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A technique of searching for ancient meteorite craters by behind-crater rings and other secondary signs inherited in the landscape

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Abstract. A technique that allows by secondary signs finding and determining the size of impact craters with a diameter exceeding 5 kilometers, whose profile has been erased by erosion processes or hidden with sediment cover is proposed.

Keywords: Astroblemes, catalog of impact structures, multi-ring morphostructure.

1. Introduction

It is known that complex impact structures are often accompanied by a system of concentric rings. According to statistics, the transformation from simple craters to complex ones (characterized by the appearance of a central uplift) occurs when the diameter exceeds 3 km in sedimentary rocks, and 10–12 km in crystalline rocks [1, 2]. The transformation from the craters with a central uplift to multi-ring structures under the Earth‘s conditions in crystalline rocks occurs in the range from $D = 24$–25 km (“Boltysh”, “Clearwater East Lake”) to $D = 32$ km and more (“Clearwater West Lake”, “Charlevoix”) [3].

V.E. Petrenko [1], considering the Earth’s complex proven impact craters in 17 from 33 craters reveals concentric rings: in nine craters — one inner ring, in two (“Deep Bay” and “Clearwater East”) — one outer ring, and six (“Wanapitei”, “Haughton”, “Ries”, “Clearwater West”, “Manicouagan” and “Popigai”) have three or more rings. Wherein, all the rings are characterized by diameters $2D$, D, $D/2$ and $\sqrt{2}D$ [3–5], i.e. the coefficient of D is a power of 2, where D is the diameter of the main, most pronounced 4th ring.

This pattern is usually summarized by the formula

$$D_n = \sqrt{2}D_{n-1}$$

explaining the other observable coefficients of D by the absence of some rings (for example, $2D = (\sqrt{2})^2D$) that were either not formed or not recognized. For the first time, this formula was proposed by Belyaev et al. [6], who discovered a pattern in the distribution of Paleozoic alkaline-ultrabasic arrays of the central type of the Kola Peninsula. They have found that these arrays are located on rings of different radii with a center located within the

"Khibinsky graben" [7]. Wherein, the radii R of the rings are 60, 85, 120, 170 km, i.e. with an error of less than 1 % obey the formula $R_n = \sqrt{2}R_{n-1}$. Let us note that it is the Kola Peninsula that is one of the areas where a large amount of data on the influence of meteorite fall on the geological structure was collected.

However, the new data (currently, the list of the Earth's proven multi-ring structures has been doubled compared with [1]; in addition, a lot of multi-ring formations have been discovered on other planets) have shown that this mathematical formula does not always reflect the reality with high accuracy. The ratio of the diameters of the two outer rings of the "Labynkyr" astrobleme [7] ($D = 63$ and 100 km) is $\sim$1.6, i.e. the accuracy of the formula in this case is 11 %. And the quantitative parameters of the "Valgalla" multi-ring structure on the Callisto (the Jupiter's satellite) and "Caloris" on the Mercury given in [8, 9] rather correspond to the law

$$D_n = \sqrt[4]{2}D_{n-1}.$$

Clarity in this matter could contribute to a model of formation of ring structures revealing the basic physical laws of this process.

2. A possible mechanism for forming ring structures

It has been established [10, 11] that the central peaks, as well as the ring elevations and depressions ones formed within large craters during a few seconds after impact, when the main part of the crushed material has not subsided yet, seeing these morphostructures control the deposition of impactites and their early redistribution at the stage of excavation [11]. This suggests a very high speed of movement of the material in these morphostructures - up to several hundred meters per second. Therefore, their formation is considered to associate with various wave processes: with the "phenomena of elastic recoil, the reflection of a shock wave in a multilayer target, the exposure to a rarefaction wave" [11–14], with the "stress waves created by the self-oscillating system of the Earth, its shells and bodies" [5, 15–17], etc. However, the mechanism of forming these waves remains unclear. Moreover, it is difficult to explain the formation of rings outside the crater, where the shock wave destructiving rocks by compression, is transformed to the elastic wave, which, by definition, cannot move the rocks. By now, all attempts to create a clear model for the formation of multi-ring structures from the point of view of the theory of linear wave processes run into serious contradictions.

