ISSN 0038-0946, Solar System Research, 2024, Vol. 58, No. 1, pp. 88–93. © Pleiades Publishing, Inc., 2024.

Analysis of Hydrogen Concentrations in a Tectonically Deformed Impact Crater in the Area of the South Pole of the Moon

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Received June 6, 2023; revised August 15, 2023; accepted September 2, 2023

Abstract—The article provides a description of the crater in the marginal zone of the southern polar region of the Moon with the coordinates of the center 126.59° W, 64.32° S The diameter of the crater is 34 km. It has a fractured bottom, which is considered a sign of magma intrusion into the subcrater space. The absolute age of formation of the crater under study was estimated to be ~3.85 billion years based on the spatial density of small craters superimposed on its rim. In the vicinity of the studied crater, low-iron anorthosite material is predominant. It can be argued that the basin of the crater under study is very dry compared to its surroundings. A significant loss of hydrogen/water and its redistribution from the bottom of the crater to the area around the crater could be caused by reworking of the surface due to the intrusion of magma under the crater, traces of which can be traced by the presence of cracks on the bottom of the crater.

Keywords: Moon, crater, fractured bottom, troughs, regolith texture, crater age, age of bottom material, magmatic activity, LEND, WEH, hydrogen, water

DOI: 10.1134/S003809462401009X

INTRODUCTION

Recently, the polar and subpolar regions of the Moon have attracted great interest from the scientific community, as there are local areas where volatile deposits, including water ice, could be preserved (see, for example, Pieters et al., 2009; Colaprete et al., 2010; Mitrofanov et al., 2010; Sanin et al., 2017). Only in 2023, two landing vehicles were launched, which, as planned, were supposed to land in the vicinity of the 70th parallel in the southern hemisphere of the Moon. Unfortunately, the Russian landing station *Luna-25* (planned landing site: 43.544° E, 69.545° S, Kazmerchuk et al., 2016; Mitrofanov et al., 2021) was lost as a result of a collision with the lunar surface. The Indian landing station *Chandrayaan-3* with a small rover Pragyan made a successful landing on August 23 at a point with coordinates 32.319° E, 69.373° S. (according to Indian Space Agency https://www.isro.gov.in/chandrayaan3_gallery.html).

It is believed that water ice may be present on the floor of permanently shadowed polar craters, where temperatures reach only a few tens of Kelvin (see, for example, Watson et al., 1961; Vasavada et al., 1999). Unfortunately, such craters are of little use and difficult to access for spacecraft landings. However, orbital studies aboard NASA's *Lunar Reconnaissance Orbiter* (*LRO*) have shown that elevated hydrogen levels are also found in illuminated areas where water ice may have persisted beneath an upper, dry, insulating layer of regolith (Mitrofanov et al., 2012; Sanin et al., 2017).

Thus, the study of any forms of lunar relief, including relatively small craters located in the circumpolar regions, is of interest from the point of view of the possible presence of volatile substances.

In the continental area in the marginal zone of the southern polar region of the Moon there is a crater with a diameter of 34 km with the coordinates of the center 126.59° W, 64.32° S. It has a fractured bottom, which is considered a sign of magma intrusion into the subcrater space (see, for example, Schultz, 1976; Jozwiak et al., 2012). Photogeological analysis of LROC WAC and NAC images showed that the crater formed ~3.85 billion years ago, and the fracturing of its bottom, indicating the intrusion of magma beneath it, arose in the interval (200–300) million to 1 billion years ago (Bazilevsky et al., 2024). The comparative proximity of this crater to the pole suggests that the regolith on its bottom may contain an admixture of ice H_2O and other volatile components. And this raises the question of how the accumulations of frozen volatiles in the regolith, typical of the polar regions of the Moon, could react with the effect of magma intrusion: 1) in no way, 2) not accumulate due to heating from below, or 3) vapors of magmatic volatiles could be an additional source for frozen regolith volatiles.

