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Sediments from Lake Cheko (Siberia), a possible impact crater for the 1908 Tunguska Event

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ABSTRACT

Cheko, a small lake located in Siberia close to the epicentre of the 1908 Tunguska explosion, might fill a crater left by the impact of a fragment of a Cosmic Body. Sediment cores from the lake's bottom were studied to support or reject this hypothesis. A 175-cm long core, collected near the center of the lake, consists of an upper $\sim$1 m thick sequence of lacustrine deposits overlaying coarser chaotic material. ^{210}Pb and ^{137}Cs indicate that the transition from lower to upper sequence occurred close to the time of the Tunguska Event. Pollen analysis reveals that remains of aquatic plants are abundant in the top post-1908 sequence, but are absent in the lower pre-1908 portion of the core. These results, including organic C, N and δ^{13}C data, suggest that Lake Cheko formed at the time of the Tunguska Event.

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Introduction

The June 30, 1908 'Tunguska Event' (TE), i.e., a $\sim$10–15 Mton explosion, that caused anomalous seismicity, heat and pressure waves and the destruction of over 2000 km^2 of taiga forest in the remote Tunguska region of Siberia, led to the hypothesis that a small asteroid or comet exploded in the atmosphere above Tunguska (Kulik, 1940; Florenskij, 1963; Chyba *et al.*, 1993). Geochemical markers of a cosmic impact in the Tunguska region (Longo *et al.*, 1994; Serra *et al.*, 1994; Hou *et al.*, 1998, 2004; Kolesnikov *et al.*, 1999, 2003), although compatible with the hypothesis of a cosmic body impact, are by no means conclusive and several different scenarios have been proposed for the TE (see Longo, 2007).

During a 1999 expedition to Tunguska, we collected sediment cores from a small lake (Lake Cheko, $\sim$350 m diameter, Fig. 1), located $\sim$8 km NW of the TE epicentre. A suggestion by Koshelev (1963) that Lake Cheko might be an impact crater was rejected by Florenskij (1963) because he felt that the several-metres-thick sediment in the lake indicated a pre-1908 origin. Accordingly, we started our work on the assumption that Lake Cheko was older than the TE and that the lake's sediments might contain natural tracers of the 1908 explosion because the lake is close to the epicentre of the explosion and supplied by a river (River Kimchu) that drains some of the devastated region. However, as our study progressed, we began to question the alleged age of the lake because sub-bottom acoustic reflection data indicated that, of a $\sim$10 m thick sediment succession, only the top $\sim$1 meter is laminated, fine-grained lacustrine sediments. Moreover, the lake's funnel-like bottom morphology contrasts with that of thermokarst Siberian lakes and cannot be explained by other 'normal' erosion-deposition processes. These data may indicate that the Cheko basin is a crater left by the impact of a cosmic fragment that survived the main explosion and hit ground $\sim$10 km downrange from the epicentre (Gasperini *et al.*, 2007). Collins *et al.* (2008) questioned this hypothesis mainly because: (i) Lake Cheko morphology differs from that of typical impact craters (low depth-to-diameter ratio and absence of a rim) and (ii) an accurate age estimate for the lake formation was lacking. An answer to the first question could be found in the nature of the target that may have caused a substantial post-impact collapse (Gasperini *et al.*, 2008).

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The origin of Lake Cheko

If the formation of Lake Cheko is bound to the TE, how were the two events related? The TE has been ascribed to a number of alternative processes, among which the most plausible are: (a) explosion in the atmosphere of a small asteroid or comet or (b) explosion in the atmosphere of gas (methane + CO_2 + air) derived from the subsurface and unrelated to a cosmic impact. An explosion in the atmosphere of gases released from below cannot be excluded; however, we consider it unlikely, also because many eyewitnesses saw a fiery ball in the sky just before the explosion (Vasilyev *et al.*, 1981). If the TE was caused by a gas explosion from below, and Lake Cheko is related to the TE, then Lake Cheko could mark one of the sites where the underground gases were released in the atmosphere. If instead we admit that Lake Cheko is connected with the TE and the TE is due to the explosion of an asteroid in the atmosphere, its disintegration must have allowed at least one fragment to survive and hit ground, triggering the formation of the Cheko crater. Numerical simulations of the TE (Chyba *et al.*, 1993; Artemieva and Shuvalov, 2007) call for disintegration and vaporization of the cosmic body in

