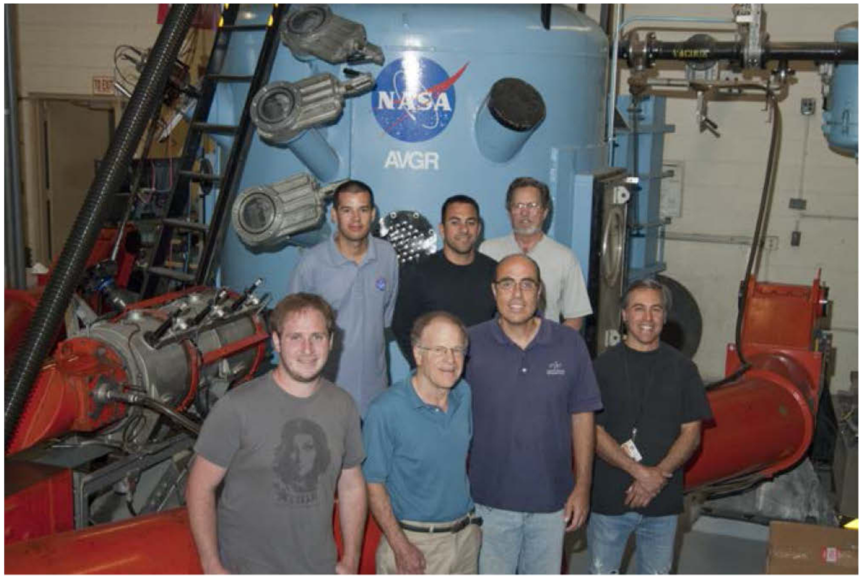
Laboratory Simulations of Martian Meteorite impacts and Their Seismic Signatures

How hard do we need to hit Mars
to see what it's made of?

Sharon Kedar (JPL)
James Richardson (Purdue - PI)
Nathaniel Harvey (JPL)
Doug Perry (JPL)
Timothy Bowling (Purdue)
Frank Webb (JPL)
Hiroo Kanamori (Caltech)
Ed Garnero (ASU)

Acknowledgements

- NASA Ames Vertical Gun Range (AVGR)
- Doug Perry & JPL Instrument Pool and the Environmental Testing Lab
- Tim Bowling & Dr. Jay Melosh – Purdue University
- Hiroo Kanamori & Dr. Don Helmberger– Caltech r. Seismological Laboratory
- The JPL Mars Yard
- Sponsored by NASA's Mars Fundamental Research Program
- Concept work funded by JPL's Purple Pigeons Program



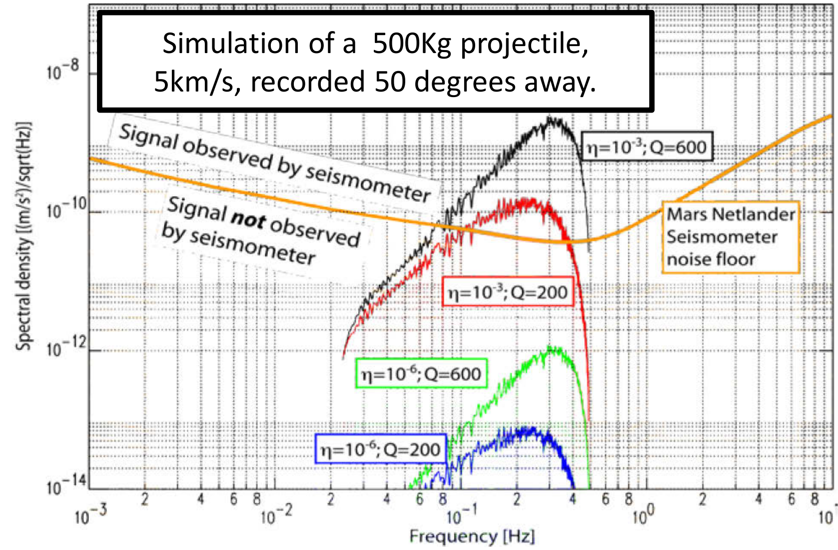
Key issues for using impacts as seismic sources for Mars

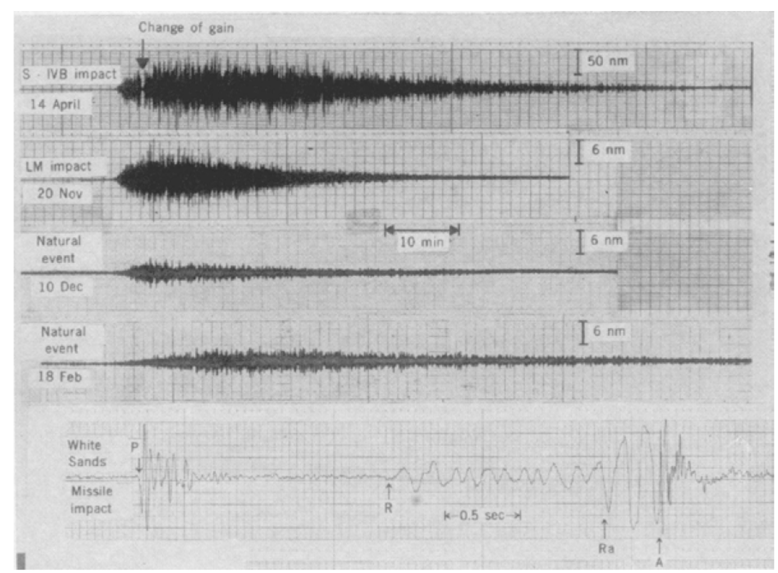
- Impacts are complex, poorly constrained sources of seismic energy: How well is the impactor momentum transferred to seismic waves?

- There are large uncertainties in the seismic response of the Martian regolith and interior.

- Given the current expectations of naturally occurring impacts what can we learn about the Martian interior?

- Beyond calibration, would a targeted impact provide additional information for scientific discovery?



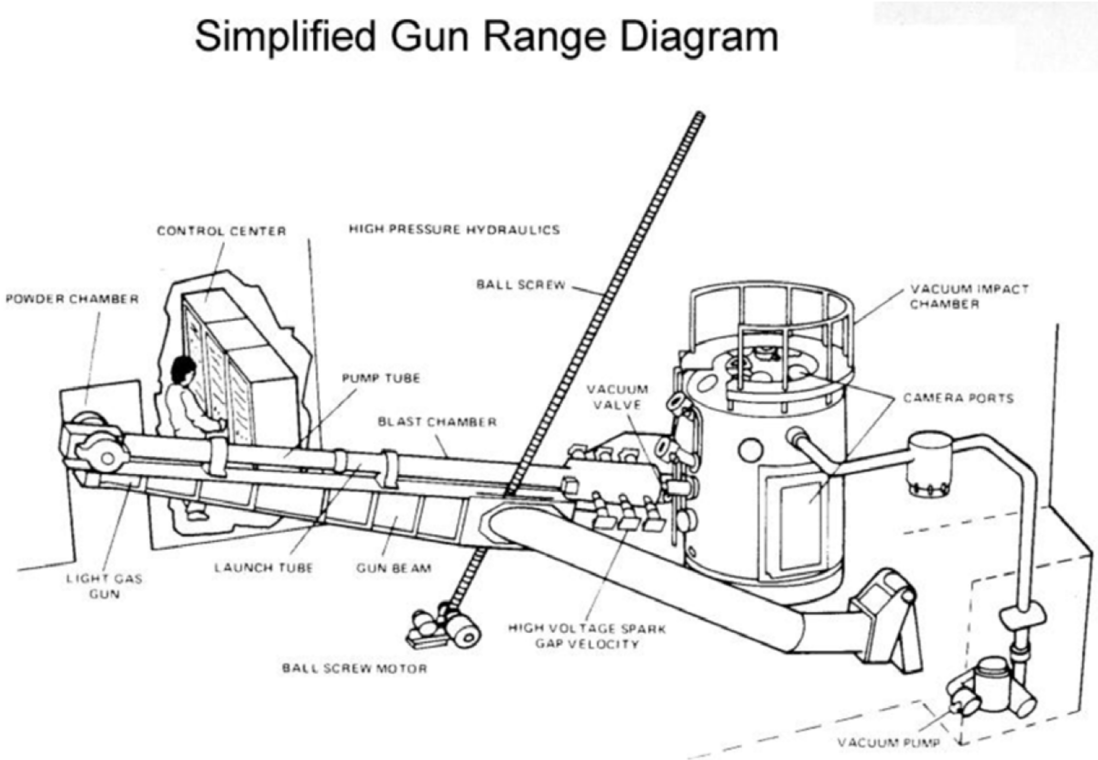


Lunar impacts recorded by the Apollo 12 Lunar seismic network [*Latham et al*, 1970].

Objectives of the Mars Analog Experiment

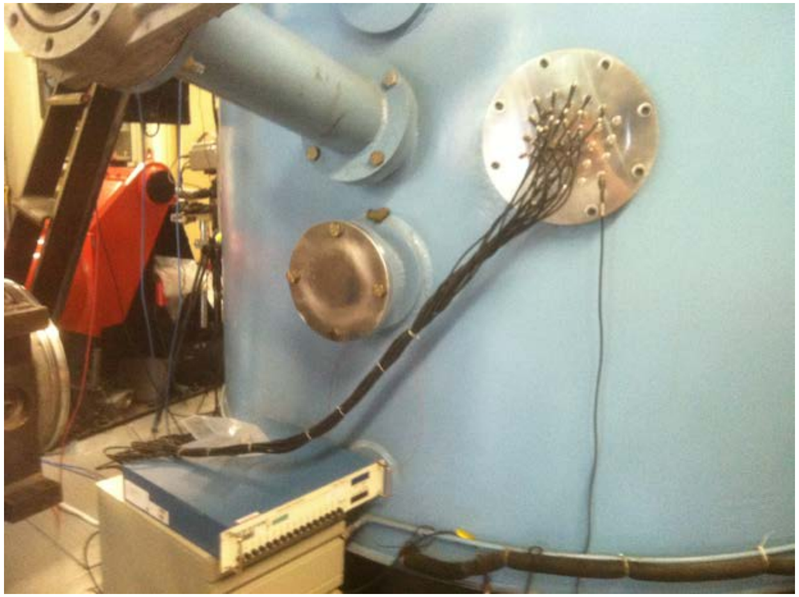
- Characterize, the transfer of momentum from an impacting object to seismic waves.
- Determine the planet's surface-impulse seismic response for a range of Martian interior models that include realistic layering, attenuation, and heterogeneity assumptions.
- Combine (1) and (2) with a modern model of the Martian impactor space-time-size distribution to estimate the amplitude and frequency of impact-induced seismicity over the planet's surface during one Martian year, and evaluate its potential for exploration of the planet's interior.

