

SELENEOLOGICAL TOMOGRAPHY - INFERRING THE COMPOSITION OF THE MOON FROM THE APOLLO LUNAR SEISMIC DATA, MASS AND MOMENT OF INERTIA. A. Khan^{1,4}, J. MacLennan², S. R. Taylor³, K. Mosegaard¹, J. Gagnepain-Beyneix⁴, P. Lognonne⁴, ¹*Niels Bohr Institute, University of Copenhagen, Denmark (amir@gfy.ku.dk)*, ²*School of GeoSciences, The University of Edinburgh, Scotland*, ³*Department of Earth and Marine Sciences, The Australian National University, Canberra, Australia*, ⁴*DGSP, Institut de Physique du Globe de Paris, France*.

Introduction. The internal structure and composition of a planet or satellite are important constraints on theories for how such bodies formed and evolved. Of all geophysical methods used to study a planet's structure, seismology is uniquely suited to determine many of the parameters that are critically important to understand the dynamic behaviour of the planet. For this reason seismology has played a leading role in the study of the internal structure of the Earth. The only other solar system body from which we have seismic observations pertinent to its interior properties is the Moon, thus giving us an opportunity to examine planetary formation in general without being tied to the Earth. Issues that, in principle, can be addressed geophysically and which hold the potential of providing constraints on lunar formation and evolution, include the question of whether the Moon has a metallic iron core, the depth of differentiation needed to produce the plagioclase rich highland crust, its bulk composition and the question whether it bears any generic relationship to that of the Earth's mantle.

From 1969 to 1972 the US Apollo program installed one short-lived and four long-lived seismometers on the Moon. The latter instruments were operated until 1977. The data collected by the Apollo seismic network provided the basis for a number of studies of lunar seismicity and internal structure published during the 1970s, early 1980s and very recently [e.g. 1, 2, 3, 4, 5]. However, as seismology does not present an end in itself, it can only be used as an indirect means to infer internal state and composition of the Moon, by, for example, comparing laboratory measurements of seismic wave velocities made on returned samples and terrestrial analogues with those obtained from the inversions. Unlike the aforementioned studies where the objective was centered on obtaining a seismic velocity model, the main purpose of the present study is to attempt to infer the composition and mineralogy of the lunar mantle directly by inverting the Apollo lunar seismic arrival time data set, mass and moment of inertia.

Purpose. We model the thermodynamic properties of minerals within the CFMAS system, comprising the elements CaO-FeO-MgO-Al₂O₃-SiO₂. Given the mineralogy at the appropriate P , T -conditions, we can calculate physical properties, such as density, P and S -wave velocity, from which we can determine lunar mass and moment of inertia, as well as a set of arrival times of seismic waves emanating from a number of diverse sources and traveling to the 4 seismic stations installed during the Apollo missions. Given this scheme, the data are jointly inverted using a Markov chain Monte Carlo algorithm, from which a range of compositions and temperatures fitting data within uncertainties are obtained. Specifically, we are able to determine the compositional range of the oxide elements in the CFMAS system, thermal state, Mg#, mineralogy and physical structure of the lunar interior, as well as

constraining core size and density, all consistent with the data.

Method of Analysis. The method of analysis is detailed in [6]. The inverse problem dealt with here of obtaining information on the lunar composition employs a Markov chain Monte Carlo (MCMC) method.

Concerning our model of the Moon, it is assumed to be spherically symmetric and divided into four concentric shells which are variable in size. The four layers correspond to crust, upper mantle, lower mantle and core. Each shell is described by the following set of model parameters, its thickness d , the wt-% of the oxides in the CFMAS-system and the temperature T . We have to note that the central layer (the core) is treated differently than the other three. Only the layers comprising crust, upper and lower mantle are modeled chemically in the CFMAS-system down to a depth of 1437 km, the core making up the rest. The physical properties of the core are modeled by its size and density, as the core is only relevant for the calculation of lunar mass and moment of inertia.

Results. The results indicate a pyroxenite upper mantle and a lower mantle made up principally of olivine-garnet cumulates (see figure 1). Figure 2 shows that the transition between the upper and lower mantle is marked by a discontinuity in seismic wave speeds and density at a depth of ~600 km, in line with earlier inferences [e.g. 3, 4]. As concerns hypotheses regarding lunar evolution, the question of whether the Moon was once totally molten or only partly so, is intimately related to the depth of the lunar magma ocean (LMO), as earlier interpretations of the upper/lower mantle seismic discontinuity of the Nakamura seismic velocity model [3], took it as representing a transition from a differentiated upper mantle to a primitive, possibly undifferentiated lower mantle [7, 8]. With respect to lunar evolution and depth of differentiation, we find that the results presented here, notably the presence of olivine and garnet in the lower mantle, are most consistent with an interpretation where these minerals crystallised naturally from the LMO, implying whole-Moon involvement and thus obviating the presence of a primordial deep lunar interior. Given the relatively high density lower mantle, a lunar metallic core is not necessarily demanded. Moreover, our results indicate that bulk lunar composition and Mg# are different to that of the Earth's upper mantle, represented by the pyrolite composition of e.g. [9], reflecting their distinct origin and evolutionary histories. This is critically reflected in a lower bulk lunar Mg#, higher lunar Al₂O₃ and SiO₂ as well as lower MgO and FeO contents in comparison to those of the Earth's upper mantle

(see figure 3).

