



Estimation of source time functions and yields of NK explosions directly from seismograms

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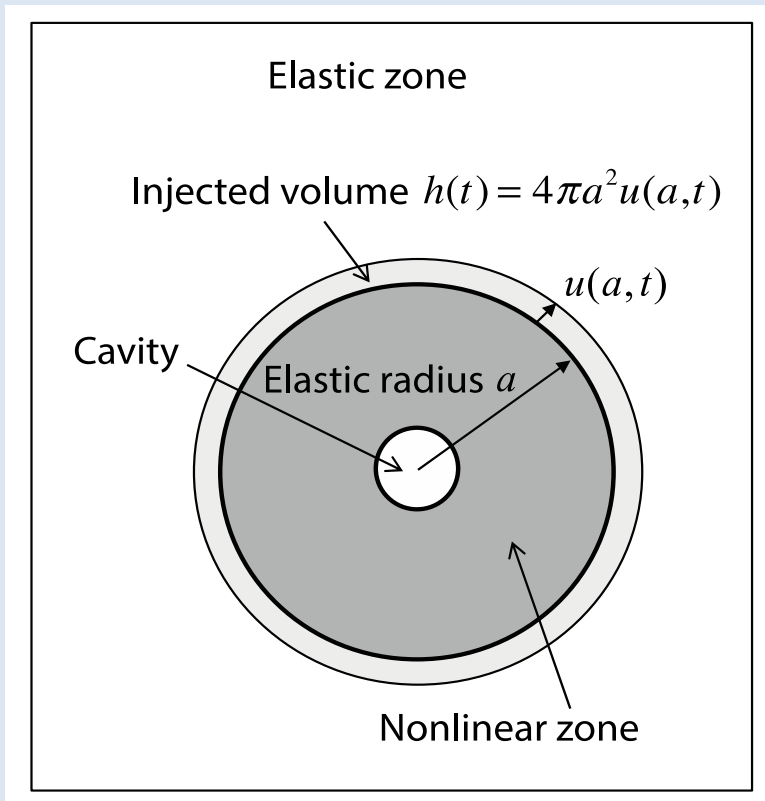
Outline

- Explosions, yield, and source time functions
- Scaling law for explosions
- Source time functions of North Korean events
- Calibration for yield of NK09
- Scaling law test on MDJ seismograms for NK events
- Conclusions

Conventional estimation of yield

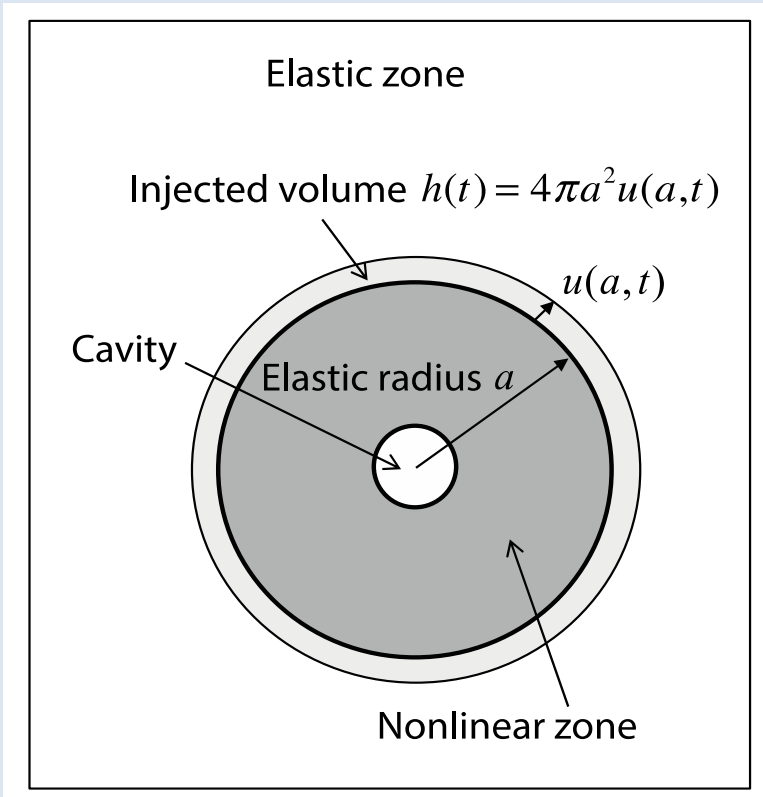
- Body-wave magnitude m_b is a measure of seismic energy released. Yield Y must be related to m_b .
- The relationship depends on the source-receiver path and the geology at the test site.
- These parameters are known for Nevada Test Site (NTS) and Semipalatinsk Test Site (STS)
- They are not known for North Korea Test Site (NKTS).

Explosion

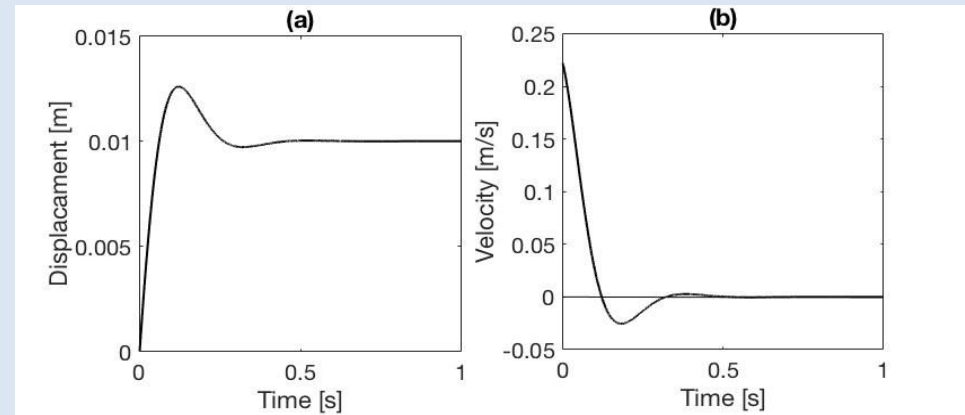
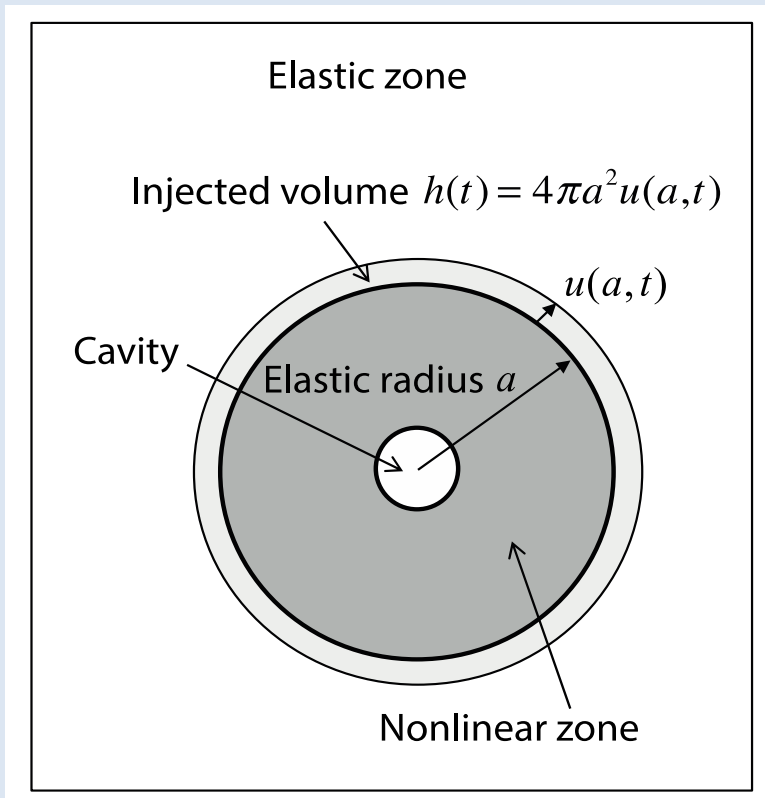


Explosion

For a contained underground test of 5 kt, the injected volume is about 2000 m^3 . The elastic radius a is about 100 m.



Explosion source time functions



Sharpe's (1942) model*

$$\rho_0 = 20 \text{ Mpa}$$

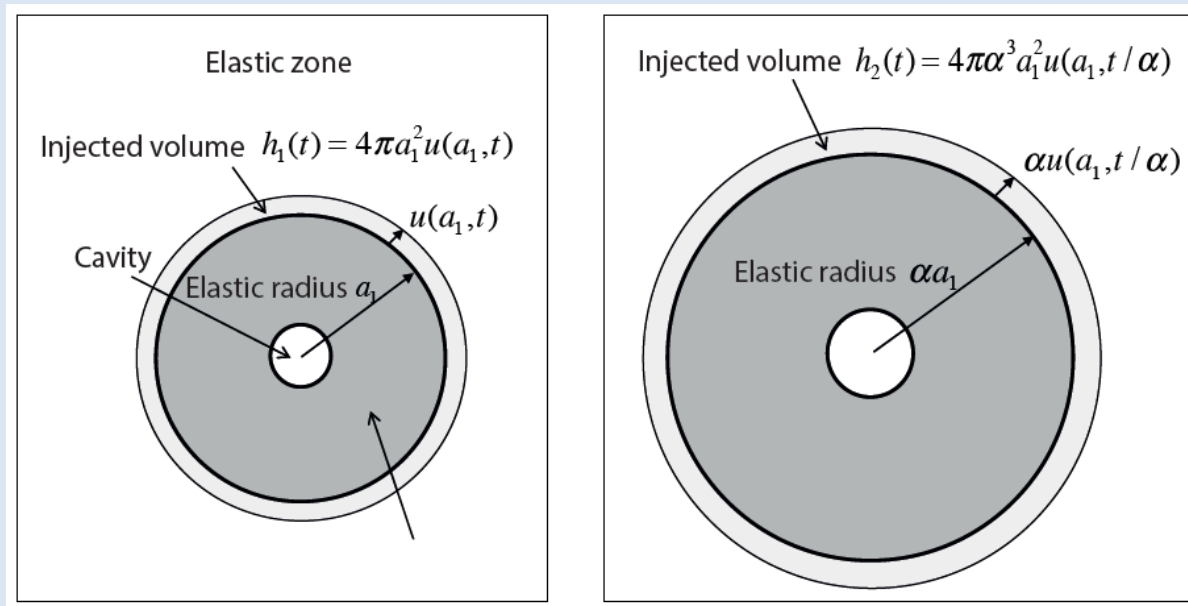
$$\mu = 50 \text{ Gpa}$$

$$a = 100 \text{ m}$$

*Sharpe, J.A., 1942, *Geophysics*, **7**, 144-154.

Most of the energy is contained by the nonlinear zone. Only a small fraction is released as elastic waves.

