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Impact Crater with Traces of Tectonic Deformation in the South Polar Region of the Moon

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Abstract—The work examines the structure of a crater with a diameter of 34 km, located on the mainland in the marginal zone of the south polar region of the Moon within the South Pole—Aitken impact basin. This crater belongs to the Dawes morphological type, which is characterized by a generally flattened, and in detail uneven, hilly-ridge bottom surface. The crater under study has a fractured bottom, which is considered a sign of magma intrusion into the subcrater space. Cracks in the bottom material are represented by hollows from 2 to 10 km long, 0.3—1 km wide and 50—150 m deep. The LROCNAC images show that in the hilly-ridge areas of the bottom the regolith surface has a “wrinkled” texture, and in the subhorizontal areas it is smooth. On one of the sections of the bottom there is a 700-meter crater, the rim of which touches one of the hollows. Judging by the morphology of this crater and the absence of meter-sized stones on its shaft, it was formed in the range of (200—300) million to 1 billion years ago, while the age of the studied 34-kilometer crater is estimated from the density of small craters superimposed on its rim as 3.83 (+0.025; –0.031) billion years. The age of the surface material of the deformed bottom of the crater under study is in the range of (200—300) million to 1 billion years. Probably, the fracturing of the bottom (formation of hollows) was caused by the penetration of an intrusive body or bodies into the subcrater space during the Copernican or early Eratosthenesian periods of the geological history of the Moon. The 34-kilometer crater in question certainly deserves further study.

Keywords: crater, fractured bottom, troughs, regolith texture, crater age, age of bottom material, magmatic activity

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INTRODUCTION

Space agencies of a number of countries are planning research in the southern polar region in the coming years, which is due to the presence of frozen volatiles in the regolith there (which is also typical for the northern polar region) and the fact that the rim of the South Pole—Aitken impact basin, the largest and the oldest known on the Moon, passes through there. On August 11, 2023, Roscosmos launched the *Luna-25* spacecraft, which was supposed to land in the vicinity of the South Pole and study the regolith and environment (Dyachkova et al., 2021; Mitrofanov et al., 2021). But on August 19 *Luna-25* switched to an off-design orbit and ceased to exist as a result of a collision with the surface of the Moon. This will probably somehow change our plans for studying the Moon. In the meantime, it is believed that in about five years, the *Luna-27* spacecraft will be launched, which should also land in the South Pole region and conduct more detailed research. And then the *Luna-28* spacecraft should deliver samples of polar regolith to Earth (Efanov and Dolgopolov, 2016). China is also planning to explore the South Pole of the Moon with missions *Chang’e-6*, *-7*, and *-8* (Xu et al., 2020). The American Artemis program is also partially aimed at this (NASA, 2020. https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf). In particular, at the end of 2024 it is planned to launch the lunar rover VIPER (Volatiles Investigating Polar Exploration Rover), which should search for ice, water, and other possible resources in the south polar region of the Moon (https://www.nasa.gov/viper/overview). The European Space Agency (ESA) is also exploring the possibility of research in the polar regions of the Moon (Carpenter and Fisackerly, 2017).

The south polar region is a continental area where the predominant landforms are impact craters. Among them, craters with cracks on the bottom are occasionally found. The same craters with cracks are found in other areas of the Moon, and the cracking of the bottom is considered to be caused by magmatic activity in the depths under this crater (see, for example, Schultz, 1976; Jozwiak et al., 2012). This combi-

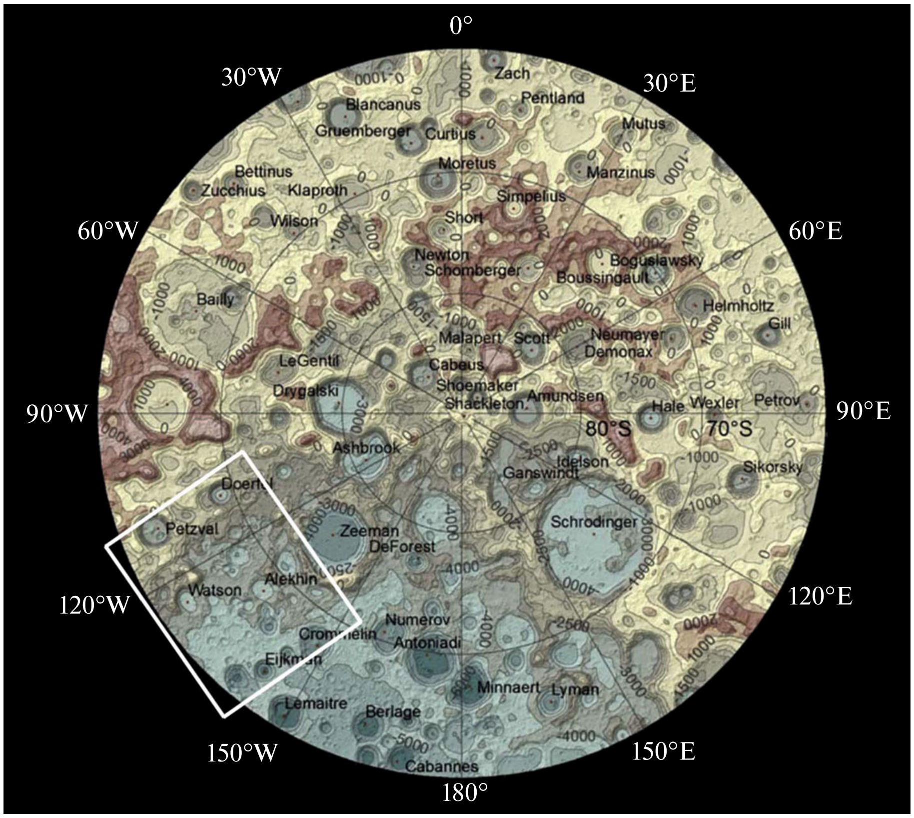

Fig. 1. Fragment of the hypsometric map of the south polar region of the Moon (Grishakina, 2014). The white rectangle shows the location of the surface area shown in Fig. 2.

nation of impact and magmatic processes is very interesting, and in this work we study one of these craters located in the south polar region. Coordinates of its center 126.59° W, 64.32° S and diameter 34 km. The location of this crater is shown in Figs. 1 and 2. The basis of our research is photogeological analysis of images obtained from the Wide Angle Camera (WAC) and Narrow Angle Camera (NAC) on the *Lunar Reconnaissance Orbiter* (NASA).

