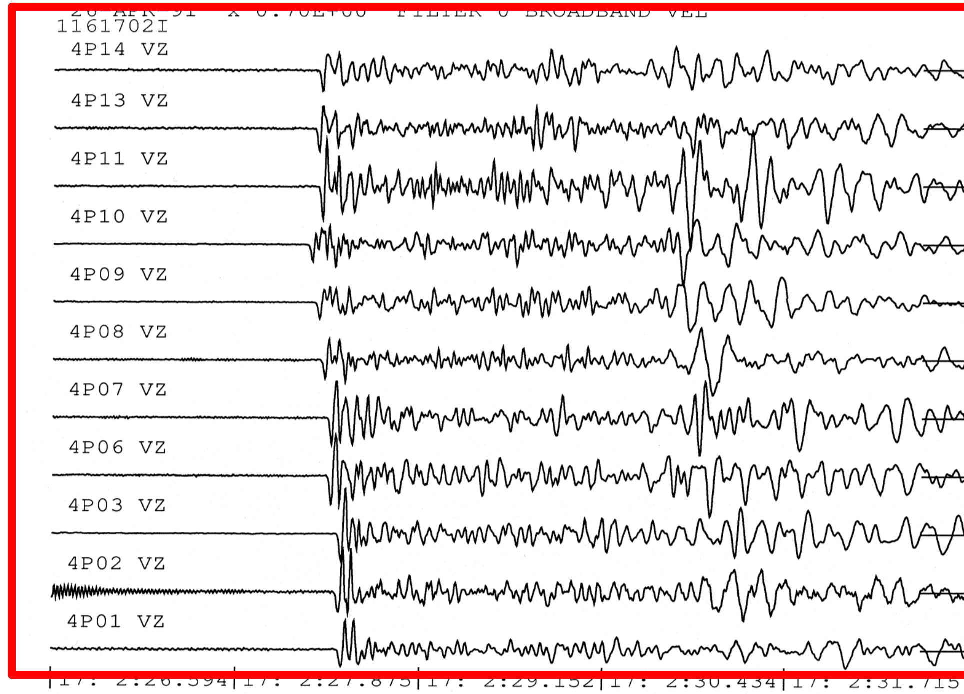
Variations and healing of the seismic velocity

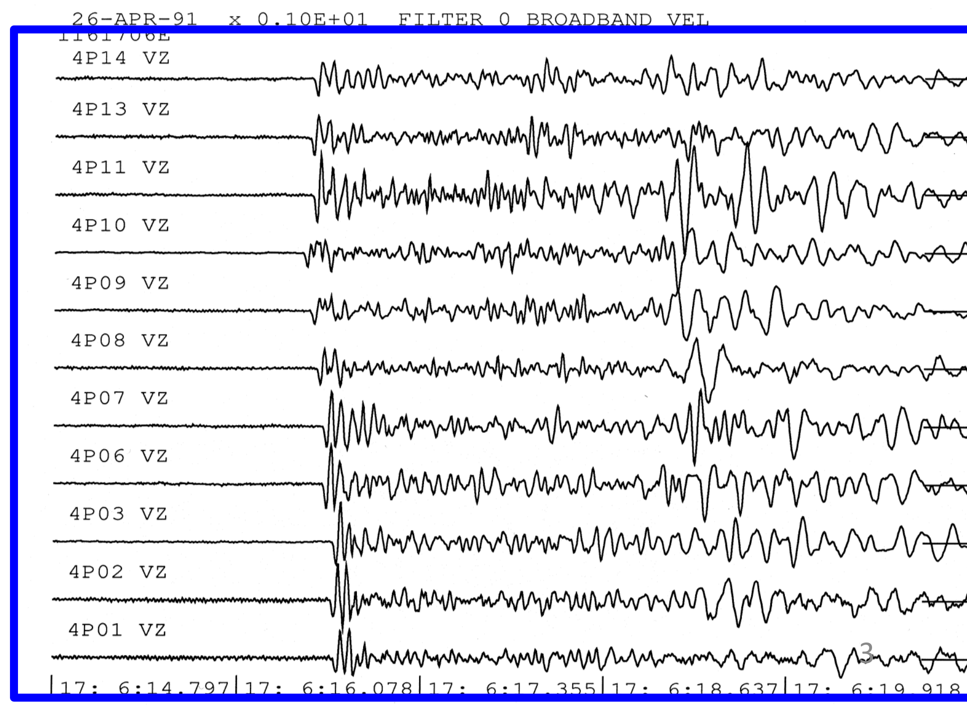
Roel Snieder

Variations and healing of the seismic velocity

Huub Douma, Alex Grêt, Chinaemerem Kanu, Ichiro Kuroda, Masatoshi Miyazawa, Nori Nakata, Ernst Niederleithinger, Carlos Pacheco, Thomas Planès, Kaoru Sawazaki, John Scales, Christoph Sens-Schönfelder, Roel Snieder

Earthquake doublets





JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 89, NO. B7, PAGES 5719–5731, JULY 10, 1984

Monitoring Velocity Variations in the Crust Using Earthquake Doublets: An Application to the Calaveras Fault, California

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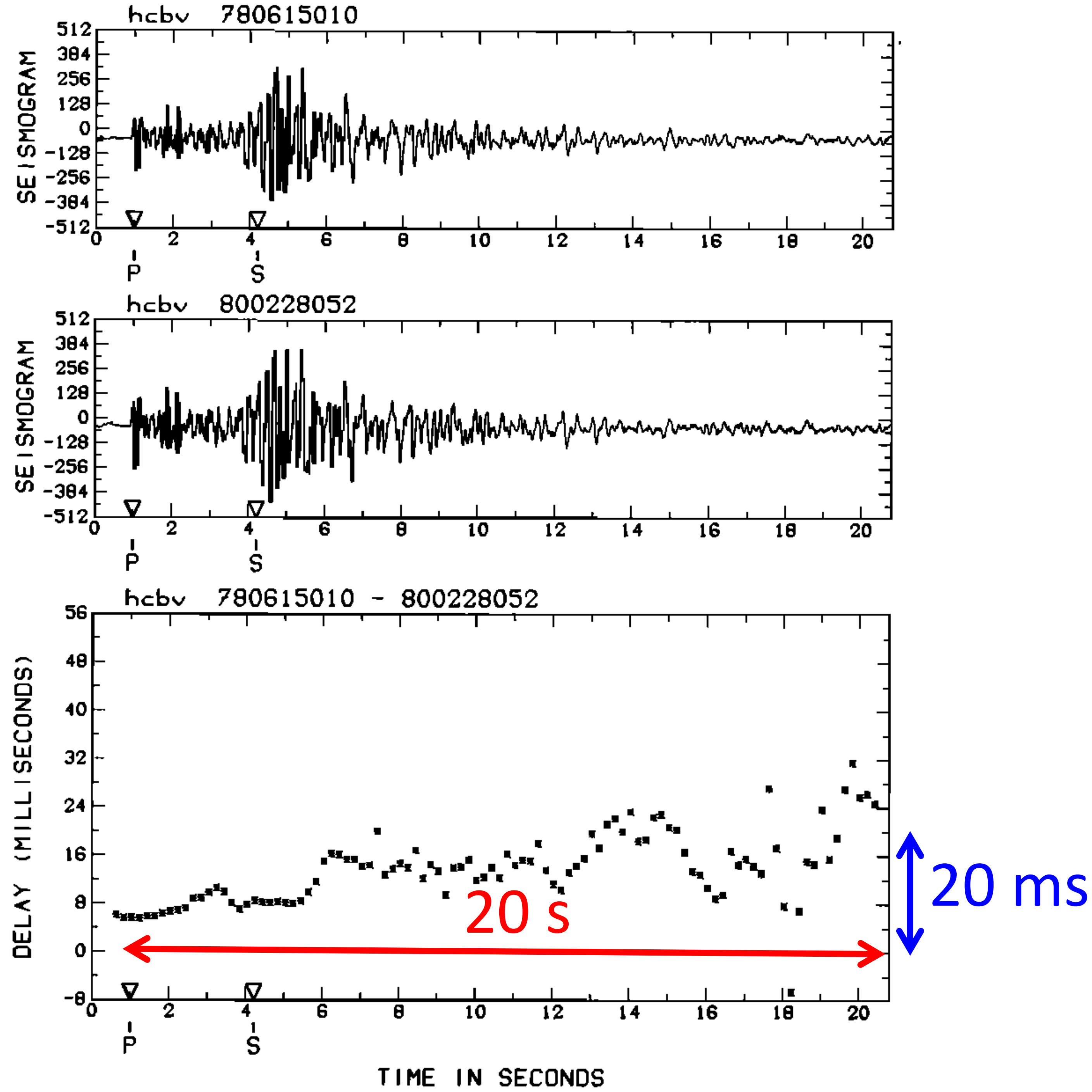
IRIGM, Universite Scientifique et Medicale de Grenoble, St. Martin d'Heres, France

W. L. ELLSWORTH

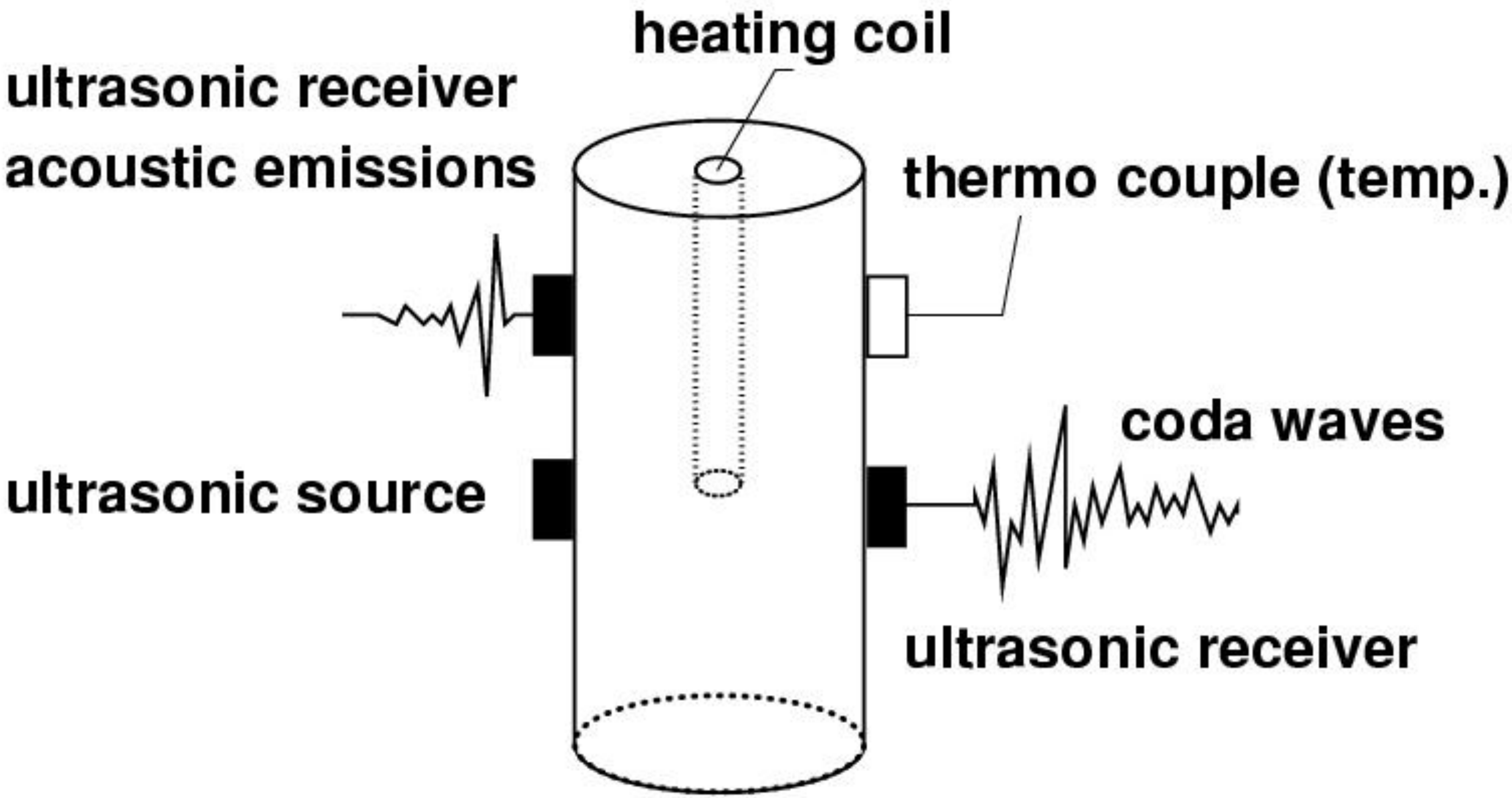
U.S. Geological Survey, Menlo Park, California

J. FRECHET

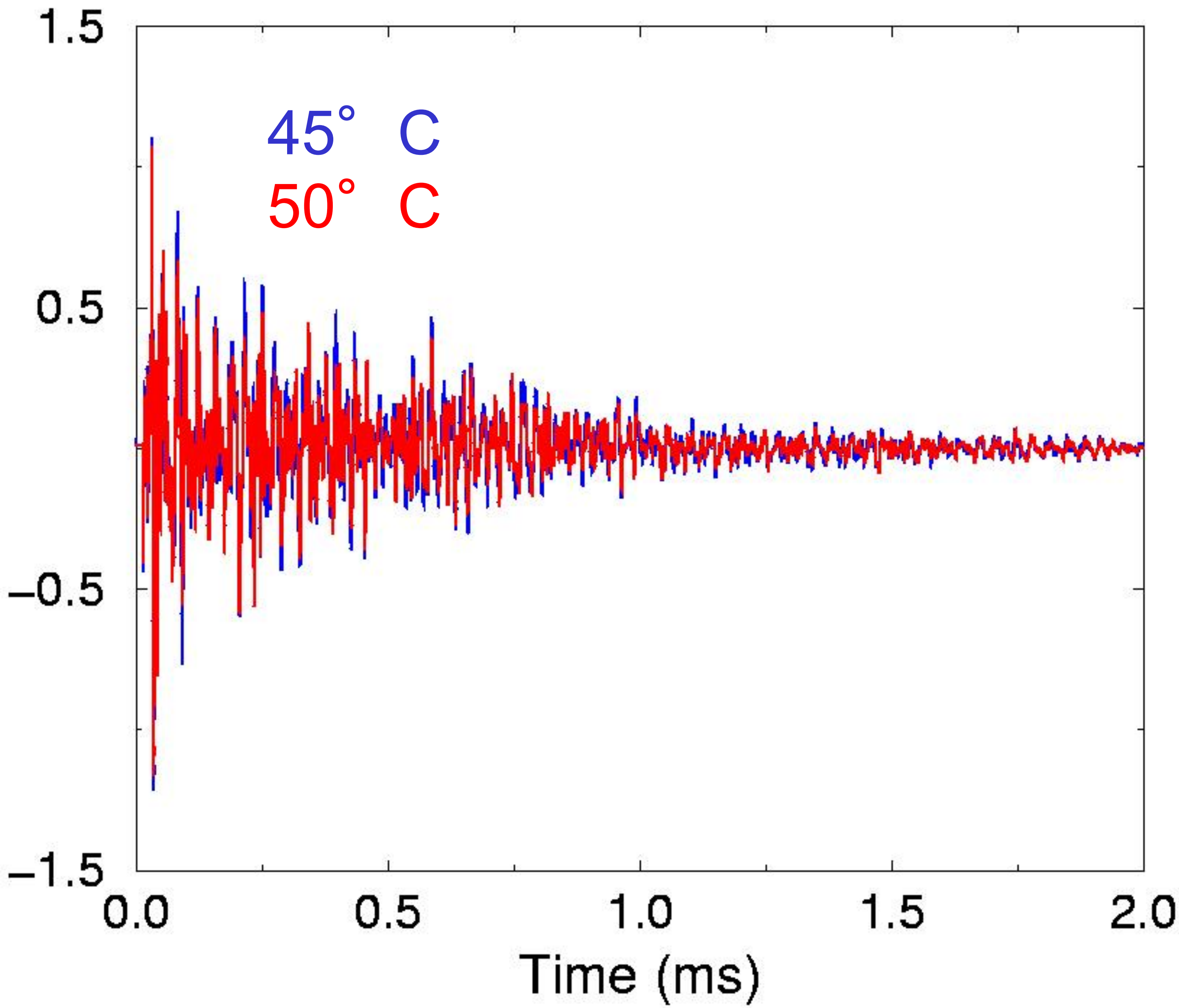
IRIGM, Universite Scientifique et Medicale de Grenoble, St. Martin d'Heres, France


hcbv 780615010
SEISMOGRAM
P
S
hcbv 800228052
SEISMOGRAM
P
S
hcbv 780615010 - 800228052
DELAY (MILLISECONDS)
P
S
TIME IN SECONDS
20 s
20 ms

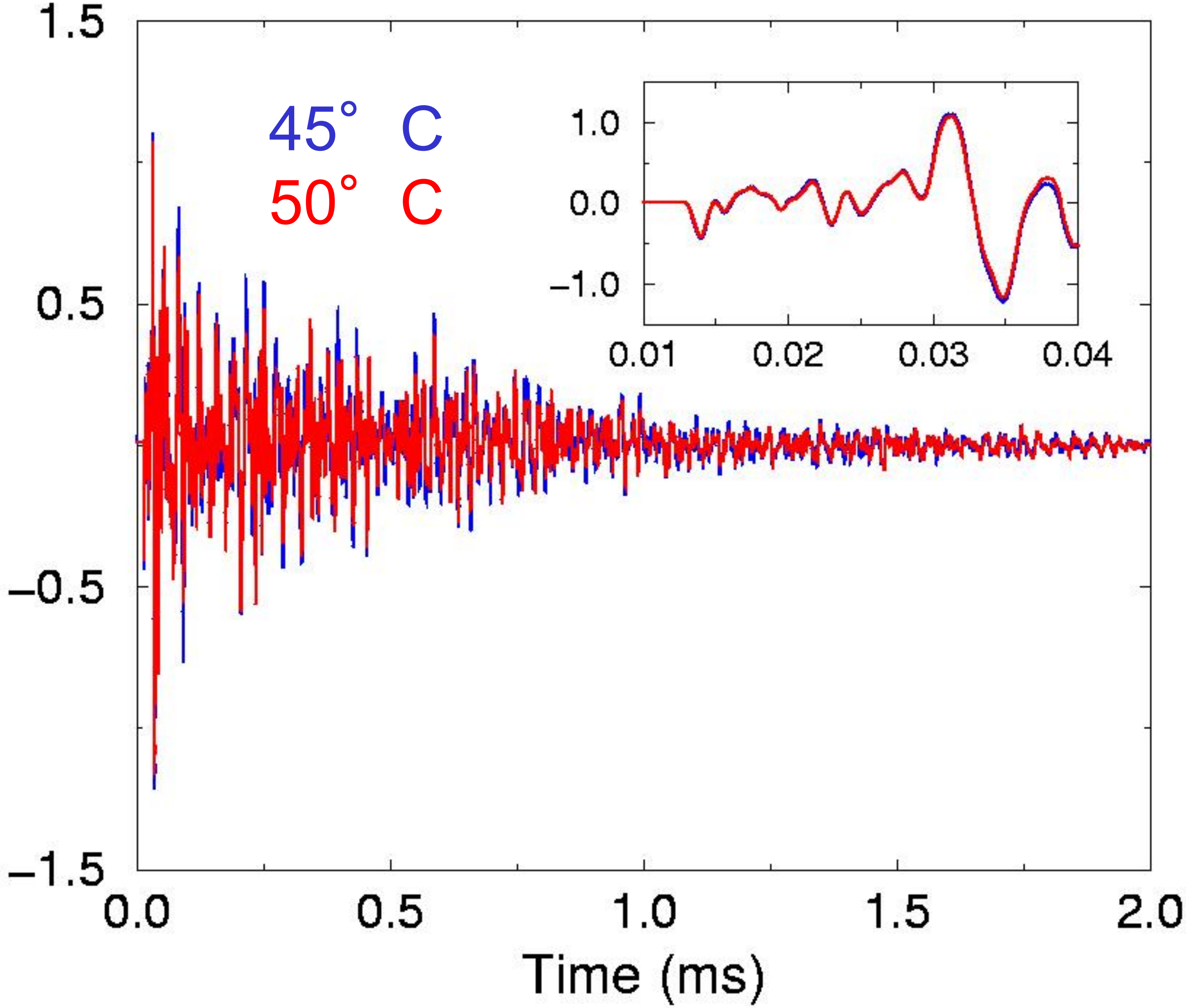
Coda wave interferometry

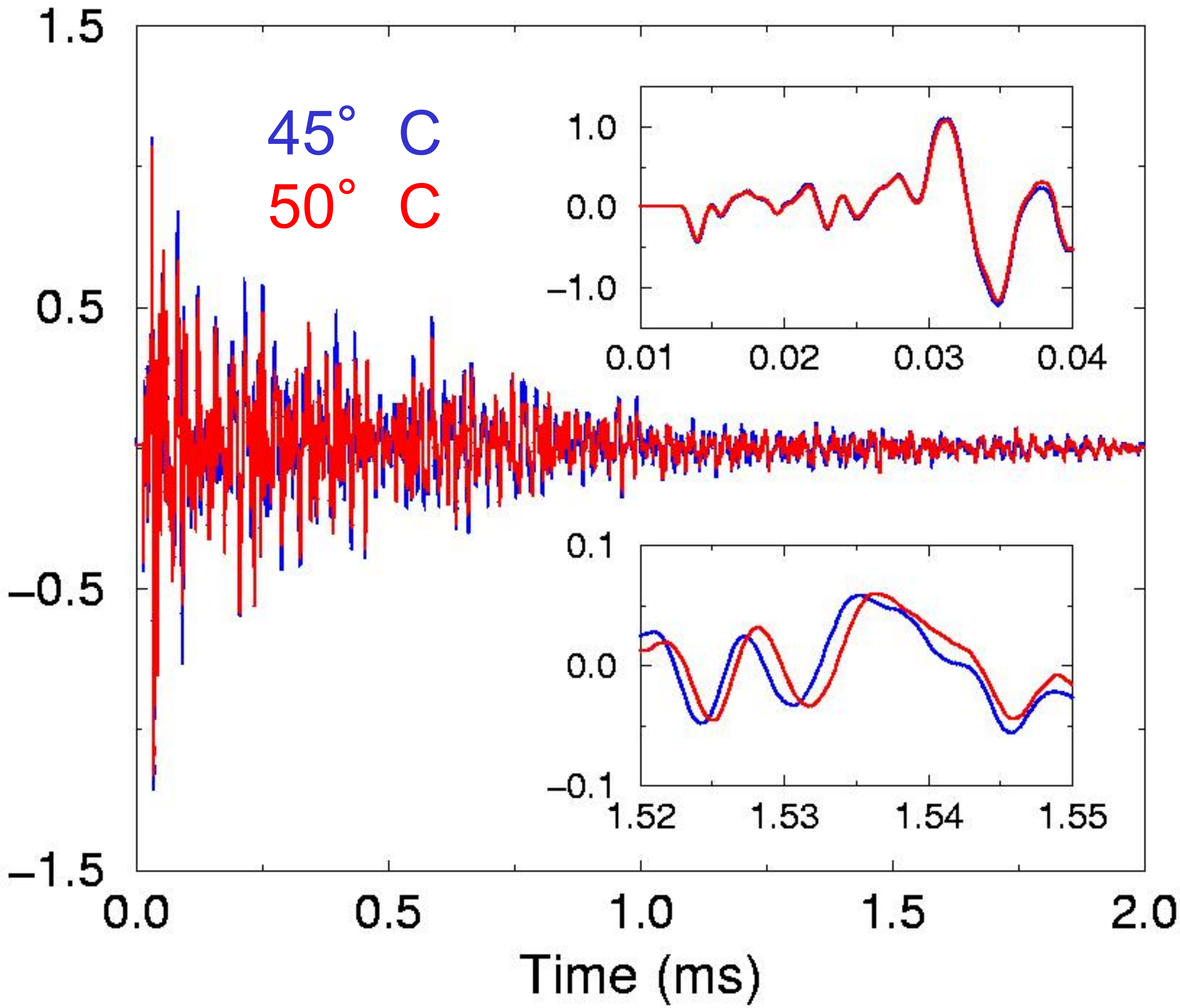


(Snieder et al., Science, 295, 2253-2255, 2002)



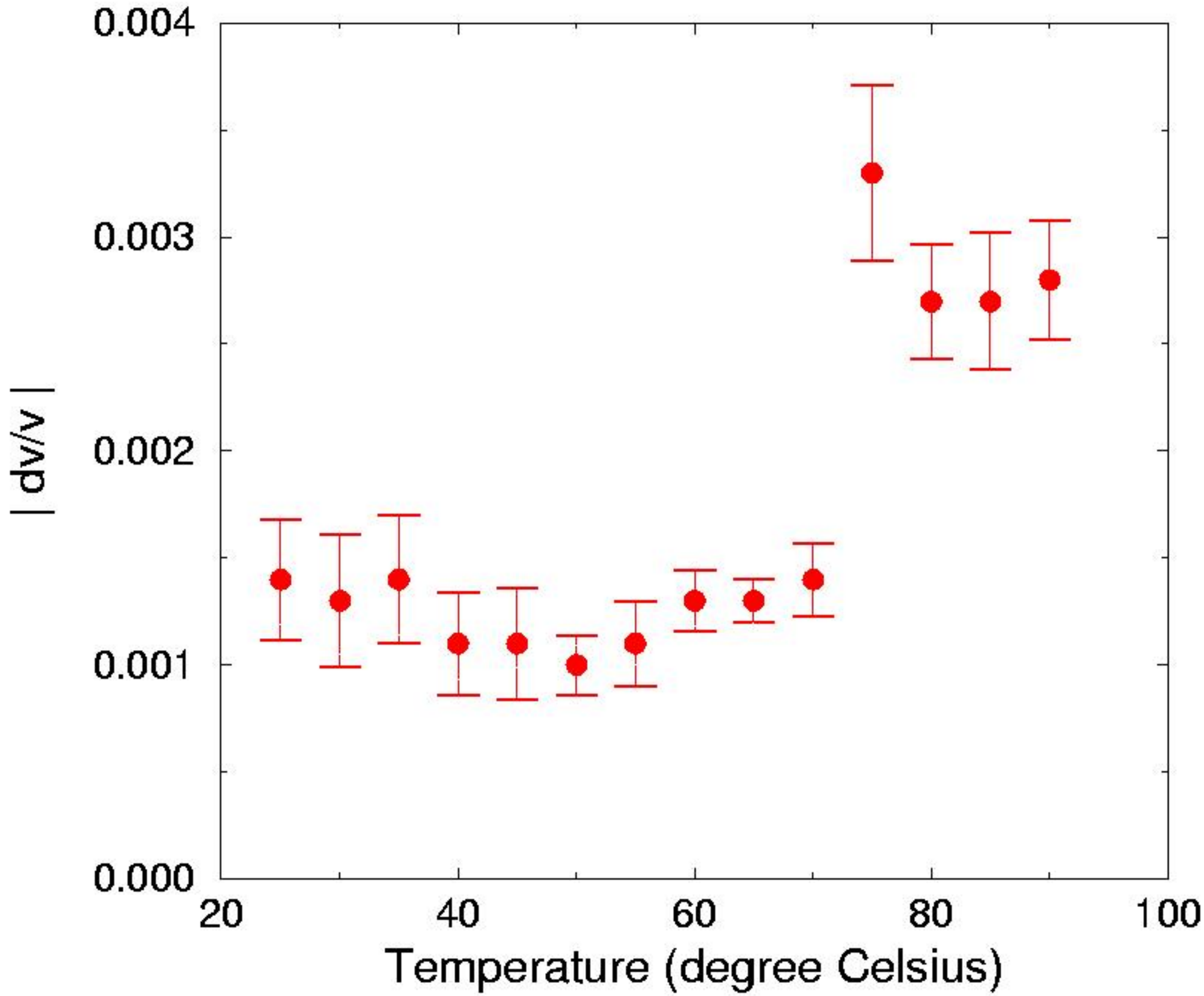
1.5
0.5
−0.5
−1.5
0.0
0.5
1.0
1.5
2.0
Time (ms)
45° C
50° C


45° C
50° C
1.5
0.5
−0.5
−1.5
0.0
0.5
1.0
1.5
2.0
Time (ms)
1.0
0.0
−1.0
0.01
0.02
0.03
0.04

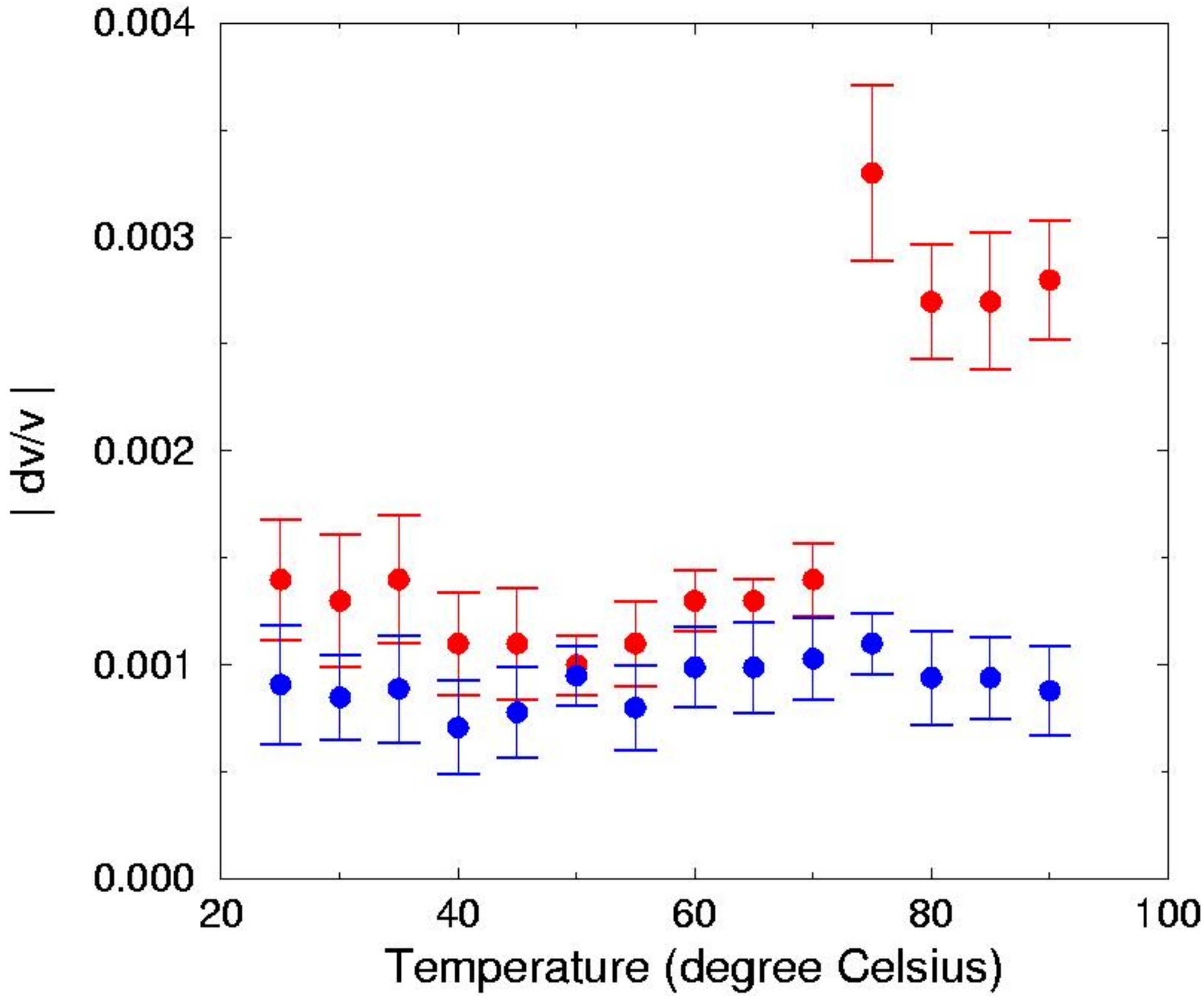


45° C
50° C
1.5
0.5
–0.5
–1.5
0.0
0.5
1.0
1.5
2.0
Time (ms)
1.0
0.0
–1.0
0.01
0.02
0.03
0.04
0.1
0.0
–0.1
1.52
1.53
1.54
1.55

Granite

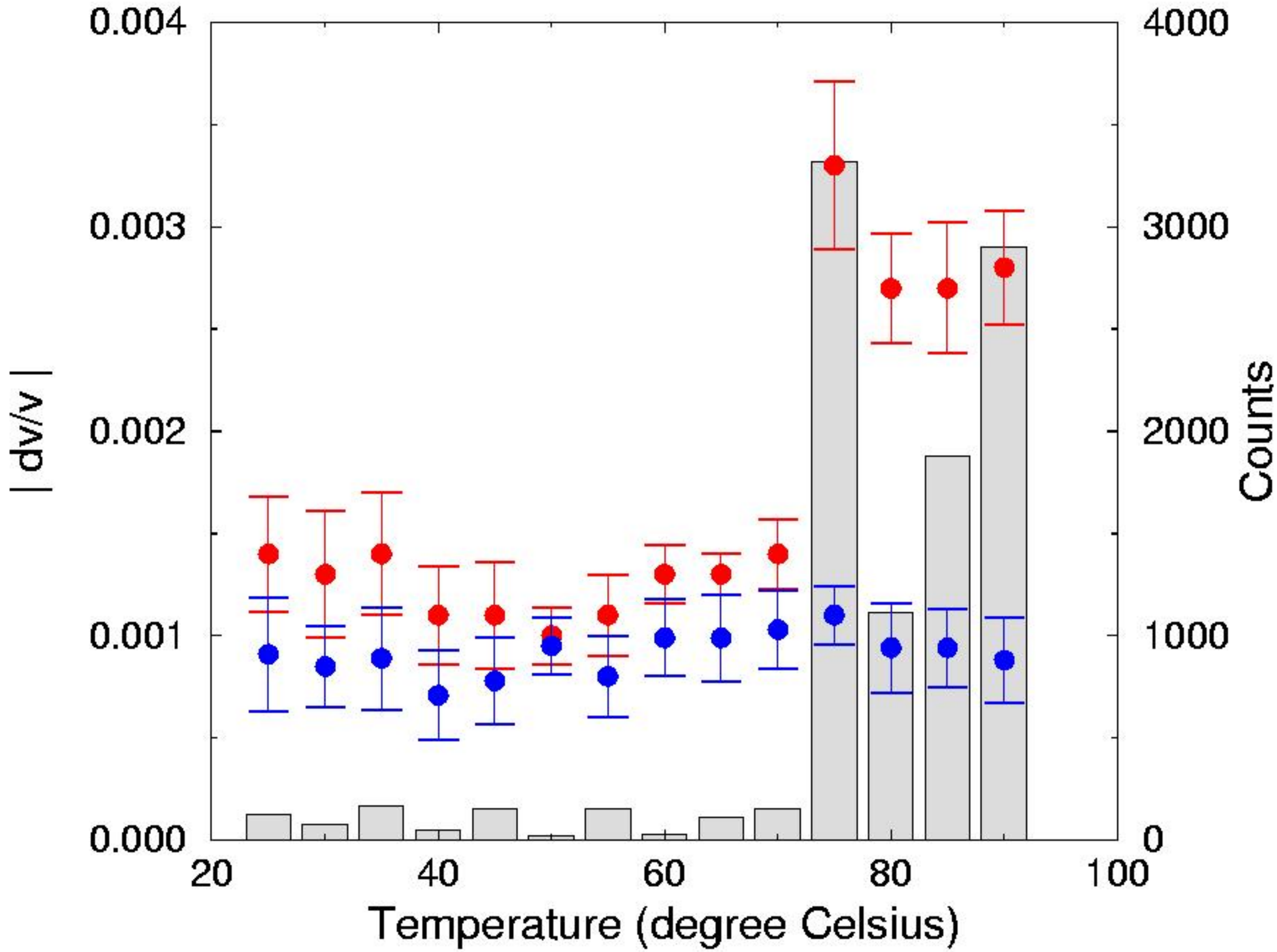

0.004
0.003
0.002
0.001
0.000
| dv/v |
20
40
60
80
100
Temperature (degree Celsius)

