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TSUNAMI EVENTS WITHIN THE BALTIC

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Abstract. During the deglacial period, Sweden was characterised by an extremely high seismic activity. The Swedish Paleosismic Catalogue includes 54 events, 16 of which were associated with tsunami events.

Key words: tsunami events, paleoseismics, the Kattegatt, the Baltic, Sweden.

INTRODUCTION

During the deglacial period, Sweden – and surrounding areas – was characterised by an extremely high seismic activity (Mörner, 1985, 1996. 2003, 2004, 2005; Sjöberg, 1994; Tröften, 1997). This is recorded both in the magnitude of individual events and in the frequency of events. The Swedish Paleosismic Catalogue includes 54 events established by multiple criteria and dated by varves or radiocarbon (Mörner, 2003, 2005).

In 1995, we found evidence of the first tsunami event, linked to the autumn 10,430 vBP paleoseismic event (Mörner, 1996). Shortly after, a second tsunami event was documented in association with the 9663 vBP paleoseismic event at Hudiksvall (Mörner *et al.*, 2000). By now, we have a record of 16 tsunami events from Sweden (Mörner, 1999, 2003) as listed in Table 1.

This paper will give a short presentation of available tsunami records. Additional base data are presented in a separate book (Mörner, 2003).

Table 1

Large earthquakes in Sweden with associated tsunami waves

Age in BP	Area affected	Estimated magnitude on the Richter scale	Observed tsunami records
12,400	Kattegatt	at least 8	very large wave
11,600	Kattegatt	at least 7	large wave
11,250	Kattegatt	~7	large wave
aut 10,430	Stockholm–Mälardalen	>>8	very large wave
9663	Hälsingland	>8	at least 10 m high wave
9428	Umeåtrakten	at least 7	unknown height
8600	Sörmland	at least 6	large wave (~20 m)
8000	Sörmland–Uppland	unknown	extensive turbidite
6100	Hälsingland	at least 8.5	at least 10–15 m high wave
4000	Umeåtrakten	~6–7	unknown height
4000	Sörmland	~6	uncertain height

