J Paleolimnol (2007) 37:49–63
DOI 10.1007/s10933-006-9022-9

ORIGINAL PAPER

Seismic investigation of the El’gygytgyn impact crater lake (Central Chukotka, NE Siberia): preliminary results

F. Niessen · A. C. Gebhardt · C. Kopsch · B. Wagner

Received: 11 August 2004 / Accepted: 1 May 2006 / Published online: 12 December 2006

Abstract The 12 km wide and about 175 m deep El’gygytgyn crater lake in Central Chukotka, NE Siberia, is of special interest for investigation as it could provide the first undisturbed 3.6 Ma terrestrial record from the Arctic realm, reaching back a million years before the first major glaciation of the Northern Hemisphere. A single-channel seismic survey was carried out on an expedition to the lake in 2000, in which both high resolution and deep penetration data were acquired. Seismic data suggest an impact crater structure in Cretaceous volcanic bedrock, indicated by velocities of >5000 m s^{-1}, whose upper 500–600 m is brecciated. The lake is filled with two units of sediments, the upper one well stratified and the lower one massive. In the center of the lake, the combined thickness of the two sedimentary units is estimated to be 320–350 m. The upper unit is draped over the location of an interpreted central peak and is locally intercalated with debris flows, mainly in the western part of the lake and at the lake margins. Most of the lower unit is obscured by multiples as a result of high reflection coefficients in the upper unit. As at least the upper unit appears to be undisturbed by glaciation, the lake should yields unique information on the paleoclimatic development of the East Siberian Arctic.

Keywords Siberia · Arctic · Lacustrine sediments · Impact crater · Seismic investigations · Paleoclimate

This is the *fourth* in a series of eleven papers published in this special issue dedicated to initial studies of El’gygytgyn Crater Lake and its catchment in NE Russia. Julie Brigham-Grette, Martin Melles, Pavel Minyuk were guest editors of this special issue.

F. Niessen (✉) · A. C. Gebhardt
Alfred-Wegener-Institute for Polar and Marine Research, Columbusstraße, D-27515 Bremerhaven, Germany
e-mail: fniessen@awi-bremerhaven.de

C. Kopsch
Alfred-Wegener-Institute for Polar and Marine Research, Telegrafenberg A43, D-14473 Potsdam, Germany

B. Wagner
University Leipzig, Institute for Geophysics and Geology, Talstr. 35, D-04103 Leipzig, Germany

Introduction

With an average diameter of 18 km and an age of about 3.6 Ma (Layer 2000), the El’gygytgyn crater in the remote Anadyr Mountains of Central Chukotka in NE Siberia (Fig. 1), is one of the largest young impact craters known on Earth (Hodge 1994). The surrounding hills are formed of nearly flat-lying Late Cretaceous volcanic rocks, mainly andesites, rhyolites, trachyrhyolites

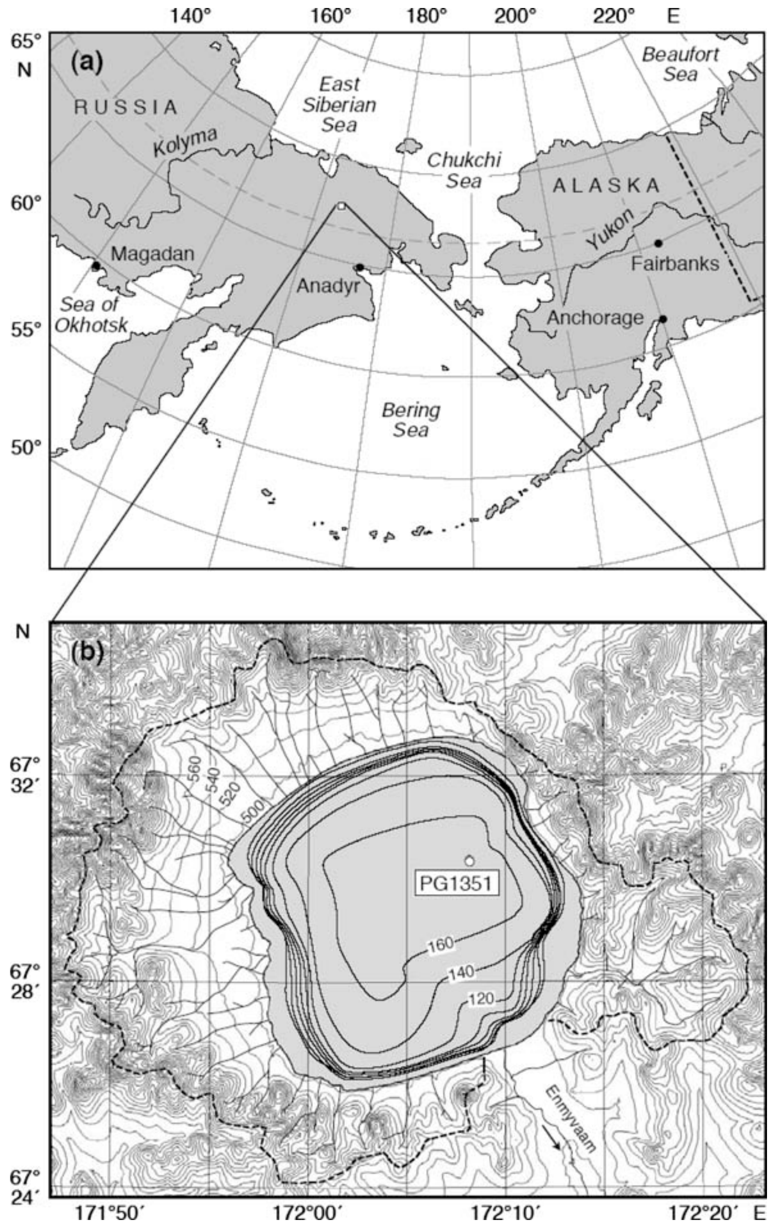

Fig. 1 Location, crater rim and bathymetry of Lake El'gygytgyn. PG1351 marks the position of the core retrieved in 1998 (Melles et al. 2007). Bathymetry and topographic contours in m

and their tuffs (Masaitis 1999, and references therein), into which the crater was excavated. The lake has a diameter of about 12 km and is slightly offset towards the south-eastern quarter of the crater by large sediment aprons that have filled parts of the basin from the west and north-west (Dietz and McHone 1976). The lake is almost circular, encompasses an area of about 110 km^2, and contains a water volume of about 14.1 km^3 with a maximum depth of about 175 m (Nolan and Brigham-Grette 2007). The flanks are characterised by steep slopes down to depths of 150 m (locally as steep as 45°) beneath which the lake bottom slopes gently to the deepest point north-east of the lake center. Most of the catchment is restricted to an area inside the crater rim (Fig. 1) and comprises 293 km^2 (Nolan et al. 2003), which includes 50 small streams draining into the lake (Nolan and Brigham-Grette 2007). The Enmyvaan River at the southern end of the lake is the only outlet stream (Fig. 1). Mean January temperatures are around –32 to –36°C, and mean June temperatures range from +4 to +8°C. Only from mid-July to mid-September, is the lake totally ice-free. Russian investigations imply that the crater and surrounding hills have never experienced glaciation (Glushkova et al. 1994), which is consistent with findings on the glacial history of other parts of Chukotka (Brigham-Grette et al. 2007). Therefore, the crater lake has the potential to provide an undisturbed paleoclimate record of the last 3.6 million years. Previous analysis of sediments recovered in a 13 m long core from the deepest part of Lake El'gygytgyn are consistent with this assumption. The core has a basal age of about 250,000 years (Nowaczyk and Melles 2007) and contains a complete and undisturbed lacustrine sequence of the last three climate cycles with no evidence of erosion during glacial periods (Melles et al. 2007).

