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The Tunguska event and Cheko lake origin: dendrochronological analysis

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Abstract: Dendrochronological research was carried out on 23 trees samples (Larix sibirica and Picea obovata) sampled during the 1999 expedition in two locations, close to the epicentre zone and near Cheko lake (N 60°57′, E 101°51′). Basal Area Increment (BAI) analysis has shown a general long growth suppression before 1908, the year of Tunguska event (TE), followed by a sudden growth increase due to diminished competition of trees that died due to the event. In one group of the trees, we detected growth decrease for several years (due to damage to the trunk, branches and crown), followed by growth increase during the following 4–14 years. We show that trees that germinated after the TE, and living in close proximity of Cheko lake (Cheko lake trees) had different behaviour patterns when compared to those trees living further from Cheko lake, inside the forest (Forest trees). Cheko lake trees have shown a vigorous continuous growth increase. Forest trees have shown a vigorous growth during the first 10–30 years of age, followed by a period of suppressed growth. We interpret the suppressed growth by the re-established competition with the surroundings trees. Cheko lake pattern, however, is consistent with the formation of the lake at the time of TE. This observation supports the hypothesis that Cheko lake formation is due to a fragment originating during TE, creating a small impact crater into the permafrost and soft alluvial deposits of Kimku River plain. This is further supported by the fact that Cheko lake has an elliptical shape elongated towards the epicentre of TE.

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Key words: Russia, Siberia, cosmic body impact, collapse crater, dendrochronology, Tunguska, tree rings.

Introduction

The Tunguska event

The Tunguska event (TE; N 60°55′, E 101°57′), occurred in the early morning of June 30th 1908. A powerful explosion over the basin of the Podkamennaya Tunguska River (Central Siberia) devastated more than 2000 km^2 of Siberian taiga. About eighty millions trees were knocked down by pressure pulses, a large area of trees and bushes were burnt down within the area containing collapsed trees. A number of eyewitnesses described the flight of a 'fire ball, bright as the sun'. Seismic and pressure waves were recorded in number of observatories throughout the world. Bright nights were observed over Northern Europe and Central Asia. These different phenomena, initially considered non-correlated, were subsequently linked together as different aspects of the TE. This event was investigated by several scientific expeditions since 1927 (Kulik 1939). Most of the expeditions and research carried out until recent times concerned the physics and the nature of the cosmic body, whose explosion occurred at 6–8 km altitude but, despite these efforts, a detailed account of this event has not yet been reached. Tunguska-like objects may be parts of comets and thus come from distant regions of our Solar System (Bunch *et al.* 2012; Gasperini *et al.* 2012) and can be monitored only using future spaced based telescopes (Moseley *et al.* 2004; Li *et al.* 2005). There may have been similar smaller impacts that may fit more or less with the TE (Fig. 1); however, the TE is truly unique. The effects of the explosion of the Tunguska Cosmic Body (TCB) on the forest have been described by many authors, and their data gave information on the released energy and the height of the explosion. The map of the fallen trees was recently reconstructed and enlarged by Longo *et al.* (2005) using aerial surveys and data collected during investigations performed on the ground (Longo & Di Martino 2002, 2003). This map suggests an azimuth trajectory $a = 110 \pm 5°$. To search for traces of the TCB, a scientific expedition was carried out by an Italian–Russian group of scientists on 1999 (the 'Tunguska99' expedition); see Di Martino & Longo, (2000). The main task of the expedition was to perform geophysical investigations and to collect core samples from the bottom of the Cheko lake, a small lake ~350 m in diameter and 53 m deep, located about ~7 km NNW from the TCB explosion epicentre. This lake has a suspicious shape (it is elongated along the direction of the flight of Tunguska object), somewhat large depth for the floodplain where it is located, and it is superimposed on the meandering

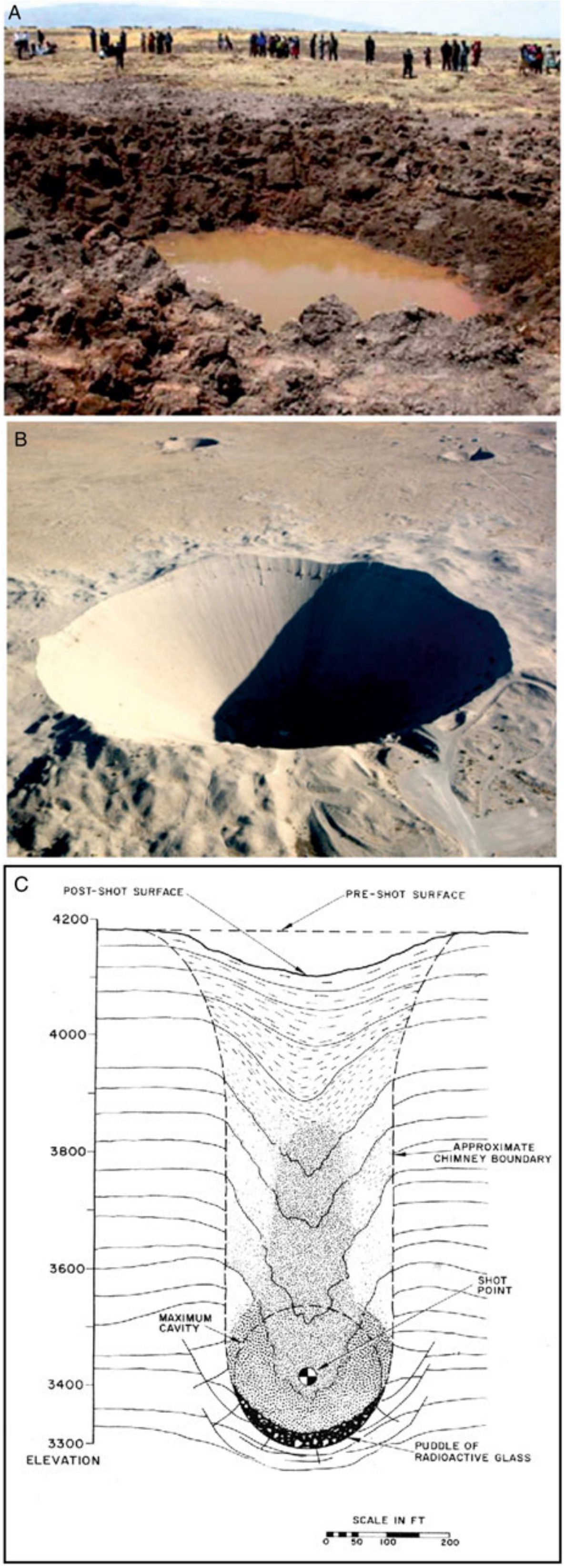

Fig. 1. Comparison between impact craters and nuclear explosion crater. (a) The Carancas meteorite crater (Peru). (b) The Sedan crater in the Nevada Test Site (Photo courtesy of the US National Nuclear Security administration/Nevada Site Office). (c) Scheme of an underground nuclear explosion (Courtesy of the US Department of the Navy).

