15th World Congress on Computational Mechanics (WCCM-XV)
8th Asian Pacific Congress on Computational Mechanics (APCOM-VIII)
Virtual Congress: 31 July – 5 August 2022
S. Koshizuka (Ed.)

Estimation of the state of matter in young impact craters on the Moon based on the orbital observations

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Key Words: *Lunar matter, Impact craters, Orbital observations, State of matter, Assessment of state, Crater structure, Forthcoming expeditions, Applied and fundamental aspects*

Abstract. *The report examines the results of a 3D-survey of the relief in young impact craters based on high-resolution images obtained from lunar orbits. The craters examined included: the Tsiolkovsky and Aitken craters on the far side of the Moon, the Ticho and Ina craters of the visible hemisphere, as well as the Orientale Mare in the marginal zone of the Moon. To build 3D-models, orbital images of the Soviet spacecraft"Zond-6,-8" and the American spacecraft "Apollo-17" delivered to Earth, as well as images transmitted to Earth from the Lunar Reconnaissance Orbiter (LRO) were used.*

1 INTRODUCTION

More than 400 years ago, the Italian scientist Galileo Galilei discovered the amazing world of lunar craters. And only 40-50 years ago, researchers began to understand that lunar craters are nothing more than traces of comets and asteroids falling on the surface of our neighbour in space.

A big role in understanding the origin of lunar craters belongs to space research. It was the first flights to the Moon by Soviet and American satellites in the 50s and 60s of the 20th century that provoked a powerful impetus in the study of the nature of craters, and the adjective "impact" was added to the term "craters".

If in the pre-space era the Moon and its craters attracted mainly the attention of astronomers, now we see what interest geologists, physicists, planetary scientists and even designers and builders show in studying lunar craters. Now it is no longer a "lunar race" of the two leading space powers, but rather a kind of "international competition", in which other countries are also becoming participants. This is primarily Japan with its outstanding lunar space project "SELENE". These are China with a whole series of spacecraft "Chan'e", India with its lunar project "Chandrayaan", as well as the European Space Agency.

2 CRATERS SELECTION

Among tens of thousands of lunar craters, young impact craters are of particular interest. The reason for this interest is quite simple and consists in the fact that fresh falls of the impactors form craters, the relief of which has not yet been distorted by later falls and contains information about the process of crater formation itself. The leading role here belongs to orbital observations, especially high-resolution observations, which reveal details of the structure of craters inaccessible to ground observations.

When it comes to young impact craters, it should be borne in mind that determining the age of a crater is a very difficult task. So, for example, the authors of the work [1] they believe that it is necessary to distinguish between the age of the Moon and the age of craters and even introduce the concept of "surface age". If the age of the Moon is estimated in modern planetology at 4.5 ÷ 4.0 billion years, then the surface of the Moon is much younger, since it is formed by periodic bombardments by high-speed impactors. At the same time, the leading role is played by the bombardment of galactic comets, the intensity and energy of which is thousands of times higher than these indicators for comets and asteroids of the Solar System [2].

Periods of galactic comets falling on the Moon and planets of the Solar System are associated with the nature of the movement of the Sun in our Galaxy and the time intervals when the Sun, together with the planets, crosses the arms of the Galaxy and the jet streams emanating from its center. In accordance with theoretical models and the Barenbaum's paradigm [2,3,4], within which the most accurate and presentable observations and calculations were carried out, galactic comets bombard the Solar System, including the Moon, Earth and other planets, exclusively during periods when the Sun crosses the spiral arms and jet streams of the Galaxy. The last comet bombardment caused by the Sun hitting the Orion-Cygnus jet stream took place from 5 to ≈0.7 Ma [5]. It was during this period that, under the influence of comet falls, a powerful rise of the surface of the continents occurred on Earth, which was called the "newest uplifts of the Earth's crust" [6], and its largest impact structures "South Pole – Aitken" (SPA) and the Orientale Mare were formed on the atmosphere-free Moon. These two unique objects were named "impact multi-ring pools".

