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Discovery of Repeating Shallow Moonquakes in the Apollo Lunar Seismic Data

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Key Points:

- Repeating shallow moonquakes were identified for the first time
- The identified repeating events exhibit equal polarity despite occurring in opposite tidal phases
- The result implies that the tidal stress does not play a dominant role in driving fault slips of the repeating shallow moonquakes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Shallow moonquakes have been considered unique due to their large magnitudes and affinities with intraplate earthquakes. However, the small number of detections (<80 events) has prevented detailed characterization. In this study, I identified a pair of repeating shallow moonquakes by analyzing a recently updated moonquake data set. Relative-phase assessment revealed that these events exhibit a consistent fault-slip direction despite their occurrence at opposite tidal phases. This differs from what was observed for repeating deep moonquakes, which are closely related to tides, implying that tidal stress does not dominantly control fault-slip initiation of the repeating shallow moonquakes. Also, the identified repeating shallow moonquakes exhibit a similar relationship between seismic moment and the spatial scale of the slip area to earthquakes. This may indicate that earthquake-like fault physics operates on the Moon, albeit with a different driving mechanism than on Earth.

Plain Language Summary Seismic activity on the Moon serves as a crucial clue to understanding present-day tectonics. Among the reported moonquakes, shallow moonquakes have been considered unique due to their large magnitudes and affinities with intraplate earthquakes. However, the small number of detections has prevented detailed characterization. Here, I report a novel nature of shallow moonquakes revealed through an investigation of a recently renewed moonquake data set that includes a threefold number of shallow moonquakes compared to the previous catalog. A quantitative evaluation of signal similarity between shallow moonquakes resulted in the discovery of a pair of repeating shallow moonquakes, whose sources are probably located close to each other. Also, investigating the relationship between the lunar tidal phase and the relative polarity of seismic signals (or relative fault-slip direction), it turned out that the tidal stress raised by the Earth and the Sun does not play a dominant role in initiating fault slips to cause the repeating shallow moonquakes. Furthermore, I found that the repeating shallow moonquakes exhibit fault-physical features similar to those of typical earthquakes, implying that earthquake-like fault physics may operate on the Moon, albeit with a different driving force from that on Earth.

1. Introduction

1.1. Apollo Observations and Reported Lunar Seismicity

Understanding the seismic activity on solid planets and moons is crucial for evaluating their present-day geological/geophysical processes. Half a century ago, the Moon was seismically explored during the Apollo missions from July 1969 to September 1977 (e.g., Nakamura et al., 1982), where two types of seismometers were used to monitor natural seismic activities: tri-axial long-period (LP) and vertical-axis short-period (SP) seismometers (e.g., Nunn et al., 2020). Quasi-continuous recordings for nearly 8 years have yielded more than 35,000 seismic events to date (Bulow et al., 2005; Knapmeyer-Endrun & Hammer, 2015; Nakamura et al., 1981; Onodera, 2024). Analyzing these events allowed us to evaluate lunar seismicity as well as the internal structure (e.g., Garcia et al., 2011, 2019; Khan et al., 2013; Nakamura et al., 1979; Onodera, 2024; Weber et al., 2011), which are essential clues to uncovering the past evolution of the Moon. Additionally, the Moon has been a cynosure lately for upcoming manned missions. As such, along with scientific interests, assessing seismic hazard will be important for securing human activities on the Moon (e.g., Watters et al., 2024; Watters & Schmerr, 2025).

So far, four types of moonquakes have been identified: deep moonquakes, meteoroid/artificial impacts, thermal moonquakes, and shallow moonquakes (e.g., Nakamura et al., 1981). Deep moonquakes are considered to occur almost halfway from the surface to the lunar center and to be associated with the tides raised on the Moon by the Earth and the Sun (e.g., Cheng & Toksöz, 1978; Lammlein, 1977; Lammlein et al., 1974; Weber et al., 2009). Regarding impacts, due to the lack of an atmosphere on the Moon, even small meteorites impact the surface and

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produce seismic signals (e.g., Dorman et al., 1978; Oberst & Nakamura, 1987). Additionally, during the Apollo seismic operations, used spacecraft sections were crashed onto the lunar surface to generate seismic signals artificially (Latham et al., 1970). Thermal moonquakes are closely related to the lunar surface temperature. Over one-lunation thermal cycles, surface rocks/boulders and also artificial structures (e.g., lunar module) experience thermal fatigue, causing cracks to release the stored strain (Civilini et al., 2023; Dimech et al., 2017; Duennebieer & Sutton, 1974; Larose et al., 2005; Onodera, 2024). Shallow moonquakes are interpreted as fault-slip events within the lunar crust or upper mantle (the expected source depth ranges from 0 to 250 km) (e.g., Blanchette-Guertin et al., 2012; Gillet et al., 2017; Khan et al., 2000; Nakamura et al., 1979; Onodera, 2024; Watters et al., 2019) and considered to be most similar to terrestrial quakes (intraplate quakes, in particular), because of their low b -value (<0.8) and poor correlation with tides (e.g., Frohlich & Nakamura, 2006; Nakamura, 1980; Onodera, 2024; Toksöz et al., 1977; Turner et al., 2025).