There is various evidence for an impact origin of the lake (Dietz and McHone 1976; Hodge 1994; Masaitis 1999). This includes a gravity profile across the crater that exhibits a positive anomaly of 15 to 20 mgals in the center of the crater. This anomaly is probably related to a central uplift of the type often seen in impact structures of the size of the El'gygytgyn crater, and is located about 3 km to the NW of the center of the present lake (Alyunin and Dabizha 1980; Dabizha and Feldmann 1982). Rocks and minerals from the crater show evidence of shock effects, ranging from planar features in quartz grains to the presence of coesite, stishovite and lechatelierite (Hodge 1994). Up to the time of our investigation, no impact breccia has been reported from El'gygytgyn although numerous tectites are found in the catchment (e.g. Gurov 1986; Gurov and Gurova 1996). Tectites were dated by Layer (2000) to approx. 3.6 Ma ago, the likely time of impact. Belyi (1997) interpreted the El'gygytgyn depression largely as a product of the neotectonic evolution of Northeast Asia, which is not consistent with any of this evidence.

As part of a multidisciplinary expedition to Lake El'gygytgyn in August 2000 (THE-IMPACT Project, Terrestrial History of El'gygytgyn—International Multidisciplinary Paleoclimate Project), we carried out the first seismic investigations of the crater lake. Due to the remote location of the lake (Fig. 1) all measurement equipment, including the vessel, had do be flown in by helicopter. The expedition faced logistic problems due to a severe kerosene shortage in Pevek, a town on the coast of the East Siberian Sea and the closest helicopter base to the lake. This fuel shortage limited helicopter flights to the lake and thus transport capacity. In order to carry out preliminary seismic investigation under these circumstances, we followed a Swiss approach for investigation of perialpine lakes (see Finckh et al. 1984 and references therein) by using a small and portable compressor, air gun, single-channel streamer and sediment echosounding equipment.

One major goal of this study was to develop a preliminary two-dimensional velocity–depth model based on sonobuoy seismic-refraction data. This model provides the first interpretation of the thickness of the sediment fill and of the presence and thickness of an impact breccia layer overlying Cretaceous bedrock. The second goal was to analyse the geometry and seismic facies of the sediment fill from both air-gun reflection and sediment echosounding data. This allows a preliminary interpretation of the seismic facies and sediment accumulation characteristics in the lake and thus an assessment of the potential of the record for future deep drilling. The seismic data obtained in 2000 were also used to improve our acoustic acquisition techniques on remote lakes which were applied during a second seismic survey of Lake El'gygytgyn in 2003. At the time of acceptance of this paper, the new results were still in the processing and interpretation stage but are now partly published (Gebhardt et al. 2006).

Data acquisition, processing, and analysis

For data acquisition, we used a 3×4 m aluminium platform ("R/V Helga") equipped with 4 inflatable tubes for flotation and a 25 HP outboard engine (Fig. 2). The maximum total loading capacity of the vessel for safe operation is about 1000 kg. A Bolt 600B airgun (5 cu inches) supplied with a diving compressor (Bauer Oceanus, capacity 140 l min^{-1}) was used as an acoustic energy source. The shot interval was 6 s with approximately 110 bar gun pressure. The

Fig. 2 Research platform ''Helga'' on Lake El'gygytgyn in summer 2000

average speed of the vessel was 4–5 km h^{-1}. For acquisition, we used a 20-element single channel hydrophone streamer (Geoacoustics AE5000), connected to a digital receiver (Octopus 360) via interface box to create digitised data in SEG-Y format. In addition to the Geoacoustics hydrophone streamer, a single hydrophone (OYO Geospace/Kalamos, Canada, model MP24-L3, 10–500 Hz) was towed some 20 m behind the vessel at about 0.5 m depth. Analogue seismic data were plotted on chart recorders (Dowty Maritime Systems Ltd., Model 3710; Ultra Electronics, Model 120–138) and stored together with the trigger signal and navigation data on a 4-channel DAT-recorder (Sony PC204Ax). Two sonobuoys (built at AWI Bremerhaven) were deployed during calm weather periods in areas where single channel reflection data indicated horizontal or almost horizontal subbottom layering in the top 200 m of sediments. The sonobuoys recorded airgun-generated acoustic pulses at a single hydrophone under the buoy (e.g., Dobrin and Savit 1988). The signals were amplified and transmitted via radio to ''R/V Helga'' where WINRADIO on a PC was used as receiver. Two sonobuoy profiles were shot and recorded in both directions along lines crossing near the center of the lake (Fig. 3). However, there is no overlap in the resulting refraction data presented in this paper because the sonobuoys were placed 4.5 km apart but only up to 2.2 km of data directly adjacent to the two buoys were used due to very low signal to noise ratios at larger offsets. After the Octopus receiver failed to digitise the sonobuoy data in the field, we used a computer programme written by one of the authors (C. Kopsch) to produce digital SEG-Y format data from the field analog DAT tapes in the laboratory.

For high-resolution data acquisition, a 3.5 kHz sediment-echosounding technique (ORE, Model 140) was applied. The 3.5 kHz data were obtained on tracks along previous airgun profiles, plus some additional profiles. Analogue printing and data storage, as well as digital storage, was done in a similar way as for the airgun profile data. During this campaign, a total length of 62.5 km of airgun reflection profiles were acquired, together with 69.4 km of high-resolution echosounding profiles (Fig. 3).

All acoustic data were processed using Reflex software (Sandmeier Software, Germany). 3.5 kHz sediment echosounding data were filtered

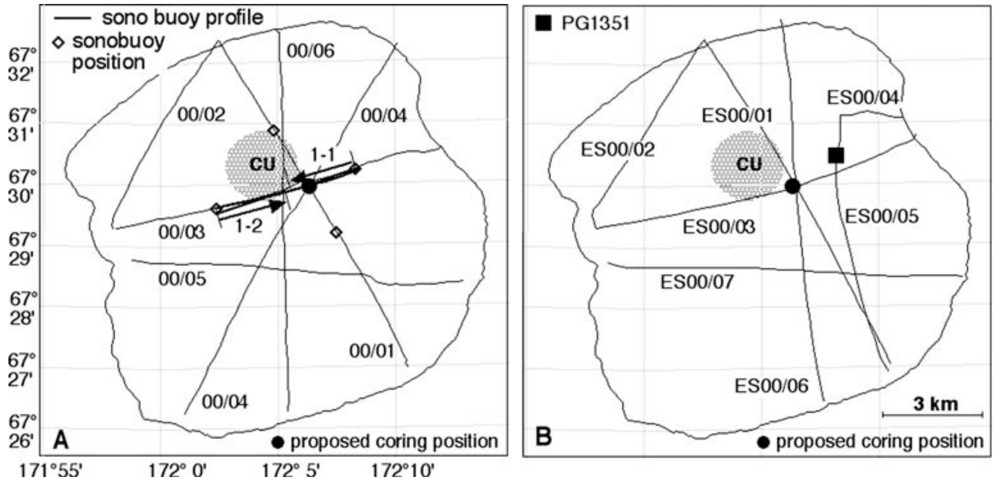

Fig. 3 Track lines of the 2000 seismic survey (Airgun single-channel reflection including sonobuoy profiles (**A**) and 3.5 kHz track lines (**B**). CU marks the area where the central uplift of the crater is expected to be located as indicated by a sedimentary drape and faults described in this paper. A new piston core was retrieved in 2003 at the proposed coring position. This position is considered suitable for deep drilling in the framework of ICDP

from 15 to 5000 Hz. Air-gun reflection data obtained by single hydrophone and 20-element streamer were bandpass-filtered from 150 to 1000 Hz and stacked (3-fold or 5-fold). Sonobuoy refraction data were bandpass filtered from 0 to 60 Hz. The slopes of the ray paths of the direct wave and refracted waves (including intercept times) were determined graphically from plots of the filtered sonobuoy data (Fig. 4). Layer velocities and thicknesses were computed according to the method in Dobrin and Savit (1988), assuming horizontal layering and increasing sonic velocities with depth.

