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Morphological elements of "Popigai" and other astroblemes as indicators to cosmic bodies' ballistic trajectory

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Abstract. In this paper, the criteria for determining a ballistic trajectory location of the Popigai cosmic body (PCB) are revised. It is concluded that this trajectory was directed not from the NE to the SW as was believed earlier, but from the SE to the NW. With this orientation, there is a close spatial relationship between the PCB trajectory and the Ortho–Yarginsk and the Starorechensk diatreme fields on the Anabar anteclise eastern slope, which suggests that their age is the same as that of the Popigai event.

Numerous morphological elements of the astroblemes that are undamaged from erosion indicate to the position of the ballistic trajectory of their formed cosmic body (CB). They include klippens, distant scattered materials out of crater and, partially, allogenic breccias. Let us examine these elements based on the "Popigai" meteorite crater, as an example.

1. The "Popigai" astrobleme ($D = 100$ km)

In the outer loop of the "Popigai" impact structure, the so-called klippen blocks described in the literature [1–4] are considered in detail. In these papers, V.L. Masaitis et al. note that within a radius of up to 50 km from the astrobleme center, centrifugal thrusts, upthrow-thrusts, klippens, various folds and faults gradually decreasing in the radial direction are of widespread occurrence. According to the most detailed description by S.A. Vishnevsky [5], zones of klippen blocks are well-developed in the "Popigai" astrobleme boundary parts and have a width of 12–14 km. Within these zones, the cover rocks are divided into blocks, whose area can reach several square km, and their apparent thickness — from several tens to several hundreds meters. Klippens are composed of the Cambrian carbonate rocks, the Proterozoic quartzite sandstones, or both of them. The outer boundary of a klippens zone, especially, where this zone is bounded by a system of convex centrifugal upthrow-thrusts, provides a scalloped shape to the astrobleme contours [5]. Outside a klippens zone, there are sedimentary cover rocks weakly dislocated or lying horizontally, framed by the crater contour. S.A. Vishnevsky proposes a klippens formation scenario, in which klippens are formed by the shock wave through 10–15 s after the fall of the Popigai

CB. As a result, the cover rocks were distended and broken up (deformed) to large blocks, which began the sub-vertical and centrifugal lateral displacements with suppositional speeds of up to several tens meters per second.

The location of klippens at the periphery of the "Popigai" impact structure was indicated in many publications [1–4] and on a 1 : 1,000,000 map, R-48 (50) [6]. There are certain destinations between the drawing patterns of klippens, especially, in the astrobleme eastern and south-eastern parts. A comparison of Figures 1 and 2 exhibits this fact. However, in their location, one can see a clear bilateral symmetry:

> Klippens shaped as horseshoe half-rings are present only in the north half of the astrobleme outer contour, where they are located at a distance of up to 63 km from the structure center.

Although the above regularity was observed earlier, it was not interpreted as a result of the location of the Popigai bolides' ballistic trajectory, probably, because it did not agree with the existing version proposed by V.L. Masaitis et al. [1–4] on the Popigai body direction of flight of 210–220° NE–SW (Case I in Figure 2). According to [1–4] this direction corresponds to the bilateral symmetry in the location of allogenic breccias and impactites. However, in this case the symmetry in impactites, according to Figure 2, is less clear than that in klippens, and for allogenic breccias it is rather associated not with a direction of 220°, but with that to the North-West. In addition, Case I proposed by V.L. Masaitis et al., is a line of asymmetry in the distribution of klippen zones, which is clearly seen in Figure 2. In the same figure, it is clearly evident that with this interpretation the zone of allogenic breccias unnaturally occupies not a vanguard, but a rear side of the structure.

> All this allows us to conclude that the direction of the Popigai asteroid arrival was from the South-East to the North-West, by the azimuth of 330–350° (Figure 1, Case II in Figure 2).

This conclusion is also supported by the following data:

1. The scattered materials that are most distant from the crater are observed in its northern boundary part, where they are present in the form of blocks of allogenic breccia at a distance of up to 65 km from the crater center (see Figure 2).
2. In the SE direction from the astrobleme, there are traces of the fall of a probable small satellite of the Popigai asteroid, namely, the meteoroid *Mohcho* (Lake Mohcho in Figures 1, 3a).

