Evidence for Recent Lunar Tectonic, Volcanic and Interior Activity

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Abstract: The Moon, which was believed that died out about 2.5～3.5 billion years ago with volcanic and tectonic activity had essentially ceased by 2.5 Ga., represents an end member in terms of terrestrial planet evolution in the inner Solar System. However, the Apollo data, especially coupled with the new data of the Moon about lunar tectonic, volcanic, moonquake and interior structure obtained by lunar orbiters and landers during the past dozen years, shows evidence that suggests the Moon remained active from deep interior to the surface, and by no means of died out totally. This will change our view of the lunar evolution history and status.

Key words: Moon; lunar tectonic; moonquake; volcanic; interior

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月球仍然活跃的构造、火成和内部特征等证据

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摘　要: 月球尽管被作为类地行星演化的最终形态的代表，被认为在 25 亿年前已经完全冷却，根据阿波罗时代以来、特别是近十余年的月球轨道器和着陆器获得的关于月球构造、火成活动、月震和内部结构等多种证据，表明月球从深层内部到表面仍然活跃，尚未彻底冷却“死亡”。这将完全改变人们关于月球演化历史和状态的观念。

关键词: 月球；月球构造；月震；火成；内部

0 Introduction

The Moon represents an end member in terms of terrestrial planet evolution, as it is the smallest planetary body (excluding asteroids and the moons of Mars) in the inner Solar System. The small size of the Moon suggests the heat engine that drove the initial differentiation via a magma ocean (Smith et al, 1970; Wood et al, 1970; Warren 1974; Elkins-Tanton et al, 2011)[1-4] and facilitated subsequent volcanism between 3～4 Ga (Nyquist and Shih, 1992; Snyder et al, 2000)[5-6] that died out about 2.5～3.5 billion years ago (Shearer et al, 2006, and references therein)[7]. As the Moon cooled, it experienced a period of contraction around 3.5 Ga (Binder, 1982), and the implication is that volcanic and tectonic activity had essentially ceased by 2.5 Ga. This paper documents evidence that suggests the Moon remained active for much longer than expected and is still active today.

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Using Apollo data coupled with new high-resolution imagery of the Lunar Reconnaissance Orbiter Camera and other orbital data, evidence is emerging that will change our view of how the Moon continues to be active.

1 Evidence for an Active Moon

Characterization of lunar activity can be made by dividing observations into two broad categories: Tectonic and Volcanic. It has been known since Apollo that the lunar surface contained features associated with tectonic movements, termed "wrinkle ridges"(Lucchitta, 1976, 1977; Solomon and Head, 1979; Plescia and Golombeck, 1986; Sharpton and Head, 1988)[8-12]. In addition, recent volcanic (fumarolic) activity was suggested to explain enhanced ^{222}Rn and ^{210}Po emissions at the edges of lunar maria and specifically from Aristarchus and Grimaldi (Bjorkholm et al., 1973; Gorenstein and Bjorkholm, 1973; Gorenstein et al., 1973, 1974)[13-17], as well as to explain relatively fresh volcanic constructs (Schultz et al., 2006)[18]. With the on-going Lunar Reconnaissance Orbiter mission, high-resolution (< 1 m/pixel) imagery of the lunar surface has added much more evidence that the Moon continued to be active long after the cessation of major volcanic activity. In a recent study, Harada et al.,(2014)[19] noticed the strong tidal heating in an ultralow-viscosity zone at the core-mantle boundary of the Moon.

1.1 Apollo Seismic Data

Seismic activity on the Moon was recorded by the Apollo Passive Seismic Experiment (APSE: Latham et al., 1969, 1970; Figure 1)[20-21], a network of four seismometers that was completed in April 1972, and operated until they were all switched off due to cost-cutting measures on 30 September 1977. During the time the network was operational, it clearly demonstrated that the Moon was seismically active, albeit on a smaller scale than Earth (Nakamura, 1980; Nakamura et al., 1982)[22-23]. This is because the Moon is a "one plate planet" and does not, therefore, contain plate boundaries where most of the large seismic events occur here on Earth. If plate boundaries are ignored, the Moon exhibits seismic activity on a similar scale to that of an intraplate setting on Earth (Nakamura, 1980; Goins et al., 1981; Oberst, 1987; Oberst and Nakamura, 1992; Figure 2)[22,24-26]. Over the last three decades, the Apollo seismic database (Nakamura et al., 1981)[27] has been mined and four different types of lunar seismic event have been identified. These are thermal Moonquakes, deep Moonquakes, meteoroid impact, and shallow Moonquakes.

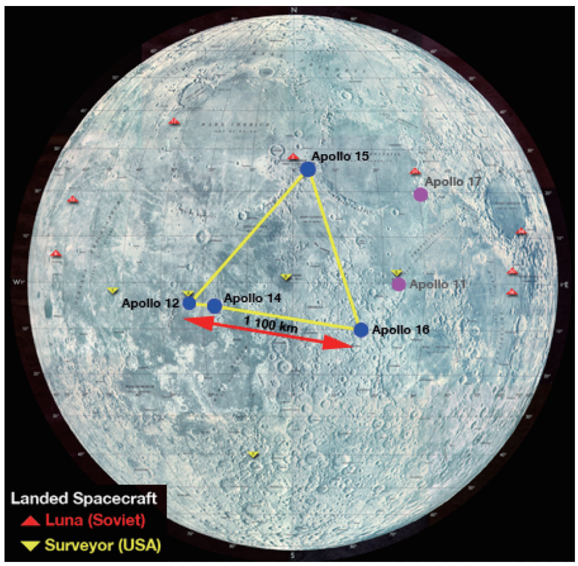

Fig. 1　Locations of the seismometers that formed the Apollo Passive Seismic Experiment (APSE) on the lunar nearside

Thermal Moonquakes: these lunar seismic events are small and were recorded mostly by the short period components of the Apollo seismometers. These are related to diurnal temperature changes and were recognized by the repetition of signals with nearly identical waveforms at the same time during each lunation (Dunnebier and Sutton, 1974a)[28]. Many thermal Moonquakes originating at different locations have been identified (e.g., 48 at Apollo 14; 245 at Apollo 15). Seismic activity begins abruptly two days after lunar sunrise and rapidly deteriorates after lunar sunset. The mechanism favored by Dunnebier and Sutton (1974a)[28] involves the slumping of soil on slopes initiated by thermal stresses and appear to be associated with young craters (Duennebier, 1976)[29]. Of the four types of Moonquakes, these events emit the lowest energy.

