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A New Seismic Velocity Model for the Moon from a Monte Carlo Inversion of the Apollo Lunar Seismic Data

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Abstract. A reanalysis of the Apollo lunar seismic data and the subsequent application of an inverse Monte Carlo method to P and S-wave arrival times has resulted in a more detailed lunar velocity structure than previously obtainable. The velocity is seen to increase from the surface down to the base of the crust at 45±5 km depth. The results furthermore indicate a constant velocity upper mantle extending to 560±15 km km depth, separated from a more complex high velocity middle mantle by an increase in velocity of 1.0 km/s. In addition, the moonquake locations have been improved. The shallow moonquakes are found to be located in the depth range 50-220 km. The majority of deep moonquakes are concentrated in the depth range 850-1000 km with an apparently rather sharp lower boundary.

Introduction

The Moon is the only planetary body besides the Earth for which there exist enough seismic data to deduce a reasonably constrained velocity structure. These data were obtained from a four-station seismic array on the lunar surface, installed during the US Apollo missions. During the eight year period (starting with Apollo 11 in July 1969) in which the experiment was underway more than 12000 events were recorded and catalogued [*Nakamura et al.*, 1981, 1982], with only 81 sources identified in terms of hypocenter coordinates and times of origin, including artificial and meteoroid impacts, shallow and deep moonquakes [*Nakamura,* 1983]. Arrival times from this set of events were used to infer information on the interior velocity structure of the Moon, with early analyses using a more limited data set [e.g. *Toksöz et al.*, 1974; *Goins et al.*, 1981; *Nakamura et al.*, 1974, 1976], while the latest study by *Nakamura et al.* (1982) and *Nakamura* (1983) employed all 81 identified events, which included a greater number of deep moonquakes. Generally, these studies were succesful in determining the gross features of the lunar interior and resulted in the recognition of the Moon as being a differentiated body with a crust and a mantle whose lower parts were thought to be partially molten. However, details remain rather perfunctory with questions concerning seismic velocity variations and possible discontinuities in the lunar mantle left unanswered.

Studies on the the lunar interior and its composition using the velocity structure and other geophysical constraints is comprehensively reviewed by *Hood* (1986) and most recently in *Hood and Zuber* (1999). Investigations in this direction were also undertaken by *Hood and Jones* (1987) and *Mueller et al.* (1988).

In this paper we present a reinvestigation of the Apollo lunar seismic data using an inverse Monte Carlo (MC) sampling method. The inverse MC algorithm is a very simple and powerful method for dealing with highly non-linear inverse problems [*Mosegaard and Tarantola,* 1995; *Mosegaard,* 1998; *Dahl-Jensen et al.,* 1998], which is the case here [*Khan,* 1998], in that the inherent non-linearities are fully incorporated into the solution and so no linearisations of the original problem have to be introduced as was done in earlier studies. The results presented here are generally in agreement with previous studies. Moreover, the method also has the advantage of providing more realistic error limits to the results for a given resolution. The present paper is only concerned with the results and a paper detailing the method of analysis is currently under preparation.

Analysis

The data used here are the same as those from the latest study [*Nakamura,* 1983]. Seismograms from these events were analysed to obtain an estimate of the uncertainty of the P and S-wave arrivals. However, given the low quality of the data the probability of erroneous arrival time readings is obvious and in order to deal with possible outliers a statistical technique known from robust M-type estimation [*Hampel et al.*, 1986; *Barnett and Lewis,* 1984] has been invoked. In this way outliers were systematically searched for and discarded through successive runs until it was found that none remained.

Our model of the Moon is assumed spherically symmetric and is described by a continuous and piecewise linearly varying velocity $v(r)$ satisfying a smoothness constraint in order to accomodate ray theory. In pratice this smoothness constraint results in a vertical resolution of approximately 5 km. In line with a previous method [*Goins et al.,* 1981], the uppermost kilometer of the crust comprising a very low velocity layer, the regolith, was not included in our velocity model, instead a local time correction to the travel times was determined. It should be noted that these corrections are surface consistent, by which we mean that the same time correction beneath a given station is added to the travel time for rays coming from different sources. Possible near-surface lateral heterogeneities among the individual Apollo seismic stations are thus taken into account by these local corrections.

