Lack of Exposed Ice inside Lunar South Pole Shackleton Crater
Author(s): Junichi Haruyama, Makiko Ohtake, Tsuneo Matsunaga, Tomokatsu Morota, Chikatoshi Honda, Yasuhiro Yokota, Carle M. Pieters, Seiichi Hara, Kazuyuki Hioki, Kazuto Saiki, Hideaki Miyamoto, Akira Iwasaki, Masanao Abe, Yoshiko Ogawa, Hiroshi Takeda, Motomaro Shirao, Atsushi Yamaji and Jean-Luc Josset
Source: *Science*, New Series, Vol. 322, No. 5903 (Nov. 7, 2008), pp. 938-939
Published by: American Association for the Advancement of Science
Stable URL: https://www.jstor.org/stable/20145227
Accessed: 30-04-2019 03:02 UTC

(based on thickness of the mantle) of 9.4×10^6 is used (21). The three-layer viscosity includes a lithosphere with constant 5×10^{22} Pa s viscosity, an upper mantle, and a lower mantle with varying viscosities to be constrained. Laterally, viscosity increases exponentially by one order of magnitude for a temperature drop of 200°C.
18. J. X. Mitrovica, C. Beaumont, G. T. Jarvis, *Tectonics* **8**, 1079 (1989).
19. P. M. Burgess, M. Gurnis, L. Moresi, *Bull. Geol. Soc. Am.* **109**, 1515 (1997).
20. H.-P. Bunge, S. P. Grand, *Nature* **405**, 337 (2000).
21. Materials and methods are available as supporting material on *Science* Online.
22. G. A. Bond, *Geology* **4**, 557 (1976).
23. G. A. Milne *et al.*, *J. Geophys. Res.* **109**, B02412 (2004).
24. J. Saleeby, *Bull. Geol. Soc. Am.* **115**, 655 (2003).
25. M.-A. Gutscher, W. Spakman, H. Bijwaard, E. R. Engdahl, *Tectonics* **19**, 814 (2000).
26. R. F. Livaccari, K. Burke, A. M. C. Sengor, *Nature* **289**, 276 (1981).
27. R. M. Flowers, *Eos* **52**, abstr. V34C-06 (2007).
28. S. Goes, S. van der Lee, *J. Geophys. Res.* **107**, 2050 (2002).
29. M. Gurnis *et al.*, *Eos* **52**, abstr. DI14A-07 (2007).
30. R. D. Müller *et al.*, *Geochem. Geophys. Geosys.* **9**, 10.1029/2007GC001743 (2008).
31. S. Zhong, M. T. Zuber, L. Moresi, M. Gurnis, *J. Geophys. Res.* **105**, 11,063 (2000).
32. This is contribution no. TO 88 of the Caltech Tectonics Observatory. The work was partially supported by the Gordon and Betty Moore Foundation through the Tectonics Observatory and the NSF through EAR-0609707. We appreciate discussions with J. Saleeby and R. D. Müller. The original CitcomS software was obtained from the Computational Infrastructure for Geodynamics (CIG) (http://geodynamics.org).

Supporting Online Material
www.sciencemag.org/cgi/content/full/322/5903/934/DC1
Materials and Methods
Figs. S1 to S3
References

8 July 2008; accepted 8 October 2008
10.1126/science.1162921

Lack of Exposed Ice Inside Lunar South Pole Shackleton Crater

Junichi Haruyama,[1] Makiko Ohtake,[1] Tsuneo Matsunaga,[2] Tomokatsu Morota,[1] Chikatoshi Honda,[1] Yasuhiro Yokota,[1] Carle M. Pieters,[3] Seiichi Hara,[4] Kazuyuki Hioki,[4] Kazuto Saiki,[5] Hideaki Miyamoto,[6] Akira Iwasaki,[7] Masanao Abe,[1] Yoshiko Ogawa,[2] Hiroshi Takeda,[8] Motomaro Shirao,[9] Atsushi Yamaji,[10] Jean-Luc Josset[11]

