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Traces of Tsunami Events in off- and on-Shore Environments. Case Studies in the Maldives Scotland and Sweden

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1. Introduction

A tsunami wave is characteristic by its large diameter (up to a couple of kilometres) and high speed of displacement (in the order of 700 km/h). Tsunami waves are generated by submarine earthquakes, by submarine slides and, occasionally, even by meteor impacts. When the wave starts to trim the seabed off a coast, it may rise to considerable heights and break in over the coast with disastrous force. The 1755 Lisbon earthquake and its disastrous tsunami effects are classical. The Boxing Day tsunami in 2004 in the Indian Ocean woke up the world in realizing what terrible effects a tsunami event may cause (NOAA, 2010). The death toll was around 230,000 persons. Suddenly, the word *"tsunami"* became known to a broad audience.

The tsunami hazard of a region can only be assessed in a meaningful way if we have a reasonable record of the past events in that region. Consequently, there is an urgent need of establishing such records; i.e. a database of the paleotsunami events of the region in question (Mörner, 2009a, 2010). This, in its turn, calls for a methodology of how to record past tsunami events. This implies a careful search of imprints left in morphology and stratigraph, and means of interpreting those imprints in terms of a past tsunami event.

This paper is devoted to the traces and imprints left in nature from former tsunami events. We explore such signals in the off-shore sediments as well as in the on-shore deposits left in three different regions from where we have primary studies of our own. Hence, we may be talking about three case studies: the Maldives, Scotland and Sweden. As other tsunami studies are lacking in those areas, this paper tends to become a compilation of our previous work with recent additions.

2. The Maldives

The Maldives are located in the middle of the Indian Ocean. They consist of some 1200 islands arranged in 20 larger atolls. The entire island archipelago rises steeply out of the deep ocean, and is directly surrounded by depths in the order of 2500 m. This implies quite specific conditions at the passing of a tsunami wave; instead of actually breaking in over land, it may rather passes over the low-lying islands (Fig. 1). This was even the case at the 2004 mega-tsunami.

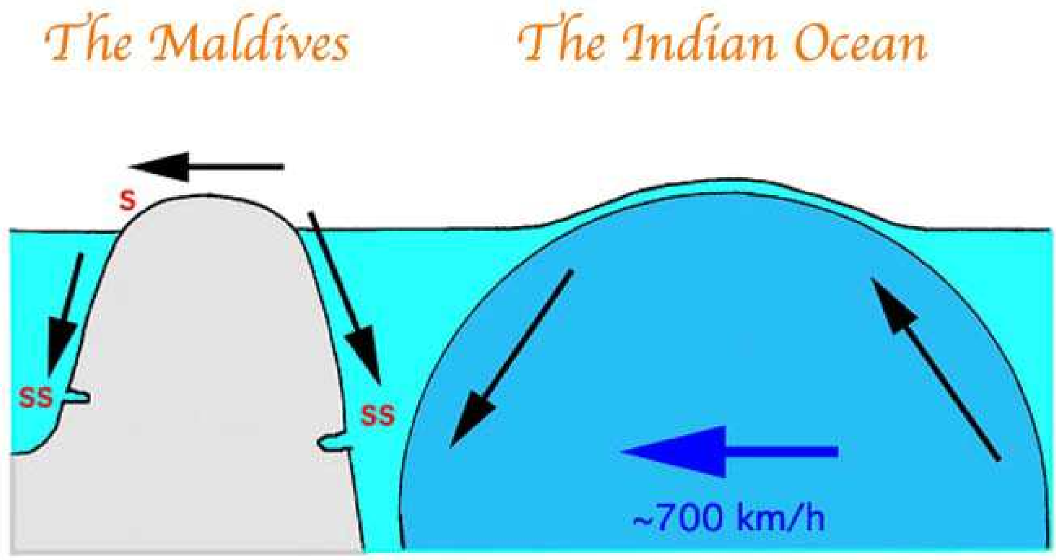

Fig. 1. A tsunami wave is characterized by its exceptional vertical diameter and by its high lateral speed. The December 26, 2004, tsunami began with a withdrawal of coastal water before the main disastrous breaking wave hit the coasts. In the Maldives, rising steeply from the abyssal plain, the wave rather washed over the islands than broke in over them (hence only 19 persons were killed). In the submarine environment, divers reposted the occurrence of "a submarine sandstorm". This gave us the idea that our dated submarine cave-fillings might be remains of submarine sandstorms (ss) from former tsunami events (Mörner et al., 2008)

We worked in the Maldives for several years in association with an international sea level project (Mörner et al., 2004; Mörner, 2007). During those studies we came across imprints of former tsunami events both as a part of our methodical studies (Mörner, 2007) but also as a total surprise (Mörner et al., 2008a).

We visited the Maldives in February 2005 in order to record the traces left after the 2004 event. The washing from east to west over the individual islands was quite clear in morphology (Fig. 2), damages of houses and other constructions, and in the erosion/deposition of sediments (Fig. 3). On the atoll of Goidhoo, we had in two cored swamps (located on opposite sides of the island) recorded a sand layer in the middle of peat deposits. In 2005, we recorded identical signals on top of both swamps. I combination with C14-dates and micropaleontological studies of the cores retrieved, we were now quite sure that we were dealing with a paleo-tsunami record. The top of the peat below the tsunami sand was dated by two C14-dates overlapping at AD 1730-1735.

In order to date former submarine sea level positions, we had sampled submarine cave-fillings and subtracted shallow-water corals and gastropods for C14-dating. This study failed completely with respect to the dating of formed sea level positions. At the 2004 tsunami, divers had reported the observation of what they called *"submarine sandstorms"*. Suddenly our cave dates made sense; instead of referring to former sea level positions, they recorded former tsunami events creating "submarine sandstorms" (Mörner et al., 2008). In the Addu Atoll, there is a cave at –27 m where two C14-dates of gastropods and corals gave ages overlapping at 1735 ±25.

Fig. 2. In lee of the tree, there is a clear ridge left after the 2004 tsunami wave that crossed straight over the island. The material eroded was deposited on the west side of the island (Fig. 3)

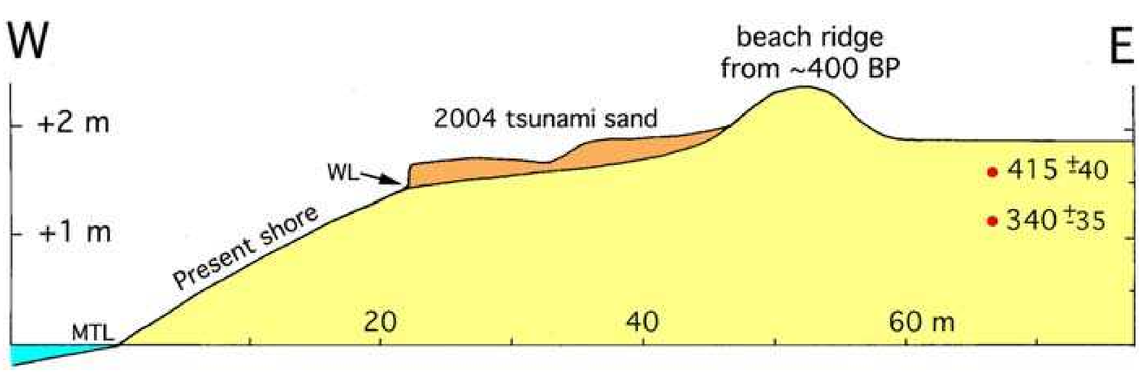

Fig. 3. Profile across the western shore of the island of Gan in the Laamu Atoll. The 2004 tsunami completely over-washed the island, eroding littoral sand from the eastern shore and depositing a 20-30 cm sand layer on the western side graded into two terrace surfaces 1.95 and 1.65 cm above MTL. The present shore has a clear washing limit (WL), an erosion notch, 1.45 cm above mean-tide level (MTL). A sub-recent beach ridge, now over-grown by trees and vegetation, post-dates two radiocarbon dates with a mean of 375 BP or AD 1575. It represents a sea level by about 0.5-0.6 m above the present one