There is no doubt that a crater itself and all the formations accompanying it are formed simultaneously under the influence of the same forces, and the waves arising from this should reflect both the energy of the shock event and numerous properties of the host rock. P.V. Florensky connects the dimensions of the diameter of a crater with the resonant properties of the planet as an elastic body [5, 15]. B.S. Zeilik considers the behind-crater formations as a consequence of the nonlinearity of high-energy processes occurring during the propagation of mechanical disturbances in the geological environment [7, 8].

According to the Zeilik hypothesis, the disturbances responsible for the occurrence of "standing" resonant waves (forming compression and expansion rings) in the environment are associated with the so-called "corrugated instability of shock waves arising from the interaction of the latter with mechanical inhomogeneities of the environment in the later stages of the wave propagation process" [18]. We consider the shock wave front, which coincides with the radius of the crater R, where spherical seismic waves of a wide spectrum are generated. Seismic waves will propagate from this boundary both into the outer and into the inner part of the crater. The intensity of the generated seismic wave will be sufficient for the destruction of rocks by the stretching mechanism "only at levels (distances from the epicenter), where on the main circumference of a hemisphere parallel to the shock wave front, an integer number of wavelengths will fit, that is, when the fundamental harmonic from the disturbance spectrum will satisfy the resonance conditions on a closed loop" [8, 9]. Let us note that in the cited paper, this basic principle is violated: the number of wavelengths is not determined by the integer.

Let us calculate the basic recursive formulas vs D for various m types of resonant standing waves: $K = 1, \dots m$, where K is the number of wavelengths $\lambda_1, \dots \lambda_m$, packed on the contour $L = \pi D$. The formulas should reflect a change in the diameter of the resonance level n relative to the crater diameter D (n_m is the maximum number of resonance levels for the wave λ_m):

$$\lambda_1 = \pi D;\ \text{2nd level: } 2\lambda_1 = \pi D_2 \Rightarrow D_2 = 2D;\ \dots;\quad n_1\text{th level: } D_{n_1} = n_1 D,$$

$$\lambda_2 = \frac{1}{2}\pi D;\ \text{2nd level: } 3\lambda_2 = \pi D_2 \Rightarrow D_2 = \tfrac{3}{2}D;\ \dots;$$
$$n_2\text{th level: } D_{n_2} = (1 + \tfrac{n_2-1}{2})D,$$

$$\lambda_3 = \frac{1}{3}\pi D;\ \text{2nd level: } 4\lambda_3 = \pi D_2 \Rightarrow D_2 = \tfrac{4}{3}D;\ \dots;$$
$$n_3\text{th level: } D_{n_3} = (1 + \tfrac{n_3-1}{3})D,$$

$$\lambda_4 = \frac{1}{4}\pi D;\ \text{2nd level: } 5\lambda_4 = \pi D_2 \Rightarrow D_2 = \tfrac{5}{4}D;\ \dots;$$
$$n_4\text{th level: } D_{n_4} = (1 + \tfrac{n_4-1}{4})D,$$

$$\dots$$

$$\lambda_m = \frac{1}{m}\pi D;\ \text{2nd level: } (m+1)\lambda_m = \pi D_2 \Rightarrow D_2 = (1 + \tfrac{1}{m})D;\ \dots;$$
$$n_m\text{th level: } D_{n_m} = (1 + \tfrac{n_m-1}{m})D.$$

Thus, if we take the radius of a true crater as the base diameter D, then the universal formula for estimating the diameter of any resonant level for any wave formed at the boundary between the shock and seismic waves is as follows:

$$D_n = \Big(1 + \frac{n-1}{K}\Big) D, \tag{1}$$

where n is the resonance level number of K-class wave.

Since for any wavelength λ_m there are many resonant levels with the number k_i, for which $k_i - 1$ multiple to K, then on the first diameters (for $l = 1 + (k_i - 1)/K = 2, 3, \ldots$) there will be an addition of the resonant levels of all the waves ($\lambda_1, \ldots, \lambda_m$), and the rings with

$$D_l = lD \tag{2}$$

should be the most pronounced. Slightly weaker, but more pronounced than the following modes (the types of waves with K multiples of 3, 4, ...) there should be the rings combining resonant levels of all types of waves with an even value K (i.e. λ_2, λ_4, λ_6, ...). Indeed, the rings obeying regularity (2) are found practically in all multiring structures (Figure 1), and in complex craters with two rings, the diameter of the inner ring being always half the diameter of the outer [1] (Figure 1a).

