An international team to create reference models and data sets for Moon seismology

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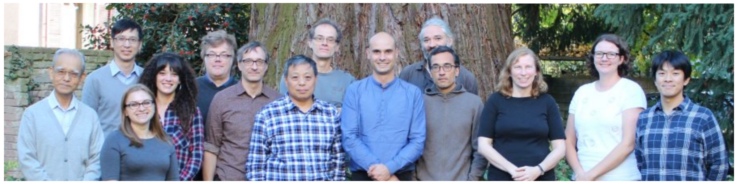

We present here the work performed by an international team on Moon seismology which gathered with the support of ISSI Bern and Beijing. Our goal is to provide to the scientific community the following elements:
- processed data sets and an analysis of their error bars
- internal structure models produced by using these processed data sets and up to date a priori information
- an analysis describing what we know and what we don't know about the internal structure of the Moon, in order to support and drive future seismological deployments

We will present the review work of a priori information and internal structure models, and the preliminary analysis of processed data sets (travel times, deep moonquake stacks...) performed up to know.
The strategy for data analysis and reference model production will also be presented. We conclude on our statement to support future lunar internal geophysics missions.

Review of internal structure models:

As a first step, we reviewed internal structure models of the Moon and underlying assumptions. Table 1 and Figures 1 and 2 summarize the previous models published and their underlying assumptions.

Model Nickname	TK74	NK83	KM02	LG03	BN06	WB11	GR11	KH14	MS15	Best estimate
Data / prior										
Body wave travel times	P only KV73ab	P+S multiple	P+S NK83	P+S+Smp own+VK01	P+S+Smp LG03+VK01	S only own	P + S LG03	None	P + S LG03	ISSI team data set
Electromag. sounding	None	None	None	None	None	None	None	H83	None	
prior source locations	KV73ab	None	None	None	None	LG03	LG03	None	LG03	
Mass ($\times 10^{22}$ kg)	None	None	None	None	None	None	7.3458	7.3463 $\pm$0.00088	7.34630 $\pm$0.00088	7.34630 $\pm$0.00088
I/MR^2	None	None	None	None	None	None	0.3932 $\pm$0.0002	0.393112 $\pm$0.000012	0.393112 $\pm$0.000012	0.393112 $\pm$0.000012
k_2	None	None	None	None	None	None	0.0213 $\pm$0.0025	0.0232 $\pm$0.00022	0.02422 $\pm$0.00022	0.02277 $\pm$0.00058 (elastic)
h_2	None	None	None	None	None	None	0.039 $\pm$0.008	None	None	0.048 $\pm$0.006
prior crust seismic model	None	None	None	None	None	LG03	LG03	None	None	unknown
prior crust density	None	None	None	None	None	None	2.6-3.0	None	None	2.5-2.6

Table 1: A priori information and data sets used to create the various models presented in figures 1 and 2.

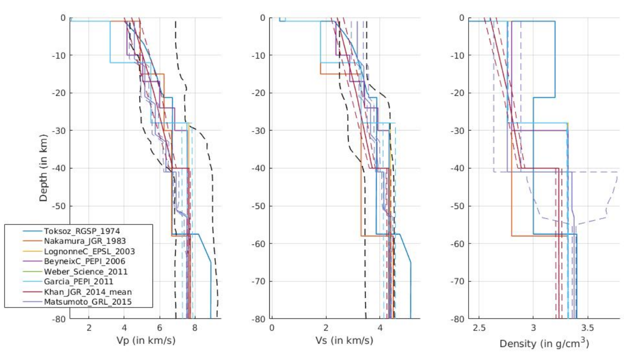

Figure 1: Zoom on the first 80km of the Moon internal structure inferred by various spherically symmetric models. From left to right, P and S wave velocities and density as a function of depth inside the Moon.

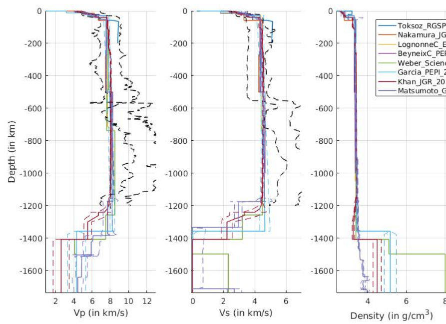

Figure 2: Compilation of spherically symmetric models of Moon internal structure produced by various researchers. From left to right, P and S wave velocities and density as a function of depth inside the Moon.

Previously published models disagree mainly on the inferred crust structure, deep mantle and core. If we exclude the earliest results, there is a general agreement in the top and mid-mantle ranges.

Review of seismic attenuation models:

Table 2 review the various seismic attenuation models published and underlying assumptions.