Granite



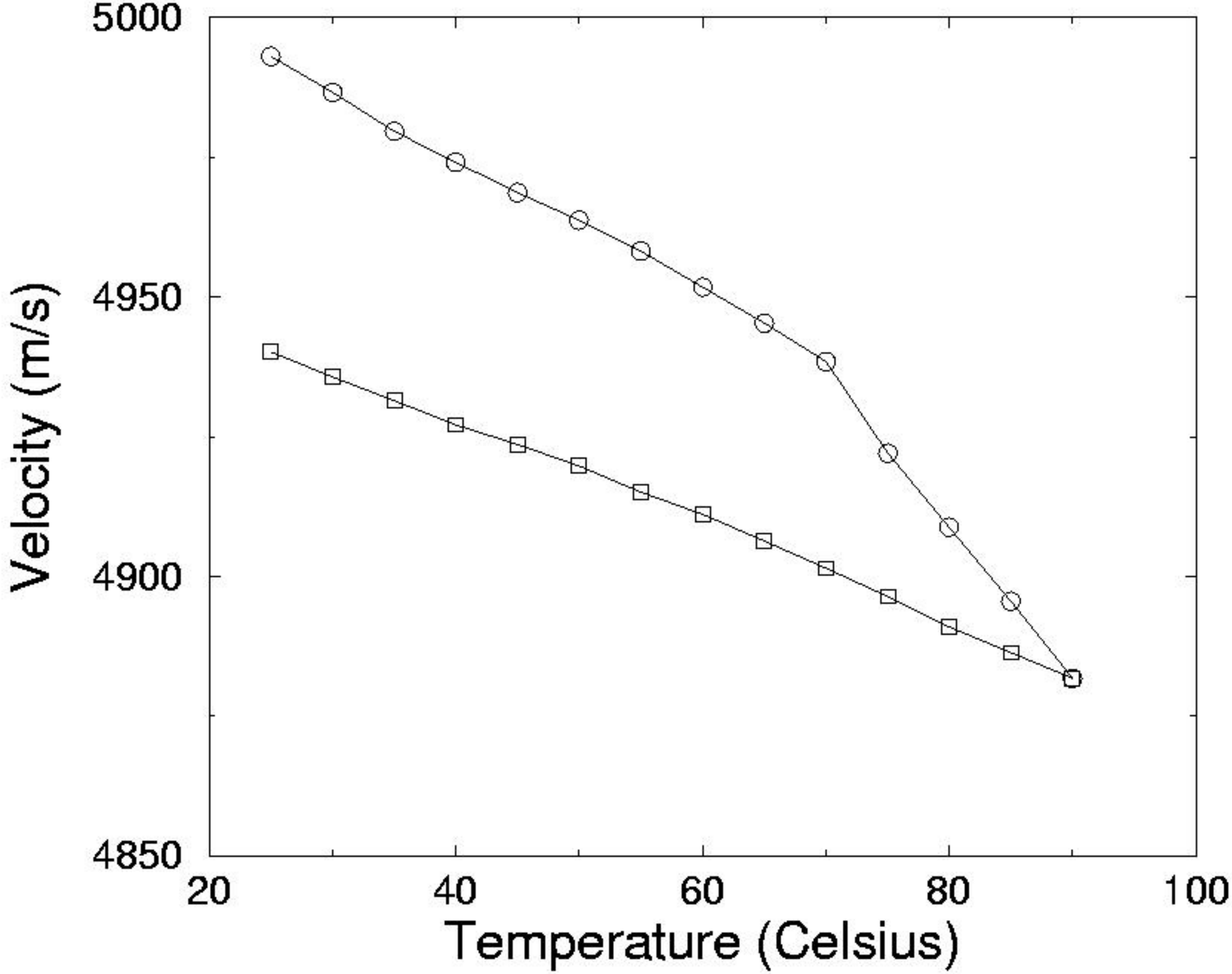
0.004
0.003
0.002
0.001
0.000
| dv/v |
20
40
60
80
100
Temperature (degree Celsius)

Granite



0.004
0.003
0.002
0.001
0.000
| dv/v |
4000
3000
2000
1000
0
Counts
20
40
60
80
100
Temperature (degree Celsius)

Granite



5000
4950
4900
4850
Velocity (m/s)
20
40
60
80
100
Temperature (Celsius)

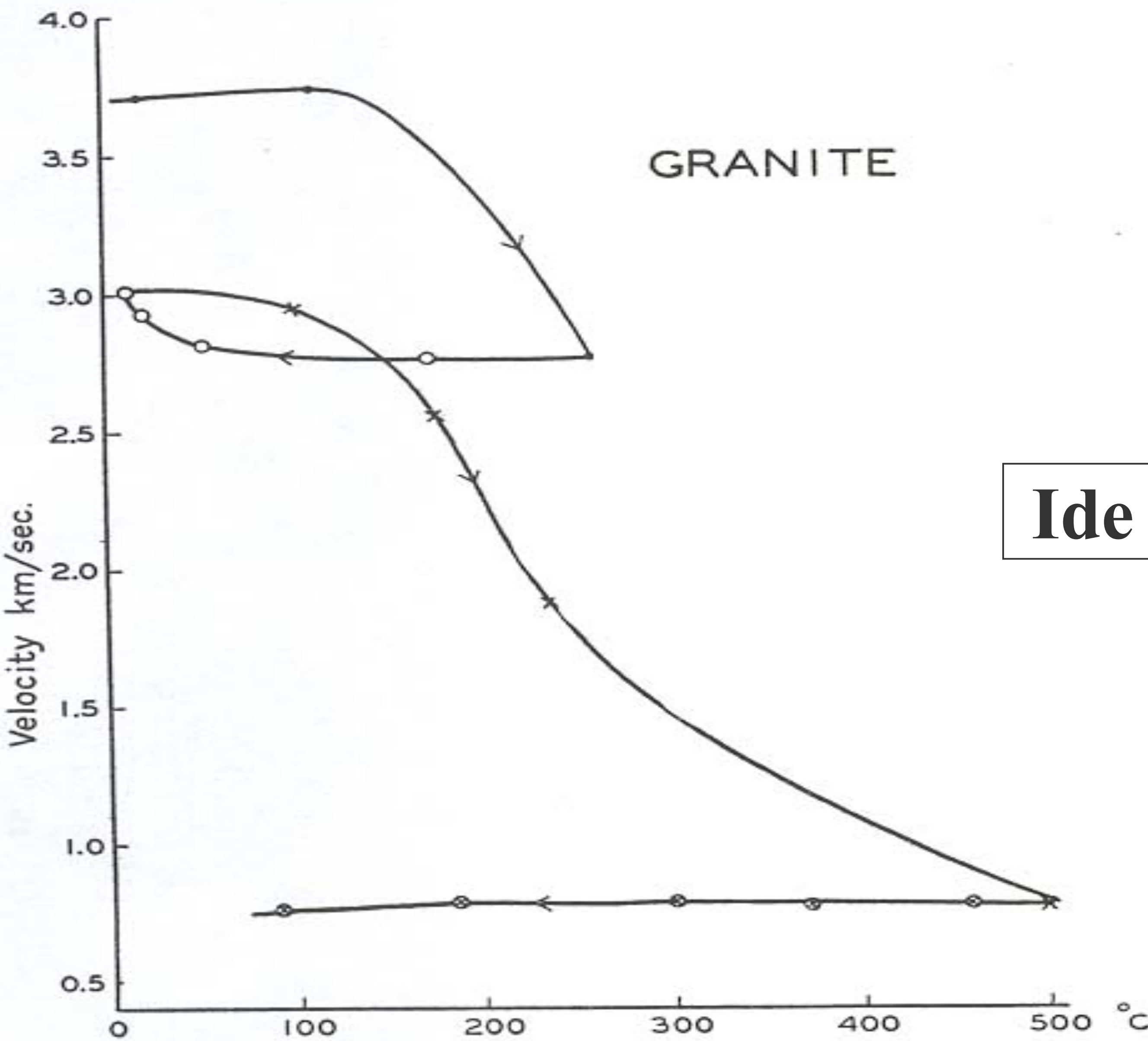


FIG. 4.—The velocity of sound as a function of temperature in Quincy granite

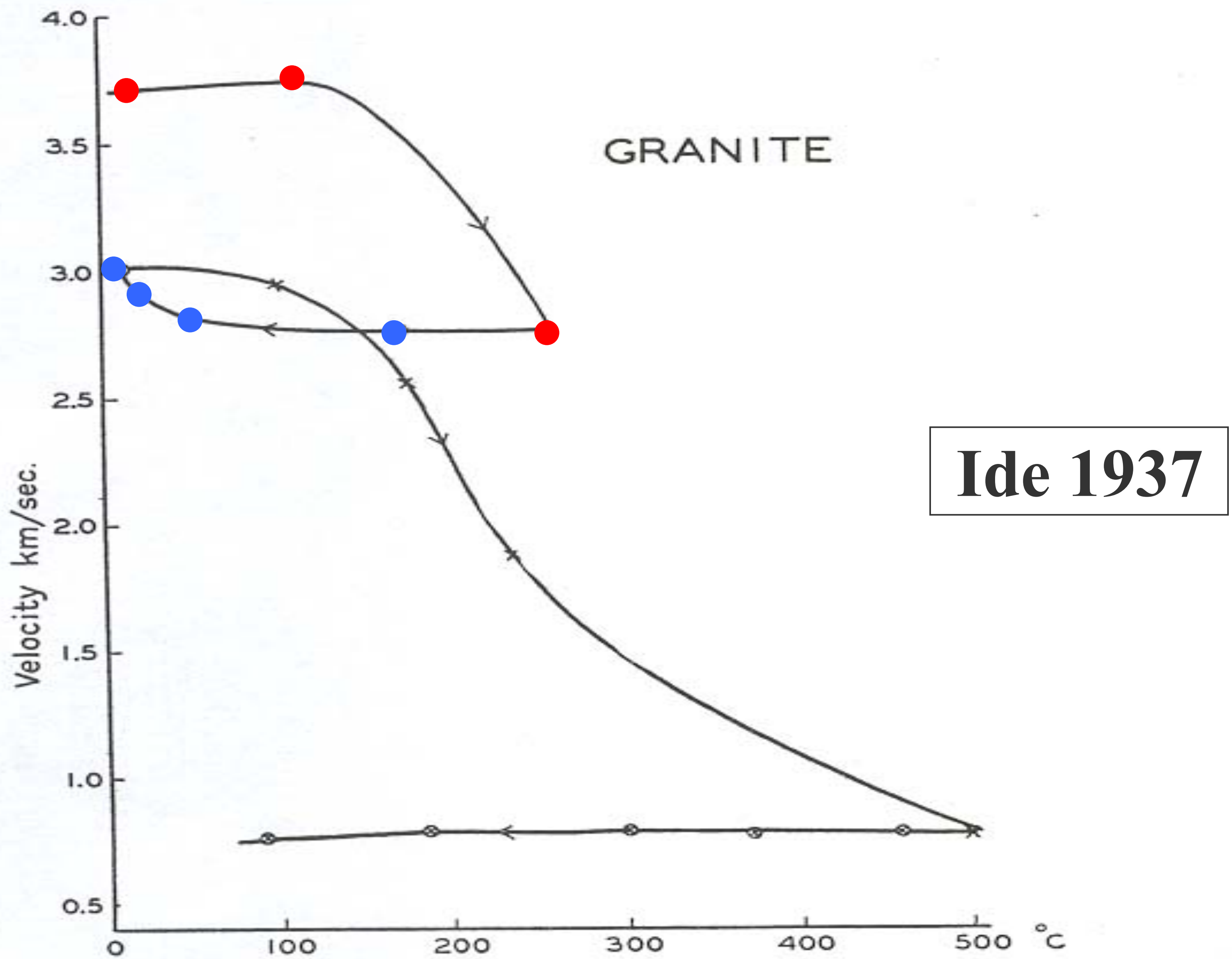
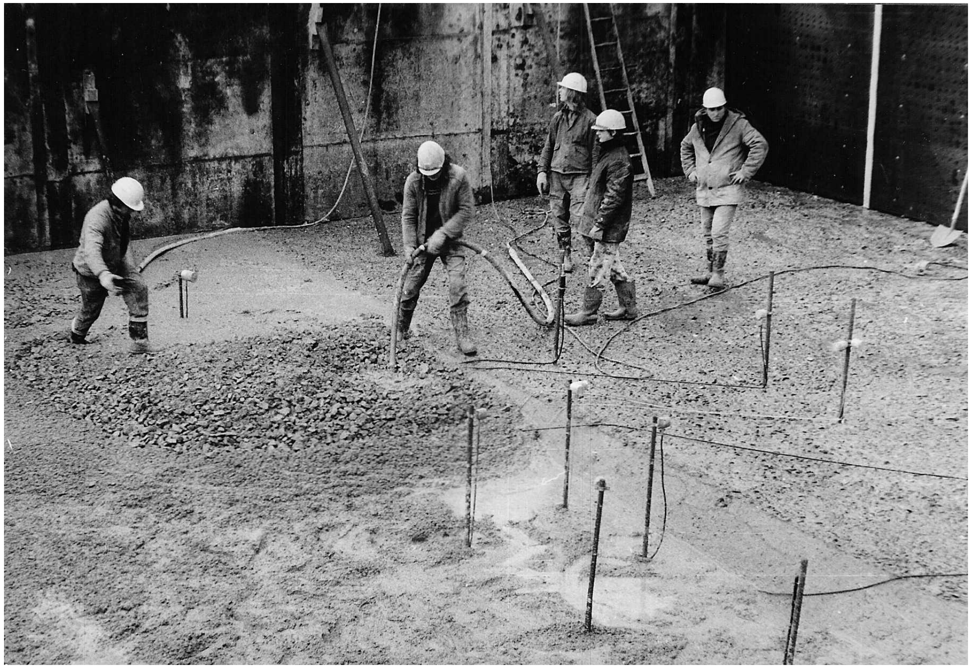


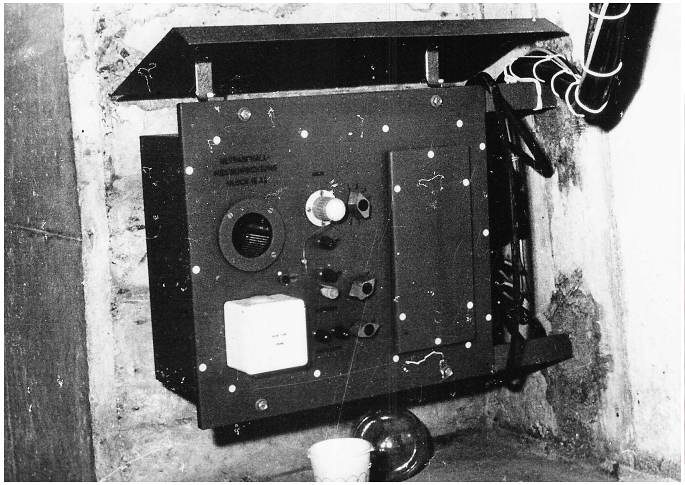
FIG. 4.—The velocity of sound as a function of temperature in Quincy granite

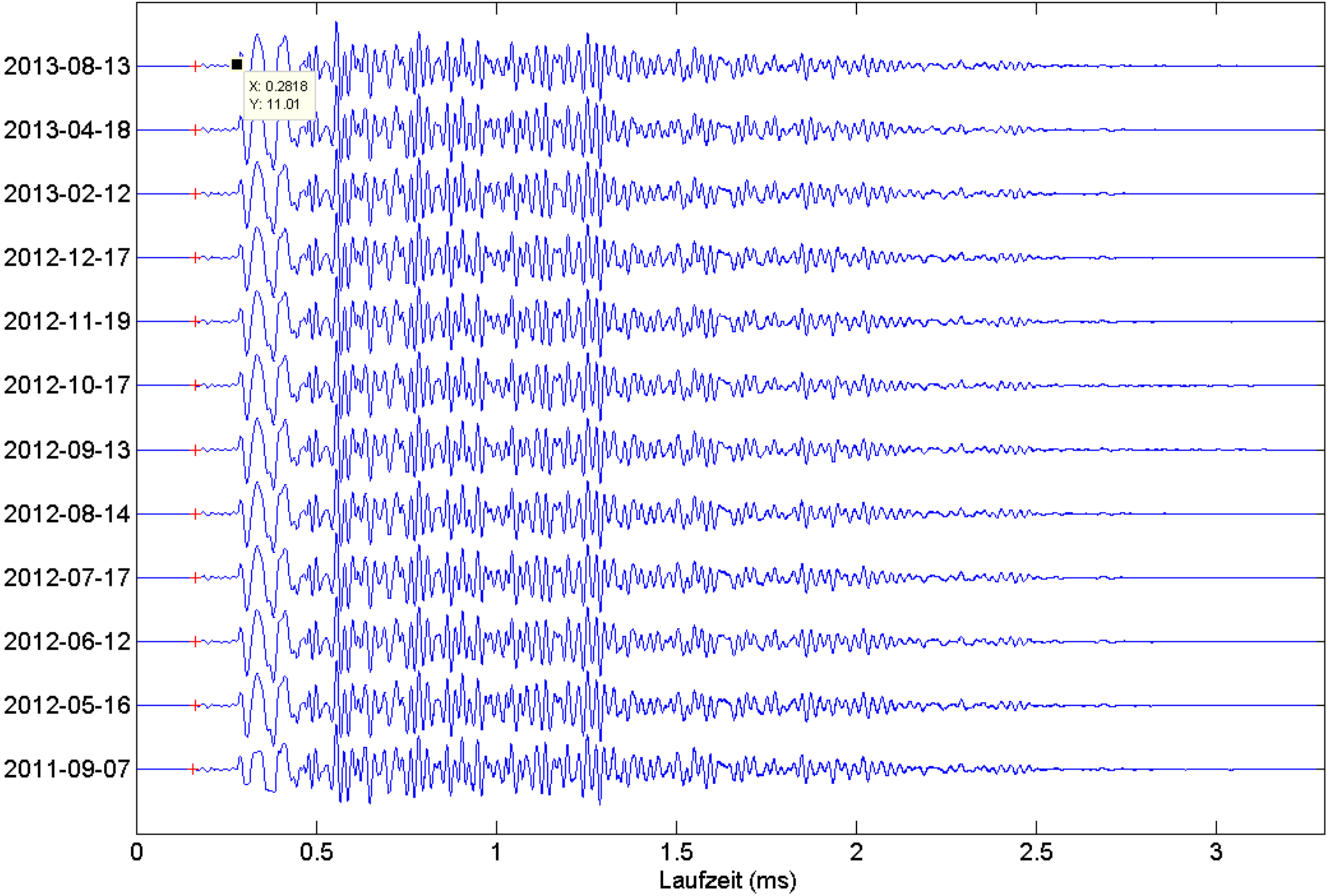
Talsperre Eibenstock

Ultraschallsensorik aus der Bauphase

- Entwicklung des E-Moduls/ Druckfestigkeit
- 8 Geber, 4 Empfänger (UNG40/SW40, 40 kHz)
- VEB Projektierung Wasserwirtschaft

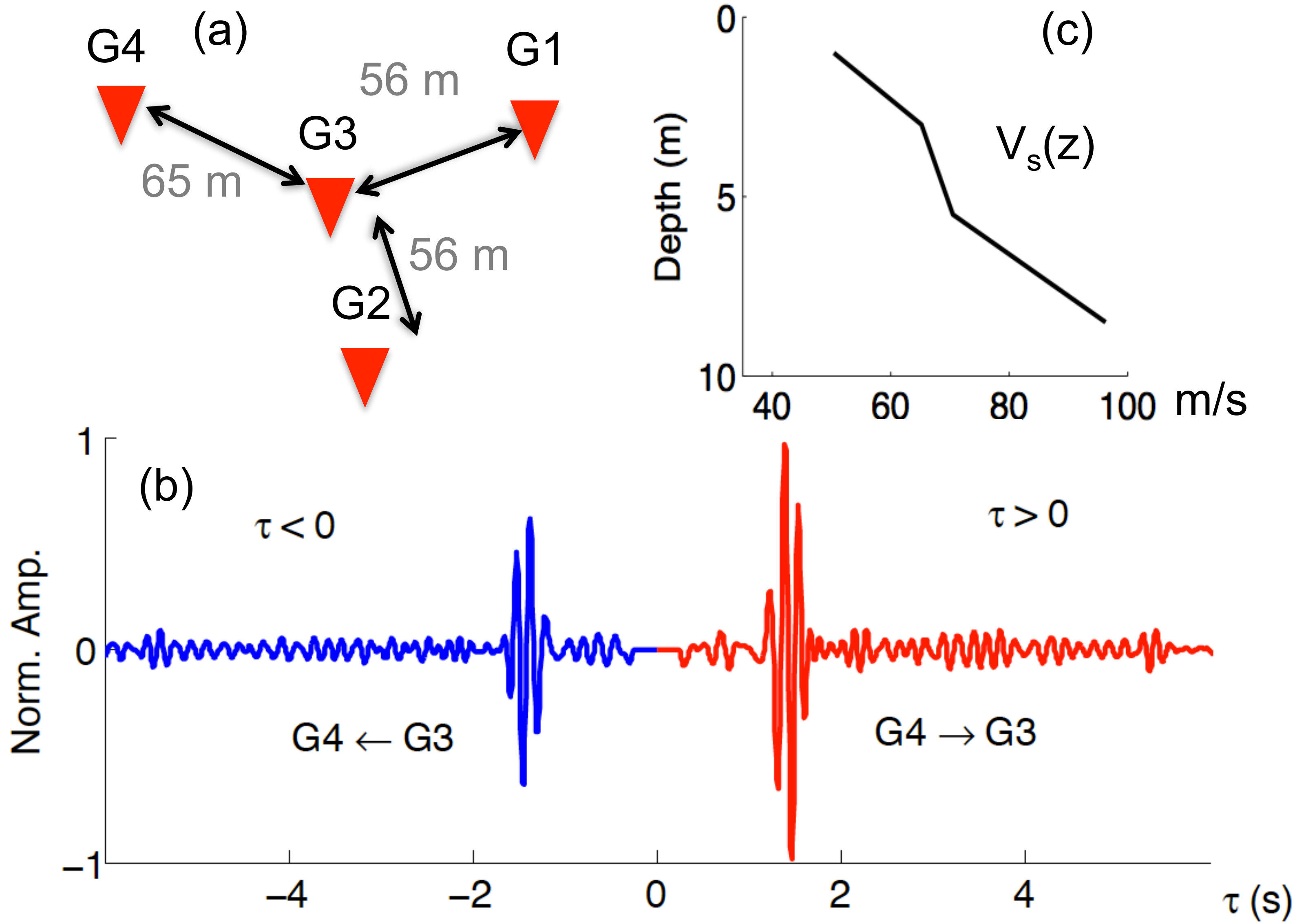






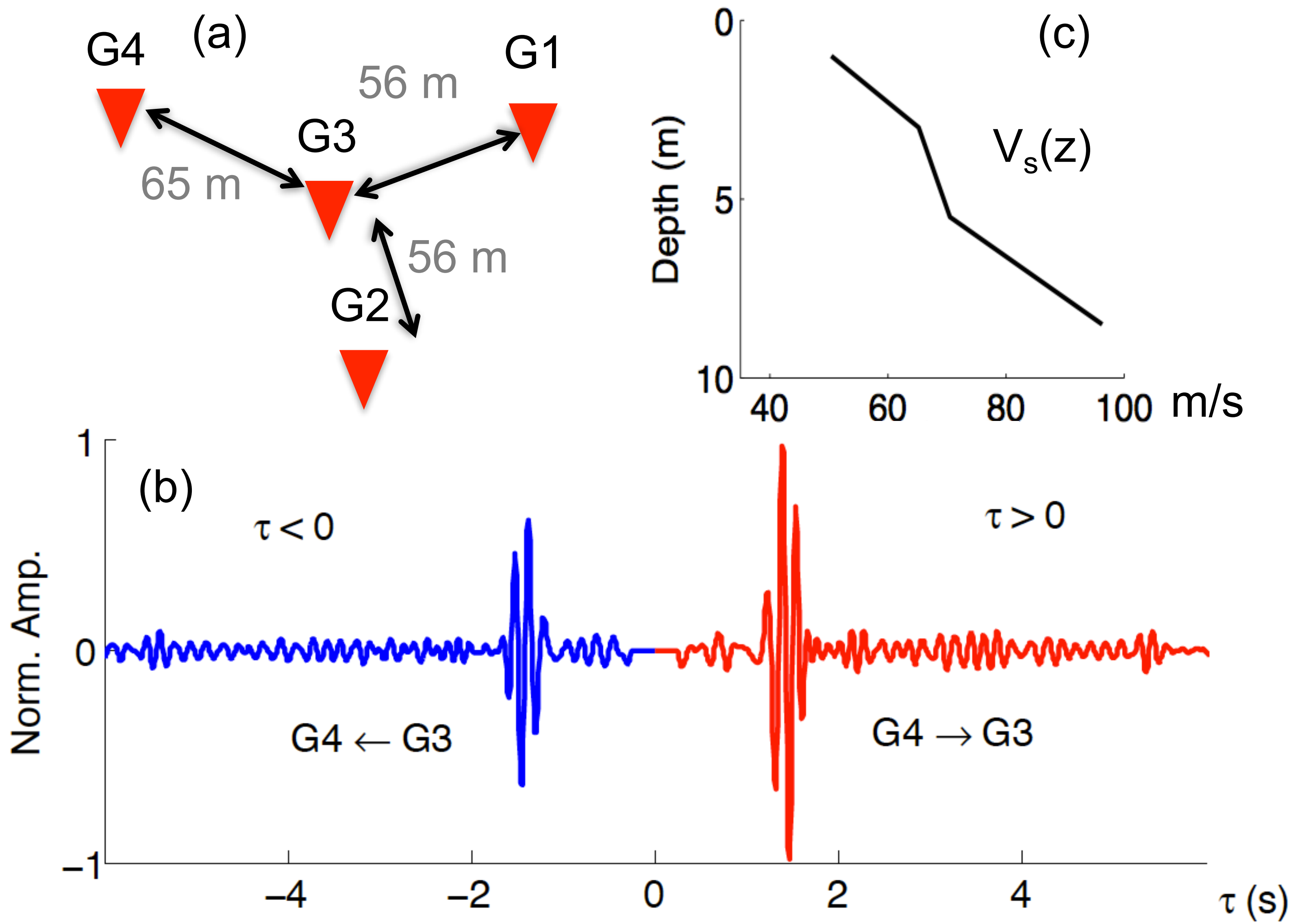
(Niederleithinger, E.; Krompholz, R.; Müller, S.; Lautenschläger, R. & Kittler, J. 36 Jahre Talsperre Einbenstock - 36 Jahre Überwachung des Betonzustands durch Ultraschall Proc. 38. Desdner Wasserbaukolloquium 2015 ''Messen und Überwachen im Wasserbau und Gewässer, 2015, 1-10)

Seismic interferometry



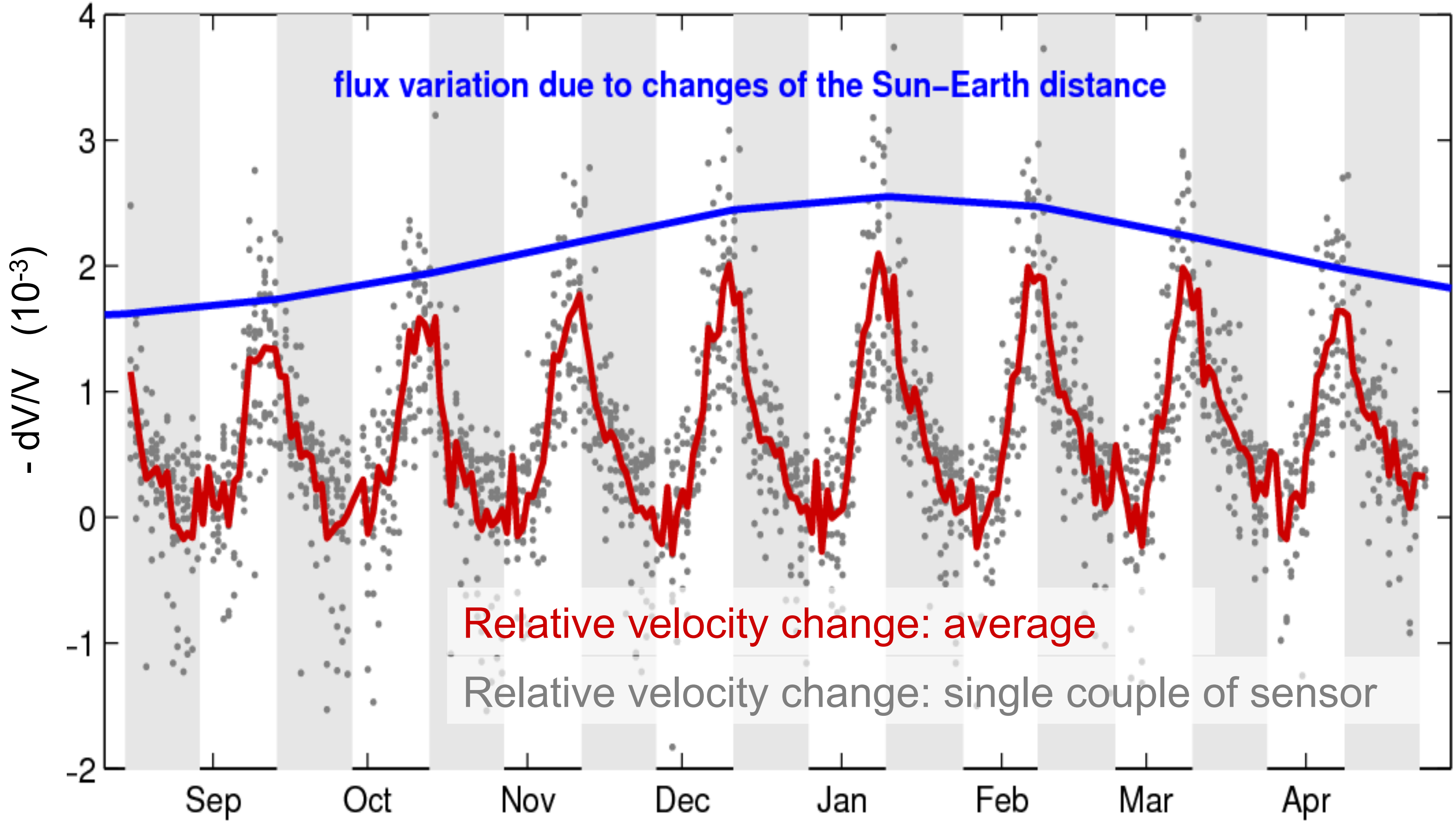
(Larose et al., Geophys. Res. Lett., 32, L16201, 2005)

Seismic interferometry on the moon!



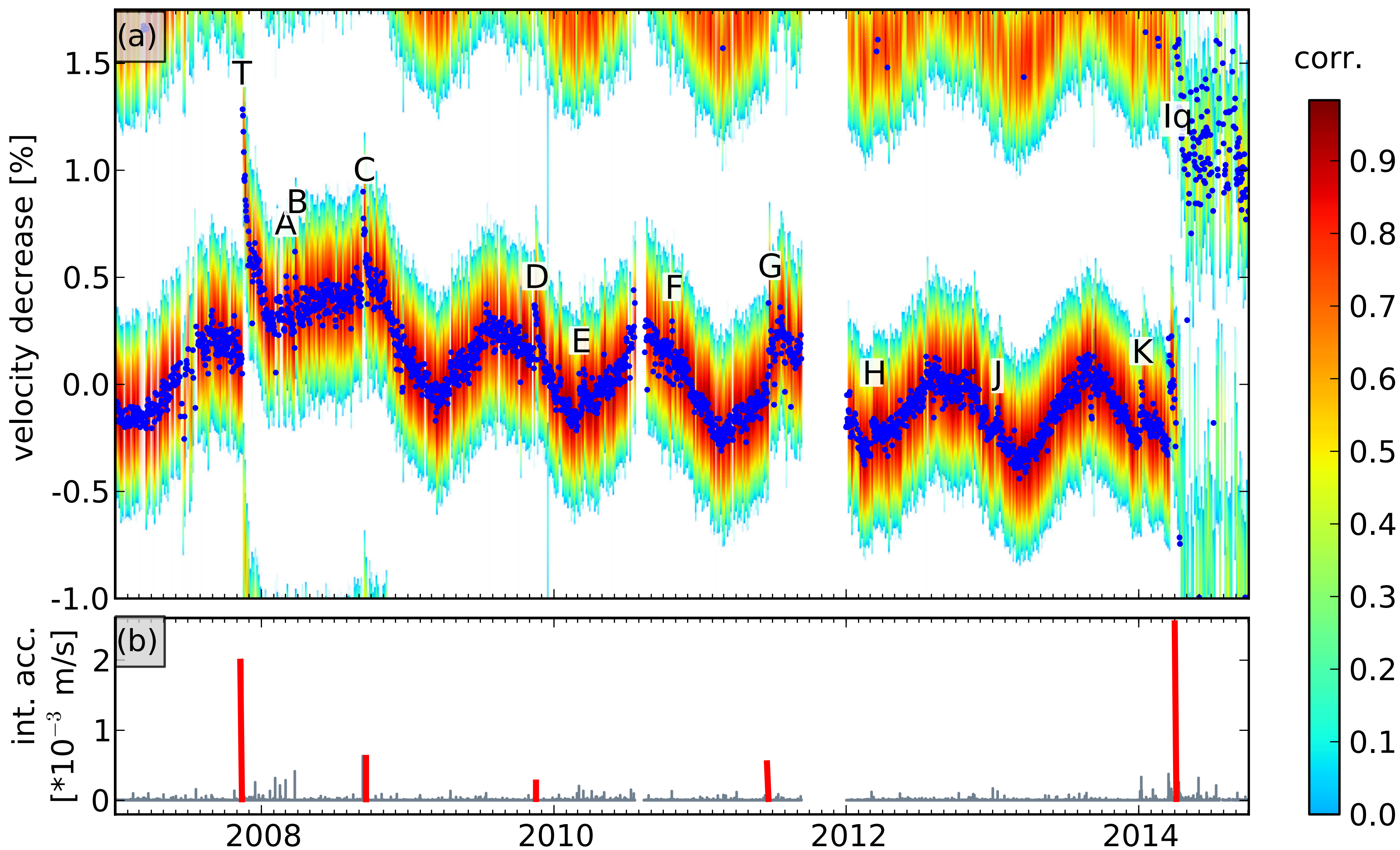
(Larose et al., Geophys. Res. Lett., 32, L16201, 2005)

