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Comment article

Evidence that Lake Cheko is not an impact crater

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ABSTRACT

In a provocative paper Gasperini *et al.* (2007) suggest that Lake Cheko, a ~300-m-wide lake situated a few kilometres down-range from the assumed epicentre of the 1908 Tunguska event, is an impact crater. In this response, we present several lines of observational evidence that contradicts the impact hypothesis for the lake's origin: un-crater-like aspects of the lake morphology, the lack of impactor material in and around the lake, and the presence of apparently unaffected mature trees close to the lake. We also show that a tensile strength of 10–40 MPa is required for an asteroid fragment to traverse the Earth's atmosphere and reach the surface intact and with sufficient velocity to excavate a crater the size of Lake Cheko. Inferred tensile strengths of large stony meteorites during atmospheric disruption are 10–100 times lower. We therefore conclude that Lake Cheko is highly unlikely to be an impact crater.

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Introduction

An impact origin for Lake Cheko and connection with the Tunguska event was dismissed by a Russian expedition in the 1960s when a tentative age of 5–10 ka for the lake was made based on the thickness (~7 m) of mud deposits (Florenskij, 1963). On the basis of new geophysical data and shallow lake sediment cores, Gasperini *et al.* (2007) argue against such an old age for the lake. They hypothesize that a ~10-m-diameter fragment of the Tunguska asteroid or comet survived the main atmospheric disturbance, continued on its course to collide with the ground at a velocity of many kilometres per second, and formed Lake Cheko.

Impact cratering is an important geological process that has catastrophically affected the global environment. Much of our current knowledge of the impact process and hazard is derived from the study of over 170 confirmed impact structures on the Earth (Earth Impact Database, 2007). Every new, 'confirmed' impact crater provides important information to further our understanding of impacts and the hazard they pose. However, every false impact crater that is proposed clouds our understanding and confuses the public (Reimold, 2007), and for this reason the burden of proof in identifying a new impact structure must lie with the proponents. Disappointingly, in the case of Lake Cheko, very little evidence has been supplied in support of the impact hypothesis for its origin, and none of it is compelling. Gasperini *et al.* (2007) provide four arguments in support of an impact origin for the lake:

1. The location of the lake is consistent with the continuation of the assumed trajectory of the Tunguska impactor beyond the epicentre of the explosion.
2. The age of the lake is unknown.
3. A bright seismic reflection is apparent in the seismic data beneath the lake. The authors claim that this might be evidence for impactor material or impact-compaction of the sediments.
4. The lake has a funnel-like morphology. The authors claim this is unusual for the area and similar to other small impact craters on Earth.

The first piece of evidence does give pause for thought, but could easily be coincidence. The second argument is key: if the lake pre-dates 1908, it was obviously not formed during the Tunguska event. At this stage, there is no convincing evidence that the lake is only 100 years old; anecdotal evidence cannot be relied on, and recent collapse features do not imply that the lake formed recently. The third piece of evidence is the weakest; geophysical anomalies can be interpreted in many ways and never provide conclusive evidence of impact. 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 in origin. Finally, the morphology of the lake is, in many ways, very different from small impact craters on Earth, as we discuss below, and therefore does not provide compelling evidence for an impact origin.

The Tunguska Event

Years of theoretical, analogue and numerical modelling work have been devoted to explaining the major consequences of the Tunguska event on 30th June 1908. The most recent numerical model, which agrees with the consensus of earlier models

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(Korobeinikov *et al.*, 1976; Chyba *et al.*, 1993; Boslough and Crawford, 1997), suggests that the Tunguska event was caused by a cosmic body 50–80 m in diameter entering the Earth's atmosphere at 20 km s^{-1} and at an inclination of 30–45° to the horizontal (Artemieva and Shuvalov, 2007). At an altitude of ~20 km, the impactor starts to deform, disrupt and evaporate strongly; the resulting jet of vaporized impactor material is totally decelerated at an altitude of 8–10 km and releases all its energy into the atmosphere (5–15 Mt, high explosive equivalent, consistent with estimates from seismic records Ben-Menahem, 1975). The mixture of hot air and vaporized impactor material is buoyant and accelerates back along the wake, while an atmospheric shock wave reaches the surface. The interaction of the shock wave with the surface causes the observed famous forest devastation and fallen tree pattern (Florenskij, 1963); the model results are consistent with observations of total area and 'butterfly' planform of the damage area, and the telegraph poles and trees that remained vertical near the epicentre. All the extra terrestrial impactor material (in the form of tiny droplets) is carried 'uprange' away from the epicentre, reaches high altitudes and may then disperse worldwide. It is most likely that this dispersal of hot condensed impactor material caused the strange optical effects (white nights) observed in Northern Eurasia (Whipple, 1930).

