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CONCERNING THE METEORITIC ORIGIN OF THE PUCHEZH-KATUNKI CRATER

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with introduction and geologic maps
by

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INTRODUCTION TO THE GEOLOGY OF THE REGION IN WHICH THE PUCHEZH-KATUNKI DISTURBANCE IS LOCATED

The accompanying article by L. Firsov suggests that a large region north of Gorkiy, U.S.S.R., may be an ancient meteorite impact crater. The Puchezh-Katunki Disturbance, denoted henceforth as PKD, is a 60 by 100 km elliptical structure of controversial origin, situated in the central part of the Russian platform, north of Gorkiy. (Index and geological maps are shown in Figs. 1 to 3). In this region the Russian platform is a typical peneplain with topographic relief determined by differential river valley erosion. The following geological summary and the geological map in Fig. 2 are adapted from Nalivkin (1960). The detailed map of the PKD in Fig. 3 is from Goretskii (1962).

Carboniferous, Permian, Triassic, Jurassic, and Cretaceous rocks are exposed; Tertiary rocks are absent. Quaternary alluvium fills the Volga River valley near Gorkiy. Carboniferous rocks are exposed in the sub-Moscow coal basin. The lowest stages of the Carboniferous are sandstones and clays with coal seams, overlain by light gray marine limestones of the higher stages. Lower Permian rocks are argillaceous marine and continental shales and sandstones and in places, south of Gorkiy toward the Urals, contain deposits of potash salts, rock salt, gypsum, anhydrite, and borates. A low stage of the Upper Permian, the Kazanian stage, is represented in the Puchezh-Katunki region by clays, limestones, dolomites, and marls. On the map, Fig. 2, the Kazanian is combined with the Lower Permian unit because of the small size of the outcrops south of Gorkiy. The Kazanian rocks and related fauna are representative of deposits from an extensive saltwater sea. The Tartarian stage of the Upper Permian consists of continental deposits of

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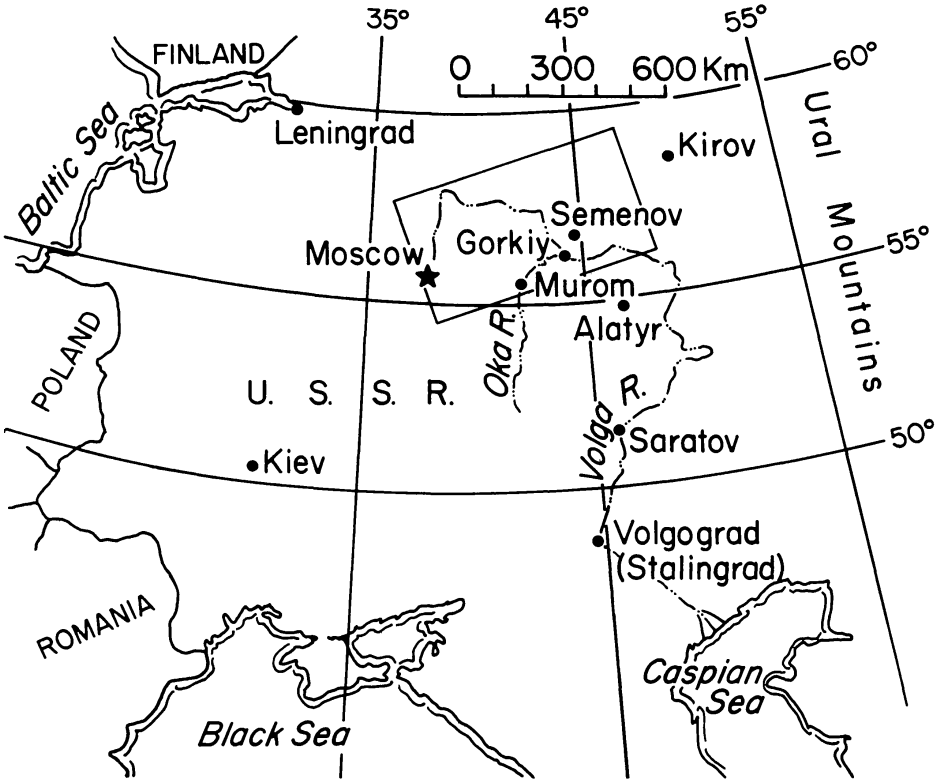

Fig. 1. Index map of the Siberian platform, showing the location of the PKD north of Gorkiy.

red beds and freshwater limestones. The Tartarian beds are continued upward as red beds of the Lower Triassic. Lower Jurassic beds are generally absent on the Russian platform.

In the region of the Volga, considerable subsidence of the Russian platform occurred during the Middle Jurassic, producing sea transgression; sand, clay, and a small amount of limestone were deposited. Maximum submergence and sea transgression occurred during the Upper Jurassic. A shallow sea or strait was formed along the Urals in the eastern half of the platform; clays and sands were deposited, facilitating the formation of glauconite-phosphorite deposits. Accumulations of organic material, mainly planktonic, formed in stagnant hollows. These have been transformed into bituminous shales. Lower Cretaceous strata occur in the same places as the Upper Jurassic rocks, and the deposits possess the same characteristics. The Upper Cretaceous rocks represent sediments deposited in a different basin than the Lower Cretaceous and Upper Jurassic sediments. During the Upper Cretaceous, the Moscow region was the northern shore of a sea extending to the south. Coarse-grained sedimentary facies are predominant in the Upper Cretaceous of the Moscow region.

