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TUNGUSKA 1908

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Abstract In the literature, the Siberian forest destruction of 30 June 1908 – north of the Stony Tunguska river – is almost unanimously explained by the impact of some huge meteorite even though no trace of it has ever been found, and even though some 20 facts argue in favour of a tectonic event. An in-depth discussion plus a comparison with smaller, more recent events suggest that we deal with the – first recorded – present-day formation of a kimberlite.

Key words: Tunguska – catastrophe – outburst – kimberlite – impact – NEOs

1 WHAT HAS HAPPENED?

In the early morning of 30 June 1908, hell broke loose around the center of the 250 Myr-old Kulikovskii volcanic crater – with epicenter at $(101°53'40''\mathrm{E}, 60°53'09''\mathrm{N})$ – more than 700 km north-northwest of lake Baikal: The ground trembled, Barisal guns were heard firing (also called 'brontides': Gold & Soter, 1979), gusts blew, and the sky was torn by columns of fire. Trees were debranched, felled, or their tops chopped off in an on-average radial pattern, over an area of 2150 km^2, and scorched in patches over a central area adding up to some 20% that extent. Hunters and herdsmen, tepees, storage huts, and reindeer were hurled aloft and/or incinerated. Even at Vanavara – the nearest trading post, at a distance of 65 km from the epicenter – people felt burning heat in their faces and were thrown off their feet (Krinov, 1966; Gallant, 1994; Zahnle, 1996; Vasilyev, 1996; Ol'khovatov, 1999).

What caused the destruction? This part of the Siberian permafrost taiga is not easily accessible; it is snow-covered throughout most of the year, and defended by clouds of mosquitos during the few summer months. The first expedition into the area, in 1910, was carried out by the wealthy Russian merchant and goldsmith Suzdalev who, on return, urged the local inhabitants to keep silent about it. Had he discovered diamonds? Thorough investigations of the site, headed by Leonid Kulik, had to wait for 20 years, and were aimed at finding iron-nickel meteoritic debris. According to eyewitness reports, a number of funnel-shaped 'holes' had been blown on that morning, of diameters $\lesssim$50 m, as well as a 'huge dry ditch', probably $\gtrsim$ 1 km long, with many small 'stones' in it. That ditch has not been found by later expeditions. For the most suspicious crater lake in the area, the 'Suslov' hole, draining revealed a preserved tree stump at its bottom, ruling against an impact origin.

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Scientific research into the cause of the destruction has continued until today, by almost yearly international expeditions. Various abundance tests on soil, peat, and tree-resin have shown distinct anomalies which were published under the headline of the 'Tunguska Cosmic Body' (TCB) but were all consistent with earthquakes or outgassing (Serra et al, 1994). If a cosmic body of weight 0.4 Mt had decomposed in the atmosphere – as evaluated e.g. by Svetsov (1996) and Foschini (1999) on energetic grounds (to flatten the woods) – it should have left an on average several mm thick layer of debris in the epicenter area, easy to detect. Even fragments of 10^5 times less massive meteorites have been recovered. This fact argues against a (stony) asteroid, in favour of a cometary fragment (or a carbonaceous chondrite), which would have largely evaporated at great height. But if decomposed at great height, such an impactor cannot explain the clustered element and isotope enrichments, and in particular cannot explain the detailed treefall pattern (to be discussed below). And an Earth-approaching comet would have been discovered weeks before impact, like comet Encke. There have been long-standing controversies, in the literature, between the rocky camp and the icy camp. Farinella et al (2001) ignore all such 'details', as well as the strong orbit uncertainties listed by Vasilyev (1998).

Instead, the preferred geography of the 1908 destruction center is clearly visible from a satellite, see Fig. 1. The Kulikovskii crater forms part of the Khushminskii tectono-volcanic complex. Several tectonic faults pass through this region, one of them running towards lake Baikal. Kulik spoke of the 'Merrill circus' surrounded by an 'amphi-theatre' when describing the geometry of the central 'cauldron'. At the 2001 Tunguska conference at Moscow, G.G. Kochemasov and I.P. Jerebchenko stressed the preferred location of the epicenter, not far from the center of the Siberian craton, at an Asian geomagnetic and heat flow maximum, surrounded also by ringlike structures of Moho isohypses and river-net patterns, of radii ranging from 50 km through as far as many hundred km. They even reported on lanes of kimberlites (see section 2), one of them straddling the Tunguska site.