Thus, many of the rings of all the described diversities can be poorly pronounced, and the ring pattern becomes quite difficult for reliable recognition (see Figure 1b), further being complicated by distortions associated with the heterogeneity of the environment: by the effects of dispersion, diffraction and interference of waves with reverse phases. However, for any expressed behind-crater ring, it is possible to find the integers K and n

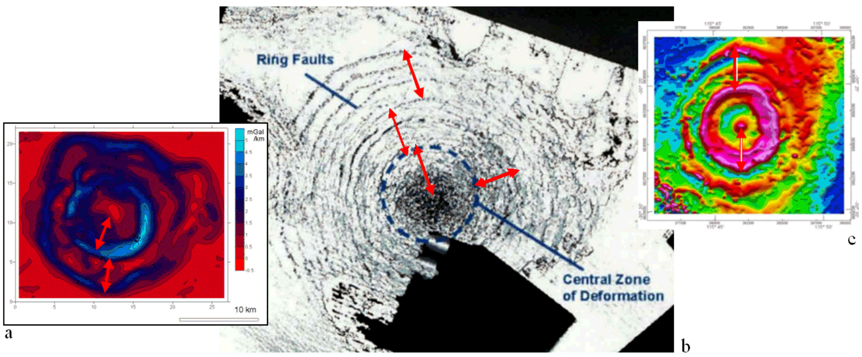


Figure 1. The horizontal gradient of the gravity residual anomaly of the "Ries" impact structure [19] (a), the seismic interpretation map of the "Silverpit" structure [20] (b) the data from a magnetic survey of the "Yalali" crater [7] (c), red arrows have the length of the crater radius R

(the class and the number of its resonance level) in order to obtain an accurate ratio (with an error of up to 3 %) of the ring-diameter to the diameter of the true crater D using formula (1).

With an oblique impact, the wave pattern ceases to be centrally symmetric. As the observations set out below show, the completeness and the number of rings decrease, and only arcs become accessible to recognition (fragments of the behind-crater rings located behind the frontal part of the crater in the direction of the shock), characterized by regularity (2) for $l = 1, 3, 5, \ldots$ That is, in this case, for the most intense wave λ_1, the rings with numbers $2, 4, 6, \ldots$ become inaccessible for identification, and the distance between the observed rings is equal to the diameter of the crater D:

$$\Delta D_n = D; \quad n = 1, 2, \ldots \tag{3}$$

3. The search for ancient meteor craters on the behind-crater rings

The specificity of the Earth is that erosion processes and sedimentation quickly erase or hide the traces of the cosmic bodies falls. The difficulties of identifying the ancient meteor craters, whose profile has been erased by erosion processes, make it necessary to find the secondary morphological signs of their identification. On the basis of a visual and comparative analysis of a large number of crater-like structures, a new class of bilateral type structures has been identified that have similar identification features in the form of a sector-truncated multi-ring structure outside the crater. The bilateral symmetry of these signs (usually characterizing the traces of impacts at small angles to the surface [21]) indicates to a possible cosmogenic origin of the structures found. In general, the structure looks as if an oblique impact forms a standing cumulative wave directed along the surface and having a greater intensity in a limited sector, whose width depends on the angle

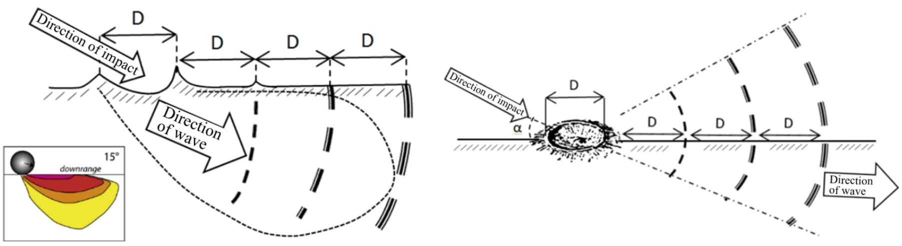


Figure 2. Schematic representation of the cumulative wave seen in the relief—cross-section and plan (in the insert of picture: the area of high shock pressures according to the results of numerical simulation of the impact of a 10-kilometer dunite asteroid on a granite target at a speed of 20 km/s at an angle 15° to the horizon [22])

of incidence (Figure 2). The length of this wave is equal to the diameter of the ring crater bank, and the energy density is sufficient to destroy the rocks along its fronts outside the crater. The ring fragments thus formed are significantly more resistant to erosion than the crater itself.

