Clim. Past Discuss., 9, 467–505, 2013
www.clim-past-discuss.net/9/467/2013/
doi:10.5194/cpd-9-467-2013

Climate of the Past Discussions

Mass movement deposits in the 3.6 Ma sediment record of Lake El'gygytgyn, Far East Russian Arctic: classification, distribution and preliminary interpretation

M. A. Sauerbrey[1], O. Juschus[2], A. C. Gebhardt[3], V. Wennrich[1], N. R. Nowaczyk[4], and M. Melles[1]

[1]Institute of Geology and Mineralogy, University of Cologne, Zuelpicher Str. 49a, 50674 Cologne, Germany
[2]Eberswalde University of Sustainable Development, Faculty of Landscape Management and Nature Concervation, Eberswalde, Germany
[3]Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany
[4]Helmholtz Center Potsdam, GFZ German Research Centre for Geosciences, Potsdam, Germany

Received: 20 December 2012 – Accepted: 2 January 2013 – Published: 23 January 2013

Correspondence to: M. A. Sauerbrey (maaret.kukkonen@uni-koeln.de)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper focuses on the characterization and genesis of mass movement deposits (MMD) in the Quaternary and Pliocene sediments of Lake El'gygytgyn, Far East Russian Arctic. The 320 m long sediment record was drilled by three partly overlapping holes at ICDP Site 5011-1 in the lake basin, representing the Quaternary almost completely, and the Pliocene down to 3.6 Ma with 52 % recovery. Mass movement deposits were investigated in all three cores, based on macroscopical core descriptions, radiographic images, and high-resolution magnetic susceptibility and gamma-ray density. Five different types of MMDs were identified: turbidites, grain flow deposits, debrites, slumps and slides. These are formed by transitional mass movement processes, and thus, can be co-generic. An initial slope failure is thought to transform into a debris flow, deforms frontal sediments and partly disintegrates and dilutes into a turbidity flow. Turbidites are by far the most frequent MMD type in the lake center. They occur throughout the record in all pelagic sedimentary facies, but they are thinner in facies formed during cold climate conditions. All other MMDs, by contrast, incise exclusively the pelagic facies deposited during warm climates. In the 123 m thick Quaternary sediment record 238 mass movement events are identified, comprising 37 % of the sediment length. Turbidites contribute 92 % of the number of Quaternary MMDs, but only 32 % of their thickness. In the Pliocene sediments between 123 and 320 m, additional 185 mass movement deposits are identified, which constitute 32 % of the recovered sediments. The mean recurrence rate for MMDs is 11 ka and 5 ka in the Quaternary and Pliocene, respectively.

1 Introduction

Lacustrine sediment records are an important archive for the reconstruction of environmental and climatic changes. Pelagic sediments, settled continuously on a lake floor from allochthonous and autochthonous supply, are widely used in such reconstructions.

CPD
9, 467–505, 2013

Mass movement events, in contrast, can transport significant amounts of sediment in lacustrine or marine basins in very short time periods (minutes to hours). They are potentially erosive, which causes a threat to the quality and continuity of the sediment record subject to paleoenvironmental and paleoclimatological studies. Identification of mass movement deposits and their effects on the pelagic sedimentation is thus of crucial importance for the successful interpretation of the pelagic record.

Basins with sharp shelf breaks dividing a lateral slope and a flat lake floor are typical settings for mass movements. This type of relief is found in fjords, fjord-type lakes and in tectonically or volcanically formed lakes (Bøe et al., 2004; Schnellmann et al., 2005; Gebhardt et al., 2011) as well as in impact crater lakes (Nolan and Brigham-Grette, 2007; Shanahan et al., 2006). Adequate sediment input is one of the most important prerequisites for the initiation of slope failure and can also control the frequency of such events.

Mass movements do not only have the potential to hamper the paleoenvironmental signal but can also be used for evaluating the frequency and magnitude of these short-lived events and their triggering mechanisms, such as climatic impacts, human or tectonic activities. For instance, Osleger et al. (2009) reported a connection between storminess and turbidite deposition in Lake Tahoe (USA). St-Onge et al. (2004) and Guyard et al. (2007) differentiated between flood-induced and slump-generated turbidites in Saguenay Fjord (Canada) and Lake Bramant (France), respectively. Strasser et al. (2006), Monecke et al. (2007) and Schnellmann et al. (2007) have assessed the earthquake history in Swiss Lakes based on the occurrence of mass movement deposits. Turbidites can also be deposited by human impact, such as damming (Lake Mead; Twichell et al., 2005). In addition, changes in lake level have been discovered to control turbidite deposition e.g. in Lake Bosumtwi (Shanahan et al., 2006).

In spring 2009 the international El'gygytgyn Drilling Project recovered the first widely continuous sedimentary record from the terrestrial Arctic that covers the entire Quaternary and penetrates further into the Mid- and Late Pliocene (Melles et al., 2011, 2012; Brigham-Grette et al., 2013). The drill cores from Lake El'gygytgyn, northeastern

CPD
9, 467–505, 2013

Russia, provide a key record for paleoclimatic reconstruction in the Arctic. However, from large alluvial fans in the northern and western lake catchment, prograding deltas on the western lake shore, and steep lake slopes down to currently 170 m water depth (Nolan and Brigham-Grette, 2007), it can be expected that the pelagic sedimentation in Lake El'gygytgyn was irregularly influenced by mass movements. This was confirmed already by the first pilot core PG1351, taken in spring 1998 from the central part of Lake El'gygytgyn, in which occasional thin, normally graded beds were discovered and interpreted as possible turbidites (Melles et al., 2007).

Seismic studies, performed during summers 2000 and 2003 (Gebhardt et al., 2006, 2013; Niessen et al., 2007) revealed thick stacked, chaotic to acoustically transparent seismic units interpreted as debris flow deposits reaching down to depths below ca. 167 m below lake floor. These deposits were further investigated with high-resolution 3.5 kHz sediment echosounding that revealed the abundance of these deposits at the lake slopes (Fig. 1c). There they have proximal thicknesses of > 20 m and reach the lake center only occasionally, where they have thicknesses up to 3–4 m between well-layered sediments. Erosive debris flow deposits are located proximally, whilst non-erosive MMDs were identified also in the lake center (Niessen et al., 2007). In 2003, one of the mass movement deposits discovered by 3.5 kHz echosounder data was sampled by two cores (Lz1039 and Lz1041) in order to study its characteristics and influence on the pelagic sedimentation in Lake El'gygytgyn (Juschus et al., 2009). Detailed investigation of these cores, as well as another, 16 m long core from the lake center (Lz1024), revealed that the acoustically transparent seismic unit consists of a basal debris flow deposit (debrite according to Gani, 2004), which is directly overlain by a dense flow deposit (densite) of wider distribution and further by a deposit settled from a suspension cloud (turbidite) that presumably covers wide areas of the lake floor. Whilst both the debrite and the densite have caused erosion of about 1 m of sediments previously accumulated on the lower slope, at least the more recent turbidites in the lake center were not associated with significant erosion according to radiocarbon dating of the bracketing pelagic sediments. In the pilot core taken at the lake center (Lz1024), a total of 26 turbidites and 3 densites were accumulated (Juschus et al., 2009) during the past 350 ka (Frank et al., 2012; Nowaczyk et al., 2013), whilst debris flows did not reach the coring location during this period.

In this paper, the mass movement deposits occurring in the entire 3.6 Ma sediment record in central Lake El'gygytgyn recovered in spring 2009 by the El'gygytgyn Drilling Project are identified, characterized and classified. In addition, we present the correlation of the mass movement deposits between the drill cores and pilot core Lz1024 (Juschus et al., 2009), as well as a chronological catalogue of the Quaternary and Mid- to Late Pliocene mass movement deposits in Lake El'gygytgyn. We also compare the occurrence of MMDs to different pelagic facies and climate conditions. Based on our findings, the processes influencing the mass movement evolution in Lake El'gygytgyn are discussed.

2 Prerequisite site information

Lake El'gygytgyn (67°30′ N, 172°5′ E), formed after a meteorite impact 3.58 ± 0.04 Ma ago (Layer, 2000), is situated in the Far East Russian Arctic, 100 km north of the Arctic Circle (Fig. 1a). The diameter of the lake is 12 km and its surface lies 492 m a.s.l. (Fig. 1b). The catchment area of 293 km^2 (lake 110 km^2) is dominated by alluvial fans that are wide and broad especially on the western shore (Glushkova and Smirnov, 2007). The outflow, Enmyvaam River, exits to the southeast of Lake El'gygytgyn. Approximately 50 inlet streams drain into the lake. Gravel bars at the shoreline block many of them and direct inflow is thus prohibited during snow free summer (Nolan and Brigham-Grette, 2007). Characteristic for the lake is its widely narrow and shallow shelf (< 10 m) with steep slopes and a comparably flat, bowl-shaped basin with water depths of up to 170 m. The slopes are steepest in the northern and eastern basin, with general angles between 15 and 30° and a maximum of more than 40° on the eastern shore, whereas they are more gently inclined with generally 5–15° on the southern and western shores (Nolan and Brigham-Grette, 2007).

CPD
9, 467–505, 2013

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

The circular-shaped impact crater has a diameter of 18 km and was formed into Cretaceous volcanic rocks, such as rhyolitic and dacitic lavas, tuffs and ignimbrites as well as andesites and tuffs of andesitic composition (Gurov and Koeberl, 2004). The mountains at the crater rim today have heights between 50 and 430 m above lake level. According to the reconstruction of the initial crater depth by Gurov and Gurova (1981) and Feldman et al. (1980), the crater rim has been eroded by approximately 400 to 500 m. Geomorphologic investigations in the area have revealed that the closest traces of glaciations are 40 km away in the Anadyr Highland, and no traces of glacial influence were found within the lake catchment (Glushkova and Smirnov, 2005a, 2007). Lake level has fluctuated during the past, with the highest preserved terrace at 35 to 40 m above present lake level formed presumably during Mid-Pleistocene (Glushkova and Smirnov, 2007). In addition, terraces at 9–11 m and 3–5 m above lake level date back to late Pleistocene and Late Glacial times, respectively (Glushkova and Smirnov, 2005b, 2007; Schwamborn et al., 2008). Brigham-Grette et al. (2005) reported of a terrace 10 m below the present lake level, which represents a lake-level lowstand during the Last Glacial Maximum (Juschus et al., 2011). On the northern shore, several pebble bars mark a gradual lake-level drop of 4 m during the Holocene (Schwamborn et al., 2008). In general, the high lake levels have been correlated to warm climate conditions, whilst lower lake levels supposed to have formed during cooler periods (Juschus et al., 2011).

