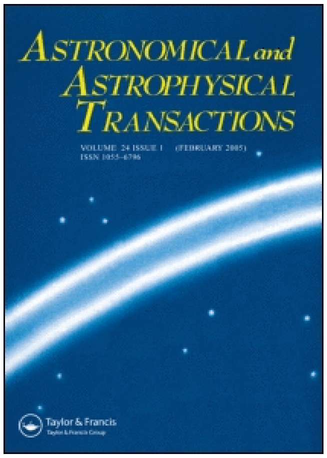

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E. M. Kolesnikov [a]; Q. L. Hou [b]; L. W. Xie [b]; N. V. Kolesnikova [a]
[a] Dept. of Geochemistry, Geological Faculty of Moscow State University, Moscow, Russia
[b] Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing, P. R. China

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Finding of probable Tunguska Cosmic Body material: anomalies in platinum group elements in peat from the explosion area

E. M. KOLESNIKOV*†, Q. L. HOU‡, L. W. XIE‡ and N. V. KOLESNIKOVA†

†Dept. of Geochemistry, Geological Faculty of Moscow State University, 119992 Moscow, Russia
‡Institute of Geology and Geophysics, Chinese Academy of Sciences, P.O. Box 9825, Beijing 100029, P. R. China

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Further evidencies of a cometary nature of the 1908 Tunguska Cosmic Body (TCB) are presented. Earlier in the event layers of the Sphagnum fuscum peat from the explosion area, anomalies, relative to Earth-materials, of the elements H, C, and N – all abundant in comets – have been found [E.W. Kolesnikov, T. Boettger and N.V. Kolesnikova, Planet. Space Sci. **47** 905 (1999); E.M. Kolesnikov, G. Longo, T. Boettger, N.V. Kolesnikova, P. Gioacchini, L. Forlani, R. Giampieri and R. Serra, Icarus **161** 235 (2003).]. At the present work we revealed a sharp increase of concentrations of platinum group elements (PGE), REE and other elements in the event layers as well. Their ratios point to a cometary nature of the anomalies observed.

Keywords: Tunguska; Peat; Isotopes; Platinoids; Comets; Carbonaceous chondrites

1. Introduction

The nature of the bright bolide and of the giant explosion happened on 30 June, 1908, in Podkamennaya Tunguska river basin, Central Siberia, is still under discussion [1]. The area with trees fallen down is more than 2000 square km, while the explosive energy has been estimated [2] to be equal to no less than 30 million tons of TNT (or to 1500 Hiroshima bombs). Nevertheless, Kolesnikov *et al.* [3] has shown that the explosion could not be of nuclear nature. Its energy was, in fact, too big to be simple fissionable ^{235}U nucleus explosion. Another two nuclear hypotheses, of annihilation and thermonuclear, have been tested by measuring ^{39}Ar radioactivity inducted from the K and Ca isotopes in rocks and soil at the explosion epicentre. This method has much more sensitivity when local neutron flow is detected than the method of ^{14}C analysis in tree rings [4]. Kolesnikov *et al.* [3] did not detect ^{39}Ar in the samples from the explosion epicentre although its estimated radioactivity was expected to be 100 times as many as the radiometric plant sensitivity (0.01 dpm).

*Corresponding author. Email: evgenkol@geol.msu.ru.

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At present we know that the main Tunguska Cosmic Body (TCB) explosion occurred at an altitude of about 5 km [2]. During the explosion, the most part of the TCB mass was dispersed, then lifted up into the upper atmosphere, and finally spread over a large area of the Earth's surface. After the explosion, turbidity of the atmosphere was fixed by Mount Wilson Observatory in California. According to the calculations of Fesenkov [5], this effect was due to mass of dispersed cosmic material of about 1 million tons. However, any gram of TCB material has not yet been found. Moreover, the search for the global fall-out of the TCB material in polar ice showed the results to be contradictory [25].

Among other more than 100 assumed hypotheses of the Tunguska event, the hypotheses of a large meteorite [6–9] and of a small comet core [10–26], are under intense discussion. On determination of the TCB nature, the most important problem is the finding and the study of its material.

