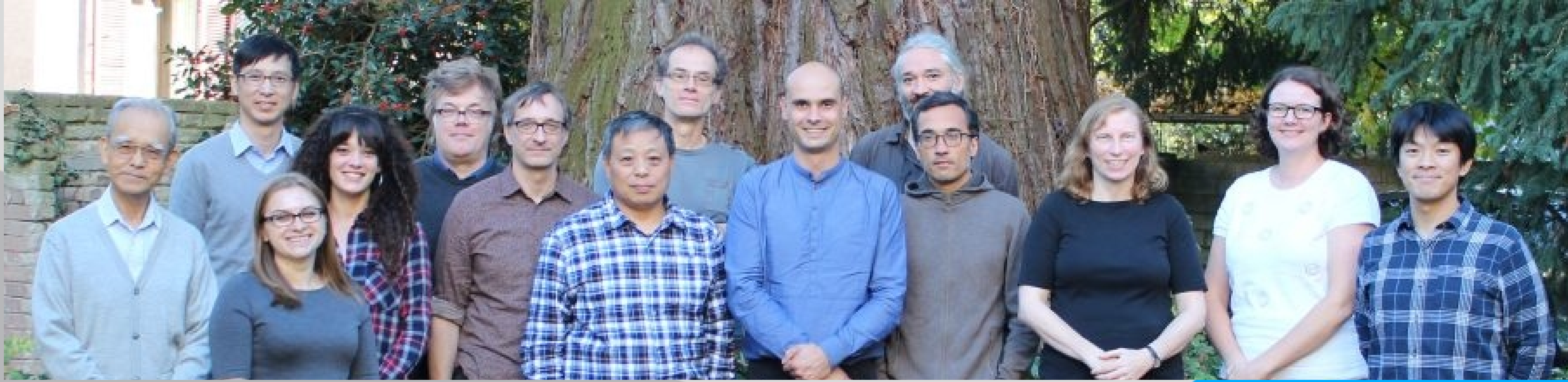
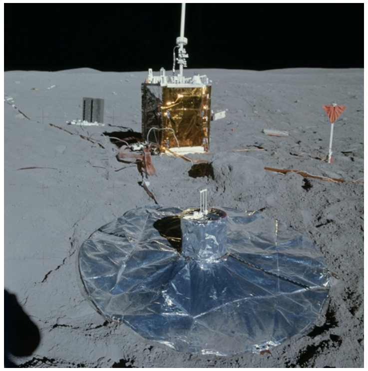


The lunar seismic environment

Gravitational wave detection at the Moon Workshop

14/10/2021

Pr Raphael F. Garcia



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isae Institut Supérieur de l'Aéronautique et de l'Espace SUPAERO

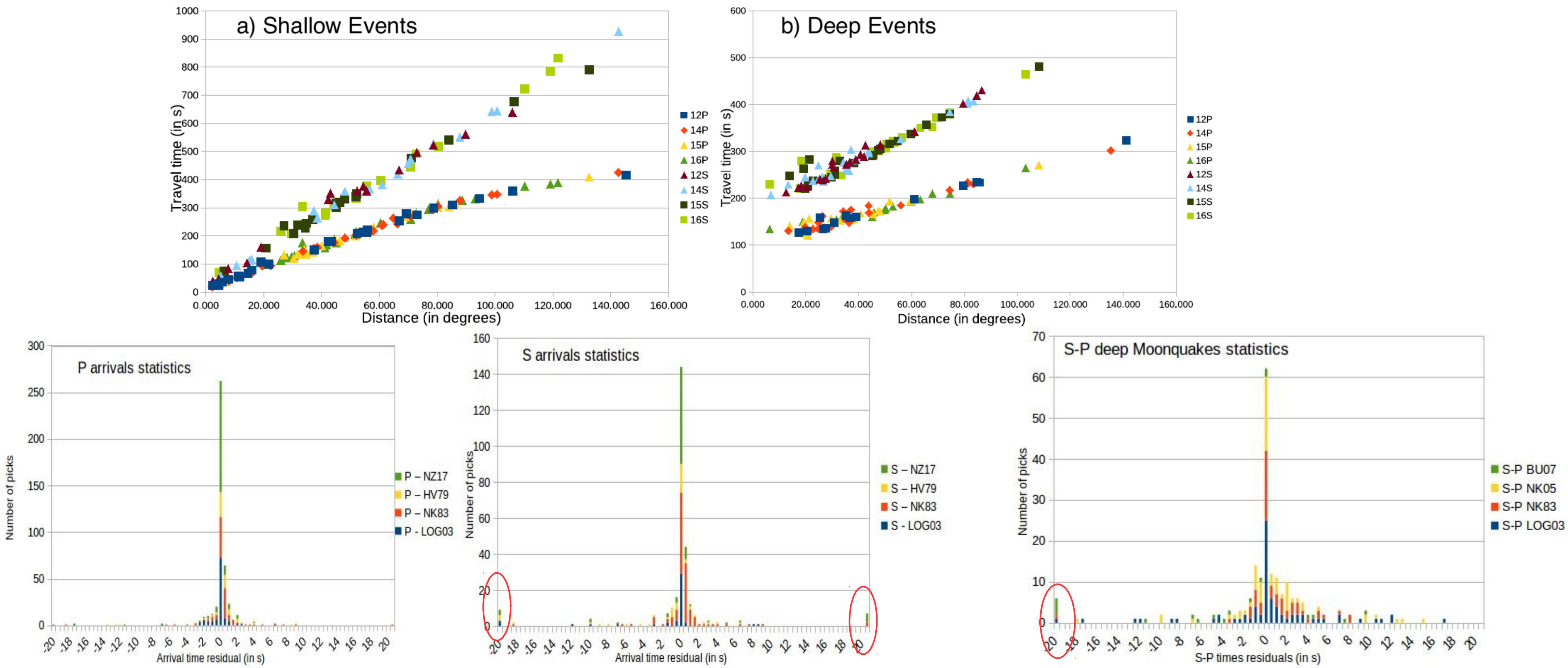
Overview

Overview

- Gathering Apollo processed data (Body wave travel times, deep Moon quakes stacks, locations...)
- Review of internal structure models
  - Seismic attenuation and scattering models
  - Seismic velocity models
- Limitations induced by Apollo instrumentation and experiments
- Moon seismicity
- Seismic signals
- Moon Background seismic noise
- Conclusion

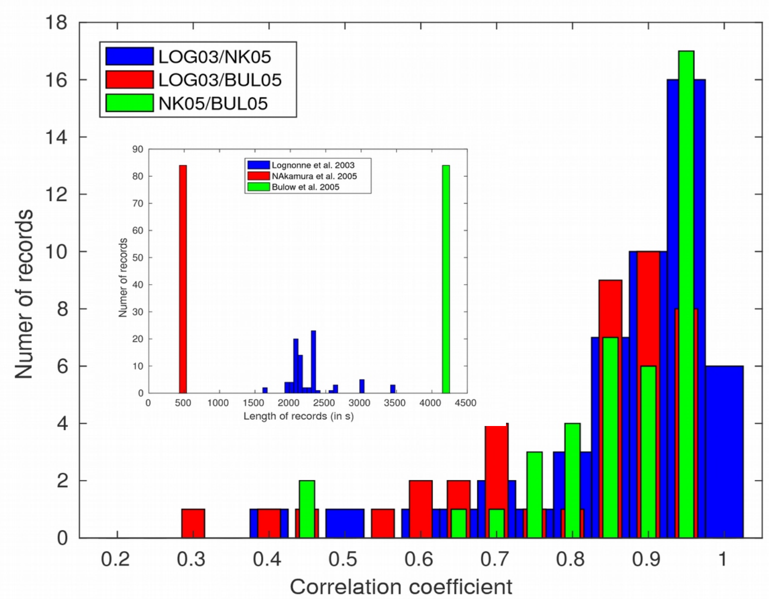
Apollo body wave travel times

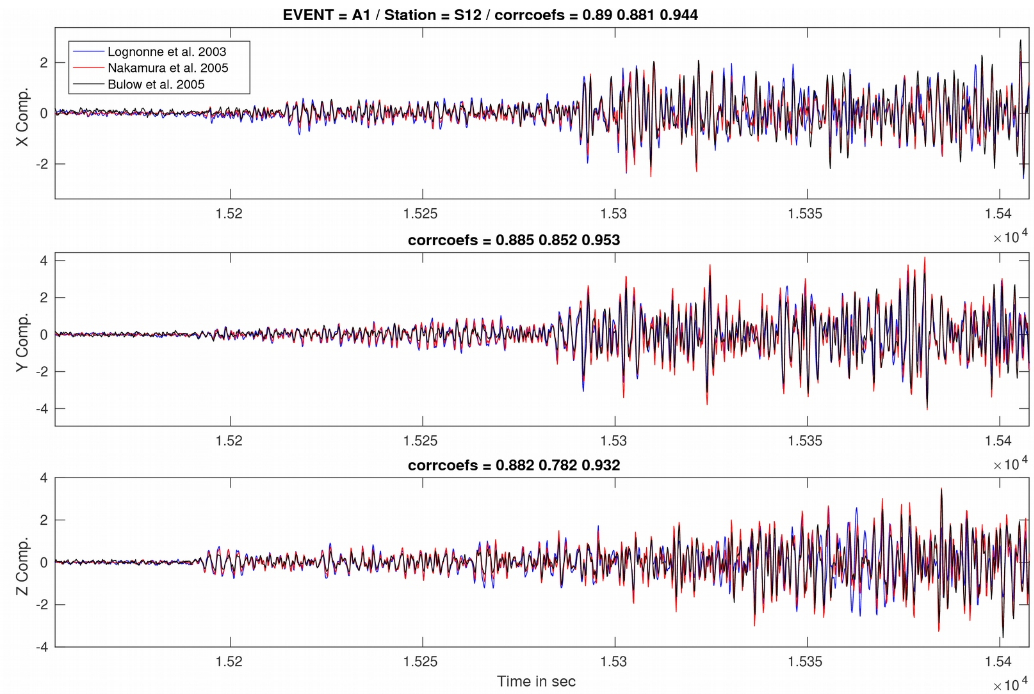
- All published arrival times gathered and cross checked :
  - Outlayers detected on S wave arrival times due to picks in the late coda
  - Dispersion ~2s for P waves and ~3-4s for S waves and S-P times
  - Better quantify error propagation and outlayers for inversion



Apollo deep Moon quake stacks

- Deep moonquake stacks :
  - Performed independently by 3 different teams
  - Converted to same format, aligned by correlation and compared
- Good similarity between waveforms
  - Very high correlation coefficients for such long records
  - Differences mainly due to different number of individual records in the stacks





Attenuation and scattering properties

Reference	Freq. (Hz)	Freq. Dep.	Depth Range (km)	D (km^2/s)	Dissipation Q_p	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	2.6×10^{-2}, 3.3×10^{-2} 2.2×10^{-2}, 2.8×10^{-2} 1.8×10^{-2}, 2.2×10^{-2}		$1600-1700$ $1900-2000$ 2300	Maximum amplitude decay with distance	Diffusion theory for moving sources
Nakamura and Koyama (1982)	1 8	Yes $Q_s \propto f^{0.7\pm1}$	< 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

Attenuation and scattering properties

Limited frequency range

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Attenuation and scattering properties

Limited frequency range

Intrinsic attenuation quality factors consistently above 1000 for all studies at all depths

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Attenuation and scattering properties

Limited frequency range

Intrinsic attenuation quality factors consistently above 1000 for all studies at all depths

Different observables and analysis methods

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A priori assumptions on internal structure models

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

A priori assumptions on internal structure models

Different seismic data sets

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	
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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

A priori assumptions on internal structure models

Different seismic data sets

Geodetic priors more and more used and precise due to GRAIL

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	
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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
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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

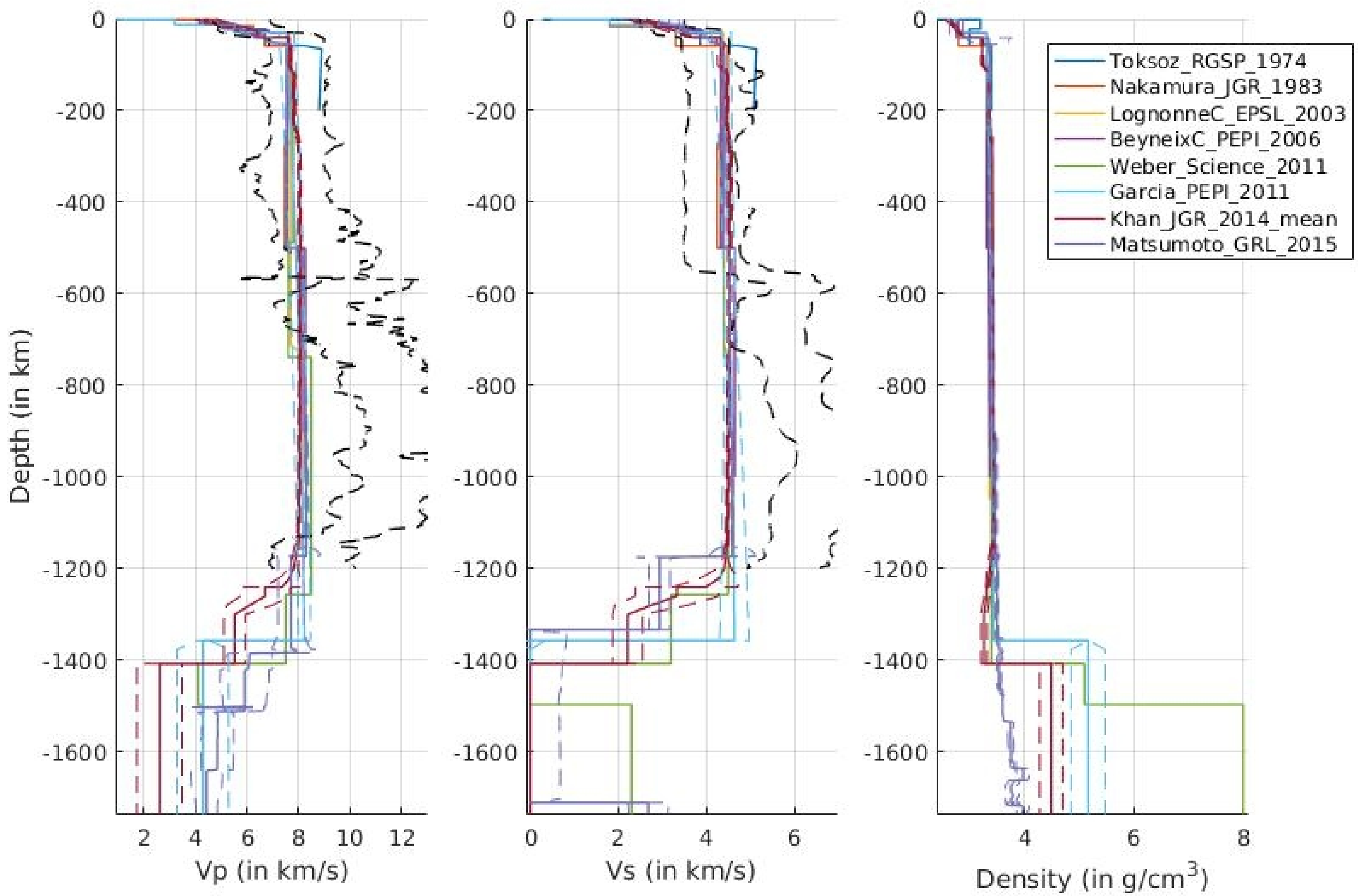
Comparison of internal structure models

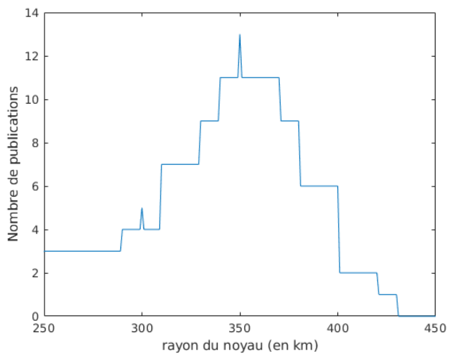
No agreement on crustal thickness

Overall agreement on mid mantle average seismic velocities and density

Deep mantle and core size still debated

Internal core structure?

