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The 1908 Tunguska catastrophe: An alternative explanation

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More than seventeen reasons are presented as to why the fiery Siberian event of 30 June 1908, near the Stony Tunguska river, was not caused by the infall of a stony asteroid, nor of an (icy) comet, but rather by the volcanic ejection of some 10 Mt of natural gas. For the volcanic (outflow) interpretation, estimates are presented of the involved mass and kinetic energy of the vented natural gas, its outflow timescale, supersonic and subsonic ranges, and buoyant escape towards the exosphere. The Tunguska event may well have been the present-day formation of a kimberlite.

ON 30 June 1908, a quarter past 7 a.m. [corresponding to 0^{h} (13.6 ± 5)^mUT], hell broke loose in the Tunguska area, more than 700 km north-northwest from lake Baikal, with an epicentre at (101°53'40"E, 60°53'09"N). The ground trembled, Barisal guns were heard firing (also called 'brontides'¹), whirlwinds or gusts blew, and the sky was torn by columns of fire. Trees were felled in an on-average radial pattern, over an area of

2150 km², and scorched in patches over a central area adding up to one fifth that size. Hunters and herds-men, tepees, storage huts and dozens (hundreds?) of reindeer were blown into the air and/or incinerated in various places of that area. Even at Vanavara, the nearest trading post (at a distance of 65 km from the epicentre), people felt burning heat in their faces and were thrown off their feet^{2–6} (Figure 1).

The Tunguska epicentre coincides with the middle of the 250 Myr-old 'Kulikovskii' volcanic crater which forms part of the Khushminskii tectono-volcanic complex; several tectonic faults pass through this region⁷. Eyewitnesses (Evenks) have reported that during that very morning, dozens of new, funnel-shaped 'holes' were formed of diameters 50 m, as well as a 'huge dry ditch' ('tear in the ground', 'dry stream', probably 1 km long). The first expedition into the area, in 1910, was carried out by a wealthy Russian merchant and goldsmith named Suzdalev, who, on return, urged the local inhabitants to keep silent about it. Had he discovered diamonds?

The present-day swamps near the epicentre had supposedly been flat forest areas and/or natural peat bogs before, also (at least) one of the hillocks². The earliest scientific expeditions, organized by Leonid Kulik, some 20 years later, found most of those holes filled with water. They spoke of the near-environment (5 km) of the epicentre as the 'cauldron', or 'amphitheatre', containing the 'Merrill circus', according to their topography and treefall pattern. Lake Cheko, some 8 km to the

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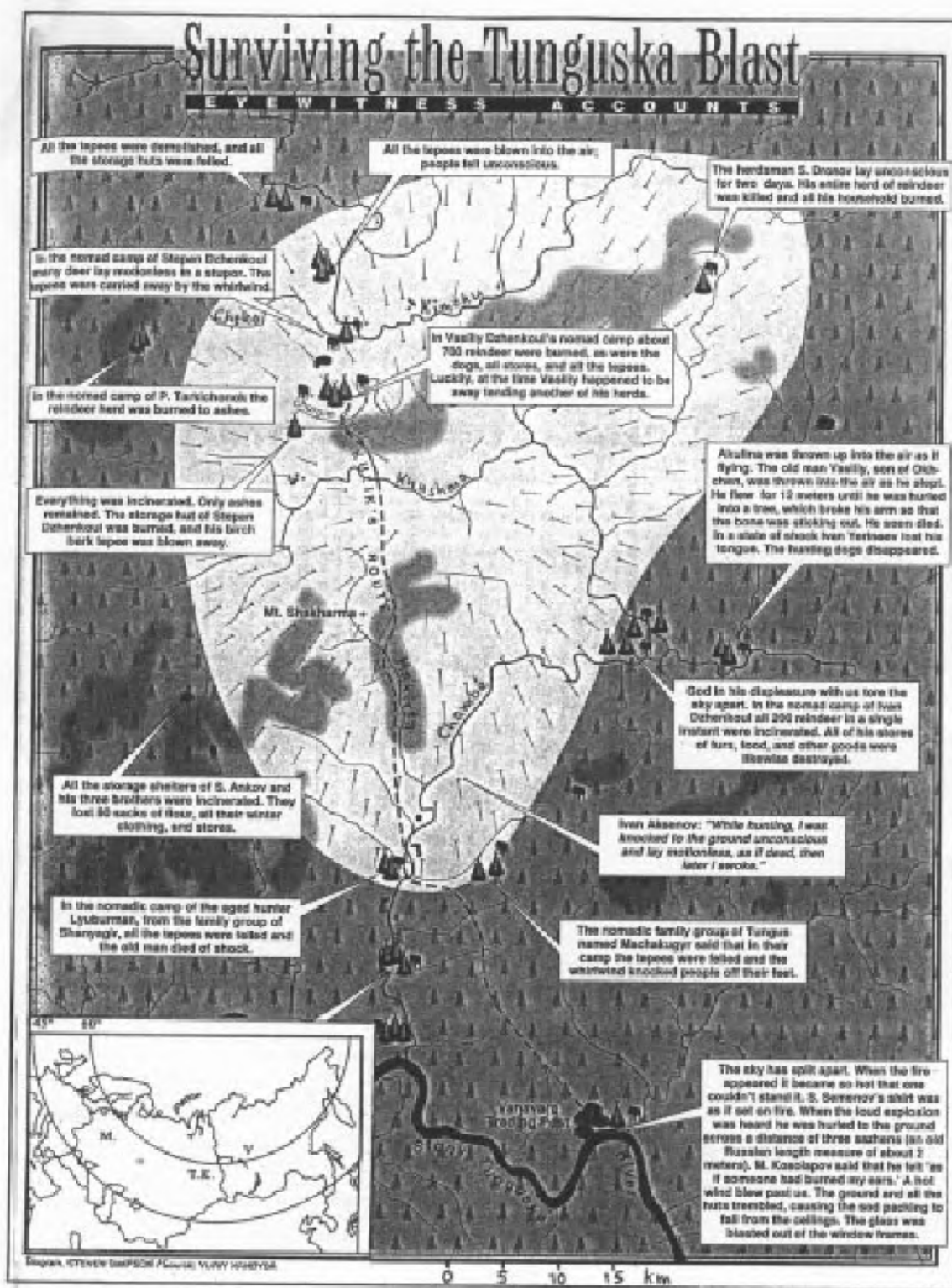