The inside of Shackleton Crater at the lunar south pole is permanently shadowed; it has been inferred to hold water-ice deposits. The Terrain Camera (TC), a 10-meter-resolution stereo camera onboard the Selenological and Engineering Explorer (SELENE) spacecraft, succeeded in imaging the inside of the crater, which was faintly lit by sunlight scattered from the upper inner wall near the rim. The estimated temperature of the crater floor, based on the crater shape model derived from the TC data, is less than ~90 kelvin, cold enough to hold water-ice. However, at the TC's spatial resolution, the derived albedo indicates that exposed relatively pure water-ice deposits are not on the crater floor. Water-ice may be disseminated and mixed with soil over a small percentage of the area or may not exist at all.

Whether or not an amount of concentrated hydrogen on the lunar poles (*1*) forms water-ice is both a scientifically intriguing issue and a potentially important research subject in order for humans to settle on the Moon and travel further into space. Possible reservoirs of hydrogen on the lunar poles are permanently shadowed areas (PSAs), which receive no direct sunlight and are extremely cold (*2*, *3*). Because the present rotation inclination of the Moon is nearly zero (~1.5° from normal to the ecliptic plane), topographic lows on the lunar poles become PSAs. Shackleton Crater, which lies at the lunar south pole, has therefore been considered as a possible water-ice reservoir in its PSA. Bistatic radar observations made by the Clementine probe (*4*, *5*) implied that there are water-ice deposits inside Shackleton Crater. However, subsequent Earth-based radar observations showed little evidence for the existence of water-ice deposits (*6*), although they could observe only an upper part of the inner wall of Shackleton.

[1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency, Sagamihara, Kanagawa 229-85105, Japan. [2]Center for Global Environmental Research, National Institute for Environmental Studies, Tsukuba, Ibaraki 305-8506, Japan. [3]Department of Geological Sciences, Brown University, Providence, RI 02912, USA. [4]NTT DATA CCS Corporation, Koto-ku, Tokyo 136-0071, Japan. [5]Department of Earth and Space Science, Graduate School of Science, Osaka University, Toyonaka, Osaka 560-0043, Japan. [6]University Museum, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan. [7]Department of Aerospace and Astronautics, The University of Tokyo, Bunkyo-ku, Tokyo 113-8656, Japan. [8]Forum Research, Chiba Institute of Technology, Narashino, Chiba 275-0016, Japan. [9]Taito-ku, Tokyo 111-0035, Japan. [10]Division of Earth and Planetary Sciences, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan. [11]Space Exploration Institute, CP 774, CH-2002 Neuchatel, Switzerland.

We investigated the interior of Shackleton Crater with the panchromatic Terrain Camera (TC), a 10-m-resolution stereo camera onboard the Selenological and Engineering Explorer (SELENE) spacecraft (also nicknamed Kaguya) (*7*). The method of our observation was based on the idea that the PSA is weakly lit by sunlight scattered from nearby higher terrains. The small lunar rotation inclination means that the maximum scattering illumination occurs during the lunar mid-summer. The first lunar south pole summer after the SELENE launch in September 2007 was during October to December 2007. Clear images of inside of Shackleton Crater were first acquired on 19 November 2007 (Fig. 1, A and B), from which we also produced a digital terrain model (DTM) (Fig. 1, C and D). Shackleton Crater is a truncated cone-shaped crater and has an almost concentric circular rim with a radius of ~10.5 km, a floor with a radius of ~3.3 km, and a depth of ~4.2 km; it is much deeper than other similarly sized lunar craters (*8*). Inside, the crater has an almost smooth but cratered inner wall. Two mounds are seen adjacent to the inner wall that are probably the result of landslides from the inner wall. A hill a few hundred meters in height occupies the crater center. A terrace structure is associated with the hill and is elongated toward the inner wall. It has a number of depressions that are probably craters.