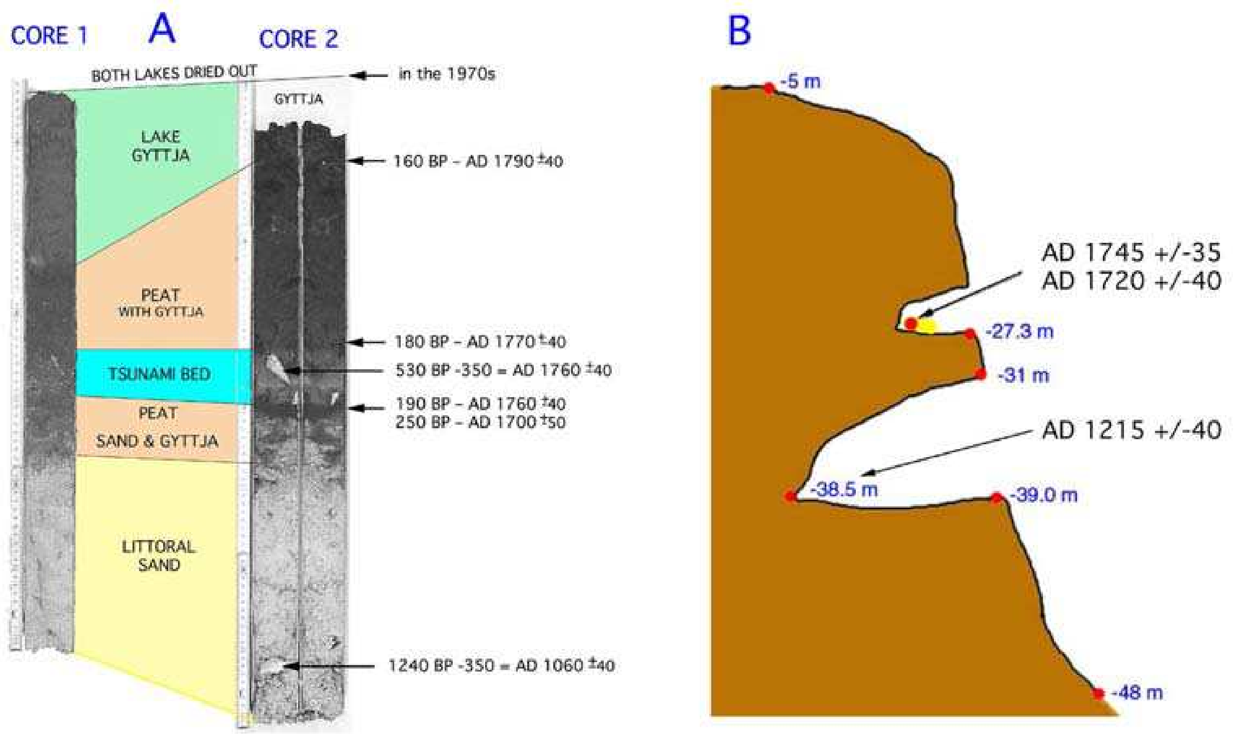

Fig. 4. Evidence of the AD 1733 tsunami. A: the 2 swamp cores on the island of Goidhoo, both recording an intra-peat layer of sand. The overlapping C14-dates give an age of about 1730-1735. B: the caves off Addu with sand fillings containing shallow-water corals and gastropods, which were used for C14-dating. The –27.3 m cave infill gives and overlapping C14-age of about 1735 ±25. The time coincidence between the two sites is striking, and fits perfectly well with the historical notation of a major flooding event in the year 1733. The –38.5 m cave infill gives a C14 age that fits with other records of a tsunami event

Finally, in the chronicle of the Maldives by Bell (1940), there is a record of a disastrous flooding event in AD 1733. The time coincidence with the intra-peat sand on Goidhoo and the submarine sandstorm filling the –27 cave at Addu is striking (Mörner, 2007; Mörner et al., 2008). Hence, we are confident that they are all expressions of one and the same tsunami event occurring in 1733.

Besides the dates, correlations and interpretation in terms of a tsunami event, we established a new methodology of recording past tsunami events; i.e. the recording of "submarine sandstorms" being deposited at great depths in submarine caves (Mörner et al., 2008).

In the Maldives, we have established 5 events of past "submarine sandstorms", viz (1) of modern age (probably 1988 or 1991) in a cave at –21 m, (2) at AD 1733 in the cave at –27 m, (3) at around AD 1550 in a cave at –20 m (with a possible simultaneous on-shore beach ridge in Fig. 3), (4) at around AD 1215 in a cave at –38 m (Fig. 4) probably also recorded by beach ridges on the islands of Viligili and Lhosfushi (where it covered the skeleton of "the reef woman", Mörner, 2007), and (5) at around 6300 BP in a cave at –26 m.

There is also a number of cases of a sudden beach ridge deposition that might – but need not – be understood in terms of a tsunami event (Mörner, 2009a). They occur at 1950 ±10 years, 1115, 850, 530 and 200 ±50 AD. They are still only considered as possible paleotsunami events. At any rate, we have the 2004 event, 5 events of "submarine sandstorms" and related effect, and 5 possible events of a sudden beach ridge formation; i.e. all together 11 events.

This is a good beginning of a long-term tsunami record. The Maldives seem to offer ideal conditions for amplified work and the establishment of a detailed long-term record of tsunami events in the Indian Ocean, which could serve as a base for improved hazard assessments.

3. Scotland

In Scotland, there are clear records of the tsunami event from the huge Storegga submarine slide dated at around 7000 C14-years BP (Dawson et al., 1988; Dawson, 1999). This event is seen as an extensive sand layer in the estuarine mud and clay beds. It is dated by several C14-dates. The characteristics of this tsunami sand layer are its content of planctonic microfossils in contrary to littoral deposits that would have a bentic, shallow-water micro fauna and flora. We use this technique (Dawson, 1999; Dawson & Smith, 2000) in the analyses of the Swedish tsunami beds.

4. Sweden

In recent years (e.g. Mörner 2003, 2004, 2005, 2008a), it has become evident that Sweden, at the time of deglaciation, was a high-seismic region, in magnitudes as well as in frequency. The driving force seems predominantly to have been the extremely high rate of glacial isostatic uplift. Event in the order of M7 have also been recorded in the Late Holocene, however (e.g. Mörner, 2009a), the last one of which occurred at 900 BP, displacing the Viking shoreline by 1 m or more.

Thanks to the Swedish varve chronology (De Geer, 1940), most of the paleoseismic events could be assigned an age with a resolution of one single year; in one case even the season of a year (Mörner, 2003).

In association with those earthquakes, tsunami events have also been recorded. Up to now, a total of 17 events (Table 1) have been documented and described (Mörner, 1996, 1998, 2003, 2008b, 2009a; Mörner et al., 2000). They are traced both in on-shore environment as intra-clay sand-layers containing a planctonic microfossil fauna and flora, and in off-shore environment as extensive turbidites (followed over distances as large as 320 km). A few of those events will be highlighted with respect to their occurrence and characteristics. We have selected the 10,430 BP, 9663 BP, 2900 BP and 2000 BP events for a more extensive analysis.

4.1 The 10,430 BP paleoseismic event

In varve-year 10,740 BP, the Baltic Ice Lake drained (Brunnberg, 1995) and the Baltic became in level with the Atlantic. As ice retreated, a straight opened across southern Sweden (Fig. 5), known as the Närke Straight. The straight remained blocked by pack-ice and icebergs, however, and the conditions in the Baltic remained lacustrine (Mörner, 1995). In the autumn of varve 10,430 BP, the situation changed totally, and the Baltic became brackish-marine within one single year. Something exceptional and revolutionary must have happened. We now know that it was a very large earthquake of a magnitude well above M8 (Mörner, 1996, 2003). The location of the epicentre was in the Stockholm region (Fig. 5) along an old fault that crosses over southern Sweden from the west to the east and probably continues in the Bay of Finland and northeastwards into Russia. Bedrock fracturing is recorded over a zone of 50x200 km. Liquefaction is recorded over a huge area of 200x320 km. Magnetic grain

age *in* BP	*area affected*	*Earthquake magnitude*	*observed tsunami record*
10,400	Kattegatt	at least 8	very high wavy, strong coastal effects
11,600	Kattegatt	at least 7	high wave with significant costal effect
11,200	Kattegatt	about 7	high wave with coastal effects
10,430	Mälardalen Valley	well above 8	very high wave, very strong effect, extensive turbidite
9663	Hälsingland	above 8	at least 15 m high wave, extensive turbidite
9428	Umeå area	at least 7	height unknown
9291	Umeå area	7–8	at least some metres run-up, coastal effects
8600	Södermanland	6–7	probably some 5–10 m wave
7800	Stockholm region	at least above 6	maybe 13 m run-up, extensive turbidite
6100	Hälsingland	around 8.5	at least 10–15 m wave on-shore and -25 m off-shore
4000	Umeå area	6–7	height unknown
4000	Södermanland	around 6	uncertain height, distinct run-up
3200	Södermanland	around 7	local lake tsunami, turbidite over 5.5 km
2900	Northern Uppland	unknown	6 to 20 m run-up, -20 m off-shore
2000	Hälsingland	explosive gas venting	at least 20 m wave height
1600	South Kattegatt	unknown	some metres run-up
900	South Kattegatt	around 7	height unknown, sudden silting over of 2 Viking ships

Table 1. Tsunami events recorded in Sweden, all in association with paleoseismic events

rotation is recorded over an immense area of 500x600 km (Mörner & Sun, 2008). A turbidite (seismite) was deposited in the autumn of varve 10,430 BP over a distance of 320 km. No doubts, this must have been a very large earthquake (Mörner, 2003, 2011).