Kimchu River flowing from East to West (Fig. 2) at elevation 390 m just South of the 440 m hill made out of tertiary intrusion. Aerial images and digital terrain models performed during the 'Tunguska99' expedition show that the lake is located within an alluvial plain covered by the quaternary sedimentary deposits of the Kimchu River, that enters the lake on its SW side, and outflows ~200 m away towards North on the same side (see Fig. 2). The eastern shore of the lake is partially bounded by the SW flank of a hill (440 m of altitude, 50 m above the lake level) made of intrusive rocks (see Fig. 3), part of the diffuse Tertiary volcanic deposits. In Fig. 3 the red zigzag line indicates the extent of the damage due to the TE. No traces of the cosmic body have been found in the lake bottom sediments, but the preliminary conclusion of these investigations was that Cheko lake was formed by the impact of an asteroid fragment, which mass has been estimated in about 1.5×10^6 kg (Gasperini *et al.* 2007, 2008, 2009, 2012). The peculiar morphology of the Cheko lake is compatible with the hypothesis that this fragment, hitting the permafrost, has triggered the formation of a '*collapsed*' crater, subsequently filled by river water.

Collapse crater

The characteristics of cosmic body impact craters are highly dependent on their final speed in the atmosphere and on the nature of the target. For a rocky target ('*hard*' impact), the maximal energy is emitted on the earth surface and is propagated at great distances causing intense devastations. The crater formed in this way is called an '*impact*' crater and has a clear rim. For a soft target ('*soft*' impact), e.g. the Tunguska permafrost, the Carancas mud and water (Peru, see Fig. 1), the Sikhote–Alin snow and permafrost, the impacting low-speed bodies make holes in the target surface with a minimal energy emission. The impacting body losses its energy below the surface with a maximal energy emission at a great depth. The energy emitted is trapped in the target matter and cannot propagate to the neighbourhood where air-blast effects are practically absent. The material scattered around the impact point is scarce and is insufficient to form a significant rim. For a low-angle trajectory of the incoming body, some material can be deposited on the opposite side of its line of arrival. The energy emission at some depth below the surface causes the collapse of the upper layers of the target and the formation of a crater. Here, we call such a crater a '*collapse*' crater to avoid confusion with the previously mentioned 'impact' craters. Recently (15 September 2007), stony meteorite created a collapse crater (Fig. 1(a)) at Carancas, in Peru. The soft impact of the meteorite on the water-saturated soil, covered by Lake Titicaca during the ice age, explains the main characteristics of the crater, 13.5 m in diameter and 5 m deep. From the crater, immediately filled by water, large chaotic chunks of soil were ejected on the crater's northern side. The impacting body was an ordinary chondrite probably of about one meter in diameter. Stony meteorites tend not to be too robust and often fragment during their atmospheric flight, giving a scatter ellipse of material on the ground. Many characteristics of a soft impact followed by the formation of a collapse crater are similar to those of an underground nuclear explosion in which the

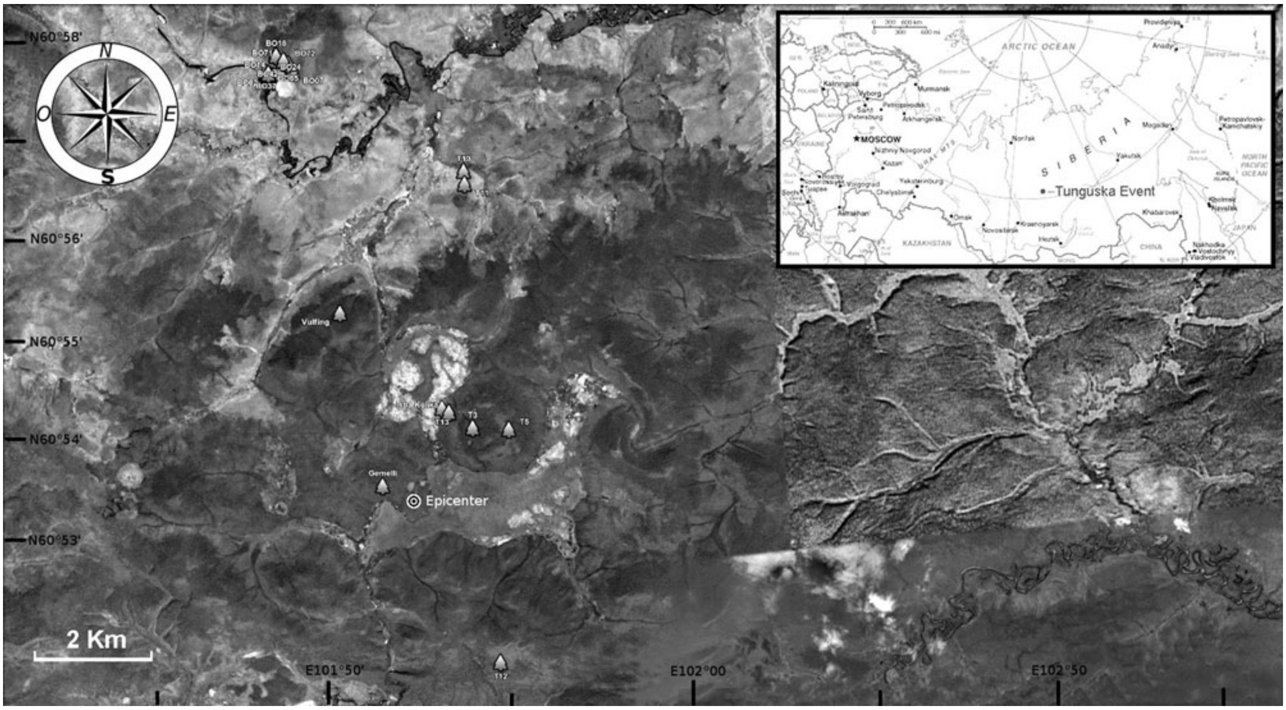

Fig. 2. Satellite map of sampled trees – Tunguska area.

emitted energy is mainly transferred to the ground at a great depth and causes limited air-blast effects in the surroundings. As an example, we show (Fig. 1(b)) the Sedan Crater, formed when a 100 kilotonnnes explosive buried under 194 meters of desert alluvium, containing 7% of water, was fired at the Nevada Test Site on 6 July 1962, displacing 12 million tonnes of material. The crater is 98 m deep, 390 m in diameter and does not have a significant rim. Glasstone & Dolan (1977) state that 'if the soil is saturated and the high water table is maintained after the detonation, the crater dimensions will change with time. Slumping of the crater sides will continue until a stable condition exists for the material'. Similarly, the US Department of the Navy has estimated that dropping from the air a 1 Megaton weapon that penetrates underground in sandy soil to a depth of 15 m before exploding; the resulting crater would be about 91 m deep and nearly 427 m in diameter. The Navfac Command (1978) estimates that 'the fraction of the energy imparted to the air in the form of blast depends primarily on the depth of burst for the given total energy yield. The greater the depth of burst, the smaller, in general, will be the portion of shock energy that escapes into the air. If the explosion is fully contained, no blast wave will form'. This is the case, schematically shown in Fig. 1(c) (Navfac Command 1978), where an explosion at a depth of ~213 m generated a collapse crater ~23 m deep, 149 m in diameter and devoid of any ring. In recent years, growing evidences have been collected in favour of the hypothesis that the formation of Cheko lake is connected to the TE (Gasperini *et al.* 2007, 2008, 2009, 2012). Gasperini *et al.* proposed that the Tunguska bolide underwent fragmentation and one of its small fragments created a collapse crater now filled by Cheko lake, while the disintegration in the atmosphere of the main body was the cause of the forest devastations. In this picture, the fragment of smaller mass, piercing the 25–30 m thick permafrost layer, has triggered a massive release of H_2O vapour, CH_4 and CO_2 that has modified the crater's dimension and geometry. Reworking and collapse of the original pre-TE riverbed may be responsible for the bean-shaped surface of the lake, while its funnel-like morphology from 5 m below the water-level, is typical for collapse craters like those in Fig. 1. Subsequently, it was suggested (Longo *et al.* 2011), that the Tunguska bolide could be one of the 15–20% of Near Earth Asteroids (NEAs) that are double bodies. These NEAs, known as binary asteroids, consist of two bodies that revolve around each other at close range. The minor of these two bodies may have acted as a small fragment in the Gasperini *et al.* description. We conducted a dendrochronological study on trees living close to the Cheko lake and in the forest trying to establish any connection with the 1908 TCB impact.

