

THE KAALIJARV METEORITE CRATERS ON SAAREMA ISLAND, ESTONIAN SSR*

E. L. KRINOV

Committee on Meteorites, U.S.S.R. Academy of Sciences, Moscow

ABSTRACT. A group of one large and six small meteoritic craters in Estonia has been investigated in some detail, both morphologically and as to content of meteoritic fragments. Arguments are presented for considering the large crater an explosion crater arising from the collision of a large meteorite at remaining cosmic velocity. The explosion destroyed the meteorite and blasted the crater in the ground. The small craters, on the other hand, although arising from members of the same meteorite shower, are impact craters. The smaller fragments responsible for impact craters had been slowed down by atmospheric drag to the extent that they had no remaining cosmic velocity on impact, and no explosion occurred. Unlike the large crater, the small craters do contain fragments of meteorites.

The Estonian craters are compared with similar groups elsewhere, notably Sikhote-Alin, U.S.S.R.; Henbury, Australia; and Brenham, Kansas. (D. Hoffleit)

INTRODUCTION

The remarkable group of craters known as Kaalijarv meteorite craters (fig. 1) are located 20 km to the northeast of the town of Kingisepp (formerly Kuressaare) on Saarema Island, in the Estonian Soviet Socialist Republic (Krinov, 1955). The craters aroused the interest of scientists as far back as the first quarter of the last century. Since then researchers have repeatedly attempted to establish the nature of the craters and explain the conditions of their formation. In 1927, I. A. Reinwald, a mining engineer, began a study proving that they were of meteoritic origin.

The group consists of seven craters located in plowland covering an area of approximately 0.75 sq km (fig. 2). Seen from above, the largest has a regular round outline (fig. 3). It is 110 m in diameter and its rim rises 6 to 7 meters above the level of the surrounding terrain. The crater is filled with water and forms a picturesque pond about 16 m deep. Hence the bottom of the crater is 9 to 10 meters below the outer surface. On and around the rim of the crater there are large trees and bushes, making this unique parklike area easily seen from a distance, like an oasis in a desert. As distinct from the main crater, the other six remain dry and are of the following dimensions:

<i>Crater No.</i>	<i>Diameter</i>	<i>Depth</i>
	<i>m</i>	<i>m</i>
1	35	4.0
2	35 x 53	3.5
3	32 x 33	3.5
4	20	3.5
5	12 x 15	0.9
6	25 x 26	0.65

For hundreds of years local inhabitants have collected the stones from the fields they tilled here and thrown them into the craters. As a result the craters became filled with stones. Like the main crater, the smaller ones are overgrown with nut trees and can easily be seen from a distance. The stones and bushes have protected the craters against various agents of eolation.

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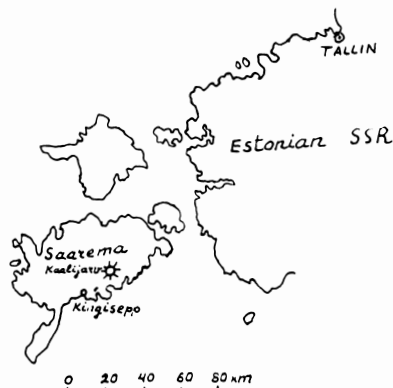


Fig. 1. Map of a section of the Estonian SSR and Saaremaa Island showing location of craters.

RECENT INVESTIGATIONS

On instructions from the Committee on Meteorites of the USSR Academy of Sciences, in the summer of 1959, L. G. Kvasha, a petrographer, I. T. Zotkin, an astronomer, and the author, accompanied by A. O. Aaloe, an Estonian geologist, investigated the craters.

The summer was dry and the water level in the main crater was considerably lower than usual, filling only the central part or very bottom of the crater. This made the crater's bowl-like shape, one of its chief peculiarities, clearly visible. The ramped layers of dolomite that rise at an angle of approximately 60° and protrude from the surface of the crater's rim (fig. 4) are especially impressive. In this area the dolomite bed, which is local sedimentary rock and consists of carbonate of lime and magnesite, is horizontal. It should be noted, as the second main peculiarity of the crater, that in all directions the elevation of the dolomite beds is radially outward from the center of the crater. Lastly, the third peculiarity is the clearly defined swell along the crater rim that rises steeply above the surrounding area.