Independently of its preferred location, the Tunguska catastrophe has a number of characteristics which qualify against an infall interpretation. To begin with, there is the treefall pattern mapped coarsely in Fig. 2. In its unresolved central area – the cauldron – Kulik identified five distinct felling centers, of mutual separations $\gtrsim 1$ km, from his air photographs taken in 1939. This central area contains islands of 'telegragh poles', i.e. standing trees which have lost all their branches (but did not necessarily die), like in the nearzone of the Hiroshima bomb. Such debranched trees require (sharp-edged, supersonic) shock waves for their formation, which break off the branches before the latter can transfer the impact momentum to the stem. At larger separations, the treefall pattern is coarsely radial, but follows the ridges and valleys, leaving islands of survival right up to the cauldron, mainly in the valleys, and islands of destruction elsewhere. Krinov (1966) has sketched a destruction profile, along the banks of the river Markita which shows unhurt trees in the valley, chopped-off tops on the slope, and felled trees on approach of the ridge.

This pattern of destruction requires several (≥ 5) successive explosions near the ground, in the cauldron area, which launched a big (subsonic) horizontal storm in the surroundings that took tens of kilometers to die off, under radial expansion. A decomposing cosmic body infalling at shallow angle – such as conceived of, e.g., by Bronshten (1991, 2000) – would produce a very different scene: its blast wave would inherit the body's infall momentum which, on transfer to the trees, would create a parallel fall pattern, and not spare the valleys. A radial pattern requires a zero-momentum explosion very near the ground; according to Krinov (1966), such explosions are set up by massive meteorites right after impact, for crater diameters $\gtrsim 100$ m.

Another peculiarity of the Tunguska destruction are the dozens of root stumps, disconnected from their stems, whose origins (pits) could not be detected by the expeditions. Some of them are still lying around today. They must have been hurled through at least dozens of meters,

