

On studying morphological features of impact craters using the Earth's remote sensing materials

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Abstract. This paper gives a brief review of the new methods of studying the impact craters morphology using real data from “Catalog of the Earth's Impact structures” (2057 events), presented at the site of the “Mathematical problems in Geophysics” laboratory of ICM&MG [1]. For the research it is offered to use one of independent versions of the geoinformation systems (GIS) for natural phenomena, named EISC-system (the Earth's Impact Structures Catalog) [2]. The new methods, allowing one to visually reveal a new structure thus refining its genesis, are presented. There are systematized and represented typical morphological elements of the structure of impact craters (astroblemes) which are urgent with their diagnostics.

Introduction

The basic hypothesis of the impact-explosive tectonics [3] consists in the fact that the Earth must be covered with the meteorite craters not less than the Moon or the Mars. The present view about the proposed number of large ($D \gg 100$ km) ring structures (RS) on the Earth can be obtained from the cosmogeological maps [4, 5] (Figure 1a), which are comprised according to the data of the Earth's surface satellite photographs and contain the enormous number (~ 4000) of the identifiable RS. Moreover, half of them have not got an established genetic characteristic yet [3].

Furthermore, underwater oceanic RS are not considered here [4, 5], but there are estimations that 70% of all meteorites are to fall into the ocean [6]. However, since the age of the oceanic crust is considerably young as compared to one of the continental plates (because of its renewing spreading-subduction mechanism), it is possible to assume that the majority of concentrated bombings fell on the earlier time periods as compared to the period of forming the current oceanic crust. And the oceanic bottom can store information about the craters, whose quantity does not exceed 0.1% of their total number.

The study of the morphology of smaller terrestrial RS (with diameters from ones to tens of kilometers) can be conducted using more detailed data of the Earth's remote sensing: satellite photographs [7] or relief digital models [8], realized in different GIS-systems (Figure 1b). At the initial stage of the search for new craters, which are often difficult to allocate in satellite images

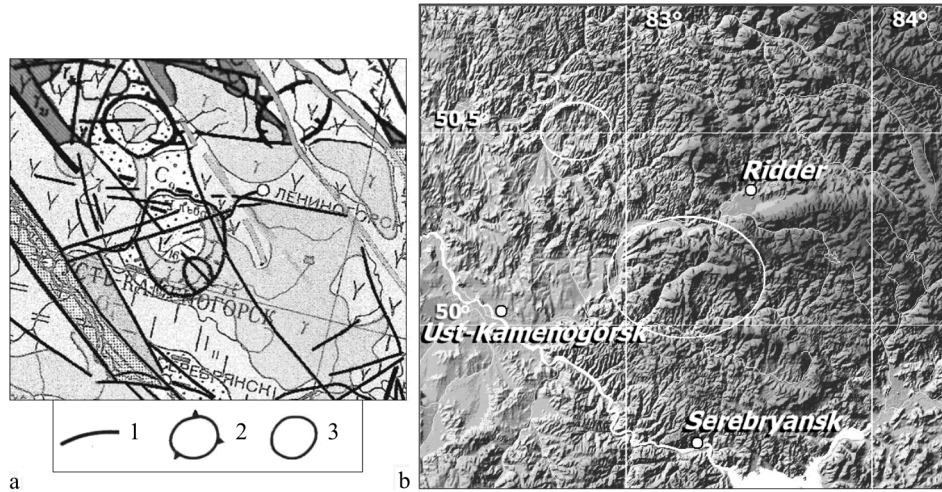


Figure 1. Fragments of two maps for the Ust-Kamenogorsk area: a) the “Cosmogeochemical map” [4]; b) the GIS system EISC [2]. Conventional sings: 1 – fault lines, 2 – arches, 3 – RS of the unestablished or complex origin

it is effective, for example, to use numerical algorithms of data processing of the digital relief [9], that allow finding RSs on the Earth’s surface.

However these means are not sufficient for diagnostics of the impact origin of revealed RS. For the determination of the potentially impact origin craters among a set of RS, it is necessary to develop the new methods of astroblemes diagnostics from typical morphological elements, using modern information technologies of image processing.

