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Platinum group element abundances in a peat layer associated with the Tunguska event, further evidence for a cosmic origin

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Abstract

We have measured excesses of Pd, Rh, Ru, REE, Co, Sr, and Y in a peat column from the Northern peat bog of the 1908 Tunguska explosion site. Earlier, in this peat column the presence of an Ir anomaly at the event layers (30–45 cm depth) has been found (Planet Space Sci. 48 (1998) 179). In these layers, Pd, Rh, Ru, Co, Sr, and Y show pronounced anomalies of a factor 4–7 higher than the background value. In the event layers there are also good correlations between the siderophile platinum group elements (Pd, Rh, Ru) and Co, indicators of cosmic material, which imply they might have the same source, i.e. the Tunguska explosive body. The patterns of CI-chondrite-normalized REE in the event layers are much flatter than those in normal peat layers and different from those in the nearby traps. Furthermore, in these layers the patterns of CI-chondrite-normalized PGEs and the element ratios (e.g. C/Pd, C/Rh, and between some siderophile elements) give evidence that the Tunguska explosive body was more likely a comet, although we cannot exclude the possibility that the impactor could be a carbonaceous asteroid. We have estimated the total mass of a solid component of the explosive body up to 10^3–10^6 tons.

Keywords: Tunguska event; Platinum group elements (PGEs); Peat layer; Cosmic body

1. Introduction

The nature of the Tunguska event has been much debated ever since in the 1920s it was recognized by the scientific community as the explosion of a cosmic body. Many investigations have concluded that the impactor was a comet, or at least that the observational data were not in contradiction with a cometary impactor (Whipple, 1930; Astapowitch, 1933; Fesenkov, 1969; Wick and Isaacs, 1974; Petrov and Stulov, 1975; Rasmussen et al., 1984, 1999; Hartung, 1993; Kolesnikov, 1989; Kolesnikov et al., 1995, 1998a–c, 1999; Lyne et al., 1996; Asher and Steel, 1998; Grigorian, 1998; Hou et al., 1998, 2000; Bronshten, 1999); however, some authors believe that it was an ordinary iron (Kulik, 1927) or stone (Krinov, 1966; Longo et al., 1994) meteorite. Theoretical studies have lead to the hypothesis of a chondritic or an asteroidal impactor (Chyba et al., 1993; Lyne and Tauber, 1995; Sekanina, 1983, 1998; Zahnle, 1996).

In determining the nature of the Tunguska cosmic body (TCB), the best approach is to find and study its remnants in the explosion area. During the explosion, most of the TCB mass was dispersed into the upper atmosphere, then spread over a large area of the Earth's surface. According to measurements of atmospheric turbidity recorded by Mount Wilson observatory in California, Fesenkov (1978) calculated that about 1 million tons of cosmic materials were globally dispersed. There are suggestions of a number of smaller explosions that occurred at lower altitudes in addition to the high-altitude giant explosion (Krinov, 1966; Golenetskiy et al., 1977; Serra et al., 1994). For example, the figure in the book of Krinov (1966) shows that in the devastated area there are three epicentres of smaller explosions besides the giant altitude one. These reports match with observations

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made by local witnesses who reported several distinct TCB explosions. These smaller explosions were probably caused by the individual pieces of impactor material. Therefore, at the explosion epicenter we should be able to discover several sites with considerable variations in abundances of the TCB material.

The presence of cosmic material in terrestrial sediments can be identified by an enrichment of the platinum group elements (PGEs) and some other siderophile elements (Alvarez et al., 1980; Alvarez, 1983). Peat *Sphagnum fuscum*, from which the "catastrophic" layer including peat grown up in 1908 can be isolated, appears to be the more appropriate object for the search for TCB remnants. The upper Sphagnum fuscum bogs are wide spread in the TCB explosion area (See Fig. 1 in Kolesnikov et al., 1999, a map of the central part of the Tunguska explosion area in which there are sites of the peat column sampling). *Sphagnum fuscum* grows annually up by 0.5–3 cm, depending on environment conditions, while its lower part dying off, giving rise to peat. Chemical composition of the peat ash depends on the dust composition fallen down in this area, because this type of peat has only aerosol nutrients. Thus, it should have incorporated the extraterrestrial fall-out of the Tunguska explosion (Vasilyev et al., 1973). Korina et al. (1987) discovered a small Ir anomaly (17.2 pg/g) in the event layer which was considered to be caused by the Tunguska explosion. In fact, even such a small Ir anomaly still points to the presence of cosmic material in the peat (Kolesnikov et al., 1999): measured Ir contents in mineral fractions (i.e. in ash) of the event layer is 735 pg/g and it is well above the range of Ir content in surrounding rocks (average 20 pg/g Ir in the upper crust, Taylor and McLennan, 1985). An attempt to find Ir in two other peat columns located at the explosion epicentre (Rocchia et al., 1996) has failed. Hou et al. (1998) analyzed the Northern peat bog, using NAA, and discovered a sharp Ir anomaly (0.24–0.54 ng/g) in the event layers (Table 2, Fig. 1). Rasmussen et al. (1999) found Ir (39.9 pg/g) anomaly and ^{14}C depletion in the "catastrophic" layer of the Nearkhushma peat bog column. This may imply that in the explosion area the distribution of the TCB fallout is highly inhomogeneous. Unfortunately, very few investigations of other PGEs (i.e. besides Ir) in the explosion area peat have been published. We have started to analyze PGEs content in the Northern peat bog column from the Tunguska explosion area (Hou et al., 2000; Xie et al., 2001a). In the present work, the anomalies of Pd, Ru, Rh, etc. have been determined in the event layers of another peat column of the same peat bog, which can provide further evidences for the TCB nature. Besides peat, in the present work, traps from the Tunguska explosion area have been analyzed, too. In fact, in the explosion area there are many hills and heights, which are made up of volcanic basalts, i.e. traps. The basalts fix the composition of terrigenic dust in this area (Golenetskiy et al., 1977). To investigate terrigenic contamination of peat with PGEs and REE, it is necessary to analyze some nearby traps.