The main peculiarity of the small craters is the presence of minute iron meteorite particles or meteoritic dust. One need only pull a magnet through the soil to collect particles of meteoritic dust; sometimes even small fragments of iron meteorites are found. In the main crater, on the other hand, despite repeated attempts no meteoritic dust has as yet been found.

Another peculiarity of the small craters is the complete absence of a swell and the elevation of the dolomite beds. Reinwald established (1928, 1939) that beneath elevated dolomite beds on the inside slope of the swell of the main crater there is a belt of dolomite which was crushed to a fine powder. In this "rock flour", lumps of soft dolomite were discovered that had been subjected to the influence of a high temperature.

In one of the small craters (No. 4), after partially excavating the matter with which it was filled, Reinwald discovered a depression about 0.5 m in diameter in the dolomite. The depression was in the lowest platform of the step-like bottom of the crater.

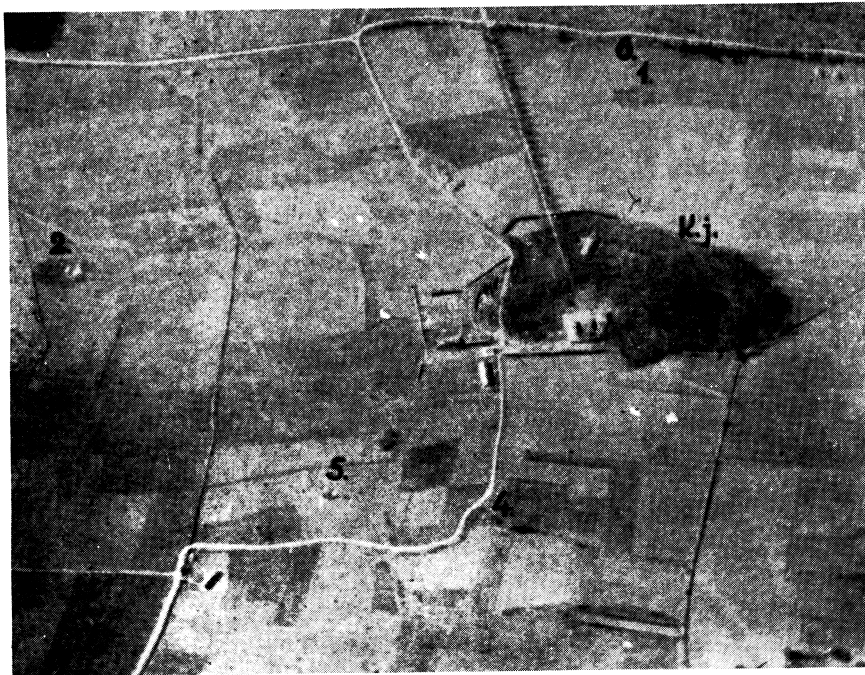


Fig. 2. Aerophoto of Kaalijarv craters. Numbered according to I. A. Reinwald.

