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Research Paper

The Tunguska Event in 1908: Evidence from Tree-Ring Anatomy

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ABSTRACT

We analyzed tree rings in wood samples collected from some of the few surviving trees found close to the epicenter (within 4-5 km) of the Tunguska event that occurred on the last day of June 1908. Tree-ring growth shows a depression starting in the year after the event and continuing during a 4-5-year period. The most remarkable traces of the event were found in the rings' anatomical structure: (1) formation of "light" rings and a reduction of maximum density in 1908; (2) non-thickened tracheids (the cells that make up most of the wood volume) in the transition and latewood zones (the middle and last-formed parts of the ring, respectively); and (3) deformed tracheids, which are located on the 1908 annual ring outer boundary. In the majority of samples, normal earlywood and latewood tracheids were formed in all annual rings after 1908. The observed anomalies in wood anatomy suggest two main impacts of the Tunguska event on surviving trees—(1) defoliation and (2) direct mechanical stress on active xylem tissue. The mechanical stress needed to fell trees is less than the stress needed to cause the deformation of differentiating tracheids observed in trees close to the epicenter. In order to resolve this apparent contradiction, work is suggested on possible topographic modification of the overpressure experienced by these trees, as is an experimental test of the effects of such stresses on precisely analogous growing trees. **Key Words: Tunguska event, June 1908—Tree rings—Deformed tracheids—Pressure on trees.** Astrobiology 4, 391-399.

INTRODUCTION

THE TUNGUSKA EVENT of June 30, 1908 has been the subject of several expeditions and numerous publications (see, *e.g.*, Chyba *et al.*, 1993; Lyne and Tauber, 1995; Vasilyev, 1998). Even so, there seems to be a paucity of relevant evidence, in part resulting from a 19-year delay between the event and the first expedition to the location in 1927 (Kulik, 1939; Krinov, 1949). Most of the

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progress that has been made relates to the physics of the event, although the energy of the explosion and the chemical composition of the postulated meteorite and its trajectory are still under discussion.

Here we present some lines of evidence based on tree rings—natural recorders of chronology and environment. Tree rings can be used to place the effects of the Tunguska event in a longer temporal perspective. For example, the role of the Tunguska event in widespread wildfire seems to have been overestimated (Nesvetailo, 1998). Tree-ring-dated fire histories indicate that 1908 was characterized by markedly greater fire occurrence than the long-term average at widely separated locations between the Tunguska and Angara rivers as well as on the left bank of the Enisey river, about 600 km to the west from the epicenter (Arbatskaya and Vaganov, 1996, 1997). This "regional fire year" was associated with an unusually hot June and low groundwater, and is similar to many such years over several centuries. Nesvetailo (1998) used dendrochronology to show that the great majority of dead trees in the "telegraph pole" forest of the region close to the epicenter died in 1908. He also examined some other lines of evidence recorded in the tree rings, and concluded that a more complete dendrochronological investigation would be of value.

We report direct tree-ring records of the Tunguska event, using wood microanatomical features from samples collected by one of us (V.D.N.). The Tunguska event occurred on June 30, 1908, during the growth season of trees in this area (Vaganov *et al.*, 1985; Kirdyanov, 1999). The growth of the current year's shoots would nearly have been finished, and needle growth would have been ongoing. The processes of xylem (wood) growth would have been in a particularly active phase, with most of the earlywood (the first, and usually largest, part of the annual ring) already formed and the production of tracheids for the transition and latewood zones commencing. Tracheids are dead cells that make up most of the wood volume, being vertically oriented tubes, many times longer than their diameter (in the range of 8-50 μm). They are dead by the end of the growing season, and so their structure forms a permanent record of the growth conditions in that season. Trees for tens of kilometers from the epicenter in all directions were felled by the ballistic and/or blast waves associated with the event. Those that survived the event, upright, in the region close to the epicenter, carried traces of the impact in the peculiarities of the structure of their tree rings.

MATERIALS AND METHODS

Wood cores were taken from these individual trees in 1990. They were used to study the anatomical structure of the 1908 annual ring and those formed in several following years. The sample included four larch (*Larix sibirica*) trees, four spruce (*Picea obovata*) trees, and four Siberian pine (*Pinus sibirica*) trees with ages that range from 125 to 160 years. The location of these trees was within 5-7 km of the estimated epicenter (Fig. 1).