For our research, we selected impact craters of the visible and far hemispheres located on the territory covered by emissions of substances from the SPA basin. These are the craters Aitken (17S, 173E, D=130 км), Tsiolkovsky (19S, 129W, D=180 км), Ticho (43S, 11W, D=85 км), as well as the small crater Byrgius A (23S, 63W, D=19 км). The Byrgius A crater is located on the ejections of material from the basin of the Mare Orientale. Since the Orientale basin itself lies on the emissions from the SPA, it should be assumed that the Byrgius A crater is the youngest of the four named. With this choice of craters, we can safely say that they are all younger than the SPA basin. Consequently, these craters appeared on the Moon recently, or rather in the range from 5 to ≈0.7 million years ago.

3 INITIAL DATA, ALGORITHMS AND RESULTS

We used orbital images of the spacecraft “Zond-6,-8”, “Apollo-15, -17” and LRO mission data to survey the relief of the selected craters. The main task was to look at the structure of the craters from different sides, at different scales, from different angles. This approach, combined with single orbital images, allows you to better examine the details of their structure, and sometimes find such relief features that are not visible in single images or are not clearly visible. To solve this problem, we built 3D-models of the named craters [7, 8, 9, 10]. The models were created at the photogrammetric stations of the Laboratory of “Remote Sensing and Photogrammetry” of the Department of Astronomy and Space Geodesy of the Institute of Physics of KFU using the software of the Russian company Geoscan [11].

The main results concern the study of the central peaks, the crater floor, as well as the surface of the outer and inner slopes of the crater wall.

For example, “glaciers-like tongues” were found in the Aitken and Tsiolkovsky craters, flowing down from the slopes of the central peak (see Figures N1, N2). We interpreted these languages by the presence of ice frozen into the lunar soil, from which the languages are composed. When they are heated, the material becomes viscous and begins to move.

What caused the heating of the substance and what caused the movement of tongues are questions that require additional research. This may be the heating of the slopes by the Sun during the lunar day. Shock-wave effects caused by falling bodies near the central peaks of these two craters are also not excluded. The reason may also be due to the state of the substance of the central peak, the mechanism of formation of which differs significantly from the mechanism of formation of the crater wall [12, 13].

As for the Tycho crater, the melt of the lunar substance of the outer slope of the crater wall is so fresh that the melt of the lunar soil, spreading out, forms whole rivers and lakes [14]. The melt is so fresh that the fall of meteorites on its surface does not form craters, since impactors simply drown in still-cold lakes of melt. See Figure 3.

The greatest impression is made by the state of matter in the Byrgius A crater [10]. Here, streams of soil heated by the Sun on the southern slope of the crater wall drain to the floor of the crater, gradually covering its central peak. And numerous lunar boulders lying at the crater floor will soon, apparently, drown in the streams flowing down from the slope. At the same time, the central peak of the crater, if the dynamics of the movement of matter in the southern part of the inner slope does not undergo significant changes, will be completely flooded. Thus, the Byrgius A crater is transformed in its evolution from the category of complex craters (with a central peak) to simple ones (craters without central peak). This means that the formation of the Byrgius A crater is happening right before our eyes.

4 THE DISCOVERY OF THE "SOUTH-WESTERN" LOWLAND AND ITS ROLE IN SOLVING THE AGE-OLD PROBLEM OF ASYMMETRY OF THE VISIBLE AND FAR SIDE OF THE MOON

