SHALLOW SUBSURFACE STRUCTURE OF THE MOON AT THE CHANG'E-3 LANDING SITE AS REVEALED BY THE LUNAR PENETRATING RADAR. Wenzhe Fa[1], Meng-Hua Zhu[2], Tiantian Liu[1], and Jeffery B. Plescia[3], [1]Institute of Remote Sensing and Geographical Information System, Peking University, Beijing 100871, China (wzfa@pku.edu.cn), [2]Space Science Institute, Macau University of Science and Technology, Macau, China, [3]The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.

Introduction: Near surface structure of the Moon not only preserves important information about the geology and impact history of the Moon, but also is critical for quantifying potential resources for future lunar exploration and engineering constraints for human outposts [1]. During the Apollo era, regoliths at a few sites were sampled to a maximum depth of 3 m through core tube experiments, showing that upper regolith is composed of numerous localized layers [1, 2]. The high frequency radar sounders onboard the Apollo 17 and Kaguya missions can detect lunar subsurface structure down to a depth from hundred meters to several kilometers, nevertheless, their coarse range resolutions (tens of meters) make them impossible to image shallow subsurface structure [3, 4].

On December 14, 2013, China's Chang'E-3 (CE-3) spacecraft successfully landed in the northern Mare Imbrium at 44.1213°N, 19.5115°W. The landing site is within a geologic unit consisting of high-titanium basalts, with a model-surface age of 2.96 Gyr [5]. The landing site is about 50 m from the east rim of a 500 m diameter crater (unofficially named as CE-3 crater). According to the inner wall slope (18°), depth/ diameter ratio (1/10), and boulder distributions, age of the CE-3 crater is estimated as about 100 Myr [6]. The lunar penetrating radar (LPR) aboard the Yutu rover provides a unique chance to map subsurface structure associated with this young crater.

The Lunar Penetrating Radar Experiment: CE-3 LPR is an ultra wide band ground penetrating radar that operates at two center frequencies, 60 and 500 MHz [7]. The bandwidths of the two channels are 40 and 450 MHz, respectively, corresponding to a range resolution of 3.75 and 0.3 m in vacuum. According to the regolith composition (19.5 wt.% FeO and 5.2 wt.% TiO_2 [8]), dielectric constant of the regolith at the landing site is estimated to be 3+0.03i [9]. This corresponds to a skin depth about 10 LPR wavelengths [9], which is about 50 m for the first channel and 6 m for the second channel.

The LPR started working on December 15, 2013, and the effective observation time is about 8.3 hours during the two-month lifetime of the Yutu rover. During its surface traverse for a distance of about 110 m (Fig. 1), 9871 and 19446 tracks of raw data were obtained in total by the first and second channels, respectively. In this study, we only show shallow subsurface structure observed from the 500 MHz channel. In order to remove the noise and increase the contrast and sharpness of the data, the raw data were processed through repetitive observation removal, horizontal band removal, band-pass filter, compensation of geometry spreading and dielectric attenuation, and range migration [10]. The processed LPR data are displayed in B-scan format as a function of horizontal distance and apparent depth (Fig. 2).

Subsurface Structure at the CE-3 Landing Site: In Fig. 2, the most prominent features within the first meter are the three to five bright layers. These layers are irregular and their thickness varies laterally with typical values of 0.3-0.5 m. The lateral continuity of these layers is typically more than three meters, but few of them extend more than 10 m (e.g., from S1 to S3). These layers are probably layers of ejecta from small local craters that were later modified by micrometeorite bombardment and solar wind. The region containing these layers represents the regolith formed on the ejecta of the CE-3 crater. This region can be interpreted as the reworked zone. Similar near-surface layering was found at the Apollo and Luna landing sites by the core tubes [11, 12].

Below the reworked zone, at an apparent depth from about 1 to 10 m, is a region with bright radar echo. There are substantial variations in the thickness of this layer. We interpreted this region as the continuous ejecta from the CE-3 crater. This region contains numerous, chaotic, irregular layers, and hyperbolic curves. The lateral continuity of these irregular layers is typically less than 3 m. These layers might result from irregular interface geometry or discontinuities of the dielectric properties, or densely distributed rocks much smaller than the LPR wavelength [13]. The hyperbolic curves are interpreted as subsurface rocks fragmentized during the formation of the CE-3 crater. Given to a 0.6 m LRP wavelength, the sizes of buried rocks are probably larger than 1 m. The eccentricity of the hyperbolic curves indicates a mean dielectric permittivity of 3.2, corresponding to a mean bulk density of 1.8 g/cm^3 for this region.

Below the ejecta layer is a region with weak radar echoes. The thickness of this layer decreases from about 9 m to 4 m with increasing distance from the CE-3 crater. The distinct features in this region are the three subsurface interfaces that occur almost throughout the entire LPR transect. This region is relatively homogeneous, and only few hyperbolic curves are visible. This region is probably the regolith layer produced on top of the mare basalts during 2.96 Gyr and was later buried by the ejecta of the CE-3 crater. Thus, this region can be regarded as a paleoregolith.

Beneath the paleoregolith layer, at an apparent depth of about 20 m, the strength of radar echoes increases and numerous chaotic irregular layers appear again, indicating an increase of subsurface rocks. This is the transition zone between the paleoregolith layer and the underlying mare basalts. During the formation of the paleoregolith, coherent mare basalt at the base of the paleoregolith was fractured or fragmented, but not excavated, resulting in a transition zone that contains numerous large fragments. Below this transition zone should be the mare basalt, but it is not observed in the LPR data because of its limited penetration depth.

