Meteoritics & Planetary Science 34, 891–895 (1999)

Evidence for a very high carbon/iridium ratio in the Tunguska impactor

KAARE L. RASMUSSEN[1]*, HANS J. F. OLSEN[2], RAYMOND GWOZDZ[3] AND EUGINEV M. KOLESNIKOV[4]

[1]Carbon-14 Dating Laboratory, National Museum and Geological Survey of Denmark,
Ny Vestergade 11, DK-1471 Copenhagen K, Denmark
[2]Astronomical Observatory, Universtity of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ø, Denmark
[3]Tracechem, Markmandsgade 2, DK-2300 Copenhagen, Denmark
[4]Department of Geology, Moscow State University, Moscow
*Correspondence author's e-mail address: kaare.lund.rasmussen@natmus.dk

(Received 1998 December 8; accepted in revised form 1999 July 30)

Abstract–We have measured excess Ir and depletion of ^{14}C, two independent indicators of cosmic material, in peat cores from the central Tunguska impact site. Both Ir and ^{14}C show pronounced anomalies in the same stratigraphical depth interval. We have estimated an integral deposition of nonradioactive cosmogenic C of 6.8 ± 1.0 mg C cm^{-2}, and an integrated Ir deposition of 5.9 ± 1.2 pg Ir cm^{-2}. The very high C/Ir ratio and a deduced $\delta^{13}C$ value of +55 ± 10‰ relative to V Pee Dee Belemnite (VPDB) of the impactor material found in this study points towards a cometary type impactor, rather than a chondritic or achondritic asteroidal type impactor.

INTRODUCTION

The nature of the Tunguska event in 1908 has been much debated ever since it was recognized by the scientific community as the impact of a cosmic body in the 1920s. Many works have concluded that the impactor was of a cometary type, or at least that the observational data were not in contradiction with a cometary impactor (Kulik, 1927; Whipple, 1930; Astapowitch, 1933; Krinov, 1966; Fesenkov, 1969; Wick and Isaacs, 1974; Rasmussen *et al.*, 1984; Hartung, 1993; Kolesnikov *et al.*, 1996; Lyne *et al.*, 1996; Asher and Steel, 1998; Grigorian, 1998); but recently, the results of model calculations have lead to a hypothesis of a chondritic or asteroidal type impactor (Chyba *et al.*, 1993; Sekanina, 1998), an idea later modified to an achondritic impactor (Zahnle, 1996).

Little experimental evidence, in terms of analyses of the remains of the impactor, has been put forward due to the scarcity of such material. Only a few investigations of Ir in the local Siberian peat deposits have been published (Korina *et al.*, 1987; Nazarov *et al.*, 1990), one in which a single sample contained ~10 pg/g and another study (Kolesnikov *et al.*, 1996) in which three samples reached 10–15 pg/g. The atmospheric explosion was estimated to have taken place ~8 km above ground (Astapowitch, 1933; Fesenkov, 1966; Ben-Menahem, 1975; Turco *et al.*, 1982), which strongly suggests that at least some of the impactor material was injected into the stratosphere. Once in the stratosphere, aerosols are known to distribute rapidly hemisphere-wide (HASL-278, 1974), that is, within 1–2 years. An attempt to detect excess Ir in the Greenland ice sheet, as would be expected if stratospheric injection and transport of dust took place, has failed (Rasmussen *et al.*, 1995); and another attempt in the Antarctic ice sheet has also failed (Rocchia *et al.*, 1990), although the latter is not as diagnostic as the failure to detect cosmic dust in Greenland, because the Antarctic sampling site is situated on the opposite hemisphere. From the study of Greenland ice (Rasmussen *et al.*, 1995), an upper limit was estimated for the Ir deposition during the Tunguska event of <1.8 kg Ir, corresponding to <3000 tons of CM material.

EXPERIMENTAL PROCEDURES

Fieldwork

In 1994, four adjoining peat cores were retrieved from site N19 ~6 km from Kulik's camp at the epicenter, near the jetty at the Kusma river in the central portion of the Tunguska blast zone (see Fig. 1). The cores were retrieved adjacent to each other and were intact from the top to ~100 cm depth. The cores were brought to Denmark in specially built sealed containers that fitted the 15 × 15 cm square-shaped peat cores completely. At present, the permafrost zone sets in at a depth of ~45 cm below the surface. A dark layer appears at 70–75 cm, and a fire horizon is evident at 80–85 cm depth.