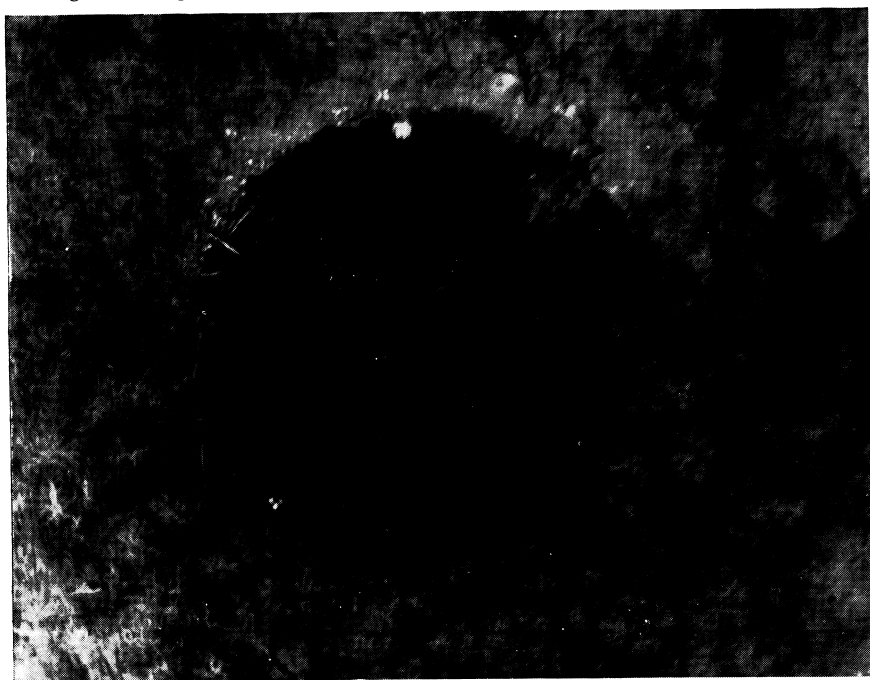


Fig. 3. Aerophoto of Kaalijarv main crater (by I. A. Reinwald).

In 1929 the diamond drilling Reinwald undertook in the main crater showed that the dolomite had been entirely or partially crushed and burnt to a depth of 4 to 5 meters. Below this level the rock was normal. Reinwald again investigated the craters in 1937, partially excavating craters Nos. 2 and 5. Excavation in crater No. 2 to a depth of 2 m showed first a layer of soft soil 10 to 15 cm thick. Beneath this there was a compact brownish mixture consisting chiefly of small pieces of dolomite, rock flour, and clay-sand glacial deposits. The entire matter filling the crater had not been disturbed since the formation of the crater. In the filling matter at a depth of one meter, the first iron meteorite fragment was discovered: it weighed 24 grams and was covered with a thick layer of rust. On deeper excavation such fragments continued to be found. In the 80 cubic meters of matter removed during partial excavation, 28 meteorite fragments were found with a total weight of 102.4 grams; the weight of the individual fragments ranged from 0.1 to 24 grams.

In the other partially excavated crater (No. 5) two meteorite fragments weighing 4.8 and 3.4 grams were discovered, also covered by a thick layer of rust. In 1938 when Reinwald again excavated this crater he found another fragment which weighed 9.1 grams.

Chemical analysis of the meteorite fragments collected showed a nickel content of 8.3 percent. This amount of nickel is typical of the most common type of iron meteorites, medium structure octahedrites. Etching of the polished surface of one of the larger fragments revealed the typical Widmanstätten figures of this type of octahedrite.

By discovering meteorite fragments in the craters, Reinwald definitely proved their meteoritic origin. Unfortunately, he died in 1941 without having completed his study of the Kaalijarv craters. At present the study of the craters is being continued by A. O. Aaloe, under the guidance of Academician K. K. Orviku of the Estonian Academy of Sciences. In 1955 Aaloe (1958) undertook partial excavation of crater No. 5, and found that the crater was formed in a stratum of basic moraine (no less than 1.2 m thick) and in layers of dolomite beneath it. In the northern part of the crater the surface of the original rock beds at a depth of 1.2 m forms steps along the inner slope of the crater (fig. 5). These steps were formed by the mechanical crushing of the dolomite by the fall of the meteorite. The bottom of the crater is in the original rock which is dolomite. Three meters from the western rim of the crater, a craterlike hole 22 cm deep and 60 cm in diameter was discovered in the meridional direction and 52 cm in the latitudinal direction. A study of this depression led Aaloe to conclude that it had been formed by the impact of a meteorite. Similar depressions, as mentioned above, were discovered by Reinwald also in crater No. 4; he, too, explained them as being due to the mechanical impact of a meteorite.

By means of a magnet, Aaloe collected 450 grams of iron meteoritic fragments, each over 1 mm in diameter, in the matter filling crater No. 5. He also collected meteoritic dust. Most of the fragments are less than 5 mm in diameter. Only 51 of them weigh over one gram each and six fragments weigh over 5 grams; the largest fragment weighed 8.62 grams. The fragments are of irregular shape and frequently have sharp edges. They are highly weathered, crusted with rust, often pierced by cracks, and break easily. Aaloe was the



Fig. 4. Elevated dolomite layers protruding from the inside slope of the swell of the main Kaalijary crater. I. A. Reinwald is seen standing near the swell (I. A. Reinwald's photo).



Fig. 5. Step-like slope of the smallest crater, No. 5, after excavation of filling material. The horizontal layers of dolomite, chipped by the impact of the meteorite, can be seen. Standing inside the crater are (left to right): I. T. Zotkin, A. O. Aaloe, and L. G. Kvasha (Photo by E. L. Krinov).

first to discover magnetite globules from 0.15 to 6.4 mm in diameter. He believes that some of these globules may be particles of the dust train of the meteorite, i.e. meteoritic dust.