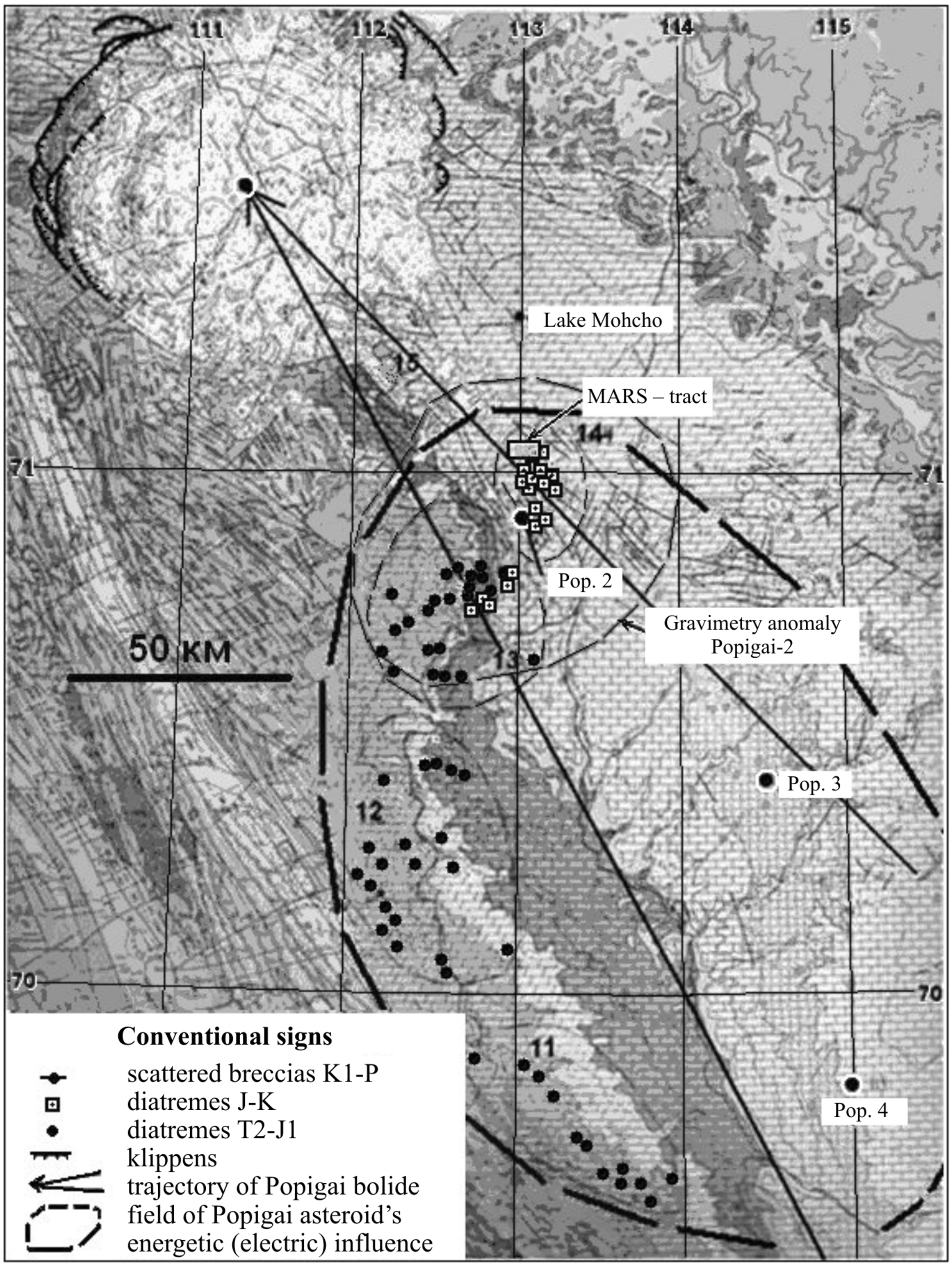

Figure 1. The geological structure of the "Popigai" astrobleme and the Anabar diatreme zone at the scale of 1 : 1,000,000 [6]. Diatreme fields: 11—Dyuken field, 12—Ary-Mastahe field, 13—Starorechensk field, 14—Ortho-Yarginsk field, 15—the field of explosion breccias according to Polyakov and Trukhalev [7]. Bold black dots are anomalies shown by the Google Earth program with the data of gravimetric maps studied by the Czech researchers [8]. The age indices are given according to the 1981 data [6]

