THE GEOLOGY OF THE SOUTH POLE OF THE MOON AND AGE OF SHACKLETON CRATER. Paul D. Spudis, Lunar and Planetary Institute, Houston TX 77058 (spudis@lpi.usra.edu); Jeffrey Plescia, Ben Bussey, Johns Hopkins University Applied Physics Laboratory, Laurel MD 20723; J.-L. Josset, S. Beauvivre and the AMIE team, Space Exploration Institute and Micro-cameras & Space Exploration, Neuchâtel, Switzerland

The south pole of the Moon is located in the rugged, heavily cratered terrain of the southern highlands [1]. Because the lunar spin axis is oriented about 1.5º from a normal to the ecliptic, sunlight is always at low incidence at the poles, creating both a unique environment and some difficulty in geological interpretation of the region. Newly obtained radar images of the lunar south pole permit us to observe several areas of this region that are in permanent sun shadow [2]. Together with earlier data for the poles from the orbital Clementine and Lunar Prospector missions [3-5], we now have an abundance of information on the geology and environment of the south pole.

Geological setting of the south pole. The dominant feature in the south polar region is the enormous South Pole-Aitken basin, one of the largest and oldest impact basins on the Moon [6]. It is over 2600 km in diameter, averages about 12 km deep, and is approximately centered at 56º S, 180º [7]. 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 [8]. In addition, as a very large impact, this basin probably excavated a significant fraction of the lunar crust and possibly, even the upper mantle of the Moon [9]. Thus, sampling the melt ejecta of this basin is a high priority in lunar science, making SPA an important target for future scientific exploration [10].

The pole itself is located on the rim of Shackleton crater, just inside the topographic rim of SPA basin (Fig. 1). The rim here seems to be split into at least two segments; the main line of massifs about 200 km towards the near side from the pole is the basin rim crest; these massifs (the Liebnitz Mountains) were postulated to represent a basin rim in the earliest days of lunar mapping [11]. The crater Shackleton is located on an interior SPA basin mountain. Although topographic data in this area of the Moon is uncertain, best estimates suggest that this massif rises 1-2.5 km above the mean lunar radius [12]; this is in contrast to the largest massifs of the main topographic rim crest, which may have elevations exceeding 5 km.

The terrain in this area is largely pre-Nectarian in age, a rugged highlands containing abundant impact craters of a wide variety of ages (Fig. 2; also, [1]). Numerous craters of tens of kilometers in size (e.g., Amundsen; 105 km dia.) occur throughout the area. Abundant basin secondary craters are scattered across the area, mostly created by the Orientale basin impact to the west and north, although a few Imbrium basin secondaries also have been identified (Fig. 2). The effects of the formation of these craters are to churn up local debris, but also to deposit a thin veneer of basin ejecta in the area. Undulating, cratered plains deposits fill several of the older large craters; these smooth highland plains are likely to be similar to other Cayley-like plains, consisting of impact breccia formed during the emplacement of distal basin ejecta [13,14].

The crater Shackleton (20 km dia.; Figs. 1, 2) 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 [3]; Earth-based radar images can only see into a fraction of its depth [2]. Lunar craters of similar size and age typically possess similar morphologies [6]; on this basis, we can infer that the interior of Shackleton probably contains a flat to slightly undulating floor, roughly 10 km across.

Age of Shackleton crater Because Shackleton is permanently shaded from the sun, it may have served as a "cold trap" to collect volatiles [15]. Both lunar poles display elevated amounts of inferred hydrogen content (e.g., [5]); if this hydrogen is present as water ice, such ice must be in permanent shadow, where it is stable. Thus, Shackleton emerged early as 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 mapping suggested that Shackleton is Eratosthenian in age [1], meaning that it formed between ~1.0 and 3.3 Ga ago [6]. Such an age could mean that the crater may have formed relatively recently (at about 1 Ga) and consequently, would have had little aggregate time to collect extra-lunar volatile material.

Because of the importance of this question, we have used the new Arecibo radar images ([2]; average resolution: ~20 m/pixel) and new AMIE images of the pole from the SMART-1 mission ([16]; average resolution: ~50 m/pixel) to count the number of superposed impact craters on Shackleton's ejecta blanket. We mapped and counted areas within a crater diameter (20 km) of the rim of Shackleton and carefully distinguished between pre- and post-Shackleton craters. In broad terms, the more impact craters present, the older the surface. Although this area is contaminated by the presence of secondary impact craters, so are all other units on the Moon and by avoiding obvious fields of secondaries, we can minimize this "artificial" aging effect. Results for Shackleton and comparative values for other lunar geological units are given in Table 1.

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. Samples returned from that mission indicate that those flows were erupted about 3.3 Ga ago [6, 17]. Thus, we infer an older age for Shackleton, recognizing that the relatively soft substrate of crater ejecta will appear slightly older than a comparably aged basalt flow [18]. Our measured crater density closely corresponds to that determined to represent "average lunar mare" in the exhaustive study by the Basaltic Volcanism Study Project [17]. They collected crater density data for a variety of mare sites all over the Moon and assigned an average age of 3.6 Ga to that crater density. Thus, we estimate an age for Shackleton of about 3.6 Ga, with slightly more uncertainty added due to the target substrate effect.

The assignment of an Eratosthenian age to Shackleton [1] was based on the apparent morphological freshness of the crater. This property is misleading and largely caused here by the extremely low incidence of lighting always present at the pole, which accentuates and enhances topography, casts long shadows, and in general suggests a younger age than would be supposed at higher illumination angles. In some early studies by the Robotic Lunar Precursor Team, it was even suggested that Shackleton could be of Copernican age (< 1 Ga old) and a Copernican-age crater (Dawes) has long been used as an alleged Shackleton morphological and topographic analog. 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 highlands crater of similar size and age as an analog.