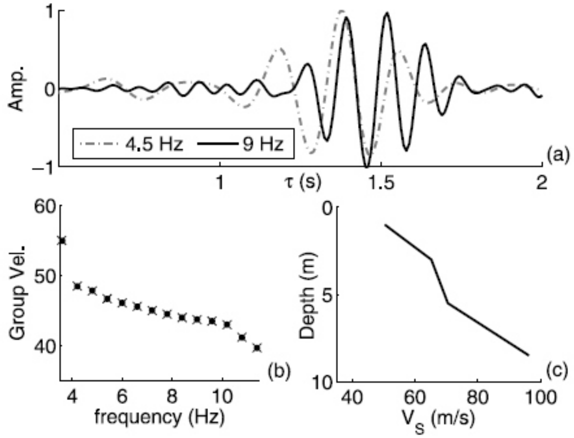


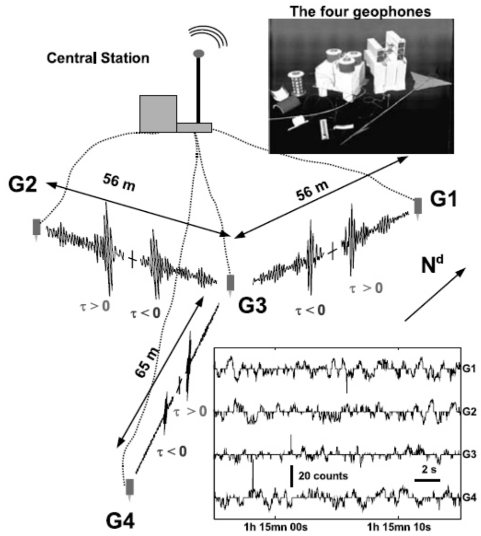


Core radius cited

Comparison of internal structure models

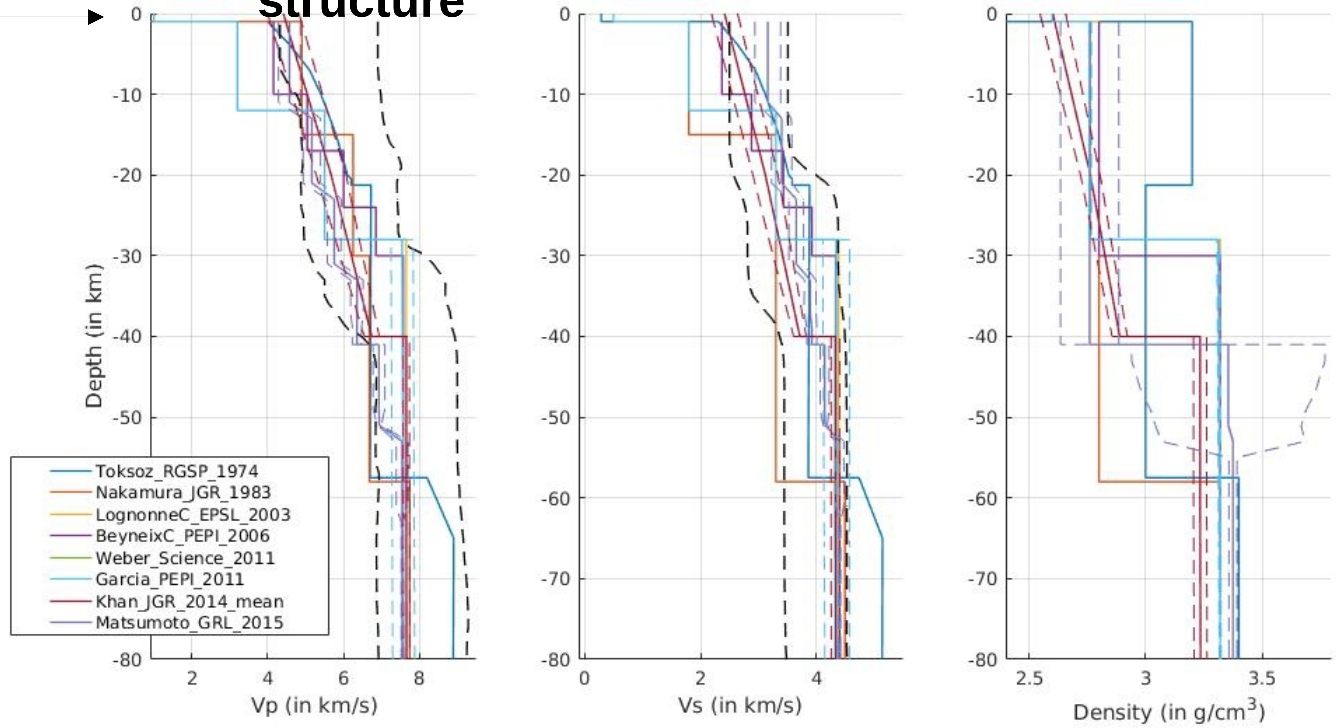
Regolit seismic properties
properly determined
from small scale networks





Larose et al.
(2005)

Zoom on crustal seismic
structure

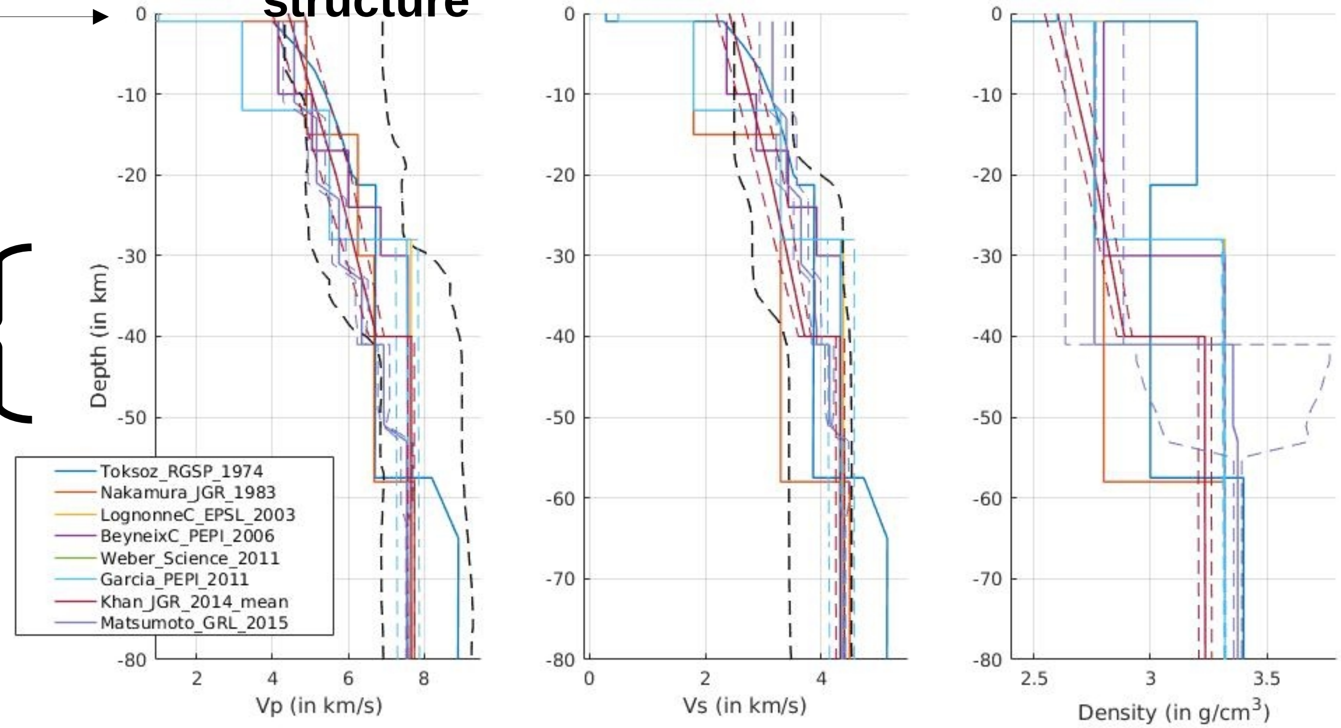


Comparison of internal structure models

Regolit seismic properties properly determined from small scale networks

Recent crustal thickness estimates in the range 30-50 km

Zoom on crustal seismic structure



Comparison of internal structure models

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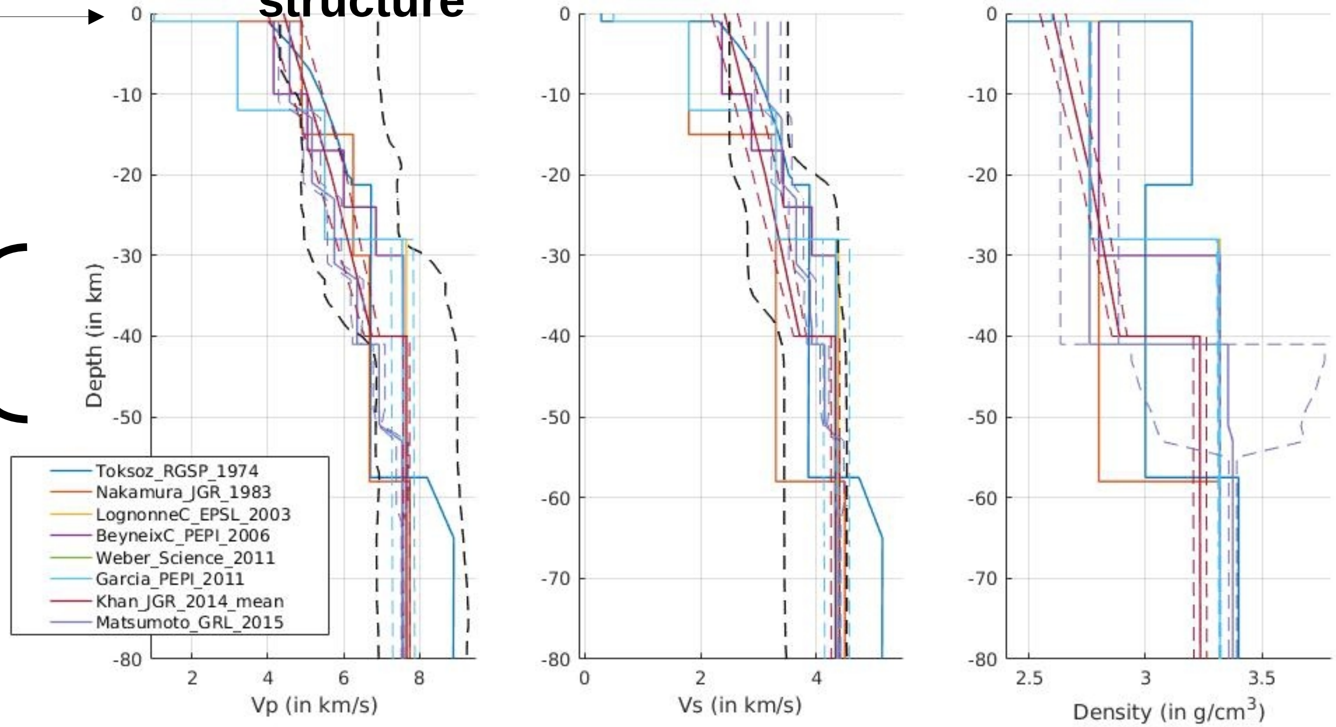
Zoom on crustal seismic structure



Recent crustal thickness estimates in the range 30-50 km

Difficulties of crust imaging:

=> Single detection of seismic waves converted at Moho (Vinnik et al., 2001)

=> Gravity models are non-unique

=> Global estimates impacted by station distributions (on thin near side crust) and lateral heterogeneities expected in the crust

Comparison of internal structure models
Zoom on the core

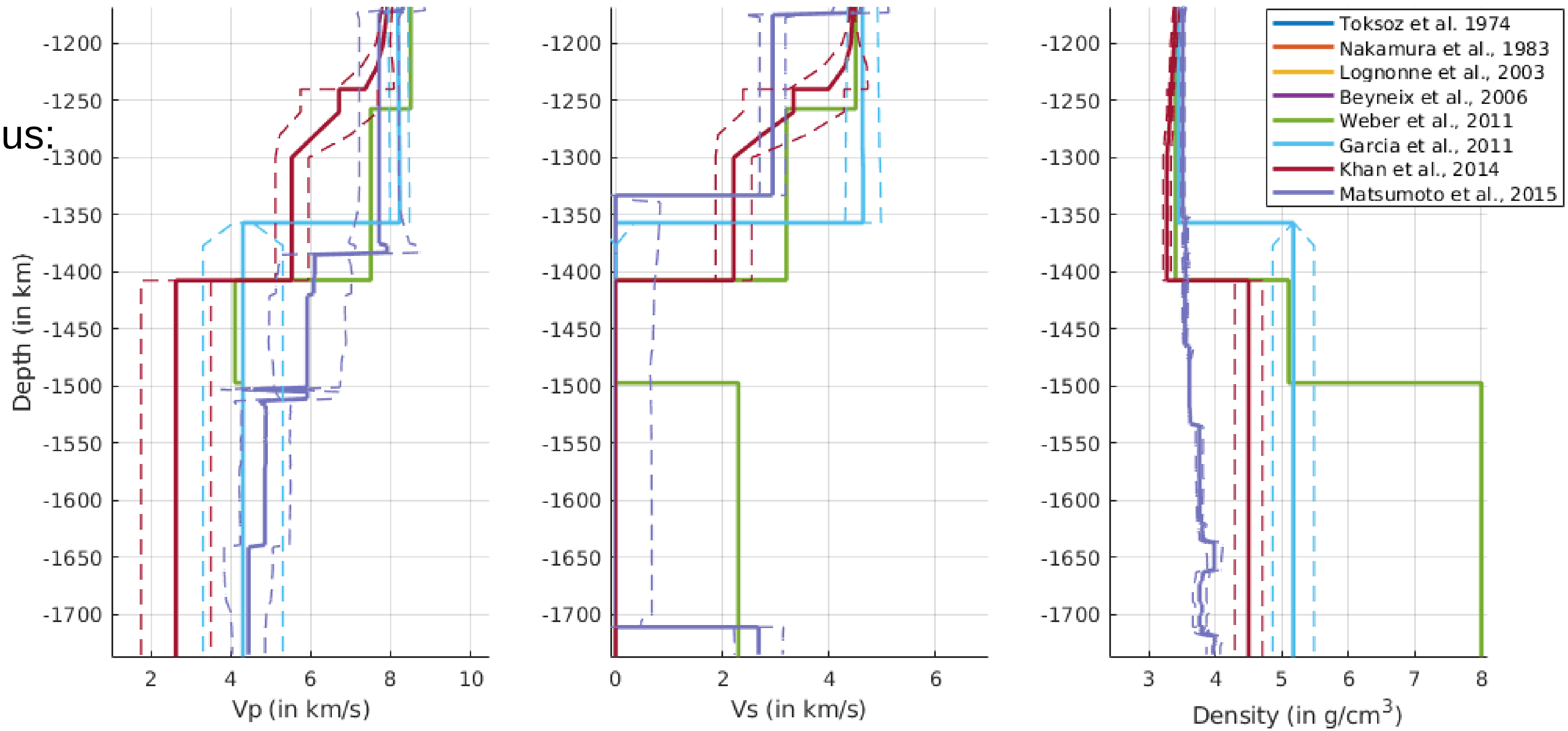
Low velocity zone for P
For some models
Vp fluid core:
3 km/s < Vp < 6 km/s

Low velocity zone for S
For most models

Fluid core densities:
3500<rho<5500 kg/m^3
Solid core estimate
significantly off

Core radius:
400 km

330km



Inversion of new processed data set

- Same data set and a priori constraints (no event relocation)
- Different model parameterizations and inversion methods

Model name	M1	M2	M3
Data / prior			
Body wave travel times	ISSI team data set	ISSI team data set	ISSI team data set (prediction)
Electromag. sounding	None	None	Table 6
Geodetic data	None	Table 5	Khan et al. (2014)
prior source locations	ISSI team compilation	ISSI team compilation	ISSI team compilation

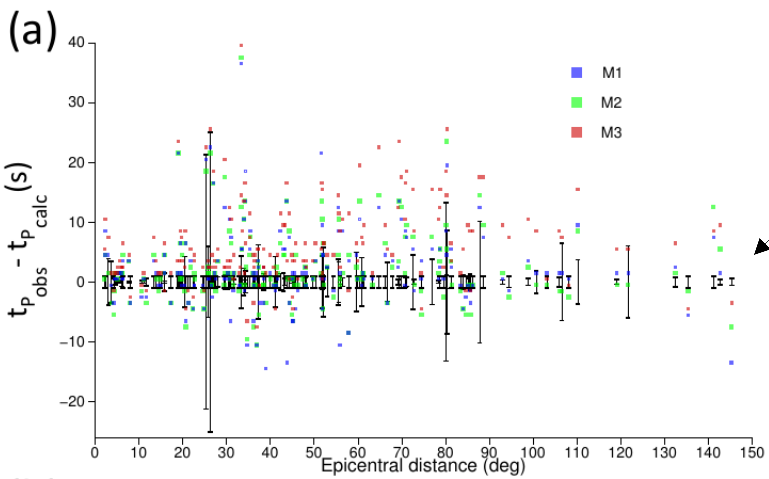
M1 (M. Drilleau)= flexible seismic parameterization, only seismic travel time data

M2 (R.F. Garcia) = strongly constrained parameterization, seismic and geodetic data

M3 (A. Khan) = parameterization constrained by mineralogical modeling and conversion to seismic wave speed,
seismic and geodetic data fit with previous ensemble of models (no inversion)

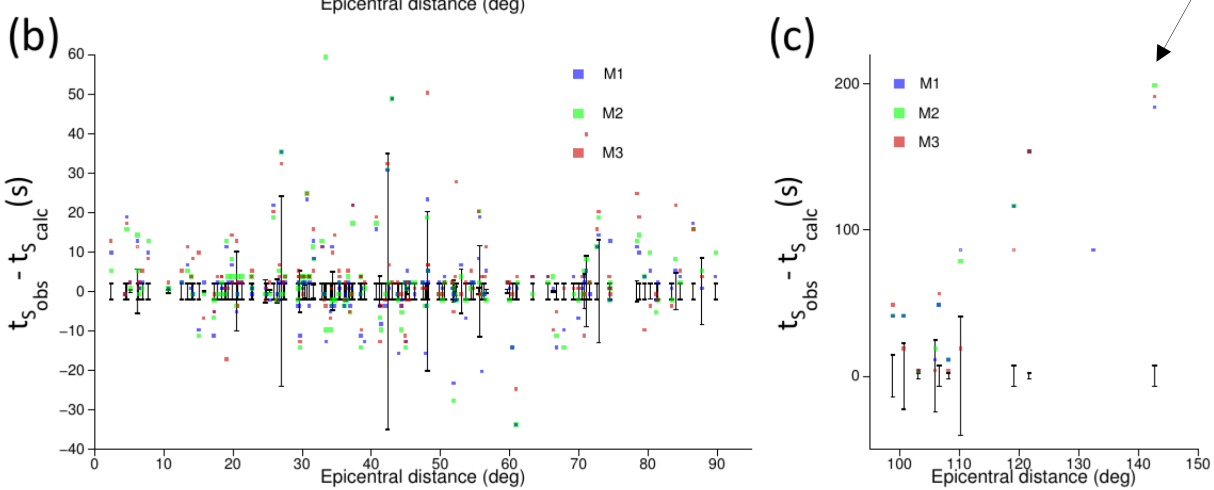
Inversion of new processed data set

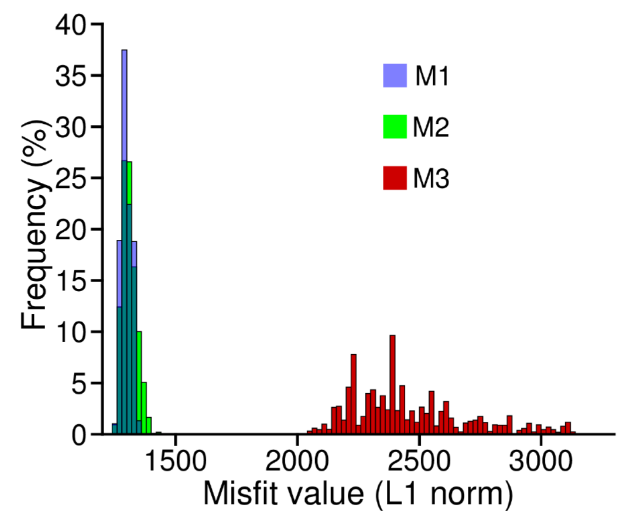
- Data fit:
  - Data fit similar except travel times not inverted for M3



