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Tree-ring dating of meteorite fall in Sikhote-Alin, Eastern Siberia – Russia

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Abstract: This research deals with the fall of the Sikhote-Alin iron meteorite on the morning of 12 February 1947, at about 00:38 h Utrecht, in a remote area in the territory of Primorsky Krai in Eastern Siberia (46°09′36″N, 134°39′22″E). The area engulfed by the meteoritic fall was around 48 km^2, with an elliptic form and thousands of craters. Around the large craters the trees were torn out by the roots and laid radially to the craters at a distance of 10–20 m; the more distant trees had broken tops. This research investigated through dendrocronology n.6 Scots pine trees (*Pinus Sibirica*) close to one of the main impact craters. The analysis of growth anomalies has shown a sudden decrease since 1947 for 4–8 years after the meteoritic impact. Tree growth stress, detected in 1947, was analysed in detail through wood microsection that confirmed the winter season (rest vegetative period) of the event. The growth stress is mainly due to the lost crown (needle lost) and it did not seem to be caused due to direct damages on trunk and branches (missing of resin ducts).

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Key words: dendrochronology, tree ring, Sikhote-Alin, impact crater, extraterrestrial impact, meteorite, Russia, Scots pine (*Pinus sibirica* Du Tour).

Introduction

The fall of the Sikhote-Alin iron meteorite on the morning of 12 February 1947, at about 00:38 h UT, in a remote area in the territory of Primorsky Krai in Eastern Siberia (Sikhote-Alin mountain range, 46°09′36″N, 134°39′22″E), was one of the unique meteoritic events of the 20th century (Fig. 1). Several scientific expeditions sponsored by the Academy of Sciences of the U.S.S.R. were active in the following years in making a detailed study of this meteorite fall, and results of this research have appeared in a large number of papers, and in two articles by Fesenkov (1959) and Krinov (1971). The shower resulted from the disintegration of the initial meteoritic body as it passed through the Earth's atmosphere. The meteorite fragmented upon entering the atmosphere and the pieces were scattered as iron rain. The larger pieces formed more than 100 holes and meteorite craters. The enormous mass of the meteorite, together with a number of other peculiarities, makes the fall of the Sikhote-Alin meteorite a unique event. The fall of the meteoritic shower was accompanied by a dazzling, bright fireball, which in the course of a few seconds flashed from north to south across a clear sky in which the sun was shining. The fireball was so bright that it blinded the eyes, and secondary shadows of different objects appeared. These turned rapidly, following the fireball. Along the path of flight a thick dust train was left, which remained visible for several hours. After the disappearance of the fireball, loud detonations resembling explosions were heard. After the detonations, rumbling and roaring followed. In inhabited places over which the fireball passed, different mechanical phenomena were observed: doors flew open, windowpanes were blown out, plaster fell from ceilings, flames and ashes together with burning pieces of fuel were thrown out of stoves, other objects fell and a trembling of the ground was felt. Nevertheless, even at the nearest seismic station at Vladivostok, about 400 km away, no seismic waves caused by the fall of the meteoritic shower were recorded. On the whole, the phenomena accompanying the fall in no way approached the strength of those which accompanied the Tunguska event. The Sikhote-Alin iron meteoritic shower was caused by the breakup in the Earth atmosphere of an initially intact meteoric body (and not by the penetration of a swarm of meteoric bodies into the Earth atmosphere). Fesenkov (1959), on the basis of eyewitness accounts of the fall, made a theoretical investigation of the conditions of motion of the meteoric body in the Earth atmosphere and calculated the orbital element of the cosmic body. These elements show that the orbit was elliptical and like that of an asteroid. The cosmic velocity of the meteoric body relative to the Earth was about 14.5 km s^{-1}. The breakup in the atmosphere of an initially intact meteoric body was established by Krinov (1971). On the basis of a morphological study of the fragments of the meteoritic shower this author established that the cosmic body before the interaction with the atmosphere was intact. Probably, not less than 1000 individual specimens of various sizes, weighing from a fraction of a gram to several hundreds of kilograms, fell on the surface of the Earth. The components of the meteoritic shower are divided into two main groups. One comprises individual intact specimens, which were formed as a result of the breakup of the meteoric body in the atmosphere. These specimens are covered by a typical fusion crust and show