A typical example of such a crater is the probable, highly eroded structure of "Kotuy 1" (D = 43 km) [7] located 200 km south of Khatanga (71° 22′ N; 102° 14′ E). In the relief image (Figure 3b), only secondary signs

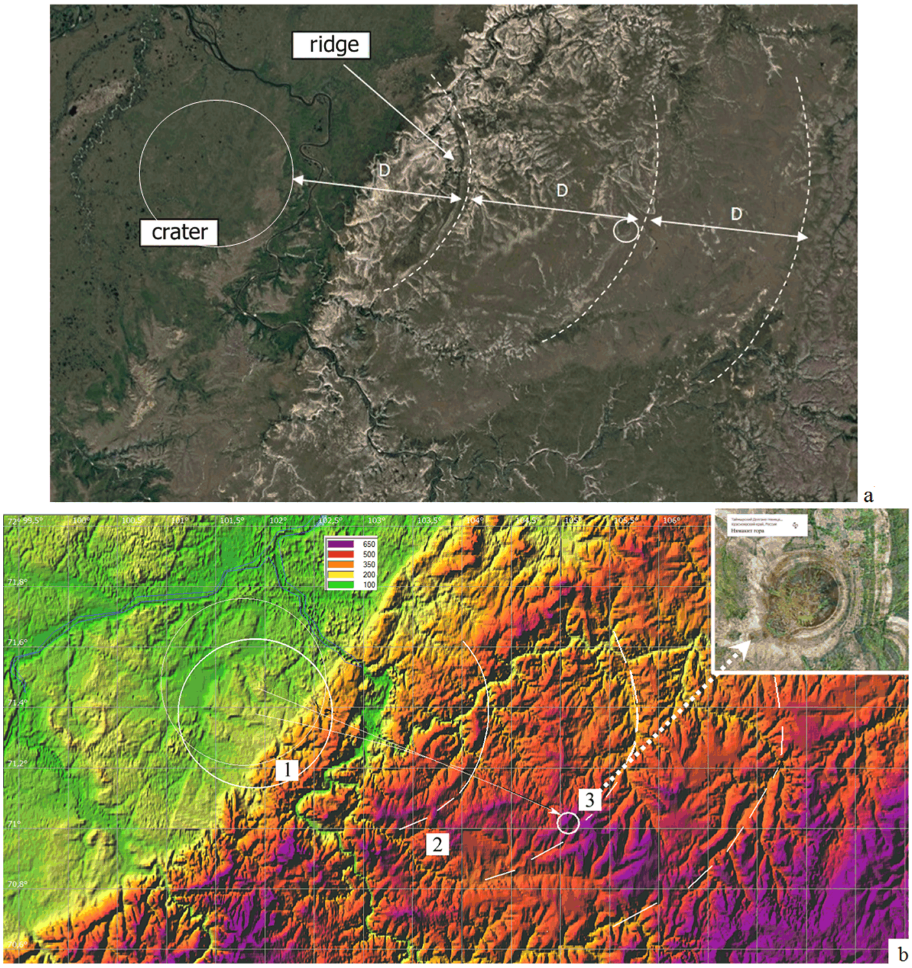


Figure 3. Maps of the "Kotuy 1" crater area, obtained by Google Earth Pro, GIS-ENDDB and Bing: a) identification of the crater rings in the Google Earth satellite image (D = 43 km); b) a surface relief in GIS-ENDDB: 1 — a possible location of the eroded crater bank [7]; 2 — the arc, contouring an arcuate ridge along the valley adjacent from the east; 3 — Mount Namakit (at a color scale: a height in meters). In the inserted picture: a satellite photography (Bing) of Mount Namakit (named as "Kotuy 1a" structure in the catalog [7]) at an enlarged scale

of the existence of a crater can be observed. The first, most noticeable and characteristic is the arc-shaped behind-crater ridge, well expressed in the relief. In form, it repeats the outer bank of the crater, but has an abnormally high altitude (up to 150–170 m relative to the adjacent valleys and up to 350–390 m relative to the center of the crater).