The search for mineral deposits on the Siberian platform has led to the sinking of many drill holes in the PKD. Compared to other great industrial regions of the world, the Moscow-Gorkiy region is devoid of

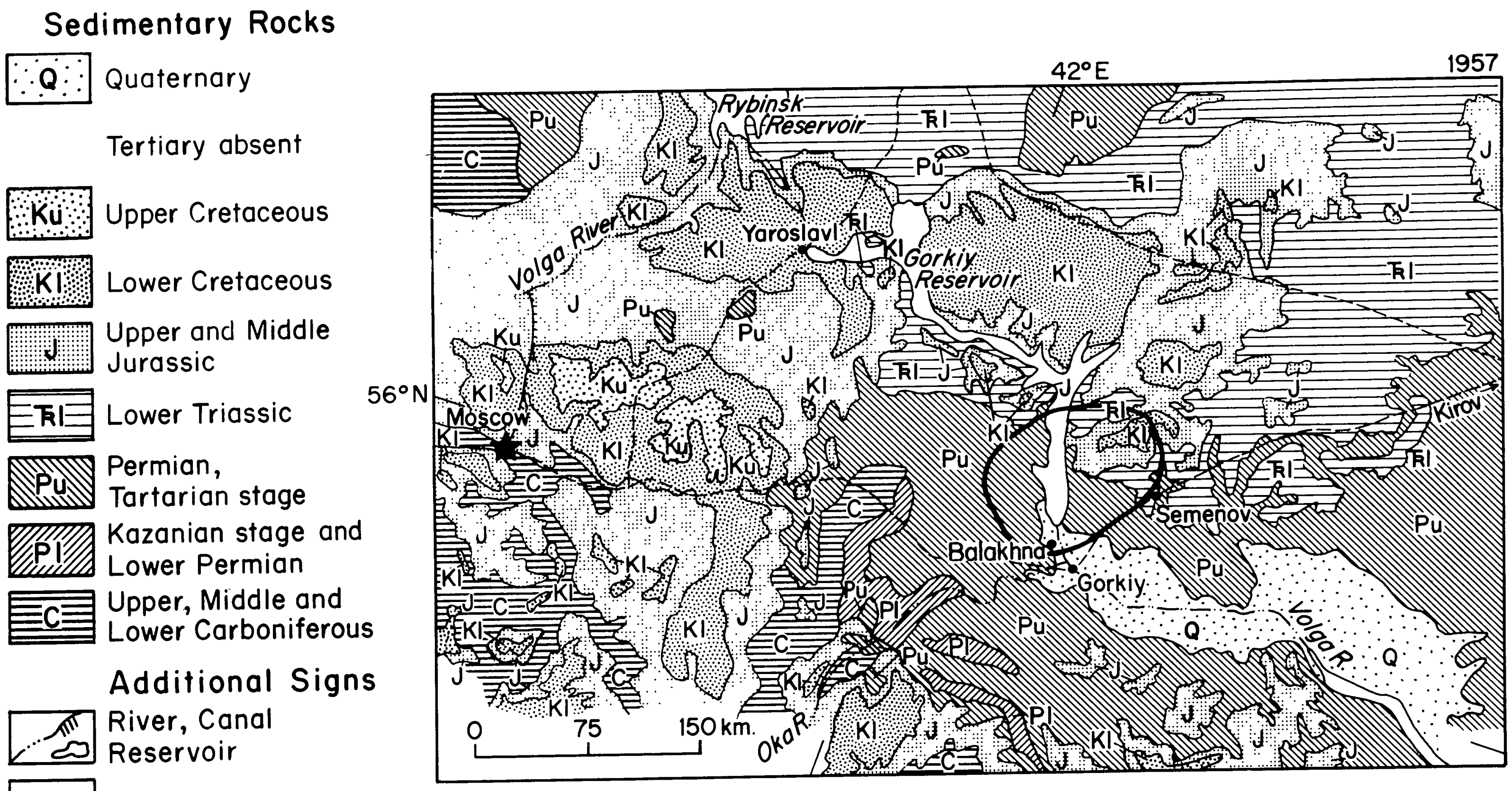

Fig. 2. Geological map of the Siberian platform in the vicinity of the PKD, adapted from D. V. Nalivkin (1960).

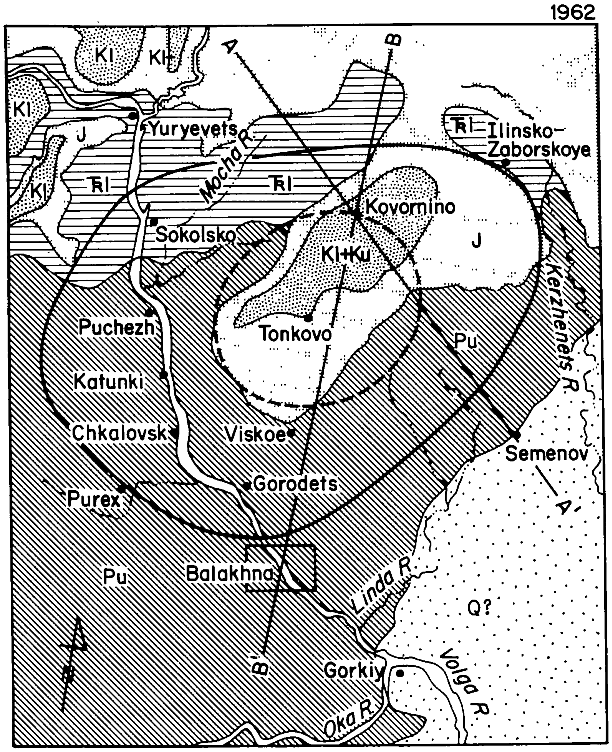

Fig. 3. **Detailed map of the PKD, from Goretskii (1962). Approximate locations of the cross sections in Figs. 4 and 5 are shown as A-A′ and B-B′. Differences in detail between the maps of Figs. 2 and 3, and the cross sections in Figs. 4 and 5, could not be reconciled using geological information available to the translator.**

raw materials and fuels, except for lignite, peat, and iron. However, the presence of abundant fuels and minerals in the Russian platform to the east and southeast and in the Urals has prompted extensive searches for economic deposits in similar geologic structures in the industrial region. Gas is found in many regions in the southwestern part of the platform, including Saratov, where natural gas occurs in crushed limestones of Lower Carboniferous age which form the core of an anticline. Gas reserves also occur near Kazan, approximately 400 km east of Gorkiy. Deposits of peat, coal, and bituminous shale occur near Moscow. Many deposits of gas and petroleum occur in anticlines and flexures which are on the surfaces of ramparts and domes. The Oka-Tzna rampart is located on the Oka River, west of Murom. It is an elongated, badly delimited anticlinal structure of 200 to 300 km length. Dips are generally less than one to three degrees. Only Carboniferous and Permian rocks are deformed in the rampart, whereas the underlying Devonian strata are everywhere horizontal. The Tokmovski dome, between Gorkiy and Saratov, is an elevation of crystalline basement rock of 800 to 1,200 m, mantled by Paleozoic deposits. The diameter of the dome is 200 to 250 km. Salt domes are conspicuous in the southeastern part of the platform; in some regions they contain petroleum.

It is in this context of economic development of regional mineral deposits that extensive exploration of the PKD has been conducted for over 75 years, giving rise to the many hypotheses of origin that Firsov has summarized in Table 1.

