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

Martin Jakobsson[1]*, Svante Björck[2], Matt O'Regan[1], Tom Flodén[1], Sarah L. Greenwood[1], Henrik Swärd[1], Arne Lif[1], Linda Ampel[1], Hemin Koyi[3], and Alasdair Skelton[1]

[1]Department of Geological Sciences, Stockholm University, 106 91 Stockholm, Sweden
[2]Department of Geology, Lund University, Sölvegatan 12, 223 62 Lund, Sweden
[3]Department of Earth Sciences, Uppsala University, 752 36 Uppsala, Sweden

ABSTRACT

Lake Vättern, Sweden, is within a graben that formed through rifting along the boundary between two Precambrian terrains. Geophysical mapping and geological coring show that substantial tectonic movements along the Lake Vättern graben occurred at the very onset of the Holocene. This is evident from deformation structures in the soft sediment accumulated on the lake floor. Our interpretation of these structures suggests as much as 13 m of vertical tectonic displacements along sections of a >80-km-long fault system. If these large displacements are from one tectonic event, Lake Vättern must have had an earthquake with seismic moment magnitudes to 7.5. In addition, our geophysical mapping shows large landslides along sections of the steep lake shores. Pollen analysis of sediment infillings of some of the most prominent sediment deformation structures places this major seismic event at the Younger Dryas–Preboreal transition, ca. 11.5 ka. We suggest that this event is mainly related to the rapid release of ice-sheet load following the deglaciation. This paleoseismic event in Lake Vättern ranks among the larger known intraplate tectonic events in Scandinavia and attests to the significance of glacio-isostatic unloading.

INTRODUCTION

Lake Vättern is the second-largest lake (1893 km^2) in Sweden; it is 135 km long and has a maximum width of 31 km. The lake occupies a graben that trends SSW-NNE and follows the Sveconorwegian front (Fig. 1). The front marks the eastern boundary of the 0.9–1.14 Ga Sveconorwegian province (Bingen et al., 2008). This province is juxtaposed against older Svecokarelian rocks. The Lake Vättern graben is suggested to have formed through rifting in the Baltic shield from the south along the Sveconorwegian front at 700–800 Ma (Andréasson and Rodhe, 1990), and was imaged in seismic reflection profiles collected to study the distribution of sedimentary bedrock beneath the soft sediments (Axberg and Wadstein, 1980). Indications of late glacial and postglacial paleoseismic activities have previously been reported from southern Sweden, including landslides and turbidites associated with a fault in northernmost Lake Vättern (Mörner, 1985). One of the best documented and widely discussed paleoseismic events of the last deglaciation occurred in northernmost Sweden, in the Lansjärv area (Juhlin et al., 2010; Lundqvist and Lagerbäck, 1976), and there are prominent postglacial faults in Burträsk and Röjnoret (Lagerbäck and Sundh, 2008) (Fig. 1). The Pärvie fault and others in the Lansjärv area are clearly visible in the landscape and were generated by massive earthquakes (magnitudes of 6.5–8) resulting from unloading of the Earth's crust during the rapid deglaciation (Arvidsson, 1996; Lagerbäck, 1990). Large landslides likely linked to the strong seismic activity are identified in the same area.

Here we show, from geophysical mapping and geological drilling and coring, striking evidence for strong paleoseismic activity along the Lake Vättern graben that likely was comparable in strength to the postglacial events in northern Sweden. The paleo-earthquake is directly evident from an abundance of structures in the soft deglacial-postglacial sediments accumulated in Lake Vättern. Large landslides along the perimeter of the lake were also mapped. Assuming that these structures are from one event, the estimated vertical tectonic displacement and length of faulting allow us to quantify the possible moment magnitude of a major earthquake that occurred following the deglaciation of the area. This estimated earthquake in Lake Vättern ranks among the largest in comparison to other known intraplate earthquakes that have occurred since the last deglaciation.

FIELD WORK AND METHODS

Geophysical mapping using multibeam echo sounder, subbottom profiler, and single-channel airgun seismic reflection equipment was carried out during field campaigns in 2008 and 2013. Sediment cores were retrieved with a 2.5-m-long gravity corer in 2008, and the upper 70 m of the sediment sequence in the southernmost part of Lake Vättern was drilled in 2012 (Fig. 1). The results from this drilling operation are not the main focus of this paper, but the recovered sediments provide important information for deciphering tectonic activity in Lake Vättern. See the Appendix for further descriptions of methods.

