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# A possible impact crater for the 1908 Tunguska Event

L. Gasperini[1], F. Alvisi[1], G. Biasini[2], E. Bonatti[1], G. Longo[3], M. Pipan[4], M. Ravaioli[1] and R. Serra[3]

[1]*ISMAR-CNR, Sezione di Geologia Marina, Bologna, Italy;* [2]*Communication Technology, Cesena, Italy;* [3]*Dipartimento di Fisica, Universita' di Bologna;* [4]*Dipartimento di Scienze della Terra, Universita' di Trieste*



## ABSTRACT

**The so-called 'Tunguska Event' refers to a major explosion that occurred on 30 June 1908 in the Tunguska region of Siberia, causing the destruction of over 2000 km$^2$ of taiga, globally detected pressure and seismic waves, and bright luminescence in the night skies of Europe and Central Asia, combined with other unusual phenomena. The 'Tunguska Event' may be related to the impact with the Earth of a cosmic body that exploded about 5–10 km above ground, releasing in the atmosphere 10–15 Mton of energy. Fragments of the impacting body have never been found, and its nature (comet or asteroid) is still a matter of debate. We report results from the investigation of Lake Cheko, located ~8 km NNW of the inferred explosion epicenter. Its funnel-like bottom morphology and the structure of its sedimentary deposits, revealed by acoustic imagery and direct sampling, all suggest that the lake fills an impact crater. Lake Cheko may have formed due to a secondary impact onto alluvial swampy ground; the size and shape of the crater may have been affected by the nature of the ground and by impact-related melting and degassing of a permafrost layer.**

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## Introduction

Unusual phenomena were detected on 30 June 1908 over Eurasia. They included seismic and pressure waves recorded at several observatories; bright luminescence in the night skies; anomalous optical phenomena in the atmosphere, such as massive glowing silvery clouds and brilliant colorful sunsets (Busch, 1908; Zotkin, 1961; Vasilyev *et al.*, 1965). These phenomena were later interpreted as being caused by the explosion of a cosmic body in a remote region of the Central Siberia, close to the river *Podkamennaya Tunguska*, where eyewitnesses observed a huge fireball crossing the sky from the SE. This is the so-called 'Tunguska Event', an explosion that is thought to have released from 10 to 15 Mton of energy in the atmosphere (Ben-Menahem, 1975) and is a major event of this kind in historical times.

Several expeditions explored the Tunguska site, starting with those led by Leonid Kulik in the late 1920s and 1930s. Kulik identified the epicenter of the explosion in a heavily forested area from the radial distribution of flattened trees, and concluded that he had discovered the remains of a large impact crater now hidden by a swamp (Fig. 1). He also found a number of secondary bowl-shaped holes of different sizes covered by peat bogs possibly caused by a fragmented body that fell in a swarm (Kulik, 1933, 1940). Other authors questioned this interpretation suggesting that the circular features observed in the area of the epicenter were not necessarily related to extraterrestrial impacts, but probably to seasonal thawing and freezing of the ground, characterized by a permafrost layer as thick as ~30 m (Krinov, 1949). All attempts at finding macro-remnants of the cosmic body in these circular depressions were unsuccessful; therefore, the hypothesis of an impact with the ground was abandoned. Subsequent expeditions have been devoted mainly to the study of tree patterns in the devastated taiga and to the search for microparticles of the cosmic body, under the assumption that it exploded 5–10 km above the ground (Florenskij, 1963).

Lake Cheko, a small lake located close to the inferred Tunguska Event epicenter (Fig. 1), was the focus of a geological/geophysical expedition that took place in July 1999 (Longo *et al.*, 2001). The objective of the study was to search the lake deposits for possible geochemical and sedimentological markers of the event. However, as the work progressed, a second objective arose, namely, to find evidence *pro or contra* the hypothesis that the lake might fill an impact crater.