Seismic interferometry on the moon



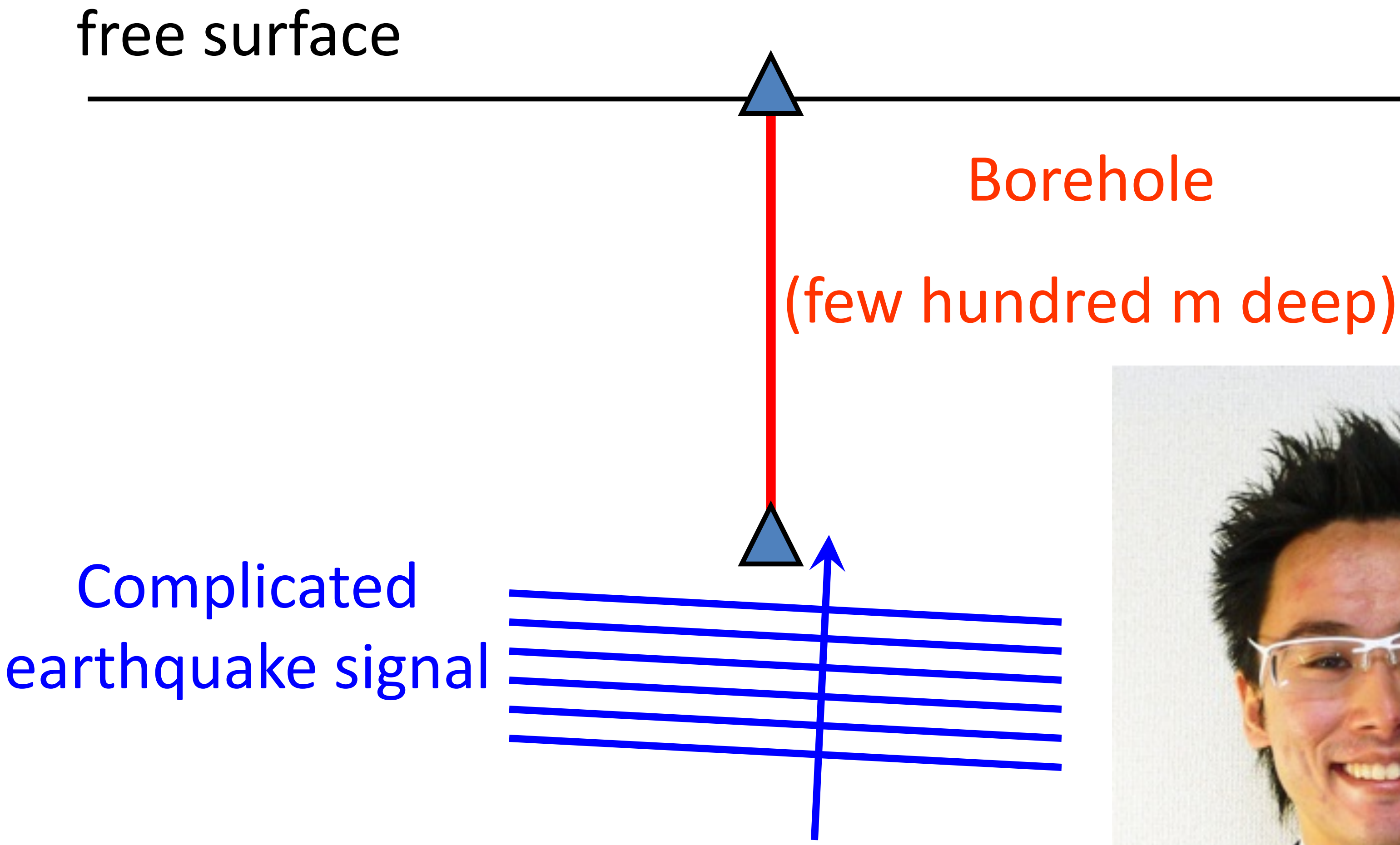
(Sens-Schönfelder & Larose, Phys. Rev. E, 78, 045601, 2008)

Velocity changes in Chili

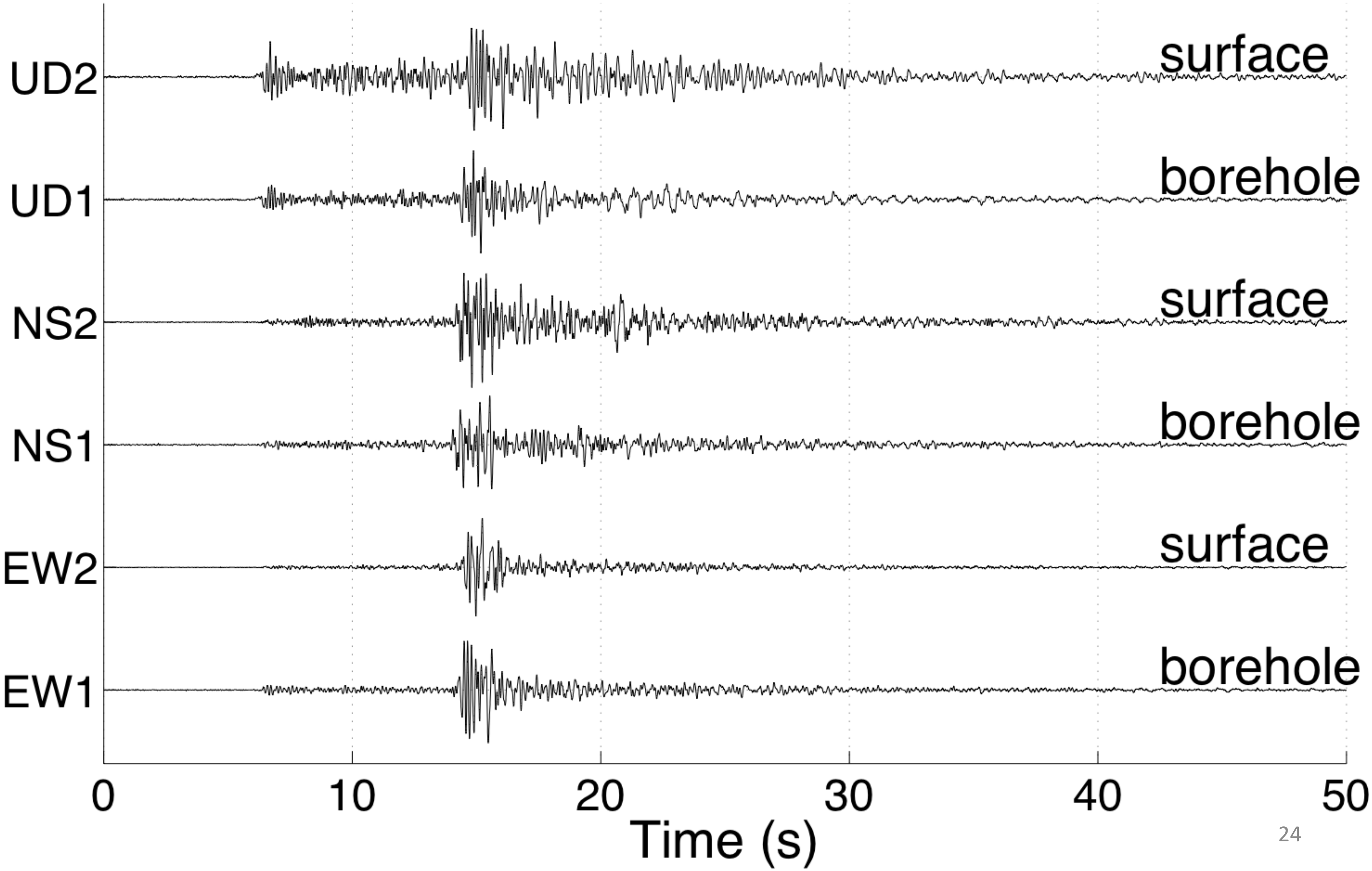


(Gassenmeier et al., Geophys. J. Int., 204, 1490-1502, 2016)

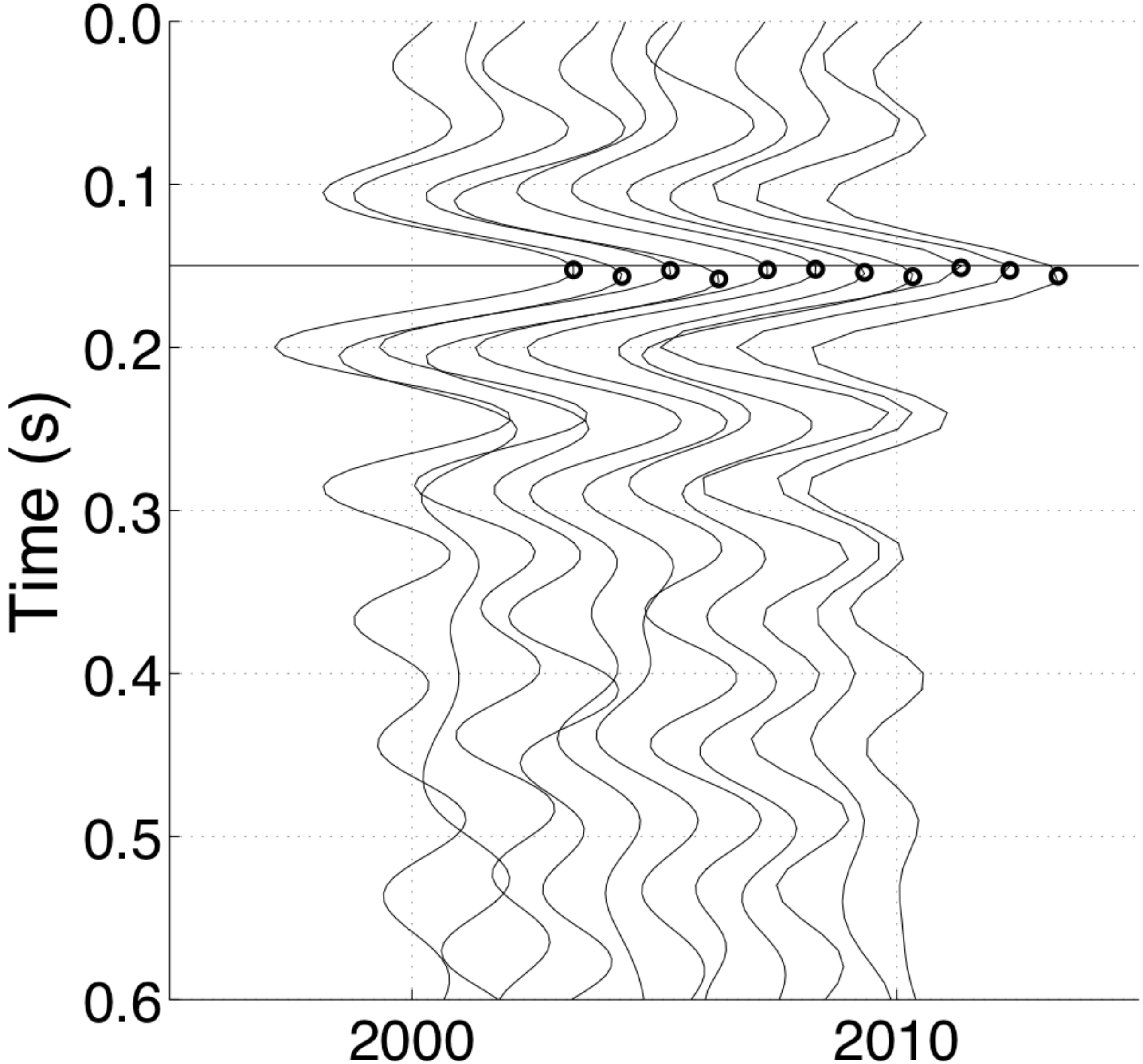
Near-surface structure from Kik-Net



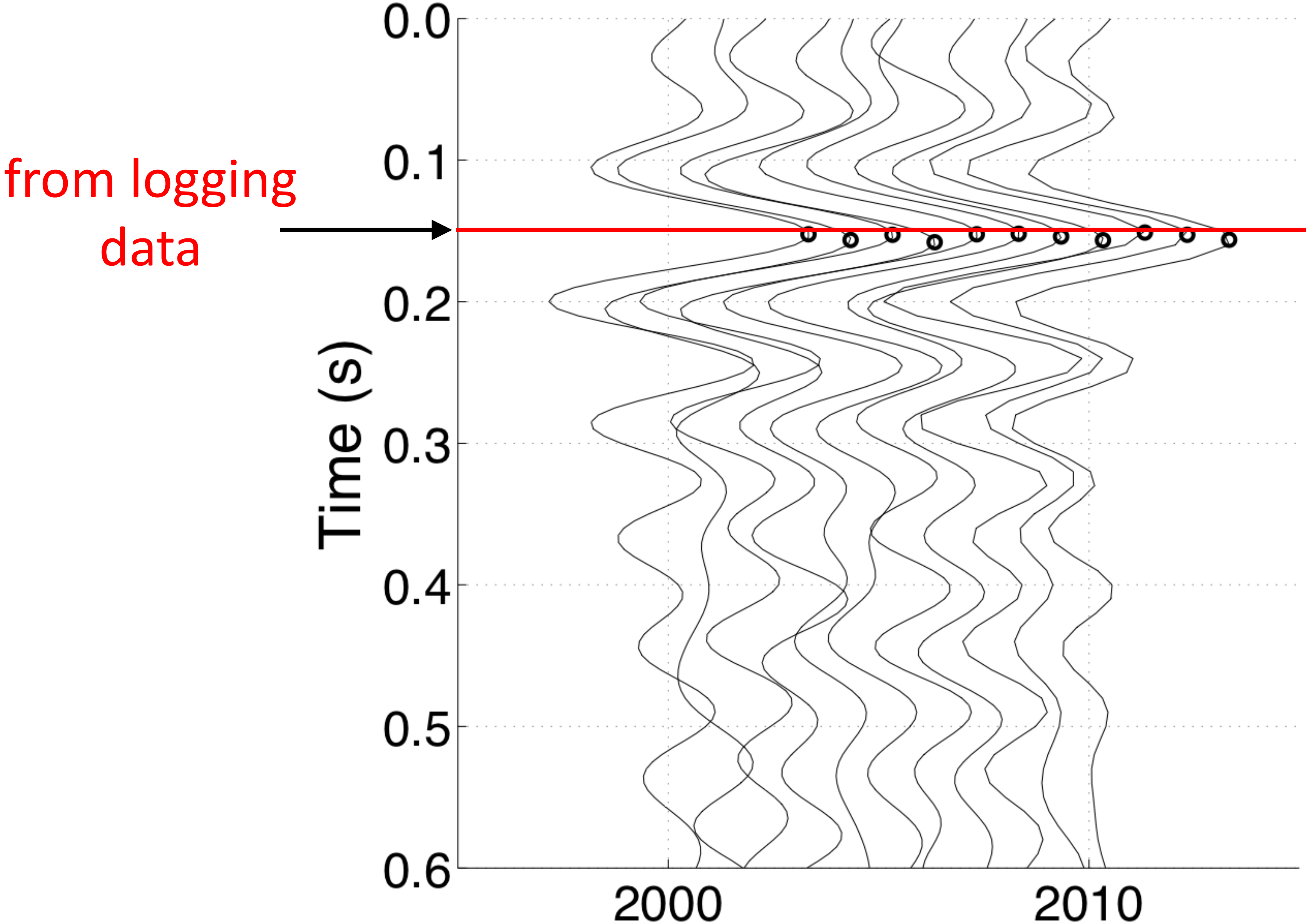
Data at station NIGH13



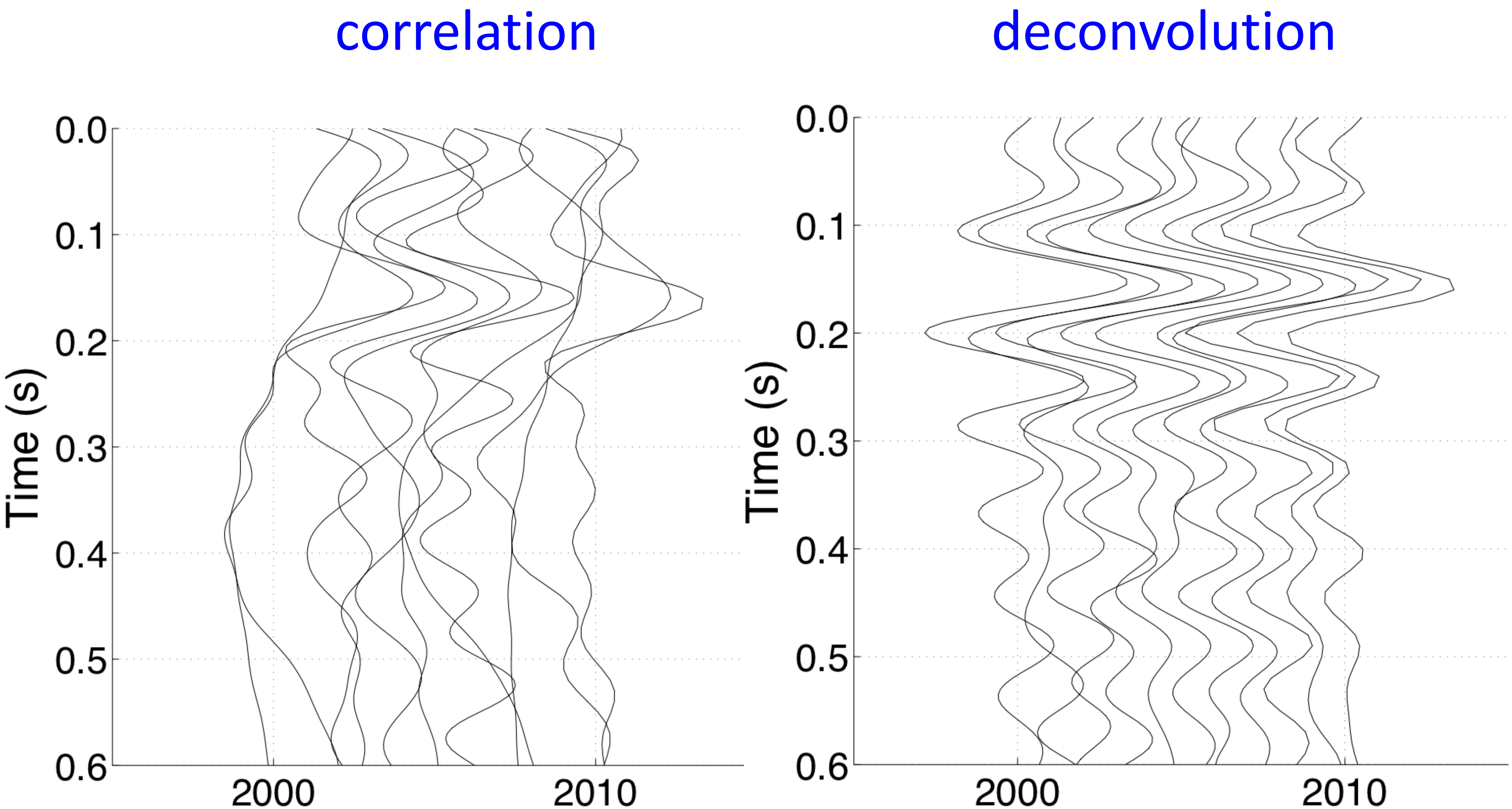
Arrival time of shear wave



Arrival time of shear wave



Annual stacks at station NIGH13

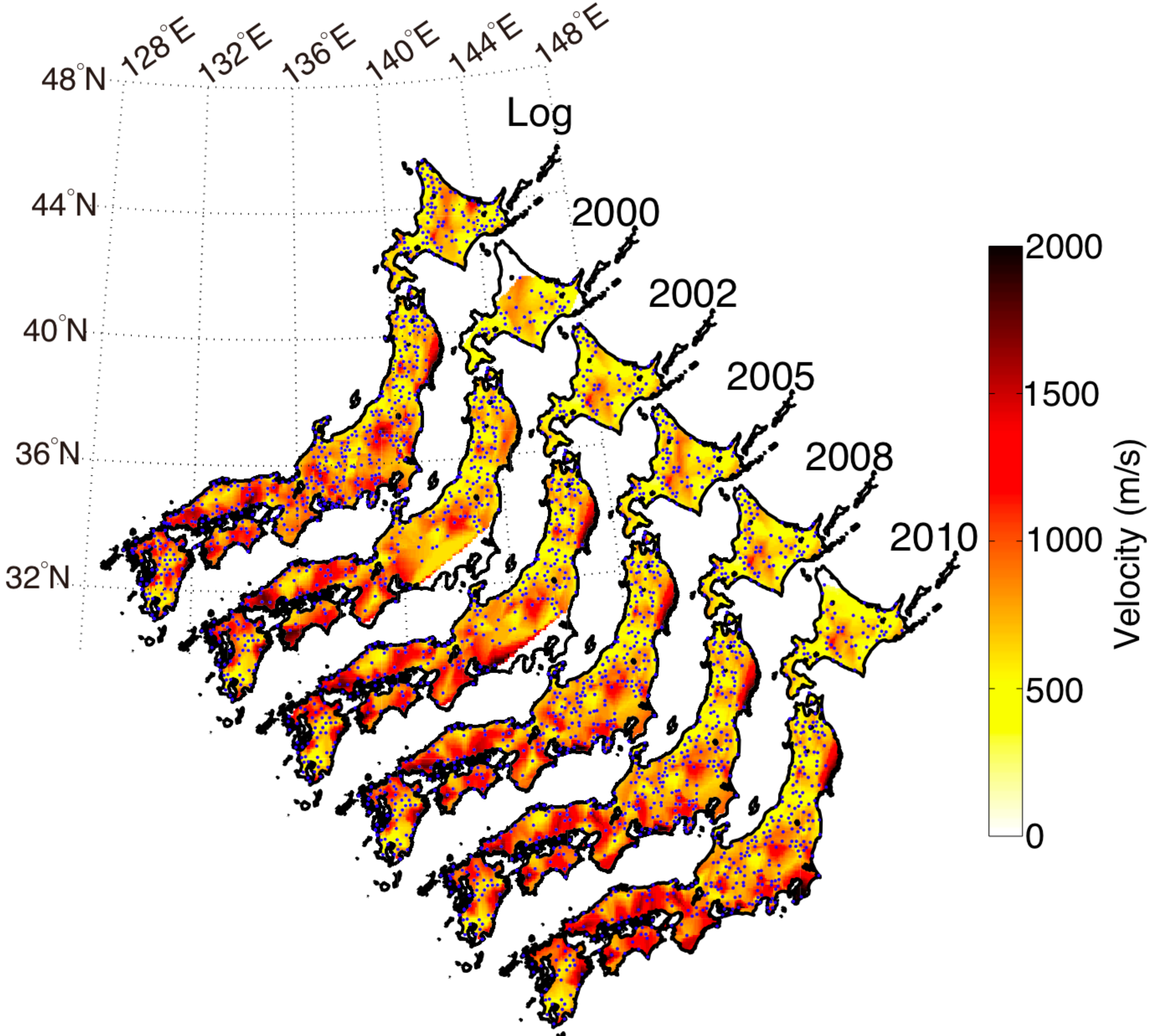


Correlation vs. deconvolution

$$u(z,\omega) = S(\omega)e^{-ikz}$$

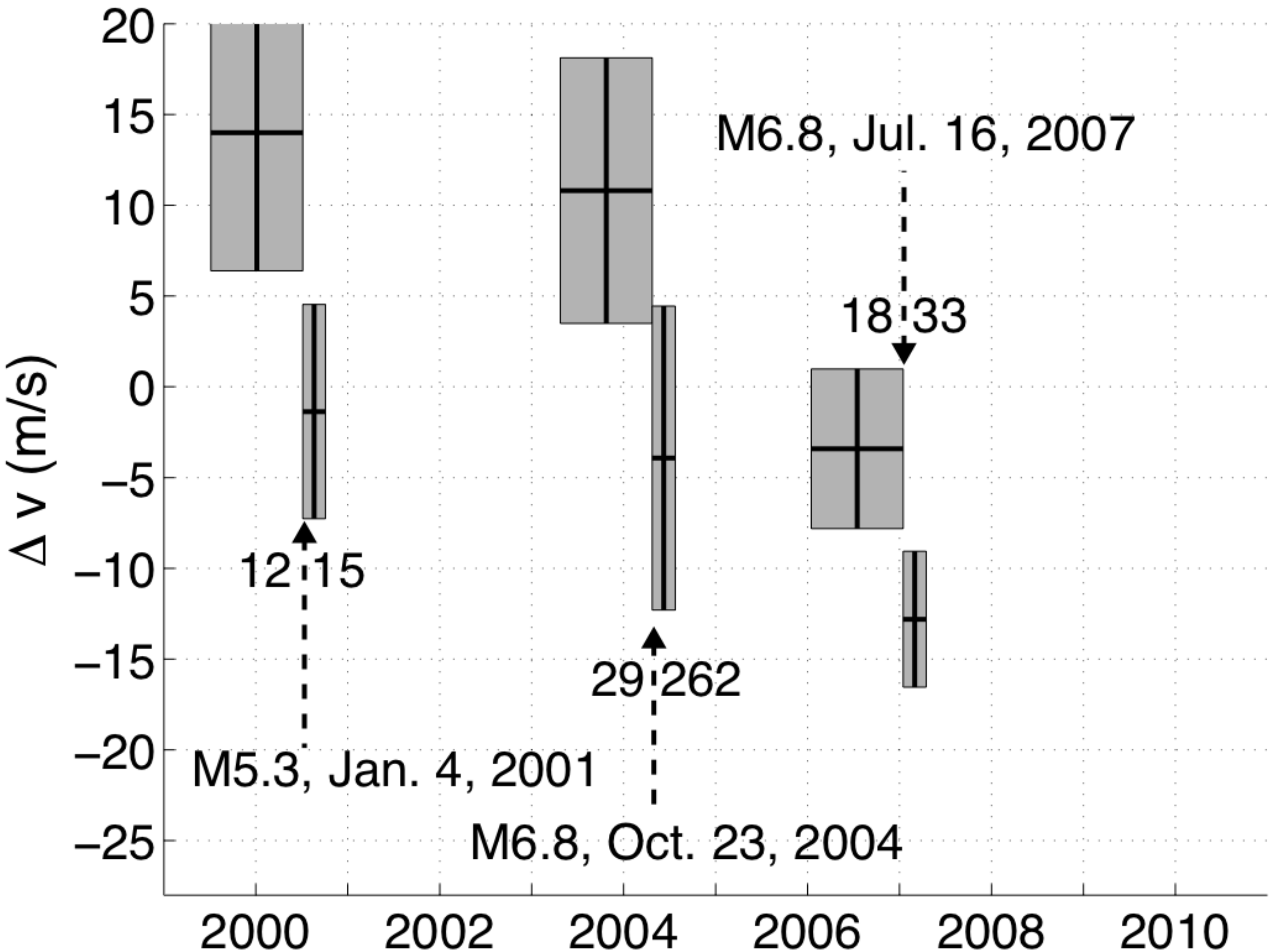
$$correlation = u(z=0,\omega)u^{*}(z=D,\omega) = \left|S(\omega)\right|^{2} e^{ikz}$$

$$deconvolution = \frac{u(z=0,\omega)}{u(z=D,\omega)} = e^{ikz}$$

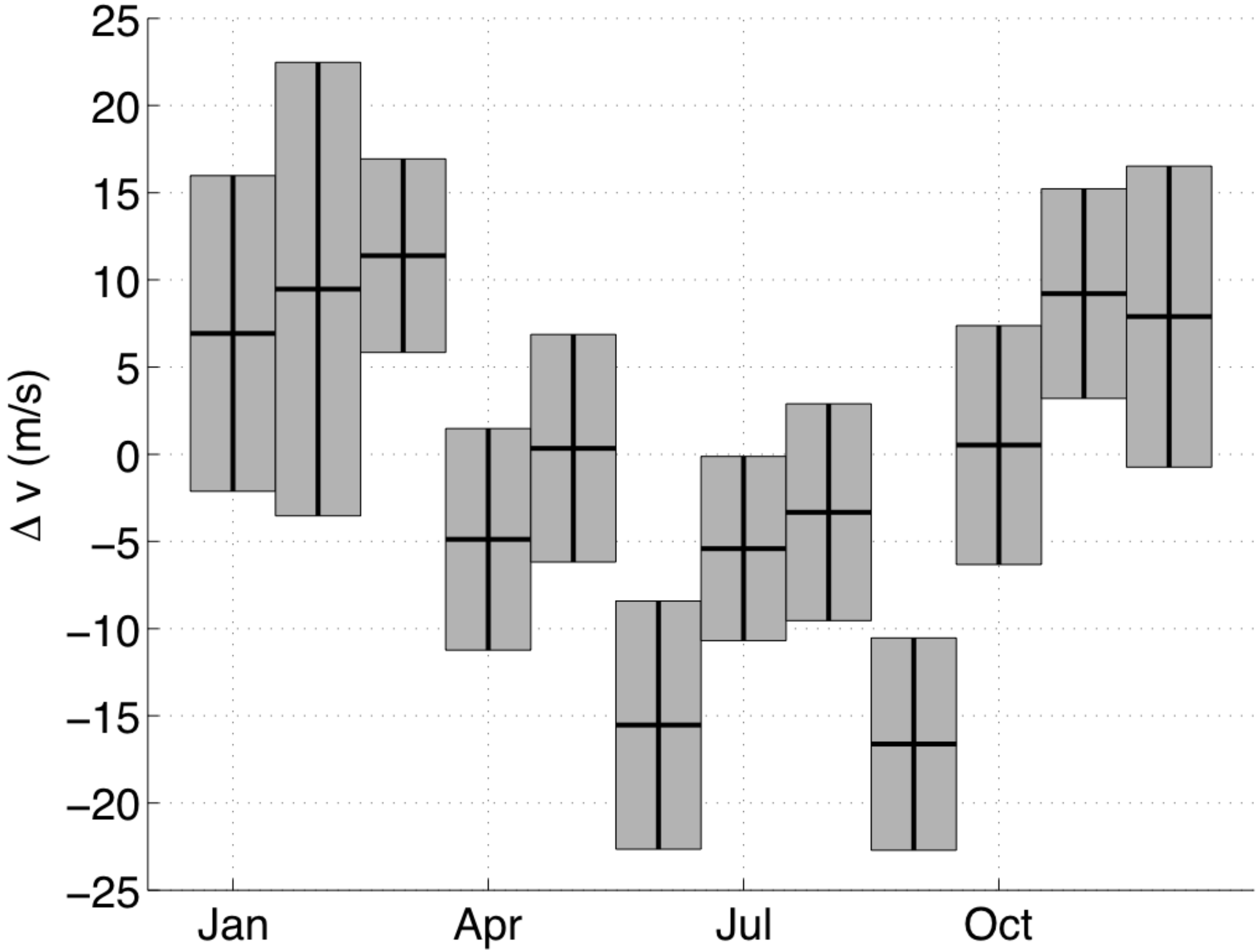


(Nakata and Snieder, JGR, 117, B01308, 2012)