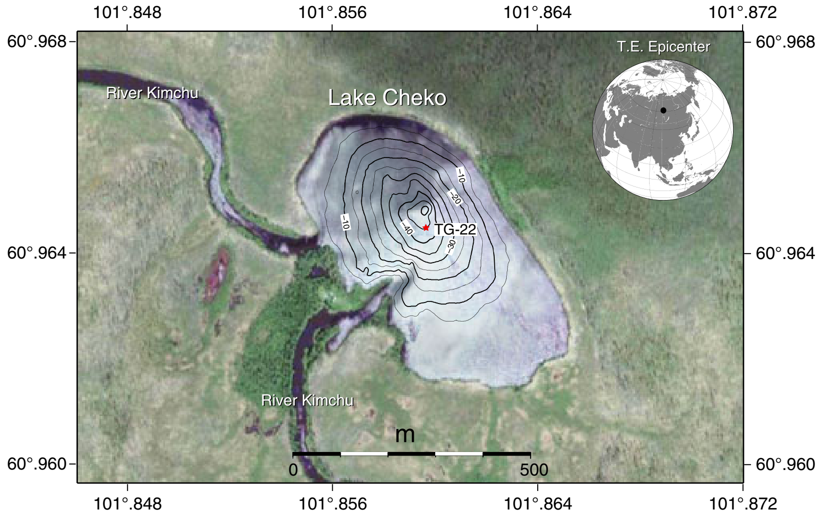

Fig. 1 Lake Cheko bathymetric map and location of sediment-core TG-22 collected during the Tunguska99 expedition.

the atmosphere, but allow for m-size fragments to survive and hit ground in the vicinity of the explosion.

A key question pro or against the impact hypothesis is the age of the lake. We address this question in a study of a 175-cm-long sediment core (TG-22) collected from Lake Cheko, which includes grain-size, porosity, magnetic susceptibility, X-ray radiography, organic C and N content, $\delta^{13}C$ isotopic ratios, palynology and radiometric (^{210}Pb and ^{137}Cs) age determinations.

Methods

Core TG-22 was collected close to the centre of the lake below 45 m of water using a 2-m long gravity corer with plastic liner. X-ray imaging and magnetic susceptibility log were carried out prior to opening. The core was subsequently sampled each 1 cm. Grain size analyses were performed by wet sieving at 250 μm, to separate organic macroremains. After a pre-treatment with H_2O_2 to remove organic matter, a subsequent wet sieving was performed at 63 μm to separate mud from sand. The former was further subdivided into silt and clay fractions by using a Micromeritics RX-5000D sedigraph. All concentrations and activities were calculated on a dry weight basis. ^{137}Cs was measured by gamma spectrometry; ^{210}Pb was determined using alpha spectrometry through its ^{210}Po daughter, after chemical extraction. Organic carbon and nitrogen were determined using a FISON NA2000 elemental analyzer. Stable isotopes analyses of organic C were determined using a FINNINGAN Delta Plus mass spectrometer.

Pollen analyses were carried out on 17 subsamples (spaced 10 cm apart) following standard treatments (Fægri and Iversen, 1989) and counting from a minimum of 500 up to 1000 pollen grains, excluding fern spores, fungal spores and algae. We determined also the abundance of charcoals fragments in the samples to estimate the frequency of forest fires in the region around the lake.

