MINERALOGICAL AND SEISMOLOGICAL MODELS OF THE LUNAR MANTLE. C. L. Johnson, L. Stixrude, C. Lithgow-Bertelloni, R. Bulow and P. M. Shearer

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Overview: The Apollo Passive Seismic Experiment provided data from which 1-dimensional models for the seismic velocity structure of the moon have been produced. In contrast to terrestrial seismic data, the lunar data are confined in spatial and temporal extent. Lunar seismograms are also noisy due to instrument limitations and scattering of seismic energy. In order to restrict the range of seismic velocity models that fit the data, a layered structure is typically assumed as a proxy for compositional or phase changes. Despite these assumptions, existing models show significant differences (Figure 1).

While lunar seismic data are inferior to their terrestrial counterparts, we can take advantage of the limited range of pressures and temperatures in the Moon, compared with Earth, to construct mineralogical models for the whole lunar mantle. We adopt a self-consistent formulation of such models, and their associated physical properties, including seismic wave velocities. We test our models against published and new travel times. This direct comparison of mineral physics models with seismological data, as opposed to derived seismological models, has not previously been done, even for Earth. The thermodynamic formulation is general so we can look at the effects on shear and compressional velocities of adding accessory or minor minerals. New thermodynamic or seismic data can also be readily incorporated and tested.

Background: The lunar seismic data recorded by the Apollo Lunar Surface Experiment Package during 1969-1977 provide a unique and valuable resource for constraining the interior structure of the moon. The lunar event catalogue documents 12,558 events from four different types of sources: artificial impacts, meteoroid impacts, shallow moonquakes, deep moonquakes and unclassified events. P- and S-wave arrival times measured from a subset of the highest quality seismograms have been used to estimate seismic profiles. Considerable variation among such models exists, hindering understanding of lunar compositional and thermal structure.

Shallow velocity structure is poorly constrained. Crustal thickness estimates vary by a factor of two. A mid-mantle low velocity zone or negative velocity gradient is permitted, although not required. Most seismic velocity models include a 500 km interface, the possible depth extent of an early magma ocean and/or the source region for mare basalts and Apollo glasses. Velocity estimates in the 270 to 1000 km region are constrained primarily by travel time picks from deep events. Seismic velocities below 1000 km are unconstrained due to source-receiver geometries; a transition to a warmer, more ductile region (in which deep moonquakes cannot occur) could result in lower seismic velocities.

Figure 1: P-wave velocity models versus depth. Nakamura (1983) – red, with uncertainties shown as dashed lines; Lognonné et al. (2003) – blue; Khan et al. (2000) – green.

Interpretations of current seismic velocity models are limited for several reasons. First, uncertainties and differences in travel time picks permit different velocity structure models. Second, there is a tradeoff between source location and velocity structure estimates. Third, imposed structures in the seismic models are naturally reflected in the inferred petrological model and vice-versa. Here we address some of these concerns by producing lunar mineralogical models and their associated seismic wave velocities. We compare predicted travel times from these seismic velocity profiles with new travel time data for deep moonquakes and previously published travel times for shallow and impact events.

Construction of Forward Models: We use the theoretical formulation of Stixrude and Lithgow-Bertelloni to predict stable phase assemblages and the associated seismic velocities of the aggregate.
Given an isolated, homogeneous system of specified bulk composition, \( X \), in thermodynamic equilibrium at pressure \( P \), temperature \( T \), the construction of the mineralogical model and its associated physical properties is as follows: 1) Find the equilibrium phase assemblage: the phases that are stable, their relative proportions and their compositions in equilibrium. 2) Determine the seismic wave velocities of the individual phases at their equilibrium compositions for the \( P \) and \( T \) of interest in the elastic limit. 3) Determine the seismic wave velocity of the aggregate in the elastic limit. The first two steps are formulated in terms of equilibrium thermodynamics.

Implementation of these steps requires the following model inputs: a temperature-depth profile (selenotherm), bulk composition (this can vary with depth), specification of a suite of possible contributing mantle species and the associated values at ambient conditions for Helmholtz free energy, volume, bulk modulus, pressure derivative of bulk modulus, Debye temperature, Grüneisen parameter and its volume derivative, the shear modulus and its pressure and temperature derivatives. Published mineral physics data encompass all lunar interior conditions enabling the prediction of seismic velocities throughout the silicate portion of the moon.

Our approach is similar to that of Kuskov [9, 10]. However, several properties of the mantle species we use, particularly those related to seismic velocities, such as the elastic moduli and their pressure and temperature derivatives, are based on more recent mineral physics experimental data.

**Results:** We present preliminary results using pyroxenite and pyrolite bulk compositions and a reasonable lower bound for the lunar selenotherm (Figure 2). Predictions for P- and S-wave velocities for both bulk compositions are within the uncertainties of the Nakamura model [2] at depths greater than 500 km, with the pyroxenite model closer to the average Nakamura model [2], as would be expected from lunar bulk composition models [11]. At shallow depths, the predictions provide a poor fit, as crustal/upper-mantle compositional structure is not considered in these preliminary models. More detailed comparisons at shallow depths will require the incorporation of sodium into the mineralogical models.

For pyrolite the plagioclase-spinel (25 km) and spinel-garnet (200 km) transitions have relatively simple structure and muted signatures in the velocity. The greater aluminum content of pyroxenite leads to larger velocity signatures and shallower transitions. The transitions are also more complex with garnet appearing near 100 km without completely consuming plagioclase or spinel. Neither composition shows a prominent change in velocity at 500 km although the final disappearance of plagioclase at this depth in pyroxenite produces a change in velocity gradient. Note the smooth, continuous nature of the velocity model structure: sharp velocity discontinuities will only occur at univariant phase transitions or at imposed compositional boundaries.

**Model Evaluation Using Travel-Time Data:** Velocity models predicted from our mineralogical models can be compared directly with P- and S-wave arrival times picked from the lunar seismograms. As described in the abstract by Bulow et al. [8] we have identified new deep events in the continuous data set and are constructing improved stacks for deep event clusters. We pick arrival times directly from these stacks, and combine them with already published values. We calculate synthetic travel times by ray tracing through the 1-D velocity models, and compare these predictions with our travel-time picks.

**References:**