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Table 1 continued

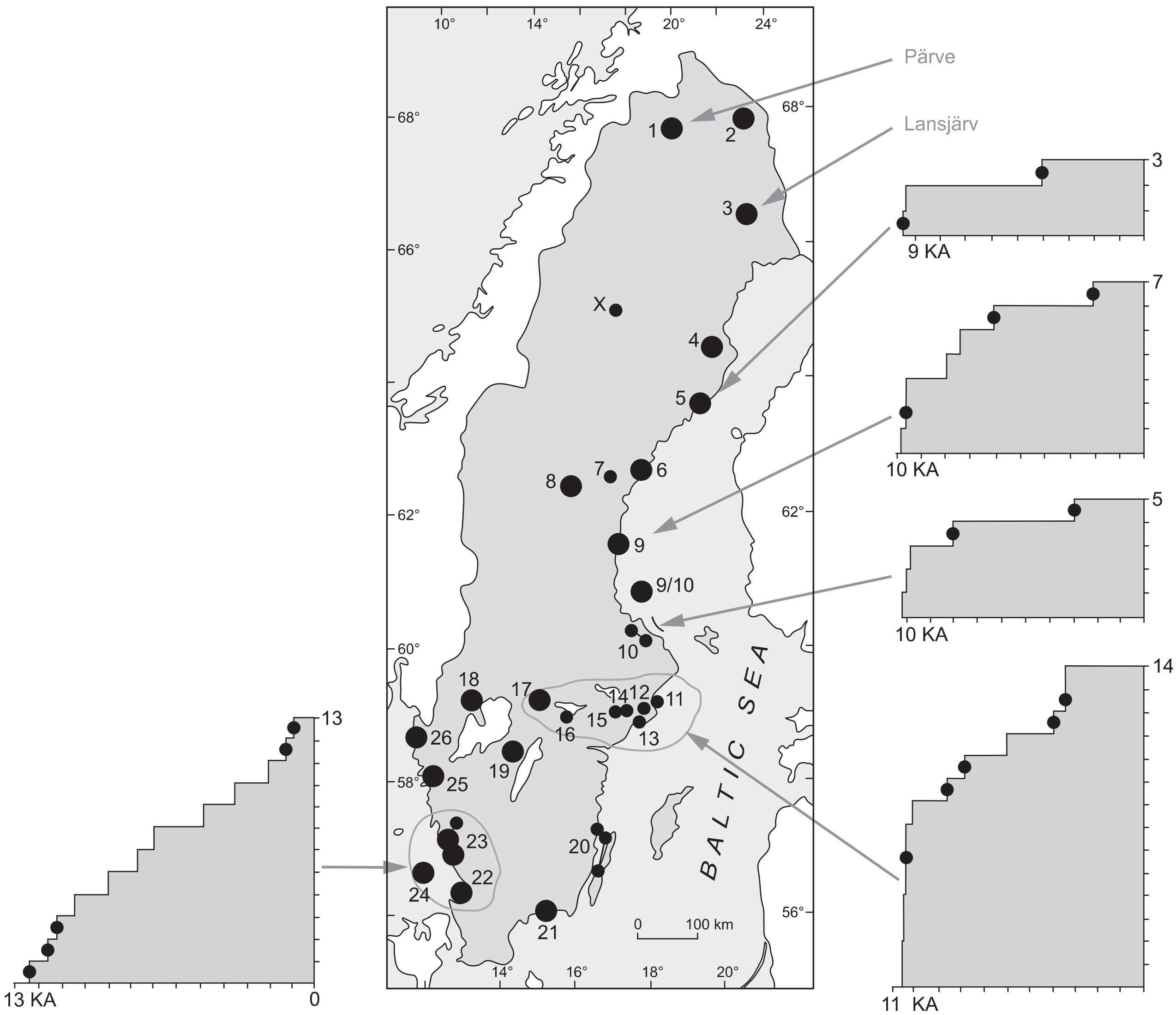
3500	Sörmland–Marvikarna	~7	local lake tsunami
2900	Uppland	unknown	at least 20 m high wave
2000	Hälsingland	very large	at least 20 m high wave
1600	Kattegatt	unknown	some metres
900	Kattegatt	~7	probable wave

PALEOSEISMIC RECORDS

Figure 1 gives cumulative recurrence diagrams of the paleoseismic events recorded in five main areas. The West Coast record includes 13 events in 13,000 years. They form a fairly straight line indicating the presence of an active fault (Mörner, 2004).

The Stockholm–Mälardalen record includes 14 events in 11,000 years with a very high frequency during the deglaciation phase followed by a fairly straight line in the last 10,000 years. In northern Uppland, 5 events are recorded. In the Hudiksball area, 7 events are recorded. In the Umeå region 3 events are recorded.

In total 54 paleoseismic events are identified and dated (Mörner, 2003, 2004, 2005), 42 (or 80%) of which were located in the five main areas of Figure 1.



TSUNAMI CRITERIA

Our tsunami events are always established in association with records of paleoseismic events. At the time of deglaciation, the sea level was significantly higher over the coasts of Sweden. Hence, there was water enough to create quite large tsunami waves. The tsunami breaks in over land, flooding land-surfaces and invading existing lakes. In the lakes, we record special tsunami signals; usually in the form of sandy layers in graded bedding (gravel-sand-silt-clay) as an odd layer in the normal lake deposits. These tsunami beds contain microfossils dominated by pelagic species typical for the water where the tsunami was generated (sea in the west and sea or lake in the Baltic). Often, it is possible to distinguish both an on-swash bed and a back-swash bed. The back-swash bed is usually the most significant one.

In the off-shore region, sandy-gravelly beds are formed. They range from tsunami beds via hybrids between tsunamis and turbidites to true off-shore turbidites. In varved clay sequences, the turbidides can be dated as to a single varve year.

Several unusual and odd varves, previously classified as "drainage varves", can now be understood in terms of paleoseismic turbidites; i.e. "seismites" (Mörner, 1980, 1985, 1996, 2003). This is the case with the famous – 1973 varve of De Geer (1940), the – 424 varve of De Geer (1940) and Strömberg (1989), and the – 189 varve of Bergström (1968). Even the famous 0-varve may, in fact, be a seismite (Mörner, 1985).

