THE SCIENTIFIC RATIONALE FOR A FUTURE LUNAR SEISMIC NETWORK.

Catherine L. Johnson[1,2], Reneé C. Bulow[3], Philippe Lognonné[3], [1]Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, B.C. V6T 1Z4. Canada (cjohnson@eos.ubc.ca), [2]Scripps Institution of Oceanography, La Jolla, CA 92093; [3]Institut de Physique du Globe de Paris, France.

Introduction: The Moon is the only body other than Earth for which we have in-situ seismic measurements. Seismic stations at Apollo sites 12, 14, 15 and 16 included a 3-component long-period seismometer and a single, vertical-component short-period seismometer [1], and transmitted data from 1969-1977. 12,558 seismic events were originally documented in the lunar event catalogue [2]. Here we review the major scientific results from this data set and highlight outstanding questions and their implications for our understanding of lunar evolution. In our presentation we will discuss how future seismic networks might address these questions.

Seismicity: Analyses of Apollo seismic data are challenging due to (a) the limited dynamic range of the 10-bit instruments, (b) the small magnitudes of most lunar events, and (c) scattering in the lunar regolith. Despite these difficulties, ~25% of catalogued events were originally classified as natural events: meteoroid impacts (~1700), and shallow (28), or deep (1360) moonquakes. The thermal signature of sunrise/sunset is also seen in the data. The station distribution leads to a detection bias toward nearside events (Figure 1).

Deep moonquakes (DMQ) appear to originate at ~900 km depth, with distinct source regions that undergo repeated failure, probably in response to tides [1]. DMQs are enigmatically low magnitude events, characterized by stress drops of less than 10 kPa [3].

The waveform coherence of deep moonquakes from a given source region has recently been exploited to enable a significant number of events to be added to the original DMQ population. The new additions are events that were either (a) previously identified but not recognizable as DMQ (*i.e.,* listed as unclassified events in the catalogue) [4], or (b) not previously recognized in the lunar seismograms (*i.e.,* not in the original catalogue) [5]. A total of almost 8000 DMQ have now been identified from at least 160 source regions [6,7]. Estimates of relative locations [8] and short period stacks [9] suggest a small spatial extent (~1km^3) for individual source regions.

Shallow moonquakes (SMQ) were originally designated as "high frequency teleseismic" events, on the basis of the frequency content of their waveforms [10]. All 28 events occurred outside the seismic network, and depths are poorly constrained; the range 0-200 km is permitted by arrival times. A sub-crustal origin is suggested by the variation in amplitude of the short period signals with epicentral distance [10]. Locations show some correlation with the edges of impact basins (Figure 1) and have been suggested to reflect lateral structural heterogeneities [10]. Most SMQ have stress drops of a few MPa, but the largest have seismic moments of ~10^{15}Nm, and stress drops >100MPa [11].

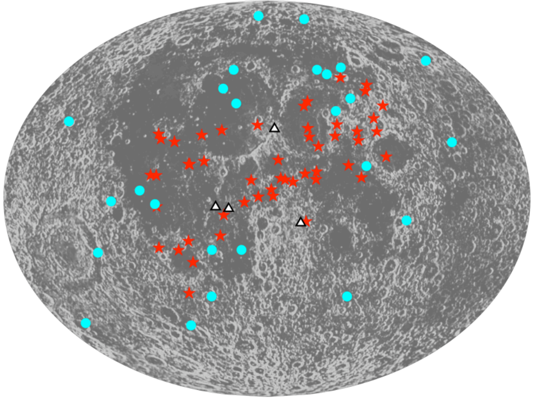

Figure 1: The 50 DMQ source regions with location errors less than 10° and depth estimates (red stars) [6]; SMQs (blue circles) [9] and Apollo sites 12, 14, 15 and 16 (white triangles). Basemap is shaded relief and spans 120°W to 120°E.

Outstanding Issues: Still unresolved are the triggering mechanisms for deep and shallow moonquakes. In particular, the limited source-receiver distributions and quality of the seismograms prevents characterization of source mechanisms, although one such attempt has been made [12]. Furthermore, uncertainties in event location can be large (see Figure 5 in [7]).

