

Impact on the Environment of the Tunguska Explosion

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ABSTRACT

The Tunguska explosion occurred on June 30, 1908 over Siberia. It was a cosmic body explosion that was accompanied by an energy release equivalent to 10 megatons of TNT. The Tunguska explosion is often used as a kind of standard of destructive action. Due to the lack of comparable events, its impact on the environment is identified with the effect of nuclear explosions. However, the impact of the Tunguska explosion on the environment was very specific. The energy released during this explosion went mainly into the formation of a blast wave, and not into heat and radiation. The blast wave was so powerful that it broke windows in houses at a distance of up to 500 km from the epicenter and went around the globe. And the radiation of the explosion was so weak that trees at the epicenter remained alive. Several hundred surviving trees were found at a distance of less than 7 km from the epicenter. According to estimates made on the basis of damage to vegetation near the epicenter, the radiation energy of the Tunguska explosion was ~1% of total energy, provided that the explosion occurred at an altitude of 5 - 10 km above the epicenter. There is an assumption that in the Tunguska catastrophe we are dealing with an explosion of the cloud of a disintegrated comet, that is to say, the explosion was volumetric.

1. INTRODUCTION

The question of the impact of cosmic bodies colliding with the Earth from time to time on the environment is always relevant. The Tunguska event associated with the explosion of a cosmic object over the Siberian taiga in 1908 is no exception. The explosion occurred at an altitude of about 5 - 10 km above the basin surrounding an ancient volcano [1]. The basin is a flat platform, ~45 km² in size, elevated by ~70 m above the Kimchu and Khushmo river valleys. This platform is surrounded by trap mountains rising up to 120 meters above it [2].

The total area of the forest massif destroyed by the explosion was 2150 ± 25 km² [3], including about 600 km² of continuous felling. The boundary of 90% tree fall in the vicinity of the epicenter depends on the direction and is located at a distance of 15 to 25 km [4, 5]. The shock wave of the explosion killed deer near

the epicenter and shattered windows in houses hundreds of kilometers away from the explosion point [6]. The waves propagated through the air went around the globe and were noted by almost all the meteorological stations of the world that were operating at that time.

The influence of radiation that took place during the Tunguska event on terrestrial vegetation is extremely specific [7]. In this work, we will consider only the damage to tree branches in a circle with a radius of 20 km around the epicenter which is associated with the action of the explosion. The effect of thermal damage to trees that survived the catastrophe was found in an area with a width of 12 km from north to south and a length of 18 km from west to east, which occupies the area around the epicenter $\sim 200 \text{ km}^2$ [8]. At the borders of this zone, burn lesions of tree branches disappear.

Many explosions are compared with the Tunguska explosion. This includes the alleged explosion $\sim 3,600$ years ago, which had a catastrophic impact on the town of Tall el-Hammam, northeast of the Dead Sea. According to Bunch *et al.* [9], it was the explosion of a cosmic body a few kilometers southwest of this city that could be the cause of its destruction. It is assumed that radiation fluxes from the explosion were so high that they were able to melt surface deposits; the temperature exceeded 1700°C for ~ 20 seconds. These conditions correspond to the melting of adobe bricks, ceramics and roofing clay half a centimeter thick.

This paper considers the impact of radiation and shock wave of the Tunguska explosion on the earth's surface.

2. THERMAL RADIATION OF THE EXPLOSION

There is an area around the epicenter of the explosion, which was called the “zone of disordered forest fall” [10]. It is located around the Southern swamp within the basin around Mount Stoikovich (paleovolcano). In this area, trees remained standing after the disaster, most in the form of vertically withered pillars. In subsequent years, the dead trees randomly fell to the ground. Radial felling of the forest begins from this area (Figure 1). The size of the zone of “disorderly felling of the forest” extends, on average, by 5 km from north to south and by 10 km from east to west [10].