2. Search for the TCB remnants in the epicentre area

In soil of the Tunguska explosion area during the 1961–1962 expeditions of the USSR Academy of Sci. [27], cosmic magnetic spherules 20–100 μm in diameter have been found [28]. Their cosmic origin has been confirmed by Ganapathy [29] and Nazarov *et al.* [30, 31]. However, it seems to be difficult to prove that these spherules belong to the TCB material because the same ones can be found everywhere.

Jehanno *et al.* [32] analysed Ni, Co, Cr, and Ir in 80 magnetic microspherules from Tunguska soil and concluded that 5 of them are obviously Fe–Ni spherules of the steady micrometeoroid rain, 72 of them are of terrestrial origin, and only 3 spherules, consisting of single iron oxide phase, could be the TCB remnants.

Peat *Sphagnum fuscum*, from which the event layer, containing the peat grown in 1908, can be isolated [33, 34], appears to be the more appropriate object for the search for the TCB remnants as compared to soil. It has the only aerosol nutrition and, thus, could have incorporated any extraterrestrial falls-out of the Tunguska event. At first, in the event layers the silicate spherules 30–150 μm in diameter have been found [35]. In the main group of these spherules 30–90 μm in diameter, the content of 11 elements was measured by NAA method [36]. Their composition was revealed to differ from those of the bigger (>100 μm) silicate Tunguska spherules [37, 38]. The spherules of the main group have an abundance in light and volatile elements (Al, Na, Zn, Cs) and a deficiency in more heavy and hard volatile ones (Fe, Co, Sc). Moreover, they prove to be not produced by melting of soil, but to be probably a product of the differentiation of the TCB material [39].

According to the data of the 'Vega' and 'Giotto' spacecraft missions to Halley's comet, the size of cometary dust particles is very small: their mean diameter is only about 0.5 μm (our calculations made on data of ref. [40]). The main part of the TCB particles found in resin of the branches of the tree survived during the Tunguska event [41] has the similar size (0.5–3 μm) as well. It seems to be very difficult to isolate from peat the ultrasmall cometary dust particles. Moreover, cometary material consists mostly of ice and organic components. Therefore, to determine the presence of the TCB material, the layer-by-layer chemical analyses of the bulk peat samples have been made. It was shown that, in the event peat layers, an abundance in the contents of Fe, Co, Al, Si, and several volatile (Zn, Br, Pb, Au) elements were probably due to the conservation in the peat of the TCB material [42]. Small particles in tree resin formed in 1908 have the similar composition as well [41]. The sharp increase of the volatile element contents in the event peat layers may be caused by the presence in them of the cometary material [24, 39]. In addition, at the same peat column we have shown that Pb in the event layer has the isotopic composition different from that in other peat layers and that of typical Pb in this area [43].

The peat column, in which the sharp increase in the contents of the several elements has been revealed [42], was sampled at the Northern peat bog, about 2 km to the north from the site situated under the main explosion epicentre. The results of the analyses of the other two peat columns from the explosion epicentre were not very successful [42]. Unfortunately, the precise location of sampling of that successful peat column was lost. On repeating sampling at the Northern peat bog, the peat columns did not show appreciable abundance in the elements. In the next peat column, sampled by us at Southern peat bog (Klyukvennyy island), the increase of Ir content has only been revealed [44]. Furthermore, the results of the layer-by-layer analyses of other peat columns made by spectral method [45, 46] were not very successful as well.

A group of investigators from Bologna University (Italy) made an offer for the more successful method of a search for the microremnants of the TCB in resin of the tree branches which stood duty as a trap for airborne particles [41]. It should be noted that Longo *et al.* [41] showed that the set of the most elements revealed in microremnants, *i.e.* Fe, Al, Si, Au, Cu, Zn, Cr, Ba, Ti, and Ni, is almost the same as that of the anomalous elements in the first peat column sampled at the Northern peat bog [42].

3. Platinum group elements (PGE) investigation

As it is known, the presence of dispersed cosmic material in the terrestrial objects is clearly registered with the content of Ir (and other PGE elements) because, for example, content of Ir in chondrites is about 25,000 times as many as in rocks of the Earth's crust. This approach has been used to identify large meteorite impacts [47]. In Antarctic ice at the depth corresponding to the Tunguska event, Ganapathy (1983) has found sharp increase of the Ir content. However, Rocchia *et al.* [48] have not shown any increase in it of the Ir content. To Prof.'s Edward Anders [49] opinion (personal communication), in the Ganapathy's lab there was a contamination of the samples with Ir.