Presently, Lake El'gygytgyn is situated within the continuous permafrost zone and its catchment has been influenced by permafrost conditions presumably since the Late Pliocene (Glushkova and Smirnov, 2007). Permafrost largely influences weathering and sedimentation processes in the catchment resulting in an active layer, whose thickness varies between 0.4 to 0.8 m depending on the grain size (Schwamborn et al., 2008, 2013).

Sediment is transported to the lake through fluvial and aeolian, as well as gravitative mass movement processes (Juschus et al., 2005; Fedorov et al., 2012; Francke et al., 2013). Even though the amount of inlet streams is high, their sediment discharge to the lake is rather small. All inlet streams transport an estimated 350 t of sediment into the lake annually, almost exclusively during spring and summer. Only ca. 1 % of this is discharged through the outlet Enmyvaam River (Fedorov et al., 2012). Fluvial sediment discharge is presently reduced by permafrost, since the ground is still frozen when the snow melts (Nolan and Brigham-Grette, 2007). It is concentrated to a very short melting period, when even coarse-grained material can be transported to the coastal zone forming sandy and gravelly fans reaching hundred meters onto the lake ice (Fedorov et al., 2012). During snow-free summers, gravel bars at the shoreline of several inlet streams today form lagoons, trapping fine-grained sediment, and thus, hinder suspension flow into the lake (Nolan and Brigham-Grette, 2007). Considerable lake-level rises may breach the lagoons, thus, transporting coarse-grained material into the lake that may result in mass movement processes (Fedorov et al., 2012). Aeolian transport, in contrast, has not been very significant in present conditions or during the Quaternary (Fedorov et al., 2012; Francke et al., 2013).

Pelagic sedimentation in Lake El'gygytgyn is fine grained (Francke et al., 2013). It can be divided into four major facies, which sensitively reflect different climate conditions (Melles et al., 2011, 2012; Brigham-Grette et al., 2013; Gebhardt et al., 2013). During colder climate stages of the Quaternary, under perennial lake ice, dark gray, finely laminated silts and clays are deposited (Facies A). The dominant facies (Facies B) contributes 79 % of the Quaternary pelagic sediment record (Melles et al., 2012) and is also widespread in the Pliocene sediments (Cook et al., 2013). It is characterized by olive gray to brownish, massive to faintly banded silt, deposited during relatively warm climate conditions under a semi-permanent ice cover. Peak warm climate, such as during marine isotope stages (MIS) 11.3 and 31, is reflected by laminated, reddish-brown silt and high amounts of biogenic silica (Facies C) (Melles et al., 2011, 2012; Vogel et al., 2012). Facies D, consisting of grayish to greenish, laminated silts and clays that coarsen upwards, occur exclusively in the Pliocene sediments (Brigham-Grette et al., 2013). A fifth facies (E) was identified at the bottom of the lacustrine record and represents a transitional zone between early lake sediments and brecciated impact-related

CPD
9, 467–505, 2013

bedrock (Raschke et al., 2012; Gebhardt et al., 2013). Sedimentation rates have significantly decreased during the lake history. During the first ca. 300 ka after the impact, the average sedimentation rate accounted for 44.5 cm ka^{-1}, and dropped to 15 cm ka^{-1} and 4.7 cm ka^{-1} during the remaining Pliocene and the Quaternary, respectively (Haltia-Hovi et al., 2013; Nowaczyk et al., 2013).

3 Methods

Drilling operations of the El'gygytgyn Drilling Project were carried out during winter and spring 2009. Drilling included three holes from the lake ice at ICDP site 5011-1 in the central, deepest part of the lake. In holes 5011-1A and 5011-1B sediment depths of 147 m and 112 m below lake floor (blf) were reached, with recoveries of 92 % and 98 %, respectively. Hole 5011-1C was drilled from 100 m down to 517 m blf, passing the boundary between lake sediments and impact rocks at 320 m blf. Down to ca. 150 m and in the lowermost 40 m of the lake sediment record the recovery was nearly 100 %, but in between it was rather poor, leading to a total recovery of 52 % of the lacustrine sediments of hole 5011-1C. Potential reasons for the low core recovery between 150 m and 277 m are technical problems (loss of tools) and the occurrence of coarser (sandy and gravelly) sediments (Melles et al., 2011).

Directly after core opening at the University of Cologne, the core halves were imaged with a GEOTEK line scanner (MSCL CIS Logger, Geotek Ltd.) and measured for their magnetic susceptibility with a point sensor at a resolution of 1 mm (SCL2.3 Logger, GFZ Potsdam). Based on the macroscopic core description, focusing on grain size, color and sediment structures, sedimentary units were determined, including mass movement deposits. Subsequently the elemental composition was measured and radiographs were obtained on the core halves with an ITRAX core scanner (Cox Analytics) in resolutions of 2 mm and 200 µm, respectively, and gamma-ray density measurements were performed at Alfred Wegener Institute in Bremerhaven, Germany with a MSCL core logger (Geotek Ltd.). For a more detailed description of the drilling operations and core

CPD
9, 467–505, 2013

processing see Melles et al. (2011, 2012), Francke et al. (2013), Gebhardt et al. (2013) and Wennrich et al. (2013).

Comparison of the drill cores to the pilot core (Lz1024) revealed that cores 5011-1A and 1B start at 5.67 m and 6.28 m blf, respectively (Nowaczyk et al., 2013). The information concerning the 10 uppermost mass movement events above the depth of 5.67 m is therefore derived from the pilot core described by Juschus et al. (2009). For the comparison and correlation of the mass movement events in each drill hole, we use corrected field depths (cfd), where the difference between the assumed and true field depth is corrected. To enable the comparison of mass movement events to other papers dealing with paleoenvironmental proxies, the events are also presented in composite depths (cd). Even though all mass movement events were given a depth in the core composite, all events thicker than 5 cm were excluded from the age model of the pelagic sediment record (Wennrich et al., 2013; Nowaczyk et al., 2013). The age/depth model for the core composite from ICDP Site 5011-1 is based on paleomagnetic data (Haltia-Hovi et al., 2013) and tuning of paleoenvironmental proxies (FTIRS-BSi, Si/Ti, magnetic susceptibility, TOC, pollen) to variations in the global marine oxygen isotope stack and local insolation (Nowaczyk et al., 2013). Ages of the mass movement deposits were calculated from the sedimentation rates derived from the age/depth model for the pelagic sediments in between.

4 Characteristics and genesis of mass movement deposits

Normal pelagic sedimentation in the Lake El'gygytgyn sequence is interrupted by at least eight tephra layers (van den Bogaard et al., 2013) and frequent mass movement deposits. The identification and classification of MMDs used in this paper is based on macroscopic core descriptions on core halves and radiographs, their comparison in parallel cores, and their magnetic susceptibilities and gamma-ray densities. The MMDs in Lake El'gygytgyn can be divided into five different types, based on their individual sedimentological characteristics. Due to new findings in deeper core sections, the terminology used by Juschus et al. (2009) for the uppermost 16 m in Lake El'gygytgyn had to be extended and modified.

4.1 Turbidites (T)

Turbidites always show clear normal grading (Fig. 2) and sharp boundaries to the underlying sediment, which makes them easy to distinguish from the pelagic facies. In some cases, the fining upward is very gradual, with diffuse grain-size boundaries. In most cases, however, a step-wise fining upward occurs, with clear intra-bed boundaries between single grain-size classes. This is more evident in the core description than in the radiographs. Grain sizes vary between sand and clay. The different sediment fractions can readily be identified based on their color: the basal sand unit is often dark gray (Munsell color 5Y 4/1, 2.5Y 4/1 to N 4/) and sometimes dark grayish brown (5Y 4/2), the silty middle unit is slightly lighter dark gray, gray or grayish brown (5Y 4/1, 5Y 5/1, 2.5Y 5/2) and the clayey top unit is lighter gray (5Y 5/1 to 6/1), grayish brown (2.5Y 5/2) or olive gray (5Y 5/2). Especially in the lowermost part of the sediment record the clayey top is often greenish grey (e.g., 10Y 5/1). Radiographs reveal that some thicker turbidites are faintly banded in the basal sand and coarse silt units. The upper boundaries of thick turbidites are sometimes concealed by a fairly homogenous but slightly darker (2.5Y 5/1-5/2) unit, which appears to be bioturbated. Greenish remnants of redox layers (10Y 5/1 to 5GY 4/1) can also occur in this unit. However, radiographs as well as magnetic susceptibility and density measurements reveal the grading of this unit (Fig. 2). Magnetic susceptibility is high in the sandy and silty units of turbidites and declines towards the clayey top unit. When redox layers remnants are preserved in the top unit, magnetic susceptibility values slightly increase. Density can be high or low in the sandy basal unit (1.3–1.6 $g\,cm^{-3}$) and is high in the silty unit (1.5–1.8 $g\,cm^{-3}$), whereas it decreases towards the clayey top, where it reaches a minimum (1.2–1.4 $g\,cm^{-3}$). Intra-bed boundaries clearly apparent in the core scan coincide with "steps" in magnetic susceptibility and density values (dashed lines in Fig. 2.). The thicknesses of individual turbidites vary considerably. In the Quaternary sediments, i.e

CPD
9, 467–505, 2013

in the uppermost 123 m, thicknesses range from 2 mm to 55.3 cm, whilst they reach up to 95.3 cm in the Pliocene.

The internal structure of the individual turbidites suggests a similarity to the "Bouma sequence" (Bouma, 1962), which are deposited by a turbidity current in the marine environment. Even tough the sedimentary structures of Lake El'gygytgyn turbidites are incomplete compared to the ideal "Bouma sequence" that is divided into five units (Ta-Te) with characteristic sedimentary structures (Bouma, 1962), a comparable process with complete suspension of the sediment has probably created the turbidites in Lake El'gygytgyn. This is supported by a similar interpretation from Lake Fagnano (Waldmann et al., 2010).

4.2 Grain-flow deposits (G)

Massive, well-sorted grayish sands (Fig. 3) with sharp contacts to underlying sediment occur only once in the Quaternary and seven times in the Pliocene sediments drilled at ICDP Site 5011-1. The thicknesses of the deposits vary between 3.3 and 26.2 cm. They lack any sedimentary structures and radiographs confirm a homogenous appearance without grading. Magnetic susceptibility values are only slightly higher compared to the adjacent pelagic sediments, whereas density is significantly increased.

