Detection of seismic events on Mars: a lunar perspective

WeiJia Sun¹,², Liang Zhao³,⁴, Yong Wei¹,⁴, and Li-Yun Fu⁵

¹Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; ²Institutions of Earth Science, Chinese Academy of Sciences, Beijing 100029, China; ³State Key Laboratory of Lithospheric Evolution, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China; ⁴College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China; ⁵Key Laboratory of Deep Oil and Gas, China University of Petroleum (East China), Qingdao 266580, China

Abstract: The interior structures of planets are attracting more and more detailed attention; these studies could be of great value in improving our understanding of the early evolution of Earth. Seismological investigations of planet interiors rely primarily on seismic waves excited by seismic events. Since tectonic activities are much weaker on other planets, e.g. Mars, the magnitudes of their seismic events are much smaller than those on Earth. It is therefore a challenge to detect seismic events on planets using such conventional techniques as short-time average/long-time average (STA/LTA) triggers. In pursuit of an effective and robust scheme to detect small-magnitude events on Mars in the near future, we have taken Apollo lunar seismic observations as an example of weak-activity data and developed an event-detection scheme. The scheme reported here is actually a two-step processing approach: the first step involves a despike filter to remove large-amplitude impulses arising from large temperature variations; the second step employs a matched filter to unmask the seismic signals from a weak event hidden in the ambient and scattering noise. The proposed scheme has been used successfully to detect a moonquake that was not in the known moonquake catalogue, demonstrating that the two-step strategy is a feasible method for detecting seismic events on planets. Our scheme will provide a powerful tool for seismic data analysis of the Interior Exploration using Seismic Investigations, Geodesy and Heat Transport (InSight) mission, and China’s future lunar missions.

Keywords: planetary seismology; event detection; interior structures; despike filter; matched filter

Citation: Sun, W. J., Zhao, L., Wei, Y., and Fu, L. -Y. (2019). Detection of seismic events on Mars: a lunar perspective. *Earth Planet. Phys.*, 3(4), 290–297. http://doi.org/10.26464/epp2019030

1. Introduction

Details of the formation and early evolution of Earth remain obscure. Investigations of interior structures of other planets in the solar system are therefore of great interest. InSight, short for Interior Exploration using Seismic Investigations, Geodesy and Heat Transport, is a Mars lander launched on May 5, 2018, and successfully landed on November 26, 2018, designed to investigate the interior of Mars, formed 4.5 billion years ago. One of the two main goals of InSight is to determine tectonic activity on Mars, including both the magnitudes and rates of occurrence of marsquakes and of meteoroid impacts. A seismometer that records ground motions created by marsquakes, meteoroid impacts, and surface vibrations has been deployed by Insight on the surface of the red planet.

Current knowledge of seismic events on Earth, Moon, and Mars suggests that they differ significantly in magnitude. Easily detected earthquakes are numerous and highly correlated with active plate tectonics. In contrast, in a Martian year (approximately two Earth years) only a few marsquakes of magnitude 5 or 6 are expected. The Moon is virtually silent, due to its lack of atmosphere and tectonic activity. The magnitudes of deep moonquakes range from 0.5–1.3 on the Richter scale; the strongest shallow events can reach magnitudes of 4–5 (Lammlein, 1977). Mars is expected to exhibit similarly low tectonic activity. In addition, unlike Moon data, data recorded by InSight’s seismometer are expected to be seriously contaminated by the massive dust storms observed in Mars’s atmosphere; these contaminating data must be removed if accurate Martian seismic event detection is to be successful.

Seismology is a powerful tool to investigate the interior structures of a planet. Seismic waves, excited by seismic events, help us understand the interior structures and structural dynamics of a planet. The first step in identifying seismic events can be visual observation. The short-time average/long-time average (STA/LTA) trigger approach and other algorithms (Withers et al., 1998; Sharma et al., 2010) are widely used to identify seismic events from continuous seismic data. All of these algorithms have their own defects and limitations (Withers et al., 1998; Sharma et al., 2010), especially for noisy small-magnitude events.

The matched-filter technique (MFT) has been successfully applied to detect previously unrecognized seismic events by the use of template waveforms to identify high similarities to known events on Earth. The template waveforms can be the detected events or synthetic seismograms (Chamberlain and Townend, 2018). These
previously unknown seismic events are generally noise-contaminated, showing low signal-to-noise ratios or even concealed in the long-during coda of a large seismic event.