There are several local and regional chronologies for larch, spruce, and pine in this region (Kirdyanov, 1999). Each of these is a mean of the time series of cross-dated and detrended ring widths from a number of trees at each site (Fritts, 1976). Wood samples taken from the trees near the epicenter are cross-dated with these chronologies, and so the annual rings formed in 1908 are

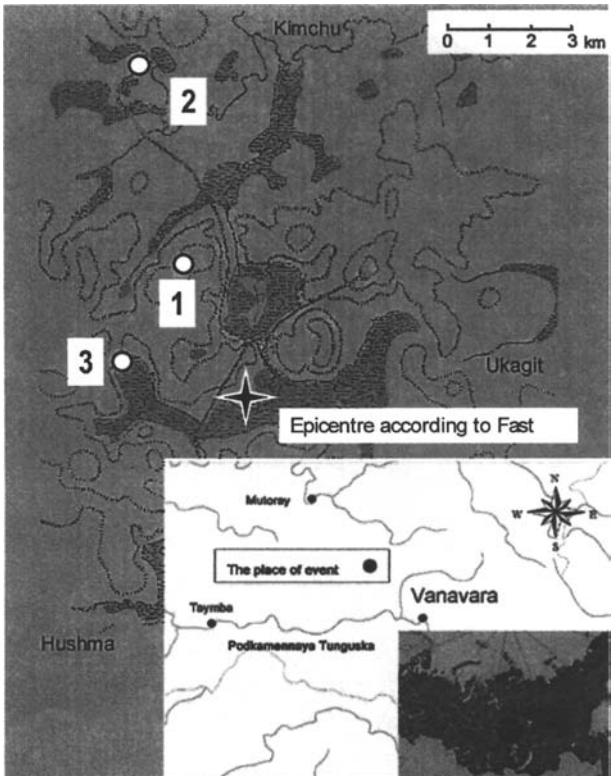

FIG. 1. Location of sample collections in relation to the epicenter of the Tunguska event: 1, the main tree-ring sample site; 2, the location of larch L1-99; and 3, the location of larch LB-80.

reliably dated. Tree-ring widths were measured using a device with an accuracy of 0.01 mm. Thin cross-sections of wood including several annual rings before and after 1908 were made, stained, and analyzed using an image analysis system. Radial tracheid diameter and cell wall thickness were measured on the thin sections because these anatomical characteristics reflect the intraseasonal dynamics of growth and represent the final result of xylem differentiation. X-ray microdensitometry was used to obtain density profiles of the rings (Parker and Henoch, 1971; Lenz *et al.*, 1976).

RESULTS

Tree-ring width and cell dimensions

Tree-ring width variations clearly indicated that the growth rate was reduced for several (4-5) years after 1908 (Fig. 2). The greatest decrease of radial growth occurred in 1909.

The most significant changes in anatomy were observed in annual rings formed in 1908. After normal earlywood tracheids with large radial diameter, the small-diameter latewood tracheids were formed with non-thickened cell walls. The number of such tracheids did not exceed five to seven (Figs. 3A and 4A). In the next few years, in spite of the depression of radial growth (narrow tree rings), normal latewood was produced, with thick cell walls (Figs. 3B and 4B) and a normal density profile (Fig. 5).

The anatomical structure of the 1908 tree rings was found to be similar to those so-called "light" rings, which are formed as a result of unusually cool temperatures or insect defoliation (Filion *et al.*, 1986; Jardon *et al.*, 1994; Liang *et al.*, 1997; Wang *et al.*, 2000). Cytologically, the origin of "light" rings is caused by an absence of cell wall thickening due to a sharp decrease of temperature or cessation of the supply of assimilate from leaves or needles (Liang *et al.*, 1997; Wang *et al.*,