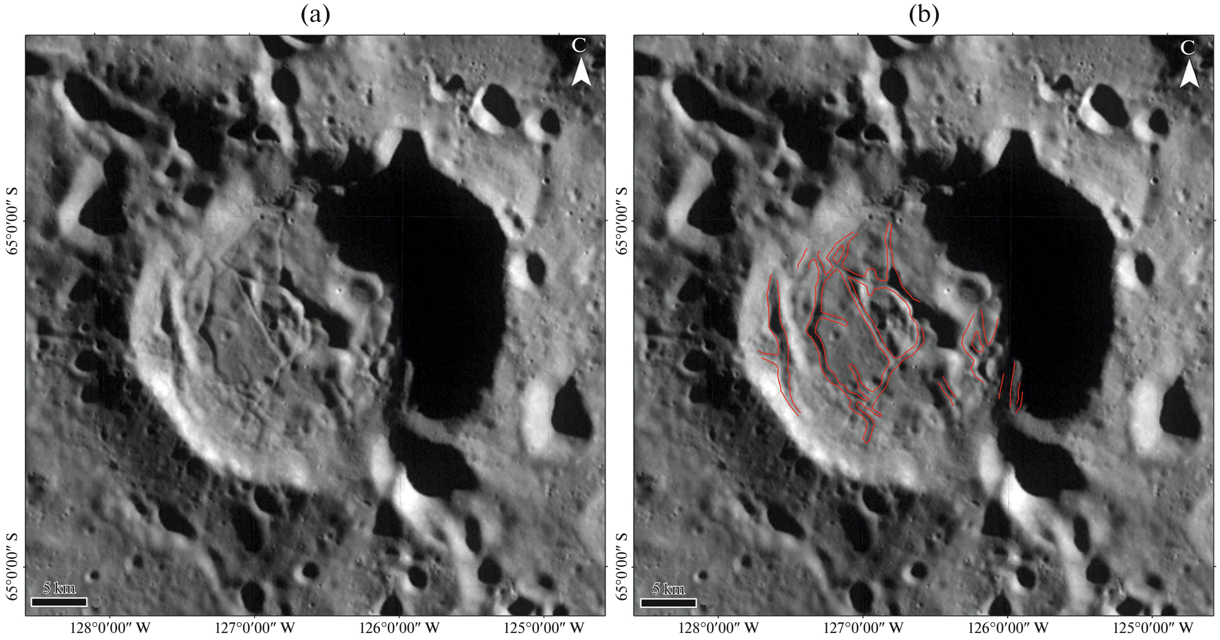

Fig. 1. Image of the crater being studied: (a) fragment of a mosaic of WAC images WAC_GLOBAL_P900S0000_100M; (b) the same with hollows (cracks) shown in double red lines at the bottom of the crater.

DESCRIPTION OF THE CRATER

The crater under study (Fig. 1) is located in a typical continental area, where the predominant landforms are impact craters with a diameter of tens of kilometers or more, superimposed on continental-type plains, apparently related to the plains of the landing site of the *Apollo-16* spacecraft (Hodges and Muehlberger, 1981).

In Fig. 1, it can be seen that the main elements of the surface relief of the bottom of the crater under study are hills and hollows, and sometimes ledges. They are gently sloping with a slope steepness of no more than 10° to 15°, in rare cases up to 20°. In a number of places, the inner slope of the studied crater turns into arcuate in plan (parallel to the outline of the crater rim) hollows with a depth of 50–150 m from the average level of the bottom surface (Bazilevsky et al., 2024). This feature of some craters with fractured bottoms was noted in the works mentioned above Schultz (1976) and Jozwiak et al. (2012). The hollows, which are a smoothed crack, are characterized by a length from 2 to 10 km, a width of 0.3–1 km and a depth of 50–150 m. The location 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.

The morphology of the crater floor was also studied using LROC NAC images with a resolution of about 1 m, obtained at solar altitudes above the horizon of 14.3° and 24.1°. These images show that there are no sharp ledges at the edges of the depressions. The steepness of their internal slopes gradually increases from top to bottom and then decreases.

At the edge of one of the troughs there is a crater with a diameter of 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 edge of the shadow is located approximately in the center of this crater. This means 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 this crater, it belongs to morphological class B, but with an unusually large depth-to-diameter ratio. According to these characteristics, the absolute age of this crater is no more than 1 billion years (Basilevsky, 1976; Bazilevsky, 2015). The crater with a diameter of 700 m at the time of formation must have penetrated through the regolith layer into the rock base. But there are no stones visible on its shaft. Apparently, they were destroyed under the influence of meteorite impacts and daily fluctuations in surface temperature. From estimations made by Basilevsky et al. (2013; 2015) and Li et al. (2018) it follows that the time required for the almost complete destruction of stones in the meter range of sizes on the surface of the Moon is 200–300 million years. Thus, the age of this 700-meter crater is probably in the range of (200–300) million–1 billion years (Bazilevsky et al., 2024).