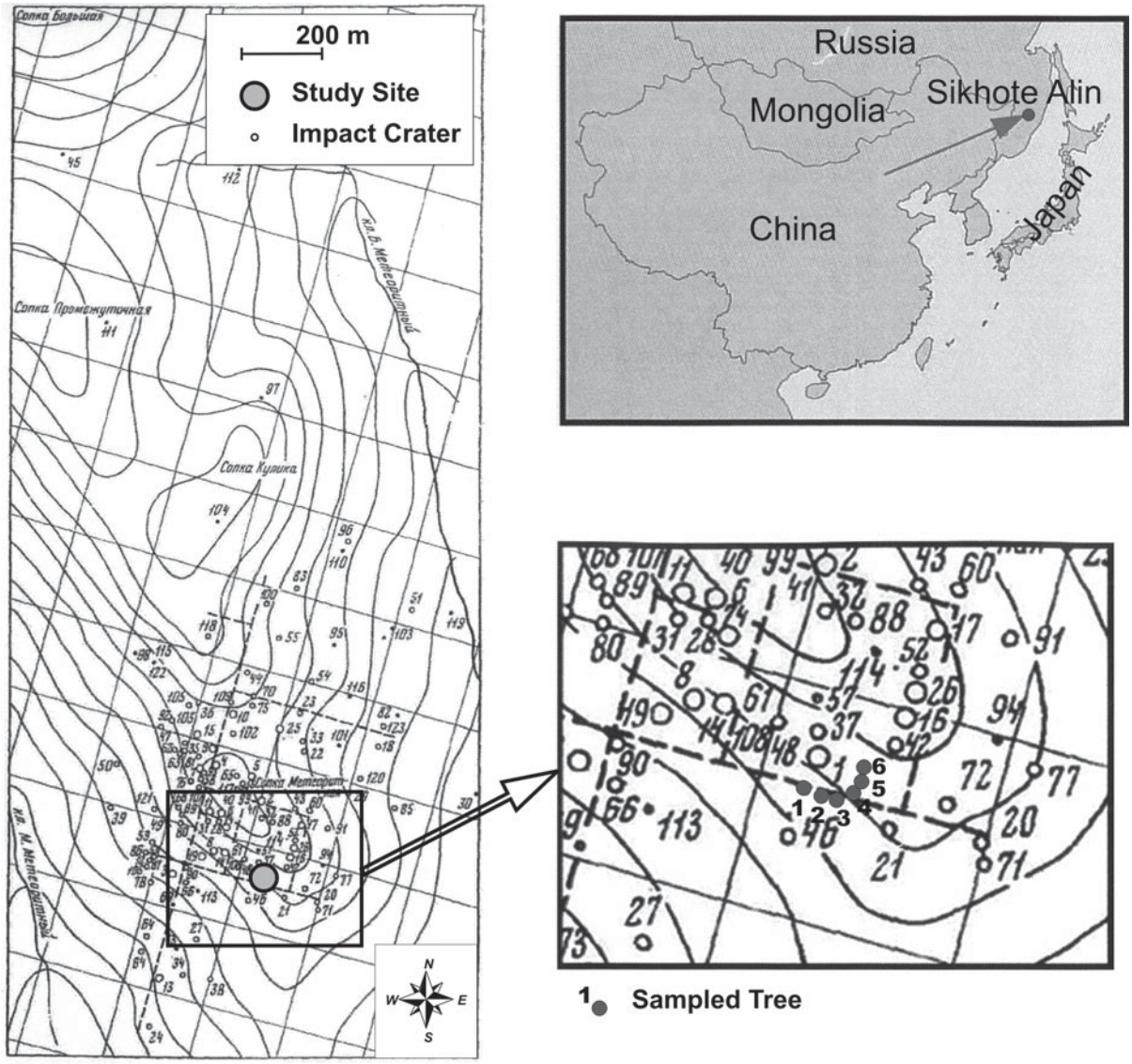

Fig. 1. Site study map with sampled trees.

