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Reply

Lake Cheko and the Tunguska Event: impact or non-impact?

Luca Gasperini,[1] Enrico Bonatti,[1,2] and Giuseppe Longo[3]

[1]*Istituto di Scienze Marine, CNR, Sezione di Geologia Marina, Bologna, Italy;* [2]*Dipartimento di Scienze della Terra, Universitá "La Sapienza", Roma, Italy;* [3]*Dipartimento di Fisica, Universitá di Bologna, Italy*

ABSTRACT

Several lines of evidence were presented in Gasperini *et al.* [*Terra Nova* (2007), vol. 19, pp. 245–251] suggesting that Lake Cheko, a small lake close to the alleged epicentre of the 1908 Tunguska Event, might be a secondary impact crater. Collins *et al.* [*Terra Nova* (2008), this volume] argue against this hypothesis. We reply here arguing in favour of an impact origin for Lake Cheko.

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Introduction

A century after its occurrence, the 'Tunguska Event' (TE) still raises strong passions, as witnessed also by the prompt response of Collins *et al.* (2008) to our suggestion that Lake Cheko (Fig. 1), located close to the alleged epicentre of the TE, might fill an impact crater (Gasperini *et al.*, 2007).

How old is Lake Cheko?

We agree with Collins *et al.* (2008) that the age of Lake Cheko is a key point: if the lake is older than 1908, it cannot be an impact crater related to the TE. A suggestion by Koshelev (1963) that Lake Cheko might be an impact crater was rejected by Florensky (1963) because he felt that the $\sim$7 m thick sediment pile found in the lake could not be deposited in <60 years, but would require over a 1000 years. Based on Florensky's argument, we started our work at Lake Cheko on the assumption that it was older than the TE: our objective was to find markers of the TE in the lake's sediments. However, as our study progressed, we began to question the old age of the lake for the following reasons:

1 Our sub-bottom acoustic reflection data show that, of a $\sim$10 m thick sediment pile, only the top 1 ± 0.5 m is laminated, fine-grained, 'normal' lacustrine sediments (Gasperini *et al.*, 2007). The lower chaotic material appears not to be deposited by normal lacustrine sedimentation.
2 ^{210}Pb and ^{137}Cs datings on sediment cores from the lake suggest sedimentation rates of roughly 1 cm yr^{-1} (Gasperini *et al.*, 2001). Assuming this rate is mostly due to fine-grained material transported into the lake from the Kimchu River, the thin lacustrine sequence is compatible with a young ($\sim$100 years) age for the lake.
3 Maps and oral accounts of whether or not Lake Cheko existed before 1908 are admittedly less reliable, because of the remoteness in space of the region and in time of the TE. Even so, we searched for evidence *pro* or *contra*. Lake Cheko is not reported on any map prior to 1928 (the year of the second Kulik expedition), including the 1883 map of Eastern Siberia compiled by the Central Headquarters of the Czarist army, and subsequently updated on the basis of traveller's information, or the sketch maps of the Tunguska site compiled by Obruchev (1925) and Suslov (1927) on the basis of Evenki testimonies. Concerning eyewitness accounts, Vasilyev *et al.* (1981) collected 708 testimonies. When 'Cheko' is mentioned, eyewitness testimonies refer generally not to 'Lake Cheko', but to a 'River Cheko', i.e. to a river that flows into the River Kimchu before the latter flows into Lake Cheko (Fig. 2). 'Lake Cheko' is named only one time by Evenk Dmitriev (born in 1924!) who reported in 1964 the hearsay by other people. He mentions 'Cheko' as a reference point without any connection to the 1908 event. Conversely, Koshelev (1963) notes that 'The Evenk Doptyna (Doptyna Praskovia Grigorevna, born in 1880), who lives in the Mutorai factory and was hunting in

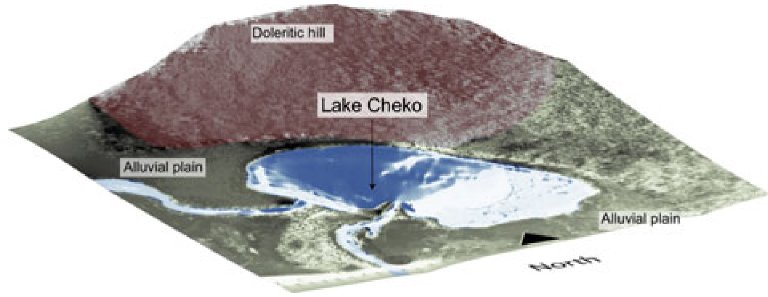

Fig. 1 3-D view of Lake Cheko superimposed on an aerial photograph collected in 1999.