Reference	Freq. (Hz)	Freq. Dep.	Depth Range (km)	D (km^2/s)	Dissipation Q_p	Dissipation Q_s	Observable	Method
Latham et al. (1970a)	1	Yes	< 20	2.3-2.5		3600	Seismogram envelope	Diffusion theory
Latham et al. (1970b)	1	Yes	< 20			3000	Coda Decay	Diffusion theory?
Dainty et al. (1974)	0.45 1	Yes	< 25 < 14	$\parallel 8 \perp ?$ $\parallel 0.9 \perp 0.4$		5000 5000	Seismogram Envelope	Diffusion Theory
Dainty et al. (1976a)	$1-10$	No	$0-500$ $500-600$ $600-950$ $950-1200$		5000 3500 1400 1100		Average P-wave amplitude	Inter-station spectral ratio
Dainty et al. (1976b)	$1-10$	No No	< 520 $520-1000$		4800 ± 900 1400 ± 300		Average P-wave amplitude	Inter-station spectral ratio
Nakamura et al. (1976)	$1-8$	No	$60-300$ $300-800$		4000 1500		Average P-wave amplitude	Inter-station spectral ratio
Nakamura (1976)	4 5.6 8		< 2	$2.6 \times 10^{-2}, 3.3 \times 10^{-2}$ $2.2 \times 10^{-2}, 2.8 \times 10^{-2}$ $1.8 \times 10^{-2}, 2.2 \times 10^{-2}$		$1600-1700$ $1900-2000$ 2300	Maximum amplitude decay with distance	Diffusion theory for moving sources
Nakamura and Koyama (1982)	1 8	Yes $Q_s \propto f^{0.7 \pm 1}$	< 400		> 4000 $4000-8000$	$4000-150000$ $7000-15000$	Average P, S amplitude	Single + Inter-station Spectral fitting
Simplified from Gillet et al. (2017)	0.5	Yes	$0-61$ $61-95$ $95-113$ $113-147$ > 147	$1.9 \pm 0.5 - 8.5 \pm 3$ $16 \pm 3 - 21 \pm 5$ 270 ± 200 $365 \pm 150 - 1000 \pm 600$ 4585 ± 2000		2500 ± 25 Id. Id. Id. Id.	Rise time and coda Q of seismogram envelope	Diffusion theory

Table 2: Seismic attenuation estimates by various authors using various methods that constrain different depth and frequency ranges

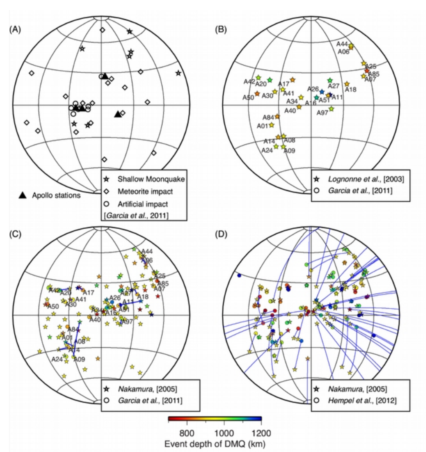

Fig. 3 Locations of moonquakes at the nearside of the Moon.(A) displays the meteorite and artificial impacts, shallow moonquakes. Dark triangles represent the locations of 4 seismic stations. (B)-(D) displays the source locations of the DMQ's from different studies. The color denotes the event depth. The difference between the locations is marked by the blue line.

Comparison of quake locations:

Our team gathered quake locations from various researchers in order to estimate quake location errors. As already pointed out by previous studies these errors appear to be quite large, in particular if constraints on the velocity models are relaxed like in Hempel et al. (2012).

Compilation of body wave arrival time picks:

Our team created a compilation of previously published P and S arrival times for the events with enough arrivals to allow a location.
Deviations relative to median arrival times are presented for surface and shallow events in figure 3, and for S-P times of deep Moon quakes in figure 4.

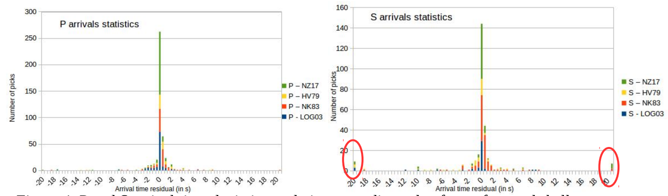

Figure 4: P and S arrival time deviations relative to median value for surface and shallow events

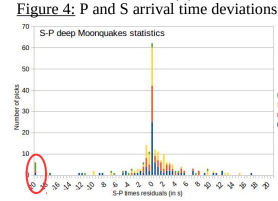

Figure 5: S-P times deviations relative to median value for deep Moon quakes

Comparison of deep moonquake stacks

Stacks for deep moonquakes have been created by three different teams over the years of Apollo data processing. Our international team gathered the stack waveforms and started a comparison of these waveforms.

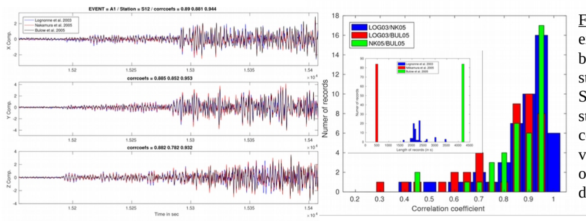

Figure 6: On the left, example of comparison between deep moonquake stacks (event A1, station S12). On the right, statistics of correlation coefficients between the various data sets, and size of records in the various data sets (insert).

Conclusions:

- Inferred internal structure models disagree on crust structure, deep mantle and core, because the data are lacking to constrain deep regions.
- Arrival time picks present a low variability (<2 s) except S waves outliers.
- Deep moonquake stacks by various teams present very similar waveforms.

Next steps:

- Invert the same data sets with the same a priori assumptions using different model parametrization to infer resolved and unresolved regions
- Finish writing two papers describing respectively data sets and models
- Provide body wave arrival time picks and deep moonquake stacks waveforms to the scientific community
- Provide recommendations and support for future seismological experiments on the Moon surface
- Initiate a core science team for an international lunar seismological network