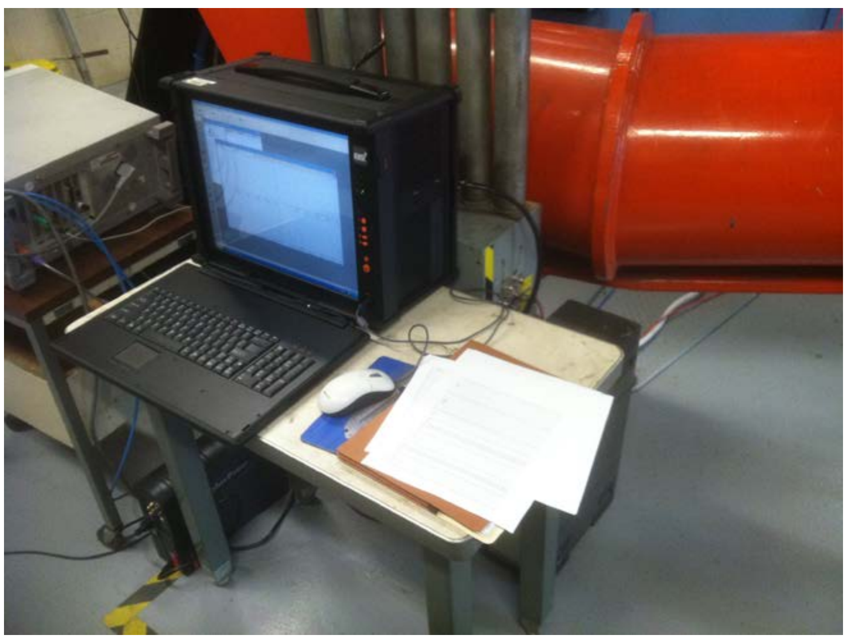
AVGR Facility

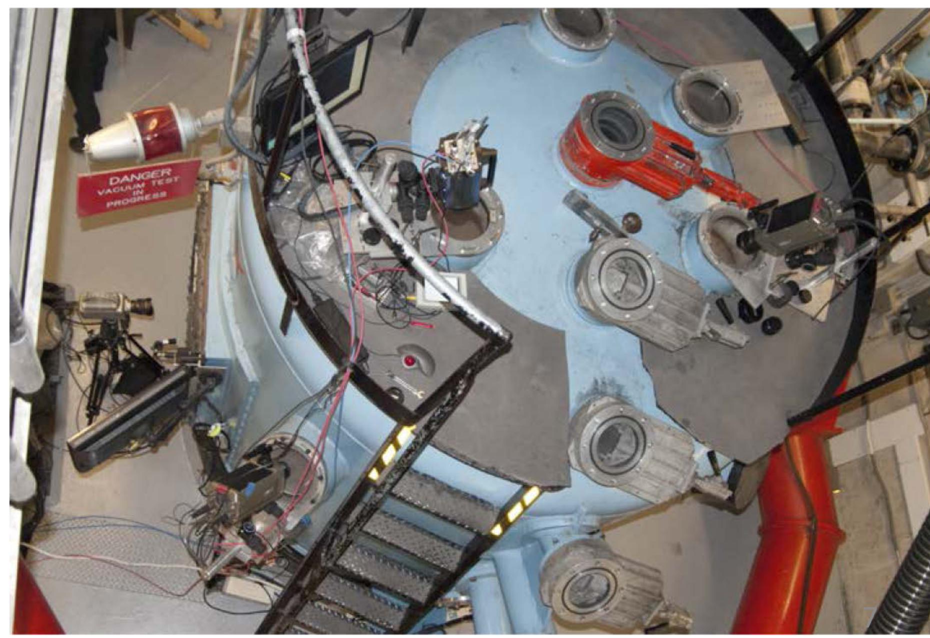


Setup

Recording System



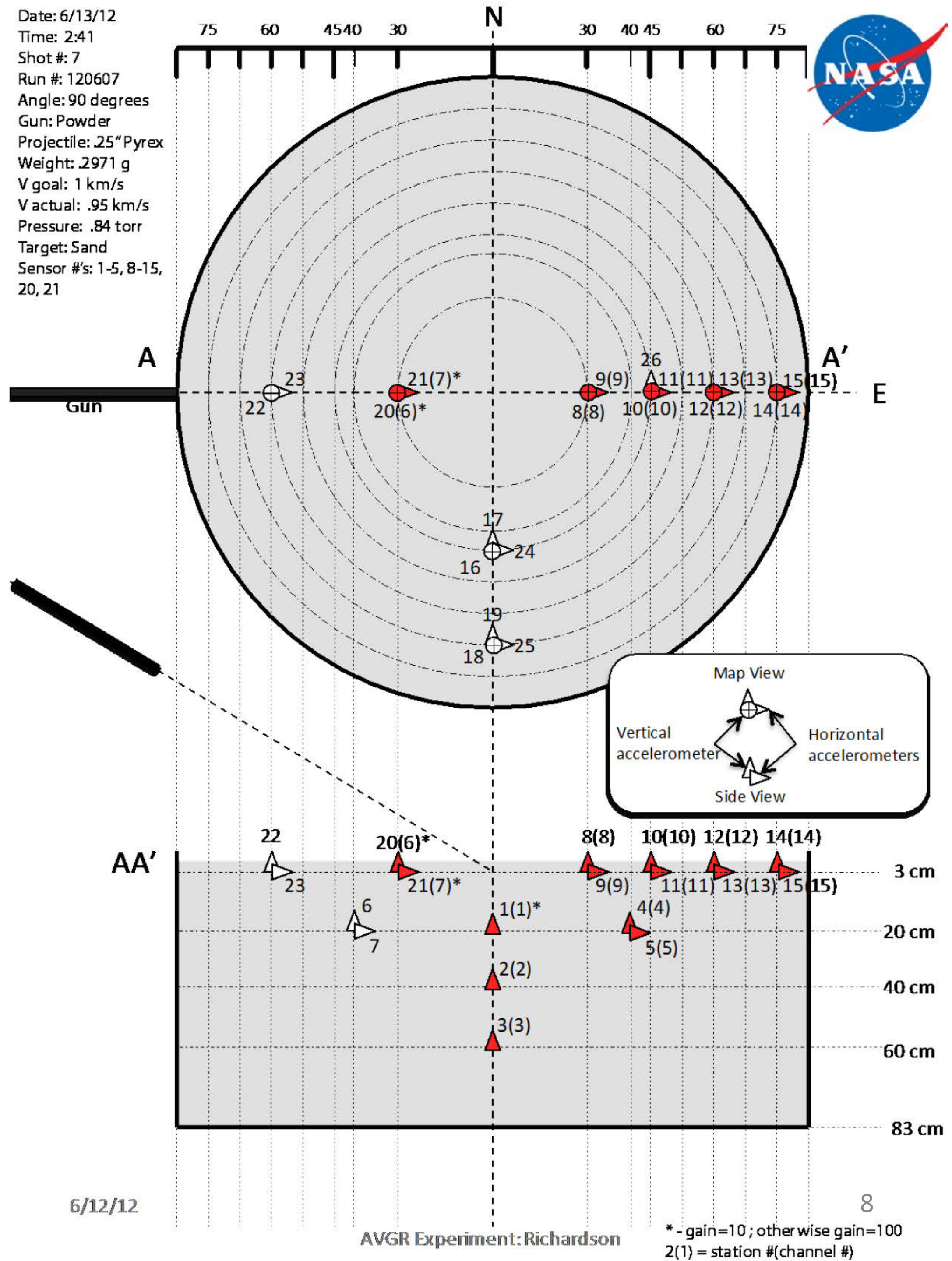




Seismic Setup

Endevco 2256A-10
Accelerometer
±500g Dynamic range

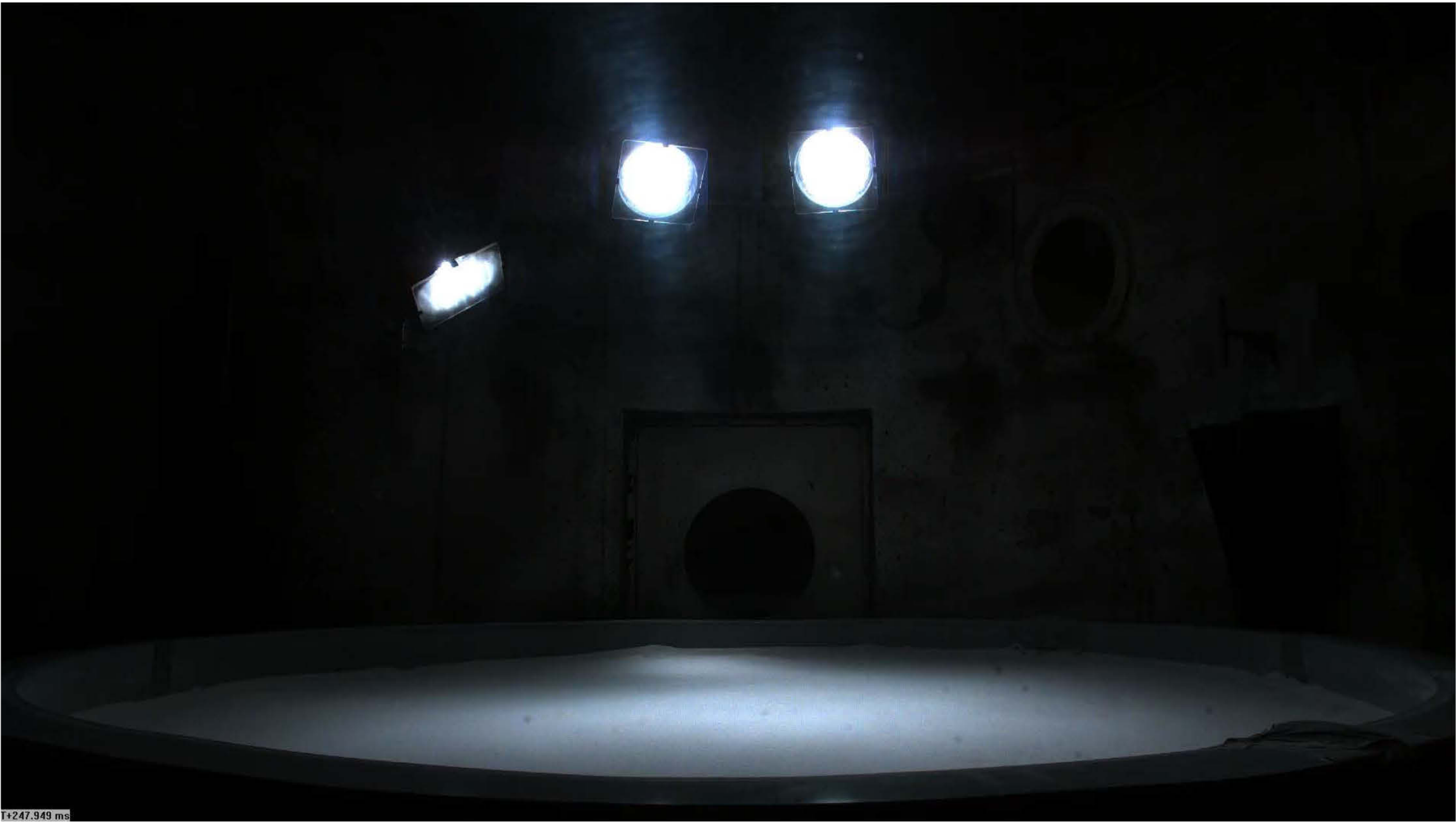
Recorded at 10^5Hz



22 shots

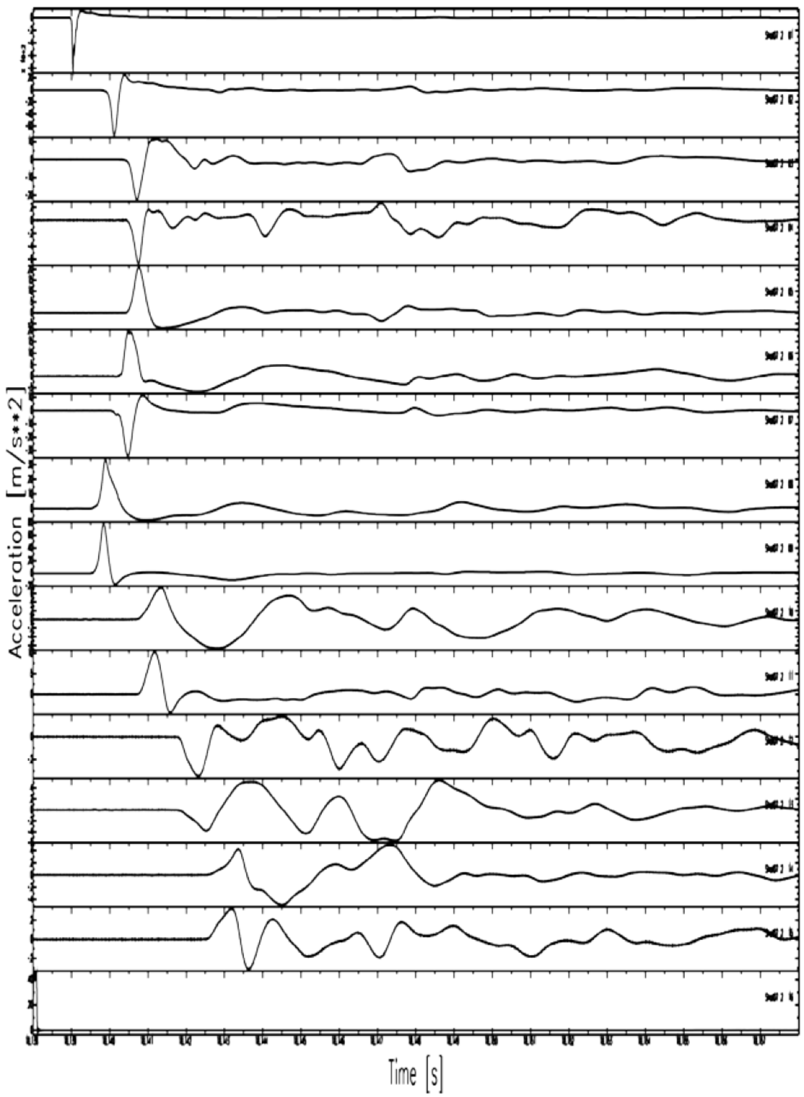
Shot #	Target Material	Projectile Weight (gr)	Projectile Velocity (km/s)	Angle from horizon (°)	Measured Pressure (Torr)	Pressure (Atm)	Pressure (psi)	% of Mars atmosphere
1	sand	0.2966	2.15	90	1.28	0.0017	0.0248	28
2	sand	0.2969	2.13	90	0.91	0.0012	0.0176	20
3	sand	0.2970	2.23	75	0.87	0.0011	0.0168	19
4	sand	0.2969	2.26	60	0.71	0.0009	0.0137	16
5	sand	0.2969	2.21	45	0.83	0.0011	0.0160	18
6	sand	0.2967	2.31	30	0.85	0.0011	0.0164	19
7	sand	0.2971	0.95	90	0.84	0.0011	0.0162	19
8	sand	0.2967	2.23	90	0.65	0.0009	0.0126	14
9	sand	0.2968	2.68	90	0.52	0.0007	0.0101	12
10	sand	0.2966	4.68	90	0.58	0.0008	0.0112	13
11	sand	0.3754	5.47	90	0.69	0.0009	0.0133	15
12	Sand	0.2965	2.36	15	0.64	0.0008	0.0124	14
13	pumice	0.2965	0.98	90	4.38	0.0058	0.0847	97
14	pumice	0.2969	2.24	90	4.74	0.0062	0.0917	105
15	pumice	0.2967	2.21	75	4.99	0.0066	0.0965	111