OBSERVATION RESULTS

General Description of the Studied Crater and its Surroundings

In the immediate vicinity of the crater under study, in addition to numerous craters with a diameter of up to several tens of kilometers, complicating the plains of the continental type, apparently similar to the plains are the landing sites of the *Apollo-16* spacecraft (Geology of the Apollo 16 Area, 1981), chains of secondary impact craters are visible, and on the bottoms of two craters (one of which is the one under study) there are troughs, apparently tension cracks (Fig. 3). It is important to note that chains of secondary craters are superimposed on the northern and southern parts of the rim of the crater under study, but they do not seem to continue on the crater floor (see also Figs. 4, 5).

In Fig. 4 it is clear that in plan the crater is somewhat elongated from west to east. In this direction its diameter is 36 km, and in the north–south direction it is 32 km. The average diameter of the crater is 34 km. The crater is also asymmetrical in the height of the shaft. The elevation of the western part of the rim above the bottom is about 1 km, and the eastern part is about 2 km. The surface of the crater bottom is uneven with low hills and hollows. According to the LOLA laser altimeter, its average altitude is approximately—4800 m from the average radius of the Moon, equal to 1737.4 km.

Below is a mosaic of NAC (Narrow Angle Camera) images of the crater under study (Fig. 5).

In Figs. 4 and 5 it can be seen that the main elements of the surface relief of the bottom of the crater under study (namely, its morphology is specific to this type of crater) are hills and hollows, sometimes ledges. This crater does not have a pronounced central hill. Hills, hollows and ledges are gently sloping with a slope steepness of no more than 10°–15°, in rare cases up to 20°, which do not produce shadows on the NAC images used for this mosaic. Shadows are visible only in a few craters with a diameter of 300–500 m or less. In a number of places, the inner slope of the crater under study turns into arcuate in plan (parallel to the outline of the crater rim) hollows 50–150 m deep from the average

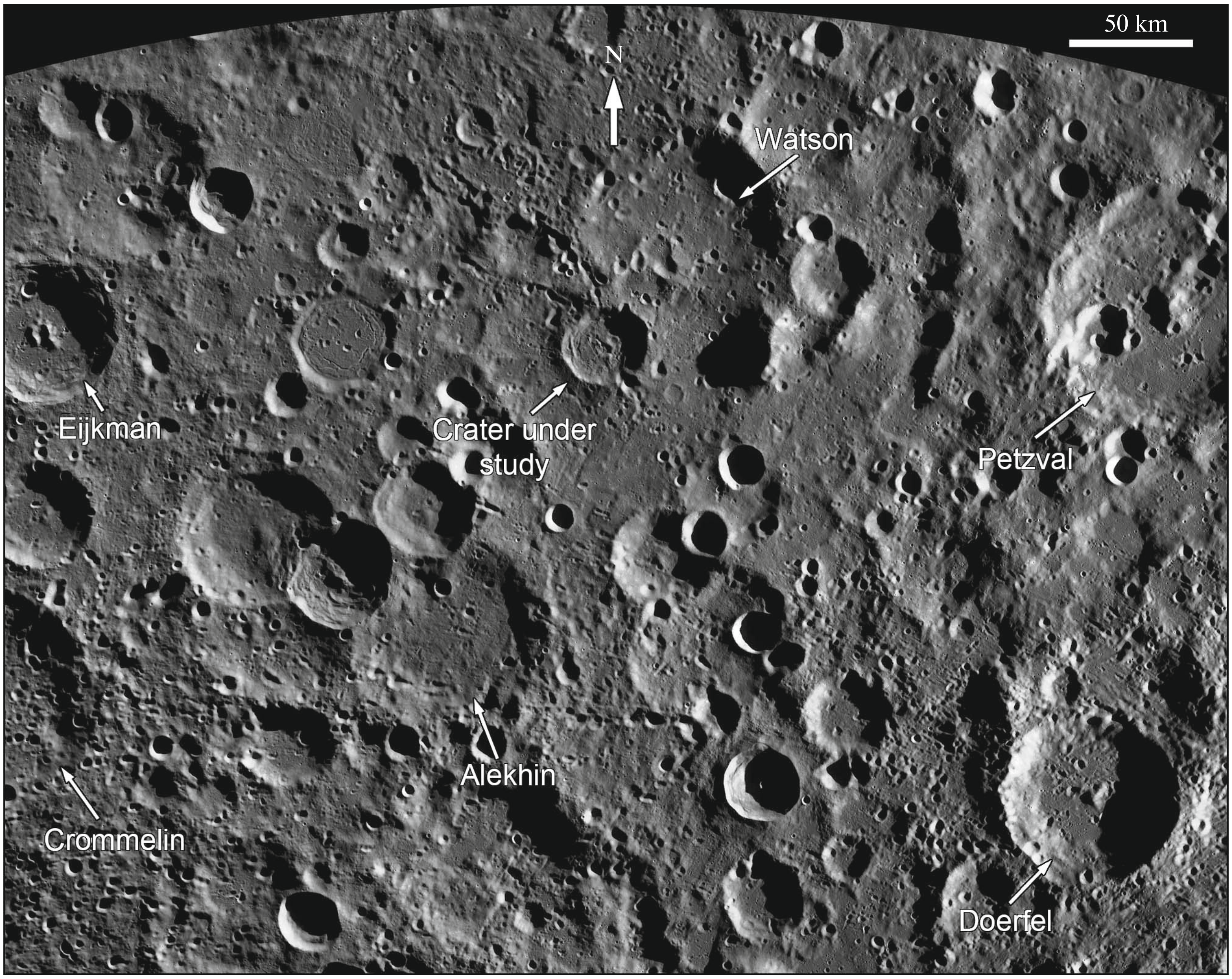

Fig. 2. The surroundings of the crater under study, location see in Fig. 1. Mosaic fragment WAC_GLOBAL_P900S0000_100M. Source: NASA.

level of the bottom surface. This feature of some craters with fractured bottoms was noted in the works mentioned above Schultz (1976) and Jozwiak et al. (2012): V-shaped moat, craters of their classes 4a, 4b and 4c.

