Lack of Exposed Ice Inside Lunar South Pole Shackleton Crater

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, Jean-Luc Jossel

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 cold surface 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 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. Because the present rotation inclination of the Moon is nearly zero (~1.5° from 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 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, although they could observe only a small upper part of the inner wall of Shackleton.

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 scattered 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 an 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 and elongated toward the inner wall. It has a number of depressions that are probably craters.

The inner wall slopes ~3°, 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° on a few days when the sub-solar point is ~70°E in longitude and ~1.5°S in latitude, 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 in 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 that the same albedo between the inner wall and the floor and that the solar elevation angle is 3° 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, were determined 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 is associated with the hill and is elongated toward the inner wall. It has a number of depressions that are probably craters.
The floor was found to be $0.23 \pm 0.05$ (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 $\sim 60^\circ$. Under such conditions, the derived hemispherical 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 $\sim 1.0$ (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 $\sim 2$ 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 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 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

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Supporting Online Material

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