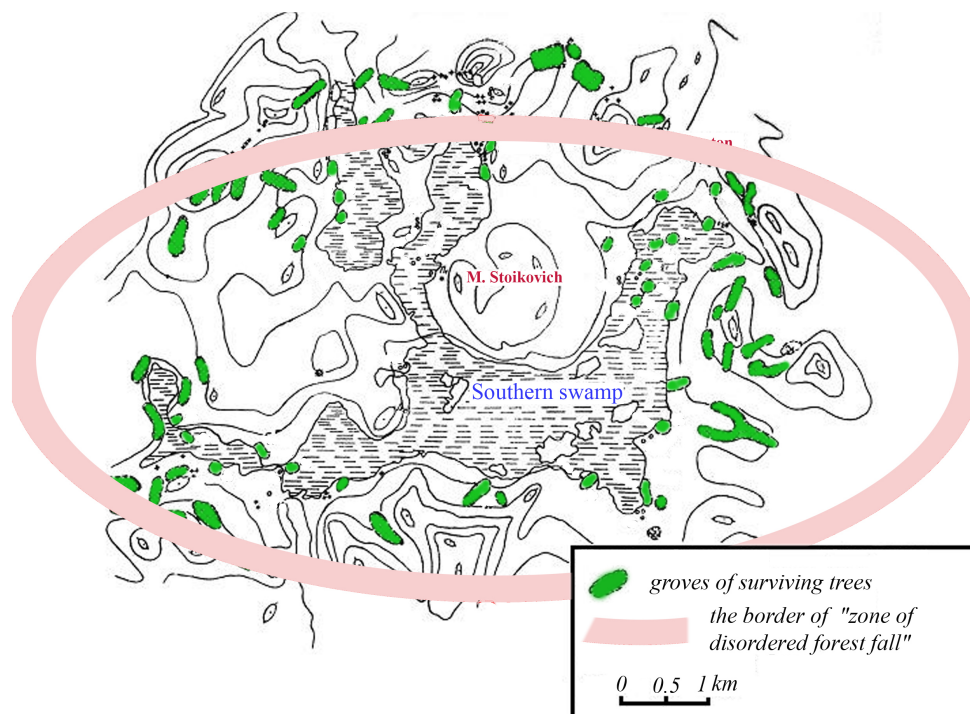


Figure 1. Locations of trees that survived the catastrophe at the epicenter according to Zenkin *et al.* [11].

It is generally accepted that the forest remained standing on the roots due to the fact that the front of the shock wave moved here vertically from above. This allows us to assume that the cloud of fragments of the cosmic body that exploded above the epicenter could reach several kilometers. According to Tsynbal and Schnittke [5], this cloud had the shape of a paraboloid of revolution, that is, it was close to a cylinder. The radius of the cylinder was ~1 km and the length was ~15 km. Thus, they concluded that the volume of the exploded cloud was ~45 km³.

Studies have shown that living trees of various species (larch, pine, cedar) remained in the area of the epicenter of the explosion, including in the zone of “chaotic fallout”, even preserving live branches. According to Zenkin *et al.* [11], several hundred trees survived the catastrophe. More than 80 groups of living trees were found within the Northern and Southern swamps at a distance of less than 7 km from the epicenter of the explosion (Figure 1).

It is important to note that coniferous trees are very sensitive to heat. The thermal effect on the trees could have been caused by the passage of the shock wave and the radiation from the explosion. The sharp temperature changes at the shock wave front apparently did not have a significant thermal impact on the vegetation at the epicenter. The experimental data showed that when heated to 60°C for even less than 1 minute, the needles of pine, spruce, and cedar die off, and the trees that lose their needles die [5, 12]. In other words, the radiation of the Tunguska explosion was clearly not enough to melt clay and ceramics.

A detailed study of living trees located around the epicenter of the disaster was carried out in the 1970s [13]. About 120 larches that survived the catastrophe were studied. The researchers climbed to a height of 15 - 20 m above the ground and examined the branches that were already growing at the time of the disaster. The height above the ground, azimuth and inclination to the horizon of each branch were determined, then branches were cut down. Further study of these branches took place in the laboratory [8]. It turned out that the branches affected by radiation make up the upper tier of the crown. The underlying thicker branches were torn off by the shock wave. It was found that the lesions are purely physical in nature, associated with overheating and the death of cadmium in small branches. The affected surface was elongated by a strip along the branch, mainly from its upper side. This makes it possible to associate damage with the light radiation of the explosion and exclude the effect of a fire [14, 15].

According to estimates [14], for the appearance of a physiological burn and the death of cadmium on a branch 10 mm thick, a radiation pulse Q of 10 ± 5 cal·cm⁻² is required. The pulse Q consists of the radiation energy flux in the visible, infrared and ultraviolet parts of the spectrum. Trees with a maximum diameter of the affected branch $D \sim 10$ mm are located at a distance of ~5 km from the epicenter [14].