Scaling law for explosions



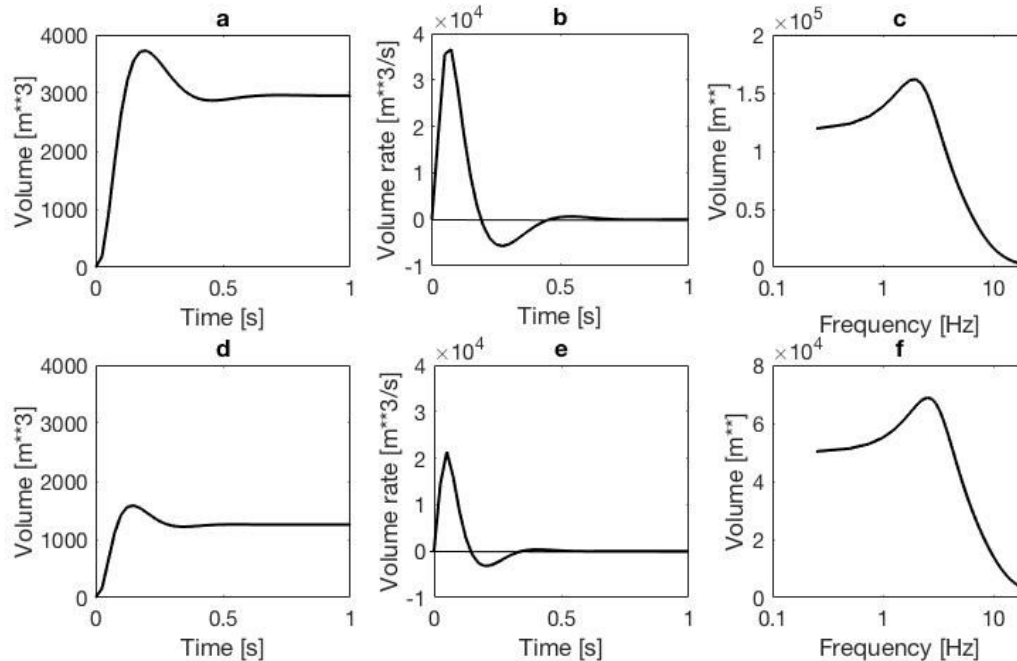
Small source

Big source

Scale factor $\alpha > 1$. Yield ratio is α^3 .

Scaling law for explosions

Big source



Small source

Injected
volume

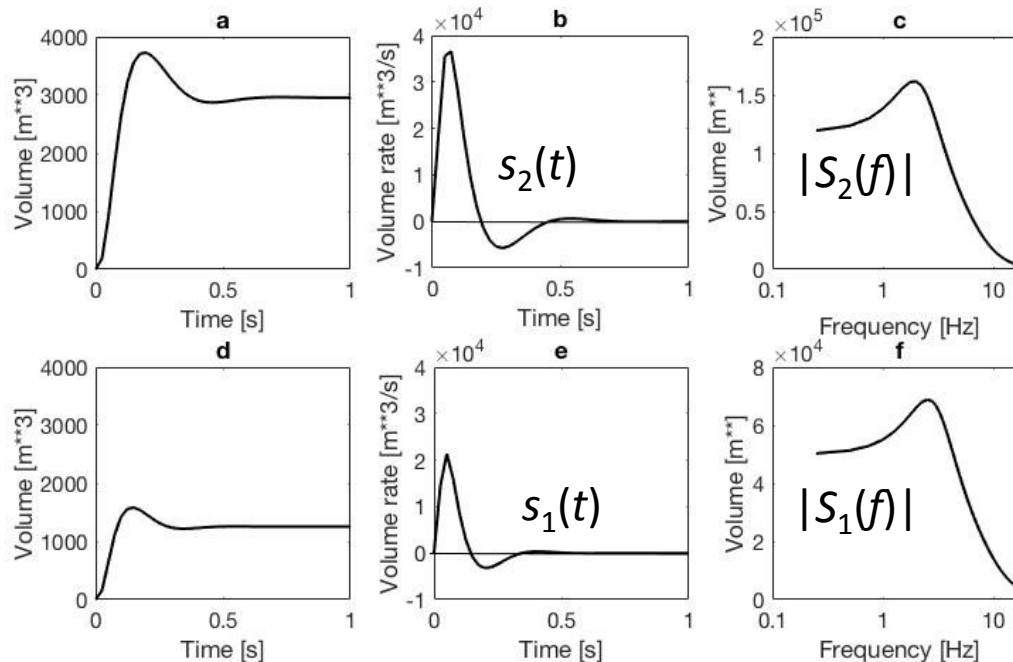
Volume
rate

Amplitude spectrum
of volume rate

Scale factor $\alpha = 1.33$. Yield ratio is α^3 .

Scaling law for explosions

Big source



Small source

Injected
volume

Volume
rate

Amplitude spectrum
of volume rate

Scaling law

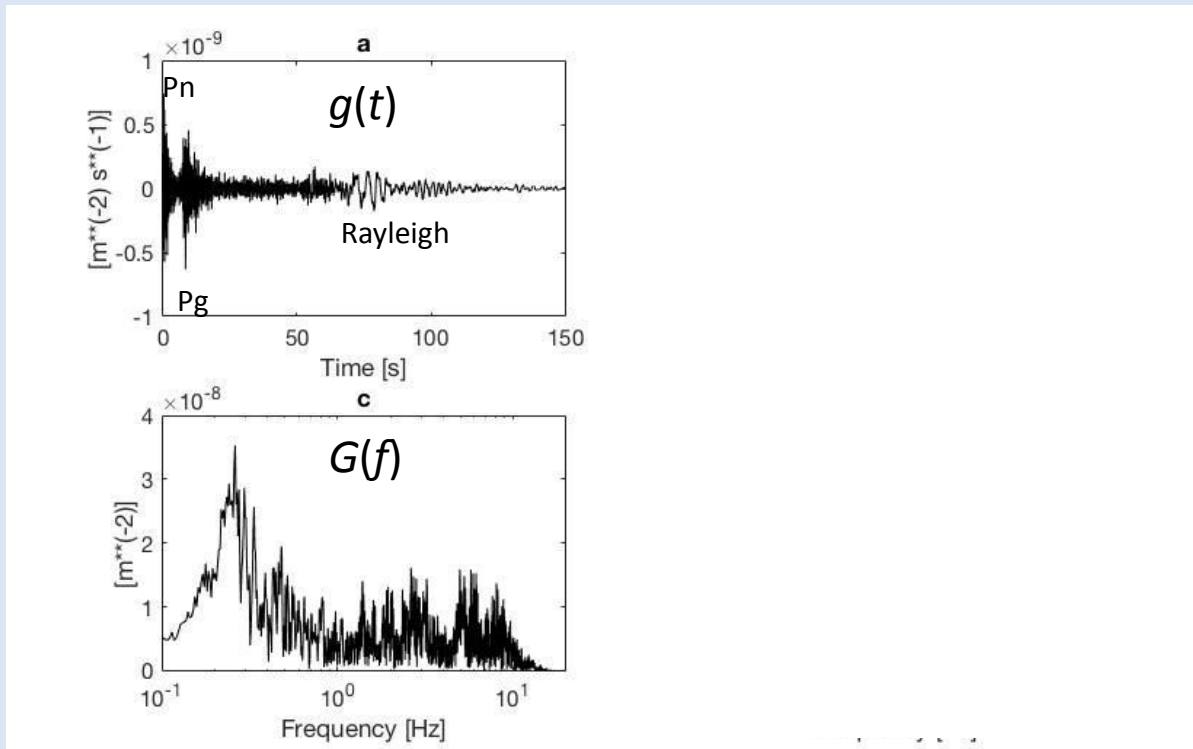
$$s_2(t) = \alpha^2 s_1(t/\alpha)$$

$$S_2(f) = \alpha^3 S_1(\alpha f)$$

Scale factor $\alpha = 1.33$. Yield ratio is α^3 .