Correspondence: Luca Gasperini, Geologia Marina, Istituto di Scienze Marine, CNR, Via Gobetti 101, Bologna 40129, Italy. Tel.: +39 051 639 8901; fax: +39 051 639 8901; e-mail: luca.gasperini@ismar.cnr.it



### Investigation of Lake Cheko

Previous information on Lake Cheko was limited to few soundings and sediment samples collected in 1960 (Koshelev, 1963). However, as the region is remote and uninhabited, there is no reliable evidence even on whether or not the lake existed before 1908. In fact, the presence of the lake was not reported in maps drafted before 1928 and is not mentioned by eyewitness testimonies (Vasilyev *et al.*, 1981). Aerial images and digital terrane models collected during our 1999 expedition show that the lake is located within an alluvial plain covered by sedimentary deposits of the river Kimchu, that flows into the lake on its SW side and outflows ~200 m away on the same side (Fig. 2). The eastern shore of the lake is partially bounded by a hill made of igneous rocks, part of the pre-Mesozoic regional basement (Sapronov, 1986). The river, like other rivers in this region, displays wide meanders due to the low topographic gradient.

We studied the lake bottom morphology using a 200 kHz echo-sounder

 

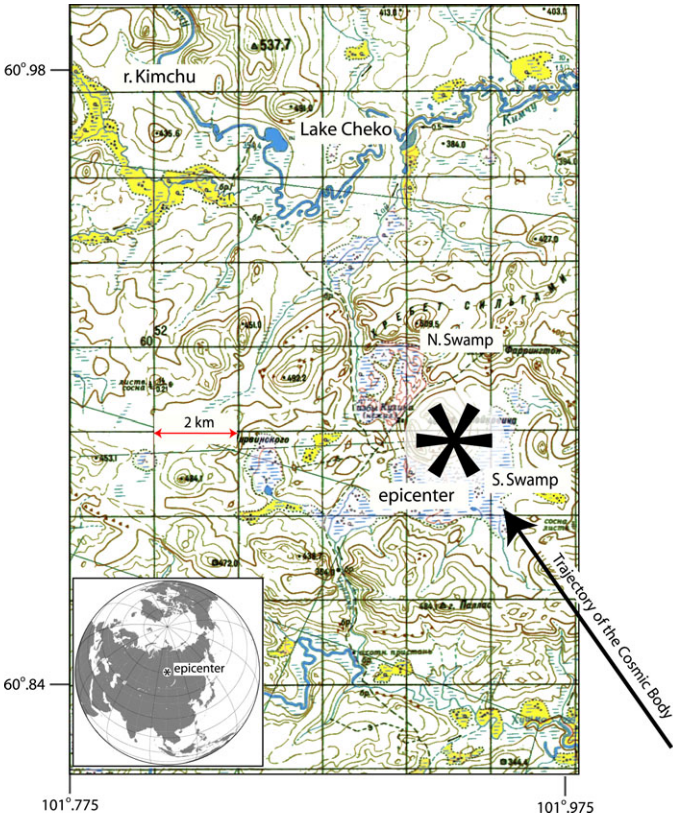


**Fig. 1** Topographic map of the Tunguska Event region. Lake Cheko and the site of the inferred epicenter are indicated, as well as the probable trajectories for the cosmic body.

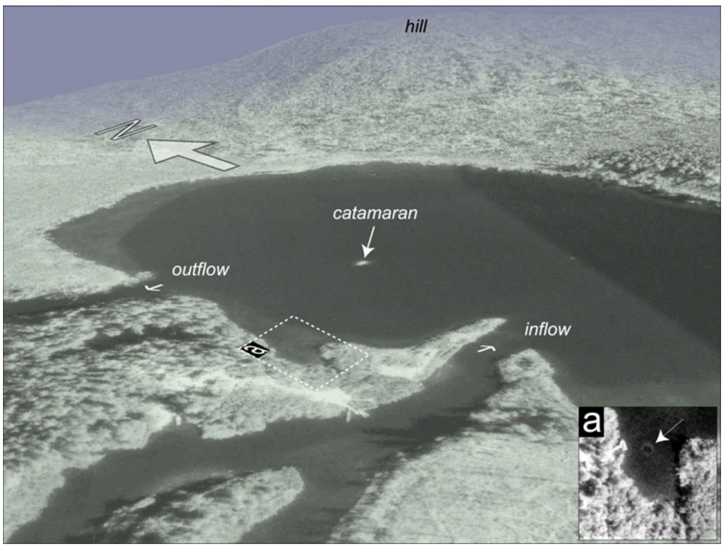


**Fig. 2** 3-D image of Lake Cheko (viewpoint from SW) obtained using aerial photographs collected during our Tunguska99 expedition. The catamaran used for the geophysical survey and core collection is also visible. (a) Close-up view of the lake near the W shore, where a circular feature marking gas-escape from the lake bottom is visible.

and a side-scan sonar system, while the internal structures of the lake sediments were imaged by mini-seismic reflection profilers, the low-frequency DataSonics 'Bubble-Pulser', and the higher frequency (high-resolution) 'ChirpII' subbottom profiler. Sediment cores up to 1.8 m long were collected using a gravity corer. In addition, a Ground Penetrating Radar (GPR) was used in the vicinity of the lakeshores to integrate the seismic grid and to link sub-aerial and sub-lacustrine stratigraphy. Profiles and samples were positioned through a DGPS receiver, with an accuracy of +/–1 m.