Previous dendrochronological research

In 1991, a dendrochronological research in the Tunguska area found five spruces and one pine, that survived the TE, and made it possible to recognize a first list of 14 atomic elements as probable constituents of the TCB (Longo *et al*. 1994, 1996; Serra *et al*. 1994). Subsequent work on a living spruce (*Picea schrenkiana*), located 7.3 km NE from the explosion epicentre, showed anomalies in tree rings at the time of the explosion (Yonenobu & Takenaka 1998). They identified 4 years of growth suppression after the event (1909–1912), followed by a sudden growth increase since 1913. Nesvetajlo (1998) made a dendrochronological analysis on standing dead trees (he referred to them as to 'telegraph poles') within the area surrounding the epicentre. These were the trees that died during or

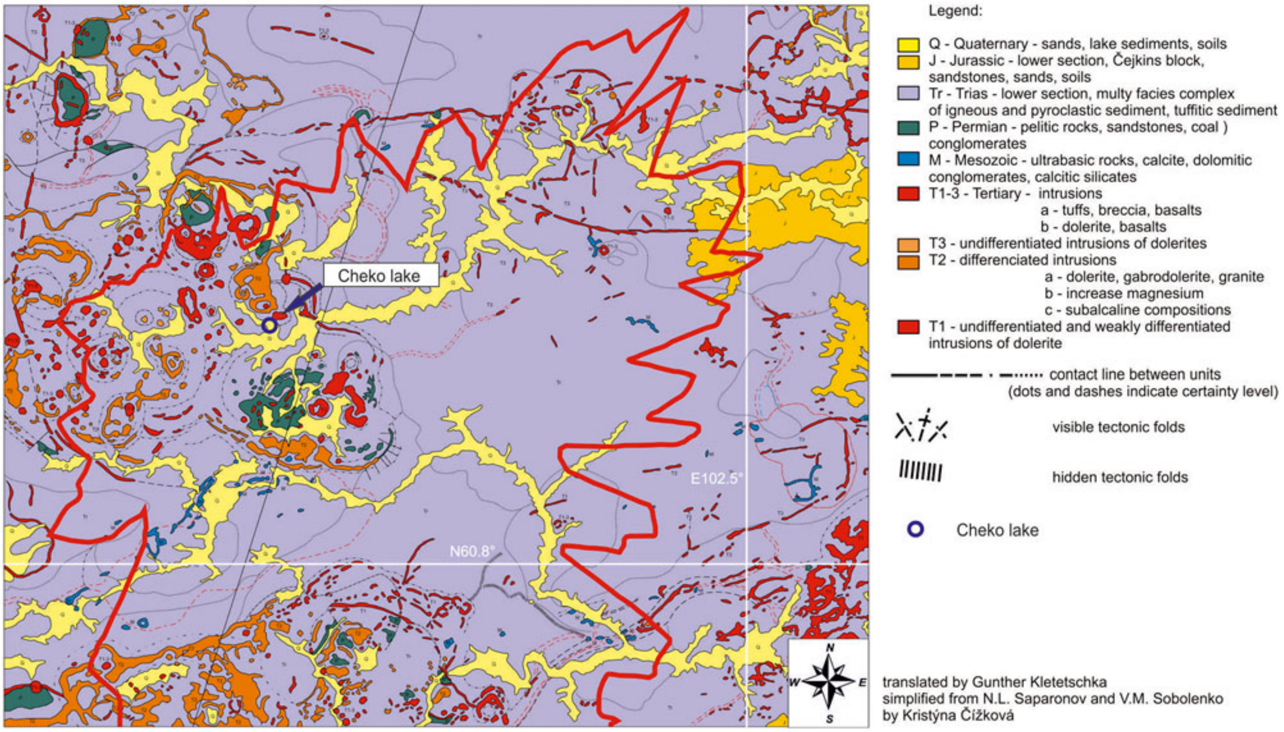

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Fig. 3. Geological map of the area Surrounding Cheko lake.

shortly after the event with a dry trunk and stripped branches. No increase of C^{14} was detected in carbon of trees within the epicentre area (Longo *et al.* 1994), compared to trees much further (about 700 km – Tomsk region), indicating that no extra radiation took place. The study by Vaganov *et al.* (2004) on Tunguska included 12 trees (larches, pines and spruces) living close to the epicentre area (5–7 km). Out of these samples, all survived TE, the ring growth decreased for 4–5 years after the event, and the greatest suppression was recorded in 1909. The 1908 anatomical ring structure have showed the so-called 'light ring', with typical lack of latewood and disrupted tracheids (strongly deformed). Deformed tracheids during the TE time seem to be related to partial or full defoliation (Vaganov & Terskov 1977; Fritts & Swetnam 1989, Savidge 1996; Schweingruber 1996). A similar effect was found on trees affected by the Chernobyl nuclear accident (Mousaev 1996; Longo & Serra 2006). The evidence of light rings in the Tunguska area were detected by CAT (Computerized Axial Tomography) (Longo & Serra 2006). Here we present the results of dendrochronological analysis on 23 tree samples, belonging to the species of larch (*Larix sibirica*) and spruce (*Picea obovata*), taken at a distance between about 3.5 and 8.0 km NE from the TE epicentre (60°53′09″N, 101°53′47″E) and collected during the 1999 expedition, mostly in the area near the Cheko lake (60°57′51″N, 101°51′36″E) and close to Kimchu River. This lake has a peculiar shape and is rather deep (~53 m) to be an oxbow lake due to a cutoff of a meander of the Kimchu river. Gasperini *et al.* (2007) suggested that Cheko lake was a possible impact crater produced by the fall of a fragment of the TCB. The aim of our research is to use dendrochronology of the trees living nearby Cheko lake and forest trees between the epicentre and the lake. Several of these trees survived and germinated after the TE.