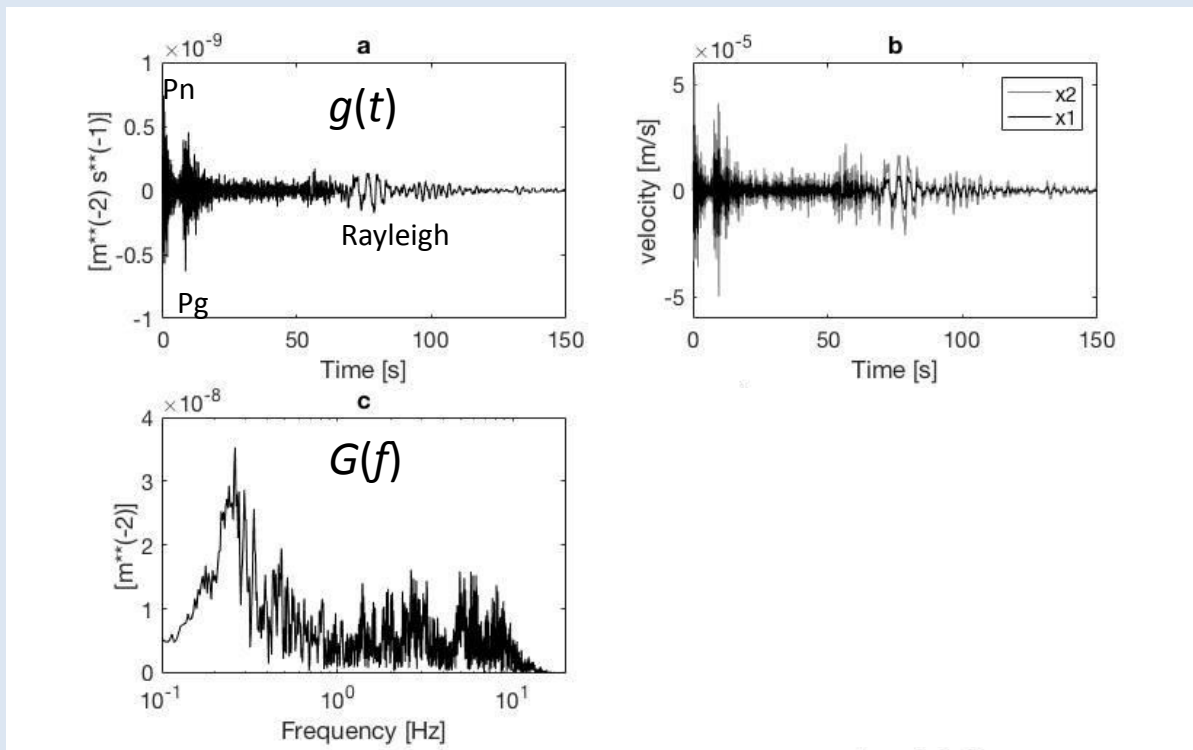
Synthetic seismograms

Start with a Green's function, or impulse response



Synthetic seismograms: two close sources, one receiver

Convolve this with the two source time functions $s_1(t)$ and $s_2(t)$

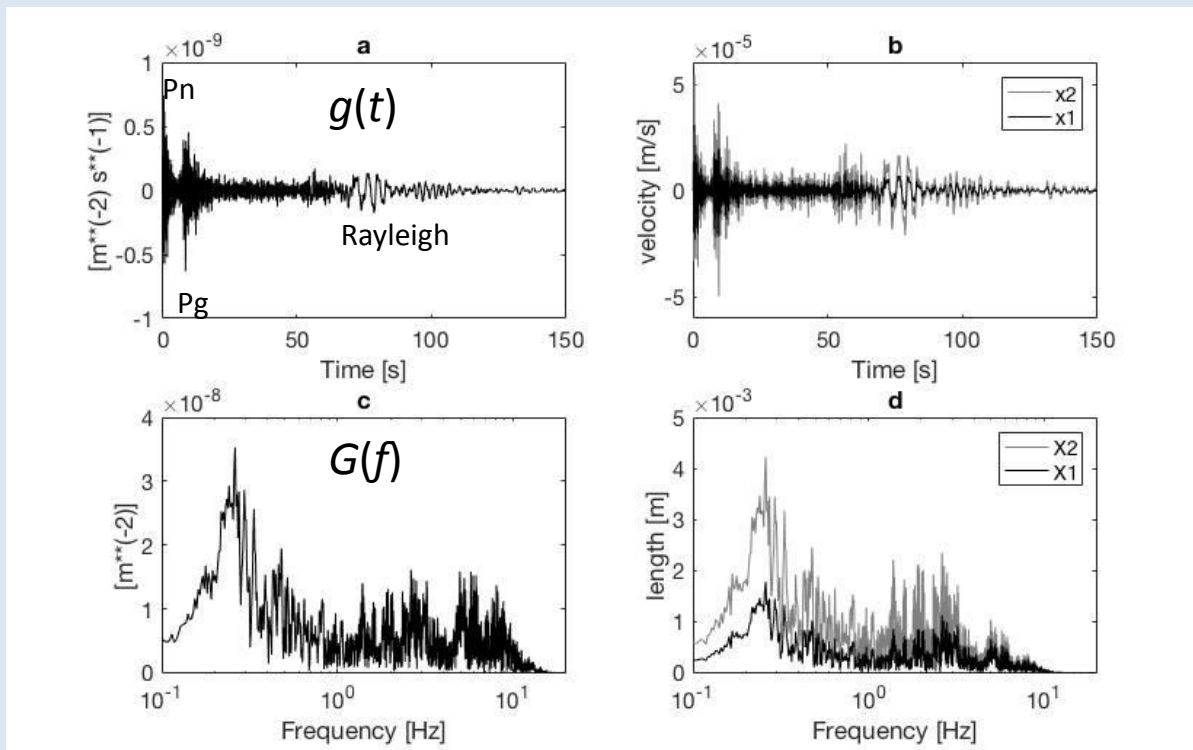


$$x_1(t) = s_1(t) * g(t)$$

$$x_2(t) = s_2(t) * g(t)$$

Synthetic seismograms: two close sources, one receiver

Transform to frequency: the convolution becomes a multiplication



$$x_1(t) = s_1(t) * g(t)$$

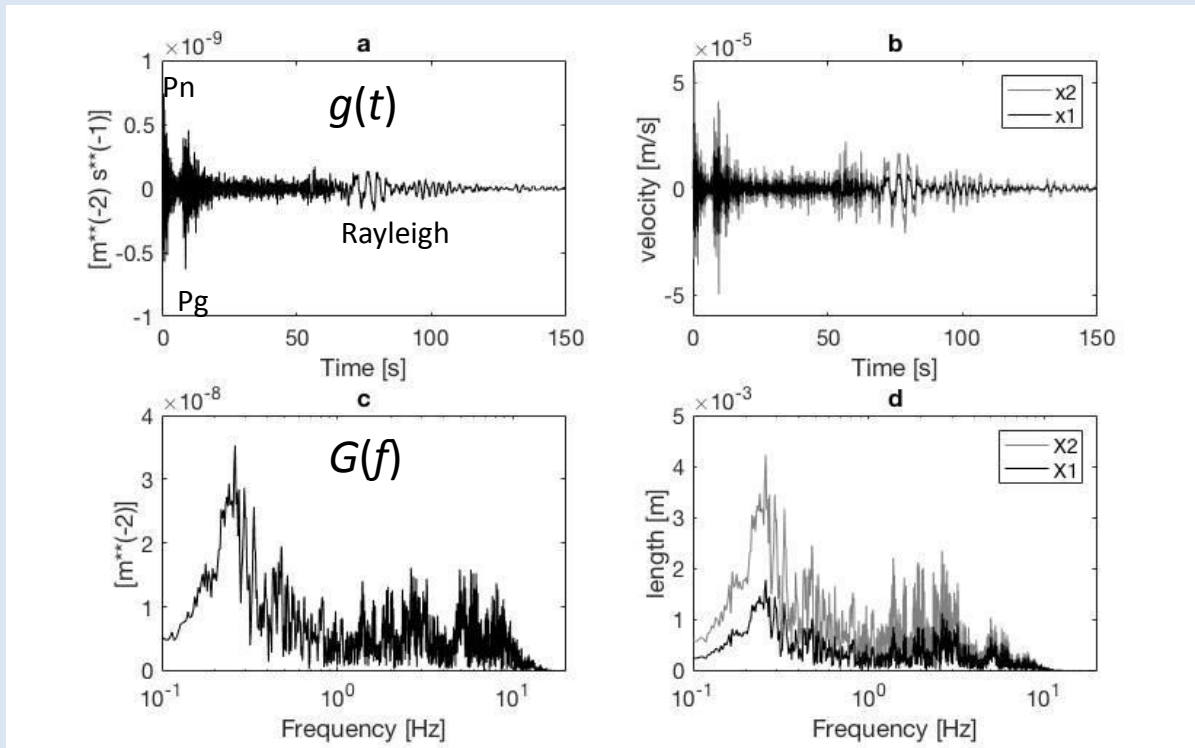
$$x_2(t) = s_2(t) * g(t)$$

$$X_1(f) = S_1(f)G(f)$$

$$X_2(f) = S_2(f)G(f)$$

Synthetic seismograms: two close sources, one receiver

Find the spectral ratio.



