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THE UNIVERSITY OF TEXAS AT AUSTIN
Institute For Geophysics

LUNAR SEISMIC DATA ANALYSIS

NASA Grant NSG-7418
Final Technical Report

30 June 1982

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INTRODUCTION

This research program, covering the 53-month period, February 1978 through June 1981, and performed under NASA Grant NSG-7418, has been a continuation of the original Apollo lunar passive seismic experiment (NASA Contracts NAS 9-5957, NAS 9-13149, NAS 9-14581 and NAS 9-14810) following the termination of the data acquisition phase of the experiment. The principal objectives of the program have been (1) to complete processing of the acquired data to provide lunar seismic data files accessible to all potential investigators, and (2) to analyze the data for timely dissemination of significant new results to the lunar and planetary science community.

This final report is a summary of accomplishment during the period of the Grant. Detailed results of the investigation have been published during the course of the study. These publications are listed in the PUBLICATIONS section of this report. Abstracts of these publications are included in the Appendix.

SUMMARY OF RESULTS

Task 1. Data processing, event identification and cataloguing

The scientific data transmitted continuously from all ALSEP (Apollo Lunar Surface Experiment Package) stations on the moon and recorded on instrumentation tapes at receiving stations distributed around the earth were sent to our Laboratory in Galveston for processing. The processing produced sets of computer-compatible digital tapes, from which various other data sets convenient for analysis were generated. We read the seismograms produced, identified and classified various types of seismic events, and catalogued the detected events. In all we catalogued 12,558 events detected on the long-period seismograms. Much more numerous events detected only on short period seismograms, representing seismic events of local nature, were not catalogued. The details of the data processing are given in Nakamura et al. [1980]*. The processed data now available are listed below. The following codes are used in parentheses to indicate the location of each data set:

N: National Space Science Data Center, NASA Goddard Space
Flight Center, Code 601, Greenbelt, MD 20771.

G: Galveston Marine Geophysics Laboratory, Institute for
Geophysics, The University of Texas at Austin,
Galveston, TX 77550-2768

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*All references are listed in PUBLICATIONS section.

1. Continuous ALSEP normal-bit-rate data on magnetic tapes (N,G).
   This set of 1151 reels of 9-track magnetic tapes and 3490 reels of 7-track magnetic tapes (G only) contains continuous digital data for the time period 1 March 1976 through 30 September 1977 for all stations. The data include all PSE (Passive Seismic Experiment) seismic data as well as those of other experiments except LSPE (Lunar Seismic Profiling Experiment). (The data before 1 March 1976 were processed at the Johnson Space Center, and are available from NSSDC.)

2. Continuous ALSEP high-bit-rate data on magnetic tapes (N,G).
   This set of 336 reels of 9-track magnetic tapes contains continuous digital data of LSPE in the listening mode for the time period 15 August 1976 through 25 April 1977.

3. Continuous, compressed-time-scale (75 mm/hr) PSE seismograms on microfilms (N,G).
   This data set continuously covers the entire duration of the experiment from 21 July 1969 to 30 September 1977. (Originals on white paper are in Galveston.)

4. Continuous, compressed-time-scale (90 mm/hr) LSPE seismograms on micorfilms (N,G).
   This data set continuously covers the duration from 15 August 1976 to 25 April 1977. (Originals on white paper are in Galveston.)

5. Long-period event catalogs (N,G).
   These catalogs list all seismic events visually detected on the long-period compressed-time-scale seismograms. The catalogs contain signal start and stop times to the nearest minute, amplitudes as measured on seismograms, availability of expanded-time-scale seismograms, quality of data, event classification, and comments. They were initially published in nine volumes, first by Apollo missions and later by the year, as listed in PUBLICATIONS section. The final version contains all 12,558 detected events in a single volume. They are available on print, microfiches, or a magnetic tape.

6. Event tapes (N,G).
   This set of 1172 reels of 7-track magnetic tapes contains digital data for all long-period seismic events listed in the event catalog except those detected only at Apollo 16 station with measured amplitude less than 5 mm.