The lake, if we exclude a shallow (< 2 m deep) flat area on its SE side, has a nearly circular shape, slightly elongated in the SE–NW direction (125°), and a funnel-like morphology, with a ~50 m maximum water-depth close to its geometrical center (Figs 3 and 4). The slopes are slightly asymmetrical, the northern being a little steeper than the southern and do not show important morphological breaks. The main irregularities are related to sedimentary features and are localized in two areas, the northern slope where a small mound (probably a slump) rises from the lake depocenter, and the SW sector, where the inflowing Kimchu river forms a small lacustrine delta; here, a sharp unconformity marks the onset of lacustrine over older alluvial/fluvial deposits (U1, Fig. 5). Processes causing these two types of features, i.e. sedimentary-wedge progradation and gravity failure, are likely to occur within short time scales, the former within decades or centuries, and the latter within seconds; therefore, their occurrence is compatible with a recent formation of Lake Cheko.

Our seismic-reflection profiles revealed a complex depositional setting within the lake. We observed an irregular pattern, with geometries varying from steeply dipping to chaotic, below a thin (0.5–2 m) finely layered sub-horizontal sequence (Figs 5 and 6). Low-frequency seismic profiles display a single flat strong reflector (reflector-T, Fig. 6) close to the lake center that appears to be produced by a localized discontinuity because it originates from a wide hyperbola visible in the unmigrated section (Fig. 6b). Our single-channel system does not allow to estimate seismic velocities above and below this reflector. However, after time-migration processing, a clear reflector is visible ~10 m below the lake

 

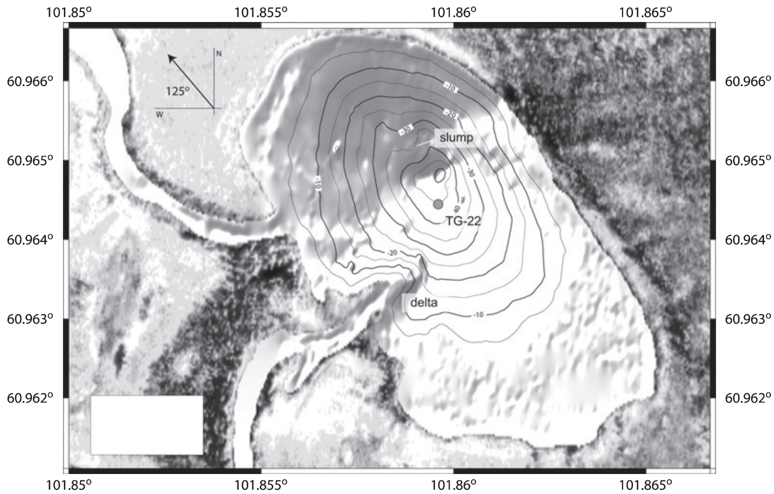


**Fig. 3** Morphobathymetric map of Lake Cheko compiled using the Tunguska99 data, superimposed on an aerial photograph collected during the same expedition. Grey circle indicates the location of core TG-22.

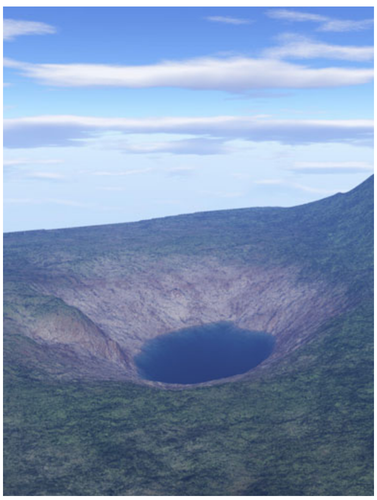

**Fig. 4** 3-D reconstruction (viewpoint from S) of the morphology of the Lake Cheko based on real topographic/bathymetric data. The water level has been placed 40 m below the actual level to enhance underwater morphological features.

bottom, marking the presence of a sharp density/velocity contrast.