In order to get a first idea of the velocities in the basement and catchment rocks of the El-gygytgyn crater, a few hand specimen of different gravels derived from the Cretacous volcanics of the surrounding hills were collected. Parallel planes were cut off on both sides of the specimen to allow p-wave velocity measurements to be made on the rocks using the p-wave device of a Multi-Sensor-Core-Logging system (MSCL, Geotek, Hazlemere, UK). The travel distance of the 500 kHz pulses through the rock between the transducers was about 6 cm. The specimens were measured under normal laboratory conditions (atmospheric pressure, 20°C room temperature).

Results

Velocity and depth analysis from refraction data

Refraction data from profiles SB00/1-1 and SB00/1-2 exhibit four traces of refracted waves at distances between 1.4 and 2.5 km from the sonobuoy, which allow ray tracing (Fig. 4) and analysis. The data defines a velocity–depth model of five layers, labelled I to V (Table 1, Fig. 4). The model exhibits a stepwise increase in layer velocities from top (1420 m s^{-1}) to bottom (5807 and 6870 m s^{-1}) at depths of 814 and 980 m sub-bottom for profiles 1–1 and 1–2, respectively. The uppermost unit (I) is the water column and has a known velocity of 1410 m s^{-1} for fresh water at a temperature of 2°C. Temperature and water depth were measured during the expedition. The temperature profile was uniform from the surface to the bottom of the lake. The model (Table 1) modifies an earlier interpretation by Niessen et al. (2000) using unfiltered field analogue plots of the same data set analysed in this paper, in which the refracted waves of unit V were not apparent.

Refracted waves are clearly visible only over limited depth and time ranges (Fig. 4), and partly

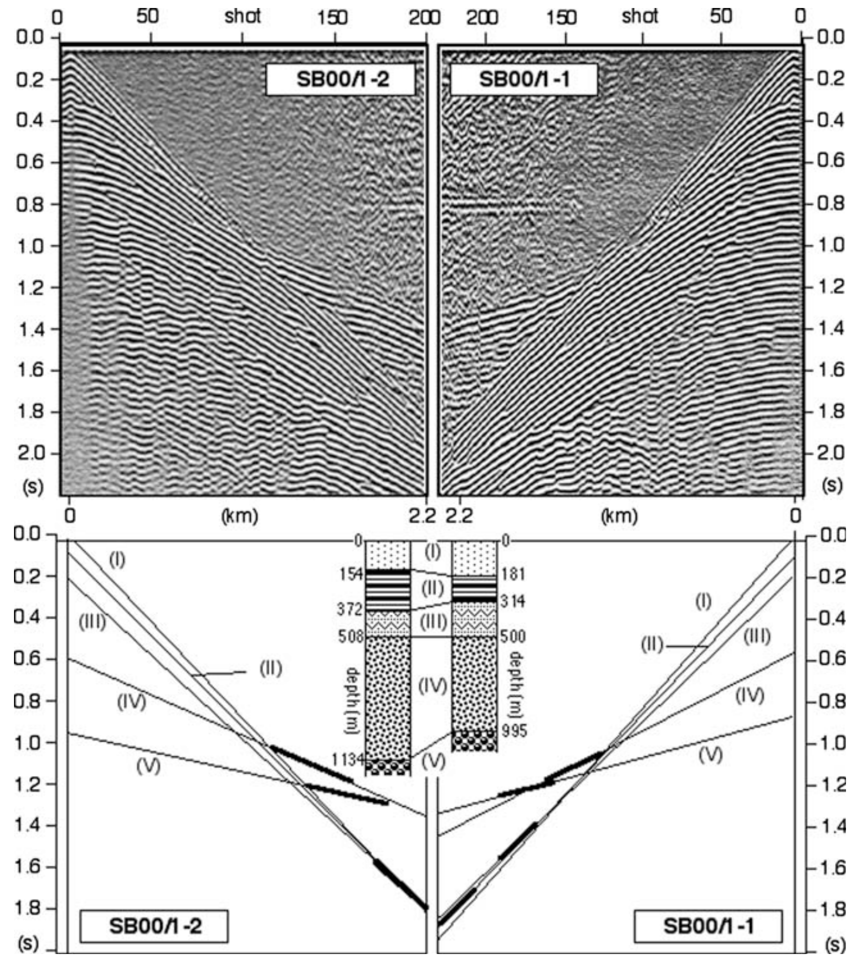

Fig. 4 Refraction data of profiles SB00/1-1 and SB00/1-2, (0–60 Hz, upper part), ray tracing and velocity–depth model for SB00/1-1 and SB00/1-2 (lower part). Bold lines mark the sections in the datasets, where refracted signals were used to calculate the velocity–depth models (Table 1). Light lines were used to detect intercept times. (I) is the direct wave through water and (II) to (V) are refracted waves from sediments to bedrock. Track lines in Fig. 3

overlap each other. Ray tracing and resulting trace-angles and intercept-times (Fig. 4, Table 1) may therefore be affected by substantial errors. In particular for the second and third unit, the angles of inclination of the refracted signals are small with respect to that of the direct wave, a relationship that has a large effect on determination of the intercept time and thus unit thickness. For example, the thickness of the first unit, the water column, whose thickness is known to be 175 m, is calculated from the refraction data to be 154 m and 181 m in the two refraction profiles

Table 1 Ray-tracing results and velocity–depth model interpreted from sonobuoy refraction data (Fig. 4)

Profile (no.)	Intercept time (ms)	Trace angle (°)	Velocity (m s^{-1})	Thickness (m)	Unit (no.)
2000/1-1	0	49	1420	181 (170*)	I
2000/1-1	103	51.5	1552	133	II
2000/1-1	196.5	53.5	1668	186	III
2000/1-1	561	68	3086	495	IV
2000/1-1	898	78	5807	—	V
2000/1-2	0	61.5	1420	154 (170*)	I
2000/1-2	93.5	64	1574	218	II
2000/1-2	196	65.5	1684	136	III
2000/1-2	580	77	3340	626	IV
2000/1-2	963	83.5	6870	—	V

Unit I is the water column of which the velocity and thickness (175 m) is known from bathymetry and temperature profiling

(Table 1), suggesting an error of about +/– 10% in the velocity–depth model.

Rock velocity measurements

The velocities measured in 11 Cretaceous rock specimens from the Elgygytgyn catchment are 5117, 5904, 7105, 3362, 4410, 4027, 3666, 4268, 6089, 4430, and 5998 m s^{-1}. The average of these velocities, about 4950 m s^{-1} can be used as a rough approximation to the sonic velocity in the bedrock under the crater basin. Lower velocities are measured on ignimbrites, medium velocities on rhyolithic rocks and high velocities, of around 6000 m s^{-1}, were measured on basalts.

Single channel reflection seismic and seismic stratigraphy

Reflection seismic data exhibit an upper, well-stratified, sedimentary unit with a relatively flat upper surface throughout almost the entire lake (unit II, Figs. 5, 6). This unit exhibits onlap against the steep slope at the lake margins. The entire basin has the geometry of a slightly asymmetric bowl, in which deposits gradually mute a formerly deeper and even steeper relief (Fig. 5). The strata are intercalated with thick debris flows that occur mainly in the marginal areas (Figs. 5, 6).