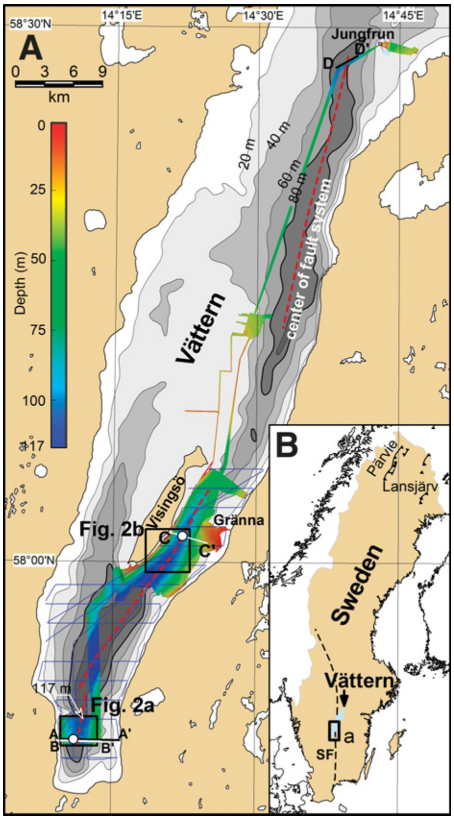

Figure 1. A: Map of southern part of Lake Vättern in south-central Sweden, showing coverage of multibeam mapping and single-channel seismic profiling (blue lines) carried out in 2008 and 2013. Profiles A-A′ and B-B′ are presented in Figure 3; C-C′ and D-D′ are in Figure 4. Red dashed line outlines location of central fault system assuming that it follows mapped bathymetric depressions. B: Overview map showing location of Lake Vättern in Sweden and inferred faults in Lansjärv area (from Juhlin et al., 2010). SF—Sveconorwegian front. General bathymetry is from Norrman (1964).

RESULTS AND INTERPRETATION

Our multibeam mapping outlines a SSW-NNE–trending lake trough forming the deepest part of Lake Vättern, with a maximum mapped water depth of 117 m (Fig. 1). In the southernmost part of this trough, the lake bottom is characterized by clearly visible bathymetric undulations, which we interpret as narrow collapse structures and/or subsidence zones (Fig. 2A). These collapse structures, as much as

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*E-mail: martin.jakobsson@geo.su.se.

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100 m wide, range from a few meters to >10 m deep. The same kind of collapse structures are abundant in the deep strait between the island of Visingsö and the town of Gränna (Figs. 1, 2B, and 2C), while along the eastern slope of the drill site area, similar morphological structures in the lake floor give it a staircase appearance (Fig. 2A). Although only ~1 m in depth, we interpret these latter features as the surface expression of small rotational slumps resulting from movement in the underlying bedrock. Mass wasting has occurred along the eastern shore of Visingsö and in the drill-site area. The slope along Visingsö exceeds 20° and has three larger slide scars (S1, S2, and S3 in Figs. 2B and 2C). The southernmost of these, S1, is the largest and involved wasting of sediments over a 1700-m-long extent of the slope.

Subbottom profiles collected along with multibeam data provide a dense grid of information of the uppermost ~25–40 m of the sediment stratigraphy. The collapse structures visible in the lake floor are clearly seen in the acoustic stratigraphy (Figs. 3 and 4). In the area of the drill site, the uppermost sediment layers closely follow the collapse structures: the layers are bent downward all the way up to the lake floor. In contrast, in the strait between Visingsö and Gränna, several subbottom profiles show that the largest collapse structure is filled with post-kinematic sediments that onlap older deformed sediments (Fig. 4; see the GSA Data Repository[1]). A subbottom profile crossing the deep section of the lake in the northernmost study area, near the island of Jungfrun, also contains clear indications of prominent sediment deformation, including extensional structures (Figs. 4C and 4D). Based on acoustic stratigraphic correlation, we conclude that the movement that formed the structures here was caused by the same tectonic event we mapped in the southern parts of the survey area ~80 km away. The airgun seismic reflection profiles depict the upper sediment-filled part of the graben along the entire study area (Fig. 3A). Previous seismic profiles by Axberg and Wadstein (1980), and the bathymetric map by Norrman (1964), show that this graben continues northward along the lake (Fig. 1). Deep drilling carried out by Asera Mining Ltd. showed that sandstone of the Visingsö series was encountered at 164 m below the lake floor (O. Göting, 2013, personal commun.), which coincides with the reflector outlining the sediment in the graben structure (Fig. 3A). Granite underlying the sandstone