In Greenland ice Rasmussen *et al.* [50] have also shown the absence of the global nitrate falls-out related to the Tunguska event being inconsistent with the data expected of Turko's *et al.* [51] calculations. Later, in Greenland ice Rasmussen *et al.* [52] have analysed 25 elements, including Ir, and shown the presence of the cosmic dust components by the increased concentrations of Ir, Ni, Cr, Au, Zn, Sb, and As as compared to terrigenic dust. However, in the 1905–1914 layers, their concentrations were within the limits of typical variations. Thus, any increased input of the cosmic material as a result of the Tunguska event was not shown. They concluded that the absence of the global falls-out of the TCB material was mysterious and the mass of the TCB solid component was probably too overestimated. These data seem to be actually inconsistent with the stone meteorite hypothesis of the TCB nature, but not to reject the cometary one because solid-dust component of the comet core, carried the Ir content increased, may be a small part of the comet core mass. Rasmussen *et al.* [52] regarded the fraction of chondrite material in the TCB as less than 5%.

Geochemical data prove that the fall-out of the TCB material at the explosion area was inhomogeneous [39, 42, 53, 54]. That is why Rocchia *et al.* [55] didn't find Ir in two peat columns from the explosion area. However, in the other peat columns from the explosion epicentre, Korina *et al.* [44], Hou *et al.* [56], and Rasmussen *et al.* [57] revealed the fall-out of cosmic dust by increase of the Ir content. Therefore, at the explosion epicentre there are sites enriched with TCB material. In fact, there are data on a number of the TCB smaller explosions at the lower altitudes in addition to the main high-altitude giant explosion [6, 7, 54]. They are in agreement with the evidences of eyewitnesses concerning the many TCB explosions.

These smaller explosions seem to be due to the explosions of the cometary ice pieces. Many eyewitnesses of the Tunguska bolide passage observed its crushing during its motion [53, 58]. Therefore, at the epicentre we shall be able to find some sites with a considerable enrichment in the TCB material.

As was mentioned above, in the Southern swamp peat column the Ir anomaly has for the first time been revealed [31, 44]. Maximum Ir content was 17.2 ppt in the event layer that is more than 3σ of a variation range of the mean Ir content, *i.e.* 3.8 ± 0.5 ppt. The content 17.2 ppt of Ir in the peat corresponds 735 ppt of it in peat ash, *i.e.* in the mineral fraction of peat. This content is much higher than the average of 20 ppt Ir for upper crust rocks [59]. Therefore, the Ir anomaly in peat can't be explained by any terrestrial reasons. Thus, this effect records the presence in the peat of the cosmic material.

In addition to the increase of the Ir content in the event layer, there is another peak of it in the lower layers which coincides with the $\delta^{13}C$ peak [25]. In the lowest layer analysed there is the third increase of the Ir concentration which coincides with an increase in the concentration of Fe, Co, Sc, and some other elements [31, 44]. Probably, a fraction of a solid component of the TCB material has dipped up into the level of the third Ir peak. The same effect has earlier been observed [42] in the peat column sampled at the Northern peat bog for Fe, Co, Zn, Sr, Au, and so on. Unfortunately, the depth, to which the Southern swamp peat column has been analysed for the elements, was limited to 62 cm. The isotopic data [25] give evidence that the part of material which carries the isotopic markers has dipped up into the level of the 1908 permafrost boundary which that time was situated at about 74 cm from the surface of the peat bog.

As was shown above, an attempt to find Ir in the other two peat columns at the explosion epicenter [55] has failed. However, Hou *et al.* [56] analysed the peat column from the Northern peat bog, using NAA, and discovered a sharp Ir anomaly (0.24–0.54 ppb) in the event and lower layers. That is about 10–20 times as many as that in Korina *et al.* [44]. In addition, anomalies in contents of Ni, Fe, Co and REE in the event layer inferred that the TCB must have been composed of material similar to CI chondrites or to the cometary core rather than to ordinary chondrites.