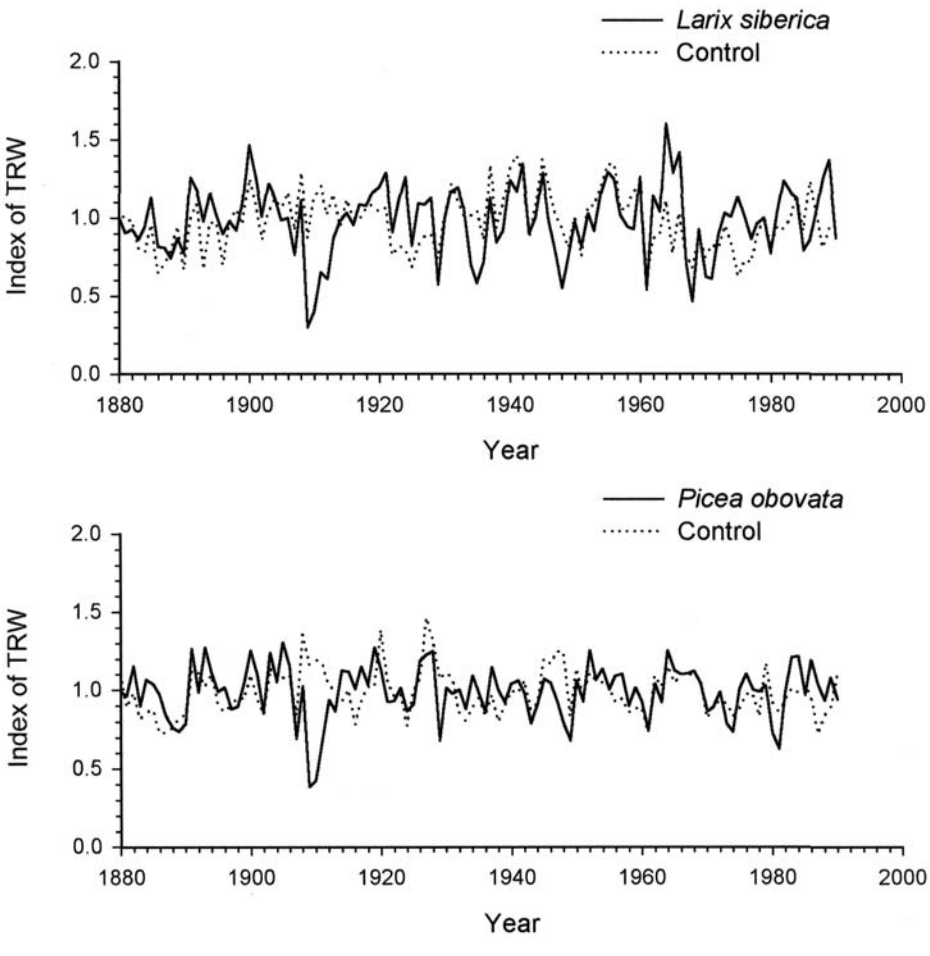

FIG. 2. Mean tree-ring width (TRW) indices for four larch trees (*L. sibirica*, upper panel) and four spruce trees (*P. obovata*, lower panel) from near the epicenter that survived the 1908 Tunguska event compared with the mean series from groups of 15 and 17 trees, respectively, from 260-280 km distant ("Control").