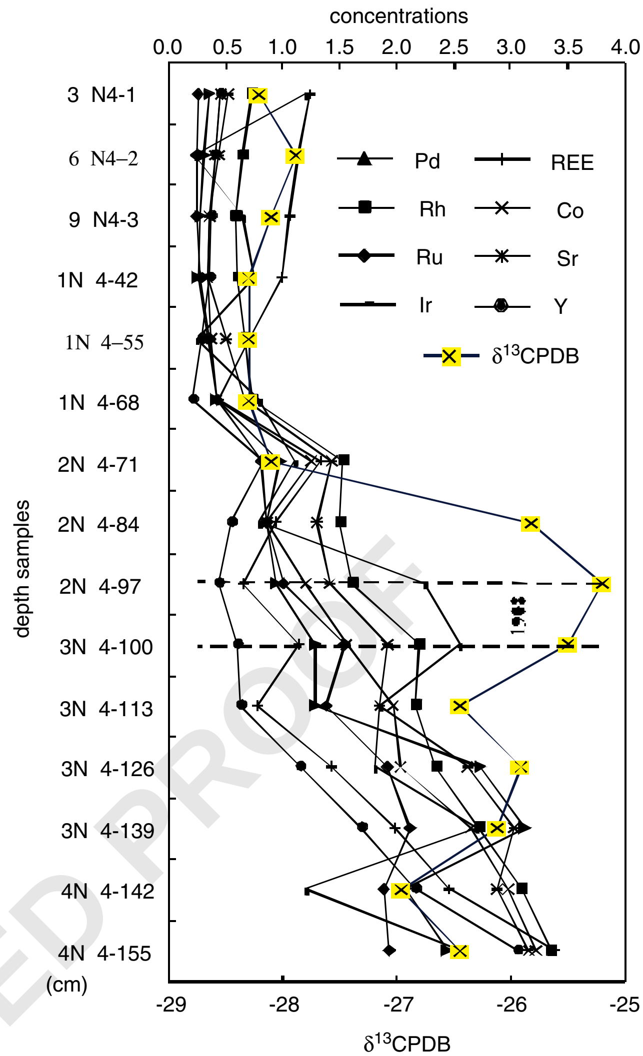

Fig. 1. Elemental abundances of the peat core at the epicenter of the Tunguska catastrophe. The "catastrophic" layer including peat grown in 1908 is at the 27–30 cm depth. The data (except Ir and $\delta^{13}C_{PDB}$) of samples N4-2 and N4-5 are the average of their adjacent samples. Pd: ppb × 10; Rh: ppb × 0.5; Ru: ppb; Ir: ppb × 0.2; REE: ppm; Co: ppm × 1/3; Sr: ppm × 10; Y: ppm × 1/3.

2. Experimental procedures

2.1. Sample collection and preparation

At the Northern peat bog, about 2 km North of the main explosion epicenter, the peat column (KEM N4) and the different types of nearby basalts of Siberian platform have been sampled by E. Kolesnikov and N. Kolesnikova in 1980 (see Fig. 1 of Kolesnikov et al., 1999).

The typical size of the peat columns sampled was 10 × 10 cm (Vasilyev et al., 1973). The peat column was cut using a stainless steel knife to a depth of 35 cm (i.e. the level to which permafrost is thawed in summer). Deeper samples within permafrost were cut out by axe. This peat col-

Table 1
Parameters for pretreatment of the peat samples

Sample No.	Depth (cm) (below present surface)	Dry weight (mg)	Ash weight (mg)	Ash yields (%)
N4-1	3	684.2	17.2	1.05
N4-2	6	748.5	3.8	0.57
N4-3	9	683.5	5.3	0.76
N4-4	12	787.1	5.4	0.69
N4-5	15	1042.1	6.3	0.61
N4-6	18	599.6	0.7	0.12
N4-7	21	1298.1	17.3	1.33
N4-8	24	1351.7	12.0	0.89
N4-9	27	1125.5	6.6	0.59
N4-10	30	1519.6	12.7	0.84
N4-11	33	1282.6	6.8	0.53
N4-12	36	1280.3	9.7	0.79
N4-13	39	1277.2	13.4	1.05
N4-14	42	660.5	2.1	0.32
N4-15	45	710.3	8.0	1.13

umn was immediately cut into 3 cm layers and packed into clean plastic bags. Fifteen peat samples were cut out from this peat column from 0 to 45 cm below the present surface (Fig. 1). In order to determine the depth of the "catastrophic" peat layer, the annual growth of peat along the extension of the peat column was estimated (Mul'diyarov and Lapshina, 1983; Lapshina and Blyakharchuk, 1986). The annual growth of peat consists of a light and a dark part of stem and of a whorl in it. Counting the annual growth in the several upper 5 cm peat layers, the age of peat plots as a function of its depth. This function is always nonlinear due to gradual peat compaction in depth. To find the depth of the "catastrophic" layer, graph is extrapolated to 1908 because in the lowest peat layers the peat stems are decomposed. Therefore, it is impossible to estimate accurately annual peat growth. For the peat column studied (KEM N4) the "catastrophic" layer including peat grown in 1908 is about at the 27–30 cm depth (Fig. 1).