$$x_1(t) = s_1(t) * g(t)$$

$$x_2(t) = s_2(t) * g(t)$$

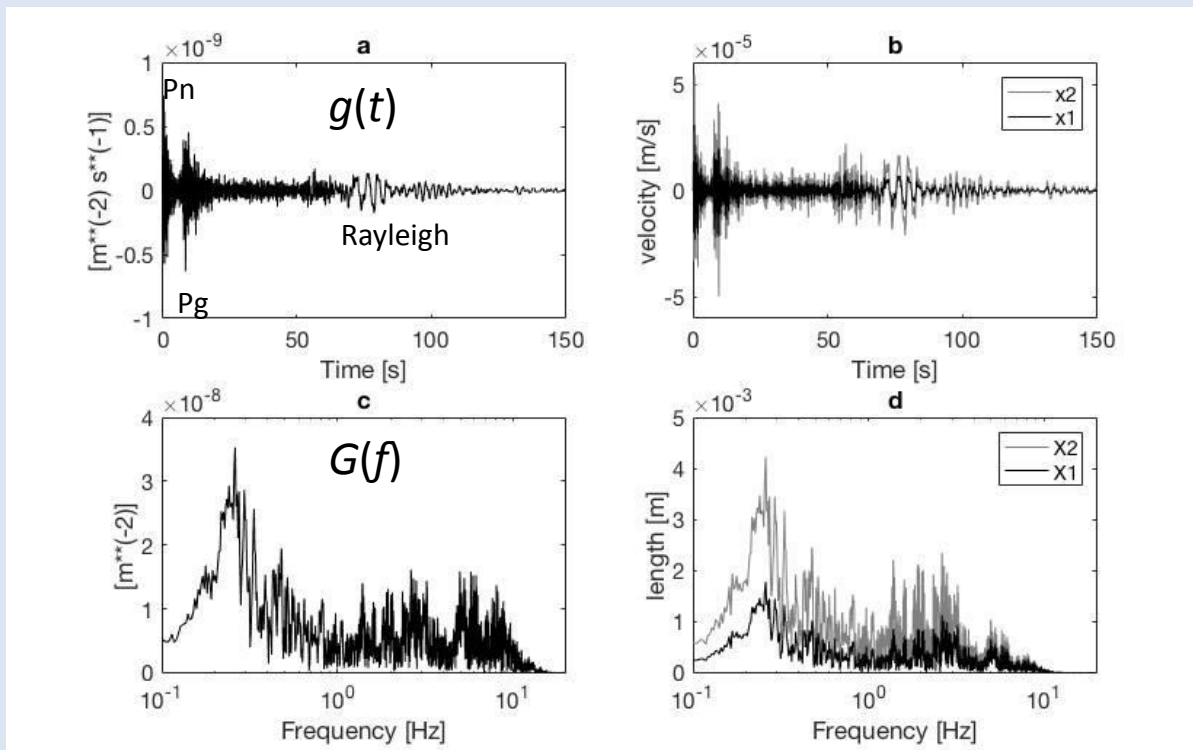
$$X_1(f) = S_1(f)G(f)$$

$$X_2(f) = S_2(f)G(f)$$

$$R(f) = X_2(f) / X_1(f)$$

Synthetic seismograms: two sources close to each other, one receiver

Spectral ratio of seismograms = ratio of source spectra



$$x_1(t) = s_1(t) * g(t)$$

$$x_2(t) = s_2(t) * g(t)$$

$$X_1(f) = S_1(f)G(f)$$

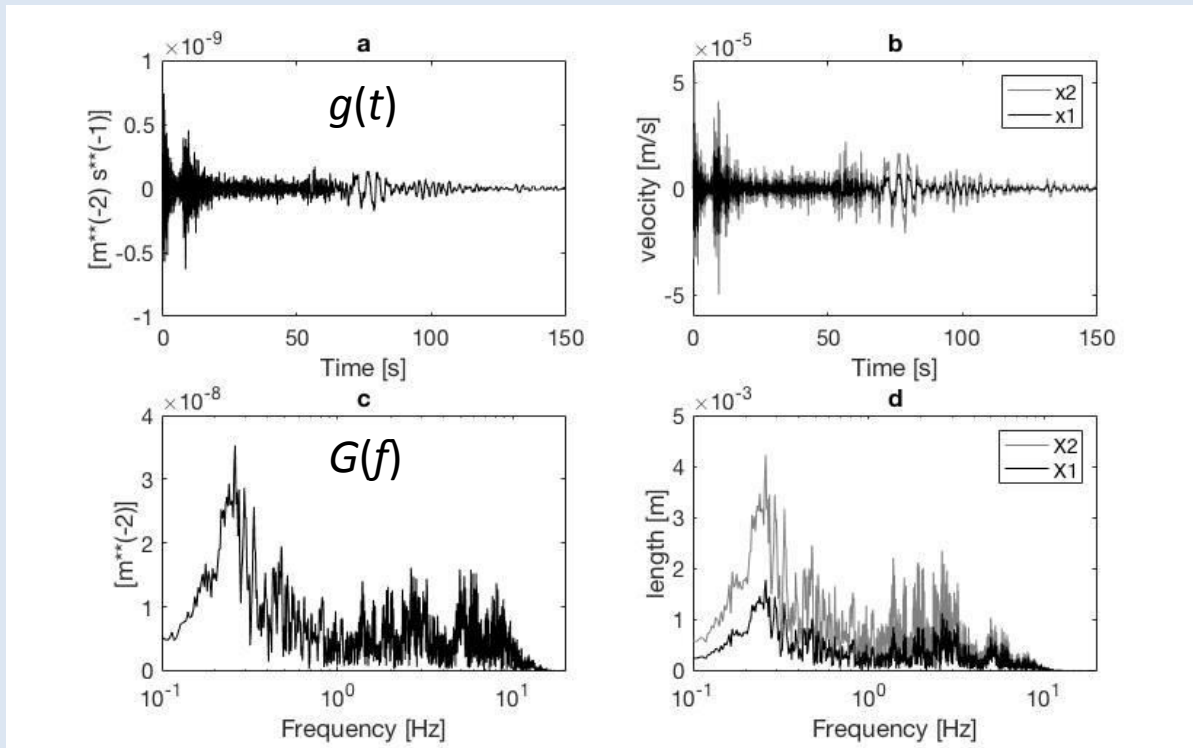
$$X_2(f) = S_2(f)G(f)$$

$$R(f) = X_2(f) / X_1(f)$$

$$R(f) = S_2(f) / S_1(f)$$

Synthetic seismograms: two close sources, one receiver

Scaling law is another relationship between the source spectra



$$x_1(t) = s_1(t) * g(t)$$

$$x_2(t) = s_2(t) * g(t)$$

$$X_1(f) = S_1(f)G(f)$$

$$X_2(f) = S_2(f)G(f)$$

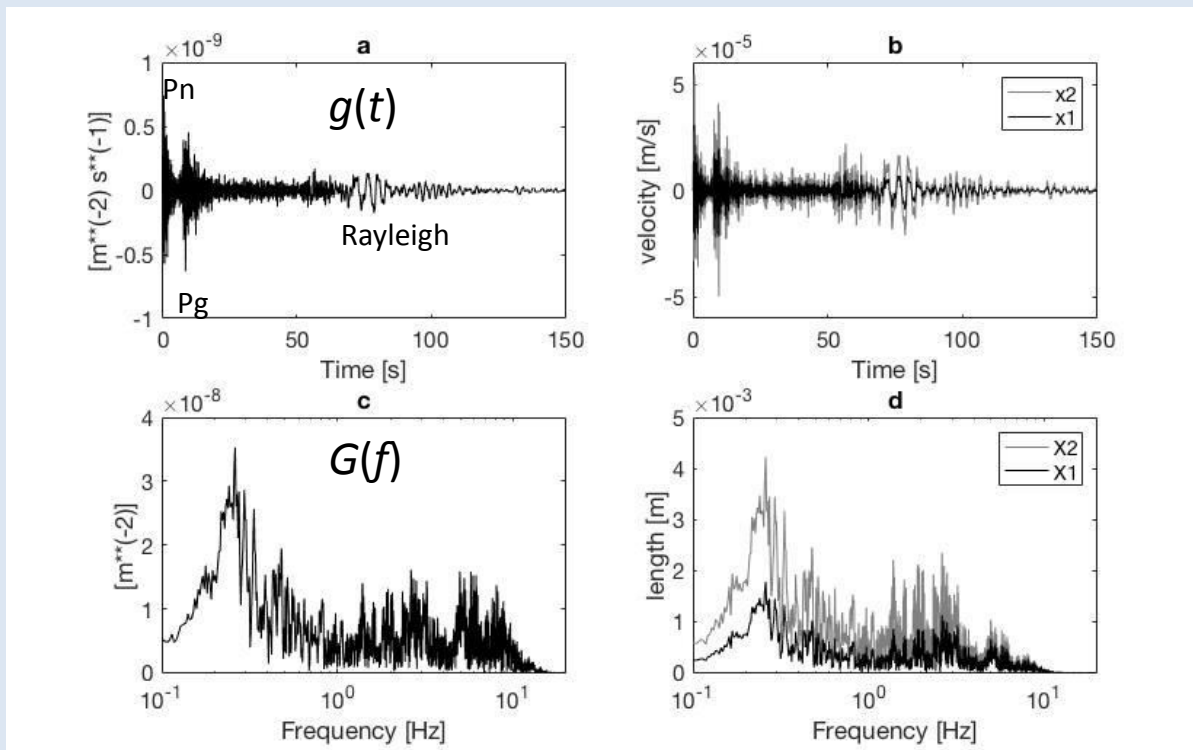
$$R(f) = X_2(f) / X_1(f)$$

$$R(f) = S_2(f) / S_1(f)$$

$$S_2(f) = \alpha^3 S_1(\alpha f)$$

Synthetic seismograms: two close sources, one receiver

We now have two equations with two unknowns: $S_1(f)$ and $S_2(f)$.



$$x_1(t) = s_1(t) * g(t)$$

$$x_2(t) = s_2(t) * g(t)$$

$$X_1(f) = S_1(f)G(f)$$

$$X_2(f) = S_2(f)G(f)$$

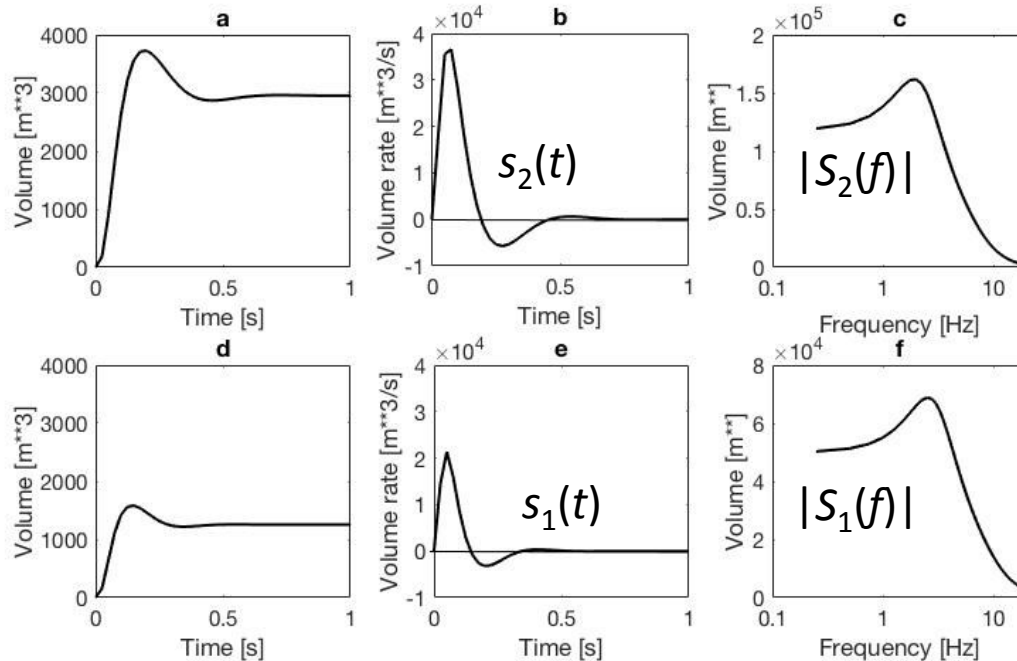
$$R(f) = X_2(f) / X_1(f)$$

$$R(f) = S_2(f) / S_1(f)$$

$$S_2(f) = \alpha^3 S_1(\alpha f)$$

We can solve the two equations for the two source time functions.

Big source



Small source

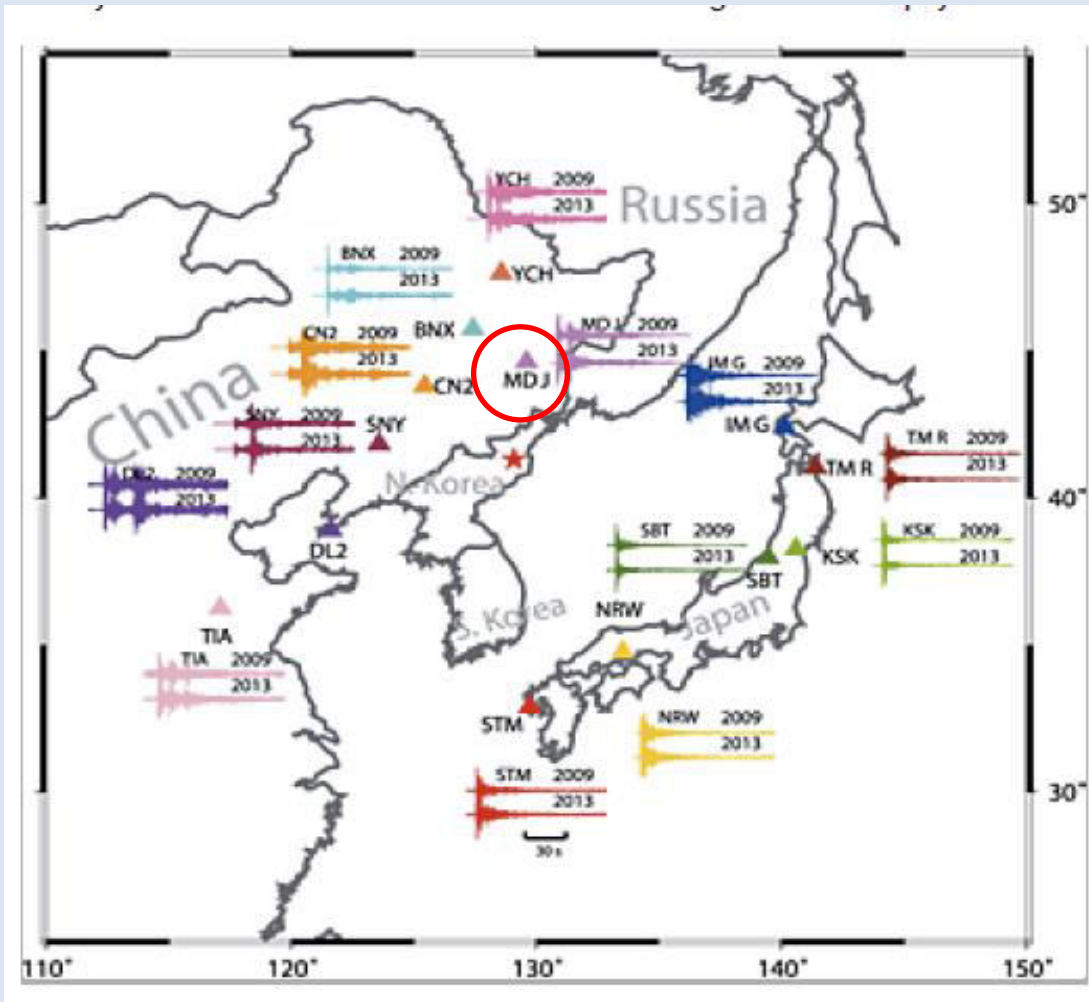
Injected
volume

Volume
rate

Amplitude spectrum
of volume rate

Scale factor $\alpha = 1.33$. Yield ratio is α^3 .