Carbon Isotopes

Core #1, subdivided into 10 cm samples, and core #4, subdivided into 5 cm samples, were used for radiocarbon dating. Penetrating roots and live ants (only in the top sample) were removed manually from the samples prior to analysis. Only the lowermost sample was slightly humified; the rest did not show any signs of humification. The samples were boiled in 1% HCl, followed by boiling in demineralized water. Subsequent to drying for at least 24 h at 120 °C, the samples were burned to CO_2 in a pure O_2 atmosphere. The CO_2, were stored for at least three weeks in order to let the majority of the ^{222}Rn decay. After further purification for ^{222}Rn and other contaminants, the samples were counted in a 2 L, 1.5 atm proportional counter, and at the same time small aliquots were taken out for $\delta^{13}C$ measurement. The $\delta^{13}C$ were measured on a Varian MAT-250 mass spectrometer with a one standard deviation accuracy better than ±0.1 ‰ VPDB. The percent modern ^{14}C and the total $\delta^{13}C$ is given in Table 1.

Instrumental Neutron Activation Analysis

Core #2 was used for instrumental neutron activation analysis (INAA) and was cut in 2 cm slices yielding 30 samples to a depth of ~70 cm below the surface. The samples were weighed in the natural wet state, dried in precleaned beakers at 80 °C for two days, and weighed again. The samples were then incinerated one at the time at three temperatures—200, 300, and finally 450 °C for 12 h in order to leave only the inorganic part without direct burning. After weighing, 40–50 mg subsamples were irradiated for two days in the heavy water reactor DR-3 at Risø National Laboratory, Denmark, in a neutron flux of approximately 4 × 10^{13} neutrons s^{-1} cm^{-2}. Counting was done on a 51% GeLi detector with a resolution of 1.9 keV at 1332.5 keV. Three counts were made after 6, 20, and 100 days. The key element, Ir, was determined with an accuracy of ~20%, see Table 2.

DISCUSSION

The uppermost samples in both core #1 and core #4 are clearly influenced by bomb-produced radiocarbon. The layers deposited during or after the fallout of the bomb-produced radiocarbon, which started ~1950, is thus at or above this depth. Because the peat is quite