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The geology of a disturbance in the Puchezh-Katunki region is reviewed and two recent hypotheses of origin are criticized. A meteoritic origin for the disturbance is proposed, since the structure and morphology of this region are similar to the sloping conical surface produced by an explosive meteor crater. The energy, mass, and size of the asteroid which could cause such a disturbance are estimated. It is shown that the probability of an impact of this size is finite [over geologic time]. The crater was formed between the end of the Triassic and the beginning of the Jurassic periods.

For about one hundred years the attention of geologists has been focused on an unusual structure, the Puchezh-Katunki or Puchezh-Balakhna Disturbance (PKD), in the Paleozoic cover of the Russian platform. The disturbances of this zone are expressed as intensely crushed and deformed rocks. The rocks outcrop in an oval north of the town of Gorkiy, surrounded by the towns of Balakhna, Yuryevets, Ryaibov, and Semenov. The center of this zone is located a little east of the village of Tonkovo. In the course of the study of the PKD, which has been considered as a prospect for oil and gas and therefore has had a fairly large number of deep holes drilled, more than ten hypotheses have been published interpreting the origin of the disturbance in one way or another. Most of these hypotheses are at present only of historical interest. The problem still has not received a unanimous solution, and it continues to be under discussion.

The most detailed summary of factual material about the PKD and the most detailed critical analysis of hypotheses of its origin are contained in the excellent work of Goretskii (1962). In this work the author also introduces a new explanation for the disturbance as due to the effect of tectonic injection. Unfortunately, the slightly earlier work of Vardanyants (1961) was not used by Goretskii, as he apparently did not know of it. In my opinion, the work of Vardanyants is significant and deserves special attention because it contains new ideas. This cannot be said of Goretskii's own hypothesis, which attributes the formation of the disturbance to penetration of an intrusion of basic and ultrabasic rocks into the Paleozoic rocks of the Russian platform. This is only an assumption; it is obvious that it has not been proved by [field] evidence. It will be shown below that, even if the intrusion were spread somewhere at depth, it could not account for the extent of the deformation in the PKD. The excellent quality of the work of Goretskii as a bibliographic reference of factual material excludes the necessity for repetition here and allows us to limit ourselves to: 1) enumeration of earlier outstanding hypotheses in Table 1; 2) a concise presentation of the basic conclusions by Vardanyants; 3) a condensed discussion of the basic peculiarities of the zone of disturbance; 4) a criticism of the works of Goretskii and Vardanyants; and 5) a detailed analysis of a new hypothesis that is by no means of geotectonic origin.

Vardanyants (1961) disagrees with all previously published hypotheses. He defines the PKD as a structure of explosive nature, an explosion pipe, and assumes that the explosion originated as a consequence of accumulation of gasses in the crystalline basement of the platform. The explosion hypothesis of the author is very well confirmed by many facts and surpasses the old theories by its originality; however, he did not have evidence to qualify this explosion as from *depth.*

In 1962, in connection with the paper by Vardanyants, I brought forth a series of calculations and considerations in favor of a *surface* explosion, caused by the fall of a large meteoritic (asteroidal) body, for the PKD. Unfortunately, an answer to my letter did not appear, apparently because of the unusual and frightening content of this nongeologic hypothesis. Nevertheless, this hypothesis becomes more convincing in light of a whole series of structural earth forms and is now piercing the wall of orthodox opinion.

Two lines of wells, from Ezhovo to Semenov at azimuth 300° and Balahkna to Ryaibov at azimuth 15°, pass exactly through the center of the PKD and enable us to develop the following picture. In the almost horizontal sequence of the Cambrian to Permian deposits and early Triassic deposits, which are about 2 km in thickness, a gently sloping crater of about 60 by 100 km size was formed. The structure is seen in plan as an oval form that is somewhat elongated in an east-northeast direction along azimuth 70°. The angle of the slopes of the crater is generally 1 to 2°, in places reaching 3°, and is determined only by profiles of a line of wells. The cone is filled with intensely crushed and shattered Paleozoic and lower Triassic rocks. Into these, especially in the district of the valley of the Volga River in the western part of the PKD, were inserted, in the most diversified orientation, numerous detached masses of slabs from these same rocks in the form of blocks up to a few hundred meters in size and up to 1.5 km^2 in cross-sectional area. Although there is not always a sharp division between undeformed and deformed Paleozoic rocks found in the wells, observations indicate that the surface of the cone sinks from the elliptical peripheral contour of the PKD toward the center, the town of Tonkovo, to a depth of 500-600 m from the surface, possibly up to 1 km in the northeastern part of the PKD. Vardanyants and other authors remark that in this same direction, toward the center of the PKD, there is an increase in the size of the fragments of Paleozoic rocks and that the intensity of deformation increases. The central part of the PKD, which is slightly shifted toward the northeast edge, is a trough filled with sedimentary rocks, generally Middle to Upper Jurassic and

Table 1
Hypotheses Concerning the Origin of the Puchezh-Katunki Disturbance

Mechanism of Formation	Author, Year *
Tectonic formation (without more precise mechanism)	N. M. Sibirtsev, 1896; M. E. Noginskii, 1932; A. D. Archangelskii, 1922, 1940; E. A. Moldavskaya, 1933; D. I. Gorgeev, 1934.
Salt tectonics	M. S. Shvetzov, 1934.
Ancient karst	V. P. Amalitskii, N. M. Sibirtsev, 1896.
Quaternary glacial disturbance	A. M. Vasilnitskii and M. E. Noginskii, 1932; E. A. Kudinova, 1939; S. Bubnov; E. A. Moldavskaya; V. P. Priobrazhenskii; A. I. Moskbitin; V. V. Asonov; A. V. Artemev.
Ancient glacial disturbance	E. I. Tikhvinskaya, 1956; V. V. Borisova, A. N. Ivanov, 1949.
Torrential or proluvium formation	M. A. Zenchenko and G. N. Frederick; G. F. Mirchink, 1946.
Ancient slide or ancient proluvium (fanglomerate)	A. A. Bakerov, 1948; M. P. Kazakov, 1950; N. S. Shatskii, 1958.
Tectonic formation of a gneissic ridge with sliding of the Paleozoic rocks	E. M. Lutkivich, 1956, 1959; E. M. Lutkivich and D. L. Frukht, 1954; D. L. Frukht, 1958.
Development of projections in the basement and tectonic formation of the breccia	C. K. Nechitailo, M. M. Veselovskaya, E. N. Skvortsova, 1959; N. S. Illina, 1961, G. I. Goretskii, 1944, 1962.
Injection tectonics	V. K. Sobolev, 1958; L. A. Vardanyants, 1961.
Pipe explosion	[Vardanyants, 1961]
Meteorite crater	L. V. Firsov, 1964 (published in this communication).