A third unit (III), more massive, is visible underlying the upper, well-stratified, unit. The boundary between the two is not very distinct and may be transitional (Figs. 5, 6). Only the upper part of unit III is resolved, as the lower part—and sometimes even the transition between units II and III—is obscured below 0.4–0.5 s two-way travel time by high-amplitude multiples (Figs. 5, 6), that could not be eliminated during data processing. In addition, unit III exhibits a low signal-to-noise ratio possibly as a result of a combined effect of poor acoustic penetration and lower reflection coefficients in this unit. The boundary between units III and IV, determined from the refraction data to occur about 500 m below the lake surface (Table 1), is not visible in the seismic reflection

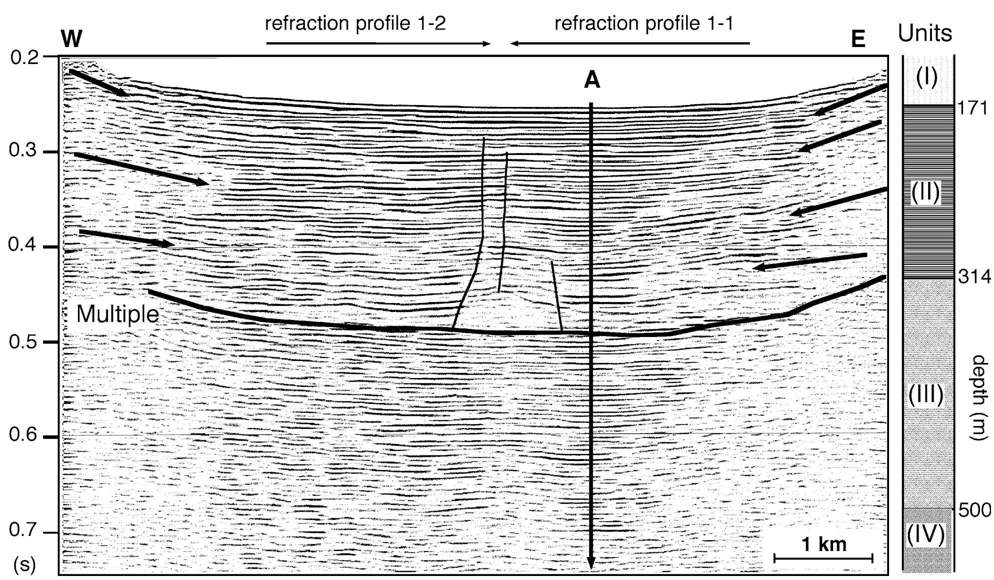

Fig. 5 Processed (5-fold stack, 150–1000 Hz) single-channel air-gun profile 00/03 (track line in Fig. 3). Faults (thin lines) are interpreted near the center of the profile down to the first lake-bottom multiple, where a sedimentary drape is visible in the lower part of unit II. Arrows in Unit II indicate the presence of debris flows. Note that sonobuoy profiles 00/1-1 and 00/1-2 were recorded almost along the same line as profile 00/03 (Fig. 3) in the east-west and west-east directions, respectively (marked by arrows above unit I). The velocity–depth model (Table 1) was used to convert travel time to depth and to add the units derived from refraction seismic to the profile (I–IV). Note that the transition from unit II to III is hardly visible and the transition from unit III to IV is not visible in the profile as a result of the dominance of multiples below 0.5 s travel time. Line A marks the position considered suitable for deep drilling, and where an additional piston core was retrieved during the expedition in 2003

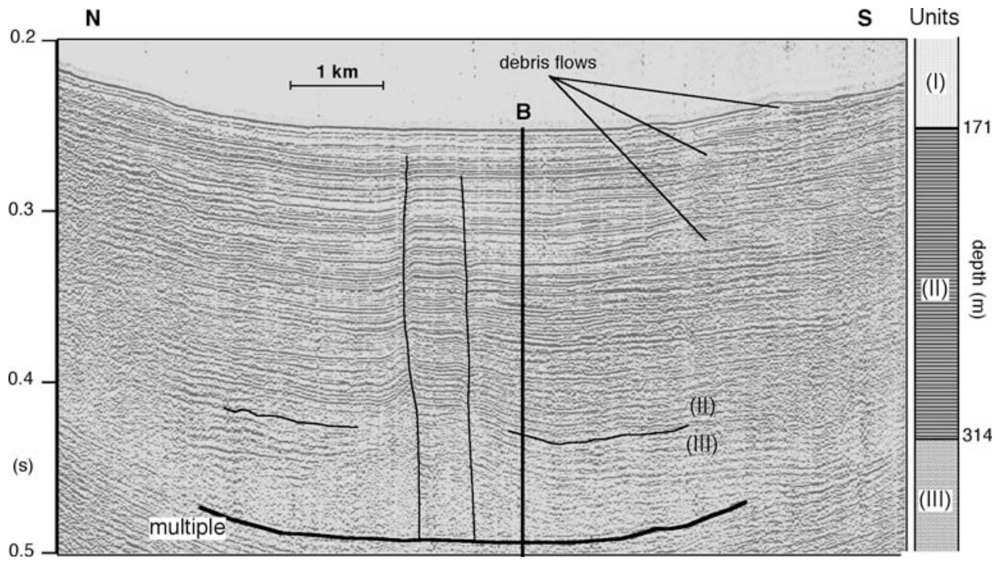

Fig. 6 Processed (3-fold stack, 150–1000 Hz) single-channel air-gun profile 00/06 (track line in Fig. 3) of units I to III. Faults (thin lines) are interpreted near the center of the profile. In the area of the faults, a sedimentary drape is clearly visible in unit II, where the central part appears to sag in a graben-like structure between the faults. The interpretation lines (thin) between 0.4 and 0.45 s mark the postulated boundary between units II and III. Line (B) marks the intersection with profile 00/03 (Figs. 3, 5)

profiles due to multiples and to the very poor signal-to-noise ratio at subbottom depths of more than 200 m (Fig. 5).

An anticline structure is observed near the center of the lake, indicated by a sedimentary drape in the lower strata of the well-stratified unit II and in unit III. This anticline is situated in the northern part of the lake (Fig. 3) and is more clearly visible in profile 00/06 (Figs. 3, 6) than in profile 00/03 (Figs. 3, 5). It has a relief of about 15 m and a wavelength of about 2 km at the bottom of unit II (Fig. 6). Normal faults occur within the anticline structure (Figs. 5, 6). At a depth of about 40 m subbottom, the displacement on these faults is about 3 m, whereas the sediment surface is not displaced by them. As a result neither the faults nor the anticline structure are apparent in present-day bathymetry.

High resolution sediment echosounding

The marginal areas of the lake yield only poor penetration of the 3.5 kHz pulses resulting in limited resolution (Fig. 7). This is likely to be the result of the presence of large quantities of gravel derived from permafrost soils, which accumulated on beaches and lacustrine slopes. In contrast, data from the deeper part of the lake show the upper 30–40 m of the well-stratified unit in great detail (Figs. 5, 7) at a resolution of about 0.3 m (Figs. 8, 9).