While we await seismic data from InSight, the Apollo passive seismic data are available, as the unique confirmed extraterrestrial waveforms on which it has been possible to prepare for analysis of the Mars data. Successful processing of these lunar observations thus has provided us a valuable opportunity to identify and verify techniques applicable to the Mars data.

Taking the seismic data recorded by the Apollo Passive Seismic Experiment (APSE), we here propose a two-step strategy and examine its feasibility to detect weak events that have small amplitudes and might be masked by ambient noise, for example as caused by dust storms on Mars. In addition, the temperature can vary by as much as 300°C on the Moon and 100°C on Mars, causing thermal expansion and contraction of the instrumental shield and perhaps leading to strong data spikes (Bulow et al., 2005). The first step is therefore to remove large-amplitude spikes using a despik filter or a running median filter. This step could greatly help in unmasking weak seismic signals. Our second step is to use MFT to detect potential seismic events by matching identified potential events with known continuous waveforms. Our investigation of the proposed scheme illustrates that the MFT can be employed to search for and detect weak marsquakes concealed in background ambient noise.

2. Instruments

2.1 The Lunar Apollo Seismometers

The Apollo Passive Seismic Experiments (APSE) deployed five seismic stations on the lunar surface during Apollo missions 11, 12, 14, 15, and 16, but Station 11 ceased operation on 04:00 UT August 25, 1969, probably due to overheating from the hot midday sun (https://moon.nasa.gov/resources/13/apollo-11-seismic-experiment/). The other four stations (12, 14, 15 and 16) began operation as early as November 19, 1969, and operated until September 30, 1977. The distribution of these lunar stations is displayed in Figure 1 (red stars). The Apollo network is in shape of an equilateral triangle with spacing of ~1,100 km, where the left-lower Station 12 is about 180 km away from Station 14.

Each station is equipped with a three-component (LPX, LPY, LPZ) long-period seismometer and a vertical-component (SPZ) short-period seismometer. The long-period seismometers have two operation modes, a flat-response mode and a peaked-response mode (Lammlein, 1977). The response curves of the long-period and short-period seismometers are shown in Figure 2. The seismometers were sometimes unstable when running in the flat-response mode, and therefore were operated primarily in peaked-response mode (Bulow et al., 2005). The long-period seismometers have natural periods of 15 and 2.2 s in the flat and peaked response modes, respectively. The short-period seismometers have a resonant frequency of 1 Hz and were much more sensitive to vertical ground motions as high as 8 Hz.

2.2 The Martian Seismometer

Similar to the lunar seismometers, the Martian station also is equipped with one three-component very broad-band (VBB) seismometer and a three-component short-period seismometer. The VBB sensors can measure ground motion in the frequency range between 0.01 and 10 Hz. The short-period seismometer is sensitive to a frequency band of 0.1–50 Hz, which partially covers the band encompassed by the VBB sensors.

Both the Moon and Mars experience much larger temperature variations than Earth. The temperature in the lunar night can be as low as ~170°C, increasing in the lunar day to about 130°C. The average temperature on Mars is about ~60°C, but its lowest temperature could be ~125°C near the poles in the winter, and its highest can reach 20°C near the equator on a summer day. A radioisotope heater was used to keep Apollo seismometers from falling below ~54°C so that they could work properly. The Martian seismometer was designed with an extra shield to protect it against the rapid and large temperature changes on Mars. A similar scheme of thermal compensation has also been applied in the design of Chang’e Yutu class rover, a part of the Chinese mission to the Moon.

Figure 1. The distributions of lunar seismic Stations 12, 14, 15 and 16 (red stars), and the different type of lunar events. The background is the relative topography of the Moon, where the reference elevation is 1737.4 km. The lunar events are observed primarily at the near side of the Moon.
3. Event Detection on Planets

3.1 The Lunar Events

During the Apollo passive seismic experiments between 1969 and 1977, three major types of lunar events were recognized: deep moonquakes, shallow moonquakes, and meteoroid impacts. More than 12,000 events have been detected in Apollo data, as shown in Figure 1 (Bulow et al., 2005).

Deep moonquakes are located at a depth range of 800–1000 km and their magnitudes vary from 0.5–1.3 on the Richter scale (Lammlein, 1977). The number of deep moonquakes detected is 6,549, which is approximately half of the total number of detected lunar events. These large-number and small-magnitude events are considered to be triggered by lunar tides, inferred from deep moon activity showing tidal periodicities of 0.5 month and 1 month (Lammlein, 1977).