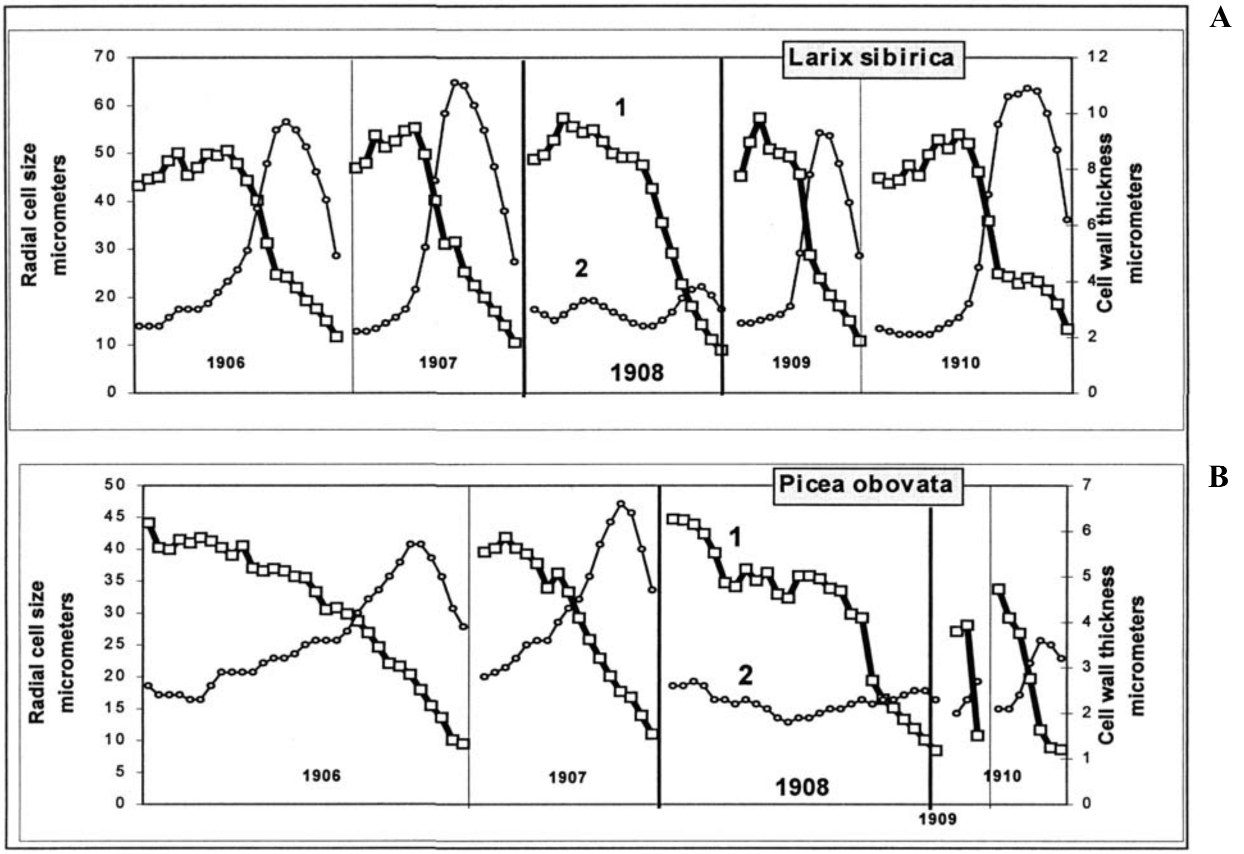

FIG. 3. Tracheid cell dimensions for the rings formed in 1906-1910. A: Radial cell size (line 1) and cell wall thickness (line 2) of each cell in sequence for a larch sample. Note failure of cell walls to thicken in 1908. **B:** As in A but for a spruce sample. Note the drastically reduced number of cells produced in 1909 and 1910, but the normal thickening of the last formed cells in each of these years.

2000). Anatomical measurements of annual rings in stems of larch, spruce, and Siberian pine were consistent with a termination of differentiation of transitional and latewood tracheids associated with the Tunguska event in the middle of the 1908 growth season.

Disrupted tracheids

Heavily deformed tracheids were found in the last portion of the 1908 ring in two wood samples of Siberian pine and larch (Fig. 6). The anatomical structure of xylem returned to normal in the next annual growth ring except for a reduction in tree-ring width. This deformation of tracheids appears to have been the result of a direct mechanical stress of the growing tissue by the ballistic or blast wave associated with the Tunguska event. This mechanical stress mainly affected tracheids in the enlargement and cambial zones, where the cell wall consists only of the middle lamella and the primary wall (Larson, 1994). It did not appear to affect already lignified tracheids. The formation of rings with normal anatomy in 1909 shows that the vascular cambium, which is found outside the xylem, was not damaged.

DISCUSSION

There are four main physical processes that could be the cause of the deformed tracheids: ionizing radiation, a sharp decrease of temperature, defoliation, and shaking of the trees violent enough to disturb the contact of tree roots with soil because of breakage of fine roots (Mousaev, 1996; Vaganov and Shashkin, 2000; Wang *et al.*, 2000). Ionizing radiation may be excluded from consideration because of the absence of the easily identified anatomical anomalies in wood structure that it produces. These include interrupted rows of tracheids, dichotomous rows, and the inclusion of short rows (Mousaev, 1996). Tem-