Figure 1. Maps of the site, on two scales; from refs 3, 20. M = Moscow; T = Tomsk; K = Krasnoyarsk; V = Vanavara. Note Lake Baykal, some 800 km south southeast from Vanavara.

north of it, is even 500 m wide and 55 m deep, and has broken trees on its ground which may or may not have been formed in an earlier outburst. A 'radonic storm' was recorded at gamma-rays near Lake Cheko in July 1999, lasting some four hours. The ditch remained undetected by the scientists.

Apparently related to the Tunguska explosion were the 'light nights' over Europe and Asia – also called 'bright nights', or 'white nights' – during which shadows were cast, and people could read newspapers still at midnight. The bright nights, began already on 29 June, culminated on 30 June, and lasted until 2 July; they were recorded^{2,8-10} down in latitude to 42°N (of Tashkent). The only other reported case of light nights was the 1883 Krakatoa volcanic eruption. Other semi-global atmospheric phenomena were sky-glow, bright noctilucent clouds, colourful sunsets and sunrises, strong and prolonged solar halos and altered Arago and Babinet neutral points – all of which faded exponentially during several weeks^{2,5}. On 30 June, starting 6 min after the Tunguska explosion, the Irkutsk Observatory measured anomalies¹¹ of the earth's magnetic field for ≥ 4 h, of strength $\lesssim 70 \gamma$ ($\gamma = 10^{-5}$ G).

Ever since the news of the Tunguska catastrophe reached the civilized world, it used to be interpreted as due to a giant meteoritic impact; the only open question was the infalling body's composition. To Kulik, there was the extra impetus of finding meteoritic nickel and iron. His disappointment was large when, after weeks of digging a 4 m deep narrow trench to drain the 'Suslov' crater lake (in May 1929), a *conserved tree stump* was found at its bottom (Figure 2). That stump would never have survived the impact of an extraterrestrial body! On the other hand, from the sphagnum moss that grew at the surface of the lake, they estimated its formation time as around 1908, and a pine cone in the crater's



Figure 2. Tree stump at the bottom of the newly drained Suslov hole, which ruled against an infall interpretation (from Krinov²).

confining rim, which was unearthed whilst digging the trench, should have been struck loose and buried near the end of June!

It apparently did not occur to Kulik and his team that the Suslov hole might have been blown from below – like the kimberlites (named after Kimberley in South Africa, but distributed over all continents^{12,13}), the Maare (in the Eifel mountains) or the craters of the mud volcanoes, and solfataras (near Baku, or in Venezuela, or Italy). The formation of each of those big holes must have been a major catastrophe for its local contemporaries. We have no reports because they happened several hundred or more years ago.

If the Suslov hole had been blown from below, one could understand, at the same time, why the hole's rim contained large prismatic ice inclusions ('lenticles'), in permanently frozen mud: During its formation, water should have intruded into its cavities. It may not be obvious how a tree stump could make its way to the bottom of an outblow crater. But there have been dozens of trees, standing on top of what is now the Suslov hole. Most of them were hurled to large distances, but one of them may have managed to fall back in, more or less upright. Alternatively, this stump could have slid back from the crater's rim along with a transient mud flow.

This tentative explanation can solve another difficulty of the hypothetical Tunguska meteorite: why did several expeditions find large numbers of detached tree stumps lying around in the cauldron and its vicinity²? How did they get there? To me, they are a clear indication of ejections, from the holes at whose surfaces they had grown.