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*These references were not listed in Firsov's original article, and the translator has not attempted to recover them.

Cretaceous, which have not been affected by deformations and overlap in sharp unconformity with the mixed and brecciated rocks. The trough is about 40 X 60 km in area and the center of the zone attains a depth of 400 m. Its formation undoubtedly was caused by the same process that led to the formation of the whole PKD at the end of the Triassic and beginning of the Jurassic, *i.e.*, 180-200 million years ago.[3] The time of the event is established quite definitely by the basin's formation in the Paleozoic and Early Triassic rocks, and by the undisturbed nature of beds of Middle and Late Jurassic and Cretaceous deposits of the basin.

Deep wells in the center of the PKD reveal a surface at a depth of 150 to 400 m, beneath Jurassic and Cretaceous deposits, under which the rocks are gneissic breccias. The body of gneissic breccia is, in plan, an oval form about 20 X 30 km, elongated in azimuth about 70°. At the periphery of this body, the gneissic breccia intermixes with deformed Paleozoic rocks. One of the wells on the line between Ezhovo and Semenov completely penetrates the gneissic breccia. Here, its thickness appears to be about 100 m, and it was determined that the gneissic breccia overlies 1.5 to 2 km of undeformed Middle and Upper Carboniferous carbonate rocks which, in turn, overlie the gneissic basement of the platform, Fig. 4. A well on the line Balakhna to Ryaibov, almost in the center of the PKD, revealed gneissic breccia at a depth of 250 m and did not penetrate the bottom of this rock mass to a depth of 850 m. It might be assumed that the body of gneissic breccia extends down here to the crystalline basement of the platform, *i.e.*, has a vertical extent of

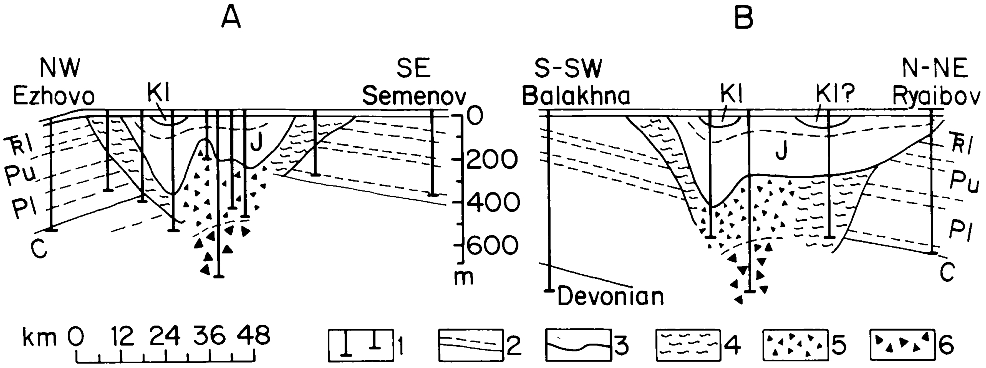

Fig. 4. Structure of the Puchezh-Katunki cone. Profiles along lines of the drilling wells (from L. A. Vardanyants, 1961); 1) wells; 2) covering rocks and stratigraphic horizons; 3) surface of crushed and disturbed Paleozoic rocks and bottom of the cone; 4) disturbed and crushed Paleozoic rocks in the peripheral circular zone; 5) gneissic breccia, relatively fine detritus; 6) gneissic breccia, coarse detritus; the symbol (Kℓ?) in B indicates that the translator has assumed the nature of the unit on the basis of the map, Fig. 2.

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[3] D. Milton points out that this age is approximately the same as that of Manicouagan, Lake St. Martin, possibly five other Canadian impact structures, and Rochechouart.

2 km or more. A series of wells indicates that with increasing depth the fragments in the gneissic breccia enlarge to gigantic blocks. It was also determined that in the center of the structure the gneissic breccia is raised in the form of a "central peak" 100-250 m above the deepest part of the trough.

Vardanyants explained the body of gneissic breccia as a plug of crushed rocks of the crystalline basement which was forced through the deformed Paleozoic rocks peripheral to the PKD. Shaking due to a deep explosion was believed to have induced the crumpling and crushing of the Paleozoic rocks of the peripheral zone. Vardanyants felt that the uplift of the gneissic breccia above the level of the crystalline basement was concurrent with later stages of development of the event, but did not bother to decipher the significance of this stage or to explain the reason for accumulation of a colossal amount of gas beneath the Paleozoic cover of the platform. At the same time he especially stressed the surficial nature of the fill of gneissic breccia, with which one must completely agree in view of the variation with depth in the size of the blocks in the breccia and of the superposition of the breccia on undeformed Paleozoic rocks at the cone surface, truncating the surface at angles of 1-2°.

Goretskii (1962, Fig. 10) visualized the formation of the gneissic breccia in approximately the same way, but connected the formation of the entire structure, both the body of gneissic breccia and the peripheral annular zone of deformed Paleozoic rocks, with the emplacement of a deep intrusive body of basic and ultrabasic rocks. He attributed all of this to an injected tectonic body, but did not give details of the dynamic interaction of the intrusion with the surrounding rocks.