Proper fit of P wave residuals at large distances for all models

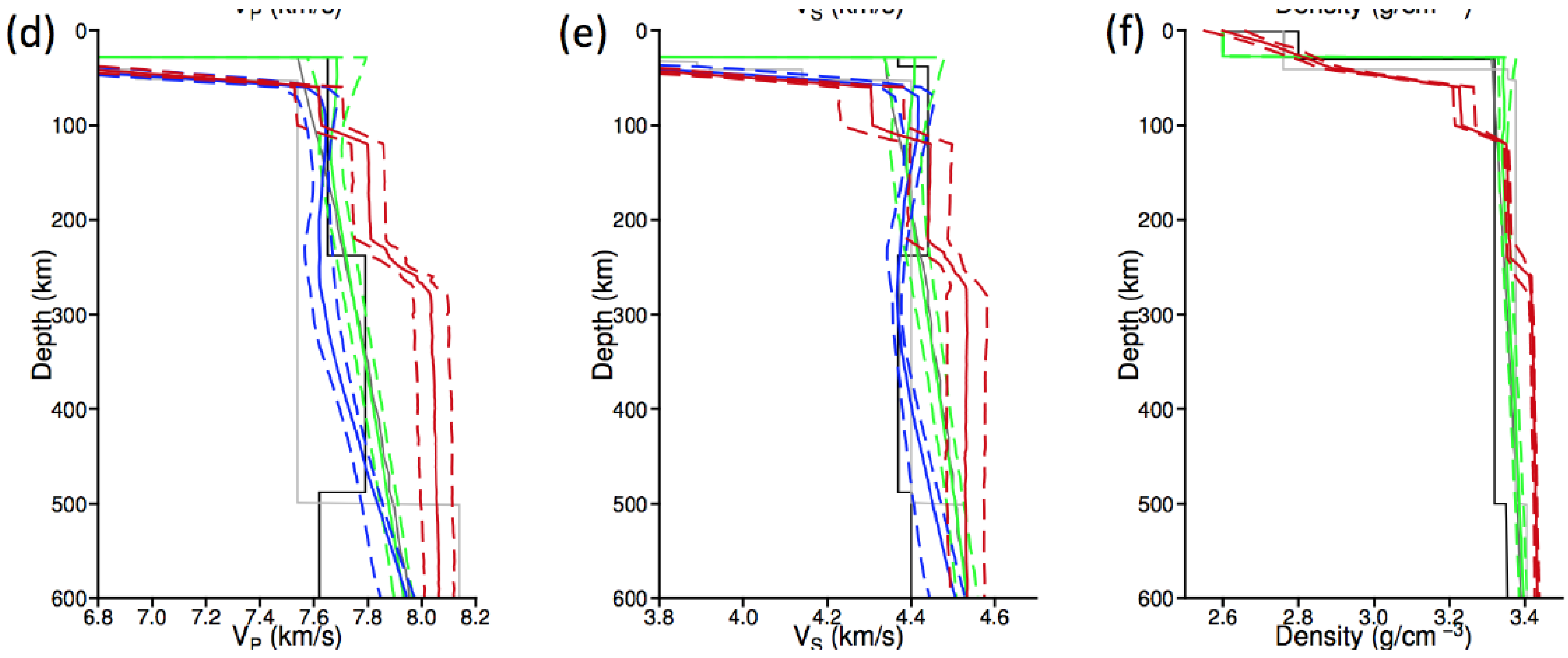
Strong S wave residuals At large distances for all models





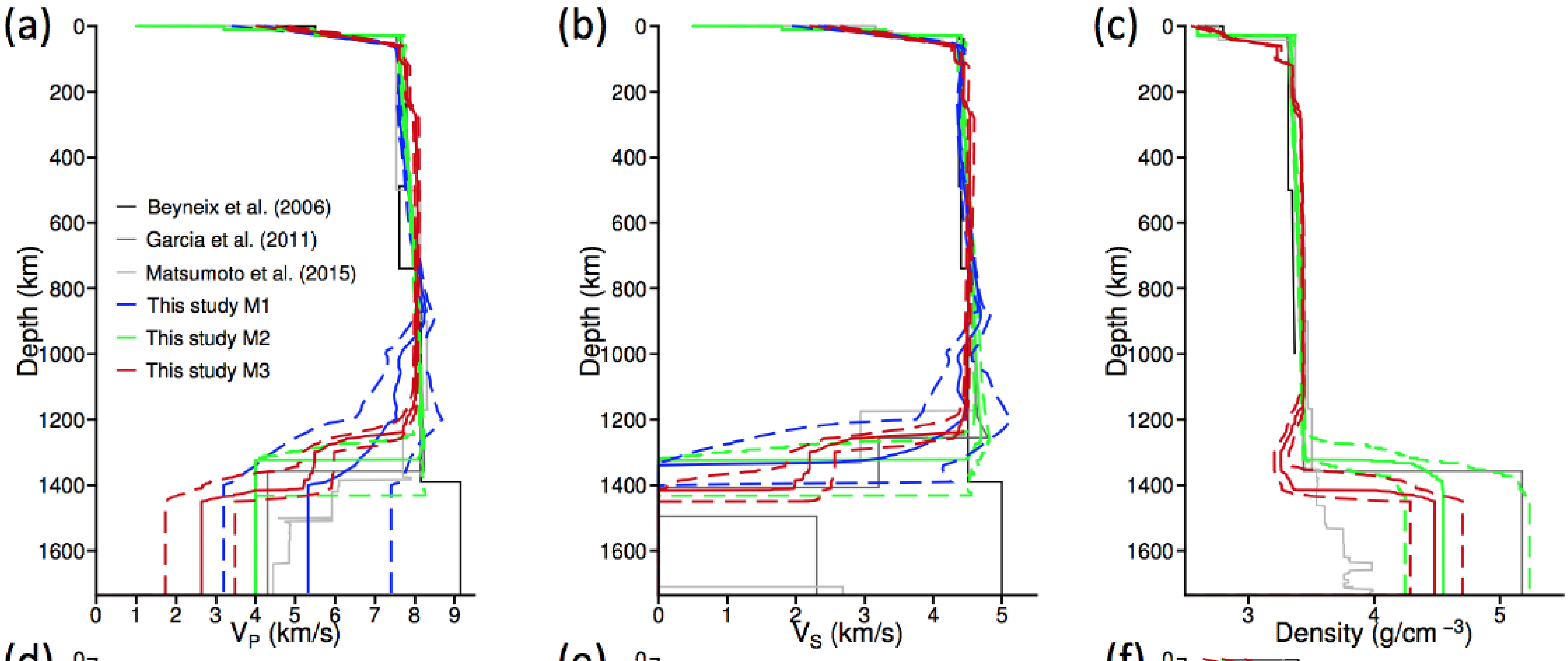
Inversion of new processed data set

- Comparison of models (upper mantle):
  - M1 (blue) and M2 (green) suggest a low velocity layer at the top of the mantle (100-250 km depth)
  - => convert to thermal gradient of 1.7±0.4°C/km
  - => Possible effect of PKT thermal anomaly (~1.4°C/km from Laneuville et al., 2013)



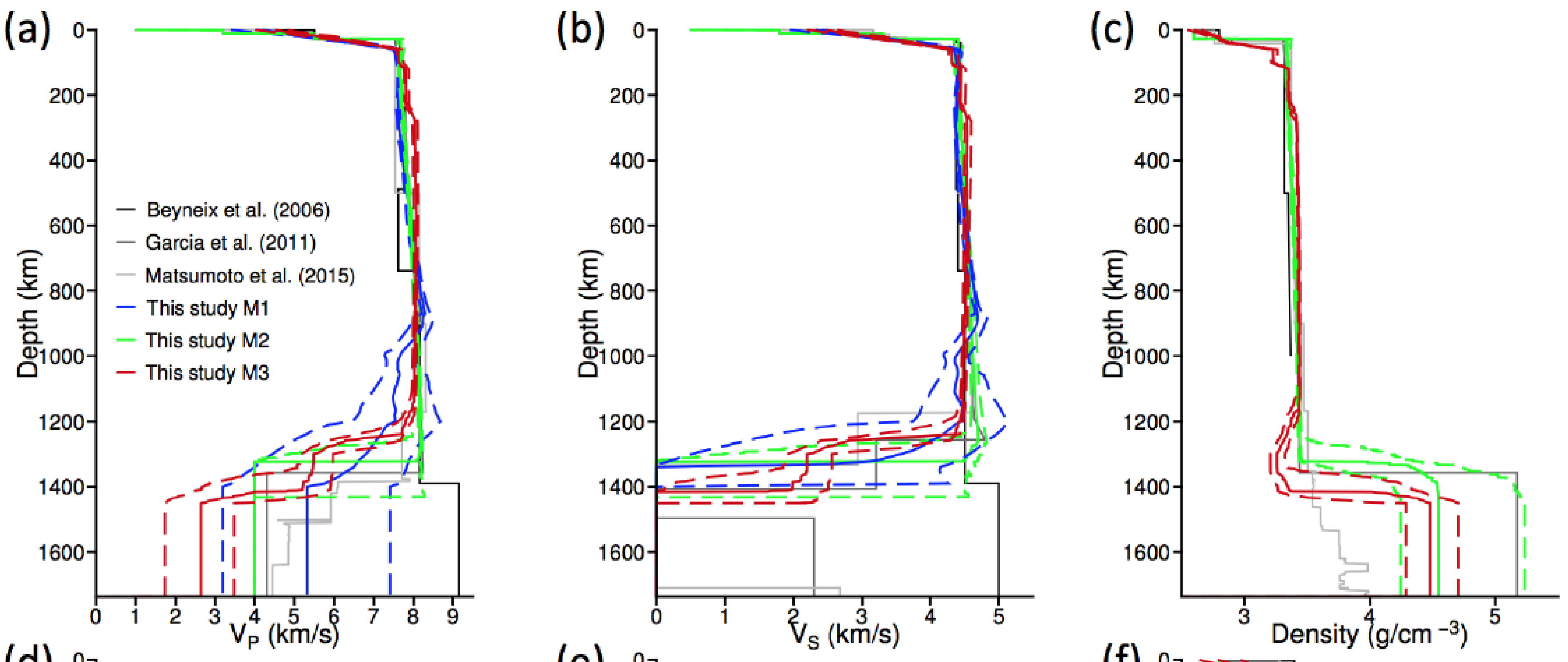
Inversion of new processed data set

- Comparison of models (lower mantle) :
  - M1 (blue) and M3 (red) present a strong P and S velocity decrease at the base of the mantle, but still not able to fit large distance S wave arrival times
  - M2 (green) has a similar data fit without this feature



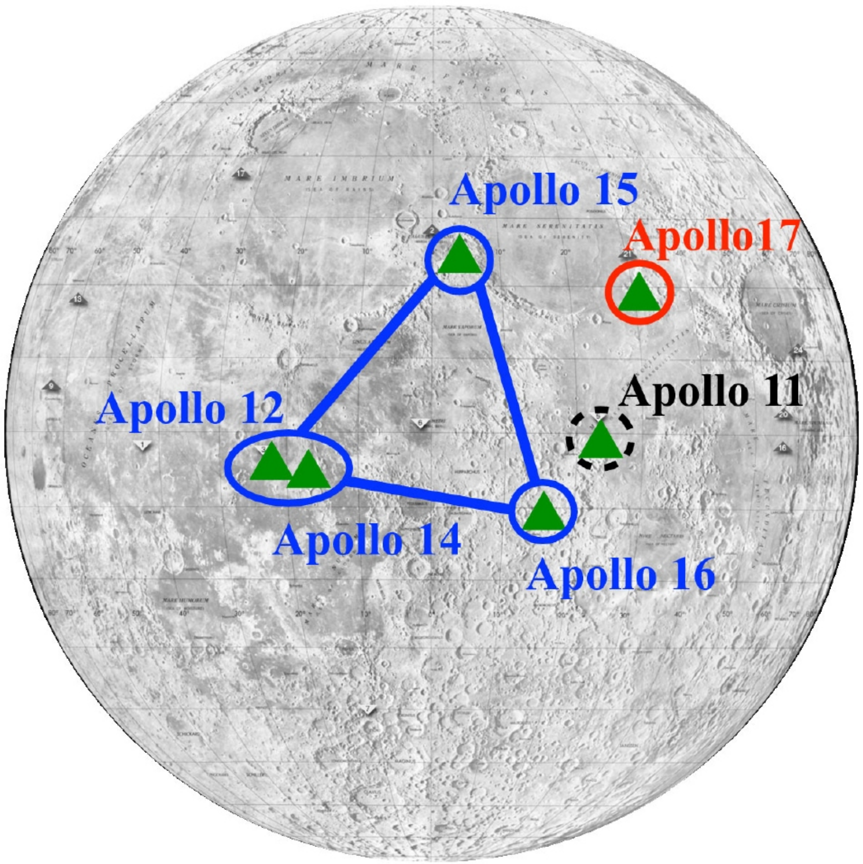
Inversion of new processed data set

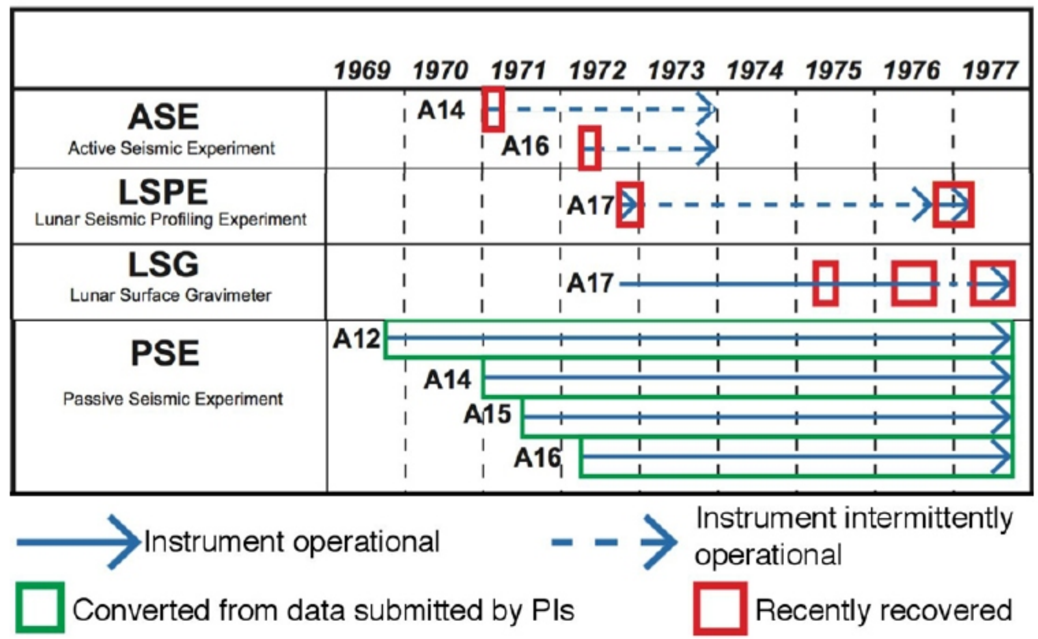
- Comparison of models (core) :
  - No constraint on core radius without core interacting phases (except may be some core diffracted phases interpreted as P waves)
  - Similar core density for M2 and M3 (~4500 kg/m³) despite different mantle profiles and core radius



Apollo instrumentation and limitations

- Limitations induced by Apollo Seismic Experiments :
  - Coverage concerns only a small part of the Moon (near side)
  - Proper data storage but duration limited (stopped in 1977)





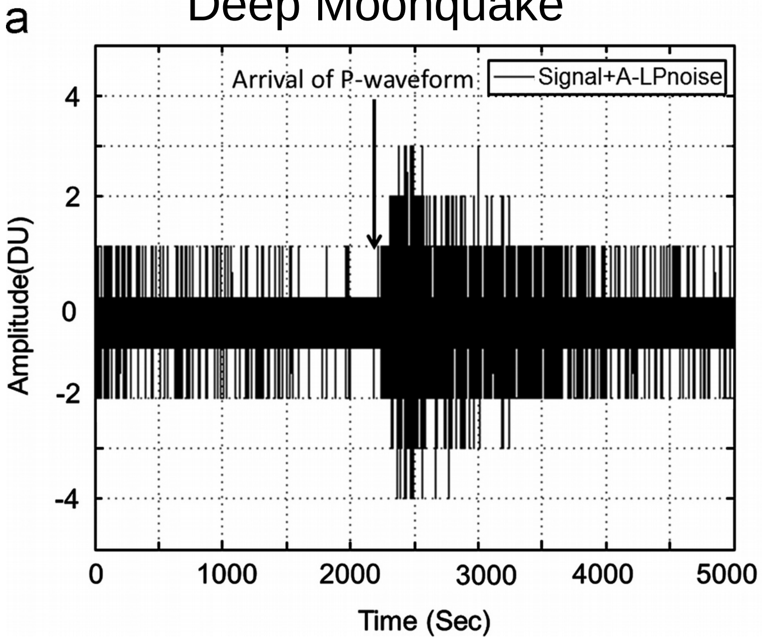
Nunn et al., SSR, 2020

Apollo instrumentation and limitations

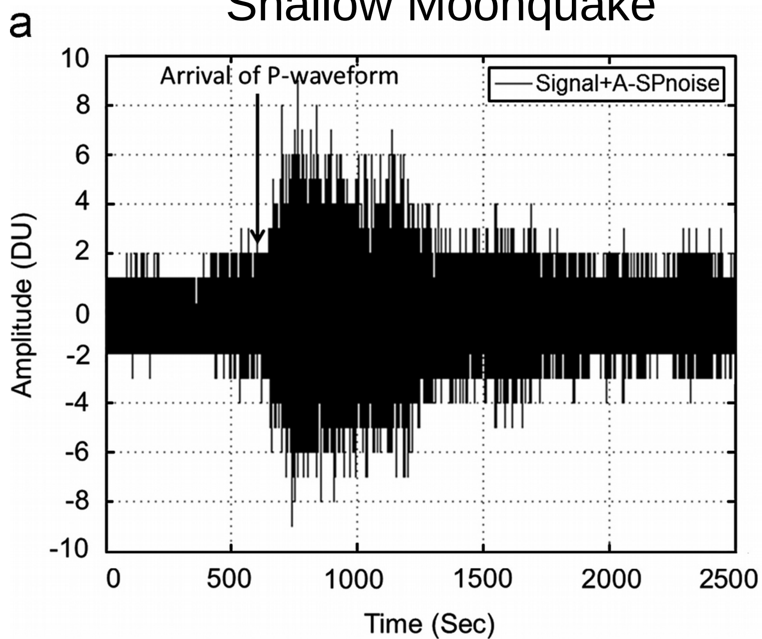
- Limitations induced by Apollo instrumentation :
  - First A/D => signals on 11 bits
  - Bandwidth limited by “peaked mode” on ALSEP data (0.3-1.5 Hz) and up to
  - Noise level does not allow to reach the background seismic noise