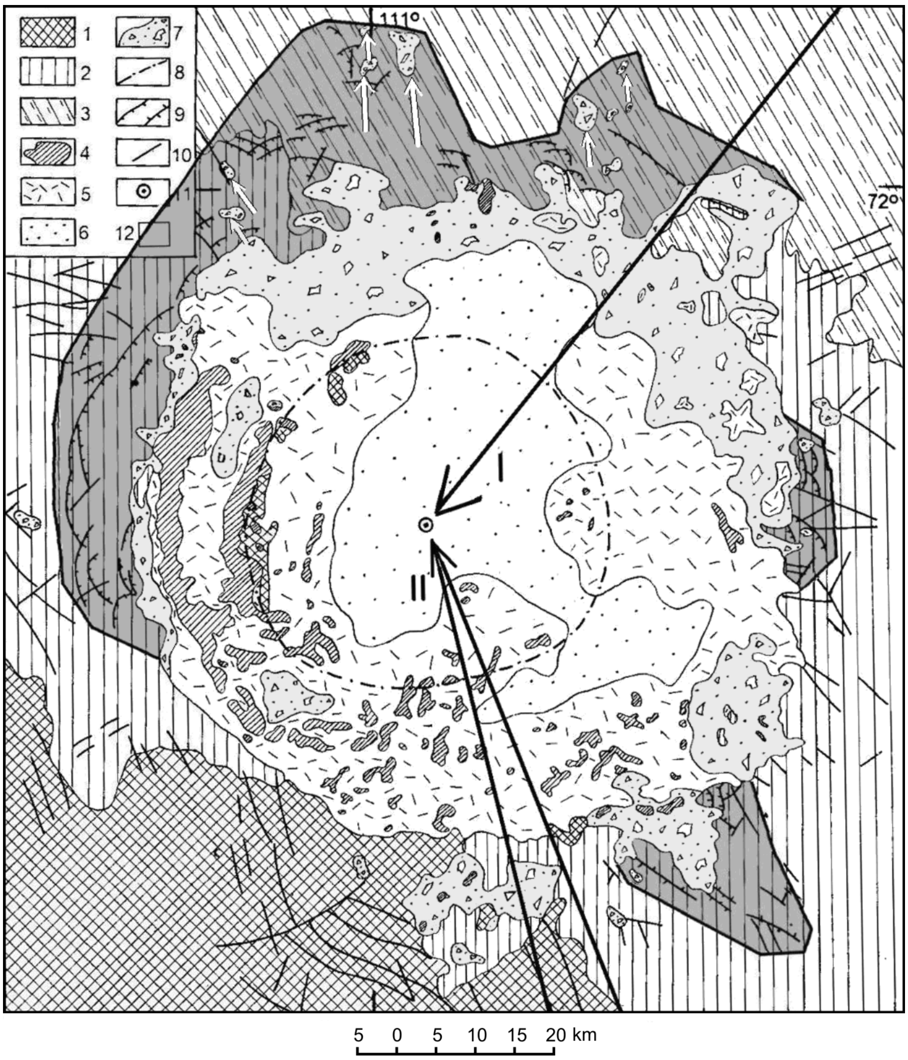

Figure 2. A schematic geological map of the "Popigai" impact structure (without Pliocene-Quaternary sediments) [4, with additions]: 1–3 — ground complex: 1 — Archean crystalline rocks, 2 — Upper Proterozoic and Lower Paleozoic sedimentary rocks, 3 — Upper Paleozoic and Mesozoic sedimentary, igneous-sedimentary, and igneous rocks, 4–7 — coptogenic complex: 4 — tagamites, 5 — suevites, 6 — coptoclastites, 7 — allogenic breccias; 8 — ring rising axis, 9 — thrusts and faults; 10 — fractures of unknown morphology, 11 — geometrical center of the astrobleme. Additions done by the authors of the present paper: 12 — probable ballistic trajectories of the Popigai body: I — according to Masaitis et al. [1–4], II — according to the authors of this paper: klippens development zone (dark gray shading), and allogenic breccias zone (light gray shading); white pointers indicate to the distant scattered allogenic breccia