One must especially emphasize that the cited profiles of the PKD from Vardanyants and Goretskii, although deduced from quite reliable facts from deep borings, cause an excessively large distortion of the real form of the PKD crater because of the colossal difference in the horizontal and vertical scale. These distorted graphs accordingly lead to the conclusion about the explosion pipe filled with a plug of gneissic breccia or to the even less-valid conclusion about a deep intrusion. Two cross sections through the PKD in the form presented, for example, in the work of Vardanyants, are shown in Fig. 4. A normal 1:1 cross section, Fig. 5, at once modifies the picture of the vertical structure of the PKD. In reality, the depression occupied by the mixed and shattered Paleozoic rocks and gneissic breccia is definitely a mildly sloping cone. The total depth of this cone, considering the thickness of the Paleozoic cover and including the gneissic crystalline basement in the deformation, is approximately 2 to 2.5 km. The depth-to-width ratio is 1:30 to 1:50. The body of gneissic breccia occupies an area of about 500 km^2, 10% of the total area of approximately 5,000 km^2. The central peak of gneissic breccia under the Middle and Upper Jurassic and Cretaceous sediments is totally insignificant in the uneven relief. The unexaggerated cross sections

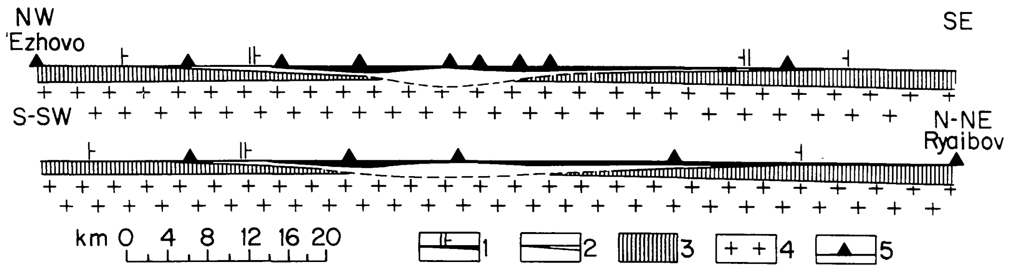

Fig. 5. **Structure of the Puchezh-Katunki cone. The same profiles as in Fig. 4 are shown, but with a normalized (1:1) ratio between the vertical and horizontal scales. 1) The basin, filled with Middle-Upper Jurassic and Cretaceous sedimentary rocks, and its surface contour. 2) The bottom of the Puchezh-Katunki cone and its contour (the central peak is very insignificant). 3) The cover of Paleozoic rocks, about 2 km in thickness. 4) The crystallographic (gneissic) basement of the platform. 5) The location of the wells shown in Fig. 4.**

clearly emphasize the wholly surficial character of the entire PKD. The conclusion about the deep origin of the dislocation is the outgrowth of graphic illusion of disproportional cross sections.

Furthermore, it is possible to present a series of intrinsic objections against the hypothesis of tectonic injection. Many examples of basic and ultrabasic intrusive plugs are known in which the plug has burst through and displaced the sedimentary cover rocks. In no case is there the smallest resemblance to the structure of the PKD, either in character or in scale of the phenomena, *e.g.*, the basic, ultrabasic, and alkaline intrusions of the Aldan shield, the subvolcanic stock and the crushed zone associated with it in Japan, etc. The batholiths, which are much larger than the intrusives and which would have to be assumed to be under the PKD, do not cause such grand and unusual deformation in the surrounding rocks. The whole complex of structural and morphologic features of the PKD remains unexplained by the hypothesis of injection tectonics. The work of Goretskii is merely a modification of the much earlier hypotheses of saline tectonics (see Table 1) in which magma replaces the salt. Every modification of the magmatic hypotheses of formation of the PKD will generally be contradicted seriously by the absence of any magmatic manifestations, *viz.*, veins or pyroclastic material, in the given profiles. None of the investigators of the PKD noted these phenomena, except for mention of the presence of zeolites in the mixed rocks and breccias, which could have been deposited from low-temperature solutions of exogenic origin.

Besides the morphologic discrepancy in the profile of the disturbance, the hypothesis of a deep diatreme explosion resulting from the accumulation of gases (Vardanyants [1961?]) also meets the following three objections:

1. In the case of a very deep explosive chamber, *e.g.*, in the crystalline basement, and in the case of the formation of a more-or-less cylindrical pipe,

e.g., at the point of intersection of any large, previously existing fractures, a shock wave must have propagated vertically upward along a narrow cylindrical channel (cumulative [pulse] action). The deformation of the Paleozoic rocks in an extensive 20 to 30 km peripheral, ring-shaped zone should not be expected in this case. Diatremes generally are not accompanied by broad and extensive peripheral zones of deformed rocks. They are, in fact, the real results of cumulative [pulse] formations.

2. If the energy of the explosion were great, but the center not very deep, *e.g.*, somewhere in the lower part of the Paleozoic cover, as assumed by Vardanyants, then the cumulative action would not be so clearly expressed as in the case of a diatreme; the explosion should probably have led to the formation of a crater with the properties of a cone formed by a colossal, concentrated charge of explosives. This cone would have different depth-to-diameter relations than the PKD, *i.e.*, about 1:5 or at maximum 1:10.

3. If the explosion were weak, a camouflet would generally be formed, *i.e.*, a rather narrow zone of crushed rocks above the center of the explosion, a camouflet-shaped bulge at the surface, without the ejection of broken blocks and without the formation of a cone.

None of these cases fits the structural and morphological data on the PKD. It should be noted that most famous African and Siberian diatremes possess such minor dimensions, a few tens of meters to one kilometer (Offman, 1959), when compared to the PKD that there is no basis to compare the structure or scale of the PKD with similar pipe phenomena. Let us assume, as in the first case cited, that the explosion was deep and took place as the result of an accumulation of gases somewhere around the depth of 2 km. The lithostatic pressure on the base is about 500 atmospheres. For the development of an explosion, however, it would be necessary to increase the pressure of the gases in the chamber several times above the lithostatic pressure, with the added requirement that this increase of gas pressure be impulsive. In this case it seems probable that the gas would be injected along several channels as the explosion took place, for example, along breakages and zones of cracks, etc., as in the formation of kimberlite pipes, and would not be a concentrated explosion. The energy of this type of explosion would still be insufficient for the deformation of colossal volumes of rocks in a vast zone. Finally, the size of the deep gas center at the depth of about 2 km, with a super-high, impulsively created pressure, would have to be no smaller than the scale of the Puchezh-Katunki explosive structure itself. Vardanyants does not even attempt to find a geologically suitable explanation for this discrepancy in scale and does not look for analogies. Indeed, even the largest of the volcanic explosions (Krakatoa, Katman, Kamchatka volcanoes) do not compare with the scale of the Puchezh-Katunki catastrophe.

The pecularities of the PKD clearly testify to its explosive origin. Considering the fruitlessness of the discussions above, in the course of which all possible and impossible geological causes have been utilized, one should no doubt turn his attention to causes of nongeological origin. The peculiarities of structure and morphology of the PKD, namely the surficial mild slope of the large crater, are fully explained by the hypothesis of a surface explosion – which could occur as the result of the fall of a large meteoritic (asteroidal) body.

