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The cometary breakup hypothesis re-examined

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Summary. The theory that a Chiron-like progenitor of both Comet Encke and the Tunguska cosmic body may have fragmented beginning around 22 000 years BP and that debris from this breakup was responsible for producing the high heavy metal concentrations observed in the Late Wisconsin stage polar ice is shown to be incorrectly founded. This paper re-examines the geochemical comparison which Clube & Napier make between the composition of the Tunguska cosmic body and elemental abundances previously reported for a sample of Sn-rich dust retrieved from the Wisconsin section of the Camp Century ice core. No evidence is found that would link these two sources to a common origin. Thus the hypothesis that a cometary breakup was responsible for modulating the Earth's climate and perpetuating the last ice age is unfounded. On the other hand, evidence is presented indicating that debris from the Tunguska explosion may be present in a firn layer at Dome C, East Antarctica. Analysis of the geochemical data for this stratum leads to an estimate of 10^6–10^7 t for the mass of the Tunguska body, in approximate agreement with previous determinations.

1 Introduction

LaViolette (1983a, 1983b, 1983c, 1985, 1987, to be published) has reported the presence of high levels of Ir, Ni, and other heavy metals in samples of ice retrieved from the Wisconsin stage portion of the 1387-m deep ice core drilled at Camp Century, Greenland. He carried out this geochemical study in order to test an astronomical hypothesis, formulated in 1979, which proposed a link between terrestrial climatic oscillations and the passage through the Solar System of strongly relativistic Galactic cosmic ray volleys, termed 'galactic superwaves' (LaViolette 1983a, 1987). He reasoned that an impacting superwave would have generated propagating hydromagnetic shocks behind the bow shock front surrounding the heliopause sheath and that these fronts in turn would have propelled large quantities of micron- and submicron-sized cosmic dust particles into the Solar System. If such light-scattering particles had entered the interplanetary environment in sufficient quantities they could have altered the Earth's climate.

In particular, astronomical and geological evidence appeared to suggest that one such superwave had passed through the solar vicinity toward the end of the last ice age, raising the local cosmic ray electron background intensity by over five orders of magnitude (LaViolette 1983a, 1987). At such high intensities the cosmic ray energy density within the bow shock front radiation belt could have been sufficiently high to vaporize the outer surfaces of comets transiting this region, thus making available for propulsion a considerable quantity of cosmic dust.

LaViolette reasoned that if such a cosmic dust incursion had occurred, it should be possible to find evidence of enhanced cosmic dust concentrations in the Wisconsin stage portion of the Earth's polar ice record. Consequently eight polar ice core samples spanning the period 20 000–14 000 yr BP were geochemically analysed to determine the content of the cosmic dust indicators Ir and Ni. The data indicated that extraterrestrial material accretion rates were at times one to two orders of magnitude higher than present rates, consistent with the superwave scenario (LaViolette 1983a, 1983b, 1983c, 1985, 1987).

Clube & Napier (1984) later proposed a different interpretation of these results. They have suggested that the high cosmic dust concentrations in polar ice indicate that a giant 100-km diameter comet (mass $\sim 10^{21}$ g) entered the inner part of the Solar System and began to disintegrate around 22 000 yr ago creating an elliptical torus of debris of major axis length 2.28 AU. They suggest that during times when the Earth passed through this torus, cometary dust entered the Earth's upper atmosphere and that the resulting stratospheric light attenuation was primarily responsible for initiating and perpetuating the most recent glaciation. They suggest that the glacial period began around 22 000 yr ago, however, it is commonly believed that the Wisconsin Ice Age began on the order of 70 000–90 000 yr BP. The date they propose would more appropriately correlate with the beginning of the Late Glacial Maximum.

Their hypothesis that the cosmic dust detected in Late Wisconsin polar ice is derived from a cometary breakup rests critically on their claim that this glacial dust and the Tunguska cosmic body, which impacted in Siberia in 1908, have a common origin and similar composition. They establish a connection between the Tunguska body and their proposed progenitor comet by citing evidence which suggests that the Tunguska body, Comet Encke, and the β Taurid meteor stream all seem to have a common origin and are quite likely fragments derived from the breakup of a single cometary body.