Similar to the airgun reflection–seismic data, sediment echosounding data exhibit a well-stratified unit intercalated with debris flows (Fig. 7). In particular, a distinct low-amplitude sediment-surface relief in the deeper part of the basin is visible in the echosounder profiles, which is only indistinctly resolved by the reflection–seismic data (Figs. 5, 6). Typically, the relief is related to distal termination lobes of debris flows where the flow thickness can rapidly decrease from about 2 m to 0 m over a lateral distance of less than 50 m (Fig. 8). Debris flows are most abundant at the marginal areas of the basin, but some are observed in the central parts of the basin (Fig. 7), where the slope is very gentle. Some debris flows exhibit an erosive base because some underlying reflectors appear truncated (Fig. 8). However, there are cases where clear evidence of erosion is absent so that flow deposits may overly older

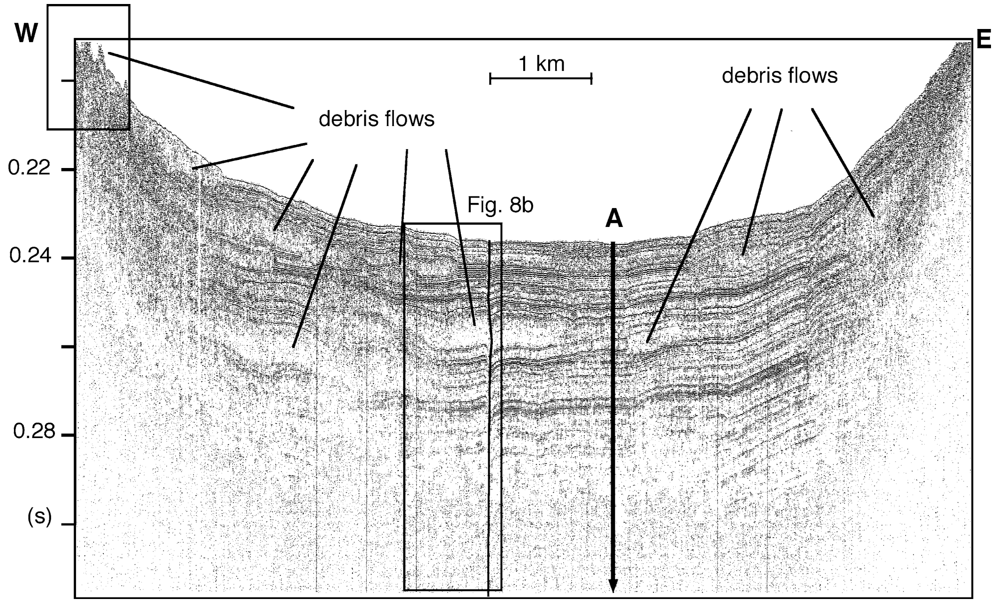

Fig. 7 3.5 kHz sediment echosounder profile ES00/03. The line provides a high-resolution image of the upper 40 m of air-gun profile 00/03 shot along the same line (Figs. 3, 5). The fault interpreted near the center of the profile is the upward extension of the westerly fault visible in Fig. 5. Line A marks the position considered suitable for deep drilling, and where an additional piston core was retrieved during the expedition in 2003

strata concordantly. In general, in the distal areas of the deeper basin, even relatively thick debris flows have over-ridden the strata with little erosion effect. The thicknesses of proximal debris flows can be more than 20 m, and those in the deeper part of the basin can still be up to 3–4 m thick (Fig. 8). Near steep slopes, particularly in the northern and western part of the lake, proximal debris flows are characterised by high relief surfaces (Fig. 8) and strong acoustic backscatter. The basal planes of proximal debris flows are not visible in 3.5 kHz profiles due to limited acoustic

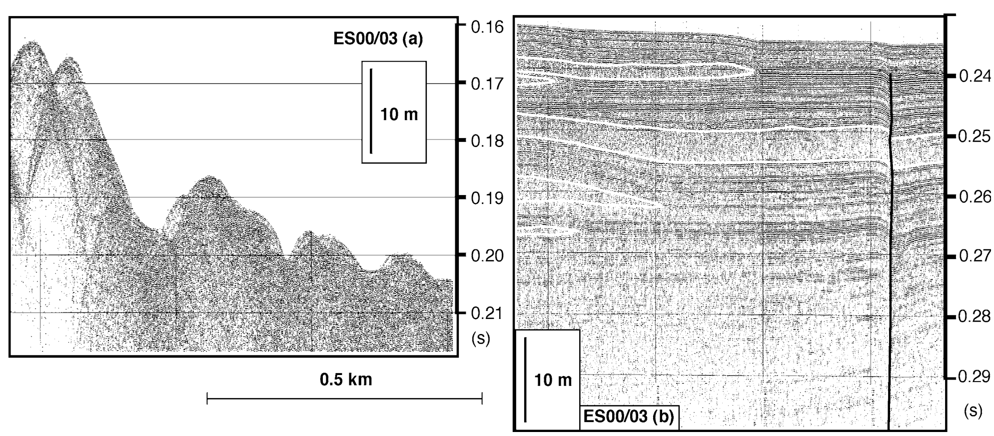

Fig. 8 Sections of sediment echosounding (3.5 kHz) profile ES00/03 (location in Fig. 7). Horizontal scale is valid for both sections (**a**) and (**b**). Section (**a**) exhibits the hummocky surface and backscatter character of a proximal debris flow exposed at the lake-floor surface, suggesting a relatively young age of the deposit. Note that the base of the proximal flow deposit is not evident in the 3.5 kHz data near the western slope. Diffraction hyperbolae between 0.17 and 0.19 s may be related to side echos. They suggest that the hummocky surface is not fully resolved within the 3.5 kHz signal footprint. Section (**b**): Typical distal facies of well-stratified sediments intercalated with debris flows (outlined by white lines) and their vertical displacement along a normal fault (interpreted by thin line)

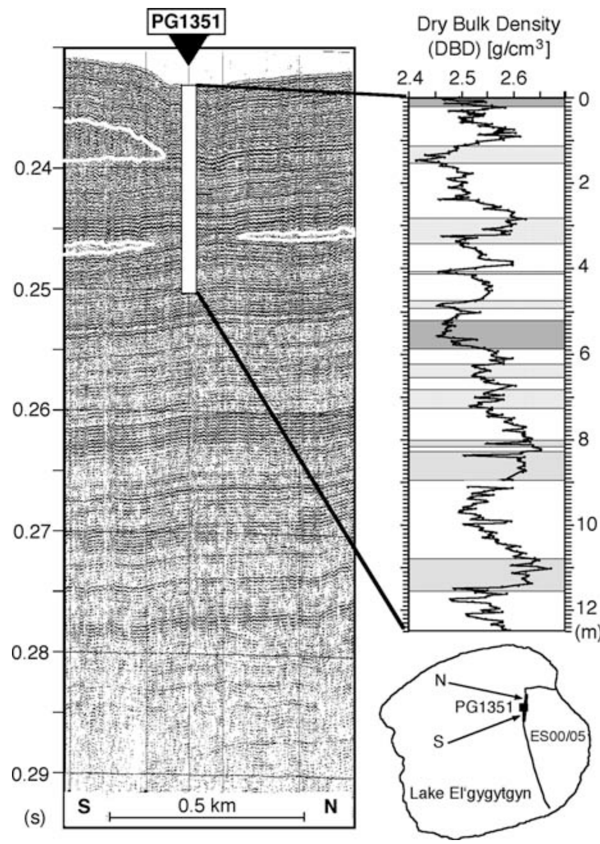

Fig. 9 Section of 3.5 kHz sediment echosounder profile ES00/05 (location in Fig. 3) in the deepest part of the lake and across the location of piston core PG1351 (Fig. 1, Melles et al. 2007). The 3.5 kHz data are correlated with the core using a sonic velocity of 1500 m s^{-1} for the uppermost sediments. The core exhibits distinct variability of climatic changes over the last c. 250 ka, here expressed by changes in dry bulk density (data and interpretation in Melles et al. 2007). Note that some debris flows visible in the acoustic image (outlined by white lines) extend almost to the coring location. No debris-flow deposits were found in the core

penetration. Most distal debris flows are almost acoustically transparent and show no internal structure (Figs. 7, 8).