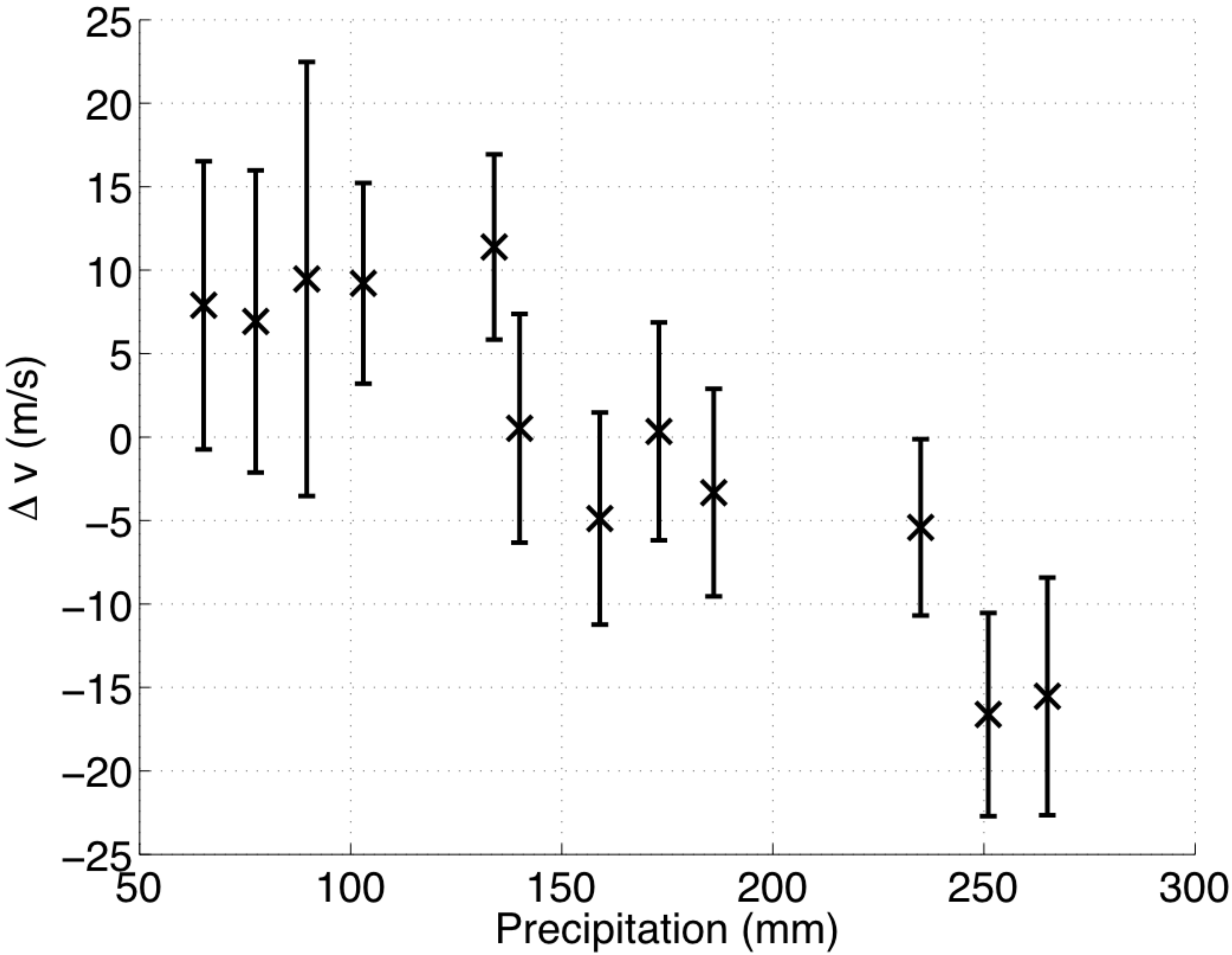
S-waves in Niigata and earthquakes



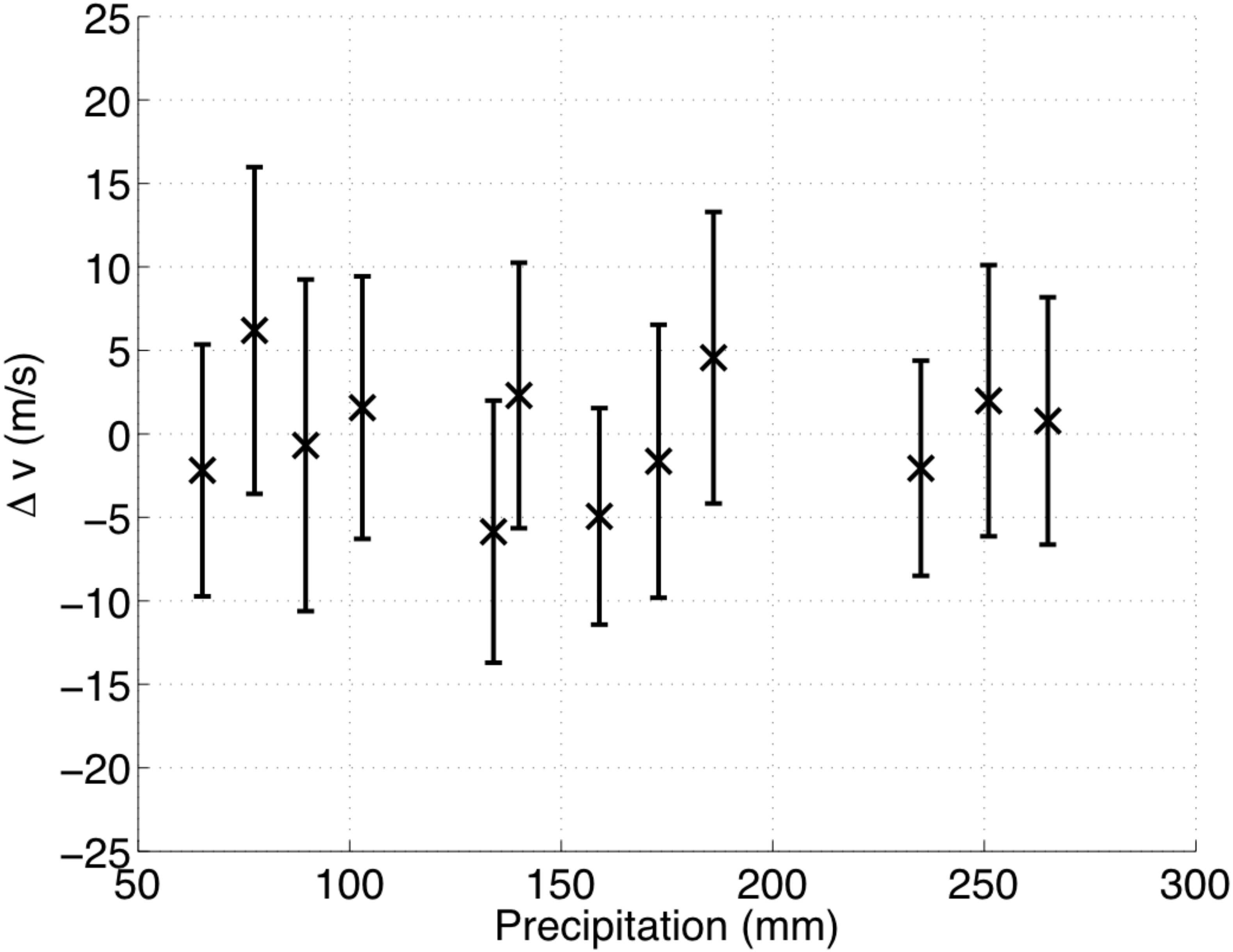
S-velocity changes with seasons



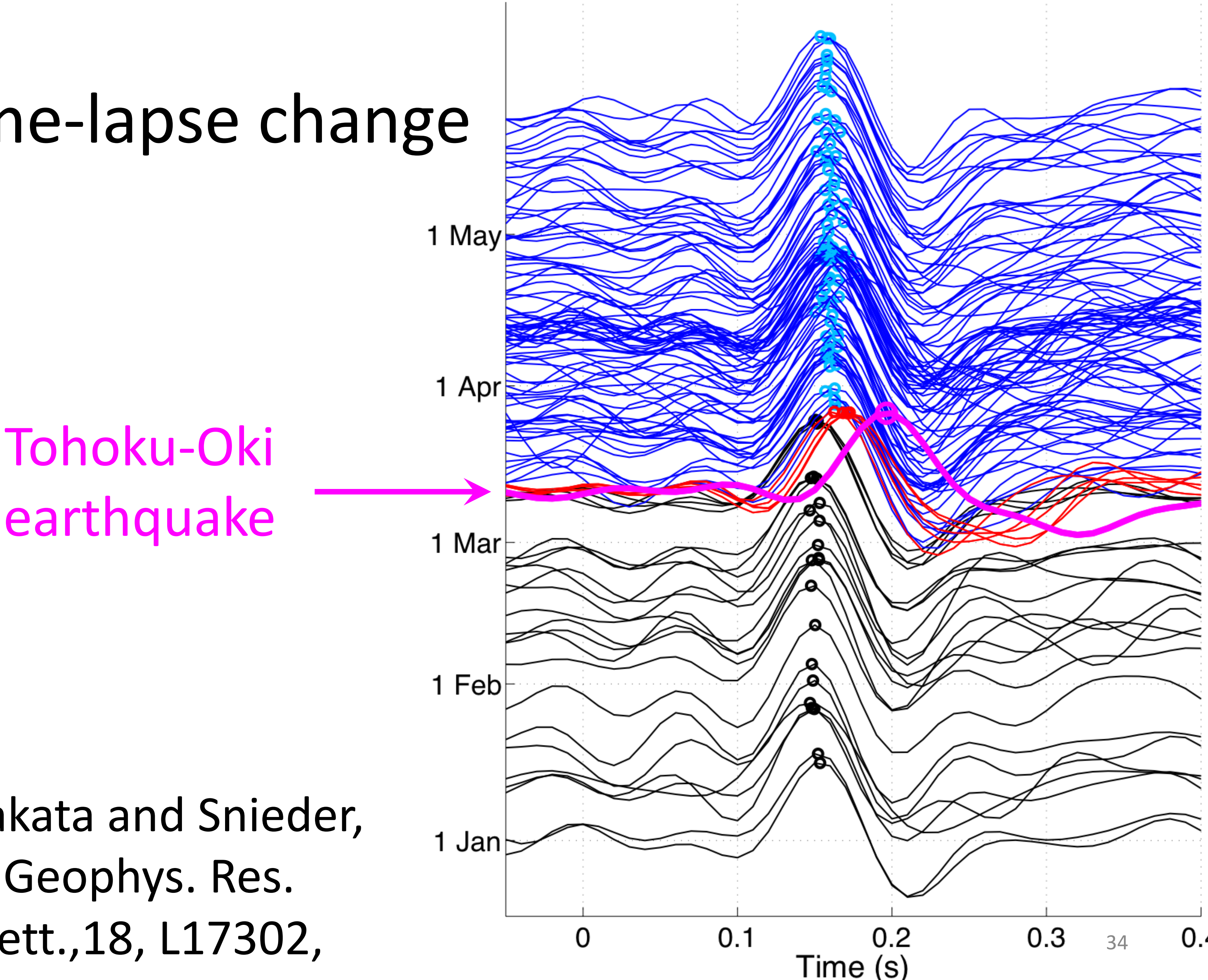
Rainfall/v_s for soft-rock sites



Rainfall/v_s for hard-rock sites

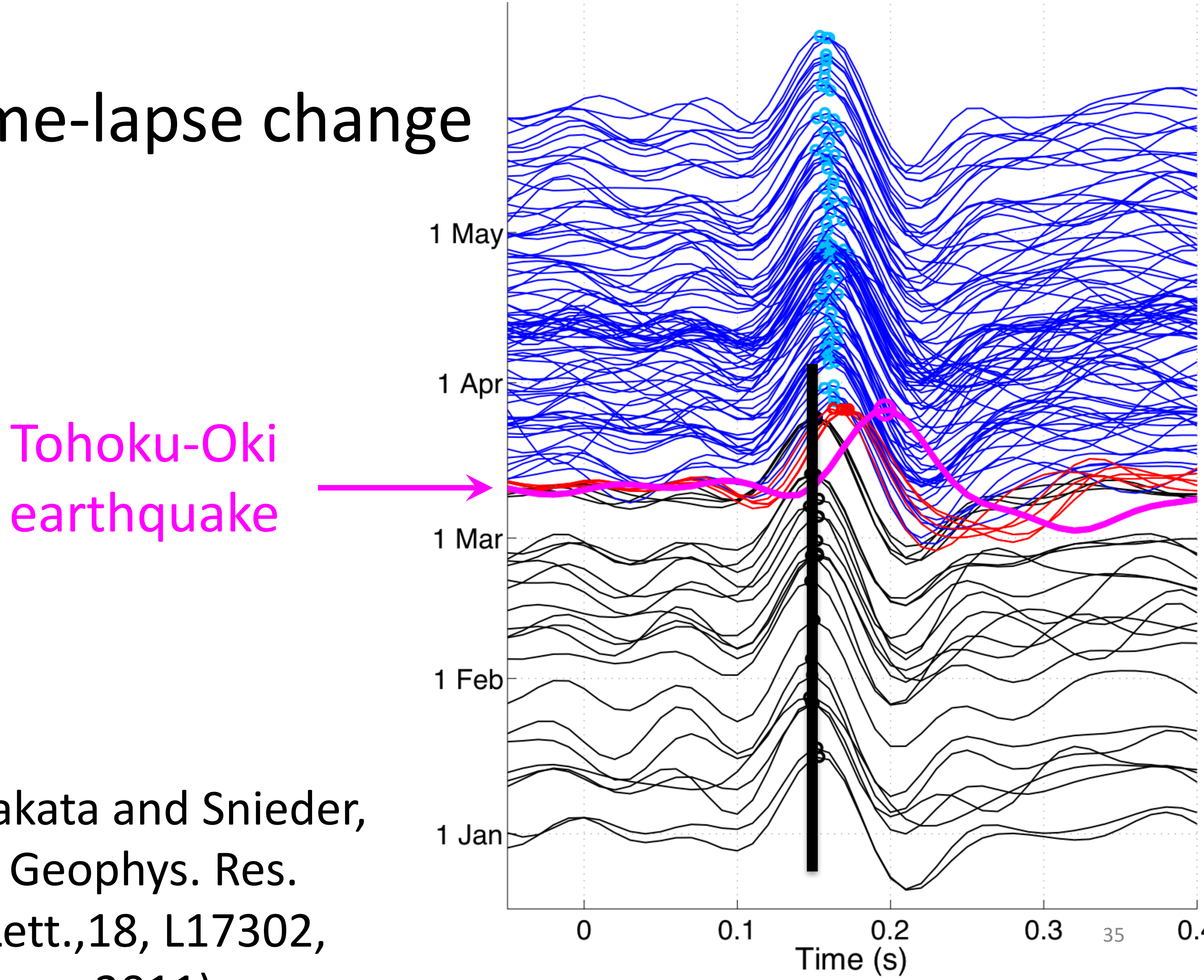


Time-lapse change



(Nakata and Snieder, Geophys. Res. Lett.,18, L17302, 2011)

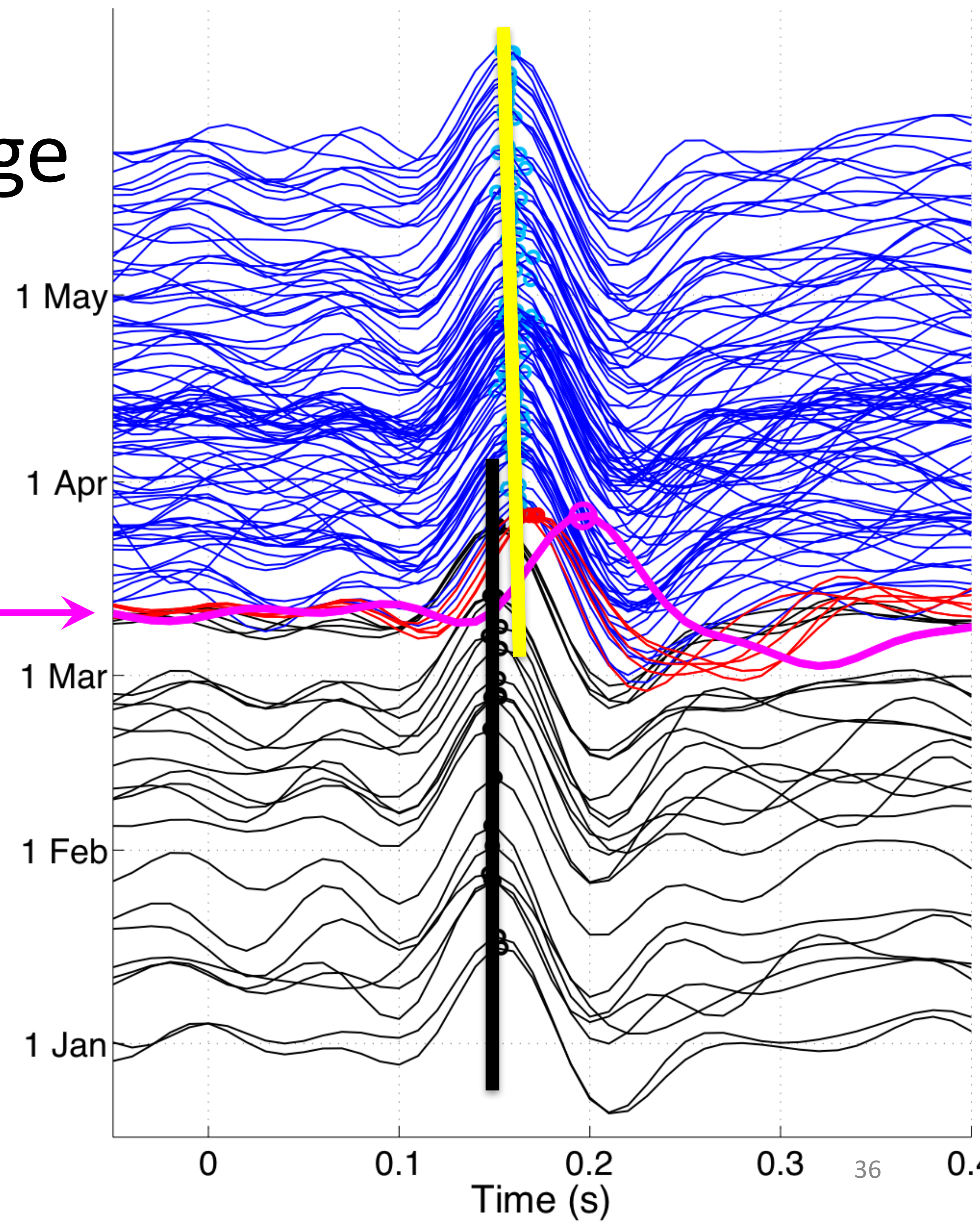
Time-lapse change



(Nakata and Snieder, Geophys. Res. Lett.,18, L17302, 2011)

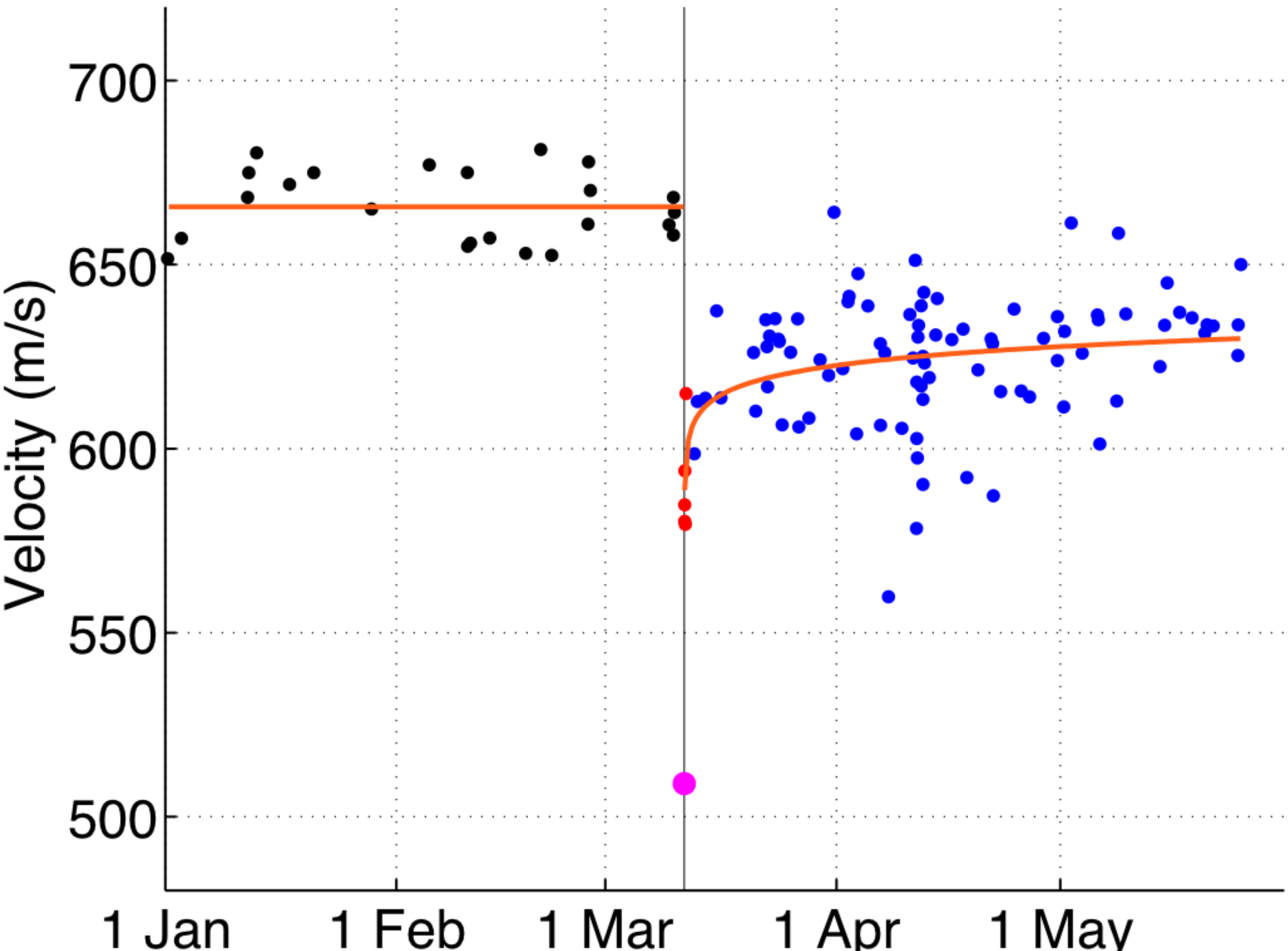
Time-lapse change

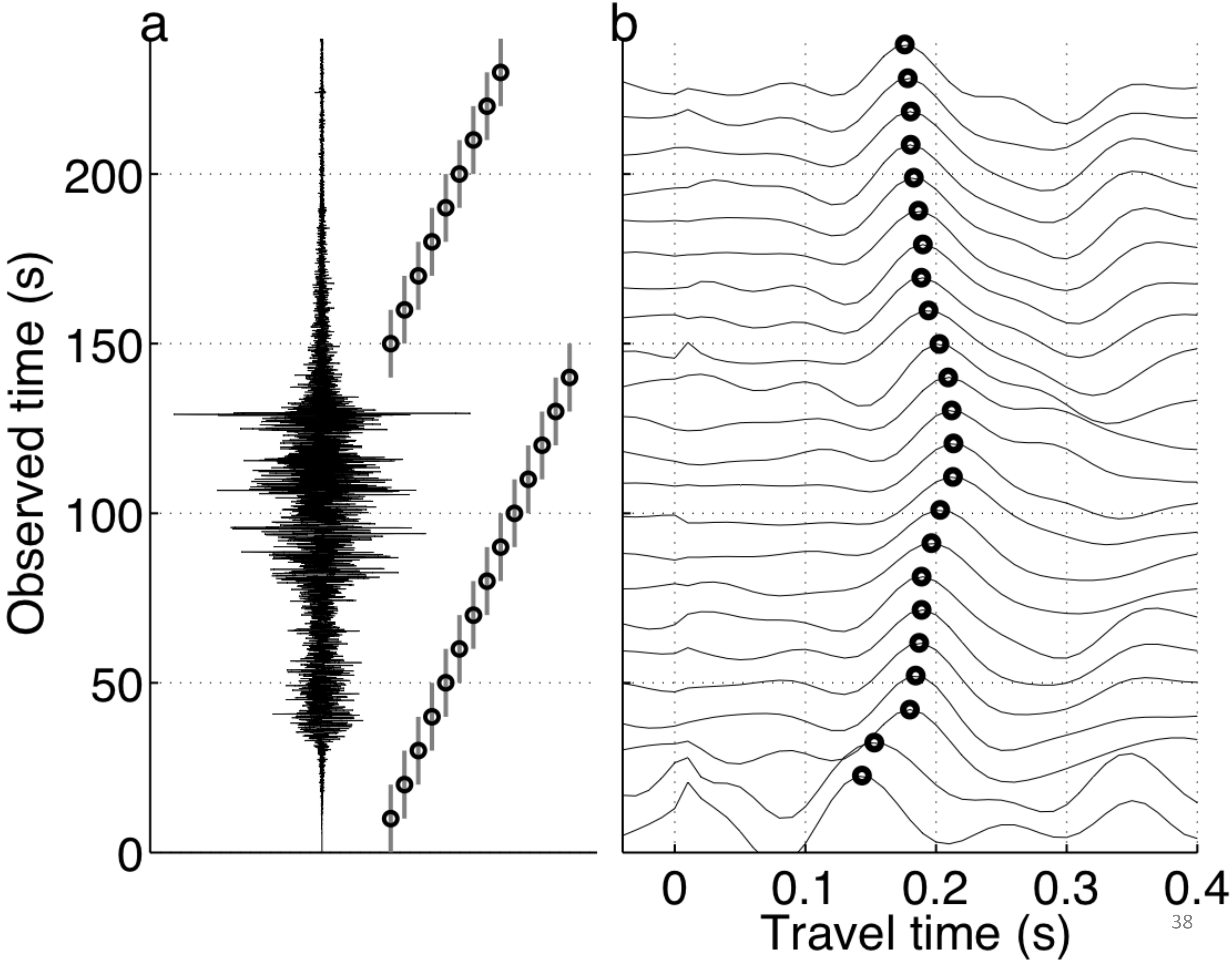
Tohoku-Oki earthquake



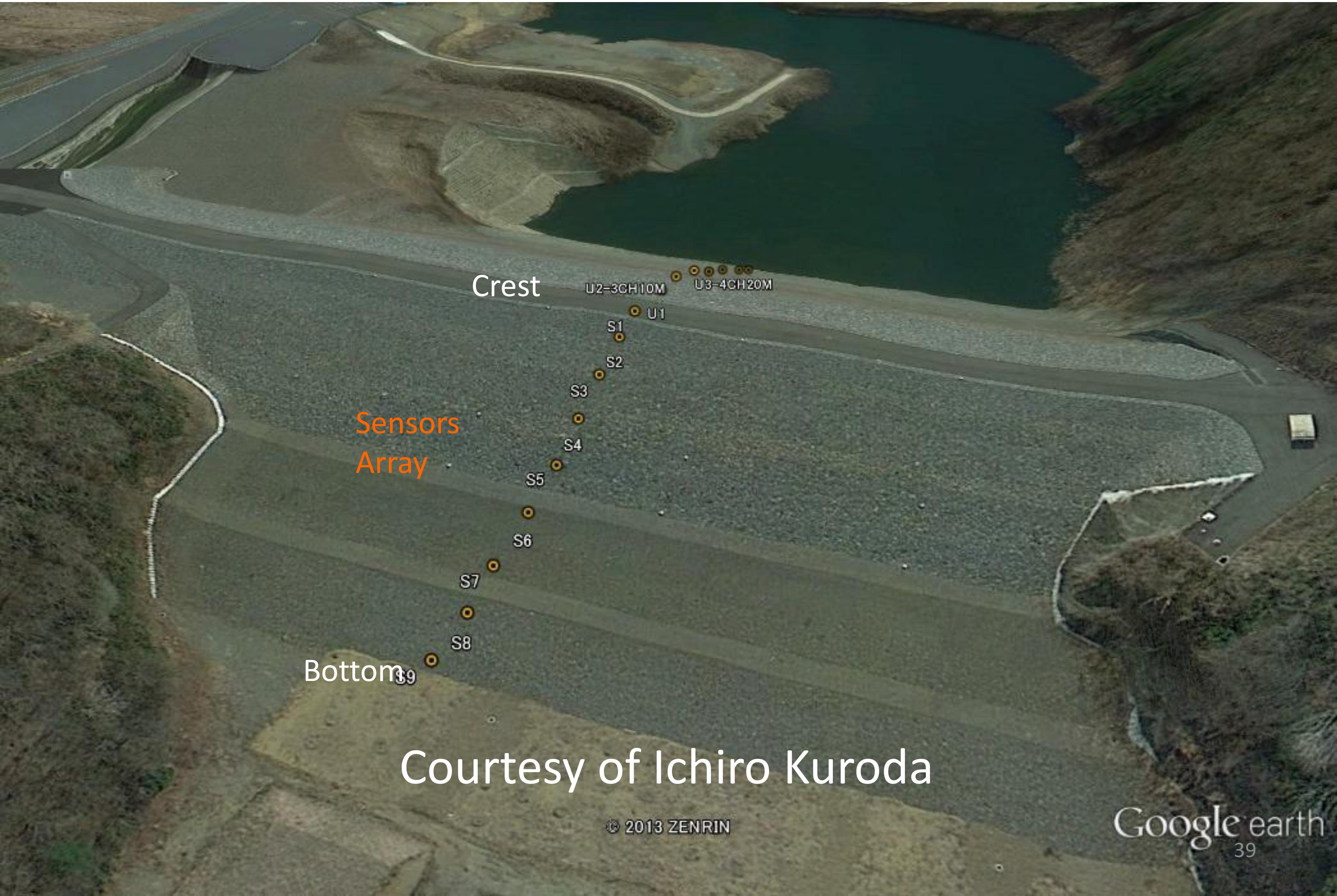
(Nakata and Snieder, Geophys. Res. Lett.,18, L17302,

Velocity change

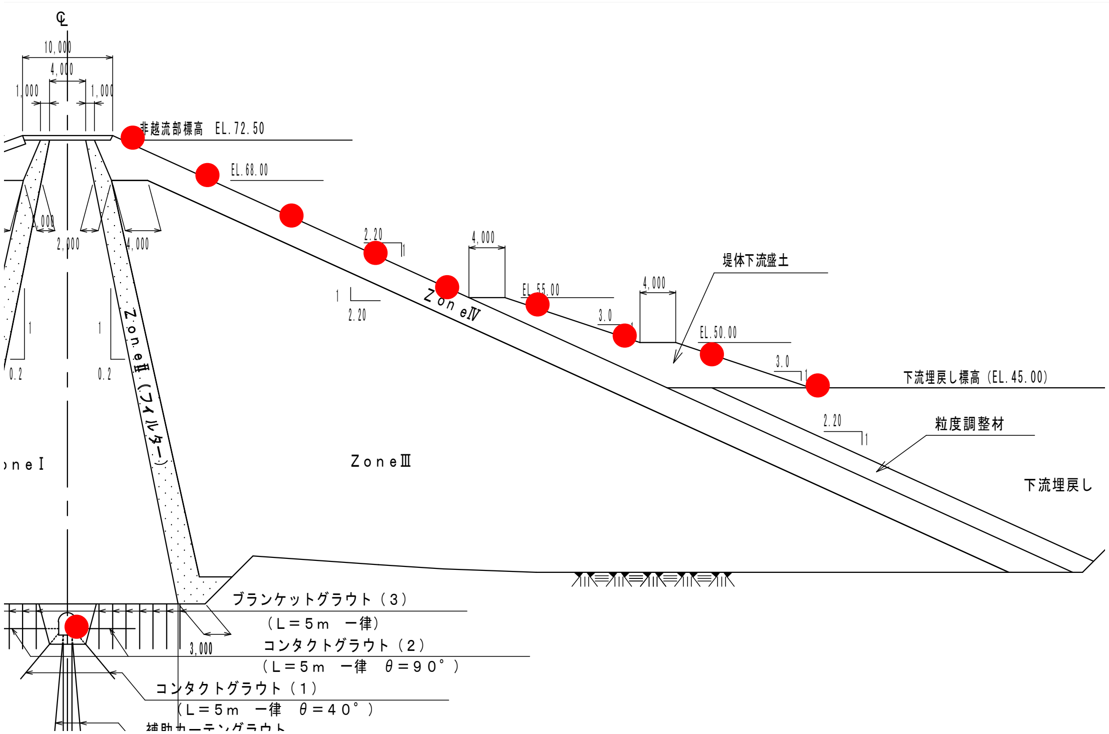


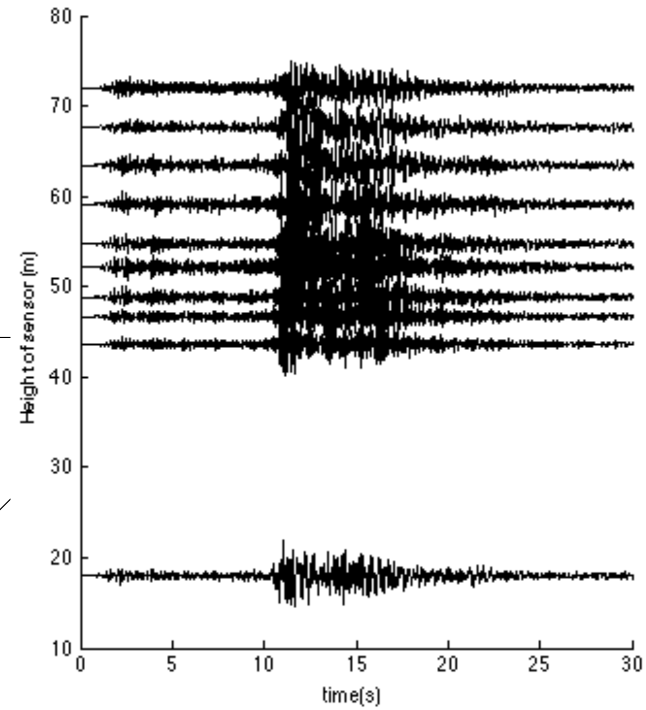

a
b
Observed time (s)
0
50
100
150
200
0
0.1
0.2
0.3
0.4
Travel time (s)

Seismic sensors array on a dam

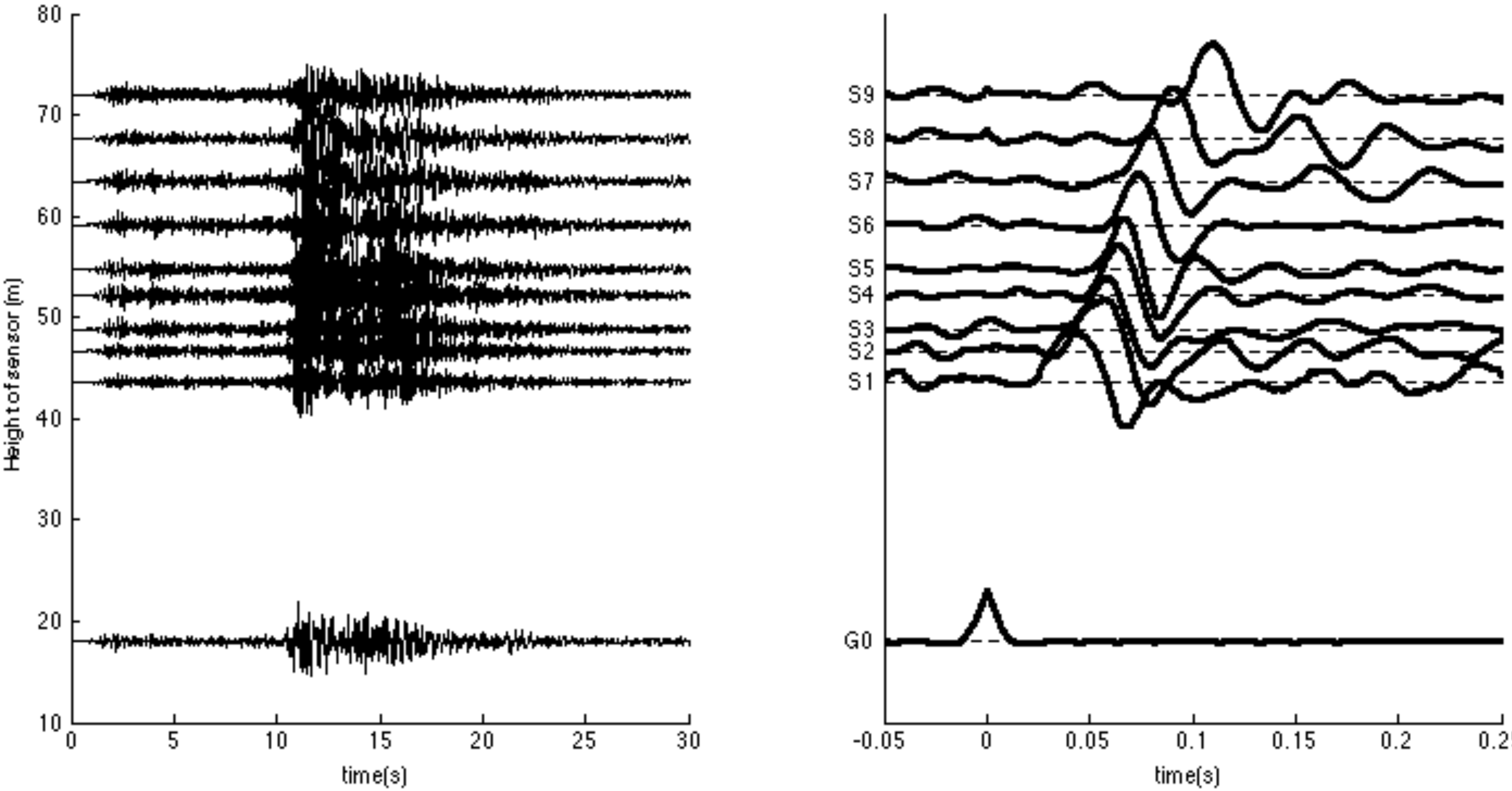


Original waveforms observed by sensors array

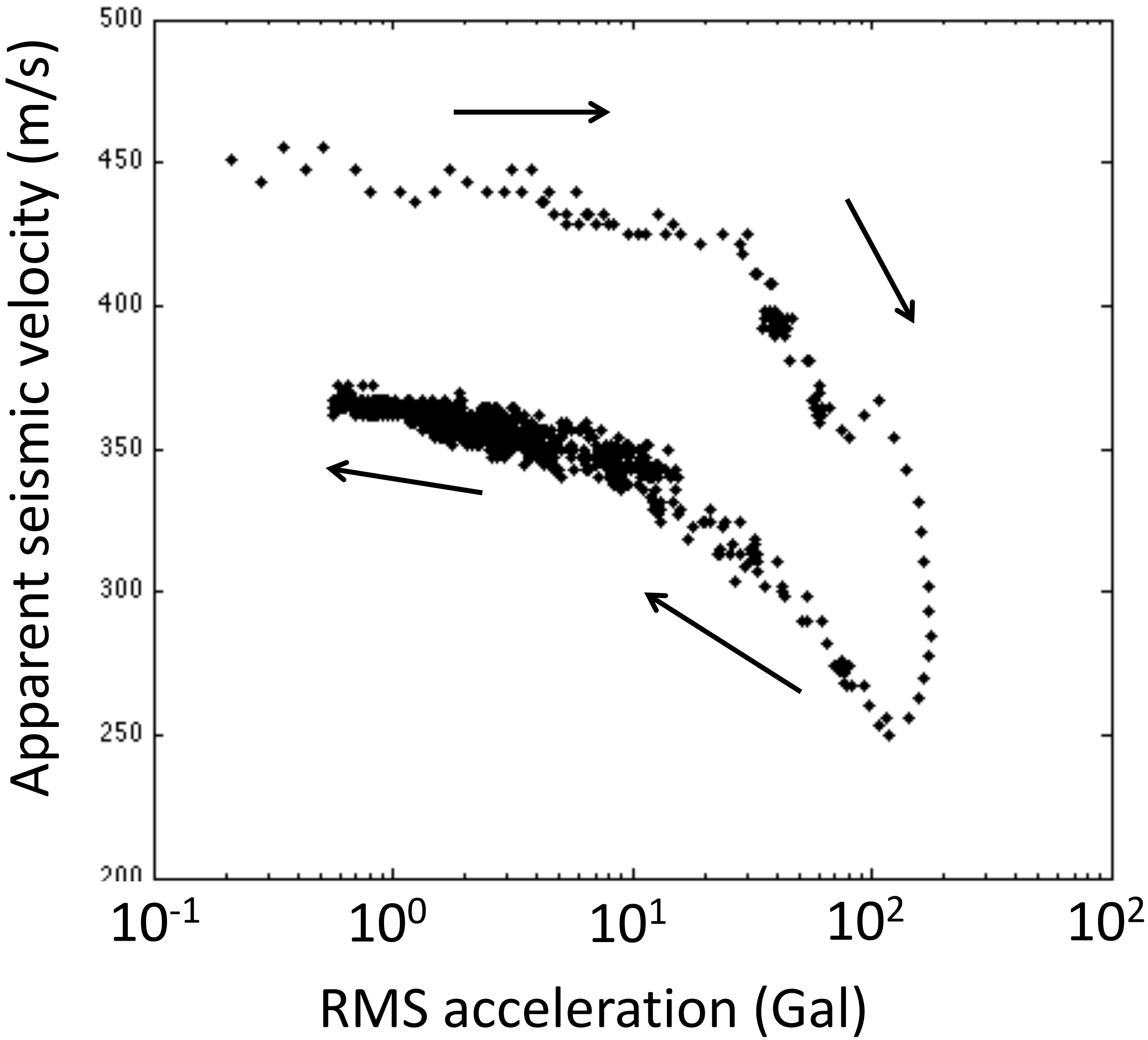




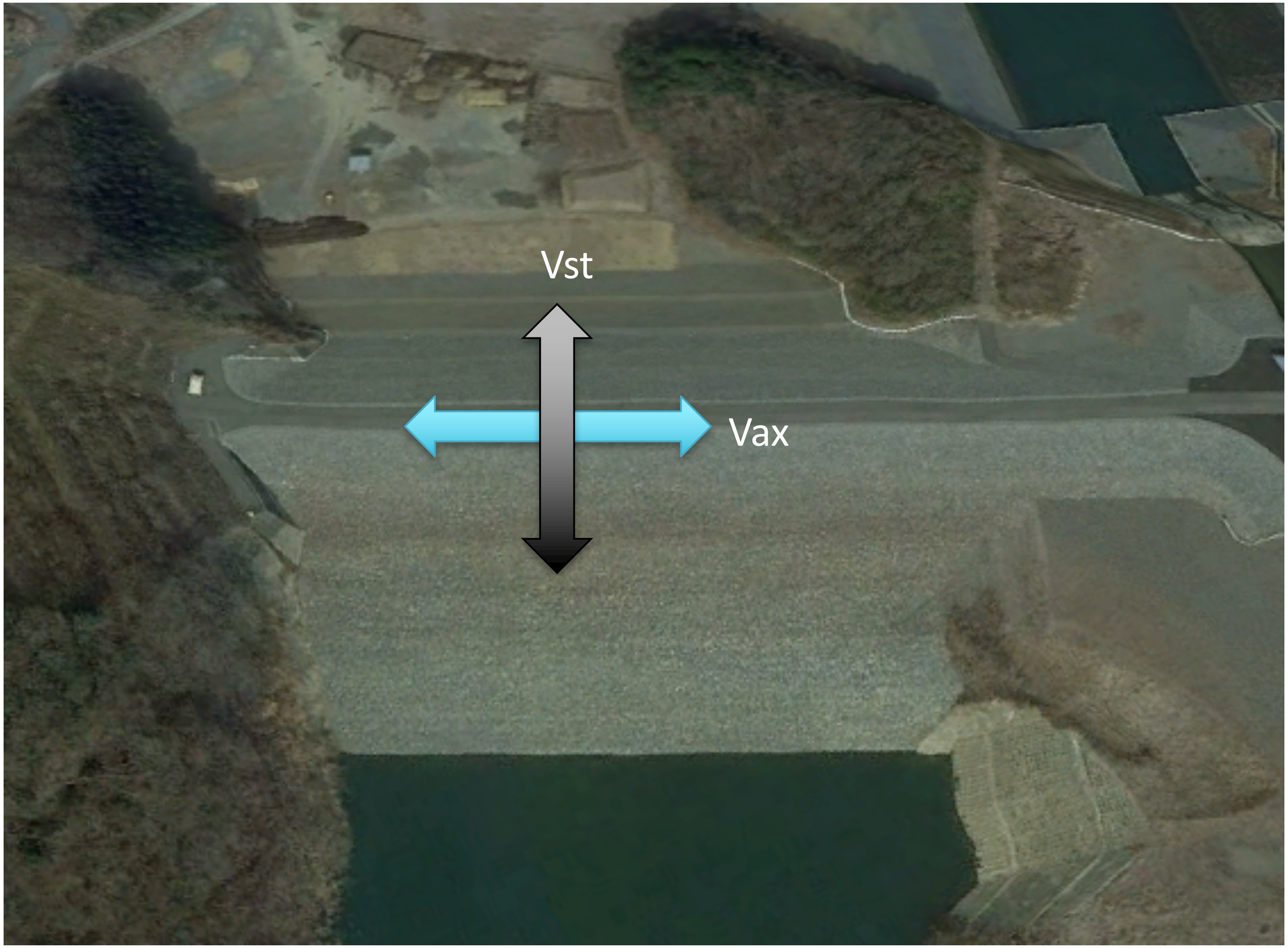
Original waveforms and deconvolution interferometry