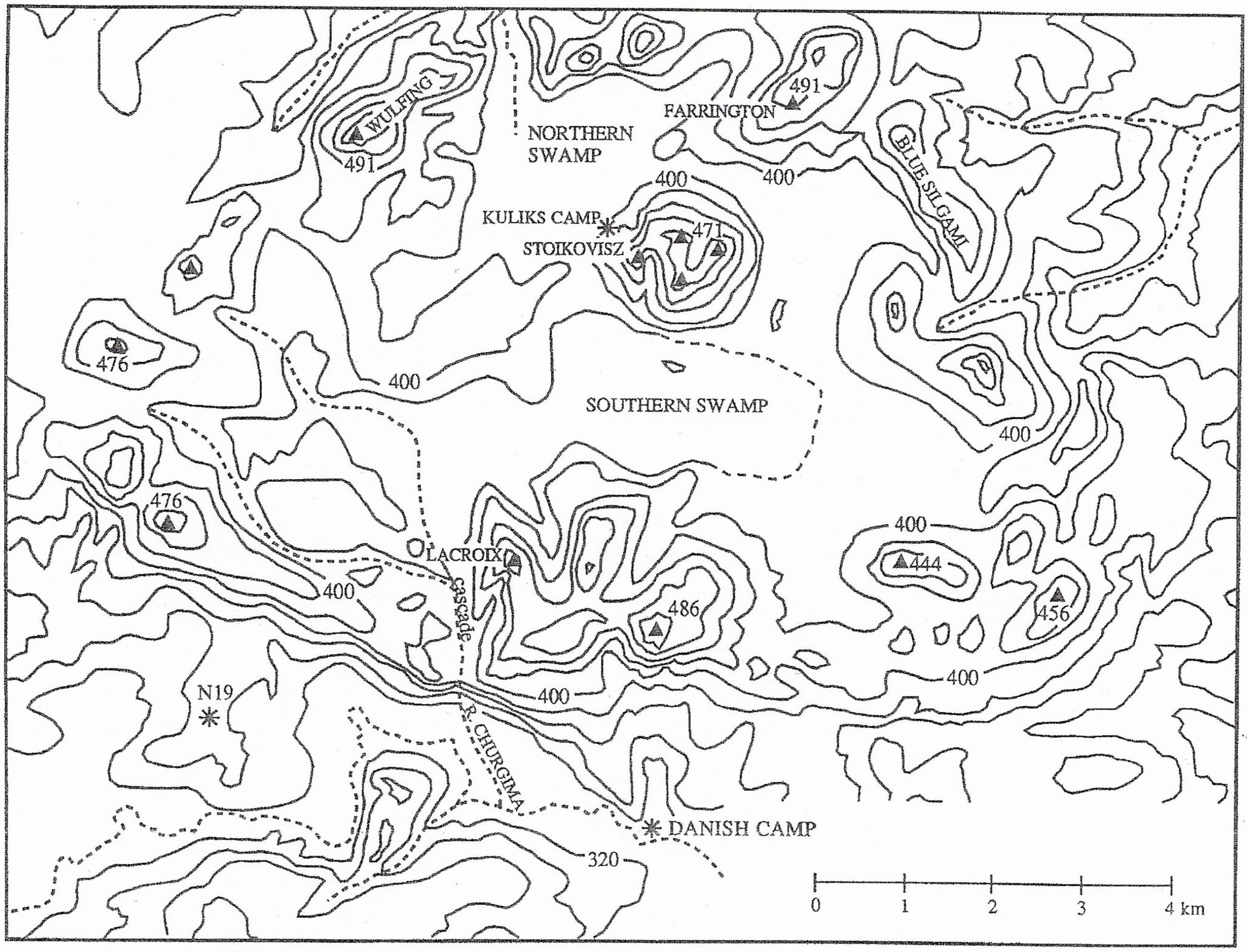

FIG. 1. The N19 sample site is located ~6 km south-soutwest of Kulik's camp at the epicenter.

TABLE 1. Results of the radiocarbon dating.

C14 Lab No./ Core designation	Depth interval (cm)	Average depth (cm)	^{14}C % modern	^{14}C-age ^{14}C-y BP	$\delta^{13}C$ ‰ VPDB
K-6317/1-1	2–12	7	116 ± 0.7	–	–27.8
K-6318/1-2	12–24	18	145 ± 0.7	–	–26.9
K-6319/1-3	24–40	32	132 ± 0.5	–	–25.6
K-6320/1-4	41–51	46	98.3 ± 0.41	140 ± 35	–24.5
K-6321/1-5	51–61	56	98.6 ± 0.59	115 ± 45	–24.7
K-6322/1-6	62–72	67	98.0 ± 0.46	160 ± 35	–24.0
K-6323/1-7	72–85	78.5	97.0 ± 0.83	250 ± 65	–25.6
K-6324/1-8	86–96	91	95.8 ± 0.63	350 ± 50	–25.7
K-6663/4-6	23–28	25.5	170 ± 0.7	–	–25.20
K-6664/4-7	28–33	30.5	129 ± 0.6	–	–25.18
K-6665/4-8	33–38	35.5	101.9 ± 0.56	–	–24.83
K-6666/4-9	38–43	40.5	101.4 ± 0.69	–	–25.36
K-6667/4-10	43–48	45.5	100.3 ± 0.55	–	–24.02
K-6668/4-11	48–53	50.5	99.45 ± 0.54	–	–23.57
K-6669/4-12	53–58	55.5	97.23 ± 0.45	–	–23.87
K-6670/4-13	58–63	60.5	97.90 ± 0.38	–	–23.75
K-6752/4-14	63–68	65.5	99.48 ± 0.44	–	–24.71
K-6753/4-15	68–73	70.5	98.07 ± 0.44	–	–25.68
K-6754/4-16	73–78	75.5	96.30 ± 0.45	300 ± 35	–25.45

Depth is given in centimeters below the peat surface. Average depth is calculated as the middle of the depth interval. Uncertainties in ^{14}C percent of the modern values are given at ±1 standard deviation. The uncertainty of the $\delta^{13}C$ measurements is better than ±0.05‰ VPDB.

porous, there is no doubt that some downwards percolation of soluble and insoluble material have taken place from a depositional layer to the layers below. Precisely how far percolation extends is uncertain, but judging from the variation in core #2, we initially estimated that a sudden geochemical event would be smeared out over ~10 cm at the top of the cores. The length of the smeared out event is, of course, gradually reduced as compaction progresses.

Guided by the above estimate of the mixing length, we sampled core #1 in 10 cm samples, yielding the slight but distinct ^{14}C anomaly seen in Fig. 2a. We interpret the anomaly to be due to an excess of nonradioactive C caused by a sudden influx of cosmic material. We would expect the cosmic influx from the Tunguska accretionary event to be almost completely devoid of ^{14}C, so this should cause a decrease in the percent-modern value, which is also observed in one sample from 41 to 51 cm below the surface. We cannot, however, be sure how much nonradioactive C is accumulated, because the sample below (51–61 cm) is most likely also depleted in ^{14}C (finely dashed line).