The sand layers are interpreted as grain-flow deposits (Mulder and Alexander, 2001). These MMDs are products of mass flows, whose sediment concentration and grain size is too high to support turbulent flow, i.e. they are laminar flows (Mulder and Alexander, 2001; Gani, 2004). Grain flows originate from areas, where well-sorted sands are present to provide the requisite source material. In Lake El'gygytgyn, this probably is the case in deltas, which occur in larger size predominantly at the western lake shore (Schwamborn et al., 2013).

4.3 Debrites (D)

These deposits are characterized by poorly sorted fine gravel and sand in a dark gray (Munsell color 5Y 4/1 to N 4/) silty to clayey matrix (Fig. 4). The subangular gravel grains present various lithologies available in the catchment. The contact to the underlying sediment is sharp. Thicknesses vary between 21.1 and 399.4 cm. These deposits may have clasts of redeposited pelagic sediment in their upper parts, and may include gray or greenish lenses of folded or bended fine sediment (e.g., at 114.6 m cfd in Fig. 4.). Additionally, they are nearly always overlain by a turbidite (Fig. 4). Magnetic susceptibility values are high, but similar to pelagic sediments of Facies B.

In contrast, density values with 1.7 up to 2.2 g ccm^{-1} are generally higher compared to other mass movement deposits as well as pelagic sediments at similar depths. In radiographs, these deposits appear dense and massive. This type of deposit occurs ten times in the sediment record, the uppermost (D74) at 37 m cfd and all others below 92 m cfd.

The characteristics of these deposits indicate complete mixing of the source material, i.e. formation by cohesive debris flows resulting in a debrite (Mulder and Alexander, 2001; Gani, 2004). A cohesive debris flow is indicated by the poor sorting, with a grain-size spectrum ranging from fine gravel to clay, and the lack of grading. Redeposited pelagic sediment clasts are transported by the debris flows and concentrated in the upper part of the deposit (Mulder and Alexander, 2001). The seismic survey at Lake El'gygytgyn (Niessen et al., 2007) yielded several debris flows on the lake slopes, especially in the west, but also in the north. The capping turbidite is interpreted as debris-flow generated.

4.4 Slumps (Su)

Altogether 17 sediment horizons have been identified in Lake El'gygytgyn record, in which the deposits are either folded, bended or the original structures are deformed (Fig. 5). Nevertheless, the facies of the source sediment is still widely identifiable indicating that the deformation and transport have been limited. The deposits are comprised of redeposited pelagic facies as well as event layers, such as tephras or turbidites, and can have basal or intercalated massive sand layers. Where a basal sandy unit is absent, the lower boundaries of these deposits are indistinct. Both magnetic susceptibility and density values vary according to the facies of the source material. These MMDs vary in thickness between 37.0 and 337.2 cm and are interpreted as slumps, where external stress leads to deformation and minor redistribution of cohesive sediments.

The identification of Su34 in the drill cores lead to the new interpretation of the comparable section in the pilot core Lz1024. Su34 is 63.2 cm and 75.9 cm thick in cores 5011-1A and 5011-1B, respectively. It consists of a basal massive sandy layer (thickness in 1A and 1B 4.4 cm and 8.2 cm, respectively), followed by folded pelagic sediment with an incised massive sandy layer. The folded sediment is directly overlain by a turbidite. The sand layers correlate with two layers at 15.016 and 15.088 m (cd) in the pilot core Lz1024 that were interpreted as densites by Juschus et al. (2009). Taking the wider picture now available from 3 parallel cores these sediments are reinterpreted to belong to the larger and more complex slump Su34, in which pelagic facies of different types (Facies A in core Lz1024, and Facies B in cores 5011-1A and 1B) got incised.

4.5 Slides (Si)

In these deposits specific sediment features are duplicated or multiplicated. The respective horizons lack visible folding and are comprised of various redeposited pelagic sediment facies, which are still widely undisturbed. In most cases, the multiplicated segments range from centimeters to tens of centimeters, whilst a 1.4 m thick duplicated segments comprises Si75 (Fig. 6) and was recovered in both holes 1A and 1B. The segment includes a basal massive silty sand unit overlain by a small pelagic lens and a turbidite (between 40.0 and 39.7 m cfd, thickness 33 cm), which in turn is overlain by pelagic sediments between 39.7 and 38.65 m cfd (thickness 107 cm). Above the intra-slide boundary this segment is duplicated. The pelagic sediment appears widely

CPD
9, 467–505, 2013

undisturbed and only the duplication of this specific sediment succession, reflected also by magnetic susceptibility and density measurements confirms that mass movement took place. The duplicated section is directly overlain by a debrite and co-generic turbidite (D74) at 36.6–37.2 m cfd. As with slump deposits, the magnetic susceptibility values vary according to the source sediment. Thicknesses of this MMD type at Site 5011-1 vary between 23.4 and 272.3 cm. Thin massive sands occasionally intercalate in the deposit. The absence of a parallel core hinders the identification of this deposit type below 150 m cd and might thus have led to overlooking of some of this deposit.

Sediment sliding is interpreted as the cause of multiplication of specific sediment sections and it may be related to debris flows, since one debrite (D74) directly overlays this deposit (Si75). Sliding would take place on a weak sediment layer and lead to disintegration of sediment packages. According to Schnellmann et al. (2005) sediments with comparable characteristics were traced back to external stress on cohesive sediments, leading to duplication of sediment units over relatively short distances along thrust faults. Other possible explanation for this deposit might be the retrogradation of an initial slope failure resulting in instability in adjacent areas (Mulder and Cochonat, 1996). As this would happen on the lake slope, which is several kilometers away from the coring site, it is unlikely that the sediments would reach the site as undeformed as they have. Additionally, the characteristics of pelagic sediments on the lake slope vary from the center and are somewhat coarser.

5 Development of mass movement events

Lake El'gygytgyn is prone to mass movement processes, since it possesses a narrow shelf and a sharp shelf break at a depth of ca. 12 m in a bowl-shaped basin. Although sedimentation rates have generally been low back to about 3.3 Ma, sedimentation has been continuous during the entire lake's past providing adequate amounts of sediment. Based on the observations made on the drill cores from ICDP Site 5011-1, a simplified model of the mass movement processes in Lake El'gygytgyn was developed (Fig. 7).

CPD
9, 467–505, 2013

We suppose that the formation of MMDs in Lake El'gygytgyn is associated with an initial sediment failure on the upper lake slope that advances towards the lake basin. In case of well-sorted sands as source material, which is the case for deltaic deposits at the western lake shore, the mass movement takes place as a laminar grain flow. This is not associated with significant turbulent flow, since the flow lacks fine-grained sediment components (Fig. 7a). Generally sharp contacts to the underlying pelagic sediments suggest that grain flow events are associated with erosion of previously deposited sediments along their flow paths.

In case of coarse-grained, poorly sorted sediment as source material, slope failures lead to the formation of debris flows (Fig. 7b and c). Debris flows are the coarsest sediments recovered in the center of Lake El'gygytgyn. Their origin from shallow water depths, outside the deltas with well-sorted sands at the western lake shore, is supported by the recovery of grayish sands and gravels in a short sediment core from 12 m water depth at the southern shelf (Juschus et al., 2011).

During their advance debris flows become partly diluted and sediment is brought into suspension. The lower density of the suspension leads to a turbid flow above the debris flow that is finally deposited in the lake basin as a normally graded turbidite, both on top and in front of the debris flow. Turbidites generated by and directly overlaying debris flows are common in lacustrine and marine settings (e.g. Schnellmann et al., 2005; Waldmann et al., 2010; Rothwell et al., 2000; Strachan, 2008). However, since the debris flows in most cases do not extend all the way to the lake center, the associated turbidites there are more widespread than other mass movement deposits (Schnellmann et al., 2005; Juschus et al., 2009). Whilst the formation of debrites in Lake El'gygytgyn has been shown to be associated with significant erosion of previously deposited sediments, erosion by turbidites is regarded as minor, despite the genesis from turbulent flow and frequently occurring sharp lower boundaries (Juschus et al., 2009). This may be explained by the considerable amount of thin turbidites identified in the 5011-1 cores, denoted by the median thickness (2.9 cm in the Quaternary and 2.3 cm in the Pliocene). The generally thin nature of turbidites suggests that most

CPD
9, 467–505, 2013

of them could be located distally, as turbidites have been observed to grade distally from the source area resulting in finer and thinner distal turbidites (Sturm and Matter, 1978; Monecke et al., 2004; Girardclos et al., 2007). Therefore, the high number of thin turbidites at the drill site of Lake El'gygytgyn, located slightly to the east of the lake center, might indicate that they may have originated from the western lake slope, which is also supported by the seismic survey.

Besides, the debris flows may deform previously deposited sediments that become partially disintegrated, thus, leading to the formation of slumps and slides (Fig. 7b and c). Slumps are associated with limited deformation of the sediments, still showing original structures and facies. This suggests that the sediments incorporated in the slumps were not transported far away from the area where they were originally deposited. Since slumps are often directly overlain by turbidites, and found overlaying debrites, at least twice in the record (D232 at 119.6–121.6 m, D279 at 144.5–148.6 m; Fig. 8), their formation is likely linked to debris flows. For most of the slumps, however, there is no indication of debris flows reaching the coring site. Hence, the folding and bending of sediment is assumed to have resulted from deformation by a debris flow, but primarily in its front and only occasionally at its base.

Rarely, debris flows can also lead to sediment sliding in the lake center, leading to the multiplication of specific sediment sections (Fig. 7c). This is suggested by a debrite (D74) found directly above a slide deposit (Si75; Fig. 6). It is presumed that slides can form in Lake El'gygytgyn, when debris flows builds up stress on sediment that is more rigid and becomes locally displaced in the form of thrust faults, without folding, homogenization, or water take-up. Another possible explanation for the slides might be the retrogradation of an initial slope failure resulting in instability in adjacent areas (Mulder and Cochonat, 1996). However, as this process would happen on the lake slope, which is several kilometers away form the coring site, it is unlikely that the sediments would reach the site as undeformed as they are. Furthermore, faults likely associated with the central uplift structure of the impact crater were found in the seismic profiles (Niessen et al., 2007). These faults are currently inactive, but were certainly

CPD
9, 467–505, 2013

active during the Pliocene and also during parts of the Pleistocene. Such faults were found west of the drilling location and may also be related to the formation of slumps and slides.

6 History of mass movement events

Mass movement deposits in each drill hole at Lake El'gygytgyn are illustrated in Fig. 8. The drill cores 5011-1A to 1C are shown in corrected field depth (cfd), whilst the pilot core Lz1024 (Juschus et al., 2009) and the composite are shown in composite depths (cd). Mass movements are numbered by events, starting from the youngest. Each event can consist of more than one type of deposit when they are interpreted as co-generic.