Deep Moonquakes: these are the most abundant type with >7 000 events having been recognized (Nakamura, 1974a, 2003, 2005; Bulow et al., 2004)[30-33]. These small-magnitude events (generally ≤2) occur ap proximately half way between the surface and the center of the Moon (700～1 200 km), at highly regular monthly intervals, and were strongly associated with tidal pull of the Earth (Lammelein et al., 1974; Lammlein, 1977)[34-35]. These deep Moonquakes originate from specific locations, or nests, that produce a quake of unique waveform. To date, over 300 nests have been identified from the Apollo data set (Nakamura et al., 1982; Nakamura, 2003, 2005)[31-32,36].

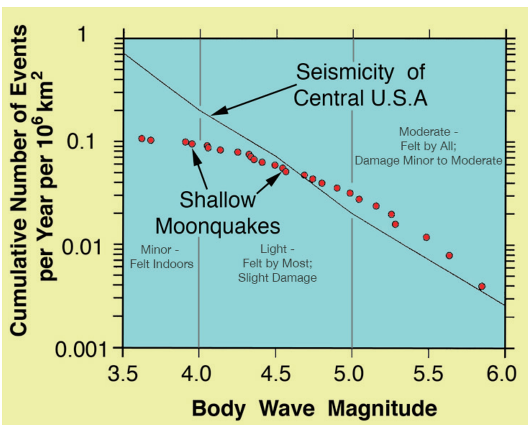

Fig. 2 Magnitude-frequency relationships of shallow moonquakes (red circles) and intraplate earthquakes (black line). The effects of earthquakes of different magnitude are indicated. Modified from Oberst and Nakamura (1992)[26]

Meteoroid Impacts: while most of the energy of an impact is expended excavating a crater, some is converted to seismic energy and >1 700 events representing meteoroid masses be tween 0.1 and 1 000 kg were recorded between 1969 and 1977. Events generated by smaller impacts were too numerous to be counted (Duennebier and Sutton, 1974b; Duennebier et al., 1975, 1976; Latham et al., 1978; Oberst and Nakamura, 1989, 1991)[37-42]. These surface seismic events exhibit characteristic amplitude variations with distance, with a relative flattening of amplitude between distances of 20° and 90° thought to represent shear waves penetrating into the lunar upper mantle (Nakamura et al., 1976)[43].

Shallow Moonquakes. These were originally referred to as "high frequency teleseismic events" (Nakamura et al., 1974b; Nakamura, 1977a; Goins et al., 1981)[24,44-45]. These are relatively rare but are the strongest type of Moonquake, with seven of the 28 recorded events being magnitude 5 or greater (Nakamura et al., 1979; Nakamura 21, 1980; Oberst, 1987; Oberst and Nakamura, 1992)[22,25-26,46]. Focal depths are "shallow", although the exact depths and locations are unknown because all recorded events were out side the Apollo seismic network (approximate locations are given in Figure 3). Evidence (Nakamura 21, 1980)[22] suggests focal depths between 50～200 km, as these events exhibit onset times of P and S waves that are separated by intervals appropriate for transmission through the Moon. However, they are not correlated with tides and while they appear to be associated with boundaries between dissimilar surface features (e.g., impact basin rims-Nakamura et al., 1979)[46], the exact origin of these events is still unclear. An extra Solar System originhas been suggested by Nakamura and Frohlich (2006)[47] and Frohlich and Nakamura[48]. These authors postulate that shallow moonquakes may originate from interaction of the Moon with nuggets of high-energy particles ("strange quark matter") originating from a fixed source outside the solar system.

Shallow moonquakes are distinct from other types of lunar seismic events because of their high-frequency content. The distinctly large amplitude of these events recorded by the short-period vertical seismometer can be ratioed to that recorded by the long-period seismometer as a qualitative measure of frequency content