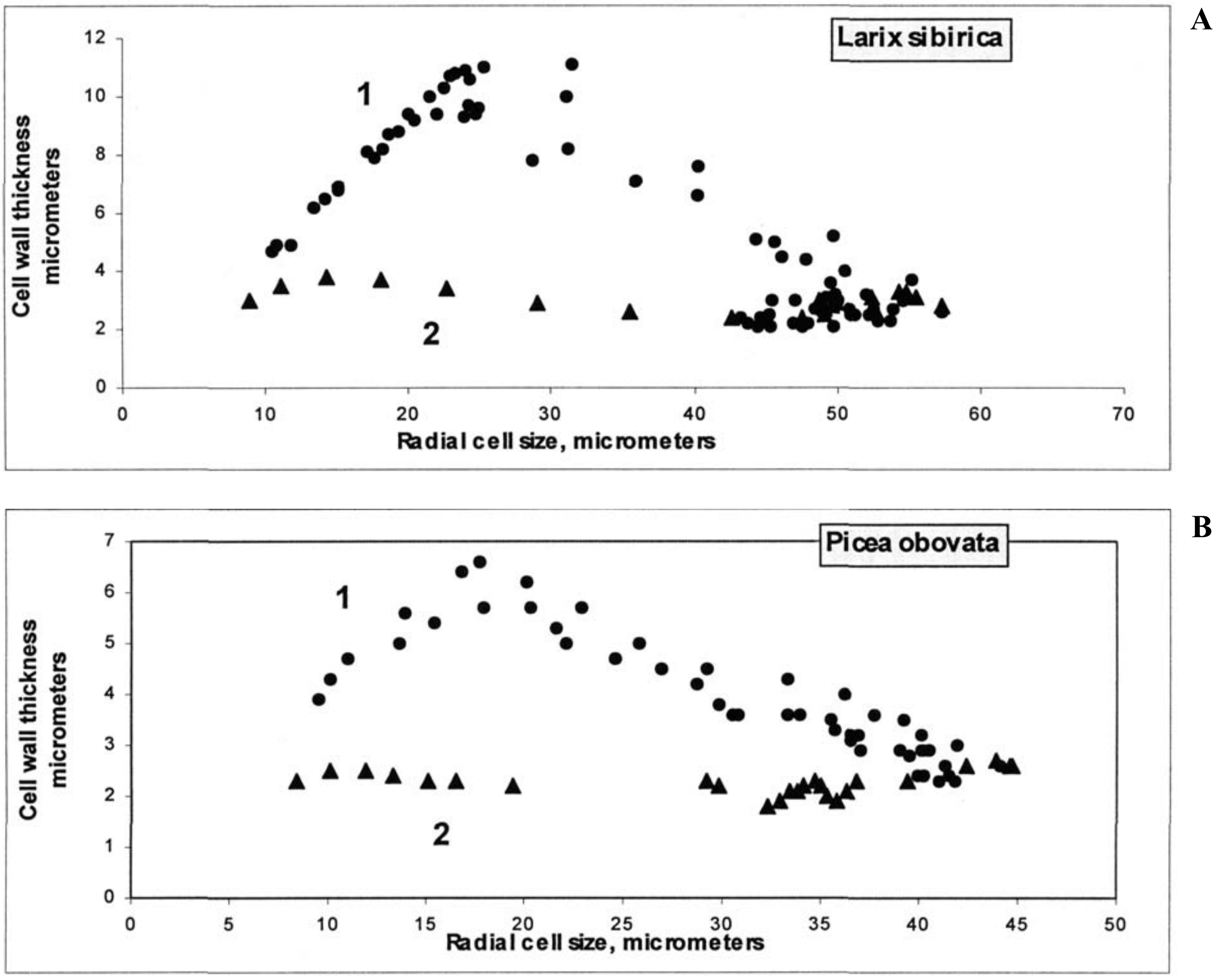

FIG. 4. Relationship between radial cell size and cell wall thickness. The two variables are plotted against one another for the 1908 data (line 2) and for 1906, 1907, 1909, and 1910 (line 1) for larch (**A**) and spruce (**B**) samples.

perature may also be excluded because a summer cold enough to produce such small rings would be at least a regional effect observed over many hundreds of kilometers. However, tree rings from trees only 150 km distant showed no sign of decreased temperature. Shaking, which may have caused the breaking of fine roots, cannot explain the post-event depression of tree growth (narrow rings were formed during the next several years) because the active growth of the root system and, in particular, of fine roots occurs later in the season than the end of June, after the active radial stem growth has reached its maximum (Kozlowski *et al*., 1991).

Partial or full defoliation seems to be the most likely cause of the light rings observed. Loss of foliage during the active period of growth leads to the cessation of the supply of assimilate and growth hormones, and finally to the termination of the processes of tracheid differentiation (Vaganov and Terskov, 1977; Fritts and Swetnam, 1989; Savidge, 1996; Schweingruber, 1996). There is further evidence that the growth reduction resulted from defoliation. After 1908, narrow rings were formed with a latewood with approximately normal microanatomy. This pattern is primarily associated with defoliation (Filion and Cournoyer, 1995). Several different conifers were studied. Larch is a deciduous conifer that loses its needles in autumn, whereas spruce and Siberian pine are evergreen conifers. Larch can be stressed by total defoliation, and yet it can survive because of dormant buds that permit the crown to recover within a few years. This is the reason why, during the next several years, the larch formed narrow tree rings. The spruce and Siberian pine, as evergreen species, cannot survive after total defoliation except on very rare oc-

