Major earthquakes at the Pleistocene-Holocene transition in Lake Vättern, southern Sweden

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Abstract

The Swedish Lake Vättern lies within a graben that formed through rifting along the boundary between two Precambrian terrains. We show from geophysical mapping and geological coring that the bounding normal faults of the Lake Vättern graben have been highly active during late glacial-early postglacial times. This is evident from abundant deformation structures in the soft sediment accumulated on the lake floor within the graben. Analysis of these structures reveals up to 13 m vertical tectonic displacements along sections of a >80 km long fault system. These large displacements indicate earthquakes with seismic moment magnitudes of about 7.5. Our geophysical mapping shows large landslides along the steep footwalls of the normal faults bounding the graben. Pollen analysis of sediment infillings of some of the most prominent collapse structures place this major seismic event at the Younger Dryas-Preboreal transition around 11 500 years BP. We speculate that this event is related to the rapid release of an ice-sheet load following deglaciation, combined with hydro-isostatic unloading from the 25 m drainage of the Baltic Ice Lake when the Scandinavian ice sheet retreated north of Mt. Billingen at the end of Younger Dryas. This paleo-seismic event in Lake Vättern ranks among the larger known intraplate tectonic events. Together with previous results from northern Sweden, these findings confirm that the deglaciation of Scandinavia was associated with substantial tectonic activities and attest to the significant power of glacio-isostatic unloading in driving tectonic instability.

Photos of field work in Lake Vättern: a,b) *RV Skidbladner equipped with a multibeam echo sounder and subbottom profiler (see photo for technical specification). RV Skidbladner is the Department of Geological Science's 6.4 m long aluminum boat made in Sweden by Arronet (http://www.arronet.se/). It has been specifically outfitted for high-resolution geophysical surveys in lakes and near shore areas.* ***c)*** *The floating barge used by the company Asera Mining to drill into the bedrock of southern Lake Vättern for mine prospecting purposes. The sediment coring system we adopted when using this platform consisted of tools added to an HQ wire line drilling system, including HQ-3 plastic liners (inner diamter of 63 mm) for collection of unconsolidated sediment. In total, we core through the upper 70 m of unconsolidated sediments.* ***d)*** *Seismic reflection profiling was carried out with a 0.3 l (20 cu in) Bolt PAR airgun and 18 m long hydrophone streamer. This was done with the 10 m long vessel Hamnen. d) Piston coring of the uppermost 6 m of the sediment stratigraphy from Asera Mining's drilling platform.*

