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## Isotopic–geochemical study of nitrogen and carbon in peat from the Tunguska Cosmic Body explosion site

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### Abstract

Isotopic–geochemical investigations were carried out on peat samples from the 1908 Tunguska Cosmic Body (TCB) explosion area. We analyzed two peat columns from the Northern peat bog, sampled in 1998, and from the Raketka peat bog, sampled during the 1999 Italian expedition, both located near the epicenter of the TCB explosion area. At the depth of the “catastrophic” layer, formed in 1908, and deeper, one can observe shifts in the isotopic composition of nitrogen (up to  $\Delta^{15}\text{N} = +7.2\%$ ) and carbon (up to  $\Delta^{13}\text{C} = +2\%$ ) and also an increase in the nitrogen concentration compared to those in the normal, upper layers, unaffected by the Tunguska event. One possible explanation for these effects could be the presence of nitrogen and carbon from TCB material and from acid rains, following the TCB explosion, in the “catastrophic” and “precatastrophic” layers of peat. We found that the highest quantity of isotopically heavy nitrogen fell near the explosion epicenter and along the TCB trajectory. It is calculated that 200,000 tons of nitrogen fell over the area of devastated forest, i.e., only about 30% of the value calculated by Rasmussen et al. (1984). This discrepancy is probably caused by part of the nitrogen having dispersed in the Earth's atmosphere. The isotopic effects observed in the peat agree with the results of previous investigations (Kolesnikov et al., 1998a, 1998b, 1999; Rasmussen et al., 1999) and also with the increased content of iridium and other platinoids found in the corresponding peat layers of other columns (Hou et al., 1998, 2000). These data favor the hypothesis of a cosmochemical origin of the isotopic effects. © 2003 Elsevier Science (USA). All rights reserved.

**Keywords:** Tunguska; Cosmochemistry; Meteorites; Asteroids; Comets

### Introduction

The Tunguska Cosmic Body (TCB) explosion occurred in 1908 over the Siberian taiga (Russia) with the discharge of a huge energy, from 10 to 40 Mt of TNT (Vasilyev, 1998). It was one of the greatest natural events of the 20th century. The nature of this event is still under discussion as the “Tunguska96” Conference held in Bologna, Italy, in July 1996 (Di Martino et al., 1998) has proved. Investiga-

tions on chemical and isotopic compositions of different kinds of samples collected in the Tunguska region are required to establish the nature of the TCB.

As we know, despite longstanding and intensive searches, until now no macrofragments of the TCB have ever been found. Scientists from Bologna University (Bologna, Italy), the UFZ Centre for Environmental Research (Leipzig-Halle, Germany), and Moscow State University (Moscow, Russia) have applied modern methods of elemental and isotopic analyses (Longo et al., 1994; Serra et al., 1994; Kolesnikov et al., 1998a, 1998b, 1999) to search for traces of dispersed TCB material in the Tunguska explosion

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area. The first results of the isotopic and geochemical studies of nitrogen and carbon in the Tunguska explosion area were published in Kolesnikov et al. (1996, 1998a, 1999). The results of the present investigation are shown below.

A number of publications favor the TCB being the core of a small comet (see, for example, review of Bronshten, 2000), which represents, as is known, a frozen dirty ice conglomerate composed mostly of volatile compounds of H, C, N, and O. However, the same elements are abundant in soils and plants; therefore, it is very difficult to detect the effects of comet material precipitation on the Earth. In order to distinguish comet material from terrestrial material we have proposed to search for traces of the TCB material by carrying out in peat layer-by-layer analyses of the isotopic composition of some light elements (H, C, N, and so on, Kolesnikov 1982, 1988, 1989), which, as is known, can be different in cosmic and terrestrial material. Four peat columns sampled at the explosion epicenter have shown pronounced isotopic shifts for hydrogen and carbon in the “nearcatastrophic” layers as compared to the normal layers (Kolesnikov 1982; Kolesnikov et al., 1996, 1999). The shifts, opposite in direction,  $\Delta^{13}\text{C}$  for carbon reaching +4.3‰ and  $\Delta\text{D}$  for hydrogen reaching –22‰, cannot be attributed to any known terrestrial processes (fallout of terrestrial dust and fire soot; emission from the Earth of oil–gas streams, climate changes, humification of peat and so on). Moreover, the effects are clearly associated with the area and with the time of the 1908 event. They are absent in the control, background, peat columns sampled far away from the explosion area. Since the calculated  $\delta^{13}\text{C}_{\text{PDB}}$  value for an admixture of carbon ranging from +51‰ to +64‰ (Kolesnikov et al., 1996, 1999) and +55‰ (Rasmussen et al., 1999), is very high relative to that of terrestrial objects these effects cannot be explained by contamination of peat with terrestrial material. In addition, the isotopic effects are in agreement with the increase of the Ir content observed in peat (Kolesnikov et al., 1999; Rasmussen et al., 1999), which presents it as evidence of their cosmochemical nature. So we concluded (Kolesnikov and Shestakov, 1979; Kolesnikov et al., 1998a, b; 1999; Rasmussen et al., 1999) that the reason for the shifts in the isotopic composition of some elements in peat was fallout of TCB material. In the present work, we continued to study these effects by measuring the concentration and isotopic composition of nitrogen and carbon in two new peat columns newly sampled in different sites of the explosion area.