2 Geochemical evidence re-examined

To support their cometary breakup scenario, Clube & Napier make a comparison in fig. 3 of their paper between the geochemical composition of the Tunguska cosmic body and a Sn-rich dust sample taken from the Late Wisconsin portion of the Camp Century ice core at a depth of 1234.7 m. For the composition of the Tunguska body they quote values from table 3 of the paper by Golenetskii, Stepanok & Murashov (1981) and for the Sn-rich sample they cite values reported by LaViolette (1983a, 1983b).

However, in carrying out this comparison, they mistakenly represent the values of Golenetskii *et al.* (1981) as being actual compositional measurements of the Tunguska body when, in fact, these values are stated by the latter authors to be *hypothetical extrapolations.* According to Golenetskii *et al.* these figures give the expected composition of a hypothetical cometary body having a Zn/Fe ratio of about 2, the listed values being based on projections of compositional trends observed in the progression from C3 to C1 carbonaceous chondrites. It is indeed true that the residues of the Tunguska body have been found to have a Zn/Fe ratio in this range. However, to adopt a general trend projection of this sort as a representation of the Tunguska body composition is to engage in speculation. Thus the geochemical comparison which Clube & Napier present is not very convincing.

When the data for this ice core sample are instead compared to actual geochemical measurements made on residues from the Tunguska cosmic body, little similarity is seen. For example, the first column of data in Table 1 lists abundance determinations for eight elements for the debris layer in core *C* penetrated in peat at the Tunguska explosion site (Golenetskii, Stepanok &

Table 1. A comparison of the composition of Tunguska cosmic body peat residues to elemental abundances for the Camp Century ice core Sn-rich dust sample.

	Tunguska Cosmic Body		Sn-rich dust
Element	Concen.[1]	EF[2]	EF[2]
Fe	7.5%	0.39	<0.13
Co	74	0.15	<0.07
Zn	19.0%	610	<10
Mo	26	28	<22
Ag	~1[3]	~5[3]	1850
Sn	20	11.6	3.5×10^5
Sb	<40	<250	1235
Cs	<260	<1300	9.2
Au	3.2	23	140

[1] All values are in parts per million except Fe and Zn (%).
[2] Enhancement factors relative to Cl chondrite abundances.
[3] Measured in silicate microspheres from the peat layer.

Kolesnikov 1977), and the adjacent column lists the corresponding enhancement factors relative to the composition of C1 chondrites. These values may be compared to the quantities listed in the last column which give enhancement factors for dust from the Sn-rich ice core sample, again normalized relative to a C1 chondrite composition. These data pairs are plotted in Fig. 1 for comparison.

As may be seen in Fig. 1, Sn is enhanced in Tunguska peat by only an order of magnitude above Solar System abundances, rather than by three orders of magnitude as Clube & Napier (1984) suggest. Hence when actual data are considered it is found that Sn is over four orders of magnitude more abundant in the polar ice core sample. The elements Sb and Cs, which Clube & Napier state to be enhanced by two orders of magnitude relative to C1 abundances, in fact showed no significant increase above background concentrations normally contained in the peat matrix at the Tunguska site; see Fig. 2.

Clube & Napier quote Ag as being present in the Tunguska body at concentrations five orders of magnitude greater than cosmic abundances, but in fact it appears to be present at concentrations over four orders of magnitude lower than this. There is no mention of the detection of silver in the Tunguska peat data reported by Golenetskii *et al.* (1977). However, Kolesnikov, Lyul' & Ivanova (1977) do report the detection of Ag in a few cosmic spherules found at the explosion site. They report concentrations of around 1 ppm, which if taken as being representative of the Tunguska cosmic body would project an enhancement factor for Ag of only five-fold above Solar System abundances.

Gold appears to be about six times less abundant in the Tunguska residues. Also it may be seen that Zn is at least 60 times more abundant in these residues. The discrepancy for Zn, however, could be greater since the ice core data only yield an upper limit concentration.

When the geochemical data are properly represented in this way, it is seen that the two dust sources actually have quite different compositions and most likely are derived from different sources. Thus Clube and Napier's claim that the Tunguska cosmic body and the Sn-rich ice core dust sample are compositionally similar appears to be unfounded.