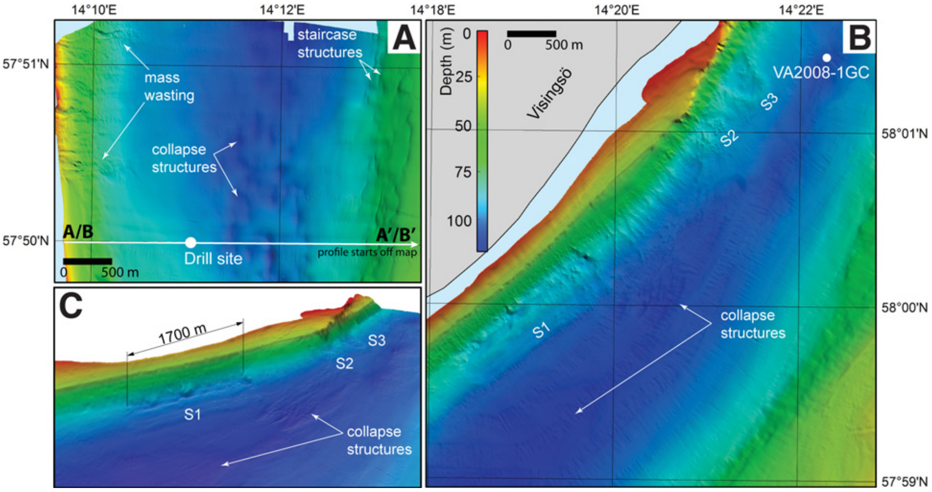

Figure 2. Multibeam imagery illustrating two areas of Lake Vättern graben, with collapse structures and slides. A: Mass wasting and collapse structures in southern part of Lake Vättern, near drill site. B: Location of sediment core VA2008–1GC, strategically placed to capture timing of major seismic event. S1–S3 are slide scars. C: Structures similar to those in A, along southeast coast of island of Visingsö (C is a perspective plot). Locations of A and B are shown in Figure 1.

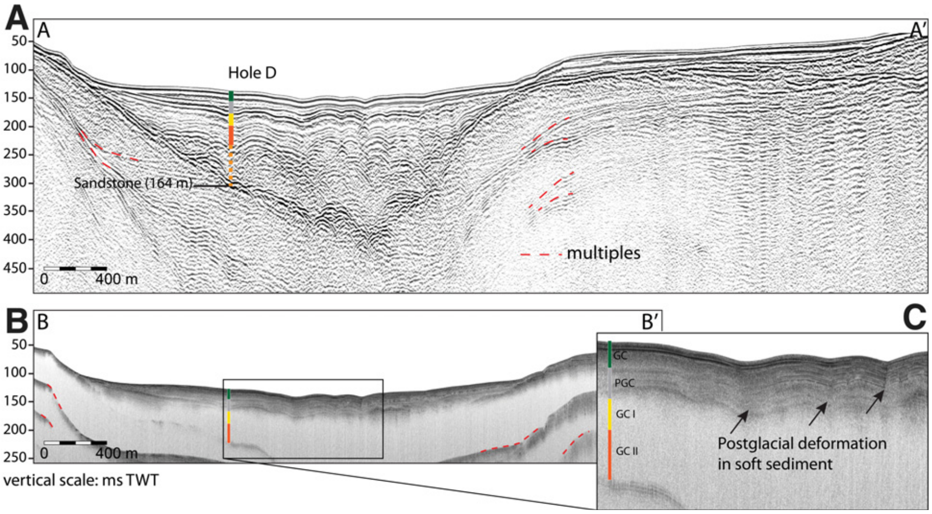

Figure 3. A: Seismic reflection profile A-A′ across graben in southern part of Lake Vättern. B: Subbottom profile B-B′ (TWT—two-way traveltime). C: Enlargement of B, with location of drilling site marked in profiles. Major stratigraphic boundaries are inserted (GC II—glacial clay unit II; GC—glacial clay unit I; PGC—postglacial clay; GC—gyttja clay). Locations of profiles are shown in Figure 1.