In contrast, the shallow moonquakes, also known as high-frequency tele-seismic (HFT) events, are more energetic; their maximum magnitudes can reach 4–5 on the Richter scale. But the number of such shallow events is small, about five per year. They are detected at depths of 50–200 km below the crust (Nakamura et al., 1979). The shallow earthquakes are scattered (see Figure 1) rather than found in a narrow belt surrounding a tectonic plate, which is the pattern on Earth. The locations of shallow lunar events correlate well with the distribution of impact basins, and Nakamura et al. (1979) have suggested that these shallow events link with intraplate moonquakes occurring at boundaries of pre-existing weaknesses in rigid plates.

Another type of lunar events is meteoroid impacts, which obviously do not reflect tectonic activity. However, it is possible to estimate the masses of meteoroids from both the long-period and the short-period seismic stations; such investigations have revealed that masses of observed impact meteoroids have ranged from 0.5 to 50 kg (Nakamura et al., 1982). The observed impacts were distributed unevenly; some meteor shower clusters were observed (Duennebier et al., 1976; Suggs et al., 2014).

3.2 The Despike Filter

Significant spikes or seismic disturbances can be observed in the continuous waveforms recorded by the Apollo seismic stations. These spikes can have amplitudes one thousand times larger than those of the real events, since the magnitudes of lunar events are typically small (as stated above). The large-amplitude spikes are observed at all stations and occur intensely near lunar sunrise and sunset (Bulow et al., 2005). It is likely that these noises are caused by thermal expansion and contraction of the shield protecting each seismometer.

Here we apply the despike filter — actually a rolling median filter (RMF). The RMF is defined as replacing original measured amplitudes with median values of amplitudes recorded in windows of a given length of time. However, many spikes have long durations, of up to several minutes, rather than presenting as sharp impulses. We thus employ a short spike and a long spike to examine the RMF, as displayed in Figure 3. For simplicity, a slant line is taken as the true signal, disturbed by a short spike (Figure 3a) and a long spike (Figure 3b). As Figure 3a demonstrates, impulses with lengths shorter than one sample can be removed almost per-
perfectly, leaving indiscernible disturbance. In addition, long spikes of length up to four samples are successfully discriminated, leaving small disturbances, by using different window lengths (of 9 and 17). As displayed in Figure 3b, the shorter the window length, the smaller the bias; it can be seen that the RMF window length should be at least twice as long as the width of a spike.

In Figure 4 we show the performance of the despike filter based on RMF. Figure 4a shows the original seismic waveforms recorded by Lunar Apollo Station 15, which were seriously contaminated by large-amplitude spikes. These spikes usually have duration of several minutes and thus cannot be effectively removed by the conventional filters, suited to single short impulses, as shown in Figure 4b. After application of the conventional filter, the spike at ~4,000 s is strongly eliminated, but the spikes at ~11,300 s in the gray dashed box are still significant, showing amplitudes as large as the raw waveforms in Figure 4a.

Figure 4c exhibits the waveforms after the despike filter. As seen, all spikes have been eliminated thoroughly, showing much smaller amplitudes (maximum value of ~0.5 of that of the raw waveform amplitudes at ~1,000). Further, we could apply the conventional filter on the despiked waveforms. As demonstrated in Figure 4c and 4d, the concealed seismic event was significantly enhanced and can be identified as a new event that was not listed in the final catalogue of lunar events (Nakamura et al., 1981). This example indicates that the despike filter is of importance in preprocessing procedures.

We further examine the despike filter over the waveform without perturbation of spikes. Here we select the North Korean nuclear test event of 3 Sep, 2017, recorded by the MDJ station, which has a very high signal-to-noise ratio. As shown in Figure 5a, the waveform after the despike filter with the time window length of 17 samples shows obvious amplitude misfits between 120 s and 175 s, but gives fewer misfits for signals after 175 s. The large misfit of the 120–175 s waveforms results from rapid changes of amplitude. To avoid the over-filter effect, we use a short time window, e.g., 3 samples, as shown in Figure 5b, or the bandpass filtered data, e.g., 0.1–1 Hz, as shown in Figure 5c. It should be noted that one must examine the raw data first and determine the processing techniques and flows to be applied.

3.3 The Matched-Filter Technique

The matched-filter technique (MFT) is used to search for previously undetected seismic events by cross-correlating between verified events and the continuous waveforms (Shearer, 1994). Recently, the MFT has become a powerful tool for detecting event sequences in foreshocks (Kato and Nakagawa, 2014), aftershocks (Peng ZG and Zhao P, 2009), and both volcanic and non-volcanic low-frequency earthquake swarms (Shelly et al., 2007; Aso et al., 2011). The technique has also been applied to detecting microseismicity in exploration geophysics (Eisner et al., 2008; Li ZF et al., 2015).