We analyzed 15 peat samples of the column N4. Before the analyses, samples of Sphagnum fuscum peat were carefully cleared of roots from other plants, sticks, leaves and so on. The pre-treatment processes of the peat samples can be described as following: (1) dried at 100°C for 2 h, (2) carbonized at 200°C for 2 h, and then (3) at 450°C for 6 h to yield ashes (see Table 1), (4) dissolved in 6 ml *aqua regia* and 1 ml perchloric acid solution for ca. 10 h at 80–100°C in Teflon vessel, (5) vaporized to nearly dryness at ca. 100°C, and (6) dissolved in 2% HNO_3 solution for ICP-MS analysis. All these pre-treatment steps were done in a super-clean laboratory of the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS), China. The basalt samples were pre-treated from the fourth to sixth steps mentioned above in the Key Laboratory of Lithosphere Tectonic Evolution, Institute of Geology and Geophysics, CAS.

2.2. ICP-MS analysis

The pre-treated peat sample solutions were analyzed using a VG Elemental Plasma-quad 3 (PQ3) inductively coupled plasma-mass spectrometer (ICP-MS) at the University of Hong Kong. Standard reference materials, W-2, AGV-1 and BHVO-1, were analyzed to control the analytical quality for the elements except for Ru, Rh and Pd. Because of a lack of suitable standard reference materials for the peat PGEs, we set up an analytical method of PGEs especially for the peat samples (Xie, 2001; Xie et al., 2001b). The procedural detection limits are 0.06 ng/ml for ^{101}Ru, 0.01 ng/ml for ^{103}Rh, and 0.001 ng/mL for ^{105}Pd, and the recoveries are more than 85% for ^{101}Ru, 95% for ^{103}Rh, and 99% for ^{105}Pd. Additionally, MISA standard solution 2 of Canada (MISA-02-1: precious metals) was used to control the analytical quality of Ru, Rh, and Pd (Table 2). Osmium was not analyzed because of losing during pre-treatment. The trap (basalt) sample solutions were analyzed with VG Elemental Plasma-quad 2 (PQ2) ICP-MS at the Lithosphere Tectonic Evolution Laboratory, Institute of Geology and Geophysics, CAS. Standard reference material, GSR-1, was used to control the analytical quality for the basalt samples. Precision and accuracy for all the elements of the peat samples are better than 10% except for Pr (better than 20%), while precision and accuracy of trap samples are better than 10% except for Sr, Eu and Gd (better than 20%), Ce and Tm (ca. 26%).

3. Results and discussion

3.1. Element distribution in the peat column

From Tables 2 and 3, it can be seen that Pd and Rh concentrations in samples N4-10–N4-15 (corresponding to a depth range of 30–45 cm, named event peat layers) vary between 12.9 and 31.3 and 1.1 and 1.7 ng/g, respectively, which is about 7 and 4 times higher than the background value of 2.6–4.3 and 0.3–0.4 ng/g above the 21 cm depth, i.e. normal peat layers. The Ru concentration ranges from 1.4 to 2.1 ng/g in the event layers, but in the normal layers it is below the detection limits (3 times procedural blanks) (Table 2). The Ir concentration and $\delta^{13}C_{PDB}$ follow Pd, Rh, and Ru concentrations (Fig. 1). No PGEs were detected in the basalt samples (see Table 2). Sr concentration ranges between 18.5 and 31.5 μg/g in the event layers, and closely follows the PGEs concentrations (Table 2, Fig. 1). Total rare earth element (REE), Co, and Y concentrations, being 0.8–3.4, 0.5–1.1, and 0.2–1.0 μg/g, respectively, are anomalies in the event layers. In addition, the element concentrations at depths of 21–27 cm less than those below 27 cm depth, but higher than those above the 21 cm depth, which may be the transitional range (Fig. 1, Tables 2, 3). In summary, Ru, Rh, Pd, Ir, Sr, Co, Y and $\delta^{13}C_{PDB}$ in the event layers are all about 4–7 times higher than those in normal layers, and

Table 2
The PGEs, Co, Sr and Y concentrations in the peat layers from the 1908 Tunguska explosion area and in the traps near the explosion site determined by ICP-MS

Sample No.	Co (ppm)	Sr(ppm)	Y(ppm)	Ru (ppb)	Rh (ppb)	Pd (ppb)	Ir (ppb)	$\delta^{13}C_{PDB}$
N4-1	0.15	5.25	0.15	0.26	0.37	3.52	0.24	−28.10
N4-2	n	n	n	n	n	n	0.23	−27.75
N4-3	0.12	3.61	0.13	0.24	0.29	2.73	0.13	−28.00
N4-4	0.11	3.45	0.12	0.28	0.30	2.61	0.15	−28.20
N4-5	n	n	n	n	n	n	0.24	n
N4-6	0.14	6.60	0.07	0.42	0.37	4.29	0.16	−28.20
N4-7	0.42	14.34	0.28	0.81	0.77	9.68	0.22	−28.00
N4-8	0.29	12.98	0.18	0.86	0.75	8.68	0.16	−25.85
N4-9	0.40	14.08	0.15	1.00	0.81	9.42	0.45	−25.20
N4-10	0.52	19.18	0.20	1.54	1.10	12.78	0.51	−25.50
N4-11	0.65	18.52	0.21	1.39	1.08	12.83	0.37	−26.40
N4-12	0.68	26.11	0.39	1.92	1.17	27.26	0.36	−25.90
N4-13	0.88	30.22	0.57	2.12	1.36	31.27	0.54	−26.15
N4-14	0.99	28.76	0.72	1.88	1.55	20.85	0.24	−26.90
N4-15	1.07	31.50	1.02	1.93	1.67	24.47	0.51	−26.35
Trap 1	63.3	210.5	32.8	n	n	n		
Trap 2	39.9	203.5	50.6	n	n	n		
Trap 3	45.7	207.4	68.2	n	n	n		
CI	502	7.8	1.56	712	134	560	481	
Standards								
MISA02				0.54	0.56	0.54		
W-2[a]	43.50	21.66	190.18					
W-2[b]	44	24	194					
AGV-1[a]	16.40	20.51	717.86					
AGV-1[b]	15.3	20	662					
BHVO-1[a]	47.62	28.02	417.56					
BHVO-1[b]	45	27.6	403					
GSR-1[a]	3.52	127.45	58.75					
GSR-1[b]	3.5	106	62					

Underlined data: <detection limits (cited as 3 times procedural blank); MISA02: PGE standards solution of Canada (0.5ppb content): n: no data; Ir: cited from Hou et al. (1998); $\delta^{13}C_{PDB}$: cited from Kolesnikov (1984); CI: cited from Anders and Grevesse (1989); N4-1–N4-15: peat samples; Trap 1–Trap 3: trap (basalt) samples.
[a]Detected value of this work.
[b]Reference value.