7. Compressed-time-scale (75 mm/hr) seismograms of events on microfilms (N,G).
   This data set contains compressed seismograms of all events recorded on the event tapes. (Originals on white paper are in Galveston.)

8. Expanded-time-scale (100 mm/min) seismograms of events (G).
   This data set, produced on translucent papers, contains expanded seismograms for the first 10 minutes of all events recorded on the event tapes.

9. Artifical impact data on magnetic tapes (N,G)
   This set of 5 reels of 7-track tapes contain digital seismic data for all 9 artificial impacts. A 9-track version is also available on a single reel (G only).

10. Major meteoroid impact data on magnetic tapes (N,G)
   This set of 32 reels of 7-track tapes contains digital seismic data for 98 meteoroid impact events which registered 10 mm or more on our standard compressed seismograms at two or more stations. A 9-track version is also available as a set of 8 reels of tapes (G only).

11. Shallow moonquake data on magnetic tapes (N,G)
   This set of 9 reels of 7-track tapes contains digital seismic data for all 28 shallow moonquakes detected. A 9-track version is also available as a set of 2 reels of tapes (G only).

12. Major deep moonquake data on magnetic tapes (G)
   This set of 196 reels of 7-track tapes contains digital seismic data for initial 45 minute sections of signals from 1074 deep moonquakes at 33 source regions from which 10 or more moonquakes were detected. A highly condensed version containing only the initial 8 minute sections of long-period signals is also available on a single reel of 9-track tape.

Not listed above, but available in Galveston are a set of 7267 reels of 7-track magnetic tapes that contain continuous PSE digital data for the period 21 July 1969 through 29 February 1976, produced at the Johnson Space Center, and various data sets produced for our own analysis use. The latter include a set of stacked seismograms for 33 major deep moonquake source regions, stacked digital seismic data on a 9-track tape, a set of 24 reels of 7-track magnetic tapes containing Fourier-transformed seismic data for major impacts and moonquakes, and 30-second low-pass filtered continuous long-period seismic data for the time period 1 March 1976 through 27 March 1977.

Task 2. Data analysis

Seismicity

We made a detailed analysis of the source mechanism of deep moonquakes at A_1 source region. Since various factors, including paucity of seismic stations and complexity of lunar seismic signals, precluded use of conventional techniques such as distribution of initial motions, we used cross-phase spectra and amplitude distributions [Nakamura, 1978] and polarization of arrivals [Koyama and Nakamura, 1980] to study the source mechanisms. The results show that all moonquake foci within the A_1 source region are distributed in a nearly horizontal planar regions less than 1 km in diameter, and that shear fractures occur along a horizontal plane with the slip direction rotating with the shifting tidal stress field. Thus we conclude that these deep moonquakes represent a process of simple storage and release of tidal energy rather than a release of accumulated tectonic stress.

We have identified 107 distinct source regions of deep moonquakes, and located 52 of them using our latest seismic velocity model of the lunar interior [Nakamura et al. 1982]. Several linear patterns of epicentral distribution are recognized. Some of them appear to reflect the bilateral symmetry of the tidal force which produce these moonquakes. There appear to be two zones where many deep moonquakes are concentrated: one is just below 800 km depth, and the other is just above 1000 km depth. These two levels may suggest internal boundaries of differing physical properties.

Shallow moonquakes appear to be the only tectonic quakes in the moon. The variation of observed seismic amplitude with distance indicates that most, if not all, of them originate in the top part of the lunar upper mantle [Nakamura et al. 1979], thus suggesting high accumulation of tectonic stress in this region of the lunar interior at present. Shallow moonquakes show a remarkable similarily to intraplate earthquakes [Nakamura, 1980]. Although they do not produce large changes in surface geologic features like earthquakes along plate boundaries, these infrequent shallow moonquakes, like intraplate earthquakes, could be very large because a large amount of strain energy can be accumulated within a lithospheric plate before it is released by a quake. The very thick lithosphere of the moon does not allow itself to break up, thus leaving only this type of tectonic quakes to occur there.

