Geology of Shackleton Crater and the south pole of the Moon

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[1] Using new SMART-1 AMIE images and Arecibo and Goldstone high resolution radar images of the Moon, we investigate the geological relations of the south pole, including the 20 km-diameter crater Shackleton. The south pole is located inside the topographic rim of the South Pole-Aitken (SPA) basin, the largest and oldest impact crater on the Moon and Shackleton is located on the edge of an interior basin massif. The crater Shackleton is found to be older than the mare surface of the Apollo 15 landing site (3.3 Ga), but younger than the Apollo 14 landing site (3.85 Ga). These results suggest that Shackleton may have collected extra-lunar volatile elements for at least the last 2 billion years and is an attractive site for permanent human presence on the Moon. **Citation:** Spudis, P. D., B. Bussey, J. Plescia, J.-L. Josset, and S. Beauvivre (2008), Geology of Shackleton Crater and the south pole of the Moon, *Geophys. Res. Lett.*, *35*, L14201, doi:10.1029/2008GL034468.

1. Introduction

[2] The south pole of the Moon is located in the rugged, heavily cratered terrain of the southern highlands [e.g., *Wilhelms et al.*, 1979]. Because the lunar spin axis is oriented about 1.5° from a normal to the ecliptic, sunlight is always at low angles at the poles, creating both a unique environment and some difficulty in geological interpretation of the region. The recent successful flight of the SMART-1 mission [*Josset et al.*, 2006] provided a new and better look at this region. Additionally, newly obtained radar images of the lunar south pole from the Earth-based Arecibo and Goldstone antennas permit us to observe several areas of this region that are in permanent sun shadow [*Campbell et al.*, 2006] (NASA, Enhanced radar imagery of lunar south pole, http://www.nasa.gov/mission_pages/exploration/mmb/022708.html, 2008, hereinafter referred to as NASA (2008); see also http://www.nasm.si.edu/ceps/research/moon/radar_south_images.cfm). Together with earlier data for the poles from the Clementine and Lunar Prospector missions [*Bussey et al.*, 1999; *Nozette et al.*, 2001; *Elphic et al.*, 2007], we now have an abundance of information on the geology and environment of the south pole. We here describe some of these new insights; a companion paper details new results on the lighting conditions of the poles [e.g., *Bussey et al.*, 2008].

2. Geological Setting of the South Pole

[3] The dominant feature that influences the geology and topography of the south polar region is the South Pole-Aitken (SPA) basin, the largest and oldest impact feature on the Moon [e.g., *Wilhelms*, 1987]. This feature is over 2600 km in diameter, averages 12 km depth, and is approximately centered at 56° S, 180° [*Spudis et al.*, 1994]. The basin formed sometime after the crust had solidified and was rigid enough to support significant topographic expression; thus, the basin is likely no older than about 4.3 Ga. Its younger age limit is more difficult to ascertain; it may be as young as 3.9 Ga if the lunar "cataclysm" took place as envisioned by some [e.g., *Ryder*, 1990]. In addition, as a very large impact event, this basin probably excavated a significant fraction of the lunar crust and possibly, even the upper mantle of the Moon [e.g., *Lucey et al.*, 1998]. Thus, sampling the impact melt of this feature is a high priority in lunar science, making the SPA basin an important target for future scientific exploration [e.g., *National Research Council*, (*NRC*), 2007].

[4] The south pole is located just inside the main topographic rim of the SPA basin (Figure 1). The basin rim is expressed here by two fragmentary segments. The first is a line of massifs about 200 km away from the pole towards the near side that make up the main rim crest of the basin — the Leibniz Mountains – and were postulated to represent a basin rim in the earliest days of lunar mapping [*Hartmann and Kuiper*, 1962]. The second occurs inside the rim crest and crosses the pole (arrow, Figure 1); the crater Shackleton lies on the edge of an SPA basin mountain.

[5] Newly obtained radar topographic data have clarified the nature of the SPA basin rim in this area (Figure 2). The most prominent feature is a very large platform-like massif named Leibniz β; this mountain rises almost 8 km above the interior shelf of the SPA basin. The pole is on an inner basin massif, similar to the inner ring massifs seen at most other lunar basins [e.g., *Wilhelms*, 1987; *Spudis*, 1993]. Clementine stereo images [*Archinal et al.*, 2006] and the Goldstone radar data (NASA, 2008) indicate that this interior massif rises 1–2.5 km above the mean lunar radius, in contrast to the largest massifs of the main rim crest, many of which have elevations exceeding 6 km.

