RECENT TECTONIC DEFORMATION IN THE SOUTH POLE AREA OF THE MOON

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INTRODUCTION:
An imaging survey of the Moon with a resolution ~0.5 m by the LROC NAC cameras onboard the Lunar Reconnaissance Orbiter [1] allowed us to identify ~3200 scarps in the lunar highlands probably formed by young (<50-100 Ma) thrust faults [2-4]; these discoveries have significantly changed our understanding of the post-mare geological history of the Moon. Here we describe several such thrust faults in the South Pole area of the Moon, which is of special interest as a location where Russian missions Luna-Glob (Luna-25) and Luna-Resource (Luna-27) will land in the near future [e.g., 5-8]. In the more distant future there are plans to build a habitable lunar base [e.g., 9].

POLAR SCARPS AND GENERAL GEOLOGY:
Several scarps interpreted to have been formed by young thrust faults identified by [2] in South pole area are shown in Figures 1 and 2.

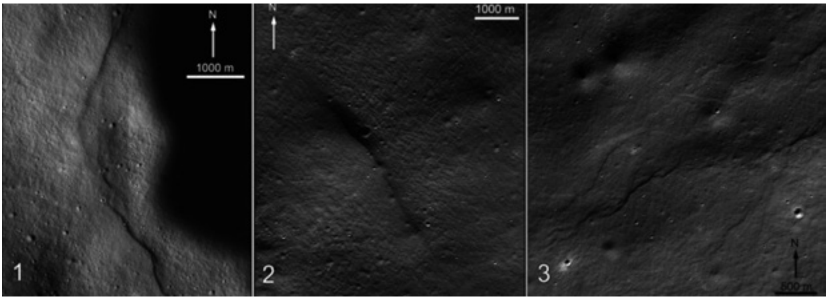

Fig. 1. Scarps of possible thrust faults in the South pole area: 1, 2, 3 – near craters Cabeus, Shoemaker and Simpelius, respectively; parts of images M1154412657LR, M108891721LR, M106807247LR, NASA/ASU.

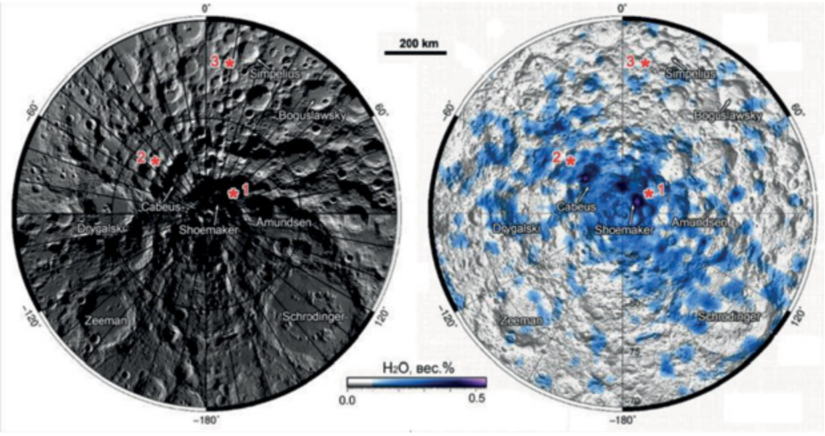

Fig. 2. South Pole area of the Moon. Left – mosaic of LROC WAC images, NASA/ASU. Right – distribution of H_2O equivalent in the upper 1 m of the surface layer ([10], modified), 1, 2, 3 - locations of scarps shown in Fig. 1.

As measured by [11] the scarps shown in Fig. 1 are 4-5 to 10-15 km long, 30 to 100 m high and their slopes are 5-10 to 15-20 degrees steep, similar to the measurements of [11]. As discussed by [3, 4], formation/movement of these scarps should be accompanied by moonquakes related to 28 near-surface moonquakes registered in 1969-1977 by the Apollo seismic network and having magnitudes (M) from 1.6 to 4.2 on the Richter scale [12-13]. Additional consideration of these results led [4] to the determination of the locations of 25 of those moonquakes. For our analysis, it is important that one of these moonquakes, with M ~4, is located in the South Pole area.

The area shown in Fig. 2 represents part of the southern segment of the largest basin on the Moon, the South Pole-Aitken basin with a diameter of ~2500 km [14-19]. It is one of the most ancient impact basins on the Moon (4.2-4.3 Ga [20]) and information on its materials, which should be sampled by the Luna-Glob and Luna-Resource missions, is very important for understanding the earliest part of the geologic history of the Moon.