There are more hollows on the bottom of the crater in its western part, but they also exist in the eastern part. They are from 2 to 10 km long, 0.3–1 km wide and 50–150 m deep. The arrangement of the hollows in plan is polygonal with arcuate elements. Bends are observed in the near-slope parts of the bottom in the north, south and southeast. Their length is 6–10 km and height 50–150 m.

Morphology of the Bottom Surface in LROC NAC Images

Below, we will consider the surface morphology in two sections of the bottom of the crater under study (Fig. 6a) using NAC images with a resolution of about 1 m, obtained at solar altitudes above the horizon of 14.3° and 24.1° (Figs. 6b, 6c). In the first section there is a branch of one of the hollows mentioned above and, accordingly, the surrounding area. In the second area there is another hollow, and in the area adjacent to it from the east there is a crater with a diameter of about 700 m.

In Fig. 6b it is clear that there are no sharp ledges at the edges of the hollows. The steepness of their internal slopes gradually increases from top to bottom and then decreases. In the lower part of the northern slope of the hollow, near its branch, a scattering of stone blocks several meters across is visible. Perhaps this is the result of excavation from craters with a diameter of 100–150 m located slightly higher up the slope. The texture of the regolith surface is “wrinkled.” This texture is characteristic of inclined surfaces and is formed due to the movement of regolith down the slope, provoked by nearby meteorite impacts and endogenous moonquakes (see, for example, Basilevsky et al., 2019, as well as images of NAC M113934743LC at the

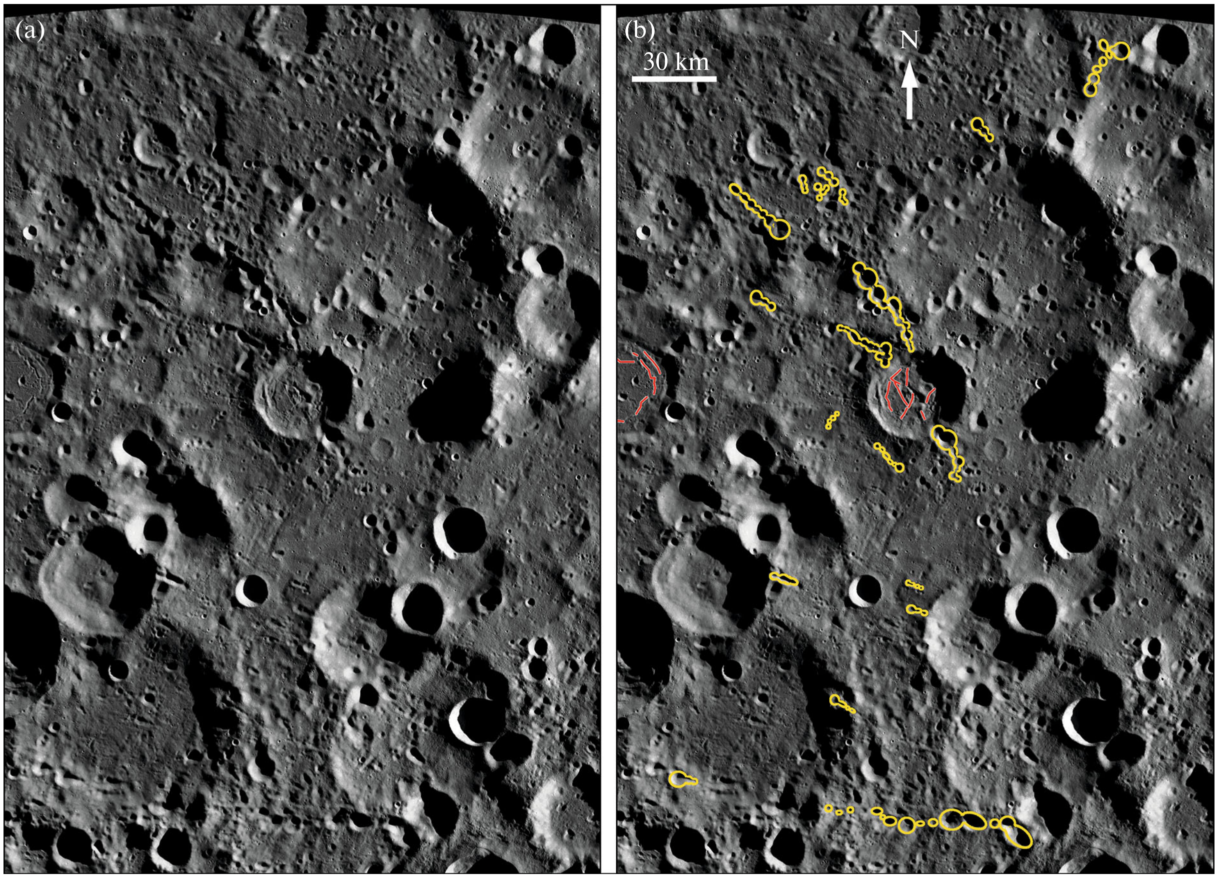

Fig. 3. The area of the crater being studied: (a) fragment of a mosaic of WAC images (NASA); (b) clusters of secondary craters (yellow) and troughs, probably tensile cracks (red) in the vicinity of the studied crater.

Apollo-15 landing site and M131447374LC at the *Apollo-17* landing site). Craters with a diameter from several meters to 100–150 m are also visible. But their spatial density is low, which is obviously due to their accelerated destruction during the movement of regolith down the slopes (see, for example, Bazilevsky and Popovich, 1976; Basilevsky, 1976).

In Fig. 6c you can see a hollow stretching from northwest to southeast. Same as on site *1*, there are no sharp ledges at the edges of the hollow. The steepness of their internal slopes gradually increases from top to bottom and then decreases. On the sides of the trough and in most of the area to the northeast of it, the surface texture of the regolith is "wrinkled." To the southwest of the depression the surface texture is relatively smooth. And the surface here is subhorizontal. Craters with a diameter ranging from a few meters to 150–250 m are visible everywhere.