Materials and methods

Investigated area

Half of the tree samples came from the area near Cheko lake (N 60°57′50′ – E 101°51′32′, altitude 354 m). This lake is located along the alluvial plain of Kimchu River, a mature meandering river flowing towards North. The lake has an elliptical shape, with the longer axis reaching 690 m directed NE–SW and the minor axis of about 350 m; the depth is about 5 m in the SW side, while it increase towards NW down to ~53 m. The placement of this lake, overlying the east side of Kimchu River meander, suggests a Holocene age. There is another, smaller lake about 2 km down the river that also has similar characteristic, having the semi-major axis more or less parallel with the trajectory of Tunguska body. Perhaps there was a smaller fragment that made that lake too (see Fig. 2). Kimchu River is a mature meandering river with several oxbow-lakes along its course. Oxbow lakes have similar depth as the river itself and once formed tend to be soon filled by sediments. Cheko lake has a depth ~53 m, ten times larger than the Kimchu local river depth, according to the field survey of 1999 (Fig. 2). Tunguska area is geologically placed into the western part of the Siberian craton made by high-grade metamorphic complexes and granites (Gladkochub *et al.* 2006), whose age goes back to 2.1–1.8 Ga (Archean). The oldest sediment is covered by a thick (3–12 km) sedimentary sequence with oil and gas

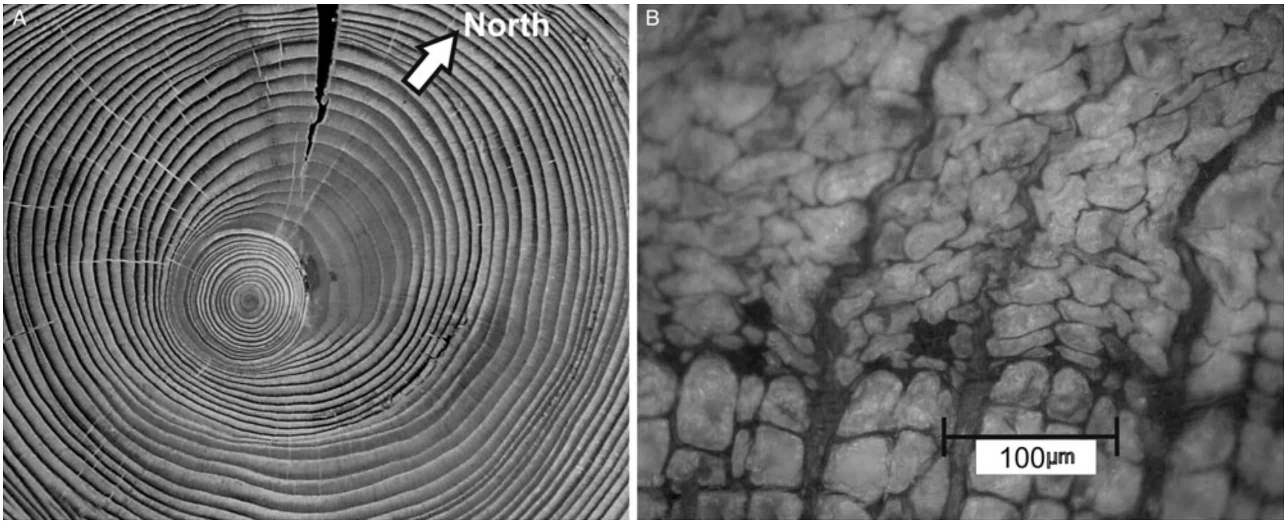

Fig. 4. (a) Survived and tilted tree with compression wood on North side; (b) disrupted tracheids during the 1908 growing season after TE.

reservoirs, trapped into shale and carbonates horizons (1 Ga – 635 Ma) overlaid by evaporatites from Cambrian (635–488 Ma) (Svensen *et al.* 2008). At the end of Permian till Triassic (252–250 Ma) the Tunguska basin was intruded by the volcanic Siberian Traps, composed by sills, dykes, followed by several millions of square kilometres thick lava flows (Kamo *et al.* 2006). On the way towards the surface these units made it through a thick pile of sedimentary rocks, forming sills and dykes abundant in the basin and sheets up to 350 m thick (Ulmishek 2001). Tunguska impact site is placed into the early Triassic volcanic Siberian Traps forming outcrops of sills and dykes in the hills of the TE zone. The alluvial plain with Cheko lake and River Kimchu is of Holocene age <1.7 Ka. The current geology knowledge of the area rules out the presence of carbonates and related karst topography and/or tectonic faults that could have produced the Cheko lake depression. The lake is not likely related to a recent volcanic activity because the known volcanism in this area is old (Triassic) (Kamo *et al.* 2006) even if it is not possible to discard the presence of a volcanic caldera or diatrema below the lake (Fig. 3). Perhaps, the Cheko lake relates to the impact of a TE fragment. Peculiar feature that support this origin is the elliptical shape, elongated NW, according to the direction of the blast wave (Gasperini *et al.* 2000). The results of seismic and bathymetric survey (Gasperini *et al.* 2012) have highlighted the presence of a delta-like deposit on the inflow side of Kimchu river into the Cheko lake. This suggests that Kimchu River formed a meander at the location where a fragment of the TCB, or the minor part of a binary asteroid, may have created Cheko lake.

Field samplings and dendrochronological analysis

During the expedition on summer 1999, tens of tree log section and cores were sampled. We examined 23 of them to find the effect of the TE on trees living near Cheko lake (0–100 m) and SE from it, in the direction of the TE epicentre (0–10 km), inside the forest (Fig. 2). Some of the trunk sections come from the dead trees and we checked their age using cross-dating. Four samples have shown eccentric growth due to TE blast wave that tilted young trees. Eccentricity was detectable by anomalies on ring growth and by the presence of reaction wood on the tilted side (Fig 4(a)). The evidence of deformed tracheids were recorded on several of these samples in correspondence of the 1908 ring (e.g. BO Gemelli), where it is clear an abrupt change of the tracheids alignment with the strong distortion (Fig. 4(b)).

Tree samples were analysed using standard dendrochronological methods (Stokes & Smiley 1986). The wood was sanded and measured with a sliding device (0.001 mm accuracy Velmex). Cross-correlation was made initially through ‘skeleton plots’ graphs (Fritts 1976), followed by tree ring widths measurement and statistical test on dating by Cofecha software (Holmes 1983). Each ring width curve was analysed to find sudden growth anomalies (suppression or increase) as reported in Schweingruber *et al.* (1990). We converted the annual ring growth to Basal Area Increment (BAI) that is the value (mm^2) of one year’s basal area growth:

$$\mathrm{BAI} = \pi R_t^2 - \pi R_{t-1}^2,$$

where R_t is the stem radius at the year t; and R_{t-1} is the stem radius at the year $t-1$. BAI is the increase in a tree’s cross-sectional area from year to year. It differs from radial growth increment because it represents growth in two dimensions, providing a measure of the amount of wood added to the stem. We used it to understand health, growth – trend and competition between trees in the forest. We compared the BAI curves in the present study to those of Le Blanc *et al.* (1992) (Fig. 5) to point out different tree-growth features. A comparison of our BAI curves revealed important differences between trees that survived the TE and those born afterward.

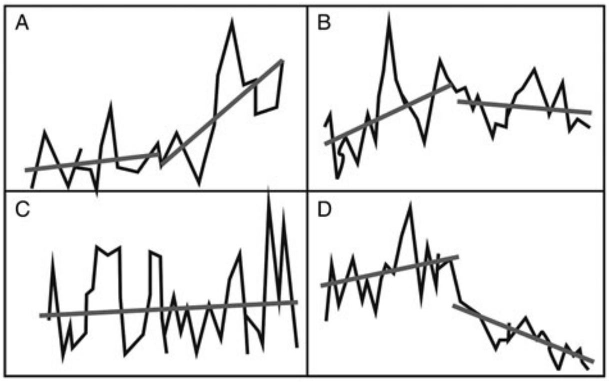

Fig. 5. Four classes of BAI: (A) young tree or not dominated anymore; (B) mature tree in closed space or with strong competition; (C) mature tree; (D) decline tree (adapted from Le Blanc, 1992).