6.1 Quaternary

Altogether 238 mass movement events are identified in the Quaternary sediments (upper 123.5 m), comprising 37 % of the total sediment thickness (Fig. 8). Juschus et al. (2009) reported that the pilot cores Lz1024 and PG1351, which comprise the last ca. 350 and 250 ka (Nowaczyk et al., 2007; Frank et al., 2013), had only 12.7 % and 7.1 % mass movement deposits, respectively. The considerably higher portion of mass movements in the drill cores is explained by new types of deposits, as well as by the increase in their thickness in deeper core sections. This reflects a significant decrease in mass movement contribution to the sedimentation in central Lake El'gygytgyn in the course of the Quaternary. The recurrence time for Quaternary turbidites is 11.7 ka.

The mass movement events (and their portion to the total sediment thickness) are divided into 220 turbidites (11.7 %), 1 grain flow (0.15 %), 6 debrites (6.9 %), 8 slumps (12.9 %) and 3 slides (5.4 %). The mean and median thicknesses of single turbidites are only 6.55 cm and 2.85 cm, respectively. Due to generally low thicknesses compared to other mass movements, turbidites account for 92 % of the number of mass movement events, but only 31 % of their thickness. Their portion of the thickness of the Quaternary

CPD
9, 467–505, 2013

sediments (11.7 %) correlates well to their percentage in core Lz1024 (10.2 %, Juschus et al., 2009), suggesting that the decrease in mass movement deposition in the course of the Quaternary is widely independent of turbidites but mainly controlled by other types of mass movements.

The majority of Quaternary turbidites (73 %) are intercalated in Facies B (warm) sediment, which contribute 79 % of the pelagic Quaternary record (Melles et al., 2012), whilst Facies A (cold) and Facies C (peak warm) hold only 23 % and 3 % of the turbidites, respectively. The remaining 1 % are underlain by another, separate turbidite. The mean thickness of turbidites in Facies A and B is 4.07 cm and 7.35 cm, respectively. This reflects the difference between turbidites deposited in cold and warm climate conditions. Debrites, grain flows, slides and slumps were deposited exclusively during warm climate conditions (Facies B), whilst slumps are intercalated also in Facies C sediments. Normal pelagic sedimentation is coarser during warm climate stages compared to cold climates (Francke et al., 2013), which could also explain the occurrence of thicker turbidites and the occurrence of other mass movement deposits during these times. Warm climates promote erosion in the catchment, as the active layer is thicker, and transport into the lake basin is supposed to be increased.

6.1.1 Late to middle pleistocene

The most significant feature of the Late to Middle Pleistocene mass movements is the dominance of turbidites (Fig. 8), which is interrupted by only 2 other events: Su34 and G59. Slump Su34 has an approximate age of early Marine Isotope Stage (MIS) 9, its lower and upper contacts are to warm Facies B, but Facies A, correlating to MIS 9b, occurs just ca. 7 cm above. Grain-flow deposit G59 is also placed in Facies B, representing MIS 17. Only a few relatively thick turbidites were deposited during the Middle Pleistocene: T19, T21 and T63. T19 (depth 8.1–8.7 m cd; thickness 55.3 cm) was formed during late MIS 6 and is one of the few thick turbidites deposited in cold climate conditions (Facies A). T21 (10.0–10.4 m cd; 34.9 cm) reached the lake center

CPD
9, 467–505, 2013

during the preceding MIS 7, and T63 (30.1–30.5 m cd; 41 cm) is found in warm Facies B sediments representing the warmest phase of MIS 18.

6.1.2 Early pleistocene

Mass movement deposition during the Early Pleistocene can be divided into two parts. During the first half of the Early Pleistocene (85–123.5 m cd, corresponding to 1.96–2.6 Ma) normal pelagic and turbidite deposition is interrupted by several slumps and debrites (Fig. 8). The second half of the Early Pleistocene (31.7–85 m cd, 0.78–1.96 Ma), in contrast, is characterized by mass movement events that intercalate normal pelagic and turbidite deposition at more regular intervals. The events Si75 (early MIS 25), Su101 (MIS 35), Su128 (early MIS 45) and Si149 (MIS 56) occur at ca. 220 ka intervals. After Si75, it took ca. 130 ka before Si66 was deposited, whilst before Si149 exclusively turbidites were deposited for ca. 290 ka (73.0–85 m cd). Three slides (Si66, Si75 an Si149) have occurred during the Early Pleistocene. The youngest slide, Si66 at 32.5–34.2 m cd, overlays Facies B sediments and was deposited during late MIS 21, whilst Si75 between 37.8–40.6 m cd (Si75) (Figs. 6 and 8) was deposited during early MIS 25. Two thick turbidites occur at depths of 57.4–57.9 m cd (T122; 46.1 cm) and 62.6–63.1 m cd (T129; 44.3 cm, corresponding to MIS 43 and MIS 47, respectively.

The mass movement history during the first half of the Early Pleistocene is characterized by several debrites and slumps between ca. 85 and 123.5 m cd, whilst at the end of the first half between MIS 59 and 73, turbidite deposition dominated. Especially at the end of this period thicker turbidites occurred, e.g., T160 (78.1–78.6 m cd; 44.3 cm) during MIS 61. The lake center was reached by thick mass movement deposits especially during MIS 75-77 (Su186, Su188, Su193, D194) and the second half of MIS 79, when the thickest mass movement event, D195 (95.2–99.2 m cd), happened. This event consists of a 296.8 cm thick debrite overlain by a 102.6 cm turbidite, which is the thickest turbidite associated with a debrite in the whole Lake El'gygytgyn record. The event has an age of ca. 2.09 Ma, placing it to late MIS 79 (Nowaczyk et al., 2013). A lower lake level during MIS 80, indicated by the existence of green algae colonies, precedes this event (Andreev et al., 2013) but cannot be directly linked to these mass movement events. Additionally, during MIS 87-93 several mass movement events entered the lake center (Su213, Su217, D218) coinciding with at least two super interglacials (MIS 87 and 91). Event D221 has occurred during MIS 95. D232 was deposited during late MIS 101. The Quaternary-Pliocene transition is marked by the first appearance of Facies A sediments (Melles et al., 2012), which overlay Si240 indicating that it was deposited during significantly colder climate. Since there are small gaps in recovery in the lowermost 15 m of the Early Pleistocene sediment record, corresponding to a time span of ca. 150 ka, some upper or lower contacts, and thus, true thicknesses of these mass movement deposits (Su213, Su217, D221), may be underestimated.

Although the debrites, slumps and slides during the first half of the Early Pleistocene are deposited during warm to exceptionally climate phases, they do also coincide with the gradual increase in frequency and duration of cold climate stages between 2.3 and 1.8 Ma (Melles et al., 2012). After 1.8 Ma glacial/interglacial cyclicity was fully developed at Lake El'gygytgyn and can be correlated to the onset of the more regular intervals for mass movement events in the second half of the Early Pleistocene.

6.2 Pliocene

In contrast to the Quaternary, the sediments deposited in central Lake El'gygytgyn during the Pliocene were not fully recovered. The findings provide a rough picture of the differences in mass movement activities between the Quaternary and the Pliocene. The recovery was nearly perfect between 123.5 and 149 m cd, as well as 280–320 m cd.

Altogether 185 mass movement deposits, contributing 31.6 % to the recovered sediment thickness, have been identified: 164 turbidites (18 % of total recovered sediment thickness), 7 grain flow deposits (0.7 %), 4 debrites (3.2 %), 9 slumps (8.4 %) and 1 slide (1.2 %) (Fig. 8). The Pliocene single turbidites have a mean and median thickness of 11.26 cm and 3.4 cm, respectively, and they account for 88.7 % of the amount of mass movement events. However, they comprise significantly more, 56.9 %, of the total thickness of mass movements in the Pliocene compared to the Quaternary. This

CPD
9, 467–505, 2013

reflects a considerable increase in turbidite thickness, as well as a decrease in the thickness of other MMD types in the Pliocene. The recurrence time for turbidites in the Pliocene until 3.51 Ma is 8.9 ka, whilst in the lowermost 38 m of the core it shortens significantly to 1.2 ka.

Pliocene turbidites are intercalated in pelagic warm Facies B (20.8 % of the thickness of turbidites). Additionally, they can overlay other single turbidites (13 %) or gaps in recovery (19.7 %). In the lowermost part of the record turbidites incise Facies D, which is characterized by clayey to silty parallel laminations (11 %), and have a significantly higher average thickness of 9.63 cm. Debrites, grain flow deposits, and slides overlay mainly Facies B sediments or core gaps.

If the poorer recovery within the Pliocene sediments were caused by higher amounts of coarser sediments, it would lead to an underestimation of mass movement deposits in the Pliocene record. Concurrently, the recovered sediments would be biased towards the fine-grained pelagic sediments. Additionally, the lack of a parallel core through most of the Pliocene sediments, as well as the occasional poorer quality of the recovered sediments, concentrated especially between ca. 223 and 245 m cd, hampers the identification of some mass movement deposits, particularly slides and slumps.

6.2.1 Late pliocene

Late Pliocene sediments were recovered widely complete in holes 1A and 1C down to 150 m cd (2.94 Ma), below which information is only available from core 1C, including gaps in recovery up to 3.0 m long. Mass movements in the upper part of the Late Pliocene are clearly dominated by turbidites. With the exception a slide at 124.2–125.8 m cd (Si240) and a slump at 127.7–128.6 m cd (Su251), turbidites are the only mass movement deposits down to 134.5 m cd (ca. 2.78 Ma). Pelagic sediments of Facies C overlie the debrite D268 at 133.6–135.6 m cd, suggesting that the event was deposited during a superinterglacial, possibly G9. Debrite D279 dominates the lowermost ca. 4 m of core 5011-1A.

CPD
9, 467–505, 2013

Interestingly, both twist-offs in holes 1A (149 m cd) and 1B (115 m cd) occurred in debrites D279 and D221, respectively. In hole 1A the lower boundary and in hole 1C the upper boundary of D221 was not recovered and in hole 1C D279 was not recovered at all. This suggests, that the twist-offs as well as gaps in recovery can be related to coarser grained sediments, i.e. mass movement deposits.

All of the Pliocene grain-flow deposits occur in the Late Pliocene sediments between 185–218 m and lack a parallel core. As seen in Su34, these massive sandy deposits might belong to slumps. Thus, a parallel core would be crucial to confirm these deposits, especially giving the fact that between 156.2 and 245.5 m cd only one slump (Su294) and no slides are identified.