There is a relatively large crater near the northeastern edge of the depression in this area. Its diameter is about 700 m. In the image obtained at a solar altitude of 14.3° The eastern part of the crater is shaded, i.e., the steepness of the upper part of its internal slope is more than 14.3°. The end of the shadow is located approximately at the center of the crater depression. It follows that the ratio of the depth of this crater to its diameter is approximately 0.25. Judging by the steepness of the inner slope of the crater in question, it belongs to morphological class B, but with an unusually large depth-to-diameter ratio. Judging by these characteristics, the absolute age of this crater is no more than 1 billion years (Basilevsky, 1976, 2015). Such a large crater at the time of formation must have penetrated to a depth of 150–200 m through the regolith layer into the rocky base. But there are no stones visible on its shaft. Obviously, they were destroyed while on the surface, under the influence of meteorite and micrometeorite impacts and daily fluctuations in surface temperature. Judging by the estimates of Basilevsky et al. (2013; 2015) and Li et al. (2018) the time required for the almost complete destruction of stones in the meter size range on the surface of the Moon is 200–300 million years. Thus, the absolute age of the discussed 700-meter crater is probably in the range of (200–300) million to 1 billion years.

The western part of the rim of this crater is in contact with the eastern edge of the hollow located here. The shaft seems to "open" into a hollow. This can be the case either if the crater formed earlier than the trough, or if the crater formed later than it. But in the

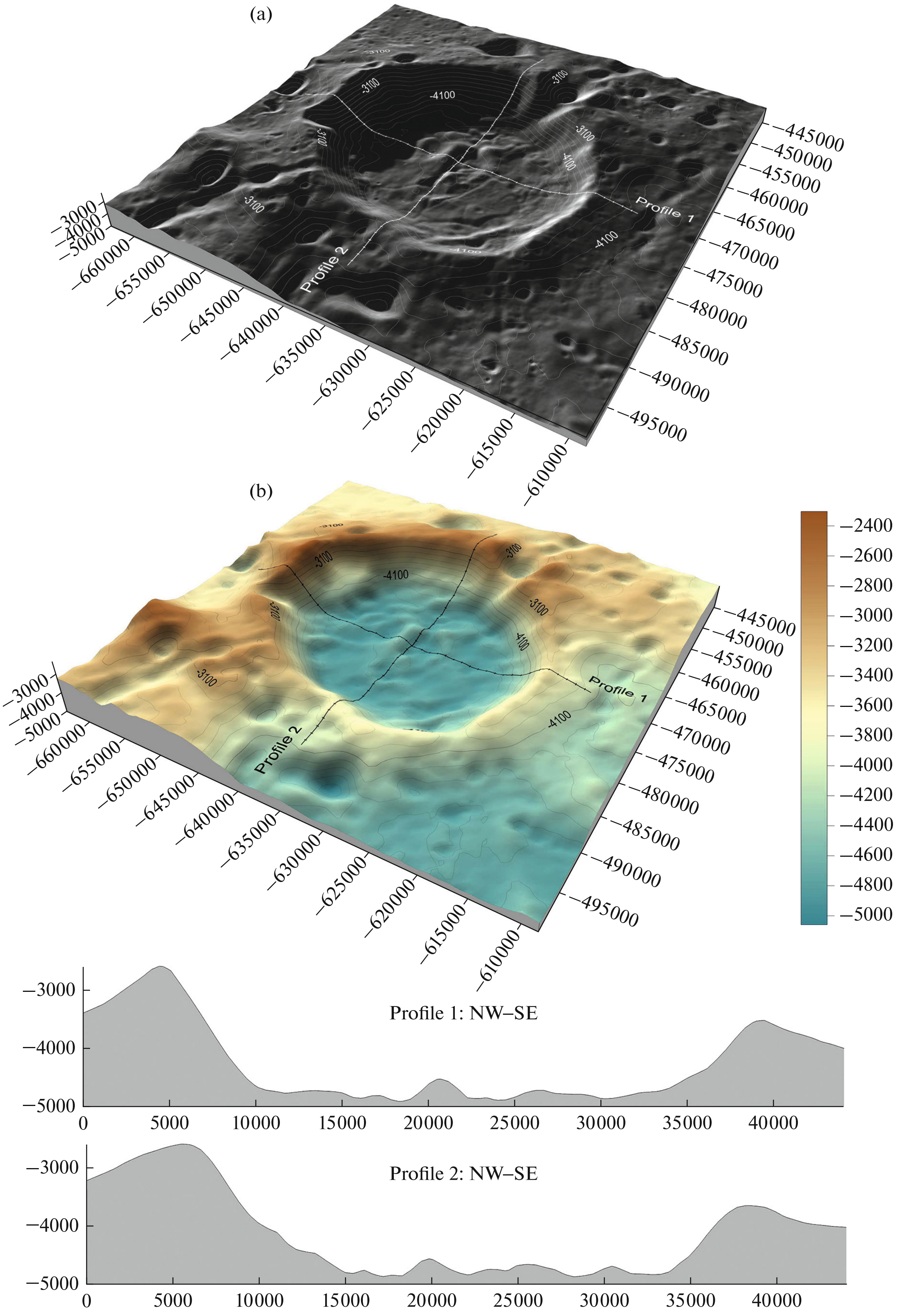

Fig. 4. Images of the crater being studied; (a) WAC image; (b) hypsometric map of this crater, compiled using LOLA laser altimeter data. Heights and distances in meters.