The main conditions contributing to the successful identification of cosmogenic ring structures (CRSs) according to [6] are their increased safety in the geotectonically stable regions (ancient shields and platforms), a minimum manifestation of endogenous processes, and the absence of a powerful cover of friable deposits. However, the entire structure of almost all proven domestic astroblemes described in [10] according to the presented geological vertical sections are buried under sedimentary or water covers, except for several craters partially remained in the surface relief and can be revealed from the data of the aero-photo-morphological analysis (“Logancha”, “Beyenchime–Salaatin”). Nevertheless, as real data have shown [1], the original cosmogenic relief was excellently stored in many Earth’s regions, for example, on the territories of Pribalkhash, Ore Altai, Kola Peninsula, Mexico, Madagascar, and South Africa. Let us note that in last one hundred years many impact craters on the Moon and other planets are diagnosed, based exclusively on the morphological criteria [11, 12]. Thus, it is possible to assume that in certain conditions the morphological elements of astroblemes are the basic, original factor of reliable diagnostics of impact

structures, and petrographic and mineralogical proofs of the impact origin are also important, but are secondary in relation to the basic factor.

In particular, according to the new methods of diagnostics of impact craters from their shape proposed in this paper, more than 40 new potential astroblemes of Ore Altai have been found and added into the Catalog [1]. Genesis of 10 craters of Madagascar, Northern Italy and Siberia has been refined. The astroblemes, revealed only from morphological elements, are marked in the Catalog [1] with Category 2 (“possible”) according to 5-mark probability scale (from 0 to 4) defined in [13].

1. The main structural elements of the impact crater identification

Let us first dwell on the main impact geological-tectonic and morphological elements of the cosmogenic craters, accepted at present as a result of the study of images, maps and vertical sections of RS.

The *geological-tectonic* features include such elements [3] as the confinement to crater-like RS of a radial-ring grid of fault lines (structures of “beaten plate”, central strike-slips, upthrows, downthrows), centrifugal reverses (klippens) on the periphery of a structure, and for the gigantic possible cosmogenic craters (so-called “giablemes” [3])—thinning of the consolidated crust, fold and seam folding in the platform cover. The arched and radial fault lines, connected with giablemes, can cut the Earth’s crust to its total thickness (astrobleme “Ishimkaya” [1, 3]), controlling the arrangement of volcanogenic mulds, intrusions, belts of the ultrabasic rocks or even of the active volcanoes on the periphery of giablemes [3]. In other words, the presence of the geological elements, associated with the trigger mechanism of the lava-effusion by the cosmic body (CB) impact, is possible [13].

For small impact structures, as an important tectonic element, it is possible to indicate to the presence of an extensive zone of weak fractures [6, 14] (for example, for the crater “Kaali” [1] it has the form of a butterfly), with diameter of up to 2 times exceeding the diameter of the crater.

Let us note that decoding the aero- and photo-data makes possible to reveal such external manifestations of tectonics genetically connected with the formation of astroblemes, as ring and radial faults (“Logancha” [15], “Manicouagan”, “Konder” and nuclear formation “Vilyuiskiy” [1]), surface outlying folding (“Zapadno-Sibirskaya” [1]), ancient and acting centers of volcanism (“Pacific Ocean” [1]).

Now let us enumerate the main *morphological* elements of the meteorite crater, therewith in this paper we will consider only those of them, which are reflected in surface relief and visual sizes of a crater. By the present time, some types of CRSs have been revealed, the basic morphological relationships being obtained: for simple and complex craters [6], impact and

shock-explosive ones [13, 14] and, also, for the craters in different targets: crystalline shields and sedimentary rocks [6, 13], and in the basaltoid formations [15] analogous to other planets surfaces. In particular, simple craters have a cup-shaped form of small diameters: up to 2–3 km in the sedimentary and up to 6–8 km in the crystalline rocks, and they are relatively deeper in comparison with complex craters [6]. In the sedimentary rocks, a relative depth of these craters is lesser than that in the crystalline [6], and a special property of craters in the basaltoid targets (for example, trap rocks) is a relatively lower height of a crater bank [15].

The general idealized picture [3, 10, 13] of the impact crater (in addition to the above-mentioned folds, faults and weak fractures zones) includes such visual elements as the negative form of relief (in contrast to volcanoes—the positive accumulative forms of relief [11]), the base bank, and for complex craters—the central rising in the form of a ring or an impact cone (CIC) and the mound bank. However, real data [1] supplement these classical morphological models of the impact crater with numerous refinements, which depend on real conditions of forming a crater.