The principle of the MFT is to find recordings in which the normalized cross-correlation (NCC) function is greater than the given threshold value. The NCC function would lie in the range \([-1, 1]\). The nominal threshold value can be determined from the median absolute deviation (MAD) of the NCC value for each template event. Here we use eight times the MAD as the threshold value. The preprocessing procedures must be applied to both the tem-
A two-pass eighth-pole 0.2–2 Hz band-pass filter is applied to the lunar seismic data. The general processing procedures are described as:

1. Calculate the NCC values between the template and continuous waveforms for each station and component;
2. Shift the NCC series to its origin time by subtracting the picked arrival time of the template waveforms;
3. Stack the NCCs of all stations and all components;
4. Calculate the MAD of the NCC sum and look for potential events with MAD beyond a nominal threshold value.

Here we use MFT to detect deep moonquakes. For example, Figure 6 shows detection of a deep moonquake. We take the first S arrival from the LPX-component recorded by the Apollo Station 12 as the template waveform (Figure 6a). The template waveform is 20 s long. The zero-phase eighth-pole 0.2–2 Hz Butterworth fil-

Figure 4. Performance of conventional and despike filters: (a) the raw waveforms of the vertical component recorded by the Apollo Station 15; (b) conventional filtered data, after use of a zerophase eighth-pole 0.2–2 Hz Butterworth filter; (c) waveforms after applying the running median filter; window length is 701 samplings; (d) filtered data over the despiked waveforms shown in (c). The gray dashed box indicates a lunar event that was seriously contaminated by spikes in the raw continuous waveforms but became visually apparent after the despike filter, i.e., the running median filter.

Figure 5. Tests of the despike filter on waveforms without spikes: (a) the length of the running median filter is 17 samples for unfiltered data, (b) the length is 3 samples for the unfiltered waveform, and (c) the waveform is bandpass filtered in the range of 0.1–1 Hz with the length of the running window set at 17 samples.
ter (Nakamura, 2005) is applied to both the template and continuous waveforms. Peng ZG and Zhao P (2009) used a time length of 4 s as a template to investigate early aftershocks of the 2004 Parkfield earthquake (MW 6.0). Since moonquakes last longer than earthquakes, a longer template waveform time length, 20 s, should be reasonable.

Figure 6b displays the cross-correlation function, in which two events are detected. One is the deep moonquake at 1970-07-20 11:44:00 in the catalogue (label A) and the other (label B), not in the catalogue (Nakamura et al., 1981), was previously hidden in the long-duration mainshock coda. Figure 6c compares the template waveforms (red) with the continuous waveforms (black) for the components of LPX, LPY and LPZ.

Figure 6. An example of an early detected waveform. (a) A deep moonquake seismogram and the self-detection of the LPX component. The black and red lines are the continuous and template waveforms. (b) Cross-correlation function of the template and continuous waveforms for the LPX component. The blue letters A and B indicate positive detections above the threshold, i.e., eight times the mean absolute deviation (MAD) shown in red lines. (c) A comparison of the template waveforms (red) and the continuous waveforms (black) for the components of LPX, LPY and LPZ.

4. Discussions and Conclusions
Probing interior structures of other rocky planets is of increasing interest, in part because such knowledge could improve understanding of the formation and early evolution of our planet. The waves of seismic events, penetrating through solid planets, can reveal details of planet interiors. A major challenge is to identify valid seismic events occurring on planets with quite low tectonic activity. In this paper, we develop a workflow to detect subtle events concealed in continuously recorded seismic data. A despike filter is first applied to eliminate large-amplitude spikes, and then a matched-filter technique is used to dig out hidden low-energy events by matching their signatures with those of known events. Using the developed scheme, signals from weak tectonic and impact events concealed in noise or in long-duration mainshock codas have been greatly enhanced and identified. The scheme could substantially improve detection of weak marsquakes and thus improve monitoring of tectonic activity on Mars in the near future. The proposed scheme can also be applied to detection of meteoroid storms, important because the distributions of meteoroids in space is not random but often takes the form of swarms (Duennebier et al., 1976; Oberst and Nakamura, 1991).