Rasmussen *et al.* [57] found the Ir (39.9 ppt) anomaly and ^{14}C depletion in the event layer of the Nearkhushma peat bog column. Unfortunately, very few investigations of the PGE (including Ir) in this local Siberian peat bogs have been published. Beginning Hou *et al.* [60], we have started to analyse a group of PGE in the Northern peat bog column from the Tunguska explosion area. The anomalies of Pd, Ru, Rh etc. were determined in the event layers of another peat column sampled at the same [56] peat bog, which can provide further evidences for the TCB nature. In the latest works [61, 62], besides the peat, nearby basaltic rocks, *i.e.* traps from the Tunguska explosion area have been analysed as well to determine input of the terrigenic dust to the anomalous PGE content in the peat.

4. Distribution of the elements in the peat columns

In the figure 1 we can see distribution of the elements in one of the peat columns from the Northern peat bog published by Xie *et al.* [61]. The concentrations of Pd, Ni, Co, Ti, Y and REE in the event and lower layers are much more than the background values for the upper layers. The Pd concentration in the event layer (317.4 ppb) is ten times as many as its background value. And the concentrations of other elements are four times as many as the background value for Ti, eight times for Ni, ten times for Co, thirty five times for Y and 15 times for REE, respectively.

In order to determine whether the enrichments of PGE and other siderophile elements in the event layers resulted from the accumulation of normal cosmic dust by the sedimentation rate

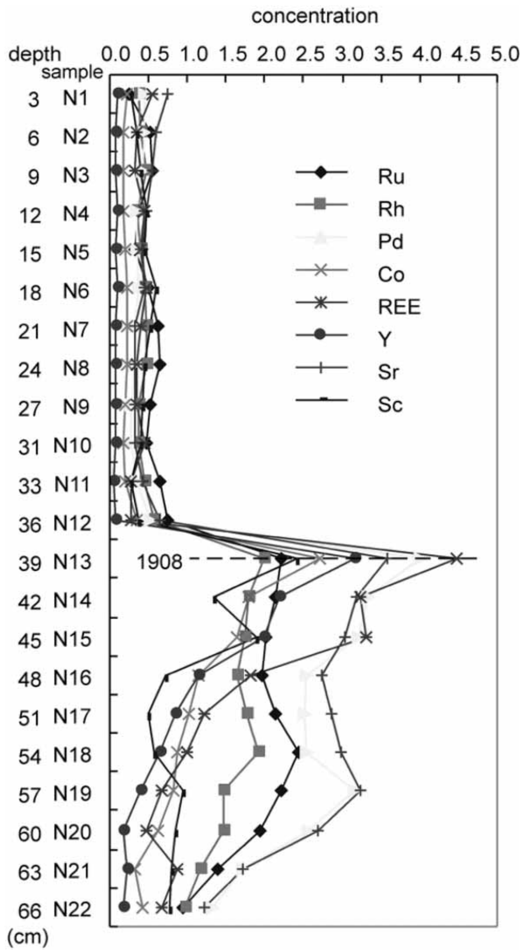

Figure 1. Elemental abundances in the peat column from the epicentre of the Tunguska catastrophe.

decrease, or by the meteoric ablation rate increase, Hou *et al.* [56] compared the distribution of Ir and Ni in the event layers in one peat column with that of ablation of spheres separated from 2 kg of red clay sediment from the mid-Pacific Ocean [29]. It is found that there is no increase in contents of cosmic material (*e.g.* by meteoric ablation and/or by sedimentation rate decrease) except for the TCB material, and hardly a redistribution of the normal cosmic dust occurs at least in the Northern swamp. Furthermore, there is a good correlation between the Rh, Pd, Ru, and Co concentrations in all our works [56, 60, 62] (see figure 2), which points to the same source of the anomalies, *i.e.* the TCB material.