A mathematical model for the morphological consequences of such an explosion was given by Stanyukovich and Fedinskii (1947). A meteorite would preserve its cosmic velocity while passing through the atmosphere. It would penetrate only a slight distance into the Paleozoic rocks before an explosion occurred due to the almost instantaneous extinction of the velocity at the moment of impact. In principle, such an explosion should be qualified as surface or near-to-surface. Part of the energy of the explosion, carried away from the explosion center by the lower half of the shock wave propagating into the rocks, would be expended in crushing and mashing the rocks and also in pressing them together and compressing the forthcoming breccia.

The properties of the rocks in the PKD do not contradict this model. The specific gravity of the undisturbed clay rocks is 2.04 to 2.08 and marl is 2.15 to 2.27, while the specific gravity of the clay breccias is 2.12–2.15 and that of the marl breccia is 2.25–2.34 (Goretskii, 1962). The extent of the deformation of the rocks is rapidly reduced from the center of the explosion, corresponding to the rapid loss of energy in the front of the shock wave. However, due to the colossal force of the explosion, these deformations encompassed a large area.

In a surface explosion, a large part of the energy is carried by the upper part of the shock wave, which propagates into air (Pokrovskii, 1964). However, for certain depths of penetration of the meteoritic body, some portion of the energy of the upper half of the shock wave (the greater the penetration, the greater the depth of the explosion) is also expended to deform and to throw out crushed rock. As a consequence of this, a crater is formed; in the case of the PKD, the central trough. Some of the broken blocks, after receiving acceleration in a direction close to vertical and expending their kinetic energy, may fall into the crater, forming something like a central peak. However, the hypothesis that the broken stones from the deepest and most central portions of the explosion, the gneissic breccia, entered the crater and formed something like a central peak is more probable than the hypothesis that the broken fragments came from the surface layers. The mass of stones with most of the initial momentum but with inclined trajectories fell beyond the borders of the cone.

The formation of the central peak near the position of the interface of crystalline basement and Paleozoic cover rocks of differing density suggests that the protruding gneissic breccia was at the front of the lower half of the shock wave reflected from this interface – in a reflected wave which still carried sufficient energy to overcome the strength of gravity and impart additional impulse to the blocks. These elements of the model show such similarity with the detailed structure of the PKD that a catastrophic surface or near-surface explosion is suggested.

The amount of energy of this phenomenal explosion can be estimated as follows: If the average external diameter of the ring-shaped zone of deformed Paleozoic rocks is taken as 80 km, the approximate depth of this zone as 600 m, the diameter of the body of gneissic breccia as 30 km, and the depth of this body filling the bottom part of the crater as a maximum of 2 km, which is the depth to 0.5 km below the crystalline basement, then the total volume of the Puchezh-Katunki crater is 2×10^{18} cm^3 or 2,000 km^3. The mass of shattered and partly ejected rocks is about 5×10^{18} g, with an uncertainty of around 10%. This rough number is somewhat minimal. The volume of the central trough or the volume of the rock ejected from the crater is not more than 15% of the indicated amount. The PKD therefore resembles an explosion crater in which the explosion chamber is relatively confined in comparison to the diameter of the cone.

Experiments (Andreev, 1956; Pokrovskii, 1964; Rossi, 1948) show that the energy expended in crushing (and partly ejecting) 1 g of rock in an explosion of a concentrated charge of high explosive, placed at a depth to yield the optimal calculated quantity (Pokrovskii, 1964), is about 1 cal, or 4.2×10^7 ergs. The experience of engineering surface explosions confirms this (Kamenka and Bozhko, 1948; Kubalov, 1957).

Adopting this value of specific energy yields the total energy of the PKD explosion as about 5×10^{18} cal, or 2×10^{26} ergs (neglecting significant losses of energy). This is a few orders of magnitude greater than the energy of a catastrophic earthquake or the energy of the Tunguska catastrophe, estimated at 10^{22} to 10^{23} ergs (Astapovich, 1958).

However, for a surface explosion or an explosion at a small depth, the quantity of specific energy in crushing and ejecting 1 g of rock sharply increases, because there is a significant loss of explosion energy in the upper hemisphere of the shock wave. Thus, in the catastrophic explosion in 1921 at the military factory in Oppau, Germany, with 4,500 tons of explosive, the size of the hole (diameter 120 m, depth 30 m) indicates that 15 cal/g were expended. In the explosion of the atomic-hydrogen bomb "Mike" on the atoll of Eniwetok on 1 November 1952, the specific expenditure of energy reached 23 cal/g or thereabouts. According to the data of Lapp (1959), the diameter of the hole was 1 mile, the depth 175 feet, and the TNT equivalent yield of the explosion was 8 megatons.

The well-known formula of Boreskova (Pokrovskii, 1964; Ryabukha, 1954; Yakhontov, 1959) and its variations, connecting the size of the with the concentration of a quantity of explosive or the energy of an explosion for an optimal explosion, specifies that $\xi = 1$ cal/g approximately, or 1 kg of explosive (for example, TNT) for 1 ton of rock. For nonoptimal explosions this is incorrect and gives a severe overestimate of the rock ejected.

Without going into detail, we note the computations resulting from the series of catastrophic explosions and explosions of atomic and hydrogen bombs and determine the following approximate dependence between the specific energy, ξ(erg/g), and the total energy, E(erg), of an explosion on the surface or in a small explosion chamber buried at a small depth relative to the diameter of the crater:

$$\ln \xi = 0.077 \ln E + 7,$$

or, for ξ in cal/g and E in cal,

$$\ln \xi = 0.077 \ln E.$$

Further by transforming the formula of Boreskova for $\xi = \phi(E)$, it is possible to relate the diameter of the hole, D, in meters, to the total energy of the explosion, E, in ergs, according to the following formula:

$$\ln E = 3 \ln D + 13.8$$

The results of this formula almost exactly match the results of the equations from theoretical and experimental models of cratering, as in the work of Rottenberg (Beals and Innes, 1964). For the case of the PKD, with a crater diameter of 8×10^4 m, the above equality gives a value for the total energy of the explosion of about 3.3×10^{28} ergs, or rounded off, 3×10^{28} ergs. This is at least five orders of magnitude above the energy of the Tunguska explosion and is equivalent to a thermonuclear explosion with a TNT equivalent of 800,000 megatons, *i.e.*, the simultaneous explosion, for example, of 16,000 50-megaton bombs! Rottenberg's model gives similar values of approximately 2.5×10^{28} to 3×10^{28} ergs. For this the specific expenditure of energy, ξ, exceeds 140 cal/g (3×10^{28} ergs $\div$ 5×10^{18} g = 6×10^9 erg/g), while that determined from $\xi = \phi(E)$ is about 37 cal/g, or 1.55×10^9 erg/g. Obviously, the assumed mass of shattered and partly expelled, altered rock of the P-K cone as 5×10^{18} g is minimal and does not take into consideration the large volume of rock with weak deformation beneath the surface structure of the cone. The volume of these rocks is probably two or three times the volume of rocks above the crater surface, by analogy to craters from thermonuclear explosions.