Results and discussion

BAI analysis

The results of tree ring analysis allowed the division of the samples into two main classes of trees: those survived and those born after the TE. Inside these classes were different groups according to their BAI trend (Table 1). Trees that survived to the TE have recorded different growth trend: Group 1 includes trees not suppressed that show a short (1–2 years) or longer (4–19 years) suppression since 1908 (Fig. 6(a)). Group 2 includes trees suppressed by the competition in the forest before the TE; these after 1908 show a sudden and extended growth increase (Fig. 6(b)). Only one sample (BO 2), rather young at the TE epoch, did not show any anomalous growth effect. The class of trees born after the TE belong to groups 3 and 4. Group 3 shows a vigorous growing phase until 50–60, followed by a growth influenced by competition between trees in the forest (Fig. 7(a)). The group 4 represents those trees living close to the Cheko lake shore, and show a continuous vigorous growth without signs of competition (Fig. 7(b)).We compared all samples to BAI growth type of Le Blanc *et al.* (1992) for classification purpose (Table 1). Many (36%) of survived trees, after decades of suppression growth before TE, belong to class B, with a young vigorous phase followed by competition when matured (Fig. 8(a)). Most of the trees (43%) show a similar initial trend like 7a, followed by a suppression period (B + D) (Fig. 8(b)) that started in 1950 or later and which cause is not considered in this work. Few trees (21%), which belong to the oldest group, form class C; they are the dominant ones without signs of competition (Fig. 8(c)). Considering the class of trees germinated after TE, those (50%) living inside the forest have a growth type B, with several decades of young vigorous phase followed by a mature growth, suppressed by competition (Fig. 8(d)). The trees (50%) close to Cheko lake shore or nearby have prolonged young growth phase (Type A) without competition till the days of collection (Fig. 8(e)). The growth of the trees near Cheko lake that germinated after TE supports the impact genesis of Cheko lake. We have not found any survived tree with a similar trend (Type A), germinating before 1908, affected by the TE in the area away from Cheko lake. This supports the hypothesis that the formation of the lake took place during the TE.

While looking in detail at the BAI of trees that survived to 1908 TE in vicinity of the shore of Cheko lake (Fig. 9), we found trees with a suppression growth, that aged 16 and 60 years, before the disturbance of the event took place (see samples BO24, BO42 in Fig. 10(a)). The temporal length of the growth suppression reflects their age at the moment of the event. Similar BAI trend of suppressed trees, lasting tens of years before the event, was found on trees living further from the lake, inside the forest (e.g. T 11 and BO Vulfing, see Fig. 10 (b)).The similarities in the growth suppression before the event probably indicate a dense forest spread throughout the region, including present extent of Cheko lake.

Assuming Cheko lake already existed before 1908, we would not expect suppressed growth trend before TE, while a typical linear and/or exponential positive growth trend, as for the trees germinated after TE, have no competitors 'group 3' living along the shore lake (Fig. 7(b)). The lack of competitors induced vigorous growth pattern in this tree group that germinated after 1908 and growing along the shoreline (see BO7 and BO37 in Fig.10(c)). Similar trend was found just after TE in tree rings of survived trees in proximity of Cheko lake (BO 42) and several years later (BO24, see also Fig. 10(a)).

So the BAI growth trend supports the hypothesis of a neoformation of Cheko lake due to TE in 1908 during which the course of Kimku River would have changed its position in respect to the new formed basin. Further dating and BAI analysis of trees living along the shoreline lake and its surroundings will provide more details of the events that took place during this event (not part of this paper).

Trees' tilting

In addition to BAI results, we detected the effect of TE from the tree trunk morphology on the 16 cross-section samples. Many of the survived trees did not show eccentric growth, except four of them near the Cheko lake, that were tilted towards N (or NE, NW) consistently with the blast wave direction coming from E 110° (Fig. 4). This suggests that these four trees were tilted after the formation of collapsed crater in the area of today's Cheko lake. Some trees could be sheltered by local topography from TE explosion blast wave, because these did not present ring grow anomaly even if very close to the epicentre. The direction of the tilted trees agrees with the updated map of fallen trees (Longo *et al.* 2005).

Discussion

We investigated the effects of TE on trees living within the impact zone, an area of about 2000 km^2. We found TE effects on trees both in morphology (trees' tilting) and in wood anomalies as sudden growth increase and/or decrease. The use of BAI, rather than ring width, allows a more comprehensive view (Nesvetajlo 1998; Yonenobu & Takenaka 1998; Vaganov *et al.* 2004; Fantucci *et al.* 2012) of the effect on tree growth and the variation of competition before and after

Table 1. *Sample details: Names, GPS Locations, Dating range, Group, Eccentricity, Release after 1908, Suppression after 1908, BAI type, and Notes*

Sample no.	Sample name (C = core, CR = cross-section, Species)	Lat °N Long °E	Dating	Group	Eccentricity No/Yes Azimuth[b]	Release after 1908 (time)	Suppression after 1908 (time)	BAI type A–B–C–D	Note
1	SE (c) PCOB	60°57′54,0″ 101°51′ 42,7″	1854–2008	1			1908–1909	B (>TE)	
2	T 10[a] (c) LASI	60°56′41,5″ 101°55′ 26,4″	1871–2007	1			1908–1909	B + D	Resin ducts
9	T 11[a] (c) LASI	60°56′31,3″ 101°55′ 24,2″	1874–2008	1			1909	C	
4	T 12[a] (c) LASI	60°51′30,8″ 101°55′ 26,6″	1778–2008	1			1908–1911	C	Resin ducts
5	BO 2 (cr) LASI	60°57′49,0″ 101°51′ 22,9″	1894–2008	–	No			B + D	TE scar North side plus recent fire scar
6	BO 14 (cr) PCOB	60°57′59,9″ 101°51′ 33,2″	1868–2008	2	No	1908–2008		B	
7	BO 24 (cr) PCOB	60°57′38,3″ 101°51′ 23,2″	1850–2008	2	**North**	1909–2008		C	
8	BO 25 (cr) PCOB	60°57′47,0″ 101°51′ 21,5″	1847–1994	1	No		1908–1912	A (before TE) B + D	
9	BO 36 (cr) LASI	60°57′47,2″ 101°51′ 21,2″	1885–1967	2	**North East**	1908–1967		B	
10	BO 39 (cr) LASI	60°57′50,0″ 101°51′ 23,5″	1887–1974	2	**North**	1908–1954		B + D	Displaced cells
11	BO 41 (cr) LASI	60°57′49,5″ 101°51′ 18,7″	1865–2008	2	**North West**	1908–2008		B	
12	BO 42 (cr) LASI	60°57′49,5″ 101°51′ 20,5″	1891–2001	2	No	1908–2001		B	
13	BO (cr) Gemelli LASI	60°54′40,4″ 101°55′ 48,2″	1870–1998	1	No		1908–1921	A (before TE) B + D	
14	BO (cr) Vulfing PCOB	60°55′58,7″ 101°55′ 47,9″	1842–1990	2	No	1908–1990		B + D	

Continued

Table 1. (*Cont.*)

