DETERMINATION OF STRATIGRAPHIC AGE OF THE LUNAR MARE SUBSURFACE BOUNDARY IDENTIFIED FROM THE SELENE RADAR SOUNDER DATA K. Ishiyama¹, A. Kumamoto¹, and N. Nakamura¹, ¹Graduate School of Science, Tohoku University(Aramaki Aza-Aoba, Aoba-ku, Sendai 980-8578, Japan. E-mail: ishiyama@stpp.gp.tohoku.ac.jp)

Introduction: Lunar mare is a region that thickly covered with the basaltic rock. The geological information of the mare region (e.g., stratigraphy, eruption age, composition, and topography) is significant for understanding the lunar volcanic activity and the tectonics process. This information is often compiled in the form of the geological map.

The many geologists has produced and updated the lunar geological map, which is mainly focused on the lunar surface information. Most geological map are produced as follows [e.g., 1, 2]: (i) The lava flow units are identified based on the surface composition (e.g., titanium and iron), (ii) The eruption age of the lava flow units are determined based on the crater chronology, (iii) The location of characteristic topographies such as crater, graben (i.e., valley), and ridge (i.e., mountain) are identified from the termini data. Through the processes mentioned above, we can infer the stratigraphy of the lava flow units also [e.g., 3].

More accurate estimation of the subsurface lava flow unit laid below the surface lava flow unit are also possible by the analysis of the ejecta composition around the impact crater on the basis of the multiband image data [e.g., 4] and the analysis of the subsurface boundary on the basis of the radar sounder data [e.g., 5]. The ALSE (Apollo Lunar Sounder Experiment) onboard the Apollo 17 spacecraft [6] and the LRS (Lunar Radar Sounder) onboard the SELENE (KAGUYA) spacecraft [7] can provide the subsurface structure data observed in the lunar mare region. The ALSE observed the mare subsurface structures in low latitude. The LRS succeeded in global observation of the mare subsurface structures. Using the LRS data, the previous study [5] roughly determined the thickness, the volume, and the flux rate of the lava flow unit in several maria. However, the information of the lunar subsurface boundary has not yet integrated into the geological map data.

In this study, we obtained the depths of the subsurface boundaries in 5 maria (Oceanus Procellarum, Mare Imbrium, Mare Serenitatis, Mare Nectaris, and Mare Crisium) by using the LRS data. This investigation provides us the three-dimensional subsurface structure image in the maria. In addition, the connections between the subsurface boundaries and the lava flow units on the surface are also investigated in order to determine the stratigraphic age of the subsurface boundary.

LRS data: The LRS radiated the electromagnetic wave (4–6 MHz) along the polar orbit and measured the time delay (Δt) between the electromagnetic waves reflected at the lunar surface and at lunar subsurface boundary [8]. Since this time delay is the same with the round-trip time of the electromagnetic wave in the subsurface layer, the actual depth of the subsurface boundary (d) is given by

\[
d = \frac{c}{\sqrt{\varepsilon_{\text{bulk}}}} \cdot \frac{\Delta t}{2} = \frac{d_{\text{radar}}}{\sqrt{\varepsilon_{\text{bulk}}}}
\]

where \(c\) is the speed of light in vacuum, and \(\varepsilon_{\text{bulk}}\) is the bulk permittivity of the basaltic subsurface layer [8]. This permittivity is 4–11 based on the Apollo basalt sample [9]. \(d_{\text{radar}}\) is the apparent radar depth [8].

We use Synthetic Aperture Radar (SAR) processed LRS radargram [10]. This processing remove the noise component caused by the electromagnetic-wave-scattering on the lunar surface. Thus, the subsurface boundary becomes clear. The synthetic aperture is 5 km, and the spatial resolution is 0.6 km in the along-track direction, ~5 km in the cross-track direction, and 75/\sqrt{\varepsilon_{\text{bulk}}} m in the vertical direction [10, 11].

Investigation of the depth of the subsurface boundary: The LRS data is generally indicated in the format of the radargram, in which horizontal axis is latitude, and vertical axis is depth [e.g., 10]. Using the radargram, we identify the subsurface boundary and obtain the depth at the intervals of 1° in the along-track direction and at the intervals of < ~2° in the cross-track direction. This investigation, however, is conducted only on the low titanium lava unit (< ~2 wt. % FeTiO₃) because high titanium lava unit strongly attenuates the electromagnetic wave radiated...
Connections between the surface unit boundary and subsurface boundary: The previous studies reported the lava flow unit boundary in mare region [e.g., 1, 3, 12]. Using it, we indicated the surface unit boundary by the arrow on the radar gram.

Results and Discussion: The numbers of subsurface boundaries found in this study are 3–5 in 5 maria. The deepest subsurface boundary are $d_{radar} = \sim 2$ km in Mare Crisium. Considering the bulk permittivity of the subsurface layer (4–11), the actual depth ($d$) is less than $\sim 1$ km from Eq. 1.

Fig. 1 shows a radar gram in Oceanus Procellarum produced from the LRS data. The depths of the subsurface boundary were identified. The edge of the deepest subsurface boundary (blue point) on the surface is consistent with the surface boundary between Unit P10 (3.44 Ga) and Unit P28 (2.94 Ga) whose ages are determined based on the crater chronology [12]. However, the ages of the lava flow units contradict the stratigraphy. This problem probably results from the resolution in the vertical direction. If Unit P28 is very thin, the LRS cannot identify the subsurface boundary between Unit P28 and P1 [13]. Thus, the stratigraphic age of the deepest subsurface boundary is 3.59 Ga, which agrees with the stratigraphy.

The edges of the middle subsurface boundary (green point) and shallowest subsurface boundary (red point) on the surface are not consistent with the surface unit boundary; the edge is connected inside of Unit 10. We can infer that these subsurface boundaries are connected to the sub lava flow units that compose Unit 10. Thus, these stratigraphic ages are 3.44 Ga.

Conclusion: The depth of the subsurface boundary in 5 maria was obtained at the intervals of $1^\circ$ in the along-track direction and at the intervals of $< 2^\circ$ in the in the cross-track direction. Since this data provides the three-dimensional subsurface image, it would update the lunar geological map data and provide new findings.


Fig. 1. Subsurface boundaries identified in Oceanus Procellarum. (a) The LRS track (red line) is shown on the SELENE/LALT elevation map. (b) The radar gram produced from the LRS data [13]. The subsurface boundaries are identified. Their depths are measured at the interval of $1^\circ$ in latitude. The different colors show the difference of the subsurface boundaries.