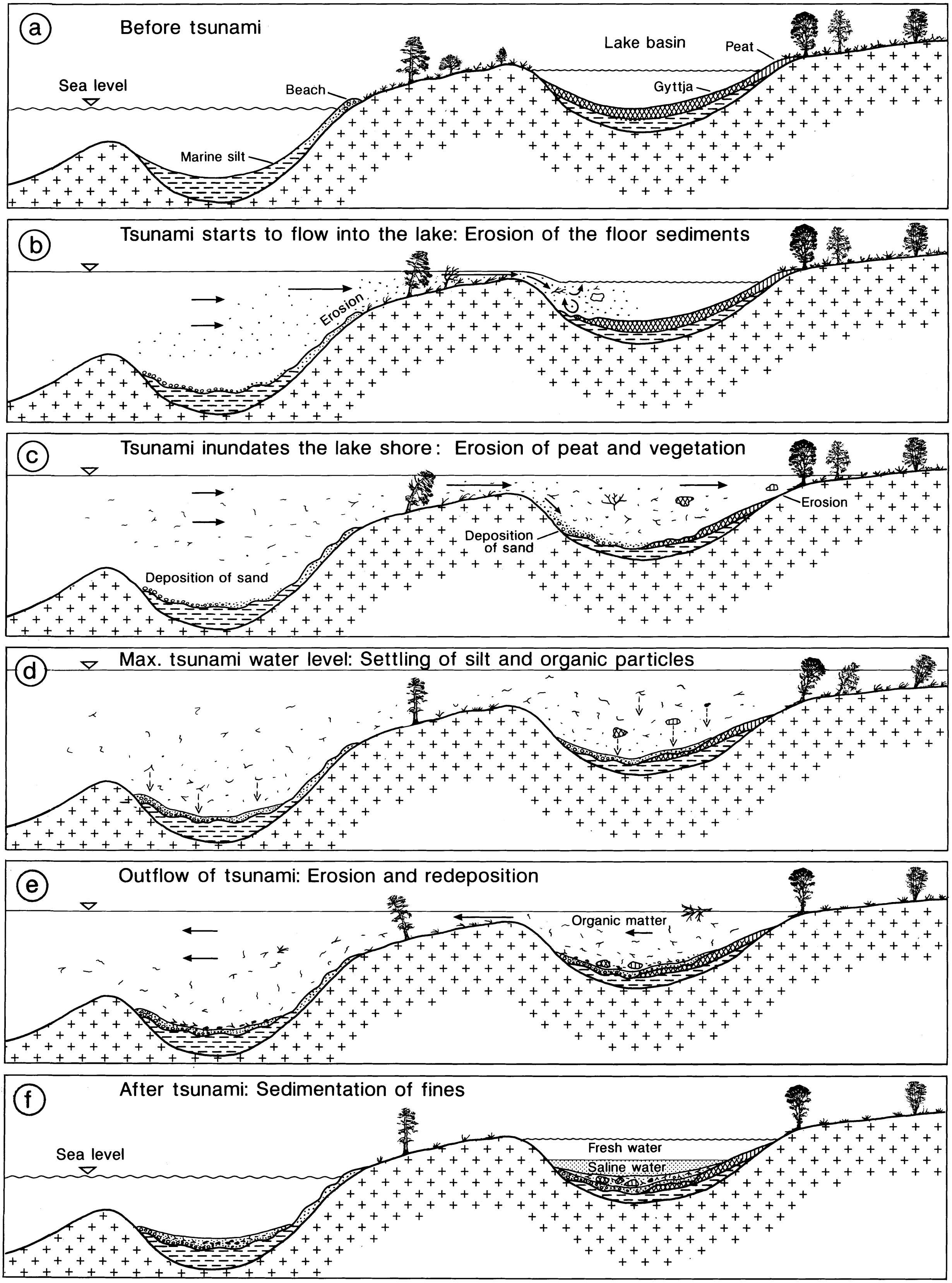
(f) Sedimentation of fines

After the withdrawal of the first wave there was a quiet period when particles in suspension, gyttja, silt and fine sand, were settled. Basins below or just above sea level experienced several waves as shown by the alternating beds of sand and organic facies, and so stages (b) to (e) were repeated. The tsunami unit as a whole fines and thins upwards, indicating that the subsequent waves had decreasing velocities.