2. The information technologies and methods used

For studying the shape of craters we use both the shady relief model realized in the GIS development EISC [2] (Figure 2a) and the satellite photographs of the program Google Earth (Figures 3: a, c, d) or its Russian analog Imp.ITRIS (Figure 3b). Satellite photographs are processed with the aid of simple operations of the selection of contrasts and half-tones, which help in obtaining a highly qualitative volumetric photo of a crater.

For constructing a shady relief model we used arrays of surface relief data of NASA: SRTM (Shuttle Radar Topography Mission) and ASTER GDEM (Global Digital Elevation Model), and, also, the digital cartography technology [16], which consists in the toning (painting with a nuance of the stipulated color) of the surface points depending on their brightness in terms of the lateral illumination of the surface. First of all, the triangulation of the entire region constructed is done, when each grid cell is divided into the necessary number of triangles depending on the size of a figure. The brightness of each surface element is determined according to the orientation of the plane of each triangle with respect to the vector of the illumination directivity. The color of an element is determined by the gradation of brightness of the corresponding color, which depends on the height of this point above the sea level. This is the user who assigns the parameters of illumination and basic colors (color scale), from which then different nuances of brightness are obtained [16].

The new method of diagnostics of the impact craters consists in selection of an optimum foreshortening of an image, or parameters of the illumination

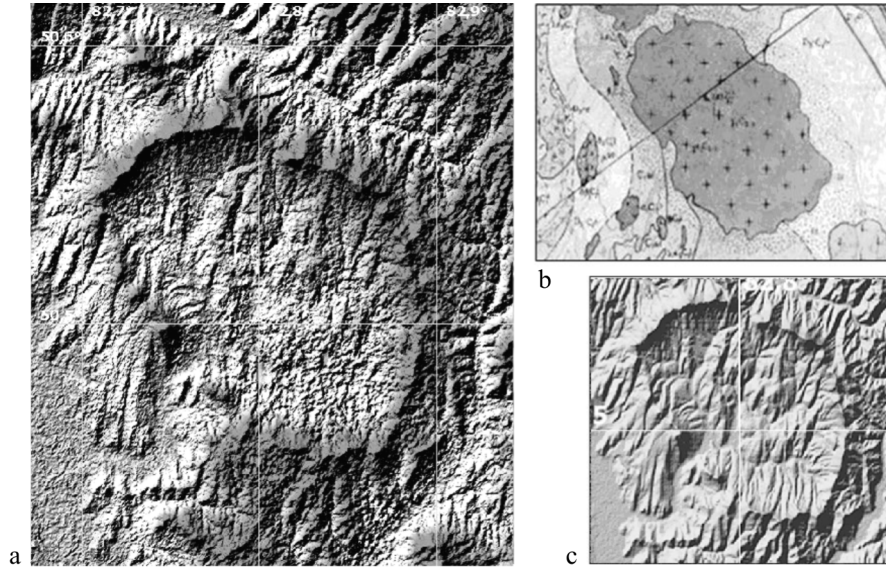


Figure 2. Probable astrobleme “Volchikhinskaya”: a) the shady relief model realized in GIS-EISC (data of ASTER GDEM), b) a geological scheme (G.V. Nazarov. Geological map of the paleozoic foundation. 1995) showing the granite composition of the crater, c) a lower resolution shady relief model (data of SRTM)