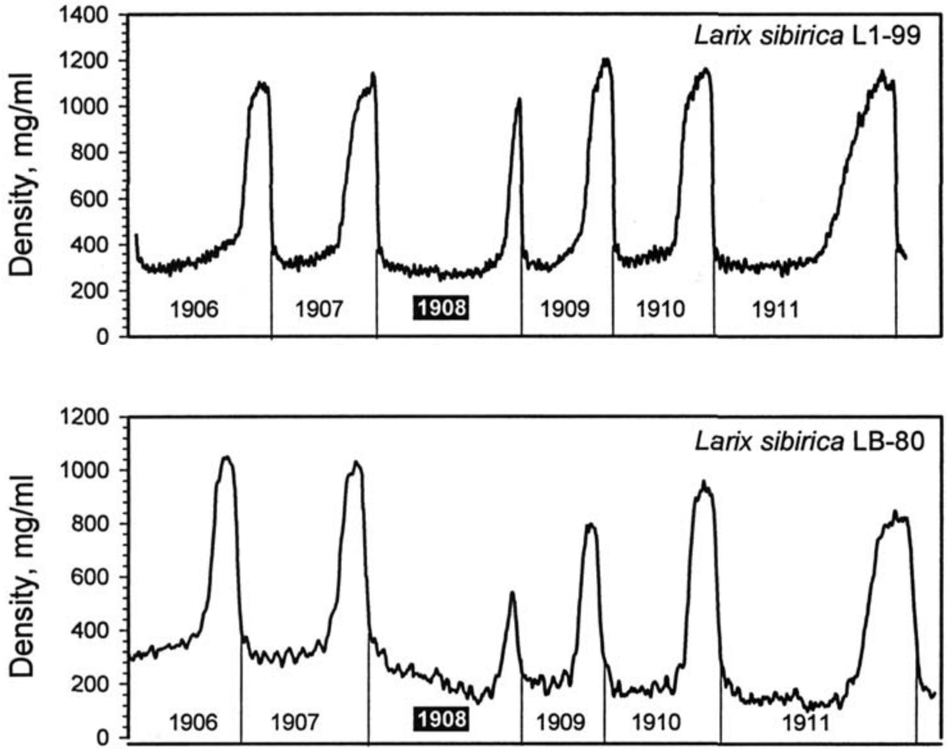

FIG. 5. Density profiles of larch tree rings. See Fig. 1 for location of trees from which they were taken.

casions. These species also cannot survive if all apical meristems (buds) are removed. On the other hand, there can be a full recovery of the normal intensity of height and radial growth after partial or total loss of needles formed in prior years. Further, the return to normal anatomical structure occurred faster than the return to pre-event levels of ring width, indicating that the recovery of the normal coordination of apical growth and tracheid differentiation was faster than the return to pre-event levels of radial growth.

Forces acting on these trees

Causes of defoliation. Defoliation could be accounted for by either a mechanical stress (needles being torn off) or radiation (burns, or heat-caused protein denaturation). Both a blast wave and a radiation wave were present as a result of the Tunguska phenomenon (Zolotov, 1961). It is unlikely that mechanical stress from a blast wave could have torn needles off without throwing the trees down. If we assume that a radiation wave caused needle death near the explosion epicenter, it should have raised needle temperature to the level at which protein denaturation occurs, while buds under the trees' bark should have survived. The radiation flux density needed to denature protein can be estimated, assuming that the radiation flux incident to a needle's side surface is completely consumed and converted into heat energy evenly throughout the needle volume. The energy flux density for cylinder-shaped needles is:

$$J_1 = \frac{\pi D P c \Delta T}{4 \Delta t} \quad (1)$$

where D = the radial size of the needle, 1.5×10^{-3} m; P = the density of the needle, 1,000 kg/m^3; c = the heat capacity of the needle, 3,330 J/(kg · K); ΔT = the difference between the temperature of protein denaturation of the needle (353K-373K) and the temperature of the air before the explosion (287K); and Δt = the time of exposure to heat radiation of incandescent gases of the large explosion (Zolotov, 1961), ~2 s.