Obviously, a major tsunami was set up by this earthquake (Mörner, 1995, 1996, 1998, 2003, 2008a, 2011). The tsunami broke into the Närke Straight and washed it free of ice-bergs and pack-ice so that the Atlantic water could enter the Baltic turning it into a marine basin; the Yoldia Sea *sensu structo* (Mörner, 1995). The tsunami wave also broke in over land and invaded separate lake basins. Nine sites are recorded spread over a distance from the epicentre of 320 km to the W and 400 km to the SW (Mörner, 2003, 2008b). The earthquake and tsunami occurred in the autumn of varve 10,430 BP, as evidenced from three independent varved clay sections located 76 km apart (Mörner, 2003, 2011, Fig. 14).

The 10,430 BP varve constitutes a true "marker varve" that stands out in the stratigraphical records. This was first noted by De Geer (e.g. 1940), and he let it be the marker of the sudden drainage of the Baltic Ice Lake and the onset of the Yoldia Sea stage. We now know that this drainage occurred some 300 years earlier, however. This left the sudden change from freshwater to marine-brackish environment unexplained. Mörner (1980) noted that the

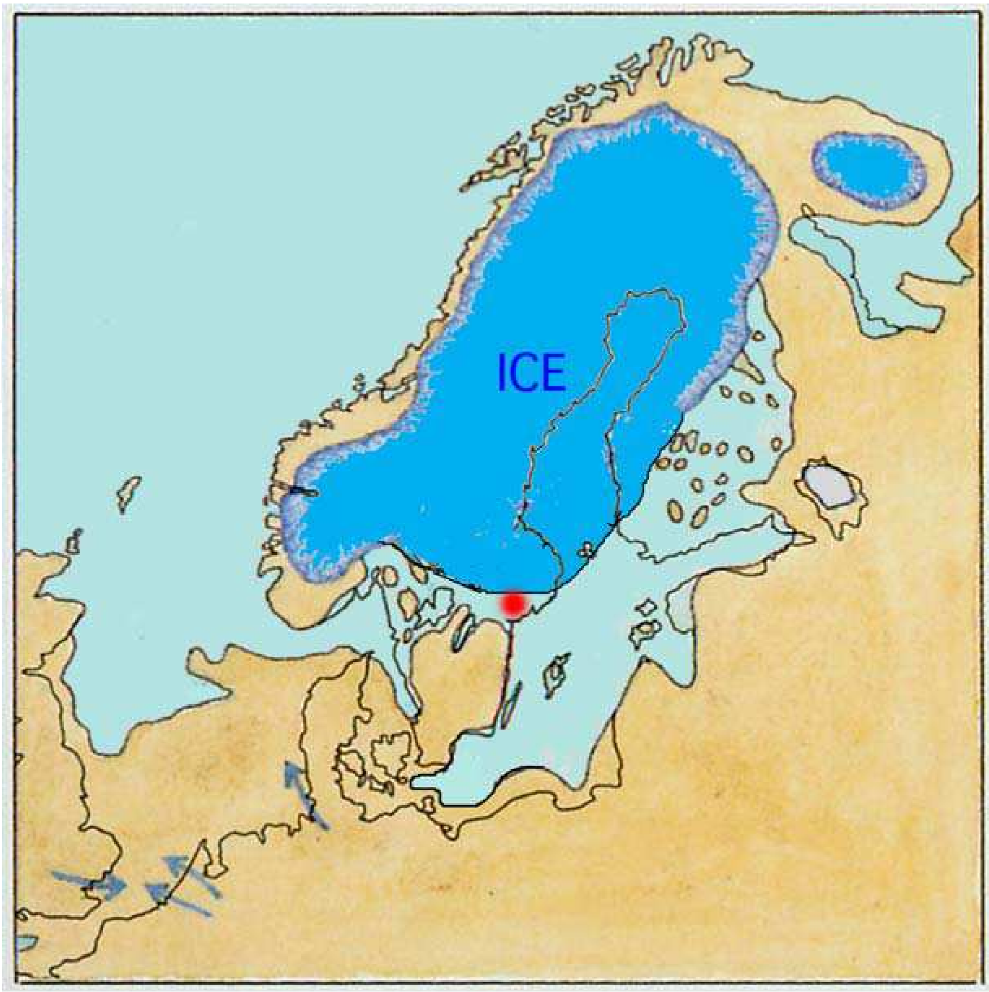

Fig. 5. Paleogeography of NW Europe at the time of the huge 10,430 BP paleoseismic event: ice cap (blue), sea (light blue), land (brown) and earthquake epicentre (red dot). The Baltic was on a level with the Atlantic via the Närke Straight, which remained blocked by pack-ice and icebergs up to the earthquake event. The 10,430 BP tsunami washed the straight free of ice allowing marine water to enter the Baltic and turn it, within 1 varve, into a brackish-marine basin; the Yoldia Sea *sensu stricto* (Mörner, 1995)

10,430 BP varve had special characteristics suggesting that it, in fact, was a seismite; i.e. formed as a consequence of an earthquake. In 1995, we found conclusive field evidence to assign it a paleoseismic origin and an age of "the autumn of varve 10,430 BP" (Mörner, 1995, 1996, 1998, 2003, 2008a, 2011; Mörner & Tröften, 1993; Tröften, 1997; Tröften & Mörner, 1997). At the time of the earthquake, the water depth was in the order of 150 m (above the assumed epicentre) implying that we may be dealing with a tsunami wave with a diameter of about 150 m. When this wave, at a high speed, moved laterally and the water-depth became shallower, it started to trim the sediment surface of the seabed (Fig. 6). This bottom erosion generated local slides, extensive turbiditic bed-loads and huge "clouds" of suspended matter (clay and silt). At many sites, we record anomalously thick varves of silt, sand and gravel that sometimes even include eroded "clay pebbles". They are easily identifiable as they stick out of the normal records (Fig. 7). They are identified over an area of 200x320 km. At other sites, we record exceptionally thick clay varves (from the setting of suspended clay particles).

The marker varve of 10,430 BP has been identified in numerous sites. It is always found at the same chronological level; varve 10,430 BP. In three sites, it has even been pinpointed at the autumn of this varve. The mechanism for its formation is proposed in Fig. 6. It should be noted that this varve year also marks the change from lacustrine to brackish-marine environment (Mörner, 1995, 2003).