Sometimes we record separate tsunami shorelines, erosion level and accumulation deposits.

The height of the breaking wave is recorded in the difference between the sea level at the time of the tsunami and the height of lakes into with the run-up water or over-washing reached depositing tsunami layers. The distance of the land area between the shore and an invaded lake is also significant. The spatial range of the tsunami event is another important parameter.

THE KATTEGATT RECORD

The West Coast data (Fig. 1, Table 1) include 5 tsunami events; at 12.4, 11.6, 11.2, 1.5 and 0.9 Ka BP. The first three evens were significant, especially the 12.4 BP event (Mörner, 2003). The last two events need further studies. The 900 BP event seems to be connected to the sudden silting-over of two ships of Viking-type dated at ~1100 AD.

THE BALTIC RECORD

The Baltic data (Fig. 1, Table 1) include 11 tsunami events dated at 10,430 vBP, 9663 vPB, 9428 vBP, 8600 cBP, 8000 cBP, 6100 cBP, 4000 cBP, 4000 cBP, 3500 cBP, 2900 cBP and 2000 cBP.

The 10,340 vBP event. It first became obvious that the classical varve – 1073 was no "drainage varve" but a "seismite" (Mörner, 1980, 1985). In 1995, extensive road sections exposed strongly shaken and liquefied beds some 70 km west of Stockholm (Mörner, 1996, 2003; Tröften, 1997). The liquefaction had vented through a lower bed of grey varved clay and mushroomed at its surface below a bed of dark varved clay. At a nearby site, the varves were concordantly ordered and easily measured. After 35 grey varves deposited under freshwater conditions, the basin suddenly turned brackish with the deposition of dark varves. Obviously, this change represents the sudden ingresion of salt water at varve – 1073. Shortly beside, there was an erosional depression in the lower grey varved clay bed. This depression was filled with dark varves of brackish origin. The first varve deposited in this depression only consisted of the winter unit. Hence, it was possible to date the paleoseismic event to the autumn of varve 10.430 vBP (Mörner, 1996, 2003, p. 243). The same autumn 10,430 vBP position was also established in a section SE of Stockholm (Tröften, 1997; Mörner, 2003, p. 231). Liquefaction structures are recorded over an area spanning 320 km, indicating that the paleoseismic even must have been of very high magnitude; i.e. well above M 8.

A 2 m sequence of 32 horizontally bedded varves (close to the main liquefaction site) was analysed with respect to paleomagnetism and magnetic fabrics (Sun, 2005). Whilst the magnetic fabric had a strict NNW–SSE orientation, the paleomagnetic record showed a 90° eastward rotation upwards. This is understood in the following way: the larger grains responsible for the magnetic fabric remained in their depositional position, whilst the small magnetic grains responsible for the remanence were free to move and reorient with respect to the shaking motions increasing upwards.

←

Fig. 1. Main sites (1–26) of paleoseismic records (central map) and cumulative recurrence diagrams from 5 main areas; the Swedish West Coast (13 events) , the Stockholm–Mälardalen region (14 events), Northern Uppland (5 events), the Hudiksvall region (7 events) and the Umeå region (3 events). Black dots mark the occurrence of tsunami events, 5 on the West Coast and 16 in the Baltic