3 The absence of cosmic microspheres

But, there are other reasons for questioning the comet breakup scenario. For example, such a fragmentation event would not only have produced dust, but sand and boulders as well, as Clube

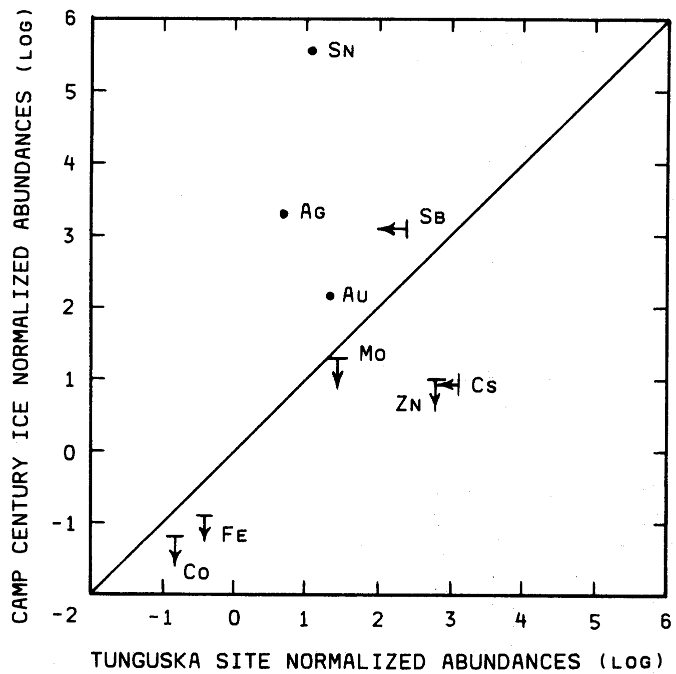

Figure 1. Logarithmic plot of elemental abundances in the 1235-m deep Camp Century ice core dust sample compared to abundances in the debris layer at the Tunguska explosion site. Values have been normalized relative to a C1 chondrite composition.

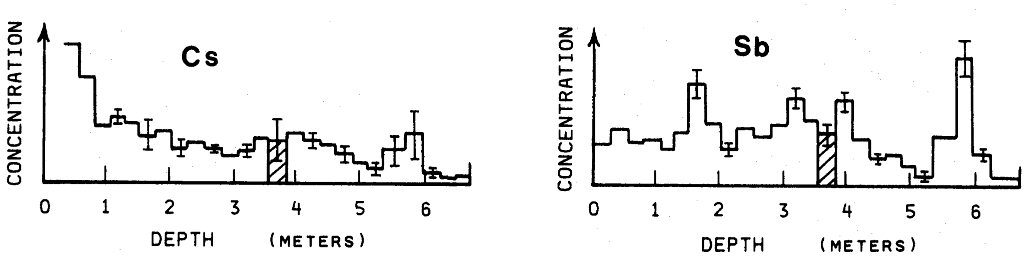

Figure 2. Layer-by-layer variation with depth in the concentration of Cs and Sb in peat column 'C' penetrated at the Tunguska explosion site. The cross-hatched region denotes the cometary debris layer (after Golenetskiy *et al.* 1977).

& Napier point out. In fact, material larger than 100 μm in size would most likely have made up the majority of the mass of this debris. But such material would have ablated upon entering the Earth's atmosphere and formed cosmic microspheres (Whipple 1951). Fluffy, low-density particles ($\varrho \sim 0.1$ g cm^{-3}), similar to the chondritic porous particles retrieved from the strotosphere, might have been able to enter the atmosphere at a sufficiently low terminal velocity to avoid melting. However, for debris of greater density ablation would have been inevitable. Consequently according to this cometary breakup scenario, one would expect to find evidence of an enhanced concentration of ablation products in the Late Wisconsin portion of the polar ice record. But as Thompson (1977) reports, both the Camp Century and Byrd Station ice cores show a relatively constant occurrence of cosmic microspheres along their entire length.

That ablatable material would have been present in large quantities is evident from recent spacecraft rendezvous with Halley's Comet. At a distance of about 8000 km from the comet's nucleus the *Giotto* spacecraft was sand blasted by a barrage of dust particles, each grain being about 0.5 mm in size and weighing about 30 μg (Henbest 1986). At a distance of about 700 km the spacecraft impacted a particularly large-sized chunk of debris and as a result temporarily lost signal contact with Earth, its television transmission apparatus being left permanently inoperable. The *Vega 2* probe also suffered major damage when it encountered a blast of large-size cometary dust particles and experienced a 50 per cent loss of power from its solar cell array. Unless Halley's Comet is a unique example, it may be concluded that the progenitor of Comet Encke would also have contained sand-grain-sized particles which would have ablated had they encountered the Earth's atmosphere.