The absolute age of formation of the 34-kilometer crater under study was estimated from the spatial density of small craters superimposed on its rim (Bazilevsky et al., 2024) and turned out to be ~3.85 billion

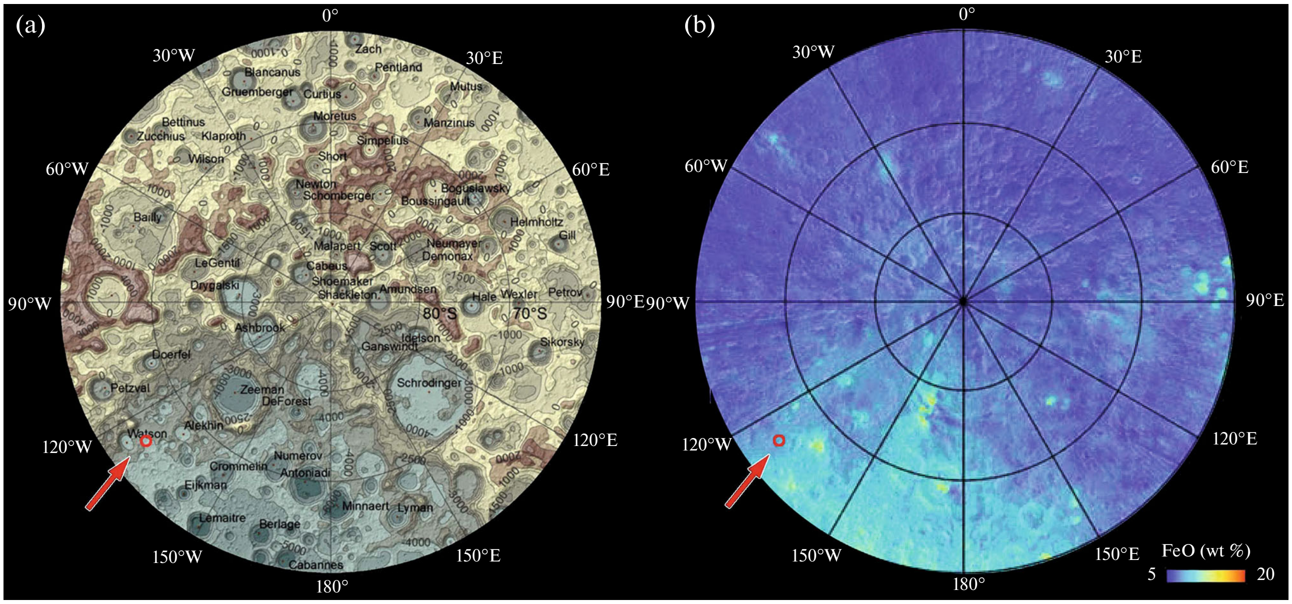

Fig. 2. Position of the crater being studied (red arrow and circle): (a) on the hypsometric map of the southern polar region of the Moon (Grishakina et al., 2014); (b) on the map of FeO content in the same area according to Lemelin et al. (2022).

years ago. It should be noted, however, that in the vicinity of the crater under study, including its rim, many secondary craters and some of the small craters used to estimate the age may be secondary. That is, the given estimate may be overestimated. Calculation of the spatial density of small craters on the bottom of the crater under study led to two estimates: ~1 Ga and ~3.5 Ga. The first, perhaps, corresponds to the age of surface reworking during the intrusion of magma under the crater and, accordingly, the age of formation of tensile cracks, which is consistent with the assessment given in the previous paragraph of this article. And the second corresponds to the age of the crater being studied. Obviously, the intrusion of magma into the subcrater space occurred much later than the formation of the crater under study (Bazilevsky et al., 2024).

The mineralogical and chemical composition of the surface of the south polar region, including the surrounding area of the study crater, has been reviewed by Lemelin et al. (2022) based on Kaguya Spectral Profiler measurements. In Fig. 2 a hypsometric map of the southern polar region is shown and the results of measurements of FeO in the surface material there.

This figure shows that in the vicinity of the studied crater, low-iron, apparently anorthositic, material is predominant. According to Taylor et al. (1991) pristine anorthosites of the Moon contain from 0.2 to 6% FeO (Table A6.11 in Taylor et al., 1991). Apparently, the crater under study was formed in an anorthosite target.