Examples of Apollo seismometers Records
Yamada et al., 2013

Deep Moonquake



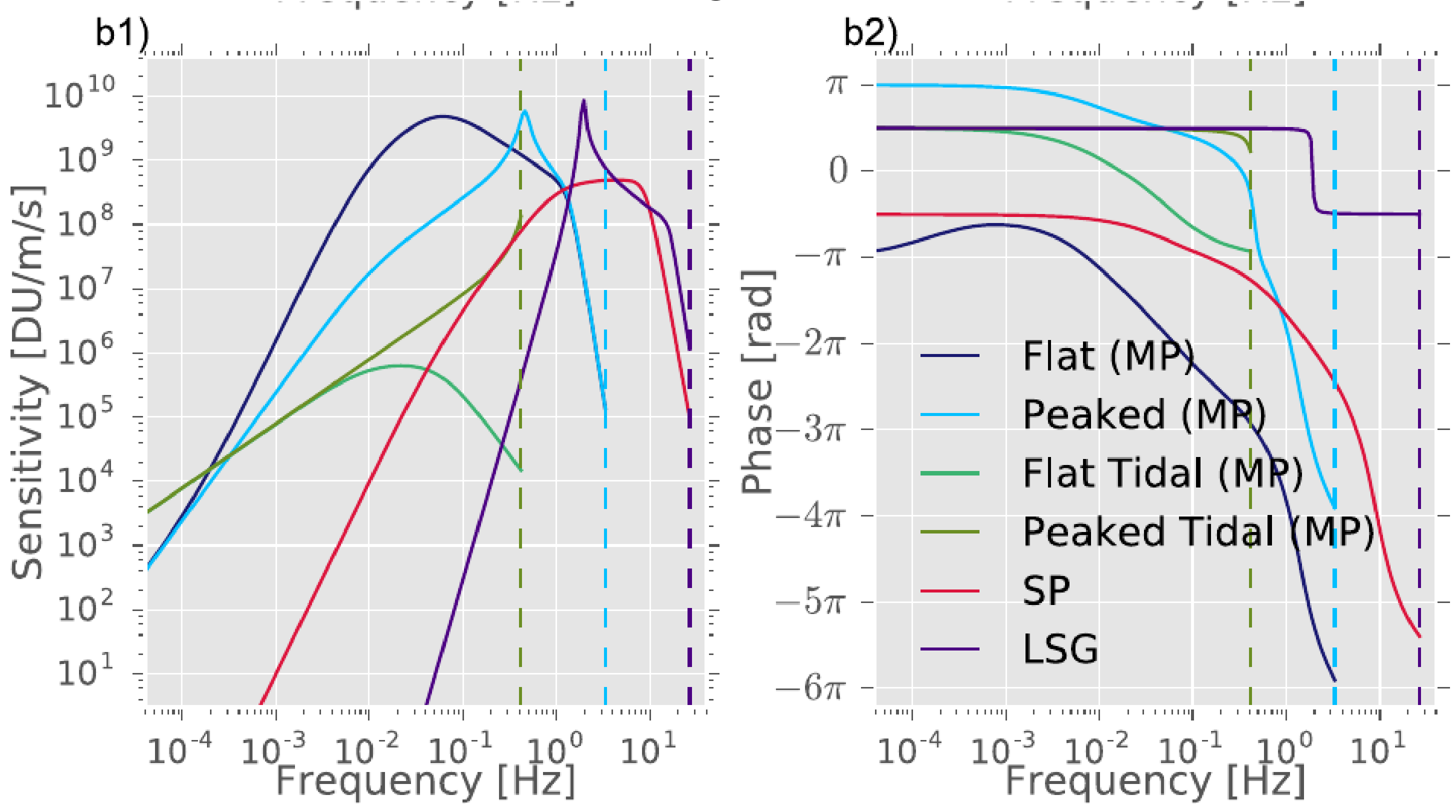
Shallow Moonquake



Apollo instrumentation and limitations

- Limitations induced by Apollo instrumentation :
  - First A/D => signals on 11 bits
  - Bandwidth limited by “peaked mode” on ALSEP data (0.3-1.5 Hz) and up to 8 Hz for Short period sensors
  - Noise level does not allow to reach the background seismic noise

Transfer functions
Apollo seismometers
Nunn et al., 2020



Apollo instrumentation and limitations

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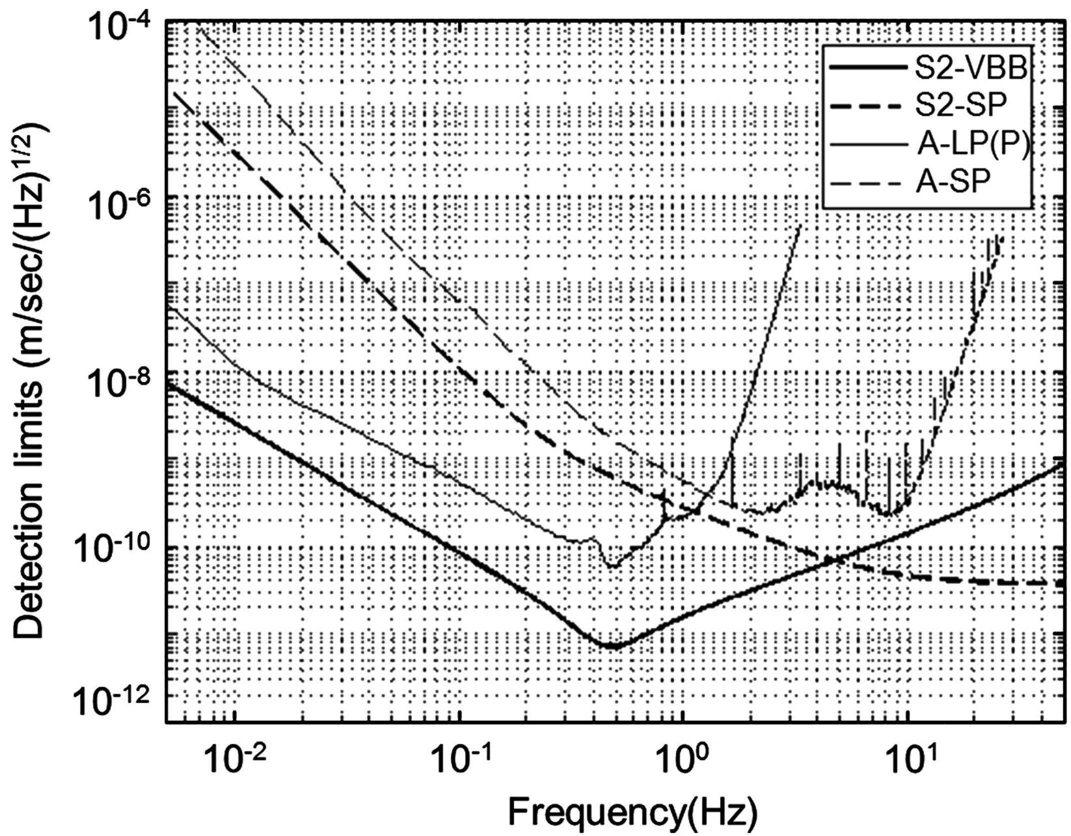
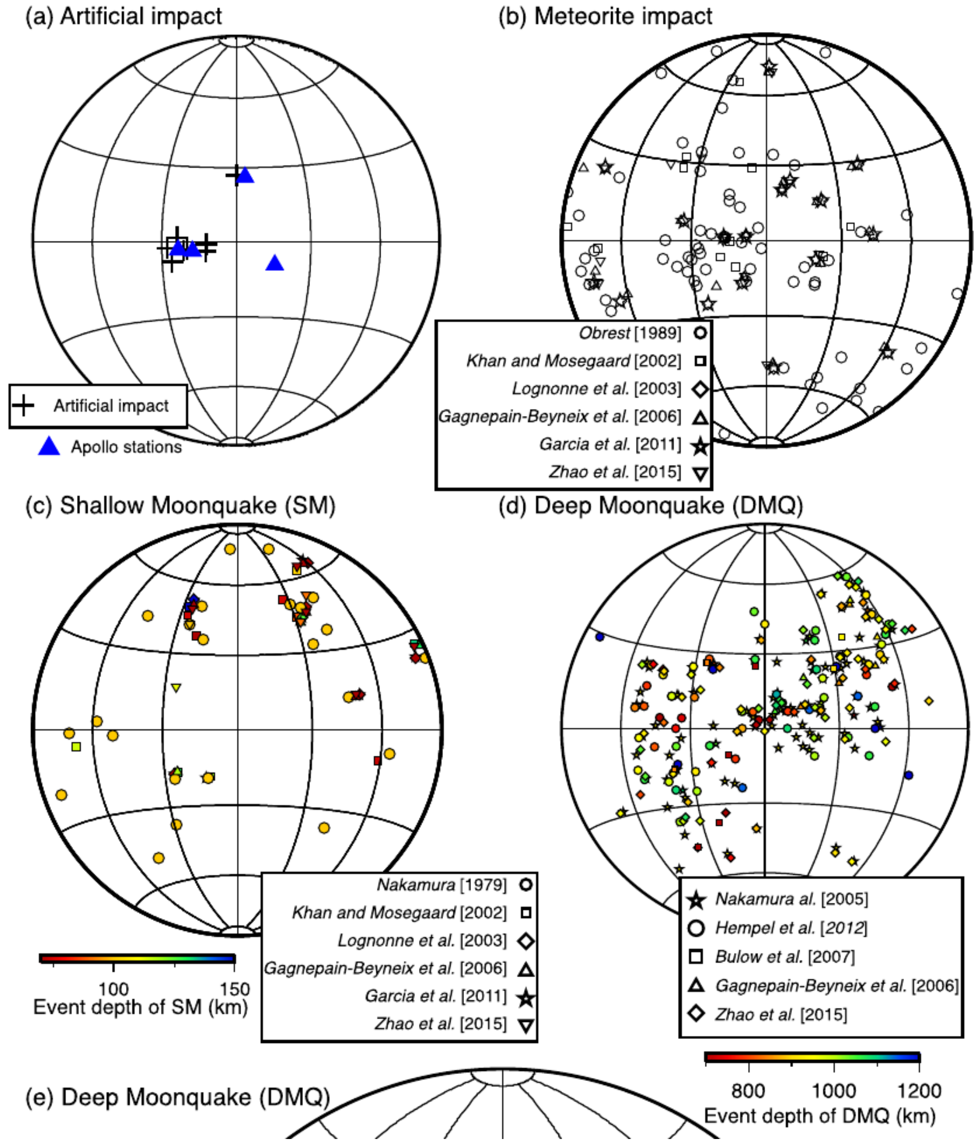
Noise levels of Apollo sensors
And sensors planned for FSS
Yamada et al., 2013



Moon seismicity

- Various types of seismic events :
  - Man-made impacts
    (Lunar module, Saturn V stage 4)
  - Natural impacts
    (more than 10 000 detected)
  - Shallow quakes
    (depth<50 km, magnitudes up to 4.5)
  - Deep Moonquakes
    (900 km < depth < 1200 km)

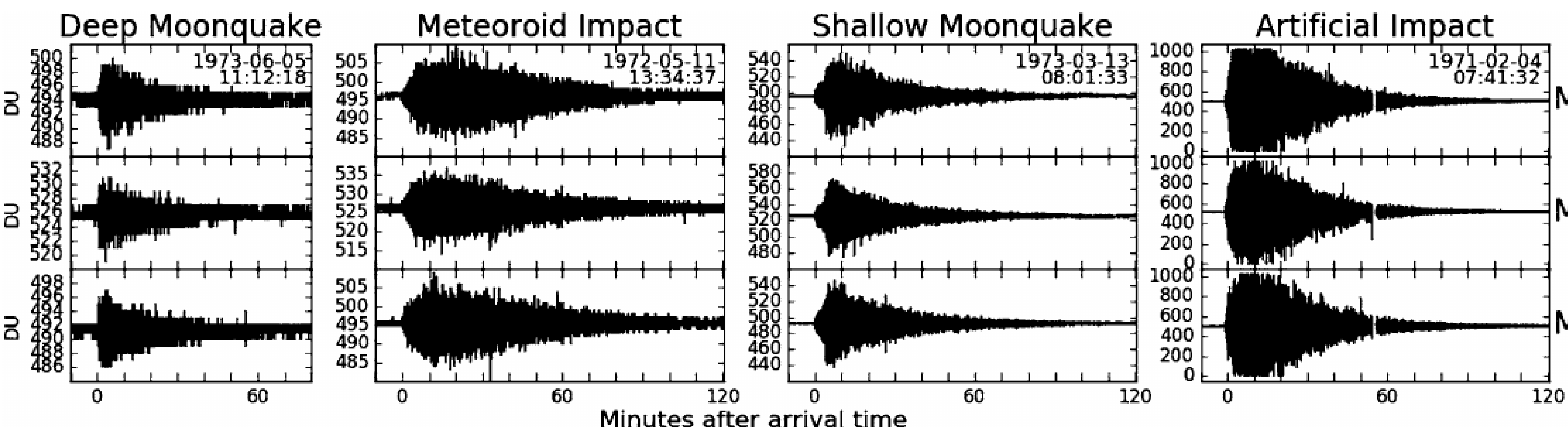


Garcia et al. 2019

Moon seismic signals

- Particularities of the Moon seismic signals :
  - Due to very low attenuation, the Moon is ringing during hours after an event
  - However small seismic magnitudes or impacts excite mainly frequencies above 0.2 Hz

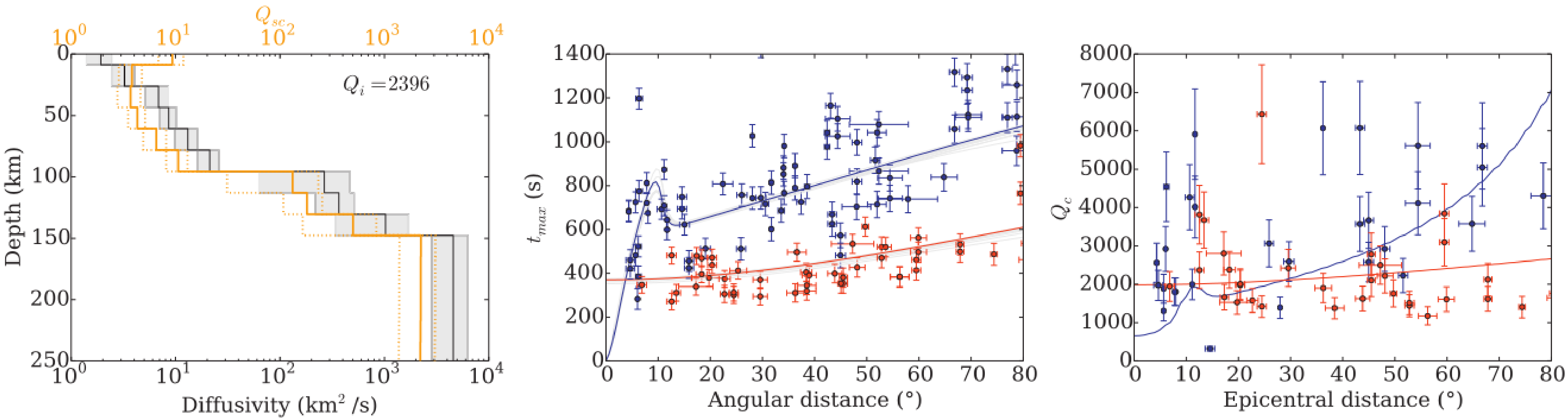
Examples of Apollo seismometers Records
Nunn et al., 2020



Moon seismic signals

- Particularities of the Moon seismic signals :
  - Due to very low attenuation, the Moon is ringing during hours after an event
  - However small seismic magnitudes or impacts excite mainly frequencies above 0.2 Hz
  - Due to high scattering the seismic wavefield is fully diffuse. Waves propagate on paths longer than Moon radius, and are scattered mainly in the crust and upper mantle.

Scattering properties in the Moon
Gillet, Margerin et al., 2017



Moon seismicity – Shallow events

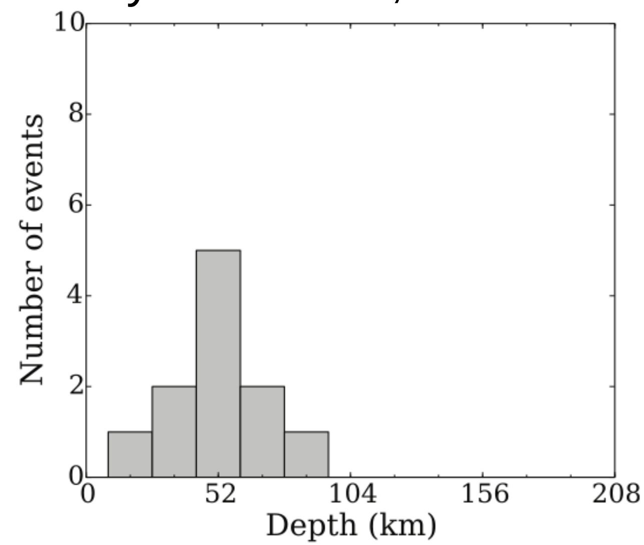
- Events probably related to the contraction of the Moon
- Present large stress drops and depths < 100 km
- Make the Moon ringing on hours time scale

Oberst et al 1987

TABLE 5. Shallow Moonquake Source Parameters

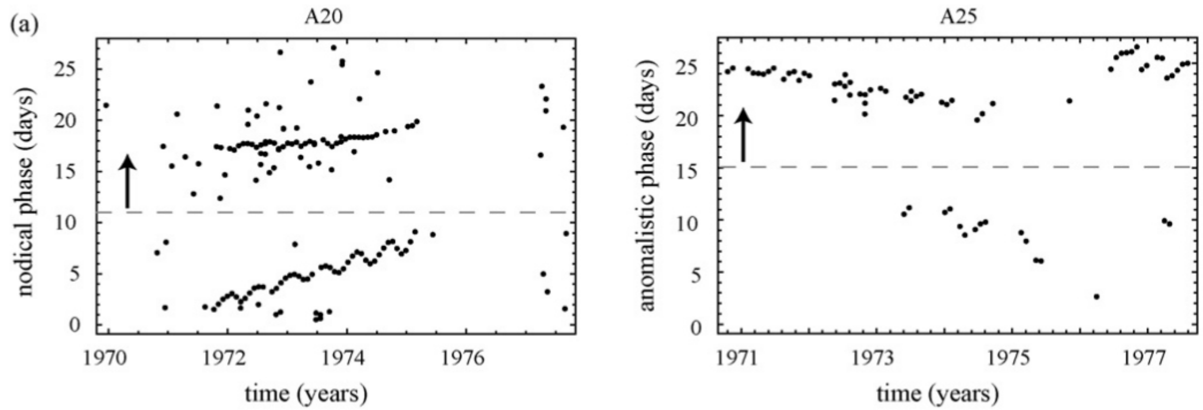
Year	Day	Minimum Corner Frequency, Hz	Seismic Moment, Nm	Energy Release, J	Stress Drop, MPa	Body Wave Magnitude
1971	107	> 12	4.4×10^{14}	> 9.2×10^{11}	> 100	> 5.5
	140	> 12	6.6×10^{13}	> 2.1×10^{10}	> 15	> 4.8
	192	> 8	5.2×10^{13}	> 3.8×10^{9}	> 3	> 4.5
1972	2	> 10	2.3×10^{14}	> 1.5×10^{11}	> 30	> 5.1
	261	> 10	1.1×10^{13}	> 3.4×10^{8}	> 1.5	> 4.0
	341	> 10	1.9×10^{13}	> 1.0×10^{9}	> 2.5	> 4.2
	344	> 8	1.2×10^{13}	> 1.9×10^{8}	> 1	> 3.9
1973	39	> 8	5.5×10^{12}	> 4.3×10^{7}	> 0.5	> 3.7
	72	> 12	6.6×10^{14}	> 2.1×10^{12}	> 150	> 5.6
	171	> 12	1.3×10^{14}	> 8.0×10^{10}	> 30	> 5.0
	274	> 8	3.4×10^{13}	> 1.6×10^{9}	> 2	> 4.3
1974	54	> 8	4.7×10^{12}	> 3.1×10^{7}	> 0.3	> 3.6
	86	> 8	1.5×10^{13}	> 3.3×10^{8}	> 1	> 4.0
	109	> 8	1.0×10^{13}	> 1.5×10^{8}	> 0.5	> 3.9
	149	> 8	6.3×10^{13}	> 5.6×10^{9}	> 4	> 4.6
	192	> 12	2.5×10^{14}	> 3.0×10^{11}	> 55	> 5.3
1975	3	> 10	1.6×10^{15}	> 6.9×10^{12}	> 210	> 5.8
	12	> 12	1.1×10^{14}	> 5.8×10^{10}	> 25	> 5.0
	13	> 12	1.0×10^{13}	> 5.3×10^{8}	> 2.5	> 4.1
	44	> 12	1.9×10^{13}	> 1.8×10^{9}	> 4	> 4.3
	127	> 10	2.9×10^{13}	> 2.4×10^{9}	> 4	> 4.4
	147	> 10	2.3×10^{13}	> 1.5×10^{9}	> 3	> 4.3
	314	> 12	4.8×10^{13}	> 1.1×10^{10}	> 10	> 4.7
1976	4	> 10	4.2×10^{13}	> 5.0×10^{9}	> 5	> 4.5
	12	> 10	1.1×10^{14}	> 3.6×10^{10}	> 15	> 4.9
	66	> 10	3.0×10^{14}	> 2.6×10^{11}	> 40	> 5.3
	68	> 12	5.6×10^{13}	> 1.5×10^{10}	> 13	> 4.7
	137		1.3×10^{13}			