H_2O IN THE STUDY AREA:

On the basis of the LEND measurements [21] the distribution of the H_2O equivalent in the South Pole area is shown in Fig. 2 (right) with variations from ~0.05 to ~0.5 mass % [10]. The lateral resolution of this parameter is ~10 km and it characterizes ~1 m thickness of the upper layer of regolith, which includes the “dry” uppermost part of indeterminate thickness [21]. It is shown in [10] that if the thickness of the uppermost “dry” layer is 90-100 cm the H_2O (ice) content in the underlying material may be 4 to 10 mass %; this agrees with LCROSS experiment results (~6% [22]). These values, if presented as volume percents, suggest that 20-30% of H_2O ice forms a significant portion of the regolith pore space. This is a high enough content of ice such that it should increase the regolith material mechanical strength and in the case of moonquakes could influence the seismic response [23, 24]; if the quake is rather strong the material might become heated along the fault and loose H_2O and other volatiles.

It is seen in Figure 2-right that two of three localities of the thrust faults considered (Shoemaker and Cabeus) are within the areas with high H_2O equivalent contents and one locality (Simpelius) is outside the H_2O equivalent anomalies.

TERRESTRIAL ANALOG:

The Meckering thrust fault in Western Australia formed by the 6.9 Richter magnitude earthquake on November 14, 1968 [25] (Fig. 3), can be considered as a terrestrial analog for the lunar thrust fault scarps.

Fig. 3. Left: Photo of the Meckering thrust fault scarp (Source: http://www.aees.org.au/gallery/1968-meckering) Right: One of the tension fractures in the vicinity of the Meckering epicenter, its width is ~1 m (Source: http://www.ydcm.com.au/2008/September/MGapA.jpg.)

The Meckering scarp (Fig. 3 left) height is up to 3 m, and the total length (with branches) is ~37 km. Analysis of the appropriate seismograms showed that the thrust fault started at the depth of 1.5 km and extended to the depth of 6 km. As part of that event there was formation of tension fractures (Figure 3 right) which may be compared with small graben associated with some lunar thrust fault scarps [3]. The Meckering quake (and other earthquakes as well) also led to seismic fluidization of dry near-surface sand [26]. Similar phenomenon may also be caused by lunar quakes.

DESTRUCTIONS CAUSED BY THE MECKERING AND OTHER EARTHQUAKES:

The town of Meckering (population 240) was essentially destroyed (Figure 4 left). Even the rails were locally buckled (Figure 4 right).

Fig. 4. Left: Building destroyed by the Meckering quake (Source http://www.ournakedaustralia.com.au/tag/meckering/) Right: Buckled rails (Source:http://www.mingor.net/images-large/meckering-eq-buckled-rail-2011/

Consideration of the Meckering event shows that seismic quakes on the Moon should be studied and taken into account as risk factor of in lunar base design and construction. Of course, the Meckering 1968 quake with M = 6.9 was much stronger that the moonquakes registered to date (M = 1.6-4.2). However, 1) there is no guarantee that moonquakes can not be higher in magnitude than these, and 2) moonquakes with known magnitudes (M = 1.6-4.2) can lead to noticeable destruction (Fig. 5).

Fig. 5. Destruction caused by earthquakes with M = 4.2. Left – Veliko Tarnovo, Bulgaria. Right – Norcia, Umbria, Italy; Sources: https://pronedra.ru/uploads/d/cP/OC/cPOCmQu3.orig.jpg and http://www.tvc.ru/news/show/id/99704#&gid=1&pid=2.

CONCLUSIONS:

We conclude that the South Pole area of the Moon shows the presence of geologically young thrust-fault scarps. The South Pole region is of special interest as a place where Russian missions Luna-Glob and Luna-Resource are planned to land in near future and in more distant future a lunar base may be built. The young thrust-fault scarp formation was accompanied by moonquakes which, in turn, could lead to seismic fluidization of surface materials as well as to mobilization and loss of volatiles from cold traps. Moonquakes also represent a factor of risk in the design, building and exploitation of a lunar base and thus should be studied and carefully taken into consideration. This study should include development of landed seismic experiments (such as the SEISMO experiment on Luna 25 and 27 [27]) and networks, and long duration observations.

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