Correspondence: Dr 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

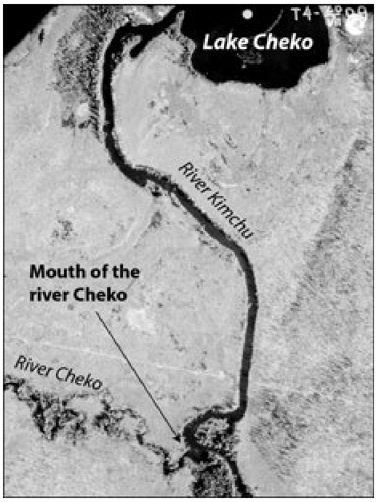

Fig. 2 Aerial photograph of the Lake Cheko southern shore and surroundings collected during the Tunguska99 expedition. The mouth of 'River Cheko' flowing into 'River Kimchu' ~1 km to the south of the lake is indicated. Note that several eyewitness testimonies refer to 'River Cheko' and not to 'Lake Cheko'.

these areas when she was young, states that only a swamp was present on the site of Lake Cheko'.

We conclude that geophysical, geological and documentary evidence are compatible with the hypothesis that Lake Cheko is young, not older than the TE.

Morphology of Lake Cheko

We stressed that Lake Cheko's funnel-like morphology is very different from that of common Siberian lakes, but is similar to that of confirmed small-diameter (< 1 km) impact craters in Gasperini *et al.* (2007). Collins *et al.* (2008) question this similarity because Lake Cheko appears to be asymmetric and lacks an elevated rim.

Lake Cheko asymmetry

The lake appears to be markedly asymmetric (elongated in a NW-SE direction) if we consider its geometry at water level. However, if we consider a level of just 5 m below the surface, the lake's morphology is similar to that of a funnel or of an inverted cone (Fig. 2). Most of the apparent ellipticity is caused by a very shallow (< 2 m depth) area that extends onto the south-eastern side of the lake. Quoting Collins *et al.* (2008): 'If Lake Cheko was formed at the same time as the 1908 TE, then its location relative to the blast epicentre (8 km down range) and the estimated altitude of the main explosion (5–10 km) imply an impact angle of 30°–50°. An impact at this angle produces an almost circular impact crater'. As shown in Fig. 3, Lake Cheko is almost circular. The slight ellipticity could be explained either by an extremely low impact angle (< 30°) or, more likely, by a combination of moderate impact angle (30°–45°) and low velocity (< 1 km s^{-1}). However, low-velocity oblique impacts on targets such as the TE site have been poorly studied and modelled. Experiments on low-velocity impact craters occurring in ice and ice-saturated soils (Croft *et al.*, 1979) fit morphological features observed on the floor of Lake Cheko, such as the prevalence of concentric over radial fractures (Fig. 8 in Gasperini *et al.*, 2007). Moreover, Croft *et al.* (1979) found that, within the same energy and velocity range, crater diameters in ice-saturated sand are ~2 times larger than those formed in competent blocks of granite, basalt and cement. This is in agreement with the hypothesis that the diameter of the impacting object was significantly smaller than predicted by scaling laws (see next section). The nature of the target could also have contributed to the crater asymmetry, because the NE shore of the lake is bounded by a doleritic hill, where the alluvial deposits of the Kimchu valley pinch out. This could have limited the post-impact growth of the Cheko crater towards the E (Figs 1 and 3).

Lake Cheko lacks a rim

The lack of an elevated rim around Lake Cheko was explained by Gasperini *et al.* (2007) as a consequence of the peculiar nature of the target, i.e. of wet, swampy forested ground underlain by a > 20-m-thick permafrost layer. Dewatering and degassing of sediments and permafrost because of the heat released by the impact followed by collapse of the walls of the crater, may well result in a crater morphology somewhat different from that predicted by standard models. The chaotic deposits detected below the thin upper layer of lacustrine sediments might represent material that collapsed and was reworked from the sides of the crater immediately following the impact. This would explain the absence of an elevated rim.

Nature of the impactor

The nature and size of an impacting body are estimated primarily from the size and shape of the resulting crater. If Cheko is an impact crater, its shape and size might have been strongly affected by the unusual nature of the target (swampy and with permafrost), and modified immediately after the impact. If so, standard reconstructions of the nature/size of the impacting body based on crater dimensions are highly uncertain.

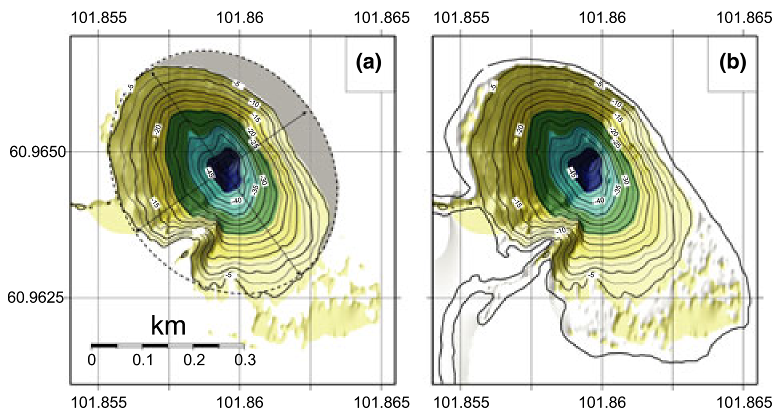

Fig. 3 Morphobathymetric map of Lake Cheko: (a) bathymetry below 5 m water depth; and (b) bathymetry including the lake's shorelines. Grey area in (a), to the east of the eastern shore, marks the difference between the -5 m contour and a best-fit ellipse centred on the lake's major axis.