WEH DISTRIBUTION

Data on the distribution of hydrogen in the vicinity of the crater under study can be obtained from measurements of the Russian LEND instrument installed on board the NASA *LRO* spacecraft. Many years of continuous work in the lunar orbit, starting from 2009, made it possible to accumulate sufficient statistics and construct maps of the distribution of hydrogen in the near-surface lunar soil (to a depth of 1 m) not only in the polar, but also in the subpolar regions, and the collimating ability of the instrument is to distinguish a crater with characteristic size 30 km from its surroundings. Lunar water equivalent of hydrogen maps (denoted by WEH, a concept in which all detected hydrogen is attributed to water equivalent) with high spatial resolution were presented in Sanin et al., (2017), where it was shown that a number of local areas in and around the permanently shadowed lunar craters can contain on average up to 0.5% water ice by mass fraction. When testing the hypothesis of a two-layer soil structure, when a dry upper layer with a thickness of several tens of cm to 1 m covers a water-containing layer, numerical estimates showed that the water ice content can reach up to several percent in mass fraction.

In this work, we used the WEH content estimation algorithm proposed by Sanin et al. (2017) and constructed a map of WEH distribution in the vicinity of the crater under study, which is shown in Fig. 3. The map clearly shows that the WEH value varies from several tens of ppm (parts per million) to 250 ppm.