The Pliocene is characterized by higher sedimentation rates compared to the Quaternary. At the end of the Late Pliocene the sedimentation rate decreased to ca. 5 cm ka^{-1}, whilst below 160 m (3.05 Ma) sedimentation with 45 cm ka^{-1} is almost ten times higher (Nowaczyk et al., 2013).

6.2.2 Middle pliocene

The transition from the Late to the Middle Pliocene is blanketed by the poorer recovery as well as the poor quality of the recovered sediments from 223–245 m cd. However, the recovered sediments are fine-grained, excluding any major mass movement deposits. Between 245 and 252.5 m cd three slumps (Su342, Su343, Su344) were deposited during a fairly short time period, having roughly the age of 3.43–3.44 Ma. The recovery remains poor down to a depth of 280 m cd (ca. 3.51 Ma), below which it increases to almost 100 % (Fig. 8). The lowermost 38 m corresponds roughly to the first 70 ka after the impact with a high sedimentation rate of ca. 50 cm ka^{-1} (Nowaczyk et al., 2013).

Several thick turbidites are deposited between 280 m and 300.5 m cd, including the thickest single turbidite event in the entire record (T364; 95.3 cm) at 281–282 m cd. This turbidite has a 7.8-cm thick deformation zone (DZ) directly below, where the laminated pelagic sediments are disturbed. Similar, but thinner, deformation zones occur also beneath a few other turbidites, such as T339 (59.6 cm, DZ 7.5 cm,

CPD
9, 467–505, 2013

222.0–222.7 m cd), T363 (39.3 cm, DZ 2 cm, 280.3–280.7 m cd), T371 (29.4 cm, DZ 1.5 cm, 283.5–283.8 m cd) and T380 (51.1 cm, DZ 1.5 cm, 288.4–288.9 m cd). Erosion of the pelagic sediments is indicated, since within these deformation zones pelagic sediment is clearly cut or mixed with the basal sand of the turbidite.

Turbidites are the only mass movement deposit found within the lowermost 38 m of the core, which could be explained by the higher relief of the basin and higher water depths. The recurrence time of turbidites is only 1.2 ka. The content of sand in the sediment increases below 295 m cd indicating higher energies in the system. Sandy sediments alternate with clayey to silty sediments that are mostly laminated until a depth of 313.4 m. The lake was formed at the end of Early Pliocene, when tectonic uplift of Anadyr lowland was still ongoing and it continued until Early Pleistocene (Glushkova and Smirnov, 2007). It is yet unknown, how long it took for the lake to form. Nevertheless, the high relief, availability of loose material in a presumably little vegetated environment, and ongoing tectonic uplift probably promoted erosion during the early stages of the crater and lake filling, resulting in a much higher sedimentation rate and frequent mass movements. Below 314.4 m cd a breccia comprised of partly layered sands and a downwards-increasing percentage and diameter of lithic clasts reflects the transition zone between lake sediment and impact rocks. The clasts include shocked rocks and impact rocks to a depth of 318 m cd (Raschke et al., 2012; Gebhardt et al., 2013). The transition zone represents the wash out of sediments and rocks within the crater shortly after the impact.

7 Conclusions

Detailed sediment descriptions of the drill cores 5011-1A, 1B and 1C from central Lake El'gygytgyn, along with measurements of magnetic susceptibility and gamma-ray density, have revealed the significance of mass movement events during the past 3.6 Ma. The following conclusions can be drawn concerning the genesis and history of mass movement events in the lake.

i. Mass movement events have frequently reached the coring site, which today is situated ca. 4 km away from the nearest shore. In the course of the lake's history at least 423 mass movement events have occurred. They contribute significantly to the sediment infill and account for 34.5 % of the total recovered sediment thickness. The significance of mass movement deposits increases downwards in the record.

ii. Five different types of mass movement deposits are identified, which have individual sedimentological characteristics: turbidites, grain-flow deposits, debrites, slumps and slides. These are deposited by transitional mass-flow processes and can, thus, be co-generic.

iii. The nearly perfectly recovered 123 m long Quaternary record is characterized by 11.6 % of turbidites and 25 % of other MMDs. The mean rate of recurrence is 10.8 ka. During the past 800 ka turbidites have dominated the mass-movement deposition at the coring site.

iv. The 195 m long Pliocene record was drilled with only 52 % recovery. The sediment recovered is characterized by 18 % of turbidites and 13.6 % other MMDs. During most of the Pliocene the mean rate of recurrence has been 7.4 ka, whilst in the early lake stage it was only 1.2 ka.

v. Turbidites occur throughout the record and they are the most frequent mass movement deposit. They contribute 91 % of the number of MMDs but only 42 % of their thickness. Turbidites occur in all pelagic facies, but they are more abundant and thicker during warm climate conditions.

vi. Debrites, grain-flow deposits, slides and slumps have a higher potential for erosion than turbidites. They are less frequent, but due to their generally greater thickness compared to turbidites they account for 58 % of the MMD thickness. Debrites, grain-flow deposits, slides and slumps incise almost exclusively facies reflecting warm climate conditions.

CPD
9, 467–505, 2013

vii. More detailed investigations are needed to fully understand the genesis of variable mass movement deposits encountered in the record, as well as their source areas.

Acknowledgements. We are grateful to the participants on the pilot expedition in 2003 and the drilling campaign in 2008/2009 at Lake El'gygytgyn for recovering the unique record and conducting initial core processing. Funding for the drilling campaign was provided by the International Continental Scientific Drilling Program (ICDP), the US National Science Foundation (NSF), the German Federal Ministry of Education and Research (BMBF), Alfred Wegener Institute (AWI) and GeoForschungsZentrum Potsdam (GFZ), the Russian Academy of Sciences Far East Branch (RAS FEB), the Russian Foundation for Basic Research (RFBR), and the Austrian Federal Ministry of Science and Research (BMWF). The Russian GLAD 800 drilling system was developed and operated by DOSECC Inc. and LacCore, at the University of Minnesota, handled core curation. This study was financially supported by the German Research Foundation (DFG, grant ME 1169/21-1) and the German Federal Ministry for Education and Research (BMBF, grant no. 03G0642A).

References

Andreev, A. A., Melles, M., Wennrich, V., and Brigham-Grette, J.: Late Pliocene/Early Pleistocene environments of the north-eastern Siberian Arctic inferred from Lake El'gygytgyn pollen record, Clim. Past Discuss., in preparation, 2013.

Belyi, V. F.: Structure and formation of the El'gygytgyn Basin (Anadyr Mountains), Geomorphologia, 1, 31–41, 2001.

Bouma, A. H.: Sedimentology of some Flysch deposits: a graphic approach to facies interpretarion, Elsevier, Amsterdam, 1962.

Bøe, R., Longva, O., Lepland, A., Blikra, L. H., Søonstegaard, E., Haflidason, H., Bryn, P., and Lien, R.: Postglacial mass movements and their causes in fjords and lakes in western Norway, Norw. J. Geol., 84, 35–55, 2004.

Brigham-Grette, J., Melles, M., and Juschus, O.: Terrace 10 m below lake level, The Expedition El'gygytgyn Lake 2003 Siberian Arctic, Rep. Polar Mar. Res., 509, 108–110, 2005.

Brigham-Grette, J., Melles M., Minyuk,P., Andreev, A, Tarasov, P., DeConto, R., Koenig, S., Nowaczyk, N., Wennrich, V., Rosén P., Haltia-Hovi, E., Cook, T., Gebhardt, C., Meyer-

Jacob, C., Snyder, J., and Herzschuh, U.: Pliocene Warmth, extreme Polar Amplification, and Stepped Pleistocene Cooling recorded in NE Russia, Science, in review, 2012.
Cook, T., Wennrich, V., Sauerbrey, M. A., Brigham-Grette, J., and Melles, M.: Lithofacies classification and stratigraphy of pelagic sediments in Lake El'gygytgyn, Clim. Past Discuss., in preparation, 2013.
Fedorov, G., Nolan, M., Brigham-Grette, J., Bolshiyanov, D., Schwamborn, G., and Juschus, O.: Lake El'gygytgyn water and sediment balance components overview and its implications for the sedimentary record, Clim. Past Discuss., 8, 3977–4001, doi:10.5194/cpd-8-3977-2012, 2012.
Feldman, V. I., Granovsky, L. B., Naumova, I. G., and Nikoshina, N. N.: Some peculiarities of the chemical composition of impactittes from the El'gygytgyn meteoric crater Chukotka, Meteoritics, 39, 110–113, 1980.
Francke, A., Wennrich, V., Sauerbrey, M. A., Asikainen, C., Melles, M., and Brigham-Grette, J.: Quaternary grain-size distribution of Lake El'gygytgyn, NE Siberia: statistic analysis and climate dependency, Clim. Past Discuss., 9, 217–244, 2013, http://www.clim-past-discuss.net/9/217/2013/.
Gani, M. R.: From turbid to lucid: a straightforward approach to sediment gravity flows and their deposits, Sed. Rec., 2, 4–8, 2004.
Frank, U., Nowaczyk, N. R., Minyuk, P., Vogel, H., Rosén, P., and Melles, M.: A 350 kyr record of climate change from Lake El'gygytgyn, Far East Russian Arctic: refining the pattern of climate modes by means of cluster analysis, Clim. Past Discuss., 8, 5109–5132, doi:10.5194/cpd-8-5109-2012, 2012.
Gebhardt, A. C., Niessen, F., and Kopsch, C.: Central Uplift Structure Identified in one of the World's Best Preserved Impact Craters, Geology, 34, 145–148, 2006.
Gebhardt, A. C., De Batist, M., Niessen, F., Anselmetti, F. S., Ariztegui, D., Haberzettl, T., Kopsch, C., Ohlendorf, C., and Zolitschka, B.: Deciphering lake and maar geometries from seismic refraction and reflection surveys in Laguna Potrok Aike (southern Patagonia, Argentina), J. Volcanol. Geoth. Res., 201, 357–363, 2011.
Gebhardt, A. C., Francke, A., Kück, J., Sauerbrey, M. A., Niessen, F., Wennrich, V., and Melles, M.: Petrophysical characterization of the lacustrine sediment succession drilled in Lake El'gygytgyn, Far East Russian Arctic, Clim. Past Discuss., in press, 2013.
Girardclos, S., Schmidt, O. T., Sturm, M., Ariztegui, D., Pugin, A., and Anselmetti, F.: The 1996 AD delta collapse and large turbidite in Lake Brienz, Mar. Geol., 241, 137–154, 2007.