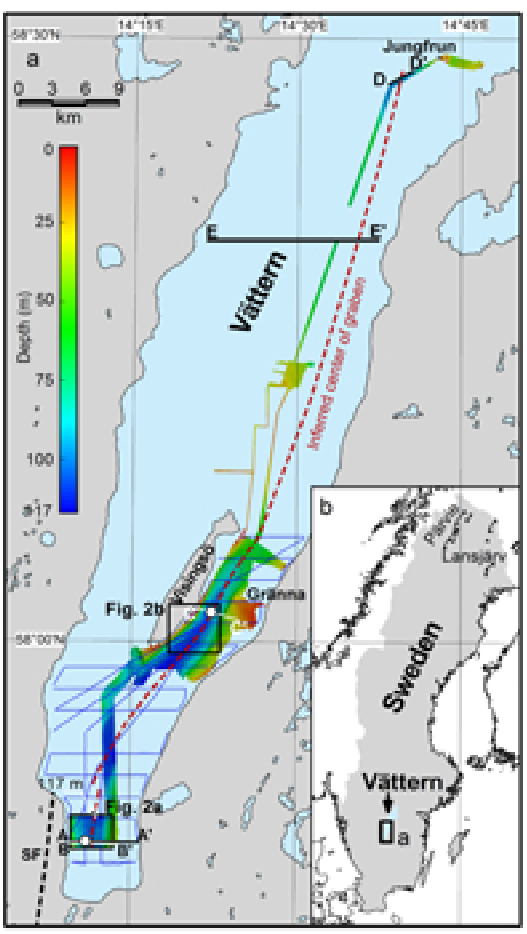

Figure 1: *a) Map of the southern part of Lake Vättern in south central Sweden showing the coverage of multibeam mapping and single channel seismic profiling (blue lines) carried out in 2008 and 2013. Profiles A-A' and B-B' are presented in Fig. 3, C-C' and D-D' in Fig. 4 and E-E' in the Supplementary information. Red dashed line outlines the location of the central active fault line. b) Overview map showing the location of Lake Vättern in Sweden and inferred faults in the Lansjärv area from Juhlin et al. (Journal of Applied Geophysics, 2010). SF=Sveconorwegian Front.*

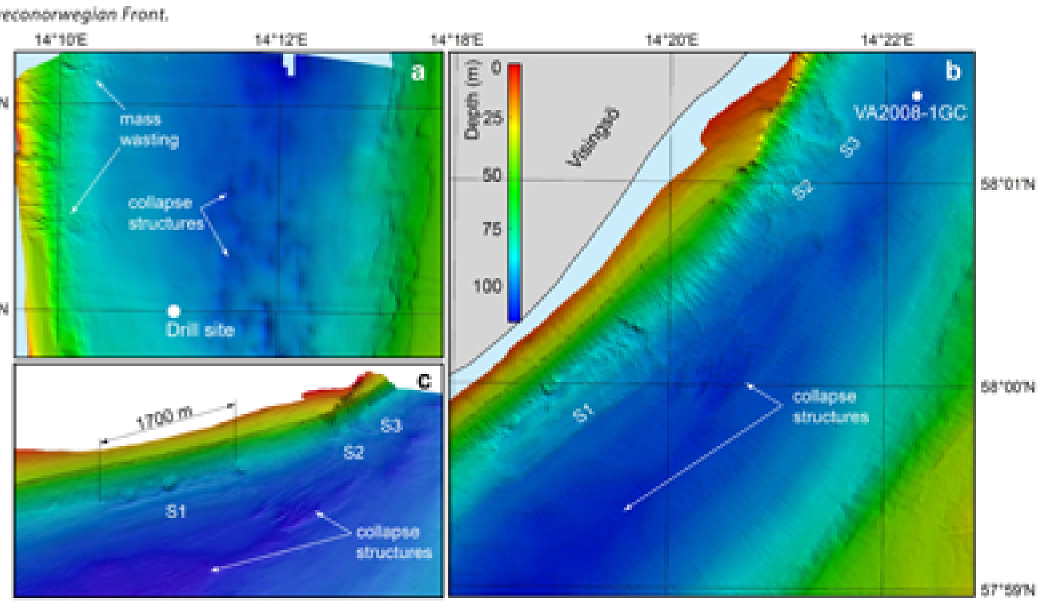

Figure 2: *Multibeam imagery illustrating two areas of the Vättern Basin graben, with collapse structures and slides.* ***2a*** *shows mass wasting and collapse structures in the southern part of the Lake, near the drill site.* ***2b*** *and* ***2c*** *shows similar structures along the SE Visingsö coast, 2c as a perspective plot. The location of sediment core VA2008-1GC, strategically located to capture this timing of the major seismic event, is shown in 2b. The locations of 2a, b, and c are shown in Figure 1.*