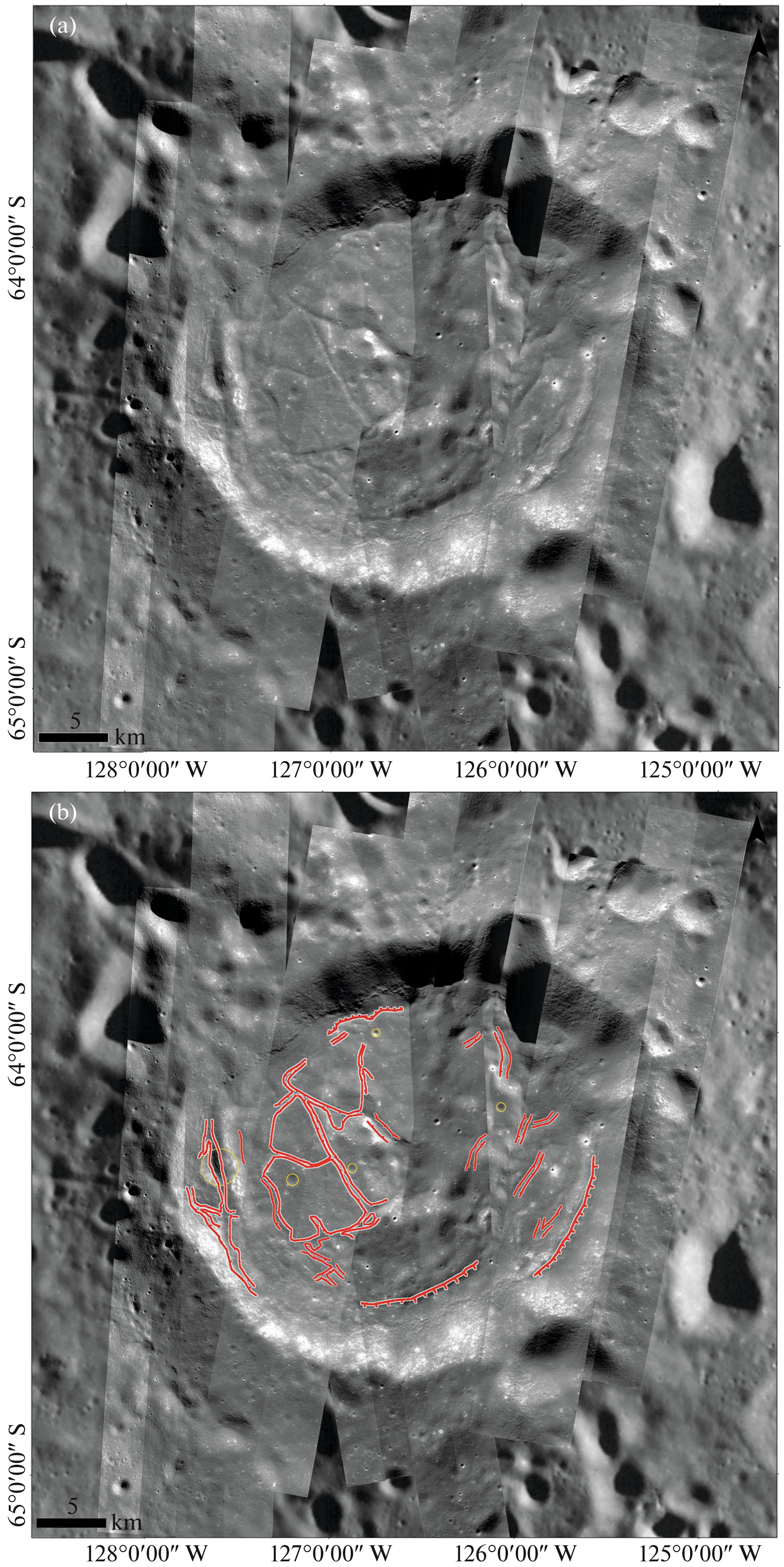

Fig. 5. Images of the crater being studied: (a) mosaic of NAC images of the studied crater; (b) the same with the hollows (cracks) shown in red lines.