Only a few thin debris flows reached the deepest area of the lake, located in the north-eastern corner (Fig. 9), where core PG1351 was recovered during the first pilot study in 1998 (Melles et al. 2007). The core contains the upper 13 m of sediment and yields an undisturbed paleoclimate record of approximately the last 250 ka (Nowaczyk and Melles 2007). Our high-resolution echosounding data show that the core was obtained in well-stratified sediments that are largely unaffected by debris flows (Fig. 9).

The anticline structure observed in the single channel reflection seismic is not visible in the sediment echosounding profiles because penetration of the 3.5 kHz pulse is not deep enough. One of the normal faults associated with the anticline, however, is clearly evident in the sediment echosounding profiles. Both stratified sediments and debris flow deposits are displaced vertically without any change in thickness on either side of the fault (Fig. 8).

Discussion

Impact features, basement depth and total sediment fill

Sonobuoy refraction data, combined with single-channel reflection–seismic data, reveal a five-layer fill in the crater lake: unit I is the water column, units II and III represent the upper and lower sediment fill, unit IV forms a transition, and unit V the target bed rock (Fig. 4). We interpret units II and III to consist of unconsolidated lacustrine sediments because of their low seismic velocities (Table 1). The 13 m long sediment core (PG1351), taken in 1998, yields a silty-clay sediment record for the uppermost 13 m of unit II (Melles et al. 2007) that is in good agreement with our findings. It is possible that the increase in velocity from unit

II to unit III (Table 1) occurs at the boundary between the upper well stratified and lower more massive sediment layers described from reflection profiles. This interpretation is preliminary because of the impreciseness of the depth determination from the refraction data within the sediment sequence (described above). Also, our approach using constant velocity layers may to be too simple because velocity gradients appear to be more likely. More processing of the sonobuoy data and elimination of multiples on new datasets must be completed before detailed interpretation of the entire sediment fill will be possible. However, since the upper surface of unit IV is clearly documented in the processed refraction profiles, the total sediment thickness in the center of the lake can be estimated as about 320–350 m in profiles SB00/1-1 and 1-2, respectively. This is slightly less than the total sediment thickness of 350–400 m estimated from the unfiltered field version of the same data set by Niessen et al. (2000).

The velocity of more than 3000 m s^{-1} in unit IV is clear evidence that this layer consists of rock, which is interpreted as a suevite layer or impact breccia. The upper part of the target rock in meteorite craters is commonly brecciated to significant depths. Such breccias have lower sonic velocities than volcanic rocks. The velocities determined for unit IV are significantly lower than the velocities measured on hand specimens of Cretaceous volcanic rocks from the El'gygytgyn catchment (4950 m s^{-1} on average). Similarly, results from seismic measurements in the Ries crater in southern Germany (Angenheister and Pohl 1976) give seismic velocities of 3.0–3.4 km s^{-1} in the suevite layer. In a recent study of the Lake Bosumtwi impact crater, Karp et al. (2002) identified the top of the breccia at a depth between 260 and 380 m and determined velocities between 2500 and 3500 m s^{-1} using an Ocean Bottom Hydrophone. Considering the fact that the Bosumtwi crater is slightly smaller than the El'gygytgyn crater, this is in good agreement with our conclusion that unit IV consists of brecciated bedrock (suevite). For the Lake Bosumtwi, the maximum thickness of the breccia layer is interpreted from different types of seismic data as about 600 m in the central part of the crater (Karp et al. 2002; Scholz et al. 2002). The thickness of the breccia in Lake El'gygytgyn is interpreted as about 500–600 m as based on the depth to the lowermost refractor in our refraction profiles. The estimated bedrock velocities (unit V) of more than 5000 m s^{-1} are in the range typical for Cretaceous volcanic rocks or basement, and are consistent with our velocity measurements on hand specimens.

As in many other craters of similar size, the breccia layer in Lake Bosumtwi shows a significant central uplift, which has a wavelength of 1.8 km and a peak height of 120 m (Scholz et al. 2002). Central uplifts are characteristic features of many medium sized impact craters and are formed as release structures in the upper part of the target rock relatively soon after the impact event (Dressler and Reimold 2001). Although our data cannot show whether the base of the observed anticline occurs at the sediment-breccia interface, we interpret this structure to be related to the central uplift of the El'gygytgyn crater. The anticline is located in the northern half of the lake, which is more or less in the center of the crater, and coincident with the location of the crater's central density anomaly some 3 km northwest of the center of the lake (Alyunin and Dabizha 1980; Dabizha and Feldmann 1982). The interpretation is also in agreement with new fully processed sonobuoy and multi-channel seismic data from Lake El'gygytgyn (Gebhardt et al. 2006). These new findings exhibit the presence of possible parts of a more complex central uplift than the simple anticline suggested here. The top of the uplift lies in a depth window strongly obscured by multiples and is thus not visible in the single-channel reflection data presented in this paper (Fig. 5).

The anticline structure seems to be associated with faults observed in the sedimentary cover of unit II because such faults are not observed elsewhere in the lake. Since the displacement extends almost to the sediment surface, the faulting must be a relatively young feature, far younger than the impact some 3.6 Ma ago. This is obvious from the geometry of a relatively young debris flow, which is displaced by one of the faults (Figs. 6, 8b). According to preliminary lateral correlation in 3.5 kHz data between the fault and core PG1351, the age of the flow is younger than 250 ka BP. If the flow is younger than the fault, removal of fault-related relief during deposition would be expected, but this is not observed. Hence, we suggest that the area of the central peak remained unstable until quite recent times, possibly due to long-term processes related to isostatic rebound. Similar faults, with vertical displacements of 1–3 m, are also visible in sediments over the Bosumtwi crater central uplift in high-resolution seismic-reflection profiles published by Scholz et al. (2002). The Bosumtwi faults are interpreted as having been initiated by sagging of the uplift and were later reactivated. Within the Eocene Chesapeake Bay impact crater (US Atlantic Coastal Plain) all postimpact depositional units are cut by numerous normal faults that are interpreted as the result of differential compaction and subsidence of the underlying breccia lens (Poag 1997). Some of these faults appear to extend to (or near) the bay bottom making them very similar to the faults observed in the El'gygytgyn and Bosumtwi craters. Therefore, differential compaction of brecciated material in the central peak may be a major process leading to fault formation in the sediments overlaying relatively young impact craters.

Because the sonobuoy data were recorded south-west and south-east of the expected location of the central peak (Figs. 1, 2), our velocity–depth model is probably more applicable to the south-eastern flank of the peak (Fig. 5). If so, the surfaces of units IV and V are expected to dip away from the central uplift, which may affect the refraction data to a significant extent. If this is the case, the basement velocities and breccia thicknesses would be overestimated in our model (Table 1), because the data from both profiles would have been recorded in an up-dip direction. Indeed, the calculated velocities for unit V, of 5807 m s^{-1} and 6870 m s^{-1}, do seem to be higher than would be expected for the target rock under the breccia. Therefore, a refractor at the top of unit V that dips, away from the central uplift is a strong possibility. The numbers given in the model for units IV and V (Table 1) should be treated as maxima until a full three-dimensional velocity–depth model of the Lake El'gygytgyn crater basin becomes available.