Lake Cheko sedimentary record

X-ray radiography and photo images of core TG-22 (Fig. 2) show an upper 80 cm zone of finely laminated sediments, underlain by a non-stratified chaotic unit, with a 20-cm thick transition zone of homogeneous deposits. High-resolution seismic reflection profiles (Gasperini *et al.*, 2007) imaged two sedimentary units below the lake floor, i.e., a 0.5–1 m thick finely laminated lacustrine unit overlaying a chaotic/massive lower unit. We assume that the two units identified in the core correspond to the two units revealed by the acoustic reflection data throughout the deeper part of the lake and we used the core to define their age and depositional environment.

^{137}Cs and ^{210}Pb radiometric dating methods

The activity-depth profiles of ^{137}Cs and ^{210}Pb radionuclides (Fig. 2) were interpreted as determining the deposition rate, assuming a constant flux/constant sedimentation model (CF-CS, Robbins, 1978). Radiometric data are reported with 1σ standard deviation, taking into account propagation of errors from counting statistics and estimated inventories. A CRS (Constant Rate of Supply) model (Appleby and Oldfield, 1978) was used to calculate Sediment Accumulation Rates (SAR: cm yr^{-1}), and Mass Accumulation Rates (MAR: g cm^{-2} yr^{-1}).

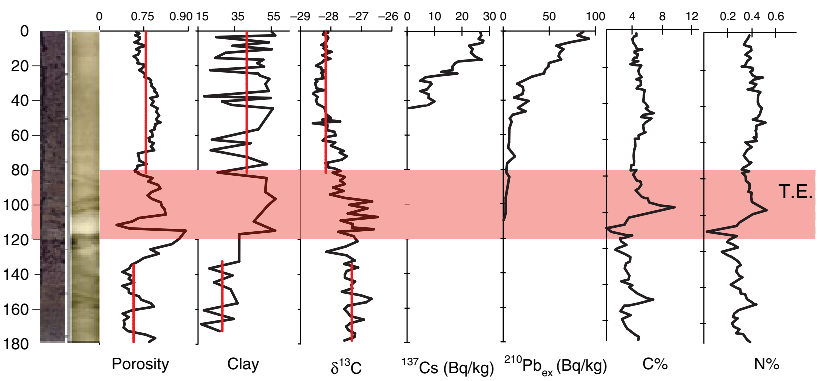

Fig. 2 Analyses carried out on core TG-22 (see text for methods). From left to right: (a) photo of the sliced core; (b) X-ray image; (c) porosity vs. depth; (d) clay content vs. depth; (e) $\delta^{13}C$ vs. depth; (f) ^{137}Cs vs. depth; (f) ^{210}Pb vs. depth; (g) C% vs. depth; (h) N% vs. depth. The inferred T.E. level is indicated, as well as the 'transitional zone' between 80 and 120 cm (red area).

^{210}Pb concentrations show a typical exponential decay, reaching equilibrium between 100 and 120 cm below the top (Fig. 2). This level would correspond to ~100 years before present. Assuming a CF-CS model, the ^{210}Pb concentration curve indicates that the 1908 TE level corresponds to the change in the sedimentary sequence 80–100 cm below the top of the core. ^{137}Cs was detected only down to 42 cm below the top. It shows peaks at 5, 18, 25 and 40 cm core depths. The 40-cm depth level probably represents the years around 1950 (start of nuclear tests in the atmosphere). The upper peak is related probably to fallout from the Chernobyl event of 1986.

Based on these age determinations, the core TG-22 sequence can be subdivided into an upper, post-TE interval from ~80 cm to the top, and a lower, pre TE interval from ~120 cm down to the bottom of the core, with a transitional zone from 80 to ~120-cm depth. The estimated average deposition rate during the last century is ~1 cm yr^{-1}.

Sedimentology

Lake's sediments are generally dark brown-blackish in colour. They have high contents of organic matter and water, and fine grain size, ranging from fine-sand to mud (Fig. 2).

Stratigraphic analysis of core TG-22 shows two main sedimentary facies: (1) an upper fine-grained, faintly-laminated, organic-rich unit, with abundant gas bubbles; (2) a massive to chaotic unit, containing coarser grained sediments, vegetation macro-remnants (herbs and larch cones) and wood fragments in the lower part of the core (Fig. 3).