The first photos of the far side taken from the board of a Soviet satellite in 1959 showed that the territory of the Moon, invisible from Earth, differs significantly from the visible one. If from Earth we see seas, lakes and mountainous territories on the Moon, there is even an Oceanus Procellarum (!), then its entire reverse side is covered with mountains and craters. Subsequent spacecraft flights to the USSR and the USA also did not find seas similar to the sea territories of the visible hemisphere on its reverse side. This was shown by the Soviet automatic station “Zond-3” (1965), as well as a series of American satellites “Lunar Orbiter” (1966-1967). This situation continued until the launch of a series of Soviet unmanned spacecraft (SC) "Zond-6,-8" in 1968 and 1970. A photo-television imaging system was installed on board the Probe-3 and the Lunar Orbiter satellites, the materials of which are not designed for accurate photogrammetric processing. The exact metric camera was installed for was developed by Professor Boris Nikolaevich Rodionov of the MIIGAiK. The task of the scientific program was to study the relief of the back side of the Moon. To solve this problem, a long-focus calibrated camera was installed on board the Probe-6 spacecraft, and shooting from lunar orbit was performed on photographic film for the first time. At the same time, the cassette with the film exposed on board the SC was delivered to Earth in a special descent vehicle. Thus, the images of another celestial body taken by a photogrammetric camera from a close distance were delivered to Earth for the first time in world practice. The geometric shooting conditions were planned so that almost the entire western hemisphere of the Moon came into the camera's field of view, and its reverse side was captured in sections perpendicular to those visible from Earth. It was this seemingly simple idea to shoot the Moon “from the side” that played a decisive role in the study of the relief of the far side of the Moon. In the images delivered to Earth, Professor B.N.Rodionov and his colleagues discovered a large, previously unknown lowland on the far side of the Moon, which they called the “South-Western Lowland” [14, 15]. In terms of its size, it turned out to be comparable to some seas of the visible hemisphere.

The descent vehicle of the “Zond-6” mission performed a landing in an emergency mode, and the photographic film was partially damaged. This circumstance caused certain doubts about the reliability of the result. Moreover, by this time, the idea that the reverse side is a continental surface devoid of seas had become established among lunar specialists. Two years later, in October 1970, “Zond-8" mission repeated the flight of the “Zond-6” spacecraft and once again photographed the far side of the Moon “in profile”. This time the film was delivered to Earth in perfect condition, and accurate photogrammetric measurements fully confirmed the presence of a vast deep lowland on the far side of the Moon [16]. In 1971, the laser altimeter of the “Apollo-15” spacecraft recorded the presence of a vast lowland on the far side of the moon. As the analysis that followed these new measurements showed, the “Apollo-15” spacecraft passed over the northern part of the South-Western lowland from west to east, confirming the discovery of the Soviet “Zond-6,-8” spacecrafts.

From that moment, geologists and planetary scientists in the USSR and the USA joined the research of the discovered lowland. As a result of a thorough analysis of ground-based and orbital observations, experts came to the conclusion that the vast deep lowland discovered in 1968 in the southwestern part of the reverse hemisphere is the central part of a large multi-ring basin. The size of the basin turned out to be such that its territory covers most of the far side of the Moon, while there is a large crater Aitken on the northern edge of the lowland, and the opposite southern edge enters the circumpolar region. Due to this selenography location, the basin was named “South Pole – Aitken” (SPA). It should be noted that the name SPA is an unofficial working name of the basin. As well as the name “South-Western lowland”, which also did not receive an officially approved status.

Scientists and specialists show undisguised interest in the SPA pool. Orbital observations of this region were carried out with the Galileo station (1989-2003), Clementine (1994), Lunar Prospector (1998-1999), SELENE (2007), GRAIL (2011-2012), Chane-4 (2019-2020), LRO (2009-2022). Therefore, it is no coincidence that the SPA basin was chosen as the landing site of the world's first expedition to the far side of the Moon [17]. As a result of many years of comprehensive research, a geological map of the Moon was built [18], which reflects in detail the structure of the SPA basin. This map shows the territories of the Moon covered by emissions of material from the SPA basin. These territories occupy almost most of the far hemisphere and a significant part of the visible hemisphere in its southern half. Given the age of the SPA basin, it is logical to believe that after its formation from 5 to 1 million years ago, there was not a single crater-forming event comparable to it on the Moon. The only impact basin formed after the SPA is the basin of the Mare Orientale. From this point of view, the uneven coverage of the lunar territory by marine areas seems quite natural. We see seas on the

Visible side of the Moon that are not affected by emissions from the SPA basin, whereas the seas of the far hemisphere (if they existed before the SPA basin) are hidden by the material of emissions from the SPA basin. Then the problem of asymmetry of the visible and Far side of the Moon finds a simple and natural explanation.