Sample no.	Sample name (C = core, CR = cross-section, Species)	Lat °N Long °E	Dating	Group	Eccentricity No/Yes Azimuth[b]	Release after 1908 (time)	Suppression after 1908 (time)	BAI type A–B–C–D	Note
15	T 3[a] (c) LASI	60°53′58,6″ 101°55′12,1″	1923–2008	3				B	
16	T 5[a] (c) LASI	60°53′56,0″ 101°55′58,6″	1933–2008	3				B	
17	T 13[a] (c) LASI	60°54′12,2″ 101°54′34,4″	1923–2008	3				B + D	
18	BO 7 (cr) LASI	60°57′57,5″ 101°51′52,7″	1923–1992	4	No			A	Near lake
19	BO 18 (cr) PCOB	60°57′58,9″ 101°51′33,4″	1958–2008	4	South – SE towards lake			A	Near lake
20	BO 27 (cr) PCOB	60°57′47,8″ 101°51′21,7″	1925–2006	–	No			–	Scar in 1989
21	BO 30 (cr) PCOB	60°57′48,2″ 101°51′22,8″	1965–2008	4	No			A	
22	BO 37 (cr) PCOB	60°57′50,3″ 101°51′18,5″	1953–2008	4	No			A	Near river and lake
23	BO Isba (cr) PCOB	60°54′09,3″ 101°54′43,0″	1929–2008	3	No			B	

[a] Dr Kletetschka's sample.
[b] Eccentricity analysed only in cross-section.
Grey cell = trees born after TE.
LASI = Larix sibirica ledeb.
PCOB = Picea Obovata Ledeb.

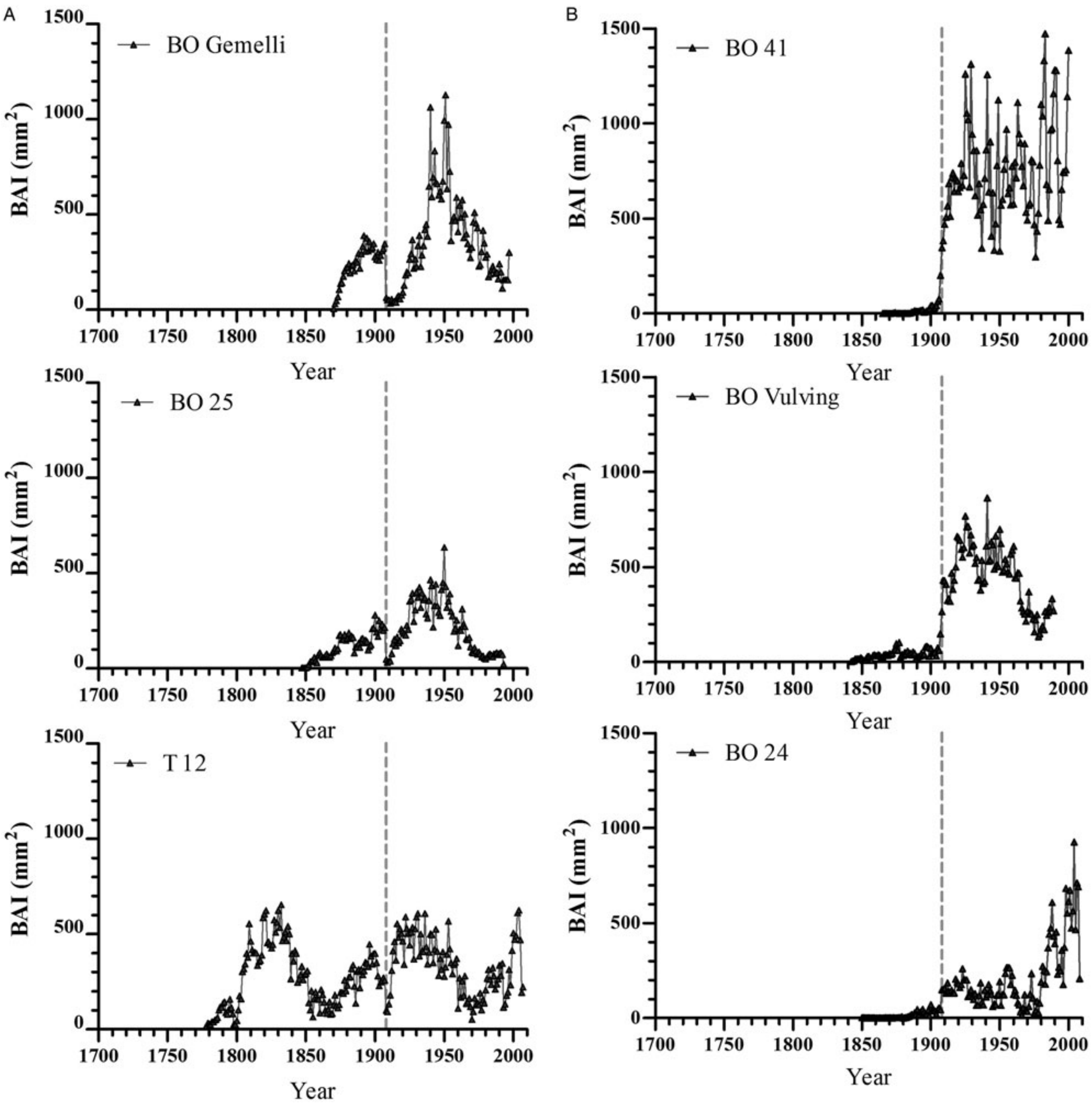

Fig. 6. (a) Trees that survived to TE with growth suppression after 1908 (Group 1). (b) Trees that survived and suppressed before TE with growth release after 1908 (Group 2).

the TE. Most of the previous work (Nesvetajlo 1998; Yonenobu & Takenaka 1998; Vaganov *et al.* 2004) detected growth stress from observing tree ring decrease lasting few years, sometimes followed by a sudden growth increase. Instead, our work suggests an existence of both suppression and increase of the growth after the TE. For the suppression case we detected a growth reduction, starting in 1908 or 1909, and lasting from a mean of 3 years up to 14 years, followed by a growth increase lasting 4–14 years (Fig. 6(a)). Trees that survived the TE have shown an accelerated growth. These trees had suppressed growth in the forest before the TE and after that, with the death of their neighbours, suddenly appeared in better living conditions without competition for the light and nutrients (Fig. 8(a) and (b)). Nesvetajlo (1998) observed similar growth trend close to the epicentral area. In addition to the survived trees, we analysed trees born after the TE, living inside the forest and near the Cheko lake shore. The oldest ones (33%) were born in 1923 (15 years after the TE). BAI analysis of trees, born after the TE, living near Cheko lake shore and within the forest has shown two different growth trends. Trees near the lake shore have continuous young vigorous growth (Type A – Le Blanc) until 1999 (the day of collection) (Fig. 8(e)). Trees living inside the forest, instead, have a trend with an initial vigorous growth followed,