Lastly, among the matter found there were many broken and whole mollusc shells which, according to Aaloe and L. Sarva, a paleontologist, are typical of this damp coastal area. On this basis, they concluded that the formation of the Kaalijarv group of craters took place soon after the retreat of the littoral sea in the vicinity of Kaali, approximately 4000 to 5000 years ago.

At the time of the excavation of crater No. 5, E. Pöbul took magnetometric measurements on crater No. 3. The measurements with two variometers were carried out according to a 1 x 1-m measuring grid. The measurements within the crater revealed weak and very local isometric micro-anomalies that are elongated in some places. On the basis of the magnetic measurements Pöbul concluded that there are no large masses of meteoritic iron and that the magnetic anomalies he had discovered were due to very small agitators at a small depth. From experiments on the magnetic influence of the meteorite fragments collected in crater No. 5, Pöbul concluded that small meteoritic fragments weighing no less than 20 grams can cause the magnetic anomalies that he discovered in crater No. 3.

It should be pointed out that in the main crater no meteorite fragments, meteorite dust or impactites—pieces of fused rock—typical of meteorite explosion craters have thus far been discovered.

A study of the fall of many meteorites (Krinov, 1955), including the remarkable Sikhote-Alin iron meteorite shower that fell in the Far East on February 12, 1947 (Krinov, 1956a, 1956b, 1959), shows that when meteoritic bodies move through the Earth's atmosphere at cosmic speed, they break up, as a rule, regardless of their composition or size (Krinov, 1958). Their breakup is caused by the extremely great atmospheric pressure on the front surface caused by their great speed, which exceeds 11 km per sec. At an altitude of 15 km above the Earth's surface this pressure reaches 100 kg per sq cm. The irregular polyhedral shape of meteoritic bodies to a considerable degree also promotes their breakup, causing uneven distribution of pressure on the surface of the meteoritic body and a steady, sometimes significant change in the atmospheric influence during the tumbling of the meteoritic body. The breakup of meteoritic bodies results in meteorite showers after which dozens, hundreds, and even thousands of individual samples may be collected. Meteorites from showers spread over an elliptical area called a dispersion ellipse. The individual samples from meteorite showers usually spread in the dispersion ellipse according to a definite order. The larger samples fall at the head or front of the ellipse, relative to the direction of motion, while the smallest samples fall in the opposite part or rear section, while samples of intermediate size fall in the middle of the ellipse.

It has, on the other hand, been established that atmospheric drag causes the meteoritic body or its remaining fragments to lose practically their entire cosmic speed at an average altitude of about 12 km. This section of the atmospheric path is called the region of delay. After passing through it, the fragments fall to the surface of the Earth like ordinary stones that have been



Fig. 6. Outline drawing of the profile of one of the craters of the Sikhote-Alin meteorite shower (by E. L. Krinov and S. S. Fonton).

thrown into the air and are attracted by the Earth's gravity. However, when meteoritic bodies have a large original mass that runs into scores or hundreds of thousands of tons, the region of delay is beneath the surface of the Earth, and what is left of the meteoritic body then strikes the surface of the Earth with the remaining cosmic speed. At the moment of impact this speed may be sufficient to emit a considerable quantity of heat energy and transform part of the meteoritic matter into heated compressed gas. As a result, at the point of impact, explosion of the meteorite and ground takes place.

Stanyukovich and Fedynsky (1947) and Stanyukovich (1950) established that when the speed of a meteorite falling on the surface of the Earth does not exceed 100 m per sec. an ordinary hole or pit is formed at the point of impact in soft ground, and the dimensions of the hole are comparable with the dimensions of the meteorite. However, when a meteorite falls at this speed on hard stony ground, both the meteorite itself and the ground break. When a meteorite strikes soft ground at an impact speed from 100 m per sec to 500 m per sec, it also breaks up. The meteorite fragments and the ground fly in all directions, resulting in a crater whose size exceeds that of the meteorite: the greater the impact speed, the larger the crater. When the speed is over 500 m per sec the size of the crater increases as the impact speed increases, but the mechanism of crater formation does not change qualitatively. However, when the impact speed exceeds 3 or 4 km per sec the picture changes sharply: a powerful blast spreads outward from the point of impact (as the center of explosion) and destroys the meteorite as well as the surrounding adjacent ground. At this speed a solid body acquires the properties of highly compressed gas, as the force of molecular cohesion is relatively small compared with the energy of the