## Samples and methods

Two new *Sphagnum fuscum* peat columns were studied: one, collected in 1998, and a second, collected in 1999 during the “Tunguska99” Italian expedition (Longo et al., 1999; Amaroli et al., 2000). The peat samples cut in permafrost (see Fig. 1) in the explosion area were collected to be examined for dispersed TCB material.

This type of peat is suitable for detecting dispersed cosmic material due to its nutrition by atmospheric aerosols alone. This makes *Sphagnum fuscum* a natural collector of cosmic and terrestrial dust (Vasilyev et al., 1973; L’vov, 1984). The two peat columns were extracted by two coauthors of this paper (E.M.K. and N.V.K., Moscow State University) who have taken part in many scientific expeditions to the Tunguska explosion area. During these expeditions they have become experienced in finding the most appropriate sites for extracting peat samples suitable for isotopic and geochemical analyses. One peat column, KEM N20, was extracted in 1998 in the Northern peat bog, which is situated about 2 km north of the point located on the Earth’s surface under the explosion point (as usual, we refer to this point as the explosion “epicenter”). The other column, KEM N21, was extracted with the help of other participants in the “Tunguska99” expedition at the Raketka peat bog (Fig. 1) about 500 m southsoutheast of Lake Cheko and about 8 km northnorthwest of the epicenter (maps of the central part of the explosion area can be seen in Serra et al., 1994, and in Kolesnikov et al., 1999).

The peat columns were cut into layers 3–5 cm thick, packed into clean plastic bags, and then carefully cleared of roots of other plants, sticks, and leaves in the laboratory. This clearing procedure requires time and skill but is necessary because other plants have a chemical and isotopic composition different from that of peat itself that prevents accurate chemical and isotopic measurements. The clearing procedure was also carried out by E.M.K. and N.V.K. using the experience of previous investigations on peat from the Tunguska explosion area (Kolesnikov, 1982, 1988, 1989; Kolesnikov et al., 1996, 1998a, b, 1999). To study peat from various depths, they prepared 22 cleared peat samples from the KEM N20 column and 21 cleared samples from the KEM N21 column.

In order to determine the depth of the “catastrophic” peat layer, the annual growth-up of peat at the different depth along the whole peat column has been counted (Mul’diyarov and Lapshina, 1983; Lapshina and Blyakhar-chuk, 1986). Every peat column sampled should be dated individually, since annual growth of peat is different in various peat bogs and even within the same peat bog.

Before measurements were taken, the samples were prepared for both N and C analyses at the mass spectrometer. First the peat samples were dried for 5 h at a temperature of  $105 \pm 1^\circ\text{C}$  and then they were weighed on a Mettler AT-20 scale with an accuracy of 0.002 mg. The 3–5 mg peat samples were subsequently packed into tin capsules and analyzed by CF-IRMS (continuous flow isotopic ratio mass spectrometry). The technique implies the combustion of the sample at  $1700^\circ\text{C}$  under an oxygen pulse in an elemental analyzer (CHNS-O mod. EA1110), with passage of the gases through an oxidation and reduction column to a TCD (thermal conductivity detector). Then the gases ( $\text{N}_2$  and  $\text{CO}_2$ ) from the elemental analyzer enter the mass spectrom-



Fig. 1. Extraction by Dr. E.M. Kolesnikov of the KEM N21 peat column from the Raketka peat bog (July 21, 1999).

eter (Delta Plus Finnigan Mat) through a capillary interface, where they are analyzed for the isotopic ratio.