a sharply defined regmaglyptic relief. The other group is composed of fragments of large individual specimens (shrapnels), formed when they struck the ground. The main mass of these fragments shows sharp deformations, bent and sharp-pointed as though exhibiting torn edges, scars, slide lines etc. The fragments have no fusion crust and were covered with rust and streaks of soil. Besides these two categories of meteoritic matter, very small meteoritic (magnetic) particles were found. Under the microscope these have a sharp-edged, splinter-like form. They were found in the top layer of the soil around craters and also in the earth that filled the craters by means of a portable magnet. These particles are the result of the breakup of individual specimens. The Sikhote-Alin meteoritic shower was distributed over an area of 1.6 km^2 of roughly elliptical form, the major axis being about 2 km long, the minor 1 km, but later Tsvetkov (1983) enlarged the dispersion ellipse to 12 × 4 km. The main mass of the meteoritic shower fell in the southern (forward) part of the ellipse, on the tops and slopes of small hills. In fact, all the largest craters are located here. The largest specimens penetrated the soil until they reached the rocks and formed craters with diameters up to several metres. The largest crater, of the more than 100, has a mean diameter of about 26 m and is 6 m deep. Altogether, 383 points of fall of individual specimens were discovered; these included craters of all sizes, holes and small individual specimens distributed on the surface. Sites have been arbitrarily divided into groups containing 122 craters with diameters from 0.5 to 26.5 m, 78 holes with diameters less than 0.5 m and 175 falls distributed on the surface. Some cases of meteorites hitting trees were recorded. In one such case, a meteorite weighing 13 675 kg hit a cedar of 70 cm in diameter and penetrated it to a depth equaling its diameter. In another case a meteorite weighing 343.8 kg cut in half a growing fir tree 40 cm in diameter. Breaking up into two parts, weighing 300.0 and 43.8 kg, this meteorite formed a crater of about 2.0 m in diameter and penetrated the ground to a depth of 0.9 m, the

Table 1. *Visual growth analysis (adapted from Schweingruber et al. 1990)*

Suppression	Amount of decrease	100%	50%
Sup.1	40–55%		
		100%	30%
Sup.2	56–70%		
		100%	20%
Sup.3	> 70%		
Release	Amount of increase	100%	200%
Rel.1	50–100%		
		100%	300%
Rel.2	101–200%		
		100%	500%
Rel.3	> 200%		

smaller one, and 2.1 m, the larger one. In the forward part of the scattering ellipse, in an area of about 0.5 km^2 many trees were damaged. Around the large craters the trees were torn out by the roots and laid radially to the craters in a radius of 10–20 m. The more distant trees had broken tops. Scattered pieces of tree trunks, branches, splinters of rocks thrown out of large craters were found everywhere. In contrast to the forward part of the ellipse, in the tail part no signs of devastation of the taigà were observed. Only rare single trees, still standing, were damaged by the falling meteorites. On the basis of the approximate mean masses of meteorites which formed craters of different diameters and taking into account the number and sizes of all the craters and holes found, the approximate mass of the meteoritic shower was estimated to be about 70 tonnes. Few studies of dendrochronology were applied to the response of trees to cosmic body impact. Most of them focused on the 1908 event in Tunguska, northern Siberia (61N; 102E) that produced an explosion with a wide destruction of the tree forest (about 2000 km^2). Other sites partially analysed through dendrochronology were the Chulym bolide explosion in 1984 (57.7N; 85.1E). Some samples collected by the same authors demonstrate the possible influence of 1873 Kola bolide impact on tree – growth (Kasatkina *et al.* 2007, 2008). In these studies the growth anomalies of trees in a very wide zone between 60–75N and 80–110E were analysed (about 1500 km of distance from Tunguska), which showed an increase in growth after the event. These researchers' hypothesis was that the growth increase was stimulated by cometary matter spread into the soil over a large territory in Eurasia; secondarily it could be due to NO produced during the event. These articles do not show the exact place, number of trees' samples and species. The site of Tunguska was investigated by other researchers more in detail (Vaganov *et al.* 2004) sampling some of the few survived trees close to the epicentre. The main stress recorded was a growth reduction on trees, starting the year after the event (1909) for the next 4–5 years. These rings had a particular structure called 'light rings' with non-thickened tracheids in the transition and latewood zones; moreover, deformed tracheids in the outer part of a 1908 ring were found. These growth anomalies on surviving trees could be induced by defoliation or mechanical stress on active xylem tissue. The research was developed on trees of different species: larch (*Larix sibirica*), spruce (*Picea obovata*) and siberian pine (*Pinus sibirica Du Tour*) at a distance between 5 and 7 km from the estimated epicentre. The evidence of light rings in Tunguska area was detected by other scientists with particular techniques such as CAT (computerized axial tomography) (Longo & Serra 2006). Dendrochronological dating carried out on standing dead trees, called 'telegraph pole' in Tunguska site (Nesvetailo 1998), clearly identified the death year as 1908 and attributed the accelerated growth of nearby surviving trees by the lack of competition. In August 2010, we carried out a scientific expedition to the Sikhote-Alin impact crater area to collect samples from trees that survived the event. This research is the first attempt to use dendrochronology to test the effect of meteorite impact fallen on the Sikhote-Alin forest (Fig. 1).