The size of the meteorite with an energy of 3×10^{28} ergs is given by equating the total explosion energy, E, to $0.5\ mv^2$. The heliocentric velocity of meteoritic and asteroidal bodies in the vicinity of the earth's orbit is about 30 to 35 km/sec (Astapovich, 1958; Krinov, 1948, 1966; Fedinskii, 1956).

The geocentric speed depends on the angle of encounter of the meteoritic body with the earth and varies from very low values for an overtaking meteorite to 70 km/sec for an oncoming meteorite. For simplicity of calculation, it is reasonable to assume an average geocentric velocity of 30 km/sec. Large and gigantic meteorites are able to penetrate the atmosphere of the earth with negligible retardation, maintaining cosmic velocity. Assuming a spherical meteorite with three typical densities; 1) 3.75, the average density of all meteoritic material, 2) 3.0, the average density of stony meteorites, and 3) 7.9, the average density of iron meteorites (Beals and Innes, 1964; Krinov, 1955), the following values for the diameters of the meteorite, d, (in m) are obtained from the magnitude of the total explosion energy, E, (in ergs), assuming a velocity of 30 km/sec:

For an arbitrary average meteorite	$d = \sqrt[3]{E}/(2.07 \times 10^6) \approx 1{,}500$ m.
For a stony meteorite	$d = \sqrt[3]{E}/(1.92 \times 10^6) \approx 1{,}650$ m.
For an iron meteorite	$d = \sqrt[3]{E}/(2.6 \times 10^6) \approx 1{,}200$ m.

Such a meteorite is in the class of asteroidal bodies.

Do facts support such a gigantic cosmic event? Yes. Well-known craters with diameters from several meters to a few kilometers occur on the various continents. Their meteorite-explosion origin is irrefutably proven by the existence of nickel-iron and coesite and by characteristic explosive deformation in the rocks (Krinov, 1958, 1962; Nininger, 1951; Rinehart, 1958). Among these craters is the widely known Canyon Diablo crater in Arizona with a diameter of about 1.2 km, formed by the explosion of an iron meteorite (Krinov, 1962; Nininger, 1956; Rinehart, 1958), and a whole series of other craters, well expressed in current relief and describable as young, even contemporary craters, from the geologic point of view. In scale, however, even these do not compare with the ancient Puchezh-Katunki crater. For example, the Arizona crater might have been formed from the explosion of an iron meteorite with a total diameter of 18 m. The calculation assumed that the total energy of the explosion was about 10^{23} ergs, as follows from a crater diameter of 1,200 m. Iron meteorites of this diameter are found on the surface of the earth and do not especially stress our imaginations.

However, for many years, and especially in recent years, very serious consideration has been given to the possibility of meteorite-explosion origin for a series of very gigantic circular and elliptical depressions on the surface of the earth. The circular Lake Chubb (Ungava, Canada) with a diameter of about 3.5 km and a depth of 400 m is attributed to a meteorite explosion crater (Beals and Innes, 1964; Massalskaya, 1951; Meen, 1950). The formation of this crater by a meteor of density 3.0 g/cm^3 and a geocentric velocity of 30 km/sec implies that the diameter of the meteorite would be about 65 m, with a total energy of explosion approximately 2×10^{24} ergs.

Deep Bay in northern Saskatchewan, Canada, with a diameter of 12 km and a present depth of 219 m, is considered to be a structure of this category (Beals and Innes, 1964). For its formation an explosion of a stony meteorite having a diameter of 250 m would be required. Beals and Innes (1964) list more than ten such structures discovered by examining aerial photographs of the Canadian shield. Some of these have been explored by boreholes, and the structure revealed is undoubtedly from a surface explosion. It is assumed also that the gigantic depressions of Ungava Bay, the Gulf of Saint Lawrence, and Hudson Bay (with diameters of 241, 289, 442 km, respectively) represent meteorite explosion craters of great antiquity. To the number of such formations must be added the depression in Ashanti on the shore of the Gulf of Guinea. There are also concealed depressed structures [astroblemes] which have not found acceptable geologic explanations. A few astroblemes exceed 5-10 km in diameter. One of these concealed crater-shaped structures of explosive origin was examined with boreholes in Glasford, Illinois, U.S.A. It has a diameter of 4 km in layers of sedimentary rocks of Upper Ordovician, Silurian, Devonian age, and carbonates. The explosion of the meteorite occurred in late Ordovician time in rock of Cambrian and early Ordovician age (Buschbach and Ryan, 1963). Even meteorite explosion craters which are well expressed in present relief on the Canadian shield may be of great antiquity, down to Precambrian.

Although it is possible to significantly continue this list of discoveries, these considerations are sufficient to produce serious respect for the meteorite explosion hypothesis in explaining crater forms foreign to the geotectonic structure of the upper zone of the crust of our planet. In concluding this review, I present data in Table 2 for the total energy of the explosion and the diameter of the cosmic body (with an assumed density of 3.0 g/cm^3 and velocity of 30 km/sec) that caused the explosion at the Puchezh-Katunki crater and several other crater forms from Beals and Innes (1964). As is apparent from these data, the Puchezh-Katunki crater is by far, not the largest.[4]

Is it possible for the earth to encounter such a large cosmic body, up to the size of an asteroidal body? Optical and radio observations of meteorites (Astapovich, 1958; Levin, 1956; Lovell, 1958; Fedinskii, 1956) enable us to determine the frequency of their falls. These measurements indicate that for a reduction in brightness of the meteorite luminosity of each stellar magnitude number, the frequency increases approximately 2.5 times. This same rule

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[4] Translator's note: Puchezh-Katunki is larger than any impact crater which is considered proven beyond reasonable doubt (see criteria, for example, in Barringer, R. W., 1967). The largest identified meteorite crater in Barringer's compilation is Manicouagan, Quebec, with a diameter of 61+ km. The Popigai Basin in Siberia, recently suggested to be a meteorite crater (Masaitis, 1971), has a diameter of 70 to 80 km and is therefore of a size comparable to the PKD. The largest suspected crater given by Barringer is Sudbury, Ontario, with a diameter of 60+ km).

