Vol 443 | 19 October 2006 | doi:10.1038/nature05167

No evidence for thick deposits of ice at the lunar south pole

Donald B. Campbell[1], Bruce A. Campbell[2], Lynn M. Carter[2], Jean-Luc Margot[1] & Nicholas J. S. Stacy[3]

Shackleton crater at the Moon's south pole has been suggested as a possible site of concentrated deposits of water ice, on the basis of modelling of bi-static radar polarization properties and interpretations of earlier Earth-based radar images[1,2]. This suggestion, and parallel assumptions about other topographic cold traps, is a significant element in planning for future lunar landings. Hydrogen enhancements have been identified in the polar regions[3], but these data do not identify the host species or its local distribution. The earlier Earth-based radar data lack the resolution and coverage for detailed studies of the relationship between radar scattering properties, cold traps in permanently shadowed areas, and local terrain features such as the walls and ejecta of small craters. Here we present new 20-m resolution, 13-cm-wavelength radar images that show no evidence for concentrated deposits of water ice in Shackleton crater or elsewhere at the south pole. The polarization properties normally associated with reflections from icy surfaces in the Solar System[4–6] were found at all the observed latitudes and are strongly correlated with the rock-strewn walls and ejecta of young craters, including the inner wall of Shackleton. There is no correlation between the polarization properties and the degree of solar illumination. If the hydrogen enhancement observed by the Lunar Prospector orbiter[3] indicates the presence of water ice, then our data are consistent with the ice being present only as disseminated grains in the lunar regolith.

The possible presence of water-ice deposits in the polar areas of the Moon has been a controversial issue since the mid-1990s. The 1.6° inclination of the Moon's rotation axis to the normal to the ecliptic plane means that there are areas near the poles, primarily the floors and lower interior walls of impact craters, that are in permanent shadow from the Sun. Several researchers[7,8] have pointed out that ice could be stable at the low temperatures (<100 K) expected in these shadowed areas, and the idea was given significant impetus by the discovery of probable ice deposits at the poles of Mercury by Earth-based radars[9,10]. The radar echoes from Mercury's poles were interpreted as reflections from water ice on the basis of their similarity to the unusual properties of radar echoes from the icy Galilean satellites of Jupiter[4]. Low-temperature water-ice surfaces can exhibit a very strong opposition effect; that is, they preferentially scatter the incident energy back towards the radar. They also preferentially reflect the same sense of circular polarization that was transmitted, leading to a circular polarization ratio (CPR, the ratio of the reflected power in the same circular (SC) sense of polarization transmitted to that in the opposite (OC) sense) greater than unity. A mirror-like reflection would have a CPR of zero, and most geological surfaces have a CPR of less than unity[11]. It is thought that these properties of the radar reflection are related to the very small propagation loss of low-temperature water ice by means of a coherent backscatter opposition effect (CBOE), the coherent addition of a ray that propagates into the ice, is scattered and emerges in the direction of the radar, with its path-reversed twin[12]. Laboratory experiments using lasers on assemblages of particles indicate that volume scattering in a low-loss medium is not necessarily required; the CBOE can also be exhibited by a rough scattering surface[13]. The polar deposits on Mercury are thought to be water ice or some other condensate[14] because they are located only on those parts of impact crater floors that are in permanent shadow[15].

The first reports that there might be deposits of water ice at the lunar south pole arose from bi-static radar observations of very low spatial resolution in 1994, with the 13-cm-wavelength telemetry system of the Clementine orbiter as a transmitter and one of the 70-m NASA/Deep Space Network antennas to receive the echo[1]. The south pole was observed at a viewing angle of 4.5–5.5° (the angle of the 70-m DSN antenna above the horizon at the lunar south pole) over a small range of bi-static phase angles centred on zero (that is, on opposition). A ~25% increase in the CPR was observed as the bi-static angle passed through zero. This increase was observed only for the pass over the south pole and was interpreted as indicating the probable presence of low-loss volume scatterers such as water ice[1]. Subsequent analysis of the bi-static data led to the suggestion that ~10 km^2 of ice might be present on the lower, permanently shadowed, part of the Earth-facing inner slope of the 19-km-diameter south pole crater, Shackleton[2]. This location was selected to be coincident with an area of high CPR discovered in 125-m-resolution radar imagery obtained in 1992 with the 13-cm radar system on the US National Science Foundation's (NSF's) Arecibo telescope in Puerto Rico[16]. The Arecibo observations were made at a south pole viewing angle of 6.1°. However, in addition to the Earth-facing inner wall of Shackleton crater, many small, probably fresh, craters exhibited CPRs with values ranging from 1.0 to 2.4 (ref. 16). Similar CPR values were observed for several small areas in Sinus Iridum that are clearly sunlit (at latitude ~47° N), leading to the suggestion that the high CPRs were due to scattering in very rough or blocky terrain[16].