5 CONCLUSIONS

- An important role in evaluation the state of matter in lunar craters is played by the idea of the age of lunar craters. Young impact craters attract the most attention, since it is in these craters that well-preserved relief forms are observed untouched by later falls.
- The age of lunar craters is much younger than the Moon itself for the reason that crater formation is a continuous, constant process of interaction of comets, asteroids and meteorites with the lunar surface. Therefore, it is necessary to distinguish between the age of the Moon and the age of its surface.
- 3D-modelling of young craters presented in our article convincingly confirms that the state of matter in young impact craters formed on the material of fresh emissions from the SPA and Orientale basins is revealed itself as a result of the analysis of high-resolution orbital observations.
- A global analysis of the structure of the lunar relief, performed taking into account the modern geological map, showed the unique role of the crater-forming event of the recent past, which led to the creation of a SPA basin on the Moon, in solving the problem of asymmetry of the visible and far side of the Moon.

REFERENCES

[1] Shpekin M.I., Barenbaum 2011 About age of lunar surface, *Proc. Ann. Conf. on Experim. Petrol., Mineral. and Geochem.* April 19-20, (2011), Moscow, Russia, GEOKHI RAS. 5p.
[2] Barenbaum A. A. Galaxy, Solar System, Earth. Subordinated Processes and Evolution Moscow: GEOS (2002), 393 p. (In Russian).
[3] Barenbaum A.A. Galactocentric paradigm in geology and astronomy. Moscow. PH: LIBROKOM. (2010), 546 p. (In Russian).
[4] Barenbaum A.A. Galactocentric Paradigm: A Scientific Revolution in Cosmic Natural Science — Moscow: PH IA REGNUM, (2022), 640 p. (In Russian ,in print).
[5] Barenbaum A.A., Shpekin M. I. Estimation of the flux density of galactic comets in the Orion–Cygnus branch based on number of shield volcanoes on Venus, craters on Mars and marine basins on the Moon *Journal Physics: Conference Series* 1787 (2021)012021.
[6] Artyushkov E.V. Recent uplifts of the Earth's crust on continents as a consequence of the rise of large masses of hot matter from the mantle *Reports of AN* (1994) Vol.336. No. 5. pp.680-683.
[7] Shpekin M.I., Salimov R.R., Semenov A.A. Orbital Photogrammetry of Selected Relief Elements with Evidences of GeologicalActivity in Aitken Crater on the Far Side of the Moon (2021) *IOP Conf. Ser.: Earth Environ. Sci.* 666 062020.

[8] Shpekin M.I., Mukhametshin Ch. R., Semenov A. A., Salimov R. R. High-resolution orbital photogrammetry on the example of modeling selected relief elements in the Tsiolkovsky crater on the Moon *Information Technologies and nanotechnologies (ITNT-2021) : collection of tr. based on the materials of the VII International Conference and Youth. shk. (Samara, September 20-24) : [in 3 volumes]. M-vo nauki i vysh. education grew. Federation, Samar. nats. research. Un-t named after S. P. Korolev (Samar. un-t), In-t processing systems. images of RAN - phil. FNIC "Crystallography and Photonics of the Russian Academy of Sciences.* – (2021) - Vol. 2. - P. 024502.
[9] Salimov R. R. Survey of topography in the area of the lunar crater Ticho from high-resolution images *Bachelor thesis* Institute of Physics KFU (2018) 50 p.
[10] Shaykhiev L. A. Orbital photogrammetry of the lunar crater Byurgius A *Bachelor thesis* Institute of Physics, KFU, (2022), 37 p.
[11] Agisoft PhotoScan Professional Edition, ver. 1.0.0, (2013) AgiSoft LLC
[12] Ferreyra R. T., Shpekin M. I. A fluid dynamical model to shape complex craters *XXXIV Intern. Conf. on Interaction of Intense Energy Fluxes with Matter (EOS-2019) Book of Abstracts*, Moscow & Chernogolovka & Nalchik, March 1-6, (2019) 397 pages. ISBN 978-5-6040595-9-3.
[13] Ferreyra R. T., Shpekin M. I. A likely dynamical balance for complex crater formation *XXXV Intern. Conf. Eqution of State for Matter(EOS-2020)* 14p. (in print).
[14] B. Rodionov, I. Isavnina, Y. Avdeev, V. V. Blagov, et al., *Preprint-41 IKI AN SSSR*, 34, (1970).
[15] B. N. Rodionov, I. V. Isavnina, Y. F. Avdeev, V. D. Blagov, et al., *Kosm. Issled*., 9, 450, (1971).
[16] B. N. Rodionov, A. A. Nefedev, M. I. Shpekin, S. G. Valeev, and V. V. Kiselev, *Cosmic Research*, 14, 624, (1977).
[17] Shpekin M.I. South Pole - Aitken" basin from first measurements ("Zond-6", 1968) to first landing of the lunar rover ("Chang'e-4", 2019) *Sci. works of the Inst. of Astron. of the RAS*. Vol 5, issue 3, pp. 157-162— M.: Janus-K PH, (2020). ISSN 2658-5669. DOI: 10.26087/INASAN.2020.5.3.014 (In Russian).
[18] Fortezzo C.M., Spudis P.D. and Harrel S.L. Digital Unified Global Geologic Map of the Moon, (2019), USGS.