The anomalies of the PGE and other trace elements observed can't be explained by contamination of the peat with terrestrial dust, which occurred during the explosion. Indeed, Golenetskiy *et al.* [42] revealed that in the explosion area the mineral component of the soil had the composition similar to that of traps. They also showed the high concentration of Sc, 41 ppm, in traps. We detected high concentrations of Co, Y and Sr, from 40 to 63 ppm, 33–68 ppm and 204–210 ppm, respectively, in traps [62]. These element concentrations in the traps were much more (>200 times, except for Sr being about 30 times) than those in the normal peat layers. In the event and lower peat layers, however, the concentrations of Co, Y, and Sr were at most 15 times higher than those in the normal layers [60]. Moreover, there are

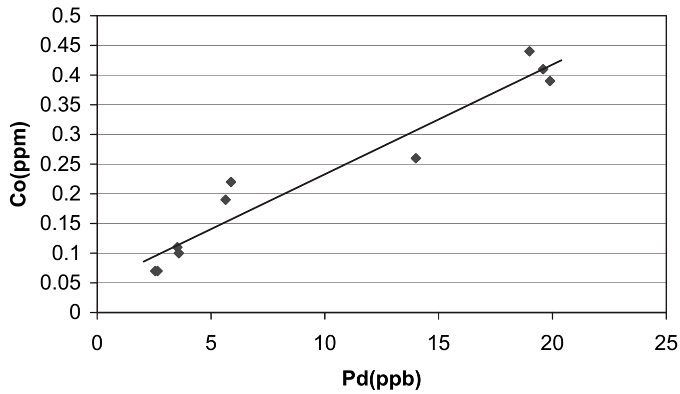

Figure 2. Correlation between Co and Pd in the peat layers of the Tunguska peat column. It indicates that both elements might have the same source, probably the TCB.

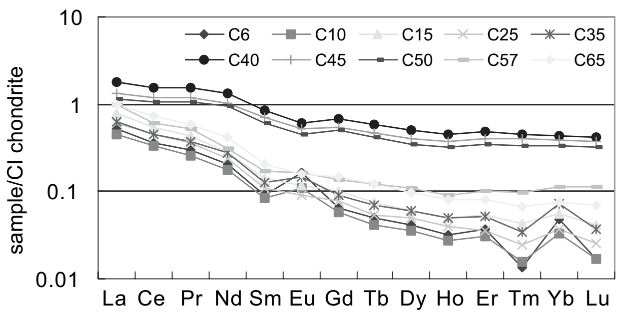

Figure 3. Patterns of CI-chondrite-normalized REE in the peat samples in the 1908 Tunguska explosion area. It shown that the patterns in the event layers (corresponding to C40–C50 samples) are different from that in the normal layers.

obviously PGE anomalies in the event peat layers, but no PGE detected in the any types of the nearby traps in our works [61, 62]. Therefore, the increase of these element concentrations in the event peat layers cannot be attributed to an extra input, during the event, of terrigenic or trap dust but, instead, is most probably caused by the fallout of the TCB material.

We found that the REE concentrations in the event and lower layers are much lower than those in the nearby traps, and clearly higher than those in the normal peat layers (figure 3). The patterns of CI-chondrite-normalized REE in the event layers are different from those of the traps and of the normal peat layers. These pattern characteristics indicate that the peat, especially in the event layers is unlikely to be contaminated by terrestrial dust. Moreover, a greatly increased concentration of Rh, Pd, Ru and Ir, as well $\delta^{13}C_{PDB}$ implies [62] the presence in the Northern swamp peat column of the cosmic material (figure 1).

5. Nature of the Tunguska Cosmic Body

In the recent our work [62], at the depth of the event layer containing peat, grown in 1908, and deeper we have found an increase of the ^{13}C content, heavy carbon isotope, relative to the upper, or normal, peat layers. In the event layer this effect was $+3‰$ as compared to the six upper layers. Earlier, in another four peat columns sampled at the explosion epicentre we have revealed the same isotopic effects for carbon [25, 63]. It should be noted that in another two peat columns, sampled far away from the explosion area, no isotopic anomalies in C and H were found [25]. Rasmussen *et al.* [57] and Kolesnikov *et al.* [25] have shown that to explain such isotopic effect for carbon from +2‰ to +4‰ in the peat it is necessary to put into it about 2–3% exogenic carbon with very heavy isotopic composition with $\delta^{13}C_{PDB}$ from +40‰ to +60‰. Such heavy carbon doesn't occur on the Earth [64, 65] and in ordinary chondrites and achondrites as well [66]. Rasmussen *et al.* [52] have revealed that this carbon is of abiogenic origin (so called "dead" carbon) due to lack in it of radioactive ^{14}C, which presents in all biologic objects on the Earth.