Observation of NK events

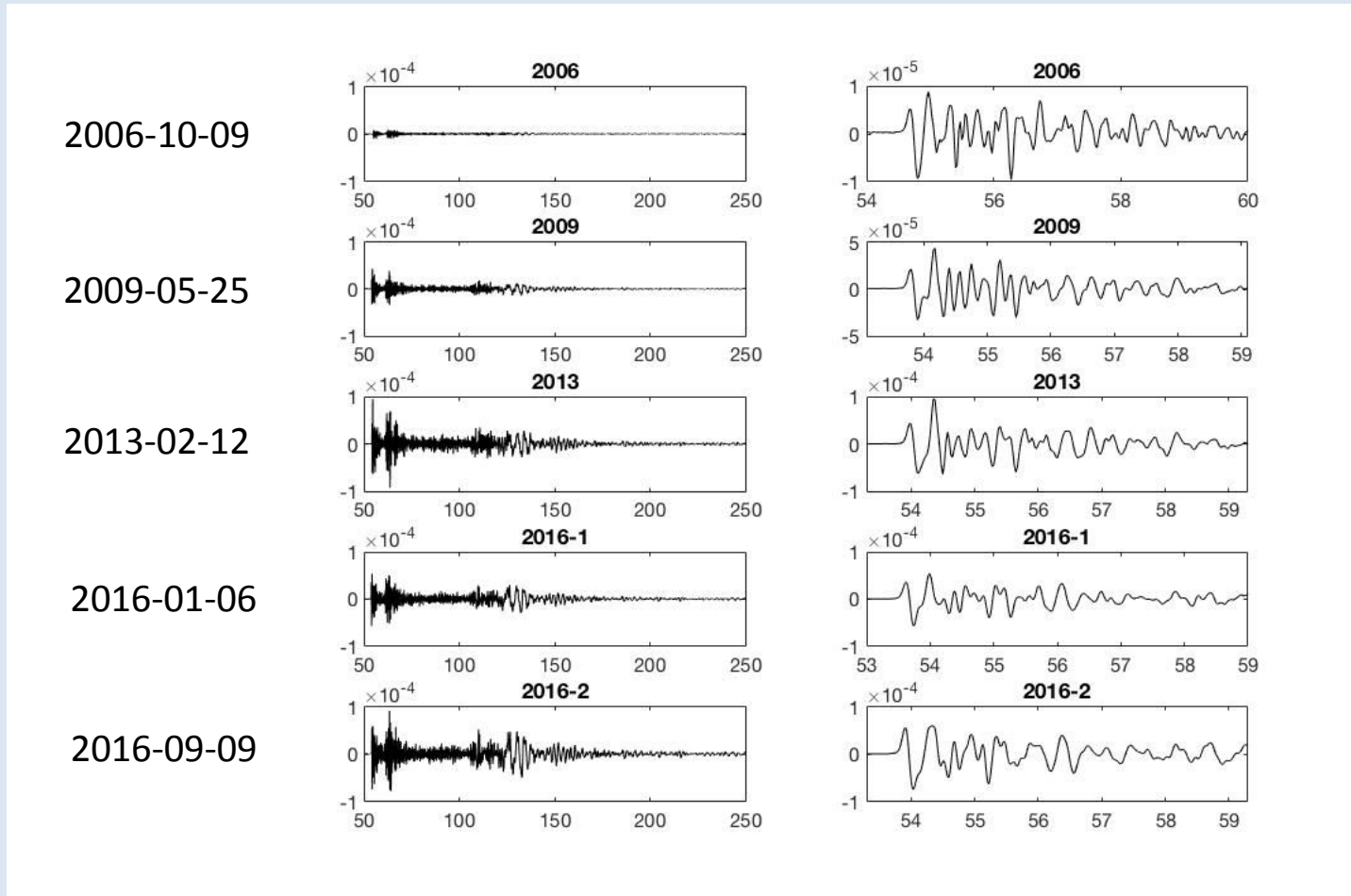


Data from MDJ is obtainable from IRIS. MDJ is 373 km from NKTS.

I was not allowed access to data from any other Chinese stations.

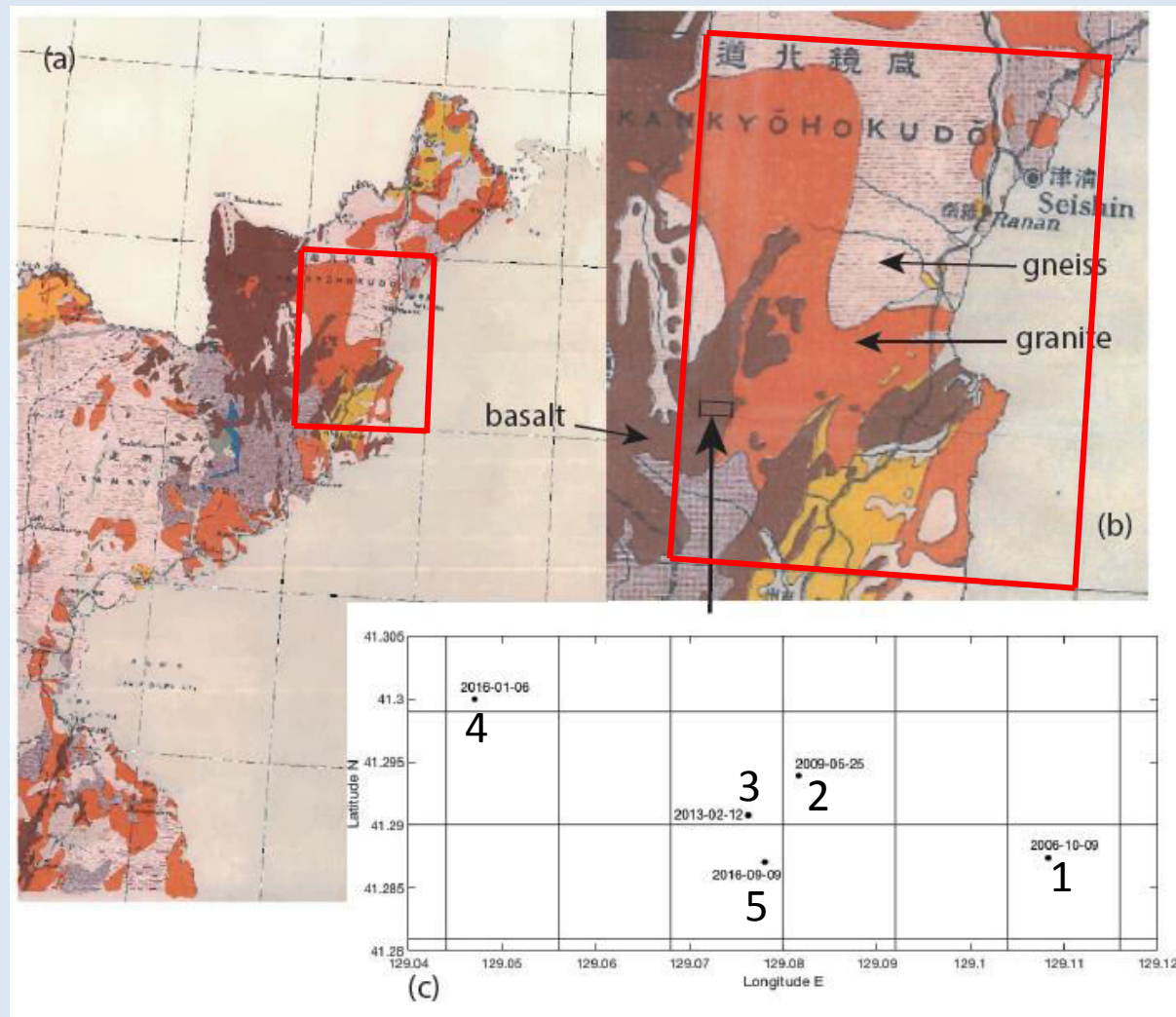
I have obtained seismograms recorded at the 65 stations on the Japan F-net, but they are too far away and too noisy.

Real data: NK events seen at MDJ



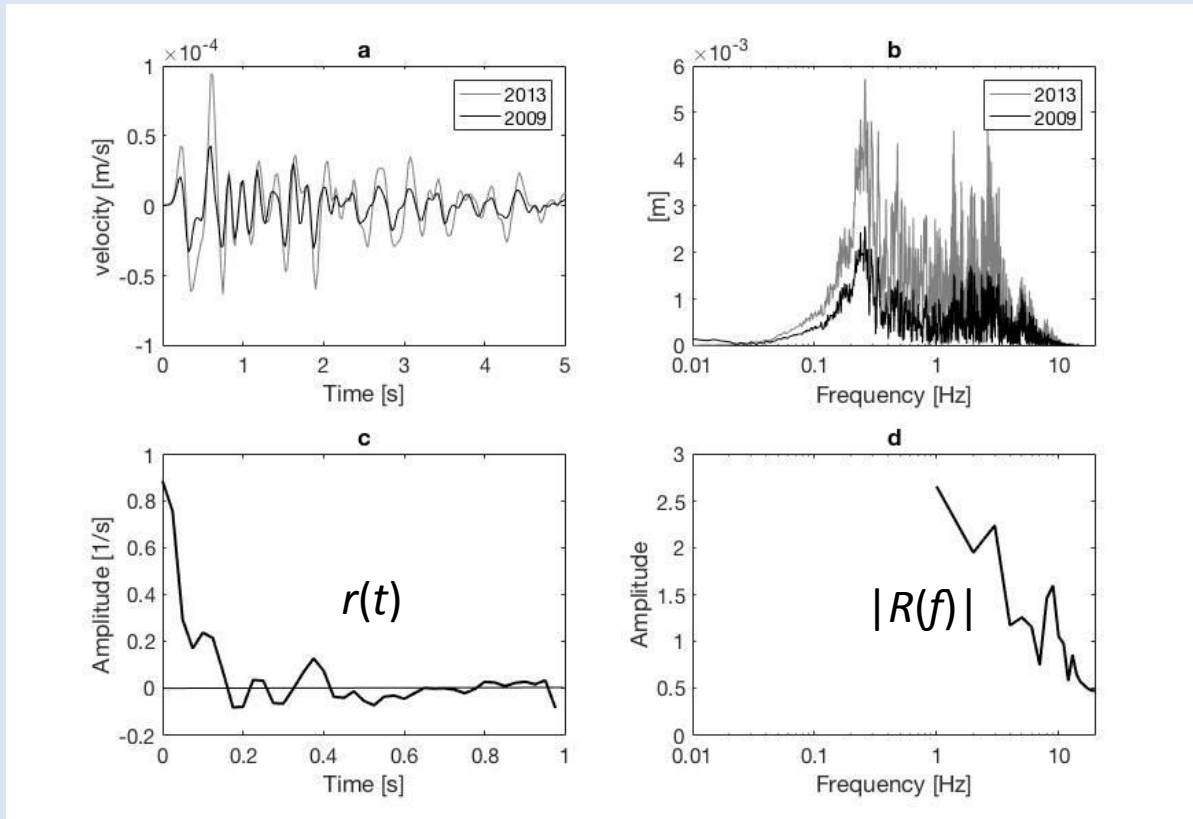
Amplitudes are m/s Time is s.