This ridge is the closest behind-crater ring to the fall site and is located at a distance D from the intended crater bank. Probably, during destruction, the volume of the rock increases, and in the zone of maximum destruction, the rocks are squeezed out in the form of an arcuate ridge. If the surface rocks do not have a sufficient brittleness (for example, a thick layer of refractory clay), a trench (ravine) is forming instead of a ridge (for example, the "Chernorechenskiy" crater [7]). The line drawn through the middle of the arc will indicate to the direction of the center of the crater (Figure 3).

With a sufficient impact power, several arcuate zones of rock destruction are formed, but, starting from the second behind-crater ring, they are less pronounced and do not have a characteristic ridge. Probably, as a distance from the crater increases, the width of the zone of destruction increases due to the dispersion of the surface wave. The distance between the arcs is also equal to D (3). They can be traced either by the arcuate scree (in mountainous areas), or by changing the character of the vegetation cover as well as along the river beds (on the plain). The presence of several rings is the second identification feature of the method described here for identifying the location of eroded craters (see Figure 3). For identification, it is sufficient to connect the midpoints of the arcs with a line; the outer crater band of interest must be located at a distance of the measured interval between the arcs.

In most cases, the crater bank is absent, and only a depression between the eroded bank and the crater central elevation is recognized in the relief.

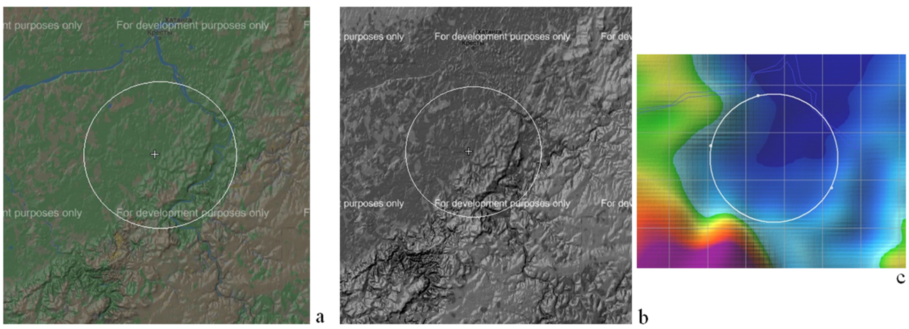


Figure 4. Revealing the contour of the buried crater by processing the images: a) the Google Earth relief; b) the Google Earth relief in black and white gamma with a high contrast; c) the crater anomaly Δg in GIS-ENDDB (color scale is in mGal)

The depression is usually filled with the waters of lakes or rivers. Therefore, the arcuate and annular bends of rivers are an additional sign of the crater identification. Sometimes, to find the best expression of the crater and its rings, it is necessary to use a variety of tools and resources (Figure 4), wherein the satellite images often give a clearer picture due to a change in the color of rocks or of vegetation on the surface of eroded morphostructures (see Figure 3a).

In the example described in Figure 3, there is another morphological feature: at the intersection of the second arc and the line of the supposed ballistic trajectory of the cosmic body there is an absolutely circular object that is not characteristic of the surrounding landscape - Mount Namakit (in the inserted picture of Figure 3b) ($71^\circ\,02'\,36.13''$ N, $105^\circ\,07'\,17.08''$ E). Its diameter corresponds to the size of a probable meteorite, but, most likely, it is a trace of the magma yield to the surface through the formed crack, which may indicate to the shock destruction of the rock to the entire thickness of the crust.

In the cases of a multiple shock (when a cosmic body falls splitting into pieces), several standing waves with different wavelengths (in the number of fragments) should form. Within their interference, discontinuity zones should form, whose shape differs from the arc and is determined by the ratio of the amplitudes and phases of the waves (Figure 5). In this case, the most narrow discontinuity, the first one behind the crater, may not form or look weakly pronounced. However, the subsequent discontinuities are usually identifiable by the equal shape and distances between them.