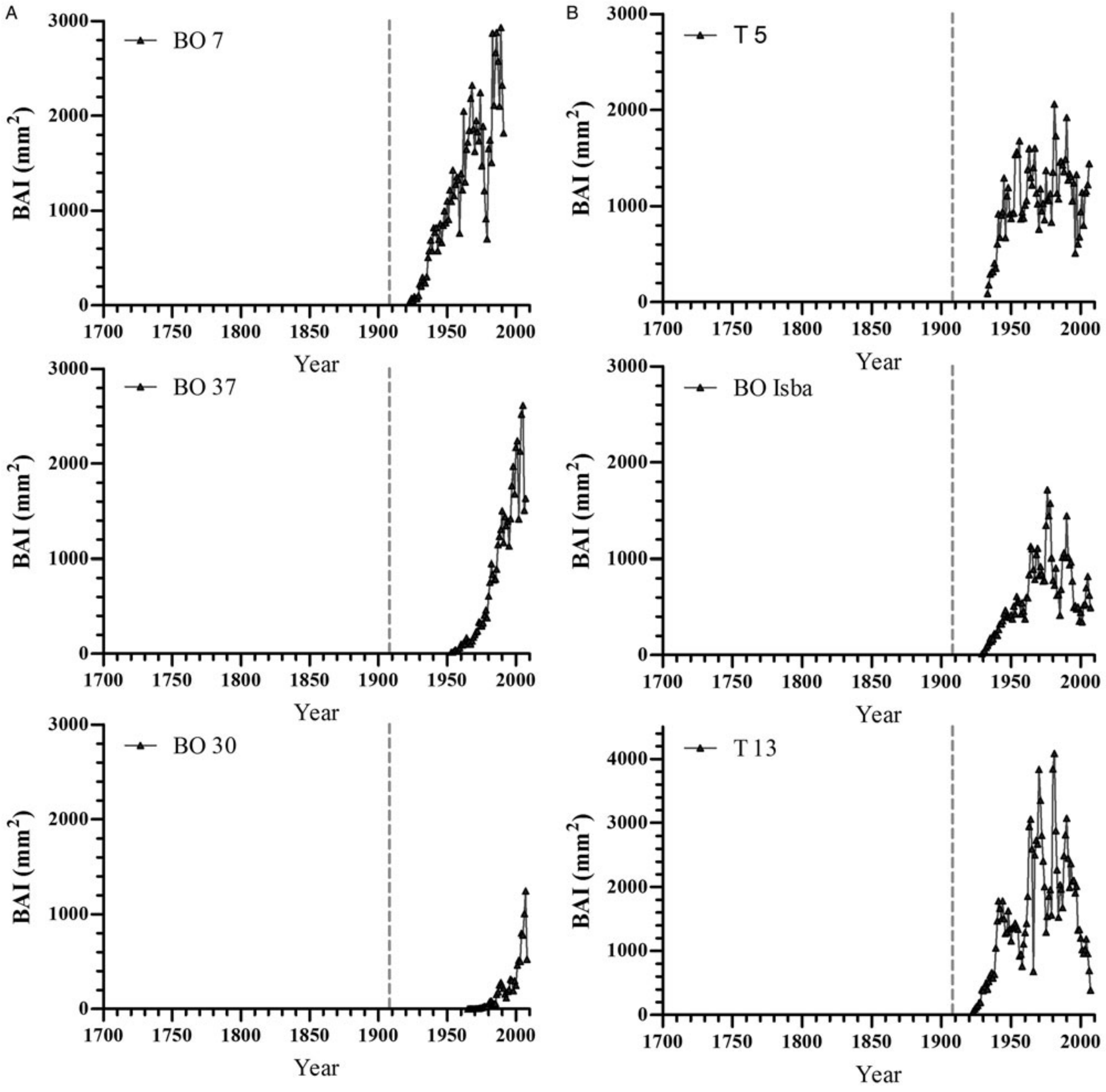

Fig. 7. (a) Trees germinated after TE living close to Cheko lake with continuous young growing trend (Group 3). (b)Trees germinated after TE living inside the forest with a young growing phase followed by competition (Group 4).

after 10–30 years, by a more suppressed trend, indicating a re-established competition (Type B – Le Blanc) (Fig. 8(d)). The difference in the growth rate between the trees born after the TE inside the forest and near the Cheko lake shore point out that they were living in a different environment. Near the lake trees do not need to compete one with each other, while inside the forest they have to. The dendrochronological analysis results suggests a recent age of the Cheko lake, and supports the hypothesis that the lake may have been formed by a TBC fragment or a smaller component of a binary asteroid impacting on permafrost and the soft alluvial deposit of the Kimchu river plain.

The last but not least point is that the TE took place at an altitude between 5 and 10 km (Foot & Yoon 2002). This is consistent with the distance of Cheko lake from the epicentre of the explosion as well as a similar recent event in Chelyabinsk, where the largest part of cosmic body flew from an altitude exceeding 20 km comparable horizontal distance prior to an impact into the Chebarkul lake (Borovicka *et al*. 2013).

Conclusion

In this study, the growth comparison between trees that survived to the TE and those born after, analysed by BAI, led

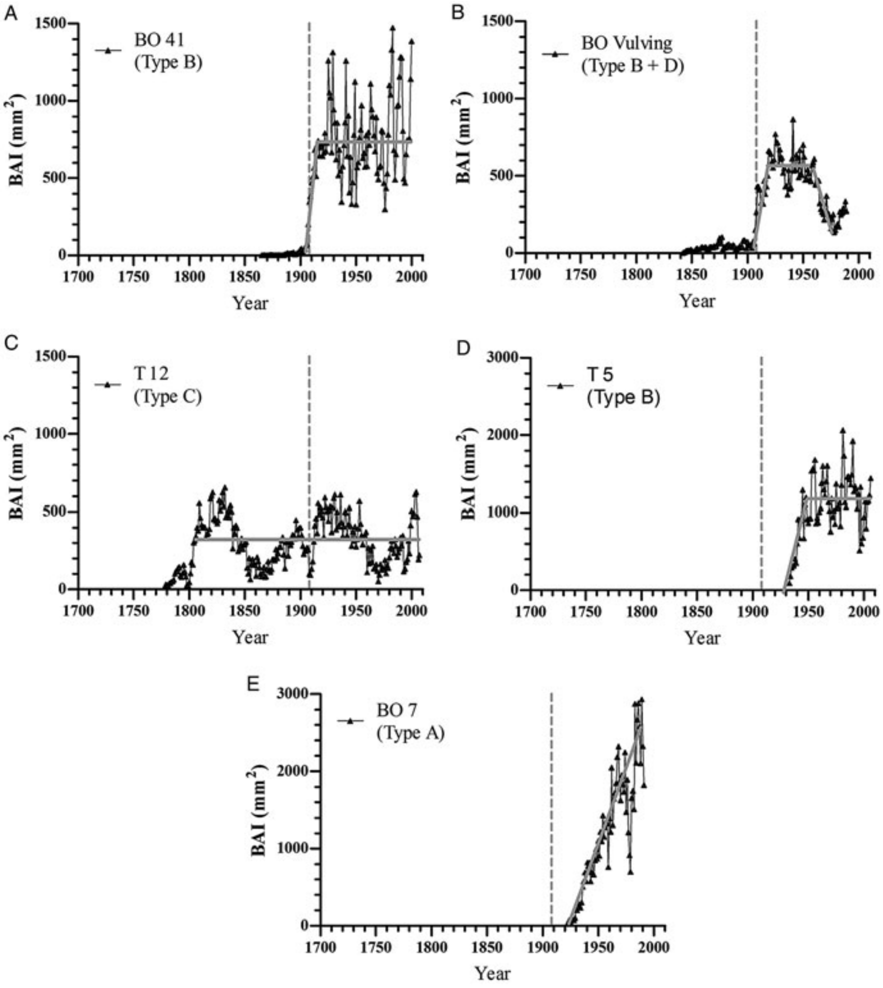

Fig. 8. Type of trees according to BAI from Le Blanc, 1992: (8a) survived tree group 2 (Type B), (8b) survived tree group 2 with growth decline (Type B + D), (8c) survived and mature tree group 1 (Type C), (8d) tree born after TE living in the forest (Type B), (8e) tree born after TE living close the Cheko lake (Type A).