Location of North Korean tests



Locations of NK tests in relation to the geology: (a) NE corner of the geological map of North Korea showing lines of latitude and longitude at 1° intervals; (b) enlargement of 1° x 1° section of (a); (c) enlargement of small rectangle in (b) showing locations of the NK tests, all of which appear to be in basalt. In (c) the squares have 1 km sides. (Geological map produced in 1926 by Imperial Geological Survey of Japan.)

Spectral ratio NK13/NK09



$$R(f) = \frac{X_2(f)}{X_1(f)} \frac{S_2(f)}{S_1(f)}$$

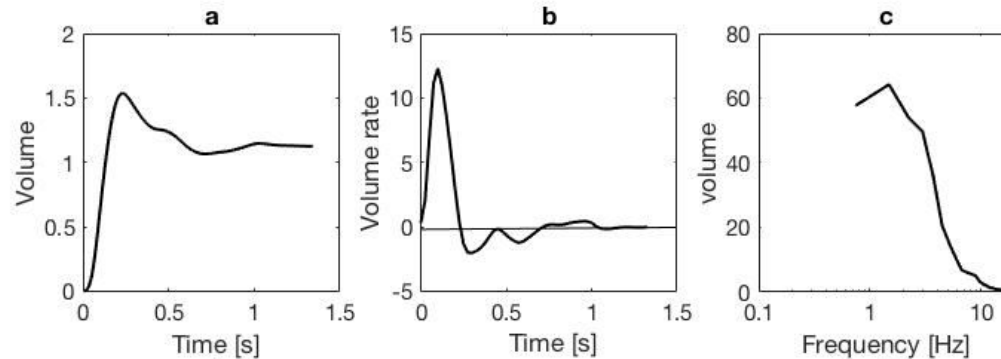
$$S_2(f) = S_1(f)$$

NK13 and NK09 were less than 1 km apart*.

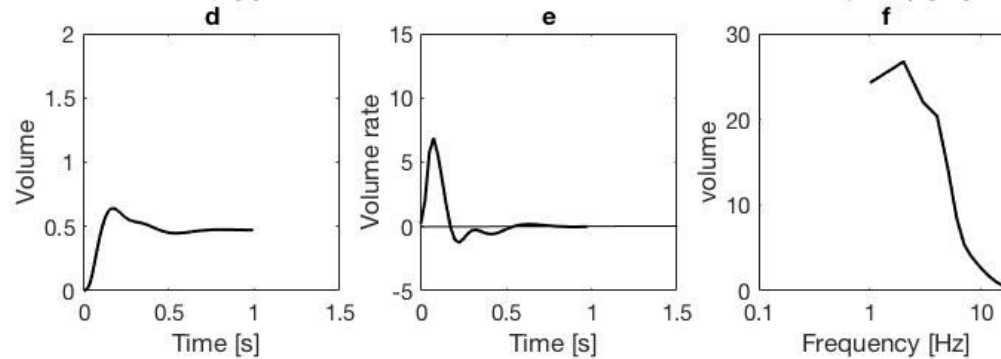
*Zhang, M. and L. Wen, 2013, High precision location and yield of North Korea's 2013 nuclear test: *Geophysical Research Letters*, 40, 2941-2946, doi:10.1002/grl.50607, 2013.

Uncalibrated source time functions: NK09 and NK13

NK13



NK09



Injected
volume

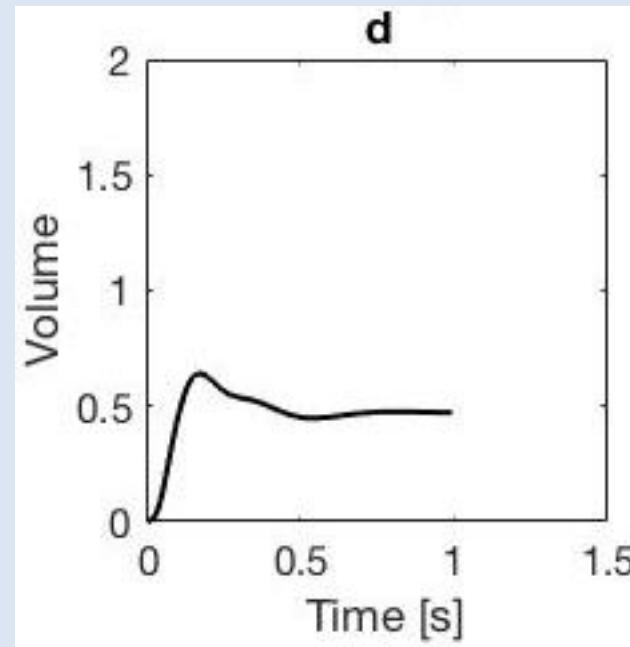
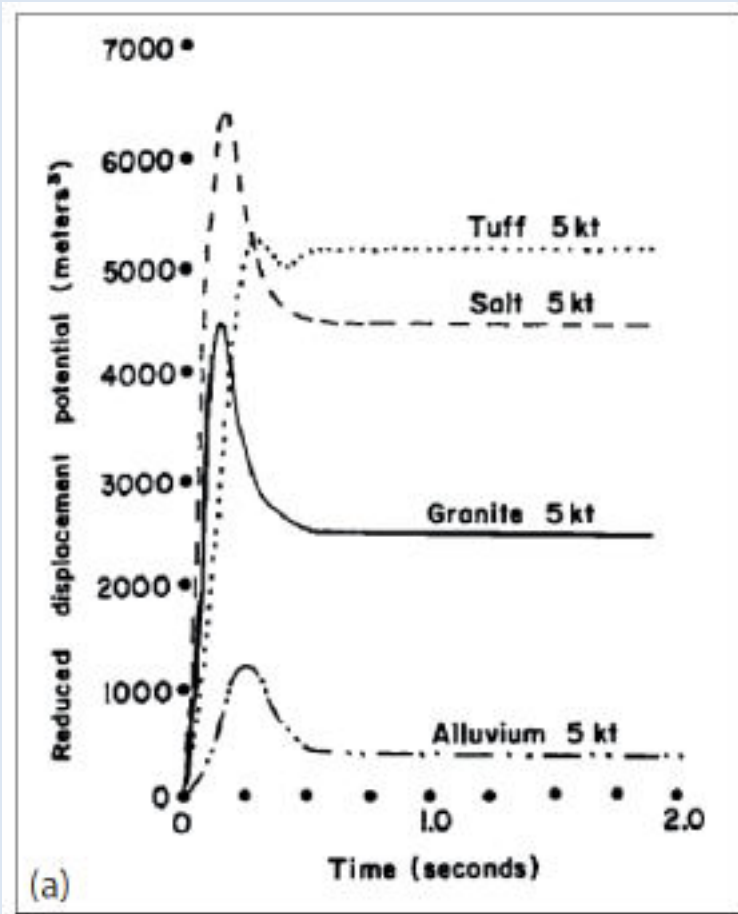
Volume
rate

Amplitude spectrum
of volume
rate

We know the timing, but not the amplitude scale.

We need to calibrate against known yields in known rocks.

Calibration for yield

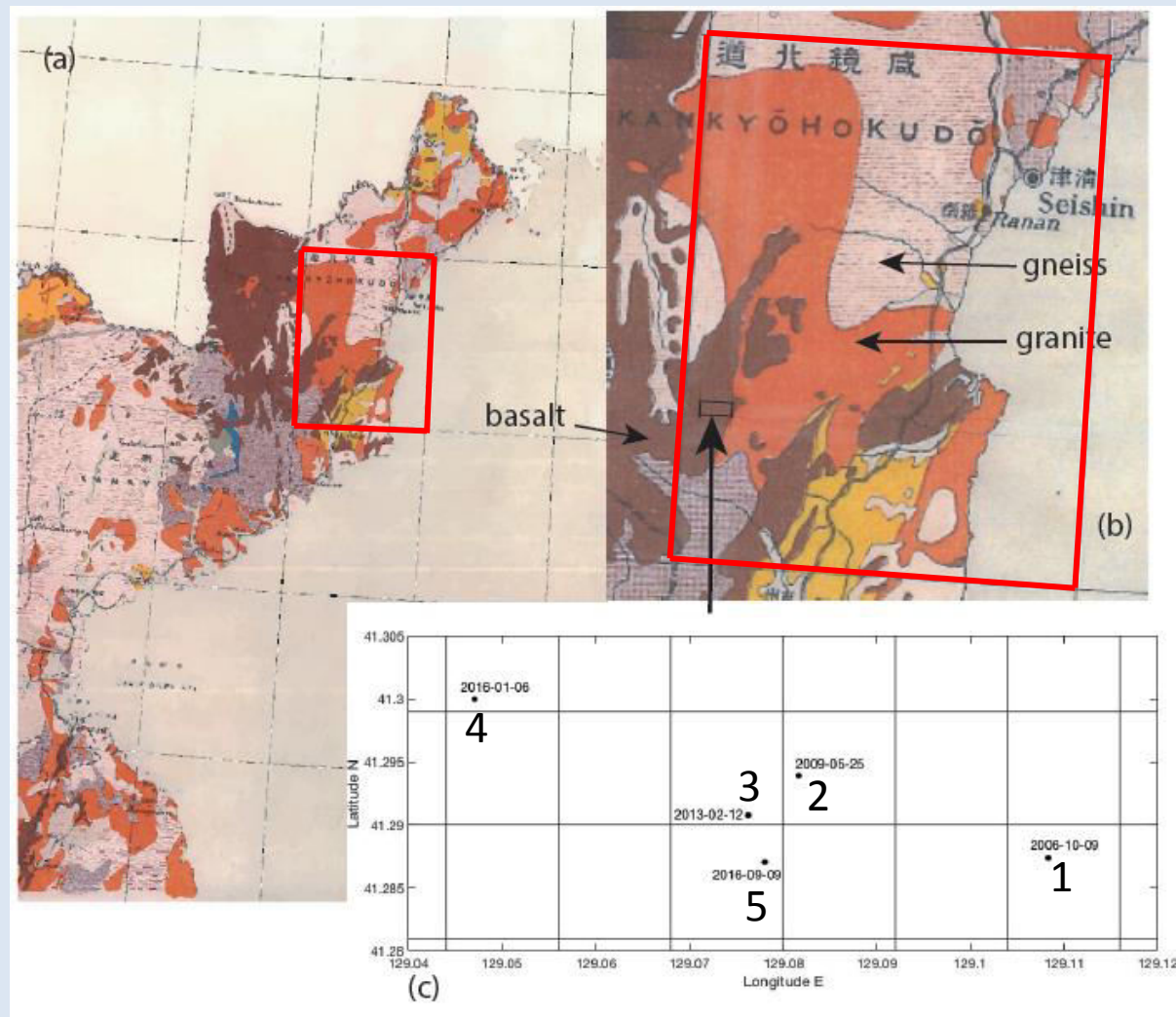


NTS measurements

Werth, G.C. and R.F. Herbst, 1963, Comparison of amplitudes of seismic waves from nuclear explosions in four mediums: *Journal of Geophysical Research*, Vol. 68, No.5, 1463-1475.