GPR profiles collected in the shallow south-eastern sector confirm a recent onset of lacustrine condition (Fig. 7), while side-scan sonar images reveal the presence at the lake bottom of alternate bands of high and low reflectivity that can be due to annular fractures, probably diagnostic of gravity slope-failures and collapse towards the lake center (Fig. 8).

Sediment cores support the geophysical observations in so far as they show the upper portion of the sedimentary column made of dark, well laminated, organic-rich lacustrine mud, overlying massive/chaotic deposits (Fig. 9).

## Origin of Lake Cheko

We review some possibilities for the origin of Lake Cheko:

1. In a hypothetical pre-lake scenario, the river Kimchu would have excavated a major meander and the inverted conical depression as it approached the basement relief, continuing then its course on a SE–NW direction, i.e. downstream the present outflowing river (Fig. 2). We find it highly unlikely that the river 'normal' erosion/redeposition processes could have created the ~50 m deep, inverted/conical depression presently filled by the lake. We find it equally difficult to explain the Cheko depression by limestone karsic chemical erosion, since limestones are absent, or by basement faulting/fissuring, because the lake is within a tectonically stable cratonic region.

2. Another possibility is that the lake filled a volcanic crater intercepted by a river meander during its migration. The region affected by the Tunguska Event is centred on the roots of the lower Triassic *Kulikovsky* palaeovolcanic complex, which extends over a 400 km$^2$ wide area displaying numerous, various sized craters (Sapronov, 1986). The Cheko depression, however, stands above the alluvial plain deposits of the Kimchu river, as shown by maps and seismic profiles (Figs 4 and 5). A topographic 'hole' such as the Lake Cheko would be completely filled by fluvial sediments in a fraction of the age of the volcanic craters observed in the region. Moreover, the rocks outcropping in the vicinity of the lake are not eruptive, but mostly dolerites and microgabbros.

3. A large number of lakes have been generated in the subarctic

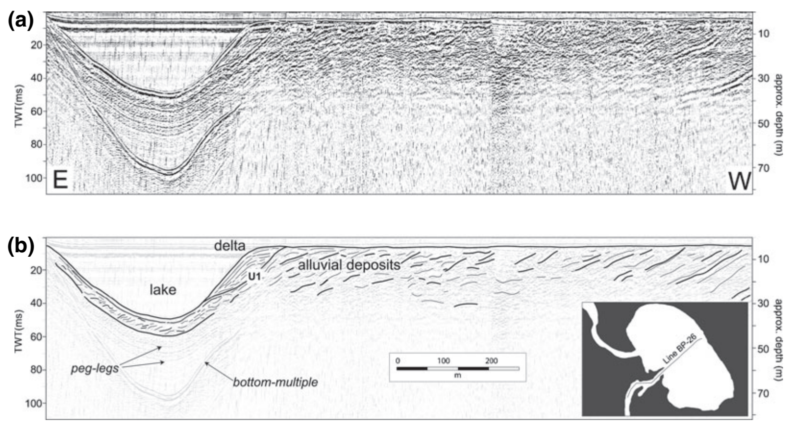


**Fig. 5** (a) E–W, low-frequency seismic reflection profile BP-26 crossing the Lake Cheko southern slope, the delta, and continuing upstream the Kimchu river. (b) Interpretation of the profile, with the main features indicated. Note the differences between seismic facies in the river and lake domains, which are separated by U1: alluvial/fluvial deposits are less homogeneous and show the typical pattern of fluvial valley infill caused by lateral migration of meanders.

 