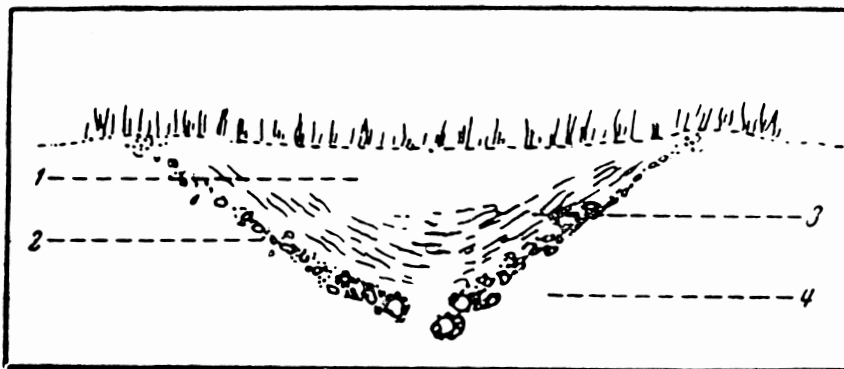


Fig. 7. Outline drawing of the profile of the Brenham meteorite crater (according to H. H. Nininger).

blast wave. The great quantity of the compressed gas immediately strives to expand leading to the explosion of the meteorite and the formation of a meteorite crater.

When the speed of the impact equals approximately 5 km per sec, the action of the entire destructive mass of the meteorite and the ground in the zone of the explosion amounts to the action of an equivalent mass of explosive material. But as the impact speed exceeds 60 km per sec, the explosive action of the meteorite mass and the adjacent ground will be 1000 times greater than the action of explosive material of the same mass. Thus, when large meteorites fall, craters of the two main types are formed: impact craters due to the mechanical destruction of the ground caused by the fall of large meteorites, and explosive craters due to the fall of giant meteorites. A characteristic feature of the impact craters is the great number of meteorite fragments they contain. Meteoritic fragments, original rock, and soft ground line the inside slopes of the craters. Moreover, the largest impact craters do not exceed several dozen meters in size, whereas it is doubtful whether the smallest explosion craters are less than a hundred meters in diameter.

The craters formed by the largest individual samples of the Sikhote-Alin meteorite shower (Krinov, 1956a, 1956b, 1959) are classical examples of impact craters. In the dispersion ellipse of this shower, 122 craters were found (not counting the small holes), of which 17 are from 10 to 26.5 m in diameter. A study of these craters showed that not a single one showed traces of explo-

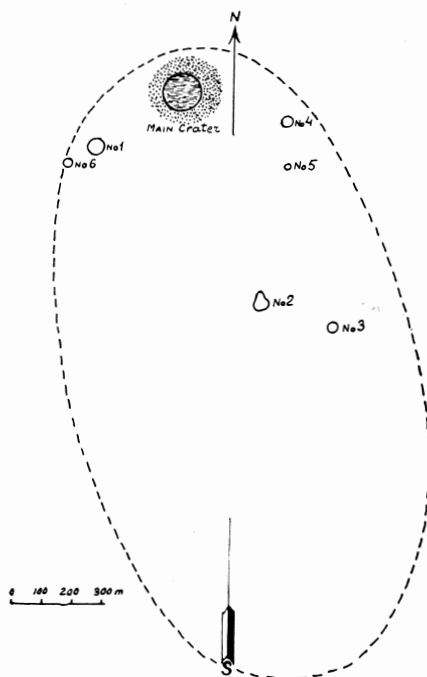


Fig. 8. Diagram of location of Kaalijarv meteorite craters.

sion, such, for example, as elevated layers of original rock around the crater rim, fused individual fragments, and burnt pieces of rock. On the contrary, the rims of the craters were formed of the filling matter, such as broken rock and soft ground. On the inside slopes of all these craters, layers of meteorite fragments were discovered mixed with broken rock and soft ground (fig. 6). In addition, particles of meteoritic dust were discovered by magnet among the matter filling the crater. Thus, the morphological properties of the largest craters of the Sikhote-Alin meteorite shower are similar to the morphological properties of the small craters of the Kaalijarv group.