Out of the eight Camp Century ice core samples that LaViolette studied, the Sn-rich sample is believed to have contained the highest percentage of extraterrestrial material, roughly 70 per cent of the total sample weight (LaViolette 1987, to be published). Over the 20-yr period spanned by this sample, extraterrestrial material is estimated to have been accumulating at the rate of about 10^{14}–10^{15} g yr^{-1}, or to an equivalent of about 10 Tunguska-sized bodies yr^{-1}. Thus of any of the samples this one should have contained the greatest quantity of ablatable material if indeed this material is derived from a cometary breakup. However, electron microscope studies carried out on portions of the Sn-rich dust sample reveal an absence of cosmic spherule ablation products (LaViolette 1987, to be published).

In view of these negative findings it may be concluded that this extraterrestrial material must have been present in the interplanetary medium primarily in finely divided form, e.g. as micron- and submicron-sized particles. This would then favour cosmic dust incursion over cometary breakup as the source of this material.

Clube & Napier (1984) also state that the influx of debris from a cometary breakup should have caused a climatic cooling due to the presence of submicron debris in the stratosphere. If this were so, then one would expect to find that high heavy metal concentrations in the ice correlate with periods of climatic cooling. But this is not found to be the case. Instead, the ice core record indicates that these element concentrations tend to correlate with climatic warming episodes (LaViolette 1987, to be published). Such observations are consistent with the cosmic dust incursion scenario since a nebular cloud of submicron particles distributed throughout the interplanetary environment should have produced a net increase in the Earth's solar energy budget (LaViolette 1983a, 1987, to be published).

4 A polar ice layer marking the Tunguska explosion?

Tunguska body compositional data might be more appropriately correlated with geochemical analyses performed on more contemporary polar ice strata. For example, there is evidence that dust from the Tunguska aerial explosion became injected into the stratosphere and eventually found its way into Antarctic ice. Ganapathy (1983) has analysed a portion of a South Pole ice core spanning the time of the explosion event, an ice core date of 1912±4 to 1918±4, and finds that during this period Ir concentration in the ice rose five- to six-fold above background levels.

Also, three years prior to Ganapathy's work, Boutron (1980) had published data for analyses performed on firn samples retrieved from Dome C, East Antarctica, covering the period 1883–1977. In two of these samples, spanning the period 1912±6 to 1916±6, the elements Zn, Pb, Cu, Cd, Al, Fe, Mn, and Ca are found to increase above background levels by one to two orders of magnitude. Using the Zn concentration peak deposited by the 1883 Krakatoa eruption as a time marker, the dating of this interval becomes recalibrated as 1909±6 to 1913±6. Thus the date for this concentration spike correlates very well with the Tunguska event.

Boutron has interpreted the 1912–16 elemental anomaly as being from a volcanic source. However, there is no clear evidence of nearby volcanic eruptions having taken place. During this period there were a series of eruptions at Deception Island (63°S, 61°W), but this volcano is located 4000 km away. By comparison the 1883 Krakatoa explosion (6°S, 185°E), the largest explosive eruption of the past century, which is estimated to have injected on the order of 10^8 t of material into the stratosphere (Mitchell 1975), produced a Zn enhancement in the Dome C record only 5 per cent as high as the 1912–16 Zn peak.

A more plausible alternative is that the 1912–16 concentration spike was produced by the Tunguska explosion event. A Tunguska origin for this elemental anomaly is supported by the observation that Zn, which made the most dramatic increase at this Antarctic site, is also reported by Golenetskii *et al.* (1977) to be a primary trace element constituent of the Tunguska debris. Moreover it is found that the Al/Fe, Zn/Fe, and Pb/Fe ratios observed at Dome C are roughly comparable to those found in residues at the Siberian explosion site. For example, Table 2 compares elemental ratios derived from Boutron's data for the '1912–16' event to ratios found in the debris layer of Core C reported by Golenetskii *et al.* (1977). The fact that these values are within an order of magnitude of one another suggests that this concentration spike was very likely produced by the Tunguska event.

Table 2. A comparison of elemental ratios observed at the Tunguska explosion site and in East Antarctic ice.