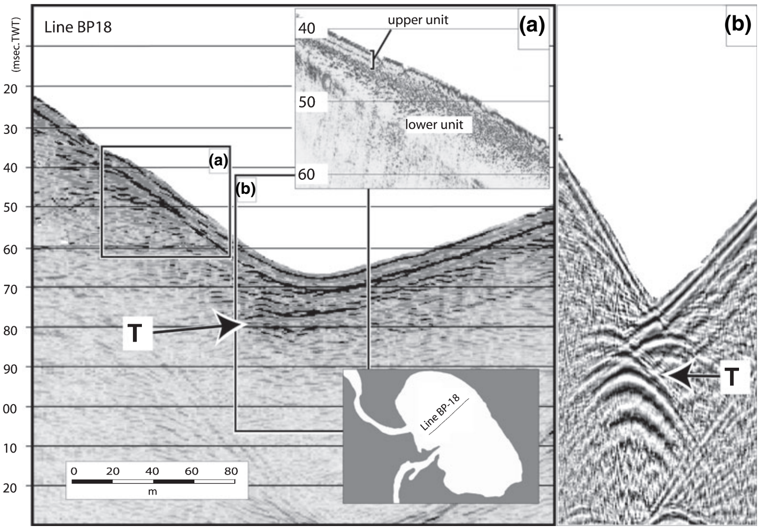


**Fig. 6** Time-migrated (constant velocity) seismic reflection profile BP-18 crossing the center of the lake. Note the absence of coherent reflectors from the lake slopes. A flat reflector (reflector T) located ~10 m below the bottom is visible at the centre of the lake. (a) Segment of high-resolution chirp sonar profile along profile BP-18, showing a diffuse diffraction noise from the very upper part of the sedimentary sequence; (b) unmigrated version of BP-18 showing diffractions marked by hyperbolas, mostly related to scatter points at the lake bottom. One of these hyperbola gives rise to reflector T after the migration processing.

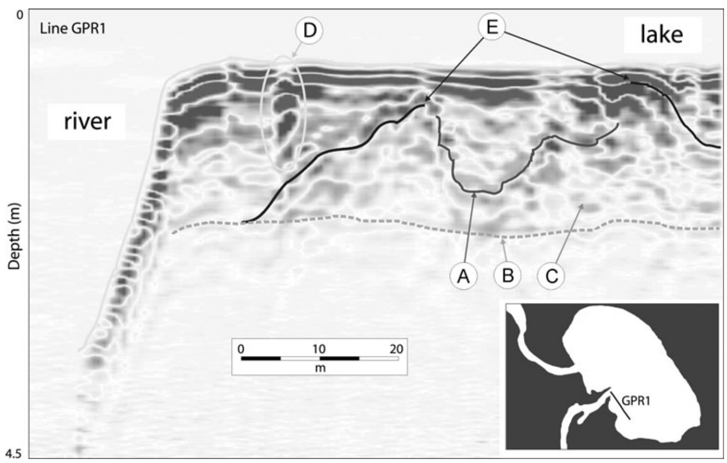


**Fig. 7** 100 MHz GPR profile across the SE sector of Lake Cheko (black line in the location map, bottom right). Several non-lacustrine features are evident below a thin, fine-grained sediment layer, suggesting a recent onset of lacustrine conditions. (A) abandoned river channel; (B) boundary between pre-lacustrine and lacustrine conditions; (C) shallow layer associated with lacustrine conditions; (D) large number of diffractors, internal chaotic texture and localized amplitude anomalies; (E) shallow and dipping reflectors in the lacustrine sequence and sigmoidal patterns marking accretionary processes.

region of Siberia by thermokarst, i.e. the process by which permafrost may become unstable and melt, resulting in water-filled depressions of the ground. Thermokarst lakes are characterized by steep slopes and nearly flat floors, quasi-circular shapes, with diameter up to several hundred metres (Czudek and Demek, 1970). The inverted conical morphology of Cheko, with –50 m water-depth near the centre, makes a thermokarst origin unlikely. Topographic profiles of Lake Cheko and of a Siberian thermokarst lake (Lake Nikolaji in the Lena Delta region) compared with a cross-section of a terrestrial impact crater (the Odessa Meteor Crater, in Texas) show that the two lakes are completely different, while the morphology of Cheko resembles that of the Odessa Meteor Crater (Fig. 10).

### *Is Lake Cheko an impact crater?*

Attempts have been made to determine the trajectory of the cosmic body responsible for the Tunguska Event, based on eyewitness accounts, modelling of the ballistic wave and patterns in the devastated forest. Earlier estimates, although differing from each other, are averaged around 110° (Sekanina, 1998), while more recent reconstructions based on eyewitness accounts (Andreev, 1990) and patterns in the devastated forest (Fast *et al.*, 1976; Fast and Golenberg, 1983) led to estimates of $120° \pm 20°$ and $99° \pm 10°$ respectively. A new analysis based on tree patterns suggests two azimuths: 110°, for a single explosion scenario, and 135° under the assumption of multiple centers (Longo *et al.*, 2005). These azimuths are close to the 125° orientation of the elliptical Cheko depression (Fig. 4). Moreover, the lake is located along the prolongation from the epicenter of the most probable track of the cosmic body (Fig. 1). Given the above, and given the difficulty to explain the lake by thermokarst or by 'normal' river sedimentation/erosion processes, we now discuss a scenario whereby Lake Cheko formed as a result of the impact of a cosmic body in a swampy taiga-covered area, close to a major meander of the Kimchu River.