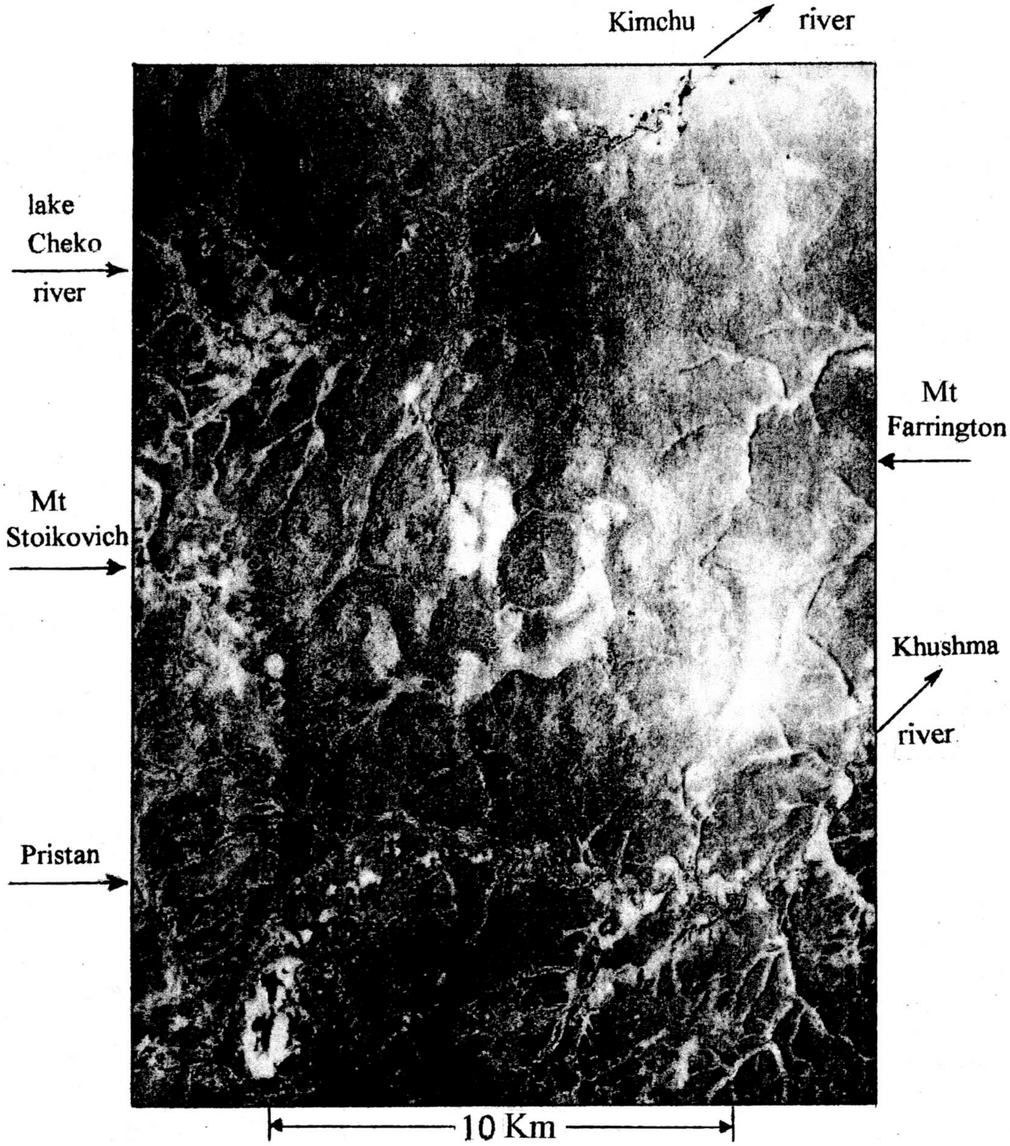

Fig. 1 False-colour near-IR satellite photograph of the central ('cauldron') region of the 1908 Tunguska catastrophe, roughly 10 km in extent, and centered on Mt. Stoikovich. Arrows in the margin continue the rough flow directions of the rivers Cheko, Kimchu, and Khushma which border the area in the north and south. The Kimchu river flows through lake Cheko (in the NW of the map). Mt. Farrington, N-NE from Mt. Stoikovich, allows a good view of the swamps and surrounding mountain chains. Note the preferred geometry of the cauldron – even detectable from space – which led Kulik to speak of the 'Merrill circus' inside an 'amphi-theatre'.