The sample combustion and its isotopic analysis were carried out on the mass spectrometer of the Bologna University. Control measurements were made in the UFZ Centre for Environmental Research in Leipzig-Halle, Germany. Analysis of content of N and C and their isotopic composition were made in the UFZ with a Delta C element ana-

lyzer from Fa. Finnigan MAT (analyzed gas species were  $N_2$  and  $CO_2$ ; Kolesnikov et al., 1996).

More than 300 measurements of the concentration and isotopic composition of nitrogen and carbon in the Tun-guska peat columns were made. Each measured result (points in Figs. 2–4) is the average of three to five parallel analyses of peat samples taken at the same depth. Results (Figs. 2–4 and in Table 1) are expressed as permil devia-

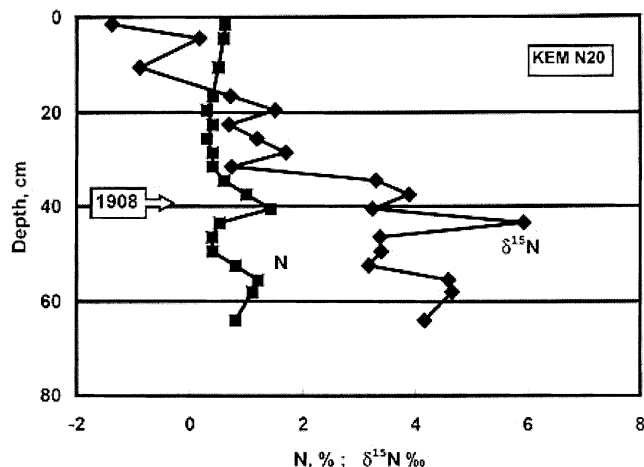


Fig. 2. Content and isotopic composition of nitrogen in the KEM N20 peat column from the Northern peat bog.

tions from atmospheric nitrogen for nitrogen (1) and from the PDB carbonate standard (*Belemnitella Americana*, Peedee Formation, Cretaceous, South Carolina) for carbon (2):

$$\delta^{15}\text{N} = \left[ \frac{(^{15}\text{N}/^{14}\text{N})_{\text{sample}}}{(^{15}\text{N}/^{14}\text{N})_{\text{atm}}} - 1 \right] \cdot 10^3 \quad (1)$$

$$\delta^{13}\text{C} = \left[ \frac{(^{13}\text{C}/^{12}\text{C})_{\text{sample}}}{(^{13}\text{C}/^{12}\text{C})_{\text{PDB}}} - 1 \right] \cdot 10^3 \quad (2)$$

Standard deviations of the given mean  $\delta$ -values were smaller than  $\pm 0.3\text{‰}$  for nitrogen and smaller than  $\pm 0.2\text{‰}$  for carbon, i.e., smaller than the size of the points on the figures.

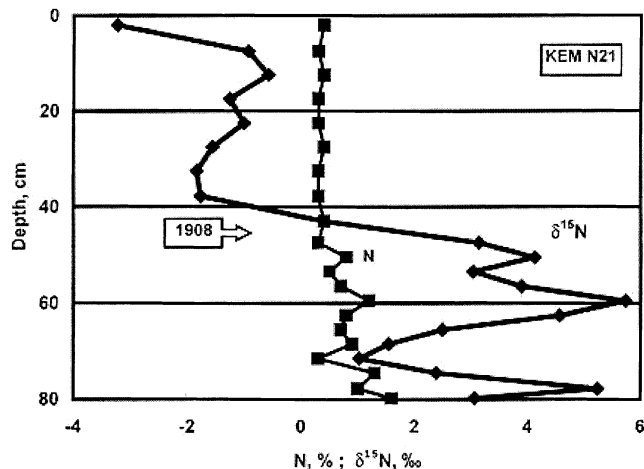


Fig. 3. Content and isotopic composition of nitrogen in the KEM N21 peat column from the Raketka peat bog.