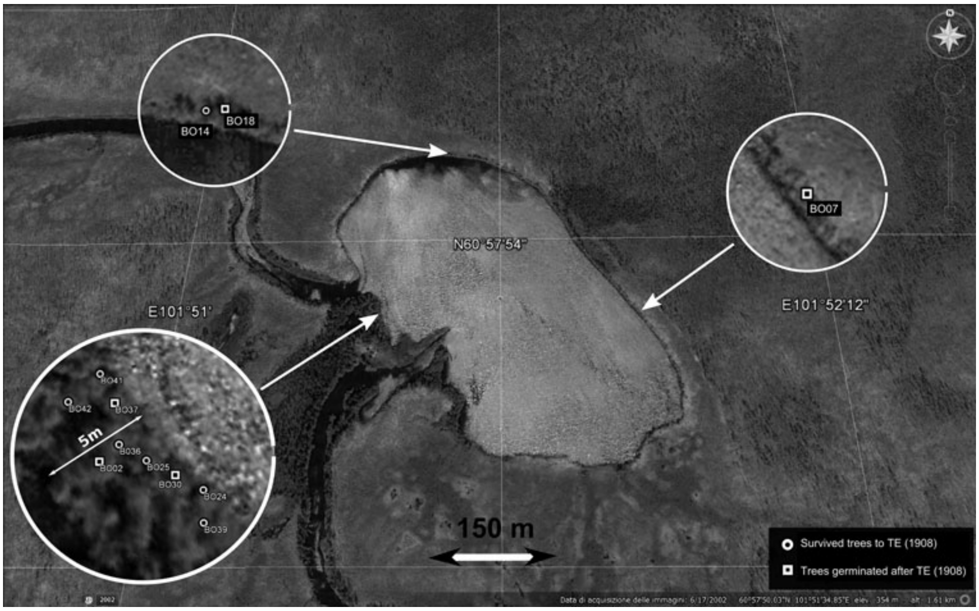

Fig. 9. Detailed map of sampled trees nearby Cheko lake.

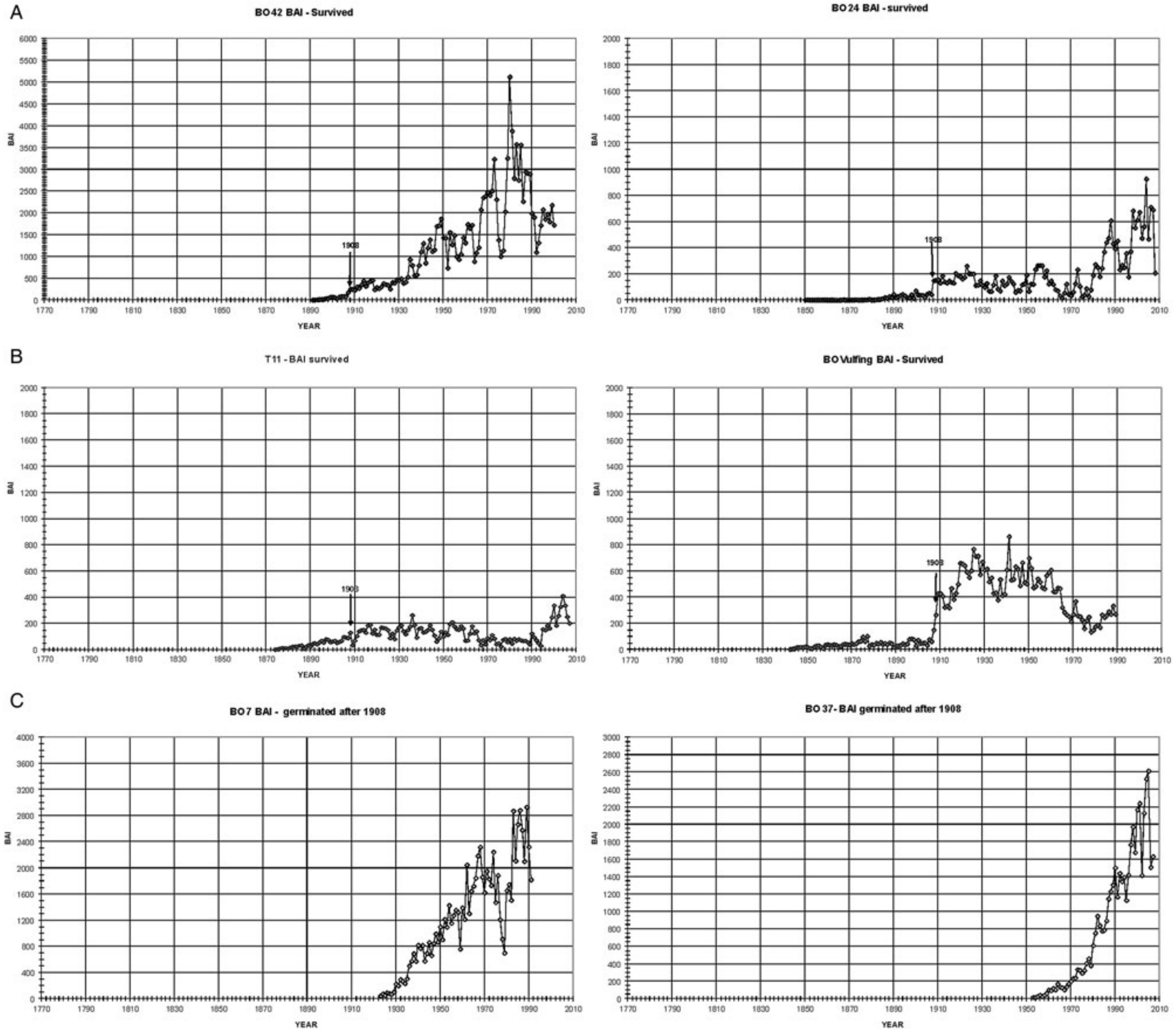

Fig. 10. BAI graphics of trees living near Cheko lake.

to a new direction of research: the state of competition between the trees. Many of the survived trees had a growth suppressed before the TE by the presence of the competing trees, and a sudden and strong increase for 10–30 years, before a new competition arises. Six trees have shown growth suppression, generally for a few years (1–5). A comparison between trees born after the TE close to the Cheko lake and those inside the forest have shown an absence of competition between trees living close the lake shore, while the others, after 10–30 years, suffered for the competition of the neighbours. The oldest tree born after the TE goes back to 1923, 15 years after the event, the time lag of resilience displayed by this research. Trees that recorded the presence of the lake before 1908 were not found; all analysed trees near the lake shore show a typical young growing phase without competition, different from those inside the forest that after a young phase show the sign of competition on the BAI curve. In summary, we do not claim that we proved that the Cheko lake is of impact origin. However, our analysis of trees around the lake and near the impact epicentre show that the tree record from this area is consistent with the impact hypothesis where the soft impact of a TCB fragment or of a component of a binary asteroid could have originated the Cheko lake.

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