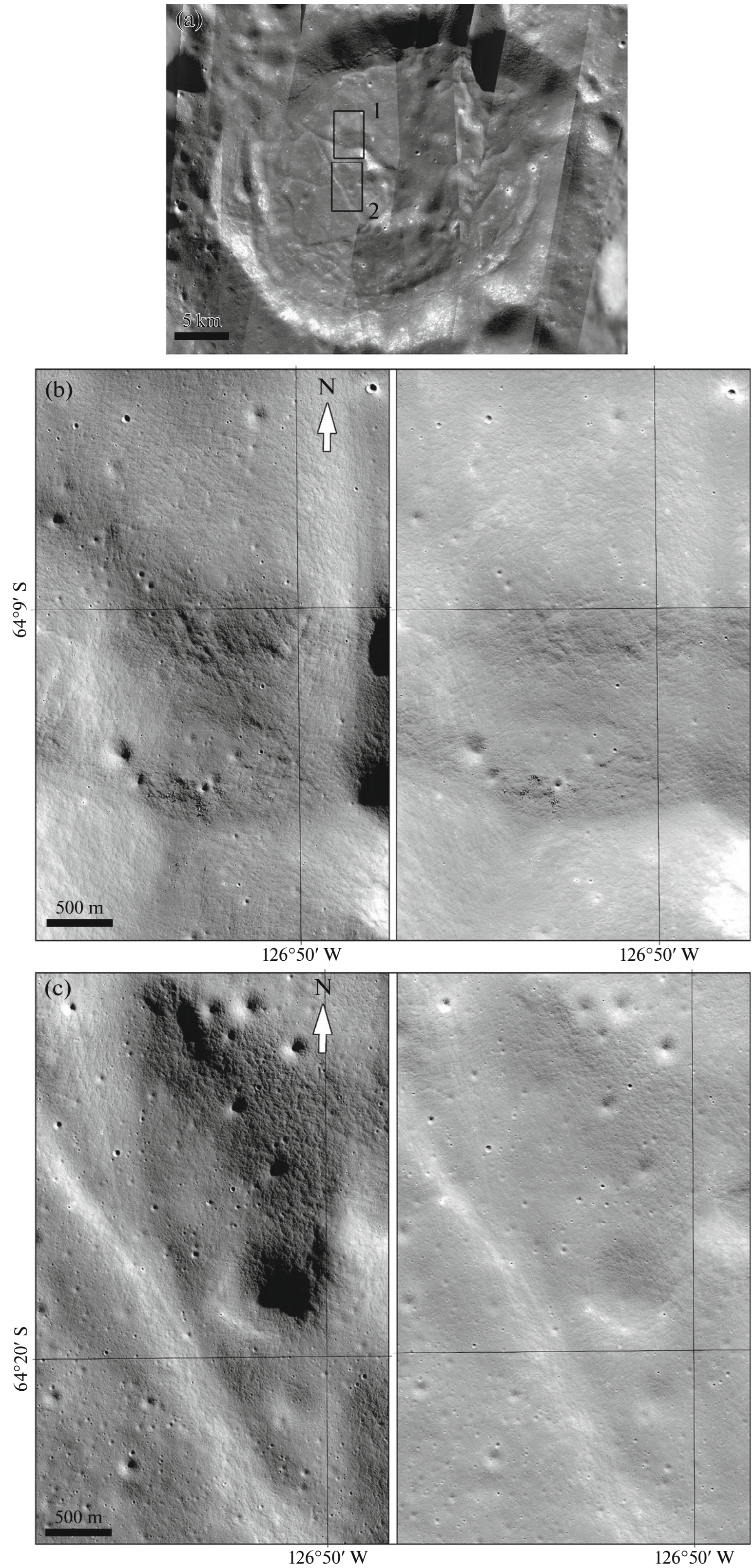

Fig. 6. Morphology of the bottom surface of the studied crater in LROC NAC images: (a) position of two sections (*1* and *2*) on the bottom of the crater under study, coordinates of the crater center 126.59° W, 64.32° S; (b) fragments of images NAC M1122039053LE and RE (left) and M135960042LE (right) with a resolution of 0.88 m and a height of the Sun above the horizon of 14.3° and 24.1°, respectively, for the area *1*; (c) fragments of images NAC M1122039053LE and RE (left) and M1359600424LE (right) with a resolution of 0.88 m and a solar height above the horizon of 14.3° and 24.1°, respectively, for the area *2*.

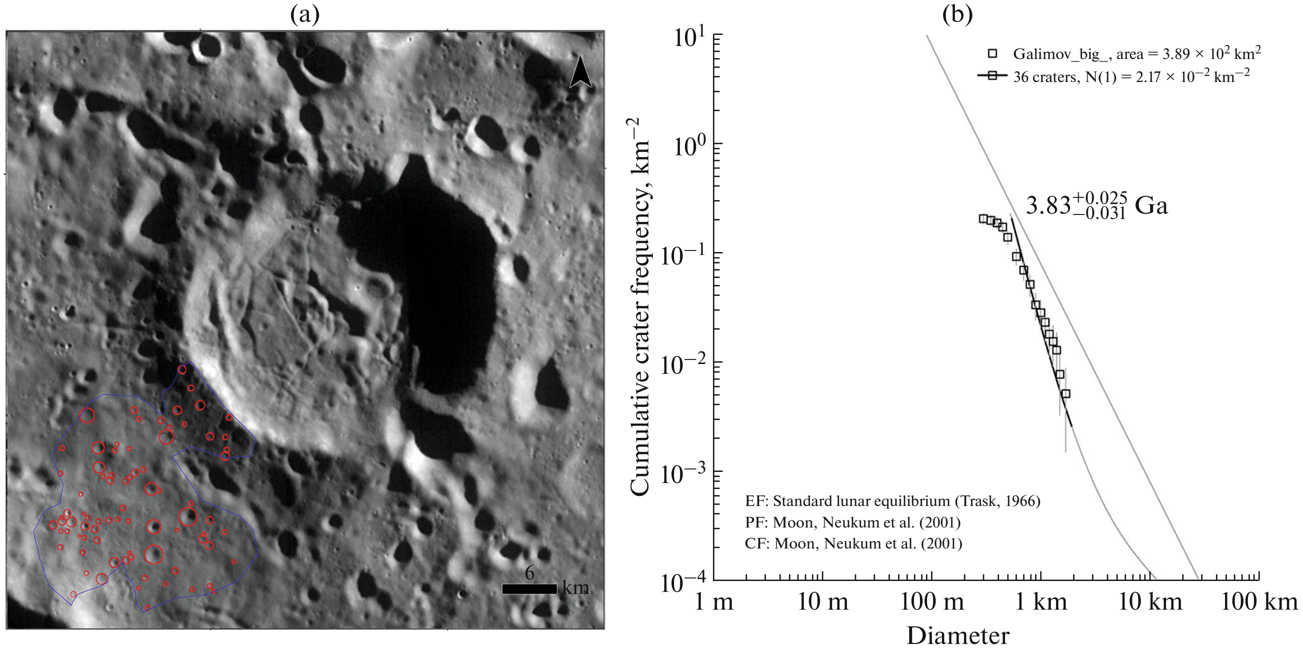

Fig. 7. Results of counting small craters on the outer slope of the crater under study: (a) crater counting area (red dots and circles); (b) graph of the spatial density of craters in this area.

second case, the material from the "open" part of the rim should have fallen into the hollow. In those shown in Fig. 6 in the images at the bottom of the hollow there is no "excess" material visible. Apparently, the hollow formed after the formation of the discussed 700-meter crater. And it follows that it was formed later than the age interval (200–300) million to 1 billion years.

Estimation of the Absolute Age of the Studied Crater and the Bottom Surface Material

To estimate the age of the crater under study, small craters on the outer slope of its rim were identified and counted. The counting area and the graph of the spatial density of small craters are shown in Fig. 7.

From the information presented in Fig. 7, it is clear that the studied crater was formed ~3.85 billion years ago, which is close to the beginning of the Imbrian period of the geological history of the Moon (Wilhelms, 1987). It should be noted, however, that in the vicinity of this crater and on its rim (see Figs. 3, 7a) there are many secondary craters and some of the small craters we used to estimate the age may be secondary. This means that our assessment may be overestimated to some extent.

To estimate the age of the material from the bottom of the crater under study using the topographic map shown in Fig. 4b, two sections with slopes less than 5° were identified on the bottom (Fig. 8a) and on them the identification and counting of craters with a diameter of more than 50 m were carried out. A graph of the spatial density of these small craters is shown in Fig. 8b.

As can be seen from Fig. 8b, the graph of the spatial density of small craters can correspond to two ages: ~1 and ~3.5 Ga. The first, perhaps, corresponds to the age of surface reworking during the penetration of magma under the crater and, accordingly, the formation of tensile cracks (hollows, see the previous section of the article). And the second is the age of the crater being studied (see also Fig. 7b). Probably, the intrusion of magma into the subcrater space occurred much later than the formation of the crater under study.

