Assessment of Lunar Seismicity Using Newly Discovered Shallow Moonquakes, K. Onodera[1,2] (onodera@eri.u-tokyo.ac.jp), [1]Earthquake Research Institute, The University of Tokyo, [2]Institut de Physique du Globe de Paris, Université Paris Cité

Introduction: About half a century ago, the installation of seismometers on the Moon opened extraterrestrial seismology (e.g., [1]). The Apollo lunar seismic observation from 1969 to 1977 brought us about 13,000 seismic events, such as deep moonquakes, shallow moonquakes, meteoroid impact events, and thermal moonquakes [2]. Analyzing these events allowed us to estimate the current lunar seismic activities and the internal structure (the latest review is given by Garcia et al. [3] and Nunn et al. [4]).

In the Apollo seismic observation, two types of seismometers were deployed on the nearside of the Moon. One is a Long-Period (LP) sensor, having tri-axial components with high sensitivity around 0.2 – 1.5 Hz, and the other is a Short-Period (SP) sensor, which has only a vertical component with high sensitivity above 1.5 Hz (e.g., [4]). While the LP data have been mainly used in the previous studies, the majority of SP data actually have remained unanalyzed until today (e.g., [5][6]) because of numerous unnatural signals and/or instrumental noises (Figure 3a). This fact triggers the following possibilities: (a) we have missed lots of high-frequency seismic events, and (b) the lunar seismicity is underestimated. These gave the motivation for this study. Here, I report some analyses using the newly discovered moonquakes by Onodera [6].

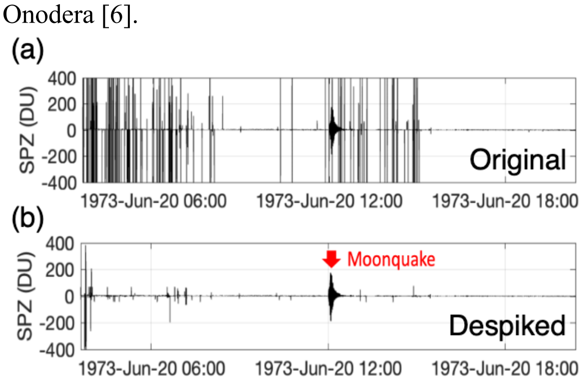

Figure 1. (a) Original and (b) denoised Apollo short-period seismic data. The horizontal axis shows time in UTC, and the vertical axis shows the amplitude in the digital unit (DU).

Discovery of New Seismic Events: Recently, Onodera [6] denoised all the Apollo SP data (Figure 1a-b) and carried out an automatic event detection (Figure 1b). As a result, he succeeded in identifying more than 22,000 seismic events, including thermal moonquakes, meteoroid impacts, and shallow moonquakes. Among them, shallow moonquakes are considered to be of tectonic origin and are usually used for the evaluation of lunar seismicity (e.g., [7]). Remarkable features of shallow moonquakes are their waveform with double energy packets, high-frequency energy contents (Figure 2), and large energy release (10^4 times larger than deep moonquakes [8]). In the following analysis, I used 28 cataloged shallow moonquakes [9] and 46 newly discovered shallow moonquakes [6].

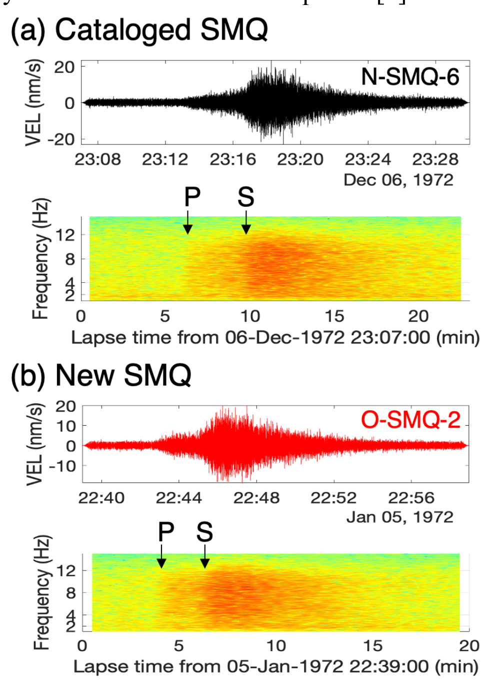

Figure 2. Waveform and spectrogram of (a) cataloged and (b) newly discovered shallow moonquakes. Two arrows indicate the P and S wave arrivals. The event ID follows the format described by Onodera [6].

Evaluation of Source Parameters: By analyzing both cataloged and newly discovered shallow moonquakes, I estimated the source parameters such as energy release (E_{rel}), seismic moment (M_0), and body wave magnitude (m_b). Following previous studies (e.g., [8][10]), each parameter is written as follows:

$$E_{rel} = 32\pi^3 {R_{ray}}^2 \rho v {\Omega_0}^2 {f_c}^3, \quad (1)$$

$$M_0 = 3\pi R_{ray} \rho v^3 \Omega_0, \quad (2)$$

$$\log_{10}(E_{rel} \times 10^7) = 5.8 + 2.4 m_b, \quad (3)$$

where R_{ray} is hypocentral distance, ρ shows the density of a near-surface material, and v is wave speed near the focal region. Ω_0 and f_c are the amplitude and the corner frequency of the source spectrum (Figure 3b). Figure 3c shows the histogram of estimated body wave magnitude. It turned out that m_b for newly identified shallow moonquakes are relatively small compared to that of the cataloged ones. This indicates that relatively large events were detected in the Apollo era (e.g., [9]), leading to the underestimation of the seismicity for smaller quakes.