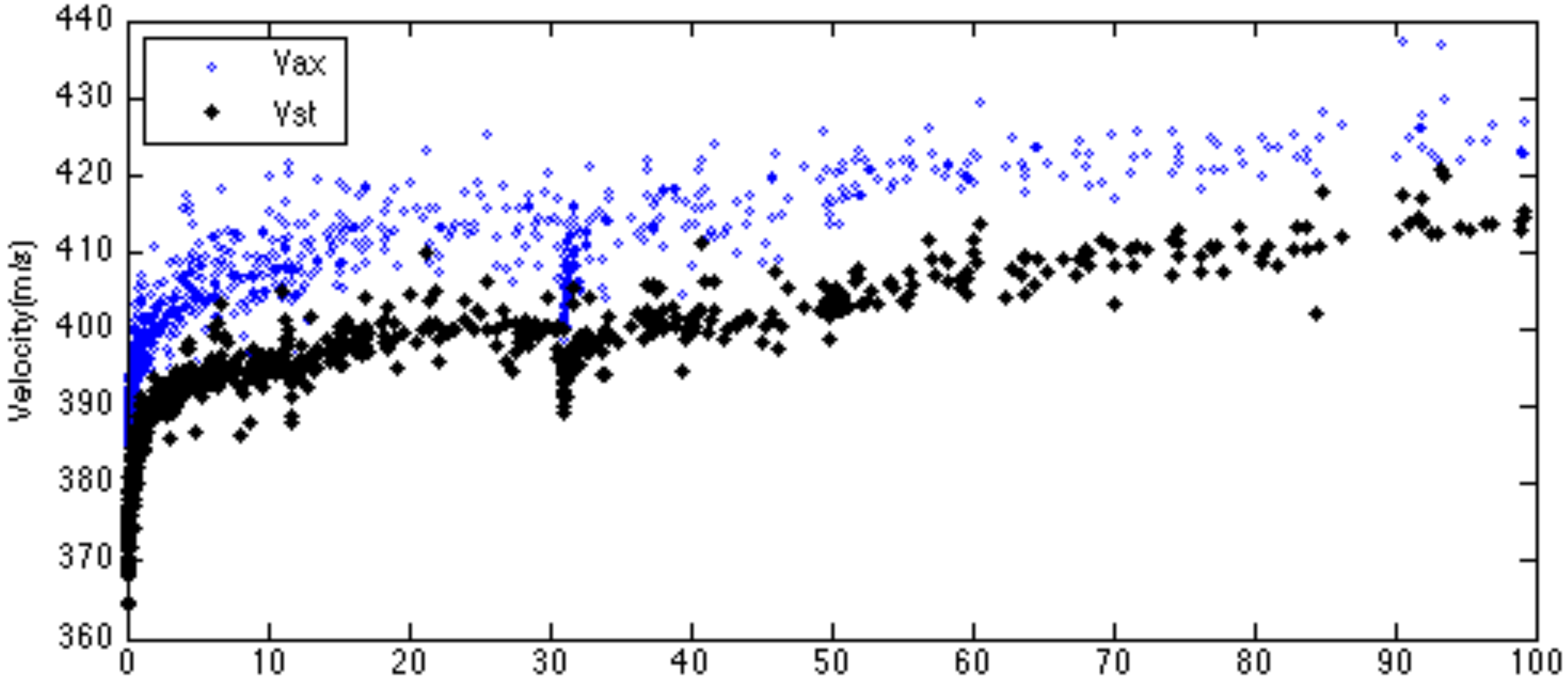


Change during Tohoku earthquake

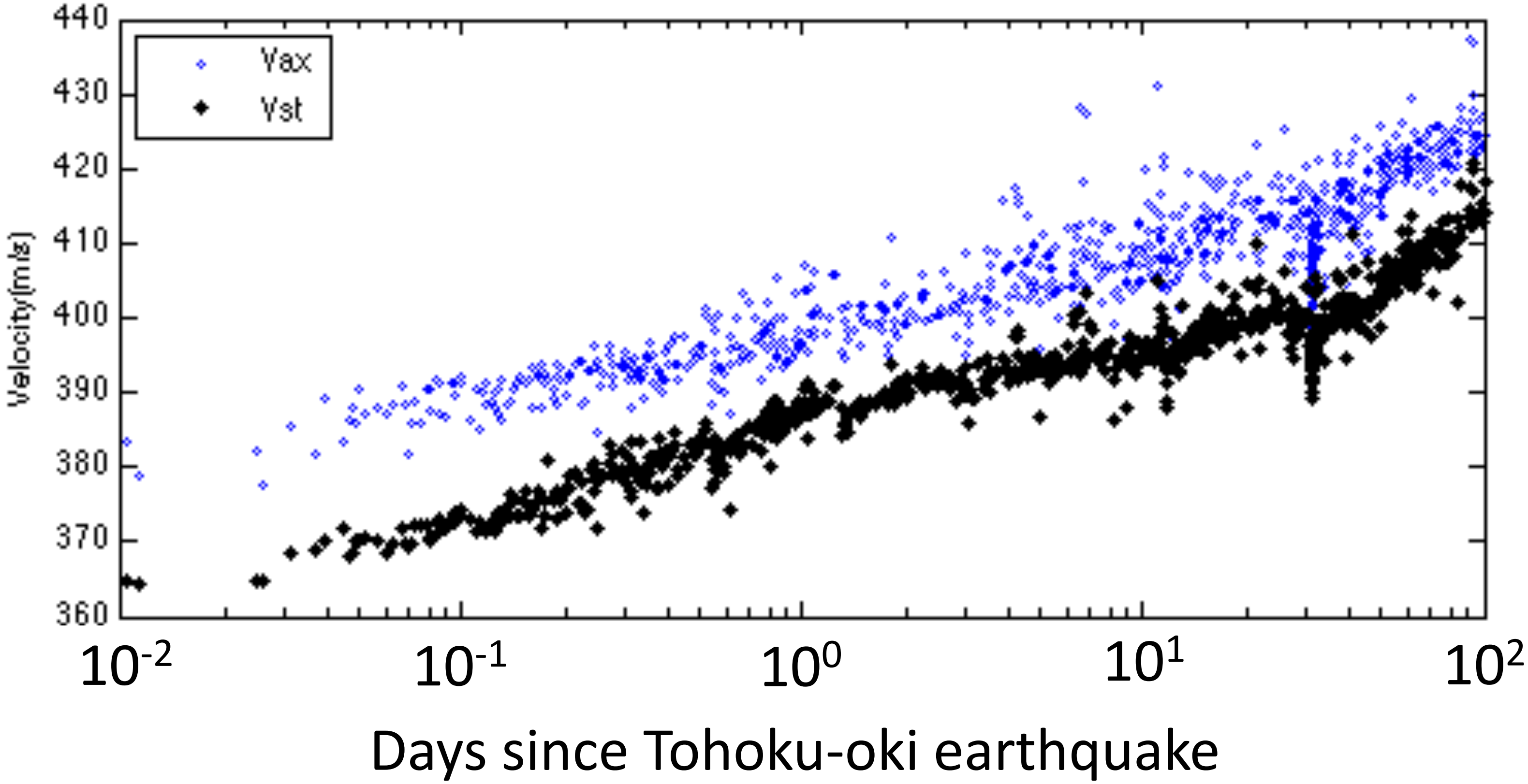


Direction components in a dam

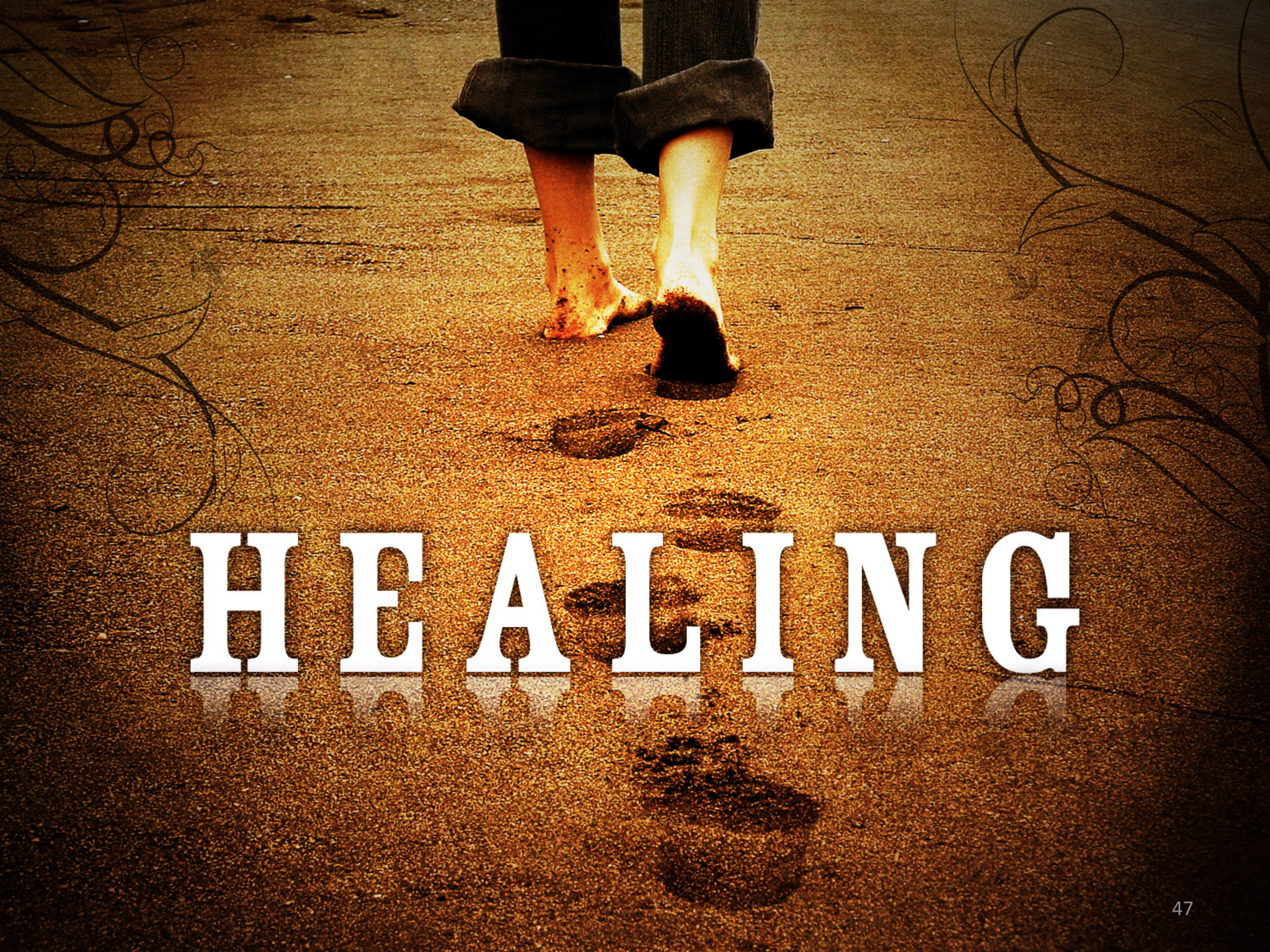




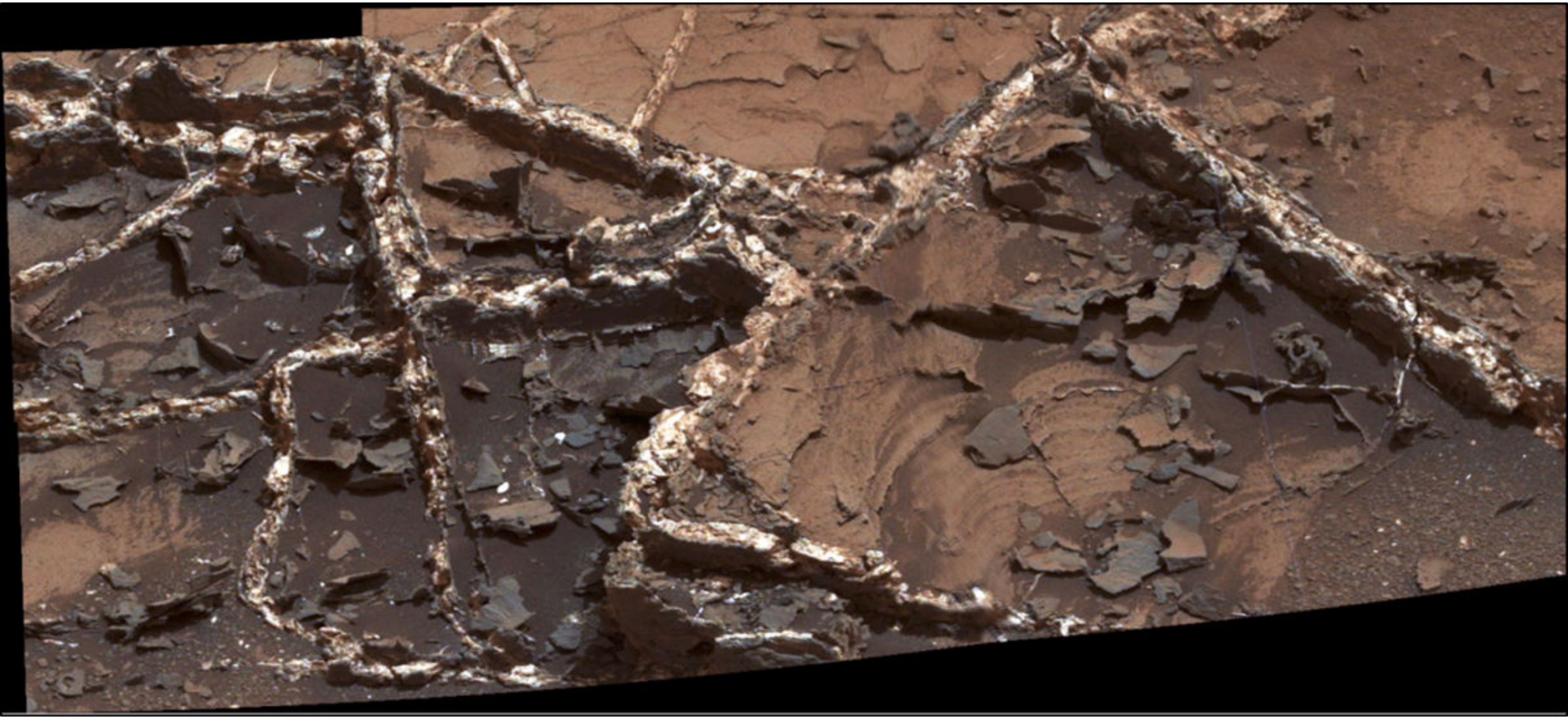
Days since Tohoku-oki earthquake


Vax
Vst
Velocity(m/s)
440
430
420
410
400
390
380
370
360
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
Days since Tohoku-oki earthquake


seek spirit create give
LIVE family guidance
LIFE HOPE gratitude PEACE
health LOVE laugh
soul thank you om
JOY kindness healing purpose
TRUTH forgive receive
JOURNEY faith
NOW believe meditate
community divine
ASK abundance
CHANGE growth

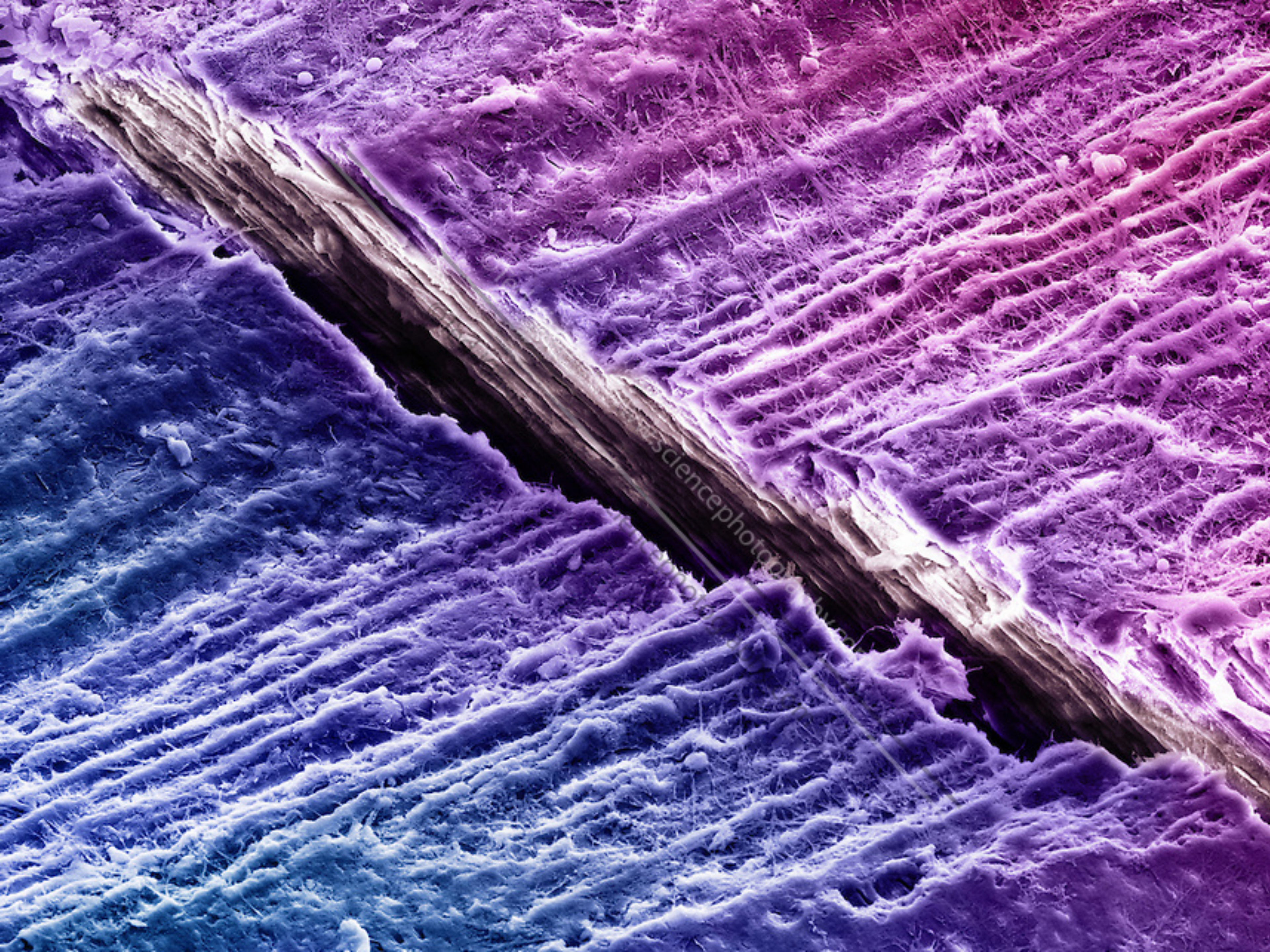

HEALING

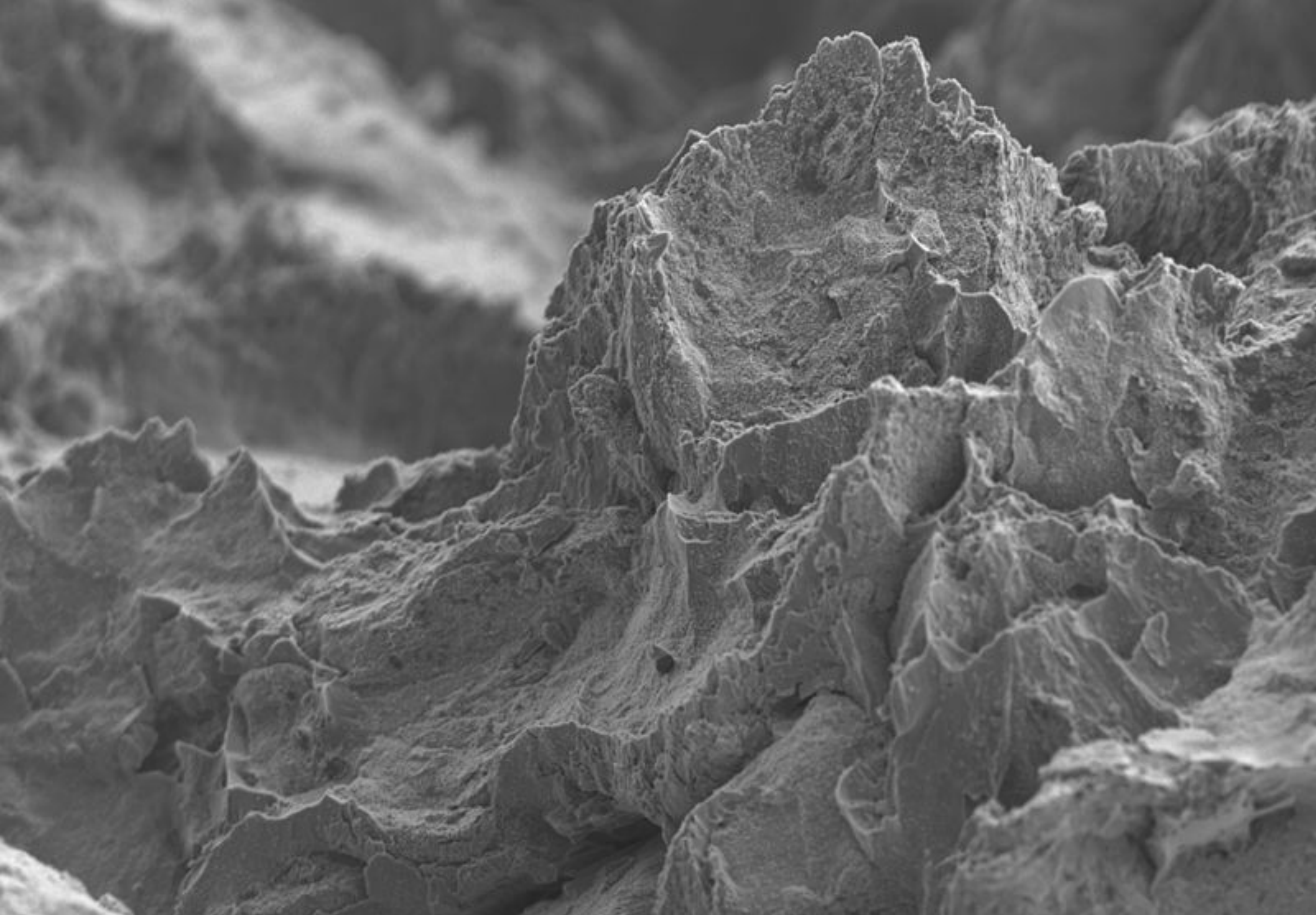
Mineralized fractures

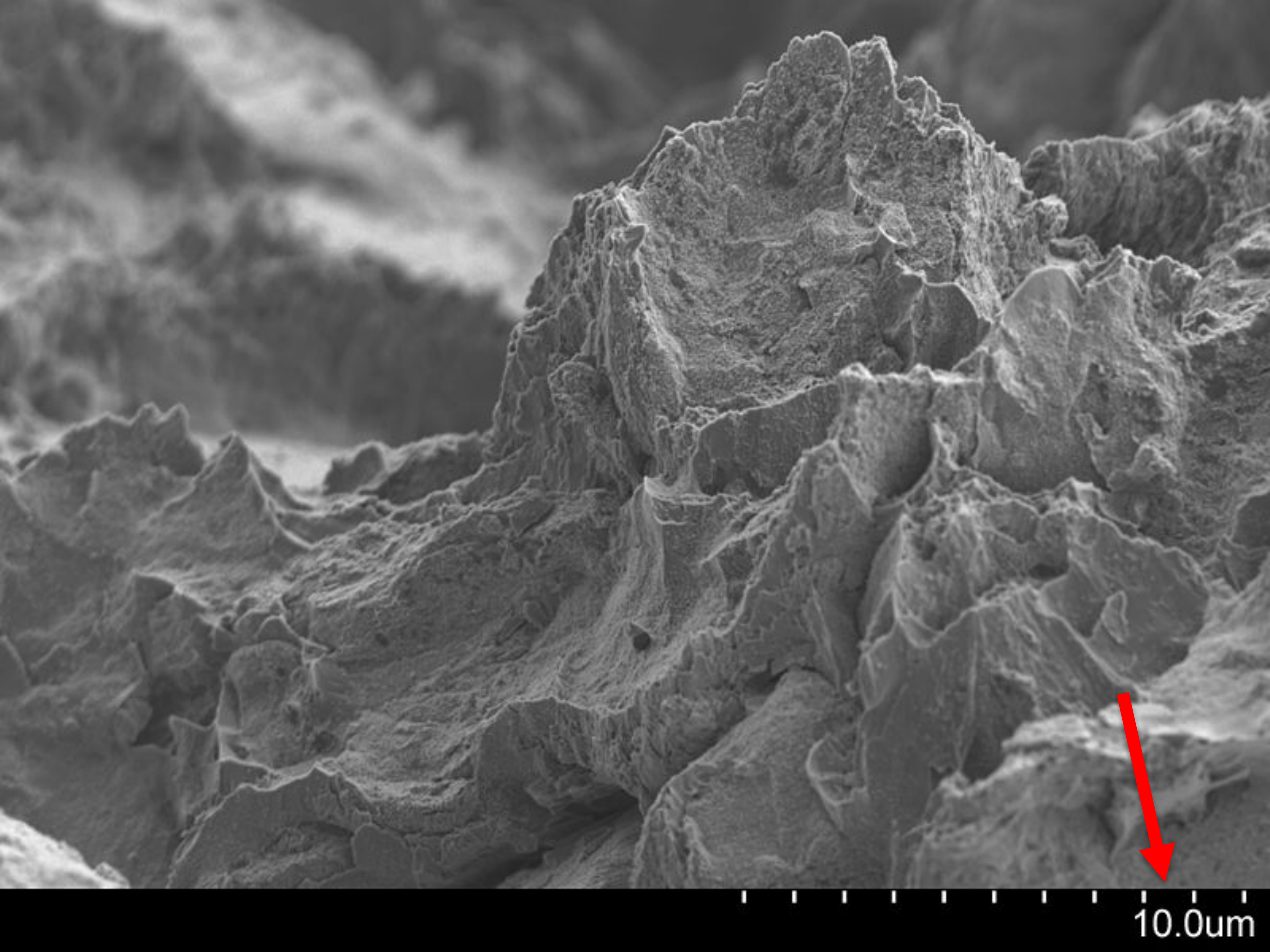


(Credit: NASA/JPL-Caltech/MSSS)

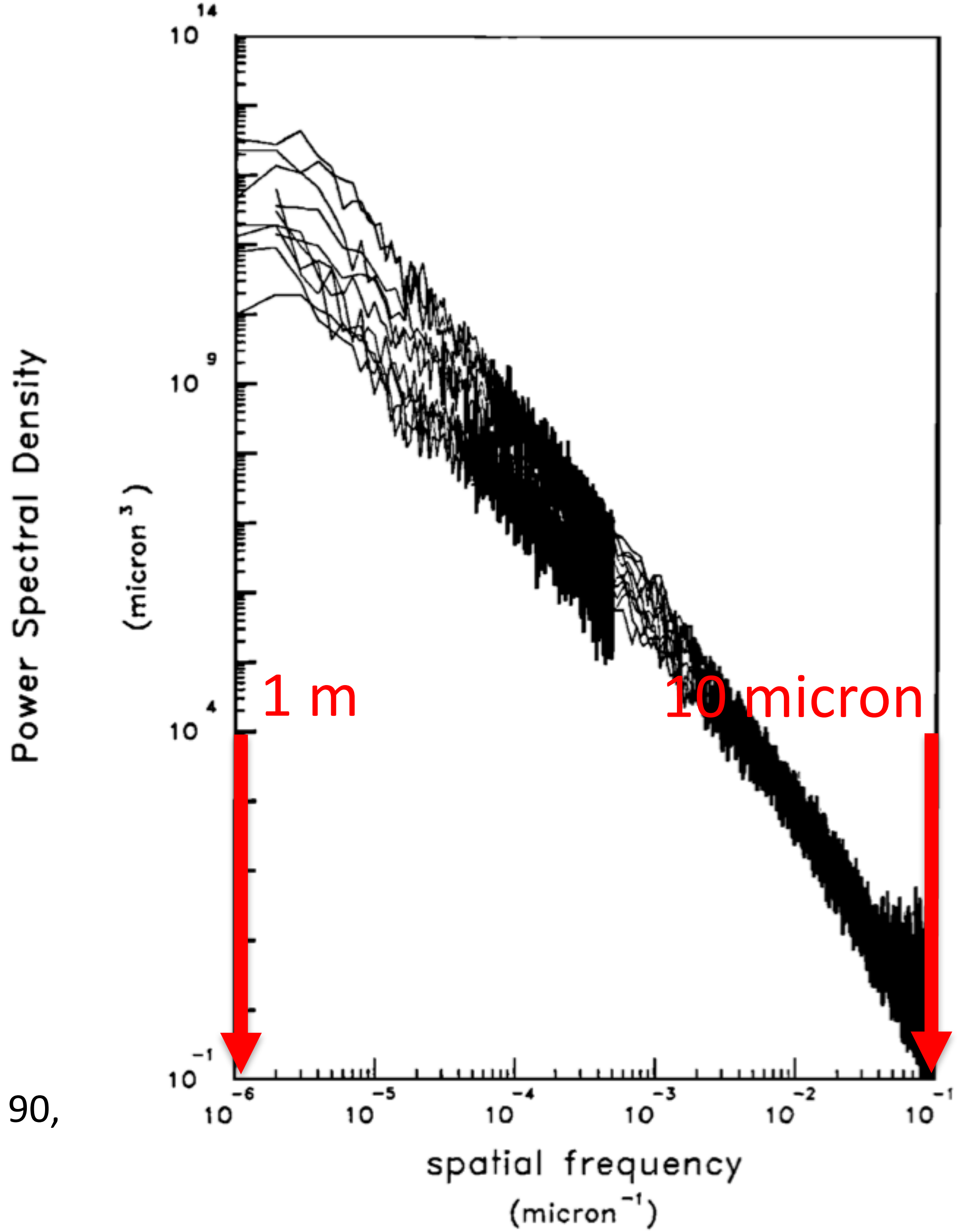
Intrusion by a dike





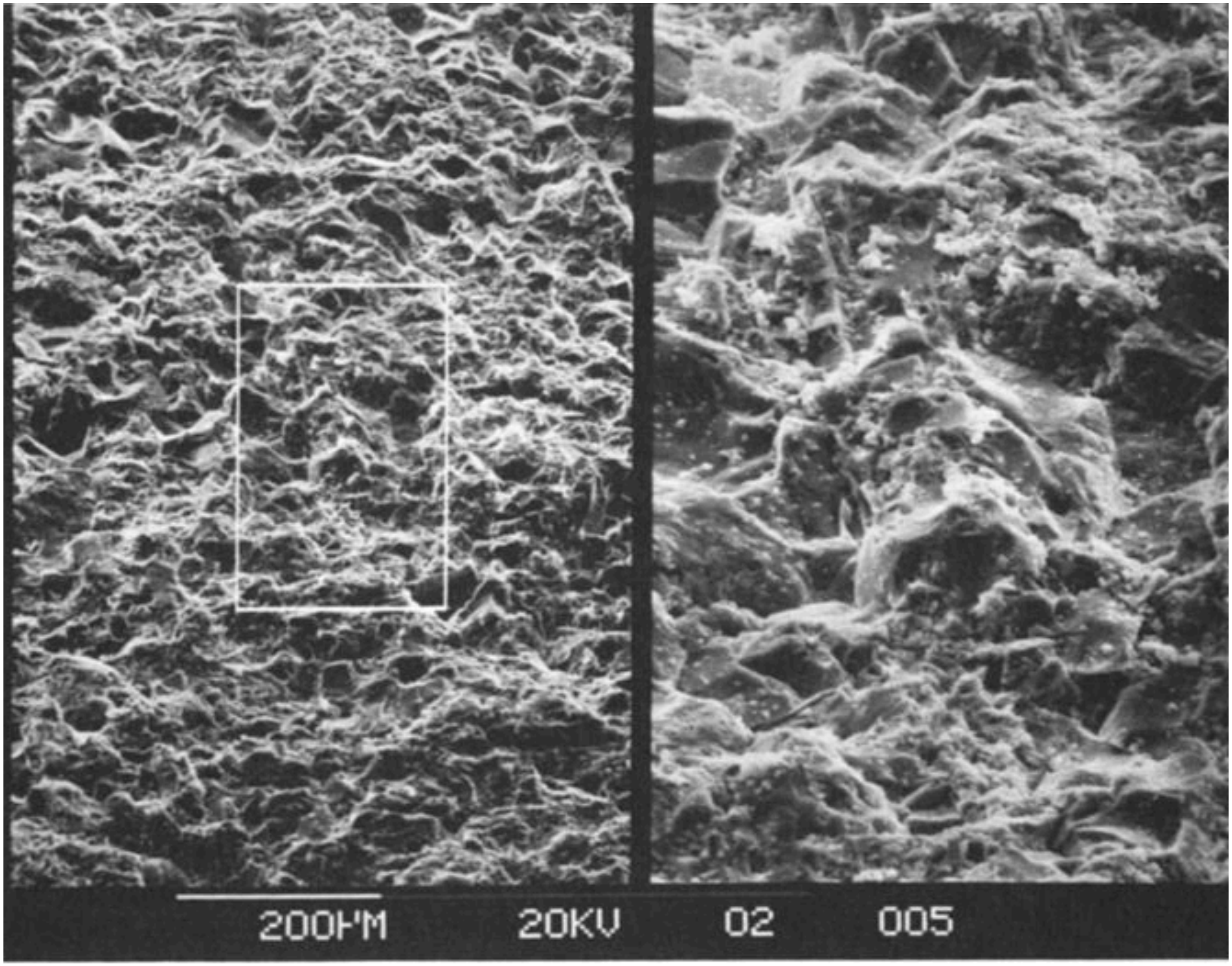

10.0um

Power spectrum of rock surface



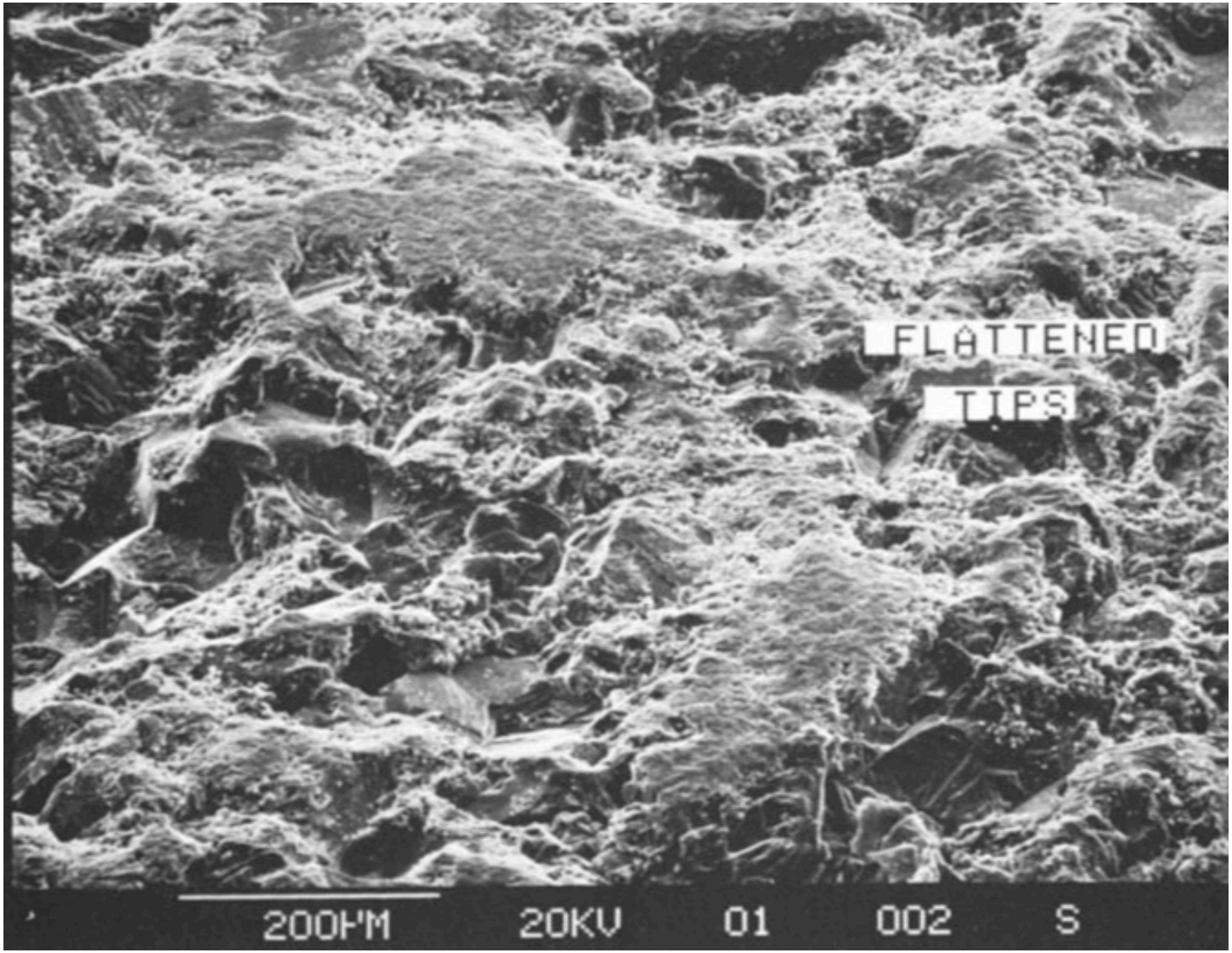
(Brown and Scholz, J. Geophys. Res., 90, 12575-12582, 1985)