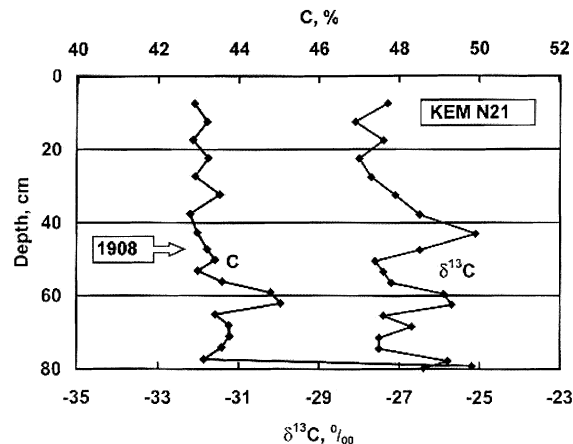


Fig. 4. Content and isotopic composition of carbon in the KEM N21 peat column from the Raketka peat bog.

## Results and discussion

### Nitrogen

The results for nitrogen show inhomogeneity of nitrogen concentration in the different sites of the explosion area. This inhomogeneity can be clearly seen in the nitrogen data relative to four peat columns located at various distances from the epicenter. The nitrogen concentration is higher (up to 1.43 %) in the “catastrophic” layer of the peat column taken at the Northern peat bog (KEM N20), which is situated 2 km from the epicenter (see Table 1). The lowest anomaly in the nitrogen concentration (up to 0.58%) is in the “precatastrophic” layer of the peat column KEM N1F collected by the same scientists in 1980 at the Tsvetkovskiy peat bog near the settlement Vanavara, 65 km south of the explosion epicentre (Kolesnikov et al., 1998a).

In the normal, upper peat layers, unaffected by the Tunguska event, the mean nitrogen concentration in the four peat columns analyzed varies from 0.34 to 0.44% (see Table 1). In the KEM N20 peat column, which was extracted from a point closer to the epicenter, deeper in the “nearcatastrophic” layers the nitrogen concentration increases, reaching its maximum value, up to 1.43%, in the “catastrophic” layer, at a depth of 40.5 cm. In this column (Fig. 2), the nitrogen concentration decreases with the depth in the layers deeper than the “catastrophic” one to the typical value of the normal, upper layers, then increases to 1.2%, and then decreases once more. One possible explanation for this second peak, at a depth of 55 cm, may be that suggested by Kolesnikov et al. (1998a): it may be due to an accumulation of acid rain traces, fallen down after the passage and explosion of the TCB, at the permafrost boundary of the summer 1908 where they have naturally been arrested.

The nitrogen isotopic composition follows the changes in the nitrogen concentration: the nitrogen is heavier in the “precatastrophic” layers, ( $\delta^{15}\text{N} = +5.9\text{‰}$ ), compared to  $+0.46\text{‰}$  in the eight upper layers of the same column (see

Table 1  
Concentration and isotopic composition of nitrogen in different peat bogs

N	Peat bog (distance from the epicenter) N of column	Mean value for the eight normal upper layers		Maximum value in the 1908 layers		Isotopic shift relative to the upper layers: $\Delta^{15}\text{N},\text{‰}$	References
		N,%	$\delta^{15}\text{N},\text{‰}$	N,%	$\delta^{15}\text{N},\text{‰}$		
1.	Northern (2 km), KEM N20	0.44	+0.46	1.43	+5.9	+5.4	Present work
2.	Raketka (8 km), KEM N21	0.34	−1.5	1.20	+5.7	+7.2	Present work
3.	Near Khushma (6 km), KEM N19	0.44	−2.4	1.41	+1.5	+3.9	Kolesnikov et al., 1998a
4.	Vanavara (65 km), KEM N1F	0.42	−1.7	0.58	+1.0	+2.7	Kolesnikov et al., 1998a

Table 1). This effect could be caused by contamination of peat by heavy nitrogen coming from the catastrophic layer. Indeed, in the eight upper layers of the KEM N20 column, the mean value for  $\delta^{15}\text{N}$  is +0.46‰, while in those of the KEM N21 peat column it is −1.5‰. In the two peat columns analyzed previously, extracted near the river Khushma, KEM N19, and extracted at the peat bog near the settlement Vanavara, KEM N1F (Kolesnikov et al., 1998a), the mean values for  $\delta^{15}\text{N}$  in the eight upper layers were −2.4‰ and −1.7‰, respectively (Table 1). In other words, in the KEM N20 column the isotopic composition of the nitrogen even in the upper layers, unaffected by the Tunguska event, is heavier than that in the normal upper layers of the other peat columns. Nitrogen is one of the main biogenic elements and therefore the heavy nitrogen that fell out during the Tunguska event may have been partially absorbed by the upper growing peat layers. This absorption of isotopically heavier nitrogen in the KEM N20 column appears as striking among the other peat columns studied. It could be due to its growth conditions in the lower part of the local terrain and probably to the higher concentration of the heavy nitrogen fallen down in this site.