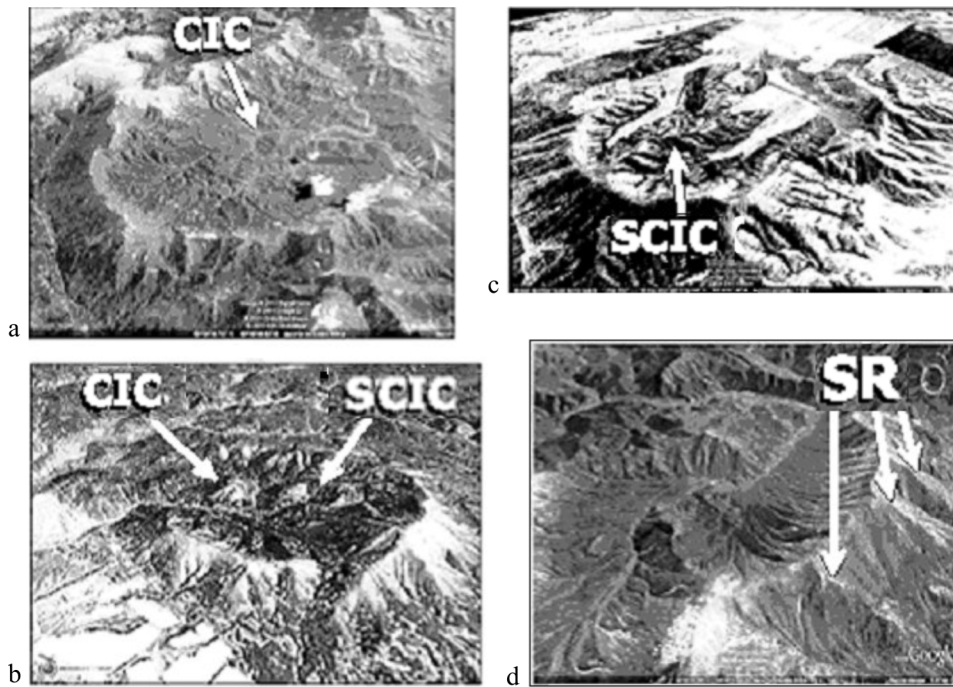


Figure 3. Satellite photographs of the possible astroblemes: a) “Chasha”, b) “Orlovsky”, c) “Nazar”, d) “Erofeevskaya”

ray and the shadow depth, to avoid image deficiencies, connected with the fact that the majority of ancient impact craters was stored only fragmentally due to the erosion, sedimentary-accumulation, tectonic and volcanic activities of the region.

This procedure of studying images allows one not only to reveal RS in a series of photographs and models of a relief, but also to gather data for establishing standard elements of CRSs identification. It is known [6], that the procedure of CRSs identification has a set of stages, including those related to the morphology:

1. Selection of typical morphostructure models for possible CRS of the region;
2. Selection of the identification criteria for the confirmation of its cosmic genesis;
3. Comparison of investigated RS with the cosmogenic structures proven for confirming the hypothesis about its cosmic genesis;
4. Clearing up the contrasting nature with the surrounding landscape of the elements discovered.

As a result, investigations conducted in the Ore Altai [17], where the primary cosmogenic relief was excellently stored, with the use of the described methods the following regional morphological types of potential astroblemes (then confirmed in other regions as well) were revealed at the first stage:

Group	Description	Examples
1a	Simple round	“Ust-Volchikhinskaya” [1]
1b	Complex round	“Volchikhinskaya” [1], Figure 2
2a	Simple shoe-shaped	“Chasha”, “Orlovsky”, “Nazar”, Figures 3a-3c
2b	Complex shoe-shaped	“Sibinskaya” [1], Figure 3d

The rocks composing the revealed typical impact structures on this territory have predominantly a granite composition [17] and, in our opinion, represent a crystalline foundation disclosed by an explosion (see Figure 2b). Granites form the central part, CIC, and, sometimes, the bank of the craters. In some cases, the bank is composed of target rocks, been the sedimentary deposits. In particular, the probable astrobleme “Volchikhinskaya” has a crater bank (see Figure 2a) made up of the hornstoning rocks of the sedimentary cover. A high stability of granites and hornstones to the erosion processes explains the excellent safe keeping of the craters relief. Further, studies of photomaterials in a variety of possible astroblemes allow us to formulate additional structural elements—“diagnostic indicators” of an impact crater.

3. Additional structural elements of the crater identification

The new structural elements were revealed according to the principles of maximum occurrence, morphological recognizability and stability to the above-enumerated processes of destroying the craters.

1. In the cases when a crater bank is made up of granites, the undulating crook — **crater bank ridge** — can be present in the transition zone between the external and internal sides of the crater bank (Figure 4). The attitude of the granite plates makes it possible to assume the genesis of this morphological structure as a result of granite plastic flow at the final stage of crater formation [17].