1.2. Most Energetic Quakes on the Moon

Among the four types of seismic events on the Moon, shallow moonquakes have the highest body-wave magnitude ($m_b = 4-6.5$), which corresponds to 10^2-10^4 times more energy than deep moonquakes ($m_b < 3$) (Goins et al., 1981; Oberst, 1987; Onodera, 2024). Moreover, shallow moonquakes are unique in terms of spectral features, occurrence frequency, and mechanism. While the main energy of deep moonquakes is limited to below 1 Hz, that of shallow moonquakes can reach up to 12 Hz (e.g., Figure S1 in Supporting Information S1). Impacts and thermal moonquakes also excite high-frequency energy (>1 Hz); however, shallow moonquakes show less frequency-dependence in energy decay (e.g., Figure S1 in Supporting Information S1) and last longer than thermal moonquakes (Civilini et al., 2023; Duennebieer & Sutton, 1974; Onodera, 2024).

Due to the limited number of events (1–2 orders fewer than the other seismic events), the detailed mechanism of shallow moonquakes remains unclear, although several hypotheses have been proposed. For instance, some studies (e.g., Kumar et al., 2019; Watters et al., 2019) propose a relation with surface tectonic features, such as lobate scarps, which are considered to host thrust faults underneath (e.g., Watters et al., 2015). Currently, the Moon is cooling and experiencing global contraction (e.g., Matsuyama et al., 2021; Watters et al., 2010). Watters et al. (2019) claimed that the combined strain accumulation caused by the global contraction and tidal deformation could trigger fault slips beneath lobate scarps (within 1 km depth from the surface). Other studies, as summarized below, consider shallow moonquakes occurring in the deeper parts (e.g., the mid-to-lower crust/upper mantle). Toksöz et al. (1977) speculated that tectonic stresses accumulated in the crust were randomly released in time, triggering shallow moonquakes. Later, their idea gained support through subsequent studies on energy attenuation features (Blanchette-Guertin et al., 2012; Gillet et al., 2017; Nakamura et al., 1979), magnitude-frequency distribution combined with laboratory experiments and terrestrial observations (Frohlich & Davis, 1993; McNutt, 2005; Mogi, 1963; Onodera, 2024; Vinogradov, 1962), and friction-stability characteristics (Zhang et al., 2024). These studies proposed that, in the mid-to-lower crust/upper mantle, shallow moonquakes are excited by fault slips triggered via global contraction. Recent systematic and statistical studies suggest that there may be sub-families within shallow moonquakes, that is, some may occur near the surface and others could occur in the deeper crust or upper mantle (Onodera, 2024; Turner et al., 2025). Besides these ideas, Frohlich and Nakamura (2006) proposed that the interaction between the Moon and high-energy particles from the extrasolar system may be a cause of shallow moonquakes. Partly because of the small number of events and observed lack of clear correlations with tides and specific tectonic features, the origin of shallow moonquakes remains enigmatic even half a century after the Apollo missions.

Recently, Onodera (2024) found that a large portion of the Apollo SP seismic data had remained unanalyzed due to a severe contamination of artifacts and larger data amounts resultant from an 8 times higher sampling rate than that of the LP. After a despiking process and a coherence-based event detection analysis, Onodera (2024) discovered more than 22,000 new seismic events in the Apollo SP seismic data. One of the paramount findings was the increase in the number of shallow moonquakes by a factor of 2.6 (from 28 to 74 events), implying that the Moon is tectonically more active than previously evaluated (Onodera, 2024). Integrating all the discovered shallow moonquakes, Onodera (2024) confirmed that a larger number of events were recorded by the Apollo 15 seismometer than by other stations (Figure 1), possibly indicating that the lunar northern hemisphere is more seismically active than the southern hemisphere.