The Monte Carlo method operates by sampling solutions to the inverse problem that fit the observed travel times within their error bars, and at the same time satisfies known or assumed physical a priori constraints. We used a Markov Chain Monte Carlo (MCMC) method [*Mosegaard and Tarantola,* 1995; *Mosegaard,* 1998] designed to sample the model parameter space according to the posterior probability density containing all the information about the system under study.

Results and Discussion

The results of the inversion are displayed in Fig. 1A and Fig. 1B, in the form of marginal posterior velocity distribu-

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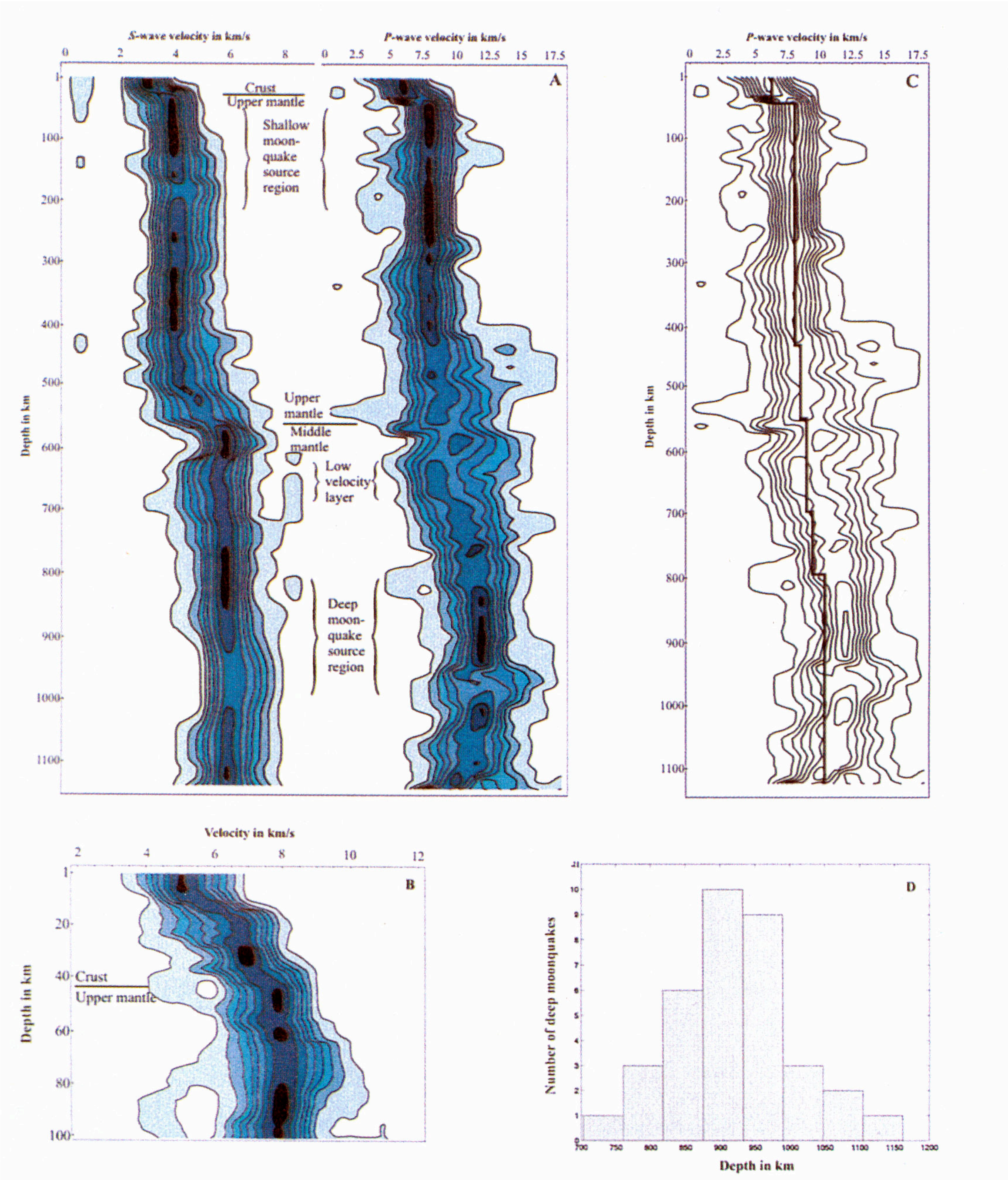