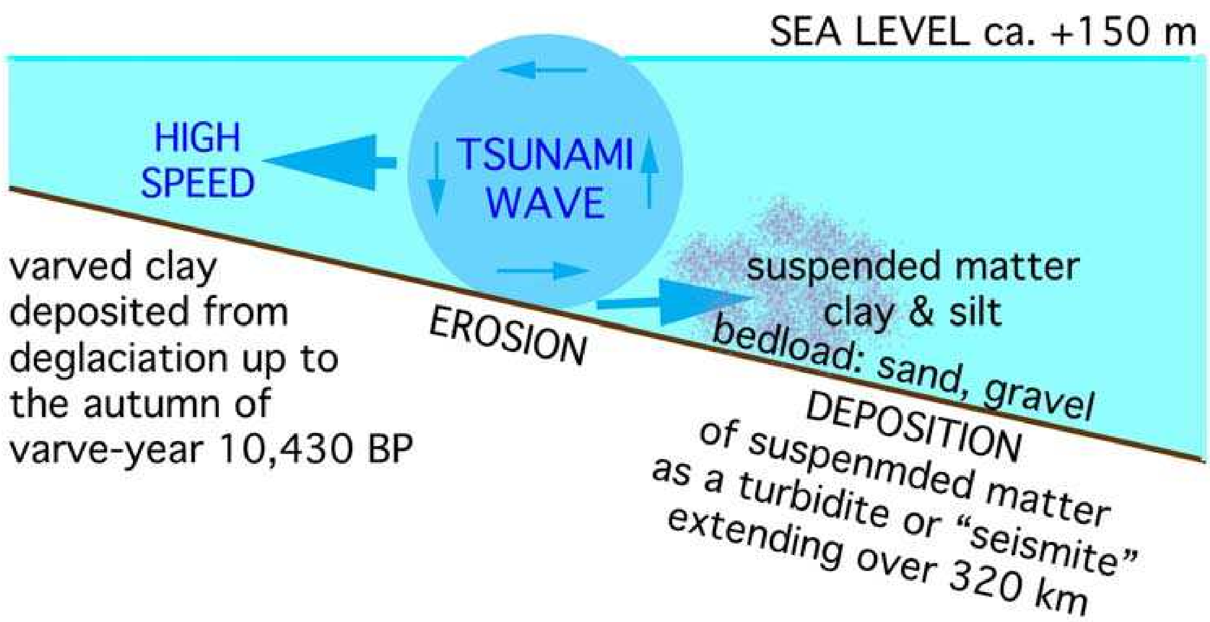

Fig. 6. In the autumn of varve 10,430 BP, a major tsunami wave rapidly moved laterally from the epicentre (primarily documented in western and southwestern directions). The diameter may have been in the order of 150 m. When the rotating wave hit the seabed, it generated erosion that set up both a bed-load of silty-sandy-gravely grains and a suspension of clay and fine silt. Sediments were also set in motion by the ground shaking. All together, it generated the deposition of a turbidite (seismite) over a very large area, viz. 200x320 km

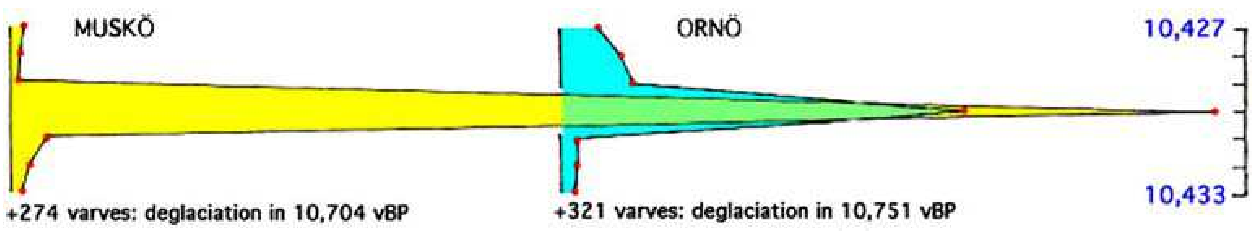

Fig. 7. The turbidite of the 10,430 vBP event as recorded by two sites south of Stockholm. After 274 and 321 normal varves, respectively, there is a very thick layer in the same varve in both sites located 20 km apart; viz. thick sandy-silty layers with incorporated pieces of contorted clay and clay pebbles, i.e. evidence of a massive turbidite flow. This turbidite (marker varve) is found over a wide area of 200x320 km

4.2 The 9663 BP paleoseismic event

In the Hudiksvall area of central Sweden, there occurred a very large earthquake in the varve-year 9663 BP (Mörner et al., 2000; Mörner, 1998, 2003, 2008a, 2011). The paleogeography of this event is very well known (Fig. 8; Mörner, 2003). Sea level was in the order of +231-236 m, and only minor islands stack out of the sea in front of the ice margin. The primary fault was along a sheer zone. A considerable up-thrusting is recorded. The water depth at the epicentre is likely to have been in the order of 250 m (allowing for a tsunami wave with the same diameter). Bedrock fracturing is recorded in some 100 sites over an area of 50x50 km. Liquefaction is recorded at 12 separate sites covering an area of 80x40 km. The liquefaction event is directly tied to varve 9663 BP.

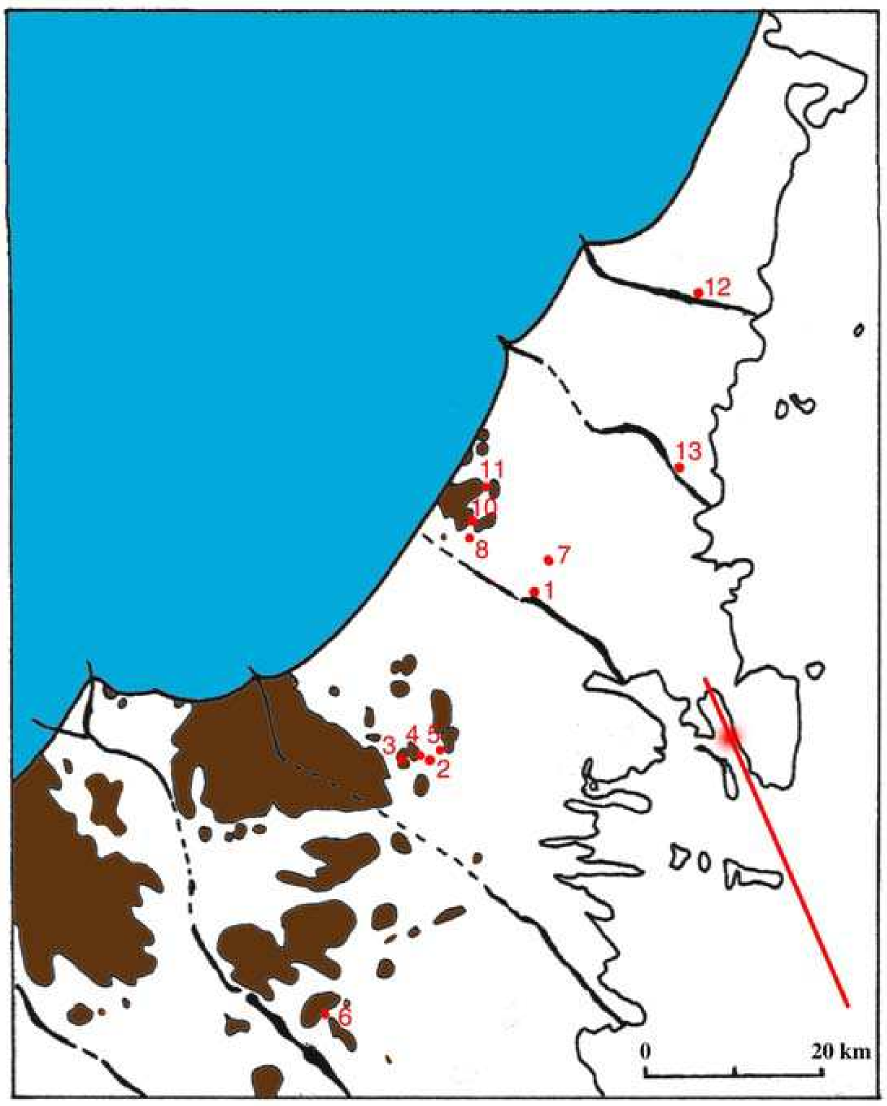

Fig. 8. Paleogeography of the Hudiksvall region at the time of the 9663 BP paleoseismic event: ice cover (blue), land (brown), sea (white) and primary fault with epicentre (red). Sea level was in the order of +231-236 m (with a NW-SE tilt). Tsunami beds were recorded at 13 sites (red dots and numbers). A related turbidite layer is recorded and dated in 27 additional sites within the region, and in numerous sites all the way down to Uppsala (Fig. 11)

The earthquake, which must have been in the order of M8 (or even above), also set up a tsunami wave. It is recorded at 13 different sites, including 9 lakes where a total of 44 cores were taken. It is dated both by varves (at 9663 varve-years BP) and by radiocarbon (at about 9150 C14-years BP). In the lakes, the tsunami event is recorded as a sand layer of graded bedding (fining upwards). The microfossil content of those sand layers is characterized by a planctonic Lake Ancylus fauna and flora (i.e. the same criteria as used in Scotland by Dawson, 1999). The investigation is closely described in Mörner (2003). We will here discuss two sites of methodological interest.