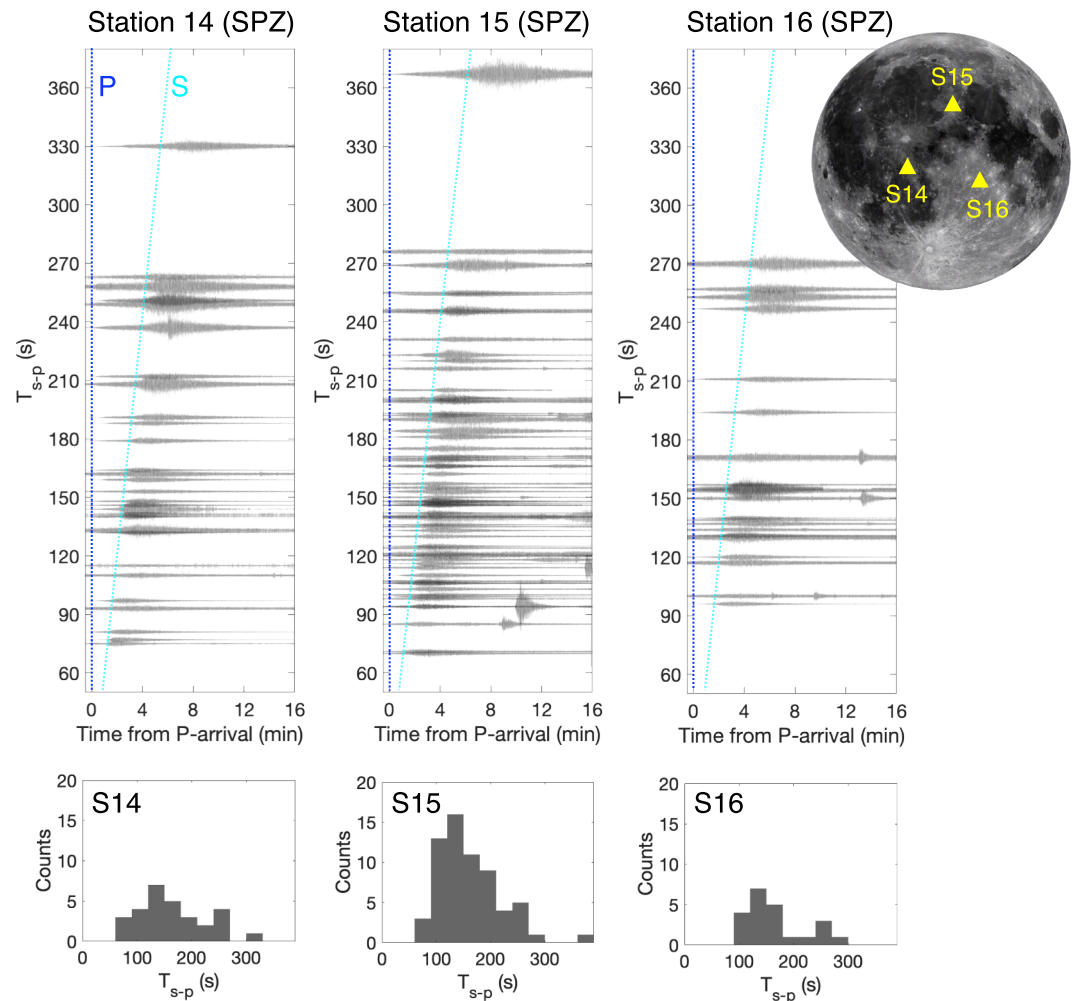


Figure 1. Shallow moonquakes recorded at each Apollo seismic station. Waveforms of shallow moonquakes recorded by SP seismometers are displayed, aligned with S–P time (Stations 14, 15, and 16 from left to right). The waveforms are bandpass filtered between 1 and 10 Hz. Their amplitude is arbitrarily scaled. The blue dotted line indicates the P arrival, and the cyan dotted line indicates the S arrival. The histograms of T_{s-p} for each Apollo station are displayed in the bottom row. The Apollo 14, 15, and 16 landing sites are shown in the top right image. The lunar disk image was taken by the Wide Angle Camera of the Lunar Reconnaissance Orbiter (Robinson et al., 2010) (the credit belongs to NASA/Goddard Space Flight Center/Arizona State University).

1.3. Main Focus and Key Questions

Following recent progress, this study seeks to enhance our understanding of shallow moonquakes by analyzing a recently updated moonquake data set, with a focus on “occurrence repeatability” that was not explored by Onodera (2024). I posit that the period of repeating moonquakes and their source locations will help us comprehend the mechanism of shallow moonquakes and further discuss how it is related to the past/current internal dynamics of the Moon. From the perspective of future manned exploration, this will be a crucial step in determining when and where magnitude-5 moonquakes occur, which should provide important information for handling natural disasters on the Moon. Thus, finding repeating shallow moonquakes would be a significant milestone to answer the key questions above.

In the following, I will present the fundamental idea for identifying repeating shallow moonquakes and showcase the discovered repeating events along with relevant fault parameters. Then, I will discuss the contribution of tides to the excitation of shallow moonquakes and provide implications for present-day lunar tectonics and similarities to earthquakes.