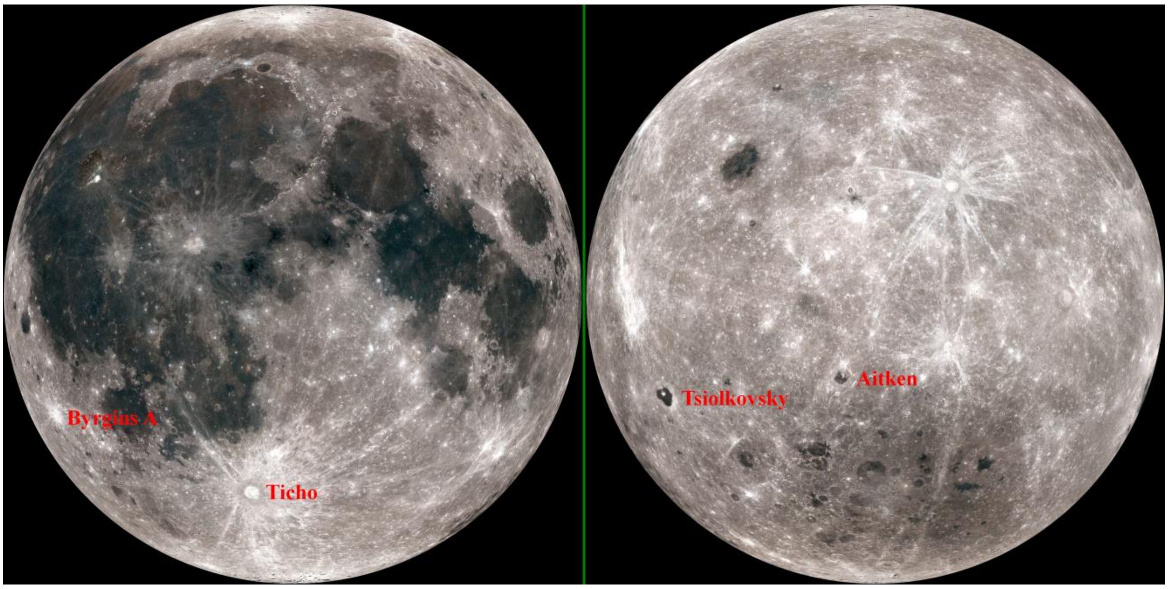

Figure 1: Selenographic position for 4 lunar young impact craters: Tsiolkovsky and Aitken (right), Ticho and Byrgius A (left)