Several lines of evidence indicate that the Tunguska Event was caused by the explosion of a main body 5–10 km above ground (Florenskij, 1963); one or more fragments of the body may have survived the main explosion and impacted the ground NW of the epicentre (Artemieva and Shuvalov, 2007). Many trustworthy eyewitnesses heard multiple explosions (Kulik, 1927); moreover, fallen trees pattern based on the 1938 aerophoto survey suggested the presence of two to four secondary centres of wave propagation (Kulik, 1940), implying possible multiple centres of explosion (Goldine, 1998).

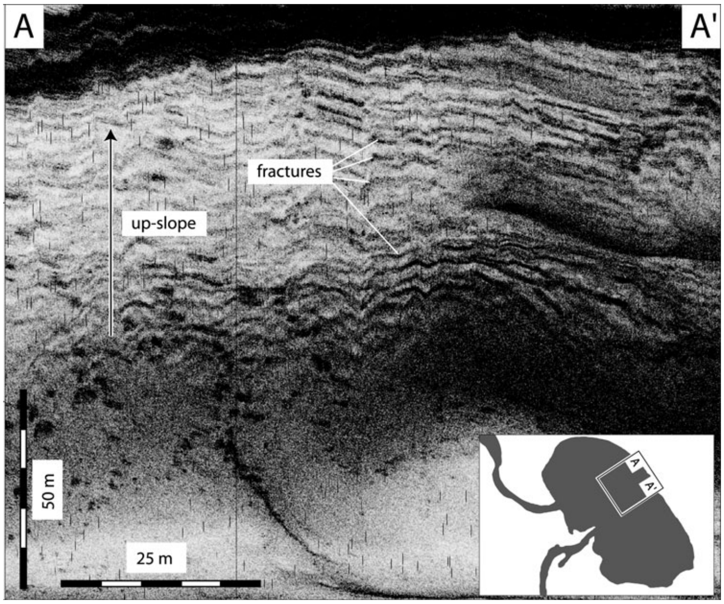


**Fig. 8** Side-scan sonar (SSS) image of the lake eastern slope. These images, produced by the acoustic backscatter from the lake bottom, reveal tiny bands of high reflectivity (dark color) running parallel to the isobaths, probably due to small scarps (vertical displacements) in the lake bottom. They are visible in the SSS record, but neither in the bathymetric profiles, nor in the underwater video images. The reason may be the presence of a thin veneer of soft sediment over annular fractures, probably caused by collapse towards the centre of the lake.

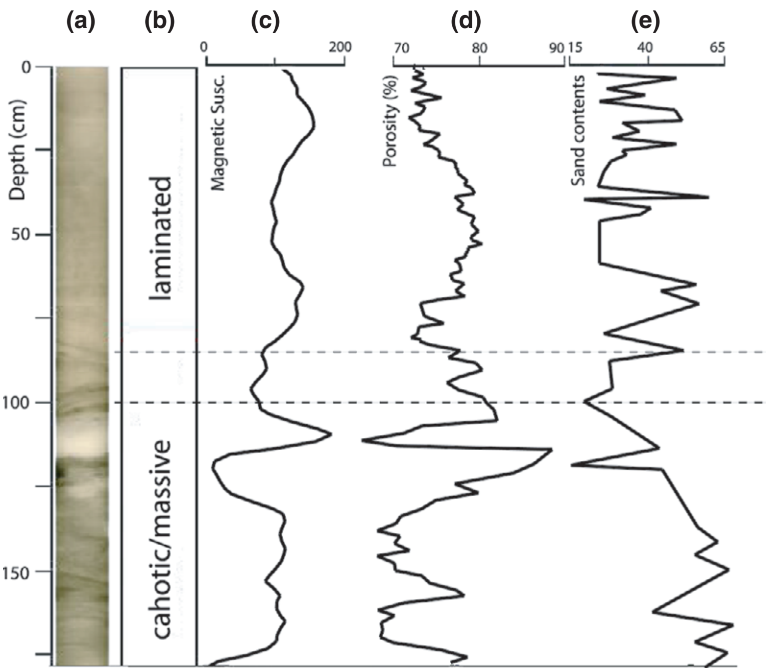


**Fig. 9** Sediment core TG-22 collected close to the lake depocenter (see Fig. 3 for location). (a) X-ray image; (b) stratigraphic units (laminated and massive/chaotic); (c) magnetic susceptibility in adimensional SI units; (d) porosity; (e) sand contents as % of dry weight.