Information on Chemical and Mineralogical Composition

The crater under study is located on the bottom of the South Pole–Aitken basin, which is delineated using topographic data (Garrick-Bethell, Zuber, 2009). The basin floor is a large anomaly of elevated iron content in the regolith, established from gamma-ray survey data from the Lunar Prospector expedition (Lawrence et al., 2002). The nature of this anomaly has not yet been determined, although it has been suggested that it may reflect differentiation of the lunar crust in terms of iron prior to the impact event that formed the South Pole Basin–Aitken (Ivanov et al., 2018). The use of spectral optical methods, traditionally used to identify chemical and mineralogical variations in regolith (Pieters et al., 1994; Lucey, 2004; Moriarty and Pieters, 2018), until recently in high polar latitudes was significantly difficult due to inevi-

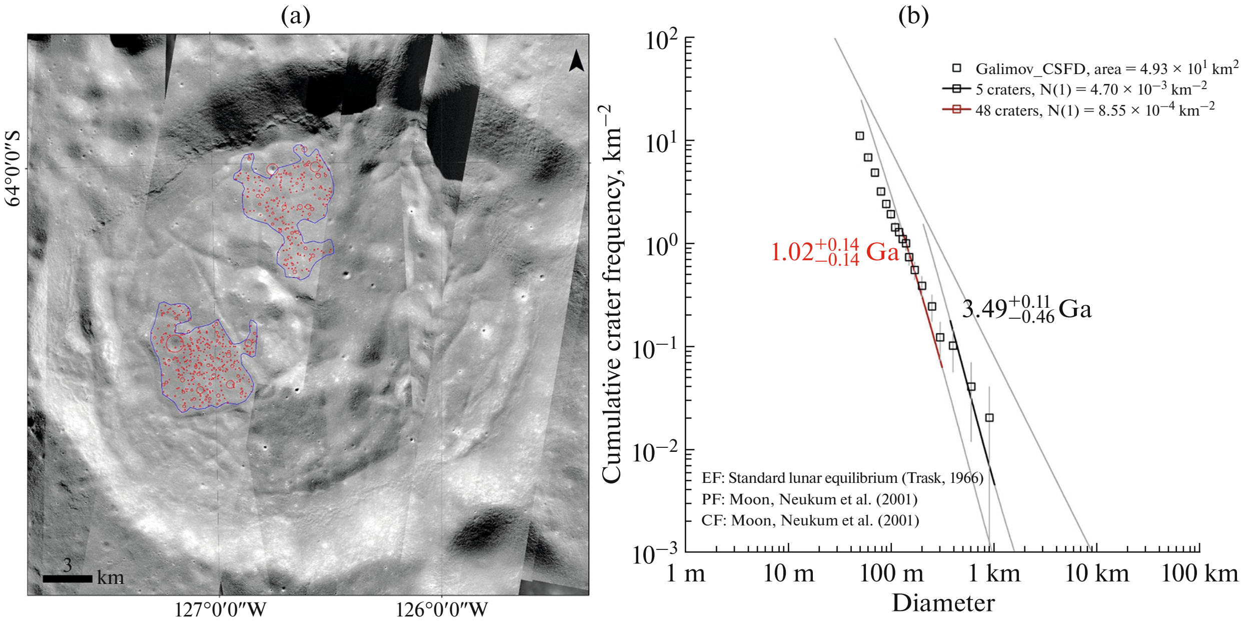

Fig. 8. Results of counting small craters on the bottom of the crater under study: (a) crater counting areas (red dots and circles); (b) graph of the spatial density of craters.

tably oblique illumination (large phase angle) and the predominant influence of the surface topography on the albedo value. A recently published work proposed a method for joint processing of optical and topographic data, which makes it possible to adequately assess a number of optical, chemical, and mineralogical properties of the surface, such as the optical maturity index of regolith, FeO content, plagioclase, pyroxenes (low- and high-calcium) and olivine (Lemelin et al., 2022).

Mineralogical maps published in (Lemelin et al., 2022) show that almost the entire floor of the South Pole basin—Aitken, which in the south polar region is characterized by increased contents of low-calcium pyroxene (at a level of more than 35–40 wt %) and relatively low contents of high-calcium pyroxene (at a level of less than 15 wt %). In this case, the increased contents of both pyroxenes exactly correspond to craters, the bottom of which is covered by volcanic (basaltic) material in areas outside the ridge of the SPA basin and in the eastern part of the basin floor. These same craters are characterized by increased concentrations of FeO in the regolith (at a level of 15–20 wt %). Thus, increased values of the content of these components indicate volcanic activity associated with the eruption of basaltic magma.

In the western part of the basin bottom, where the studied crater is located, there are no clear morphological signs of basaltic volcanism, and the contents of high-calcium pyroxene are characterized by a much lower contrast. Elevated contents of low-calcium pyroxene and FeO are associated mainly with two impact craters, Dawson (135.08° W., 67.01° S, diameter 45 km) and Eijkman D (136.94° W, 62.06° S, diameter 25 km). Both craters have a pronounced ridge, but the Dawson crater is devoid of ejecta, which is typical for craters of the Eratosthenesian period of the geological history of the Moon, and the Eijkman D crater is surrounded by a zone of continuous ejecta, which is characteristic of craters of the Copernican period (Wilhelms, 1987). The floors of both craters show no evidence of volcanic activity, which, combined with elevated pyroxene and FeO contents, means that these craters ejected basalt-like material during their formation from below the surface from a depth estimated to be 1/10 of the crater diameter (Melosh, 1989).

Such material could be a component of a cryptomare (an extensive lava plain completely covered by ejecta from later craters (Schultz and Spudis, 1979)), located at a significant (more than 1 km) depth. This hypothesis, however, can be rejected on the grounds that nearby craters with a diameter of 50 km or more are not characterized by anomalous values of pyroxene and iron contents. It is likely that the material ejected from the Dawson and Eijkman D craters is a component of a limited intrusive body rather than an extensive basaltic plain. Fractured bottoms of the studied crater, as well as an unnamed crater (134.03° W, 64.03° S, 40 km diameter) may thus provide further evidence for the existence of localized intrusive bodies (e.g., dike complexes) beneath the surface in the lunar south polar region.