The Brenham (Haviland) meteorite crater in Kansas is probably an impact formation also (fig. 7). It is about 17 m in diameter but before excavation it was a depression that was hardly noticeable. When H. H. Nininger excavated the crater to a depth of 2 m, he discovered countless fragments of this remarkable stony-iron meteorite (pallasite) that changed over to an iron meteorite (octahedrite). The fragments were covered with earth, abundantly permeated with rust. The largest fragment weighed 39 kg; most of the fragments, however, had already been completely transformed into rust (Nininger and Figgins, 1933).

At present there are about a dozen craters throughout the world that have been reliably identified as meteorite craters. In almost every case there are groups of craters that include one or two craters which are larger than the rest. The groups of craters indicate that large and sometimes giant meteoritic bodies break up in the atmosphere and meteorite showers occur. At the same time, the presence of the craters of larger size in each group shows that they are explosion craters while the others in the group are impact craters.

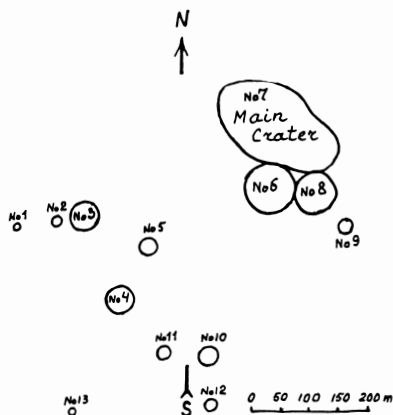


Fig. 9. Diagram of location of Henbury meteorite craters.

A map of the location of the Kaalijarv meteorite craters is shown in figure 8. The main crater is in the north-northwest section of the area while all the small craters are to the south-southeast of it. The relative locations of the craters prompts the conclusion that the meteoritic body moved from south-southeast to north-northwest. Under atmospheric pressure, it broke up into

parts. One of the fragments was so large that it reached the Earth's surface with the remaining cosmic speed. Hence, when it struck the ground there was an explosion and the meteorite crater was formed. That the main crater is of the explosion type is indicated by the layers of elevated dolomite that spread radially from the center and the presence of pieces of burnt dolomite. All the other fragments of the meteoritic body probably had a relatively small mass and therefore lost their cosmic speed at some altitude above the Earth's surface. They then fell according to the Earth's gravity, forming impact craters where they struck the ground. This explains the great difference between the size of the main crater and all the other craters. However, the difference in the sizes of the various small craters is relatively small, substantiating the conclusion that all the small craters (Nos. 1 to 6) of the Kaalijarv group are impact craters.

There is complete similarity between the regularity in distribution of the Kaalijarv craters, which clearly defines the dispersion of the separate meteorite masses and the isolation of the explosion craters, and the group of 13 Henbury craters in Australia, discovered in 1931 (Spencer, 1933). The main crater in the latter group, 220 and 110 m in diameter (there are probably two main closely connected explosion craters), is situated in the northeast section of the area and all the others, which are considerably smaller, are to the southwest of the main crater (fig. 9). Consequently, we may conclude that the meteoritic body in this case moved from southwest to northeast.

During the meteorite shower at Kaalijarv, besides crushing the layers of dolomite and forming craters, the smaller meteorites themselves split up into a multitude of fragments and meteoritic dust that have been preserved to this day in the matter filling the crater. It may be supposed that farther to the south-southeast still smaller samples fell, forming craters of correspondingly smaller size (fig. 8). Perhaps, on careful study of the locality, traces of such craters in the form of slight depressions may still be discovered. Lastly, further to the south-southeast, small individual samples weighing from a few grams or less to hundreds of kilograms must have fallen. The larger samples possibly lie preserved in the ground. It may therefore be assumed that on careful study of the locality with instruments such as mine-detectors they may still be found.

In conclusion it should be emphasized that the Kaalijarv meteorite craters are of outstanding scientific significance. A careful and thorough study of these formations will undoubtedly yield important data on the circumstances of the fall of giant meteorites and the nature and magnitude of the accompanying explosion phenomena. A study of the locality to the south-southeast of the craters with the help of the proper instruments may lead to the discovery of meteorite masses.

The craters of the Kaalijarv, the Tunguska fall and the Sikhote-Alin iron meteorite shower are the three outstanding phenomena in meteoritics within the territory of the Soviet Union.

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