Meteoroid impacts detected by the long-period seismometers of the Apollo lunar seismic network reveal the distribution of small interplanetary bodies near the earth-moon orbit in the mass range from about 100 g to 100 kg. The observed impacts are not random, but show clustering. Some, but not all, of the clusters appear to be correlated with known meteor streams [Dorman et al. 1978]. Further studies of these impacts and much more numerous smaller impacts detected by the short-period seismometers are needed to clarify the nature of these interplanetary bodies.

Internal structure

Seismic data can be used in several different ways to infer the structure of planetary interior. Though perhaps the most common way is to use travel times of body wave arrivals, such things as dispersion and polarization of surface waves and amplitudes of body waves can be used. We noticed that observed amplitudes of seismic coda were significantly different for horizontal and vertical components and that they were also frequency dependent. Interpreting this to be due to the ellipticity of Rayleigh wave particle motion, we derived the near-surface velocity structure at the Apollo 12, 14, 15 and 16 landing sites [Horvath et al. 1980]. At these sites, the shear-wave velocity-depth functions are generally represented by a rapid increase in the top 10 to 25 m layer followed by a more gradual increase to a depth of 150 to 200 m. Details of velocity variations appear to be correlated with the history of the landing sites.

Structure of the deep interior of the moon can be estimated from the arrival times of distant seismic events. An inversion of our latest set of arrival-time readings show that both P and S waves show a negative velocity gradient in the upper mantle and an increase of velocity in the middle mantle between the depths of 500 and 1000 km [Nakamura, 1982]. Such velocity variations are consistent with an upper mantle of nearly uniform composition consisting of a mixture of olivines and pyroxenes, and a middle mantle of higher concentration in Mg-rich olivines. The olivine enrichment may suggest melting of the moon at least to a depth of 1000 km in its early history.

We have attempted to identify secondary seismic arrivals reflected from possible discontinuities in the deep lunar interior using various signal enhancement techniques [Horvath, 1981]. The results, however, were inconclusive. Attempts to detect coherent surface waves and free oscillations of the moon have been unsuccessful.

Seismic Q in the moon except its deep interior is extremely high. A recent study shows that S-wave Q in the lunar upper mantle is frequency dependent and is significantly higher than P-wave Q at high frequencies [Nakamura and Koyama, 1982]. In absence of other dissipation mechanisms normally operating in the earth, compressional heat loss may be a dominant dissipation mechanism in the lunar upper mantle.

Lunar seismograms are very complex because of intense scattering of seismic waves near the lunar surface. Certain simplified mathematical models can explain some of the observed characteristics of lunar seismograms [Malin and Nakamura, 1981], but further studies are needed for a better understanding of this phenomenon.

In summary, the analysis of the lunar seismic data has revealed many interesting properties of the lunar interior. The moon is clearly differentiated, having a distinct crust and a mantle, and possibly a core. The interior of the moon is still of high temperature. However, because of its great thickness, the lithosphere of the moon is not broken up into separate plates like those on the earth. Rare but large tectonic moonquakes, similar to intraplate earthquakes, occur in the shallow part of the lithosphere, while numerous but small tidally induced moonquakes occur near the bottom of the lithosphere. Overall reviews of the results of the lunar seismic experiment are found in Nakamura [1981] and Nakamura *et al*. [1982].

Acknowledgments

The following people materially contributed to the success of this program:

Dr. Junji Koyama, now with Tohoku University, Japan,
as Post Doctoral Research Associate

Dr. Peter Horvath, now with Atlantic Richfield Company,
as Graduate Research Assistant

Dr. Abou-Bakr K. Ibrahim, now with U.S. Nuclear Regulatory Commission,
as Research Scientist

Dr. Peter E. Malin of University of Southern California,
as Visiting Research Scientist

Mr. John S. Kunselman, now with Chevron Oil Field Research Company,
as Systems Analyst

Mr. James E. Harris, now with University of Texas Medical Branch,
as Supervisor of Computer Operations

Mr. Raul Serenil as Principal Computer Operator

The NASA Technical Officer for this grant is Dr. William L. Quaide, NASA Headquarters, Code SL-4. His encouragement throughout this study is greatly appreciated.