Another, major problem for the impact interpretation is, of course, the absence of any secured meteoritic debris: An iron object would have rammed a big, lasting crater and can therefore be excluded¹⁴. The best candidate for an impactor still seems to be a stony asteroid that decomposed^{15,16} at a height above some 8 km. But an object of weight some 0.4 Mt would have left either big fragments, or at least a $\pi D^3/6A = 4$ mm thick dust layer (for a diameter D of 60 m and an impact area A of 30 km²), which would have been easily detected by the many expeditions¹⁷. The chemical and isotopic analyses of peat columns from the area have ruled it out¹⁸. The latter would allow for a body of cometary material. But comets – and carbonaceous chondrites – would disrupt and evaporate too high in the atmosphere (≥ 20 km, a controversial number) for the localized isotopic anomalies (of C and H), and (mild) Ir enrichments¹⁸, also disrupt much too high for the multicentred treefall pattern to which we will turn soon. These anomalies may alternatively allow a volcanic interpretation¹⁹.

In their chemical analysis of resin of trees that have survived the 1908 catastrophe, Longo *et al.*²⁰ find the same enrichments (of 14 elements) as 'after earthquakes' and 'during degassing in active tectonic zones'.

An enrichment of rare-earth elements is reported from sphagnum peats in the cauldron, and less so from a much larger area downwind from the explosion, which may or may not be responsible for an accelerated growth of all species of trees after the catastrophe⁵.

Kulik's 1938–39 original aerial photographs of the Tunguska treefall pattern (of mainly birch trees and aspens) seem to have disappeared, but Serra *et al.*²¹ have reproduced one of his re-drawings (Figure 3), which shows two distinct centres of the explosion in the Southern Swamp. The multiple (≥ 4 mentioned) centres suggest a large number of successive pressure maxima, perhaps as many as craters that were formed on 30 June.

The treefall pattern has more peculiarities, inconsistent with one large blastwave. It is wiggly rather than straight-line radial, following the local surface topography (see figure 2 of ref. 20). Moreover, it shows islands of tree survival right up to the cauldron, in particular in the valleys, and islands of destruction elsewhere. And it involves 'telegraph poles' near the epicentre – like near the nuclear bomb of Hiroshima – i.e. tree stems whose branches were blasted off by a sharp-edged shock wave. Such fine structure of blasting and felling requires several successive localized explosions near the ground; it is inconsistent with one big explosion at some height. Further, Krinov's sketch² of the destruction profile along the banks of the river Markita, Figure 4, suggests that the blasts blew almost horizontally. Bronshten²² ignores all these details.

Another difficulty for the meteoritic explanation are the bright nights, and even more so their onset one day early, on 29 June (which, for tectonic events, is a familiar phenomenon: Outgassing tends to build up hours to

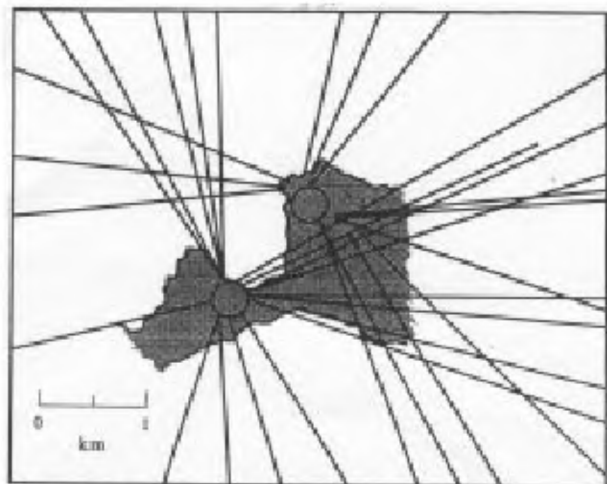


Figure 3. Kulik's re-drawing of his aerial photographs of the tree-fall pattern in the western part of the Southern Swamp (from Serra *et al.*²¹). Two destruction centres are obvious. At least two further centres are mentioned by Serra *et al.*²¹.

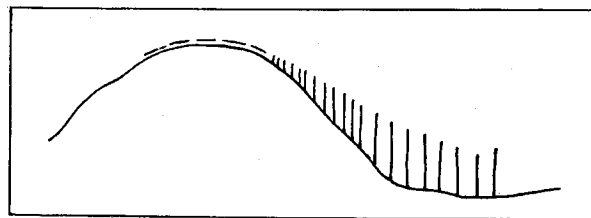


Figure 4. Krinov's sketch of the 'shearing' tree-destruction pattern on the hill tops along the bank of the Makirta river, ranging from no destruction (in the valley) through losing their tops, to being flattened (from Krinov²).

days before major earthquakes; the leakages yield due to an increasing pressure from below). Scattered sunlight at midnight, during mid-summer, down to 42°N and from considerable elevations ($\lesssim 30^\circ$), requires cloudlets at heights above 10^{2.7} km, in the exobase (see Figures 5, 6 and also later in the article). Here again, I disagree with Bronshten^{22,23} who holds dust from the envelope of a comet responsible for the glow: Dust would traverse the exobase unbraked within half a minute (rather than during four days); its scattered light would flicker on that timescale, and its integrated mass – required to intercept more light than the full moon – would exceed several Gt. Mesospheric dust, on the other hand, cannot scatter light down in latitude to 42°N. (Only comet Encke was recorded in those days.)