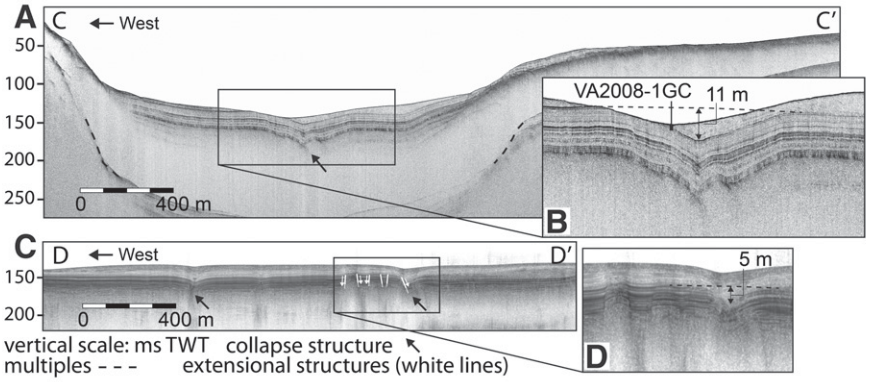

Figure 4. Subbottom profiles across Lake Vättern graben. A,B: Profile C-C′ east of island of Visingsö. C,D: Profile D-D′ near island of Jungfrun in northern part of study area. Locations of profiles are shown in Figure 1. Estimation of vertical displacement is inferred in B and D.

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[1] GSA Data Repository item 2014142, Figure DR1 (chirp sonar profile crossing the deep strait between the mainland and the island Visingsö) and Figure DR2 (seismically induced faulting and deformation in sediments from Southern Lake Vättern), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

was encountered at ~353 m below the lake floor. We find no clear reflector that can be tied to this boundary. The drill core contains abundant small-scale deformation structures indicating compression (see the Data Repository); we suggest that these formed when the sediment slid down toward the deeper part of the trough due to the earthquake.

The larger collapse structures (sinks, depressions) with sharper synclines and posttectonic sediment infilling allow us to constrain the timing of the main tectonic activity and the onset of posttectonic sedimentation. Gravity core VA2008–1GC is strategically located to record this timing. The unit directly overlying the tectonically disturbed sediments consists of faintly laminated, slightly organic clay. Regionally, this type of deposit is typical for the post–Baltic Ice Lake stage sediments deposited during the Yoldia Sea stage. Radiocarbon dating of a bulk sediment sample from this unit resulted in an age of 19,000 ^{14}C yr B.P; because the area was ice covered at that time (at the Last Glacial Maximum), we regard this as a maximum age due to the presence of old reworked organic material, a common phenomenon in deglacial organic-poor sediments (Björck and Wohlfarth, 2001). Pollen analysis revealed an assemblage dominated by *Betula*, *Juniperus*, and *Pinus* together with some cold-tolerant types (*Salix*, *Artemisia*, *Chenopodiaceae*, and grass pollen; Table 1). The only postdeglacial pollen zone with these characteristics is the so-called Younger Dryas–Preboreal transition zone (Berglund, 1966), common from sites on Mount Billingen, west of Lake Vättern (Björck and Digerfeldt, 1986). It closely postdates the Younger Dryas stadial as well as the drainage of the Baltic Ice Lake (Björck et al., 1996), and only lasted a few hundred years until birch and pine totally dominated the pollen spectrum. Its occurrence immediate above the tectonically deformed sediments in Lake Vättern places the paleoseismic event at the very beginning of the Holocene.