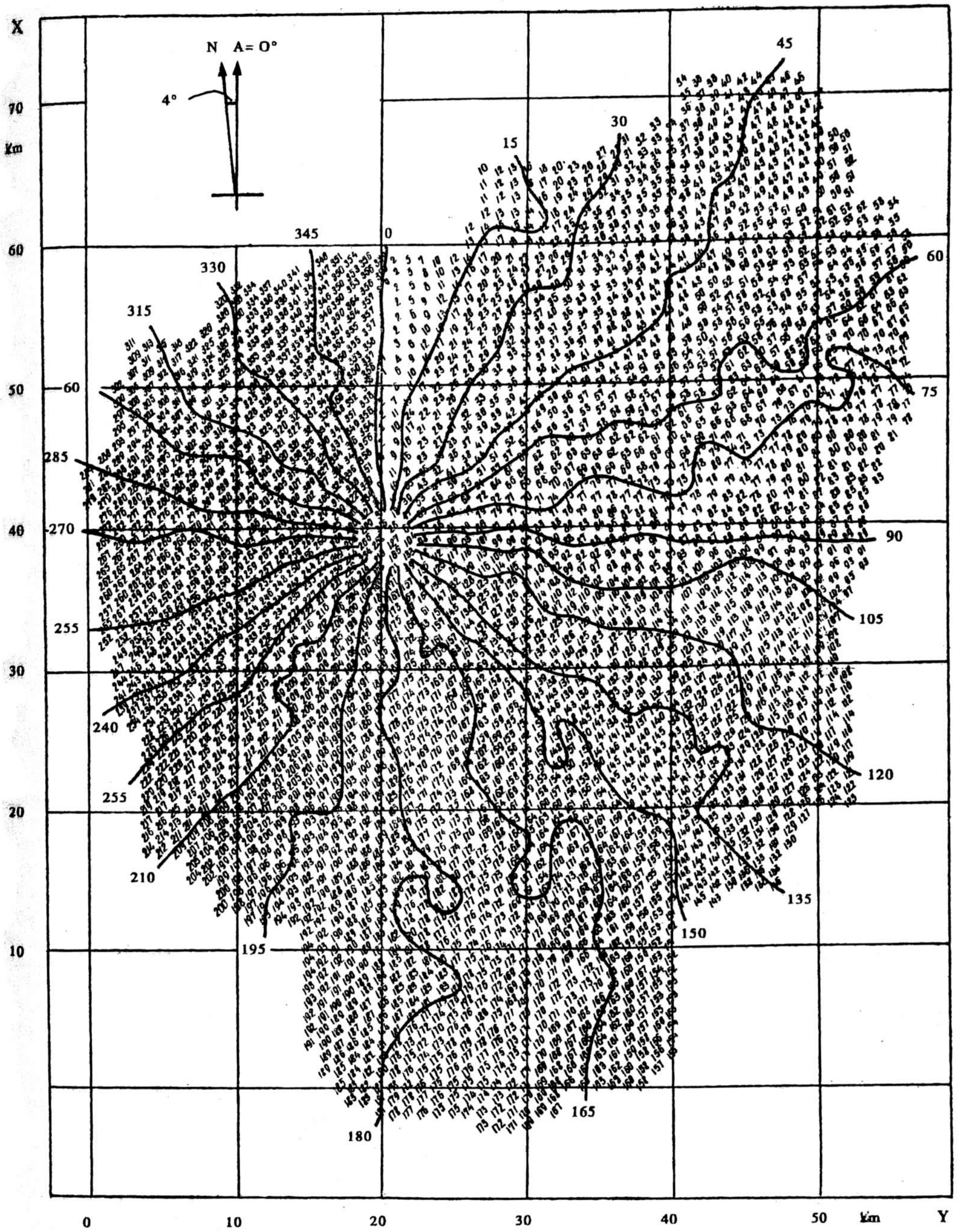

Fig. 2 Isolines of the Tunguska treefall pattern, taken from Serra et al (1994): Connected are points on the map in whose 1 km^2 neighbourhoods the felled trees had the same average orientation, as noted on the outer edge of the destruction area (in degrees). Obvious is a coarsely radial pattern with strong local deviations.

like 'John's stone', a rock weighing 10 t which landed on the slope of Mt. Stoikevich with at least sonic speed. Such structured ejecta cannot be formed by impact; they require forces from below.

2 TUNGUSKA OF TERRESTRIAL ORIGIN?

In the preceding section, a number of reasons have already been given in favour of a terrestrial origin of the Tunguska catastrophe, such as the (i) radial but distorted treefall pattern with (ii) islands of survival and destruction and with (iii) Krinov's (inverted) tree-chopping profile, (iv) telegraph poles around the five centers, (v) many funnel-shaped holes in the swamps, with a tree stump at the bottom of the Suslov hole, (the most suspicious one), (vi) detached root stumps, (vii) John's stone, (viii) absence of meteoritic debris, (ix) chemical anomalies reminiscent of outgassings, (x) decade-long debate among scientists that neither an asteroid nor a comet would qualify as the TCB, (xi) preferred geography of the cauldron (described by Kulik) and (xii) its long-distance surroundings, being near the center of the Siberian craton, with radiating fault lines, and (xiii) eyewitness reports speaking of 'columns of fire' (xiv) preceded by 'barisal guns', whereas a quasi-horizontal luminous trail would be expected with subsequent noise (from the trail and impact). Here it should be mentioned, as a follow-up on item (xii), that deposits of natural gas are being found within a few 10^2 km of the site, as well as (xv) arrays of kimberlites, and that (xvi) a radonic outburst was recorded by the 1999 Italian expedition to lake Cheko, lasting four hours.