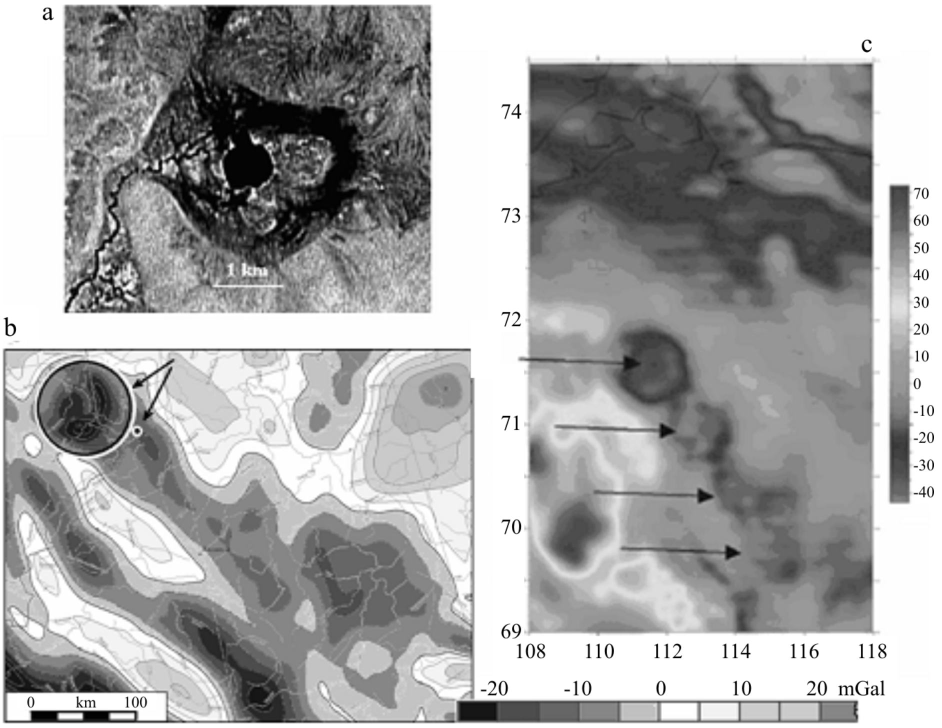

Figure 3. a) Meteorite crater “Mohcho”, probably resulting from the fall of a small satellite of the Popigai asteroid (Google Earth); b–c) Location of negative gravimetric anomalies to the SE of the “Popigai” astrobleme showing the Popigai bolide trajectory of the NW direction on the Gravimetric map of Russia (VSEGEI), 1 : 2,500,000, 2010 (b) and on the data from [8] (c). The “Popigai” and “Mohcho” structures are shown by circles and pointers (b), the “Popigai II-IV” [13] structures are shown by pointers (c)

3. In one straightened chain in the NW direction together with the “Popigai” impact structure, which is a clearly defined negative gravimetric anomaly, there are three other similar anomalies discovered by the Czech geodesists [8] (Figures 1 and 3b).These anomalies can be due to rock loosening as a result of forming the diatreme cavities and their filling with low-density rocks (for instance, tuffisites). It should be noted that diatremes in the zone of two southernmost anomalies are still unknown, and it is not clear what factors have caused gravimetric anomalies in this case.

In combination with the klippens zone location, *the listed spatial regularities are in a striking agreement with each other, which does not allow us to explain their presence as a random coincidence.*

2. The "Zhamanshin" crater ($D = 14$ km)

The bilateral symmetry of the other crater elements, in particular, the impactive area, is also an important indicator to the CB ballistic trajectory if such elements are well defined. For example, the "*Zhamanshin*" crater, according to the data available [3], has a clear bilateral symmetry of the following two groups of features: the morphological structure (according to gravimetric observations and geological mapping) and the distribution of scattered rocks (according to geological observations) (Figure 4).

In the first group, "oblateness" of the structure ring elements across an expected trajectory of the CB impact serves as indicator. This feature of the inner structure elements of the crater was also observed for the "Boltysh", "Kara", and "Goses Bluff" astroblemes. In addition, the "Zhamanshin" crater has an axial distribution of deformations (scattered rocks, folds, thrusts) in the astrobleme front part, which coincides with the bilateral symmetry axis of allogenic breccias and impactites. "The deformation structures are most distant from the central rising within the northwestern sector of the outer crater" [3]. "The location of individual clusters of large blocks of solid rocks in the form of chains radially extending from the structure center... into the northwest calls our attention, too" [3]. Also, the NW sector has rock masses of the basement with a clearly dominant scattered material volume and individual occasional blocks of the Upper Cretaceous rocks most distant from the center. Apparently, confirmation of

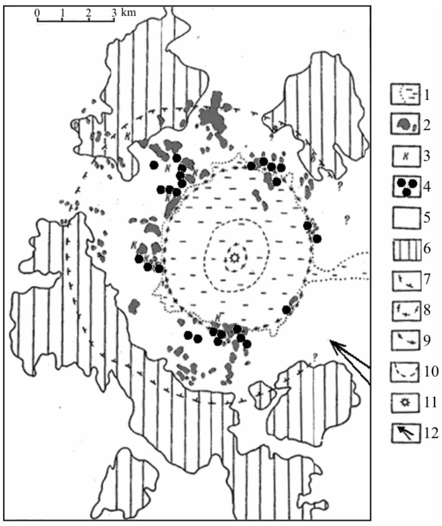

Figure 4. A schematic geological map of the "Zhamanshin" astrobleme [3]: 1 — the filling rocks complex (the outer contour of propagation of lake-alluvial quaternary deposits); 2–4 — formation of the coptogenic complex: 2 — the allogenic breccias, 3 — the chunk of the Maastricht rocks in the allogenic breccias, 4 — impact glass and impactites; 5, 6 — the formation of the socle complex: 5 — clays, sands of the Chegan, Saksaul and Tesaran formations of the late-average Paleogen, partially deformed inside the crater funnel, 6 — alevrolites, sands of the Chiliktin formation of late Paleogen; 7 — a reconstructed axis of the embankment; 8–10 — the axis of gravity anomalies: 8 — the positive one (a central rising), 9 — the positive one (the ring rising of the Paleozoic and late-Precambrian basement), 10 — the negative one (the ring groove); 11 — projection of the impact point; 12 — simulated projection of the CB ballistic trajectory

bilateral symmetry using such different elements of this crater can be considered to be its characteristic feature associated with a slanting CB impact [3]. Here the axes of symmetry of all the elements are the same, which allows us to confidently "diagnose" the impact direction from the SE to the NW. This example can be considered to be a classical one.