To investigate further the radar scattering properties of the terrain at the south pole of the Moon, and of Shackleton crater in particular, we have made radar imaging observations at spatial resolutions as fine as 20 m. In April and October 2005 we used the Arecibo telescope to transmit a right circularly polarized signal at 13 cm wavelength and received the echo in both senses of circular polarization with the NSF's 100-m Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, USA. The GBT is ~2,300 km from Arecibo, corresponding to a bi-static angle of 0.37°. Results of our observations on 16 April and 24 October 2005, when the viewing angle for the south pole was close to maximum at ~6.5°, are reported here. The April data provided imagery, with a high signal-to-noise ratio, at 20 m resolution, significantly higher resolution than for any previous observations. However, the relative calibration between the channels was poor,

[1]Department of Astronomy, Cornell University, Ithaca, New York 14853, USA. [2]Center for Earth and Planetary Studies, Smithsonian Institution, Box 37012, Washington, DC 20013-7012, USA. [3]Defence Science and Technology Organization, Box 1500, Edinburgh, SA 5111, Australia.

making absolute measurements of the CPR difficult. Well-calibrated 100-m-resolution data from October were used to calibrate the CPR values obtained from the April data.

Figure 1a is the OC radar backscatter image from October covering the south pole and terrain on the lunar nearside north to about 68° S. The CPR values overlaid on this image are shown in Fig. 1b. The geology of the south-pole region is dominated by highland terrain formed by overlapping ejecta from nearby craters and the major basins. Shackleton (Fig. 2a) seems to be younger than neighbouring craters such as de Gerlache, Shoemaker or Faustini, and probably dates to the Eratosthenian period, consistent with earlier geological mapping[17]. Low-lying areas between the highland massifs (for example the region to the west of de Gerlache), and many of the radar-visible older crater floors, are characterized by smooth-textured terrain that has been mapped as basin-related ejecta, most probably from Orientale[18,19]. These deposits have high CPRs relative to the surrounding terrain at both 13-cm (Fig. 1b) and 70-cm wavelengths[18], indicating a greater abundance of centimetre-scale to decimetre-scale rocks within the upper few metres of the regolith.

Figure 1b shows many locations with CPRs ranging from 1.0 to 1.5 or more. The measured values of the CPR are within 20% of those obtained from the 1992 lower-spatial-resolution 13-cm imaging[16]. As was postulated on the basis of the lower-resolution data[16], there is a clear correlation between high values of the CPR and the walls and ejecta deposits of both large and small craters. These high values raise two questions: first, are they in any way indicative of the presence of water ice, and second, if not water ice, then what combination of surface morphology and scattering mechanism is responsible?

Shackleton crater (Fig. 2a) is of considerable interest for NASA's lunar exploration programme because of the suggested presence of water ice on its Earth-facing inner slope[2], and because a few locations on its rim may be permanently sunlit for periods of up to 200 days each year, making them suitable for extended human habitation[20]. The upper portion of Shackleton's Earth-facing inner rim can be seen in both Lunar Orbiter and Clementine visible imagery, indicating that it is sunlit at least part of the time; any detected ice deposits would have to be located on areas lower down on the wall. Our new, high-resolution data (Fig. 2b) show that there is no systematic variation in the CPR with distance down the (radar) visible part of the inner slope, and high CPR values occur in seasonally sunlit regions of the crater wall and the near-rim ejecta blanket.

Shackleton is morphologically similar to the 17 km crater Schomberger G (77.1° S, 7.7° E; Fig. 2c). Both seem to have layered outcrops, or terraces, within the upper few hundred metres of their interior rim deposits, which could make access to the interior walls very challenging. The CPR values for the inner Earth-facing slope of Schomberger G (Fig. 2d), which is sunlit during the lunar diurnal cycle, are almost identical to those of Shackleton. The inner and outer walls and floor of the nearby 31-km Copernican-period crater Schomberger A (78.8° S, 24.4° E) have CPR values of 1.5 and greater (Fig. 1b), as do many other smaller young craters. It is clear that CPR values greater than 1 do not require the presence of water ice and are therefore not necessarily indicative of the presence of ice. For Schomberger A and G, and numerous other craters, the high ratios must instead be associated with scattering from the rocks and blocky material that comprise the proximal ejecta or that have cascaded down the steep inner slopes. This scattering could exhibit an opposition effect that, like its optical counterpart, includes a component arising from a CBOE. High CPR values are not confined to the Moon. They have also been observed for three near-Earth asteroids with measured values between 1.0 and 1.2 (ref. 21), for Maxwell Montes on Venus with similar values[22], and for the SP lava flow near Flagstaff,