Re-estimate of shallow Moonquakes depths By Gillet et al., 2017

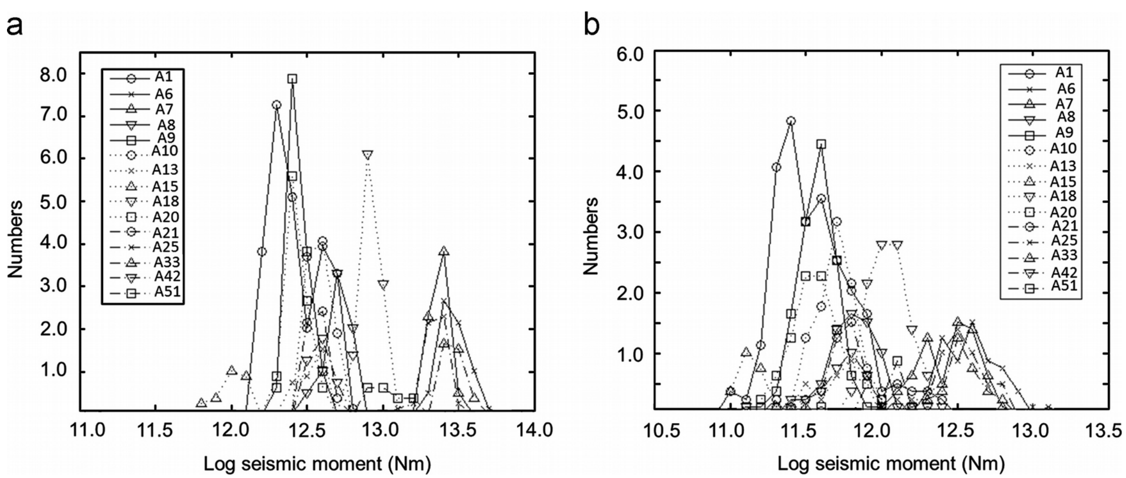


Moon seismicity – Deep Moonquakes

- Repeating in clusters at a given same position (at km scale)
- Repeating with a period linked to the Earth's tidal forces
- Very low magnitude



Weber et al., 2010

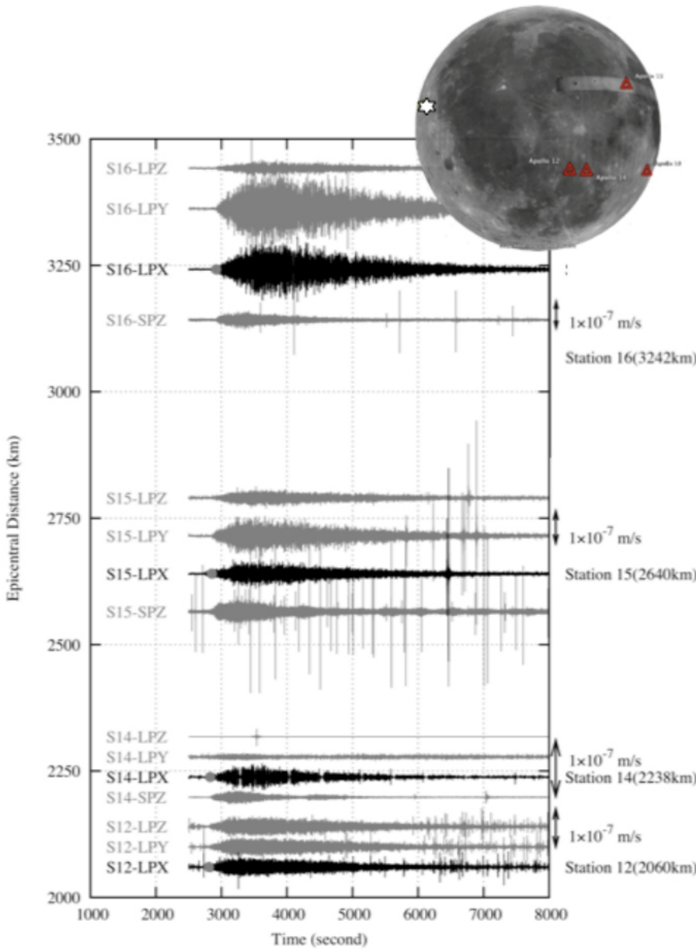


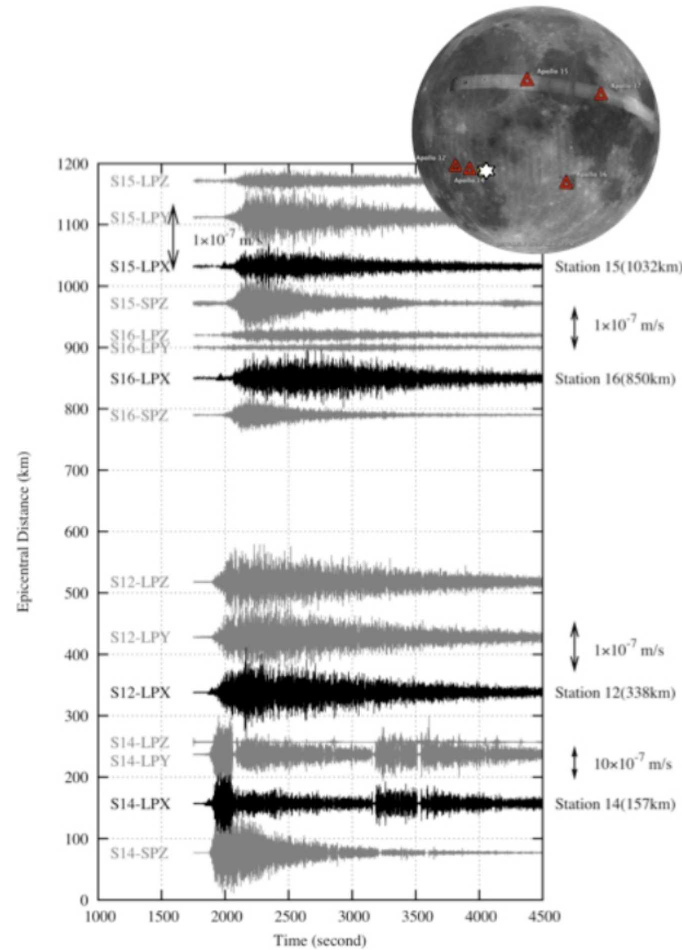
Yamada et al., 2013

Moon seismicity – Natural impacts

- High number of impacts detected

Examples of impact records from Lognonné and Kawamura 2015

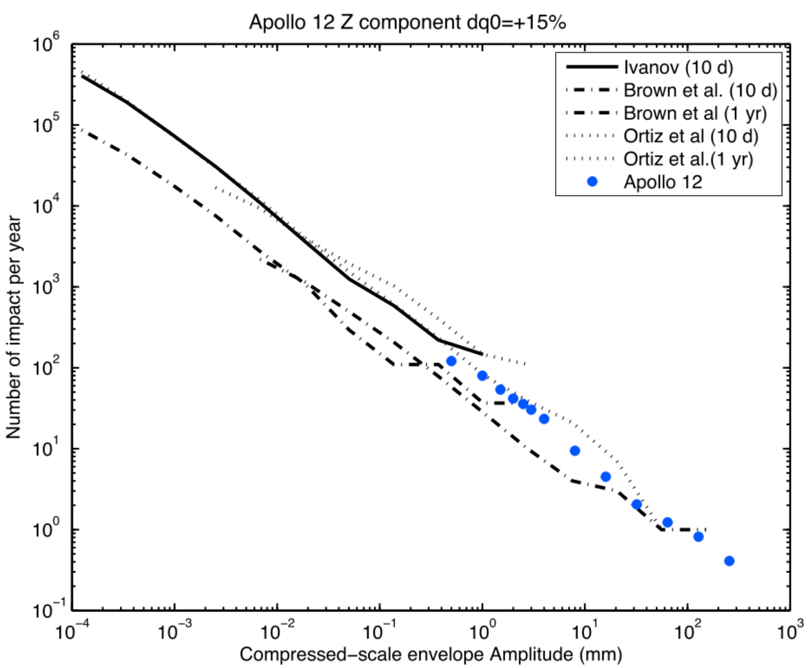




Moon seismic background noise : impacts

- Global seismic background noise is thought to be dominated by micro-meteorite impacts

Estimates of global seismic background Noise by Lognonné et al. (2009)



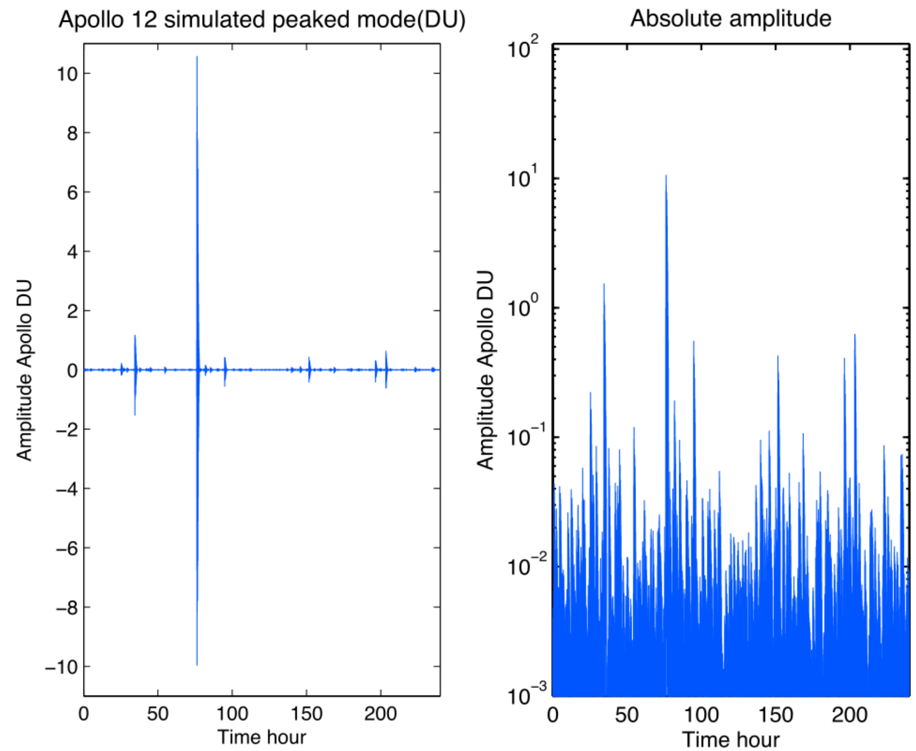


Figure 15. Composite waveform for impacts simulated using the Brown model. The duration of each waveform (corresponding to an individual impact) summed is 1 h, while the plot shows 10 days of signal. (left) The computed seismogram in Apollo DU. (right) The absolute value of the seismogram, on a logarithmic scale.

Moon seismic background noise : thermal cracks

- Local seismic background noise is dominated by thermal cracks occuring mainly during the cooling phase

Observed background noise variations from Apollo geophones (1-10 Hz range)

Tanimoto et al., 2008

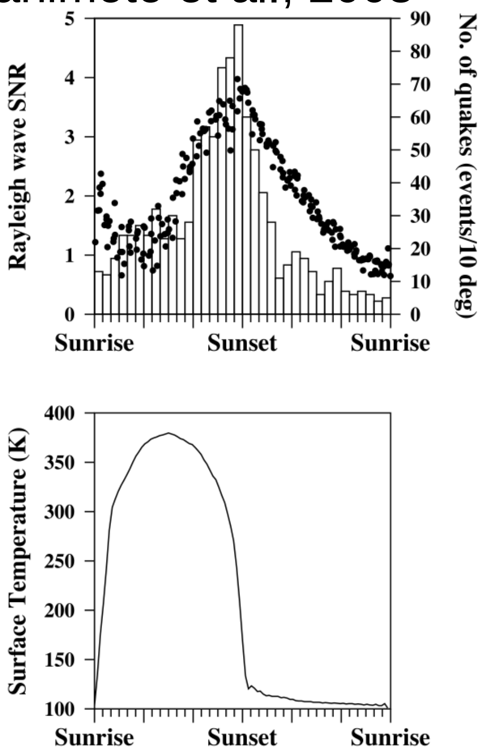


Figure 14. (top) Variation of Rayleigh wave amplitude (solid) and the statistics of thermal moonquakes [*Duennebier*, 1976]. Both data peak at sunset. (bottom) Surface temperature for the diurnal cycle.

Sens-schonfelder and Larose, 2010

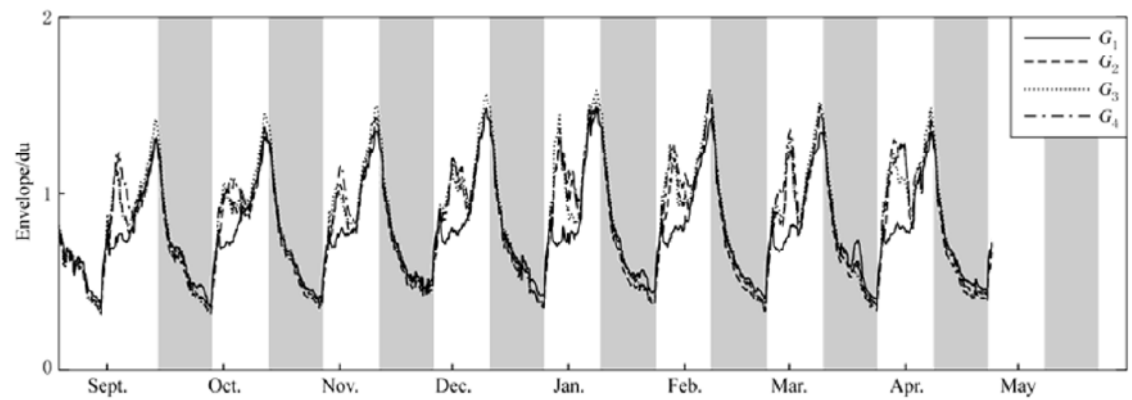


Figure 3 Envelopes of the continuous seismic records of the four geophones in the Apollo 17 short period network. Scale is in digital units of the raw traces. Shaded background indicates lunar night. Note the difference between the geophones in the morning and the high similarity during afternoon and night of the lunation.