However, most important for us is the similarity of criteria for determining the CB trajectory position for the "Popigai" structure (used by us) and for the "Zhamanshin" astrobleme (used by V.L. Masaitis): in both cases one of the principal criteria is the volume predominance of the scattered material in the vanguard part of the structure and its bilateral symmetry according to this element. V.L. Masaitis et al. [3] successfully used the latter morphological element for a series of astroblemes, but they did not examine it for the "Popigai" crater. In [3], as the basis of determining the position of the CB trajectory other, less clear criteria, were accepted, namely, the distribution of the impactites through the area. The position of the klippens zone and its bilateral symmetry remained unnoticed.

3. The "Kara" and the "Ust'-Kara" astroblemes ($D = 65$ and 25 km)

An additional evidence of the regular arrangement of klippen zones relative to the bolide trajectory is clear in the double (binary) "*Kara*" and the "*Ust'-Kara*" astroblemes. An advantage of this pair of structures as compared to other ones is their relative position allowing one to determine the direction of a cosmic body flight.

As a rule, the pair and the group crater fields are formed after an explosion in the atmosphere of an originally solid cosmic body and its fragmentation into two or more objects. These objects are subject to the atmospheric sorting, thus lining up the fragments in order of decreasing mass [10].

Let us consider this regularity in greater detail, as the one having independent significance in assessing the CB fall direction. As stated earlier [11], the regularity of the differentiated size distribution of craters is widely used in practice to "diagnose" astroblemes by their external morphological features, which is especially important in the regions with a high preservation of craters in the relief. For instance, the ring structures discovered not long ago in the Ore Altai, namely, the "*Volchihinskaya*" ($D = 10$ km) and "*Sibinskaya*" ($D = 15$ km) ones [11, 13], are considered to be possible astroblemes in terms of their morphological features, including a differential distribution of "mini-craters" (a mini-crater is an impact crater, which is a part of a common crater and formed by the impact of a CB fragment). According to V.F. Kuznetsov's classification [12], the "Volchikhinskaya" and the "Sibinskaya" astroblemes belong to different morphological groups: 1b (round complicated) — for the "Volchikhinskaya" astrobleme, and 2b (horseshoe-