After the final withdrawal of the tsunami, fines settled from suspension. In Kvennavatnet, a distinct silt lamina (facies 8) drapes the tsunami deposit (Fig. 6), and in Audalsvatnet (Fig. 5) a thicker silt of facies 8 is present. In shallow basins such a facies is missing, and there is a gradual transition from the organic detritus facies to the normal lacustrine gyttja. The reason is likely that larger and deeper lakes have a larger water column, and thus much more material in suspension.

Radiocarbon ages of the sediments immediately above the tsunami facies are typically older than the youngest dated plant fragments within or underneath the tsunami deposit (Fig. 11), (Bondevik *et al.*, 1997). This suggests that after the tsunami impact there was a period with deposition of 'older' organic-rich matter. This could be due to reworking of tsunami sediments deposited above the lake level or increased erosion around

Fig. 12. Erosion and depositional model for a tsunami inundating a shallow basin on the sea floor and a lake: (a) before tsunami inundation, normal sedimentation; (b) the tsunami inundates and erodes the shore and flows into the lake where it rips up clasts from the lake floor. Sand is deposited in the marine basin (facies 4 & 5); (c) the tsunami inundates and erodes peat and vegetation at the lake shore. Sand brought in by the tsunami is deposited in the lake basin (facies 4 & 5); (d) suspended material such as rip-up clasts, twigs, gyttja, sand and silt settles producing normal graded organic beds (facies 6 followed by facies 7); (e) withdrawal of the wave, erosion and redeposition of the tsunami deposits, organic material carried out of the lake; (f) after the tsunami, deposition of suspended fines in addition to organic matter from reworking of tsunami sediments deposited above the lake. Stage (b)–(e) represents the inundation and withdrawal of one tsunami wave. Basins closer to sea level experienced several waves as is shown by the alternation of sand and organic beds.


a
Before tsunami
Sea level
Beach
Marine silt
Lake basin
Peat
Gyttja
b
Tsunami starts to flow into the lake: Erosion of the floor sediments
Erosion
c
Tsunami inundates the lake shore: Erosion of peat and vegetation
Deposition of sand
Deposition of sand
Erosion
d
Max. tsunami water level: Settling of silt and organic particles
e
Outflow of tsunami: Erosion and redeposition
Organic matter
f
After tsunami: Sedimentation of fines
Sea level
Fresh water
Saline water

the lake margin due to the damage of the vegetation.

Minoura & Nakaya (1991) observed that seawater remained in lagoonal lakes (max 2 m deep) as a bottom layer for over 5 months after the Japan Sea tsunami in 1983. Lakes with saline bottom water commonly have laminated sediments as water stratification favours the development of anoxic bottom waters which hinder bioturbation (Anderson *et al.*, 1985). In four lake basins we have found a few laminae (facies 9) immediately above the tsunami deposits in the deeper parts of the lakes. The laminae might be explained by a prolonged period with saline and anoxic bottom water in the lakes immediately after the tsunami. Diatom analysis shows that the photic zone was fresh water during accumulation of the laminated sediments. The basins where facies 9 has been recognized are characterized by a small drainage area, which would favour trapping of seawater.

CONCLUSIONS

A detailed study of sediments in small lake basins and bogs situated close to the 7000 years BP shoreline along the Norwegian coast, reveals the presence of a distinctive deposit, very different from the sediments above and below. The deposit, classified into six facies, was deposited by a tsunami, most likely triggered by the Second Storegga slide.

The main characteristics of the deposit are:

1 It is underlain by an erosional unconformity with the most extensive erosion at the seaward portion of the lake.
2 A distinctive normally graded or poorly sorted sand to fine gravel overlies the erosive surface. Locally the sand contains shell fragments and foraminifera.
3 The sand is overlain by mixed organic sediments characterized by rip-up clasts of peat, lacustrine gyttja or marine silt in a matrix of redeposited gyttja, plant fragments, silt and sand.
4 In the lower basins (<3 m above sea level) the redeposited organic facies may be interbedded with several sand beds, whereas in the higher basins (6–11 m above sea level) only one sand bed is found.
5 Within each basin, and from lower to higher elevated basins there is a thinning of the sand bed and a decrease in grain size in a landward direction.
6 The sequence generally fines and thins upwards.

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