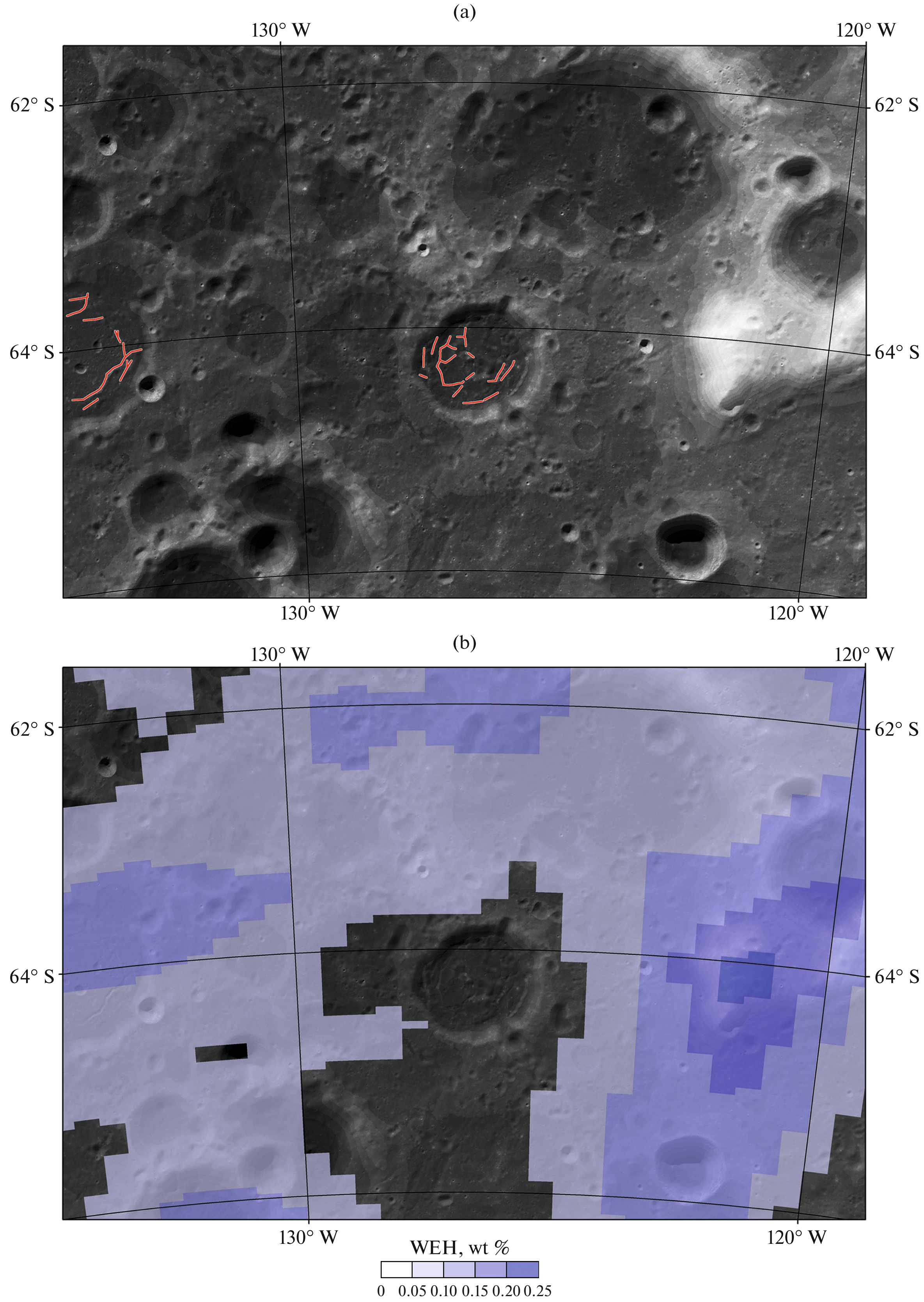

Fig. 3. The surroundings of the studied crater: (a) LROCWAC image; red lines are cracks/hollows on the bottom of the studied crater (in the center of the image) and on the bottom of another crater located 70 km to the west of the studied one; (b) concentration of water equivalent of hydrogen (WEH), at concentrations <0.05% there is no blue fill and the LROCWAC image is visible.

DISCUSSION OF RESULTS AND CONCLUSION

The greatest interest in the result is the fact that with high statistical significance it can be stated that the basin of the crater under study is very dry compared to its surroundings (Fig. 3). This ratio is not unique. So in the work of Starr et al. (2018) examined 300 craters with a diameter of 30–100 km located in middle and high latitudes. Analysis of the epithermal neutron count rate measured by the LEND instrument showed lower hydrogen content in the interior of the craters compared to typical values in the outer vicinity of the crater at a given latitude. It was shown that the count rate of epithermal neutrons in the inner part of the crater, on average, increases by 0.1 counts/s, and the significance of this effect is ~9σ. Lawrence et al. (2015), comparing the epithermal neutron count rate data (LPNS instrument on board the *Lunar Prospector* spacecraft) and the albedo values of the lunar surface in the near-infrared range of 750 nm according to the Clementine spacecraft showed that there is a connection between the presence of hydrogen in the lunar regolith at moderate latitudes and parameters maturity of lunar regolith. More “fresh” and unprocessed lunar regolith is less saturated with hydrogen/water molecules, which are formed when the lunar surface is irradiated by protons of the solar wind (so-called solar water). In turn, Starr et al. (2018) also investigated the correlation between neutron count rate and surface maturity. It has been shown that a subset of 30 craters exhibiting the highest epithermal neutron flux values exhibit very high values of the OMAT parameter (a combination of surface albedo in the 750-nm and 950-nm ranges (Lucey et al., 2000)), which characterizes the degree of surface maturity. In this case, high values of the OMAT parameter correspond to the youngest and most immature craters.

The age of the crater under study, according to various estimates (see the previous section of the article), ranges from 3.5 to 3.85 billion years, and the age of reworking of its bottom ranges from hundreds of millions to 1 billion years. This does not allow it to be distinguished by optical maturity parameters, which work for a surface whose age does not exceed several hundred million years and are poorly distinguished for a surface whose age is up to 1 billion years (Lucey et al., 2000). It can, however, be assumed that the solar water accumulated in this rather old crater could experience significant variations on the time scale and one of the important factors here is the reworking of the surface due to the intrusion of magma under the crater, traces of which can be traced by the presence of cracks on the bottom of the crater. This could lead to a significant loss of hydrogen/water and its redistribution from the crater floor to the area around the crater.

ACKNOWLEDGMENTS

The authors are grateful to S.S. Krasilnikov and M.A. Ivanov for assistance in this work.

FUNDING

The work on assessing the concentration of water/hydrogen was carried out within the framework of the state assignment of the Ministry of Science and Higher Education of the Russian Federation, Topic DEVELOPMENT, No. 122042500014-1 (for A. B. Sanin, I. G. Mitrofanova, M. L. Litvak and M. V. Dyachkova).

The work was financially supported by the Russian Science Foundation grant No. 21-17-00035: Estimation of the rate of exogenous renewal of the lunar surface (for A.T. Bazilevsky)

CONFLICT OF INTEREST

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

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