Note that ordinary clouds form at heights of up to 10 or 14 km (beyond which the rising water vapour has condensed); plumes from nuclear detonations reach 30 km; and noctilucent clouds form at heights just above 83 km, from meteoritic dust. The 1815 Tambora volcanic plume reached 65 km (ref. 24). The atmosphere extends in height up to the exosphere, some 10³ km, from which atomic hydrogen leaves earth for good. In its upper parts, above 200 km, it consists mainly of atomic oxygen, at pressures between 10⁻⁹ and 10⁻¹² bar (ref. 25). In order to form clouds at heights much above 90 km, a huge volume of light gases must be released, as light as atomic oxygen (at thermospheric temperatures, $\lesssim 10^3$ K), such as methane (80%), helium and (marginally) water vapour, the main constituents of natural gas as well as of many volcanic eruptions; the latter can also, however, be rich in CO₂. Krakatoa (1883) proves that volcanic outbursts can do it. Moreover, the bright nights occurred at longitudes between 10°W and 80°E, distinctly west of the event, reminiscent of the 10% subrotation of the exobase²⁶.

Among the further difficulties of the meteoritic interpretation are the many (≈ 60) eyewitness reports which Krinov² has to permanently correct, even though he states that they tended to be 'remarkably accurate'. Several Evenks spoke of 'two columns (pillars) of fire', (not just one, more or less horizontal trail) and of



Figure 5. Glow and shining clouds seen by Rudnev in the former Orlov Province, on the night of 30 June–1 July 1908 (from Krinov²).

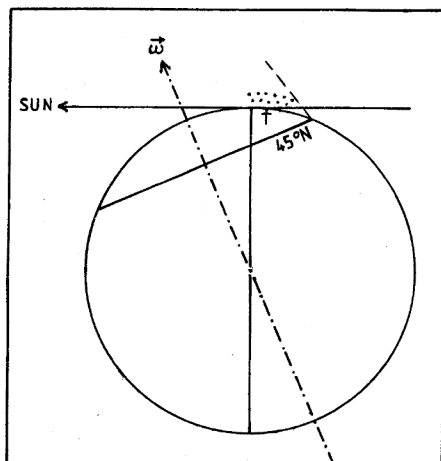


Figure 6. Sketch of the sunlight-scattering geometry for an observer at 45°N, at summer midnight: The required cloudlets are indicated, if launched at Tunguska's latitude of 61°N.

directions which implied various infall trajectories (along fault lines), even requiring in-flight manoeuvres. They spoke of durations (of the epoch of trembling, of ≈ 14 shots, gusts and flames) between a few minutes and an hour (not seconds, as for an impact: one man even washed in the bath house, to meet his death clean). In places, they heard noises before they saw flames and they spoke of spots of molten soil and sand^{5,7}.

Some information is also available from seismograms, barographs and magnetometres (already mentioned above). Several earthquakes are reported during the year 1908 in the Baikal region, peaking on 30 June with a 90 min ringing at the Irkutsk station; (epicentre locations have only been determined after 1912). The Krasnoyarsk instrument was out of operation on 30 June and the instrument at Kabansk – beyond lake Baikal – showed no signal²⁷. All this is consistent with – though it does not imply – a volcanic event, whereas the signal

shapes look strange for an impact. Barographs show similar signals to those of nuclear explosions, given the poorer time resolution²⁸ of the latter (of 1 inch/h; the Tunguska signal may not have been recorded at higher time resolution).

Yet another difficulty for the meteoritic interpretation is event statistics: Both external and internal catastrophes obey power-law distributions (Figure 7), whereby for the same destruction energy, the internal events distinctly dominate in rate. For the meteorites in Figure 7, I have used Krinov's²⁹ tables of large meteorites during the past 200 years, together with two famous earlier cases, the (largest known) 65 My-old Chicxulub crater³⁰ and the 50 ky-old Arizona (Barringer) crater. For the partially controversial non-meteoritic events, my knowledge is based on the 'examples' in ref. 7. During the 8 years between 1990 and 1997, for example, there were the destructions in the Hudson Bay (Canada, 27 June 1997), in Honduras (22 November 1996), Perth (Australia, 1 May 1995), Cando (Spain, 18 January 1994), Banjawarn (West Australia, 28 May 1993), Jerzmanowice (Poland, 14 January 1993), Sasovo (350 km south-east of Moscow, 12 April 1991), and Petrosavodsk (NW Russia, 29 March 1990), also the Greenland fireball (9 December 1997). Ostensibly volcanic eruptions, like the 18 May 1980 eruption of Mount St. Helens, caused comparable destructions (of the woods and animals in its environs) and is estimated to have ejected no less than 0.3 Gt of ashes.

Figure 7 tells that for comparable destruction energies, internal events are at least 20 times more frequent. Note that the meteoritic curve is consistent with the well-known power-law distribution of small bodies in the solar system given by $M^2 \dot{N}_M = 10^{-18 \pm 2} \text{ kg/m}^2 \text{ s}$ for $10^{-21} \lesssim M/\text{kg} \lesssim 10^{15}$. Tunguska, if classified as meteoritic, would raise the curve of impact hazards to unrealistically high rates.