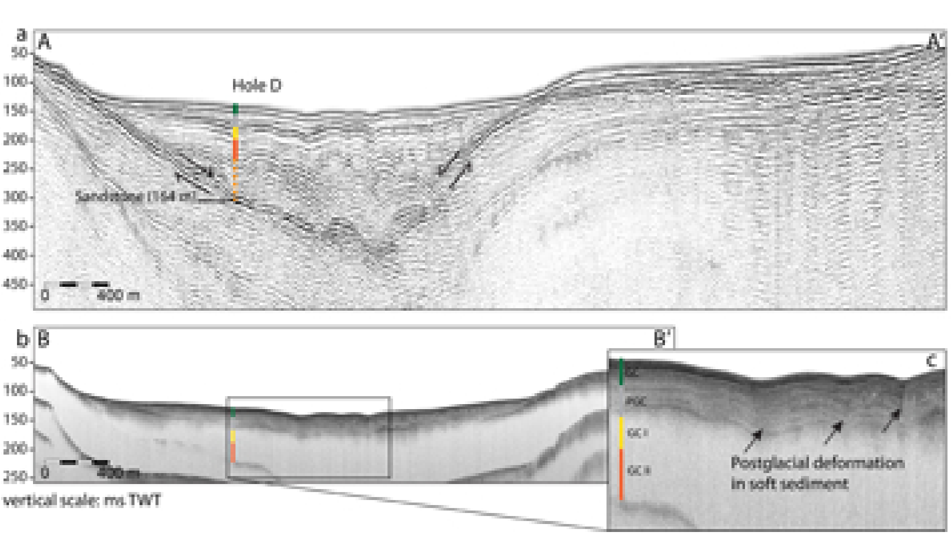

Figure 3: *Seismic reflection profile (**3a:** A-A') and subbottom profile (**3b:** B-B') across the graben in the southern part of the Lake. Location of the drilling site is marked in the profiles, in the enlargement (**3c**) with major stratigraphic boundaries inserted (GC II=Glacial Clay Unit II; GC=Glacial Clay Unit I; PGC=Post-Glacial Clay; GC=Gyttja Clay). The locations of the profiles are shown in Figure 1.*

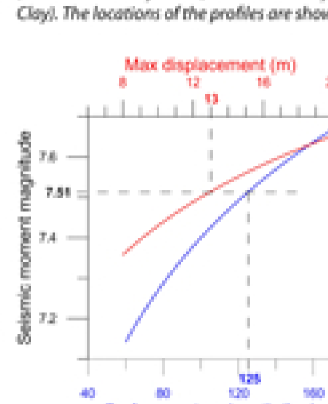

Figure 5. *Estimated seismic moment magnitude using equation (1) and maximum displacement d_{max} (red curve) and equation (2) using surface rupture length L (blue curve). Equations are from Wells and Coppersmith (Bulletin of the Seismological Society of America, 1994).*

Equations

$$Mw = 6.69 + 0.74\log(d_{max}). \qquad (1)$$

$$Mw = 5.08 + 1.16\log(L). \qquad (2)$$

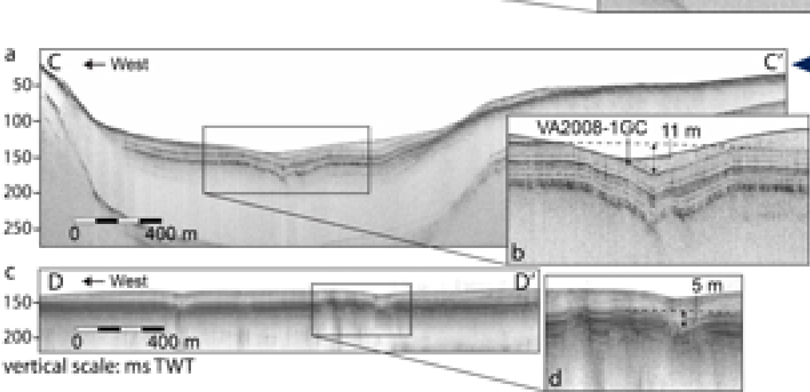

Figure 4: *Subbottom profiles across the Lake Vättern graben, (**4a:** C-C') east of Visingsö and (**4b:** D-D') near the island Jungfrun in the northern part of the study area. The locations of the profiles are shown in Figure 1. Estimation of vertical displacement is inferred in panel b and d.*

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