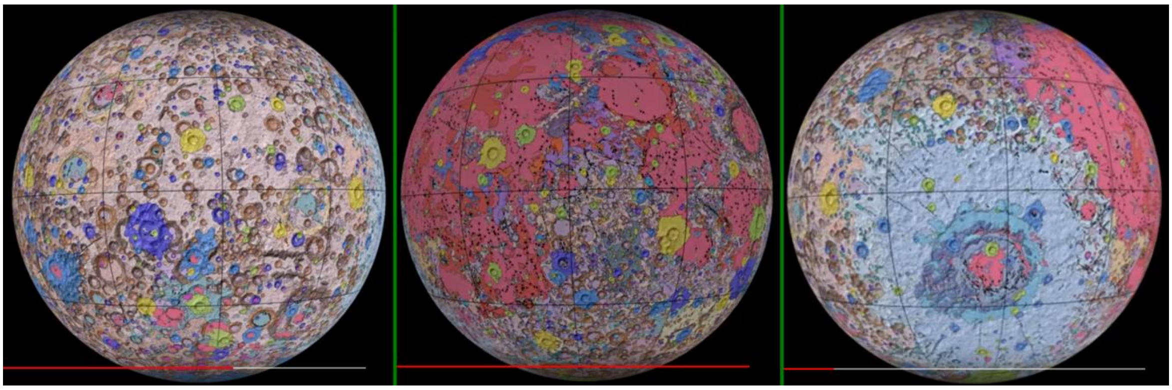

Figure 2: Near side of the Moon, Far side of the Moon and West hemisphere with Basin Orientale on the first Digital Unified Global Geologic Map of the Moon

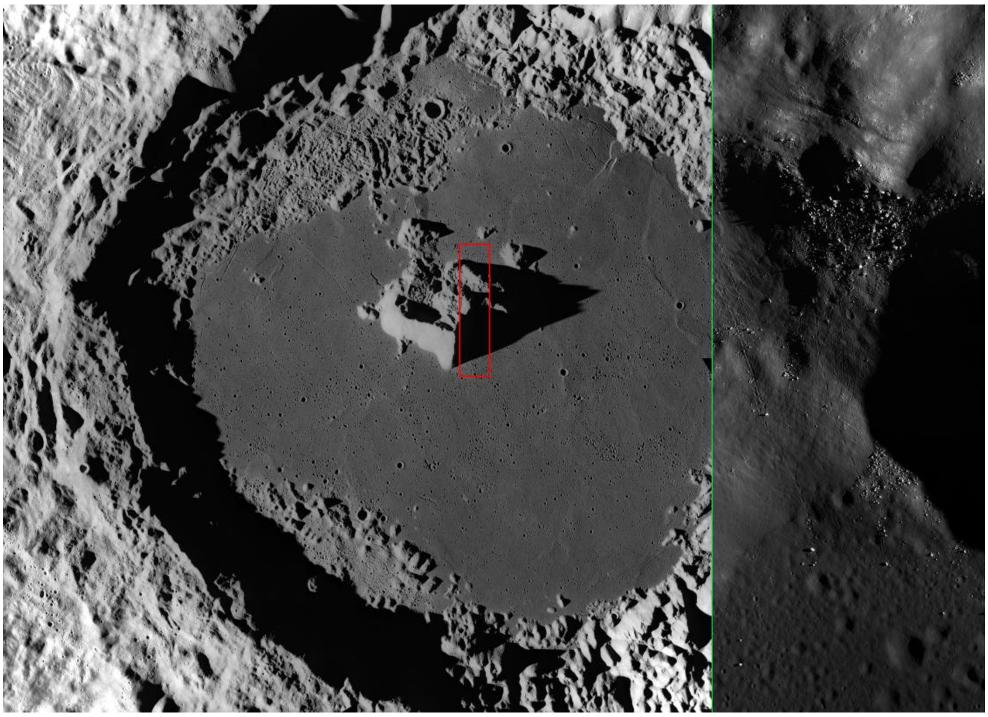

Figure 3: The Tsiolkovsky crater in the “Apollo-17” image taken by metric camera from altitude about 120 km in 1972. On the right is the fragment of the central peak, outlined by the red rectangle. This image was taken with narrow-angle camera on board the LRO, its resolution is about 1 meter. With such resolution, numerous boulders (lunar "stones" ranging in size from 1 to 40 meters) are confidently visible, rolling along the southern slope of the central peak on the crater floor. Unfortunately, in the magazine article it is not possible to show high-resolution orbital images with the same quality as the original images. High quality digitized images are available on the University of Arizona website and on the LRO website.