REE are about 2 times higher (Tables 2, 3, Fig. 1). The majority of element concentrations appear roughly to increase below and decrease above the "catastrophic" layer (1908) (Fig. 1). Because the peat is quite porous, there is no doubt that some downwards percolation of soluble and insoluble materials have taken place from a depositional layer to the layers below, although we cannot judge the precise percolation extension. On the other hand, the aerosols injected into the upper atmosphere during the explosion would gradually fall to the Earth's surface for few years after the explosion, and cosmic material may partially be utilized from the deposited layer by the growing peat. Similar behavior was reported for some elements including K, Na, Sb, Fe, Ni, REE and C in the Northern swamp peat column (Golenetskiy et al., 1977; Hou et al., 1998, 2000; Rasmussen et al., 1999), in the Southern swamp peat column (Korina et al., 1987) and in the Nearkhushma peat column (Kolesnikov et al., 1998b, c).

3.2. The probable causes of element anomalies

There are several possibilities for the cause of positive elemental anomalies in the event layers: (1) decrease in sedimentation rate, and/or increase in meteoritic ablation rate and cosmic dust fallen out; (2) extraterrestrial material and terrestrial dust accretion associated with the Tunguska explosion; and perhaps (3) forest burning and anthropogenic dust with subsequent redistribution, and deposition of normal cosmic dust from the large area of foliage.

In order to determine whether the enrichments of PGEs and other siderophile elements in the event layers resulted from the accumulation of normal cosmic dust by a decrease in sedimentation rate, or by an increase in meteoric ablation rate and cosmic dust, Hou et al. (1998) compared the distribution of Ir and Ni in the event layers in this peat column with that of cosmic ablation spheres separated from 2 kg of red clay sediment from the mid-Pacific Ocean (Ganapathy,

Table 3
The REE concentrations (ppb) in the peat samples from the 1908 Tunguska explosion area, in the traps of the Siberian platform (ppm), in the standards (W-2, AGV-1, BHVO-1, GSR-1) (ppm), and in the CI chondrites (ppm)

Sample No.	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho
N4-1	260.5	531.3	64.13	239.1	37.52	11.30	34.35	4.76	25.74	4.63
N4-3	214.9	452.3	53.47	193.6	35.94	8.83	31.22	4.53	22.82	4.50
N4-4	200.2	431.0	49.20	167.6	32.80	8.27	29.72	4.33	27.69	4.31
N4-6	92.4	187.7	22.48	77.65	14.36	5.13	13.53	1.88	10.64	2.21
N4-7	244.7	518.5	65.62	254.6	50.54	13.52	49.05	7.64	42.80	9.44
N4-8	179.2	365.9	46.44	178.5	35.40	9.10	34.31	5.14	28.56	5.91
N4-9	112.2	237.4	31.67	120.4	29.18	7.89	27.58	4.25	24.06	5.05
N4-10	221.2	464.5	56.61	201.1	39.84	10.46	38.18	5.63	31.10	6.71
N4-11	123.7	282.7	39.81	162.0	35.08	10.07	33.50	5.13	28.72	6.86
N4-12	207.6	484.6	70.20	310.7	69.12	18.04	66.86	10.41	61.40	14.04
N4-13	299.8	674.4	96.34	423.0	95.12	24.75	94.61	14.66	87.51	19.85
N4-14	393.9	862.3	120.4	516.2	109.5	29.77	109.0	16.59	97.34	21.61
N4-15	496.8	1148.2	166.5	738.6	162.2	44.08	164.4	25.28	146.5	32.72
Trap 1	9.84	51.17	3.31	15.59	4.61	1.56	5.82	0.97	6.00	1.33
Trap 2	21.40	51.56	6.82	30.88	8.43	2.64	10.45	1.69	10.30	2.17
Trap 3	27.00	50.90	8.34	38.44	10.04	3.07	13.25	2.11	13.51	2.82
Standards										
W-2[a]	10.70	23.35	3.23	14.28	3.46	1.08	3.61	0.63	3.72	0.82
AGV-1[a]	40.41	72.85	8.75	35.51	6.51	1.94	5.49	0.74	3.61	0.71
BHVO-1[a]	15.91	39.73	5.65	27.69	6.96	2.05	6.26	1.02	5.42	1.08
GSR-1[a]	57.48	136.65	13.88	49.74	10.84	0.99	11.34	1.78	10.69	2.25
W-2[b]	11.40	23.50	5.90	14.00	3.25	1.10	3.60	0.63	3.80	0.76
AGV-1[b]	38.00	67.00	7.60	33.00	5.90	1.64	5.00	0.70	3.60	0.67
BHVO-1[b]	15.80	39.00	5.70	25.20	6.20	2.06	6.40	0.96	5.20	0.99
GSR-1[b]	54	108	12.7	47	9.7	0.85	9.3	1.65	10.2	2.05
CI	0.31	0.81	0.12	0.60	0.20	0.07	0.26	0.05	0.32	0.07