TABLE 1. POLLEN ANALYSIS OF CORE VA2008 FROM LAKE VÄTTERN, SWEDEN

Most common pollen types (>1%)	Percent	Concentration (grains/cm^3)
Betula pubescens	25	762
Juniperus communis	16	504
Pinus sylvestris	13	413
Cyperaceae	10	295
Gramineae*	7	221
Artemisia	4	115
Salix	4	115
Betula nana	3	103
Rumex	2	53
Empetrum nigrum	2	53
Rosaceae	1	37
Chenopodiaceae	1	37
Total		3109

*Also called Poaceae. Note: 241 pollen grains counted. Core length is 130 cm.

DISCUSSION

Our geophysical mapping and geological coring show that faults along the graben of Lake Vättern were active during the last deglaciation of the area. We mapped the sediment-filled main graben structure starting from our drill site in the southern part of Vättern and northward to the island of Jungfrun, a distance of ~80 km (Fig. 1). The airgun seismic reflection profiles only provide information about the sediments and uppermost bedrock structure; we are therefore not able to identify any signs of recent faulting in the bedrock. It is the geometric expression of the mapped soft lake sediments that reveals postglacial tectonic activity. We suggest that the collapse structures in the lake floor formed when the soft sediments bent downward in response to tectonic movements in the underlying bedrock. From these depressions, the maximum vertical displacement (d_{max}) measured in our subbottom profiles is 13 m and is located between Visingsö and Gränna, ~800 m north of the VA2008–1GC coring site (Fig. 1). The maximum displacement of a fault ideally occurs at its center with the fault tapering in both directions such that its displacement reduces to zero at its tips (Kim and Sanderson, 2005). The collapse structures in the south near the drill site show several meters of subsidence. In the northern part near the island of Jungfrun, ~5 m of subsidence is seen (Fig. 4), implying that the tip of the fault is located beyond the limits of the study area. For this reason, the mapped fault length of 80 km must be regarded as a minimum. While the type of faulting that occurred is not possible to decipher from available data, it is known that glacial isostatic adjustment (GIA) is capable of reactivating movements along old faults (Steffen et al., 2014). The general stress field of the Baltic shield is mainly compressive (Lund and Zoback, 1999), although rapid rebound from GIA may cause localized extension (Muir-Wood, 2000). Studies from northern Germany have revealed faults that began as normal faults but were reactivated as reverse faults in the forebulge region of the Late Weichselian ice sheet (Brandes et al., 2012).

Using the empirical relationships between seismic moment magnitude (M_w), maximum displacement, and fault surface rupture length (L) established by Wells and Coppersmith (1994), we can estimate the size of the earthquake that could have caused the observed displacement along the Lake Vättern graben (Fig. 5); using their empirical relationship

$$M_w = 6.69 + 0.74\ \log(d_{max}), \qquad (1)$$

we estimate M_w = 7.5 for d_{max} = 13 m; using this result,

$$M_w = 5.08 + 1.16\ \log(L), \qquad (2)$$

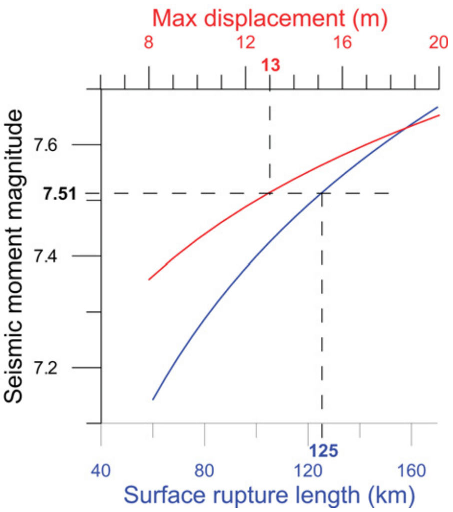

Figure 5. Estimated seismic moment magnitude using Equation 1 (see text) and maximum displacement (max; red curve) and Equation 2 using surface rupture length (blue curve).

we obtain a surface rupture length of 125 km. This is similar to the minimum fault length measured in our study of 80 km and approaches the full length of the lake (Fig. 5). Using the empirical relationship derived by Leonard (2010), relating fault length and width (W),

$$W = C_1 L^{\beta}, \qquad (3)$$

where the constants C_1 = 1.7 and β = 2/3, we obtain a fault width of ~40 km, which corresponds to typical crustal widths.