Conclusions: According to the LPR data, near surface structure at the CE-3 landing site can be constructed as: a surface reworked zone with a thickness less than 1 m, followed by an ejecta layer with a thickness of 2-6 m, a paleoregolith layer of 4-9 m thickness, a transition zone with large fragments, and the underlying mare basalts. Even for a lunar surface as young as 100 Myr, subsurface stratigraphic structure can be very complex. In addition, there are substantial variations in the thickness of each zone, implying that each small region experienced a unique history. These results provide valuable information for understanding the modification of lunar surface and evolution of the regolith, and are also important as a reference for future lunar sample return missions.

Acknowledgements: CE-3 data were provided by the Lunar and Deep Space Exploration Department, National Astronomical Observatories, Chinese Academy of Sciences (NAOC).

References: [1] Heiken G. H. et al. (1991) New York: Cambridge Univ. Press. [2] Vinogradov A. P. (1971) *LPSC II*, 1–16. [3] Ono T. et al. (2010) *Space Sci. Rev.*, *154*, 145–192. [4] Porcello L. J. et al. (1974) *Proc. IEEE, 62*, 769–783. [5] Hiesinger H. et al. (2000) *JGR, 105*, 29239–29275. [6] Lu Y. et al. (2014) *LPSC XXX XV*, Abstract #1116. [7] Fang G. Y. et al. (2014) *RAA, 14*, 1607–1622. [8] Prettyman T. H. et al. (2007) *JGR, 111*, E12007. [9] Fa W. (2013) *JAG, 99*, 98–108. [10] Daniels D. (2004) London: IEE Press. [11] McKay D. S. et al. (1980) *LPSC XI*, 1531–1550. [12] Mitchell J. K. et al. (1973) *LPSC IV*, 2437–2445. [13] Liu L. et al. (2013) *JAG, 99*, 68–75.

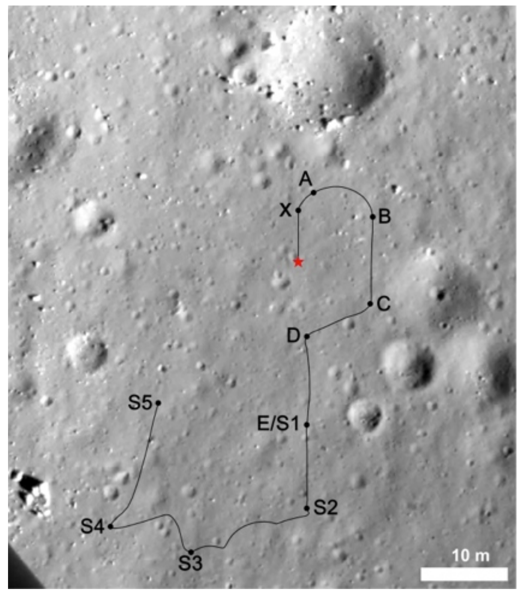

Figure 1. An optical image from CE-3 landing camera showing the route of the Yutu rover, the red star is the CE-3 landing site, and X, A, … S4, S5 are surface navigation points.

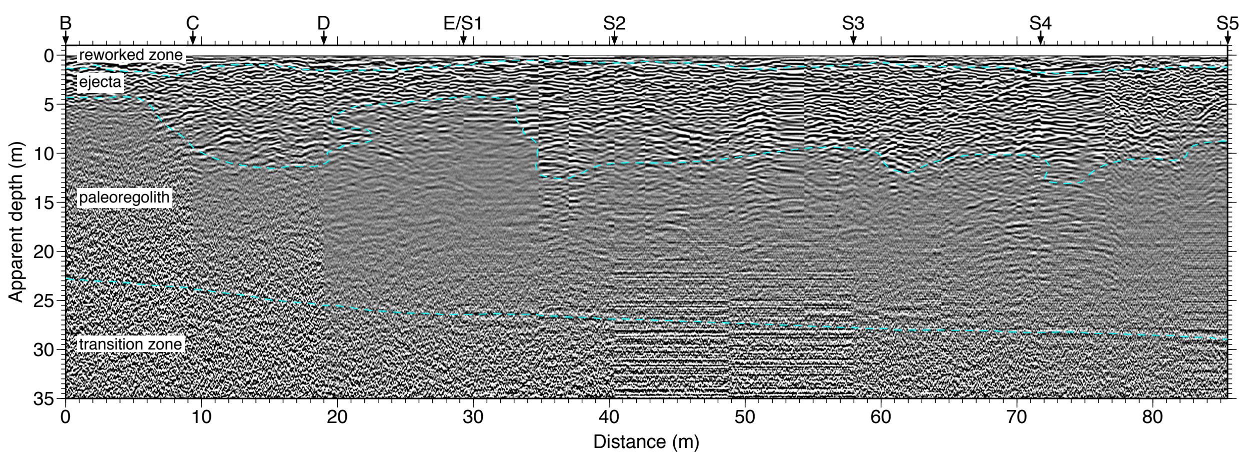

Figure 2. LPR image at 500 MHz from Point B to S5 along the Yutu survey line. The image is processed after band removal, band-pass filter, and compensation for geometry spreading and dielectric attenuation.