Micro-structure of a fracture



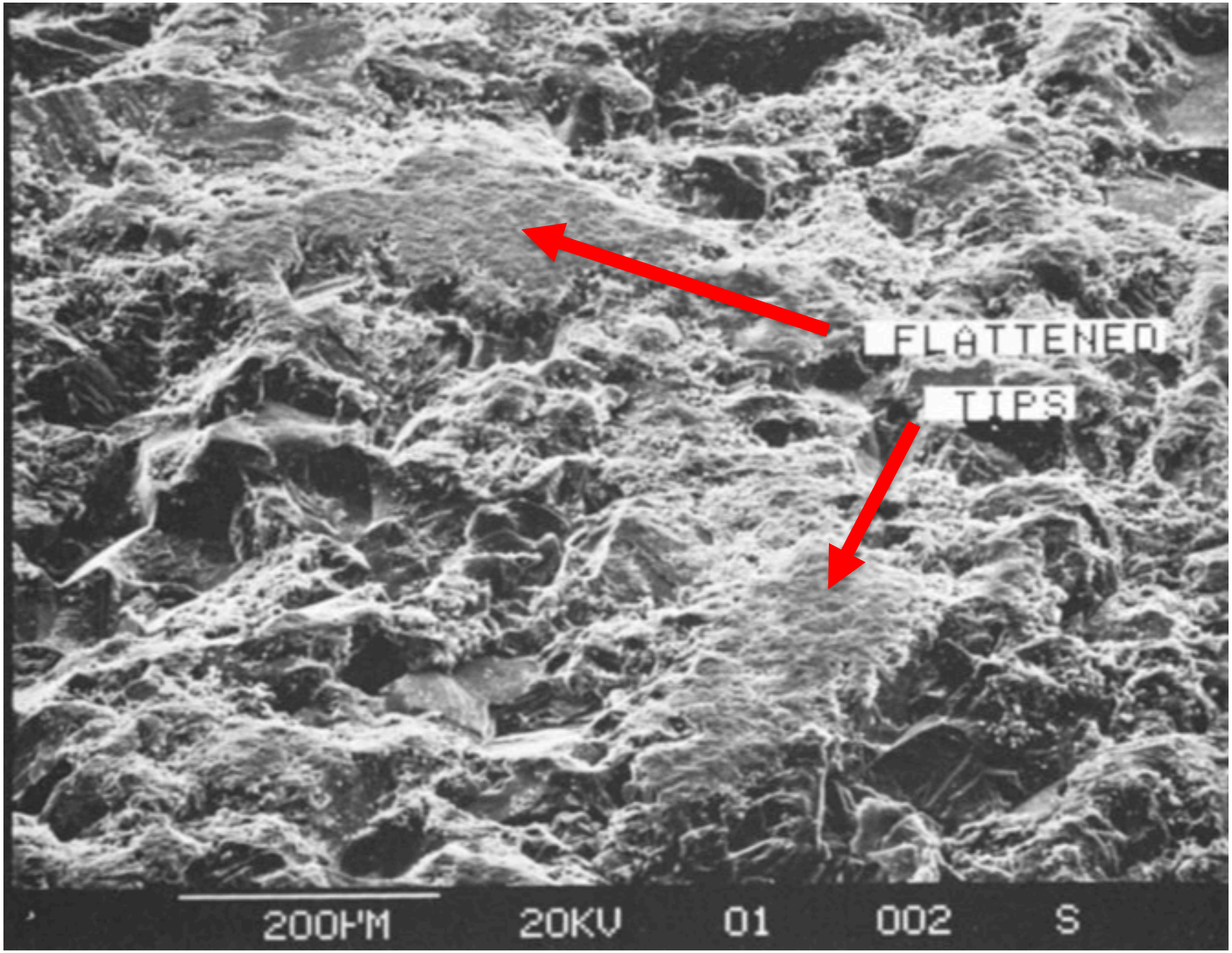
(Brown and Scholz, J. Geophys. Res., 91, 4939-4948, 1986)

Healing of a fracture



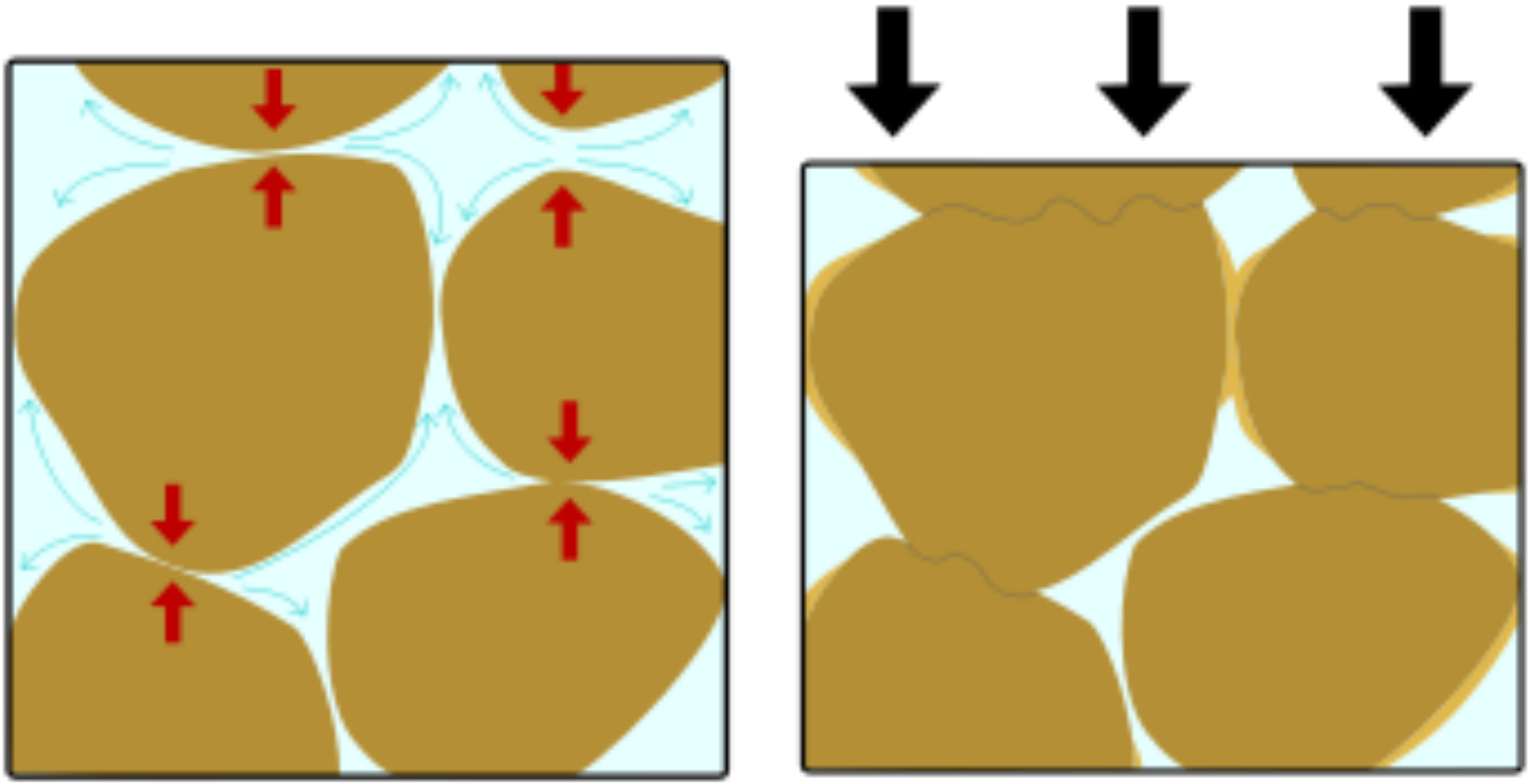
(Brown and Scholz, J. Geophys. Res., 91, 4939-4948, 1986)

Healing of a fracture

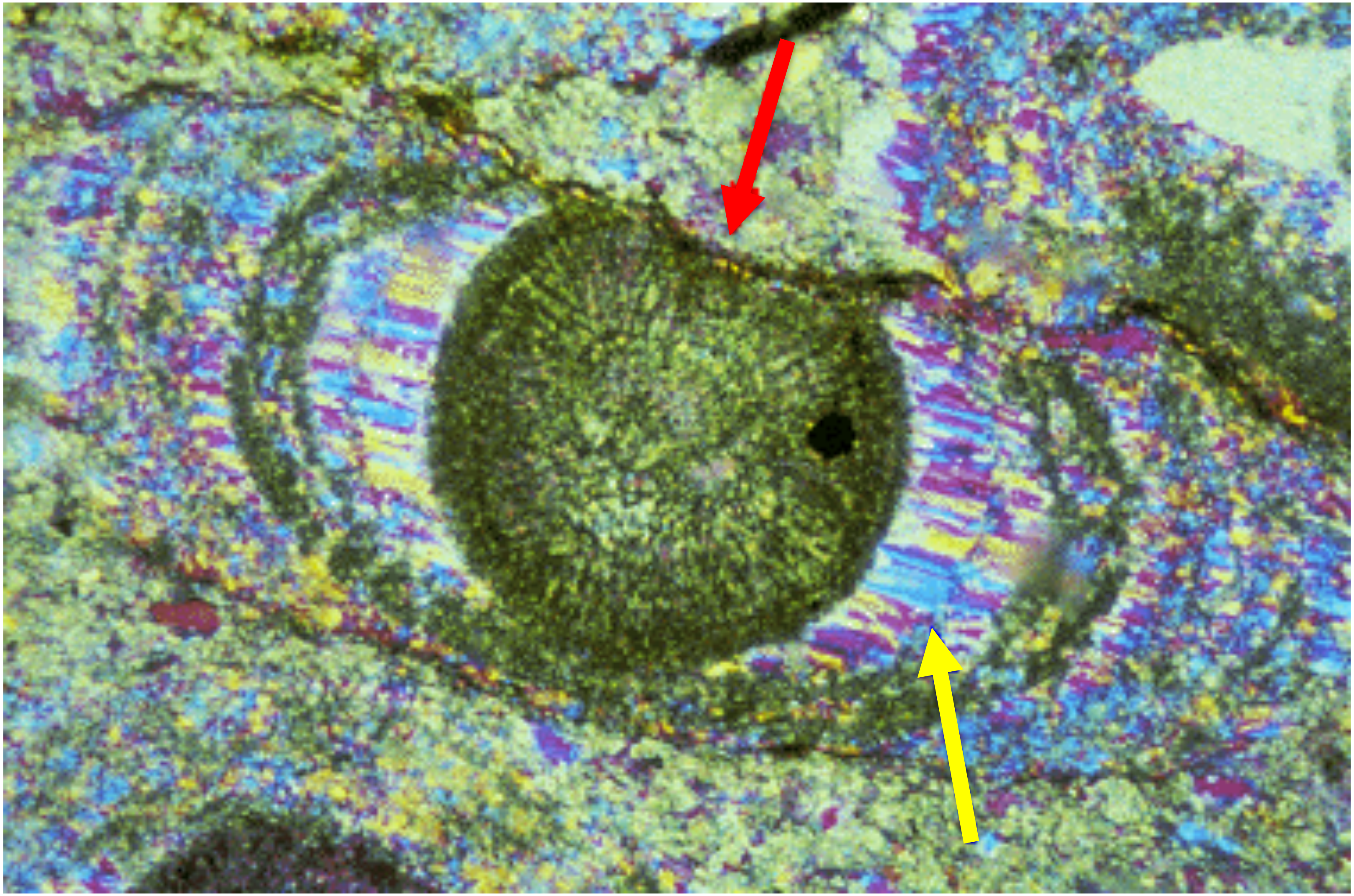


(Brown and Scholz, J. Geophys. Res., 91, 4939-4948, 1986)

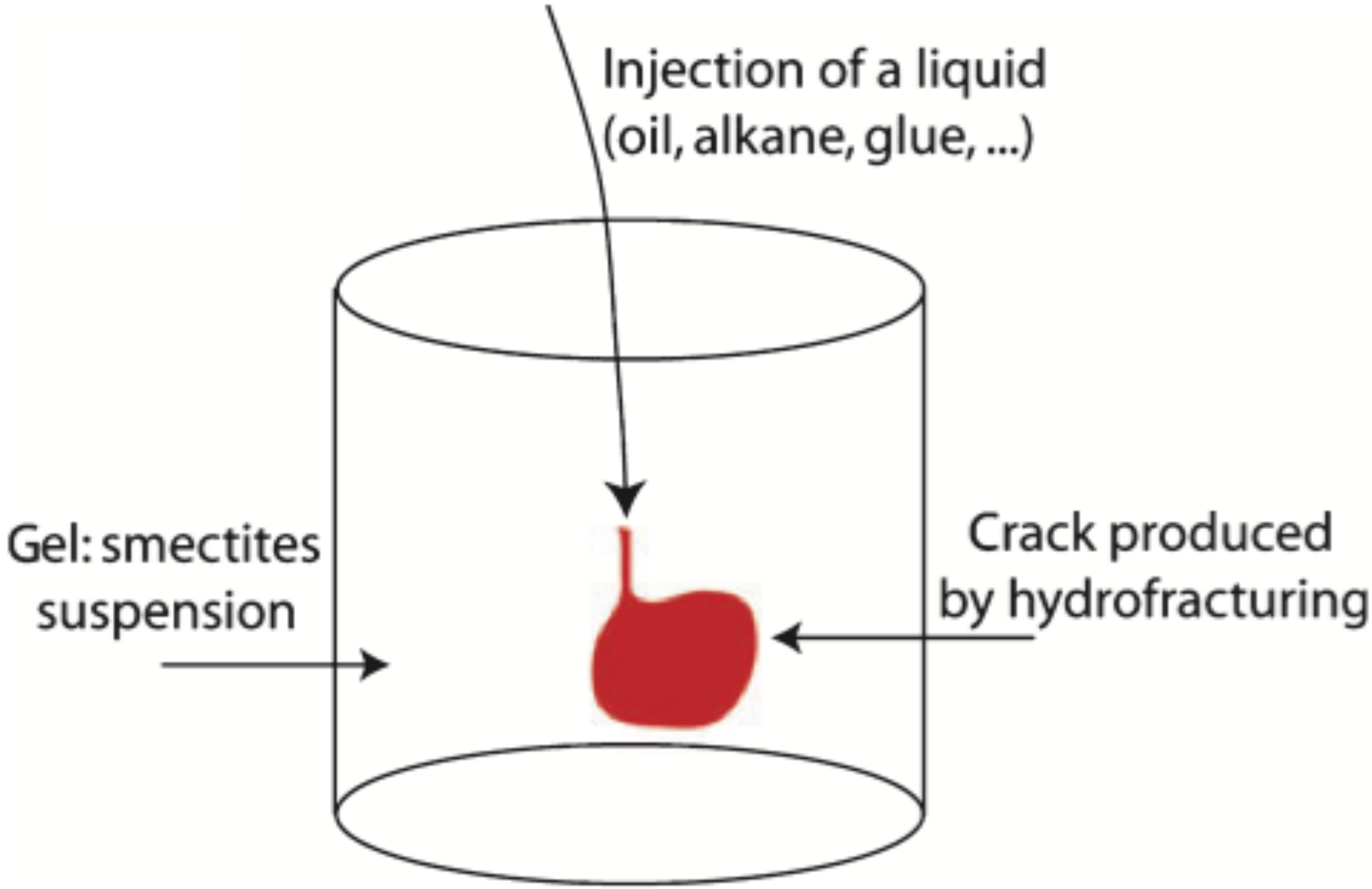
Pressure solution



Pressure solution of oolitic limestone

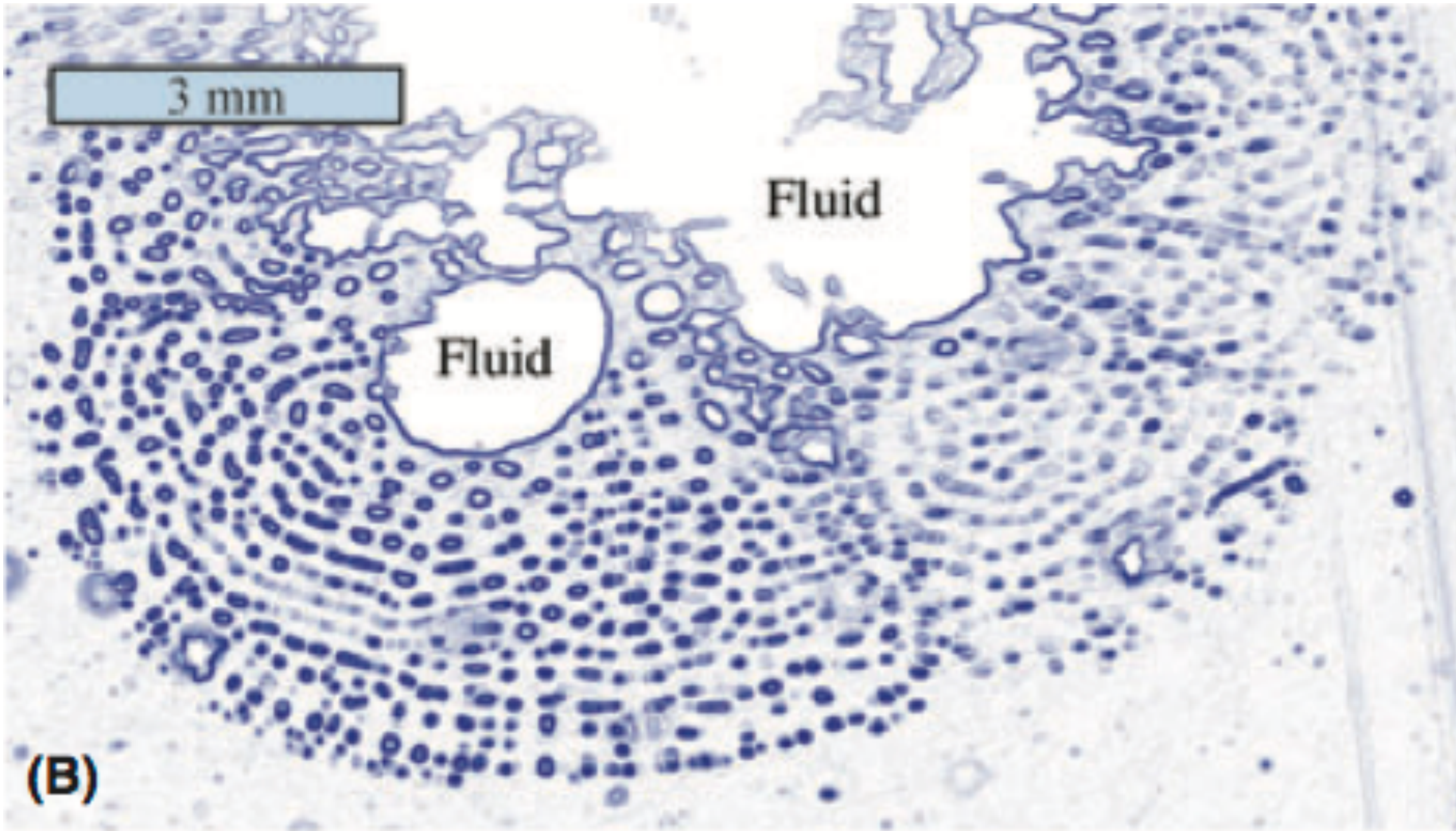


Analogue model for cracks



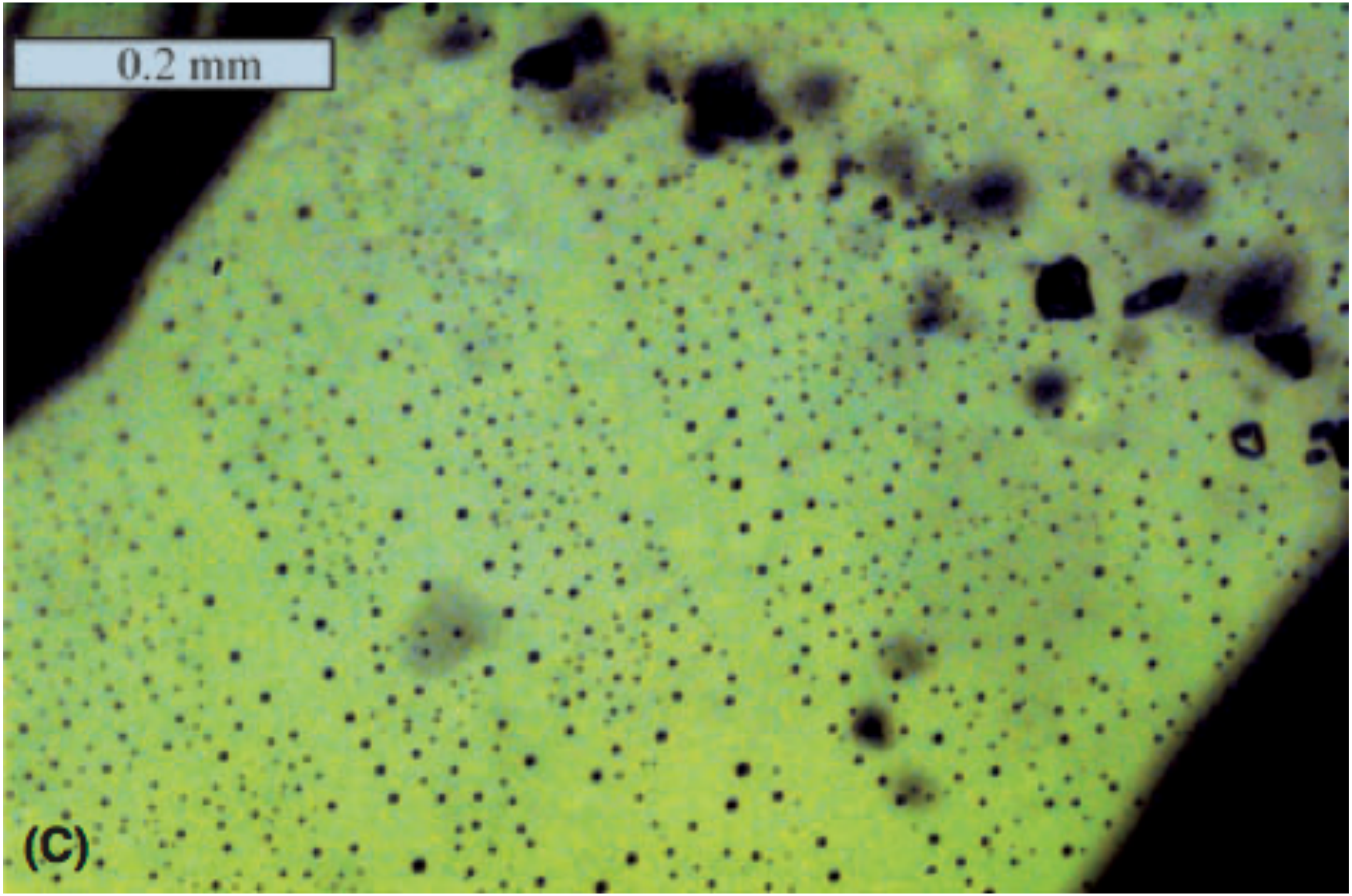
(Renard et al., Geofluids, 9, 365-372, 2009)

A healing crack in a gel



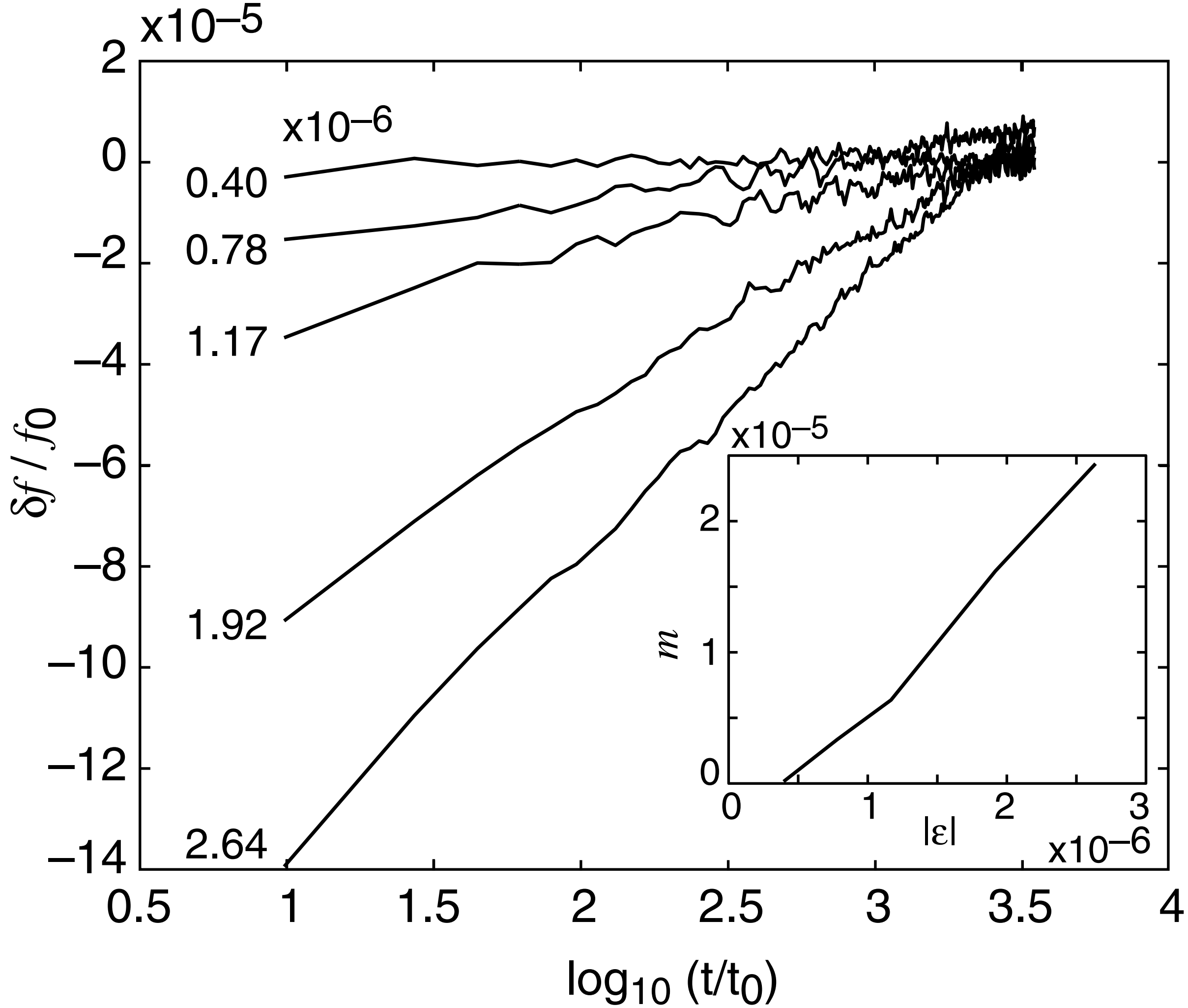
(Renard et al., Geofluids, 9, 365-372, 2009)

A healing crack in a quartz



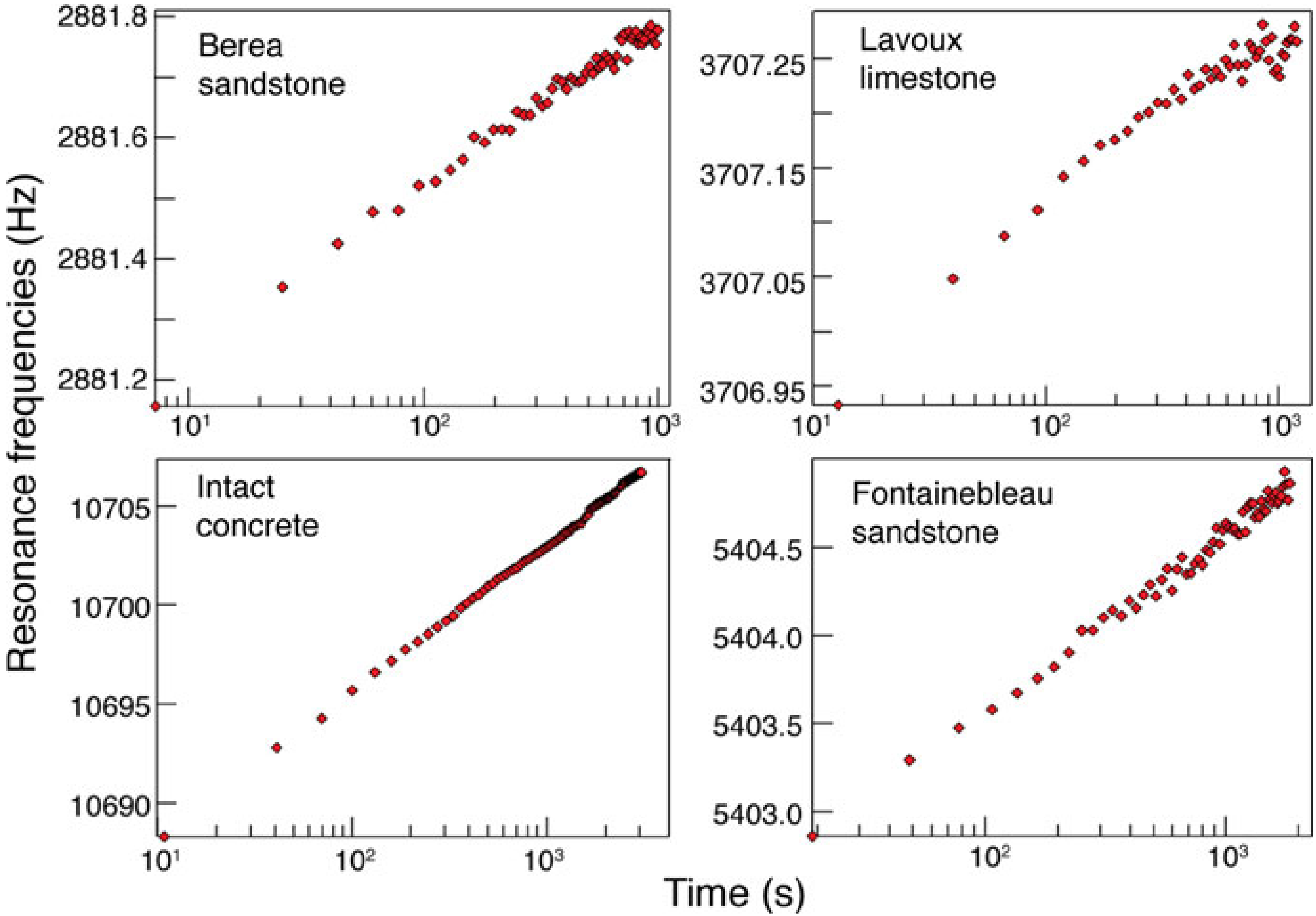
(Renard et al., Geofluids, 9, 365-372, 2009)