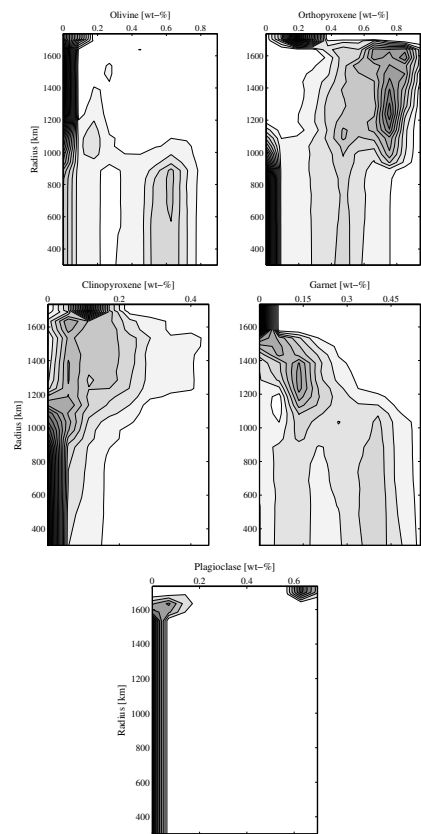


Figure 1: Marginal posterior probability distributions (*pdd*'s) of major mineral phases, showing the wt-% of each individual phase as a function of radius. At a number of fixed depth nodes a histogram reflecting the marginal probability distribution of sampled mineral phase proportions (in wt-%) has been set up. By lining up these marginals, the mineral phase proportions as a function of radius are envisioned as contours directly relating their probability of occurrence. As noted only the major mineral phases are shown here. Minor phases, including spinel, coesite, kyanite, quartz, siliminate and peridotite all occurred in proportions < 0.1 wt-% and are therefore not included here. Colour coding: white least probable and black most probable.

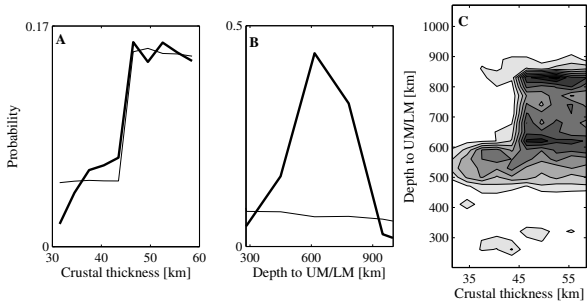


Figure 2: Prior and posterior *pdf*'s, (A) and (B), depicting depths to compositional boundaries, delineating (A) crust, (B) upper (UM) and lower mantle (LM). Very little information is provided on the crustal thickness, as prior and posterior are nearly coincident. Much more information is seen to be provided on the depth to the upper/middle mantle transition, where data turn a flat distribution into a spiked one, centered at ~600 km depth. (C) shows the correlation that exists among these parameters, which seem to be nearly independent.

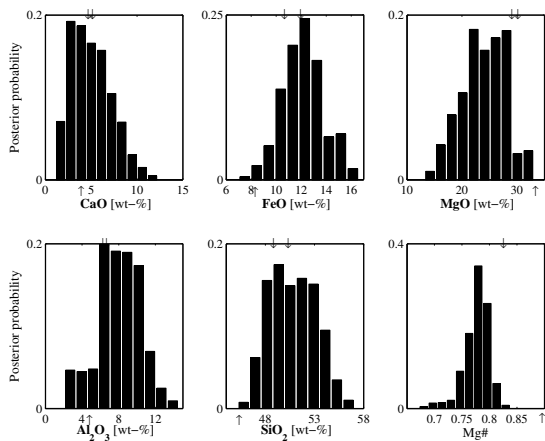


Figure 3: Marginal posterior *pdf*'s displaying bulk lunar composition and Mg# for the silicate part of the Moon (Crust, upper and lower mantle). Downward pointing arrows indicate the values obtained by *Kuskov & Kronrod* [1998] for the bulk silicate portion of the Moon and upward pointing arrows indicate the composition of the Earth's upper mantle estimated by *McDonough & Sun* [1995].

References. [1] M. N. Toksöz et al., *Rev. Geophys.*, 12, 539, 1974. [2] N. R. Goins et al., *J. Geophys. Res.*, 86, 5061, 1981. [3] Y. Nakamura et al., *J. Geophys. Res.*, 87, A117, 1982. [4] A. Khan et al., *J. Geophys. Res.*, 107 (E6), doi10.1029/2001JE001658. [5] P. Lognonné et al., *Earth Planet. Sci. Lett.*, 211, 27, 2003. [6] A. Khan et al., *Geophys. J. Int.*, submitted 2004. [7] L. L. Hood and J. H. Jones, *J. Geophys. Res.*, 92, 396, 1987. [8] S. Mueller et al., *J. Geophys. Res.*, 93, 6338, 1988. [9] W. F. McDonough and S. S. Sun, *Chem. Geol.*, 120, 223, 1995.