The InSight mission is successfully collecting seismic data. As reported by the Centre National d’Etudes Spatiales (CNES) on 23
April, 2019, four events have been recognized — on 14 March (Sol 105), 6 April (Sol 128), 10 April (Sol 132) and 11 April (Sol 133); the Sol 128 event has been confirmed to be a marsquake. However, ‘The seismic event is too small to provide useful data on the Martian interior’ (https://presse.cnrs.fr/en/world-first-french-seis-instrument-detects-marsquake).

Wei Y et al. (2018) has elaborated a detailed plan for China’s exploration of Earth’s sister planets, based on the ‘Thirteen Five-Year Plan’. For China’s future lunar missions, e.g., Chang’E 7 and 8, exploration of the lunar interior has been ranked at the top of the list of scientific goals. Most lunar events detected from the APSE project have been located on the nearside of the Moon, as displayed in Figure 1; about 30 deep moonquake nests have been identified on the farside of the Moon, but no definitive epicenters are available (Nakamura, 2005). This leads to a key issue or uncertainty — whether no moonquakes occur or whether moonquakes have just not been detected. It is possible that moonquakes happen only on the nearside, or that difficulties in identification of farside moonquakes from Nakamura (2005) has been due to limitations of both the small seismic array of the Apollo project and the uncertainties of lunar velocity models.

We revisit our observation that the magnitudes of lunar events are rather small, as determined by the APSE data. We can still expect the existence of events in the farside hemisphere that may not have been detected, so far, due to their subtle level of released energy. If China or other countries were to place one or more seismometers in future lunar exploration projects, such new deployments of seismometers on the farside of the Moon would help to detect and monitor both seismic events and lunar impacts from meteoroids, further improving our understanding of primitive interior lunar structures.

Overall, detection of events is the fundamental step to investigate the interiors of solar system bodies. Therefore, our scheme, useful in detecting seismic events in extraterrestrial bodies with rather weak tectonic activity, can be a powerful tool to enhance the usefulness of data collected by future space missions.

Besides seismometers to investigate the Mars interiors, an extra heat flow sensor was loaded on Insight to measure the thermal status of deep Mars. Heat flow from interior to surface is another useful geophysical measurement that would provide direct information of deep mantle tectonic activity. Cratons are considered to be the oldest and the most stable tectonic units on Earth, with heat flow values as low as 40 mW/m² or lower, e.g., the West Australian Craton (Sun WJ et al., 2018), but also twice or triple that value, reaching ~100 mW/m², for example, in the destructed North China Craton (e.g., Sun WJ and Kennett, 2017).

Developments and deployment of seismological and heat flow sensors has thus been encouraged and has been assigned top priority by the Key Laboratory of Earth and Planetary Physics, Chinese Academy of Sciences. In addition, on January 6, 2019, the University of Chinese Academy of Sciences approved the establishment of Planetary Science as a first-level discipline, aiming to educate young scientists to join future missions probing the interiors of planets.

Acknowledgments
Lunar global topographic data were accessed from Japan Aerospace Exploration Agency. The instrumental responses of Apollo stations were retrieved from the IRIS Data Management Center. Support from the Youth Innovation Promotion Association CAS (2017094) is acknowledged. The research is also sponsored by National Natural Science Foundation of China (grant no. 41720104006 and 41774060).