As a further reason in favour of a terrestrial (tectonic) origin – discussed in (Kundt, 2001) – there is the (xvii) heat felt in the faces of eyewitnesses at Vanavara. Such a sensation is reminiscent of bonfires, and requires a large spherical angle of the sky to be filled with hot matter (gas) of large column density, larger than provided by a (distant) meteoritic trail. Moreover, (xviii) during the nights between 29 June and 2 July, the sky did not fall dark in Europe and western Asia, down to the northern latitude of 42° (of Tashkent). This phenomenon, reminiscent of the 1883 Krakatao volcanic eruption, requires transient scatterers in the thermosphere, above 500 km, at heights which only methane and hydrogen are light enough to reach in sufficient quantity, molecules whose weight does not exceed that of atomic oxygen. Bronshten (1991, 2000) tries to explain these 'bright nights' by softly braked cometary dust, settling to mesospheric heights (50–70 km), but has to make a number of unrealistic assumptions – among them a twofold sunlight reflection from dusty clouds – and still falls short of explaining the four successive bright nights, starting during the (European) late night of the explosion, culminatig on 30 June, and terminating around midnight of 2 July.

Instead, (xix) fast rising natural gas has been repeatedly detected in recent years, in the form of 'mystery clouds' – by airplane pilots and satellite photography – and indirectly as 'pockmarks' on 6% of the sea floor (Walker, 1985). The clouds rise from an unresolved spot on the surface – land or water – and expand and bend downwind as they rise. They tend to ignite near the ground when escaping from land, due to self-generated lightning, but rise unburnt when issuing from the sea; cf. Kundt (2001).

Finally, there is the statistical argument that (xx) only some 3% of all craters on Earth are of meteoritic origin, the rest are due to volcanic eruptions, or outgassings (Alvarez, 1997). Volcanism has many different faces, ranging from supersonic ejections and the formation of mountains, 'maars', and kimberlites through lava flows, mud volcanoes, burning torches, and solfataras to quasi-steady outgassings, depending on the viscosity of the magma, on the magma supply rate, and on the transmissivity of the surface layers. Driving – in all cases – is natural gas, dissolved in liquid magma, often from as deep as the molten core of Earth (Kundt & Jessner, 1986; Kundt, 1991; Gold, 1999). Highly viscous (acid) magma leads to explosive eruptions (like Mt. St. Helens) whereas in rising low-viscosity (mafic) magma, the natural gas often separates