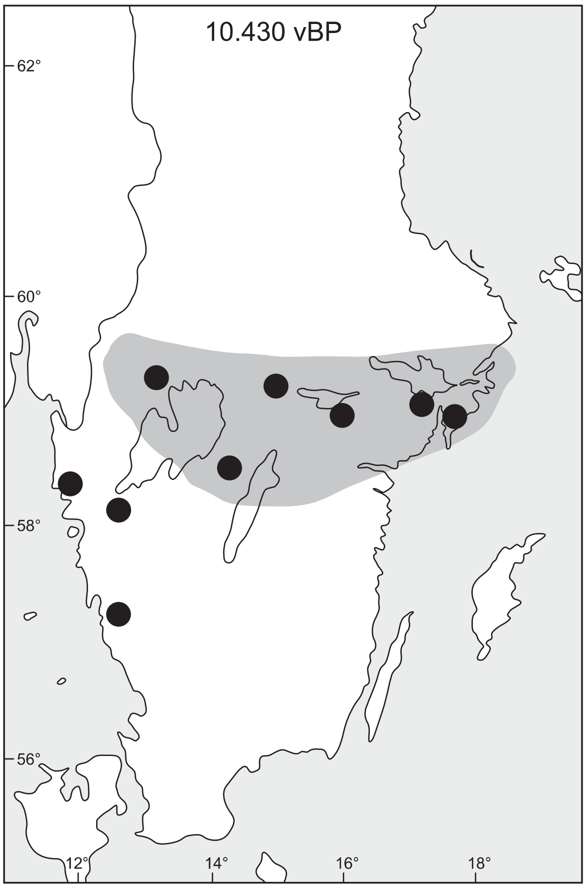


Fig. 2. The autumn 10,430 vBP event; shaded zone gives area of liquefaction and dots give sites of tsunami records

The Baltic had been on the same level as the Kattegatt for 300 years connected via the Närke Strait. All drainage water of the Baltic had to go via this strait. Still, the Baltic basin had a freshwater character. The typical freshwater mollusc *Ancylus fluvialilis* may even have lived along the shores of the Island of Gotland (Mörner, 1995).

Therefore, it seems likely that the Närke Strait was blocked by pack-ice, ice-bergs and semi-permanent ice-cover. When the huge earthquake in the autumn of varve 10,430 vBP struck the area, a tsunami wave was generated. This wave washed the Närke Strait free of blocking ice so that marine conditions could be established within the Baltic basin in one year's time; the Yoldia Sea *sensu stricto* (Mörner, 1995). The tsunami invaded numerous lakes and basins (Fig. 2) as further discussed in Mörner (2003).

This event must be possible to record even along the eastern and southern shores of the Baltic. If so, it may be used as an important stratigraphic maker.

The 9663 vBP event. This event has been described by Mörner *et al.* (2000) and Mörner (1999, 2003). The paleoseismic event was well recorded by multiple criteria. The tsunami was traced in 43 cores from 9 lakes. The corresponding shorelevel is recorded. This level lies 7.8 m below the Baltic Limit. There is about 25 varves between the deglaciation and the tsunami event givint a rate of shore displacement of 31 cm per year.

A lake located just above the highest Baltic level and 9 m above the shore at the tsunami event was invaded by the wave over-washing a land area for 700 m and depositing sandy layers of graded bedding in the lake deposits. These beds contain a diatom flora of planctonic, deep-water species from the open Baltic basin (the Ancylus Lake stage). Both on--swash and back-swash beds were recorded.

The 9428 vBP event. The violent paleoseismic event recorded at Umeå in the varve-year 9428 vBP seems to be connected with a tsunami event. Further analyses are required, however.

The 8600 cBP event. In the Katrineholm–Hjärmaren area, there are records indicating partly the occurrence of a major earthquake at about 8600 cBP and partly a tsumani event with a run-up of 20 m covering alluvial peat and gyttja (dated at 8600 cBP) by a 1 m layer of littoral sand (Mörner, 2003).

The 8000 cBP event. There are several records of tsunami-like beds at ~8000 cBP in the provinces of Sörmland and Uppland. A paleoseismic event is recorded (Mörner, 2003). This event generated a very extensive turbidite. This turbidite has a stratigraphic position close to the onset of the Littorina Sea stage of the Baltic.

The 6100 cBP event. In the Hudiksvall area, archeological sites had been observed that were covered by littoral sand. This could not be understood in terms of sea level oscillations because of the rapid rate of uplift. The solution was to come from an unexpected tsunami event.

In the gravel pit at Hög, west of Hudiksvall, a remarkable liquefaction venting is recorded (Mörner, 2003). Gravel vented through varved clay and was carried laterally in regressional sand that could be assigned an approximate age of 6100 cBP. Venting of gravel calls for a very high earthquake magnitude; viz. M >8.5 on the Richter scale. Earth slides were recorded over an area of at least 100 km with independent dating at 6100 cBP.

A tsunami bed was identified that contained early Littorina planctonic deep-water species. A number of lakes were cored. A tsunami bed was recorded in all of them up to a bog located 15 m above the sea level position at the time of the tsunami event (+75 m). Hence, the tsunami run-up must have been at least 15 m.