[6] The terrain in this area is primarily pre-Nectarian in age, a rugged highlands area containing abundant impact craters of a wide variety of ages (Figure 3) [also *Wilhelms et al.*, 1979]. The extreme elevation changes here are largely caused by the SPA basin rim, although numerous craters of tens of kilometers in size (e.g., Amundsen; 105 km dia.) also occur throughout the area, contributing to the area's kilometer-scale roughness. The region is covered by abun-

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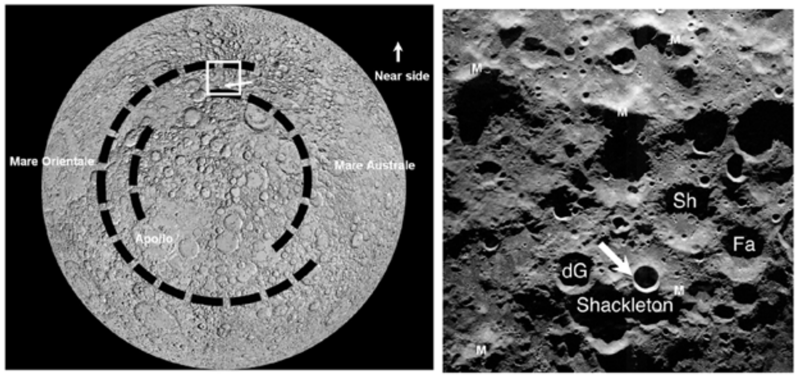

Figure 1. Location and setting of the lunar south pole. (left) Shaded relief map of the Moon centered on the SPA basin. The pole is located on an inner basin ring. Dashed lines indicate inferred rings of SPA basin. (right) Numerous massifs in vicinity (M) are all part of the SPA basin. Crater names: Sh, Shoemaker; Fa, Faustini; and dG, de Gerlache. Pole location shown by arrow. S-band (13 cm) radar image from *Campbell et al.* [2006].

dant irregular craters and crater clusters, interpreted to be secondary impact craters created mostly by the Orientale basin to the north along 90° W. A few secondaries of the Imbrium basin also have been identified (Figure 3). The effects of the formation of such craters are to churn up local debris and to deposit a thin veneer of basin ejecta. Undulating, cratered plains deposits fill several of the older large craters; these smooth highland plains are similar to other Cayley-like plains on the Moon, consisting of impact breccia formed during the emplacement of distal basin ejecta [*Oberbeck*, 1975; *Spudis*, 1993].

[7] The crater Shackleton (20 km dia.; Figure 4) has been the subject of intense study, largely because of its location nearly coincident with the south pole. In and of itself, it is a fairly unremarkable crater whose interior is almost completely in permanent sun shadow [*Bussey et al.*, 1999]; Earth-based radar images can only see into a fraction of its depth [*Campbell et al.*, 2006]. Lunar craters of similar size and age typically possess similar morphologies [e.g., *Wilhelms*, 1987] – slumped masses of flat to undulating floor materials about 10 km across and relatively smooth walls. New images from the Kaguya mission support this expectation [*Haruyama et al.*, 2008]. Shackleton is situated on the northern slope of an irregular platform-like massif, roughly 120 by 50 km in dimension (Figure 3); its location on the side of this massif results in a regional tilt to the crater, with the lower part of the crater rim to the northeast near side. This tilt is evident in the crater's appearance in the SMART-1 images; when the sun illumination is from the west, a small sliver of the crater interior is lit whereas when illumination is coming from the east and northeast, a much larger fraction of the interior wall is lit. On this basis, we estimate the regional slope of the massif on which Shackleton crater lies to be on the order of 15° or less.

3. Age of Shackleton Crater

[8] Because Shackleton is permanently shaded from the sun, it may have served as a ''cold trap'' to collect volatiles [*Arnold*, 1979]. Both poles display elevated amounts of inferred hydrogen content [e.g., *Elphic et al.*, 2007]; if this hydrogen is present as water ice, such ice can be located only in permanent shadow, where it is stable. Thus, Shackleton is a potential candidate for such ice deposits. A key question in determining the potential of a given crater as a lunar ''cold trap'' is the age of the feature. Initial geologic mapping suggested that Shackleton is Eratosthenian in age [*Wilhelms et al.*, 1979], meaning that it formed between ~1.1 and 3.3 Ga ago [*Wilhelms*, 1987]. Such an age might mean that the crater formed relatively recently (~1 Ga ago) and consequently, would have had little time to collect extra-lunar volatile material.