Materials and methods

Field samplings and dendrochronological analysis

In summer 2010 n.6 Siberian pine (*Pinus Sibirica*) trees were sampled with a non-destructive method (incremental corer) that extracts 'wood cores' of 0.5 cm diameter from the tree. These samples were examined with dendrochronological methods to find out the effect of meteorite impact on trees living close to the impact crater. The wood cores were glued to wood supports, cut, sanded and then measured with a sliding device with 0.001 mm accuracy (Velmex). Cross correlations were made first through 'skeleton plots' graphs (Fritts 1976), followed by measurement of tree ring widths and their statistical test by Cofecha software (Holmes 1983). Each ring width curve was analysed to find sudden growth anomalies (suppression or increase) with a qualitative method introduced by Schweingruber *et al.* (1990). Sudden growth decrease (suppression) that occurs for at least four continuous years were grouped in three classes, according to the intensity of decrease, with respect to the mean growth of previous years (Table 1). In the same way, sudden growth increase (release) was also grouped in three classes. The results of visual growth analysis were used to create a graph of the Index value (It%) that is computed as cumulative values of suppression or release in relationship to the number of samples living in the year, firstly introduced to date landslides by Shroder (1978).

$$I_t = \left(\sum_{i=1}^{t} Ri\right) \Big/ \left(\sum_{i=1}^{t} Ai\right) \times 100$$

(adapted from Shroder 1978)

where R_i: are cores that have shown the anomalies in the year t and A_i is the total number of cores sampled for the year t.

Tree ring growth stress, detected in 1947, was then analysed more in detail through microsection (10 μm) to infer the season of the anomaly, looking at the wood structure. The event could occur in fact in the rest vegetative phase or the growing season of the tree (summer in this area).