A kimberlite interpretation of the Tunguska catastrophe is tempting: As stated in Dawson's book¹², see also Haggerty¹³, kimberlite diatremes are narrow funnels, growing from a few metres across at a kilometre's depth to a dome-shaped tuff ring at the top, of diameter some kilometre, and occasionally enclosing a crater lake (reminiscent of the cauldron). They 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. Gold¹⁹ mentions that there is no evidence of frozen lava in kimberlites.

The phenomenon of 'mystery clouds', observed routinely by satellite photography as well as by airplane pilots, may likewise have to be explained by rising big blobs of natural gas³¹. The clouds start from an

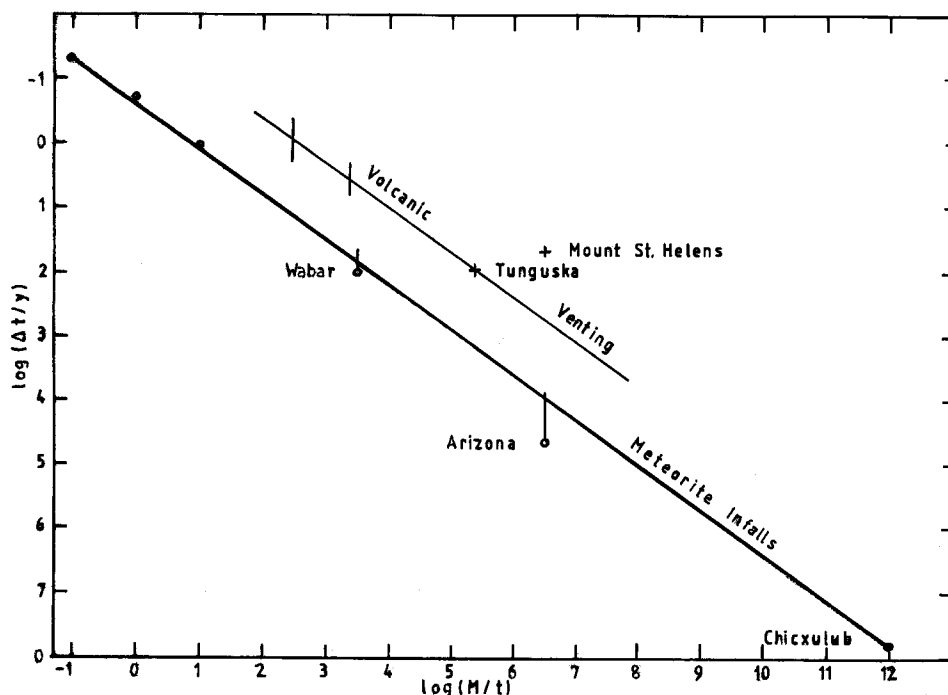


Figure 7. Repetition time Δt versus (estimated, equivalent) impact mass M , for meteorites (circles) and volcanic gas vents (crosses) (after Krinov² and Ol'khovarov⁷). Vertical lines denote estimated error bars; note that, for example, the Arizona event must be considered a lower bound to the infall rate at this mass, because of incompleteness. A straight line has been drawn through the extreme rates at the high-mass end (Chicxulub) and low-mass end (0.1 t). For the volcanic events, the equivalent mass has been calculated from the (estimated) destruction energy by assuming that it impacted at typical meteoritic speed (rather than at outgassing speed). In reality, the mass of the venting natural gas is estimated some 10^2 times larger. A straight line has been drawn through the Tunguska event, parallel to the 'meteorite infalls' line; it is consistent with guesses at lower destruction energies. Note that real volcanoes, like Mount St. Helens, eject even much larger masses. This figure revises an estimate by Chapman and Morrison³⁶, as well as estimates made by Rabinowitz *et al.*³⁷ and by Jewitt³⁸, though its emphasis is well known to geophysicists³⁰. See text for further details.

unresolved spot on the surface – land or water – and expand and bend downwind as they rise. Satellite IR shows that at a height of 10 km, the clouds are ≥ 20 deg colder than their surrounding air, apparently caused by adiabatic expansion. A condensation sheet at the air contact makes them look white. Tom Gold has reported to me that towards the end of 1998, a United Airlines plane on the way from Tokyo to Honolulu in calm air experienced a sudden sharp upward bump followed, in a fraction of a second, by a mightier downward movement with a recorded speed implying a downward excess acceleration of 4 g. He explains it as the crossing of a methane cloud rising at high velocity, whence the upward bump, whereupon the methane–air mix above the plane was ignited by the engines; its explosion forced the plane downward and injured many people seriously. The plane returned to Tokyo to attend the wounded.