After observing that only one sample in core #1 was definitely depleted in ^{14}C, we decided to sample the remaining core, core #4, into 5 cm samples. This yielded a ^{14}C depletion over four samples as shown in Fig. 2b. The two samples from 23–28 and 28–33 cm were dominated by bomb-produced ^{14}C. The next two samples (33–38 and 38–43 cm) were slightly above the modern 1950 value, which is undoubtedly due to some downwards percolation of modern bomb-influenced material from the overlying layers. The next four samples (from 43 to 63 cm) fall distinctly below the expected smooth curve, as indicated in Fig. 2b by the dashed line. The expected smooth curve reappears again below 63 cm. The influx of non-radioactive C is represented by the area between the dashed line (expected values) and the actual measurements. The average excess in ^{14}C over the four samples in core #4 is calculated to be 1.73 ± 0.24 %-modern. If we assume a dry peat C content of 50 ± 5 wt% (Mook and Waterbolk, 1985), and we use the measured dry peat density at each sample level (varies between 0.035 and 0.044 g cm^{-3}), our estimate of the total amount of C deposited by the Tunguska impactor at the N19 location becomes 6.8 ± 1.0 mg cosmogenic C cm^{-2}.

The depth interval from 43 to 63 cm, in which we find the radiocarbon depletion, is comparable to the depth of the 1908 layers found in previous studies (*e.g.*, Kolesnikov *et al.*, 1996). There are no signs of fire in the cores at or near the depleted layer. One fire horizon was observed in the cores at a much greater depth (80–85 cm depth in core #4). The age at this depth can roughly be inferred from the radiocarbon dates. The sample from 86–96 cm depth in core #1 gives 350 ± 50 ^{14}C-y BP (K-6324), which gives a calibrated age at $\pm 1\sigma$ of cal A.D. 1480–1640 using Stuiver *et al.* (1998), and the sample from 73–78 cm depth in core #4 gives 300 ± 35 ^{14}C-y BP (K-6754), which gives a calibrated age at $\pm 1\sigma$ of cal A.D. 1520–1650, so the fire horizon probably dates to some time in the fifteenth century. These dates and the fact that the upper 33 cm in core #4 and 40 cm in core #1 are influenced by bomb-produced radiocarbon shows that a pronounced compaction has taken place in the peat deposit. The average deposition rate in the interval 0–33 cm of core #4 is 0.7 cm/year, whereas the average deposition rate is ~0.2 cm/year in the interval 0–90 cm.

Iridium was above the detection limit in four samples between 43 and 57 cm depth in core #2 (see Table 2). The Ir values are in the range 6–40 pg/g of dry peat, well in accordance with previous studies (Korina *et al.*, 1987; Nazarov *et al.*, 1990; Kolesnikov *et al.*, 1996). This is consistent with an Ir deposition at a depth of 43 cm followed by downwards percolation to a depth 14 cm below this level in the subsequent years. These findings are entirely in agreement with the radiocarbon measurements (see Fig. 2b), which showed a depletion in ^{14}C between 41 and 51 cm in core #1 and between 43 and 63 cm in core #4. It should be noted that due to the fluffiness of the top of the cores and to surface topography the intercorrelation between the depth scales of the cores are no better than ~5 cm.