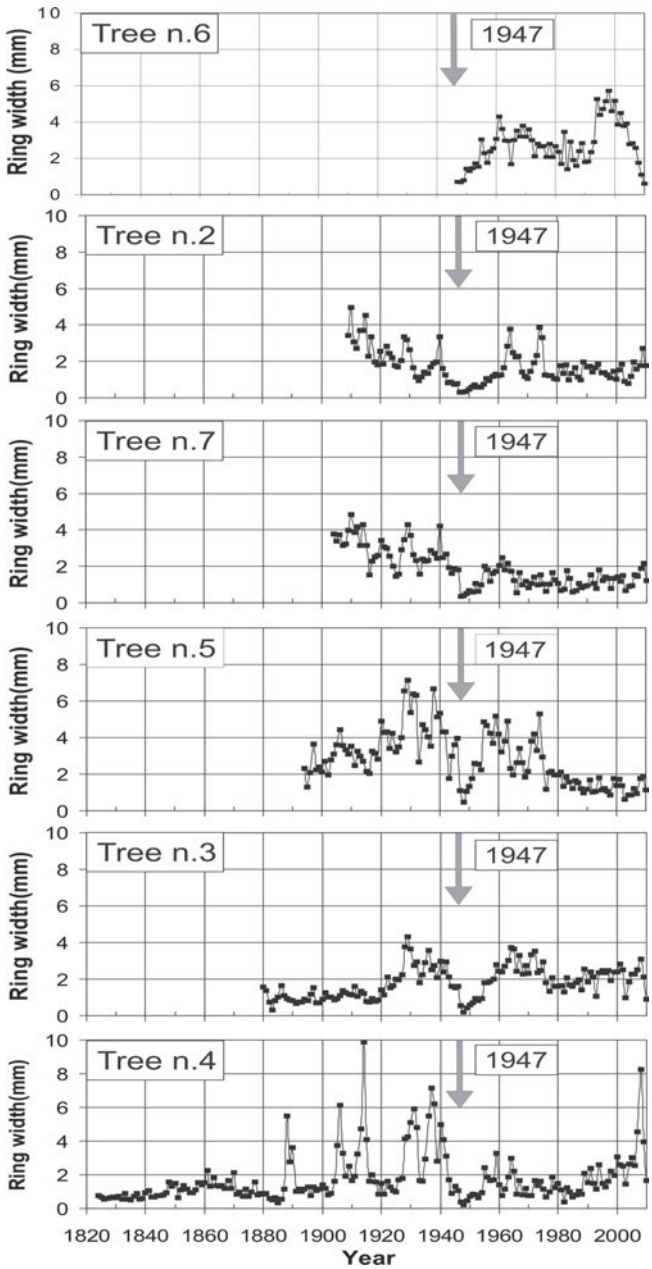

Fig. 2. Tree ring growth curves.

Results

Dendrochronological results

The results of tree ring analysis inferred from some trees living close to one of the main impact crater (n.1) of meteorite fall, in Sikhote Alin (Fig. 1), are mostly a 'stress' that caused a sudden decrease of growth for a period between 4 and 8 years (Fig. 2). The visual growth analysis pointed out a sudden decrease of class II (51–70%) or class III (> 70%) starting from the growing season after the meteorite impact, occurred in the dormant period (12 February 1947); in the cores lighter suppression growth of class I were not found. The oldest tree sampled is 186 years old (Tree n.4), while most of them belong to (1880–1907) between 130–103 years. One sample is younger, with only 63 years (Tree n.6) without suppression but increase in growth.

Table 2. *Results of visual growth analysis*

Year	Suppression class I (%)	Suppression class II (%)	Suppression class III (%)	Index It %
1947	0	33	50	83
1948	0	17	67	83
1949	0	67	50	83
1950	0	67	0	67
1951	0	33	0	67
1952	0	17	0	17
1953	0	17	0	17

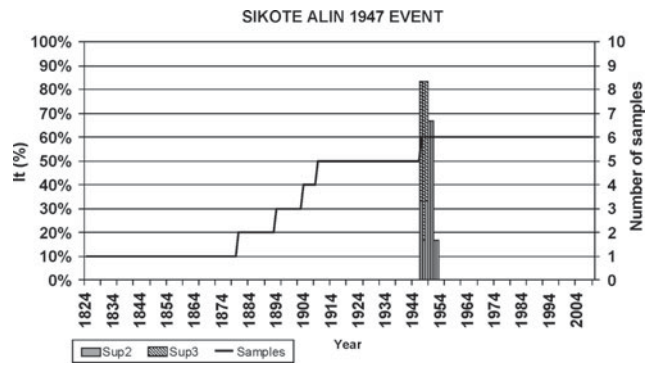

Fig. 3. Index values (It%) of growth anomalies (suppression).