The sediment mainly consists of sandy-mud (mud fraction ranges from 50% to 83% d.w.); the sand content increases in the lower unit ranging from 25% to 60%.

Lower and upper units are separated by a 'transitional zone' (between 80 and 120 cm) that shows sub-horizontal layering and is constituted by coarser-grained sediments (from silt to fine-sand); the contact between lower unit and transitional zone is sharp (Fig. 3).

Deposits from the lower, pre-TE section appear to be coarser than those from the upper, post-TE interval, in line with the hypothesis that the lower section is made of reworked river sediments, deposited from a relatively high-energy system capable of transporting coarser grains. In contrast, the finer deposits of the upper section are compatible with deposition from a low-energy environment similar to present-day Lake Cheko.

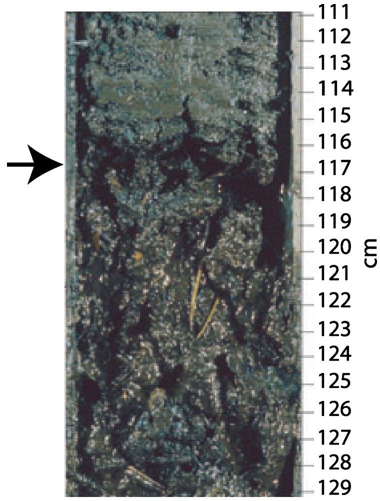

Fig. 3 Close-up view of core TG-22 showing in detail the texture of the lower 'chaotic' unit. Below the sharp contact at about 117 cm (black arrow), we observe sediments and heterogeneous material such as vegetation macro-remnants and wood fragments mixed in the lacustrine sediments.

Organic nitrogen and carbon

Both organic C and N are more abundant in the upper, post-TE unit than in the lower section. The C/N ratio is rather constant in the upper sequence, while it displays high amplitude variations in the lower section (Fig. 2). This distribution is compatible with the upper sediments having been deposited from a lake with relatively high organic productivity and deposition rates, vs. a lower section of reworked river deposits less affected by biological productivity. We can speculate that a sharp peak in both organic C and N content at the transition from the lower to the upper section may have resulted from accumulation of organic debris transported into the Cheko basin by Kimchu River after the TE devastation.

Nitrogen and carbon isotopes

While δ^{15}N remains about constant below and above the TE level, δ^{13}C is a few units more negative in the upper, post-TE sequence than in the lower zone (Fig. 2). This may reflect the presence in the upper zone of δ^{12}C-enriched, algal material typical of lacustrine environments (Shultz and Calder, 1976; Sherr, 1982; Meyers, 2003).

Pollen analysis

Pollen assemblages confirm the presence of two different units, above and below the ~100-cm level (Fig. 4). The upper 100-cm long section, in addition to pollen of taiga forest trees such as *Abies*, *Betula*, *Juniperus*, *Larix*, *Pinus*, *Picea*, and *Populus*, contains abundant remains of hydrophytes, i.e. aquatic plants probably deposited under lacustrine conditions similar to those prevailing today. These include both free floating plants and rooted plants, growing usually in water up to 3–4 meters in depth (*Callitriche*, *Hottonia, Lemna*, *Hydrocharis*, *Myriophyllum*, *Nuphar*, *Nymphaea*, *Potamogeton*, *Sagittaria*). In contrast, the lower unit (below ~100 cm) contains abundant forest tree pollen, but no hydrophytes, suggesting that no lake existed then, but a taiga forest growing on marshy ground (Fig. 5). Pollen and micro-charcoal show a progressive reduction in the taiga forest, from the bottom of the core upward. This reduction may have been caused by fires (two local episodes below ~100 cm), then by the TE and the formation of the lake (between 100 and 90 cm), and again by subsequent fires (one local fire in the upper 40 cm).