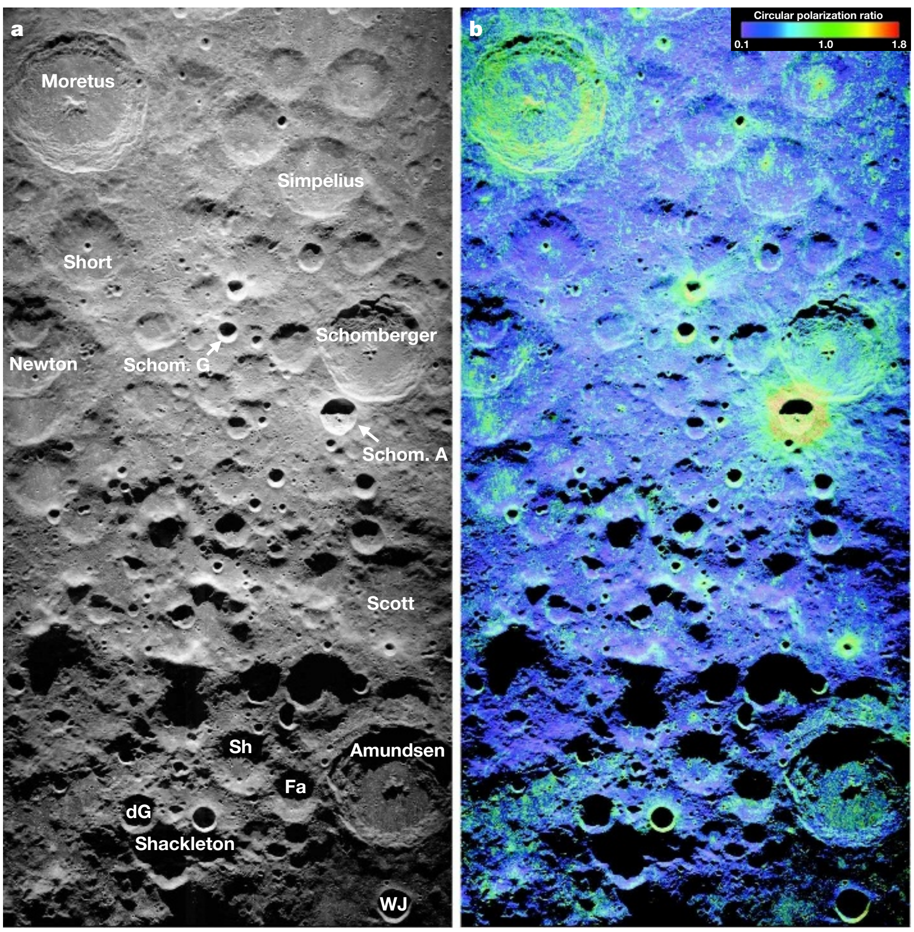

Figure 1 | Radar image data from 24 October 2005, for a region covering the south pole and the nearside to latitude ~68° S. The south pole is on the left rim of Shackleton. North is 3.5° anticlockwise from the centreline of this image (0° longitude grazes the east rim of Moretus). Spatial resolution 100 m per pixel; polar stereographic projection. **a**, OC radar image at 100 m resolution. Major craters labelled: Sh, Shoemaker; Fa, Faustini; dG, de Gerlache; WJ, Wiechert J. **b**, CPR at 500 m resolution presented as a colour overlay on the radar backscatter image. Note the very high CPRs for Schomberger A and many other smaller craters.