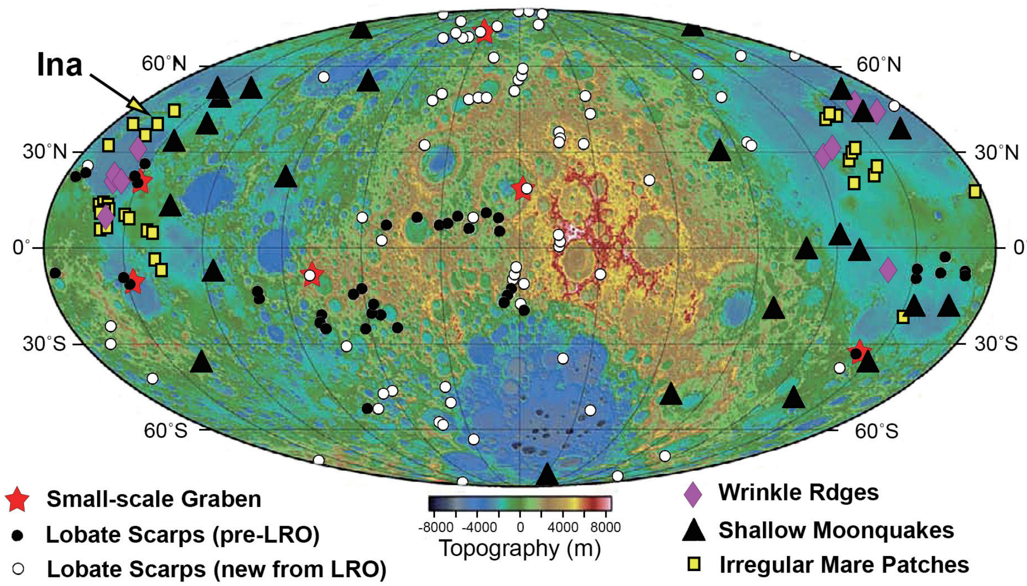

Fig. 3　Location map for recent tectonic and volcanic features. Modified from Watters et al. (2012). Shallow moonquake locations are approximate

(Nakamura et al., 1974b; Figure 4)[44].

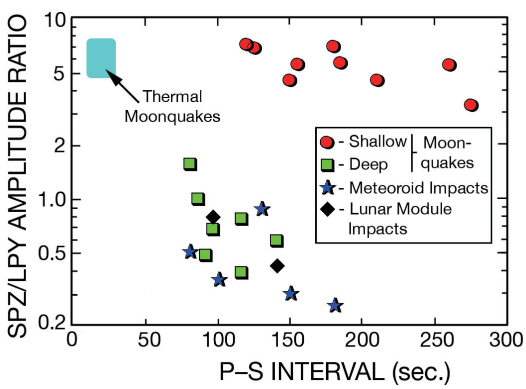

Fig. 4　SPZ/LPY amplitude ratio vs. S-P time interval of the high-frequency teleseismic events and other selected events at Apollo 14. The field for Thermal moonquakes is approximate. Modified from Nakamura et al. (1974)[44]

Relevance of Moonquakes. Two types of Moonquakes pose potential (and very real) hazards to establishing a long-term habitable facility on the Moon. These are the shallow Moonquakes and those caused by meteoroid impacts. [Note: although the seismicity generated by the latter generally should not threaten any structure, unless the impactor is on the order of tons in mass and the impact is close by, a direct impact at the site of the Moon base most certainly would.] While sur face waves are scattered due to the nature of the regolith and prevent efficient long-range propagation, lunar seismic waves are much less attenuated than in Earth (Nakamura and Koyama, 1982)[23]. Oberst and Nakamura (1989, 1991, 1992)[26,38-41], presented evaluations of these types of lunar seismic events and noted that meteoroid impacts were somewhat clustered. As with locating the shallow Moonquake epicenters, locating the sites of meteoroid impact is also difficult. As can be seen from Figure 1, the APSE seismometers were located on the lunar nearside in a triangle with a baselength of 1 100 km. This positioning, coupled with the fact that the Moon's rotational axis is almost perpendicular to the ecliptic plane (so the seismic array was always facing towards the same latitude), produced a much larger error in heliocentric latitude relative to longitude for the radiant meteoroids (see figures 4 and 5 of Oberst and Nakamura, 1991)[42].

There are distinct differences in terms of seismic wave transmission between the Moon and Earth. For example, the maximum signal from a shallow Moonquake can last up to 10 minutes with a slow tailing off that can continue for hours in total duration, demonstrating that damping is less efficient in the Moon than it is in the Earth. This suggests the mechanical properties of lunar rocks are unique, which is demonstrated by their high "seismic Q"(the attenuation of seismic energy; or seismic dissipation — Q^{-1}) value of the Moon relative to the Earth, which is in excess of an order of magnitude greater (Warren et al., 1974; Tittmann et al., 1976, 1977, 1978, 1979, 1980; Richardson and Tittmann, 1980; Nakamura and Koyama, 1982)[2,36,49-54]. Studies have demonstrated the dramatic damping effect water has on seismic energy (Pandit and Tozer, 1970; Tittmann et al., 1976, 1980)[49, 53,55]. As seismic energy is more efficiently propagated through the Moon and is not damped as effectively as it is through the Earth, especially at higher frequencies (Tittmann et al., 1980; Nakamura and Koyama, 1982)[36,53], the lunar interior must be dry. Therefore, the recent identification of significant volatiles in volcanic glass beads (Saal et al., 2008)[56], in olivine-hosted melt inclusions (Hauri et al., 2011)[57], and in phosphates from mare basalts (Boyce et al., 2010; McCubbin et al., 2010)[58-59] present a dichotomy with this observation that remains to be resolved.

Significantly, moonquakes tend to produce seismic waves of higher frequency than earthquakes. This is an important consideration for wave transmission through the lunar interior as well as interaction with the regolith. The lunar regolith has been formed through continual comminution of rock through both micro-and macro-meteoroid impact. This dry unconsolidated material tends to scatter seismic waves. Modeling of this scattering using frequency-dependent diffusion appears to allow a statistical approach to quantifying the data recorded by the APSE network (Nakamura, 1977; Blanchette-Guertin et al., 2012)[60-61]. The diffusion model accounts for the apparent lack of coherence between the three orthogonal components of ground motion and the extremely prolonged signal. Among others, Nakamura (1977b)[60] highlighted the fact that there is very low attenuation of waves in the surface zone. Blanchette-Guertin et al. (2012)[58] suggested that scattering in a near-surface global layer dominates the records of shallow events (thermal and shallow moonquakes, meteoroid impacts), especially at frequencies above 2 Hz.

1.2 Surface Tectonic Activity

Apollo-era imagery facilitated the discovery of both compressional and extensional features on the surface of the Moon. Such features were confined exclusively to mare basalt regions and included wrinkle ridges, graben, and floor-fractured craters. However, Apollo imagery did not provide global coverage. With the coverage now provided by LRO with both the wide-and narrow-angle cameras of the LROC system, more tectonic features have been discovered.