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APPENDIX

Proc. Lunar Planet. Sci. Conf. 9th (1978), p. 3589–3607.
Printed in the United States of America

A_1 moonquakes: Source distribution and mechanism

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Abstract—Two novel analysis techniques have been used to study focal mechanisms of A_1 moonquakes, which occur at the most active of the 80 deep-moonquake source regions identified to date. The first is the cross-spectral analysis of matching signal waveforms. Cross phase spectra clearly show relative polarity of signals and give precise time relationships between signals, thus enabling accurate determination of relative source locations within the source region. The second is the analysis of amplitude ratios, which reveal the patterns of P- and S-wave radiations around the source region. A_1 moonquake foci are found to be concentrated in a nearly horizontal planar region less than 1 km in diameter. Their focal mechanism may be described by slippages along a horizontal plane with the slip direction rotating with and predominantly controlled by the shifting tidal stress field. Thus, A_1 moonquakes represent a process of simple storage and release of tidal energy with no evidence for a release of accumulated tectonic stress.

Proc. Lunar Planet. Sci. Conf. 9th (1978), p. 3609–3613.
Printed in the United States of America

Passive seismic experiment: a summary of current status

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Abstract—The data set obtained from the 4-station Apollo seismic network is now complete. It includes signals from approximately 11,800 events of various types. Four data sets for use by other investigators, through the NSSDC, are in preparation. Some refinement of the lunar model based on seismic data can be expected, but its gross features remain as presented two years ago. The existence of a small, molten core remains dependent upon the analysis of signals from a single, far-side impact. Analysis of secondary arrivals from other sources may eventually resolve this issue, as well as continued refinement of the magnetic field measurements. Evidence of considerable lateral heterogeneity within the moon continues to build. The mystery of the much lower meteoroid flux estimate derived from lunar seismic measurements, as compared with earth-based estimates, remains; although, significant correlations between terrestrial and lunar observations are beginning to emerge.

Proc. Lunar Planet. Sci. Conf. 9th (1978), p. 3615-3626.
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On the time-varying properties of the lunar seismic meteoroid population

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Abstract—Strong short-term fluctuations of meteoroid impact rates are evident in a list of 1557 events derived from Apollo lunar seismic data. Times of fall and seismic signal amplitudes are considered in relation to the possible orbits and identification of the impacting objects. The entire lunar surface is the effective collector; and the Apollo network data, gathered between 1970 and 1977, reflect the recognized abundance of large meteorite falls from early April through July. There is also some indication that briefly increased counts represent fragments of about 100 g or greater belonging to several meteor streams: Quadrantids, Aquarids, Perseids, Orionids, Leonids, Geminids, and possibly others as well.

VOL. 6, NO. 6 GEOPHYSICAL RESEARCH LETTERS JUNE 1979

MARTIAN WIND ACTIVITY DETECTED BY A SEISMOMETER AT VIKING LANDER 2 SITE

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Abstract. The seismic 'background noise' detected by the seismometer on the Viking lander 2 has an extremely high correlation with the measured wind speed at the landing site. When displayed in a compressed form, the nearly continuous seismic data clearly exhibit the diurnal as well as seasonal variations of the Martian wind activity. A preliminary spectral analysis of the long-term variation of the background noise indicates persistent spectral peaks at periods near 1.5, 3, 7 and 10-20 sols for the first 560 sols (0.84 Martian year) of observation.