Most of the theoretical analogue and numerical modelling devoted to explaining the consequences of the TE, including that of Artemieva and Shuvalov (2007), suggest that the Tunguska body disintegrated and vaporized 5–10 km above ground, with broad dispersion of the resulting debris/gaseous jet. However, these models do not exclude that one or more fragments can survive the entry process and hit the ground in the vicinity of the explosion. Quoting Artemieva and Shuvalov (2007): 'Although we cannot properly resolve fragments smaller than a cell size in this model, only cm-m-sized fragments may move differently from an average hydrodynamic flow. Eventually, a few of them can survive the entry process. It means that we still cannot totally eliminate the probability of finding some fragments not far from the Tunguska impact site (but they would be really large fragments, not dust)'. Accordingly, it is possible that one of these 'large fragments' hit the ground at a relatively low (45°) angle forming a crater subsequently enlarged by expulsion of H_2O and CH_4 from sediments and permafrost, and finally filled by water from the Kimchu river.

Reflector-T, identified by Gasperini *et al.* (2007) ~10 m below the deepest part of the lake, may or may not represent a fragment of the impactor. Collins *et al.* (2008) state that: 'For the bright reflector to be caused by the impacting body implies an unrealistically large and robust impactor, to survive impact intact and be resolvable in the seismic data. It is far more likely that the bright reflector is sedimentary'. We believe that this statement is misleading; in fact, our single-channel seismic reflection data were time-migrated using a constant velocity function (seismic velocity estimates cannot be obtained with these data). Because the observed geometries at depth are strongly affected by the choice of the velocity function, these seismic sections cannot provide information either on dimensions and shape of the reflecting objects, or on their mechanical properties. Reflector-T tells us only that a density/velocity discontinuity exists ~10 m below the bottom at the centre of the lake. It is also the only discontinuity present in the lake sediments, and is visible only in its centre. As stated in Gasperini *et al.* (2007), although Reflector-T does not prove an impact origin for the lake, it is certainly a promising target for further investigation.

Survival of trees

The relatively low energy of the impact and the effect of the 'soft' target that favoured an efficient energy transfer to the ground, could have attenuated the effects in the surroundings and may have allowed the survival of some trees at a short distance from the lake centre. Collins *et al.* (2008) state that 'aerial photos of the lake from 1938 and 1999 show mature trees that pre-date 1908 lining the rim of the lake. It is hard to imagine how a violent impact event could excavate a 300-m-wide hole without affecting trees < 50 m away'.

We found that those trees close to the lake shores, that survived the 1908 explosion, were young at the time of the impact, and probably protected by larger trees that did not survive. Their tree-ring patterns indicate that the trunks were heavily bent roughly 100 years ago, probably by a pressure wave and a thermal burst, although they were located at the northern edge of the devastated forest area. These effects are compatible with an oblique, 'soft' impact scenario, considering also that: (1) the bending direction of the trees is parallel to the lake's major axis (~125º) and (2) the tree rings indicate an enhanced post-1908 growth, probably as a consequence of increased light and space. This is not explained if Lake Cheko existed before TE, if we consider that surviving trees showing this pattern are presently facing the lake shores, and are consequently not competing with other trees for light and space (see http://www-th.bo.infn.it/tunguska/2002adds/contents02.htm, point 3).

Conclusions

We have no 'smoking gun' for the impact theory for Lake Cheko, just as Collins *et al.* (2008) admit not having unambiguous and compelling evidence for the 'no-impact' theory. On the key question of the age of the lake, evidence from (a) acoustic stratigraphy of lake deposits; (b) preliminary radiometric datings; (c) documentary reports and (d) tree-ring pattern analysis, all strongly favour a young age (~100 years), compatible with an origin related to the TE. The 'inverted cone' morphology of the lake is very different from that of Siberian lakes, and difficult to explain by 'normal' erosion/deposition processes from the small River Kimchu in a region with low-topographic gradients. Considering secondary processes, such as post-impact dewatering and degassing in a 'wet' swampy target with permafrost, Lake Cheko's morphology is compatible with an impact origin.

Perhaps impactologists can be challenged to verify if models that can explain the particular features of Lake Cheko are viable, rather than exclude Cheko from the accepted list because it does not fit smoothly into existing models.

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