Figure 1. The marginal posterior velocity distributions depicting the velocity structure of the Moon (A-B). (A) A total of 50000 models have been used in constructing the two results. For each kilometer a histogram reflecting the marginal probability distribution of sampled velocities has been set up. By lining up these marginals, the velocity as a function of depth is envisioned as contours directly relating their probability of occurence. The contour lines define nine equal-sized probability density intervals for the distributions. The uncertainties on the results are in part due to the large uncertainty in arrival time readings. These are of the order of 1 s for the artificial impacts, 4-26 s for the shallow moonquakes and meteoroid impacts and 4-7 s for the deep moonquakes. It should be kept in mind that the velocity models are depicted using marginal probability distributions and as such a model incorporating velocities of maximum probability does not necessarily correspond to the most likely model.
(B) The upper part of (A) has been enlarged showing the P-wave velocity structure of the crust and upper mantle down to a depth of 100 km. The reason that the S-wave velocity structure for the lunar crust is not shown is due to the fact that this part of the lunar interior is being constrained by the artificial impacts only for which the S-wave data are of extremely poor quality and have therefore been disregarded.
(C) This inversion was undertaken without reference to the lunar mass and moment of inertia. However, to show that our results are indeed consistent with these parameters, we have calculated a simplified density model from our estimated seismic velocities. Our density model has been obtained by invoking an approximate relationship between density ρ and P-wave velocity v_p, $\rho = 0.39 \cdot v_p$, using estimates from the "PREM" and "iasp91" model of the Earth's mantle. A density model in agreement with known lunar mass, $7.4{\cdot}10^{22}$ kg and moment of inertia, $8.7{\cdot}10^{34}$ kg$\cdot$m^2 and converted to equivalent P-wave velocities using $v_p = \rho/0.40$ for crust and upper mantle and $v_p = \rho/0.39$ for the middle mantle, is depicted in fig. C together with the P-wave results thereby highligthing consistency with the obtained velocity models. The slightly higher value for the upper part of the moon is permissible given that no water is present. It should be noted that the density for the remaining 600 km, not contained in the figure, assumes the same value as the lower mantle (800-1138 km depth). (D) Depth distribution of deep moonquakes.

tions for the lunar interior, while Fig. 1C shows a simple density model being in agreement with total lunar mass, moment of inertia and the P-wave velocity model obtained. Fig. 1B comprising the crust and the uppermost mantle down to a depth of 100 km, shows a steady increase in P-wave velocity from the surface to the base of the crust. The results do not seem to substantiate the existence of a dichotomous lunar crust with a constant velocity of 6.7 km/s in the range from 20 to 57.5 km depth as suggested in an earlier study [*Toksöz et al.,* 1974]. Our estimate for the crustal thickness is 45±5 km indicating a somewhat thinner crust than earlier studies [*Toksöz et al.,* 1974; *Nakamura et al.,* 1982]. The obtained P-wave velocity increase between crust and upper mantle is $\sim$1.0 km/s, with evidence for a somewhat more gradual transition (see Fig. 1B) as opposed to a sharp increase in velocity of 1.5 km/s in the range from 54.5 to 57.5 km depth as noted earlier [*Toksöz et al.,* 1974]. Concerning the upper mantle our results indicate an almost constant velocity zone with P and S-wave velocities of 8.0±0.8 km/s and 4.0±0.4 km/s just below 45 km to a depth of roughly 500 km, suggesting a homogenous upper lunar mantle, in contrast to earlier models incorporating velocity decreases with depth in this region [*Goins et al.,* 1981; *Nakamura,* 1983]. In the depth range from 500 km to just above 560 km, the P and S-wave velocities are seen to increase to 8.5±1.5 km/s and 4.8±1.1 km/s. The transition depths reported here have been obtained by examining individual models and noting their distribution of depths were a velocity jump was encountered. The uncertainty is equal to one standard deviation of the distribution. Estimation of the shallow moonquakes revealed these to be located in the upper mantle between 50 and 220 km depth (see Table 1) which is in agreement with an earlier conclusion [*Nakamura et al.,* 1979].