[9] We used newly obtained AMIE images (average resolution: ~50 m/pixel) and the new Arecibo radar image (~20 m/pixel) to determine the number of superposed

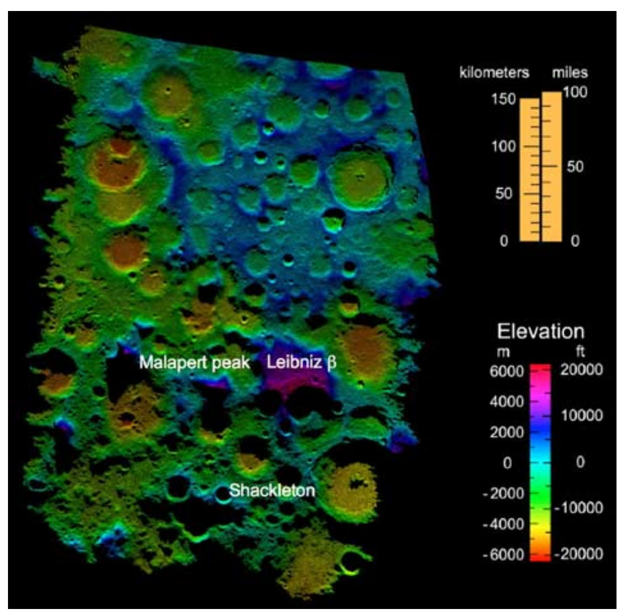

Figure 2. Topographic data for the south pole of the Moon from the Goldstone radio antenna (NASA, 2008). Leibniz β is the prominent massif that makes up the rim of the SPA basin in this part of the Moon. The pole and the crater Shackleton (S) lie on an inner basin massif or roughly 1–2 km elevation above the basin floor.

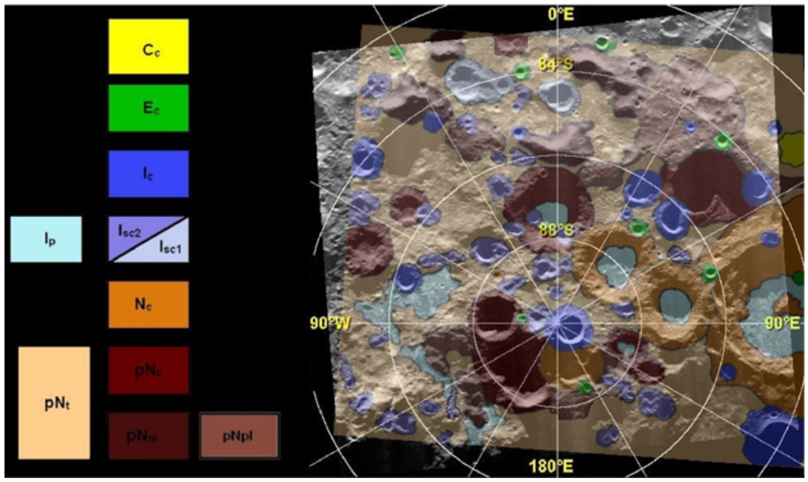

Figure 3. Geological map of the south polar area of the Moon. Units: c, crater materials; Ip, plains materials; m, massif material; pl, platform massif material; and sc, satellitic (basin secondary) crater material (1, Imbrium basin; 2, Orientale basin secondaries; and t, terra material). Colors indicate relative ages, yellow being youngest (Copernican), followed by green (Eratosthenian), Imbrian (blue) and browns the oldest (Nectarian (N) and pre-Nectarian (pN)). Base map is Arecibo S-band (13 cm) radar image of *Stacy et al.* [1997].

impact craters on Shackleton's ejecta blanket. We mapped and counted areas within a crater diameter (20 km) of the rim crest of Shackleton and attempted to carefully distinguish between pre- and post-Shackleton craters. In broad terms, the more impact craters present on a unit, the older it is. Although this area is contaminated by the presence of secondary impact craters, by avoiding obvious fields of secondaries, we can minimize this "artificial" aging effect. Results are shown in Figure 5 and comparative values for other lunar geological units are given there and in Table 1.

[10] Shackleton is older than previously thought. Our data indicate that Shackleton possesses a crater density almost twice that of the Apollo 15 mare landing site (Table 1). Samples returned from that mission indicate that those mare lava flows erupted about 3.3 Ga ago [*Basaltic Volcanism Study Project (BVSP)*, 1981; *Wilhelms*, 1987]. We estimate an age for Shackleton of about 3.6 Ga, recognizing that crater ejecta will appear to be slightly older than a contemporaneous basalt flow due to substrate effects [e.g., *Schultz and Spudis*, 1983]. Our measured crater density corresponds closely to that determined to represent the "average lunar mare" in the exhaustive study by the *BVSP* [1981], which assigned an average age of 3.6 Ga to that measured crater density.