Such isotopically heavy carbon is only typical of some mineral fractions of the CI carbonaceous chondrites [67, 68]. Moreover, it is known from the Halley's comet investigation the composition of a cometary dust is very close to that of carbonaceous chondrites [69–71]. Thus, we suggest that in this area the peat substance was contaminated by extraterrestrial material, and compositionally similar probably to the cometary dust.

In the event peat layers all anomalous elements (PGE and other siderophile elements) have probably the same source, *i.e.* the TCB material. They should then provide some evidences for the TCB nature. In the table 1 the element ratios Ir/Co, Ir/Cr, Ir/Sr, Ir/Ni, and Ni/Cr (ca. 10^{-3}–10^{-4}, 10^{-3}–10^{-4}, 10^{-5}, 10^{-4}, and 2–7, respectively) in the event layers of this column are much closer to those in the CI chondrites (10^{-4}, 10^{-4}, 10^{-2}, 10^{-5}, and 4) and in the meteoritic ice (Ir/Co $\approx 10^{-3}$, Ir/Cr $\approx 10^{-4}$, Ir/Sr $\approx 10^{-3}$) from Southeastern China probably originating from a comet.

Moreover, the Ni/Co and Co/Cr ratios, 2–5 and 1–2, respectively, in the event layers are much closer to their ratios in the meteoritic ice Co/Cr $\approx$ 1 and in the Halley's comet, ~1.2 and 1, respectively, but very different from their ratios in the CI carbonaceous chondrites, ~22 and 0.2, respectively) (table 1). Furthermore, Sr/Co ratio ~30 in the event peat layers are closer to their ratio ~1 in the meteoritic ice than to that $\sim 10^{-2}$ in the CI. The much larger Sr/Co ratio in the event layers compared to that in meteoritic ice may be due to: (1) during the explosion Co was more volatile than Sr and (2) the TCB material contained (composed of) less siderophile elements. Indeed, Kolesnikov *et al.* [24] showed that the TCB material, as compared to the CI carbonaceous chondrites, are much lower in some siderophile elements, *e.g.* Fe, Co, and Ni. As was noted, according to the results of the spacecraft missions to the Halley's comet, the composition of cometary dust is similar to the CI chondrite. Therefore, these element ratios imply that hard volatile portion of the TCB material is similar to the CI chondrites. So, the TCB more possibly was a comet.

Rasmussen *et al.* [57] have measured exceptionally high C/Ir ratio of $12 \pm 3 \times 10^8$ in the dry peat, which is at least a factor 10^4 higher than that in the meteorites. Various physical and,

Table 1. Comparing of the element ratios in the Tunguska event peat layers to those in the meteorite ice, Halley's comet, and CI chondrite.

Ratios	Peat of Tunguska	Meteorite ice	Halley Comet	CI
Ir/Co	10^{-3}–10^{-4}	10^{-3}	–	10^{-4}
Ir/Cr	10^{-3}–10^{-4}	10^{-4}	–	10^{-4}
Ir/Sr	10^{-5}	10^{-3}	–	10^{-2}
Ir/Ni	10^{-4}	–	–	10^{-5}
Ni/Co	2–5	–	1.2	22
Ni/Cr	2–7	–	1.3	4
Co/Cr	1–2	1	1	0.2
Sr/Co*	30	1	–	10^{-2}

*Data from ref. (62); all other data calculated by us, respectively, from ref. (56) in the Tunguska peat samples, Mao *et al.* [72] in meteorite ice, Jessberger *et al.* [71] in Halley's comet, and from Wasson [73] in CI.

conceivably, chemical processes may have influenced the C/PGE ratios of the TCB material from the time of atmospheric entry to the time of surviving in peat, but it is hard to imagine severe loss of PGE rather than C. The loss of C is much more likely than the loss of PGE, but the loss of C will only make the initial C/PGE ratio of the TCB more impressive. So, we are forced to conclude that the high C/PGE ratio is not very well in accordance with any chondritic or achondritic type of the explosive body. These data point towards rather a cometary type of the explosive body. These results are supported by the data on studies of the isotopic composition of C and H in peat [20, 21, 25, 57].