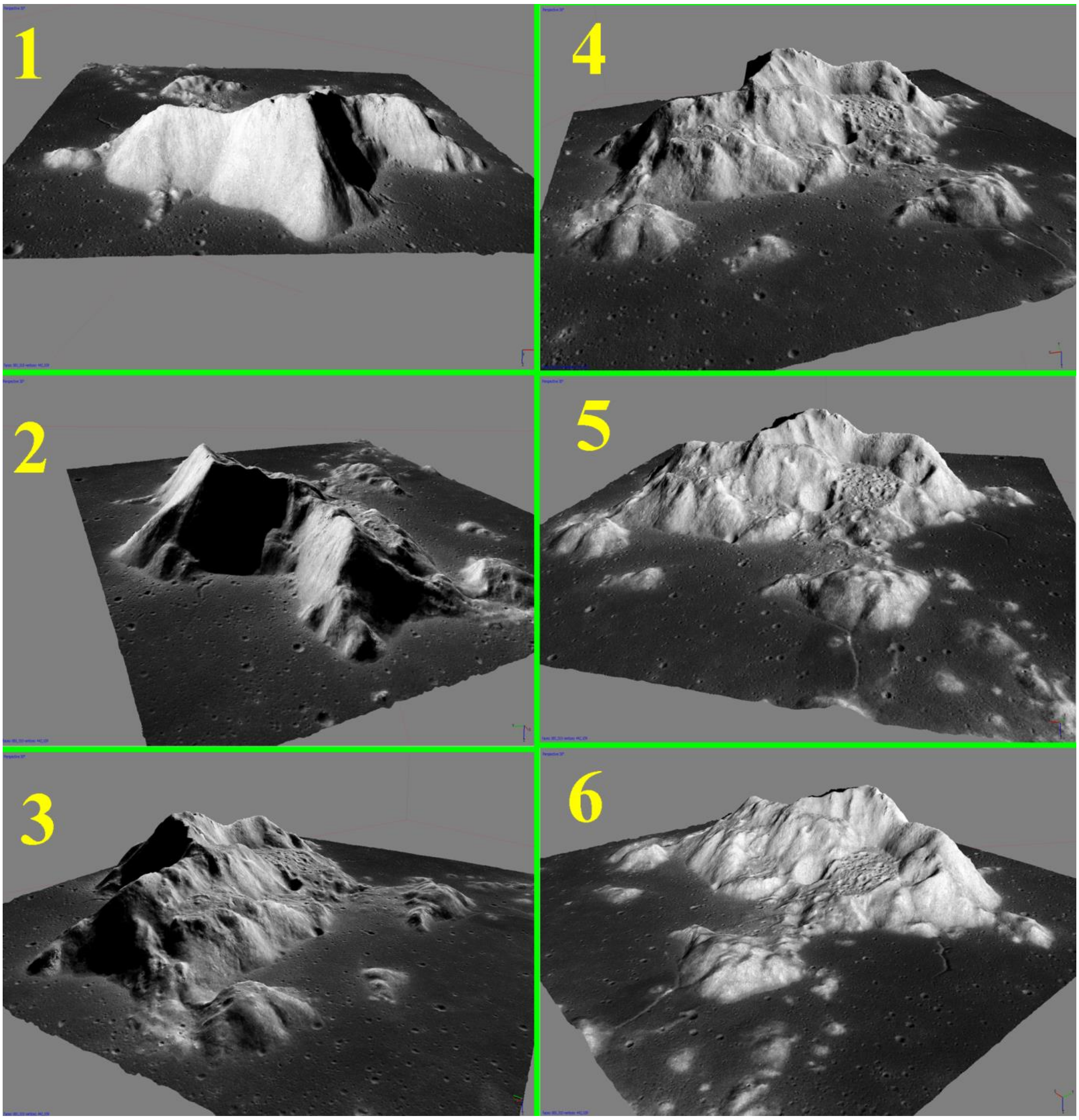

Figure 4: Fragments of a 3D-model of the central slide of the Tsiolkovsky crater: 1 - northern slope, 2 - east slope, 3 – 6 - south slope in four angles. Created by AgiSoft Photoscan 1.3 Pro (Geoscan, St. PeterSburg, Russia). Source data: digitized orbital images of the A-17 metric camera.