2. Search for Repeating Moonquakes

2.1. Data Set and Preprocessing

This study utilized the Apollo 14, 15, and 16 short-period (SP) seismic data because almost all recently discovered shallow moonquakes by Onodera (2024) were identifiable only in the SP data. Apollo 12 station was excluded from the analysis since its SP seismometer was not well-functioning for most of the observation period (Nunn et al., 2022). All the preprocessing, such as despiking and correction for instrumental response, follows Onodera (2024). For the shallow moonquake analysis, referring to the event times provided in previous studies (Nakamura et al., 1981; Onodera, 2024), I retrieved the 12-min-long data, which corresponds to a longer time window than a typical duration for the target shallow moonquakes (see waveforms for $T_{s-p} = 70\text{--}280$ s in Figure 1). Note that T_{s-p} is the time interval between the S-wave arrival and the P-wave arrival.

2.2. Underlying Postulate and Previous Examples

If certain quakes share the same source and path, the observed seismic signals recorded at a given station show almost identical characteristics in both time and frequency domains. In previous studies, repeating moonquakes were reported. For example, deep moonquakes are known to correlate with tides and occur periodically depending on the orbital configuration of the Earth-Moon-Sun system (e.g., Cheng & Toksöz, 1978; Lammlein, 1977; Lammlein et al., 1974; Weber et al., 2009). It is known that some deep moonquakes share the same source, called “nest,” and seismic signals radiated from a certain nest and recorded at the same station show similar features. Nakamura (2003) searched for unidentified deep moonquakes by computing the cross-correlation between reference deep moonquakes and the continuous LP seismic data. As a result, Nakamura (2003) increased the number of deep moonquakes from 1,360 to 7,245. So far, more than 320 deep moonquake clusters have been identified, although the source locations or nests are constrained for only 1/3 of the whole clusters (e.g., Nakamura, 2005; Yuan et al., 2021).

2.3. Cross-Correlation Analysis

Building on the approach of Nakamura (2003), I search for repeating moonquakes through cross-correlation computation. The histograms in Figure 1 show that some shallow moonquakes occurred within a similar range of T_{s-p} , which can be translated to the distance between a source and a seismic station. Therefore, a certain number of events occur at similar distances, and these are regarded as potential candidates for repeating shallow moonquakes.

In the analysis, referring to Table S1 in Supporting Information S1, I first selected event pairs with similar T_{s-p} times (i.e., the difference in T_{s-p} between the two events is within their error ranges resultant from phase-picking uncertainties). Then, 12-min-long time series were trimmed starting from 1 min before and 11 min after the P-wave arrival. After applying a bandpass filter between 1 and 10 Hz, the normalized cross-correlation function was computed between the selected two events. While almost all event pairs showed a low correlation coefficient ($CC < 0.2$), only one pair of shallow moonquakes showed a distinctly higher correlation than the others ($CC > 0.5$), as shown in Figure S2 in Supporting Information S1. This value is actually higher than the CC threshold previously used for a deep moonquake clustering (0.28: Yuan et al., 2021) or for detecting repeating marsquakes (0.17: Garcia et al., 2025).

3. First Detection of Repeating Shallow Moonquakes

Through cross-correlation analysis between pairs of events with similar T_{s-p} (Section 2.3), I detected a candidate pair of repeating shallow moonquakes. Figures 2a–2c compare the cross-correlation analysis results for three different cases. In the case of identical events, the cross-correlation coefficient (CC) reaches 1.0 and rapidly decreases with lag time, resulting in a sharp-peaked function as shown in the bottom panel of Figure 2a. On the other hand, the correlation function shows an emergent shape with a low maximum CC value for independent shallow moonquakes (Figure 2c). While almost all shallow-moonquake pairs show low CC values and emergent correlation functions, I found one shallow-moonquake pair (KO-26 and KO-40 listed in Table S1 in Supporting Information S1) showing a sharp-peaked function with a high CC value (Figure S2 in Supporting Information S1 and Figure 2b). In addition, their spectral contents are similar to each other (Figure 2d). These lines of evidence