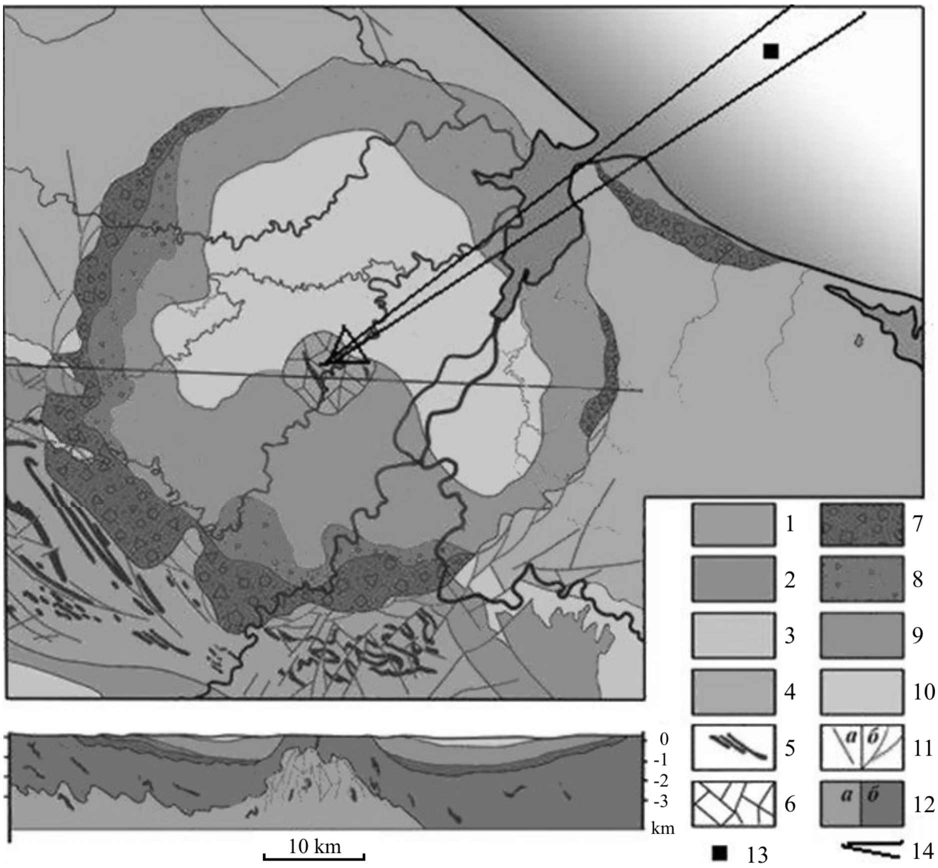

Figure 5. A schematic geological map of the "Kara" astrobleme and the "Ust'-Kara" astrobleme southern part [9, with additions]: 1 — Silurian and Ordovician sedimentary rocks, 2 — Devonian shale, limestone, and sandstone, 3 — Carboniferous clay and siliceous shales, 4 — the lower Permian sandstones, mudstones, and siltstones, 5 — dikes and layered bodies of the Paleozoic diabases and gabbro-diabases, 6 — the Silurian rocks of the central rising (authigenous breccias), 7 — blocky, mega-, and klippen-breccias, 8 — blocky suevites, 9 — lapillie-agglomerate suevites, 10 — psammite-siltstone breccias, 11 — faults: a) of unknown nature, b) thrusts and downthrows, 12 — (for the cross-section, only): a) the Proterozoic shale, b) the Paleozoic sedimentary rocks, 13 — the alleged center of the "Ust'-Kara" astrobleme, 14 — the Kara asteroid ballistic trajectory (13 and 14, according to the authors' data)

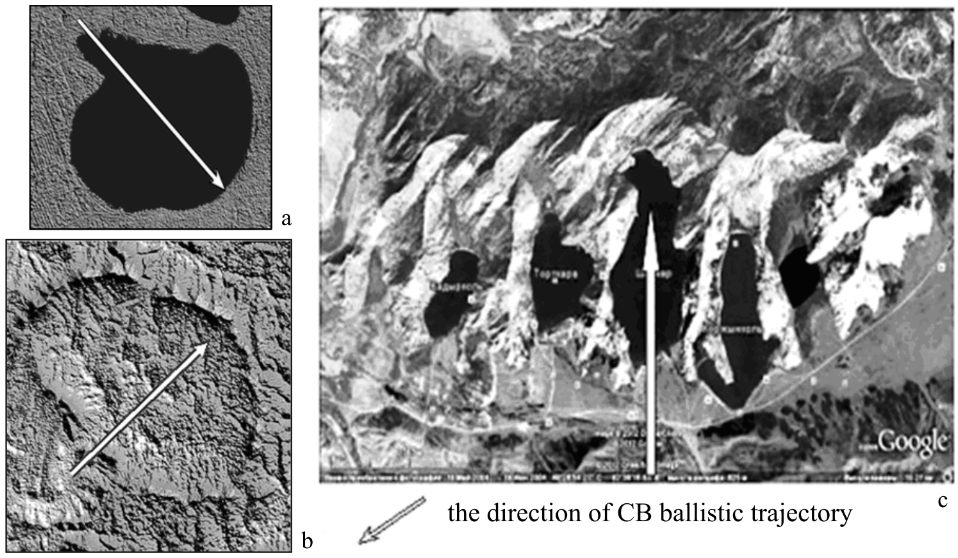

Figure 6. Determining the CB ballistic trajectory direction by the front mini-craters location in "Chalkar-Yega-Kara" (a), "Volchihinskaya" (b) and "Sibinskaya" (c) astroblemes. The shape of craters is supposedly the imposition of (a, b) or more (c) impact structures of different diameters with the general external bank resulted from the fall of fragments of the original single CB [11]

shaped complicated) — for the "Sibinskaya" astrobleme, respectively. Nevertheless, their images (Figure 6) clearly show that the largest mini-crater occupies the front position in the center of the common crater.

In the case of "*Kara*" astroblemes, when there is a chain of asteroid fragments located at a larger distance from each other, we can also estimate, with a sufficient precision, the direction of their motion before their fall on the Earth by the sizes of the meteorite craters they form: the larger one is to be ahead of the smaller one. The line connecting the centers of "Kara" astroblemes is directed by azimuth of 210–220° SW. The bilateral symmetry in the location of the "Kara" astrobleme klippen breccias and, partially, the "Ust'-Kara" ones, is connected with the same trajectory direction (see Figure 5). As noted by M.S. Mashchak [9], in the northern and northeastern parts of the "Kara" astrobleme, suevites lie directly at the crater edges, but there are no klippen breccias, which emphasizes the horseshoe shape of their structure. In the zone of their outcrop, breccias shaped as 5–6 km-wide plates lie directly on deformed rocks of the underlying complex and form a non-closed half-ring in the southern, northeastern, and northwestern parts of the crater, which agrees with the direction of the bolide trajectory. Also, in the southern, western, and southeastern parts of the astrobleme in the Silurian and Ordovician limestones, there are faults, thrusts, and downthrows (accompanying elements of klippens), forming the same scalloped structure as the "Popigai" klippens (see Figure 2). Klippen breccias also form the southeastern part of the "Ust'-Kara" astrobleme whose major part is, in fact, below the water level and cannot be observed.