In the “catastrophic” layers of the KEM N21 peat column extracted about 8 km from the epicenter, the values of the nitrogen anomalies are slightly smaller than those of the KEM N20 column: its maximum content is 1.2% and the maximum  $\delta^{15}\text{N}$  is +5.7‰.

In the KEM N20 and KEM N21 columns, the layer-by-layer variations in nitrogen content and isotopic composition agree with one another (see Figs. 2 and 3). It is unlikely that they have been induced by peat humification, which should be greater in the lower, precatastrophic peat layers. One possible explanation of the nitrogen effects observed may be that they are due to the input, during the TCB explosion, of nitrogen which is isotopically heavier than that of the peat itself.

As was already mentioned, the lowest nitrogen effects were observed in the KEM N1F peat column sampled near the settlement Vanavara, 65 km south of the epicenter (Table 1): its concentration increased only from 0.42% in the normal upper layers to 0.58% in the “nearcatastrophic”

layers and  $\delta^{15}\text{N}$  varied in the same layers from −1.7‰ to +1‰. Moreover, both maximum effects occurred at the level of the permafrost boundary in the summer 1908 (Kolesnikov et al., 1998a). The same effects have been observed at the 1908 permafrost boundary in the KEM N19 column. In both these columns the effects for nitrogen were caused by fallout of acid rains.

Earlier, an increase in the nitrogen content and a positive shift in  $\delta^{15}\text{N}$  have already been found in sediments at the K/T boundary, where they represent traces of acid rains (Gilmour and Boyd, 1988; Robert et al., 1990). They were caused 65 My ago by the impact of a giant asteroid or a comet that resulted in the global extinction of many living organisms, including dinosaurs. As was shown by Gilmour and Boyd (1988), in the stratigraphic layer of the K/T deposits from Woodside Creek, New Zealand, the nitrogen content was 20 times as great as that in the surrounding layers of these geological sequences. This enrichment in the nitrogen content corresponds well with high positive nitrogen isotopic shifts. The authors concluded that nitrogen fallen down as acid rains had  $\delta^{15}\text{N}$  about +10‰ as compared to atmospheric nitrogen. The traces of acid rains were found in several K/T boundary profiles (Gilmour and Boyd, 1988; Robert et al., 1990; Gardner et al., 1992). The enrichment in the nitrogen content and the high positive nitrogen isotopic shifts (from +3 to +18‰) correspond well with the sharp increase of the iridium concentration which, as is known, is a good indicator of input of cosmic material: chondrites, for example, have iridium 25,000 times as many as rocks of the Earth’s crust (Alvarez et al., 1980). Our results on the KEM N20 and the KEM N21 show also the increase in the nitrogen content and the positive shift in  $\delta^{15}\text{N}$ .

Earlier in the KEM N1F and the KEM N19, Kolesnikov et al. (1998a) found traces of soluble nitrogen compounds, as an increase in the nitrogen content, not in the “catastrophic” layer but deeper, at the permafrost boundary of summer 1908, and suggested that this effect was as caused by the fallout of strong acid rains. In the present study we, for the first time, revealed, in addition to the above-mentioned, an increase in the nitrogen content exactly at the

depth of the “catastrophic” layer, which may be due to the presence of insoluble nitrogen compounds accumulated in it in addition to the soluble ones. The part of the insoluble compounds of the nitrogen seems to come from the TCB material. The present results point out that TCB material might have contained large quantities not only of carbon and hydrogen (Kolesnikov et al., 1999; Rasmussen et al., 1999), but also of nitrogen.