Surviving atmospheric entry

Importantly, the model of Artemieva and Shuvalov (2007) requires that the comet or asteroid had little strength (< 5 MPa). This is consistent with stony meteorite strength estimates of 0.1–1 MPa, based on observed atmospheric break-up events (Ceplecha *et al.*, 1993), and implies that an iron impactor is unlikely. The model does not predict that solid fragments greater than a few centimetres can reach the ground, consistent with the absence of extraterrestrial material near the epicentre (Florenskij, 1963). Some fine material not resolved by the model may fall out from the plume, travelling at terminal velocity (tens of metres per second for cm-size objects), but this would occur close to, and up range of, the epicentre.

For a high-velocity impact crater to form as part of the atmospheric disturbance over Tunguska in 1908, therefore, is contrary to our current understanding of the event. Nevertheless, Gasperini *et al.* (2007) estimate that a ~10 m diameter[1] Asteroid fragment impacting at a velocity of 1–10 km s^{-1} is required to form an impact crater the same size as Lake Cheko. For this putative impactor to survive passage through the atmosphere from an altitude of ~8 km (the assumed height of the air blast centre) to the ground, the fragment must have a tensile strength of at least 10 MPa if it strikes the ground at 5 km s^{-1}, and of at least 40 MPa if it strikes the ground at 10 km s^{-1}. Although these values are within the range of laboratory measurements of tensile strengths of cm-sized meteorite samples (Grady and Lipkin, 1980; Medvedev *et al.*, 1985; Petrovic, 2001), the dynamic strength of larger objects (1–20 cm), observed disrupting as they enter the Earth's atmosphere, are substantially lower, rarely exceeding 1 MPa (Ceplecha *et al.*, 1993). The low strength of stony objects is further indirectly confirmed by an absence of large stony meteorites on the Earth. Hence, the impact hypothesis for Lake Cheko requires that the impactor must have been an exceptionally strong and large fragment of a much weaker body that disrupted catastrophically to cause the Tunguska event.

Hard evidence

To confirm unequivocally that Lake Cheko was the result of the collision of an extraterrestrial body with Earth would require discovery of meteoritic impactor material and/or impact melt in or around the lake. In ten out of twelve confirmed, 0.1- to 1-km-diameter meteorite impact craters on Earth, bona fide impactor material in the form of iron meteorite fragments or Fe-Ni metal grains and spherules has been found (Table 1). No trace of impactor material has yet been found in or around Lake Cheko, and if it exists it is extremely unlikely to be iron. If Lake Cheko is a ~300-m-diameter impact crater formed by a stony meteorite, it would be anomalous in terms of its impactor composition.

Another important observation is that all young (< 10 ka), 0.1- to 0.3-km-diameter meteorite craters are not isolated craters, but are part of crater 'strewn fields', formed by the near-simultaneous collision of a number of dispersed fragments of the same original meteoroid (Table 1). Given the obvious disruption that occurred to the bulk of the Tunguska impactor, it is very hard to explain how Lake Cheko could have formed by impact in isolation. If Lake Cheko is an impact crater, and depending on the composition of the impactor and exact impact velocity, a number of solid fragments of the impactor should be preserved in and around the lake.

Other observational evidence

In addition to hard evidence of impact that is lacking for Lake Cheko, there are several observable differences between the lake and small meteorite impact craters on the Earth. Gasperini *et al.* (2007) compare Lake Cheko's cross-section with Odessa crater, Texas (actually the largest crater in the Odessa crater strewnfield; ~170 m diameter), and use this alleged similarity as evidence in support of the Lake Cheko impact hypothesis. However, in many other ways, Odessa crater and Lake Cheko are very different.

All fresh impact craters have raised rims, surrounded by a continuous blanket of ejected material. At Odessa crater, for example, the rim of the crater is uplifted by 4 m and surrounded by a proximal layer of ejected material up to 1 m thick (Holliday *et al.*, 2005). This is despite erosion of the crater rim and ejecta blanket in the ~63 000 years since formation (Holliday *et al.*, 2005). At Lake Cheko, there is no evidence of uplift of the rim, although it is possible that some of the uplifted rim collapsed into the crater if the target material was weak.

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[1] In fact, the ~10-m diameter estimate is appropriate only for an impact velocity of 10 km s^{-1}. At lower impact velocities, the asteroid fragment must be larger than 10-m diameter; for example, a ~20-m-diameter asteroid is required at an impact velocity of 5 km s^{-1} (Holsapple, 1993).

Table 1 Confirmed terrestrial impact craters with diameter between 0.1 and 1 km and inferred impactor types.