Discussion

The results obtained from the study of Cheko's core TG-22 can be summarized as follows.

1. Based on ^{137}Cs and ^{210}Pb, the time of the TE corresponds to the transition from the finely laminated upper sequence down to about 80 cm of depth in the core, to the chaotic unit below about 100 cm.
2. The post-TE sequence, from ~80 cm to the top, consists of laminated, fine-grained, clay-rich sediment containing abundant aquatic plant

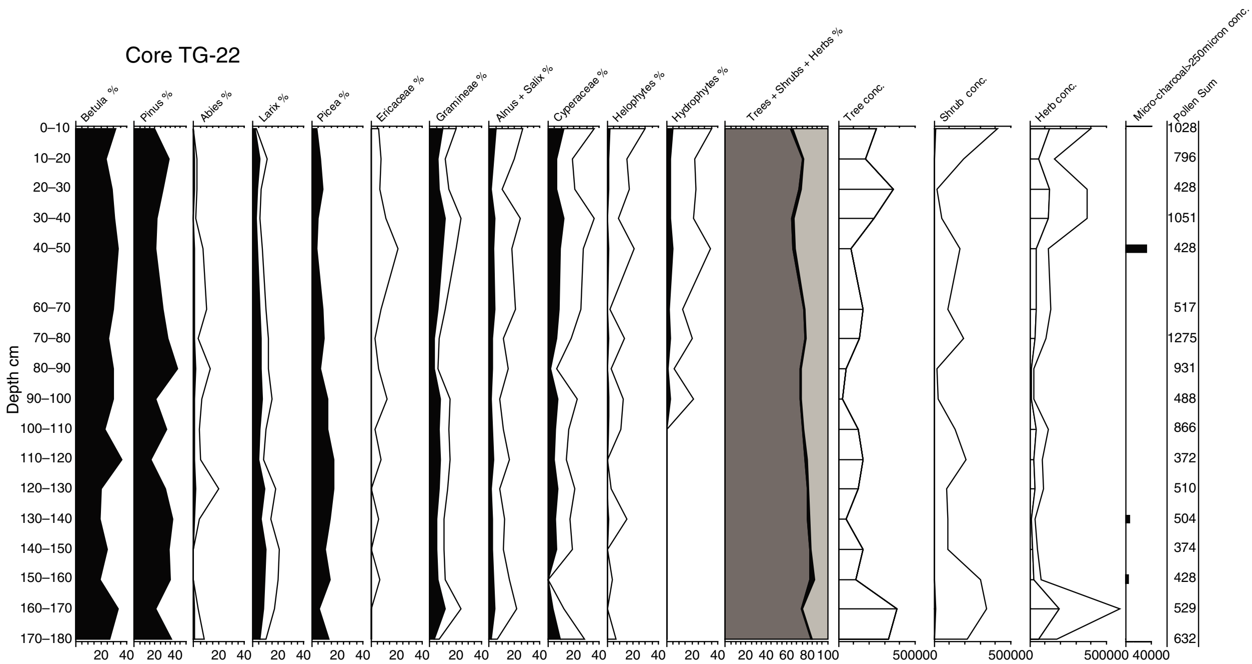

Fig. 4 Pollen and micro-charcoal diagram of core TG-22 (selected taxa, pollen sum = total pollen; concentration = n cm^{-3}). ~120 pollen types were detected, mostly indicative of a taiga environment dominated by conifers (*Abies, Larix, Pinus, Picea*) and birch (*Betula*), with very few shrubs (mainly *Erica, Ledum palustre*, *Vaccinium*) and few herbs (mainly *Gramineae* and *Cyperaceae* with *Aconitum*, *Artemisia*, *Caryophyllaceae*, *Filipendula*, *Plantago*, *Potentilla*, *Pyrola*, *Ranunculus*, *Sedum*, *Thalicrum,* ecc). Periodical local fires are suggested by peaks in > 250 μm micro-charcoal coinciding with a decrease in tree pollen concentrations. Two different pollen zones are visible: Zone I (below ~100 cm), indicative of taiga forest growing on a wet ground; Zone II (above ~80 cm), with taiga pollens plus: (a) hydrophytes (free floating plants such as *Hydrocharis, Lemna,* and rooted plants growing usually in 3–4 meters water depth, such as *Callitriche, Hottonia, Myriophyllum, Nuphar, Nymphaea, Potamogeton, Sagittaria*); (b) increasing hygrophytes (*Alnus, Salix,* Cyperaceae) and (c) increasing helophytes (*Alisma*, *Caltha palustris*, *Menyanthes trifoliata*, *Phragmites, Typha latifolia*).