Compressional Features. The observation of "wrinkle ridges" in mare regions of the Moon has been attributed to reverse to thrust faulting, indicating compressional stresses (Plescia and Golombeck, 1986; Watters, 1988)[11,62]. However, it was unclear as to the approximate age that deformation took place. Watters et al. (2010)[63] used the high-resolution imagery of the LRO camera (LROC) to not only discover new compressional structures (Figure 3), but also to suggest a relatively young age for their formation (<1 billion years) as some of these feature cross-cut Copernican age (about 800 Ma) craters. Using the topography and slope data from the Lunar Orbital Laser Altimeter (LOLA), Watters et al. (2010)[63] estimated the magnitude of the thrust/reverse faults are consistent with thermal models for a Moon with an early magma ocean (either whole or partial Moon melting; Solomon and Chaiken, 1976; Binder, 1982, 1986; Binder and Oberst, 1985; Solomon, 1986)[64-68], but that the new observations suggest late-stage global contraction.

Lobate scarps were also known from Apollo imagery (Binder and Gunga, 1985)[69]. Results from LROC suggest that these faults occur from the surface down to depths of hundreds of meters, have dip angles of 35°～40°, and have typical maximum slips of tens of meters (Williams et al., 2013)[70].

Extensional Features. Prior to LRO, extensional features were only known in mare basalt-filled basins and floor-fractured craters. These presumably formed due to viscous relaxation and/or igneous intrusions (Luchitta and Watkins, 1978; Hall et al., 1981; Wichman and Schultz, 1995; Dombard and Gillis, 2001)[71-74]. Luchitta and Watkins (1978)[71] suggested that graben formation stopped about 3.6±0.2 b. y. ago.

Watters et al. (2012) reported the first extensional structures from the non-mare highlands regions as well as new structures in the maria. Relatively small-scale grabens were noted, with vertical motion usually resulting in <15 m of relief. Using cross-cutting relationships with impact craters as small as 10 m diameter, a lack of superposed craters, and graben depths as shallow as ~1 m, led Watters et al. (2012)[75] to conclude that these extensional features are <50 m. y. old. The relatively pristine appearance of these features supports the young age. These results are inconsistent with a the Moon having supported a magma ocean that encompassed whole-Moon melting, as this would produce larger scale extensional features that would be older than the observations suggest. Rather, a more modest magma ocean encompassing the outer ~500 km of the Moon is more likely.

The distribution of tectonic features and shallow moonquake epicenters can be found in Figure 3. The implications from the presence of these features place constraints on the early evolution of the Moon. For example, the compressional features argue for a global contraction, but not immediately after the magma ocean had solidified. However the lack of distributed large-scale lobate scarps and thrust faults argues against secular cooling of an entirely molten early Moon (Watters et al., 2012)[75]. Similarly, the presence and distribution of extensional features also argues against a totally molten early Moon because thermal history models for this scenario predict a high level of late-stage compressional stress that would likely suppress graben formation. Therefore, these features give us a potential constraint on the size of the lunar magma ocean that can aid our understanding of the early evolution of the Moon.

1.3 Volcanic Activity

The return of Apollo samples facilitated two major breakthroughs in terms of understanding lunar volcanic activity: 1) direct age dating of the samples suggested that major lunar volcanism ceased about 3 billion years ago (Nyquist and Shih, 1992; Shearer et al., 2006)[5,7]; 2) constraints on relative age dating using impact crater counts could be made, thus allowing volcanic terrains away from the Apollo landing sites to be semi-quantitatively age dated. With high resolution imagery becoming available from spacecraft that have visited the Moon since 2000 (SMART-1; Selene/Kaguya; Chang'e—1, —2, —3; Chandrayaan—1; Lunar Reconnaissance Orbiter) better crater counts have been conducted and have shown that some mare basalt terrains maybe as young as 1 billion years (Hiesinger et al., 2000, 2010)[76-77]. Significantly, these younger basalt terrains lie within the Procellarum KREEP Terrain (PKT: Jolliff et al., 2000)[78], which is characterized by relatively high Thorium (and other heat-producing elements).

Recently, as global datasets have been acquired by the spacecraft listed above, and combined with those from the Lunar Prospector and Clementine missions, it is becoming evident that some volcanic features could by as young as 10 Ma. Schultz et al.[18] suggested the Ina structure near the Apenine Mountains on the lunar nearside (Figure 3) represented evidence for recent (<10 Ma) gas release. This was based upon the preservation state of relief, the number of superimposed small craters, and the 'freshness' (spectral maturity) of the regolith. Interestingly, the Apollo missions noted increased Radon and

Polonium levels over mare regions, especially at the edges of mare basins, Mare Imbrium, and the Aristarchu Plateau (Bjorkholm et al., 1973; Gorenstein and Bjorkholm, 1973; Gorenstein et al., 1973, 1974a, b)[13-17]. On the basis of these observations, Schultz et al. (2006)[18] suggested that the Ina structure was still active today.

Braden et al. (2013, 2014)[79-80] have used LROC narrow angle camera imagery to define over 75 structures similar to Ina. These have been called Irregular Mare Patches (IMPs, 100 ~ 5 000 m maximum dimension; Figure 3). Crater count ages on the largest three IMPs (Cauchy-5, Ina, and Sosigenes) suggest an upper age limit of 100 Ma.