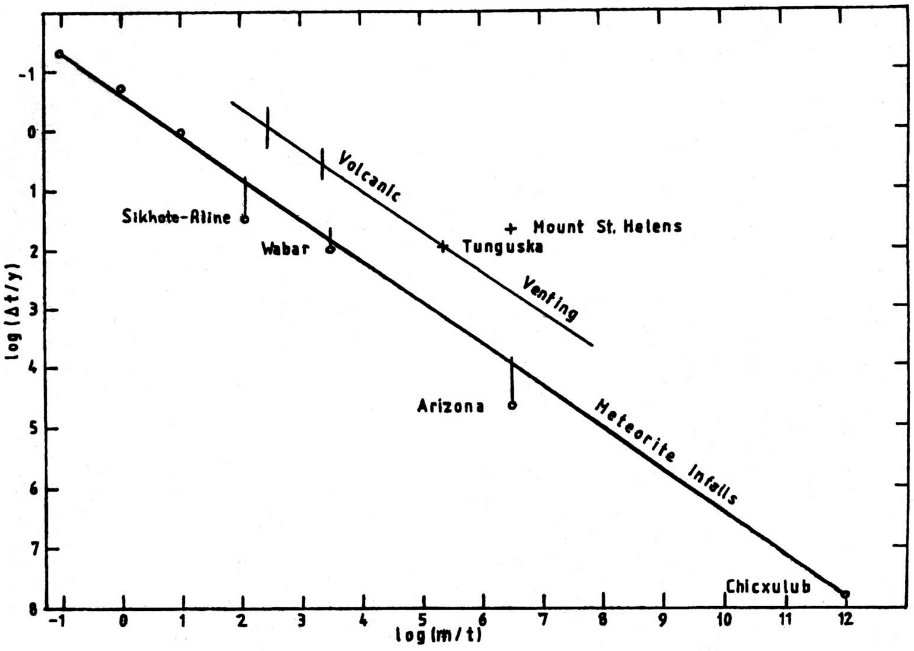

Fig. 3 Repetition rates for (i) meteoritic impacts and (ii) tectonic blowouts, as functions of their liberated energy $E = mv^2/2$, or rather their equivalent mass m; updated from Kundt (2001). For an easier comparison of the two classes of events, the estimated tectonic masses (ii) have been reduced by a factor of 100, in order to account for outblow velocities v being some 10 times lower than infall velocities. These estimates are at variance with those by Chapman & Morrison (1994), Jewitt (2000), and Rabinowitz et al (2000), though their emphasis is well known to geophysicists: Alvarez (1997).

from the melt before reaching the surface, forming a mystery cloud. In all likelihood, this is what happened at Tunguska.

More specifically, Tunguska may have been the present-day formation of a kimberlite. Kimberlites are called after the south-African town Kimberley, where diamonds and gold have been found by digging. They are huge, narrow funnels, growing in diameter from a few meters, at a kilometer's depth, to a dome-shaped tuff ring at the top, some km across, and occasionally enclosing a shallow crater lake (Dawson, 1980, Haggerty, 1993). They occur in all continents, lie at the intersection of major fracture zones, in old, stable cratons, are intruded by ultra-alkaline rock types containing high amounts of volatiles, and show several spasmodic – often cold – intrusions. An explosive injection from great depth is indicated, driven by volatiles. In Russia, the 'Zanitsa pipe' was discovered in 1954, in the headwaters of the Markha river in Siberia. Gold (1999) mentions that there is no evidence of frozen lava in kimberlites.

In the case of Tunguska, I have estimated a natural-gas mass of 10 Mt, required both for blowing the funnel-shaped holes (and the ditch?), and for setting up an overpressure dome – the cauldron – big enough to drive the storm field for felling the trees, out to some 30 km distance (Kundt, 2001). On venting, this expanding, initially liquidized gas – some 80% methane – escapes supersonically, and thereby creates the 'telegraph poles', until it has sufficiently expanded to be stalled by the ambient air mass. It then shoots up vertically, again supersonically, in the form of a giant mushroom, many times higher than the mushrooms of nuclear explosions (30 km) because of its much lower molecular weight m and lower adiabatic index κ (both of which enter as $m[\kappa$-1]), whilst the surrounding air mass is pushed radially outward, in the form of a big storm field. This same gas will burn partially wherever it gets mixed with ambient oxygen and ignited, and will continue burning at great height wherever it meets the surrounding atomic oxygen, thereby heating up and rising further. The newly formed water vapour will freeze out and remain frozen even when embedded in the hot thermosphere, because it gets radiatively cooled by seeing the cold night sky. In this way, snow clouds can reach the exosphere, and give rise to the bright nights, for a few days.

If Tunguska was not an infall event, our estimated rates of the latter go down because it has been used, for some 20 years, as the most reliable data point (Shoemaker, 1983; Kundt, 2002). In Fig. 3, I have tried to discriminate between the two sets of destruction events – volcanic (or tectonic) and meteoritic – in order to get more reliable numbers for their repetition rates as functions of the involved energy E, or rather 'equivalent mass' m. So far, our knowledge is consistent with power-law rates, in both cases. The biggest known impact record ever is the 65 Myr old Chicxulub crater on the Yucatan peninsula (Melosh, 1997). It has been difficult to detect, and may have a younger, somewhat less massive 'brother' in Naimibia's Etosha Pan (with its encircling fresh-water ponds), whose estimated age is $\lesssim$ 50 Myr.