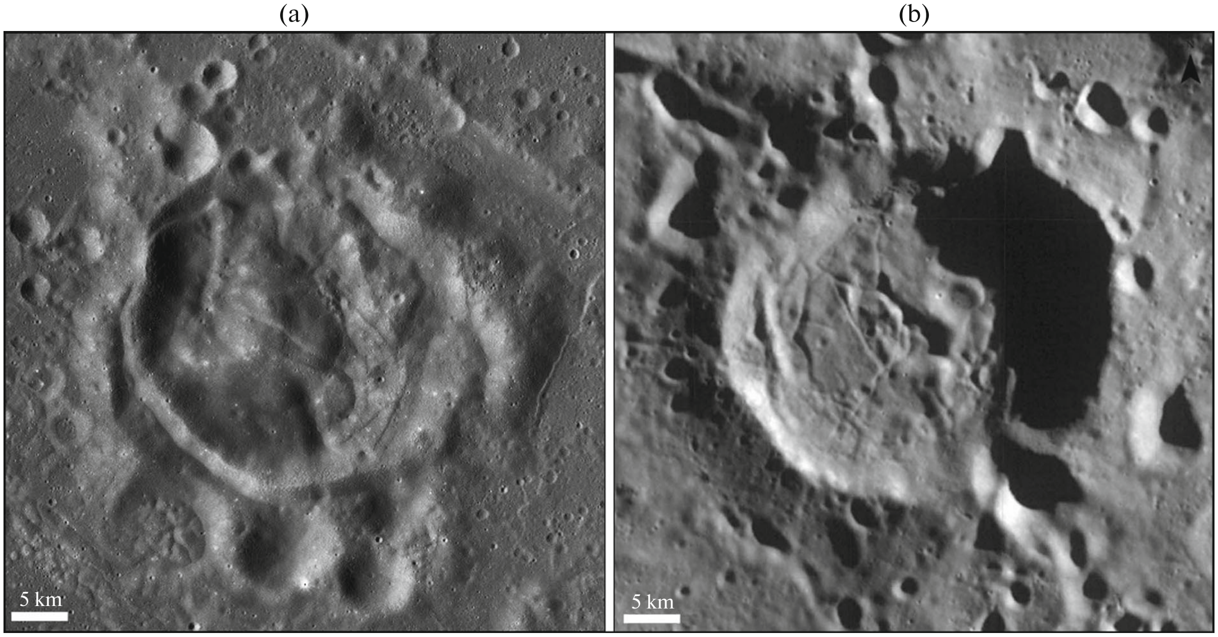

Fig. 9. Image of the Gaudibert craters and the crater under study: (a) Gaudibert crater, coordinates of the crater center 10.93° S, 37.82°; (b) crater under study, center coordinates 126.59° W, 64.32° S LROC WAC pictures.

DISCUSSION OF THE RESULTS

As follows from the above characteristics of the crater under study, it belongs to the morphological type of craters with a fractured bottom (see, for example, Schultz, 1976; Jozwiak et al., 2012). It is not among the craters of this type studied in the work Jozwiak et al. (2012). This is apparently due to the fact that at the time of this paper, imaging of the lunar surface with the WAC *Lunar Reconnaissance Orbiter* (Robinson et al., 2010) was still at an early stage and it may simply not have been included in the available surface images.

If we ignore the problem of fracturing at the bottom of the crater under study, it belongs to the Dawes morphological type. Craters of this type have a generally flattened, and in detail uneven, hilly-ridge surface, which has a characteristic “vortex” pattern in plan (Florensky et al., 1976; Bazilevsky et al., 1983). This type is typical for craters with a diameter of 15 to 30 km with small extensions beyond these limits. Smaller diameter craters are usually cup-shaped. Larger diameter craters have a central peak.

Among those studied, Jozwiak et al. (2012) there is at least one crater very similar to the one we studied. This is the Gaudibert crater, an impact crater 33 km in diameter on the northeastern border Seas of Nectar on visible side of the Moon (Fig. 9). The coordinates of the crater center are 10.93° S, 37.82° E; (Jozwiak et al., 2012) classify it as class 4b.

Craters of this class are characterized by a relatively shallow depth, measured from the crest of the ridge. In this case, the height of the ridge crest above the surface surrounding the crater is the same as in relatively young, unaltered craters of the corresponding size. In addition, between the foot of the inner slopes of these craters, on a significant part of the perimeter of the bottom, there is a V-shaped hollow. These structural features of such craters allowed Schultz (1976) and Jozwiak et al. (2012) to conclude that the fracturing (troughs) of the floor of these craters is caused by the emplacement of magmatic intrusion. Its upward pressure caused a “piston-like” rise of the material under the crater, which led to the raising of the bottom, its bending and the formation of tensile cracks. Probably, the fracturing of the bottom of the crater under study (the formation of hollows) could also be caused by the penetration of an intrusive body into the subcrater space. Judging by the above estimates of the time of formation of one of the troughs and estimates of the age of the material on the bottom surface, this probably occurred during the Copernican or early Eratosthenesian periods of the geological history of the Moon. Such young (by lunar standards) manifestations of magmatic activity had not been identified until recently. However, an analysis of modern images of the lunar surface obtained with the LROCWAC and NAC cameras has shown that manifestations of magmatic activity on the Moon may be very young, almost modern (see, for example, Braden et al., 2014).

The 34-kilometer crater in question certainly deserves further study. In particular, it will be interesting to see whether possible young magmatic activity has somehow affected the details of the mineral composition and the concentration of ice or chemically bound water in the regolith of the crater floor. We plan to appeal to the International Astronomical Union with a proposal to give this crater the name "Galimov," in honor of the late geochemist and planetary scientist, Academician Erik Mikhailovich Galimov, who for a long time was the director of the V.I. Vernadsky Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences. We are sure that there will be many publications on the crater in question and Galimov's name will be mentioned in them.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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