Elements	Tunguska site	East Antarctica
Al/Fe	0.25	0.9
Zn/Fe	2.5	0.8
Pb/Fe	4.5×10^{-3}	0.1

Based on the Fe and Zn concentrations observed in the Dome C firn record, it should be possible to estimate the initial mass of the Tunguska body. For example, based on Boutron's data it may be estimated that during the 1912–16 interval Fe and Zn had excesses above background averaging 3.5 and 2.8 μg l^{-1}, respectively. Taking the concentrations of these elements to be 7.5 and 19 per cent, respectively, consistent with the figures reported by (Golenetskii *et al.* 1977) for the Tunguska debris, the total dust concentration in this firn section would have averaged 30 ± 15 μg l^{-1}. Given that the snow at Dome C accumulates at the rate of 4 cm yr^{-1} and assuming that the material distributes globally in a uniform manner, a total ejected mass of $2.6\pm1.3\times10^6$ t is estimated, which is comparable to the estimate of Bronshten & Boyarkina (1975) of 2×10^6 t for the Tunguska body mass; also see Levin & Bronshten (1986). If it is instead assumed that the dust deposition rate at Dome C would have been four-fold lower than the global average, as Ganapathy (1983) has assumed in arriving at his estimate from his South Pole measurements, then a total ejected mass of $1.0\pm0.5\times10^7$ t is estimated, which is in agreement with Ganapathy's estimate of 7×10^6 t.

The estimate of the cometary dust mass derived here argues against the suggestion made by Golenetskii *et al.* (1981) that the mineral remnants of the explosion only amounted to 2×10^3 t. Thus if volatiles were a principal component of the Tunguska body, as the latter argue, it would be necessary to project a much greater mass for the Tunguska body. However, in view of the mass and density estimates discussed by Levin & Bronshten (1986), a large cometary mass dominated by frozen volatiles seems unlikely.

5 Conclusion

It is quite possible that Clube & Napier are correct in their suggestion that Comet Encke and the Tunguska body are both remnants of a larger parent body which once entered the Solar System and broke up. However, in view of the lack of supporting ice core data, their suggestions that this progenitor comet had a mass as large as 10^{21} g and that it began its breakup about 22 000 yr ago are largely circumstantial. Also circumstantial are their claims that climatic fluctuations of the Late Wisconsin might be linked to a cometary breakup.

On the basis of the comparison made in Table 1, really all that can be stated is that the Tunguska cosmic body and the Sn-rich Camp Century ice core dust sample both exhibit anomalously high abundances of low-melting-point elements in varying degrees. Taking into account the suggestion of Golenetskii *et al.* (1981) that comets contain high concentrations of volatile and low-melting-point elements, it may be concluded that the Tunguska body and the extraterrestrial dust deposited in Late Wisconsin ice are similar only to the extent that they both are most probably of cometary derivation.

References

Boutron, C, J., 1980. *Geophys. Res.*, **85,** 7426.
Bronshten, V. A. & Boyarkina, A. P., 1975. In: *Problemy Meteoritiki,* Nauka (Siberian branch), Novosibirsk, 47.
Clube, S. V. M. & Napier, W. M., 1984. *Mon. Not. R. astr. Soc.*, **211,** 953.
Ganapathy, R., 1983. *Science,* **220,** 1158.
Golenetskii, S. P., Stepanok, V. V. & Kolesnikov, E. M., 1977. *Geokhimiya,* **11,** 1635.
Golenetskii, S. P., Stepanok, V. V. & Murashov, D. A., 1981. *Astr. Vestn.*, **15,** 167.
Henbest, N., 1986. *New Scient.*, March 20, 37.
Kolesnikov, E. M., Lyul', A. Yu. & Ivanova, G. M., 1977. *Astr. Vestn.*, **11,** 209.
LaViolette, P. A., 1983a. *PhD thesis,* Portland State University.
LaViolette, P. A., 1983b. *Meteorit.*, **18,** 336.
LaViolette, P. A., 1983c. *EOS,* **64,** 286.
LaViolette, P. A., 1985. *Meteorit.*, **20,** 545, 803.
LaViolette, P. A., 1987. *Earth, Moon, and Planets,* **38,** 1.
Levin, B. Yu. & Bronshten, V. A., 1986. *Meteorit.*, **21,** 199.
Mitchell, J. M., 1975. In: *The Changing Global Environment,* p. 149, ed. Singer, S. F., Reidel, Hingham, Massachusetts.
Thompson, L. G., 1977. In: *Isotopes and Impurities in Snow and Ice, Proc. Grenoble Symp., 1975, IAHS Publ. No. 118,* P. 351.
Whipple, F. L., 1951. *Proc. Nat. Acad. Sci.*, **37,** 19.