16	pumice	0.2969	2.22	60	4.61	0.0061	0.0891	102
17	pumice	0.2965	2.21	45	4.77	0.0063	0.0922	106
18	pumice	0.2967	2.33	30	5.02	0.0066	0.0971	112
19	pumice	0.2965	2.29	15	4.94	0.0065	0.0955	110
20	pumice	0.2966	2.82	90	4.80	0.0063	0.0928	107
21	pumice	0.2964	4.54	90	4.86	0.0064	0.0940	108
22	pumice	0.3765	5.82	90	4.90	0.0064	0.0948	109

Shot #13 – Sand – 1Km/s - Vertical

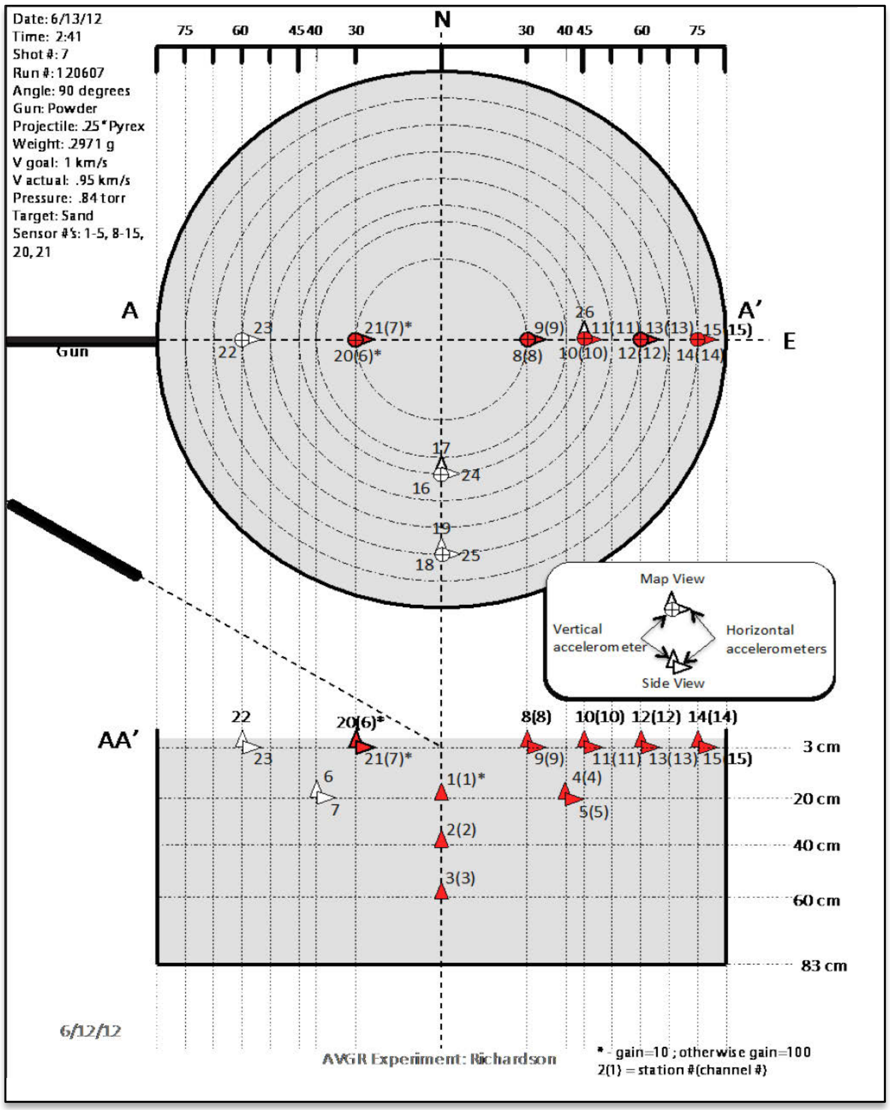


Post shot measurements

Shot #07 data



Acceleration [m/s**2]
Time [s]



Date: 6/13/12
Time: 2:41
Shot #: 7
Run #: 120607
Angle: 90 degrees
Gun: Powder
Projectile: .25" Pyrex
Weight: .2971 g
V goal: 1 km/s
V actual: .95 km/s
Pressure: .84 torr
Target: Sand
Sensor #'s: 1-5, 8-15, 20, 21
N
A
A'
E
Gun
AA'
Map View
Vertical accelerometer
Horizontal accelerometers
Side View
3 cm
20 cm
40 cm
60 cm
83 cm
6/12/12
AVGR Experiment: Richardson
* - gain=10 ; otherwise gain=100
2(1) = station #(channel #)

Obtaining a Source Time Function

- Measure Material properties (*Vp, Vs, Qp, Qs*)
- Calculate a Green's function *g(t)* for the laboratory setting
- Deconvolve Green's function from Data *d(t)* to obtain source time function *f(t)*