1.4 Ultra-Low Viscosity Zone

Nakamura (1973, 2005, 2012)[32,42] found that the attenuation of seismic waves in the deep lunar interior is consistent with a low-viscosity layer at the core-mantle boundary. After reprocessing deep moonquake data of the Apollo era using modern computational methods, Weber et al. (2011)[81] were able to show that the Moon had a solid inner core of radius 240 km with a liquid outer core layer about 90 km thick, and a partial molten lower mantle layer about 150 km thick. Recently, Harada et al. (2014)[19] noticed the strong tidal heating in an ultralow-viscosity zone at the core-mantle boundary of the Moon. The full scenario is similar to the Earth. Usually, the tidal heating of a planetary body such as the Moon occurs by viscous dissipation of orbital and rotational energy (Ross et al., 1986, Khan et al., 2004, 2005)[82-84]. Considering the viscoelastic tidal response of a Moon that contains a low-viscosity layer at the core-mantle boundary, Harada et al (2014)[19] calculated the response of the Moon to tidal forces considered the Moon's interior structure using a numerical model. In this calculation, the presence of a layer with a viscosity of about 2×10^{16} Pas leads to frequency-dependent tidal dissipation within the Moon that matches tidal dissipation measurements at both monthly and annual periods. The calculated viscosity values are extremely low, and are consistent with partial melting at the lunar core-mantle boundary. This calculation also finds that simulated tidal dissipation is not evenly distributed in the lunar interior, but localized within this low-viscosity layer, which implies that the low-viscosity layer may act as a thermal blanket (Stegman et al. 2003)[85] on the lunar core and may have influenced the Moon's thermal evolution. The strong tidal heating at the core-mantle boundary of the Moon implies that the lunar interior is still very hot and dynamic.

2 Discussion

The evidence from the Apollo seismic data, coupled with the tectonic and volcanic features documented by Apollo and LROC data, demonstrate that the Moon remained active long after the cessation of major volcanism at about 3 Ga. The seismic data show there are three types of induced lunar seismicity:

1) Thermal moonquakes-induced by the expansion/contraction of the regolith as the terminator passes over a given region;

2) Deep moonquakes-induced due primarily to the gravitational influence of the Earth;

3) Meteoroid impact-seismicity induced by impacts.

Shallow moonquakes, which have the highest magnitude of any recorded lunar seismic event, may be the only true endogenous type of seismicity recorded on the Moon, although an extra-Solar-System origin for these seismic events has also been postulated (Nakamura and Frohlich, 2006; Frohlich and Nakamura, 2006)[47-48].

The narrow aperture of the APSE on the lunar nearside (Figure 1) had two major drawbacks: 1) locations of seismic events outside of the network are poorly constrained; 2) information regarding the nature of the lunar interior below approximately 500 km depth is limited, as solutions are non-unique. It is important, therefore, to establish a global lunar geophysical network. After the Vision for Space Exploration was announced by President George W. Bush in 2004[86], NASA led an effort to establish an international lunar network. This resulted in a Science Definition Team final report that described the concept (Cohen, Veverka, et al., 2009)[87]. While NASA has abandoned the ILN concept since the change of administration, the idea of establishing a global lunar geophysical network lives on. The latest decadal survey for the NASA Planetary Sciences division has a Lunar Geophysical Network mission as a named medium-class (New Frontiers) mission that should be accomplished (subject to the New Frontiers competition through the proposal process) in the next decade (NRC, 2011)[88]. This does not, however, mean that such a mission will occur.

It is imperative for both science and exploration reasons that a global geophysical network be established on the surface of the Moon (including the farside) as soon as possible. For science, the Moon is an end-member for understanding planetary evolution (Figure 5) and the interior structure may preserve the initial differentiation all terrestrial planets experienced. The enhanced heat engines of terrestrial planets larger than the Moon have destroyed all evidence of this initial differentiation. The Moon represents out best chance of defining how terrestrial planets underwent initial differentiation. For exploration, the exact locations and causes of shallow moonquakes need to be identified especially if a permanent base is to be established.

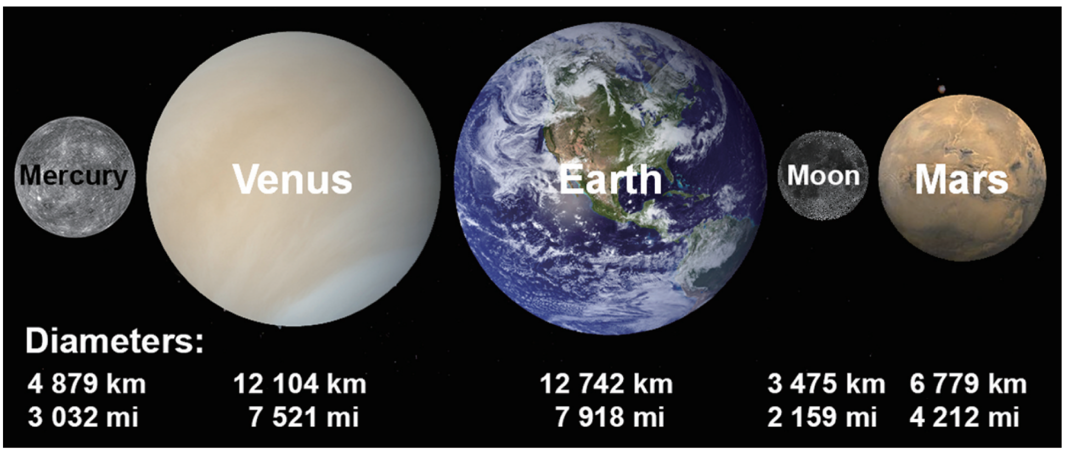

Fig. 5 Comparison of inner planetary body diameters in kilometers and miles. The Moon is the smallest terrestrial planetary body in the inner Solar System (not including the small Martian moons, Phobos and Deimos) and, by inference, has the smallest heat engine so planetary differentiation stopped at an early stage

Shallow moonquakes represent an enigma. Are they a result of movements along the faults involved with the surface features that are visible with LROC imagery (i. e., could they be a result of movements along faults associated with the lobate scarps and/or grabens)? Are they associated with recent volcanic activity? The locations on Figure 3 would seem to suggest not. However, much remains to be learned about recent and current lunar activity and a global geophysical network will be an important part in improving our understanding of how the Moon continues to evolve, not least of which will be pinpointing the epicenters of shallow moonquakes and possibly tracing normal and reverse/thrust into the interior of the Moon.