The inner wall slopes ~30°, which is consistent with a result from the Earth-based radar observation of the upper portion of the Shackleton Crater inner wall that is opposite the Earth (*6*). The entire rim of Shackleton Crater is tilted ~1.5° toward a direction of 50° to ~90° from the Earth-side hemisphere. Thus, under the illumination conditions of the lunar summer, the solar elevation angle from the opposite-side rim occasionally becomes a maximum ~3.0° on a few days when the sub-solar point is ~70°E in longitude and ~1.5°S in latitude, such as on 19 November 2007. Meanwhile, when the sub-solar point becomes far from ~70°E in longitude, the illuminated areas on the inner wall of Shackleton decreases, and the floor remains in darkness. Similarly bright conditions occurred around 18 December 2007 as anticipated, and we obtained additional clear images of the crater interior then. After December 2007, the solar elevation angle decreased, and the inside of Shackleton was less lit. The next time the bottom of Shackleton Crater will be maximally lit will occur around 7 November 2008. Based on the observed shape parameters from the TC DTM, we were able to estimate the surface temperature of the PSA of the crater floor [see the supporting online material (SOM) text] (Fig. 1E). We assumed that the crater has a Lambert diffusive surface and the same albedo between the inner wall and the floor and that the solar elevation angle is 3.0° on the date of its most illuminated condition (for example, 19 November 2007), as in Fig. 1A. As is seen in Fig. 1E, the highest estimated temperature is ~88 K in the center of the floor. The floor temperature was largely determined by the radiation in the infrared range and not by that in the visible range. Thus, the shape parameters, particularly its depth, predominated because the infrared radiation in the crater rapidly decreases as its area increases. The surface visual albedos and scattering laws were almost negligible in estimating the temperature. The loss rate of any ice by vaporization at 90 K is approximately 10^{-26} to 10^{-27} m/s (*9*). Therefore, any water vapor brought here by comets or meteorites could have been trapped for billions of years.

However, we could not find any conspicuously bright areas in Shackleton Crater. The hemispherical visual albedo around the center of the crater