3 THE SIKHOTE-ALINE METEORITE OF 1947, AND THE CANDO BLOWOUT OF 1994

On 12 February 1947, at 10.30 local time, an iron meteorite struck the easternmost edge of Siberia, in the western part of the Sikhote-Aline mountain range. Eyewitnesses reported a bolide crossing the atmosphere within $\leq$5 s, though noises were heard for (10$\pm$5) minutes (Krinov, 1966). The bolide left a gigantic trail, or smoke band which got increasingly wiggly but disappeared only towards the evening. According to eyewitnesses, the bolide split up successively at the four heights of 58, 34, 16, and 6 km, towards a final diameter of 0.6 km. From infall channels in the ground and tree destructions, its infall angle could be measured as (30$\pm$8) deg w.r.t. the vertical.

Within the four succeeding years, over a hundred small craters were detected in that area, the largest of diameter 26.5 m. They formed three concentrations, spread over an ellipse of diameters 1 and 2 km. All craters were formed by meteoritic fragments whose impact channels penetrated between 1 and 8 m into the ground, depending on their shape and orientation. The summed weight of all the collected iron-rich fragments was 23 t, and estimates yielded about 70 t total for the impacted mass, corresponding to an iron bolide of diameter 6 m, some $10^{-3.5}$ in mass of the hypothetical Tunguska bolide. Even if a comparable amount of rocky material had been left behind in the atmosphere, in the shape of the dust trail, the Sikhote-Aline meteorite was still some 1000 times lighter than Tunguska's hypothesized one.

No impactites were found at Sikhote-Aline: explosions after impact tend to occur (only) for crater diameters $\gtrsim$100 m. Telegraph poles and snapped-off tree tops were plentiful. Trees were felled radially around craters, but only in directly adjacent ringlike domains, of width $\lesssim$30 m. Some of them took bizarre appearances, see Fig. 4.

In 1838, meteoritic fragments were secured at Gibeon, Naimibia; they may stem from an impact event similar to Sikhote-Aline.

A quite different destruction of comparable energy was the bolide of 18 January 1994, seen and heard at 7.15 UT in the parish of Cando, NW of Spain, (Docobo et al, 1998). It took three months until a newly formed crater was reported, of size 29 × 13 m, 1.5 m deep, whose former (big) pine trees were hurled downhill through 50 to 100 m, see Fig. 5. An in-between

Fig. 4 Krinov's book (1966) shows this remarkable photograph where the Sikhote-Aline iron shower has deposited a tree-trunk segment in the crown of another tree. Some intelligence may be required to convincingly explain how this master piece of natural acrobacy has been achieved.

road remained clear of soil from the ejection, eliminating the possibility of a landslide - which did, however, occur on the same day 300 m NW of the main crater, knocking down two pines. No meteoritic debris were recovered; the authors prefer a high-speed gas-eruption explanation.

4 HOW TO DISCRIMINATE BETWEEN CAUSES?

Tunguska, Sikhote-Aline, and Cando are three catastrophical events of the last century – the first of them some 10^3 times more energetic than the two others – which have found quite different explanations in the literature. Whereas Krinov spends 129 pages of his 397-page book (1966) on giant meteorites on the "Tunguska meteorite", Ol'khovatov (1999) prefers a tectonic interpretation. Even Sodom and Gomorrah have been recently interpreted as former cities on the SE bank of the Dead Sea, blown up and/or slid to the bottom of the Sea by a volcanic eruption. How can we discriminate between the terrestrial and the extraterrestrial interpretation?

Whereas with the former interpretation you can be rejected from peer-reviewed journals, even when based on sober and friendly arguments, the latter interpretation may only apply to a 3% minority of all events. Eyewitnesses speak of bolides – or fireballs – in all cases, and of barisal guns lasting for many minutes. Trees are felled, or debranched, or their tops chopped off, craters are formed, and fires are ignited in all cases.