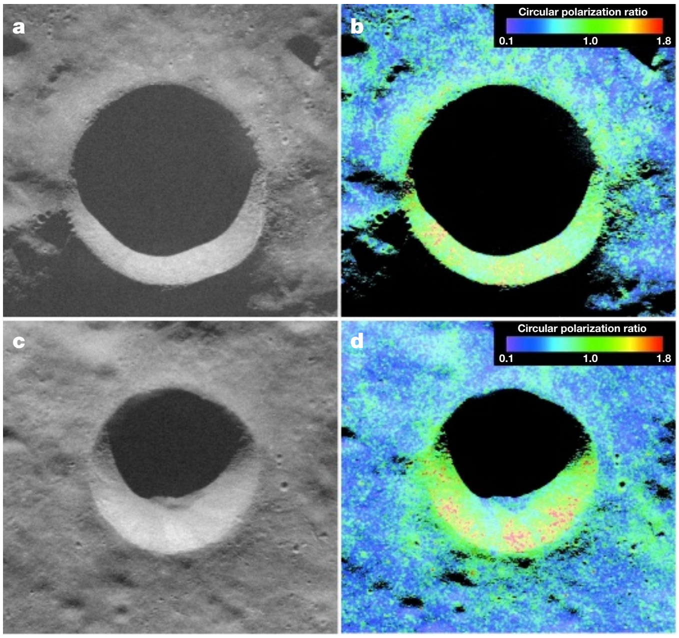

Figure 2 | Comparison of the radar-scattering properties of Shackleton and Schomberger G craters from the 16 April 2005 data. a, The SC radar image at 20 m resolution for the 19-km diameter Shackleton crater at an incidence angle of ~83.5°. **c**, A similar image for the 17-km Schomberger G crater at an incidence angle of ~70°. The two craters seem to be of similar ages. Terraced structures can be seen in the top few hundred metres of the interior deposits, and the inner wall of Schomberger G shows evidence for down-slope mass wasting. **b**, **d**, The CPRs for Shackleton (**b**) and Schomberger G (**d**) at 220 m resolution overlaid on the radar images. The CPRs have been adjusted to be identical to the calibrated but lower-resolution values of Fig. 1 (see the text).

Arizona, USA, which has CPR values of up to 2.0 at 24 cm wavelength[23]. Water ice clearly has no function in radar scattering from these surfaces.

Strong evidence that the CPR values in Shackleton are due to a component of volume-scattering ice must certainly include a high degree of correlation between the occurrence of high CPR values and the transition from seasonally sunlit to permanently shadowed portions of the crater wall. Although available topographic data[24] do not show the precise location of this transition, it is within the area viewed by our mapping. The area of strongest CPR within Shackleton (at about the 8 o'clock position in Fig. 2b), cited as supporting the existence of a CBOE effect in the shadowed terrain on the basis of the lower-resolution 1992 data[2], is resolved here into a collection of high-CPR points that occur in both permanent shadow and seasonal illumination. In the absence of any strong difference in properties with solar illumination, the possibility that these features are linked with rocky debris, as observed at Schomberger G and elsewhere, remains the more likely explanation.

Neutron spectrometer measurements from the Lunar Prospector orbiter in 1998 indicated the presence of significant concentrations of hydrogen in the lunar regolith at the south pole[3]. Assuming that the hydrogen is in the form of water molecules, modelling[25] shows that the neutron measurements are consistent with a concentration of $1.5 \pm 0.8\%$ by mass of ice in the upper 1 m or so of the lunar regolith. If this ice is distributed as grains in the regolith at this concentration, or locally at higher concentrations, then it would not be observable with radar. If it is in the form of deposits of ice that are decimetres to 1 m or more thick, then it might be observable with radar by means of the CBOE.

Our high-resolution radar data show no evidence that high CPR values in Shackleton, or elsewhere in the south polar region, are correlated with solar illumination conditions. Rather, these high CPR values are associated with the rugged inner walls and proximal ejecta of impact craters. This is consistent with the presence of any water ice being only as disseminated grains at 1–2% abundance[25]. Any planning for future exploitation of hydrogen at the Moon's south pole should be constrained by this low average abundance rather than by the expectation of localized deposits at higher concentrations.

Received 3 April 2006; accepted 15 August 2006.