We can estimate the amount of radiation energy of the explosion (for the explosion heights of 5 and 10 km) required to create such a burn. Neglecting the absorption of radiation by the atmosphere, we estimate the radiant energy E_R of the explosion based on the relationship:

$$Q = \frac{E_R}{4\pi L^2}, \quad (1)$$

where L is the distance from the center of the luminous sphere. We can determine the value of the radiation energy, assuming that the light pulse of the Tunguska explosion Q was 10 cal·cm⁻² at a distance of 5 km from the epicenter. Calculations show that the radiation energy of the explosion, which took place at a height of 5 - 10 km above the epicenter, should have been in the range from $2 \cdot 10^{21}$ erg to $7 \cdot 10^{21}$ erg. If we consider the total energy of the Tunguska explosion as 10 megatons of TNT equivalent, then the radiation energy will be ~1% of this energy.

3. EXPLOSION WAVE

The first information about the unusually powerful air wave of the Tunguska explosion was obtained by Voznesensky [16]. Seismographs of the Irkutsk Observatory, located 893 km from the epicenter, recorded an earthquake consisting of two parts. According to Voznesensky [16], the first wave, with an onset at 0 h 19.2 m and a maximum at 0 h 20.1 m, is undoubtedly a seismic and, most likely, local earthquake, the second

wave, with an onset of about 1 h 03.1 m and ending at 1 h 10 m, was of some unusual origin. Voznesensky admitted that the record, which was unusual for seismic vibrations, was caused by air waves, or rather by the shaking of the earth during the passage of sound waves. Seismic waves covered the distance from the explosion site to Irkutsk in 1 minute 58 seconds. Air waves, propagating at the speed of sound, moved for about 45 minutes [16].

The sound wave from the explosion of the Tunguska cosmic body was “noted” on the barogram in Kirensk, after which similar records were found at other meteorological stations. The passage of sound waves in Turukhansk (820 km from the epicenter), Olkhon (860 km), Kultuk (970 km), Kabansk (990 km), Khata-tanga (1110 km), Chita (1130 km), Sretensk (1230 km) and even in Verkhoyansk (1680 km) was noted by instruments installed at the meteorological stations of that time. The oscillation amplitude turned out to be quite significant, up to 2.45 mm at the maximum.

In the 1930s, a recording of the same sound wave was found on the barograms of St. Petersburg and Slutsk (now Pavlovsk), located at a distance of ~3740 km. In this case, the amplitudes turned out to be about 0.2 mm. A trace from the passage of a wave formed as a result of the explosion of the Tunguska body was noted on microbarograms in Berlin (5050 km), Schneekopp (5090 km), Potsdam (5080 km), Batavia (7470 km), Washington (8910 km), etc. Surprisingly, in Potsdam, the instruments also registered a second wave, which arrived after 30 hours, that is, it circled the globe (34,920 km).

Whipple [17] presented a generalized picture of the air wave on the basis of data from recorders in Great Britain (Figure 2(a)). The microbarogram of the Tunguska explosion has specific features. The initial, rather smooth rise in pressure at the wave front is replaced by a much deeper rarefaction, after which damped oscillations follow. In a nuclear explosion wave [18], the magnitudes of the compression and rarefaction waves are practically symmetrical with respect to the level of unperturbed conditions (Figure 2(b)).