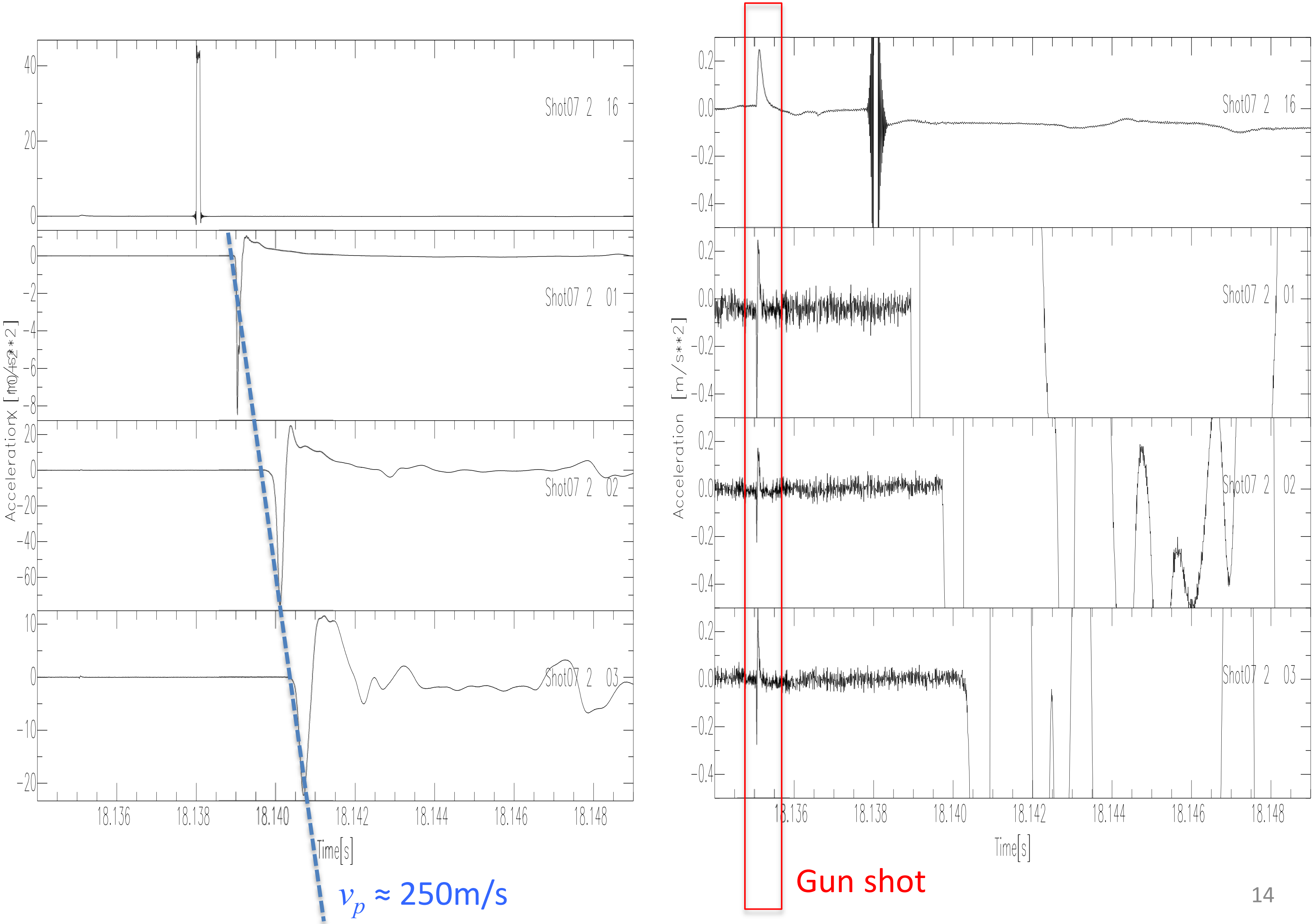
$$d(t) = f(t) * g(t) \Leftrightarrow D(\omega) = F(\omega)G(\omega)$$

- **Compare impact to known projectile momentum**

$$P \equiv \int_0^{\infty} f(t)\,dt \approx mv$$

- Estimate seismic energy and compare to projectile kinetic energy

Shot #07; Channels 1-3



Estimating Q

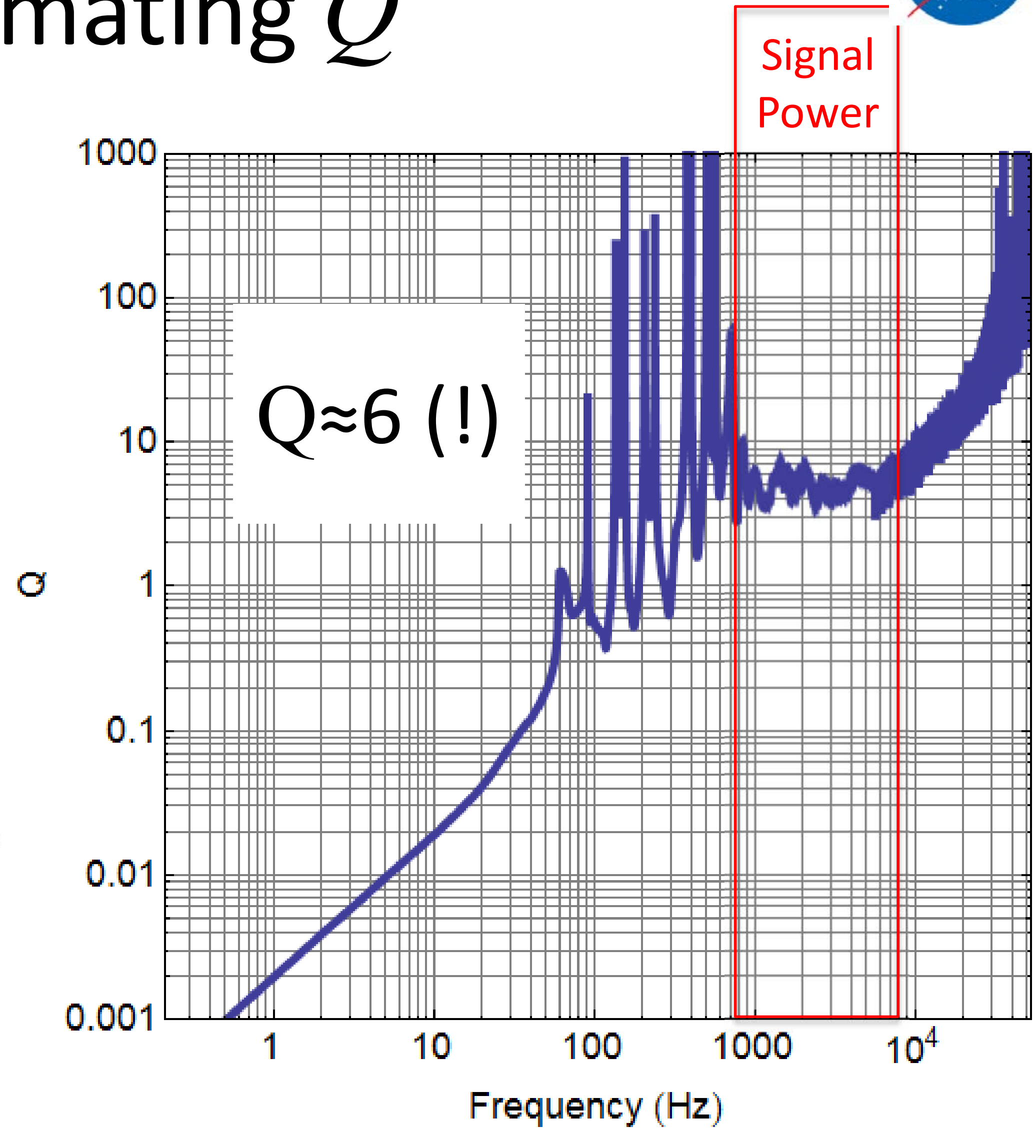
$$\frac{1}{Q(\omega)} \equiv -\frac{\Delta E}{2\pi E}$$

⇩

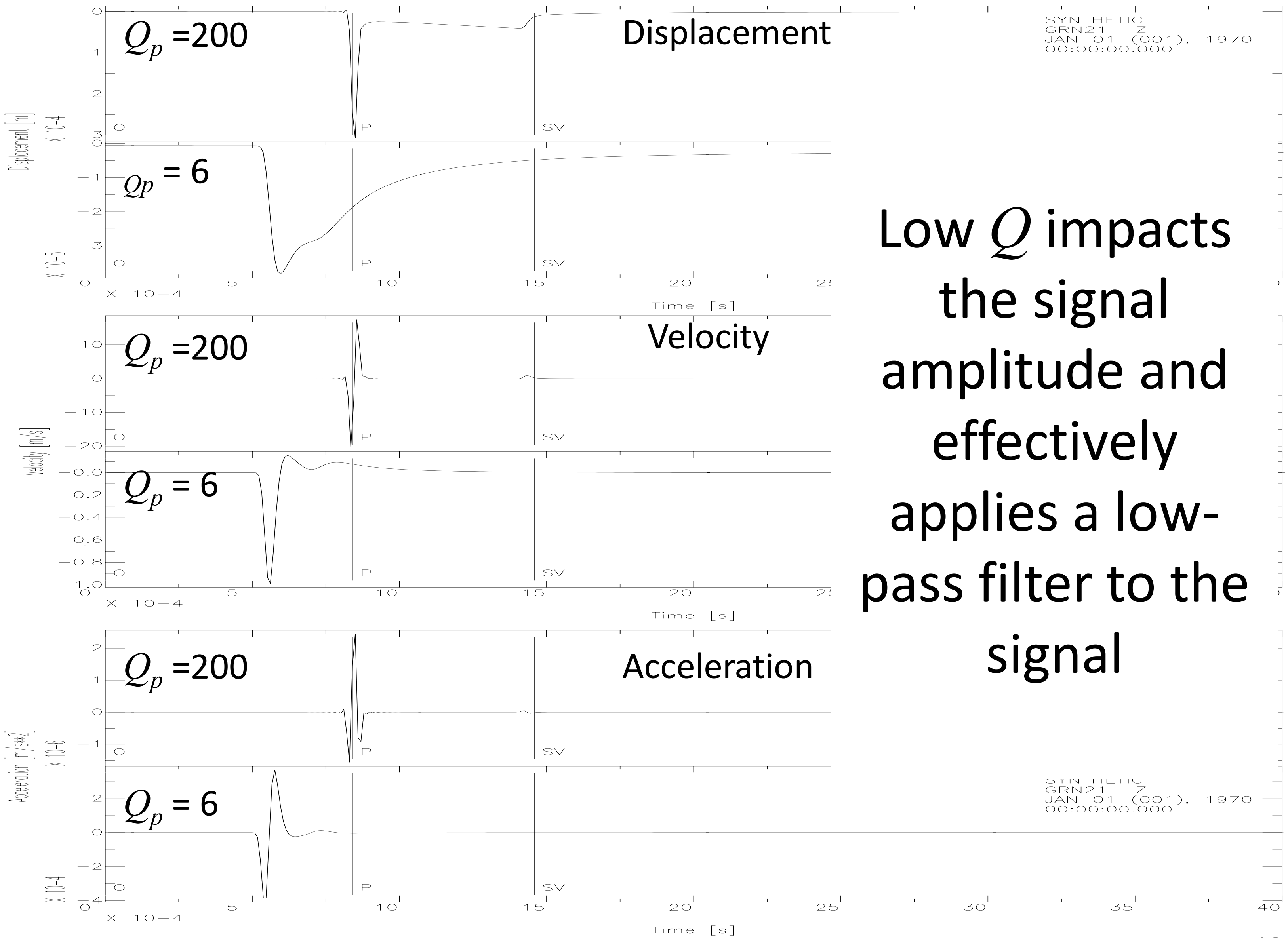
$$A(x) = A_0 \exp\left[-\frac{\omega x}{2cQ}\right]$$