In Table 2 and Fig. 3 are shown the percentage of sampled trees with anomalies and their Index value (It%). The growth stress due to the impact of meteorite was strong, recorded by most of trees examined (83%) with decrease of class II and class III, but not class I (the percentage could increase at 100% if the younger Tree n.6 was not included). The second year after the event (1948) had usually the narrowest ring. This effect has a biological meaning and was often detected on trees hit by different geomorphologic stress as landslides, earthquakes, shore erosion etc. (Alestalo 1971; Begin & Filion 1988; Fantucci & Sorriso Valvo 1999). A detailed wood anatomy analysis was made on Tree n.4 to detect in which season the stress event occurred (Fig. 4). This analysis was carried out on a microsection of wood core and showed that the previous year before the event (1946) the growth was regular. Then the event occurred during the dormant season (12 February 1947) and the effect on tree growth started since the next growing season (1947) with earlywood and latewood density reduced and cell walls of the earlywood also slightly reduced, because of the damage to the crown. As usually occur after a stress, the second year after the event has a stronger suppression (1948) with small earlywood and latewood (small ring) and latewood density. Trees' energy is in fact transferred mainly to the crown to form new phytosynthetic mass after its damage. The next year (1949) was shown still earlywood, latewood and cell wall thickness reduction, but the regeneration that can be seen in 1950 is beginning. The fourth year after the event (1950), even if the width is still reduced, the regeneration process is finished and the wood structure of the rings starts to be normal. This analysis suggested that the growth stress is mainly due to the lost of crown (needle lost) and it did not seem to be caused due

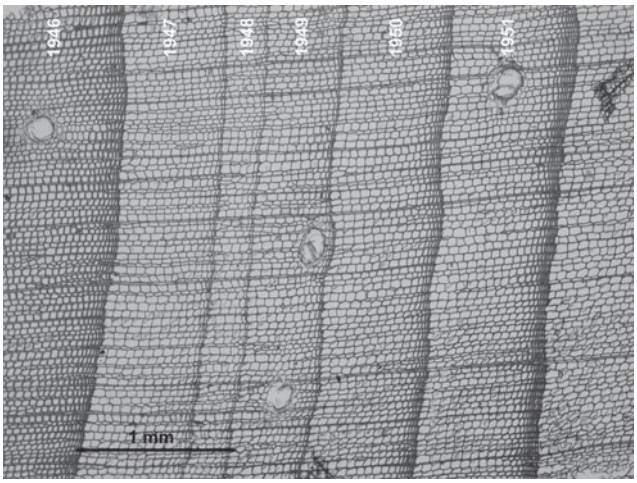

Fig. 4. Transverse wood section of sample n.4 showing growth anomaly in 1947.

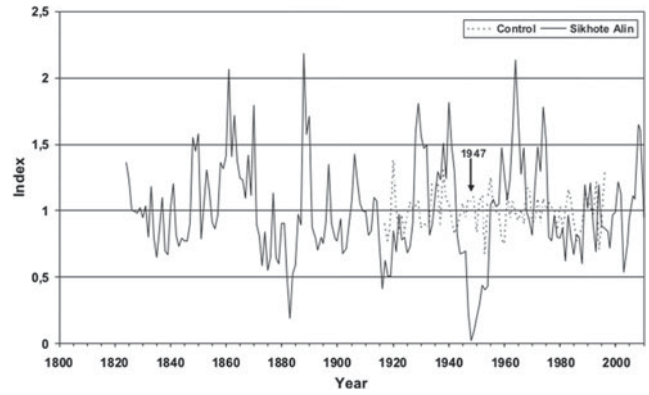

Fig. 5. Control chronology versus Sikhote Alin chronology, evidence of stress in 1947–1954.

to direct damages on trunk and branches (missing of resin ducts). Tree rings affected by suppression, found in Sikhote Alin often showed a light colour due to the lack of latewood cells, similar to the so-called 'light rings', frequently detected in arctic and subarctic areas, sometimes related to major volcanic eruptions into the world like the 1816 Tambora one (the year without a summer) (Filion *et al.* 1986). Although the limits of few cores, a chronology for the site was developed with the software Arstan (Cook & Holmes 1984) that was compared to the closest one available from NOAA/NCDC Paleoclimatology Program, Boulder, Colorado, USA for the same species located at a distance of 1590 km in the northwest direction (56.50N, 118.50E Tschita Dÿnen S., Scots pine (PISY) by Fritz Schweingruber RUSS173L) (Fig. 5).