Such venting clouds of natural gas may often ignite near the ground when escaping from land, due to self-generated lightning, but rise unburnt when issuing from

the sea. A. G. Judd has informed me that some 6% of the seabed is covered by 'pockmarks' in soft, silty clay sediments, shallow spherical depressions comparable in size to the lakes of the Tunguska cauldron, which are formed by seepage of natural gas. An outburst from one of them, the Witch's Hole in the North Sea, may have caused the sinking of a last century's steam trawler which has recently been found undamaged at its centre.

Now I shall offer rough estimates for the masses and energies which may have been involved in the 1908 Tunguska destruction. I assume^{19,32} that a certain number N (≥ 14) of large, funnel-shaped holes of radius R (some 20 m), were blown by pressurized natural gas from underground vents. For simplicity of calculation, the holes will be assumed of conical shape with spherical base and 90° angle at the apex, i.e. of equal radius and height (Figure 8), so that their mass equals ρR^3 . The gas is assumed to have segregated from the (mafic) lava in whose company it has risen, perhaps all the way up from the molten core of the earth³³. Its average molecular weight ($\mu = 15$) is almost half that of air ($\mu = 28.4$).

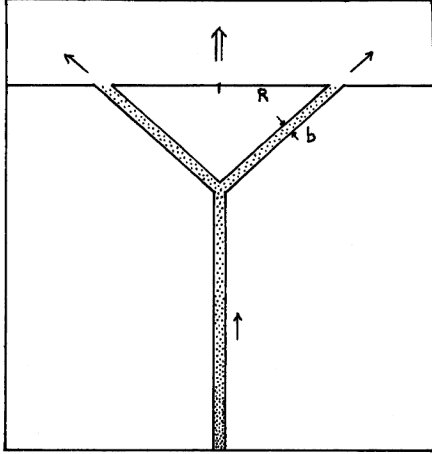


Figure 8. Assumed geometry for a typical (conical) outflow crater, in profile. R is its radius, and b is a typical assumed width of the escape 'nozzle'.

Its initial temperature should be somewhere between $10^{2.5}$ and 10^3 K, depending on its thermal contact to the (molten) lava and its mass density should be between that of water and air, probably near 10 kg/m^3 , depending on the weight of the overlying material.

Such venting gas has an initial sound speed twice that of air: $c_s = (\kappa kT/m)^{1/2} \approx 10^{2.8} \text{ m/s}$ (for $\kappa \lesssim 7/5 = 1.4$). When it escapes through a deLaval nozzle, it reaches³⁴ a $(2/\kappa - 1)^{1/2} \gtrsim 2.2$ times higher velocity: $v_{\text{esc}} \gtrsim 10^{3.2} \text{ m/s}$. The Tunguska holes may have been blown by natural gas escaping with this speed. It is tempting to identify the 'Merrill Circus', the near-zone 'telegraph forest' around the holes – of standing tree trunks with blown-off branches – with this supersonic near zone: In order to remove the branches of trees without uprooting the latter, the onset of blowing has to be fast enough for the branches to break off before they can transfer the gust load to the stem; it is the switch-on speed that counts. Supersonic speeds appear to be essential.

We want to calculate the gas mass, ΔM , required to blow the holes, flatten the woods and cause the bright nights. Let us begin by estimating the ejected mass: $N \approx 10$ holes, each of average radius $R = 20 \text{ m}$, average mass density $\rho \approx 10^{3.5} \text{ kg/m}^3$, have contained a total (blowout) mass M given by

$$M \approx N\rho R^3 = 10^{8.5} \text{ kg.} \quad (1)$$

Quite plausibly, the escaping gas mass exceeds this value by a large factor.

In principle, a mass M can be ejected by an even smaller mass, ΔM , if fired at sufficient speed. For a reliable lower bound, let us estimate ΔM from the vertical momentum Mv_{ff} that must be transferred to the mass M in order to be thrown to a height $h \gtrsim 10^2 \text{ m}$ (just think of the displaced root stumps!), where $v_{\text{ff}} = (2gh)^{1/2}$ is the required takeoff speed:

$$\Delta M \gtrsim M(2gh)^{1/2}/v_{\text{esc}} = 10^7 \text{ kg}/h_2^{1/2}, \quad (2)$$

(for M from eq. (1), v_{esc} as estimated above, and h_2 standing for $h/10^2 \text{ m}$), i.e. the minimum gas mass required for ejection is as low as 10 kt.

But the Tunguska catastrophe did not only blow funnels, it also felled trees throughout $10^{3.3} \text{ km}^2$; a much larger ΔM is required to set up the storm system. For a quantitative estimate, let us simplify the geometry to just one blowout centre, of net area $\lesssim N2\pi Rb = 10^{2.5} \text{ m}^2$ (where $b = 10^{-0.5} \text{ m}$ is an assumed gap width through which a significant amount of gas escapes, see Figure 8), and let us assume that the supersonic outflow is hemispherical, up to a distance r_i , where it is (transiently) stalled. Its ram pressure $\rho_{\text{gas}} v_{\text{esc}}^2$ drops as r^{-2} with distance, from its initial value of order $10^{7.4} \text{ N/m}^2$ ($= 10^2 \text{ bar}$), and reaches the atmospheric value (1 bar) at a distance of $r_i = 10^{2.2} \text{ m}$. The inner shock radii r_i around each venting centre are thus of order 10^2 m .