Sample No.	Er	Tm	Yb	Lu	ΣREE	$(La/Yb)_N$	$(La/Sm)_N$	$(Gd/Yb)_N$
N4-1	12.69	1.54	11.37	1.36	1240.2	15.44	4.37	2.44
N4-3	12.99	1.83	12.71	1.89	1051.5	11.40	3.76	1.98
N4-4	12.66	1.78	12.84	1.78	984.2	10.51	3.84	1.87
N4-6	6.77	0.98	8.46	1.21	445.3	7.36	4.05	1.29
N4-7	30.05	4.56	34.09	5.41	1330.5	4.84	3.05	1.16
N4-8	19.04	2.76	21.60	3.26	935.2	5.59	3.18	1.28
N4-9	16.47	2.64	20.28	3.19	642.3	3.73	2.42	1.10
N4-10	22.64	3.69	28.21	4.27	1134.1	5.29	3.49	1.09
N4-11	21.40	3.49	26.21	4.13	782.9	3.18	2.22	1.03
N4-12	45.93	7.64	54.46	8.83	1429.8	2.57	1.89	0.99
N4-13	63.90	10.46	72.47	11.69	1988.6	2.79	1.98	1.05
N4-14	70.60	11.22	82.74	12.65	2453.8	3.21	2.26	1.06
N4-15	106.88	16.52	118.83	18.09	3385.7	2.82	1.93	1.12
Trap 1	3.71	0.54	3.34	0.51	108.30	2.05	1.39	1.39
Trap 2	6.05	0.89	5.19	0.80	159.27	2.87	1.66	1.61
Trap 3	8.00	1.17	7.21	1.13	267.57	2.61	1.75	1.47
Standards								
W-2[a]	2.15	0.35	2.22	0.32				
AGV-1[a]	1.78	0.30	1.82	0.26				
BHVO-1[a]	2.51	0.39	2.37	0.30				
GSR-1[a]	6.91	1.34	7.63	1.16				
W-2[b]	2.50	0.38	2.05	0.33				
AGV-1[b]	1.70	0.34	1.72	0.27				
BHVO-1[b]	2.40	0.33	2.02	0.29				
GSR-1[b]	6.5	1.06	7.4	1.15				
CI	0.21	0.03	0.21	0.03				

CI: Cited from Anders and Grevesse (1989); Samples, N4-2 and N4-5, are no data in this work.
[a]Detected value of this work.
[b]Reference value.

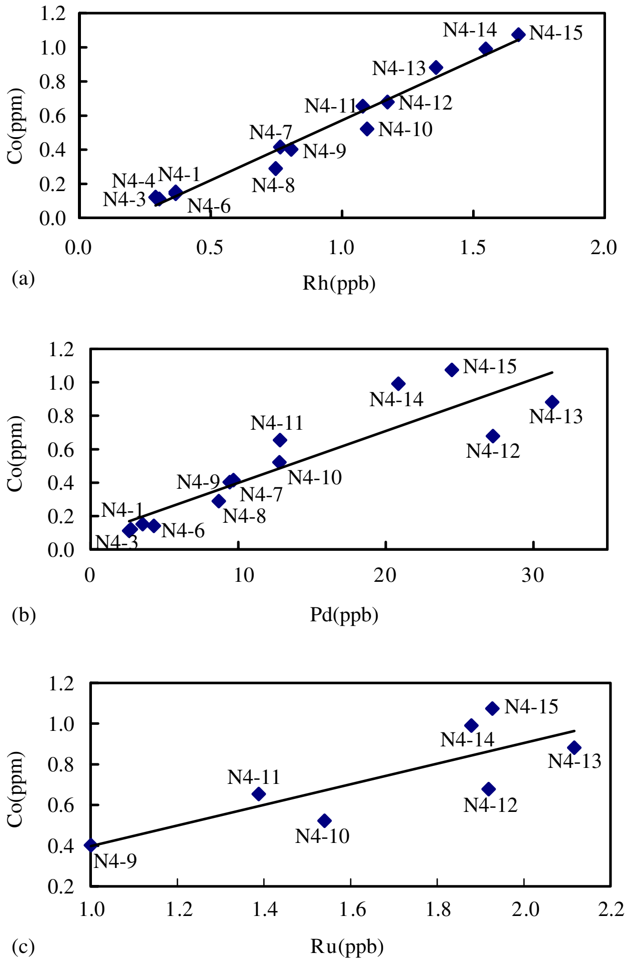

Fig. 2. Correlations between (a) Co vs. Rh, (b) Co vs. Pd, and (c) Co vs. Ru in the peat layers of the Tunguska peat columns. The good correlations between them indicate that these elements might have the same source, probably the TCB.

1983). They found no increase of cosmic material (e.g. by meteoric ablation rate increase and/or sedimentation rate decrease) except for the TCB material. Hardly a redistribution of the normal cosmic dust occurs at least in the Northern swamp (See Hou et al., 1998). Very few anthropogenic dusts even during the industrial revolution contributed in so desolate and uninhabited area. Furthermore, there is a good correlation between the Rh, Pd, Ru, and Co concentrations in the preliminary (Hou et al., 2000, another peat column) and in the present investigations (Fig. 2), which points to the supposition that the anomalous siderophile elements came from a single object, i.e. the TCB.

The anomalies of PGEs and other trace elements observed cannot be explained by contamination of peat with terrestrial dust produced during the explosion. Indeed, Golenetskiy et al. (1977) revealed that in the explosion area the mineral component of the soil has a composition similar to that of nearby volcanic rocks (basalt), i.e. traps, where they found a high concentration of Sc, 41 μg/g. In the traps we detected high concentrations of Co, Y and Sr, 40–63, 33–68 and 204–210 μg/g, respectively (Table 2). These element concentrations are more than 200 times higher (except for Sr being about 30 times) than those in the normal peat layers (Table 2). In the event peat layers at the 27–45 cm depths, however, the concentrations of Co, Y, and Sr were at most 15 times higher than those in the normal layers (Table 2, Fig. 1). On the other hand, there are obvious PGEs anomalies in the event peat layers, but we have not been able to detect any PGEs in any of the nearby traps. Therefore, the increase of PGEs concentrations in the event peat layers cannot be attributed to an input of terrigenic or trap dust, leaving the TCB materials fallout as the most probable cause.