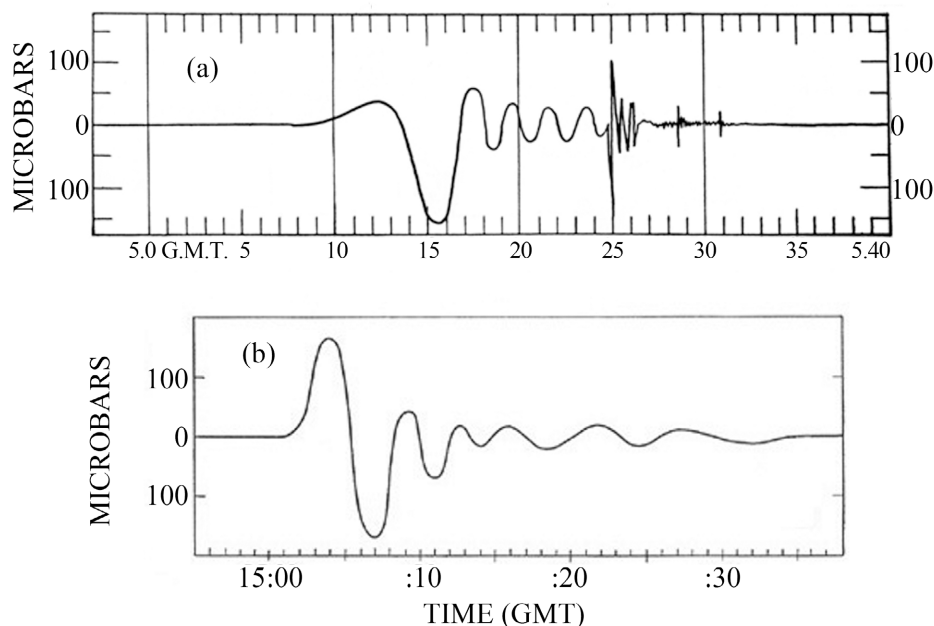


Figure 2. Air waves of explosions. (a) Tunguska explosion wave recorded in Great Britain (~5700 km) obtained by Whipple [17]. (b) Wave of a nuclear explosion that took place in October 1961, recorded in Washington (~7000 km) [18].

The catalog of Vasiliev *et al.* [6] contains about 700 eyewitness accounts of the Tunguska catastrophe. Reports note the deaths of people and deer during this event. The damaging effect of the shock wave, leading

to death, was observed near the epicenter (up to 8 km). At distances of more than 30 km, people died from fright or injury. The deafening effect of the shock wave was noted up to 200 km from the epicenter; in some cases people were unconscious for 2 - 3 days (**Supplement 1**). The destruction of windows and glass occurred mainly at distances from 200 to 400 km, however, individual cases were recorded up to 570 km (**Figure 3**).

According to Pokrovsky [19], if the excess pressure of the shock wave $\Delta P \geq 2$ atmospheres (200 kPa), people (and deer) are killed. The destruction of capital buildings occurs at an overpressure at the shock wave front of ≥ 50 kPa [19, 20]. The huts survived in Vanavara, located 65 km from the epicenter, that is, the pressure in that place was less than 50 kPa. At $\Delta P \approx 0.2$ atmospheres (20 kPa), contusion occurs. To destroy glass, an excess pressure of 2 - 7 kPa is required [19]; we can assume that at 300 and 500 km ΔP was 7 and 2 kPa, respectively (**Table 1**). The excess pressure recorded in Tulun (660 km from the epicenter), Irkutsk (910 km) and England (5400 km) was 3.26 hPa, 2.20 hPa and 0.55 hPa, respectively [5, 21].

Table 1. Shock wave of the Tunguska explosion.

R (km)	8	65	100	300	500	660	910	5700
ΔP (kPa)	200	<50	20	7	2	0.3	0.2	0.06

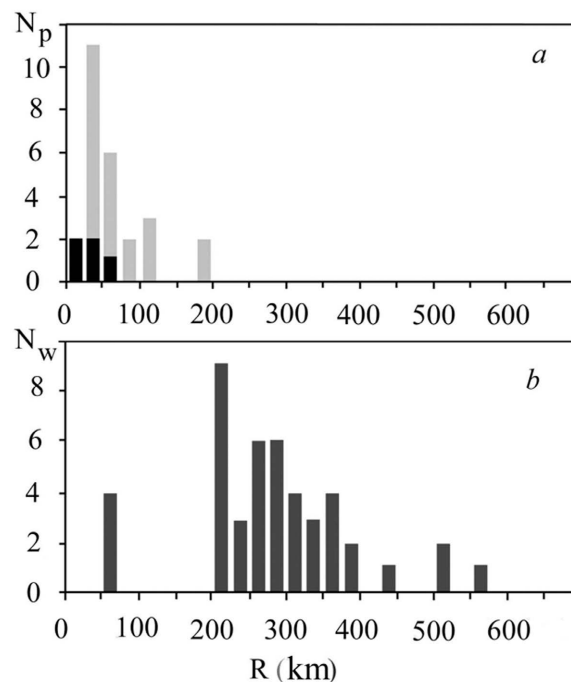


Figure 3. Impact of destructive factors depending on the distance R from the epicenter of the Tunguska explosion. (a) The number of reports N_p of the death of people and deer (dark bars), as well as loss of consciousness by people (light bars). (b) The number of reports N_w about the destruction of windows (glasses).

The position of points in **Figure 4** (**Table 1**) is best described by a power law. We can determine the wave parameters, imagining the attenuation of excess pressure on the shock wave front ΔP with a distance R , power function

$$\Delta P = k \cdot R^{-a} \quad (2)$$

The approximation of the data gives us the exponent $a = 1.387$ (**Figure 4**), that is, to a rough

approximation the shock wave decreases with distance as $R^{-1.4}$ for the Tunguska explosion. To construct a more accurate model of shock wave propagation, it is necessary to take into account the inhomogeneities of the atmosphere. The explosion occurred at an altitude of ~ 7 km, so the relief features (~ 0.1 km) can probably be neglected at this scale.