The data in Table 1 show that the quantity of heavy nitrogen in the “catastrophic” layers depends not only on the distance of the peat bog from the explosion epicenter but also on the peat bog location relative to the TCB trajectory. In fact, the highest values of  $\delta^{15}\text{N}$  are found in the “catastrophic” layers of the KEM N20, and of the KEM N21 (+5.9‰ and +5.7‰), which are closer to the possible TCB trajectory. This fact indicates that in the peat the main source of the heavy nitrogen fallen down is acid rains, which originated in the shock-heated atmosphere, after passage and explosion of the TCB, as a result of reaction between oxygen and nitrogen of the atmosphere (Prinn and Fegley, 1987).

How much NO fell on the Tunguska epicenter area as soluble compounds as a result of acid rains? In the three peat columns studied in the explosion area, KEM N19, KEM N20, and KEM N21, an increase in the nitrogen content is found in the lowest peat layers, i.e., in the lowest 30 cm of the columns (see Figs. 2 and 3 and Fig. 2 in Kolesnikov et al., 1998a).

In comparison with the normal upper peat layers, the mean nitrogen enrichment in the 30-cm lowest layers is about 0.3%. If we consider that the mean density of dried peat is  $0.12\text{ g/cm}^3$ , approximately 100 g of nitrogen would have fallen over an area of  $1\text{ m}^2$  of ground in the epicenter area and thus about 100 tons of nitrogen over an area of  $1\text{ km}^2$ . Therefore a total of about 200,000 tons of nitrogen fell over the devastated forest area (about  $2000\text{ km}^2$ , Fast et al., 1967). This is about 1/3 of the quantity of 600,000 tons estimated by Rasmussen et al. (1984) for the TCB explosion. This discrepancy is probably because part of the nitrogen may have been injected into the upper atmosphere and distributed over a large area of the Earth. However, the quantity of NO produced during the Tunguska event, estimated by Rasmussen and his colleagues, is a factor of 50 lower than that calculated by Turco et al. (1982).

### Carbon

Figure 4 shows the results of carbon analyses in the KEM N21 peat column. In the “catastrophic” layer of this column, at a depth of 43–45 cm, as in previous carbon investigations (Kolesnikov et al., 1999; Rasmussen et al., 1999), one can see the shift, of about +2‰, in the carbon isotopic composition. The effect observed could not be explained by probable contamination of peat with organic and mineral dust during the explosion. For example, carbon of the most terrestrial plants has  $\delta^{13}\text{C}_{\text{PDB}}$  ranging from –23 to –32‰

(Galimov, 1968; Faure, 1986), which is close with that of peat carbon. The explosion area mineral component of the soil has a composition similar to that of nearby volcanic rocks, i.e., trapps. Carbon in these rocks is similar in isotopic composition to peat carbon (Galimov, 1968). Therefore, neither terrestrial organic nor mineral dust could be responsible for the isotopic shifts observed.

Kolesnikov et al. (1999) have shown that, compared to typical peat *Sphagnum fuscum*, the carbon concentration in bush and birch roots is increased by 15% but  $\delta^{13}\text{C}$  decreases by –1‰. The same results were obtained for the sample with obvious fire signs. It has increased carbon content and slightly varied  $\delta^{13}\text{C}_{\text{PDB}}$  as compared with typical peat at the same depth. Thus, fallout of burnt material on peat does not weight the isotopic composition of peat carbon dramatically. In order to test the influence of gaseous hydrocarbon streams released from the Earth, we have analyzed oil sampled at the same region, at the river Dyulyushma oilfield, gaseous hydrocarbon streams from which may have affected peat bogs. Oil carbon, however, proved to be strongly depleted in  $^{13}\text{C}$  ( $\delta^{13}\text{C}_{\text{PDB}} = -33.7\%$ ). Finally, the varying degree of humification of the peat substance, which is mainly associated with the degradation of cellulose, ought to indicate the depletion of  $^{13}\text{C}$  as well (Galimov, 1993). We, therefore, conclude that (i) peat insufficiently clearing from other plants, (ii) contamination by oil hydrocarbons, and (iii) an increasing degree of humification do not lead to more positive  $^{13}\text{C}$  values observed in peat, but always to more negative ones and (iv) fallout of terrestrial dust on the peat could not explain the isotopic effects, either. Thus, we suggest that in the TCB explosion area the peat substance could be contaminated by extraterrestrial material.