We found that the REE concentrations in the event layers are much lower than those in the nearby traps, but higher than those in the normal peat layers (Fig. 1, Table 3). The patterns of CI-chondrite-normalized REE in the event layers (Fig. 3b) are different from those of both the traps (Fig. 3c) and the normal peat layers (Table 3, Fig. 3a), showing two main characteristics (Fig. 3d): (1) The $(La/Yb)_N$ (slope rate of the curve) in the event layers (~ 3 except for sample N4-10 which is ~ 5) is much lower than those in the normal layers (> 8), and higher than those in the traps (~ 2); the LREE follow similar trends; and (2) The $(Gd/Yb)_N$ in the event layers (ca. 1) is lower than those of both the normal layers (ca. 2) and the traps (ca. 1.5). 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 the presence of cosmic material in the Northern swamp peat column (Fig. 1).

In the present work, at 26 cm depth containing the peat grown in 1908, and deeper we found an increase of ^{13}C, heavy carbon isotope, relative to the upper, or normal peat layers. In the "catastrophic" layer this effect was +3‰ as compared to the six upper layers. Earlier, in the near catastrophic layers of another four peat columns from the explosion epicenter, there have been revealed anomalies in the isotopic composition of C and H. The shifts for carbon ($\delta^{13}C$ reaches +4.3‰) and hydrogen (δD reaches −22‰) were opposite in sign (Kolesnikov et al., 1999). The authors gave evidence that these anomalies may not be explained by the ordinary terrestrial reasons: fall-out of terrestrial mineral and organic dust and of fire soot, humification of peat, emission from the Earth of oil–gas streams, climate changes, and so on. Moreover, the isotopic effects are clearly connected with the area and the time of the TCB explosion, and were absent in the control peat columns sampled at the places far away from the explosion area. Rasmussen et al. (1999) and Kolesnikov et al. (1999) have shown that to explain such an isotopic effect for carbon from +2‰ to +4‰ in the peat, it is necessary to put about 2–3% exogenic carbon into it with very heavy isotopic composition, i.e. $\delta^{13}C_{PDB}$ from +51‰ to +64‰. Such heavy carbon does not occur on the Earth and in ordinary chondrites. Rasmussen et al. (1999) have revealed that this carbon is of abiogenic origin

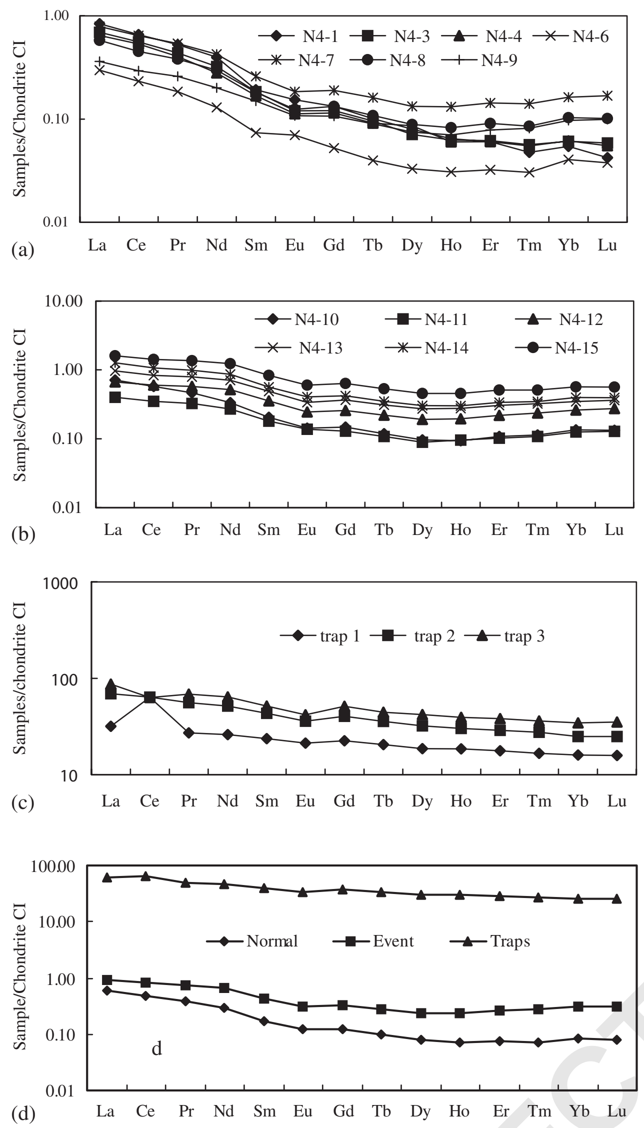

Fig. 3. The CI-chondrite-normalized REE patterns for the 13 peat samples from the 1908 Tunguska explosion area and the three traps of the Siberian platform. The patterns in the event layers (corresponding to N4-10–N4-15 samples) are different from those in the normal peat layers and in the traps. (a) The Tunguska normal peat layers; (b) the Tunguska event peat layers; (c) the traps (volcanic basalts) of the Siberian platform; (d) compare the event layers with the normal layers and traps in average.

(so called "dead" carbon) due to lack of radioactive ^{14}C, which is present in all biologic objects on the Earth.

Such heavy carbon (i.e. $\delta^{13}C_{PDB}$ from +51‰ to +64‰) is only typical of individual mineral fractions in carbonaceous chondrites (Halbout et al., 1985, 1986). Moreover, it is known from Halley's comet investigation that the composition of cometary dust is very close to that of carbonaceous chondrites (Jessberger et al., 1988). Thus, we suggest that in this area the peat substance was contaminated by extraterrestrial material that may be compositionally similar to carbonaceous chondrites.