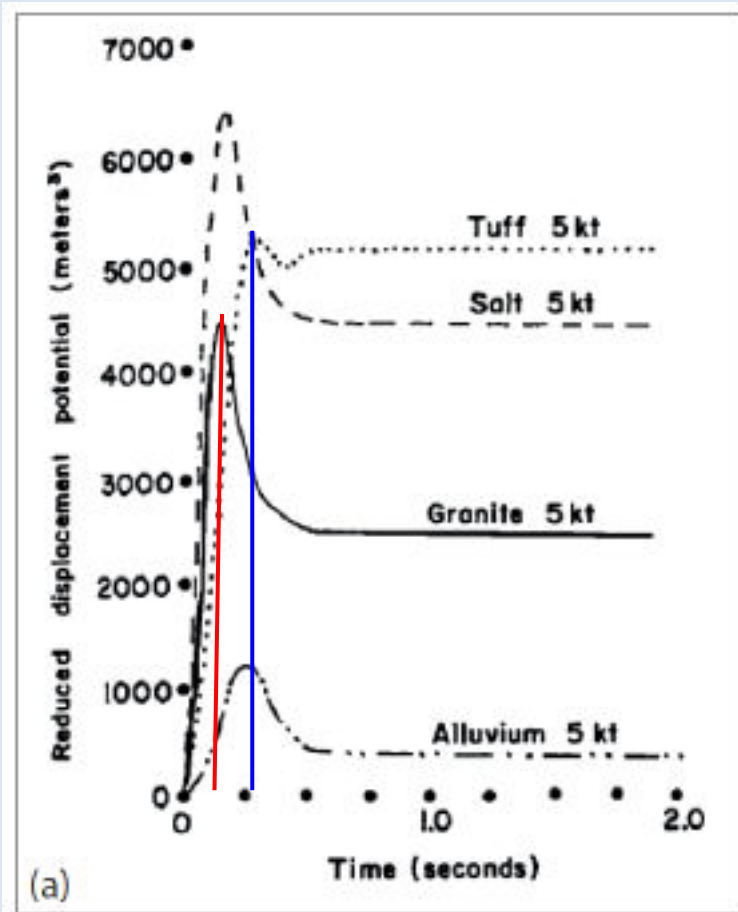
Shape is between granite and tuff

Location of North Korean tests

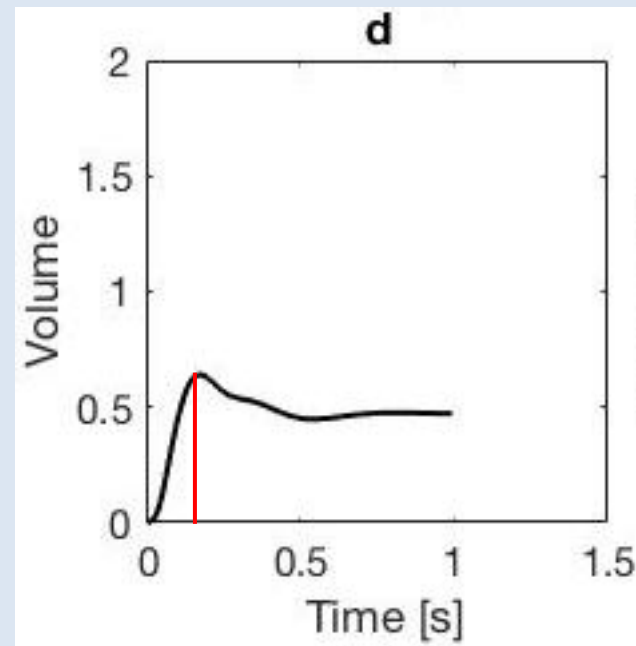


Locations of NK tests in relation to the geology: (a) NE corner of the geological map of North Korea showing lines of latitude and longitude at 1° intervals; (b) enlargement of 1° x 1° section of (a); (c) enlargement of small rectangle in (b) showing locations of the NK tests, all of which appear to be in basalt. In (c) the squares have 1 km sides. (Geological map produced in 1926 by Imperial Geological Survey of Japan.)

Calibration for yield



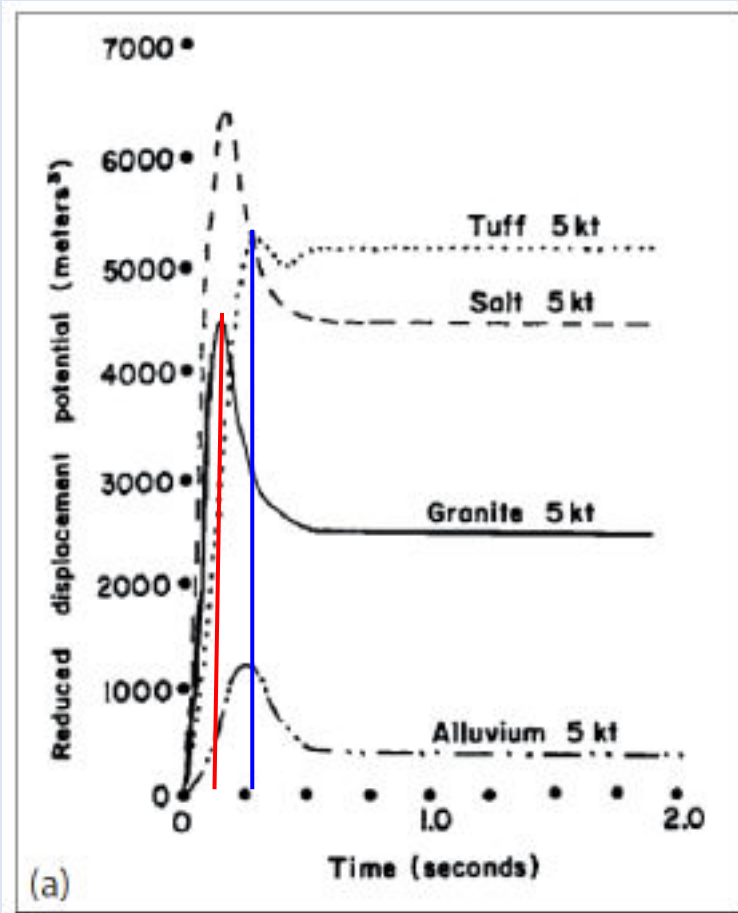
The time to the peak allows the yield to be obtained using the scaling law.



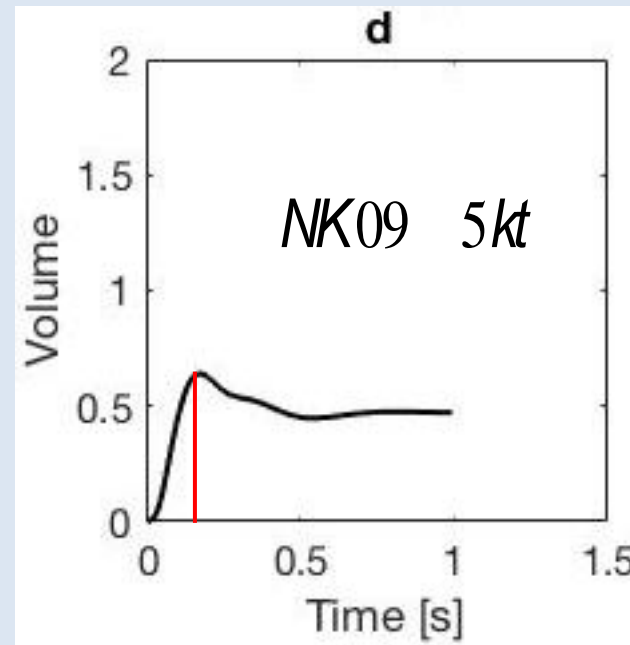
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Calibration for yield



The time to the peak allows the yield to be obtained using the scaling law.