2. Simple shoe-shaped craters of the elongated form (Group 2a) with diameter of up to 4 km are characterized by the presence of the so-called **shadow of central impact cone** (SCIC) in the form of a ridge along the major axis of the crater ellipse (see Figures 3b, 3c). In this case, SCIC is located between CIC and the frontal part of an astrobleme crater bank, i.e. in the shady zone (“dead zone”) of CIC, and can be emphasized from the sides by the “plowing” chutes. The research into the RSs of this subgroup that differ in the size allowed us to reveal the following laws:

- In craters with $D \gg 4$ km, CIC is present, but SCIC is present in embryo only (see Figure 3a);
- In craters with $D \sim 4$ km, both CIC and SCIC can be clearly expressed (see Figure 3b);
- In craters with $D \ll 4$ km, clearly expressed SCIC is present, but CIC is either completely absent or present in embryo only (see Figure 3c).

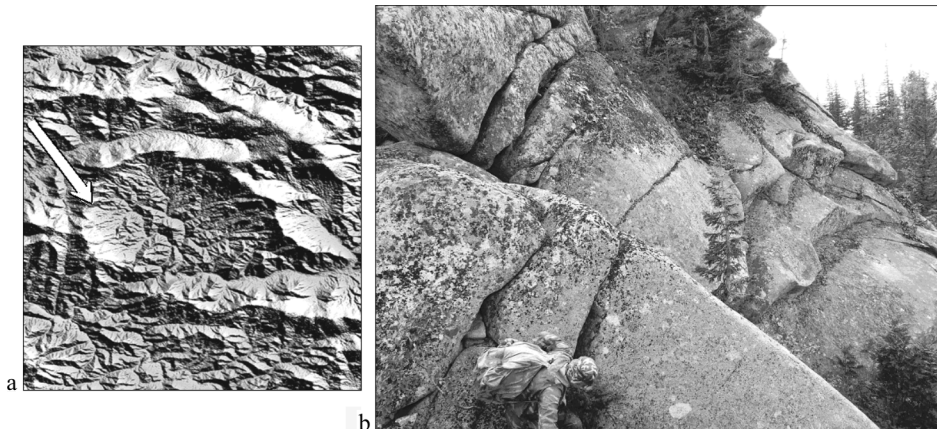


Figure 4. The crater bank ridge of the probable astrobleme “Chasha”: a) a shady relief map, b) a photo. The pointer in the shady model indicates to the point of taking this photo

3. For the shoe-shaped craters on its outer side, the **stiffening ribs** (SR) are located that are dispersed in directions perpendicular to the frontal part of the crater (see Figure 3d). The number of SR varies depending on individual ballistic parameters of CB.

4. The reason for the formation of complex craters of Groups 1b or 2b could be the CB disintegration in the atmosphere and a simultaneous drop in the large number of fragments differentiated according to their size around the largest CB. As a result, the formation of the general impact crater occurs, which consists of the smaller **mini-craters**.

Let us name as mini-crater the impact crater, which is formed with the explosion of CB fragment and which is part of a larger crater. The size differentiation of the arrangement of mini-craters in the composition of the general impact crater is the most important principle of the complex crater structure: in the frontal part, the largest mini-crater is located; to the periphery, the sizes of mini-craters symmetrically decrease (see Figure 3d; Figure 5). This differentiation results from the interfering shock waves, generated by the CB fragments when passing the atmosphere. More massive fragments have a higher kinetic energy, and thus form a more powerful shock wave, which rejects less massive fragments to the periphery. The degree of manifestation in the relief of mini-craters depends on the degree of the flying-away of fragments. In particular, if the flying-away was insignificant (the sum of radii of adjacent mini-craters exceeds the distance between the explosion epicenters), the common crater forms the overall outline consisting of “grown together” arcs of the crater banks of a different diameter, which belong to mini-craters entering its composition (see Figure 5).

It is known, that in the cases of the even greater flying-away of the meteoritic mass fragments, when the general crater is no longer being formed,