Table 4
Comparing element ratios in the Tunguska event peat layers to those in meteorite ice, Halley 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[a]	30	1		10^{-2}

[a]Data from the present work; all other data calculated from Hou et al. (1998) in the Tunguska peat samples, Mao et al. (1987) in meteorite ice, Jessberger (1988) in Halley comet, and Wasson (1985) in CI, respectively.

3.3. Nature of the Tunguska cosmic body

In the event peat layers all anomalous elements (e.g. PGEs, and other siderophile elements, etc.) appear to have the same source, i.e. the TCB material. They should then provide some clues on the nature of the TCB. 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, calculated from the data of Hou et al., 1998) in the event peat layers (in this column) are much close to those in CI (10^{-4}, 10^{-4}, 10^{-2}, 10^{-5}, and 4) and in meteoritic ice (Ir/Co $\approx 10^{-3}$, Ir/Cr $\approx 10^{-4}$, Ir/Sr $\approx 10^{-3}$; calculations based on data of Mao et al., 1987) from Southeastern China and also probably originating from a comet (Table 4). Moreover, the Ni/Co and Co/Cr ratios ($2-5$, $1-2$, based on data of Hou et al., 1998) in the event peat layers are much close to their ratios in meteoritic ice (Co/Cr $\approx$ 1, based on data of Mao et al., 1987) and in Halley's comet ($\sim$ 1.2, and 1, based on data of Jessberger et al., 1988), but very different from their ratios in CI ($\sim$ 22, and 0.2) (Table 4). Furthermore, the ratio Sr/Co ($\sim$ 30) in the event peat layers is closer to that ($\sim$ 1) in the meteoritic ice from Southeastern China, than to that in CI ($\sim 10^{-2}$) (Table 4). The much larger Sr/Co in the event layers compared to that in meteoritic ice may be due to: (1) Co is more volatile than Sr during the explosion; or (2) the TCB material contains less siderophile elements. Indeed, some investigations implied that the TCB material, as compared to the CI carbonaceous chondrites, could be much lower in some siderophile elements, e.g. Fe, Co and Ni (Kolesnikov et al., 1998b, c). According to the results of the comet Halley missions, the composition of cometary dust is similar to CI chondrite. Therefore, these element ratios in the event peat layers support the point that the hard volatile portion of TCB material could be similar to CI chondrite in composition, and the TCB more possibly was a comet, although we cannot completely rule out the possibility of an asteroid.

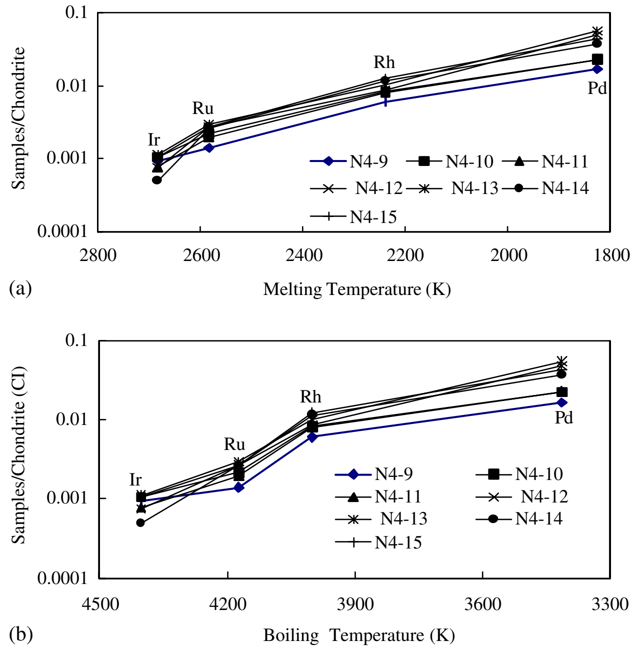

Fig. 4. The patterns of CI-chondrite-normalized PGEs vs. melting temperature (a), and boiling temperature (b) in the event peat layers (including N4-9) in the 1908 Tunguska explosion area. The smooth curves indicate the PGEs in the event layers may have an initial source and suffer roughly the same fractionation during and/or after the explosion.

Table 5
Melting point and boiling point temperatures of the PGEs[a]

	Ir	Ru	Rh	Pd
Melting point (K)	2683	2583	2239	1825
Boiling point (K)	4403	4173	4000	3413

[a]This table was cited from "Inorganic Chemistry" (in Chinese), Higher Education Press, Beijing, 1981.

Fig. 4 shows the CI-chondrite normalized PGEs in the event peat layers (including N4-9) (values listed in Table 2), and plotted according to decreasing order of their melting and boiling temperatures (Table 5). The curves show a similar shape (e.g. positive slope), and good correlation between the element abundances and the volatility. Unfortunately, we cannot compare the PGEs patterns in the event peat layers with those in the normal layers, because the Ir and Ru concentrations in the normal layers are lower than the detection limits (Table 2). The PGEs patterns imply that the four PGEs (Ir, Ru, Rh, Pd) in the event layers should come from the same source, and suffer roughly the same fractionation (Fig. 4). Siderophile elements (including PGEs) fractionation can take place at $\geqslant 680$ K for carbonaceous chondrites, which is lower than the temperature for the lithophile elements fractionation, 1300–1350 K (Larimer and Anders, 1970). Thus, it is possible that the PGEs were fractionated from the time of atmospheric entry and explosion at very high temperature to the time of deposition in sediments and plants at normal temperature. The positive slope of all these PGEs curves shows that the relative volatile PGEs were enriched in the event peat layers (Fig. 4). It is not hard to imagine that the relative volatile PGEs more likely formed chemical compounds at high temperatures and survived in sediments and plants.