Small, bowl-shaped impact craters on Earth all have similar geometries, i.e. a deep cavity with a typical depth-to-diameter ratio (~1:3) and an overturned flap of ejected material around the rim (Melosh, 1989). Lake Cheko fits these proportions, although with a relatively low depth-to-diameter ratio (~0.16) that suggests a 'wet' target (Kenkmann *et al.*, 2007) but lacks an overturned flap of ejecta. Moreover, it is slightly elliptical in shape. Elliptical craters result either from low-velocity (0.5–10 km $s^{-1}$), moderately oblique (30–60°) impacts, or from extremely oblique ( < 10°) higher-velocity impacts. In order to form a ~300-m diameter crater within the first scenario, scaling laws require an impactor with a 10–50 m diameter (Melosh, 1989). The upper limit is not realistic, being very close to pre-atmospheric entry size estimated for the Tunguska bolide. The low-velocity suggests that the bulk of the impactor may have survived the collision and, if so, should be buried below the lake. Concerning this point, reflector-T observed in profile BP-18 (Fig. 7) is compatible with the presence of a buried object or a compacted sedimentary layer below the centre of the lake.

### *The effect of permafrost melting and $H_2O$ release at impact*

The morphology of the lake floor and subbottom images of the sedimentary sequence are compatible with the hypothesis of a 10-m diameter stony object impacting the ground with relatively low velocity (1–10 km $s^{-1}$), and impact angle (≤45° over the horizontal). A probable scenario implies that a single fragment survived the airburst, continued along its trajectory and impacted down range of the air blast epicentre.

Estimates of the size of the impacting body derived from the size of the crater are affected by the nature of the ground where the impact took place. In the Lake Cheko case, it consisted of a $H_2O$-logged, swampy and forested taiga underlained by a layer of permafrost ranging up to 25 m in thickness. In addition to its mechanical effect, the impact must have caused a strong thermal effect that may have melted the permafrost layer in the vicinity of the impact,