Lake Svartsjön has a present elevation of +223.4 m. The highest Baltic level (BL) is closely determined at +231.3 m and the level at the tsunami event (TL) is determined at +223.5 m. This means that Lake Svartsjön was close to sea level at the time of the tsunami (that is the western side). To the east, facing the open Baltic, there was a 10 m high sill, however. We have 15 cores from this lake basin. In varve-year 9663 BP (and at about 9150 C14-years BP), a tsunami wave broke over the sill in the east and deposited a graded on-swash bed (fading from east to west). It was followed by a graded back-swash bed deposited from west to east. This is illustrated in Fig. 9. The diatom content of the tsunami sand contains planctonic deep-water species from the open Lake Ancylus basin (*Aulacosira islandica, Aulacosira ambigua, Alacosira italica, Aulacosira arenaria, Gyrosigma attenuatum, Fragilaria construens*, etc.). This implies the same tsunami bed characteristics as recorded in Scotland (Dawson, 1999; Dawson & Smith, 2000). We believe that this is a good methodology of identifying tsunami beds, and discriminate them from littoral beds.

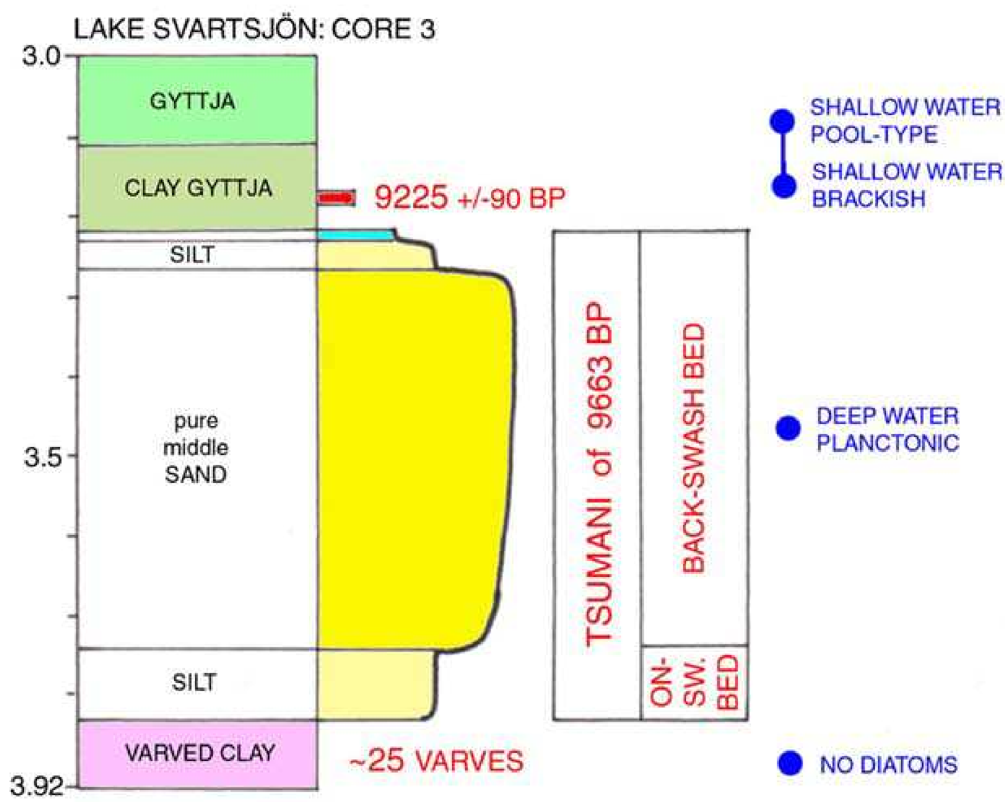

Fig. 9. Lake Svartsjön is densely cored. In 9663 BP, a tsunami wave broke over the 10 m sill in the east and deposited down-washed material (wedging out from east to west). It was followed by a back-swash wave that deposited a graded sand-bed wedging out from west to east. The tsunami bed is characterized by a planctonic deep-water diatom flora from the open Baltic basin (the Lake Ancylus stage)

Lake Källsjön is located above the highest coastline and has had no open connection with the Baltic. It has a present level of +232 m but a former damming sill seems to have had an elevation of about +236 m. The highest Baltic level (BL) is determined at +231,3 m. The shoreline at the tsunami event (TL) was at +223.5 m. The situation is illustrated in Fig. 10. The lakebed was cored at 3 sites (5 cores), and a graded tsunami sand-bed was recorded in all cores. Its fining-upward bedding is consisting with a tsunami wave ingression. The very evidence of a tsunami comes from the microfossil content of the sand-bed, which records a planctonic diatom flora of the Baltic Lake Ancylus stage with species like *Aulacosira islandica, Gyrosigma attenuatum, Aulacosira ambigua, Aulacosira italica, Aulacosira distans* and *Gomphonema angustatum*. To enter the lake, the tsunami wave must have crossed a 700 m long land area at a height of 12.5 m above the tsunami shore level (Mörner, 2003, 2011). In this lake (contrary to other lakes in the area), there occur a small fish *Osmerus eperlanus* (smelt), which is likely to be a relict from the Ancylus Lake. It can only have arrived into this lake basin via the 9663 BP tsunami event. This tsunami may even be recorded in sites 300 km to the south (Mörner, 2003).

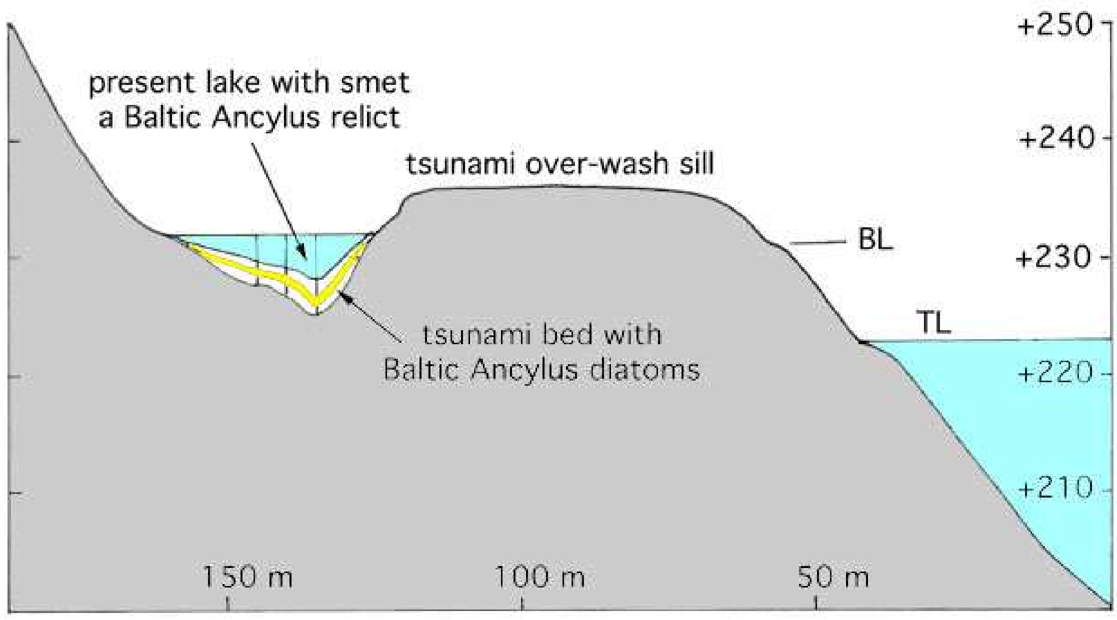

Fig. 10. The situation at Lake Källsjön (+232 m). This lake was located above the highest Baltic level (BL at +131,3 m). The sill in-between had an original level of about +236 m. At the time of the 9663 BP tsunami, the Baltic level was at +223,5 m (TL). In the lakebed, there is a sandy tsunami bed (in fining-upward sequence) that contains a Baltic Lake Ancylus diatom flora. In order to enter the lake basin, the tsunami wave must have been more the 12,5 m high and to have over-wasted a sill at +236 m for about 700 m. Therefore, the tsunami wave is likely to have been, at least, 15 m high. In today's lake, a small fish, smelt, is living, which is likely to be a relict from the Lake Ancylus water, washed into the lake by the tsunami wave

The 9663 BP tsunami left extensive records in the offshore environment, too. It is recorded (and dated) as a turbidite (seismite) within 27 varve records in near-field area. In total, it is recorded in numerous varved clay records extending from Sundsvall in the north to Uppsala in the south; that is over 320 km along the coast (Fig. 11). This layer cannot be a strict density-driven turbidite. Obviously, we are dealing with a seismite strongly affected by the bottom effect of the tsunami wave as illustrated in Fig. 6 (above).