We revisited the archeological site located in the +75–80 m elevation and recorded a lower horizon with cooking stones and a few artefacts, covered by 20–30 cm of littoral sand on to of which there was a new horizon of cocking stones and a few artefacts. Obviously, the littoral sand was deposited by the tsunami event 6100 cBP as a back-swash accumulation.

The 4000 cBP event at Umeå. A violent liquefaction event was recorded at Ume? when sea level was in the order of +35 m. This event seems to have generated a tsunami. Our lake-coring program has not yet started. Archeological sites at an elevation of about +40 m are covered by littoral sand that may signify a major tsunami event at around 4000 cBP, however (Mörner *et al.*, 2003).

The 4000 cBP event in Södermanland. Old records from Tystberga, NE of Nyköping (Florin, 1961), seem to indicate the occurrence of an earthquake and a major tsunami event some 4000–4500 cBP (Mörner, 2003, p. 253). Further analyses are required, however.

The 3500 c BP Lake Marviken event. In the Lake Marviken area in Sörmland, a significant earthquake occurred at around 3500 cBP (Mörner, 2003, p. 250). A fault lineament is recorded for 4 km. Nine earth slides are recorded along this lineament. Even a grave of the Bronze Age slid down-slops. Sediments became liquefied. A major earth slide went into the lake where it set up a local lake tsunami in Lake Marviken depositing a tsunami bed for, at least, 5.2 km. Even the name "marviken" may lead its origin from fractured rock.

This site is interesting as it indicates that tsunami events may also be generated in lakes.

The 2900 cBP event. A major tsunami event was recorded in several lake-basins in northern Uppland. A coring and dating program was conducted in 2004 (Mörner, unpublished). A tsunami bed was recorded in lakes in off-shore position, shore-zone position and land position up to an elevation of 20 m above the corresponding sea level. A run-up of 20 m implies a very significant tsunami. A full presentation is in preparation.

The 2000 cBP event. In an area shortly north of Hudiksvall, a methane venting explosion was recorded (Mörner, 2003, p. 105). It occurred at around 2000 cBP when sea level was at about +18 m. Tsunami beds were recorded in 5 lakes ranging from +8 to +38 m. At the +38 m site, 2.65 m of gravel with numerous sells (Baltic brackwater species) was deposited between freshwater gyttja and peat. This implies a very strong and high tsunami wave.

I was later informed that Lake Dellen, now at – 37 m, previously had a 3 m lower level dated at about 2000 cBP. In view of the discovery of the tsunami event at 2000 cBP, it seems reasonable to interpret the 3 m pounding of Lake Dellen as an effect of the tsunami.

DISCUSSION AND CONCLUSIONS

The observed sea level changes in the Baltic are the function of (1) regional eustatic changes, (2) crustal movements primarily the glacial isostatic rebound factor or rather factors, and (3) local Baltic conditions such as pounding and run-off gradient. The field records are also affected by various coastal dynamic factors such as extreme storms and tsunamis.

In this paper, I have made a short presentation of the 16 tsunami which, up to now, have been recorded along the Swedish coasts of the Kattegatt and the Baltic. Special emphasis was given to the Baltic events.

Tsunamis in the Baltic introduce a novel factor in sea level analysis and general sediment stratigraphy.

1. True tsunami events have occurred in the Kattegatt and in the Baltic all from the deglacial period up to the Lake Holocene.

2. The occurrence of tsunamis in the Baltic and in the Kattegatt is a new factor that, by necessity, has to be taken into account for a sound interpretation of sea level oscillations as well as general sediment stratigraphy.

3. Some of the tsunami events may, in the future, serve as excellent marker horizons of inter-regional correlation.

4. The establishment of a peri-Baltic research group for the study of postglacial tsunami events seems highly motivated and is hereby proposed.

Acknowledgements. This paper was presented at the workshop in Gdansk, June 19.20, 2005, on "Relative Sea Level Changes – from subsiding to uplifting coasts". The 9663 vBP tsunami was investigated in collaboration with Sue Dawson. Both of us hope to be able to transfer the tsunami research into the entire peri-Baltic region in collaboration with relevant regional experts.

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