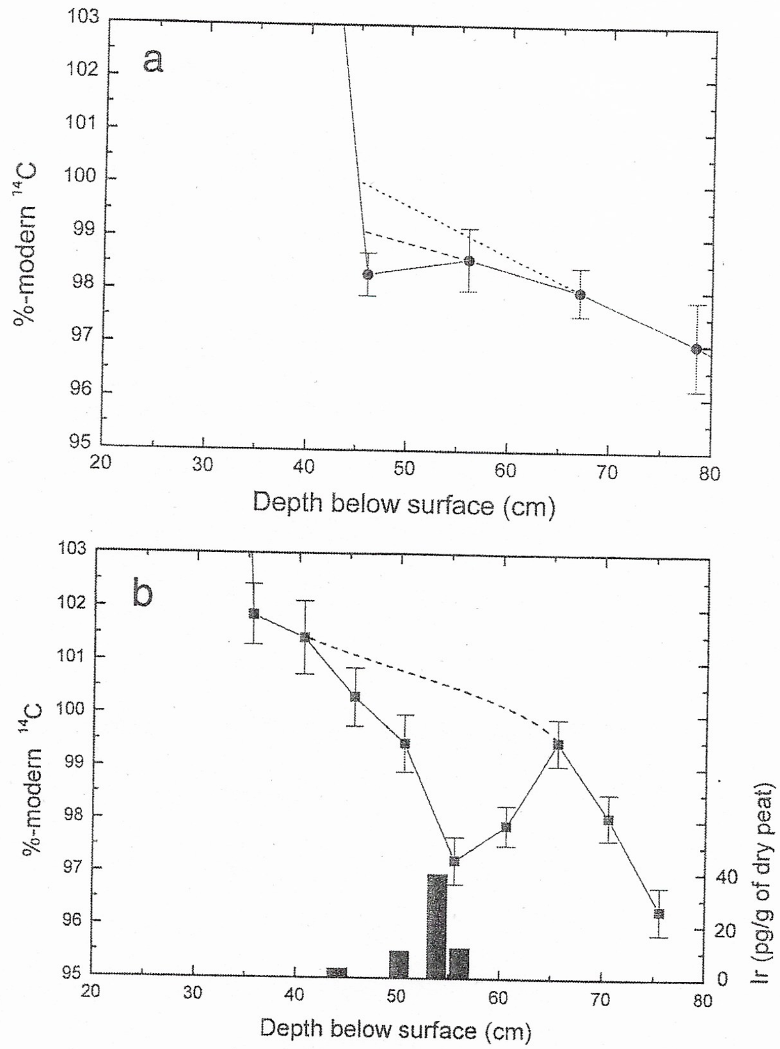

FIG. 2. Results of the radiocarbon measurements. The ^{14}C content measured as a percent of the modern (1950) value. The samples above 35 cm are influenced by bomb-produced ^{14}C. The dashed curve is an extrapolation of the points below and is the expected ^{14}C content. The excess caused by cosmic influx of nonradioactive C is seen between the dashed curve and the measurements. (a) = Core #1; (b) = Core #4. Also shown is the Ir values that are above the detection limit (from Core #2).

TABLE 2. Iridium determined by instrumental neutron activation analysis.

Chem Lab No./ Core designation	Depth interval (cm)	Average depth (cm)	Ir ng/g of ash	Ir pg/g of dry peat	Ir ng of Ir/ cm^{-2}	CI μg of CI/cm^{-2}	Ash (wt%)
KLR-525/2-18	37–39	38	<0.27	–	–	–	1.87
KLR-526/2-19	39–41	40	<0.18	–	–	–	1.16
KLR-527/2-20	41–43	42	<0.18	–	–	–	1.03
KLR-528/2-21	43–45	44	0.77	6.4	0.50	1.09	0.83
KLR-529/2-22	45–47	46	<0.16	–	–	–	0.85
KLR-530/2-23	47–49	48	<0.17	–	–	–	0.89
KLR-531/2-24	49–51	50	1.17	10.4	0.99	2.15	0.89
KLR-532/2-25	51–53	52	<0.15	–	–	–	0.85
KLR-533/2-26	53–55	54	4.81	39.9	3.36	7.31	0.83
KLR-534/2-27	55–57	56	1.31	12.8	1.04	2.26	0.97
KLR-535/2-28	57–60	58.5	<0.13	–	–	–	1.10
KLR-536/2-29	60–64	62	<0.18	–	–	–	1.38
KLR-537/2-30	64–70	67	<0.84	–	–	–	7.05

The approximate uncertainty of the Ir determination is ±20%.

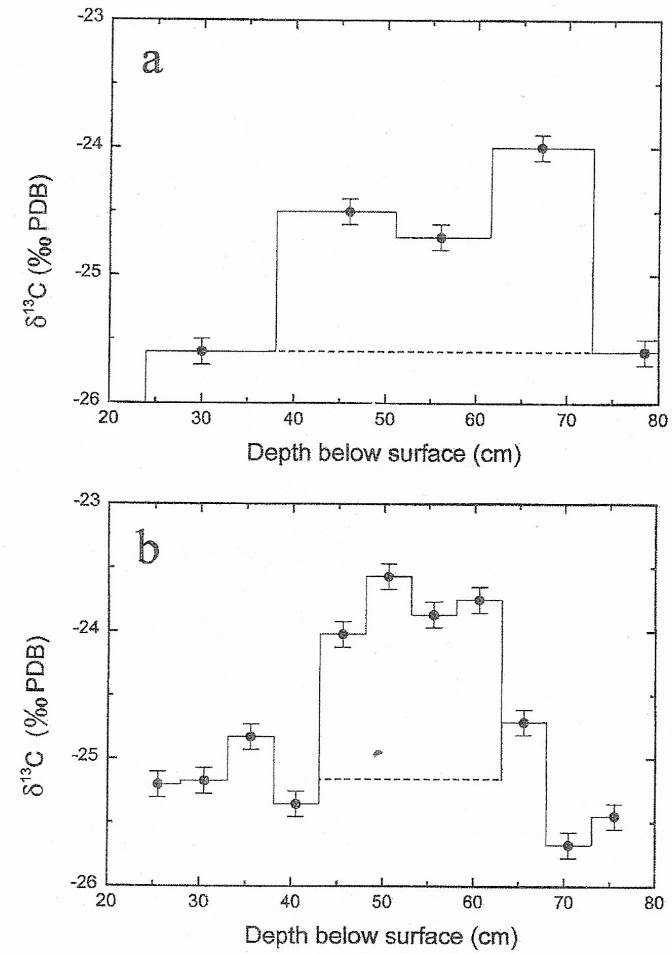

FIG. 3 The $\delta^{13}C$ measurements given in *per mille* relative to VPDB. The excess in $\delta^{13}C$ is seen between the dashed line and measurements. (a) = Core #1; (b) = Core #4.