The two chronologies have a common time interval between 1824 and 1996. Even if there is not a perfect agreement between the two because of their distance, it is evident the stress recorded in Sikhote Alin chronology, respect to the other one, with very low indexes (between 1947 and 1954).

Discussion

The results of tree ring analysis on survived trees to the impact of meteorite in the Sikhote Alin zone are comparable to those of Tunguska site, even if remnants of extraterrestrial body were not found in that area. The regular growth suddenly changed (decreased) because of the impact of meteorite on the forest. Trees showing quite strong suppression of ring growth did not show evidence of deformed tracheids like in Tunguska (Vaganov *et al.* 2004). This can prove that the cosmic event in Sikhote Alin (48 km^2) hit a much smaller area and with less intensity with respect to those of Tunguska (2000 km^2). Trees from Sikhote Alin did not show the presence of continuous raw of resin ducts that usually are linked to very strong damages on stem and branches like in many geomorphological sites (Stoffell 2008), but they show besides suppression (4–8 years) the typical form of 'light rings' (rings without the development of latewood) for few years since 1947 (Fig. 2) like in Tunguska site (Vaganov *et al.* 2004). Light rings generally occur because of partial or full defoliation or low-temperature stress (Fritts 1976; Schweingruber *et al.* 1979). One tree (n.6), very young in 1947 displayed a growth increase (Fig. 2), typical of close canopy, because of decrease in competition due to the felled neighboring trees, as found in the Tunguska site (Nesvetailo 1998).

The wood structure analysis of the 1947 event, through microsection, gave detailed seasonal dating: in Sikhote Alin the event occurred during the dormant vegetative period (winter 1947) so that the effect on tree ring started the next vegetative year (summer 1947) (Fig. 4). The usefulness of wood anatomy in dendrochronological analysis for extraterrestrial events was confirmed again (Hitoshi & Chisato 1998; Vaganov *et al.* 2004). Long tree ring chronology was investigated in Russia to detect the main significant periods linked to solar cycles (Kartavykh 2002) as the 200 years Gleissberg; in Russian chronologies near Tunguska there seems to be a break on 50–80 years cyclicity at the beginning of the 20th century, probably due to the 1908 event (Kartavykh 2002). Dating of impact crater due to extraterrestrial impact is very important to understand better the cosmic activity and the extraterrestrial impact hazard on the world (Baille 2007). There are many small craters very difficult to be identified as impact derived, because of lack of historical and archeological interest in inhabited regions that could be interesting for tree ring dating. Good dating, moreover, is important to give the input for historical research. Some of AD 1500 tsunami signs along the Australia coast, in not tectonic active zone, could be related to some very large extraterrestrial impact, linked to Taurid complex (Bryant 2001). Some of the strong suppression detected on tree ring chronologies all around the world (like AD 536–545), connected also to some historical black period, could be related to some global catastrophe that did not seem to be related to volcanic activity, because of lack of acid signal in ice cores. This event could be related to a large comet observed on the sky by a medieval historian (Britton 1937). Moreover, after AD 540, the Great Plague took place that claimed one-third of the European population (Baille 2007).

Conclusion

Dendrochronological analysis carried out on a few trees that survived 12 February 1947 in Sikhote Alin has clearly detected the effect of the meteorite impact on the forest, with a strong growth decrease for 4–8 years since 1947. Moreover, the wood structure microsection increased the accuracy of dating to the rest vegetative period during the winter of 1947 in accord to the known date. The local chronology developed from trees sampled shown a clear difference in period 1947–1954 with a control chronology of the same species in Russia. This methodology can be very useful in dating the effect of extra-terrestrial impact on forested regions. This kind of analysis could also be used in other regions with evidence of impacts where there is no historical dating to increase the knowledge of these events. The precise tree ring dating of stresses on vegetation and the age of trees living in particular regions hit by extraterrestrial impact (like Tunguska) could give much more data to reconstruct the event and to understand local anomalies still unknown like the presence of a deep elliptic lake (lake Cheko) into a flood plain region.

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