1. Nozette, S. *et al.* The Clementine bi-static radar experiment. *Science* **274**, 1495–1498 (1996).
2. Nozette, S. *et al.* Integration of lunar polar remote sensing data sets: Evidence for ice at the lunar south pole. *J. Geophys. Res.* **106**, 23253–23266 (2001).
3. Feldman, W. C. *et al.* Fluxes of fast and epithermal neutrons from Lunar Prospector: Evidence for water ice at the lunar poles. *Science* **281**, 1496–1500 (1998).
4. Campbell, D. B., Chandler, J. F., Ostro, S. J., Pettengill, G. H. & Shapiro, I. I. Galilean satellites—1976 radar results. *Icarus* **34**, 254–267 (1978).
5. Harmon, J. K., Arvidsen, R. E., Guinness, E. A., Campbell, B. A. & Slade, M. A. Mars mapping with delay-Doppler radar. *J. Geophys. Res.* **104**, 14065–14090 (1999).
6. Black, G. J. & Campbell, D. B. Rhea's surface: Ice properties measured by radar. *Bull. Am. Astron. Soc.* **36**, 1123 (2004).
7. Watson, K., Murray, B. C. & Brown, H. The behavior of volatiles on the lunar surface. *J. Geophys. Res.* **66**, 3033–3045 (1961).
8. Arnold, J. R. Ice at the lunar poles. *J. Geophys. Res.* **84**, 5659–5668 (1979).
9. Slade, M. A., Butler, B. J. & Muhleman, D. O. Mercury radar imaging: Evidence for polar ice. *Science* **258**, 635–640 (1992).
10. Harmon, J. K. & Slade, M. A. Radar mapping of Mercury: Full disk images and polar anomalies. *Science* **258**, 640–643 (1992).
11. Campbell, B. A. *Radar Remote Sensing of Planetary Surfaces* (Cambridge Univ. Press, Cambridge, 2002).
12. Hapke, B. Coherent backscatter and the radar characteristics of the outer planet satellites. *Icarus* **88**, 407–417 (1990).
13. Nelson, R. M., Hapke, B. W., Smythe, W. D. & Horn, L. J. Phase curves of selected particulate materials: The contribution of coherent backscattering to the opposition surge. *Icarus* **131**, 223–230 (1998).
14. Sprague, A. L., Hunten, D. M. & Lodders, K. Sulfur at Mercury, elemental at the poles and sulfides in the regolith. *Icarus* **118**, 211–215 (1995).
15. Harmon, J. K., Perillat, P. J. & Slade, M. A. High-resolution radar imaging of Mercury's north pole. *Icarus* **149**, 1–15 (2001).
16. Stacy, N. J. S., Campbell, D. B. & Ford, P. G. Arecibo radar mapping of the lunar poles: A search for ice deposits. *Science* **276**, 1527–1530 (1997).
17. Wilhelms, D. E., Howard, K. A. & Wilshire, H. G. *USGS Map I-1162* (US Geological Survey, Washington DC, 1979).
18. Campbell, B. A. & Campbell, D. B. Regolith properties in the south polar region of the Moon from 70-cm radar polarimetry. *Icarus* **180**, 1–7 (2006).
19. Campbell, B. A. & Hawke, B. R. Radar mapping of lunar cryptomaria east of Orientale basin. *J. Geophys. Res.* **110** (E9), E09002 (2005).
20. Zuber, M. T. & Garrick-Bethell, I. What do we need to know to land on the Moon again? Perspective article. *Science* **310**, 983–985 (2005).
21. Benner, L. A. M. *et al.* Radar detection of near-Earth asteroids 2062 Aten, 2101 Adonis, 3103 Eger, 4544 Xanthus, and 1992 QN. *Icarus* **130**, 296–312 (1997).
22. Campbell, B. A., Campbell, D. B. & DeVries, C. Surface processes in the Venus highlands: Results from analysis of Magellan and Arecibo data. *J. Geophys. Res.* **104**, 1897–1916 (1999).
23. Campbell, B. A., Arvidson, R. E. & Shepard, M. K. Radar polarization properties of volcanic and playa surfaces: Applications to terrestrial remote sensing and Venus data interpretation. *J. Geophys. Res.* **98**, 17099–17114 (1993).
24. Margot, J. L., Campbell, D. B., Jurgens, R. F. & Slade, M. A. Topography of the lunar poles from radar interferometry: A survey of cold trap locations. *Science* **284**, 1658–1660 (1999).
25. Feldman, W. C. *et al.* Evidence for water ice near the lunar poles. *J. Geophys. Res.* **106** (E10), 23231–23252 (2001).

Acknowledgements We thank the staff of the Arecibo and Green Bank Observatories for their assistance with the observations, and J. Chandler for providing the lunar ephemeris observing files. This work was supported in part by grants from the NASA Planetary Astronomy and Planetary Geology and Geophysics Programs. The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the US National Science Foundation. The Green Bank Telescope is part of the National Radio Astronomy Observatory, a facility of the NSF operated under a cooperative agreement by Associated Universities, Inc.

Author Contributions The work was initiated by D.B.C., who also wrote the initial draft of the paper. D.B.C., B.A.C., L.M.C. and J.-L.M. planned and made the observations. Software development and data reduction were done by B.A.C, L.M.C.and J.-L.M. All authors participated in the interpretation of the results.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Correspondence and requests for materials should be addressed to D.B.C. (campbell@astro.cornell.edu).