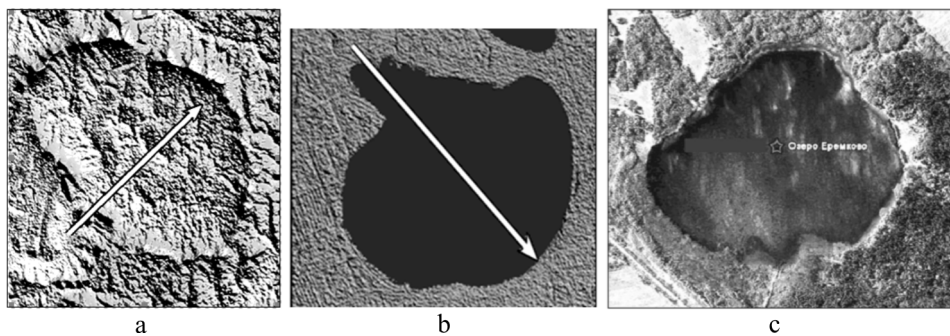


Figure 5. Probable and possible astroblemes: a) “Volchikhinskaya” (a shady model with different parameters of illumination in GIS-EISC), b) “Chalkar–Yega-Kara” and c) “Eryomkovo ozero” in Google Earth. The shape of craters is supposedly the imposition of three impact structures of different diameters with the general external bank, formed in the fall of fragments of the original single CB

there is a sense to speak about the crater fields (groups of craters) [18, 19]. In this case, the concentration ellipse of individual meteorite craters is located behind the front side of a field (“Henbury” and “Sikhote-Alin” [13], “Baiyang dian” [1] and “Contozerskiy graben” [1, 19]).

Let us note, that in proven impact structures only some signs indirectly associated with the enumerated morphostructural impact elements were earlier noted, for example, the existence of the radial valleys (divided by the rudimentary SRs) on the external slopes of a crater bank in the structures “Logancha” [1], “Kara”, and “Shunak”, and, also, of the intra-crater radial “plowing” chutes in the astroblemes “Boltysch” and “Popigai” [10].

4. Post-impact environmental effects on the crater shape

It is necessary to take into account the factors of the post-impact environmental influences on the original crater shape, due to which the diagnosis of CRSs can involve difficulties. For example, the effect of erosion should be considered, which changes in varying degrees the proportions of the crater structural elements. In some cases, erosion destroys the filling of a crater funnel (“Chukcha” [1, 20]), reduces the height of the observed CIC (“Logancha” [1, 15]), significantly changes the shape of a crater as a result of non-uniformity erosion (“Ilyinets” [1, 6]), and sometimes deprives the crater isometric shape and other morphological attributes (“Vredefort” [1, 13]). However, as real data of many regions storing the original cosmogenic landscape have shown [1, 17] for the craters with diameters exceeding 1 km — due to their sufficient strength — erosion has significantly lesser destructive effects than subsequent cosmic impact events and tectonic movements. In particular, the collision of two tectonic plates: Hindustan and Asia, has formed a strong collision system: Himalayas–Altai–Sayan, where many ancient astroblemes can be “milled”. Therefore, for the diagnostics of an impact crater it is unavoidably necessary to consider the possibility of a crater shape modification under the influence of subsequent tectonic movements (“Sudbury” [1, 6]).

Let us consider an illustrative example of the possible influence of the regional tectonic activity on the impact craters morphology. Application of the described diagnostic techniques to recognize possible astroblemes “Madagascar 1–5” [1] detected as early as in 2006 by Matteo Chinellato (Tessera, Venetia, Italy) made it possible, in particular, to identify for the crater “Madagascar 1” ($L = 290$ km) not only the main morphological elements of an astrobleme, but its post-impact tectonic evolution (Figure 6).

With agreement of the coastal outlines (Figures 6, 7) it is possible to determine a probable location of the joint of the African plate and Madagascar (they were separated not earlier than 150 million years ago). Thus, the posi-