⇩

$$Q(\omega) = -\frac{\omega x}{2c\ln\left[A(x)/A_0\right]}$$



Green's function for a vertical impulse

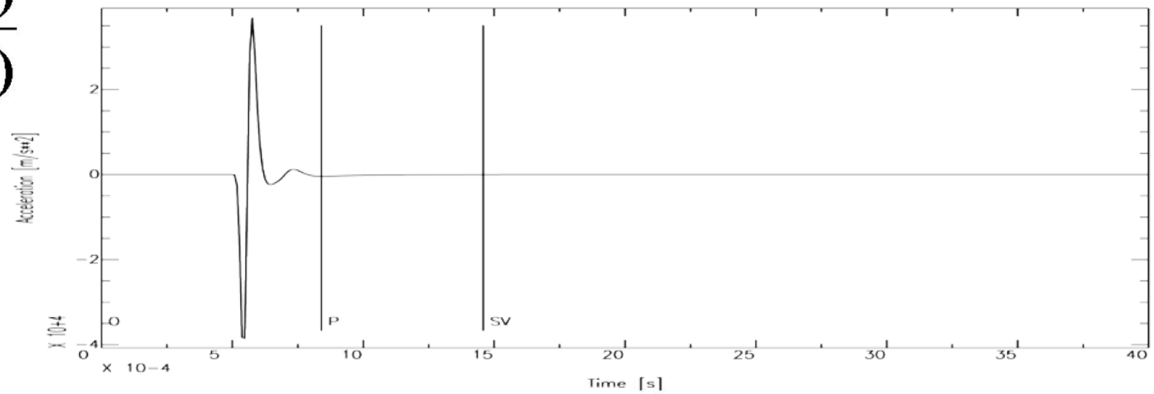


Low Q impacts the signal amplitude and effectively applies a low-pass filter to the signal

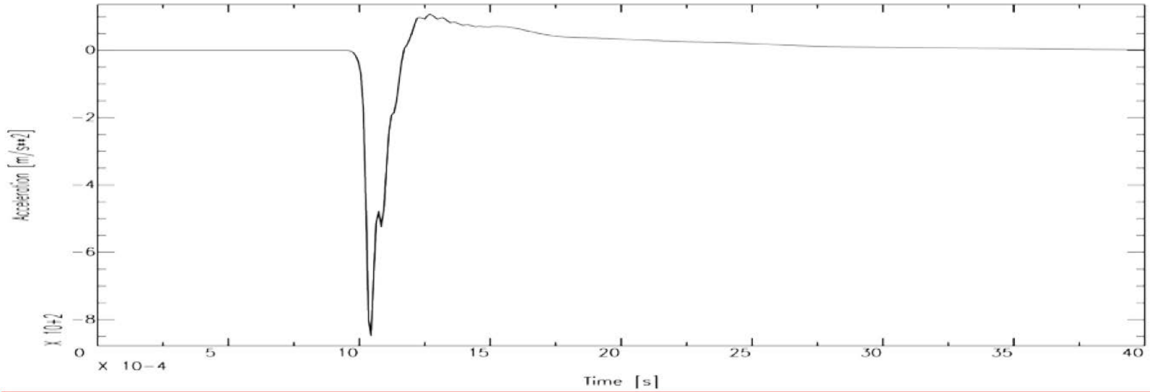
Obtaining the STF through deconvolution

$$f(t) \Leftrightarrow F(\omega) = \frac{D(\omega)}{G(\omega)}$$

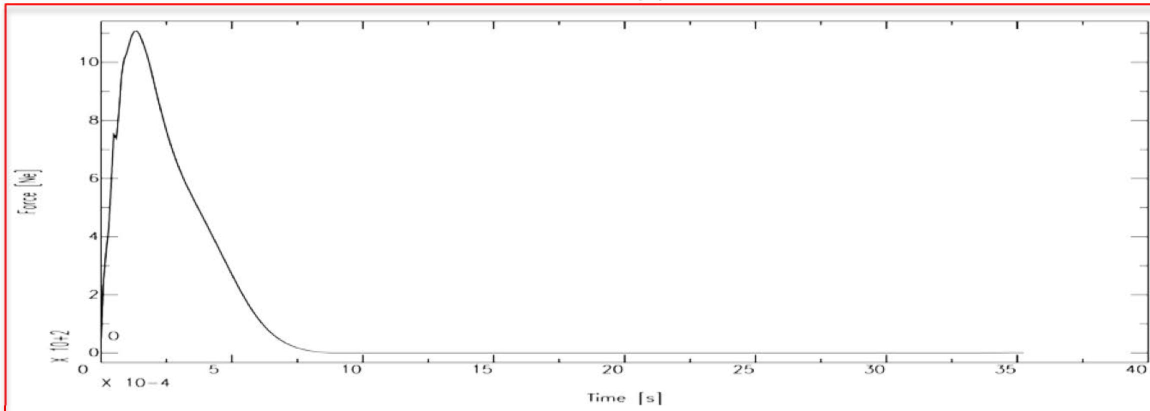
Deconvolve *g(t)*



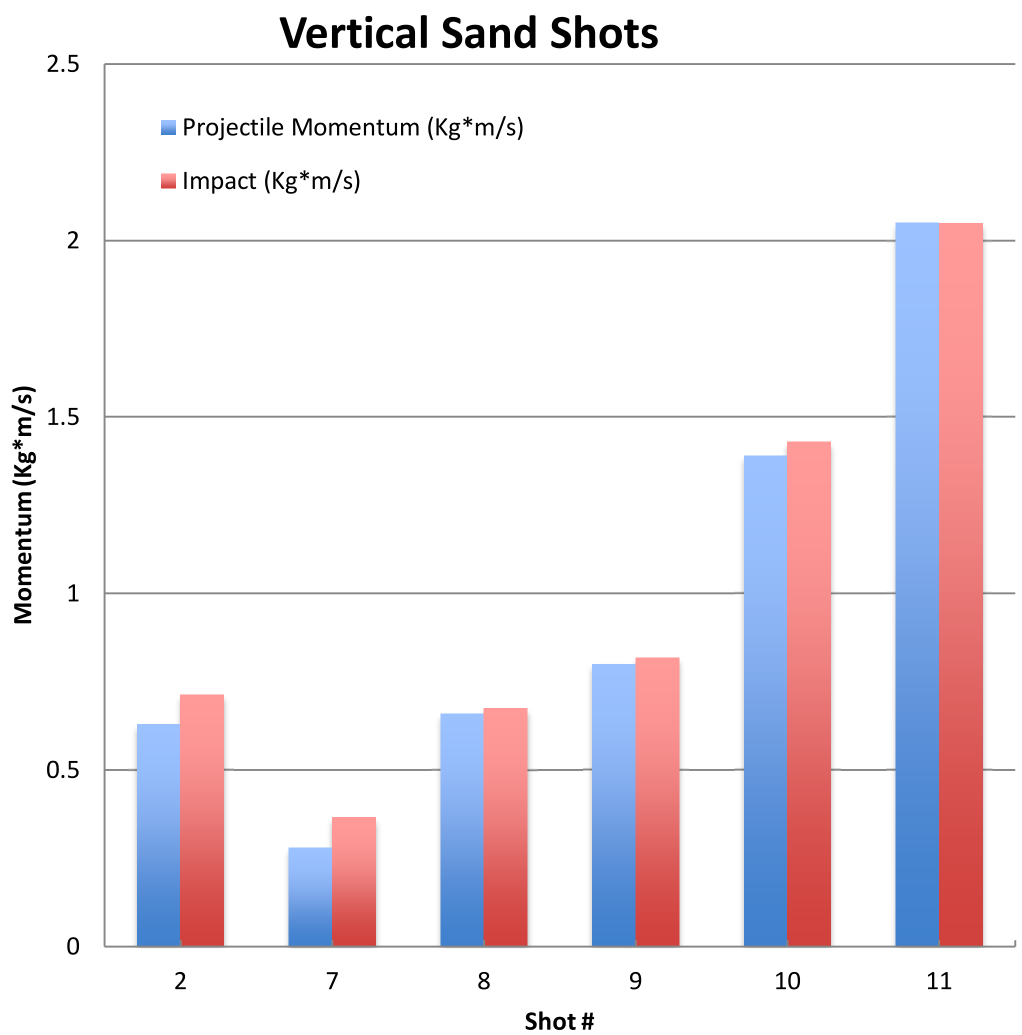
From *d(t)*



To obtain *f(t)*



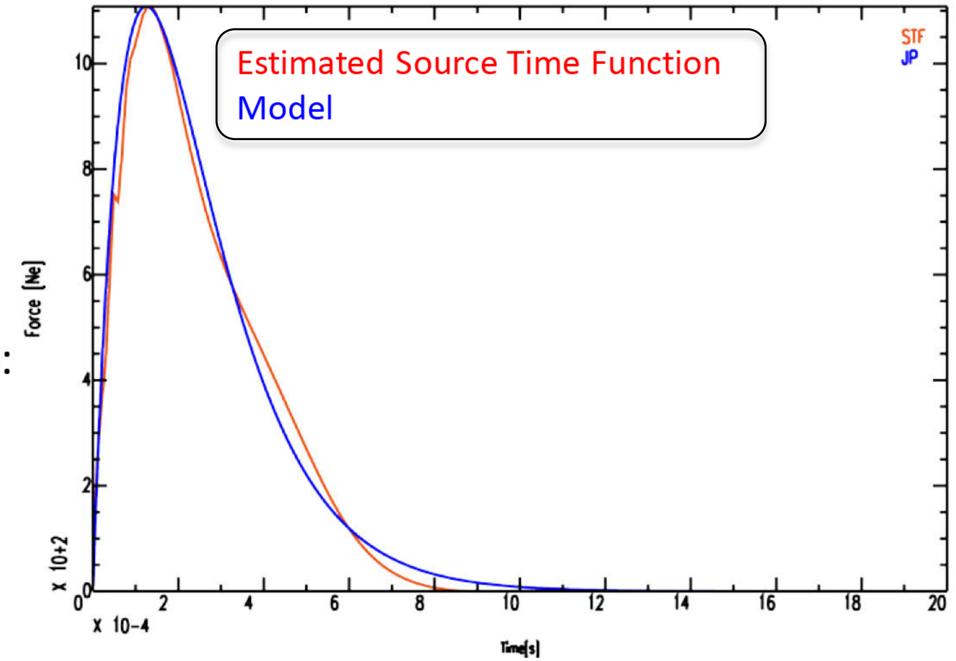
Estimated Impacts vs Measured Projectile Momentum