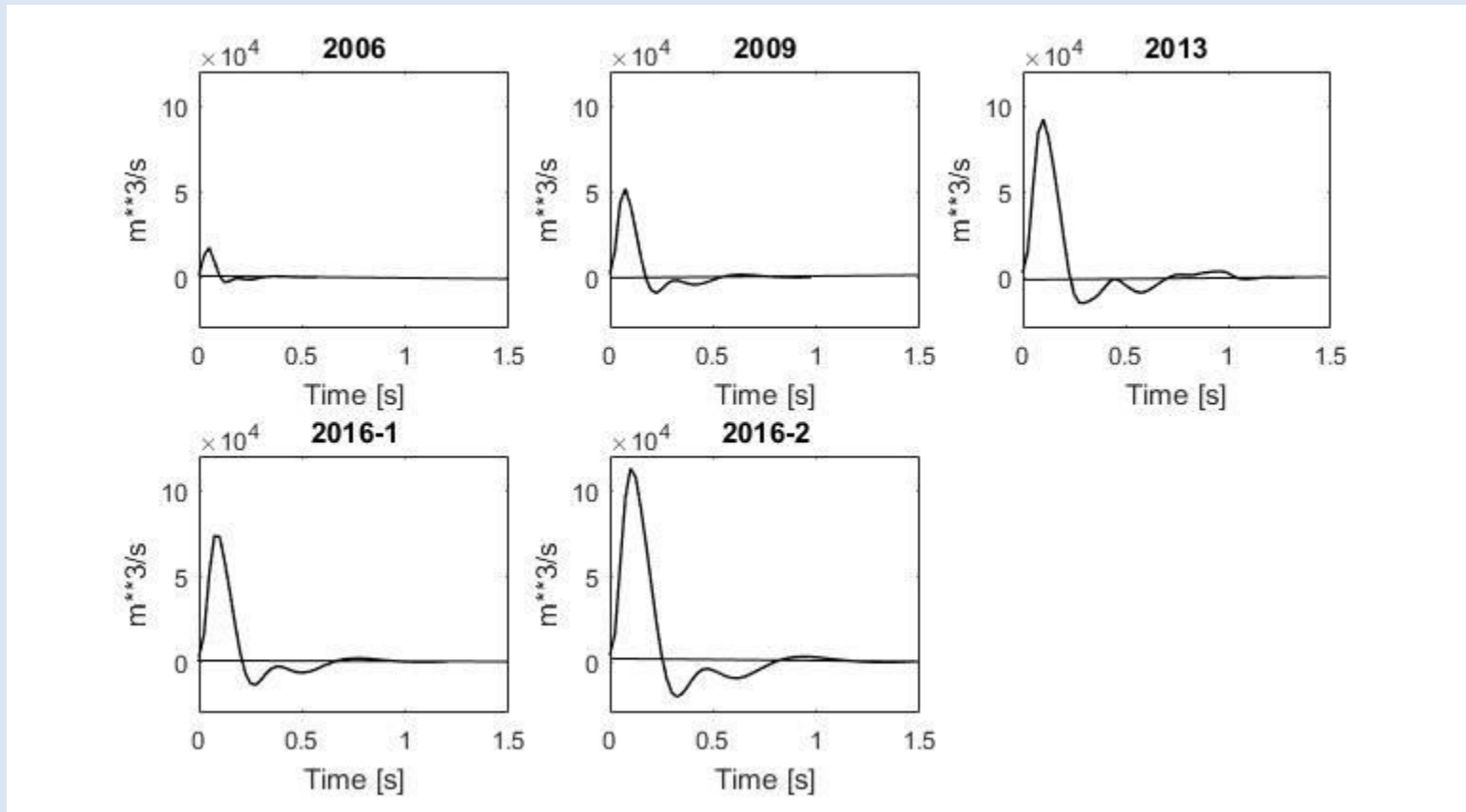


NTS measurements

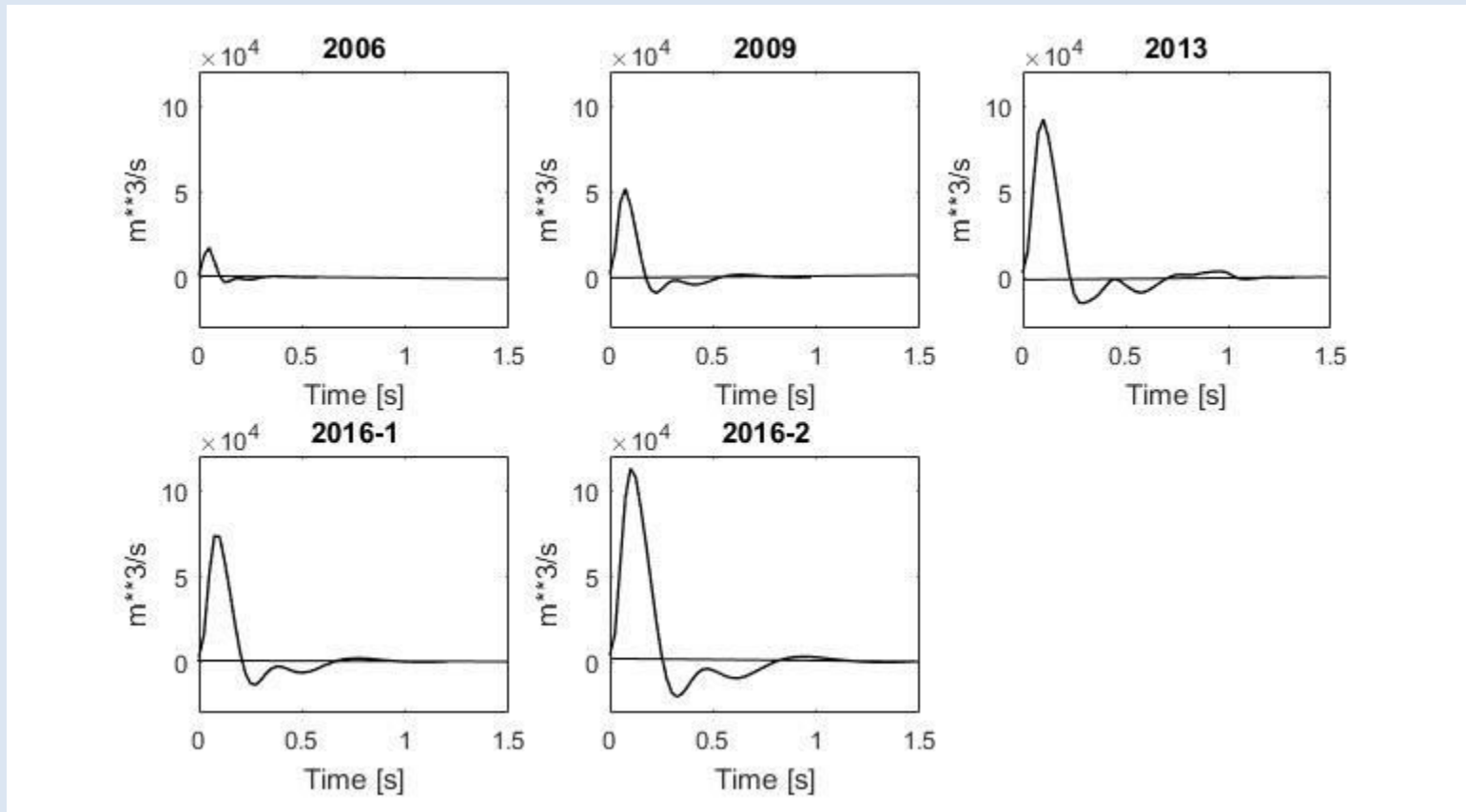
Werth, G.C. and R.F. Herbst, 1963, Comparison of amplitudes of seismic waves from nuclear explosions in four mediums: *Journal of Geophysical Research*, Vol. 68, No.5, 1463-1475.

The explosions took place in weathered basalt.

Estimated DPRK source signatures

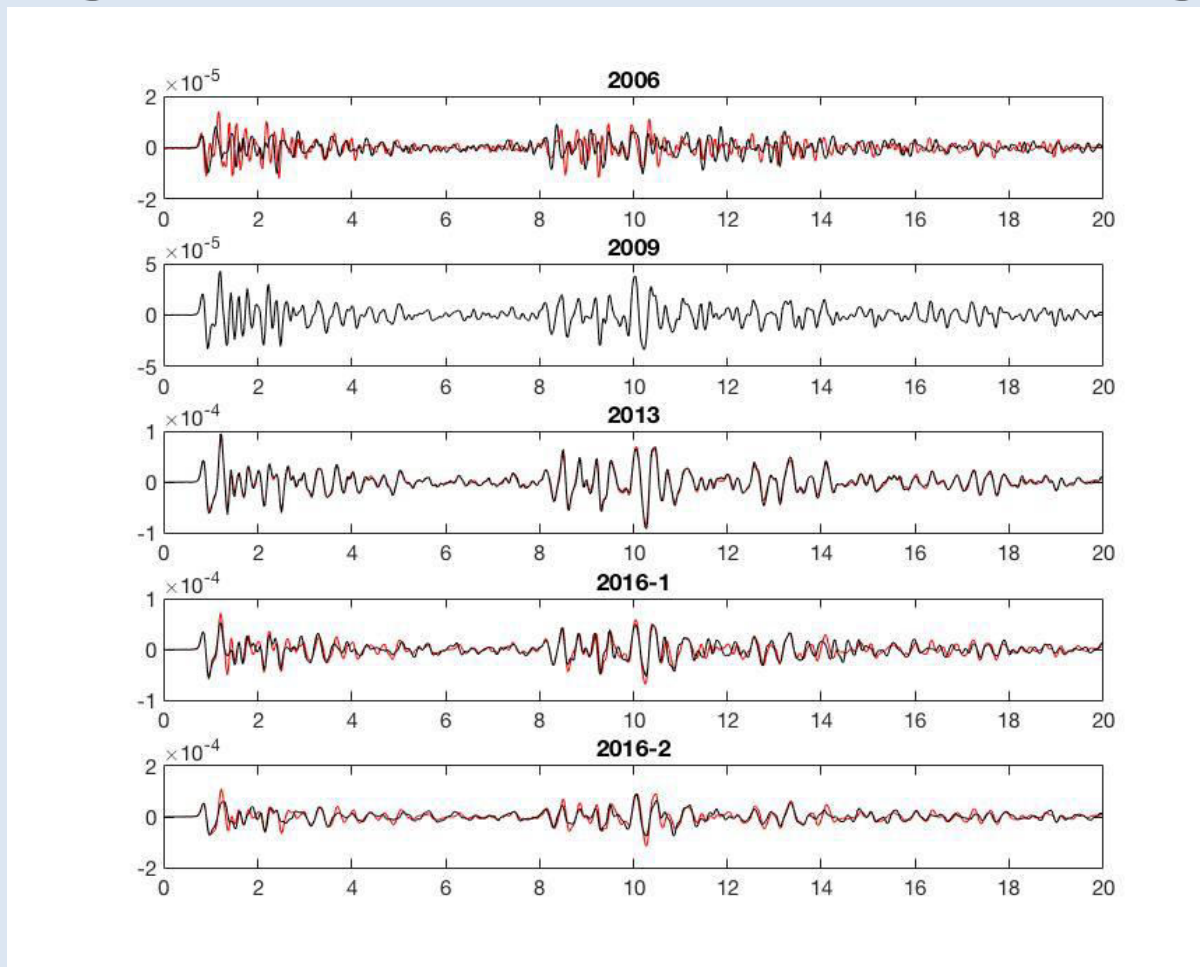


Estimated DPRK source signatures



Now convolve each one with the same Green's function and compare with the measured MDJ seismograms.

Scaling law test on MDJ seismograms



Measured seismograms are black. Synthetics are red. Green's function obtained from NK09 by deconvolution. Source time functions obtained from NK09 source time function by scaling. Synthetics obtained by convolution of Green's function with source time functions.

Estimated yields

Event	Scale factor	Yield kt
NK06	0.59	1
NK09	1	5
NK13	1.35	12
NK16-1	1.21	8.9
NK16-2	1.48	16.2

Estimated yields

Event	Scale factor	Yield kt
NK06	0.59	1
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NK16-1	1.21	8.9
NK16-2	1.48	16.2

±?



The ratios are more precise than the absolute values.

Conclusions

- Source signatures for the NK events have been found directly from the MDJ seismograms.
- The scaling-law is approximately correct.
- NK yield ratios are more precise than yields.
- The Green's function has higher resolution than the seismograms.