In the “catastrophic” peat layer of the KEM N21, similarly to the results obtained for the KEM N19 (Kolesnikov et al., 1996, 1999), the positive carbon isotopic shift, +2‰, is not accompanied by an increase in the carbon content. Moreover, in the “nearcatastrophic” layers, a slight decrease in the carbon content can be observed. This effect could be due to the input of TCB material containing less carbon than the peat. Therefore, this peak of  $\delta^{13}\text{C}$  cannot be connected to a fire because burning of peat leads to an increase in the carbon content (Kolesnikov et al., 1999). In the “catastrophic” layer we could not find any visible signs of a fire in 1908, namely darkened peat, soot, or charcoals. As is known, this fire was rather short-term and not extensive. However, deeper in the KEM N21 column, at a depth of 60–63 cm, there is another heavy carbon peak, which is in good agreement with the increased carbon content at the same depth (Fig. 4).

At the same depths of the KEM N21 column the nitrogen effect is also observed (Fig. 3). This depth, 60–63 cm, corresponds to the level to which permafrost thawed in the summer 1908. At this depth there is also darkening of peat, due probably to traces of soot from a fire which happened at the end of the 19th century. Burnt dark material has carbon about 8% higher than peat itself (see Fig. 5 in Kolesnikov et

al., 1999) that is marked by a peak in the carbon concentration. When organic material burns up completely to produce charcoal,  $\delta^{13}\text{C}$  increases due to the predominant removal of the  $^{12}\text{C}$  isotope, as a component of  $\text{CO}_2$ , into the atmosphere (Faure, 1986). In addition,  $\delta^{15}\text{N}$  in ash, produced as a result of the burning, increases as well after the complete loss of the volatile compounds of nitrogen during this process (Drechsler and Stiehl, 1977).

If the upper peaks of C and N in the “catastrophic” layer were caused by the presence of the insoluble part of the TCB material in the peat, i.e., the dust fraction, then the lower peaks may have been due, in addition to traces of an old fire, to the easily soluble fraction of the TCB material, and to the traces of acid rains for N, which seeped down from the “catastrophic” layer as far as the level of the permafrost boundary of the summer 1908. This level, in its turn, is a natural barrier, or trap, that may have caught the soluble compounds of the nitrogen, carbon and other elements.

The lowest peaks in the KEM N21 peat column are due to a strong ancient fire, which produced a sharp increase in the nitrogen and carbon content. At this depth there were found a lot of small charcoals which represent residues of fired plants to which should be attributed the peaks in the content of carbon and nitrogen and sharp peaks of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$ .

Kolesnikov et al. (1999) and Rasmussen et al. (1999) have revealed that the isotopic effect for carbon, up to  $\delta^{13}\text{C} = +4.3\%$ , observed in the “catastrophic” layer of the KEM N19 can be explained by an admixture of 3.6% of heavy cosmic carbon with  $\delta^{13}\text{C}_{\text{PDB}}$  ranging from  $+40\%$  to  $+60\%$ . The isotopic effect for carbon  $\delta^{13}\text{C} = +2\%$ , observed in the KEM N21, is two times lower, than in the KEM N19. It can be estimated as an admixture of 1.8% of carbon with the  $\delta^{13}\text{C}_{\text{PDB}}$  mentioned above. Such isotopically heavy carbon is absent on the Earth and therefore the isotopic anomalies observed in the peat cannot be attributed to terrestrial reasons. Isotopically heavy carbon is not typical of ordinary chondrites and achondrites, either, but is found in some mineral fractions of carbonaceous chondrites, reaching even  $\delta^{13}\text{C}_{\text{PDB}} = +1164\%$  (Halbout et al., 1985, 1986).

As it is known, the TCB mass was high, most probably two million tons (Bronshen, 2000). If the TCB was an ordinary carbonaceous chondrite then there was a high input of the iridium within the explosion area. However, the low iridium concentration in the peat, mean value 0.1 ppb for five measurements in the “nearcatastrophic” layers (Nazarov et al., 1990; Rocchia et al., 1996; Hou et al. 1998; Rasmussen et al., 1999), relative to 481 ppb in the carbonaceous chondrites (Anders and Grevesse, 1989), would suggest that the isotopic effects observed cannot be accounted for by the destruction, over the explosion area, of a ordinary carbonaceous chondrite. Indeed, during the breakdown of a two-million-ton-carbonaceous chondrite CI over the 2000  $\text{km}^2$  of the devastated forest area (Fast et al.,

1967),  $5 \times 10^{-8} \text{ g/cm}^2$  of iridium has to have fallen. The iridium value 0.1 ppb really measured in the peat, taking into account the density of dried peat as  $0.12 \text{ g/cm}^3$ , gives us only  $2 \times 10^{-11} \text{ g/cm}^2$  of iridium fallen over the devastation area. This is a factor of 2500 less than the value of the iridium calculated for CI chondrite. So the mineral fraction of the TCB, which was responsible for the input of the iridium in the peat, had to constitute only an insignificant portion of the TCB mass. Such a body could be a comet core.