CPD
9, 467–505, 2013

Mass movement deposits in the 3.6 Ma sediment record

M. A. Sauerbrey et al.

Glushkova, O. Y. and Smirnov, V. N.: General geology and geography, in: The Expedition El'gygytgyn Lake 2003 Siberian Arcticedited, edited by: Melles, M., Minyuk, P., Brigham-Grette, J., and Juschus, O., Rep. Polar Mar. Res., 509, 14–18, 2005a.
Glushkova, O. Y. and Smirnov, V. N.: Coastal Morphology, in: The Expedition El'gygytgyn Lake 2003 Siberian Arctic, edited by: Melles, M., Minyuk, P., Brigham-Grette, J., and Juschus, O., Rep. Polar Mar. Res., 509, 104–108, 2005b.
Glushkova, O. Y. and Smirnov, V. N.: Pliocene to Holocene geomorphic evolution and paleogeography of the El'gygytgyn Lake region, NE Russia, J. Paleolimnol., 37, 37–47, 2007.
Gurov, Y. P. and Gurova, Y. P.: El'gygytgyn meteoric crater on Chukotka as an example of young morphologically expressed crater, in: Geology and petrology of meteorite impact craters, edited by: Ryabenko, V. A., Science Thought Dumka, Kiev, 125–135, 1981.
Gurov, Y. P. and Koeberl, C.: Shocked rocks and impact glasses from the El'gygytgyn impact structure, Russia, Meteorit. Planet. Sci., 39, 1495–1508, 2004.
Guyard, H., St-Onge, G., Chapron, E., Anselmetti, F. S., and Francus, P.: The AD 1881 Earthquake-triggered slump and Late Holocene flood-induced turbidites from proglacial Lake Bramant, western French Alps, in: Submarine Mass Movements and Their Consequences, edited by: Lykousis, V., Sakellariou, D., and Locat, J., 279–286, 2007.
Haltia-Hovi, E. and Nowaczyk, N. R.: Paleomagnetic age constraints for the sediments from Lake El'gygytgyn (NE Siberia) during the last 3.6 Myr, Clima. Past Discuss., in preparation, 2013.
Juschus, O., Fedorov, Wennrich, V., and Quart, S.: Aeolian Supply, in: The Expedition El'gygytgyn Lake 2003 Siberian Arctic, edited by: Melles, M., Minyuk, P., Brigham-Grette, J., and Juschus, O., Rep. Polar Mar. Res., 509, 52–54, 2005.
Juschus, O., Melles M., Gebhardt A. C., and Niessen, F.: Late Quaternary mass movement events in Lake El'gygytgyn, north-eastern Siberia, Sedimentology, 56, 2155–2174, doi:10.1111/j.1365-3091.2009.01074.x, 2009.
Juschus, O., Pavlov, M., Schwamborn, G., Preusser, F., Fedorov, G., and Melles, M.: Late Quaternary lake-level changes of Lake El'gygytgyn, NE Siberia, Quaternary Res., 76, 441–451, doi.10.1016/j.yqres.2011.06.010, 2011.
Kopsch, C.: Bathymetric measurements, in: The Expedition El'gygytgyn Lake 2003 Siberian Arctic, edited by: Melles, M., Minyuk, P., Brigham-Grette, J., and Juschus, O., Rep. Polar Mar. Res., 509, 129–131, 2005.

Layer, P. W.: $^{40}Ar/^{39}Ar$ age of the El'gygytgyn impact event, Chukotka, Russia, Meteorit. Planet. Sci., 35, 591–599, 2000.
Melles, M., Brigham-Grette, J., Glushkova, O., Y., Minyuk, P., Nowaczyk, N. R., and Hubberten, H.-W.: Sedimentary geochemistry of a pilot core from El'gygytgyn Lake – a sensitive record of climate variability in the East Siberian Arctic during the past three climate cycles, J. Paleolimnol., 37, 89–104, 2007.
Melles, M., Brigham-Grette, J., Minyuk, P., Koeberl, C., Andreev, A., Cook, T., Fedorov, G., Gebhardt, C., Haltia-Hovi, E., Kukkonen, M., Nowaczyk, N., Schwamborn, G., Wennrich, V., and El'gygytgyn Scientific Party: The El'gygytgyn Scientific Drilling Project – conquering Arctic challenges through continental drilling, Scientific Drilling, 11, 29–40, doi:10.2204/iodp.sd.11.03.2011, 2011.
Melles, M., Brigham-Grette, J., Minyuk, P. S., Nowaczyk, N. R, Wennrich, V., DeConto, R. M., Anderson, P. A., Andreev, A. A., Coletti, A., Cook, T. L., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A. V., Rosén, P., Tarasov, P. E., Vogel, H., and Wagner, B.: 2.8 Million Years of Arctic climate change from Lake El'gygytgyn, NE Russia, Science, 307, 315–310, doi:10.1126/science.1222135, 2012.
Monecke, K., Anselmetti, F. S., Becker, A., Sturm, M., and Giardini, D.: The record of historic earthquakes in lake sediments of Central Switzerland, Tectonophysics, 394, 21–40, 2004.
Monecke, K., Anselmetti, F. S., Becker, A., Schnellmann, M., Sturm, M., and Giardini, D.: Earthquake-induced deformation structures in lake deposits: A Late Pleistocene to Holocene paleoseismic record for Cental Switzerland, Eclogae. Geol. Helv., 99, 343–362, 2007.
Mulder, T. and Alexander, J.: The physical character of subaqueous sedimentary density flows and their deposits, Sedimentology, 48, 269–299, 2001.
Mulder, T. and Cochonat, P.: Classification of offshore mass movements, J. Sed. Res., 66, 43–57, 1996.
Niessen, F., Gebhardt, A. C., Kopsch, C., and Wagner, B.: Seismic investigation of the El'gygytgyn impact crater lake Central Chukotka, NE Siberia: preliminary results, J. Paleolimnol., 37, 49–63, 2007.
Nolan, M. and Brigham-Grette, J.: Basic hydrology, limnology, and meteorology of modern Lake El'gygytgyn, Siberia, J. Paleolimnol., 37, 17–35, 2007.
Nowaczyk, N. R., Melles, M., and Minyuk, P.: 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., 37, 65–76, 2007.

CPD
9, 467–505, 2013

Mass movement deposits in the 3.6 Ma sediment record

M. A. Sauerbrey et al.

Nowaczyk, N. R., Haltia-Hovi, E. M., Ulbricht, D., Wennrich, V., Sauerbrey, M., Rosén, P., Vogel, H., Francke, A., Meyer-Jacob, C., Andreev, A., and Lozhkin, A. V.: Chronology of Lake El'gygytgyn sediments, Clim. Past Discuss., in preparation, 2013.

Osleger, D. A., Heyvaert, A. C., Stoner, J. S., and Verosub, K. L.: Lacustrine turbidites as indicators of Holocene storminess and climate: Lake Tahoe, California and Nevada, J. Paleolimnol., 42, 103–122, 2009.

Raschke, U., Reimold, W. U., Zaag, P., Pittarello L., and Koeberl, C.: Lithostratigraphy of the impactite and bedrock section in ICDP drill core D1c from the El'gygytgyn impact crater, Russia, Meteorit. Planet. Sci., accepted, 2012.

Rothwell, R. G., Reeder, M. S., Anastasakis, G., Stow, D. A. V., Thomson, J., and Kähler, G.: Low sea-level stand emplacement of megaturbidites in the western and eastern Mediterranean Sea, Sediment. Geol., 135, 75–88, 2000.

Schnellmann, M., Anselmetti, F. S., Becker, A., Sturm, M., and Giardini, D.: Mass movement-induced fold-and-thrust belt structures in unconsolidated sediments in Lake Lucerne Switzerland, Sedimentology, 52, 271–289, 2005.

Schnellmann, M., Anselmetti, F. S., Giardini, D., and McKenzie, J. A.: 15 000 Years of mass-movement history in Lake Lucerne: Implications for seismic and tsunami hazards, Eclogae. Geol. Helv., 99, 409–428, 2007.

Schwamborn, G., Fedorov, G., Schirrmeister, L., Meyer, H., and Hubberten, H.-W.: Periglacial sediment variations controlled by late Quaternary climate and lake level change at Elgygytgyn Crater, Artic Siberia, Boreas, 37, 55–65, 2008.

Schwamborn, G., Fedorov, G., Ostanin, N., Schirrmeister, L., Andreev, A., and the El'gygytgyn Scientific Party: Depositional dynamics in the El'gygytgyn Crater margin: implications for the 3.6 Ma old sediment archive, Clim. Past, 8, 1897–1911, doi:10.5194/cp-8-1897-2012, 2012.

Shanahan, T. M., Overpeck, J. T., Wheeler, W., Beck, J. W., Pigati, J. S., Talbot, M. R., Scholz, C. A., Peck, J., and King, J. W.: Paleoclimatic variations in West Africa from a record of late Pleistocene and Holocene lake level stands of Lake Bosumtwi, Ghana, Palaeogeogr., Palaeocl., 242, 287–302, 2006.

St-Onge, G., Mulder, T., Piper, D. J. W., Hillaire-Marcel, C., and Stoner, J. S.: Earthquake and flood-induced turbidites in the Saguenay Fjord Québec: a Holocene paleoseismicity record, Quatern. Sci. Rev., 23, 283–294, 2004.

Strasser, M., Anselmetti, F. S., Fäh, D., Giardini, D., and Schnellmann, M.: Magnitudes and source areas of large prehistoric northern Alpine earthquakes revealed by slope failures in lakes, Geology, 34, 1005–1008, 2006.
Sturm, M. and Matter, A.: Turbidites and varves in Lake Brienz Switzerland: deposition of clastic detritus by density currents, Sp. Publ. Int., 2, 147–168, 1978.
Twichell, D. C., Cross, V. A., Hanson, A. D., Buck, B. J., Zybala, J. G., and Rudin, M. J.: Seismic architecture and lithofacies of turbidites in Lake Mead Arizona and Nevada, USA, an analogue for topographically complex basins, J. Sed. Res., 75, 134–148, 2005.
van den Bogaard, C., Foese, D., and Ponomareva, V.: Chemical fingerprints of tephra layers in Quaternary sediments of core D1 from Lake El'gygytgyn, Ne Russia, Clima. Past Discuss., in preparation, 2013.
Vogel, H., Meyer-Jacob, C., Melles, M., Brigham-Grette, J., Andreev, A. A., Wennrich, V., and Rosén, P.: Detailed insight into Arctic climatic variability during MIS 11 at Lake El'gygytgyn, NE Russia, Clim. Past Discuss., 8, 6309–6339, doi:10.5194/cpd-8-6309-2012, 2012.
Waldmann, N., Anselmetti, F. S., Ariztegui, D., Austin, J. A. Jr., Pirouz, M., Moy, C. M., and Dunbar, R.: Holocene mass-wasting events in Lago Fagnano, Tierra del Fuego (54° S): implications for paleoseismicity of the Magallanes-Fagnano transform fault, Basin Res., 23, 171–190, doi: 10.1111/j.1365-2117.2010.00489.x, 2010.
Wennrich, V., Minyuk, P., Borkhodoev, V., Francke, A., Ritter, B., Nowaczyk, N., Haltia-Hovi, E. M., Brigham-Grette, J., Melles, M., and El'gygytgyn Science Party.: Pliocene and Pleistocene climate and environmental history of Lake El'gygytgyn/NE Russia based on high-resolution inorganic geochemistry data, Clim. Past Discuss., in preparation, 2013.