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References

[1] Wood J A, Dickey J S J, Marvin U B, et al. Lunar anorthosites and a geophysical model of the Moon[C]//Proc. Apollo 11 Lunar SCI. Conf., 1970:965–988.

[2] Warren N, Trice R, Stephens J. Ultrasonic attenuation: Q measurements on 70215, 20p[C]//Proc. Lunar Sci. Conf. 5th, 1974:2927–2938.

[3] Elkins-Tanton L T, Burgess S, Yin Q-Z. the lunar magma ocean: Reconciling the solidification process with lunar petrology and geochronology[J]. Earth Planet. Sci. Lett., 2011(304):326–336.

[4] Smith J V, Anderson A T, Newton R C, et al. Petrologic history of the Moon inferred from petrography, mineralogy, and petrogenesis of Apollo 11 rocks[C]// Proc. Apollo 11 Lunar Sci. Conf., 1970:897–925.

[5] Nyquist L E, Shih C-Y. The isotopic record of lunar volcanism. Geochim. Cosmochim[J]. Acta, 1992(56): 2213–2234.

[6] Snyder G A, Borg L E, Nyquist L E, et al. Chronology and isotopic constraints on lunar evolution[M]// Canup R, Righter K. Origin of the Earth & Moon, 2000:361–395.

[7] Shearer C K, Hess P C, Wieczorek M A, et al. Thermal and magmatic evolution of the Moon[J]. New Views of the Moon, Reviews in Mineralogy & Geochemistry, 2006(60): 365–518.

[8] Lucchitta B K. Mare ridges and related highland scarps-result of vertical tectonism[C]//Proc. Lunar Sci. Conf. 8th, 1976: 2761–2782.

[9] Lucchitta B K. Topography, structure, and mare ridges in southern Mare Imbrium and northern oceanus procellarum [C]// Proc. Lunar Planet. Sci. Conf. 8th, 1977: 2691–2703.

[10] Solomon S C, Head J W. Vertical movement in mare basins: relation to mare emplacement, basin tectonics, and lunar thermal history[J]. J. Geophys. Res., 1979(84): 1667–1682.

[11] Plescia J B, Golombeck M P. Origin of planetary wrinkle ridges based on the study of terrestrial analogs[J]. Geol. Soc. Amer. Bull. 1986(97):1289–1299.

[12] Sharpton V L, Head J W. Lunar mare ridges: Analysis of ridge-crater intersections and implications for the tectonic origin of mare ridges[C]// Proc. Lunar Planet. Sci. Conf. 18th, 1988:307–317.

[13] Bjorkholm P J, Golub L, Gorenstein P. Distribution of ^{222}Rn and ^{210}Po on the lunar surface as observed by the alpha particle spectrometer[C]// Proc. Lunar Sci. Conf. 4th, 1973:2793–2802.

[14] Gorenstein P, Bjorkholm P J. Detection of Radon emanantion from the crater Aristarchus by the Apollo 15 alpha particle spectrometer[J]. Science, 1973(179):792–794.

[15] Gorenstein P, Golub L, Bjorkholm P J. Spatial features and temporal variability in the emission of Radon from the Moon: An interpretation of results from the alpha particle spectrometer[C]// Proc. Lunar Sci. Conf. 4th, 1973: 2803–2809.

[16] Gorenstein P, Golub L, Bjorkholm P J. Detection of Radon emission at the edges of lunar maria with the Apollo alpha particle spectrometer[J]. Science, 1974(183):411–413.

[17] Gorenstein P, Golub L, Bjorkholm P J. Radon emanation from the Moon, spatial and temporal variability[J]. The Moon, 1974(9):129–140.

[18] Schultz P H, Staid M I, Pieters C M. Lunar activity from recent gas release[J]. Nature, 2006(444):184–186.

[19] Harada Y, Goossens S, Matsumoto K, et al. Strong tidal heating in an ultralow-viscosity zone at the core – mantle boundary of the Moon[J]. Nature Geoscience, 2014(7): 569–572. doi:10.1038/ngeo2211.

[20] Latham G V, Ewing M, Press F, et al. The Apollo passive seismic experiment[J]. Science, 1969(165):241–250.

[21] Latham G V, Ewing M, Press F, et al. Passive seismic experiment[J]. Science, 1970(167):455–457.

[22] Nakamura Y. Shallow Moonquakes: how they compare with earthquakes[C]// Proc. Lunar Planet. Sci. Conf. 11th, 1980:1847–1853.

[23] Nakamura Y, Latham G V, Dorman H J. Apollo lunar seismic experiment-final summary[C]//Proc. Lunar Planet. Sci. Conf. 13th, J. Geophys. Res., 1982 (87): A117–A123.

[24] Goins N R, Dainty A M, Toksöz M N. Lunar seismology: The in ternal structure of the Moon[J]. J. Geophys. Res., 1981(86):5061–5074.

[25] Oberst J. Unusually high stress drops associated with shallow Moonquakes[J]. J. Geophys. Res., 1987(92): 1397–1405.

[26] Oberst J, Nakamura Y. A seismic risk for the lunar base[C] //Lunar Bases & Space Activities 2. Houston: Lunar & Planetary Institute, 1992:231–233.

[27] Nakamura Y, Latham G V, Dorman H J, et al. Passive seismic experiment long-period event catalog, final version [R]. Tech. Rep. 18, Galveston: Inst. of Geophysics, Univ. of Texas, 1981.