A secondary effect recorded and dated thanks to the varve chronology, is the seepage of methane gas through the clay up to varve 9663 BP where it ends (Mörner, 2003). This is understood as an earthquake effect triggering methane ice stored in the bedrock to transfer to methane gas that tried to seep through the seabed at the time of the earthquake (i.e. varve 9663 BP). This methane gas venting was, at some sites, explosive, which must have added to the bed-load and turbidite formation (Fig. 11).

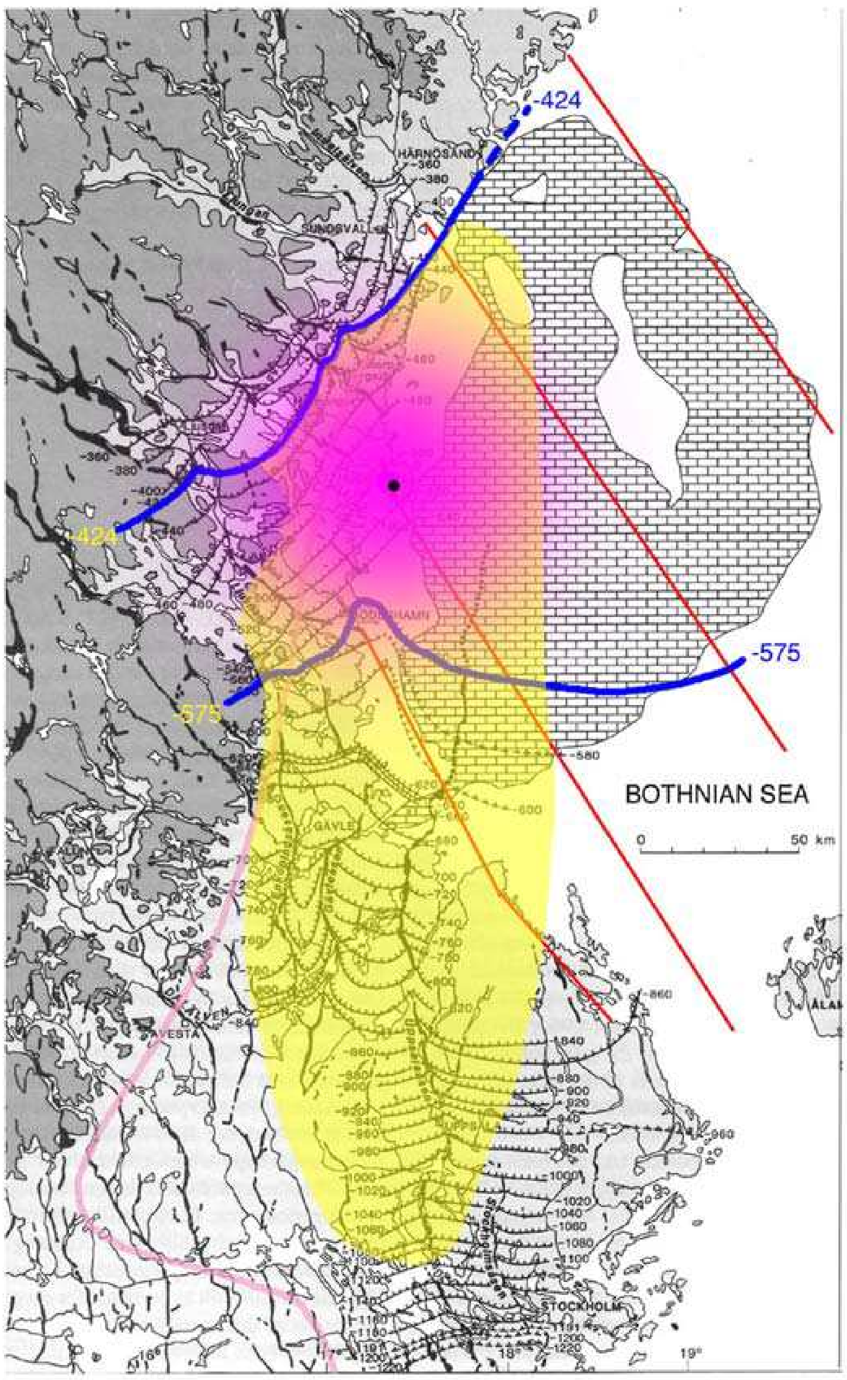

Fig. 11. At the 9663 BP earthquake, a turbidite (seismite) was spread over the seabed for a distance of at least 320x100 km (yellow zone). The ice margin is marked by a blue line with figure –424. The epicentre is marked in purple along the fault zone in red. This extensive turbidite must have been formed by interacting forces setting sediments in motion along the seabed; viz. ground shaking, tsunami wave trimming (Fig. 6) and gas venting

4.3 The 2900 BP tsunami event

The coastal area of northern Uppland is traversed by the Singö Fault zone. This zone seems to have been reactivated during the deglaciation phase some 10,000 years ago (Mörner, 2003, 2004). A Late Holocene tsunami event has been described from the same area (Mörner, 2008b, 2009b). The age is 2900 BP. The event is only recorded in lakes and bogs. No simultaneous faulting is recorded. We suspect, however, that it is another reactivation event of the Singö Fault zone.

A tsunami bed was recorded in offshore sediments, in shore-zone sediments and in lake and bog sediments; all together ranging in elevations from 20 m below to 20 m above (or, at least, 6 m above) the corresponding sea level (Fig. 12). We followed the tsunami beds from offshore basins (15 to 35 cm sand and gravel in graded bedding), via lagoonal basins (with 70 cm sandy beds at the clay/gyttja interface) up into lake basins above the corresponding shore (40–50 cm sandy-gravelly beds erosively deposited between the marine clay and lacustrine lake gyttja). Six C14-dates provide a close age of the offshore and lagoonal sites and a strong erosive effect in the lake basins at least up to a level 5 m above the corresponding shore as illustrated in Fig. 12. The data record a vertical spread of the tsunami beds from –20 m to +6 m. The lake and bog coring suggests that the tsunami may have had a run-up of 20 m. This is not yet supported by dates; only a 6 m run-up (Fig. 12).

The recording of tsunami beds in offshore environment is important. Ordinary waves have been shown only to leave sedimentary signals down to a depth of maximum 10 m. All the 3 beds recorded in offshore environment have identical C14-ages that differ significantly from the ages of the isolations of the lake basins (Fig. 12). This fits perfectly well with an interpretation in terms of a tsunami event, but is totally inconsistent with a normal uplift history. The on-shore run-up might be in the order of 20 m, judging from field observations. This has not yet been confirmed by C14-dates, however.

4.4 The 2000 BP explosive gas venting event

An event of violent methane venting was recorded north of Hudiksvall (Mörner, 2003, 2009b). It occurred at about 2000 C14-years BP when local sea level was at about +18 m. It set up a tsunami wave of significant height. Five bogs ranging from +8 m to +38 m were investigated by coring (Fig. 13). The +38 m record is especially interesting. The basin was isolated from the Baltic (due to uplift) some 4000 BP. Above the isolation level and between a freshwater gyttja and a covering peat, there is a 2.65 m thick bed of gravel with numerous shells of Baltic brackish-water origin. This implies a tsunami wave that reached, at least, from +18 m to +38 m; i.e. having a run-up of 20 m or more. Consequently, this was a very strong event. Tsunami beds were also recorded in basins located at +23, +18 and +14 m. A core taken at +8 m recorded, at the 2000 BP level, a black layer of FeS-rich clay (i.e. strongly reducing environment interpreted as a result of the methane venting), which rested on older deposits with a significant erosion contact (i.e. a hiatus of about 7000 years).

Lake Dellen is a large lake located 25 km to the west. Today it has a level of +37 m. A peat layer found 3 m below the present water level indicates that the lake must once have had a level, at least below +34 m. Because the peat is C14-dated at about 2000 BP, the rise in water level seems coincidental with the tsunami event recorded further to the east. Therefore, it seems likely that also the Lake Dellen pounding was an effect of this tsunami event (Fig. 13). The pounding of Lake Dellen was in the order of 3–4 m.