Results of the spacecraft mission to Halley's comet point to a composition of cometary dust similar to CI chondrite, but with distinctly higher H, C, N contents, in fact, four-, 12-, and 7.5-times, respectively (Jessberger et al., 1988; Jessberger and Kissel, 1991; Jessberger, 1999). The dust/ice ratio in Halley's comet is ~ 1 (Jessberger, 1999), so we can roughly calculate the C, Pd and Rh contents of 38.5 wt%, 280 and 67 ng/g in Halley's comet, respectively, considering nearly no PGEs in the ice, thus yielding C/Pd and C/Rh ratios of 1.4×10^6 and 5.7×10^6 for Halley's comet. Using the PGEs concentrations in the event peat layers from which the background was deducted, we get concentrations of Pd and Rh, coming from the TCB, to be 14.2 and 0.81 ng/g in the event peat layers, respectively, corresponding to 46.0 and 2.6 ng cm^{-2} (considering the dry peat density of ~ 0.12 g cm^{-3}) (Fig. 1, Table 2).

Rasmussen et al. (1999) proposed a cosmic C content of 6.8 ± 1.0 mg cm^{-2} (corresponding to ~ 2.1 wt%) in the Nearkhushma peat bog column. If we assume both columns to be representative for the average cosmic element contents (from the TCB) in the explosion area, these yield C/Pd and C/Rh ratios of $\sim 1.5 \times 10^6$ and $\sim 2.6 \times 10^7$, which is close to or a little higher (~ 4 times) than for Halley's comet (1.4×10^6 and 5.7×10^6). These ratios, however, are on average about 10^2–10^4 times higher than for meteorites: CI chondrites have C/Pd $\approx 5.7 \times 10^4$, C/Rh $\approx 2.4 \times 10^5$; H chondrites have C/Pd $\approx 1.2 \times 10^3$, C/Rh $\approx 6.3 \times 10^3$; and EH chondrites have C/Pd $\approx 4.6 \times 10^3$, C/Rh $\approx 1.7 \times 10^4$ (calculated from the data of Wasson, 1985; Kring et al., 1996).

Additionally, Rasmussen et al. (1999) 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 meteorites. Various physical and, conceivably, chemical processes may have influenced the C/PGEs ratios of the TCB material from the time of atmospheric entry to the time of deposition in the peat, but it is hard to imagine severe loss of PGEs rather than C. The loss of C is much more likely than the loss of PGEs, but the loss of C will only make the initial C/PGEs ratio of the TCB more impressive. So, we are forced to conclude that the high C/PGEs ratios are not in good agreement with any chondritic or achondritic composition for the explosive body. Rather, these data point towards a cometary composition for the exploding body, supported by the data of the isotopic composition of C and H in peat (Kolesnikov et al., 1995, 1999; Rasmussen et al., 1999).

In comets PGEs are mostly localized in dust. Therefore, high C/PGEs ratios point to a small dust content in the Tunguska cometary body. This is in agreement with the evidences of eyewitnesses. Among more than 700 of witnesses, nobody could see an intense smoky track after the TCB passage (L'vov, 1984; Plekhanov, 1997). This fact may be only explained by an absence in its content of hard volatile (dust) components. Very low content of hard volatile components in the TCB is, therefore, in good agreement with the negative results of searching for traces of a global deposition of cosmic dust in 1908 in both Antarctic (Rocchia et al., 1988) and Greenland ice fields (Rasmussen et al., 1995). On the other hand, Golenetskiy et al. (1977) and Kolesnikov et al. (1998b, c) found positive anomalies of several volatile elements (Li, Na, Rb, Cs, Cu, Zn, Ga, Br, Ag, Sn, Sb, Pb, and Bi) in the "catastrophic" peat layers, which were probably due to the conservation of the TCB material in peat and the fact that the TCB contained high volatile components.

It should again be noted that at the different sites of the explosion area the anomalies observed in peat do not have the same magnitude. It may be caused by the inhomogeneous fallout of the cosmic material over the explosion area. Golenetskiy et al. (1977), Kolesnikov (1980), and Kolesnikov et al. (1999) inferred from their data the same conclusion. Serra et al. (1994) 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 may be caused by (1) multiple explosions of the TCB fragments; (2) an enrichment of the surface with finely dispersed material at those sites where pieces of cometary ice fell and thawed; and (3) both atmospheric and depositional effects during and/or after the explosion.

3.4. Estimation of the TCB weight

In the previous section, we estimated a cosmic Pd and Rh deposition of 46.0 and 2.6 ng cm^{-2} in the peat column. If we assume that the whole mass of the TCB was spread out over the ~ 2000 km^2 of devastated forest area and we use this column site to be representative for the deposition in the whole area, we calculate a net deposition of cosmic Pd of ~ 920 kg and Rh of ~ 52 kg. If, as discussed above, the chemical composition of the TCB's solid component is similar to a carbonaceous chondrite (CI, Pd = 560 ng/g; Rh = 134 ng/g), we estimate that the chondritic material (solid component) of the explosive body weigh $\sim 1.6 \times 10^6$ tons by Pd, and 0.4×10^6 tons by Rh. If any site in the explosion area had same PGEs concentrations as this peat column in the present investigation, these estimates should represent lower limits, because this peat column is only 45 cm deep, and, the TCB material redistributed below 45 cm cannot be estimated (see Fig. 1). As mentioned above, however, the TCB material distribution in the explosion area peat is very inhomogeneous, such as at some sites Ir anomaly of only 5 pg/g in the event peat layers were detected (See Rocchia et al., 1996). According to this data (Ir = 5 pg/g), we estimate that the solid component of the TCB weigh $\sim 10^3$ tons. Therefore, the weight of the TCB solid component may be roughly between 10^3 and 10^6 tons.

4. Uncited reference

Pasechnik (1976)

Acknowledgements

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