Conclusions

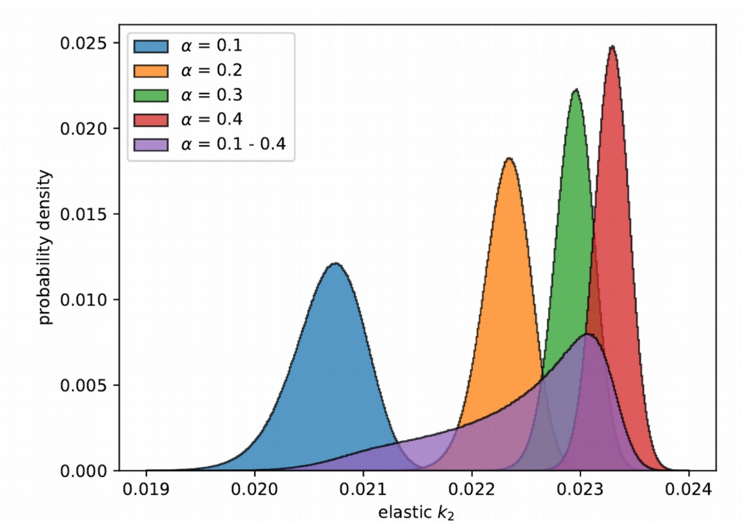
- Internal structure of the Moon and seismicity are quite well constrained by Apollo data
- But...
  - Deep mantle and core still debated
  - Farside seismicity remains mainly unknown
  - Seismic signals below 0.2 Hz not quantified
  - Seismic background noise is not measured except for local thermal cracks above 1 Hz
- However new seismic deployments are planned
  - Farside Seismic Suite and Lunar Geophysical Network by NASA
  - Chang’e 7 will include a seismometer
  - Various projects on ESA side but still in phase zero
- And new seismic instruments are currently developed by PIONEERS EC project (https://h2020-pioneers.eu/)

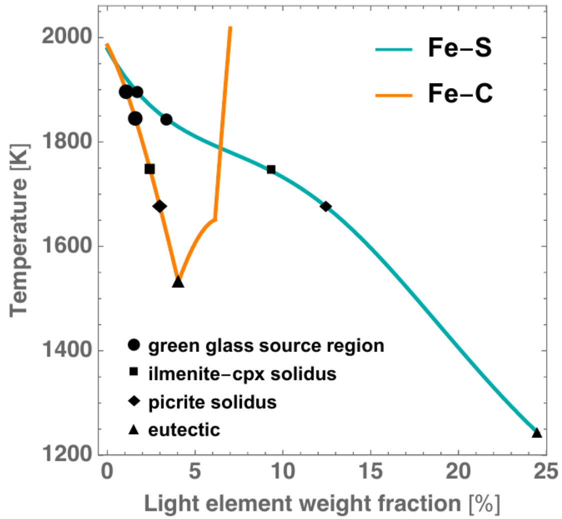
Back-up slides

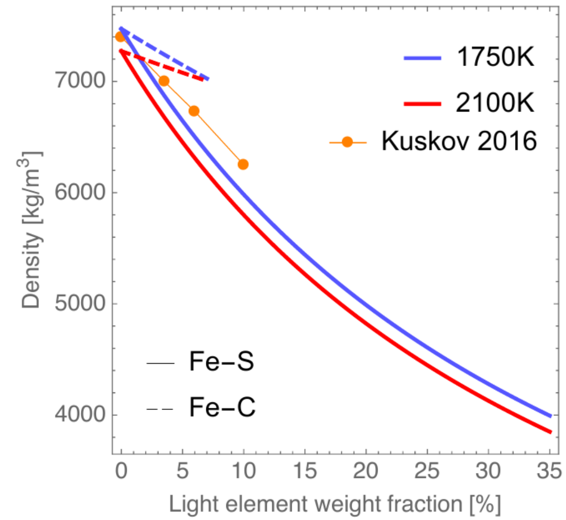
BACK-UP SLIDES

Review of a priori constraints on Moon internal structure

- In orbit imaging of seismic sources and receivers
- Geodetic constraints :
  - Crust density is critical for the Mass, MoI budget and thickness variations can be used to correct
  - Modeling error is dominating elastic k2 estimates
- HP/HT mineralogy experiments:
  - Constraint range of parameters for the core

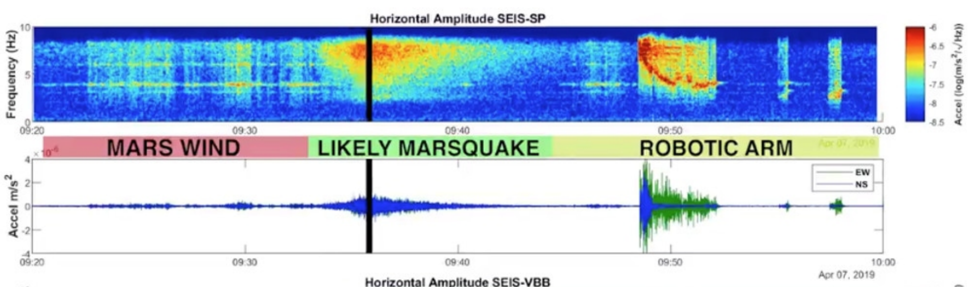


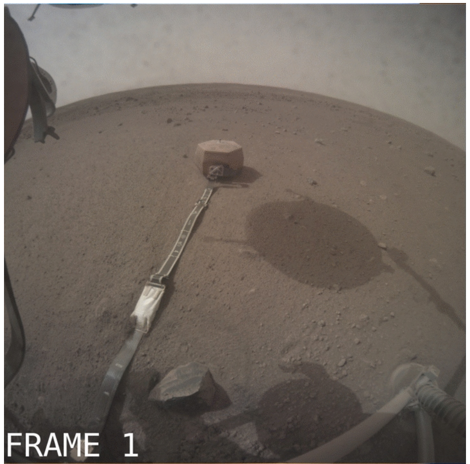




Conclusions

- Work done by the team :
  - New processed seismological data set for the Moon
  - Review of various a priori constraints
  - New models of Moon interior => upper mantle low velocity zone
  - Contributions to the debate on lower mantle structure
  - Low level requirements for future seismological deployments
- What's next?:
  - Include event relocation, redo search of core reflected phases
  - Need new deployments of broad band sensors far from Apollo network
- Happy New Planetary Seismology! (every 40 years)





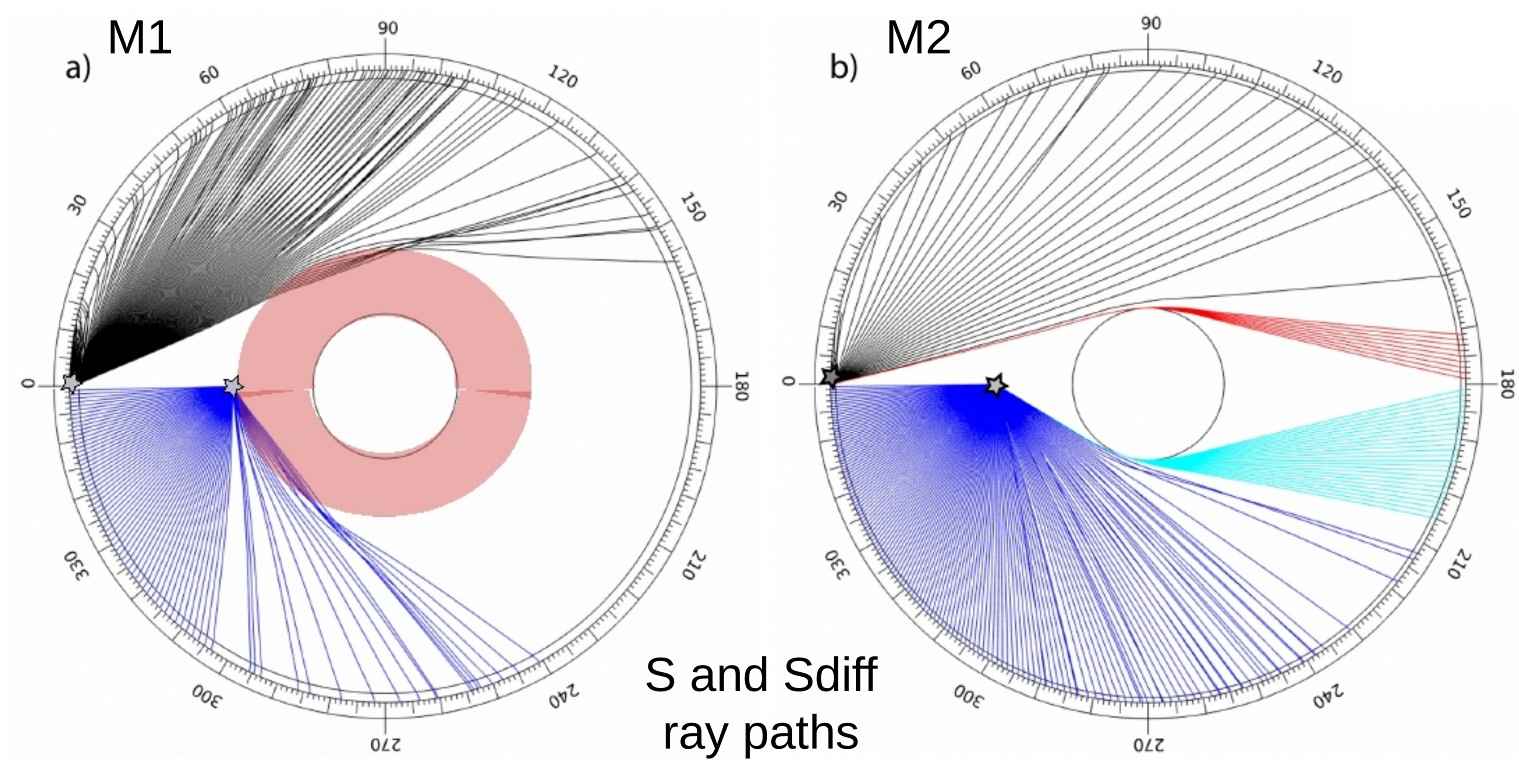
Debate on melt at the base of the mantle (1/2)

- Different seismological structure at the base of mantle (for sure) :
  - P wave arrivals are slightly delays
  - S wave arrivals present large delays but cannot be fit by models (outlayers)
  - Love numbers require a more soft layer at the base of the mantle
- Melt or no melt ?

Pros Melt	Cons Melt
Very low S wave velocities due to delayed large distance S waves	Lack of data fit demonstrate that these data are **outlayers**
Love numbers require a soft material at the base of the mantle	**Rheological models without melt** can explain the data (Nimmo et al., 2012)
No clear S wave arrivals at large distances implies a **strong attenuation at the base of the mantle**	A decrease of S wave velocities at mantle base generates a **shadow zone for S wave** above the core Or **S diffracted waves** have low amplitude

Debate on melt at the base of the mantle (2/2)

- About S wave velocity structure and S wave amplitude at large distance : 2 different models with similar effects
  - Low S wave velocities generate a shadow zone for S waves
  - A large core generate diffracted S waves which amplitude is decreasing quickly with distance



S and Sdiff ray paths

What’s next for the seismological constraints on the Moon core?

- With the current data set:
  - Large variability of crust and mantle models induces large error on core radius even if core reflected phases are detected
  - Whole Moon scattered waves should sample deep Moon structure => core shadow effect on coda waves?

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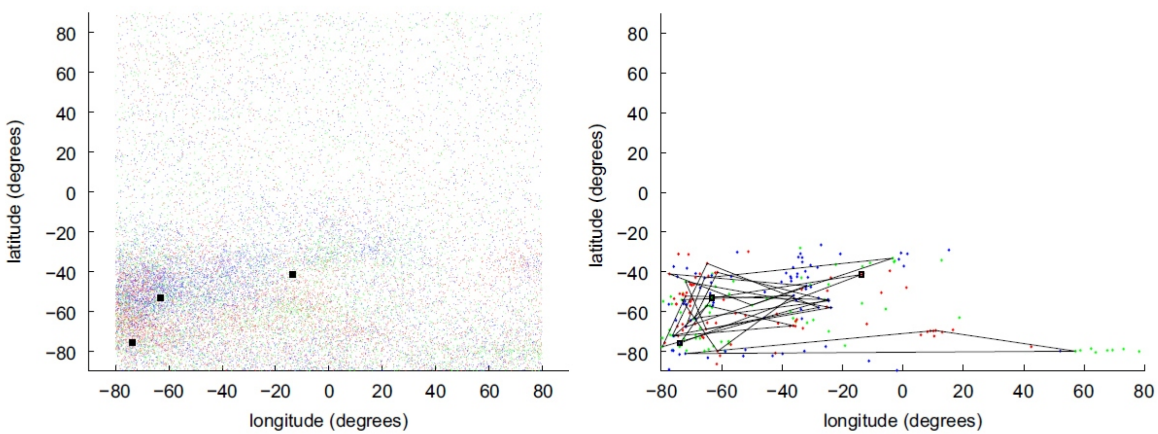
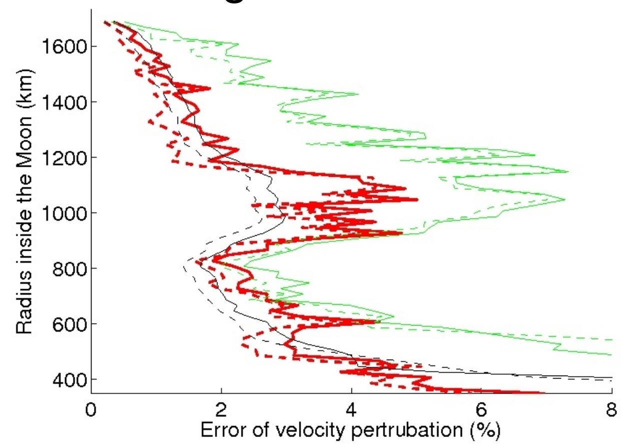
- With next seismic sensor deployments:
  - Same deep Moonquakes being active => virtually add a station to ALSEP
  - Best geometry for a station far from Apollo network (SPA or far side) (Yamada et al., 2011)

Best station locations for 3 stations



Adding a far side station



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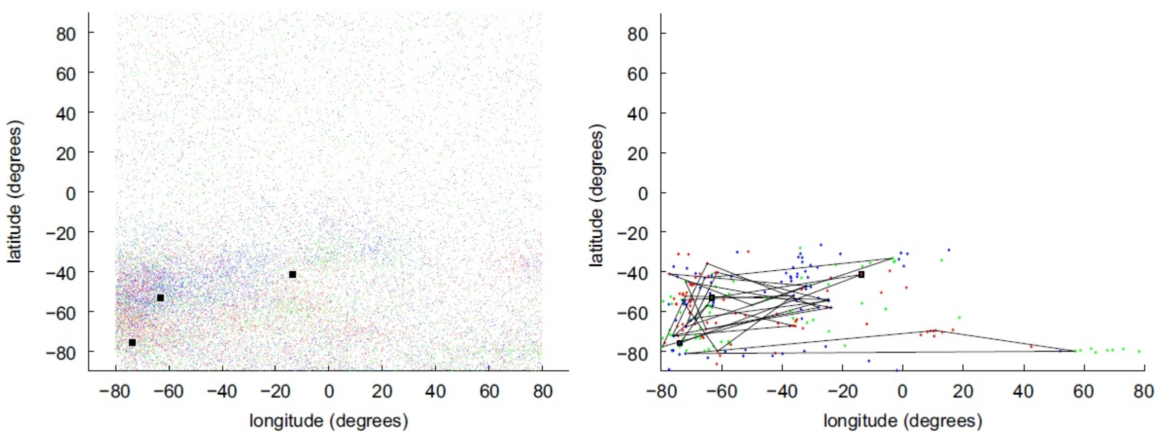

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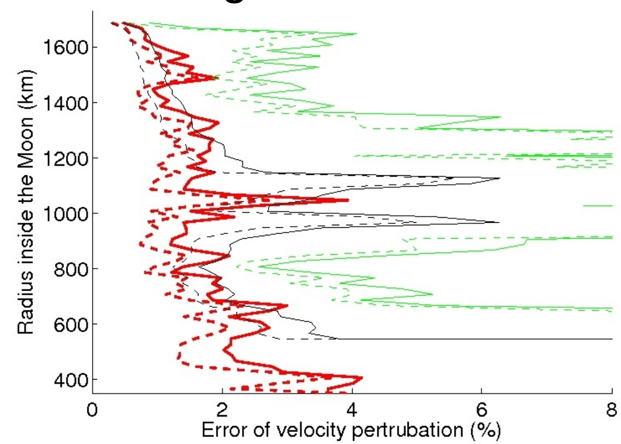


Recommendations and requirements for future missions

- Requirements to ensure inter-operability of future deployments :
  - Low level requirements flow down (scientific → station → instrument)
  - More at http://www.issibern.ch/teams/internstructmoon

L0 and L1 requirements

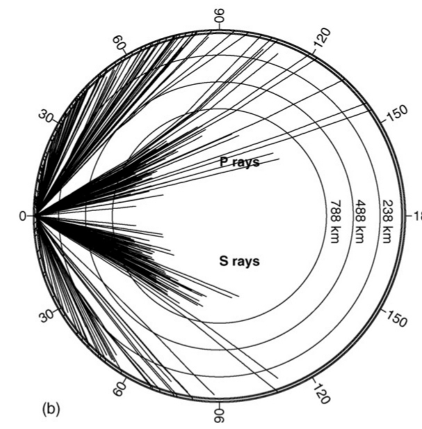
		OBJECTIVE	
	ILN-REQ-0	Interoperability of Stations for Network Analysis	Data from geophysical stations deployed on the Moon must allow an international community of researchers to locate events, perform waveform analysis and develop structural models.
		SCIENTIFIC AIMS	
ILN-REQ-0	ILN-REQ-0.1	Source Timing	The origin time of geophysical events detected by the seismic network must be recovered with an accuracy better than the sampling rate of the recording stations.
ILN-REQ-0	ILN-REQ-0.2	Source Location	The source location of geophysical events detected by the network must be recovered with an accuracy better than a quarter of the wavelength of the signals used to locate the source.
ILN-REQ-0	ILN-REQ-0.3	Source Energy	The energy of the source of geophysical events detected by the network must be recovered with an accuracy better than 20%.
ILN-REQ-0	ILN-REQ-0.4	Source Radiation	The radiation pattern of the geophysical sources detected by the network must be recovered with an accuracy better than 10°.
ILN-REQ-0	ILN-REQ-0.5	Data Access	Proper recording and archiving of all data and metadata is necessary to allow scientific analysis by an international community of researchers.
		STATION REQUIREMENTS	
ILN-REQ-0.1	ILN-REQ-1.1	Source timing: back propagated error level = X*dt	Time synchronization between stations must be provided with an accuracy that ensures that timing errors for the geophysical signals are smaller than the sampling rate of the sensor.
ILN-REQ-0.2	ILN-REQ-1.2	Source location: back propagated error level = X * max wavelength	Station information must be provided with an accuracy that ensures that the errors on the location of the source of geophysical signals are smaller than a quarter of a wavelength of the signal used for finding the location.
ILN-REQ-0.3	ILN-REQ-1.3	Source energy = X%	Characteristics of instruments deployed by the station must be provided with an accuracy ensuring that the errors on the estimate of the source energy are smaller than 20%.
ILN-REQ-0.4	ILN-REQ-1.4	Source radiation = X°	The orientation of the instruments must be provided with a precision ensuring that the errors on the estimate of the source radiation are smaller than 10°.
ILN-REQ-0.5	ILN-REQ-1.5	Data archiving and documentation	Data content, documentation, storage and archiving must ensure that an international community of researchers are able to understand these data and to implement research activities.