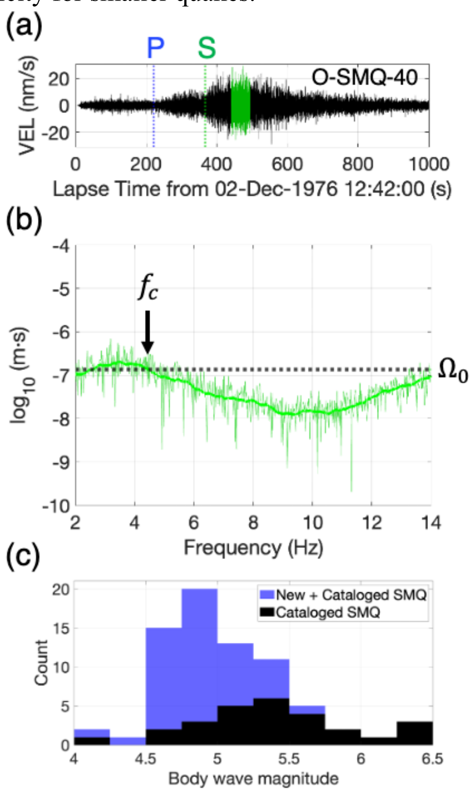

Figure 3. (a) Waveform of O-SMQ-40. The dotted blue and green lines indicate the P and S wave arrivals. The green signal shows the main S-wave energy and was used for the spectral analysis. (b) Source spectrum of the main S-wave signal shown in (a). (c) Histogram of body wave magnitude (m_b) for cataloged and new shallow moonquakes.

Assessment of Seismicity Parameters: On Earth, it is known that earthquakes obey an empirical law called Gutenberg-Richter (G-R) law. Following the definition by Mignan and Woessner [11], it is written as:

$$\log_{10}(N_m) = a - b(m - m_c) \quad \text{for} \quad m \geq m_c, \qquad (4)$$

where N_m is the cumulative number of quakes whose magnitude is greater than m, a is the constant defining the seismicity rate in a certain area, and b describes the relative magnitude distribution from small to large quakes. m_c is the magnitude of completeness, which is the lowest magnitude for 100% event detections in a certain region (Here I focus on the Apollo 15 site). As shown in Figure 4, by adding the newly discovered events, the lower m_c was obtained, meaning the seismicity for smaller events became to be evaluated more precisely. For the b-value, using the maximum likelihood method [12], I obtained 0.8, which is smaller than the Earth's global average value (~1) but is similar to the intraplate environment (~0.7) (e.g. [13]). Considering that the Moon lacks plate tectonics, my result is consistent with the qualitative idea about lunar seismicity. Discussion about the similarity between shallow moonquakes and intraplate quakes is ongoing.

Although shallow moonquakes have been the most mysterious seismic events because of their small number of detections, further analyses on newly discovered events could give us new insights into their spatial and temporal distribution, source mechanism, and crustal structure.

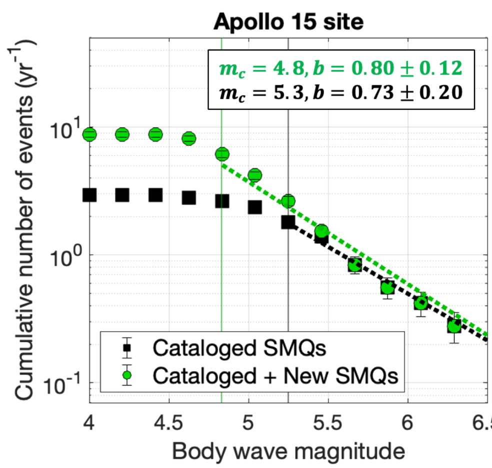

Figure 4. Frequency-magnitude distribution of shallow moonquakes recorded at the Apollo 15 landing site. The black squares are for cataloged shallow moonquakes and the green circles are for both cataloged and new shallow moonquakes. The vertical solid lines show the magnitude of completeness, and the dotted lines are the best fits assuming the G-R law (Equation 4).

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References: [1] Latham et al. (1969), *Science*, 165(3890), 241-250. [2] Nakamura (1981), UTIG Technical Report, No. 118. [3] Garcia et al. (2019), *Space Sci. Rev.*, 215(8), 50. [4] Nunn et al. (2020), *Space Sci. Rev.*, 216(5), 89. [5] Knapmeyer-Endrum & Hammer (2015), *JGR: Planets*, 120(10), 1620-1645. [6] Onodera (2023), *ESSAOr*, DOI: 10.22541/essoar. 169841663.38914436/v1/. [7] Banerdt et al. (2020), *Nature Geoscience*, 13(3), 183-189. [8] Goins et al. (1981), *JGR: Solid Earth*, 86(B1), 378-388. [9] Nakamura et al. (1979), *Proc. Lunar Planet. Sci. Conf., X*, p. 2299-2309. [10] Oberst (1987), *JGR: Solid Earth*, 92(B2), 1397-1405. [11] Mignan and Woessner (2012), *CORSSA*, doi:10.5078/corssa-00180805. [12] Aki (1965), BER, 43, 237-239. [13] Al-Heety (2013), Arab. J. Geosci., 6.1, 193-204.