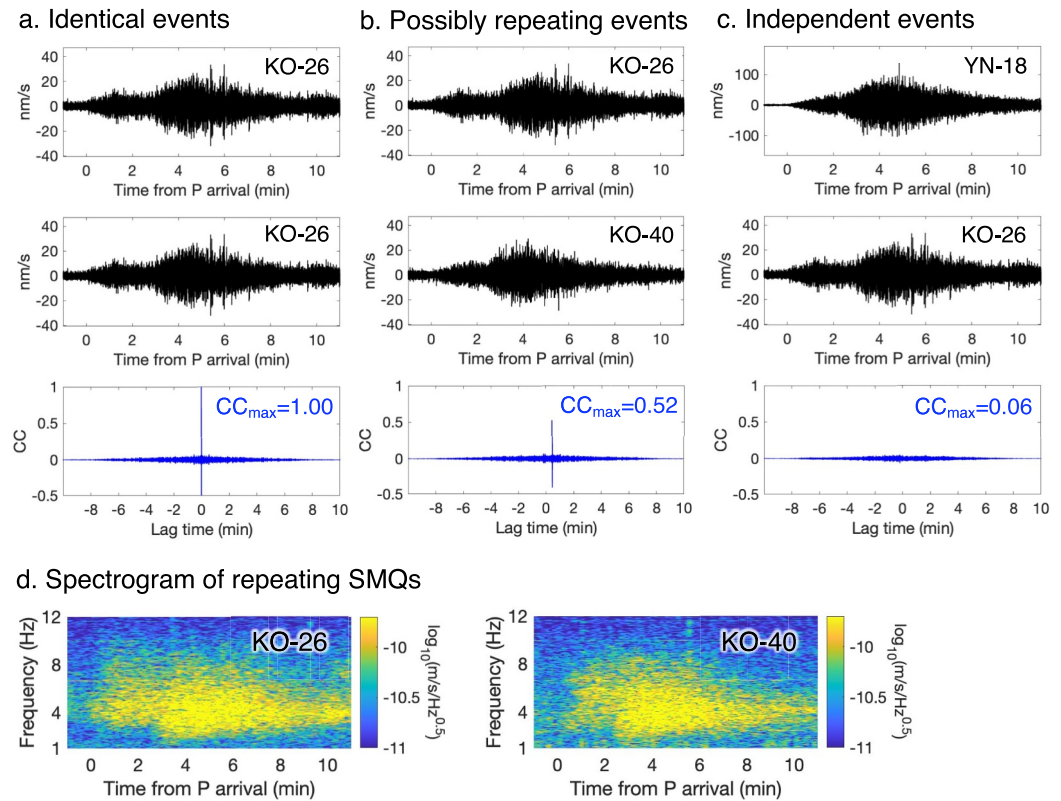


Figure 2. Cross-correlation functions and characteristics of repeating shallow moonquakes. (a–c) Two waveforms (black signals) used to compute a cross-correlation function (blue signal) are shown for three different cases (a: identical events, b: possibly repeating shallow moonquakes, and c: independent events). The event ID is from Table S1 in Supporting Information S1. In the bottom panels, the horizontal axis shows lag time (temporal shift to match two input signals), and the vertical axis shows the cross-correlation coefficient. (d) Spectrograms of the events shown in panel (b).

positively support that the KO-26 and KO-40 shallow moonquakes are repeating events, which is the first example of the corresponding moonquake type. Following the designation of the deep-moonquake clusters (e.g., A1: Lammlein et al., 1974; Nakamura et al., 1981), hereafter the discovered shallow-moonquake pair is called “H1.”

4. Implications for Present-Day Lunar Tectonism

4.1. General Description and Relation With Tides

The observation of repeating shallow moonquakes has important implications for lunar tectonism. My results indicate that the magnitude-5 shallow moonquakes are repeatedly occurring at 1,500–1,900 km apart from the Apollo 15 landing site (Table 1). Since the majority of newly discovered shallow moonquakes (Onodera, 2024) are smaller in magnitude than those in the original catalog (Nakamura et al., 1981), most of them are not detectable at multiple stations, resulting in poor constraints on the H1 source location (or nest). Nevertheless, this study’s findings suggest that phenomena analogous to repeating earthquakes may occur on the Moon even today (not as active as on Earth, though).

According to previous studies (e.g., Lammlein et al., 1974; Nakamura, 1980; Onodera, 2024; Toksöz et al., 1977), shallow moonquakes do not exhibit a clear correlation with tides, unlike deep moonquakes. However, considering the H1 events occur at near-apogee or near-perigee (star symbols in Figure 3a) where the highest tidal stress is attained (e.g., Watters et al., 2019), there could be a potential contribution of tides to exciting these particular shallow moonquakes. To investigate the role of tides, I checked the relative polarity between the H1 shallow

Table 1
Event Information of H1 Shallow Moonquakes

Event ID	KO-26	KO-40
Year	1975	1976
Day of year	82	337
Event time	21:10	12:45
T_{s-p} (s)	175 ± 18	146 ± 15
Epicentral distance (km)	$1,879 \pm 242$	$1,515 \pm 212$
Minimum body-wave magnitude	5.0	4.8
Cut-off frequency (Hz)	4.5	4.0
Seismic moment (Nm)	5.9×10^{14}	4.3×10^{14}
Stress drop (MPa)	7.6	3.9

Note. The original information is from Onodera (2024).

moonquakes. The base idea was introduced by Nakamura (1978) to investigate the relative polarity of deep moonquake signals in the same cluster, for example,

If two waveforms (f_a, f_b) are correlated, the relation between them is ideally expressed as

$$f_b(t) = kf_a(t - \tau_d), \quad (1)$$

where k is a constant and the main indicator of relative phase, t is time, and τ_d is the time difference between the two signals (Nakamura, 1978). In practice, τ_d can be interpreted as lag time assessable by computing the cross-correlation function while the signal of k (positive or negative) corresponds to the peak signal of the cross-correlation coefficient. Following Nakamura (1978), the relative-phase indicator (Φ_0) is defined as

$$\Phi_0 = \frac{\pi}{2} [1 - \text{sig}(k)] = \begin{cases} 0 & \text{for } k > 0 \\ \pi & \text{for } k < 0 \end{cases}, \quad (2)$$