[28] Dunnebier F, Sutton G H. Thermal Moonquakes[J]. J. Geophys. Res., 1974(79):4351–4363.

[29] Duennebier F. Thermal movement of the regolith[C]// Proc. Lunar Sci. Conf. 7th, 1976:1073–1086.

[30] Nakamura Y, Latham G V, Lammlein D, et al. Deep lunar interior inferred from recent seismic data[J]. Geophys. Res. Lett, 1974a(1):137–140.

[31] Nakamura Y. New identification of deep moonquakes in the Apollo lunar seismic data[J]. Phys. Earth Planet. Int., 2003(139):197–205.

[32] Nakamura Y. Farside deep Moonquakes and deep interior of the Moon[J]. J. Geophys. Res.，2005(110)：E01001. doi：10.1029/2004JE002332.

[33] Bulow R C，Johnson C L，Shearer P M. New events discovered in the Apollo lunar seismic data[C]// Lunar Planet. Sci. XXXV，abstract #1184，CD-ROM. Houston：Lunar & Planetary Institute，2004.

[34] Lammelein D R，Latham G V，Dorman J，et al. Lunar seismicity，structure，and tectonics[J]. Rev. Geophys. Space Phys.，1974(12)：1－21.

[35] Lammelein D R. Lunar seismicity and tectonics[J]. Phys. Earth Planet. Int.，1977(14)：224－273.

[36] Nakamura Y，Koyama J. Seismic Q of the lunar upper mantle[J]. J. Geophys. Res. 1982(87)：4855－4861.

[37] Dunnebier F，Sutton G H. Meteoroid impacts recorded by the short-period of Apollo 14 lunar passive seismic station [J]. J. Geophys. Res.，1974(79)：4365－4374.

[38] Duennebier F，Dorman J，Lammlein，D. et al. Meteoroid flux from passive seismic experiment data[C]//Proc. Lunar Sci. Conf. 6th，1975：2417－2426.

[39] Duennebier F，Nakamura Y，Latham G V，et al. Meteoroid storms detected on the Moon. Science，1976(192)：1000－1002.

[40] Oberst J，Nakamura Y. Monte Carlo simulations of the diurnal variation in seismic detection rate of sporadic meteoroid impacts on the Moon[C]//Proc. Lunar Planet. Sci. Conf. 19th，1989：615－625.

[41] Latham G V，Dorman H J，Horvath P，et al. Passive seismic experiment：a summary of current data[C]//Proc. Lunar Planet. Sci. Conf. 9th，1978：3609－3913.

[42] Oberst J，Nakamura Y. A search for clustering among the meteoroid impacts detected by the Apollo lunar seismic network[J]. Icarus. 1991(91)：315－325.

[43] Nakamura Y，et al. New seismic data on state of deep lunar interior[J]. Science，1973(181)：49－51.

[44] Nakamura Y，Dorman J，Duennebier F，et al. High-frequency lunar teleseismic events[C]// Proc. Lunar Sci. Conf.，1974b(5)：2883－2890.

[45] Nakamura Y. HFT events：shallow Moonquakes[J]. Phys. Earth Planet Inter，1977(14)：217－223.

[46] Nakamura Y，Latham G V，Dorman H J，et al. Shallow Moonquakes：Depth，distribution and implications as to the present state of the lunar interior[C]//Proc. Lunar Planet. Sci. Conf. 10 th，1979：2299－2309.

[47] Nakamura Y，Frohlich C. Possible extra-solar-system cause for certain lunar seismic events[C]// Lunar Planet. Sci. XXXVII，abstract # 1048，CD-ROM. Houston，Texas：Lunar and Planetary Institute，2006.

[48] Frohlich C，Nakamura Y. Possible extra-solar-system cause for certain lunar seismic events[J]. Icarus，2006(185)：21－28.

[49] Tittmann B R，Ahlberg L，Curnow J. Internal friction and velocity measurements[C]// Proc. Lunar Sci. Conf. 7th，1976：3123－3132.

[50] Tittmann B R，Ahlberg L，Nadler H，et al. Internal friction quality-factor Q under confining pressure[C]// Proc. Lunar Sci. Conf. 8th，1977：1209－1224.

[51] Tittmann B R，Nadler H，Richardson J M，et al. Laboratory measurements of p-wave seismic Q on lunar and analog rocks [C]// Proc. Lunar Planet. Sci. Conf. 9th，1978：3627－3635.

[52] Tittmann B R，Nadler H，Clark V，et al. Seismic Q and velocity at depth[C]// Proc. Lunar Planet. Sci. Conf. 10th，1979：2131－2145.

[53] Tittmann B R，Clark V A，Spencer T W. Compressive strength，seismic Q，and elastic modulus[C]//Proc. Lunar Planet. Sci. Conf. 11th，1980：1815－1823.

[54] Richardson J M，Tittmann B R. Phenomenological theory of attenuation and propagation velocity in rocks[C]// Proc. Lunar Planet. Sci. Conf. 11th，1980：1837－1846.

[55] Pandit B I，Tozer D C. Anomalous propagation of elastic energy within the moon[J]. Nature，1970：226(5243)：335.

[56] Saal A E，Hauri E H，Cascio M L，et al. Volatile content of lunar volcanic glasses and the presence of water in the Moon's interior[J]. Nature，2008(454)：192－195.

[57] Hauri E H，Weinreich T，Saal A E，et al. High pre-eruptive water contents preserved in lunar melt inclusions [J]. Science，2011(333)：213－215.

[58] Boyce J W，Liu Y，Rossman G R，et al. Lunar apatite with terrestrial volatile abundances[J]. Nature，2010(466)：466－469.