TABLE 3. Average C and Ir concentrations and C/Ir ratios for various meteorite groups.

	C (wt%)	Ir (ng/g)	C/Ir (×10⁴)
Carbonaceous Chondrites			
CI	3.2	450	7.1
CM2	2.0	592	3.3
CO3	0.38	736	0.5
CV3	0.54	771	0.7
Ordinary Chondrites			
H	0.13	796	0.2
L	0.25	510	0.5
LL	0.12	367	0.3
Unequilibrated OC	1	600	1.7
Enstatite Chondrites			
EH4	0.42	541	0.8
EL6	0.32	519	0.6
Achondrites			
Eucrites	0.07	190	0.4
Howardites	0.14	17	8.2
Ureilites*	2.9	240	12.1
Model comets (75% ice)	1.6	113	14.0
Tunguska peat†			120 000

*Data from Warren and Kallemeyn (1992).
†Data from present work; all other data from Kring *et al.* (1996).

Integrating the total amount of Ir over the depth interval from 43–57 cm, taking the ash content and dry peat weight into consideration for each of the four samples showing Ir above background, we get an integral Ir deposition following the Tunguska impact event of 5.9 ± 1.2 pg Ir cm^{-2}. Assuming a CI Ir concentration of 460 ng/g (Wasson, 1985), this corresponds to a CI deposition of 12.8 ± 2.6 μg CI cm^{-2}.

These deposition rates yield a C/Ir ratio of $12 \pm 3 \times 10^8$, which is exceptionally high. Comparing it to various meteorite groups (see Table 3) shows that the Tunguska impactor had a C/Ir ratio of at least a factor 10^4 higher than the meteorites: Ureilites have 12×10^4, howardites have 8×10^4, CI chondrites have 7×10^4, and CM chondrites have 3×10^4. Various physical and, conceivably, also chemical processes may have influenced the C/Ir ratio of the impactor material from the time of atmospheric entry to the time of permafrost fixation, but it is hard to imagine severe loss of Ir, especially so because no excess Ir has been detected in remote regions where stratospheric transport was necessary (*e.g.*, in Greenland, Rasmussen *et al.*, 1995). Loss of C is much more likely than loss of Ir, but C loss will only make the initial C/Ir ratio more impressive. So we are forced to conclude that the very high C/Ir ratio determined experimentally is not very well in accordance with any achondritic or chondritic type impactor. Our data more likely point towards a cometary type impactor. Kring *et al.* (1996) made model predictions of cometary compositions and proposed a C content of 1.6 wt% and an Ir content of 113 ng/g, yielding a C/Ir ratio of 14×10^4 for a comet with 75% water ice. This value is also far from the $12 \pm 3 \times 10^8$ found in this study. If, however, some of the 75% water ice were substituted by CO, CO_2, or hydrocarbons, the C content of the model comet could be much higher. Consider, for the sake of argument, a comet with a CI content approaching 1% and an icy component approaching 99% methane; the C/Ir ratio of such an object would approach 1.6×10^8, a value within the order of magnitude found here. We do not wish to advocate such a bizarre composition of comets, but just point out that the C/Ir ratio found here is not entirely impossible.

As part of the normal radiocarbon dating procedure, we have also measured the $\delta^{13}C$ of the samples in core #1 and core #4. Distinct anomalies are found in both cores coinciding with the ^{14}C and Ir anomalies (see Fig. 3a,b). Using the determined excess ^{14}C and the calculated cosmic C deposition rate, we can estimate the $\delta^{13}C$ of the impactor material. For core #4, this yields $\delta^{13}C$ = +55 ± 10‰ VPDB for the impactor material. This value is similar to that found in a previous study on Tunguska peat, where $\delta^{13}C$ of the extraterrestrial material were estimated to be between +51 and +64‰ VPDB (Kolesnikov *et al.*, 1996). The same study of Kolesnikov *et al.* (1996) failed, however, to detect a pronounced ^{14}C anomaly. A possible cause for the success of the present work to detect a ^{14}C anomaly could be the utilization of larger samples, which gives a better average over the 2–3 cm depth interval sampled.

The positive $\delta^{13}C$ value of the impactor material compares well with bulk carbonaceous chondrite values, $\delta^{13}C$ = +40 to +60‰ VPDB (Halbout *et al.*, 1985). Whereas there is rather poor agreement with achondrites, for HED meteorites $\delta^{13}C$ = –30 to –20‰ VPDB (Grady *et al.*, 1997), or ordinary chondrites, $\delta^{13}C$ = –60 to –10‰ VPDB (Mostefaoui *et al.*, 1997; Alexander *et al.*, 1996).