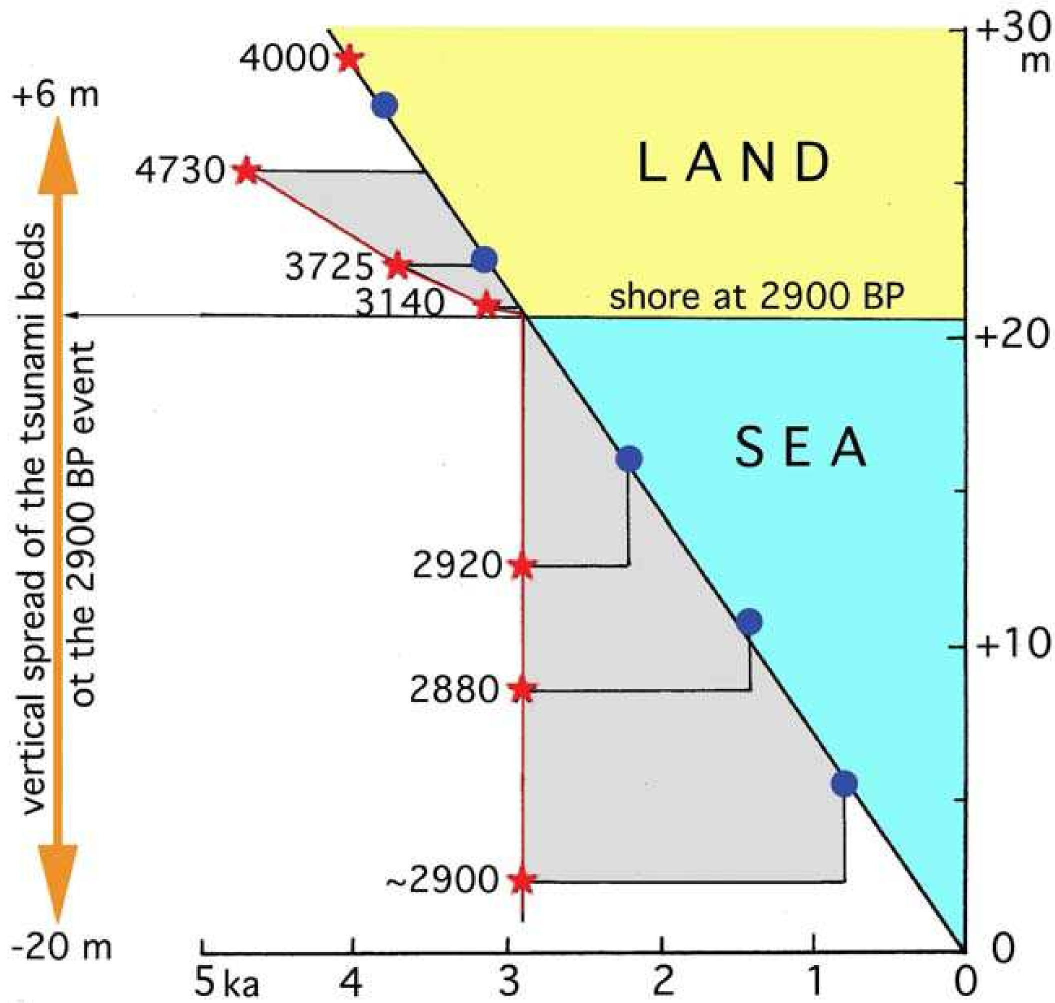

Fig. 12. The 2900 C14-years BP tsunami event in northern Uppland with respect to the rate of land uplift and shore displacement over the last 4000 years (the oblique line of ~7 m uplift per millennia passing through dated anchor points marked by black dots). At 2900 C14-years BP, the shore was at +20.7 m with land above (yellow) and sea (blue) below as marked on the right side of the diagram. The stars mark tsunami beds recorded and dated in off-shore sediments (all falling sharply at the 2900 BP level), in coastal deposits and in lakes and bogs on land where the tsunami beds have eroded down into the older sediments. The supposed tsunami bed in the +29 m basin has an age that coincides with the time of isolation. Therefore, we can in this case not discriminate between a normal shore sand from the isolation and a subsequent tsunami bed. Consequently, the graph gives evidence of a tsunami event that deposited typical tsunami beds over a vertical range from –20 m to +6 m. The tsunami run-up might have reached even 20 m above the shore level, judging from lake and bog coring at higher altitudes, however

5. Perspectives

The examples studied shed light, we hope, on the general processes of tsunami deposits and their characteristics to be used in order to be able to identify the deposits as traces of past tsunami events. Long-term records of past tsunami events offers means of assessing the tsunami risk for a given region.

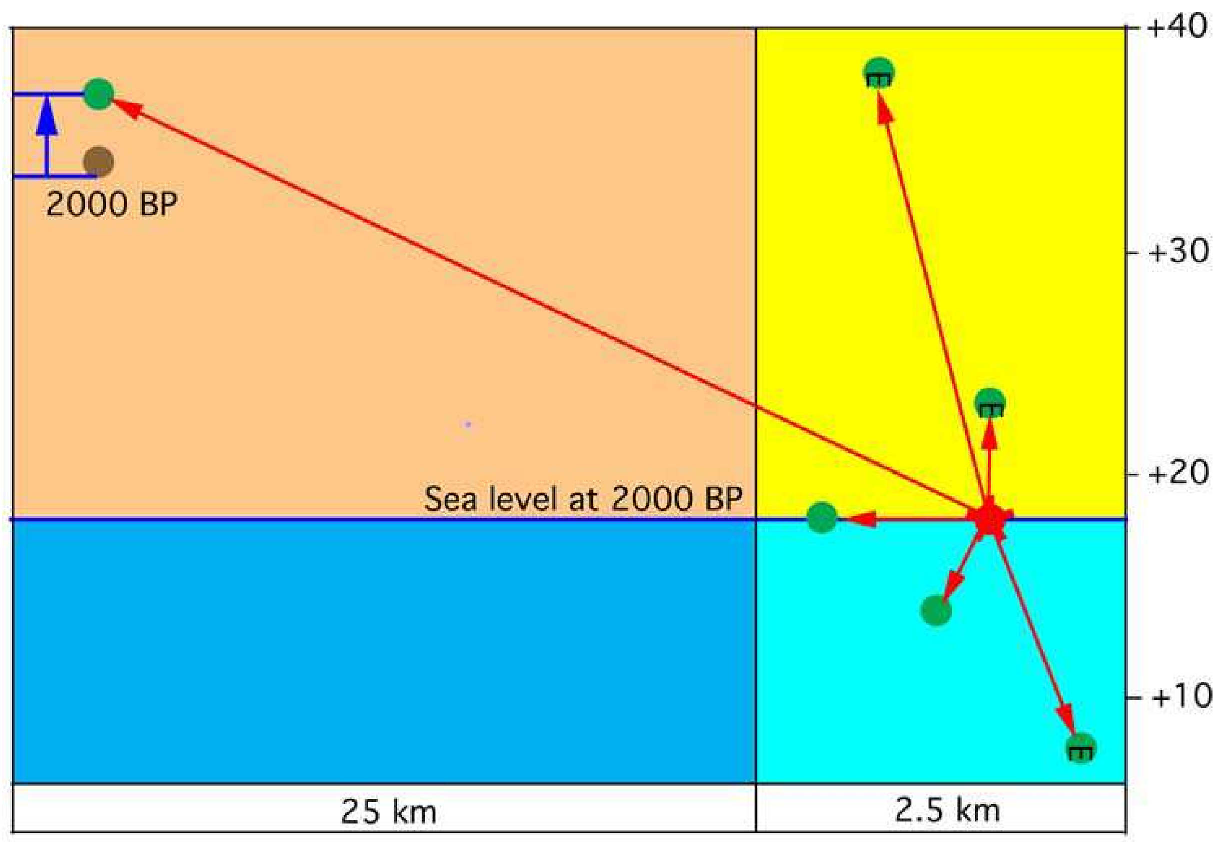

Fig. 13. Vertical and horizontal spread (red arrows) of the 2000 BP tsunami generated by an explosive venting of methane gas (at red dot). Green dots mark bogs invaded by the tsunami. Lying E-signs mark erosion below tsunami bed

In the Maldives, for example, we have traced 11 potential events; out of which 1 is the 2004 event, 5 refer to submarine sandstorms (and additional facts) and 5 refer to occasional beach ridge events of possible tsunami origin.
The Swedish records include 17 events (Table 1). This is not only of academic interest but also a serious fact to consider when it concerns super-long future safety predictions in the case of nuclear waste handling, which calls for a safe deposition for, al least, 100,000 years.