[59] McCubbin F M，Steele A，Hauri E H，et al. Nominally hydrous magmatism on the Moon[J]. Proc. National academy of Sciences，2010(102)：11223－11228.

[60] Nakamura Y. Sesimic energy transmission in an intensively scattering environment[J]. J. Geophys，1977(43)：389－399.

[61] Blanchette-Guertin J-F，Johnson C L，Lawrence J F. Investigation of scattering in lunar seismic coda. J. Geophys. Res.，2012(117)：E06003. doi：10.1029/2011JE004042.

[62] Watters T R. Wrinkle ridge assemblages on the terrestrial planets[J]. J. Geophys. Res.，1988(93)：10236－10254.

[63] Watters T R，Robinson M S，Beyer R A，et al. Evidence of recent thrust faulting on the Moon revealed by the lunar reconnaissance orbiter camera[J]. Science，2010(329)：936－940.

[64] Solomon S C，Chaiken，J. Thermal expansion and thermal stress in the Moon and terrestrial planets：Clues to early thermal history[C]// Proc. Lunar Sci. Conf. 7th，1976：3229－3243.

[65] Binder A B. Post-Imbrian global lunar tectonism：Evidence for an initially totally molten Moon[J]. Moon and Planets，

1982(25):117－133.
[66] Binder A B. The initial thermal state of the Moon[M]//Origin of the Moon. Hartmann W K, Phillips R J, Taylor G J, editors. Houston: Lunar & Planetary Institute, 1986: 425－434.
[67] Binder A B, Oberst J. High stress shallow moonquakes: Evidence for an initially totally molten Moon[J]. Earth Planet. Sci. Lett. , 1985(74):149－154.
[68] Solomon S C. On the thermal state of the Moon[M]//Hartmann W K, Phillips R J, Taylor G J. Origin of the Moon. Houston: Lunar & Planetary Institute, 1986: 435－452.
[69] Binder A B, Gunga H-C. Young thrust-fault scarps in the highlands: Evidence for an initially totally molten Moon[J]. Icarus, 1985(63):421－441.
[70] Williams N R, Watters T R, Pritchard M E, et al. Fault dislocation modeled structure of lobate scarps from lunar reconnaissance orbiter camera digital terrain models[J]. J. Geophys. Res. , 2013(118):224－233.
[71] Lucchitta B K, Watkins J A. Age of graben systems on the Moon[J]. Proc. Lunar Planet. Sci. Conf. 9th, 1978: 3459－3472.
[72] Hall J L, Solomon S C, Head J W. Lunar floor-fractured craters: evidence for viscous relaxation of crater topography [J]. J. Geophys. Res. , 1981(86):9537－9552.
[73] Wichman R W, Schultz P H. Floor-fractured craters in Mare Smythii and west of oceanus procellarum: implications of crater modification by viscous relaxation and igneous intrusion models[J]. J. Geophys. Res. , 1995(100): 21201－21218.
[74] Dombard A J, Gillis J J. Testing the viability of topographic relaxation as a mechanism for the formation of lunar floor-fractured craters[J]. J. Geophys. Res. , 2001(106): 27901－27909.
[75] Watters T R, Robinson M S, Banks M E, et al. Recent extensional tectonics on the Moon revealed by the lunar reconnaissance orbiter camera[J]. Nature Geosci, 2012(5): 181－185.
[76] Hiesinger H, Jaumann R, Neukum G, et al. Ages of mare basalts on the lunar nearside[J]. J. Geophys. Res. , 2000(105):29239－29275.
[77] Hiesinger H, Head J W, Wolf U, et al. Ages and stratigraphy of lunar mare basalts in Mare Frigoris and other nearside maria based on crater size-frequency distribution measurements[J]. J. Geophys. Res. , 2010(115): E03003. doi:10.1029/2009JE003380.
[78] Jolliff B L, Gillis J J, Haskin L A, et al. Major lunar crustal terranes: surface expressions and crust-mantle origins[J]. J. Geophys. Res. , 2000(105):4197－4216.
[79] Braden S E, Robinson M S, Stopar J D, et al. Age and extent of small, young volcanic activity on the Moon[C]//Lunar Planet. Sci. XLIV, abstract # 2843. Houston: Lunar & Planetary Institute, 2013.
[80] Braden S E, Stopar J D, Robinson M S, et al. Evidence for recent basaltic volcanism on the Moon[J]. Nature Geosci. , 2014.
[81] Weber R C, Lin P Y, Garnero E J, et al. Seismic detection of the lunar core[J]. Science, 2011:331, 309－312.
[82] Ross M, Schubert G. Tidal dissipation in a viscoelastic planet [J]. J. Geophys. Res. , 1986(91):D447－D452.
[83] Khan A, Mosegaard K, Williams J G, et al. Does the Moon possess a molten core? probing the deep lunar interior using results from LLR and lunar prospector[J]. J. Geophys. Res. , 2004(109): E09007.
[84] Khan A, Mosegaard K. Further constraints 1 on the deep lunar interior[J]. Geophys. Res. Lett. , 2005(32):L22203.
[85] Stegman D R, Jellinek A M, Zatman S A, et al. An early lunar core dynamo driven by thermochemical mantle convection[J]. Nature, 2003(421):143－146.
[86] NASA. Vision for Space Exploration. [EB/OL]. [2014-07-18]. http://www. nasa. gov/pdf/ 55583main_vision_space_exploration2. pdf.
[87] Cohen B A, Veverka J, et al. ILN Final Report: Science Definition Team for the ILN Anchor Nodes[R]. 2009:45. http://sservi. nasa. gov/wp-content/uploads/drupal/ILN_Final_Report. pdf
[88] National Research CouncilVision and Voyages for Planetary Science in the Decade 2013－2022[EB/OL]. (2011). http://www. nap. edu/catalog/13117. html.

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