Another sign of the fall of a meteorite can serve a boundary of the rock discarding by a shock wave having a clear arcuate or circular contour. The

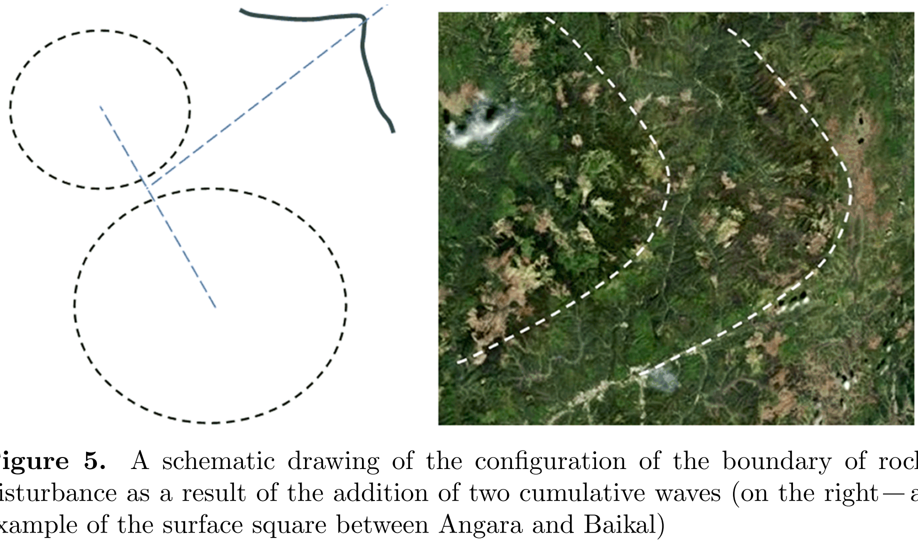
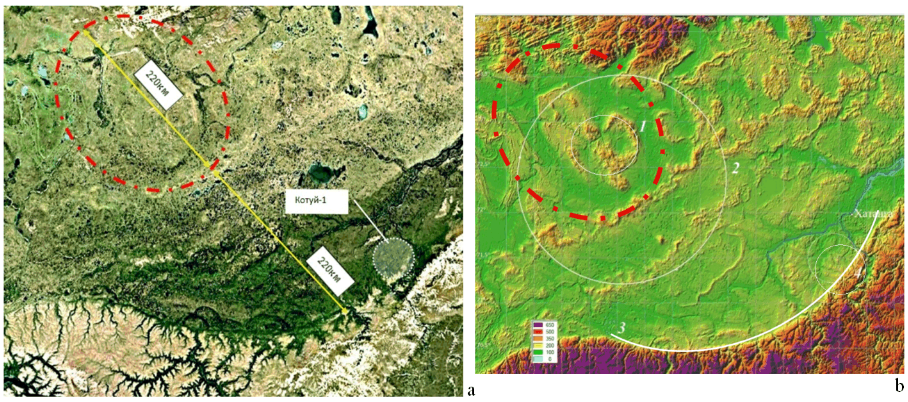
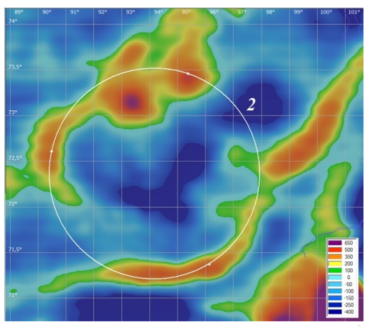


Figure 5. A schematic drawing of the configuration of the boundary of rocks disturbance as a result of the addition of two cumulative waves (on the right — an example of the surface square between Angara and Baikal)

formation of such shapes is possible when a meteorite falls at an angle close to the ricochet (with forming an arc), or when the gas-dust comet falls vertically, when all the energy lies in its speed, and penetration of the impactor into the target is practically absent (with forming a circle). In this case, the shock wave travels along the surface and destroys the top layer of a rock, and the airflow from the place of impact discards it. The clarity of the boundary indicates to a strictly limited radius of the zone of destruction. It is difficult to imagine a geological process capable of forming such a geometrically regular boundary between a plain and a hill (Figure 6b). Nevertheless, the destruction of the upper layers of the rock under the action of the surface wave, which has an additional horizontal component in the direction of movement of the CB, can lead to exactly this result. In Figure 6, the former border of the Anabar shield is clearly visible by the river bed that flowed along it. The described shock event could have caused the disappearance of the "Kotuy 1" crater: Figures 3b, 4 clearly show that the boundary of the rock discarding passes inwards this crater.