What differs are the details, of which I listed more than 17 above. Volcanic flames in the sky can last for minutes whereas a meteoritic infall trail flashes only for a few seconds, and is

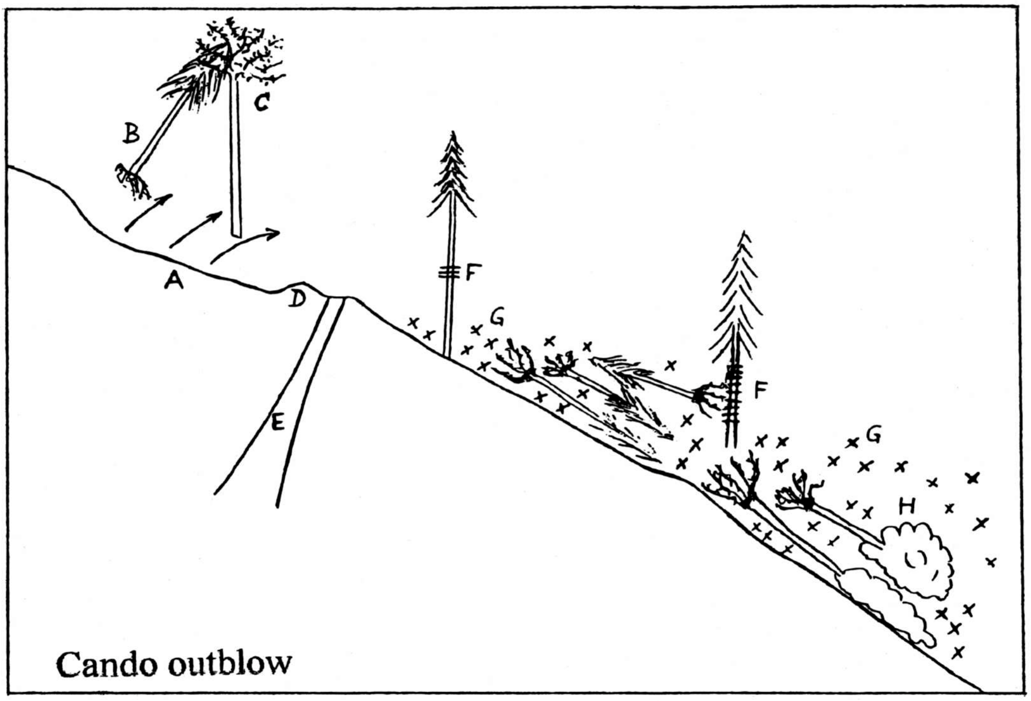

Fig. 5 Sketch, by Docobo et al (1998), of the destruction achieved by the 1994 Cando event. A crater was formed at A, with "closed" low edge at D. Big trees (H; of diameters 0.6 m, height 13 m) were thrown downhill to distances between 50 and 100 m. The footpath E remained clear of soil or trees. Soil was thrown to the places marked F and G.

hardly sensed hot in the faces of eyewitnesses, because of too small an extent in space and time. But a meteoritic trail tends to stay visible for hours, unlike volcanic flames. Barisal guns, on the other hand, are heard for comparable times in both cases by distant eyewitnesses ($d \gtrsim 70\,\mathrm{km}$), because sound echos from warm layers above the stratosphere take that long. For tree falls, their pattern matters: how many centers? Telegraph poles require supersonic shock waves. Craters, if blown from below, can contain tree stumps, whereas those formed by infall show an impact channel plus debris. Volcanic outblows can throw trees, or root stumps, or stones through several hundred meters, whereas non-explosive infalls (with small craters) redistribute the impacted soil in their immediate surroundings. Meteoritic debris tend to be recovered for impact masses in excess of fractions of a ton.

There are additional criteria. Volcanic blowouts require pressurized vertical exhaust pipes from a deep-lying fluid reservoir, which have their imprints on the local geography, like the Kulikovskii crater shown in Fig.1. Moreover, when megatons of natural gas – mainly methane – are suddenly released into the atmosphere, they will rise, burn, and form clouds in the thermosphere for several days, at heights above 500 km, where they scatter the sunlight. Such scattered sunlight at night is known as the bright nights of both Krakatoa (1883) and Tunguska (1908). We live on a tectonically active planet. Exploring it can be great fun.

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