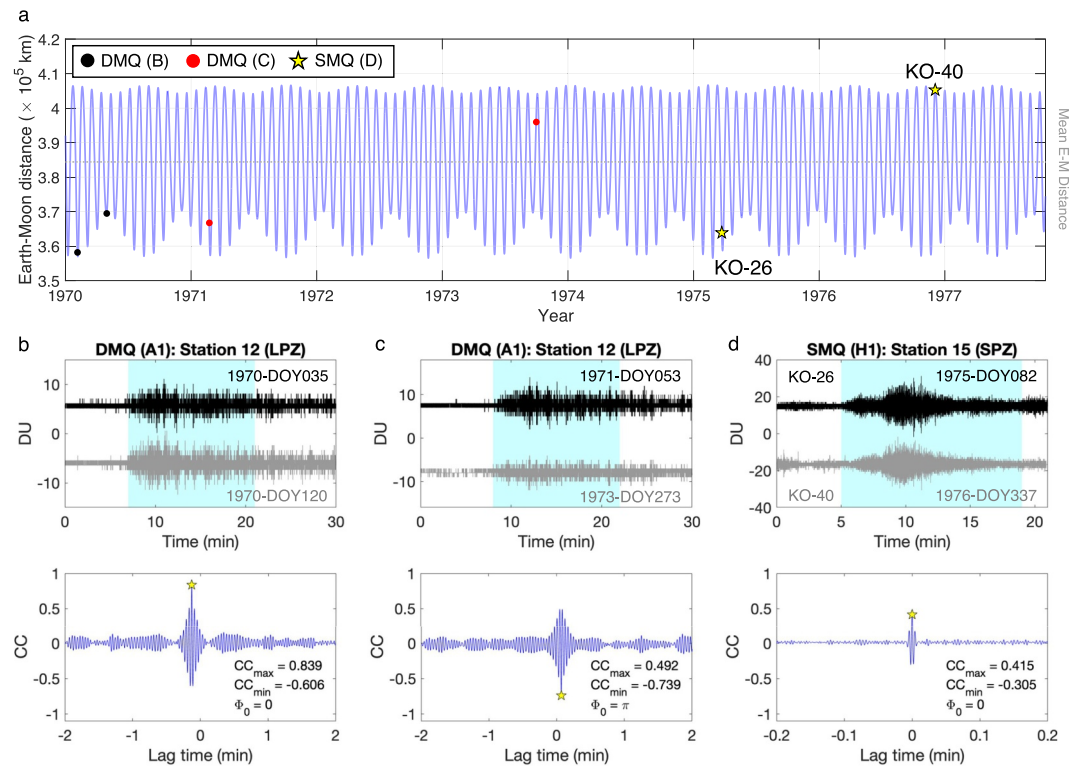


Figure 3. (a) Temporal distribution of analyzed A1 deep moonquakes and H1 shallow moonquakes superposed on the Earth-Moon distance as a function of year. The distance between the Earth and the Moon was computed with SPICE's “mice_spkpos” function (Acton, 1996; Acton et al., 2018). The black dots indicate the equal-polarity A1 deep moonquakes presented in panel (b), the red dots indicate the opposite-polarity A1 deep moonquakes presented in panel (c), and the star symbols indicate those of repeating shallow moonquakes displayed in panel (d). (b–d) Cross-correlation functions for A1 deep moonquake pair recorded on DOY035, 1970 and DOY120, 1970 (DOY stands for day of year), A1 deep moonquake pair recorded on DOY063, 1971 and DOY273, 1973, and H1 shallow moonquakes, respectively. In the top panel, continuous LPZ data (for deep moonquakes) and SPZ data (for shallow moonquakes) are shown as black or gray lines. The cyan-filled time-window data were used to compute cross-correlation functions presented at the bottom. In the bottom panels, the maximum or minimum correlation coefficients used to obtain the relative-phase indicator (Φ_0) are indicated with star symbols, and the relevant values are displayed at the bottom right corner in each panel. Note that the CC of H1 events shows a lower value than that in Figure 2b because a longer time window was used in this analysis.

where $\text{sgn}(k)$ is either $+1$ ($k > 0$) or -1 ($k < 0$). If $\Phi_0 = 0$, the two signals have equal polarity, that is, the slip direction of a fault is consistent with each other. On the other hand, if $\Phi_0 = \pi$, the two signals have opposite polarity, meaning that the slip direction is opposite between the two events.