Summary 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 and already identified as a key target for future scientific exploration [10]. The Imbrian-aged crater Shackleton occurs on the edge of an SPA basin massif, suggesting that it has probably excavated most if not all of the massif material cropping out in this region of the Moon. Thus, study and sampling of the ejecta of Shackleton should prove fruitful in the attempts to reconstruct the absolute age and likely effects of the ancient SPA basin-forming impact.

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 (~2 Ga; [19]). 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 lunar polar volatiles is a critical task for the long-term inhabitation of the Moon. Shackleton will be an important target for future exploration, both from orbit and the surface.

REFERENCES [1] Wilhelms D.E. *et al*.(1979) *U. S. Geol. Survey Map* **I-1162**. [2] Campbell D.B. *et al*. (2006) *Nature* **443**, 835; see also http://www.nasm.si.edu/ceps/research/moon/radar_south_images.cfm [3] Bussey, D.B.J. *et al*. (1999) *Geophys. Res. Lett*. **26** , No. 9 , 1187. [4] Nozette S. *et al*. (2001) *J. Geophys. Res.* **106**, E19, 23253. [5] Elphic R.C. *et al*. (2007) *Geophys. Res. Letters* **34**, doi:10.1029/2007GL029954 [6] Wilhelms D.E. (1987) *U. S. Geol. Survey Prof. Paper* **1348**, 302 pp. [7] Spudis P.D. *et al*. (1994) *Science* **266**, 1848. [8] Ryder G. (1990) *EOS* **71**, 313. [9] Lucey P.G. *et al*. (1998) *J. Geophys. Res*. **103**, E2, 3701. [10] National Research Council (NRC) (2007) *The Scientific Context for Exploration of the Moon, Final report.* 113 pp. [11] Hartmann W.K. and Kuiper G. (1962) C*ommunications Lunar Planet. Laboratory* **1**, Univ. Arizona, 55. [12] Archinal B.A. *et al*. (2006) *U.S. Geological Survey Open File Report* **2006-1367**, 18 pp. [13] Oberbeck V. R. (1975) *Rev. Geophys. Space Phys.* **13**, 337. [14] Spudis P.D. (1993) *Geology of Multi-ring basins.* Cambridge Univ. Press, Cambridge UK, 264 pp. [15] Arnold J. (1979) *JGR* **84**, 5459. [16] Josset J.-L. *et al*. (2006) *Adv. Space Res*. **37**, 14. [17] Basaltic Volcanism Study Project (1981) *Basaltic Volcanism on the Terrestrial Planets*, Pergamon Press, Chapter 8, 1050. [18] Schultz P.H. and Spudis P.D. (1983) *Nature* **302**, 233. [19] Ward W.R. (1975) *Science* **189**, 377.

Table 1. Crater densities of Shackleton ejecta and some other lunar geological units.

Feature	Density (#>500 m x 10^{-2} /km^2)	Absolute age (Ga)	Reference
Copernicus	1.6 ± 0.3	0.9 ± 0.1	[18]
Apollo 15 mare	5.0 ± 1.0	3.3 ± 0.1	[18]
Shackleton	10.5 ± 1.0	~ 3.6 ± 0.4	this study
Average lunar mare	11 ± 2	~ 3.6 ± 0.3	[17]

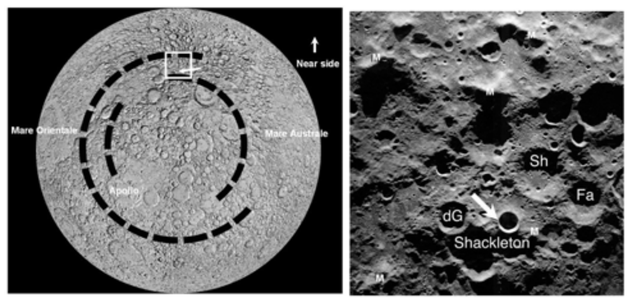

Fig. 1 Lunar south pole is located on an inner ring of the South Pole-Aitken basin, the largest and oldest impact feature on the Moon; numerous massifs in vicinity (M) are all SPA basin rim. Crater names: Sh – Shoemaker, Fa – Faustini, dG – de Gerlache. Pole location shown by arrow. Radar image from Campbell *et al.* [2].

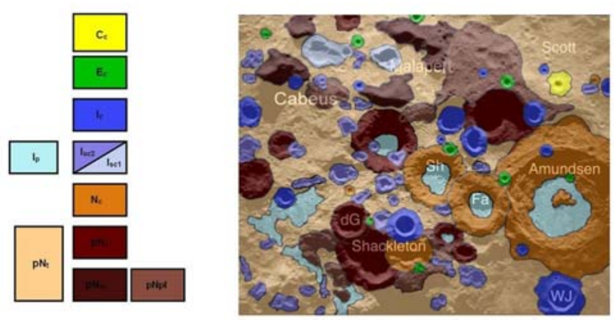

Fig. 2 Geological map of the south polar area of the Moon. Units: c – crater materials, Ip – plains materials, m – massif material, pNp – platform massif material, sc – satellitic (basin secondary) crater material. Colors indicate relative ages, yellow being youngest (Copernican), followed by green (Eratosthenian), Imbrian (blue) and browns the oldest (Nectarian and pre-Nectarian) Base map is radar image of Campbell *et al*. [2].