Name	Country	Diameter (km)	Age (ka)	Location	Impactor type	References
Morasko	Poland	0.1*	<10	N 52°29′ E 16°54′	IIICD Iron	Korpikiewicz (1978)
Kaalijarvi	Estonia	0.11*	4 ± 1	N 58°24′ E 22°40′	IAB	Buchwald (1975)
Wabar	Saudi Arabia	0.12*	0.14	N 21°30′ E 50°28′	IIIAB Iron	Morgan *et al.* (1975)
Henbury	Australia	0.16*	4.2 ± 2	S 24°34′ E 133°8′	IIIAB	Taylor (1967)
Odessa	USA	0.17*	63	N 31°45′ W 102°29′	IIIAB	Buchwald (1975)
Boxhole	Australia	0.17	54 ± 1	S 22°37′ E 135°12′	IIIAB	Buchwald (1975)
Macha	Russia	0.3*	<7	N 60°6′ E 117°35′	Iron	Gurov (1996)
Aouelloul	Mauritania	0.39	3000 ± 300	N 20°15′ W 12°41′	Iron	Morgan *et al.* (1975); Koeberl *et al.* (1998)
Amguid†	Algeria	0.45	<100	N 26°5′ E 4°23′	Unknown	
Monturaqui	Chile	0.46	<1000	S 23°56′ W 68°17′	IAB	Bunch and Cassidy (1972); Buchwald (1975)
Kalkkop‡	South Africa	0.64	<1800	S 32°43′ E 24°34′	Chondrite?	Koeberl *et al.* (1994); Reimold *et al.* (1998)
Wolfe Creek	Australia	0.88	<300	S 19°10′ E 127°48′	IIIAB	Attrep *et al.* (1991)

Adapted from Koeberl (1998) and Earth Impact Database (2007).

*Crater strewnfield; largest dimension of largest structure is given.

†No data are available for Amguid.

‡Kalkkop has only tentatively been connected with a chondritic impactor type (Koeberl *et al.*, 1994; Reimold *et al.*, 1998).

Neither is there evidence of any ejected material; in fact, aerial photos of the lake from 1938 and 1999 show mature trees that pre-date 1908 lining the rim of the lake (Longo and Di Martino, 2003). It is hard to imagine how a violent impact event could excavate a 300-m-wide hole without affecting trees so close. The ground movement and ejecta deposition alone should have been enough to flatten all proximal vegetation.

Very few impact craters are elliptical in plan view like Lake Cheko, which has an ellipticity of ~4/3. Impact experiments and statistical analysis of crater shapes on the terrestrial planets show that crater ellipticity is controlled by impact angle (to the target plane) and that departure from circularity occurs only for very oblique (< 10°) impacts (Gault and Wedekind, 1978; Bottke *et al.*, 2000). If Lake Cheko was formed at the same time as the 1908 Tunguska event, then its location relative to the blast epicentre (8 km downrange) and the estimated altitude of the main explosion (5–10 km) imply an impact angle of 30–50°. A high-velocity impact at this angle produces an almost circular crater.

Summary

The Tunguska event is well explained by models that employ a weak impactor strength, consistent with observed stony meteorite break-up events; these models do not predict that large, high-velocity fragments of the impactor could reach the surface. No evidence for meteoritic material, or any other hard evidence of impact, has yet been found in or near Lake Cheko. The lake is in many ways substantially different from confirmed, young, terrestrial impact craters of the same size. It is also surrounded by trees that would have been flattened as a consequence of the impact. Taken individually, none of these arguments can conclusively rule out the impact hypothesis for the origin of the lake. The easiest way to do so would be to establish an accurate age for the lake. However, together this evidence makes it extremely unlikely that Lake Cheko is of impact origin.

References

Artemieva, N. and Shuvalov, V., 2007. 3D effects of Tunguska Event on the ground and in the atmosphere. Lunar and Planetary Science Conference XXXVIII, Lunar and Planetary Institute, Houston, TX, abstract no. 1537.

Attrep, M., Orth, C.J., Quintana, L.R., Shoemaker, C.S., Shoemaker, E.M. and Taylor, S.R., 1991. Chemical fractionation of siderophile elements in impactites from Australian meteorite craters. Lunar and Planetary Science XXII, Lunar and Planetary Institute, Houston, TX, 39–40.

Ben-Menahem, A.A., 1975. Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations. *Physics Earth Planet. Int.*, **11**, 1.

Boslough, M.B.E. and Crawford, D.A., 1997. Shoemaker-Levy 9 and plume-forming collisions on Earth. *Ann. N.Y. Acad. Sci.*, **822**, 236–282.

Bottke, W.F., Love, S.G., Tytell, D. *et al.*, 2000. Interpreting the elliptical crater populations on Mars, Venus, and the Moon. *Icarus*, **145**, 108–121.

Buchwald, V.F., 1975. *Handbook of Iron Meteorites: their History, Distribution, Composition and Structure*. University of California Press, Berkeley.