4. "The Ilyinets" crater ($D = 4.5$ km)

From the point of view of the authors [13], the asymmetry in the distribution of allogenic breccias and klippen blocks is also observed in the "*Ilyinets*" astrobleme (40 km to the SE of the city of Vinnitsa, Ukraine). In fact, investigation into the schematic geological map compiled for this astrobleme [14] reveals the following regularities (Figure 7):

a) the astrobleme has an elongated oval configuration along the axis oriented from SE to NW;

b) well defined klippen blocks and isolated outcrops of allogenic breccias are present at the NW-side of the structure; some blocks have a scalloped shape.

These data, together with the above regularities for the "Popigai", "Kara", and "Zhamanshin" astroblemes, are a convincing evidence for the direction of the Ilyinets body flight from SE to NW (see Figure 7).

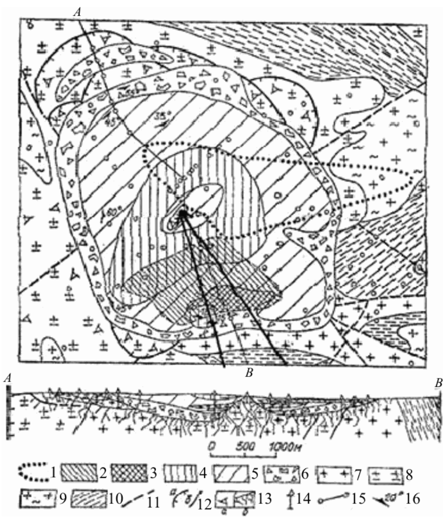

Figure 7. A schematic geological map (without Cenozoic sediments) and the "Ilyinets" astrobleme section [14]: 1 — the boundary of Devonian shales, mudstones, and siltstones; 2 — distribution area of tagamites under suevites and the Cenozoic rocks; 3 — the same under the Cenozoic rocks, 4 — crystalline-vitroclastic suevites, 5 — vitro-crystalline-clastic suevites; 6 — allogenic breccias, 7 — granite aplite-pegmatides, 8 — biotite granites, 9 — amphibole migmatites, quartz diorites, gabbro-amphibolites; 10 — gneisses, 11 — faults of unknown morphology, 12 — alleged thrusts (a — on the map, b — in the cross-section); 14 — wells, 15 — cross-section line, 16 — fledley[1] orientation in suevites. The arrow indicates the expected Ilynets cosmic body trajectory (according to the authors of this paper)

[1]Fledley — flattened glassy bomb in suevites with the size of 10–20 cm.

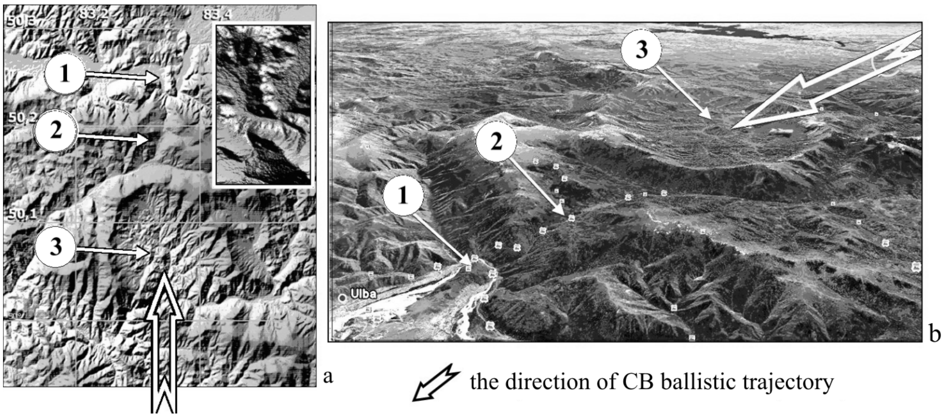

Figure 8. The astrobleme “Chasha”: a) in the shadow relief model of GIS EISC [15]; b) in a satellite image of the Google Earth program. Symbols: 1 — klippen; 2 — the klippen breakaway place; 3 — CIC. The insert in the left picture: zooming elements 1 and 2 with other parameters of relief illumination

Another example of the location of klippens in the astrobleme front part is the “*Chasha*” crater ($D = 14$ km, Ore Altai) [12, 13]. A klippen of such a structure is distinct both in the satellite Google images of the Earth (Figure 8b), and in the shadow relief model (Figure 8a) implemented in the EISC GEO-system [15]. Here the term “klippen” corresponds to a rock massif “pulled out” by a cumulative wave from the first band behind the crater and shifted approximately by 6 km along the ballistic trajectory to the second band outside the crater. On the relief (see Figure 8), it is clearly visible that the klippen is morphologically different from the surrounding relief. Its long axis lies on one line with an expected place of breakaway and the CIC (the central impact cone).