Calculating Seismic Energy

$$u(t) = \frac{f(t)}{4\pi\mu r}$$

u(t) – Displacement
μ – Rigidity
r – Radial distance



We choose an integrable source time function *f(t)* (aka Jeffreys Pulse) defined as:

$$f(t) = cte^{-\alpha t}$$

$$P \equiv \int_0^\infty f(t)\,dt = mv$$

P – Impact

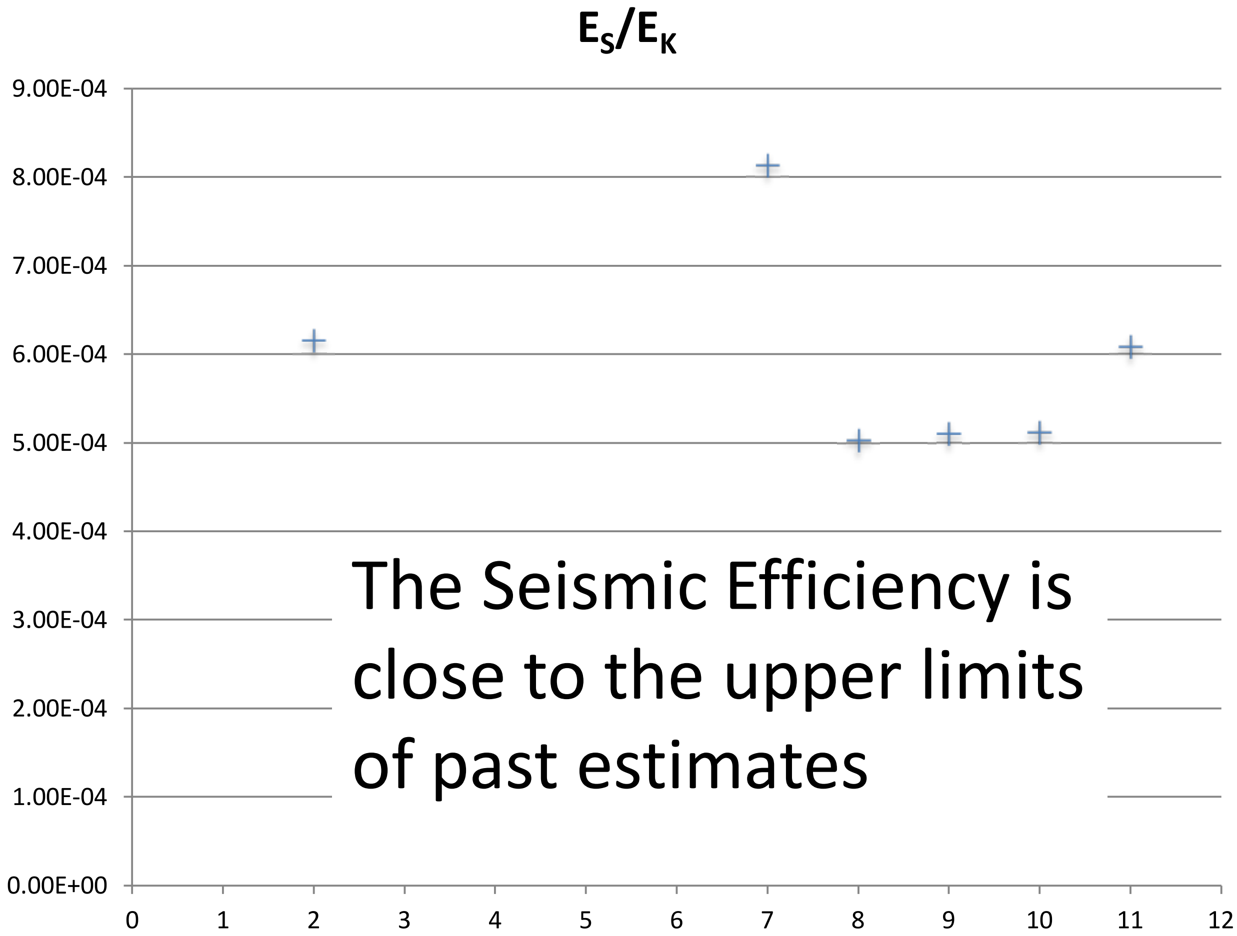
$$c = \alpha^2 P$$

α – Time decay constant derived from estimate of *f(t)*

It can be shown that the Seismic Energy E_s is approximately

$$E_s \approx 4\pi r^2 \rho v_p \int_0^\infty \dot{u}(t)^2\,dt = \frac{\rho v_p \alpha^3 P^2}{16\pi\mu^2}$$

Calculation of traditional Seismic Efficiency from estimated impact

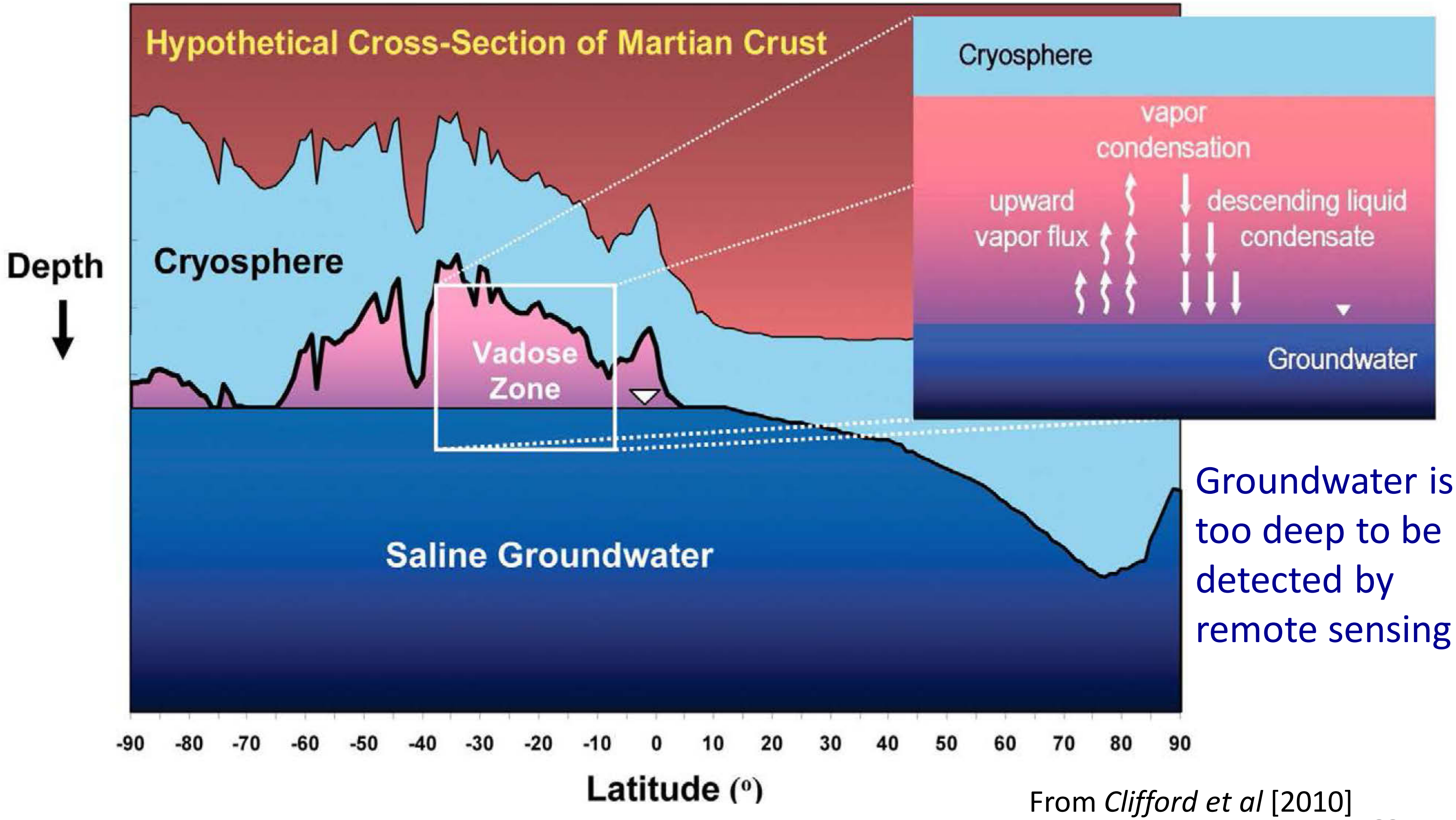


The Seismic Efficiency is close to the upper limits of past estimates

Open Issues

1. How do the laboratory experiments scale up to meteorite size impact? (Does the fact that we get nearly perfect momentum transfer at small scales apply at large scale?)
2. What is the effect of a soft low Q , thin (10s of meters) layer of regolith on signal strength from:
   – Meteorites / Projectiles ?
   – Marsquakes ?
3. Given (1) What we have learned (and will continue to learn) about the impact process; (2) The range of estimated elastic properties of Mars; and (3) The knowledge of Martian meteorites size and frequency distribution – Could we bound the contribution of meteorite seismic sources towards achieving InSight's mission objectives?
4. Could a targeted impactor(s) be used to calibrate seismic measurements on the Martian surface (and help towards achieving the mission objectives)?