The energy flux density obtained from Eq. 1 ranges from 1.3×10^5 to 1.7×10^5 J/(s · m^2), and the total heat impulse during the explosion time is, thus, 2.6×10^5 to 3.4×10^5 J/m^2.

We can also estimate the energy flux density required for complete water evaporation from a needle:

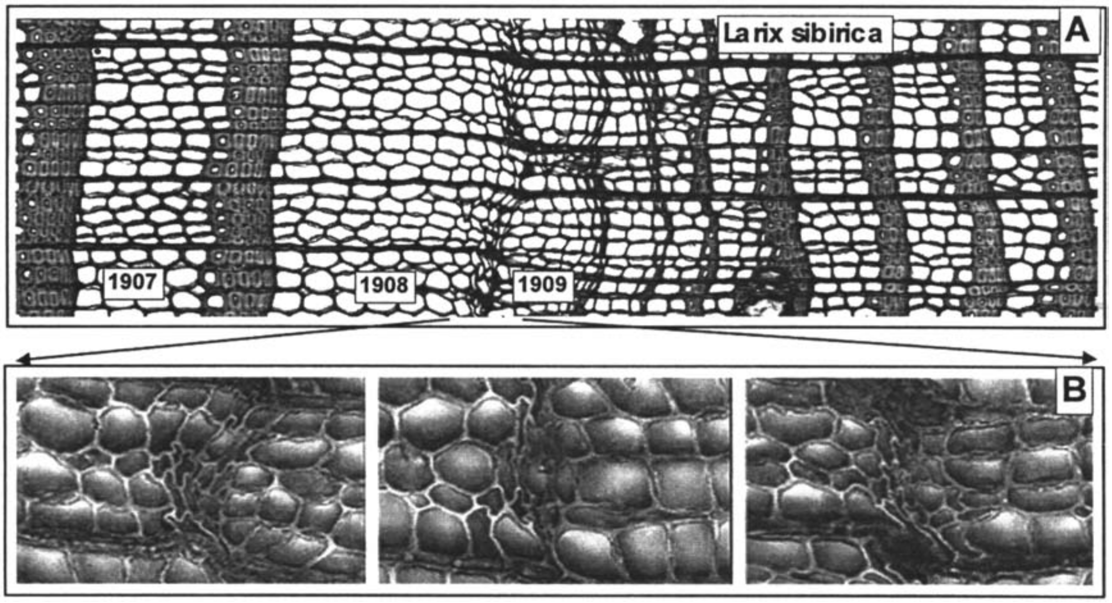

FIG. 6. **A:** Transverse section of a larch sample showing the rings for 1907-1915. **B:** Three views of the disrupted tracheids in the 1908 ring. The normal anatomy in the rings formed in the subsequent years can be seen in A.

$$J = J_1 + \frac{\pi \lambda DP}{4\Delta t} \qquad (2)$$

where J_1 = the energy flux density needed to raise the temperature of the needle contents to the boiling temperature of water, 1.7×10^5 J/(s · m²), and λ is the specific heat of evaporation of water, 2.26×10^6 J/kg.

The energy flux density obtained from Eq. 2 is 1.5×10^6 J/(s · m²), and the total explosion heat impulse is 3×10^6 J/m².

Some researchers have attempted to estimate the explosion heat impulse. For example, the estimates of Zolotov (1961) of the explosion radiation impulse obtained from scars in trees at the edge of the scarred forest zone is 2.5×10^6 J/m². Zlobin (1996, 1997) estimated the Tunguska explosion heat impulse based on scars in tree branches and thermoluminescent annealing of quartz schlich concentrate within the explosion epicenter area. He found that the lower threshold of the heat impulse resulting in light burns of Scots pine branches is 1×10^5-1.3×10^5 J/m². The upper value of the heat flux obtained by Zlobin (1997) from thermoluminescent annealing appears to be 2.9×10^5 J/m². Korobeynikov *et al.* (1990) estimated the heat impulse to range from 6.7×10^5 to 2.2×10^6 J/m². Thus the heat impulse value we established as lethal for needle protein is slightly greater than the highest estimate of the actual exposure. Given the complexities of tree canopy geometry, and the uncertainties of our estimates, it appears quite possible that a large proportion of the forest canopy was destroyed by the explosion heat impulse, resulting in a disruption of the growth of wood and other plant parts.