Nolan et al. (2003) described characteristic circular structures in the winter ice cover of Lake El'gygytgyn from satellite backscatter images. A central darker area of ice occurs more or less in the same location as the buried anticline structure introduced here. This coincidence suggests a possible relationship. One of several explanations is linked to the likehood that lake-ice physics depends on biological productivity under the ice. Among other factors, the latter is likely to respond to water temperature, which could be slightly increased over the central peak due to a higher geothermal gradient in this region of significantly thinner sediments (Nolan et al. 2003). In addition, it may be possible that the ring structures in the ice cover are related to gas or fluids, migrating upward along the faults in the basin fill. If so, differential compaction, which controls fault development also has a significant effect on the modern limnology of Lake El'gygytgyn. However, although the center of the ring structures observed in the ice is some distance north of the center of the lake it is still south of the center of the crater. Our 2000 seismic-profile cover is not dense enough to exactly map the anticline structure in the sediments, in order to localise the highest point of the peak. Therefore, a possible correlation of the observed features remains open until more data is available.

Sediment characteristics and depositional environment

There is no evidence in unit II for the erosional features typically formed by glaciers in association with basal till deposits like those, for example, described in seismic profiles from Swiss Alpine lakes by Finckh et al. (1984). Hence, the general pattern in the upper sediment unit indicates a glacially undisturbed record for at least the upper 200 m of the sediment fill (Figs. 5, 6).

Numerous debris flows intercalated with well-stratified sediments in the lake's uppermost sediment unit are evidence for substantial lateral sediment transport from the slopes into the basin. Understanding these debris flows is of great importance for paleoenvironmental interpretation of the sedimentary record. According to high-resolution sediment echosounding (3.5 kHz), the debris-flow deposits account for a significant proportion of the total sediment thickness in the deeper part of the lake and thus influence the sediment budget of the lake basin. During their down-slope motion, most debris flows generate turbidity currents (Fisher 1983; Hsü and Kelts 1985), which is of importance for the interpretation of sediment cores because both debris flows and turbidites can erode previously deposited material and thus affect the completeness of a record.

Only a small number of thin turbidites were observed during the 250 ka record in core PG1351 (Melles pers. commun.), although some relatively thick debris flows terminate not far away from the core position (Fig. 9). Therefore, despite the large number of debris-flow deposits, Lake El'gygytgyn is not a typical turbidite basin, which is consistent with the lithology of core PG1351. In seismic images, typical turbidite lakes are ponded with nearly horizontal stratification in the deepest part of the basins, often associated with high sedimentation rates (e.g., Schröder et al. 1998). Ponding is not seen in our study, and sedimentation rates are quite low (13 m in 250 ka) in the deepest part of the lake, where core PG1351 was retrieved (Fig. 9). This implies that debris flows in Lake El'gygytgyn rarely or never developed into turbidity currents that carried significant loads of sediments to the deepest part of the basin.

In marine debris-flow fans associated with glaciated continental margins (such as the Bear Island Trough Mouth Fan, e.g., Laberg and Vorren 1995, 2000, 2003), debris can travel long distances over slopes with inclination angles as small as $<1°$. Such flows leave deposits several meters thick, that are transparent in subbottom acoustic images, and have well-defined margins and fronts, indicating that they did not experience a transition into turbidity currents (Laberg and Vorren 1995). Although the behaviour of subaqueous flows is still not well understood, the observations are explained by the hypothesis of hydroplaning of the debris flow front (Laberg and Vorren 2003) where a thin layer of water separates the flow from the bed, thereby reducing bed drag (Mohrig et al. 1999). Hsü and Kelts (1985) provide text-book examples of different types of debris deposits from Swiss lake sediments. For example, in Lake Zug, sandy carbonaceous muds on the upper slopes became unstable and were transported some distance into the basin by a thick viscous or, more probably thixotrophic flow. The homogenised muds form a distinct tongue of sediments extending some 1.2 km from the shore and exhibit a typical termination lobe in acoustic images (Hsü and Kelts 1985). Only a small low-density turbidity current was generated by the Lake Zug slide (Hsü and Kelts 1985). The ratio of turbidite to slide mass is small for thixotropic flows as compared to other debris flows, where a large part of the slump mass can be dispersed to form suspension and eventually settle as turbidity current deposits of significant thickness (Hsü and Kelts 1985).

At the present level of investigation, one can only speculate about similar processes controlling sediment flow behaviour in Lake El'gygytgyn. Studies to work out whether the occurrence of these debris flows is cyclic, and possibly related to climate-sensitive processes in the catchment permafrost, are under way. This includes mapping debris flows in space and time using seismic data, and correlation with dated sediment cores to better understand the physical signature and origin of the flows.

A chronological model was developed for core PG1351 (Nowaczyk et al. 2002; Nowaczyk and Melles 2007) that suggests a basal age of about 250 ka BP at 13 m below the lake floor. Based upon an extrapolation of sedimentation rates during the last 250 ka, the transition between unit II and III possibly coincides with the first major glaciation of the northern hemisphere at around 2.6 Ma ago (e.g., Shackleton 1984). Because climatic variability was more pronounced during the Quaternary than the Pliocene, climatic deterioration may be the reason for the change of seismic character from unit III (more massive) to unit II (well-stratified). If this is true, the lower sedimentary unit could have been accumulated before 2.6 Ma ago with sedimentation rates almost twice as high as for the upper sediment unit and with less variability. To test this hypothesis, additional research at the El'gygytgyn Lake is under way. In 2003, more seismic profiling using multi-channel techniques, was carried out to investigate in particular the lower part of the sediment fill, its contact with the breccia and the morphology and structure of the central uplift. These data are presently being processed.

Conclusions

As revealed in refraction- and reflection–seismic data, Lake El'gygytgyn has developed in an impact crater that is comparable to other impact craters of similar size (e.g., Ries Crater, Germany, or Bosumtwi Crater, Ghana). It is likely that the surface of the target rock forms a depression with a central uplift structure, although our evidence for this is only indirect (faults and sedimentary drape) because the actual contact between sediments and the uplift structure is obscured by multiples and not visible in the data presented here. However, we are confident that, according to our new velocity–depth model, the target rock was brecciated to a depth of up to 500–600 m. In the center of the present lake, a few km to the SE of the assumed central uplift of the crater, the total sediment fill is 320–340 m thick, possibly. Our findings, together with previous gravimetric data and the occurrence of shock-metamorphic rocks, are strong evidence for an impact origin for the El'gygytgyn crater.

After its creation, the crater was filled with sediments derived from its rim. Our working hypothesis is that in a first phase, of about one million years duration, a massive sedimentary fill with a maximum thickness of about 130–190 m was deposited in the ring basin and on top of the central peak, but did not entirely bury the uplift structure. The sedimentation rate during this first phase was likely to have been relatively high, as it occurred under a warmer, more humid climate and with a relatively young high relief in the surrounding hills. About 2.6 Ma ago, during the first major glaciation of the Northern Hemisphere, the erosional/depositional regime in the crater area changed, resulting in the deposition of a well-stratified seismic unit with significantly higher reflection coefficients, suggesting distinct variability in sediment composition, possibly as a consequence of climatic change and more pronounced variability. The geometry and reflection characteristic of the lacustrine fill result in strong multiples that do not allow a complete resolution of the lower sediment fill and its contact with the breccia. This situation may be alleviated when fully processed multi-channel seismic data become available.

Input of terrestrial sediments, particularly from the western and north-western area of the catchment, asymmetrically filled the lake so that the present basin is now displaced a few kilometers to the southeast of the center of the crater. This sediment input is documented by slope instability and formation of numerous debris flows. It is concluded from acoustic images and sediment cores that the flow behaviour leads to minor erosion and that the formation of turbidity currents in the deepest and distal areas of the lake is rare. For the future, deep drilling is planned in Lake El'gygytgyn within the framework of the International Continental Drilling Program (ICDP). We suggest that areas distal from debris flows bear a great potential for paleoclimatic studies from long sediment cores.