Figures 3a–3c show two test examples of A1 deep moonquakes. One pair occurred in a similar tidal condition (black dots in Figure 3a) and the other occurred in a different condition (red dots in Figure 3a) (i.e., one is in the perigee side and the other is in the apogee side). In this case, it is expected that the former pair (pair B) shows equal polarity and the latter (pair C) shows opposite polarity. In fact, I confirmed reasonable results by applying the relative-phase evaluation approach above (bottom panels in Figures 3b and 3c), where $\Phi_0 = 0$ for pair B and $\Phi_0 = \pi$ for pair C. As discussed by Nakamura (1978), the consistent trend between the Earth-Moon distance and the relative polarity of seismic signals supports a strong connection between deep moonquakes and tides.

In the same way, the H1 shallow moonquakes were also investigated. Since the KO-26 and KO-40 shallow moonquakes occurred near the opposite phases (star symbols in Figure 3a), it is expected that Φ_0 is equal to π (i.e., opposite polarity) if tides play a dominant role in triggering these events. The result for the H1 events is presented in Figure 3d. Unlike the A1 deep moonquakes presented in Figure 3c, the H1 shallow moonquakes showed equal polarity even though they occurred in the opposite tidal phases (Figure 3a). This implies that the tidal stress does not play a dominant role in driving fault slips of the H1 shallow moonquakes. This interpretation might explain the scarcity of the H1 events. If tides are closely associated with the repeating shallow moonquakes, we should observe them more frequently in the Apollo seismic data; however, that is not the case. Thus, it might be reasonable to think that these shallow moonquakes are attributed to the random stress release in the crust/upper mantle as previously proposed (e.g., Nakamura, 1980; Onodera, 2024; Toksöz et al., 1977).

4.2. Spatial Scale of Slip Area and Relationship With Seismic Moment

To characterize the fault parameters of the H1 shallow moonquakes, I estimated the spatial scale of the fault slip based on the circular shear crack model (Brune, 1970) as performed by Nakamura (1978) for A1 deep moonquakes. In terrestrial seismology, the circular shear fault is interpreted as asperities on a fault plane (Lay & Kanamori, 1981; Uchida & Bürgmann, 2019), and the radius of the circular fault disk (a) is modeled as follows:

$$a = \frac{C\beta}{2\pi f_c}, \quad (3)$$

where I assume the constant value $C = 2.81$ (Brune, 1970), S-wave velocity $\beta = 4.4$ km/s (Garcia et al., 2019), and the cut-off frequency $f_c = 4.0$ – 4.5 Hz (Table 1). This gives us $a = 0.36$ – 0.41 km.

The relationship between the spatial scale of fault slip and seismic moment can be described as

$$\log_{10} M_0 = 1.5 \log_{10}(\pi a^2) + \log_{10} \Delta\sigma + 20.6, \quad (4)$$

where M_0 is seismic moment in dyn-cm and $\Delta\sigma$ is stress drop in bar (Kanamori & Anderson, 1975). Referring to the seismic moment and stress drop values in Table 1 and a obtained using Equation 3, I obtained Figure 4, where the H1 shallow moonquakes are compared with interplate earthquakes, intraplate earthquakes (e.g., Abercrombie, 1995; Archuleta et al., 1982; Boatwright, 1994; Heaton, 1990; Kanamori & Anderson, 1975), and the A1 and A6 clusters of deep moonquakes (Kawamura et al., 2017). It turned out that the H1 shallow moonquakes fall in a similar stress drop range to that of typical earthquakes (1–10 MPa), and the relation between slip disk radius and seismic moment is in good agreement with that of similar-magnitude earthquakes (Figure 4). On the other hand, deep moonquakes are plotted away from the main stream of the typical earthquakes. It is still too early to generalize the observed trends; yet, my results could be another piece of evidence that shallow moonquakes have more in common with typical earthquakes.

It is still under debate whether the thrust faults underneath young lobate scarps really cause shallow moonquakes (e.g., Onodera, 2024; Toksöz et al., 1977; Watters et al., 2019; Zhang et al., 2024). Yet, the proposed fault parameters would serve as a milestone for future stress-accumulation modeling combined with the expected stresses imposed on the lunar crust (Matsuyama et al., 2021).