Although DMQ are clearly related to tides, they are poorly understood. Their repeated nature and the small stress drops associated with individual events suggests the source regions are maintained close to failure. Shear failure has often been assumed on the basis of large S (compared with P) amplitudes; however other failure criteria (*e.g.*, Coulomb failure) cannot be ruled out. Tidal stresses have been interpreted as too small to result in failure, and temperatures at DMQ depths indicate a regime where ductile, rather than brittle, behavior is expected. A recent suggestion is that phase transitions may play a role in deep moonquake triggering. If so, DMQ depths could correspond to well-defined sets of temperature-pressure conditions in the lunar interior. Investigating such a hypothesis requires an observationally unbiased, well-located population. Specific questions that should be addressed with future observations include: (1) Do DMQs occur on the far-side? (2) Is the absence of DMQs beneath the near-side lunar highlands significant? (3) Do DMQs depths vary with geographical position?

Precisely why SMQs occur is unknown, although a tectonic origin has been suggested [10]. The low number, apparent association with perimeters of some impact basins, and in some cases quite large magnitudes of these events warrants further study. An important future objective should be to establish whether these are crustal or upper mantle events.

Internal Structure of the Moon: Body wave arrival times allow modeling of 1-D seismic velocity to ~1200 km depth. Recent crustal thickness estimates of ~30 km [9] are most representative of the Apollo 12 and 14 region, and less than previously suggested (~60 km in [13]). Details of crustal velocity structure varies among models because of the limited data set and different model parametrizations. Mantle velocities are v_p ~7.7 kms^{-1}, v_s ~4.4 kms^{-1}, to about 300 km depth. Sensitivity in the mid-mantle (300 – 700 km) is poor, and depends on the crustal structure [14]; consequently a range of models including those with negative seismic velocity discontinuities/gradients at ~300 km depth, and those with sharp positive discontinuities at ~500 km depth are permitted [14]. Seismic velocity estimates in the deep moonquake zone differ, but all models show higher velocities than in the upper mantle. Seismic attenuation in the upper mantle is low [15], but has been suggested to increase at depths below 1000 km, possibly indicating the presence of partial melt (see review in [16]). Because few ray paths samples depths below 1000 km, there is no direct evidence for the core, and unambiguous detections of free oscillations are lacking [14]. However, joint inversions of density, moment of inertia, Love number, and sesimic data place some bounds on core size and density, and favor a core containing light elements [14].

Seismic velocity profiles have been used to for thermal and mineralogical modeling of the lunar interior (see reviews in [14] and [16]). In general, models that assume differentiation of the upper mantle and that are more aluminous in bulk composition than the terrestrial mantle are favored. Overall, the increase in seismic velocity with depth is consistent with a change in bulk composition and magnesium number from a dominantly orthopyroxene upper mantle to a dominantly olivine lower mantle [16].

A focal point of many earlier studies was the ability to predict a velocity discontinuity at 500km observed in the seismic velocity model of [13], and phase changes or compositional boundaries at this depth were inferred [*e.g.,* 17,18 and review in 16] . Compositional boundaries are of interest because they may constrain the bulk composition of the mantle, the depth extent of of an early magma ocean, and/or the maximum depth of the source region for mare basalts. However, uncertainties in velocity models caution against over-interpretation of mantle structure at 300-700 km depth.

Outstanding Issues: Critical to understanding the present (and past) thermal and compositional state of the lunar interior are (1) direct seismological evidence for the size and state of the lunar core, and (2) additional crustal thickness estimates for the near-side and far-side. Current data limitations lead to the following issues in interpreting seismic models: (1) a geographical bias toward sampling the lunar mantle below the maria, (2) trade-offs of velocity structure with source location, (3) the inability to distinguish between mantle velocity gradients versus sharp discontinuities, (4) large variations in crustal structure among different models, (5) lack of seismic velocity estimates for the lowermost mantle. Future network design should attempt to address these issues. Discrimination among models for the early differentiation of the Moon requires improved knowledge of crustal and mantle structure, including sufficient resolution to detect mantle seismic discontinuities if present.

Surface waves have not been observed by Apollo, because even the largest impact events (10^{18} Ns) yielded acceleration amplitudes comparable to the nosie level of the Apollo seismometer. Improved sensitivity and bandwidth should allow future seismometers to detect at least the largest impacts, providing key constraints on mean crustal structure along these wave paths. Supporting experiments, both ground and satellite-based (e.g. radar sounding) that can help image the shallow crust should be considered. Finally, the small number of SMQs, and the presence of 205 day and 6 year tidal periods in DMQ occurrence times advocates long time series of observations.

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