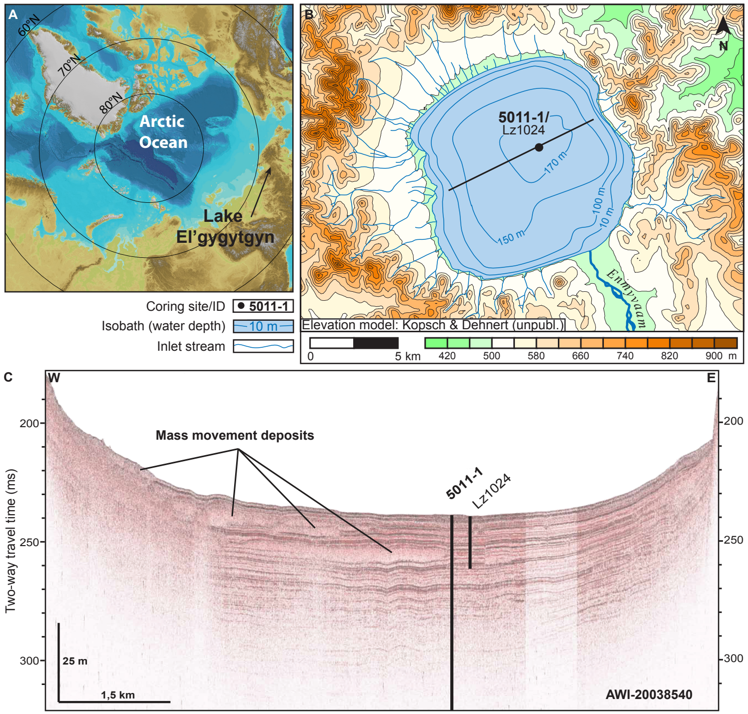

Fig. 1. (A) Location of Lake El'gygytgyn in northeastern Russia. **(B)** Position of the drill site 5011-1 and pilot core Lz1024 and seismic profile (black line) AWI-20038540. Digital elevation model is after Kopsch (2005) and lake bathymetry after Belyi (2001). **(C)** Sediment echosounder profile AWI-20038540 (3.5 kHz) in a WSW-ENE direction crossing the coring site and showing multiple mass movement deposits as acoustically transparent units on the western slope and lake floor.

CPD
9, 467–505, 2013

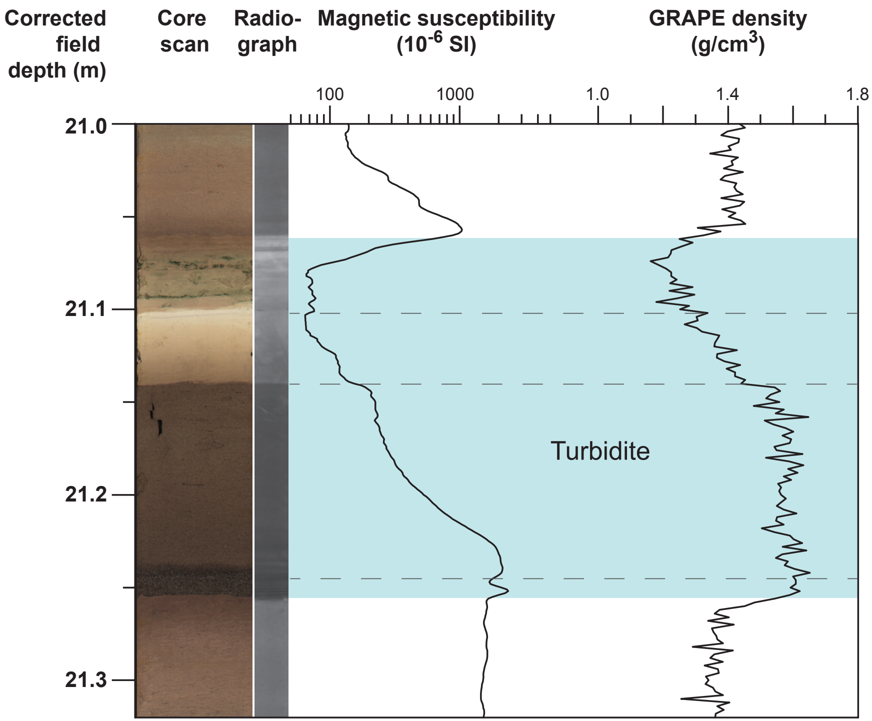

Fig. 2. Turbidite T42 (age 482 ka) in a core scan from 5011-1A-6H-1 resembles a "Bouma sequence" (Bouma, 1962). The different subunits of the turbidite are readily identifiable from the reddish pelagic sediment based on color. The upper boundary of T42 is obscured by a greenish redox layer but compositional grading is revealed by radiograph, magnetic susceptibility and density. Both magnetic susceptibility and density are high at the base of the turbidite and decrease towards the clayey top. Intra-bed boundaries (dashed line) between subunits are marked by "steps" in magnetic susceptibility and density values.

CPD
9, 467–505, 2013

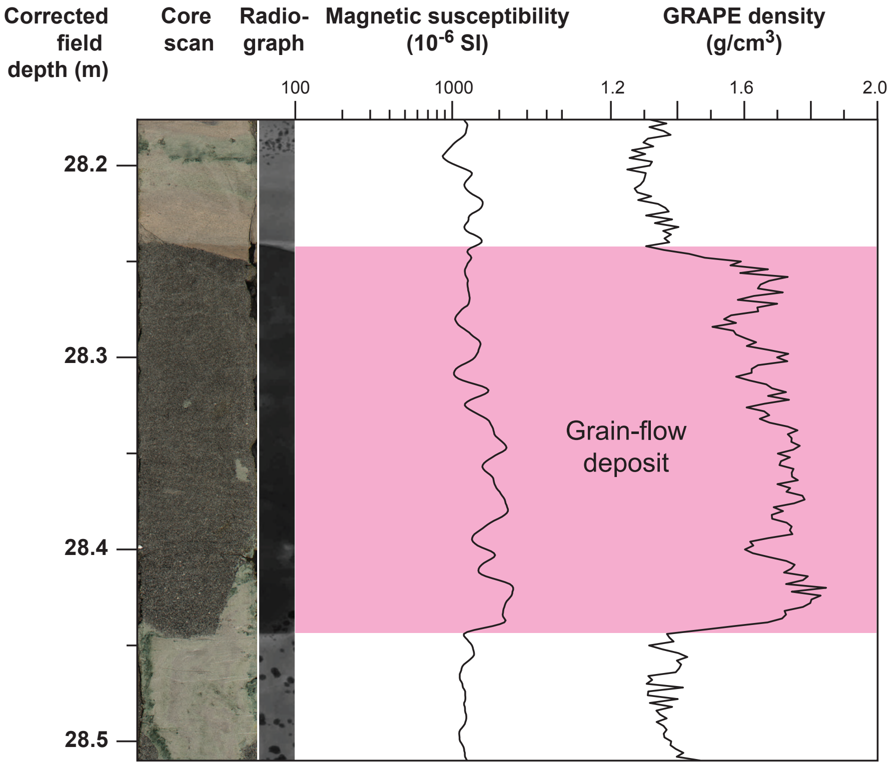

Fig. 3. Grain flow deposit G59 (age 666 ka) in a core scan from 5011-1B-8H-1. Radiograph confirms the massive nature of the deposit. Magnetic susceptibility is somewhat higher, whilst density is clearly higher within the grain flow deposit compared to pelagic sediments.

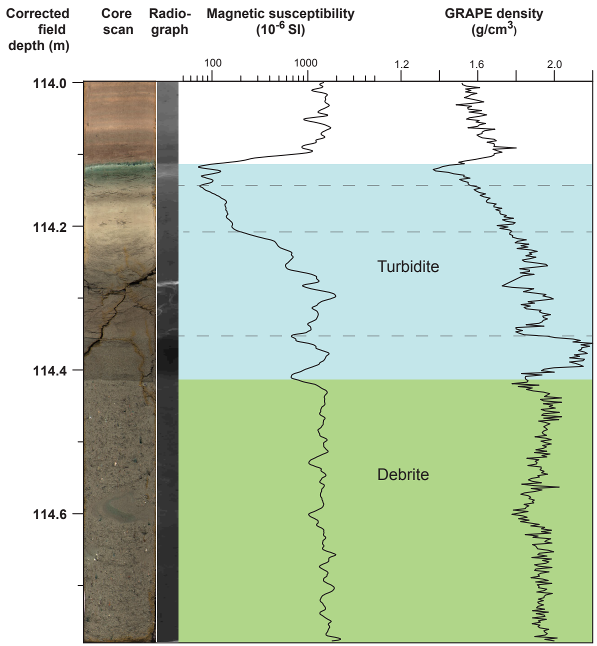

Fig. 4. A section of debrite D221 (age 2.43 Ma) in a core scan from 5011-1A-38H-3. It consists of a basal debrite and a directly overlying debris-flow induced turbidite. Both magnetic susceptibility and density are high throughout the debrite. Density increases in the basal sand of the turbidite, whilst generally density values are the same or lower. Variation of magnetic susceptibility and density within the sandy and silty parts of the turbidite (114.25–114.38 m cfd) are caused by cracks in the core. Both parameters decrease towards the clayey top. Intra-bed boundaries (dashed line) between subunits of the turbidite are marked by "steps" in magnetic susceptibility and density values.