Returning to our results, earlier attempts to identify velocity variations in the middle mantle, comprising the depth range 500-1100 km, were not successful [*Goins et al.,* 1981; *Nakamura et al.,* 1982], although they were believed to be present [*Nakamura,* 1983]. However, in this study we have obtained certain variations, although it should be noted that the standard deviations are quite large, being in part due to the large scatter of arrivals on the travel time data from the deep moonquakes. The data seem to imply a sharp increase in P and S-wave velocity from 8.5±1.5 km/s and 4.8±1.1 km/s at 560 km depth, the base of the upper mantle, to 9.9±1.9 km/s and 5.9±0.9 immediately below 560 km depth. At a depth just below 620 km our findings are indicative of a low velocity layer and from about 700 km depth the data suggest a second P and S-wave velocity increase from 9.0±1.9 km/s and 5.5±0.9 km/s to 11.0±2.1 km/s and 6.0±0.7 km/s at about 780 km depth. Moreover, the depth range from 800 km to about 1000 km is seen to comprise a high velocity layer coinciding with the deep moonquake source region. Due to the distribution of seismic sources our analysis does not extend below 1100 km depth and the structure of the middle mantle as well as the possible existence of a lunar core can therefore presently not be resolved.

Table 1. Depth distribution of shallow moonquakes

Event		Source Depth
Year	Day	km
1971	107	75 ± 21
1971	140	48 ± 46
1971	192	221 ± 49
1972	002	173 ± 55
1973	072	49 ± 35
1973	171	115 ± 23
1974	192	133 ± 41
1975	003	75 ± 16
1975	012	102 ± 26
1975	044	130 ± 70
1975	314	73 ± 19
1976	004	88 ± 39
1976	066	74 ± 27
1976	068	120 ± 24

The deep moonquake hypocenters indicate a well defined source region consistent with earlier studies [*Goins et al.,* 1981; *Nakamura et al.,* 1982], although our results reveal a slightly narrower distribution for the majority of the quakes within the range from 850 to 1000 km depth (Fig. 1D). Whether the relatively high velocities in the deep moonquake source region as reported here are due to a phase change is difficult to assess. However, given the fact that the deep moonquakes originate in a well defined zone, with by far the largest number coinciding with the high velocity zone extending from 800 km to 1000 km, this assumption is not implausible. The mechanism that generates the deep moonquakes is believed to be some structural heterogeneities that produce concentrated tidal stresses which are subsequently released as quakes by shear dislocations along some horizontal plane in the deep lunar interior [*Lammlein,* 1977; *Toksöz et al.,* 1977; *Nakamura,* 1978; *Koyama and Nakamura,* 1980]. The results presented here show a slight decrease in P and S-wave velocity at a depth of about 1000 km coinciding with the apparent decline in the number of deep moonquakes, with only 4 sources located below 1000 km depth (Fig. 1D). Moreover, the greatest number of sources are also located just above the transition. These observations could be interpreted as a transition representing a boundary between a rigid mantle and a partially molten zone beneath it. If this is the case, it might be speculated that the deep moonquakes are caused by shear movement due to the tidal deformations of the rigid part of the mantle where it is least supported, which also explains the concentration of the deep moonquakes right above the transition.