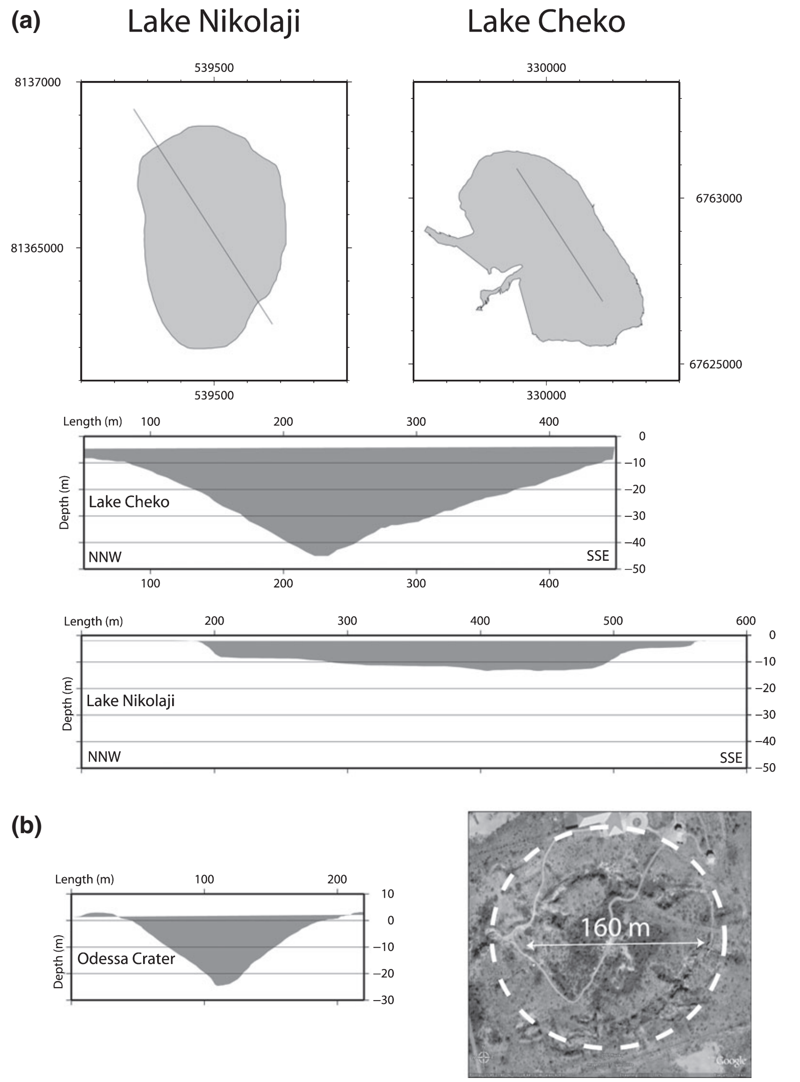


**Fig. 10** Comparison between the morphology of (a) Lake Cheko and Lake Nikolaji (a typical thermokarst lake; Schwamborn *et al.*, 1998), and (b) the Odessa Impact Crater in Texas (Maysell, 2004).

with a volume reduction of the ground material mainly due to evaporation and/or drainage of interstitial $H_2O$, and degassing of $CH_4$. Subarctic Siberian permafrost stores large quantities not only of $H_2O$-ice, but also of $CH_4$, partly derived from the decay of ancient Pleistocene organic matter; Siberian lakes are a major source of $CH_4$ to the atmosphere (Zimov *et al.*, 1997, 2006; Walter *et al.*, 2006). Assuming a 10-m diameter stony object (density 3000 kg $m^{-3}$) impacting the ground with a speed of 10 km $s^{-1}$, we obtain $0.8 \times 10^{14}$ J of kinetic energy released by the impact. It has been estimated that, in an average impact case, ~1/2 of the kinetic energy is transferred to the ground (Melosh, 1989). This amount depends on several parameters, including the strength and the nature of the target. Due to the soft nature of the swampy taiga we expect an efficient energy transfer to the ground. However, assuming conservatively that $0.4 \times 10^{14}$ J were transferred to the ground, ~25% of the total crater volume may have melted, thus enhancing significantly its final dimensions.

This scenario, i.e. the formation of a crater due to the 'soft' impact of a small body, subsequently enlarged by the expulsion of $H_2O$ and gas from the ground, would explain the unusual morphological/stratigraphical features observed in the lake. It would also explain the limited air-blast effects in the lake surroundings, and the absence of a rim that, if formed during the impact would have been rapidly obliterated by collapse and gravity-failures during the subsequent degassing phase. Moreover, it would explain the presence in the bottom of the lake of a chaotic/massive sediment unit below a well-layered 'normal' fine grained lacustrine sedimentary sequence. Our cores (max 1.80 m) did not reach the impact level and the pre-impact sediments, and do not allow us to confirm or reject our hypothesis. Obtaining longer cores of the lake sediments will be crucial to verify our reconstruction.

## Conclusions

Cheko, a small lake located 8 km from the alleged epicentre of the 1908 Tunguska Event, has an unusual funnel-like bottom morphology, with ~50 m maximum water-depth near the center and a 0.16 depth-to-diameter ratio. This morphology is different from that of subarctic Siberian thermokarst lakes, and is also hard to be accounted for other 'normal' Earth-surface tectonic or erosion/deposition processes, but is compatible with the impact of a cosmic body. Based on diameter, depth and morphology of the lake crater, and assuming that the impacting object was an asteroid, a mass of $1.5 \times 10^6$ kg (~10 m diameter) was estimated for the projectile. However, this estimate is probably too large, because the crater was enlarged by permafrost melting and release of $H_2O$, $CH_4$ and other volatiles induced by the impact into a soggy ground. The projectile that formed Lake Cheko might have been a fragment of the main body that exploded in the atmosphere 5–10 km above ground. A prominent reflector observed in seismic reflection profiles ~10 m below the bottom at the center of the lake indicates a sharp density/velocity contrast, compatible with either the presence of a fragment of the body, or of material compacted by the impact. Drilling could solve this dilemma.

 

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