Proc. Lunar Planet. Sci. Conf. 10th (1979), p. 2299–2309
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Shallow moonquakes: Depth, distribution and implications as to the present state of the lunar interior

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Abstract—The observed seismic amplitudes of HFT (high-frequency teleseismic) events do not vary with distance as expected for surface sources, but are consistent with sources in the upper mantle of the moon. Thus, the upper mantle of the moon is the only zone where tectonic stresses deriving from differential thermal contraction and expansion of the lunar interior are presently high enough to cause moonquakes. The distribution of shallow moonquake epicenters suggests a possible correlation with impact basins, implying a lasting tectonic influence of impact basins long after their formation. The finite depths now assigned to these shallow moonquakes necessitate further revision to the seismic structural model of the lunar interior.

Physics of the Earth and Planetary Interiors, 21 (1980) 218–224

HOW WE PROCESSED APOLLO LUNAR SEISMIC DATA *

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The Apollo lunar seismic station network gathered data continuously at a rate of 3×10^8 bits per day for nearly eight years until the termination in September, 1977. The data were processed and analyzed using a PDP-15 minicomputer. On average, 1500 long-period seismic events were detected yearly. Automatic event detection and identification schemes proved unsuccessful because of occasional high noise levels and, above all, the risk of overlooking unusual natural events. The processing procedures which were finally chosen consist of plotting all the data on a compressed time scale, visually picking events from the plots, transferring event data to separate sets of tapes and performing detailed analyses using the latter. Many problems remain, especially in the automatic processing of extraterrestrial seismic signals.

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 85, NO. B11, PAGES 6572-6578, NOVEMBER 10, 1980

Lunar Near-Surface Shear Wave Velocities at the Apollo Landing Sites as Inferred From Spectral Amplitude Ratios

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We reexamined the horizontal-to-vertical amplitude ratios of the long-period seismograms to determine the shear wave velocity distributions at the Apollo 12, 14, 15, and 16 lunar landing sites. Average spectral ratios, computed from a number of impact signals, were compared with spectral ratios calculated for the fundamental mode Rayleigh waves in media consisting of homogeneous, isotropic, horizontal layers. The shear velocities of the best fitting models at the different sites resemble each other and differ from the average for all sites by not more than 20% except for the bottom layer at station 14. The shear velocities increase from 40 m/s at the surface to about 400 m/s at depths between 95 and 160 m at the various sites. Within this depth range the velocity-depth functions are well represented by two piecewise linear segments, although the presence of first-order discontinuities cannot be ruled out.

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Shallow moonquakes: How they compare with earthquakes

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Abstract—Of three types of moonquakes strong enough to be detectable at large distances—deep moonquakes, meteoroid impacts and shallow moonquakes—only shallow moonquakes are similar in nature to earthquakes. A comparison of various characteristics of moonquakes with those of earthquakes indeed shows a remarkable similarity between shallow moonquakes and intraplate earthquakes: (1) their occurrences are not controlled by tides; (2) they appear to occur in locations where there is evidence of structural weaknesses; (3) the relative abundances of small and large quakes (b-values) are similar, suggesting similar mechanisms; and (4) even the levels of activity may be close. The shallow moonquakes may be quite comparable in nature to intraplate earthquakes, and they may be of similar origin.

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Focal mechanism of deep moonquakes

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Abstract—To elucidate the focal mechanism of deep moonquakes, we analyzed S-wave polarizations of deep moonquake signals from the A_1 source region. At station 12, where the available data are of the highest quality, the variation of polarization angle with the anomalistic phase of the moon indicates agreement with that expected from the focal mechanism model of Nakamura. Focal mechanism solutions were derived for eight A_1 moonquakes assuming that moonquakes are, like earthquakes, caused by a shear fracture on a fault plane. The mechanism solutions generally indicate a nearly horizontal or almost vertical faulting. The slip directions estimated from the solutions are different from one another, again suggesting variation of focal mechanisms as a function of the tidal phase of the moon.