remains. This upper sequence accumulated at a rate of about 1 cm yr^{-1} (Fig. 2) by quiet deposition in a body of water, similar to the present-day Lake Cheko.

3 The lower, pre-TE, deeper than ~100 cm portion of core TG-22 is made of non-laminated sandy mud, coarser and poorer in organic matter than the post-TE upper deposits. In contrast to the upper section, it contains no aquatic plant remains. These observations suggest that Lake Cheko did not exist when the lower pre-TE sequence was deposited. An interval of transition between the upper post-TE and the lower pre-TE sections, made of compact sandy mud deposits, lies in the 80–100 cm depth interval.

Points (1), (2) and (3) above imply that Lake Cheko formed at about the time of the TE. This could either be considered a coincidence or we could view it as implying a cause-and-effect relationship between the two phenomena.

Let us first consider the 'coincidence' hypothesis. Lake Cheko has a funnel-like morphology, with a diameter of ~300 m at 5 m depth level, and a maximum depth of ~50 m near the centre (Gasperini *et al*., 2007, 2008). This morphology is highly unusual. It is different from that of Siberian thermokarst lakes and is difficult to explain through 'normal' erosion/deposition processes by a small meandering river in a relatively low-energy environment. It hardly could be a volcanic crater because volcanism remains unknown in this region since the Cenozoic and an ancient volcanic crater would have been filled by sediments long ago. It follows that the 'coincidence hypothesis' requires really a 'double coincidence': not only Lake Cheko formed at the time of the TE (coincidence 1), but also it must have formed through a highly unusual process (coincidence 2).

If we exclude the coincidence hypothesis, we are left with the 'cause-and-effect' hypothesis, namely, the origin of Lake Cheko is somehow related to the 1908 TE. Gasperini *et al*. (2007, 2008) proposed that the formation of Lake Cheko was caused by the low-speed impact of a m-size fragment, that upon hitting ground may have triggered a massive release of H_2O vapor, CH_4, and CO_2, partly from the 25–30 m thick permafrost layer ubiquitous in this region. Regardless of whether this gas release was or was not explosive (CH_4–air mixtures can indeed be explosive), it certainly would have modified the crater's dimension and geometry. Reworking and collapse of the original 'soft' pre-TE river deposits could explain the absence of an elevated rim around the crater; this reworked pre-TE material could represent the chaotic deposits imaged below the top 1 meter by acoustic reflection profiles and identified in the lower pre-TE sequence of core TG-22.