As is known from spacecraft missions to Comet Halley, the mineral part of comet material, or dust, which includes iridium, is close, in its chemical composition, to carbonaceous chondrites CI but contains about 10 times more carbon and nitrogen relative to these (Jessberger et al., 1986; Jessberger and Kissel, 1991). We concluded that the isotopic effects in the peat could be attributed to the conservation in the peat of comet core material with a low mineral dust fraction. Rasmussen et al. (1995) were careful to make this distinction in TCB material, a low content of mineral dust fraction in it, when they tried to find an increase in iridium and other cosmic element concentrations in the 1908 Greenland ice core. They failed and then came to the conclusion that the dust, or chondrite, fraction of the TCB was less than 5% of the exploded mass.

In addition to the very high  $\delta^{13}\text{C}_{\text{PDB}}$  of the carbon admixture in the KEM N19 (Kolesnikov et al., 1999; Rasmussen et al., 1999) and to the increased iridium concentration, 0.05 ppb, in the “catastrophic” layer (Rasmussen et al., 1999), the cosmic nature of the carbon admixture is also corroborated by the decreased radioactivity of  $^{14}\text{C}$  in the “nearcatastrophic” layers, which reveals the presence in the peat of “dead” cosmic carbon (Rasmussen et al., 1999, 2001). Besides, Rasmussen et al. (1999) and Kolesnikov et al. (1999) observed a very high C/Ir ratio in the peat. This means that, if the TCB was a comet, its core would have probably been almost pure ice with admixtures of soot, hydrocarbons, and other organic compounds. Such a core, with a very low content of dust, is very different from the core of Halley’s comet, which has a high dust fraction content of approximately 40% (Gruen and Jessberger, 1990).

Evidence from local eyewitnesses also confirms very low dust content in the TCB. No eyewitnesses reported the observation of an intense smoky trace, which is typical of stone and iron meteorites during their passage in the Earth’s atmosphere (Mason, 1963). One possible explanation of these testimonies could be the absence in the Tunguska fireball of hard volatile compounds, which means dust content in it (L’vov, 1984; Plekhanov, 1997).

Studies on the chemical composition of the acid-soluble fraction of the TCB in the peat (Kolesnikov et al., 1998b) and analyses of iridium and other platinum group elements (Hou et al., 1998, 2000) have also been carried out in previous works in addition to isotopic and other geochemical investigations. From these data we also can conclude

that the insoluble, or dust, fraction of the TCB seems to be close, as to chemical composition, to CI carbonaceous chondrites. However, compared to CI chondrites, the TCB material appears to be very rich in volatile elements (Kolesnikov et al., 1998b) that would point to the cometary nature of the TCB. The present results do not contradict this conclusion. At the same time, the results of recent theoretical calculations give evidence in favor of both the comet (Bronshnten, 2000) and asteroid (Farinella et al., 2001) hypotheses. This distinction has lost its sharpness after the recent discovery of asteroids that behave like comets and comets that behave like asteroids and the double designation of some of these objects (Yeomans, 2000).

In our opinion, if the TCB was an asteroid then, and here we agree to the opinion of the second reviewer of this paper, it might be similar in its composition to Mathilde 253, a C-type asteroid, the density of which, measured directly by the NEAR-Shoemaker space probe, is about  $1.3 \text{ g/cm}^3$ . It is enriched in carbon and seems to be an ex-comet (Basilevsky, 1987). If the TCB was the core of a comet with a very high C/Ir ratio (Rasmussen et al., 1999; Kolesnikov et al., 1999) then it probably would be similar to the core of comet Borelly which, unlike comet Halley, has a tar-like surface recently explored by the NASA Deep Space-1 probe (Soderblom et al., 2002).

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