[11] The assignment of an Eratosthenian age to Shackleton by *Wilhelms et al.* [1979] was based on the apparent morphological freshness of the crater. This property can be misleading and is caused largely by the low angles of sun lighting always present at the pole, which accentuates and enhances subtle topography, casts long shadows, and in general suggests a rougher, fresher surface (and hence, younger age) than would be inferred if the images were available at higher illumination angles. In some early studies by the Robotic Lunar Precursor Team, it was suggested that Shackleton could be of Copernican age (<1 Ga old) and a Copernican-age crater (Dawes) has been proposed as a morphological and topographic analog for Shackleton crater [e.g., *Lavoie*, 2006]. Clearly this analogy is inappropriate; we now estimate a much older age for Shackleton and future studies needing detailed topography (that we do not yet have) should use a more age- and morphologically appropriate analog. A number of potential candidates exist, such as the crater Hipparchus G, a 15 km diameter Imbrian age crater located at 5° S, 7.4° E. This feature has good topographic coverage (LTO 77B3) and closely resembles the age and morphology of Shackleton; it can serve as an analog feature until we obtain complete high resolution coverage of Shackleton from the many orbital

Figure 4. SMART-1 image mosaic of the crater Shackleton.

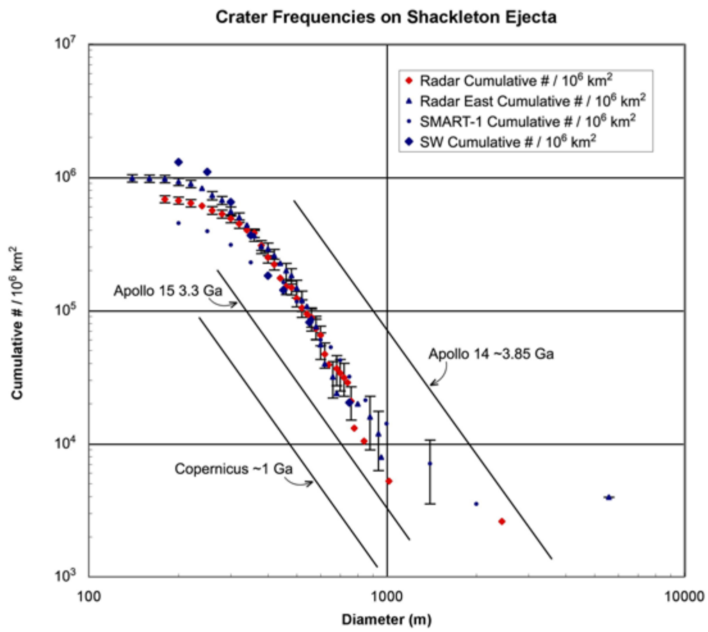

Figure 5. Crater frequency diagram of Shackleton ejecta. ‘‘Radar’’ refers to counts done on the Arecibo S-band (13 cm) radar image of *Campbell et al.* [2006]; SMART refers to counts done on new SMART-1 images of poles. Reference lines for the Apollo 14 and 15 landing sites and Copernicus shown for comparison [after *Neukum et al.*, 1975; *Neukum and König*, 1976].

mapping missions, such as the Kaguya, Chandrayaan-1 and Lunar Reconnaissance Orbiter missions.

4. Summary

[12] The south pole of the Moon is an interesting and complex region of the lunar highlands. Its geology is dominated by the presence of the enormous South Pole-Aitken basin, the oldest and largest basin on the Moon, already identified as a key target for future scientific exploration [*NRC*, 2007]. The Imbrian-aged crater Shackleton occurs on an SPA basin massif, suggesting that this crater has excavated most if not all of the SPA massif. As such, its ejecta likely contain products of that basin-forming impact. Thus, study and sampling of the ejecta of Shackleton should allow us to reconstruct the absolute age and likely effects of the formation of the SPA basin.

[13] The crater Shackleton is about 3.6 Ga old, significantly older than previous estimates and also older than the current estimate of the age of the orientation of the spin axis of the Moon and present pole location (∼2 Ga) [*Ward*, 1975]. Such a relation indicates that its floor has been in permanent shadow (and thus has had the potential to collect volatiles) for at least the last 2 billion years. Determining the presence, state and extent of polar volatiles is a critical task for the long-term habitation of the Moon. Shackleton will be an important target for future exploration, both from lunar orbit and on the surface.

Table 1. Crater Densities of Shackleton Ejecta and Some Other Lunar Geological Units

Feature	Crater Density (# $\geq$ 500 m $\times$ 10^{-2}/km^2)	Absolute Age (Ga)	Reference
Copernicus	1.6 ± 0.3	0.9 ± 0.1	*Schultz and Spudis* [1983]
Apollo 15 mare	5.0 ± 1.0	3.3 ± 0.1	*Schultz and Spudis* [1983]
Shackleton	10.5 ± 1.0	∼3.6 ± 0.4	this study
Average lunar mare	11 ± 2	∼3.6 ± 0.3	*BVSP* [1981]

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