a b



c

Figure 6. Morphostructural elements of the potential impact crater "Igolkin" (72° 43′ N, 93° 22′ E) according to Google Earth Pro and GIS-ENDDB: a) in high contrast Google Earth image; b) in relief (color scale: height in meters): 1 — central uplift eroded, 2 — crater bank expressed in the gravitational field (c), 3 — the boundary of the rock discarding under the action of surface wave, 4 — "Kotuy 1" crater (see Figure 3); c) Δg anomalies (color scale in mGal) slightly displaced forward relative to the visible boundary on the surface (the red dotted line in figures a and b) may indicate to a directional configuration of the shock wave (see Figure 2)

As a result of the application of the technique, which includes the described signs of the identification of eroded astroblemes, a number of new impact structures of validity degree 2 (potential) were identified and added to Catalog [7]: Agulsky, Akhmerovo, Akhmetka, Arkhangelsk 1-2, Artvin, Baku, Bogatka, Borjomi, Bratskaya, Budennovsk, Chernorechenskiy, Chiatura, Eromo, Goncharnoye, Igolkin, Ilinskaya 1-2, Kapkara, Karam, Kepino, Kholmovka, Kirnosstream, Kirov, Klyaksa 1–2, Koynas, Krasnaya Zarya, Kunki, Kurdamir, Mezen, Mongol 1-9, Motma, Nagornoye, Navakhi, Neftekamsk, Novokhayskaya, Pasha, Pinega, Pinezhsky 1-2, Preobrazhenka, Pyasinskaya, Round island, Samsari Caldera (Kvemo Kartli), San Yurjakh, Sevastopol, Sharoy, Siloga, Sinyaya, Sogra, Sorovo, South coast, Srednekolymskaya, Sura, Surovoye, Svetlaya, Taimyr 1, Talyany, Tekle, Toksha, Tsenogorskoe, Tsikhisdzhvari, Tura trail, Tyuryushlya, Ust-Ilimskaya, Valna, Vasilyevka, Vasilyevo, Vitimerova Beam, Volgograd Big, Vysokoye, Yangory, Yula, Zima. According to B. Savelyev, of 85 new impact structures recently added, 25 have these signs in the most pronounced form. They are listed in the table.

List of 25 potential impact structures added to the Catalog [7] by the presence of behind-crater rings

Name	Land	Co	Lat	Long	*D*
1. Akhmerovo	Russia, Bashkiria	Eu	54.2202849	55.9870148	8.2
2. Akhmetka	Russia, Bashkiria	Eu	54.0960469	56.4093018	6.5
3. Arkhangelsk 2	Russia, Arkhangelsk area	Eu	65.4901841	42.2149658	80
4. Artvin	Armenia	As	41.299476	42.2094727	35
5. Baku 2	Azerbaijan	As	40.3538702	49.6842957	14
6. Bogatka	Russia, Arkhangelsk area	Eu	63.1211575	44.2364502	36
7. Bratskaya	Russia, Angara	As	55.961	102.441	120
8. Chernorechenskiy	Russia, C. Ural	As	56.51053	57.458814	18
9. Eromo	Russia, Yakutia	As	67.628885	103.006983	60
10. Igolkin	Russia, Taimyr	As	72.7640647	93.4716797	80
11. Kapkara	Russia, Krasnoyarsk area	As	56.603382	97.261577	60
12. Karam	Russia, Irkutsk ar.	As	54.666768	108.070971	28
13. Koynas	Russia, Arkhangelsk area	Eu	64.88018	48.102908	16
14. Kunki	Russia, Dagestan	As	41.9513199	47.4094391	17.5
15. Neftekamsk	Russia, Bashkiria	Eu	56.34694	55.64397	250
16. Pasha	Russia, Arkhangelsk area	Eu	63.785216	44.1210938	7
17. Sharoy	Russia, Chechen Rep.	As	42.7127141	45.6976318	80
18. Sinyaya	Russia, Arkhangelsk area	Eu	63.0026403	44.6923828	90
19. Sura	Russia, Arkhangelsk area	Eu	63.4572605	45.1991272	21
20. Surovoye	Russia, Taimyr	As	74.818333	101.407917	22
21. Ust-Ilimskaya	Russia, Angara	As	58.295818	101.607246	320
22. Valna	Russia, Arkhangelsk area	Eu	63.2796	44.292233	0.34
23. Valna 1	Russia, Arkhangelsk area	Eu	63.263525	44.305533	0.39
24. Vasilyevka	Russia, Crimea	Eu	45.159478	34.778579	9.79
25. Yangory	Russia, Arkhangelsk area	Eu	63.0051338	37.6062012	73