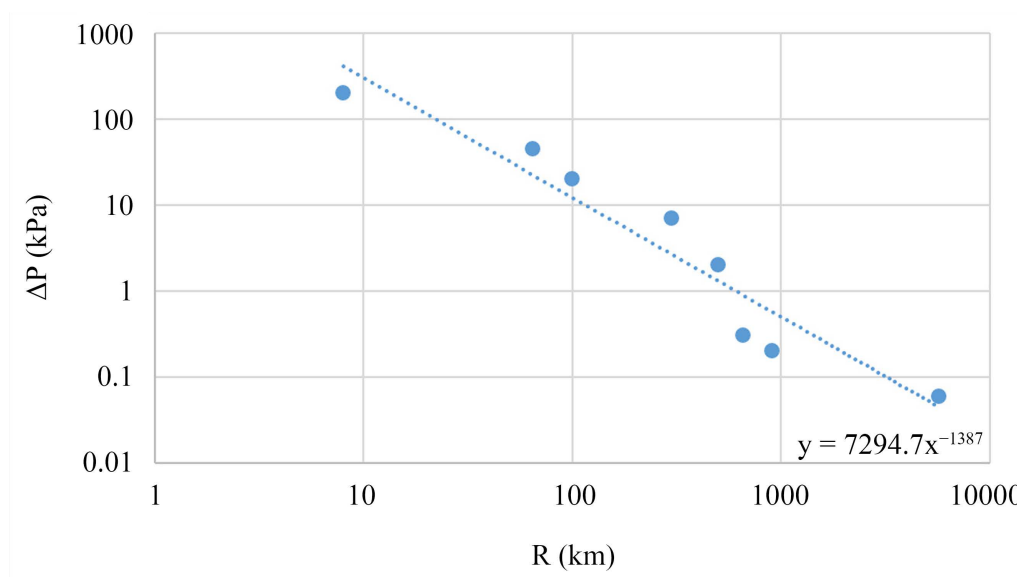


Figure 4. Change in excess pressure ΔP with distance R . The dotted line is the trend line and the formula for it.

4. DISCUSSION

If we consider the total energy of the Tunguska explosion as 10 megatons of TNT equivalent, then the radiation energy will be $\sim 1\%$ of this energy. Thus, the Tunguska explosion differs significantly from nuclear explosions, in which light radiation accounts for about a third of the explosion energy [20]. Experiments have shown an interesting feature in chemical explosions. If you blow up the same amount of explosive in solid form and in the form of an aerosol, then the blast wave from the aerosol will be larger. That is to say, the energy of a volumetric explosion mainly goes into the blast wave, and not into heat and radiation.

Blast wave of the Tunguska explosion went around the globe and turned out to be comparable to waves of much more powerful explosions. The air wave formed as a result of the explosion of the Krakatoa volcano in 1883 circled the globe several times. However, it should be noted that the explosion energy of this volcano is estimated at 100 - 200 megatons of TNT, which is an order of magnitude greater than the explosion energy of the Tunguska cosmic body. An atmospheric nuclear explosion over the island of Novaya Zemlya was carried out in October, 1961. The release of energy in this explosion was equivalent to 58.6 megatons of TNT. The air wave circled the Earth three times. The zone of destruction of buildings extended up to 120 km. Window panes were partially broken at a distance of up to 900 km. Obviously, the physical mechanisms of energy release in volcanic eruptions, nuclear explosions and the Tunguska event are completely different.

Based on the comet nature of the Tunguska body, it can be concluded that in this case, we are dealing with a volumetric explosion. Space experiments have shown that cometary matter consists of micron-sized granules containing dust, water and organic matter [22, 23]. It is generally accepted that comets contain $\sim 30\%$ organic matter, including methane, ethylene, propane-butane, gasoline, kerosene, and so on, as well as $\sim 30\%$ of water. The interaction of a cometary object with the Earth's atmosphere is accompanied by an explosive release of matter [24]. Water and organic matter are released from the granules ejected from the comet. Water interacts with the atmospheric components and decomposes into hydrogen and oxygen. In this way, a cloud is formed in the form of the gas-air mixture of dispersed fragments of the comet mixed

with atmospheric oxygen. The explosion of this cloud is most likely associated with a lightning between the Earth's surface and positively charged large fragments of the Tunguska body.