Log(time) behavior in resonance



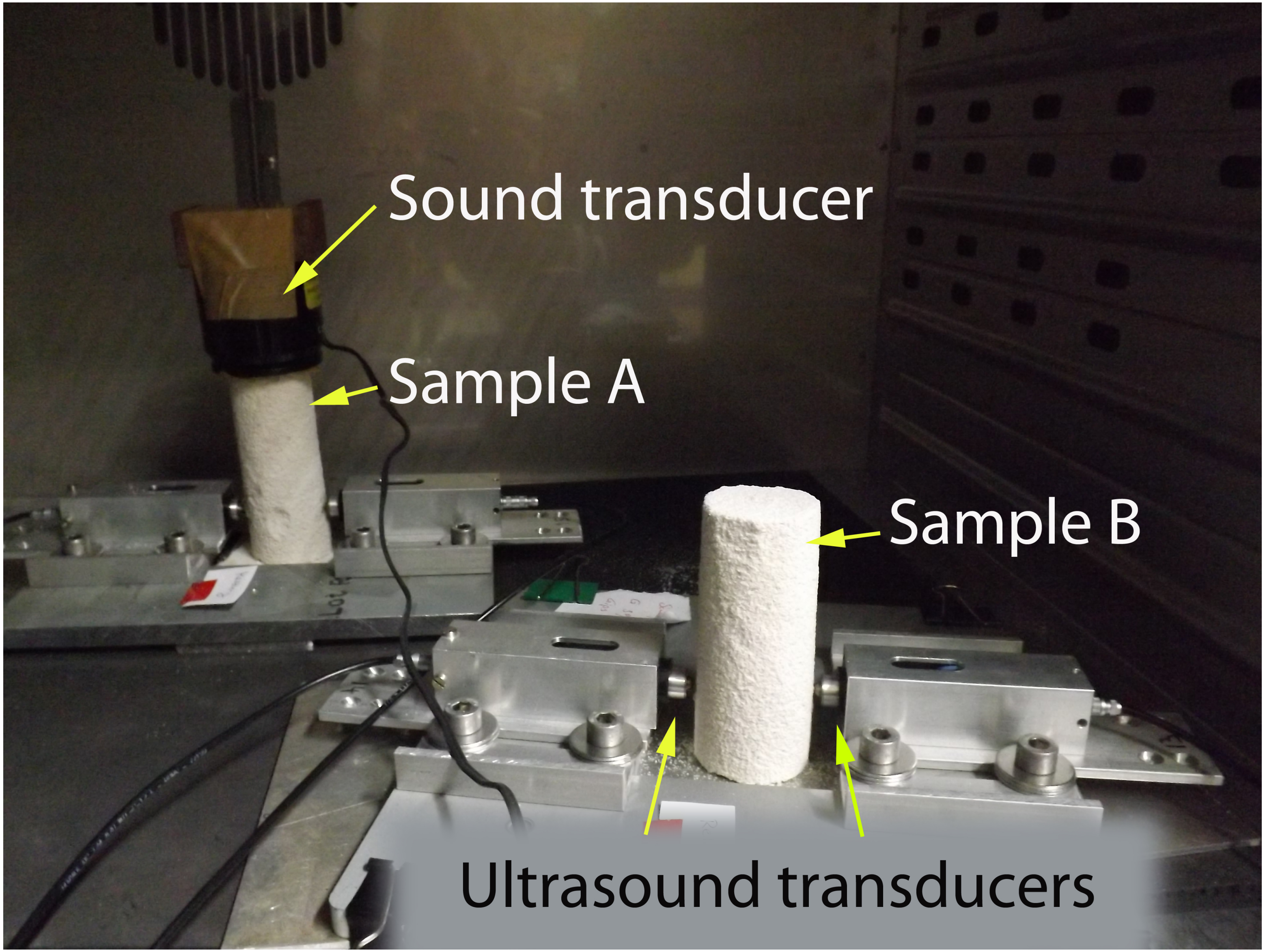
(Ten Cate et al., Phys. Rev. Lett., 85, 1020-1023, 2000)

Log(time) behavior in resonance



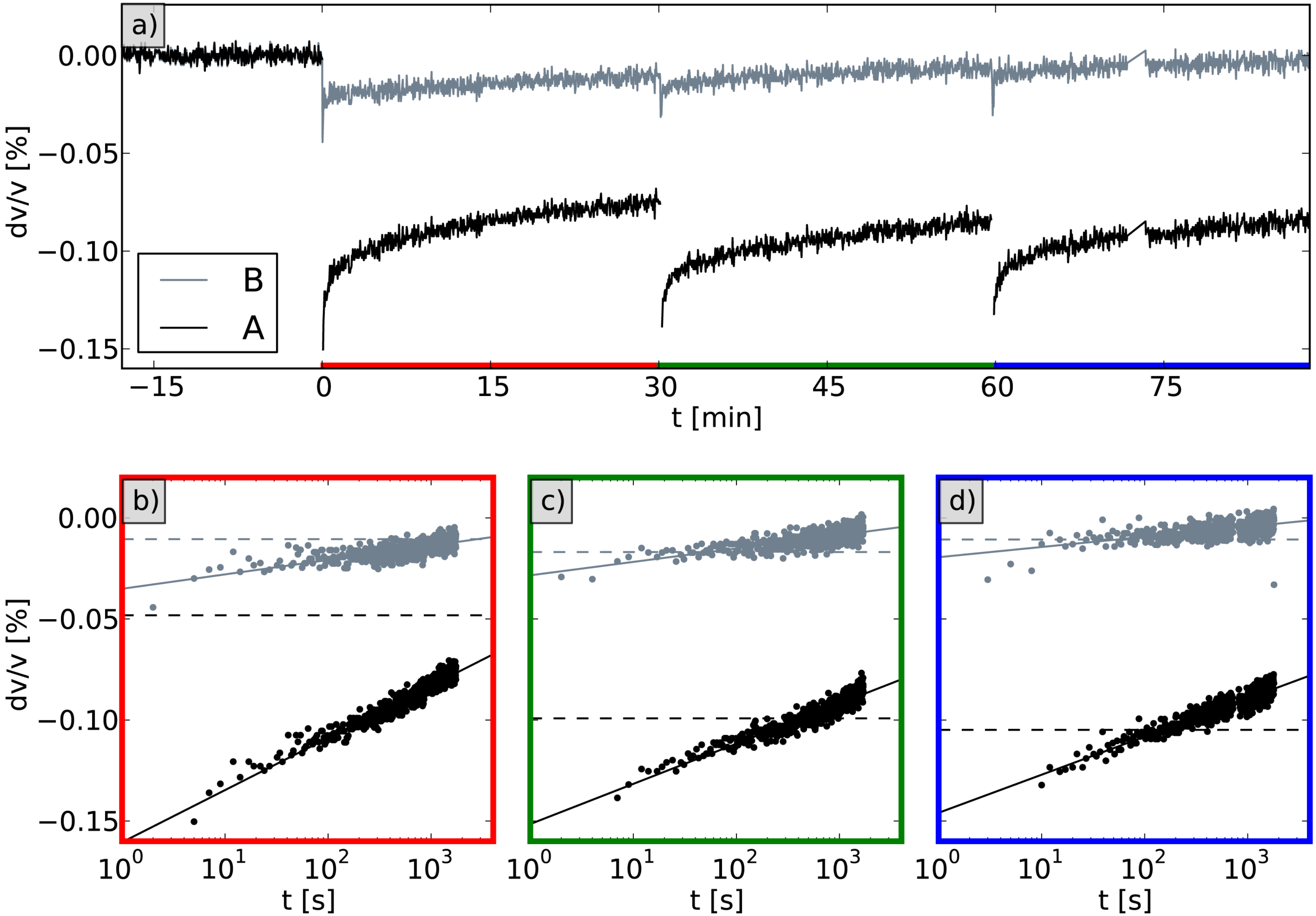
(Ten Cate et al., Pure Appl. Geophys, 168, 2211-2219, 2011)

Perturbing samples



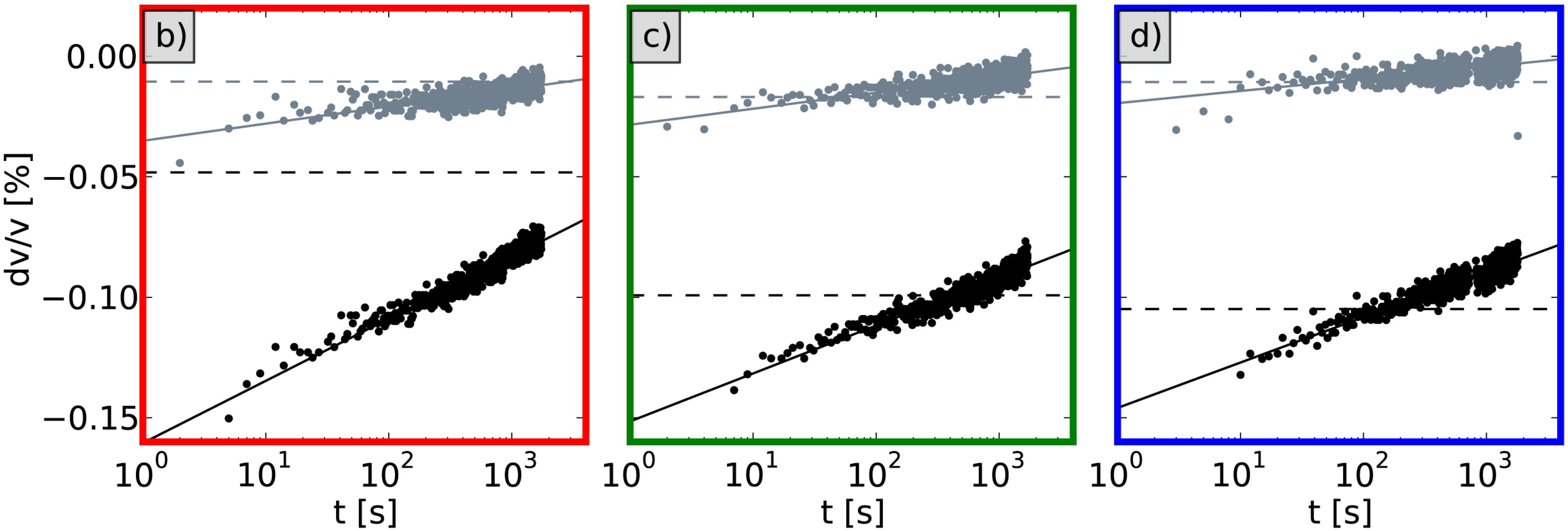
(Gassenmeier, 2015, PhD thesis, Universität Leipzig)

Healing of rock samples

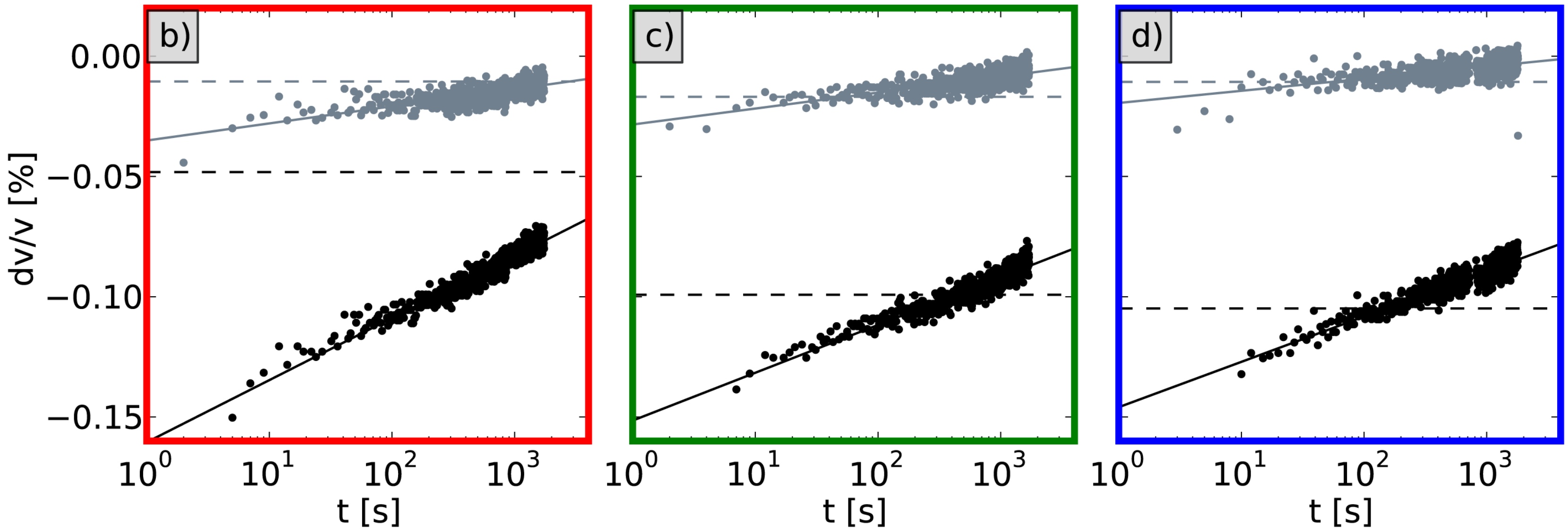


(Gassenmeier, 2015, PhD thesis, Universität Leipzig)

So rock healing clearly goes as log-time



So rock healing clearly goes as log-time



But it can't because …

$$\ln(t) \to -\infty \text{ as } t \to 0$$

$$\ln(t) \to \infty \text{ as } t \to \infty$$

Logarithm means there is no time-scale

$$\ln(t/\tau) = \ln(t) - \ln(\tau)$$

any time-scale corresponds to an offset

Relaxation process for one relaxation time

$$R(t) = e^{-t/\tau}$$

(Snieder, R., C. Sens-Schoenfelder, and R. Wu, Geophys. J. Int., 208, 1-9, 2017)

Relaxation process for one relaxation time

$$R(t) = e^{-t/\tau}$$

Superposition of relaxation processes

$$\boxed{R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-t/\tau} d\tau}$$

$\frac{1}{\tau}$ follows from Arrhenius' law

How to get log-time behavior?

$$R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-t/\tau} d\tau$$

How to get log-time behavior?

$$R(t) = \int_{\tau_{min}}^{\tau_{max}} \frac{1}{\tau} e^{-t/\tau} d\tau = \int_{t/\tau_{max}}^{t/\tau_{min}} \frac{1}{u} e^{-u} du$$

$$u = t/\tau$$

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$$u = t/\tau$$

$$\frac{dR(t)}{dt} = \frac{1}{t}\left(e^{-t/\tau_{min}} - e^{-t/\tau_{max}}\right)$$

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when $\tau_{min} \ll t \ll \tau_{max}$

$$\frac{dR(t)}{dt} = \frac{1}{t}(0 - 1) = -\frac{1}{t}$$

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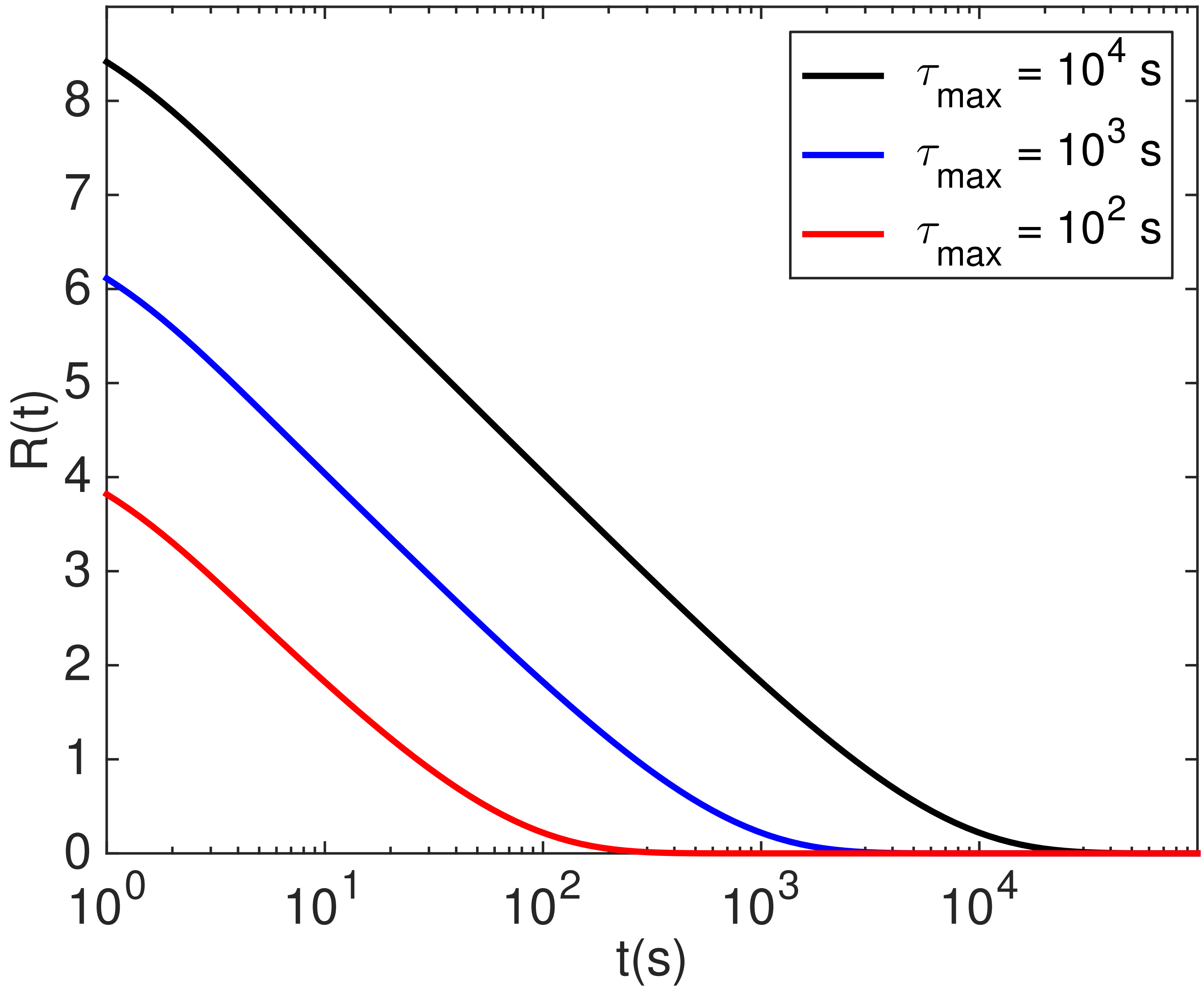
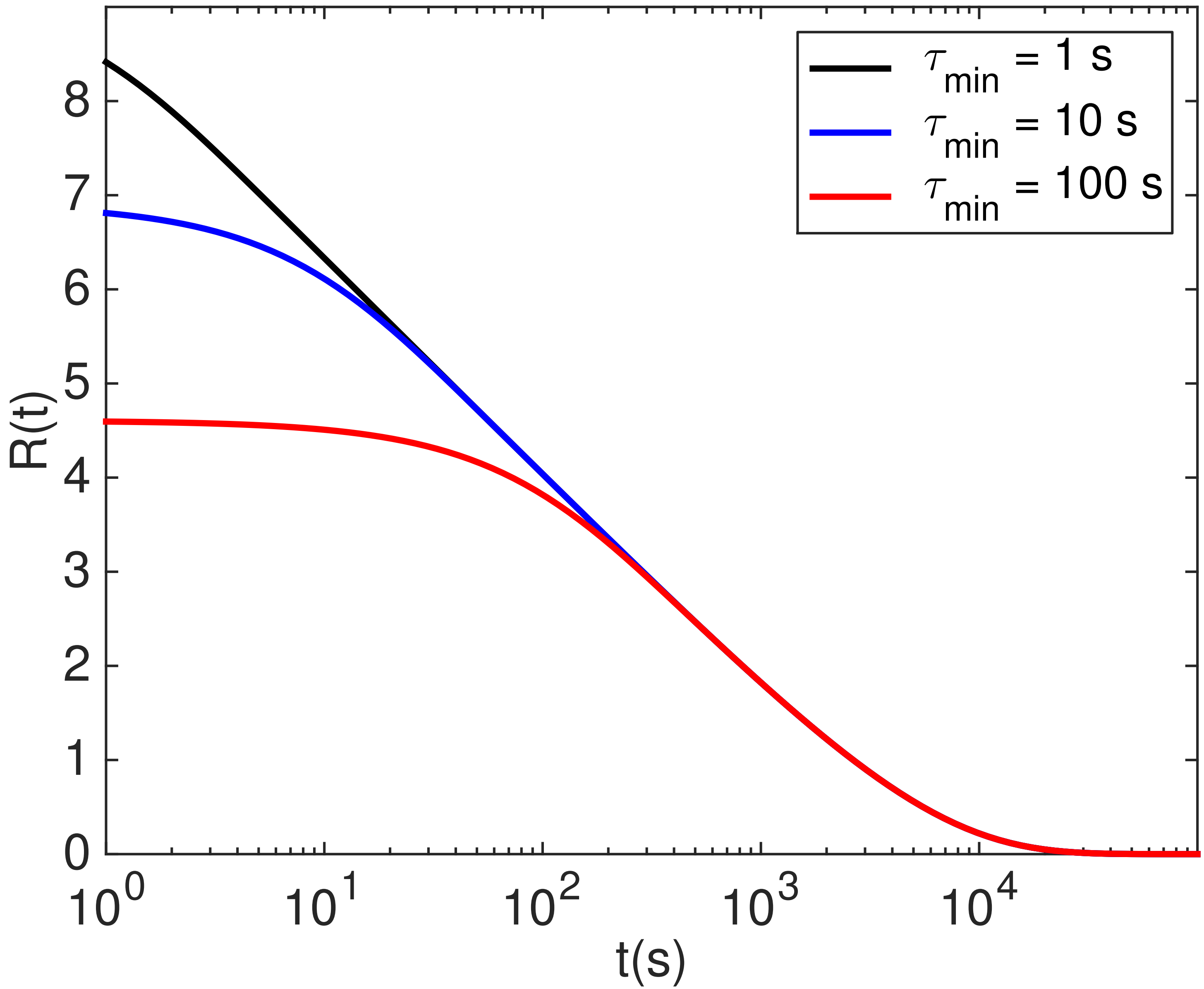
$$\frac{dR(t)}{dt} = \frac{1}{t}(0 - 1) = -\frac{1}{t}$$

$$R(t) = B - \ln(t)$$

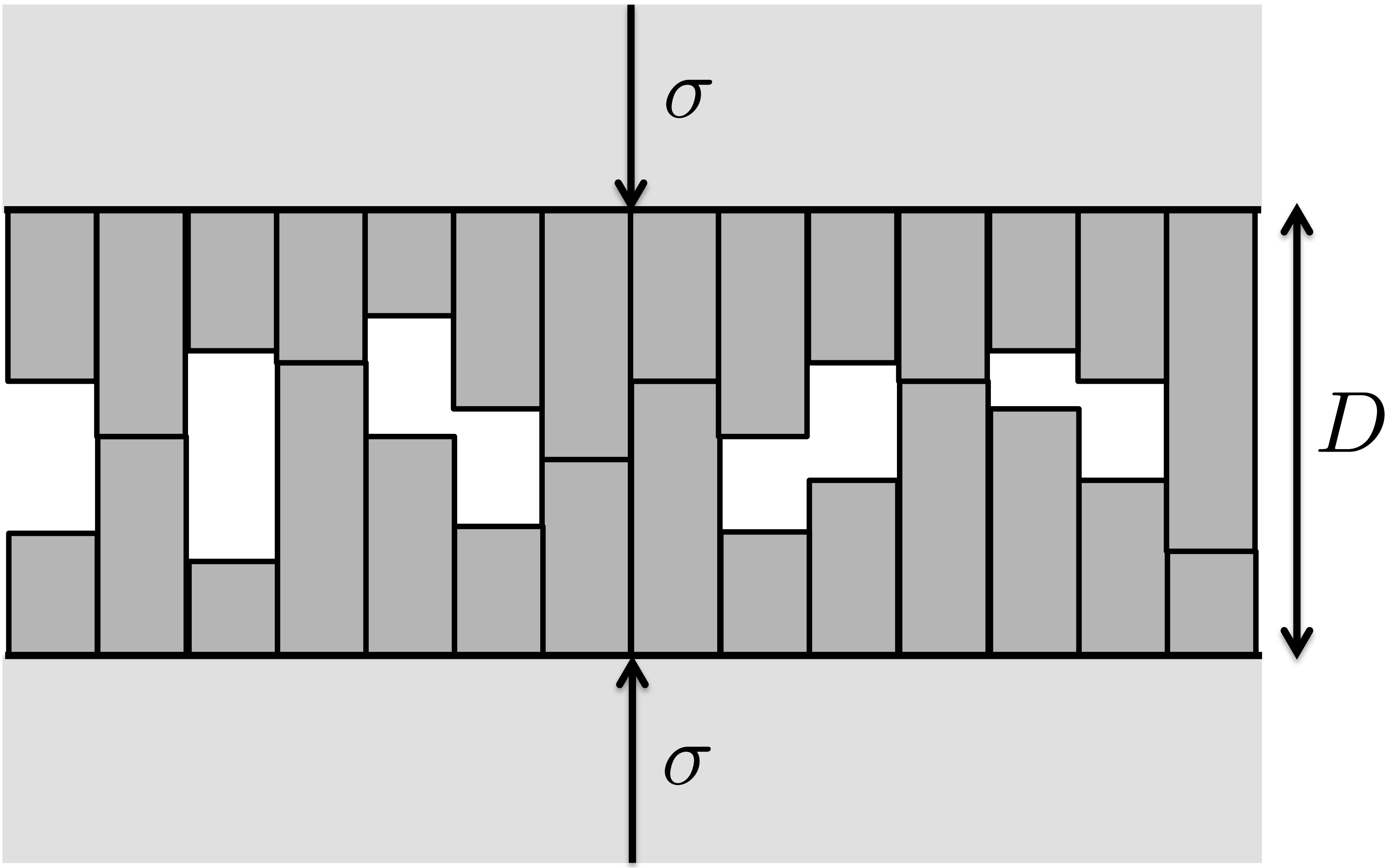
Relaxation function



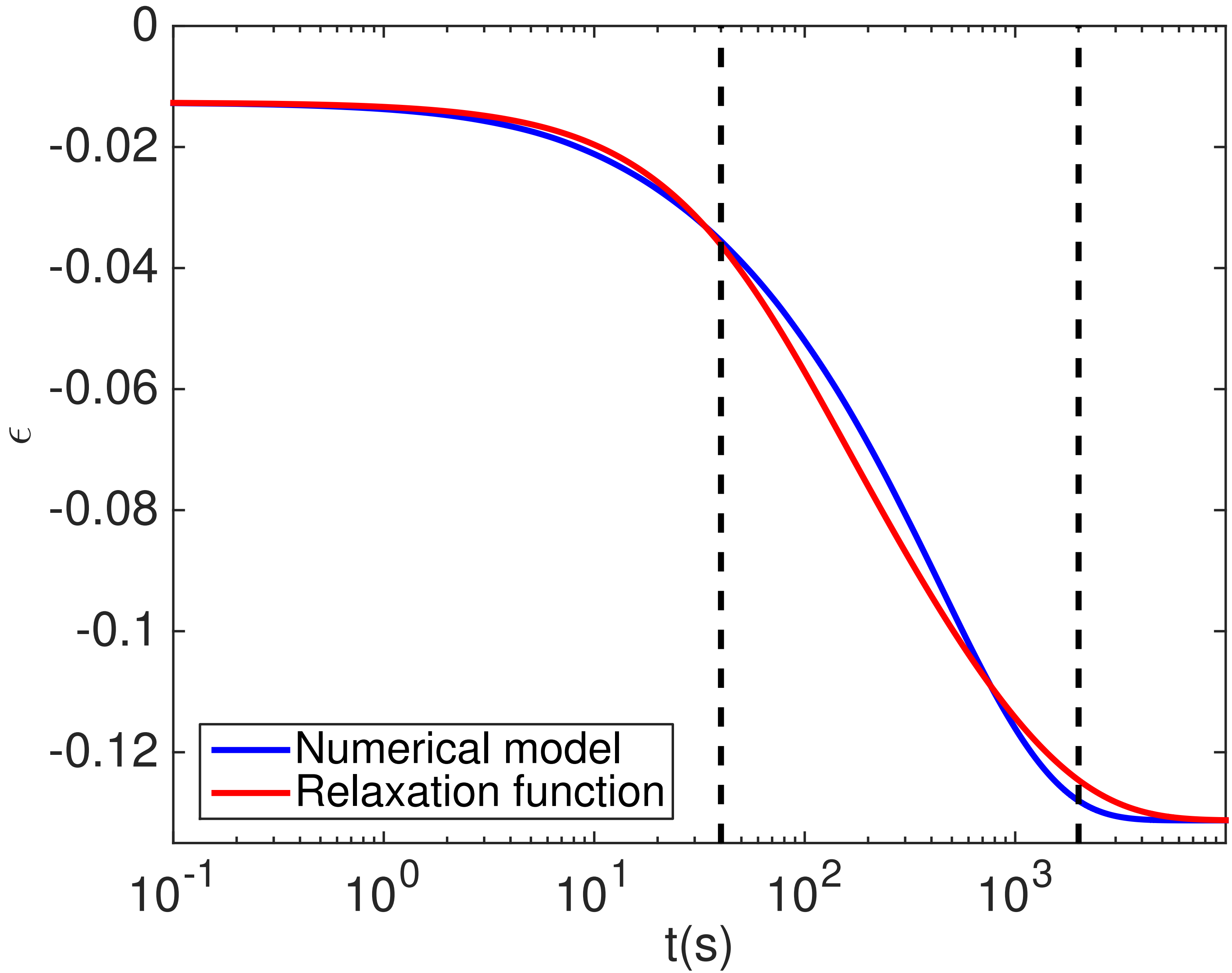
Relaxation function



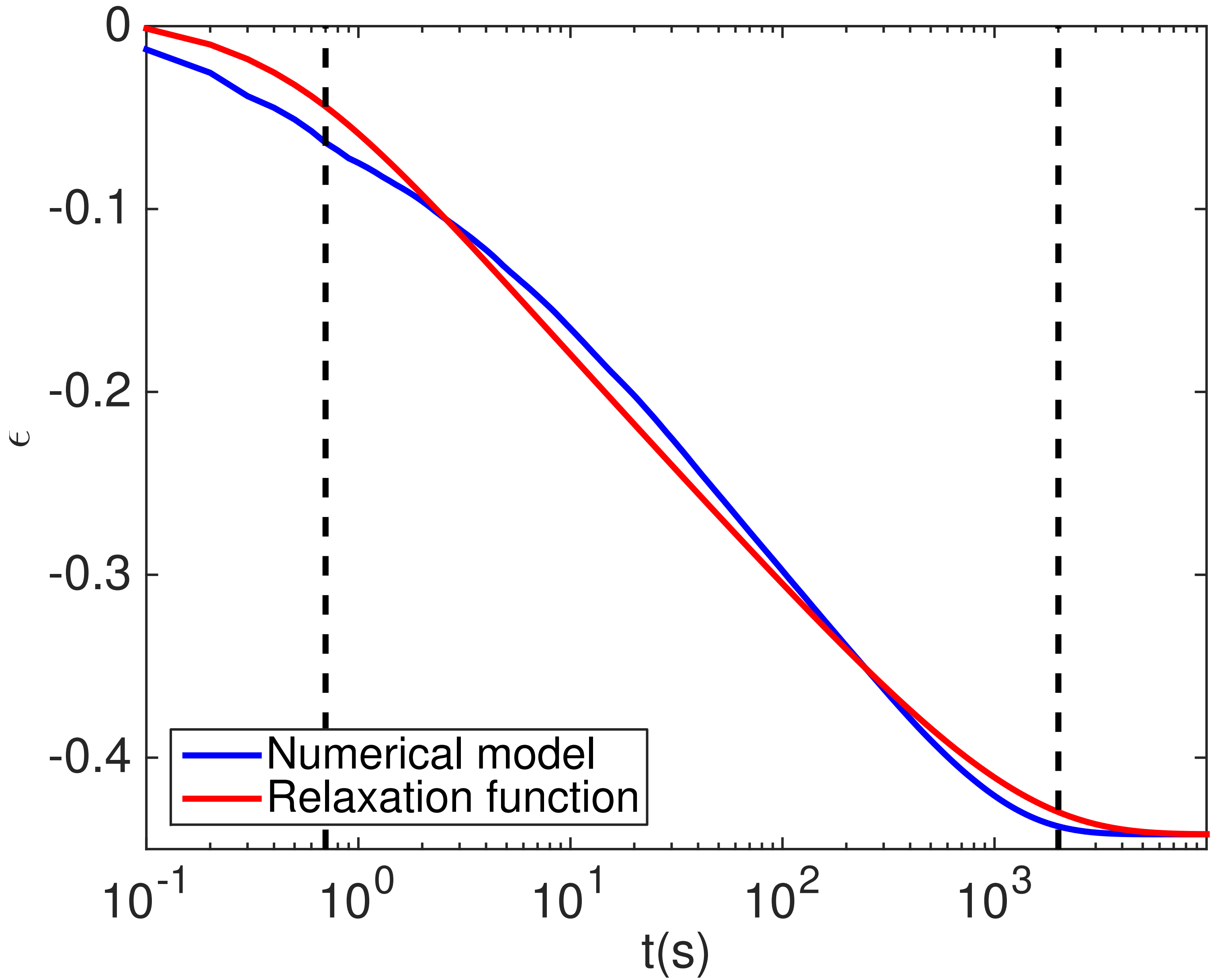
Fracture model



Uniform distribution of pillar heights



Normal distribution of pillar heights



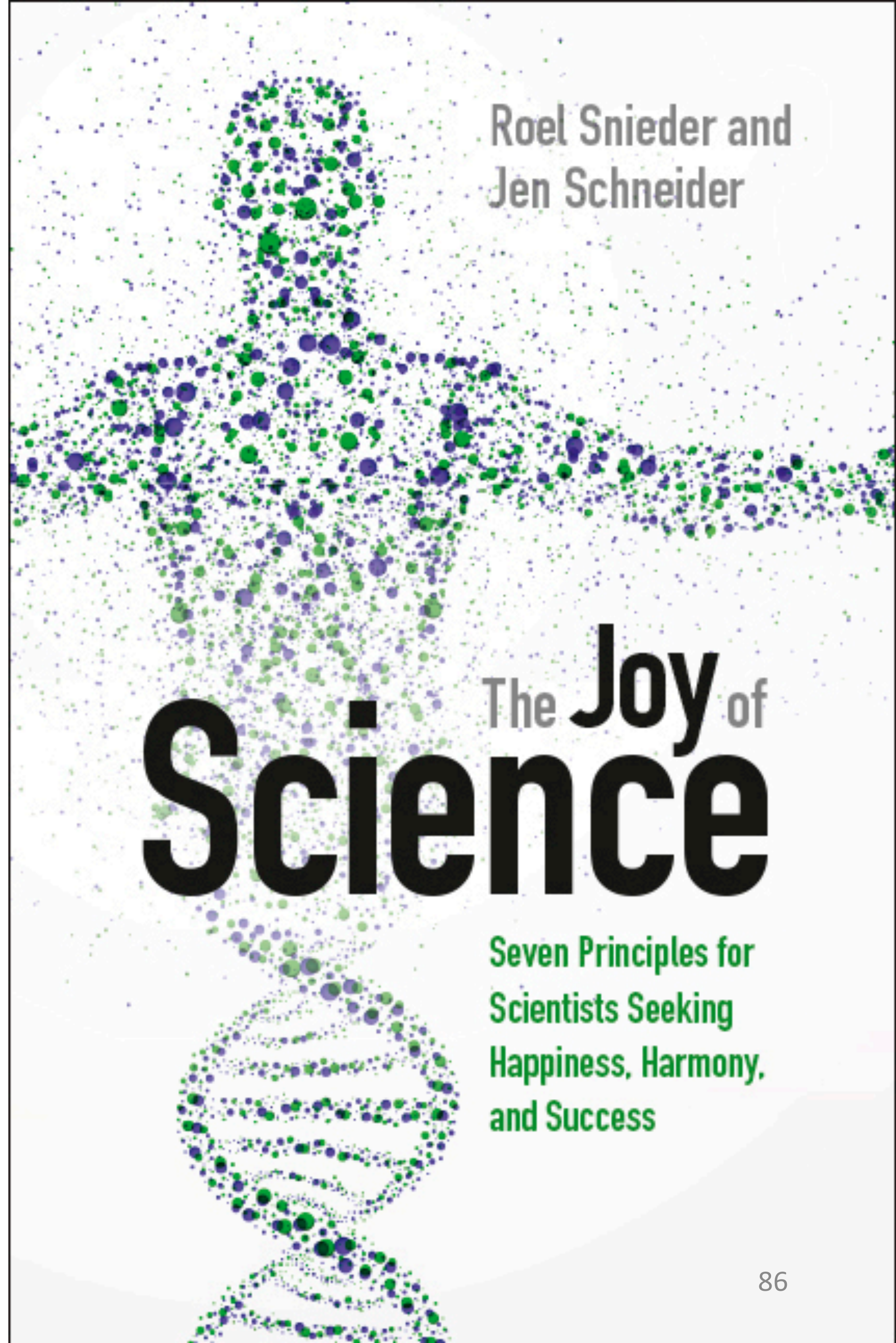
Universal behavior (?) that depends on:

- superposition of relaxation phenomena
- largest contribution comes from fastest relaxation processes
- minimum and maximum relaxation times

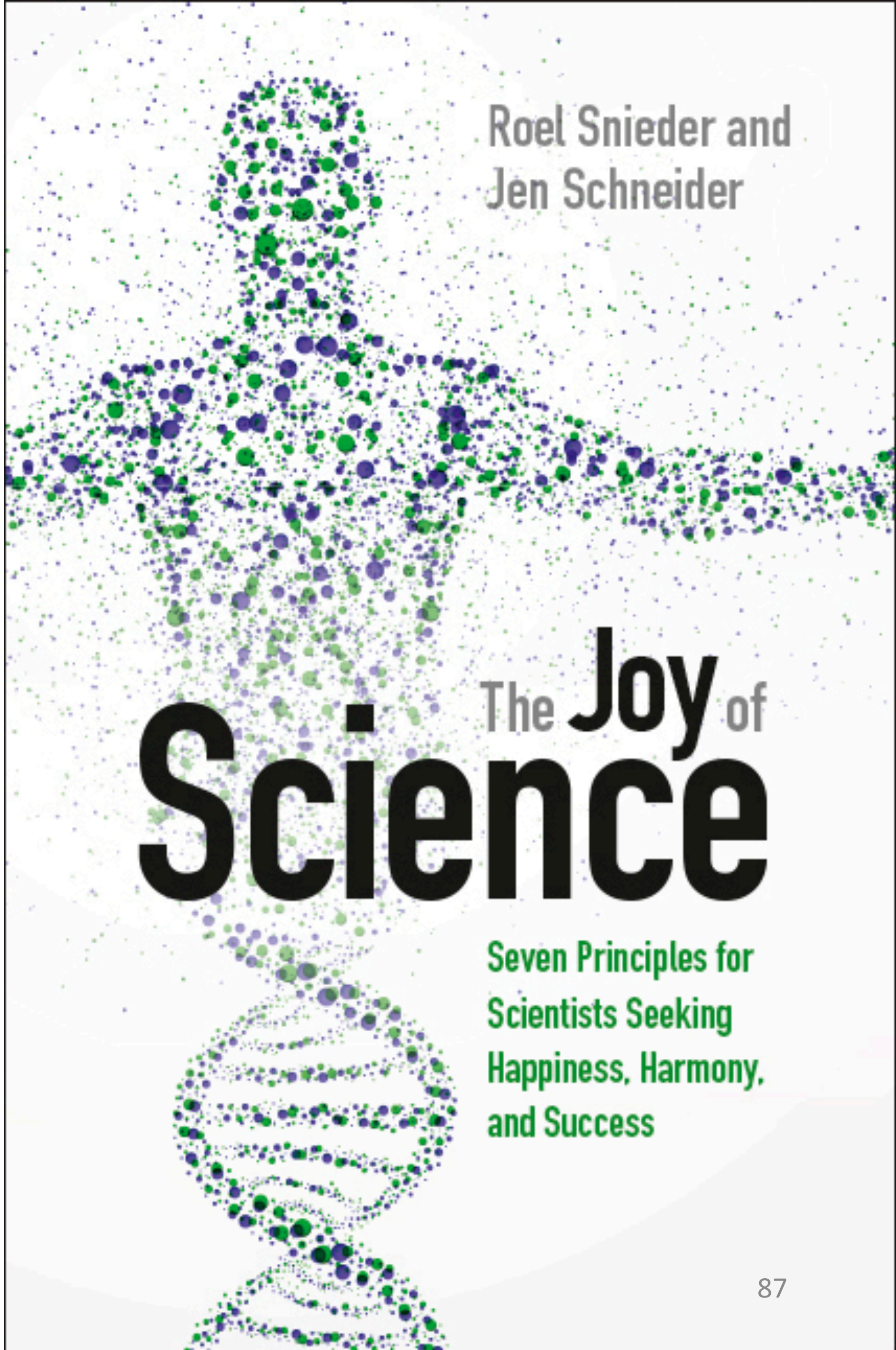
Universal behavior (?) that depends on:

- superposition of relaxation phenomena
- largest contribution comes from fastest relaxation processes
- minimum and maximum relaxation times

A new diagnostic of earth materials?