The question arises in what form the C-rich material arrived at the surface of the Earth. If we assume as a rough estimate that the whole mass of the impactor was spread out over the ~2000 km^2 area of devastated forrest and we can take the N19 site to be representative for the deposition in this area, we arrive at a net deposition of 136 000 ±

20 000 tons of cosmic C. The estimates of the mass of the Tunguska impactor varies from 1×10^6 to 10×10^6 tons (Turco *et al.*, 1982). Precisely what chemical reactions took place during and shortly after the impact is not clear, but it may not be unrealistic to think that somewhere between 1.4 and 14% of the mass was C and became trapped in the tundra, either by adhesion to the peat or in the time after the impact by entering the peat, presumably acting like a fertilizer. Once converted to a nonvolatile form, there would be little chance later for the C to escape the vast level and vadoze tundra zone above the permafrosted ground.

The Ir deposition of 5.9 pg Ir cm^{-2} corresponds to 118 g of total Ir if equal amounts fell over a 2000 km^2 area. This number is puzzling low. Our findings are, however, in good agreement with the lack of excess Ir depositions found in both Greenland (Rasmussen *et al.*, 1995) and Antarctic ice fields (Rocchia *et al.*, 1990). From the present results, we are forced to conclude that the Tunguska impactor was indeed very depleted in Ir, but high in C. This points unambiguously to a cometary or icy type impactor, leaving anything with more than 0.1–1 % of CI complement unlikely, and also ruling out an achondritic parent body, because it is unlikely that an achondritic body would be so C-rich.

As has been noted several times before (*e.g.*, Fesenkov, 1966; Krinov, 1966; Rasmussen *et al.*, 1984; Zahnle, 1996) a cometary or icy type impactor may explain the white nights observed over northern Europe as the result of ice particles in the atmosphere, particles that may last only one or two days before they evaporate.

Acknowledgments–We are most thankful to the team of enthusiastic Danish amateur astronomers who made the trip to the Tunguska site and helped recover the core. Karen Skov, Birgit Rønne, Anette Sandbjerg, Pia Jessen, Birthe Warming, and Tove Nyberg are thanked for technical assistance. Bjørn Buchardt and the Geological Institute, University of Copenhagen, are thanked for assistance with the mass spectrometric measurements of $\delta^{13}C$. Henrik B. Clausen is thanked for discussions, and David A. Kring, Paul H. Warren, and Frank T. Kyte are thanked for helpful and constructive reviews. The support of the Carlsberg Foundation is gratefully acknowledged.

Editorial handling: W. K. Hartmann

REFERENCES

ALEXANDER C. M. O'D., ARDEN J. W., ASH R. D., GRADY M. M., RUSSEL S. S. AND PILLINGER C. T. (1996) The C and N isotopic composition of insoluble organic matter in chondrites (abstract). *Meteorit. Planet. Sci.* **31 (Suppl.),** A6.

ASHER D. J. AND STEEL D. I. (1998) On the possible relation between the Tunguska bolide and comet Encke. *Planet. Space Sci.* **46,** 205–211.

ASTAPOWITCH I. S. (1933) New data about the fall of the great meteorite on June 30, 1908, in central Siberia (in Russian). *Astron. Zh. Moskva* **10,** 465–486.

BEN-MENAHEM A. (1975) Source parameters of the Siberian explosion of June 30, 1908, from analysis and synthesis of seismic signals at four stations. *Phys. Earth Planet. Int.* **11,** 1–35.

CHYBA C. F., THOMAS P. J. AND ZAHNLE K. J. (1993) The 1908 Tunguska explosion: Atmospheric disruption of a stony asteroid. *Nature* **361,** 40–44.

FESENKOV V. (1966) A study of the Tunguska meteorite fall. *Soviet Astronomy* **10,** 195–213.

FESENKOV V. (1969) Nature of comets and the Tunguska phenomenon. *Solar System Res.* **3,** 177–179.

GRADY M. M., WRIGHT I. P. AND PILLINGER C. T. (1997) Carbon in HED basaltic achondrites. *Meteorit. Planet. Sci.* **32,** 863–868.

GRIGORIAN S. S. (1998) The cometary nature of the Tunguska meteorite: On the predictive possibilities of mathematical models. *Planet. Space Sci.* **46,** 213–217.

HALBOUT J., MAYEDA T. K. AND CLAYTON R. N. (1985) Carbon isotopes in bulk carbonaceous chondrites (abstract). *Lunar Planet. Sci.* **26,** 314–315.