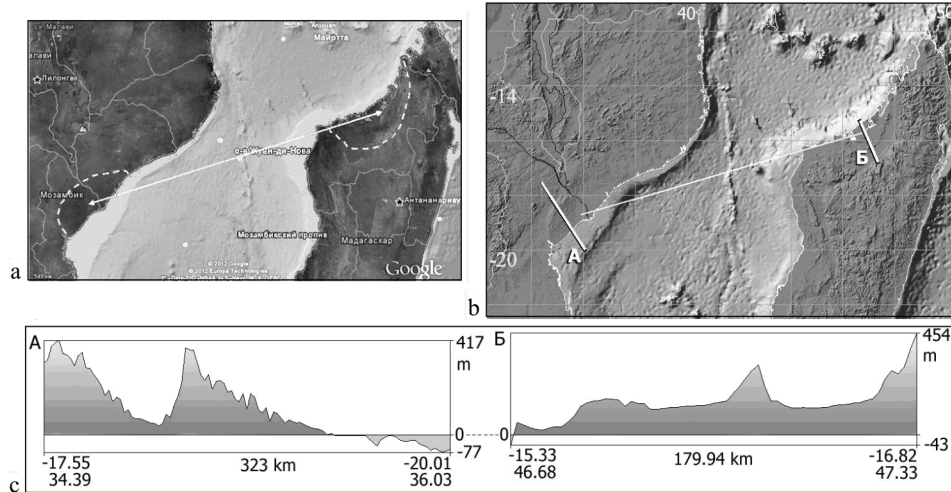


Figure 6. The contours of the crater “Madagascar-1”: a) the dotted line tracing the bank by means of Google Earth, b) the relief loop, manifesting in the digital relief model of GIS-EISC, c) sections of profiles A and B showing the entire-crater ring rise (in GIS-EISC)

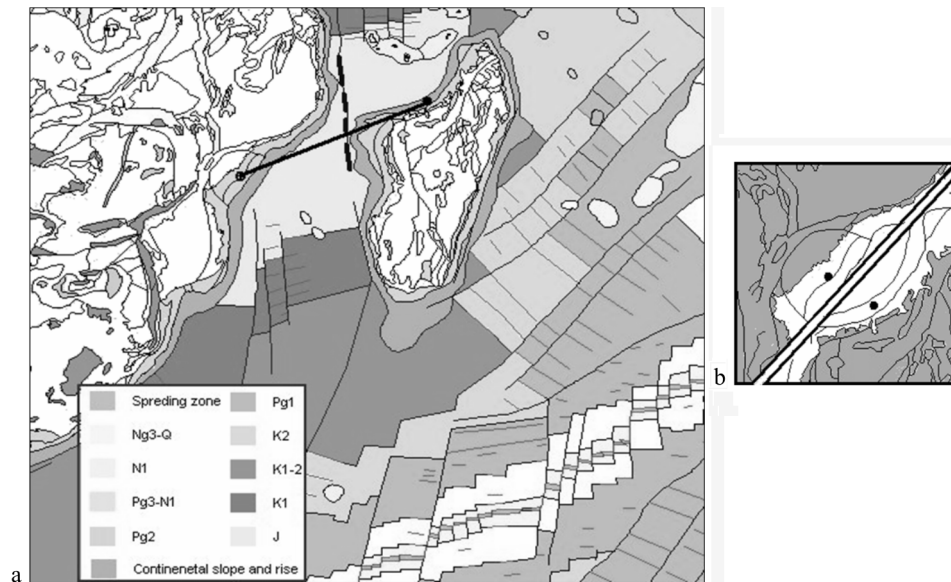


Figure 7. A map of linear magnetic anomalies [21] in the region of crater “Madagascar-1”: a) the line of extrapolating the shorelines; b) the result of extrapolation (black dots correspond to the ends of the segment)

tion on the African continent of the second-half of the crater “Madagascar-1” was detected.

As a result of decoding images from Google Earth, not only the “locking” coincidence (in full detail) of the crater parts described but also their consistency with each other in size and in a darker color of the hemispheres has been found. The line of the fault (the underwater relief line in Figure 6b; the dotted black line in Figure 7a) cracking the RS in half coincides with the direction of its major axis and, possibly, with a ballistic trajectory of CB falling (the direction of impact). A relative displacement of a half of the probable astrobleme belonging to Madagascar can be explained by a difference in the drift velocities of Madagascar and the African plate. The direction of the oceanic bottom displacement is read well in the map of linear magnetic anomalies, which relate to the nearest zone of the oceanic spreading (see Figure 7a).

Thus, using the technique described it appeared possible to recognize on the African tectonic plate the second part of giableme “Madagascar-1” [1] revealed earlier on the Madagascar Island. In this case, in addition to the main interpretive elements of RS decoding [22], there were revealed basic morphological elements of an impact structure: the negative form of relief, the crater bank (see Figure 6a) and the central ring rising (see Figure 6c).

5. Conclusion

The presence on the Earth (as compared with other planets) of the atmosphere and active geological processes contributes to the formation of a huge variety of impact structures both at the moment of an impact and in the process of their modifications in the post-impact period. These effects complicate the task of impact craters diagnostics from their morphology and make it necessary to develop the new approaches to their study, to refine the criteria and typical elements of astroblems, using the materials of remote sensing regions with a good undamaged state of craters on a relief.

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