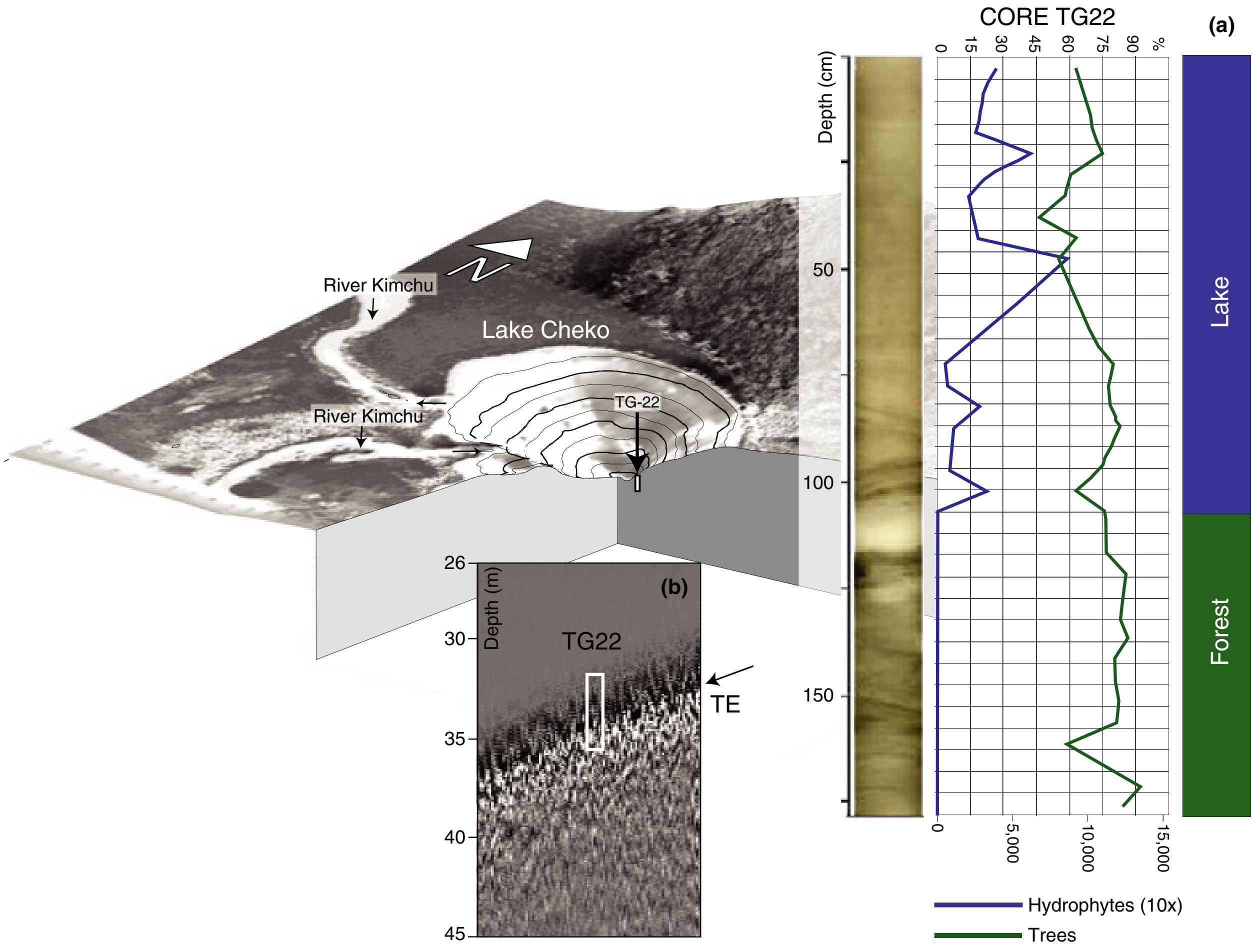

Fig. 5 3-D model of the lake bottom and surrounding based on a Digital Terrain Model and aerial photos, with location of core TG-22; (a) X-ray image of core TG-22 with summary of palynology: while pollen from taiga forest are present throughout the core, hydrophytes disappear below 90–100 cm; (b) chirp-sonar seismic profile collected above the TG-22 site, indicating the presence of 2 different units (Gasperini *et al.*, 2007).

Conclusion

Analysis of sediments from Lake Cheko, including geochemistry, ^{137}Cs, ^{210}Pb radioisotopes dating, and pollen content, together with the funnel-shaped morphology of the lake's bottom and its peculiar acoustic stratigraphy, are all consistent with the idea of a very young (~100 years) lake, filling an impact crater. This crater could have been produced by the impact of a small, m-size fragment of the Tunguska asteroid/comet that survived the atmospheric blast. Drilling the centre of the lake could provide a final test of this hypothesis.

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