Water is believed to reside in the Martian Crust in two thermally distinct reservoirs: Shallow Cryosphere, and deeper groundwater



Groundwater is too deep to be detected by remote sensing

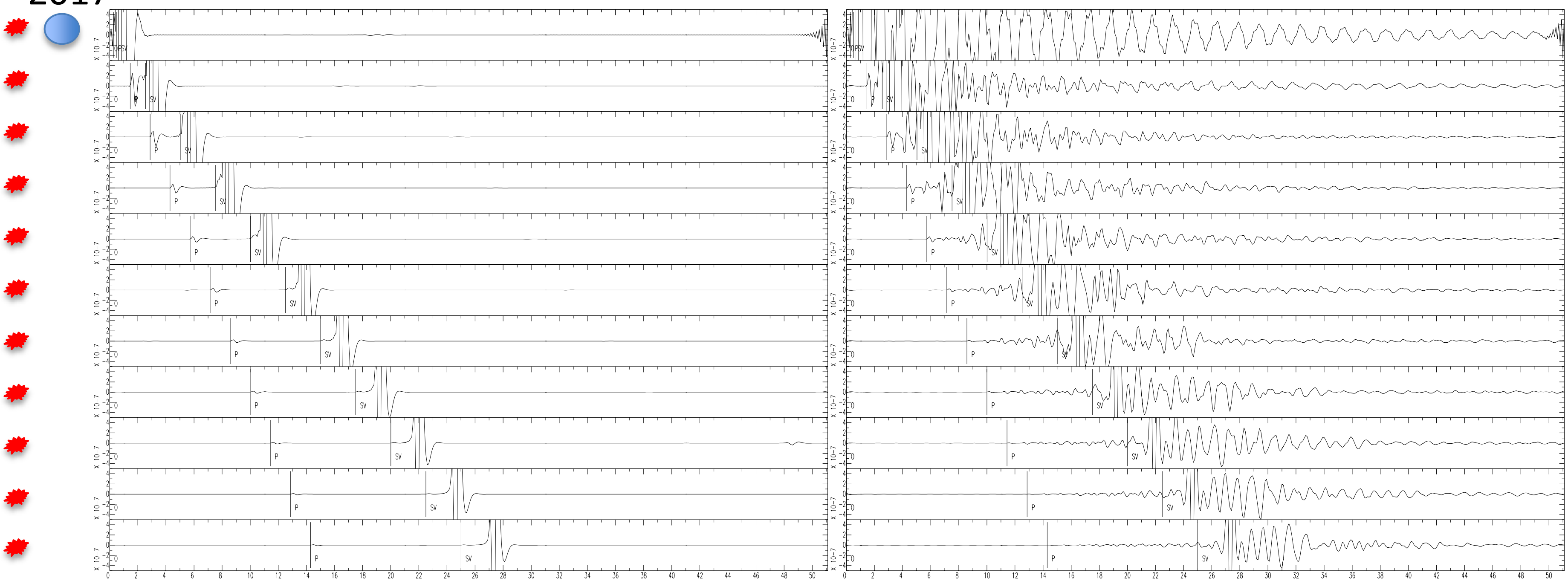
From *Clifford et al* [2010]

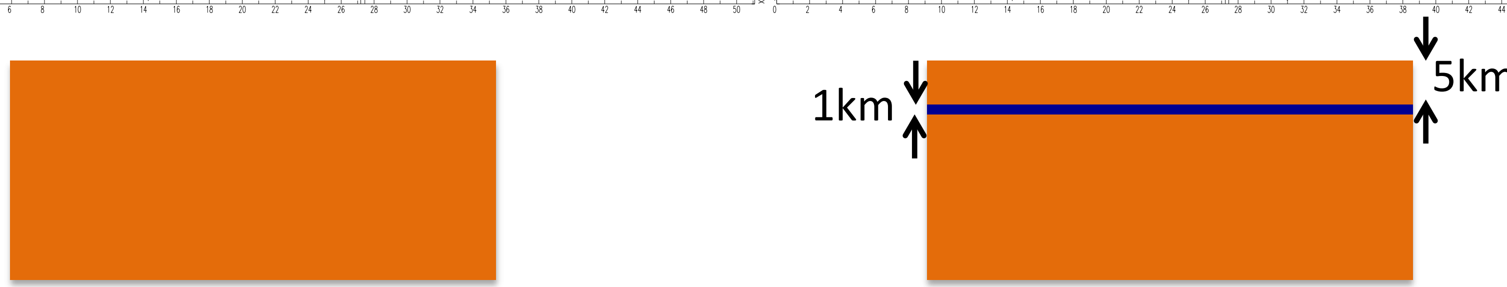
Prospecting for water with artificial impacts and a single seismometer (InSight)

InSight 2017

Crust without Water Layer

Crust with Water Layer

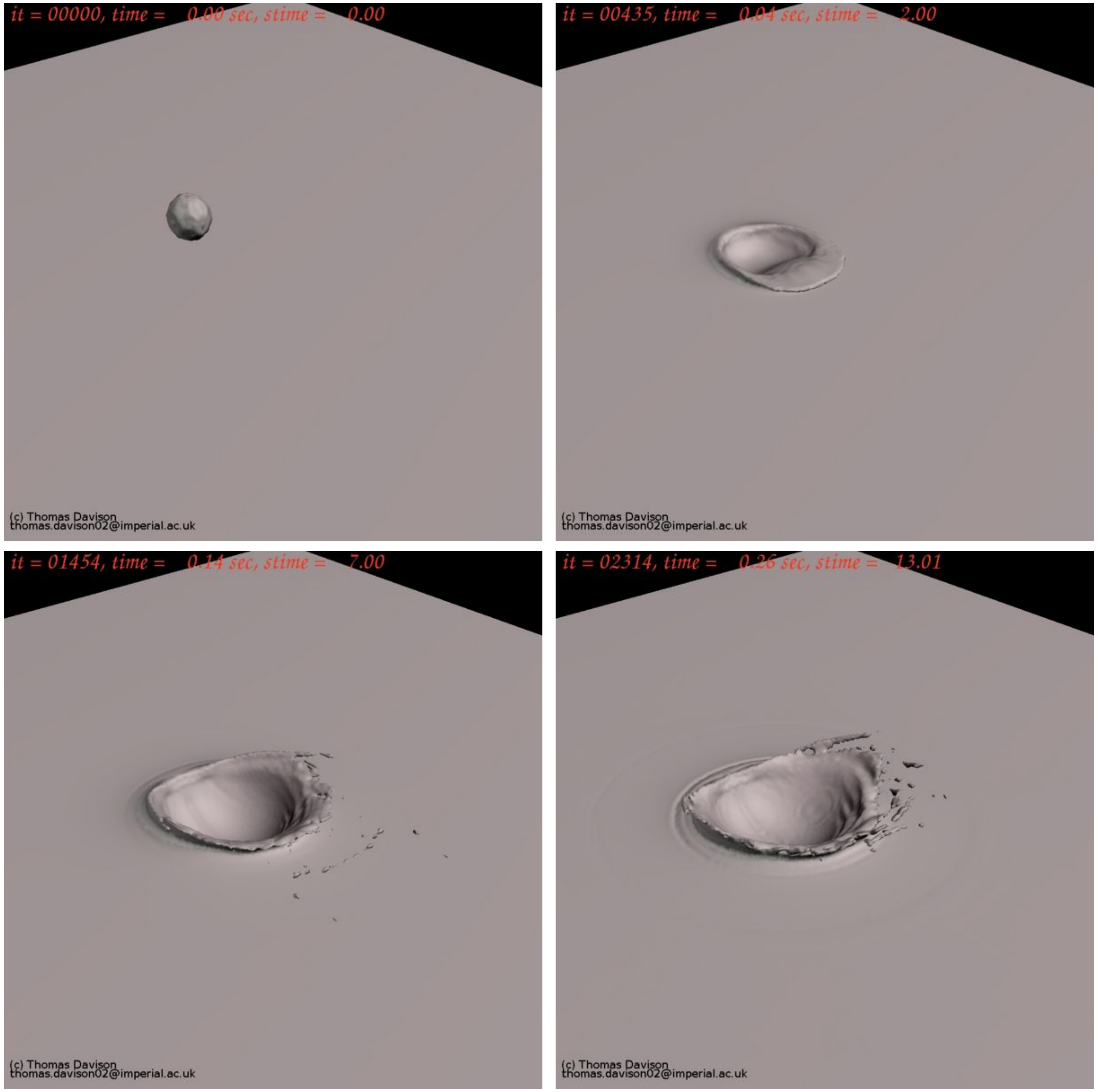




Backup Slides

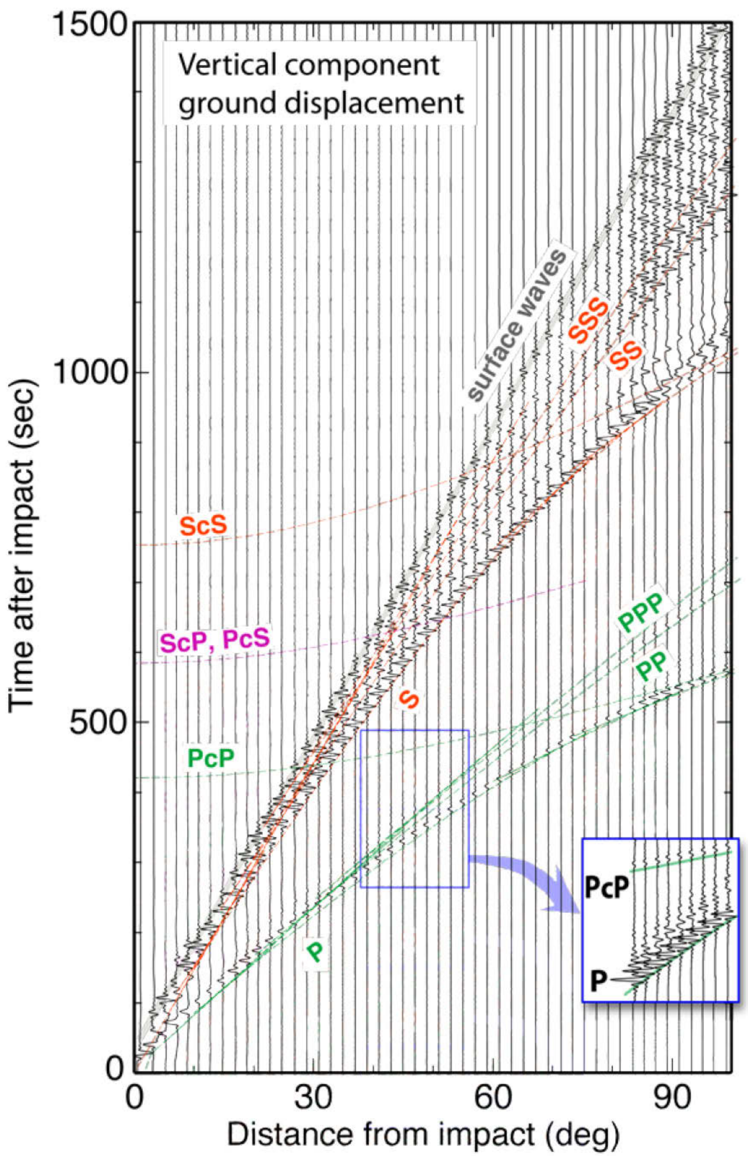
Scaling up the laboratory measurement

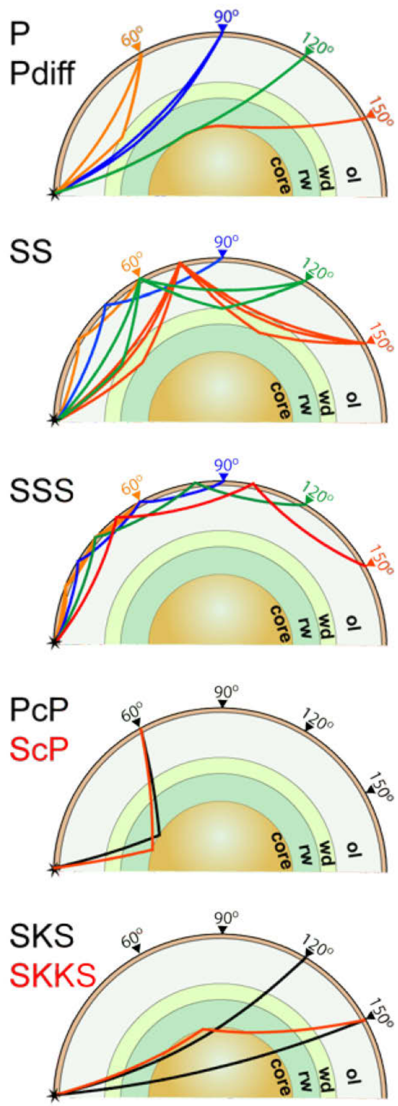
1. Simulate laboratory impacts using ICL's I-SALE Hydrocode
2. Match numerical simulation with:
   - Dynamic impact measurements (i.e. movies)
   - Crater measurements
   - Seismic measurements
3. Obtain understanding of the impact process under Martian conditions
4. Simulate real size meteorites
5. Obtain a source time function for meteor-scale impacts on Mars