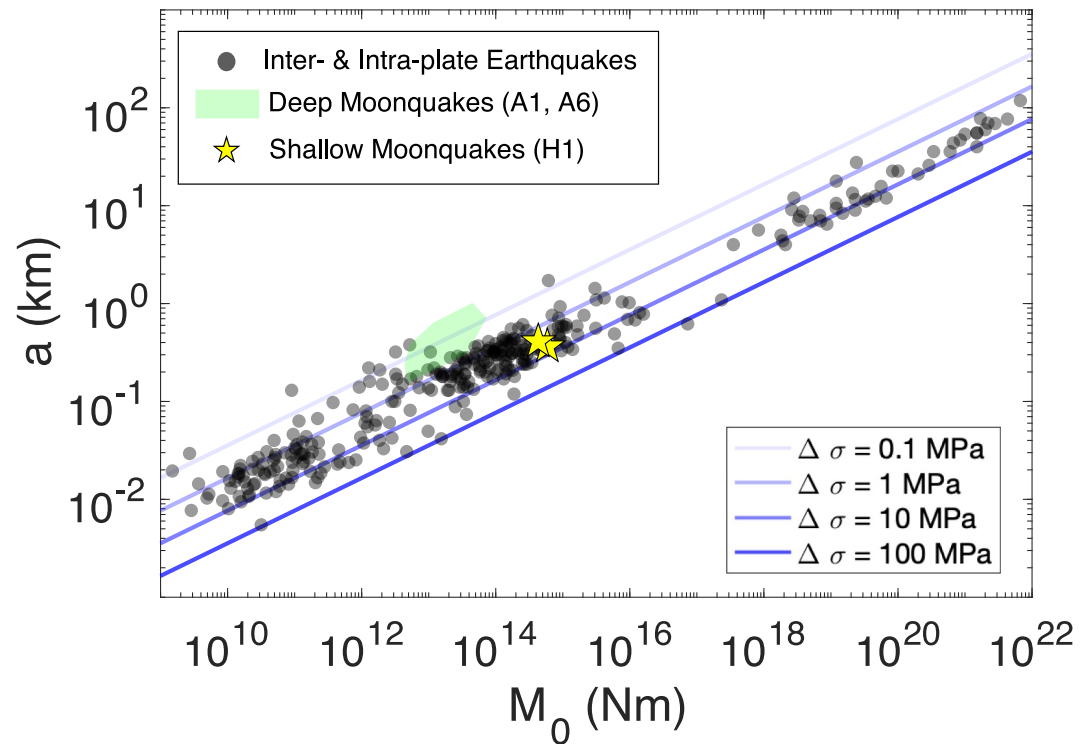


Figure 4. Relation between seismic moment and the radius of circular shear fault. The horizontal axis shows seismic moment on a log scale, and the vertical axis shows the radius of the circular shear fault on a log scale. Blue lines indicate the constant stress drop models (0.1, 1, 10, 100 MPa, respectively). Gray dots correspond to interplate and intraplate earthquakes (Abercrombie, 1995; Archuleta et al., 1982; Boatwright, 1994; Heaton, 1990; Kanamori & Anderson, 1975). Green-filled area corresponds to deep moonquake clusters (A1 and A6). Source parameters are from Kawamura et al. (2017). Star symbols correspond to H1 shallow moonquakes discovered in this study.

5. Concluding Remarks

To improve our understanding of the nature of shallow moonquakes, I analyzed the renewed shallow moonquake data set by Onodera (2024). By computing cross-correlation functions between shallow moonquakes with similar T_{s-p} values, I discovered a pair of repeating shallow moonquakes (H1 events) for the first time (Figure 2). Superposing their occurrence times onto the time evolution of the Earth-Moon distance, I found that these events occurred near perigee and apogee, where the maximum tidal stress is induced (Figure 3a). To further discuss the contribution of tides to the excitation of the H1 shallow moonquakes, I evaluated relative polarity (Figures 3b–3d). The results showed that the H1 events had equal polarity despite their occurrences at opposite tidal phases, unlike deep moonquakes. This implies that the tidal stress is not a dominant cause to initiate fault slips to excite the repeating shallow moonquakes. Also, using the circular shear crack model (Brune, 1970), I estimated the spatial scale of the slip portion and obtained the relationship between the size of the slip section and seismic moment (Figure 4). The comparison between shallow moonquakes with intraplate/interplate earthquakes and deep moonquakes showed that the H1 shallow moonquakes fell in a similar stress drop range to that of typical earthquakes (1–10 MPa), and the relation between slip disk radius and seismic moment is in accordance with that of similar-magnitude earthquakes. The occurrence of shallow moonquakes is rare compared to other lunar seismic events, and they have been considered atypical and unique events on the Moon. However, my results indicate that the H1 shallow moonquakes share more similarities to typical earthquakes than deep moonquakes that are more commonly observed on the Moon. Although this fact cannot yet be generalized, this study may provide another line of evidence that shallow moonquakes are analogous to typical earthquakes and that similar fault physics is at work on our moon.

Conflict of Interest

The author declares no conflicts of interest relevant to this study.

Availability Statement

All the Apollo seismic data used in this study were retrieved from the Earthscope Data Center (IRISDMC) (Nunn, 1969; Nunn et al., 2022). Readers can download the events used in this study, referring to the event times in Table S1 in Supporting Information S1, along with a sample program in public (https://researchmap.jp/blogs/blog_entries/view/809479/a18e2217da20189c9584a0eab58b5309?frame_id=1470639), for example.

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