Table 2
Comparison of the Puchezh-Katunki Crater With Others According to Diameter, Total Energy of Explosion and Diameter of Cosmic Body Causing the Explosion

Crater	Diameter of Crater (km)	Total Energy of Explosion (ergs)	Diameter of Cosmic Body (m)
Holleford, Canada (drilled)	2.35	8.0×10^{23}	48
Brent, Canada (drilled)	3.5	2.7×10^{24}	72.5
Deep Bay, Canada (drilled)	12.2	1.1×10^{26}	250
Clear Water Lakes,	24	8.9×10^{26}	500
Canada (partly drilled)	32	5.2×10^{27}	900
Puchezh-Katunki, SSSR (drilled)	80	3.3×10^{28}	1,650
Ungava Bay, Canada	241	8.9×10^{29}	5,050
Arc of Gulf of St. Lawrence	289	1.6×10^{30}	6,100
Hudson Bay	442	5.6×10^{30}	9,300

gives the distribution of the asteroids (Putilin, 1953) and serves as one proof of the genetic relationship between meteorites, observed in the atmosphere of the earth as meteors (from telescopic meteorites to fireballs), and asteroids (Astapovich, 1958; Fedinskii, 1956).

It is possible to estimate the mass, size, and the frequency of bodies impacting over the whole surface of the earth by extrapolating the data for telescopic-meteors, meteors, and fireballs from +17 to −14 stellar magnitude in the direction of brighter stellar magnitude (to −50). This extrapolation corresponds to larger and larger cosmic bodies impinging on the earth's atmosphere. These numbers, averaged over five stellar magnitudes for groups of meteors, are given in Table 3. It is obvious that they are not very exact,

Table 3
Limiting Size and Probable Encounters of Large Meteorites and Small Asteroids With the Earth Extrapolated from Statistical Material on Meteors

Bodies Grouped According To Stellar Magnitudes	Average Mass of The Body In Grams	Average Diameter Of Body (Density of 3.0)	Frequency of Falls to the Surface of the Earth		
			One Fall Per Time Interval	Total Falls 650 m.y.	Total Falls 5 b.y.
-15 to -20	1	0.86	2 days	1.25×10^{11}	9.5×10^{11}
-20 to -25	100	4.0	193 days	1.25×10^{9}	9.5×10^{9}
-25 to -30	10^{4}	18.5	53 years	1.25×10^{7}	9.5×10^{5}
-30 to -35	10^{6}	86	5.3×10^{3} yr	1.25×10^{5}	9.5×10^{5}
-35 to -40	10^{8}	400	5.3×10^{5} yr	1,250	9,500
-40 to -45	10^{10}	1,850	5.3×10^{7} yr	12.5	95
-45 to -50	10^{12}	8,600	5.3×19^{9} yr	–	1

but the order of magnitude of the quantities scarcely changes significantly with the accumulation of new statistical material on the meteor.

A body of the size calculated for the Arizona meteorite will fall approximately once every 50 years. The Tunguska and Sikote-Alin meteorites, the Barringer meteorite crater, the Odessa crater, and others would apparently be included in the same class. The earth will encounter a body of sufficient diameter to produce the Puchezh-Katunki catastrophe (about 1,650 m diameter) once in somewhat more than 50 million years. For 9 km cosmic bodies which could form Hudson Bay, the probability of encounter with the earth is less than one per 5 billion years of the planet's history – or about one encounter. Therefore, the rarity of large crater forms of such origin agrees with the theoretical premise and stresses the small, but nevertheless positive, probability of a cosmic cataclysm.

Of the more than two thousand asteroids for which orbital parameters have been measured at the present time, about ten approach the earth at quite a close distance, from 600 thousand km to 30 million km, and have periods of revolution from 1.12 to 4.34 years: Eros, Ganymed, Albert, Amor, Alinda, Apollo, Adonis, and others (Putilin, 1953). On 28 to 30 October 1937, the now-lost asteroid, Hermes, was observed in passage at 580,000 km from the earth, or only 1½ times the distance of the orbit of the moon. The diameter of Hermes, according to its brightness, was estimated at 1 to 1.5 km. At the time of another approach, Hermes may be captured by the gravitational field of the earth, and this would be, ultimately, the equivalent of a new Puchezh-Katunki catastrophe.

Finally, the most significant argument against the meteorite explosion hypothesis for the formation of the PKD is that meteoritic material has not been mentioned in a single one of the multiplicity of works devoted to this phenomenon. For that matter, none has been found in the series of Canadian craters that have been thoroughly drilled. One must realize that, in the first place, no one, up to now, has been occupied with a specialized search for meteoritic material in the rocks of the PKD, and special geochemical, metallometric investigations have not been made there. In the second place, in the 180 to 200 million years since the moment of the Puchezh-Katunki catastrophe, the meteoritic material may have been eroded and scattered by exogenic processes. We know that in contemporary craters the meteoritic material is detected with difficulty after the lapse of only a few tens or hundreds of years. In the third place, the explosion should lead to ultramicroscopic and even ion-molecular dispersion of the cosmic body. Finally, in the fourth place, the fall of an iron-nickel body of this extreme size is four times less probable than a silicate. In this latter case, the petrochemical contract between the material of this body and the material of terrestrial rocks would be insignificant. It is impossible to say that the study of the Puchezh-Katunki disturbance is finished. The time has come to look at it from another point of view.

The meteorite-explosion (ballistic) hypothesis of formation of craters is certainly not new and is well known in selenology, meteoritics, etc., but the conservative character of geologic tradition has, up to this time, hindered its attractiveness for interpreting the genesis of structures. Exceptionally great contributions to the development of this hypothesis, as applied to craters on the moon and to terrestrial crater forms, have come from the American astronomers and geologists. It would be pleasant to note a shift in this direction for Soviet geologists. I would especially like to emphasize that this publication is not a product of the times, not a tribute to fashion. For more than ten years the collection of data has been in agreement with the meteoritic theory and has led to conflict with previous tectonic hypotheses for the origin of the PKD.

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