Beyond r_i , the shocked natural gas tries to expand (at almost sonic speed), and still has almost all its blowout energy, sufficient to drive a big explosion. Shocking has raised its temperature back to $(mv^2/k)2(\kappa - 1)/(\kappa + 1)^2 \lesssim 0.6 \text{ kK}$, so that its sound speed is \lesssim twice that of the surrounding air. It expels this air in all directions, initially at almost the air's sound speed (for an initial excess pressure of order 1 bar), and at the same time rises by buoyancy, and thrusts its way up. Because of its light weight, its boundary layer – the 'contact discontinuity' – is Rayleigh–Taylor unstable, hence the two media will partially mix. Figure 9 illustrates a tentative snapshot during this explosion, with the gas shooting up in the shape of a hollow flame whilst the cool ambient air is expelled horizontally in the shape of a flat dome.

For an estimate of the radius r_c of the contact discontinuity – the radius of the flame – we must apply radial-momentum and energy balance to the outflow scenario between r_c and a 'peripheral' distance r_p at which the explosive gusts still act like a hurricane, with speeds reaching 220 km/h ($= 10^{1.8} \text{ m/s}$). Call Δp the pressure excess exerted at r_c , H a typical height of the gust region, and assume that the surrounding air is accelerated at a constant (average) rate $(\Delta v)^{\bullet} = \Delta v/\Delta t$ throughout a time interval Δt . Momentum balance then yields $2\pi r_c^2 \Delta p = 2\pi r_p^2 H \rho (\Delta v)^{\bullet}$, and energy balance: $2\pi r_c^2 \Delta p \Delta r_c = 2\pi r_p^2 H \rho (\Delta v)^2/2$. These two equations can be simplified to:

$$\Delta r_c/\Delta t = \Delta v/2 = 10^{1.5} \text{ m/s}, \quad (3)$$

and

$$(r_p/r_c)^2 = \Delta p \Delta t / H \rho \Delta v. \quad (4)$$

The treefall pattern wants r_p to be of order $10^{1.3} \text{ km}$ for $\Delta v = 10^{1.8} \text{ m/s}$. With $\rho = 1 \text{ kg/m}^3$, $\Delta p \lesssim 1 \text{ bar}$ and

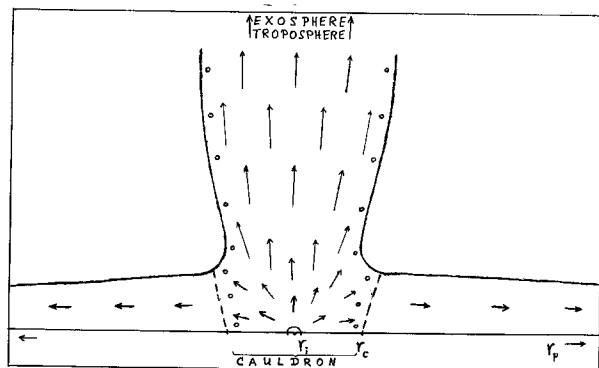


Figure 9. Estimated snapshot geometry through the blowout event, not strictly to scale: Pressurized natural gas escapes supersonically from one of the many (≈ 10) blowout craters – lumped symbolically into the origin in this drawing – and is stalled at the inner shock radius r_i , (at $\approx 10^2$ m). Beyond r_i , it drives the ambient air into an extended radial storm field, and escapes by buoyancy upwards through the flaming region. The contact discontinuity between natural gas and air, at r_c (\approx km), is strongly Rayleigh–Taylor unstable, hence leads to strong mixing of the two media (symbolized by small circles). The outer edge of the storm field, at r_p , is beyond the mapped snapshot scenario.

$H \lesssim 1$ km, eqs (3) and (4) suggest: $\Delta r_c \lesssim 10^{3.5}$ m, $\Delta t \lesssim 10^2$ s and $r_c \lesssim 10^{3.2}$ m, i.e. the main explosion lasts little over a minute, during which the piston (contact discontinuity) moves through a few kilometres – the size of the ‘amphitheatre’.

These results yield an estimate of the driving gas mass, as the mass enclosed in the core of the ‘flame’ region during the explosion. Note that matter in this volume will be somewhat mixed so that its net radius may not exceed $r_c = 10^{3.2}$ m. We thus get

$$\Delta M \approx 2\pi r_c^3 \rho \approx 10^{10} \text{ kg} = 10 \text{ Mt}, \quad (5)$$

(for a mass density $\rho = 10^{-0.4} \text{ kg/m}^3$ of the shocked gas), 10^3 times the minimum mass for blowing the holes. Tunguska may have been blown by 10 Mt of natural gas.

Once we know the involved mass ΔM , we get the involved energy E by multiplication with $v_{\text{esc}}^2/2 = 10^{6.1} (\text{m/s})^2$:

$$E = \Delta M v_{\text{esc}}^2/2 \approx 10^{16} \text{ J}, \quad (6)$$

similar to the meteoritic estimate. Note that the volcanic interpretation involves 10 times slower initial velocities (than the infall interpretation), hence involves 10^2 times larger masses.