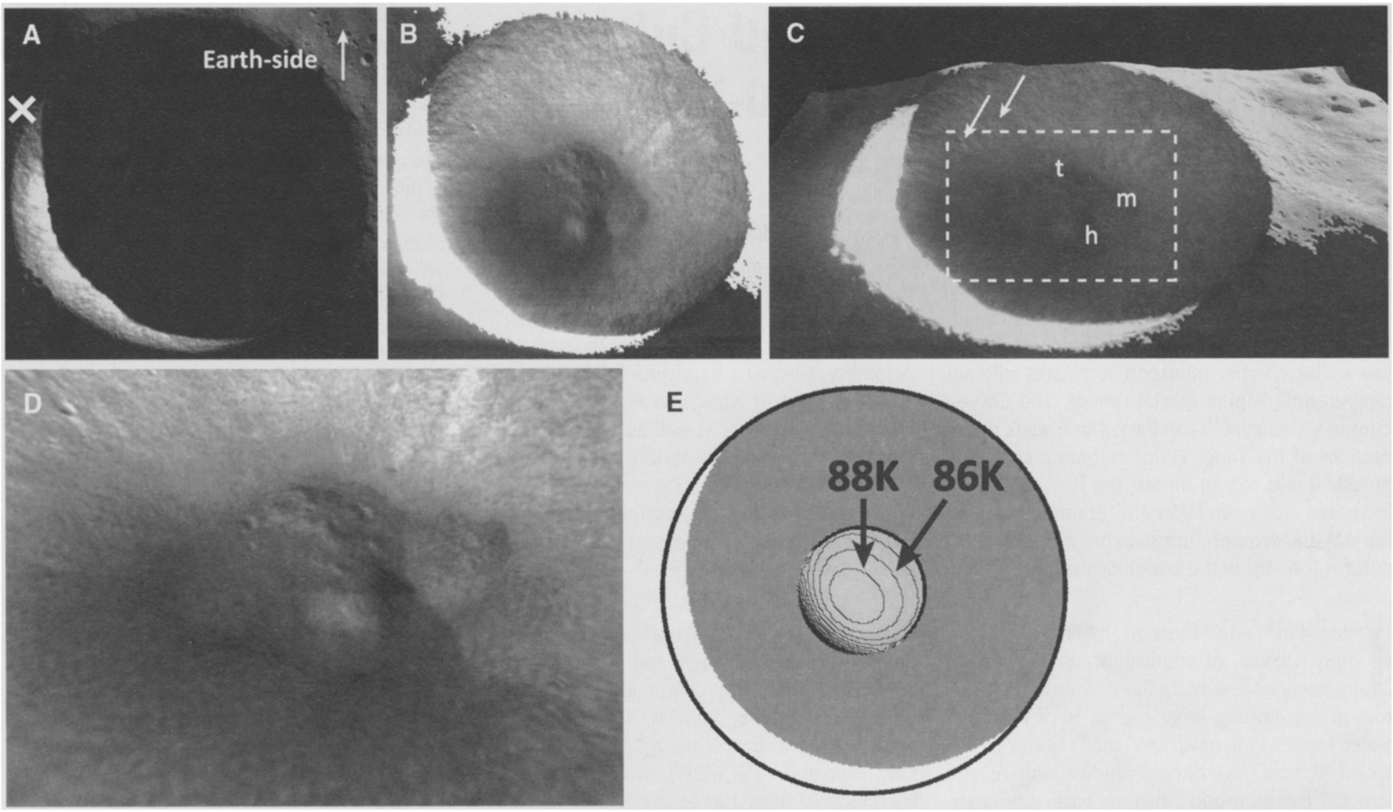

Fig. 1. Inside Shackleton Crater, a crater ~10.5 km across near the lunar south pole. **(A)** Image taken by the SELENE TC on 19 November 2007. The crescent in the image is the portion of the crater's inner wall illuminated by sunlight. The lunar south pole is on the upper left, indicated by cross. **(B)** An enhanced image of (A). The permanently shadowed area inside Shackleton Crater is lit by scattered light from the illuminated portion of the upper wall. No deposit with a significant albedo anomaly is exposed on the floor. **(C)** A perspective view of Shackleton Crater, produced from the DTM that was based on TC stereo-pair data and the brightness-enhanced image [similar to (B)]. A few craters hundreds of meters in diameter exist on the inner wall; some examples are indicated by arrows. The mound-like feature (m) (~300 to 400 m in thickness) is probably the result of downslide movements of materials from the inner wall. The central hill (h) is ~200 m in height and associated with a terrace-like terrain (t) with several hundred-meter–scale craters. **(D)** A closer view of the rectangular area marked in (C). **(E)** Simulated temperature distribution inside the crater floor made with data from 19 November 2007 (see the SOM text for details of the simulation). The contour interval is 2 K. The maximum temperature of the floor is ~88 K near the center, which is cold enough to retain water-ice; however, temperature information alone does not settle whether there is water-ice on the lunar poles. The temperature distribution of the inner wall is not indicated in this figure.

floor was found to be 0.23 ± 0.05 (SOM text), which is similar to that around the crater. The incident angles for the inner wall, which is illuminated by direct solar radiation, and for the floor, which is illuminated by the scattered light from the inner wall, were both ~60°. Under such conditions, the derived hemispherical visual albedo, assuming the Lambert diffusive law, is probably overestimated (*10*). Considering that the lunar far-side averaged albedo is 0.22 (*11*) and that of pure water-ice is ~1.0 (*9*), we conclude that there is no extensively exposed pure water-ice deposit occupying an area larger than that seen in the TC's spatial resolution.