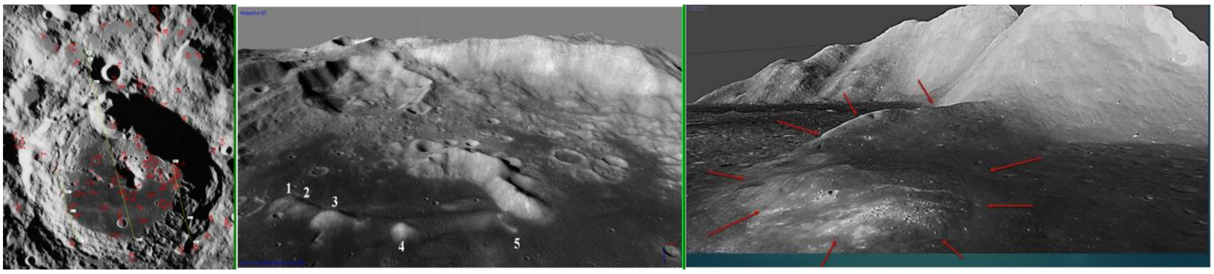

Figure 5: Fragments of a 3D model of the Aitken crater with five isolated peaks on the crater floor to the west of the central hill (center), a glacier-like tongue on the southwestern slope of the central hill (right), tracks of the laser altimeter of the Clementine station on the bottom and slopes of the crater (left)

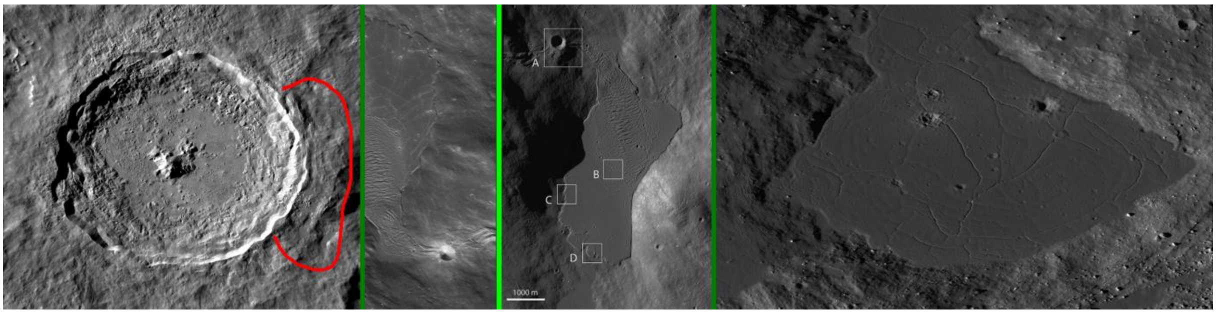

Figure 6: Ticho crater according to observations from the LRO station: general view of the crater (left), sectionsof the outer slope of the crater shaft with rivers and lakes of fresh molten lunar soil (center and right), impactors falling on the surface of the lake and sinking into its depths without forming a crater at the point of impact (right)

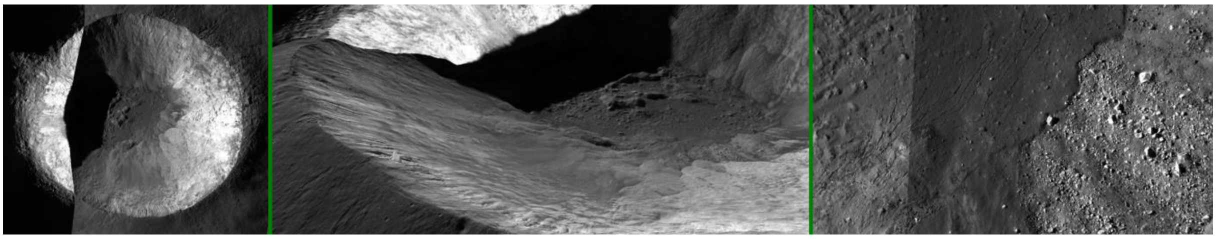

Figure 7: Fragments of the Byurgius A crater and its surroundings: general view (left), view of the inner slope of the crater and its bottom (center), a section of the crater bottom with boulders and molten soil material that descended from the southern inner slope of the crater (right)