CPD
9, 467–505, 2013

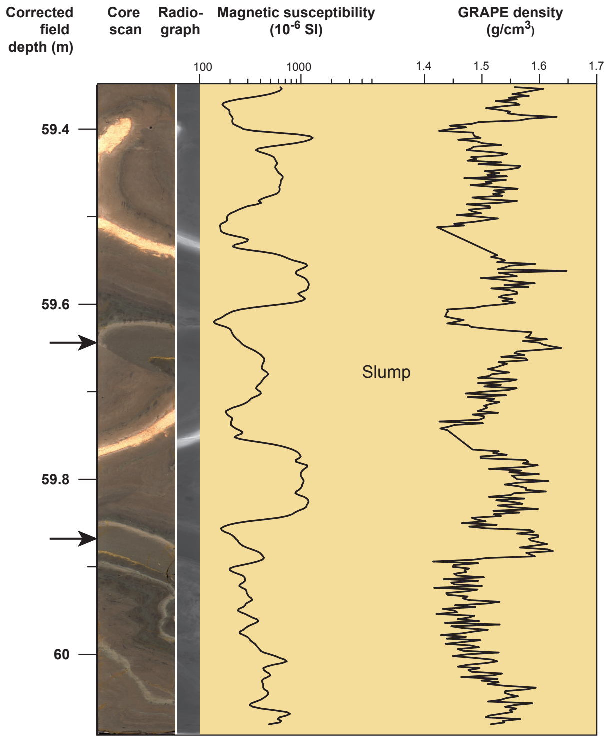

Fig. 5. A 75 cm thick section of slump Su128 (age 1.41 Ma) in a core scan from 5011-1B-18H-2. This section includes a folded tephra layer (orange in core scan) and a bended turbidite occurring twice (arrows). The sediments right above and below the duplicated turbidite (thickness < 3 cm) belong to facies A, whereas the remaining sediments belong to facies B. Both magnetic susceptibility and density vary according to the pelagic facies or event layer. Some unusually low density values in the tephra layers were deleted resulting in gaps in the data.

CPD
9, 467–505, 2013

Mass movement deposits in the 3.6 Ma sediment record

M. A. Sauerbrey et al.

CPD
9, 467–505, 2013

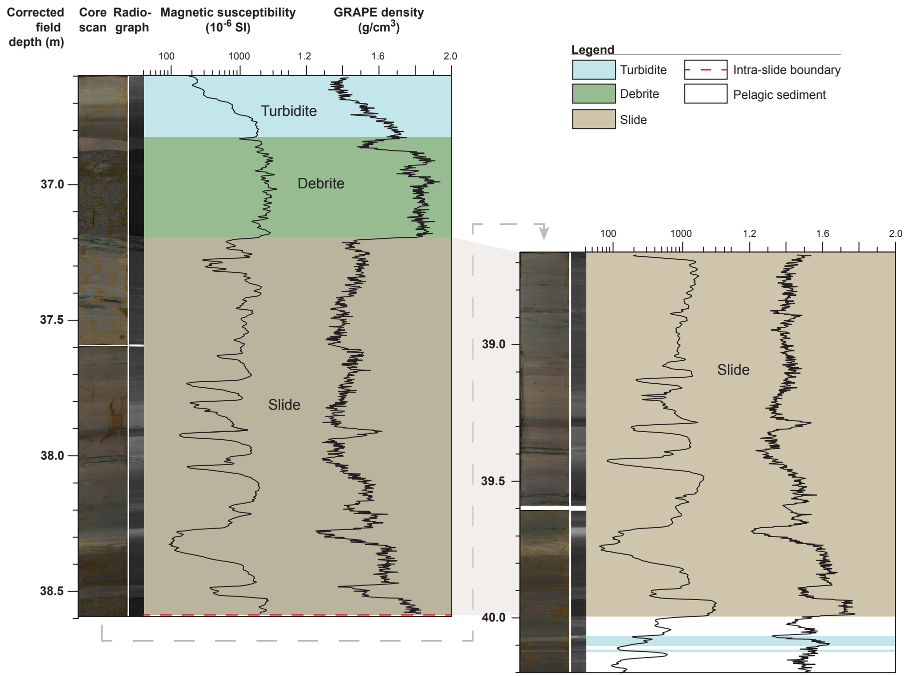

Fig. 6. Slide Si75 (age 930 ka) and overlaying debrite D74 in core scans 5011-1A-11H-2 to 1A-12H-2. Slide Si75 consists of a ca. 140 cm thick duplicated section above and below the intra-slide boundary. The section is divided into a basal co-genetic debrite-turbidite (39.7–40.0 m cfd; thickness 33 cm) overlain by a 1 m segment of facies B sediments (38.65–39.7 m cfd). Both magnetic susceptibility and density of facies B sediments correlate nearly perfectly above and below the intra-slide boundary.

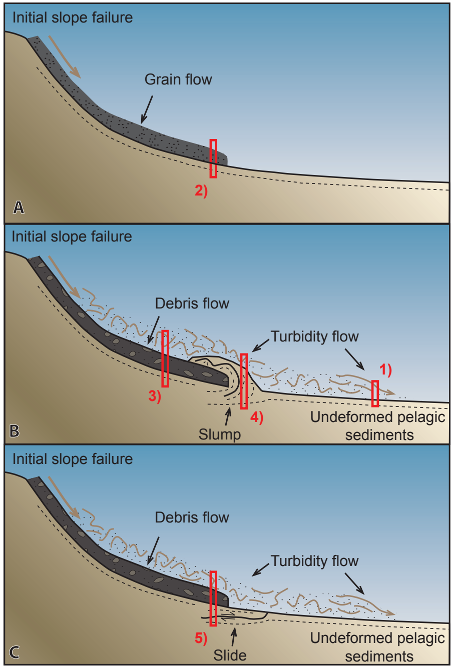

Fig. 7. Illustration of the evolution of mass movements in Lake El'gygytgyn. **(A)** Delta collapses of well-sorted material result in grain flows where the sediment density and grain size is too high to support turbulence. **(B)** Debris flow deforms pelagic sediments and creates co-generic turbidity current in front and on top of the debris flow. **(C)** Slide deposits encountered at the lake center may be caused by debris flows. Red rectangles indicate examples of the mass movement types (1) turbidite (Fig. 2), (2) grain-flow deposit (Fig. 3), (3) co-generic debrite-turbidite (Fig. 4), (4) slump (Fig. 5) and (5) slide-debrite (Fig. 6).

CPD
9, 467–505, 2013

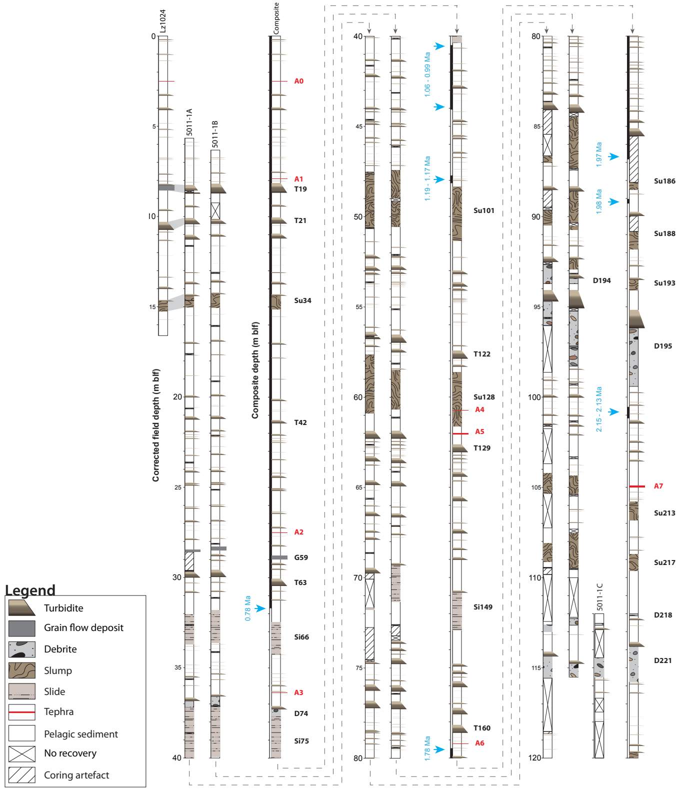

Fig. 8. Distribution of mass movement deposits during the past 3.6 Ma from parallel cores at Lake El'gygytgyn (note: Lz1024 against composite depth and 5011-1A to 1C against corrected field depth). Composite of the mass movement events is against composite depth, which explains the small differences compared to the corrected field depth. Numbered mass movement events are mentioned in the text. Paleomagnetic polarity is indicated by black (normal) or white (reversed) rectangles and ages of reversals (Haltia-Hovi et al., 2013; Nowaczyk et al., 2013) are marked.

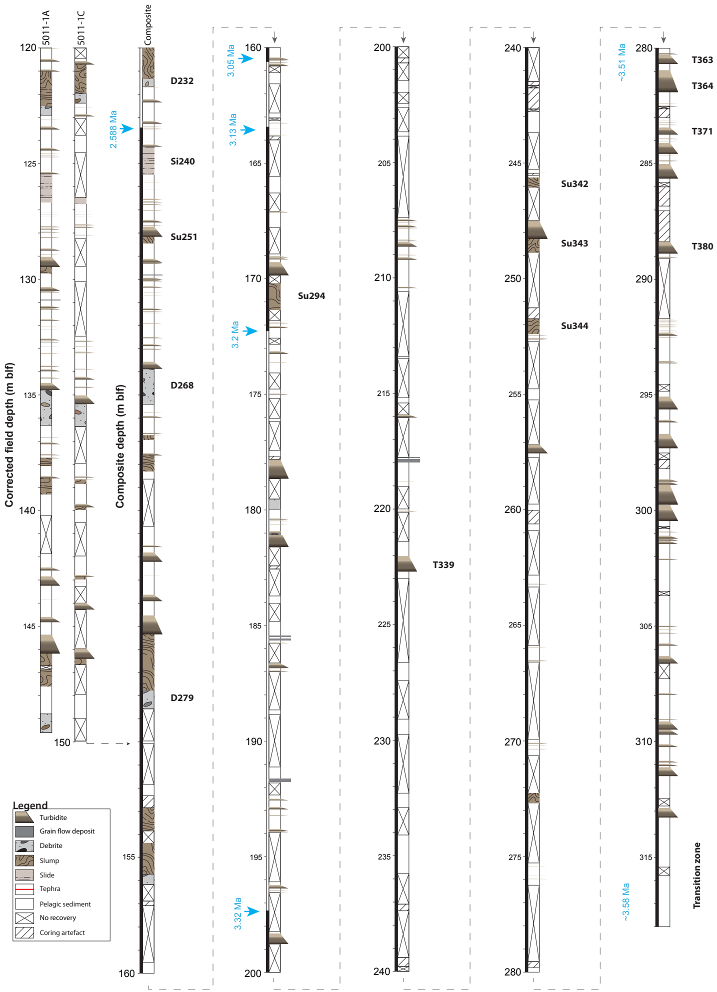

Fig. 8. Continued.