6. Conclusions

We need to have long records of past tsunami event in order to be able to present meaningful hazard assessments for the future. This calls for the use of a reliable methodology. We have tried to give some case studies where the methodology plays an important role.
In the Maldives, we have introduced the concept of "submarine sandstorms" in association with tsunami events, and we have shown that such "sandstorms" may reach considerable depths where they are even depositing significant sand wedges in the submarine caves (Mörner et al., 2008). Radiocarbon dating of shallow-water coral and gastropod species provide ages that can be compared with land records (swamp stratigraphy, coastal stratigraphy and morphology) and historical descriptions.
In Scotland, there are excellent records of the Storegga tsunami. The identification of planctonic deep-water species (not shallow-water bentic or lagoonal species) in the tsunami

sand layers offers means of discriminating its origin as to a tsunami wave deposit and not a shallow sea deposit (Dawson, 1999; Dawson et al, 2000).

In Sweden, we have identified a very high number – 17 – of past tsunami events. The reason is not so strange. Because of the postglacial land uplift, present land was previously covered by water. As most of the paleoseismic events seem to have been normal fault events, those events in submarine position are likely also to generate tsunamis. Finally, we have undertaken quite extensive studies of those paleoseismic events (Mörner, 2003). We have cored numerous lakes and basins, and identified potential tsunami beds. Their graded character (fining upwards) and their sudden appearance in otherwise unbroken deposits (e.g. marker varves of turbidite character) provide sedimentological characteristics suggesting a tsunami origin. The micropaleontological analyses revealing planctonic deep-water faunas and floras provide more conclusive indications of a tsunami origin. The data are integrated with the other paleoseismic data. Only by applying this integrated, multi-parameter methodology, we feel confident in assigning a paleotsunami origin.

The evidence in the offshore environment is important. The very extensive turbidites (e.g. those of the 10,430 and 9663 BP events) are not simple density driven turbidites. They are seismites formed in response to ground shaking, tsunami wave trimming of the seabed and violent gas seepage. At the 2900 BP event, the deposition of a sandy-gravely-pebbly tsunami seismite goes, at least, 20 m below sea level (at the time of the event). This is important, as normal waves in the Baltic never have effect reaching such depths.

We learn that we need to consider observational facts in the on-shore environment as well as in the off-shore environment. Besides this, we should consider historical observations. Sometimes, even the core of some myths has a message to tell.

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8. References

Bell, H.C.P. (1940). The Maldive Islands. Monograph on the history, archaeology and epigraphy. Ceylon Government Press, Colombo, 204 pp.

Brunnberg, L. (1995). Clay-varve chronology and deglaciation during the Younger Dryas and Preboreal in the easternmost part of the Middle Swedish Ice Marginal Zone. Quaternaria, Ser. A, No. 2, 1-94.

Dawson, A.G., Long, D. & Smith, D.E. (1988). The Storegga slides: evidence from eastern Scotland for a possible tsunami. Marine Geology, Vol. 82, 271-276.

Dawson, S. (1999). Flandrian relative sea level changes in northern Scotland. Ph.D.-thesis, Coventry University, 370 pp.

Dawson, S. & Smith, D.E. (2000). The sedimentology of Middle Holocene tsunami facies in northern Sutherland, Scotland. Marine Geology, Vol. 170, 69-79

De Geer, G. (1940). Geologia Suecia Principles. Kungl. Sv. Vet. Akad. Handl., 3rd, No. 18:6, 1-360.

Mörner, N.-A. (1980). A 10,700 year's paleotemperature record from Gotland and Pleistocene/Holocene boundary events. Boreas, Vol. 9, 283-287.

Mörner, N.-A. (1995). The Baltic Ice Lake – Yoldia Sea transition. Quatern. International, Vol. 27, 95-98.

Mörner, N.-A. (1996). Liquefaction and varve disturbance as evidence of paleoseismic events and tsunamis: the autumn 10,430 BP event in Sweden. Quaternary Science Revue, Vol. 15, 939-948.

Mörner, N.-A. (2003). Paleoseismicity of Sweden – a novel paradigm. A contribution to INQUA from its Sub-commission of Paleoseismology, Reno 2003, ISBN-91-631-4072-1, 320 pp, Stockholm.

Mörner, N.-A. (2004). Active faults and paleoseismicity in Fennoscandia, especially Sweden. Primary structures and secondary effects. Tectonophysics, Vol. 380, 139-157.

Mörner, N.-A. (2005). An investigation and catalogue of paleoseismology in Sweden. Tectonophysics, Vol. 408, 265-307.

Mörner, N.A. (2007). Sea Level Changes and Tsunamis. Environmental Stress and Migration over the Seas. Internationales Asienforum, Vol. 38, 353-374.

Mörner, N.-A. (2008a). Paleoseismicity and Uplift of Sweden. Guidebook, Excursion 11 at 33rd IGC, Oslo 2008, 107 pp, www.33IGC.org.

Mörner, N.-A. (2008b). Tsunami events within the Baltic. Polish Geological Institute, Special Papers, No. 23, 71-76.

Mörner, N.-A. (2009a). Paleo-tsunami events in the Maldives and surrounding areas. Proceedings GeoDev 2009, Daka, Bangladesh.

Mörner, N.-A. (2009b). Late Holocene earthquake geology in Sweden. Geological Society in London, Spec. Publ., Vol. 316, 179-188.

Mörner, N.-A. (2010). Natural, man-made and imagined disaster. Disaster Advances, Vol. 3, No. 2, 3-5.

Mörner, N.-A. (2011). Multiple parameter interaction in paleoseismology. Submitted.

Mörner, N.-A., Laborel, J. & Dawson, S. (2008). Submarine "sandstorms" and tsunami events in the Indian Ocean Journal of Coastal Research, Vol. 24, 1608-1611.

Mörner, N.-A. & Sun, G. (2008). Paleoearthquake deformations recorded by magnetic variables. Earth Planetary Science Letters, Vol. 267, 495-502.

Mörner, N.-A., Tooley, M. & Possnert, G. (2004). New perspectives for the future of the Maldives. Global Planetary Change, Vol. 40, 177-182.

Mörner, N.-A. and Tröften P.E. (1993). Paleoseismotectonics in glaciated cratonal Sweden. Zeitschrift für Geomorphologie N.F., Vol. 94, 107-117.

Mörner, N.-A., Tröften, P.E., Sjöberg, R., Grant, D., Dawson, S., Bronge, C., Kvamsdal, O. & Sidén, A. (2000). Deglacial paleoseismicity in Sweden: the 9663 BP Iggesund event. Quaternary Science Revue, Vol. 19, 1461-1468.)

NOAA, (2010). NOAA Centre for Tsunami Research. December 26, 2004 Indonesian Sumatra earthquake and tsunami Web link compilation and data. http://nctr.pmel.noaa.gov/sumatra20041226.html

Tröften, P.E., (1997). Neotectonics and paleoseismicity in southern Sweden with emphasis on sedimentological criteria. Stockholm University, Ph.D.-thesis, P&G No. 8, 1-124.

Tröften, P.E. and Mörner, N.-A. (1997). Varved clay chronology as a means of recording paleoseismic events in southern Sweden. Journal of Geodynamics, Vol. 24, 249-258.

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Submarine earthquakes, submarine slides and impacts may set large water volumes in motion characterized by very long wavelengths and a very high speed of lateral displacement, when reaching shallower water the wave breaks in over land - often with disastrous effects. This natural phenomenon is known as a tsunami event. By December 26, 2004, an event in the Indian Ocean, this word suddenly became known to the public. The effects were indeed disastrous and 227,898 people were killed. Tsunami events are a natural part of the Earth's geophysical system. There have been numerous events in the past and they will continue to be a threat to humanity; even more so today, when the coastal zone is occupied by so much more human activity and many more people. Therefore, tsunamis pose a very serious threat to humanity. The only way for us to face this threat is by increased knowledge so that we can meet future events by efficient warning systems and aid organizations. This book offers extensive and new information on tsunamis; their origin, history, effects, monitoring, hazards assessment and proposed handling with respect to precaution. Only through knowledge do we know how to behave in a wise manner. This book should be a well of tsunami knowledge for a long time, we hope.

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