Water-ice on the floor of Shackleton Crater may be "dirty" (mixed with soil and disseminated) at only 1 to ~2 weight percent (*12*). Small amounts of water-ice in a soil mixture do not strongly affect the surface brightness. Because the maximum floor albedo is 0.28, and assuming the albedo of lunar soil to be 0.22 and the albedo of water-ice to be 1.0, the area fraction of the exposed surface ice in an area of TC's resolution (10 by 10 m) is probably less than a few percent [(0.28 – 0.22)/(1 – 0.22)/(a factor due to overestimating the floor albedo)]. Alternatively, water-ice that is present may be buried by a thin regolith (lunar soil) layer and, when exposed by impacts, may be largely removed from the uppermost surface by various space weathering processes (*13*). Another possible explanation of the lunar pole hydrogen is that it is from the direct implantation of solar-wind protons into the lunar surface (*14*). This latter interpretation does not require the presence of any water-ice.

References and Notes

1. W. C. Feldman *et al.*, *Science* **281**, 1496 (1998).
2. K. Watson, B. C. Murray, H. Brown, *J. Geophys. Res.* **66**, 3033 (1961).
3. J. R. Arnold, *J. Geophys. Res.* **84**, 5659 (1979).
4. S. Nozette *et al.*, *Science* **274**, 1495 (1996).
5. S. Nozette *et al.*, *J. Geophys. Res.* **106**, 23253 (2001).
6. D. B. Campbell *et al.*, *Nature* **443**, 835 (2006).
7. J. Haruyama *et al.*, *Earth Planets Space* **60**, 243 (2008).
8. R. J. Pike, in *Impact and Explosion Cratering*, D. J. Roddy, R. O. Pepin, R. B. Merrill, Eds. (Pergamon, New York, 1977) pp. 489–509.
9. T. Mukai *et al.*, *Adv. Space Res.* **19**, 1497 (1997).
10. B. Hapke, in *Theory of Reflectance and Emittance Spectroscopy*, (Cambridge Univ. Press, NY, 1993).
11. NASA, "Lunar surface models NASA space vehicle design criteria" (Technical Rep. SP-8023, NASA, Washington, DC, 1969).
12. W. C. Feldman *et al.*, *J. Geophys. Res.* **105**, 4175 (2000).
13. D. H. Crider, R. R. Vondrak, *J. Geophys. Res.* **108**, 5079 10.1029/2002JE002030 (2003).
14. L. V. Starukhina, *Icarus* **147**, 585 (2000).
15. We thank all the contributors to the SELENE (Kaguya) project, especially members of the project management group (Y. Takizawa, M. Kato, S. Sasaki, R. Nagashima, K. Tsuruda, and H. Mizutani) and the Lunar Imager/Spectrometer (LISM) working group (H. Otake, H. Kawasaki, R. Nakamura, S. Kodama, S. Minami, S. Takechi, A. Akiyama, T. Yokota, T. Arai, T. Sugihara, Y. Yamaguchi, S. Sasaki, N. Asada, H. Demura, N. Hirata, J. Terazono, T. Hiroi, T. Hashimoto, T. Michikami, K. Kitazato, M. Higa, P. Pinet, T. Nimura, T. Yamamoto, N. Harada, K. Iseki, T. Hodokuma, S. Kikuchi, S. Kawabe, S. Okuno, and T. Takayama) for their efforts in the development, operation, and data processing of SELENE and LISM/TC. We thank the three anonymous reviewers for their helpful comments. This work was supported by KAKENHI (grants 20540416 to J.H. and C.H. and 20.9211 to T. Morota).

Supporting Online Material

www.sciencemag.org/cgi/content/full/1164020/DC1
SOM Text
References

31 July 2008; accepted 30 September 2008
Published online 23 October 2008;
10.1126/science.1164020
Include this information when citing this paper.