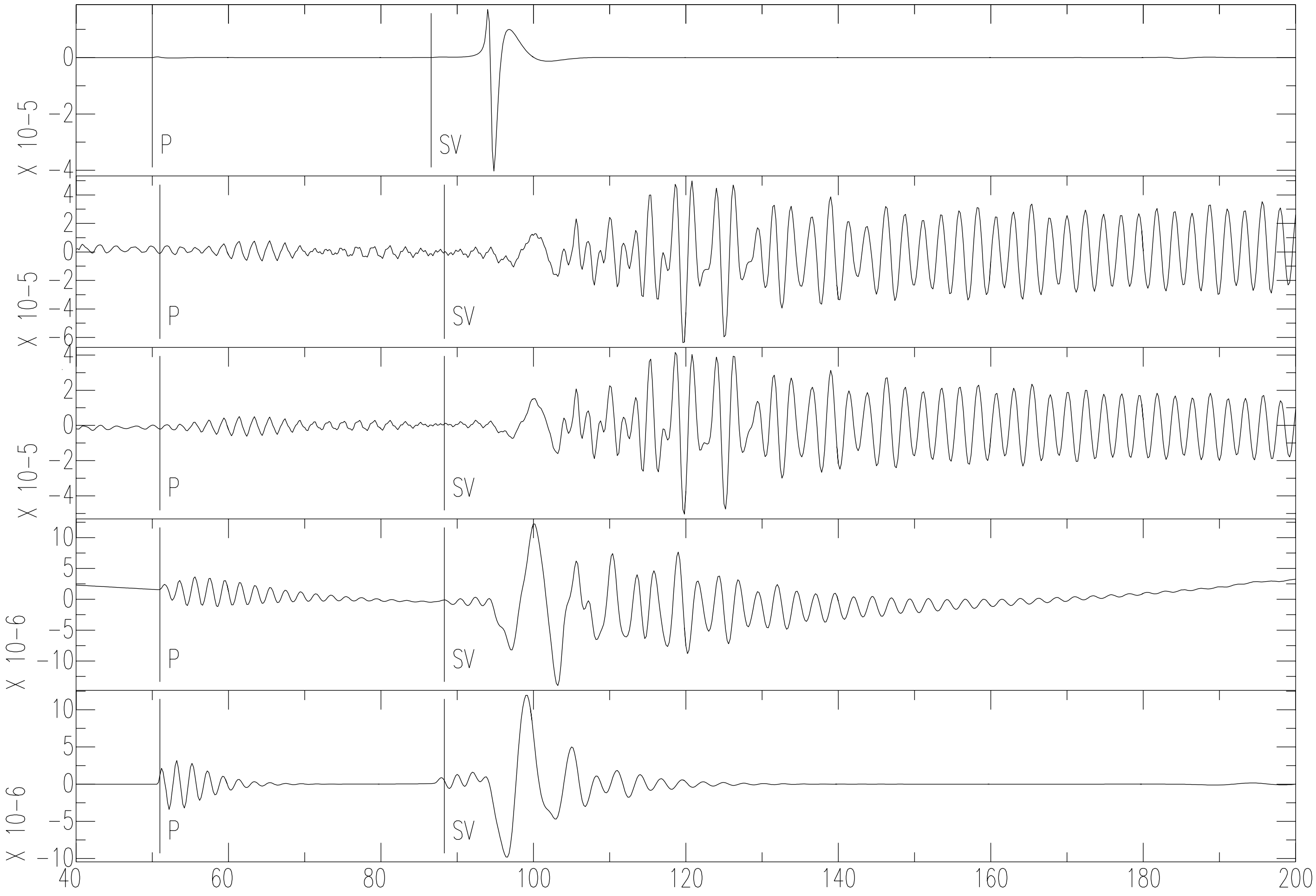
http://amcg.ese.ic.ac.uk/index.php?title=Crater_formation_in_high_strength_targets

Feed STF into a spectrum of Mars seismic mode

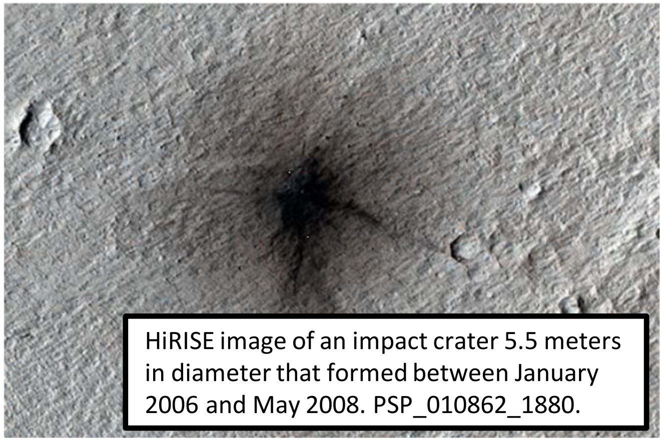




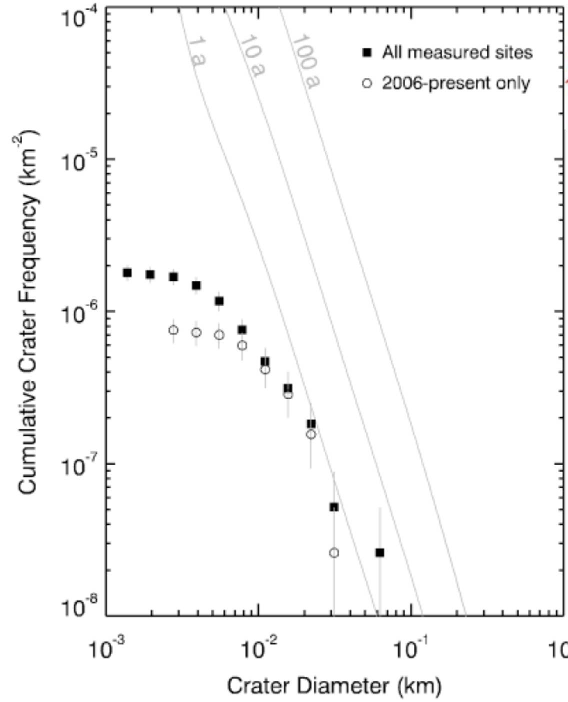
The effect of a soft attenuating layer

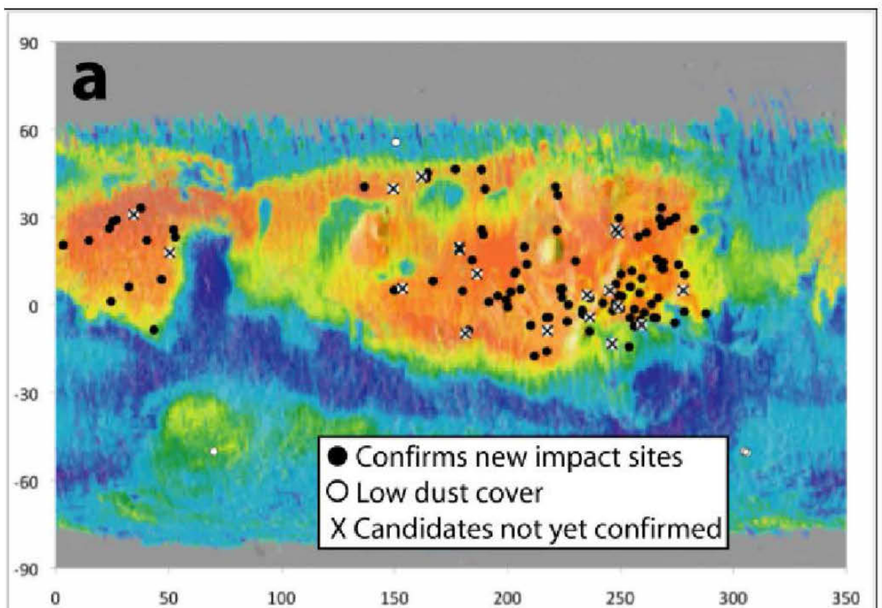


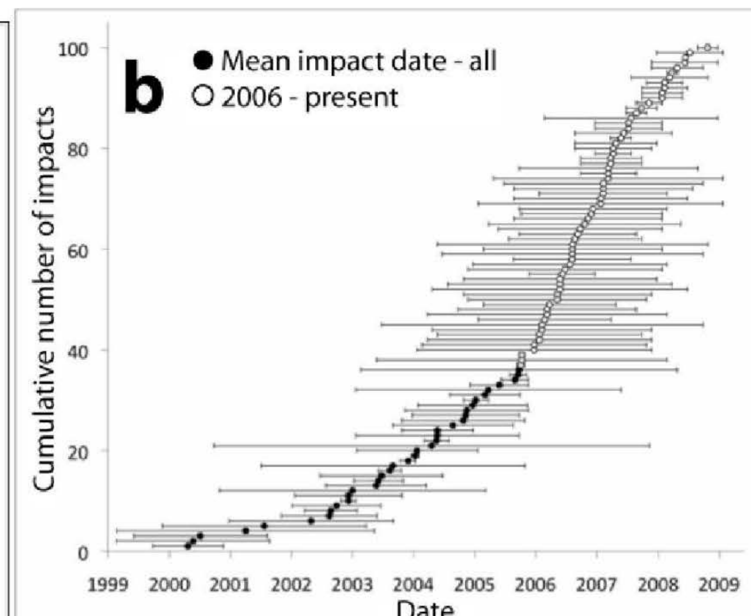
What is the size and frequency distribution of Martian meteorites?



HiRISE image of an impact crater 5.5 meters in diameter that formed between January 2006 and May 2008. PSP_010862_1880.







Daubar et al, [2010]