HARTUNG J. B. (1993) Giodano Bruno, the June 1975 meteoroid storm, Encke, and other Taurid Complex objects. *Icarus* **104,** 280–290.

HASL-278 (1974) *United States Atomic Energy Commission. Health and Safety Laboratory 1974. Appendix. Fallout program; quarterly summary report, January 1, 1974.* U.S. Atomic Energy Commission, New York.

KOLESNIKOV E. M., BÖTTGER T., HILLER A., JUNGE F. W. AND KOLESNIKOVA N. V. (1996) Isotope anomalies of carbon, hydrogen and nitrogen in peat from the area of the Tunguska cosmic body explosion (1908). *Isotopes Environ. Health Stud.* **32,** 347–361.

KORINA M. I., NAZAROV M. A., BARSUKOVA L. D., SUPONEVA I. V., KOLESOV G. M. AND KOLESNIKOV E. M. (1987) Iridium distribution in the peat layers from the area of the Tunguska event (abstract). *Lunar Planet. Sci.* **18,** 501–502.

KRING D. A., MELOSH H. J. AND HUNTEN D. M. (1996) Impact-induced perturbations of atmospheric sulfur. *Earth Planet. Sci. Lett.* **140,** 201–212.

KRINOV E. L. (1966) *Giant Meteorites.* Pergamon, Oxford, U.K. 397 pp.

KULIK L. A. (1927) Report of the meteorite expedition. *Dokl. Acad. Nauk. SSSR Ser. A* **23,** 399–402.

LYNE J. E., TAUBER M. AND FOUGHT R. (1996) An analytical model of the atmospheric entry of large meteors and its application to the Tunguska event. *J. Geophys. Res.* **101,** 23 207–23 212.

MOOK W. G. AND WATERBOLK H. T. (1985) *Handbooks for Archaeologists, No. 3, Radiocarbon Dating.* European Science Foundation, Strasbourg, Germany. 65 pp.

MOSTEFAOUI S., ZINNER E., HOPPE P. AND EL GORESY A. (1997) In situ survey of graphite in unequilibrated chondrites: Morphologies, C, N, and H isotopes (abstract). *Lunar Planet. Sci.* **23,** 989–990.

NAZAROV M. A., KORINA M. I., BARSUKOVA L. D., KOLESNIKOV E. M., SUPONEVA I. V. AND KOLESOV G. M. (1990) Material traces of the Tunguska bolide (in Russian). *Geokhimiya* **5,** 627–638. *Geochemistry International* **27,** 1–12 (in English).

RASMUSSEN K. L., CLAUSEN H. B. AND RISBO T. (1984) Nitrate in the Greenland ice sheet in the years following the 1908 Tunguska event. *Icarus* **58,** 101–108.

RASMUSSEN K. L., CLAUSEN H. B. AND KALLEMEYN G. W. (1995) No iridium anomaly after the 1908 Tunguska impact: Evidence from a Greenland ice core. *Meteoritics* **30,** 634–638.

ROCCHIA R., BONTE P., JEHANNO C., ROBIN E., ANGELIS M. AND BOCLET D. (1990) Search for the Tunguska event relics in the Antarctic snow and new estimation of the cosmic iridium accretion rate. In *Global Catastrophes in Earth History* (eds. V. L. Sharpton and P. D. Ward), pp. 189–193. GSA Spec. Publ. **247,** Boulder, Colorado, USA.

SEKANINA Z. (1998) Evidence for asteroidal origin of the Tunguska object. *Planet. Space Sci.* **46,** 191–204.

STUIVER M., REIMER J., BARD E., BECK J. W., BURR G. S., HUGHEN K. A., KROMER B., MCCORMAC G., VAN DER PLICHT J. AND SPURK M. (1998) INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40,** 1041–1083.

TURCO R. P., TOON O. B., PARK C., WHITTE R. C., POLLACK J. B. AND NOERDLINGER P. (1982) An analysis of the physical, chemical, optical, and historical impacts of the 1908 Tunguska meteor fall. *Icarus* **50,** 1–52.

WARREN P. H. AND KALLEMEYN G. W. (1992) Explosive volcanism and the graphite-oxygen fugacity buffer on the parent asteroid(s) of the ureilite meteorites. *Icarus* **100,** 110–126.

WASSON J. T. (1985) *Meteorites—Their Record of Early Solar-System History.* Freeman, New York, New York, USA. 267 pp.

WHIPPLE F. J. W. (1930) The great Siberian meteor and the waves, seismic and aerial, which it produced. *Quart. J. Roy. Meteorol. Soc.* **56,** 287–304.

WICK G. L. AND ISAACS J. D. (1974) Tungus event revisited.. *Nature* **247,** 139–140.

ZAHNLE K. (1996) Leaving no stone unburned. *Nature* **383,** 674–675.