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Correction of lunar seismograms for instrumental and near-surface effects and constraints on the velocity structure of the lunar interior

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Abstract—Predictable digitizing errors were removed from the long-period lunar seismograms, and inverse filters were applied to correct for the seismometer response, for the coupling of the seismometer to the ground, and for the near-surface structural effects. These signal processing steps improved correlations among the long-period seismograms from the various recording sites and permitted reading the shear wave arrivals with smaller uncertainty than is possible from the original seismograms. To explore the constraints that direct compressional (P) and shear (S) arrival times could impose on the velocity structure of the lunar interior, the largest natural impacts and shallow moonquakes were located using two velocity models. The first model consisted of a thicker crust (55 km) and higher compressional and shear velocities (8.1 and 4.6 km/sec, respectively) in the upper mantle, and the second model had a thinner crust (45 km) and lower upper-mantle velocities (7.7 and 4.4 km/sec). The P and S arrival times observed for impacts and shallow moonquakes could not be used to distinguish between these two models because the travel time residuals for both models are similar and are well within the uncertainty of the observed travel times. The deconvolved seismograms have also been used to search for secondary arrivals and thereby to obtain additional constraints on the velocity structure. The identification of possible secondary arrivals suggests that a velocity discontinuity exists in the crust at a depth between 20 and 30 km, and that the crust is thinner than 50 km. Although evidence for a discontinuity in the mantle was inconclusive, discontinuity at a depth of about 200 to 220 km can be inferred from secondary arrivals.

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Seismic *Q* of the Lunar Upper Mantle

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We have determined the frequency dependence of anelastic attenuation for both *P* and *S* waves in the upper mantle of the moon in the frequency range of roughly 3 to 8 Hz. The method used is a combination of a single-station method, in which Q^{-1} is obtained as an integral with an unknown constant, and a multiple-station method, the result of which is used to determine the integration constant. The *Q* determined for *P* waves (Q_p) appears to decrease with increasing frequency, though it is not significantly different from a constant *Q*, while the *Q* for *S* waves (Q_s) increases with frequency, becoming significantly greater than Q_p at high frequencies. All *Q* values remain greater than 4000 within this frequency range. Q_s above 5 Hz is approximately proportional to the 0.7th power of frequency. The high *Q* for shear waves at high frequencies suggests that compressional heat loss may be a dominant dissipation mechanism. Some uncertainties in the absolute *Q* values remain because the detailed velocity structure of the lunar upper mantle is largely unknown.

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APOLLO LUNAR SEISMIC EXPERIMENT — FINAL SUMMARY

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Processing and initial analysis of the entire set of Apollo lunar seismic data collected continuously from 1969 through 1977 have now been completed. Recent results include: 1) better defined deep moonquake locations, which appear to be bounded rather sharply between about 800 km and 1000 km depths with concentrations near both boundaries; and 2) middle mantle (∿500 to 1000 km depth) seismic velocities of $V_p = 8.3 \pm 0.4$ km/sec and $V_s = 4.6 \pm 0.2$ km/sec, which are significantly higher than previous estimates and represent an increase of velocities from the upper mantle as opposed to a decrease in previous estimates. (Lunar seismic data, moonquakes, meteoroids, seismic velocities).

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Seismic Velocity Structure of the Lunar Mantle

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Abstract

I have inverted the recently completed set of seismic arrival times from the Apollo lunar seismic network to estimate the average seismic velocities in three sections of the lunar mantle: two for the upper mantle and one for the middle mantle. The method used is a variation of the linearized least-square inversion where the inversion is accomplished in steps. The stimated average velocities in the upper mantle decrease from $V_p = 7.74$ km/s and $V_s = 4.49$ km/s in the section above 270 km depth to $V_p = 7.46$ km/s and $V_s = 4.25$ km/s in the section between 270 and 500 km depth, confirming the earlier finding of negative gradients based on seismic amplitude variations. The average velocities in the middle mantle between the depths of 500 km and 1000 km of $V_p = 8.26$ km/s and $V_s = 4.65$ km/s are significantly higher than those in the upper mantle, contradicting earlier estimates based on more limited data. The higher velocities may suggest initial melting of the moon down to at least 1000 km depth.