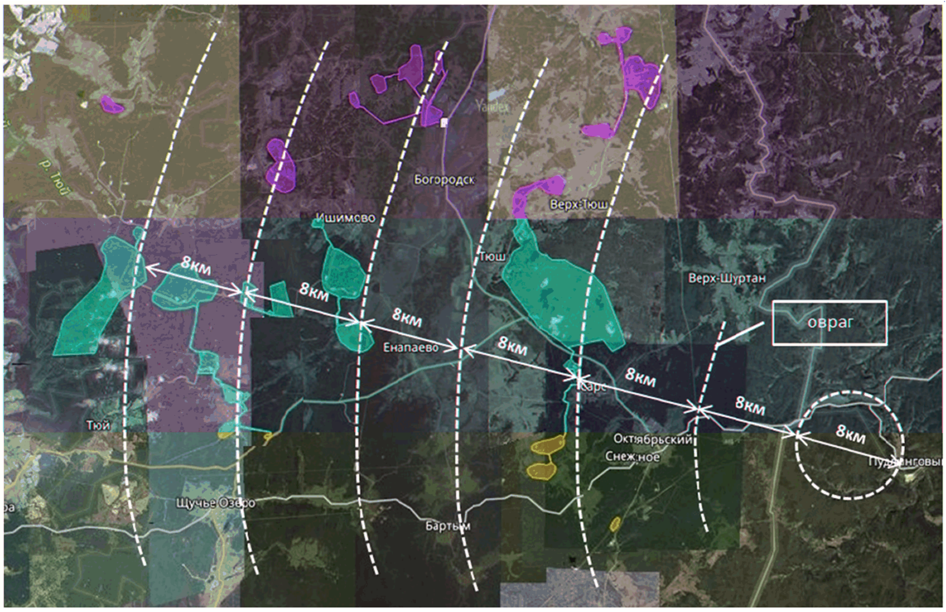


Figure 7. Mutual arrangement of oil fields and the "Chernorechenskiy" crater [7] in the Wikimapia map

In addition to the purely scientific value, this technique has an applied one. The crust fractures and a crushed rock beneath the crater visible bottom serve as a natural reservoir for the forming mineral deposits [9]. These include the stockwork deposits of copper in town of Kounrad and of gold in Raygorodok near town of Schuchinsk in Kazakhstan. In the crater "Ashapsky" [7] of the Perm Territory (presumably of the impact origin) a copper plant is functioning for 200 years.

In Figure 7, there is a clear association of promising oil fields with a zone of seismic waves propagation from the "Chernorechenskiy" crater [7] ($56^\circ\,30'$ N, $57^\circ\,27'$ E).

Conclusion

Despite a wide variety of hypotheses explaining the formation of multi-ring structures on the planets, most of them are based on models of various wave processes arising during a strong meteorite impact or immediately after it. This allows the use of the multi-ring morphology to identify impact craters eroded by present. The study by means of GIS-systems of the relief and satellite images on the territory of Russia and the adjacent states has revealed a high prevalence of this identification feature in the form of arcs truncated by the radial segments, which indicates to the interference nature of their formation. The wavelength that has formed the rings is assumed to be equal to the diameter of a true crater. The revealed patterns have formed the basis for the recognition of eroded impact craters, due to which more than 80 new records were added to the Catalog of Earth's Impact Structures [7].

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