5. CONCLUSIONS

An influence of the Tunguska explosion on the environment turned out to be very specific. The shock wave of this explosion (with a power of about 10 megatons of TNT equivalent) circled the globe, similar to significantly more powerful events: the explosion of the Krakatoa volcano (>100 Mt) and the nuclear test of 1961 (~59 Mt).

The light energy released during the destruction of a cosmic body at an altitude of ~7 km above the earth's surface amounted to only ~1% of 10 megatons. It was determined by the level of damage to vegetation in a circle of about 15 km around the epicenter. Several groves of trees that survived the disaster were discovered in the immediate vicinity of the epicenter.

It is likely that the explosion during the Tunguska event was a volumetric explosion of a giant cloud of disintegrated comet matter mixed with oxygen in the air.

CONFLICTS OF INTEREST

The author declares no conflicts of interest regarding the publication of this paper.

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SUPPLEMENT 1. SHOCK WAVE ACTION

Catalog number	The source of information	Observation point. Coordinates. (Distance to epicenter)	What was observed?
7/11	L.V. Dzhenkoul	(~10 km)	At the mouth of the CHEKO, many deer lay as lumps (balls)... (they were stunned, and they died). From the top of the POLNOTY (CHURGIM) stream, the forest was scattered in different directions. Chums (reindeer breeder's houses) flew into the air, people fell unconscious, then consciousness returned.
6/4	S.B. Semenov	Vanavara 60°20'N; 102°17'E (65 km)	...And there was a strong blow, and I was thrown to the ground three fathoms. At the first moment I lost consciousness, but my wife ran out of the hut and led me into the hut. After the impact, there was such a noise, as if stones were falling or firing from cannons, the earth was trembling... From the north a hot wind had shot forth (blew) past the houses, like from a cannon which left tracks in the form of paths on the ground and damaged a growing bow. Then it turned out that many of the windows were broken, and the iron padlock at the door of the granary had broken.
6/8	P.P. Kosolapov	Vanavara 60°20'N; 102°17'E (65 km)	There was a blow, the soil was dropping from the ceiling, a stove damper flew out of the Russian stove onto the bed opposite it, and one pane of glass was knocked out of the window into the room.
7/3	E.S. Daonova and D. Pikunova	Evenk's camp near the Tetera River 60°05'N; 102°19'E (92 km)	They were awakened by strong sounds resembling rifle shots, and then there was an incredible roar. The roof of their yurt was blown off, and for two days afterwards the whole family lay unconscious.
10/244	K.G. Panov	Panovo 58°58'N; 101°54'E (213 km)	Then the earth shook, the horses fell, the end of the world came. In the village of Panovo, roofs were torn off, windows flew out.
10/46	Irina Ivanovna Bryukhanova	Kezhma 59°00'N; 101°05'E (214 km)	The Grashy's windows, in the center of the village, flew out, flew down the street to the lane (100 meters, along Gagarin Street now).

Continued

10/123	Mikhail Nikiforovich Suslov	Yarkino 59°09'N; 99°22'E (238 km)	The storm passed and the windows broke. The stoves were being used and the flame flew out the window. The wind was angry, hot with fire... They thought it was a fire. They ran for water with buckets, but the village, it turns out, was not on fire.
10/194	Mikhail Zahiridonovich Rukosuev	Yarkino 59°09'N; 99°22'E (238 km)	The earth trembled, the windows flew out... Cast iron pots were flying, glass was trembling. The wind has passed, the hair has raised.
10/71	Aksinya Grigorievna Verkhoturova	Aleshkino 58°35'N; 100°27'E (268 km)	In the village, the stoves broke, the windows flew out. It rumbled for half an hour.
10/87	Praskovya Vasilievna Karamysheva	Kostino 57°54'N; 100°40'E (339 km)	There were logs laid on the hut fell down. The windows fell out.
10/7	Alexey Nikiforovich Stupin	Vorobyevo 57°23'N; 102°18'E (390 km)	The corners were torn off from the huts and the glass flew out. The sound was similar to cannons firing. There was a jolt later. The rocking continued for several minutes.
10/216	Evdokia Andreevna Potapova	Rybnoe 58°10'N; 94°18'E (523 km)	She remembers the trembling of the earth, the hut and dishes in the hut. Many glasses flew out and the trees were bending. "We were scared. We thought it was the end of the world."