Disruption of tracheids. Given the observations of disrupted tracheids, we can make some preliminary estimates of the forces acting on these trees at the time of the Tunguska event. Zolotov (1961, 1967) estimated the pressure needed to fell a tree as being from 9.8 to 13.7 kPa, while that needed to break large branches was between 2.9 and 49 kPa. Zotkin and Tsikulin (1966), using physical models in experiments, found that, near the boundary of the area with completely felled trees, the pressure was about 34.3 kPa. Experiments and theoretical calculations of the tensile strength and elasticity of tracheids under tension (Mark, 1976) showed that the normal failure stress, f_β, of cells that have only middle lamellae and primary walls reaches 58.8 MPa in air dry conditions (Table 10-2 on p. 249) and is significantly less (*i.e.*, probably 9.8-19.6 MPa, p. 33) for wet conditions. This last value, probably most relevant to the condition of tracheids on June 30, 1908, is between 20 and 30 times greater than that needed to fell the trees (Zolotov, 1961, 1967; Zotkin and Tsikulin, 1966). It is clearly difficult to explain the disruption of tracheids in surviving, standing trees near the epicenter from the point of view of an isotropic blast wave front. Tracheid deformation, however, was observed for a group of trees located between the southern and northern peaks of Wulfing summit. Uneven pressure distribution can be supposed to have occurred as a result of interaction of the blast wave front with local topographic elements that induced the front crashing and backscattering. In this case, it can be hypothesized that the relief-disturbed blast wave, whose excessive pressure is higher than that of the initial wave, "grips" a tree instead of throwing it down, and this leads to tracheid deformation in a standing tree. The presence of clumps of living trees and single unscreened trees in the vicinity of the explosion epicenter is consistent with an uneven blast wave front spread pattern, consistent with this hypothesis.

Tracheid transformation could have been caused by other factors. For example, live trees were found close to the explosion epicenter that had vertical or twisted stem cracks of varying depths differently oriented relative to the epicenter (Zenkin *et al.*, 1963). These may be scars produced by lightning strikes associated with the Tunguska event. Whatever the factor, however, its impact was strong enough to cause the tree-ring cell deformation we observed. Therefore, a better understanding is needed of the local overpressures at the scale of individual trees on the real landscape before any inferences concerning the scale of the Tunguska event may be drawn from these new results. We propose that a renewed field survey be conducted of the detailed microtopographic relationships between the affected, standing trees located near the epicenter and local relief, as well as a careful examination of such trees for the orientation of "1908-related" damage on each tree with respect to topography. The damage to be recorded would include a reexamination of the stem cracks reported by Zenkin *et al.* (1963), as well as microanatomical features such as those discussed in this report. It would also be valuable to conduct experimental tests of the effects of the various levels of heat and mechanical stress discussed here on precisely analogous growing trees, at exactly the same stage of ring development as found in late June in the Tunguska region. In particular, it would be helpful if an experiment could be conducted in which living wood at the same stage of development (*i.e.*, with outer tracheids expanded but not yet differentiated) could be subject to a range of stresses so as to confirm the applicability of the calculations and experiments of Mark (1976) to the situation at Tunguska.

CONCLUSIONS

The heat impulse associated with the Tunguska explosion could well have initiated tree defoliation, and, consequently, it would have stopped the development of the 1908 annual ring, as seen in the microanatomical studies reported here. The minimum heat impulse needed for this would have been 2.5×10^5 J/m^2. It is unlikely, however, that the heat impulse exceeded 3×10^6 J/m^2, since there are no signs of crown fire. One should be cautious with the latter estimate, because the blast wave that followed the heat impulse could have torn off the ignited dry needles and thereby prevented crown fire.

The event that occurred in the Tunguska taiga in 1908 left signs of several kinds of mechanical impact on trees, as recorded in the annual rings of trees that survived the event, even though they grew close to the epicenter. The mechanical stress needed to cause the deformation of differentiating tracheids seen in trees close to the epicenter is greater than that needed to fell the trees. Taken at face value these results on tracheid deformation would require an upward revision of at least an order of magnitude in the pressure on the trees resulting from the hypothesized bolide arrival and impact. To resolve this contradiction, work is suggested on the possible topographic modification of the overpressure experienced by these trees, as is an experimental test of the effects of such stresses on precisely analogous growing trees.

More tree-ring samples should be collected in the area affected by the Tunguska event. This would permit a more comprehensive and detailed examination of the anatomical characteristics of the trees that managed to survive in the explosion epicenter, and of their precise location relative to local topographic features.

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