In comets the PGE is mostly localized in dust. Therefore, the high C/PGE ratio points to small content of dust in the Tunguska cometary body. 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% [74].

This is proved to be true by the evidences of eyewitnesses. Among more than 700 of them nobody could see an intense smoky track after the TCB passage which is typical of stony and iron meteorites during their passage in the Earth's atmosphere [82]. This can only be explained by the low content of hard volatile components, *i.e.* mineral dust, in the TCB [53, 75]. This is in good agreement with the negative results of searching for the traces of a global deposition of iridium in 1908 in both Antarctic [48] and Greenland ice fields [52].

Golenetskiy *et al.* [42] and Kolesnikov *et al.* [36] found positive anomalies of several volatile elements (Zn, Br, Pb etc.) in the event peat layers, which were probably due to the conservation in the peat of the TCB material. In addition, we have shown that Pb in the 'catastrophic' layer has the isotopic composition different from that in other peat layers and that of typical Pb in this area [43]. The sharp increase of many volatile elements (Li, Na, Rb, Cs, Cu, Zn, Ga, Br, Ag, Sn, Sb, Pb, and Bi) in the peat below the event layer [24] can be caused by the presence of these elements in cometary material [24, 39].

6. Estimation of the TCB weight

We have got the cosmic Pd and Rh deposition of 46.0 ng cm^{-2} and 2.6 ng cm^{-2} in the peat column from the Northern peat bog [62]. If we assume as a rough estimation that the whole mass of the TCB was spread out over the $\sim$2000 km^2 of the devastated forest area [76] and we can take this column site to be representative for the deposition in this area. If, as discussed above, the chemical composition of the TCB's solid part is similar to the CI carbonaceous chondrite (Pd = 560 ng/g; Rh = 134 ng/g, Wasson, 1985) we can estimate that the chondritic materials (solid component) of the explosive body weigh $\sim 1.6 \times 10^6$ tons by Pd, and 0.4×10^6 tons by Rh. The rough consistency between the two results estimated by anomalies of the Pd and Rh contents, supports the general reliability of our estimation.

It should be noted that at the different sites of the explosion area the anomalies observed in the peat do not have the same magnitude. We interpret this as an implication of the inhomogeneous fallout of the cosmic material over the explosion area. Golenetskiy *et al.* [42], Kolesnikov [39] and Kolesnikov *et al.* [25] inferred from their data the same conclusion. Serra *et al.* [54] found a clear inhomogeneity in the density of fallout of the TCB micro-remnants (from 18 to 132 particles/cm^2) at different sites over the explosion area. This inhomogeneity was probably caused by (1) multiple explosions of the TCB fragments and by (2) an enrichment of the surface with finely dispersed material at those sites where pieces of the cometary ice fell and thawed.

7. Conclusions

Analyses of iridium and other platinum group elements [56, 60–62] have been carried out in addition to the isotopic ones [20–23, 63] and other geochemical investigations. From these data we can conclude as well that the insoluble, or dust, fraction of the TCB seems to be close, as to the chemical composition, to the CI carbonaceous chondrites. However, compared to them, the TCB material appears to be very rich in volatile elements [24, 39] that would point to a cometary nature of the TCB.

At the same time, the results of recent theoretical calculations give evidence in favour of both comet [77] and asteroid [78] hypotheses. This distinction has lost its sharpness after the recent discovery of asteroids that behave themselves like comets, and comets that behave themselves like asteroids and the double designation of some of these objects [79].

To our opinion, if the TCB was an asteroid then it might be similar in its composition to Mathilde 253, C-type asteroid, which density, measured directly by the NEAR-Shoemaker space probe, is about $1.3\ g/cm^3$. It is enriched in carbon and seems to be an ex-comet [80]. If the TCB was a core of a comet with the very high C/Ir ratio [16, 57] then it would probably be similar to the core of comet Borelly which, unlike Halley's comet, has the tar-like surface recently explored by NASA Deep Space-1 probe [81].

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