5. The location of diatreme fields relative to astroblemes

According to the *method of the search for diatreme fields* using the “Fireball model” [16–19], in the projection of a cosmic body ballistic trajectory under certain conditions (the sloping angle of the body incidence, its asteroid size, shallow zones of high electric conductivity, etc.) there can be electric discharge interactions between a charge induced by a cosmic body on the Earth’s surface and its interior. This method can be used only in one case among the four examples given.

Thus, the direction, opposite to the one of the **Zhamanshin** asteroid entry holds much promise in terms of the diatremes. In this direction it is expedient to conduct the study of magnetic anomalies for the purpose of revealing promising territories.

The **Kara** body trajectory is under the Barents Sea waters now, and if kimberlite pipes were formed here, currently they are not available for study. The zone stretching to SW of the astrobleme, the so-called Rundquist zone [16] — was considered to be promising from the point of view of diatremes without allowance for data on the flight direction of the Kara bodies, and they should not be used.

The **Ilyinets** body was probably not large enough (several hundred meters in diameter) to initiate electric breakdown from the Earth's interior. Nevertheless, local geologists should study the magnetic field in the direction opposite to that of the body flight, i.e., to the SE of the structure, at a distance of up to 300 km from the crater. If magnetic anomalies of the pipe type are detected here, they should certainly be tested by boring.

And, finally, as one can see in Figure 1, the new version of the **Popigai** asteroid ballistic trajectory is, surprisingly, associated with the location of kimberlite fields in the southeastern slope of the Anabar anteclise. What is this: a random coincidence or a regularity not yet proved by geologists? It should be borne in mind that the energy (electric) influence zone of the asteroid was much wider than that of a probable location of the Popigai body trajectory. This zone is schematically shown in Figure 1: it contains all kimberlite fields of the Anabar area. We do not yet have a direct and indisputable evidence that the Popigai event and the formation of the Kuonamka area diatremes were simultaneous. However, the geological considerations, the presented details of the geological structure of the "Popigai" crater and its surroundings, and the data on the location of the Popigai body ballistic trajectory show that it is highly probable that the Orto-Iarginsk and Starorechensk diatreme fields are of the Popigai age.

Finally, let us note that according to the data by V.F. Kuznetsov (Figure 9a) in the above probable astroblemes of the Ore Altai, there are also

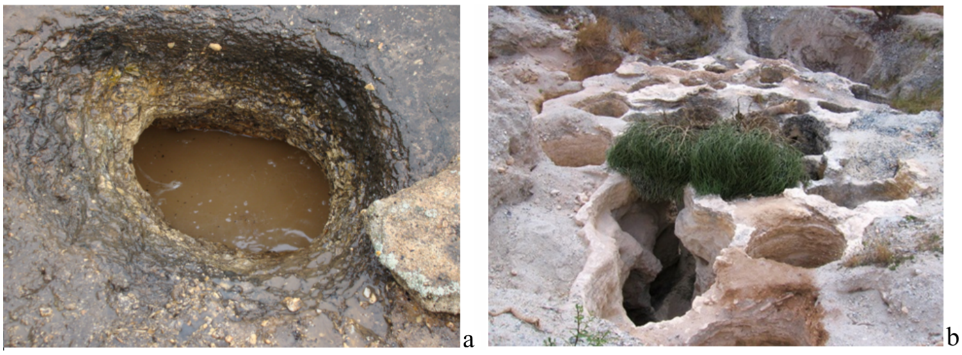

Figure 9. The formations possibly connected with the electric breakdowns of astroblemes: a) "Delbegetey" [13], D = 20 km (V.F. Kuznetsov's photo); b) "Madagascar-2" [13], $D = 98.5$ km (Google Earth's photo)

present formations possibly connected with the electric breakdowns, but in another form — in the form of round tube-shaped cavities in the granites of the epicentral part of the craters. The scale of these formations is incomparably less than diatreme, but the assumed mechanism of its formation is possibly the same. The same situation occurs in the "*Slate Islands*" astrobleme, where diatremes are developed inside the impact crater [16].

6. Conclusions and recommendations

1. The distribution of klippen zones around astroblemes is an important indicator to the direction of a ballistic trajectory of CB entry, and can be used to reconstruct this process.
2. The revealed regularities in the distribution of klippen zones are, most likely, due to the shock wave motion, which is in agreement with the direction of a moving cosmic body, the place of its fall and explosion.
3. Determining the location of the cosmic body ballistic trajectory is an important feature to identify diatreme fields of the same age in the zone of energy (electric) action on the Earth's surface and Earth's interior on the side of the asteroid.
4. The major ultrabasic alkaline pipe formations on the Anabar anteclise eastern slope can probably have "age analogs" to the "Popigai" event, which should be taken into account in the process of geological exploration surveying.
5. The task of geological exploration organizations should consist in identifying real causes of the existence of the negative gravity anomalies "Popigai" 3 and 4.

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