L2 requirements

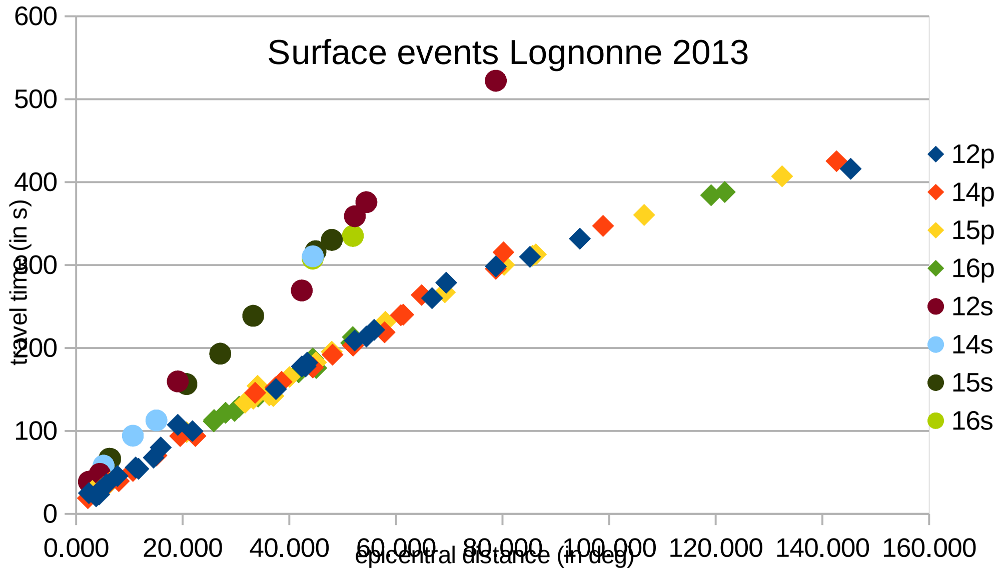
		INSTRUMENT REQUIREMENTS	
ILN-REQ-1.1; ILN-REQ-1.2	ILN-REQ-2.1	Time Stamp/Time Accuracy and Precision	Accuracy on the dating of the samples must be better than one tenth of the average sampling rate of the data channel.
ILN-REQ-1.1; ILN-REQ-1.2	ILN-REQ-2.2	Time Reference	Data samples must be provided in Coordinated Universal Time (UTC Time).
ILN-REQ-1.5	ILN-REQ-2.3	Sampling Rate	For a given data channel, data acquisition should be designed to be performed at constant sampling rate in the time reference of the instrument.
ILN-REQ-1.5	ILN-REQ-2.4	Format	Data and metadata must be provided in a format prescribed by the International Federation of Digital Seismograph Networks (FDSN) for the exchange of seismic data.
ILN-REQ-1.6	ILN-REQ-2.5	Units	Data must be provided in units of the international reference system (SI units).
ILN-REQ-1.3; ILN-REQ-1.5	ILN-REQ-2.6	Calibration Information	The amplitude of the instrument response must be provided with an accuracy better than 10% over the bandpass of the instrument during the entire lifetime of the instrument.
ILN-REQ-1.3; ILN-REQ-1.5	ILN-REQ-2.7	Calibration Information	The phase of the instrument response must be provided with an accuracy better than 10° over the bandpass of the instrument during the entire lifetime of the instrument.
ILN-REQ-1.5	ILN-REQ-2.8	Metadata and processing	Metadata must contain a description of all the processing steps from the physical unit to the digital (count) output of all data channels.
ILN-REQ-1.3; ILN-REQ-1.5	ILN-REQ-2.9	Compression/ Decompression	If lossy compression is applied, it should allow signal reconstruction with an accuracy better than 10% of the signal energy.
ILN-REQ-1.3; ILN-REQ-1.5	ILN-REQ-2.10	Aliasing	The instrument must be designed so that less than 0.1% of the signal above the Nyquist frequency is aliased in the bandpass of the instrument.
ILN-REQ-1.5	ILN-REQ-2.11	Noise Estimates	Sensor and instrument noise must be estimated over the bandpass of the instrument and provided for each seismic channel in $m/s^2/\sqrt{(Hz)}$.
ILN-REQ-1.5	ILN-REQ-2.12	Archiving	Data and metadata for all the instrument channels must be archived both in planetary databases and in geophysical sensor databases.
ILN-REQ-1.5	ILN-REQ-2.13	Naming	A network code and a station code must be assigned to the geophysical station by the International Federation of Digital Seismograph Networks (FDSN).
ILN-REQ-1.2; ILN-REQ-1.5	ILN-REQ-2.14	Station Location	The station location must be provided in a standard reference system defined by the International Astronomical Union (IAU).
ILN-REQ-1.2	ILN-REQ-2.15	Station Location	The station location coordinates must be provided with an accuracy better than 25 m.
ILN-REQ-1.4	ILN-REQ-2.16	Axis Orientation	The sensing direction of the instrument data channels must be provided with an accuracy better than 10°.
ILN-REQ-1.5	ILN-REQ-2.17	Operations	Mission, platform and instrument operation activities impacting the signals above instrument noise level must be time-stamped, recorded and archived in the metadata for the instrument.

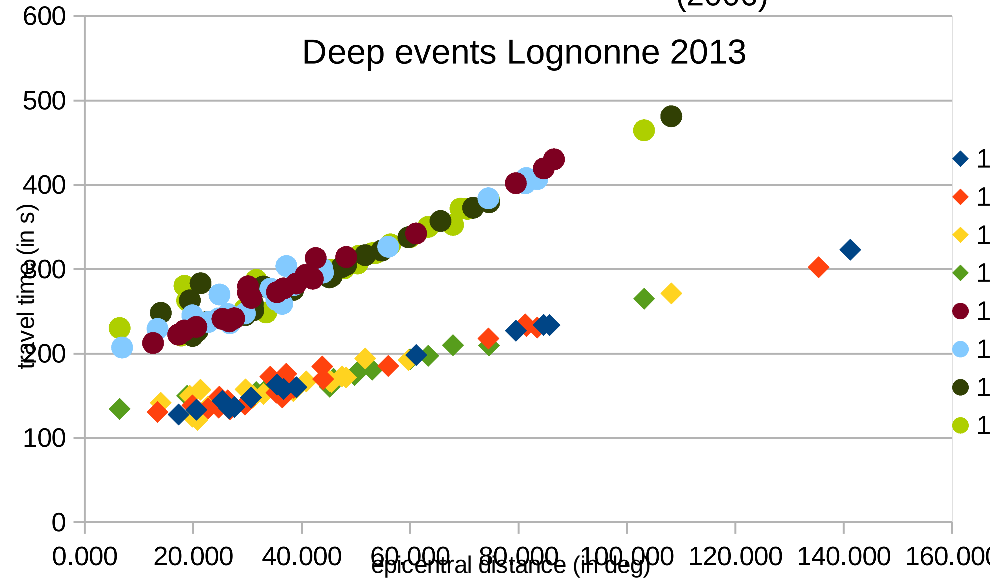
Comparison of seismic body waves arrival times measurements

- Body wave arrival times are the main constraints on seismic structure AND seismicity
- Evaluation of their error bars is critical to known error on seismic model



Beyneix, et al. (2006)





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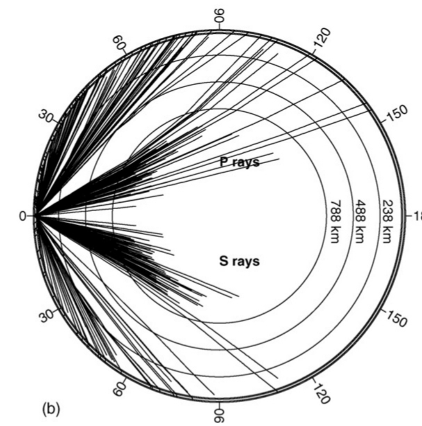
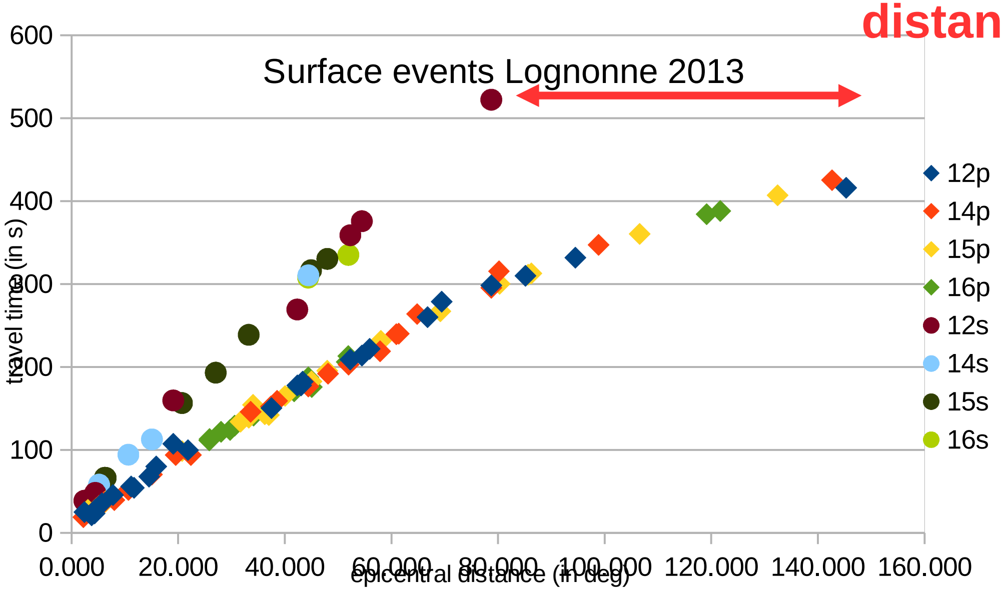
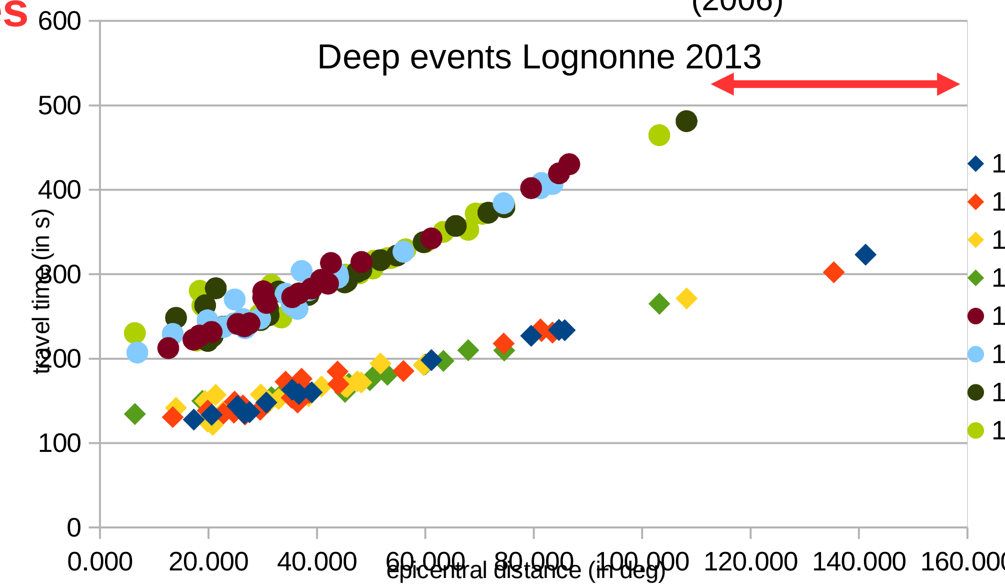


Beyneix, et al. (2006)

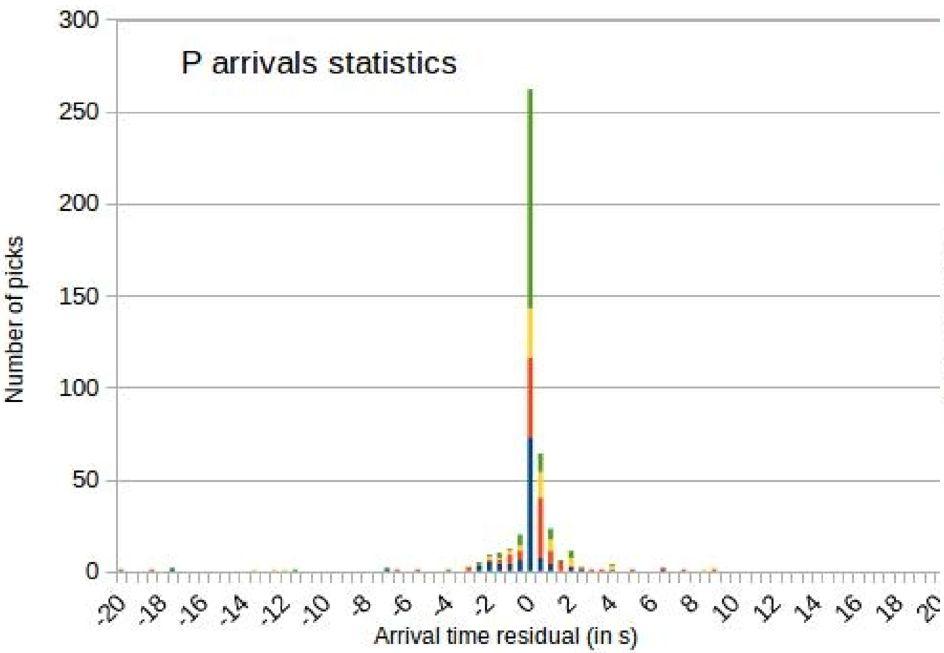
No deep S waves at large distances

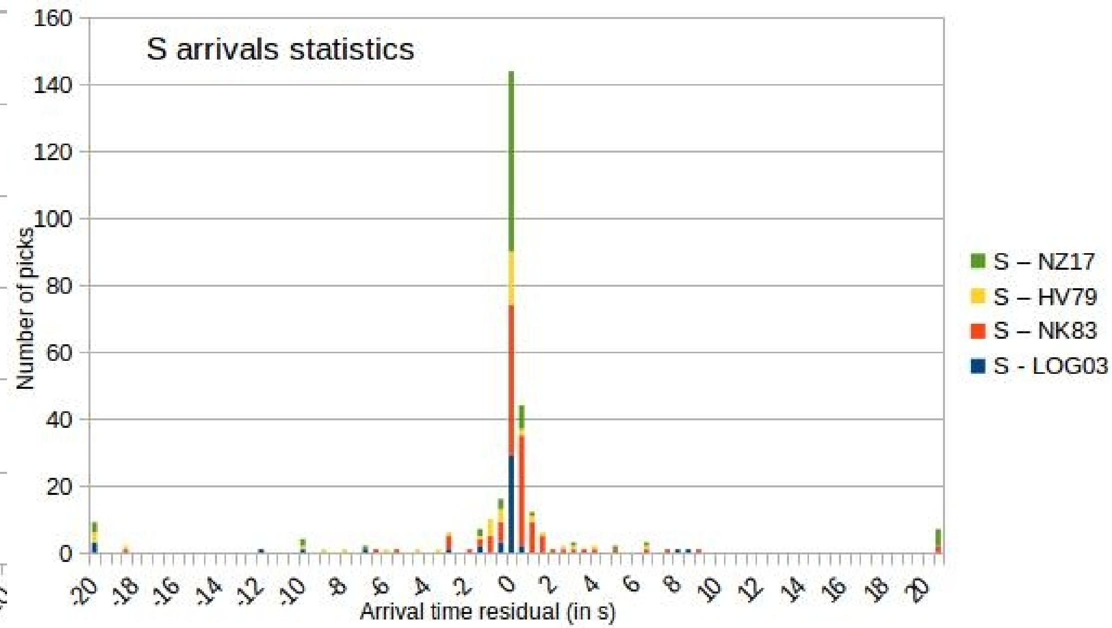




Comparison of seismic body waves arrival times measurements

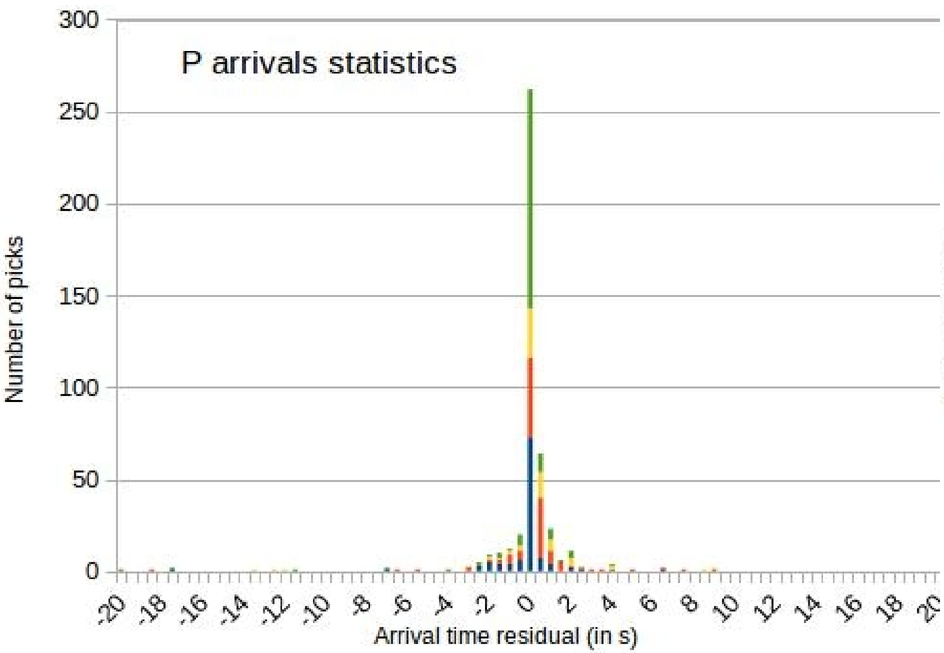
- P and S arrival times present a poisson statistics (relative to median) with a dispersion < 2s

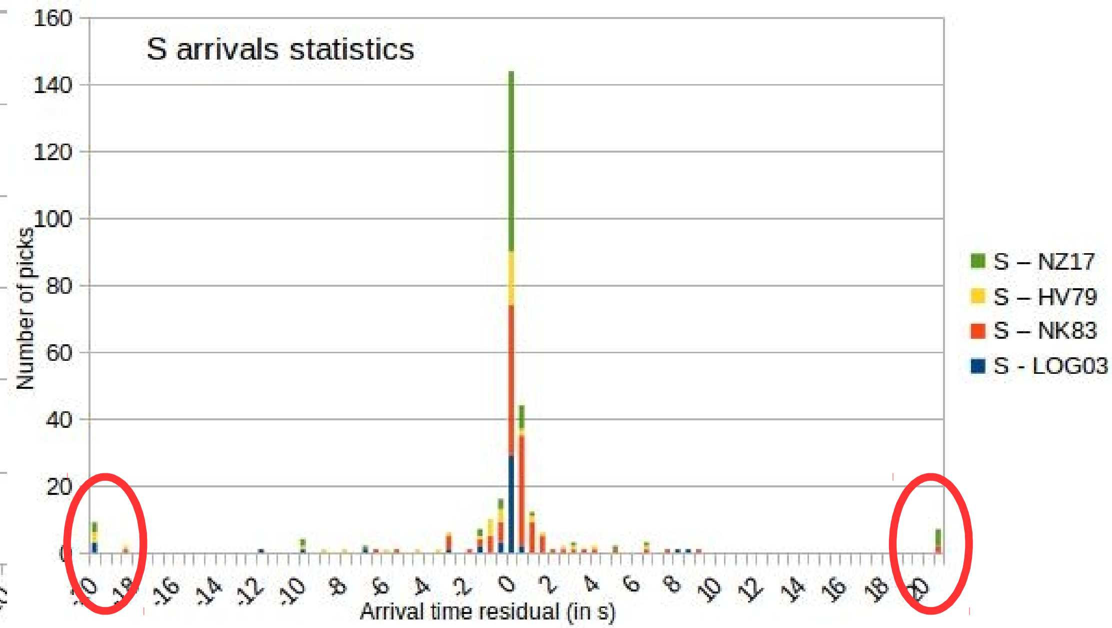




Comparison of seismic body waves arrival times measurements

- P and S arrival times present a poisson statistics (relative to median) with a dispersion < 2s
- Outlayers on S wave arrivals due to arrivals in coda