So far we have ignored the observed fires which, among others, scorched an inner fifth of the treefall area. Natural gas – containing predominantly methane – is ready to burn as soon as it is brought into contact with oxygen and ignited. Such ignitions are likely to happen via sparks, during exit from narrow vents, as

well as via (self-made) lightning. They should considerably contribute to the overpressure exerted by the core region if the ignition happens deep enough, say, below a few kilometres of height; our estimates, eqs (5) and (6), are low in this sense. When eyewitnesses at Vanavara sensed the heat of this flame on their skin, it must have exceeded 10^2 solar fluxes, corresponding to a luminous area of order 10^{-2} in spherical angle on the sky, if of comparable surface brightness to the sun. Note that a meteoritic trail cannot easily reach such a high brightness because it is narrow; it would have had to pass quite near to Vanavara with a rather large infall speed³⁵.

A final estimate concerns the mode in which the venting natural gas is thought to rise into the thermosphere; it will explain the white nights. This gas has a 5 times larger scale height $H = kT/\text{gm}$ than the surrounding atmosphere. From nuclear explosions, it is known that pressurized light gas rises supersonically in the shape of a mushroom, with a narrow shaft and a broad head. In our case, the buoyantly rising gas will thrust upward near the centre, thereby gaining increased overpressure w.r.t. its surroundings until a nozzle forms beyond which it rises supersonically. Its resistance drops exponentially with height so that its speed is essentially controlled by gravity. The head of the mushroom forms when its vertical speed has dropped to the ambient sound speed, at a height z given by³⁴ $[v_{\text{launch}}^2 - 2gz]^{1/2} = c_{\text{atm}}$, or

$$\begin{aligned} z &= [2c_{\text{gas}}^2/(\kappa - 1) - c_{\text{atm}}^2]/2g \approx c_{\text{gas}}^2/g(\kappa - 1) \\ &= 10^{2.3} \text{ km } T_{2.7}. \end{aligned} \quad (7)$$

where T is the gas temperature at launch. In this estimate, I have assumed that methane (at the assumed high T) has a low adiabatic index, $\kappa \lesssim 17/15$, and that c_{atm} is still moderate at 200 km. Note that the height z in eq. (7) is some 10 times larger than that of nuclear explosions because of the lower molecular weight of the rising gas and because of its much lower adiabatic index κ .

During its supersonic rise, the partially burnt natural gas will cool adiabatically, according to $T \sim p^{1-1/\kappa}$, so that its water vapour is likely to freeze out in the form of snow flakes. The (small percentage of) flakes will be lifted into the mushroom’s head. Here, the risen gas is shock-heated again and expands more or less horizontally through several 10^3 km, in adjusting to the ambient pressure, replacing the upper thermospheric air over the huge terrestrial area (of $10^{6.9} \text{ km}^2$) that has experienced the bright nights. During this renewed expansion, the cooling gas is steadily heated both by solar illumination and by slow burning of the methane, embedded in largely atomic oxygen. The CO_2 thus produced will diffuse downward whilst the freshly heated methane, helium and water vapour will continue to rise

to heights of $\lesssim 600$ km, beyond which the atmosphere gets forbiddingly light. Angular-momentum conservation during this last rise, through $\lesssim 10\%$ of the earth's radius, will make it move westward at $\lesssim 10\%$ of a full revolution per day.

Whilst the gas rises, its load, the snow flakes, will stay at a much lower temperature T_f , near 10^2 K, given by the equilibrium between partial solar absorption plus particle bombardment balanced by thermal radiation:

$$T_f \gtrsim (\pi n k T_g v_{th} / \sigma_{SB})^{1/4} \lesssim 10^2 K T_3^{3/8}. \quad (8)$$

They will scatter the sunlight and give rise to bright nights. Note that such small flakes, or ice crystals, even though heavy, would not fall fast because Stokes' friction grows inversely with the dynamic viscosity η which is independent of density, and grows with the square root of gas temperature: $v_{ff} = mg/6\pi R\eta$, $\eta \sim T_g^{1/2}$. Their free-fall speed can be smaller than that in the troposphere.

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Detrital zircons constraining basement age in a late Archaean greenstone belt of south-eastern Rajasthan, India

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We report a $^{207}\text{Pb}/^{206}\text{Pb}$ age of ca. 3230 Ma age for detrital zircon grains from the quartzite of the greenstone association in the Rakhial area, east of Udaipur, south-eastern Rajasthan. The age helps to constrain the maximum age of the greenstone belt of the region.

In central and south-eastern Rajasthan, in the north-western part of the Indian Shield, a number of large outcrops of gneissic basement rocks of Archaean age occur within the belts of Proterozoic supracrustal rocks assigned to the Aravalli and the Delhi Supergroups¹ (Figure 1). Structural investigations² and available geochronological data^{3–5} indicate that some of the basement

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