We cannot exclude the possibility that fault displacement resulted from a short-lived sequence of smaller earthquakes, although we favor one major event. The M_w of up to 7.5 that we estimate for a single main event suggests that it was comparable to the largest known paleoseismic events in northernmost Sweden, e.g., 7–7.8 estimated for the Lansjärv fault (Arvidsson, 1996; Lagerbäck, 1990) and ~8.2 for the Pärvie fault (Arvidsson, 1996). These northern events were similarly associated with large sublacustrine landslides. While it has not been possible to precisely date the landslides in Lake Vättern, their location next to the collapse structures suggests that they were triggered by the earthquake. A minimum estimation of the volume of sediment contained in the largest slide displaced along the eastern shore of Visingsö (S1; Figs. 2B and 2C) is ~2.8 × 10^6 m^3. This is a conservative estimate made through analysis of the slide scar in the multibeam bathymetry. If we instead calculate the volume of mass-wasted sediment at the base of the slide scar using the subbottom profiles, a volume several times larger is obtained. It is likely that these subaqueous slides generated significant inland-type tsunamis with substantial impacts on the surrounding shores.

The pollen analysis of gravity core VA2008–1GC shows that the major earthquake in Lake Vättern occurred slightly after the catastrophic drainage of the Baltic Ice Lake at the end of Younger Dryas, when the Scandinavian ice sheet, which had acted as a dam, retreated north of Mount Billingen (Björck, 1995). As much as 7800 km^3 of lake water is estimated to have drained toward the North Sea when the ice dam broke over a period of 1–2 yr (Björck et al., 1996; Jakobsson et al., 2007). It may be tenable to suggest that the stress release causing a magnitude 7.5 earthquake could have been triggered by a combination of crustal unloading from the rapidly retreating Scandinavian Ice Sheet and the nearly instantaneous drainage of 25 m water level. Although this drainage is small compared to the loss of the ice sheet, the rapidity of the drainage event could have taken part in triggering the earthquake.

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APPENDIX: FIELD WORK AND METHODS

The southern half of the strait between the island of Visingsö and Gränna, Sweden (Fig. 1), was mapped in 2008 with a Kongsberg EM3002D, 300 kHz 1.5° × 1.5° multibeam (MB) bow mounted on the 11-m-long vessel *Cappella*. Positions were acquired with a Hemisphere A100 GPS using satellite-based augmentation system corrections and motion sensor data with a Seatex MRU5. Along with MB bathymetry, subbottom profiling was carried out with an EdgeTech SB216 tow fish (20 ms long, 2–12 kHz chirp pulse). MB mapping was continued in 2013 with a Kongsberg EM2040, 200–400 kHz 1° × 1° MB bow mounted on the 6.4-m-long survey boat RV *Skidbladner*. Positions were acquired using a Hemisphere R320 GPS, corrected by the Swedish SWEPOS system (a network of permanent GPS reference stations) to obtain full real-time kinematic accuracy. Motion sensor data were acquired with a Seatex MRU5+ and subbottom profiles with a Kongsberg EA600 15 kHz echo sounder. Except for the southern half of the strait between Visingsö and Gränna, all areas shown in Figure 1 were mapped in 2013. Sound velocity profiles for correction of the MB data were acquired with an Applied Microsystems sound velocity probe. All MB data were processed and analyzed using a combination of Caris and Fledermaus software. Depths are referenced to the mean lake level between 1940 and 2000, which is 88.5 m above the vertical datum RH2000. Seismic reflection profiling was carried out in 2013 with an ~0.3 l (20 in^3) Bolt PAR airgun and 18-m-long hydrophone streamer on the 10-m-long vessel *Hamnen*. In 2008, 3 short cores were taken between Visinsgö and Gränna with a 1.5-m-long gravity corer (Fig. 1). In October 2012, sediment coring and drilling were conducted from a floating barge equipped with a drill rig by Asera Mining Ltd., which drilled down into the bedrock of southern Lake Vättern for mine prospecting purposes. The sediment coring system consisted of tools added to an HQ wireline drilling system, including HQ-3 plastic liners (inner ϕ 63 mm) for collection of unconsolidated sediment. Five holes were drilled in total. The drill holes, named holes A–E, are located too close to each other to be shown separately in Figures 1 and 2A. Sediments were recovered down to 70 m below the lake floor (Fig. 1).

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