Acknowledgements The financial contribution of the American National Science Foundation (grant from the Office of Polar Programs and the Earth System History Program to J. Brigham-Grette) and of the German Alfred-Wegener-Institute for Polar and Marine Research (AWI), which made the expedition in 2000 possible, is greatly appreciated. We thank our colleagues, J. Brigham-Grette, Celeste Asikainen, Matt Nolan, Mike Apfelbaum, Pavel Minyuk, Griguriev Federov, Olga Glushkova and Wladimir Smirnov for their help in the field. Without the great effort of Pavel Minyuk, who was responsible for dealing with the difficulties of logistics in Russia, the expedition would not have been successful. The support and hospitality in Pevek, provided by Michael Baranov of the local Mining Institute, is much appreciated. We are particularly grateful to Yuri Gapkailo from Pevek for letting us use his cabin at the outlet of Lake Elgygytgyn. Hartmut Martens (AWI-Bremerhaven) built and provided the sonobuoys and Gerald Müller (AWI-Potsdam) helped with the logistics to prepare the cargo of the German expedition equipment. We thank our colleague Graham Shields and the two anonymous reviewers, whose comments and suggestions improved the quality of the manuscript significantly.

References

Alyunin AV, Dabizha AI (1980) Geophysical characteristics of meteoritic crater. Lunar Planet Sci 11:21–23

Angenheister G, Pohl J (1976) Results of seismic investigations in the Ries Crater area (Southern Germany). In: Giese P, Prodehl C, Stein A (eds) Explosion seismology in Central Europe; data and results. Springer-Verlag, Berlin, pp 290–302

Belyi VF (1997) Impectogenesis and volcanism of the El'gygytgyn depression. Petrology 6:86–99

Brigham-Grette J, Melles M, Minyuk PS (2007) Overview and significance of a 250 ka paleoclimate record from El'gygytgyn Crater Lake, NE Russia. J Paleolimnol DOI 10.1007/s10933-006-9017-6 (this issue)

Dabizha AI, Feldman VI (1982) Geophysical characteristics of some astroblems. Meteoritica 40:91–101 (in Russian)

Dietz RS, McHone JF (1976) El'gygytgyn: probably world's largest meteorite crater. Geology 4:391–392

Dobrin MB, Savit CH (1988). Introduction to geophysical prospecting. McGraw-Hill Book Company, New York, 867 pp

Dressler BO, Reimold WU (2001) Terrestrial impact melt rocks and glasses. Earth Sci Rev 56:205–284

Finckh P, Kelts K, Lambert A (1984) Seismic stratigraphy and bedrock forms in perialpine lakes. Geol Soc Am Bull 95:1118–1128

Fisher RV (1983) Flow transformations in sediment gravity flows. Geology 11:273–274

Gebhardt AC, Niessen F, Kopsch C (2006) Central ring structure identified in one of the world's bestpreserved impact craters. Geology 34(3):145–148

Glushkova OY, Lozhkin AV, Solomatkina TB (1994) Holocene stratigraphy and paleogeography of El'gygytgyn Lake, northwestern Chukotka. Proc. Intern. Conf. Arctic Margins, Magadan, Sept. 6–10, Magadan, NEISRI FEB Russian Acad. Sci.: 75–80

Gurov EP (1986) Elgygytgyn crater glassy bombs. From impactities to tektites. Lunar Planet Sci 17:301–302

Gurov EP, Gurova EP (1996) Glassy bombs of the El'gygytgyn impact crater. Abstr. 59, Ann. Meet. Meteoritical Soc., Berlin 1996, Meteoritics 31, Supplement:A56

Hodge P (1994) Meteorite craters and impact structures of the Earth. University Press, Cambridge, 124 pp

Hsü KJ, Kelts K (1985) Swiss lakes as a geological laboratory. Part I: Turbidity currents. Naturwissenschaften 72:315–321

Karp T, Milkereit B, Janle P, Danuor SK, Pohl J, Berckhemer H, Scholz CA (2002) Seismic investigation of the Bosumtwi impact crater: preliminary results. Planet Space Sci 50:735–743

Laberg JS, Vorren TO (1995) Late Weichselian submarine debris flow deposits on the Bear Island Trough Mouth Fan. Mar Geol 127:309–330

Laberg JS, Vorren TO (2000) Flow behaviour of the submarine glacigenic debris flows on the Bear Island Trough Mouth Fan, western Barents Sea. Sedimentology 47:1105–1117

Laberg JS, Vorren TO (2003) Submarine glacigenic debris flows on the Bear Island Trough Mouth Fan, Western Barents Sea: aspects of flow behaviour. In: Mienert J, Weaver P (eds) European margin sediments dynamics: side-scan sonar and seismic images. Springer-Verlag, Berlin, pp 83–85

Layer PW (2000) Argon-40/Argon-39 age of the El'gygytgyn impact events, Chukotka, Russia. Meteoritics Planet Sci 35:591–599

Masaitis VL (1999) Impact structures of northeastern Eurasia: The territories of Russia and adjacent countries. Meteoritics Planet Sci 34:691–711

Melles M, Brigham-Grette J, Glushkova OY, Minyuk PS, Nowaczyk NR, Hubberten HW (2007) Sedimentary geochemistry of a pilot core from Lake El'gygytgyn — a sensitive record of climate variability in the East Siberian Arctic during the past three climate cycles. J Paleolimnol DOI 10.1007/s10933-006-9025-6 (this issue)

Mohrig D, Elverhøi A, Parker G (1999) Experiments on the relative mobility of muddy subaqueous and subaerial debris flows, and their capacity to remobilize antecendent deposits. Mar Geol 154:117–129

Niessen F, Kopsch C, Wagner B, Nolan M, Brigham-Grette J (2000) The impact project: seismic investigation of Lake Elgygytygyn, NE Russia — implication for sediment thickness and depositional environment. EOS suppl, Trans Am Geophys Union 81(48):230

Nolan M, Liston G, Prokein P, Brigham-Grette J, Sharpton V, Huntzinger R (2003) Analysis of lake ice dynamics and morphology on Lake El'gygytgyn, Siberia, using SAR and Landsat. J Geophys Res 108(D2):8062

Nolan M, Brigham-Grette J (2007) Basic hydrology, limnology, and meteorology of modern Lake El'gygytgyn, Siberia. J Paleolimnol DOI 10.1007/s10933-006-9020-y (this issue)

Nowaczyk NR, Minyuk P, Melles M, Brigham-Grette J, Glushkova OY, Nolan M, Lozhkin AV, Stetsenko TV, Anderson PM, Forman SL (2002) Magnetostratigraphic results from impact crater Lake El'gygytgyn, northeastern Siberia: a 300 kyr long high-resolution terrestrial palaeoclimatic record from the Arctic. Geoph J Intern 150:109–126

Nowaczyk NR, Melles M (2007) A revised age model for core PG1351 from Lake El'gygytgyn, Chukotka, based on magnetic susceptibility variations correlated to northern hemisphere insolation variations. J Paleolimnol DOI 10.1007/s10933-006-9023-8 (this issue)

Poag CW (1997) The Chesapeake Bay bolide impact: a convulsive event in Atlantic Coastal Plain evolution. Sediment Geol 108:45–90

Scholz CA, Karp T, Brooks KM, Milkereit B, Amoako PYO, Arko JA (2002) Pronounced central uplift identified in the Bosumtwi impact structure, Ghana, using multichannel seismic reflection data. Geology 30:939–942

Schröder HG, Wessels M, Niessen F (1998) Acoustic facies and depositional structures of Lake Constance. Arch Hydrobiol Spec Issues Advanc Limnol 53:351–368

Shackleton NJ (1984) Oxygen isotope calibration of the onset of ice-rafting and history of glaciation in the North Atlantic region. Nature 307:620–623