In interpreting the results certain limitations have to be kept in mind. We assume radial symmetry and our model should thus be seen as an average over the area covered by the four stations. Furthermore, possible lateral heterogeneities close to the seismic stations may also introduce systematic errors, especially between stations 12 and 14, since these are only 181 km apart as compared to stations 15 and 16 situated 1100 km from each other as well as from stations 12 and 14. Thus if there are differences in local structure among the two sites causing the delay of arrivals at one station relative to the other, this will be directly reflected in large systematic errors in the structural parameters thus determined, as pointed out by *Nakamura* (1983). In the present study we have tried to incorporate these lateral variations using the local corrections. The local correction beneath a given station is only to be seen as an average over the 1 km surficial layer which has been stripped off and it represents a very simple way of dealing with a locally low velocity and thus does not hold any clue to actual geological differences. Furthermore, the stated uncertainties on the results from the middle mantle are less on the S-waves than on the P-waves. This fact is directly related to the amount of information contained in the respective data. Deep moonquake first arrivals are highly ambiguous, whereas the S-waves are characterised by prominent shear arrivals, reflecting a higher uncertainty on the P-wave arrival times. In addition, a comparison of the P and S-wave velocity structure reveals a somewhat more constant velocity in the middle mantle for the S-waves than the P-waves. This discrepancy in the outcome might be related to the fact that less information results in a broader posterior probability distribution (*ppd*) which requires more samples for full coverage than does a more sharp (*ppd*) as is the case for the S-waves. The apparent inhomogeneities in the middle mantle might therefore be a result of insufficient sampling.

Constructing compositional models from the present results is outside the scope of this paper. However, if the velocity models including the inhomogeneities are real this has considerable impact on models of lunar evolution. The model put forward by *Hood and Jones* (1987) and *Mueller et al.* (1988) assumes a highly fractionated upper mantle, with a transition at roughly 500 km depth to a middle mantle never having been fully molten. The discontinuity at 500 km depth based on the seismic velocity profile by *Nakamura* (1983) was found to be consistent with a transition to more garnet-rich compositions. This model might be a possibility with the current results. On the other hand *Nakamura* (1983) noted that an increase of seismic velocities below 500 km may be accounted for by an increased concentration of Mg-rich olivines associated with an initial melting down to a depth of at least 1000 km. This idea of initial whole-moon melting and differentiation including early crystallisation and sinking of MgO-rich olivine has also been investigated by *Hood* (1986) and *Hood and Jones* (1987). However, since it was found that density decreases occured at the upper/middle mantle transition which appeared to violate stability arguments, this model was deemed as not being likely given that subsolidus convective mixing was a significant evolutionary process in early lunar history. A phase transition had also been advanced as a possible explanation for the velocity discontinuity at 500 km depth by *Nakamura* (1983). A phase-change model may describe the observed increase in velocity between the upper and middle mantle. However, the manifest differences between a very uniform upper mantle and a heterogeneous middle mantle might not be simply explained within this model. Alternatively it could be tentatively envisioned that the homogeneity of the upper mantle was due to convective stirring in a molten layer. The subsequent crystallisation evolved toward increasingly FeO-rich materials, resulting in an unstable layering in the accumulated crystals. At the end of magma ocean crystallisation or even slightly before, this is thought to result in gravitational overturn with the dense phases transported down toward the base of the upper mantle. As the FeO-rich material migrates downward it undergoes considerable mixing. This concept of one-time, irreversible gravitational overturn of magma ocean cumulates has become a very common theme in petrological models for evolution of the lunar mantle and especially models for the origins of mare basalts and has most recently been studied in detail by *Parmentier and Hess* (1999). In this scenario the discontnuity at 560 km depth does not imply the base of the magma ocean. Instead, it marks the top of the region where in general FeO-rich material concentrated, being unable to participate in the convection within the main part of the mantle.

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