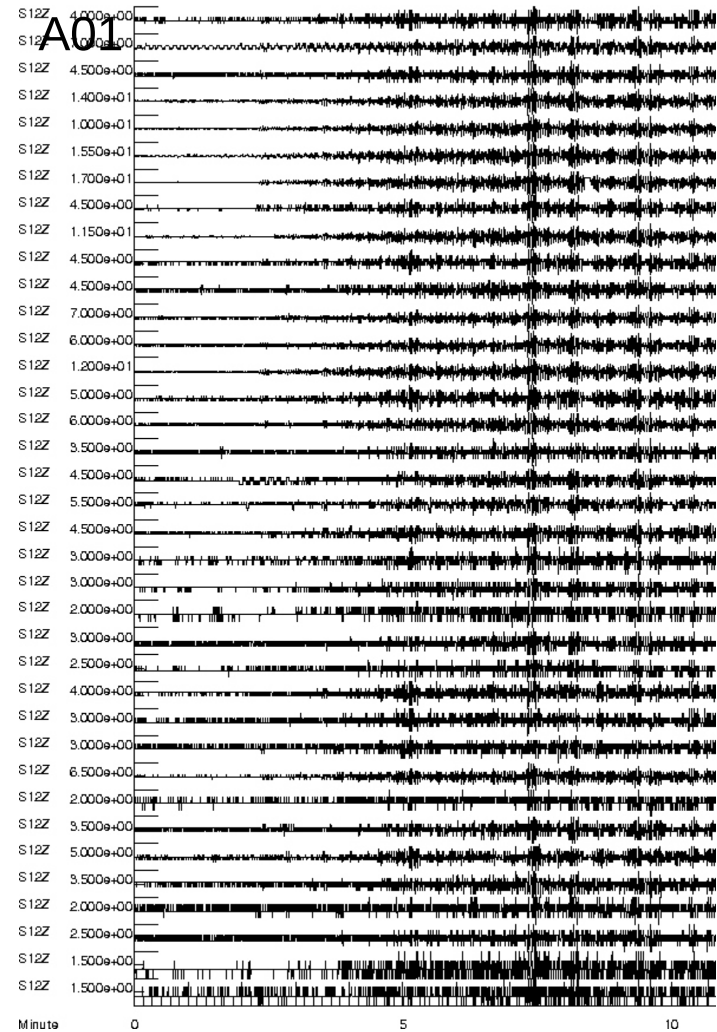




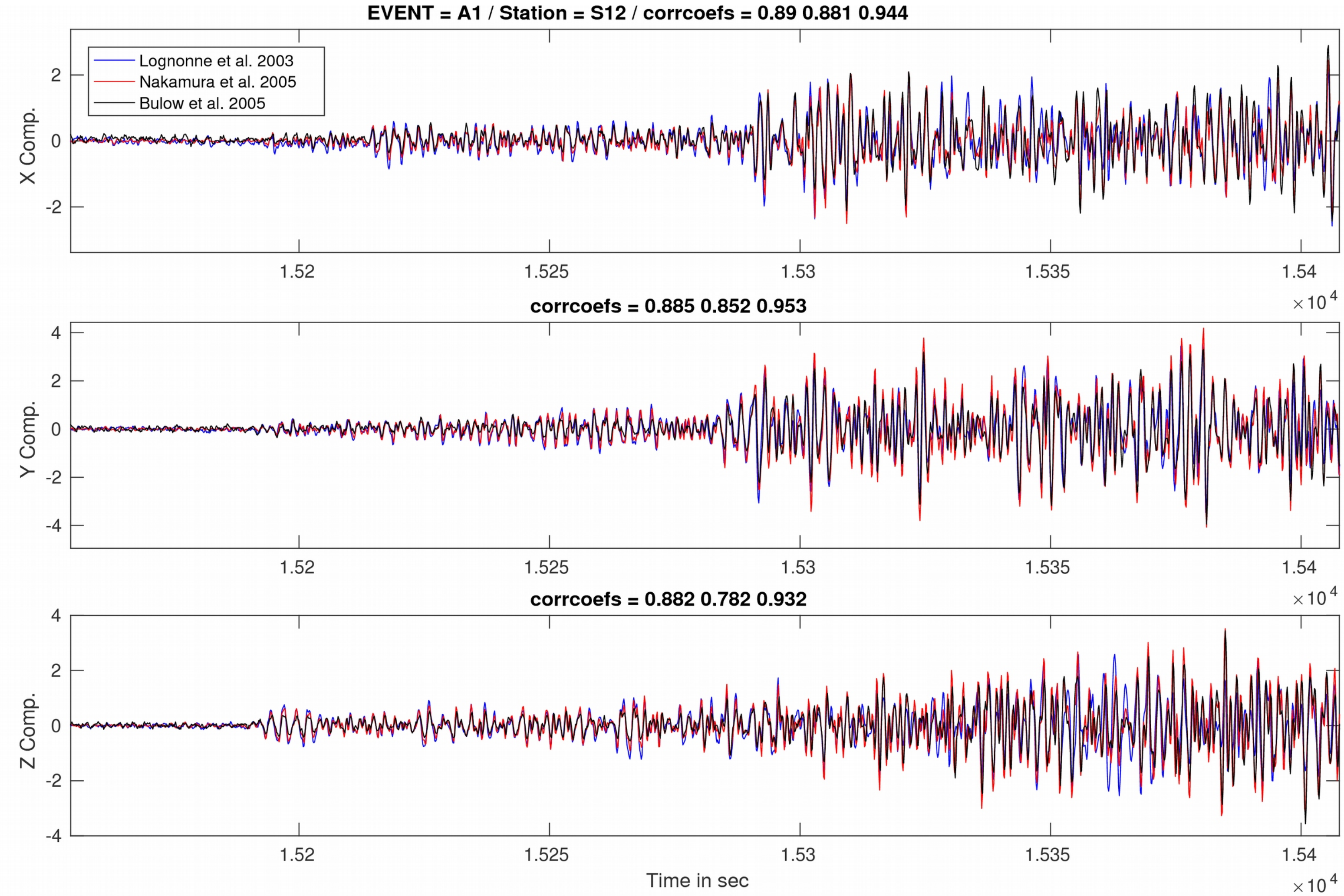
Comparison of deep moonquake stacks

- Deep Moon quakes repeat on the same fault, but we should stacks these events to increase S/N ratio
- Performed by 3 different teams with different input data, different processings : Nakamura, Lognonné/Beyneix, Bulow(Weber)
- But :
  - Not available for comparison
  - Used to infer Moon core and deep mantle
- Validation is needed

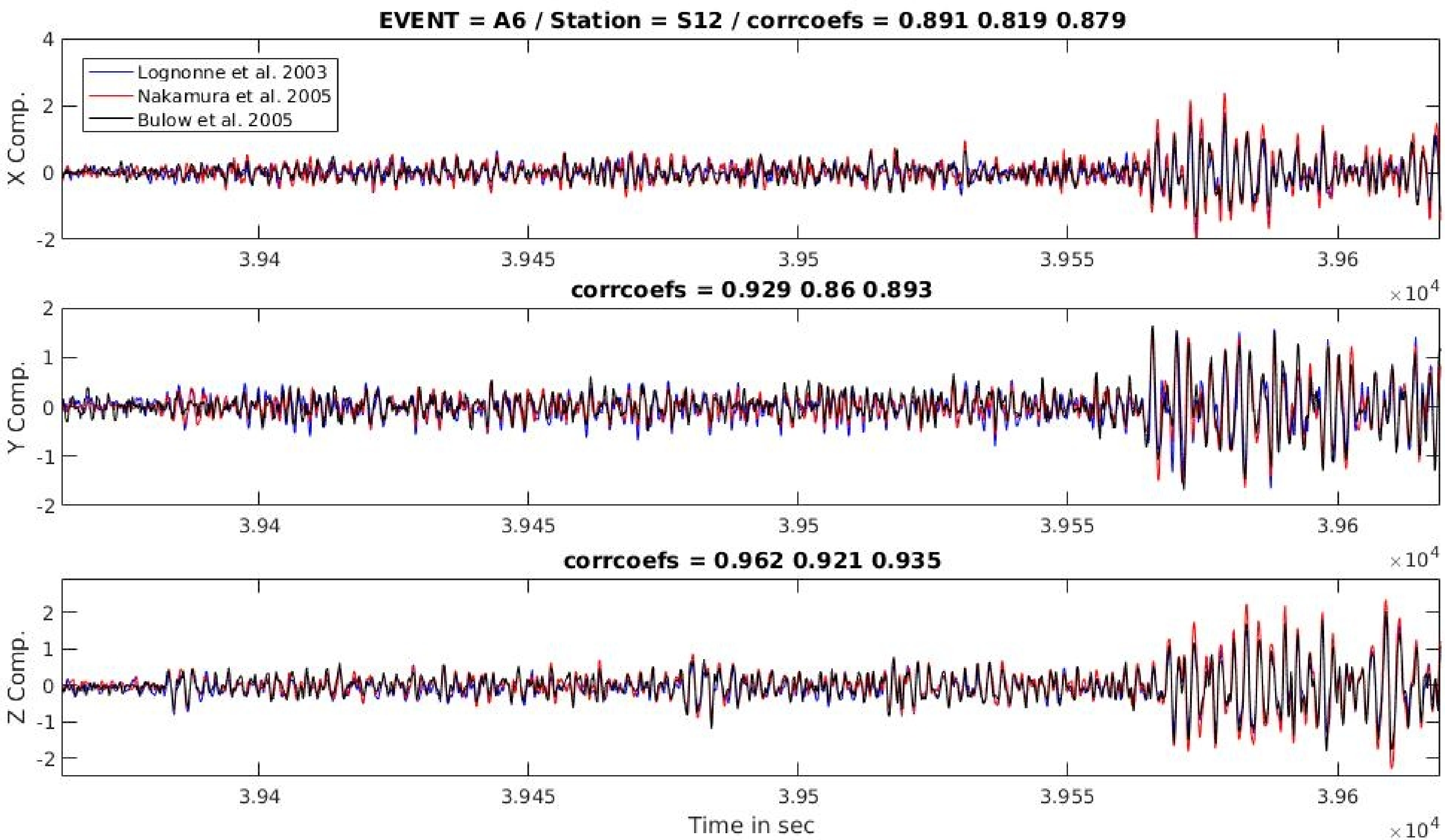
Raw data S12 event cluster A01



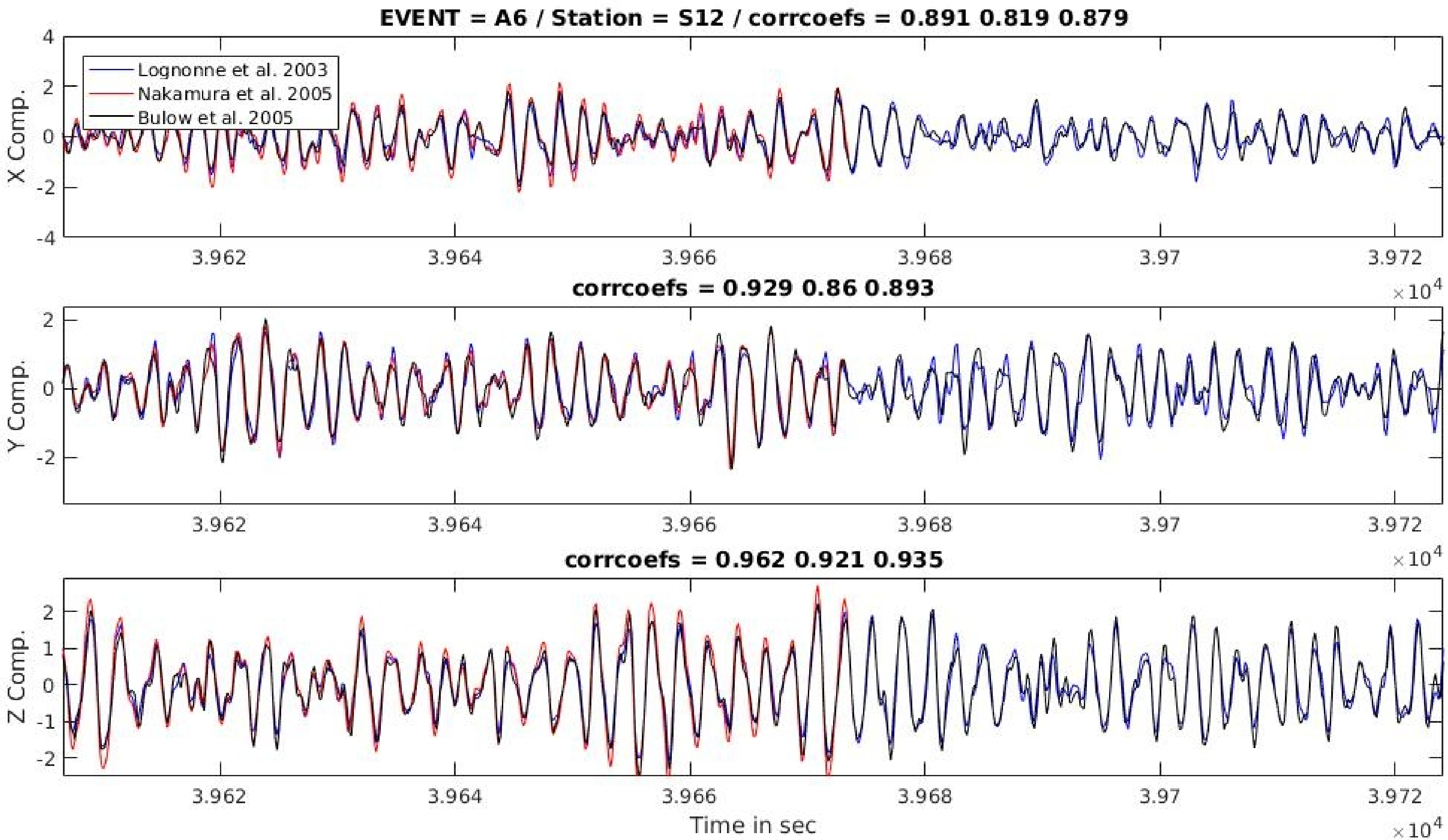
Comparison of deep moonquake stacks
Examples : A01 best S/N quake



Comparison of deep moonquake stacks
Examples : A06 used for core detection

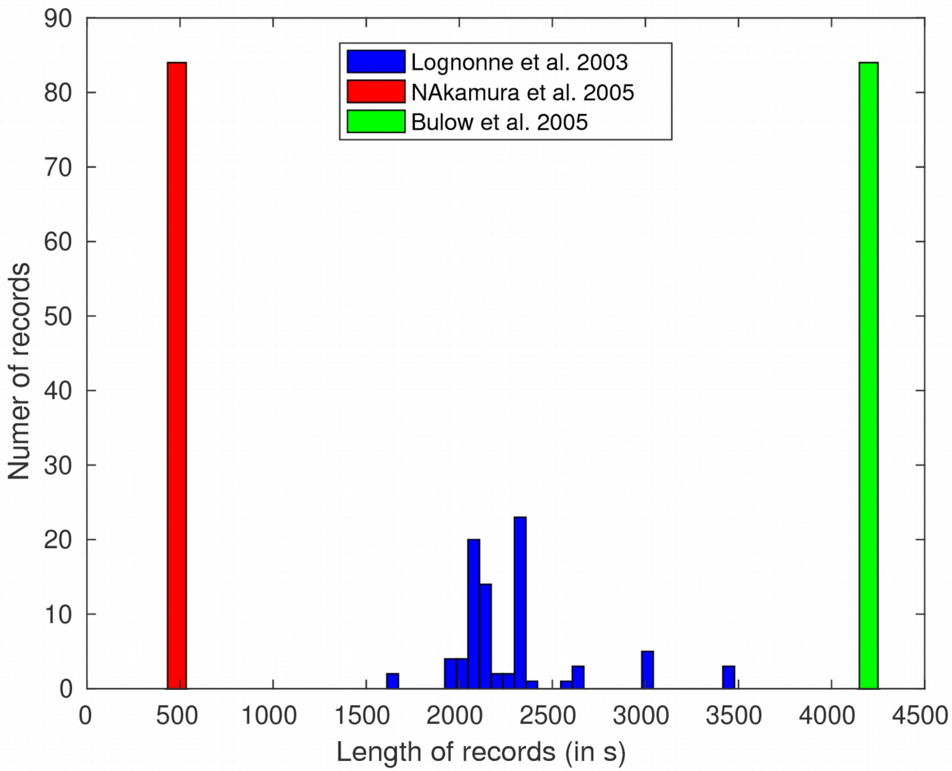


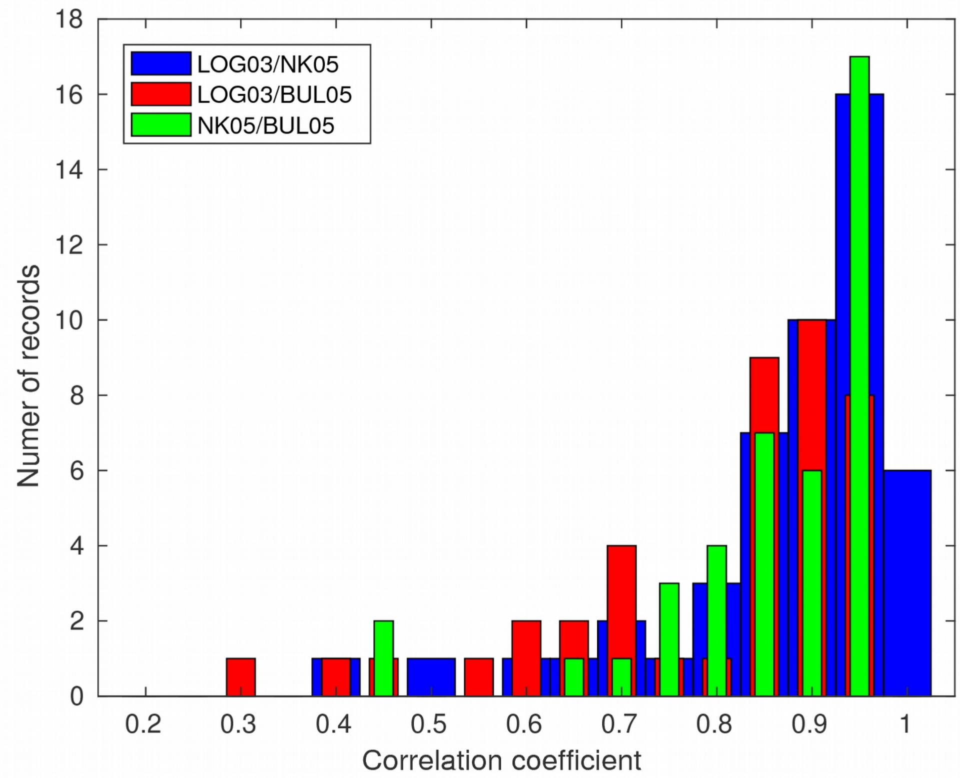
Comparison of deep moonquake stacks
Examples : A06 used for core detection



Comparison of deep moonquake stacks
Statistics

- Very high correlations coefficients (over 500s records)
- => Data not limited by sensor/env. noise but by A/D LSB
- => Can be used for waveform analysis





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