Bunch, T.E. and Cassidy, W.A., 1972. Petrographic and electron-microprobe study of Monturaqui impactite. *Contrib. Mineral. Petrol.*, **36**, 95–112.

Ceplecha, Z., Spurny, P., Borovicka, J. *et al.*, 1993. Atmospheric fragmentation of meteoroids. *Astron. Astrophys.*, **279**, 615–626.

Chyba, C.F., Thomas, P.J. and Zahnle, K.J., 1993. The 1908 Tunguska explosion – atmospheric disruption of a stony asteroid. *Nature*, **361**, 40–44.

Earth Impact Database, 2007. http://www.unb.ca/passc/ImpactDatabase/ (accessed 6 July 2007).

Florenskij, K.K.P., 1963. Predvaritelnyje rezultaty Tungusskoj meteoritnoj kompleksnoj ekspeditsii 1961. *Meteoritika*, **23**, 3.

Gasperini, L., Alvisi, F., Biasini, G., Bonatti, E., Longo, G., Pipan, M., Ravaioli, M. and Serra, R., 2007. A possible impact crater for the 1908 Tunguska Event. *Terra Nova*, **19**, 245–251.

Gault, D.E. and Wedekind, J., 1978. Experimental studies of oblique impact. Proc. Lunar and Planet. Sci. Conf. 9th, Pergamon Press, New York, 3843–3875.

Grady, D.E. and Lipkin, J., 1980. Criteria for impulsive rock fracture. *Geophys. Res. Lett.*, **7**, 255–258.

Gurov, E.P., 1996. *The group of Macha craters in Western Yakutia*. Lunar and Planetary Conference XXVII, Lunar and Planetary Institute, Houston, TX, 473–474.

Holliday, V.T., Kring, D.A., Mayer, J.H. *et al*., 2005. Age and effects of the Odessa meteorite impact, western Texas, USA. *Geology*, **33**, 945–948.

Holsapple, K.A., 1993. The scaling of impact processes in planetary sciences. *Annu. Rev. Earth Planet. Sci*., **21**, 333–373.

Koeberl, C., 1998. Identification of meteoritic components in impactites. In: *Meteorites: Flux with Time and Impact Effects* (M.M. Grady, R. Hutchison, G.J.H. McCall and D.A. Rothery, eds), pp. 133–153. Geological Society, London.

Koeberl, C., Reimold, W.U., Shirey, S.B. *et al*., 1994. Kalkkop Crater, Cape Province, South-Africa – Confirmation of impact origin using osmium isotope systematics. *Geochim. Cosmochim. Acta*, **58**, 1229–1234.

Koeberl, C., Reimold, W.U. and Shirey, S.B., 1998. The Aouelloul crater, Mauritania: on the problem of confirming the impact origin of a small crater. *Meteorit. Planet. Sci*., **33**, 513–517.

Korobeinikov, V.P., Chushkin, P.I. and Shurshalov, L.V., 1976. Mathematical model and computation of the Tunguska meteorite explosion. *Acta Astronaut*., **3**, 615–622.

Korpikiewicz, H., 1978. Meteoritic shower Morasko. *Meteoritics*, **13**, 311–326.

Longo, G. and Di Martino, M., 2003. Remote sensing investigation of the Tunguska explosion area. International Conference Remote Sensing for Agriculture, Ecosystems, and Hydrology IV, SPIE, USA.

Medvedev, R.V., Gorbatsevich, F.I. and Zotkin, I.T., 1985. Determination of the physical properties of stony meteorites with application to the study of processes of their destruction. *Meteoritika (in Russian)*, **44**, 105–110.

Morgan, J.W., Higuchi, H., Ganapathy, R. and Anders, E., 1975. Meteoritic material in four terrestrial meteorite craters. 6th Lunar Science Conference, Lunar and Planetary Institute, Houston, 1609–1623.

Petrovic, J.J., 2001. Mechanical properties of meteorites and their constituents. *J. Mater. Sci*., **36**, 1579–1583.

Reimold, W.U., 2007. The impact crater bandwagon (some problems with the terrestrial cratering record). *Meteorit. Planet. Sci*., **42**, 1467–1472.

Reimold, W.U., Koeberl, C. and Reddering, J.S.V., 1998. The 1992 drill core from the Kalkkop impact crater, Eastern Cape Province, South Africa: stratigraphy, petrography, geochemistry and age. *J. Afr. Earth Sci*., **26**, 573–592.

Taylor, S.R., 1967. Composition of meteorite impact glass across the Henbury strewn field. *Geochim. Et Cosmochim. Acta*, **31**, 961–968.

Whipple, F.J.W., 1930. The great Siberian meteor and the waves, seismic and aerial, which it produced. *Quart. J. Royal Meteorol. Soc*., **56**, 287–304.

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