References
Aso, N., Ohta, K., and Ide, S. (2011). Volcanic-like low-frequency earthquakes beneath Osaka Bay in the absence of a volcano. Geophys. Res. Lett., 38(8), L08303. https://doi.org/10.1029/2011GL046935
Bulow, R. C., Johnson, C. L., and Shearer, P. M. (2005). New events discovered in the Apollo lunar seismic data. J. Geophys. Res., 110(E10), E10003. https://doi.org/10.1029/2005JE002414
Chamberlain, C. J., and Townsend, J. (2018). Detecting real earthquakes using artificial earthquakes: on the use of synthetic waveforms in matched-filter earthquake detection. Geophys. Res. Lett., 45(21), 11641–11649. https://doi.org/10.1002/2018GL079872
Duennebier, F. K., Nakamura, Y., Latham, G. V., and Dorman, H. J. (1976). Meteoroid storms detected on the Moon. Science, 192(4243), 1000–1002. https://doi.org/10.1126/science.192.4243.1000
Eisner, L., Abbott, D., Barker, W. B., Thornton, M. P., and Lakings, J. (2008). Noise suppression for detection and location of microseismic events using a matched filter. In 2008 SEG Annual Meeting (pp. 1431–1435). Las Vegas, Nevada: Society of Exploration Geophysicists.
Kato, A., and Nakagawa, S. (2014). Multiple slow-slip events during a foreshock sequence of the 2014 Iquique, Chile M 8.1 earthquake. Geophys. Res. Lett., 41(15), 5420–5427. https://doi.org/10.1002/2014GL061138
Khan, A., Mosegaard, K., and Rasmussen, K. L. (2000). A new seismic velocity model for the Moon from a Monte Carlo inversion of the Apollo lunar seismic data. Geophys. Res. Lett., 27(11), 1591–1594. https://doi.org/10.1029/1999GL008452
Lammlein, D. R. (1977). Lunar seismicity and tectonics. Phys. Earth Planet. Inter., 14(3), 224–273. https://doi.org/10.1016/0031-9201(77)90175-3
Li, Z. F., Peng, Z. G., Meng, X. F., Inbal, A., Xie, Y., Hollis, D., and Ampuero, J. P. (2015). Matched filter detection of microseismicity in Long Beach with a 5200-station dense array. In 2015 SEG Annual Meeting (pp. 2615–2619). New Orleans, Louisiana: Society of Exploration Geophysicists.
Nakamura, Y., Latham, G. V., Dorman, H. J., Ibrahim, A. B. K., Koyama, J., and Horvath, P. (1979). Shallow moonquakes-depth, distribution and implications as to the present state of the lunar interior. In Proceedings of the 10th Lunar and Planetary Science Conference (pp. 2299–2309). Houston: NASA.
Nakamura, Y., Latham, G. V., Dorman, H. J., and Harris, J. E. (1981). Passive Seismic Experiment Long Period Event Catalog, final version. University of Texas Institute for Geophysics Technical Report No. 18.
Nakamura, Y., Latham, G. V., and Dorman, H. J. (1982). Apollo lunar seismic experiment—Final summary. J. Geophys. Res. Solid Earth, 87(501), A1117. https://doi.org/10.1029/JB087iS01pA1117
Nakamura, Y. (2005). Farside deep moonquakes and deep interior of the Moon. J. Geophys. Res. Planets, 110(E1), E01001. https://doi.org/10.1029/2004JE002332
Oberst, J., and Nakamura, Y. (1991). A search for clustering among the meteoroid impacts detected by the Apollo lunar seismic network. Icarus, 91(2), 315–325. https://doi.org/10.1016/0019-1035(91)90027-Q
Peng, Z. G., and Zhao, P. (2009). Migration of early aftershocks following the 2004 Parkfield earthquake. Nat. Geosci., 2(12), 877–881. https://doi.org/10.1038/ngeo0697
Sharma, B. K., Kumar, A., and Murthy, V. M. (2010). Evaluation of seismic events detection algorithms. J. Geol. Soc. India, 75(3), 533–538. https://doi.org/10.1007/s12594-010-0042-8
Shearer, P. M. (1994). Global seismic event detection using a matched filter on long-period seismograms. *J. Geophys. Res. Solid Earth*, 99(B7), 13713–13725. https://doi.org/10.1029/94JB00498

Shelly, D. R., Beroza, G. C., and Ide, S. (2007). Non-volcanic tremor and low-frequency earthquake swarms. *Nature*, 446(7133), 305–307. https://doi.org/10.1038/nature05666

Suggs, R. M., Moser, D. E., Cooke, W. J., and Suggs, R. J. (2014). The flux of kilogram-sized meteoroids from lunar impact monitoring. *Icarus*, 238, 23–36. https://doi.org/10.1016/j.icarus.2014.04.032

Sun, W. J., Fu, L. Y., Saygin, E., and Zhao, L. (2018). Insights into layering in the cratonic lithosphere beneath Western Australia. *J. Geophys. Res. Solid Earth*, 123(2), 1405–1418. https://doi.org/10.1002/2017JB014904

Sun, W. J., and Kennett, B. L. N. (2017). Mid-lithosphere discontinuities beneath the western and central North China Craton. *Geophys. Res. Lett.*, 44(3), 1302–1310. https://doi.org/10.1002/2016GL071840

Wei, Y., Yao, Z. H., and Wan, W. X. (2018). China’s roadmap for planetary exploration. *Nat. Astron.*, 2(5), 346–348. https://doi.org/10.1038/s41550-018-0456-6

Withers, M., Aster, R., Young, C., Beiriger, J., Harris, M., Moore, S., and Trujillo, J. (1998). A comparison of select trigger algorithms for automated global seismic phase and event detection. *Bull. Seismol. Soc. Am.*, 88(1), 95–106.