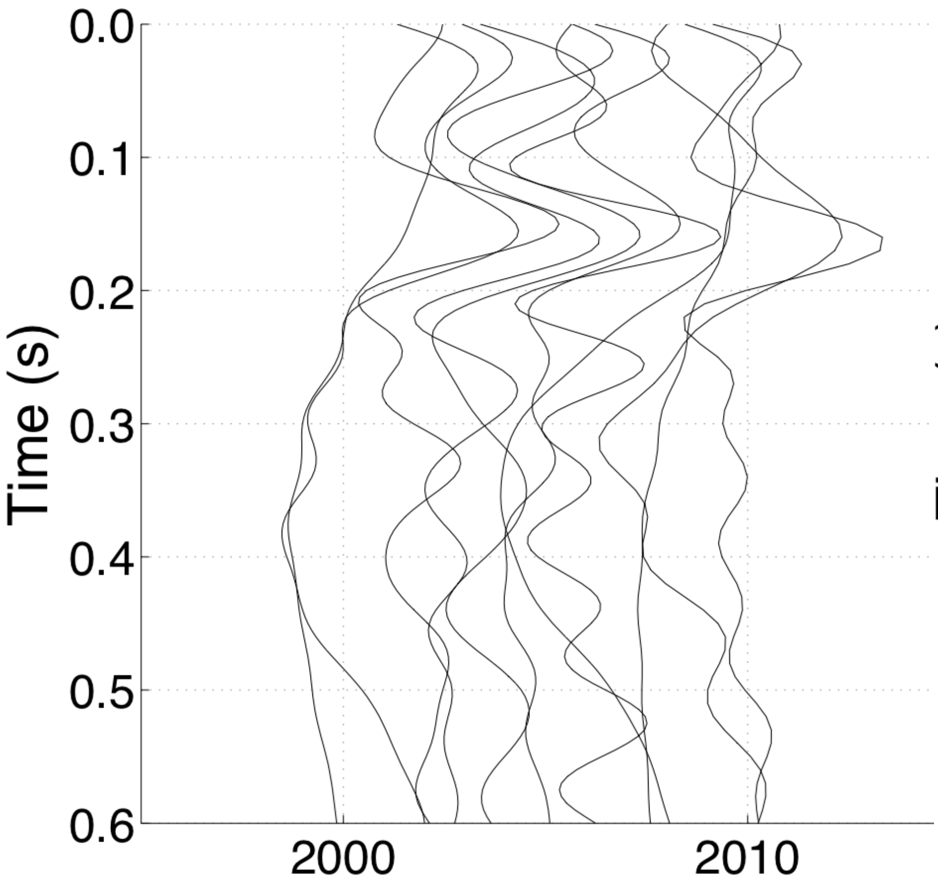

Roel Snieder and
Jen Schneider
The Joy of
Science
Seven Principles for
Scientists Seeking
Happiness, Harmony,
and Success

Once a semester, I will engage in a professional or personal activity that frightens me a little but which makes me feel alive.

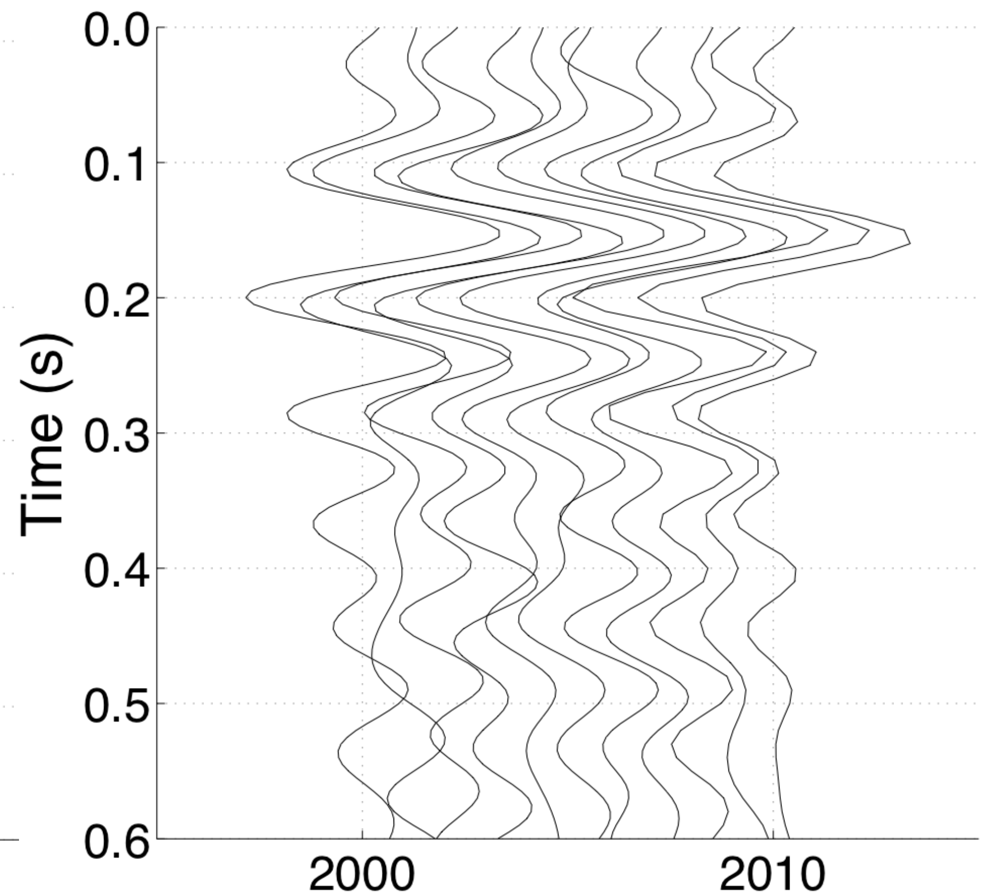


Annual stacks at station NIGH13

correlation



deconvolution

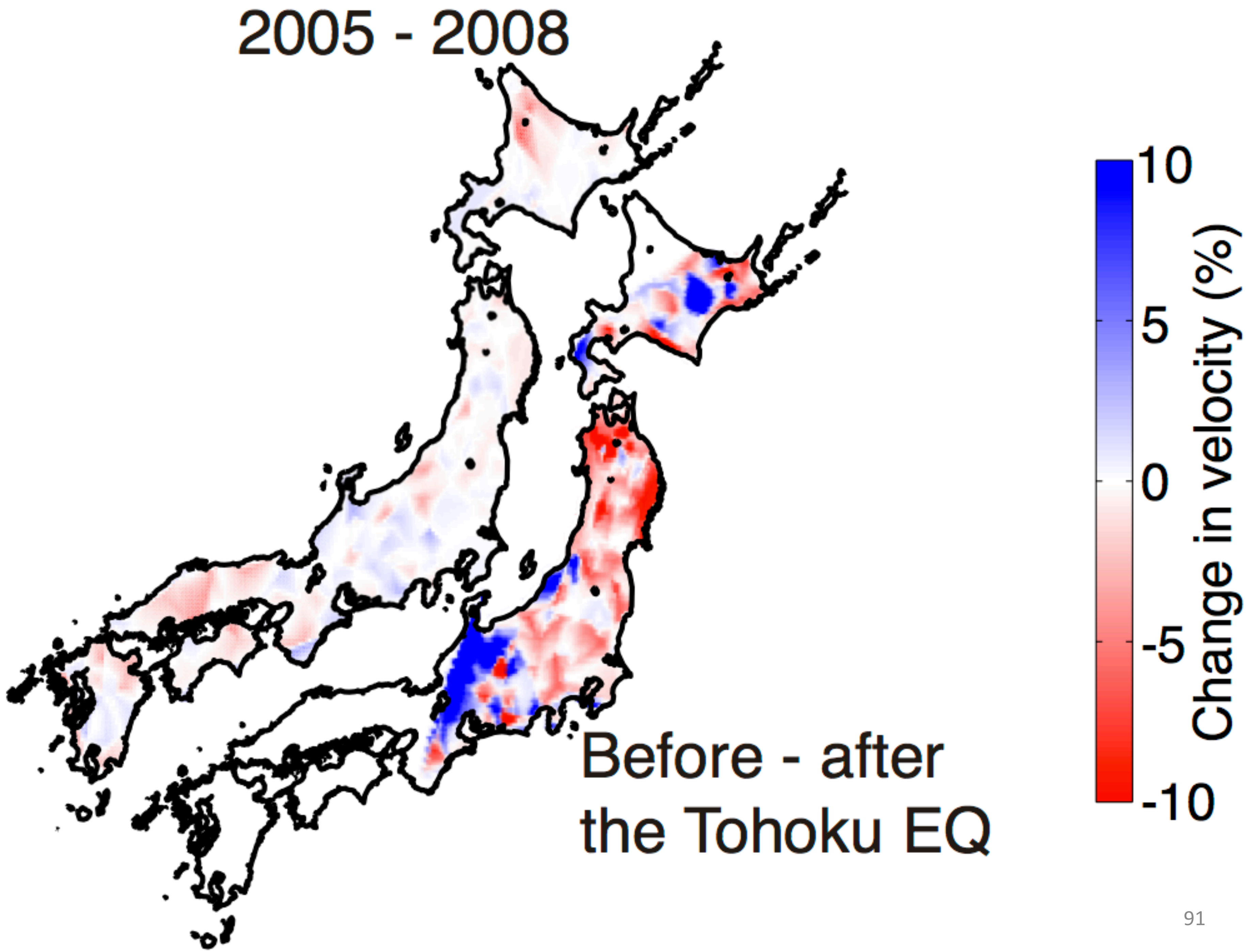


Correlation vs. deconvolution

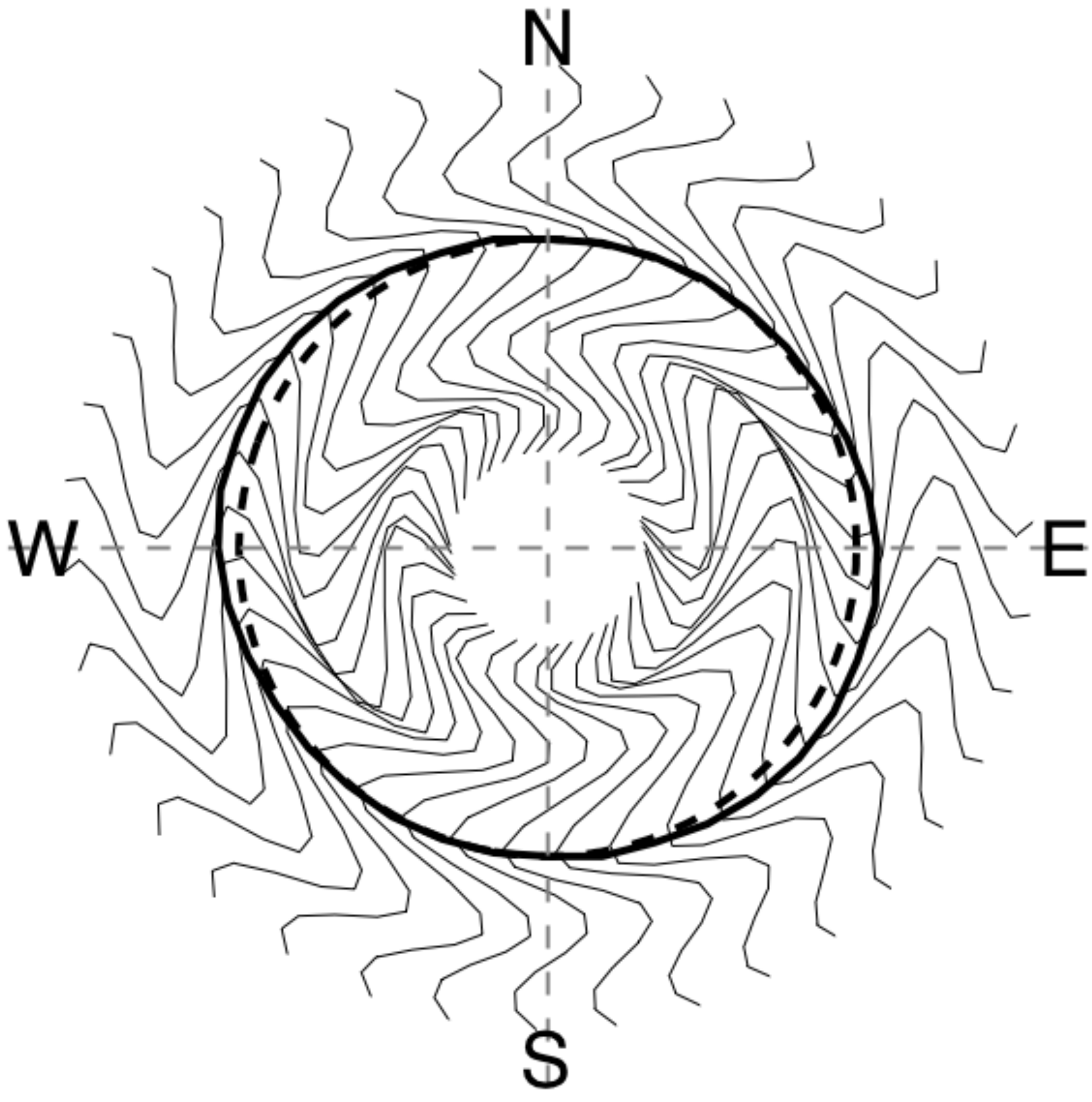
$$u(z,\omega) = S(\omega)e^{-ikz}$$

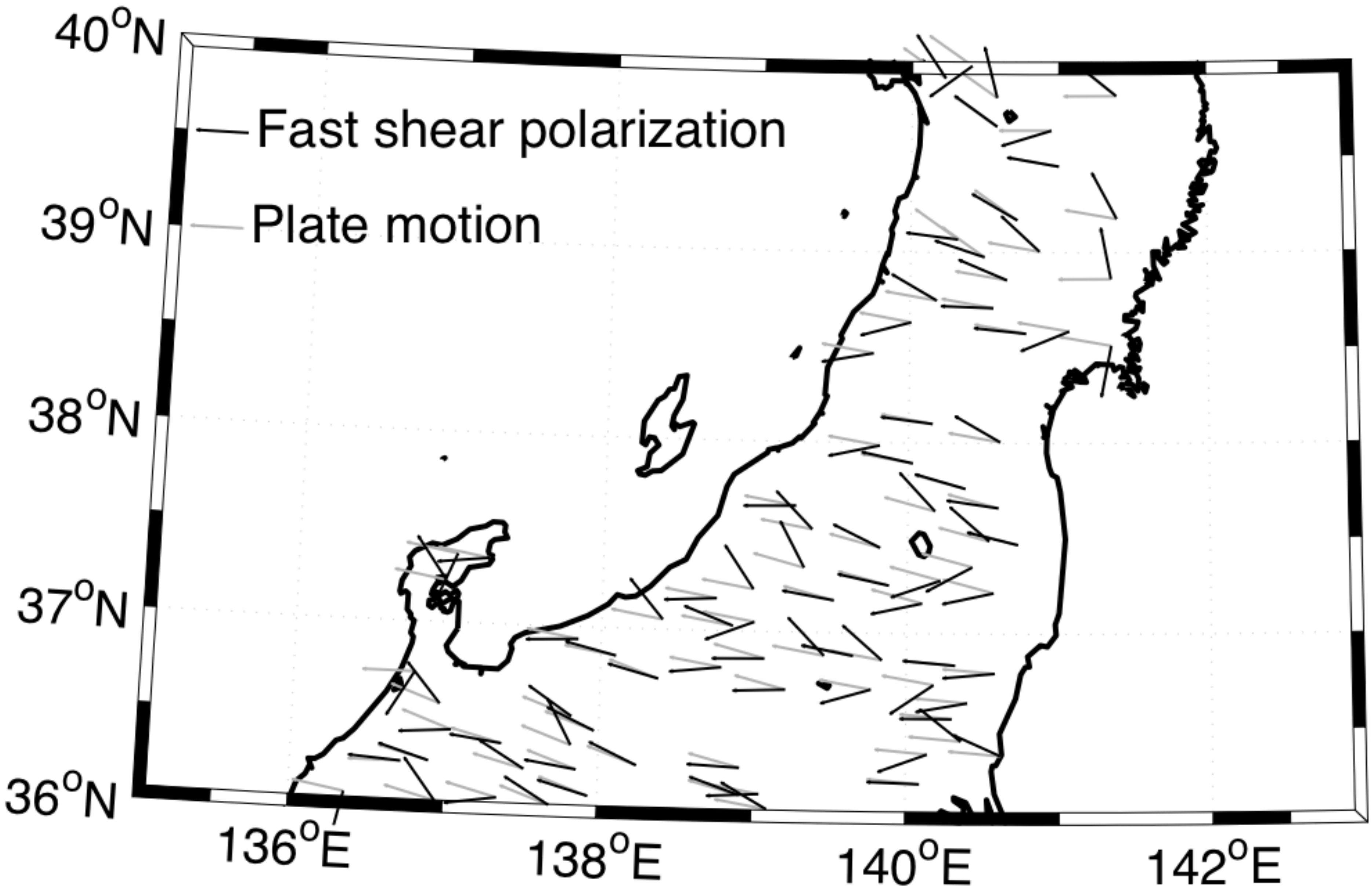
$$correlation = u(z=0,\omega)u^{*}(z=D,\omega) = \left|S(\omega)\right|^{2} e^{ikz}$$

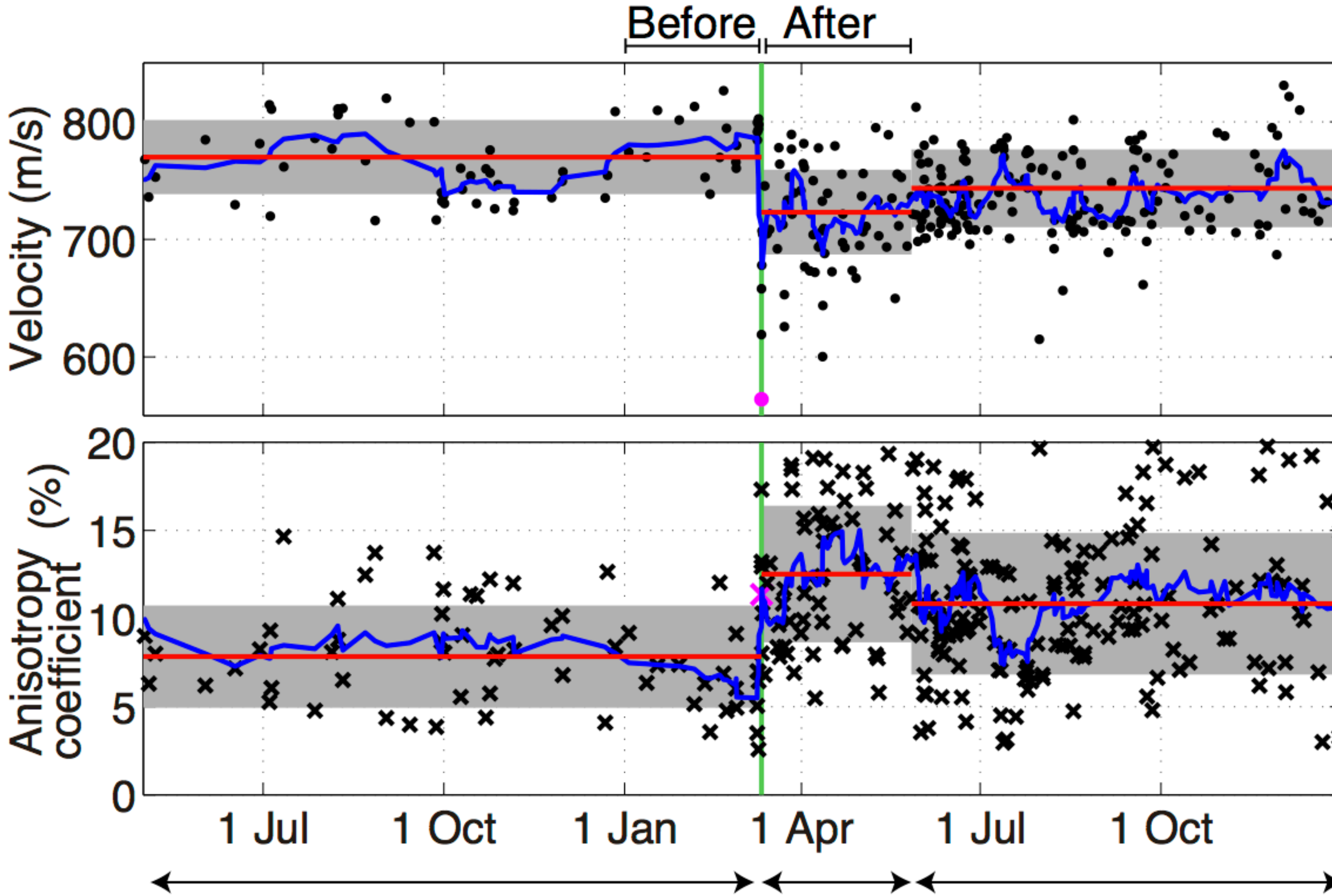
$$deconvolution = \frac{u(z=0,\omega)}{u(z=D,\omega)} = e^{ikz}$$


2005 - 2008
Before - after
the Tohoku EQ
10
5
0
-5
-10
Change in velocity (%)

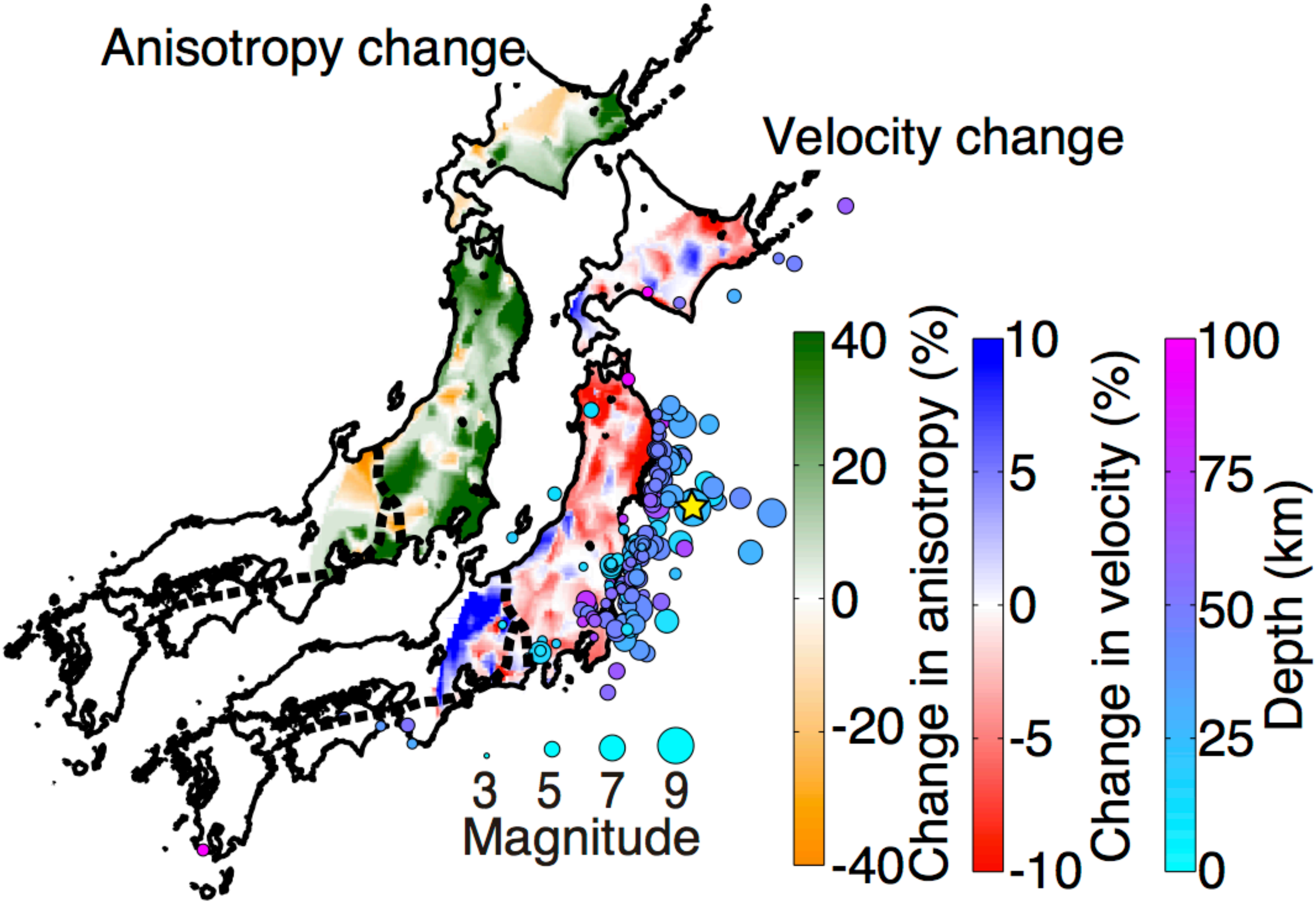
Shear-wave splitting



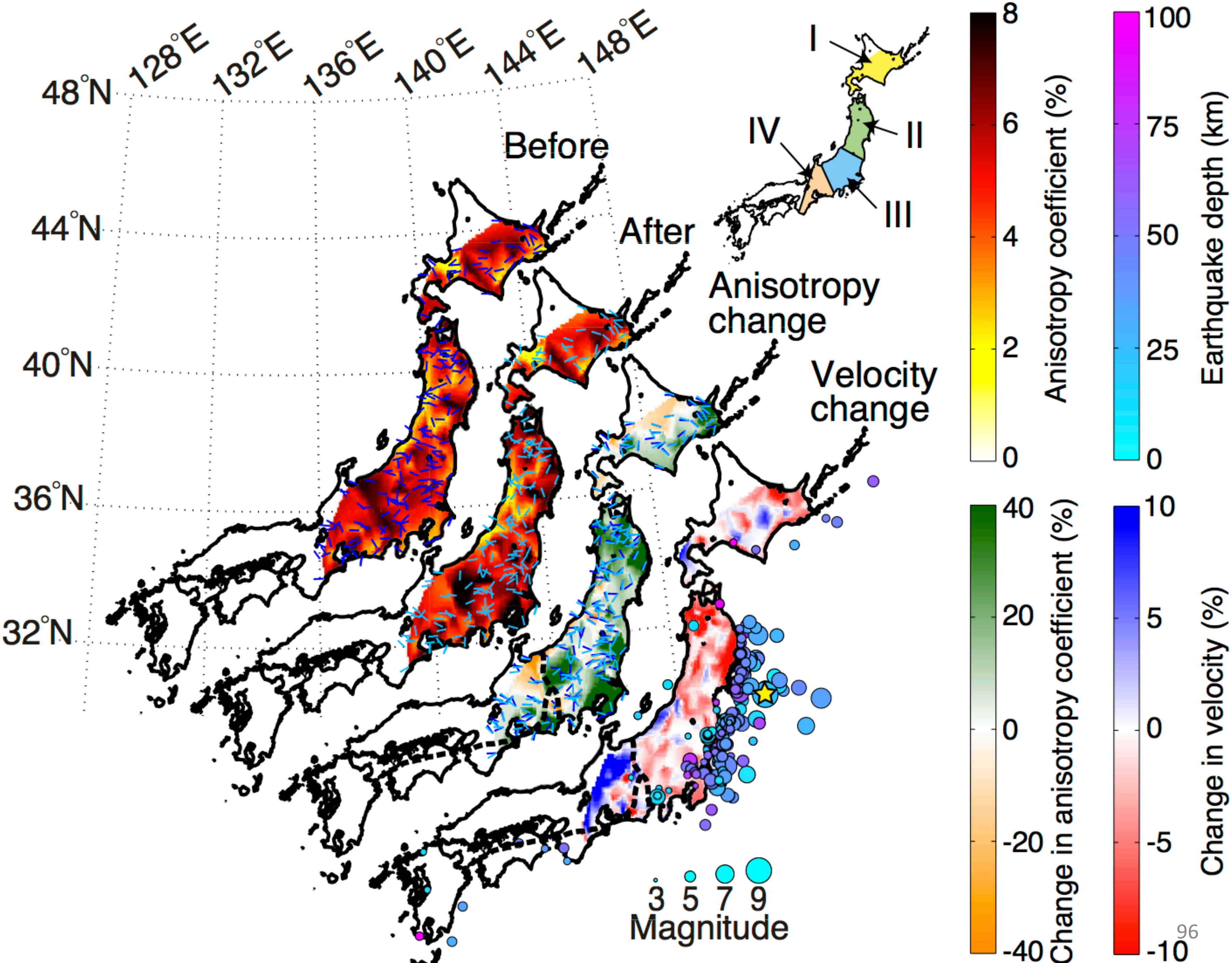

Fast shear polarization
Plate motion
40°N
39°N
38°N
37°N
36°N
136°E
138°E
140°E
142°E



Number of earthquakes	61	61	162
Isotropic velocity (m/s)	763–777	714–732	739–747
Anisotropy coefficient (%)	7.2–8.4	11.7–13.3	10.3–11.3

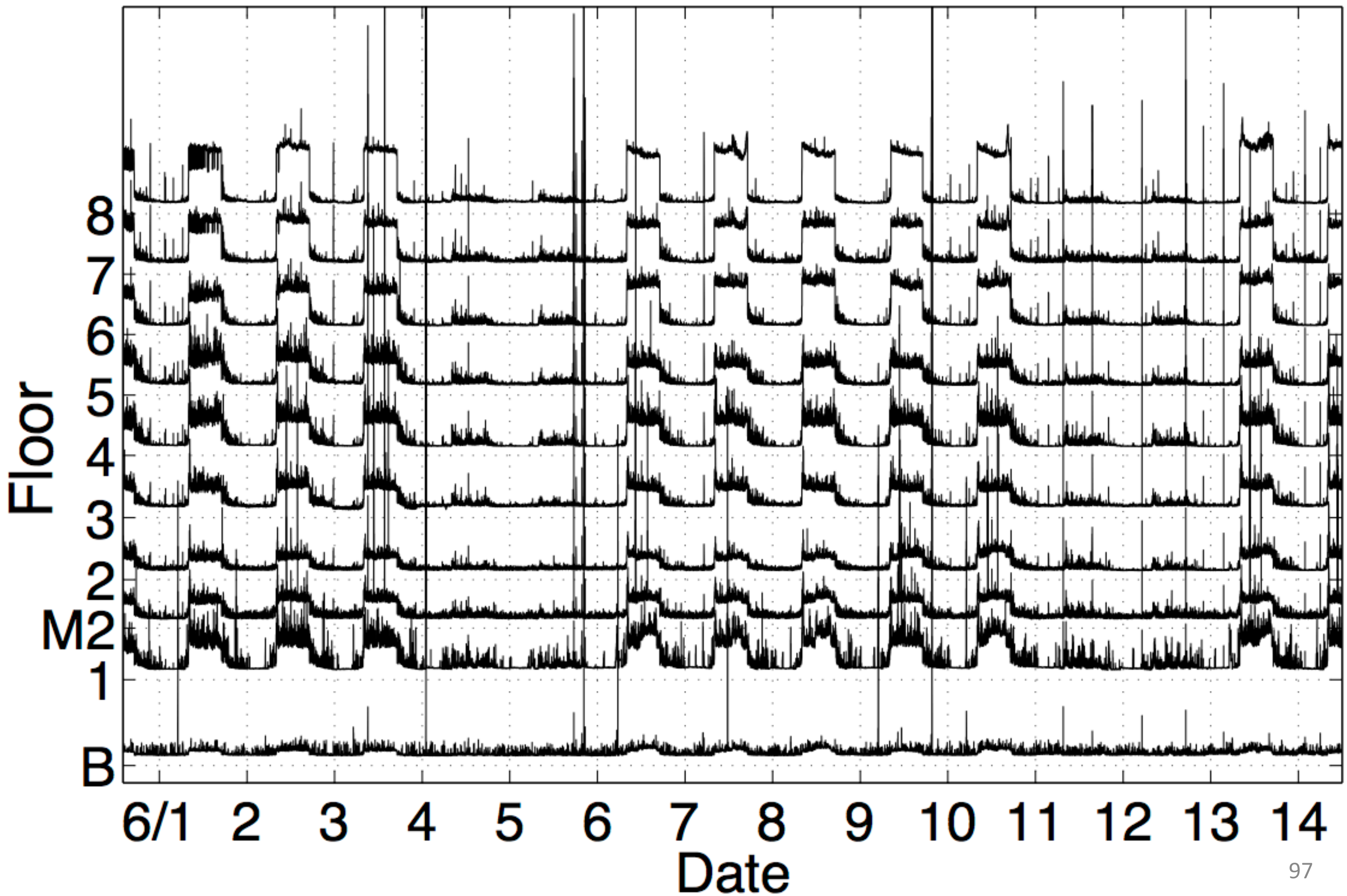


Anisotropy change
Velocity change
40
20
0
-20
-40
Change in anisotropy (%)
10
5
0
-5
-10
Change in velocity (%)
100
75
50
25
0
Depth (km)
3 5 7 9
Magnitude

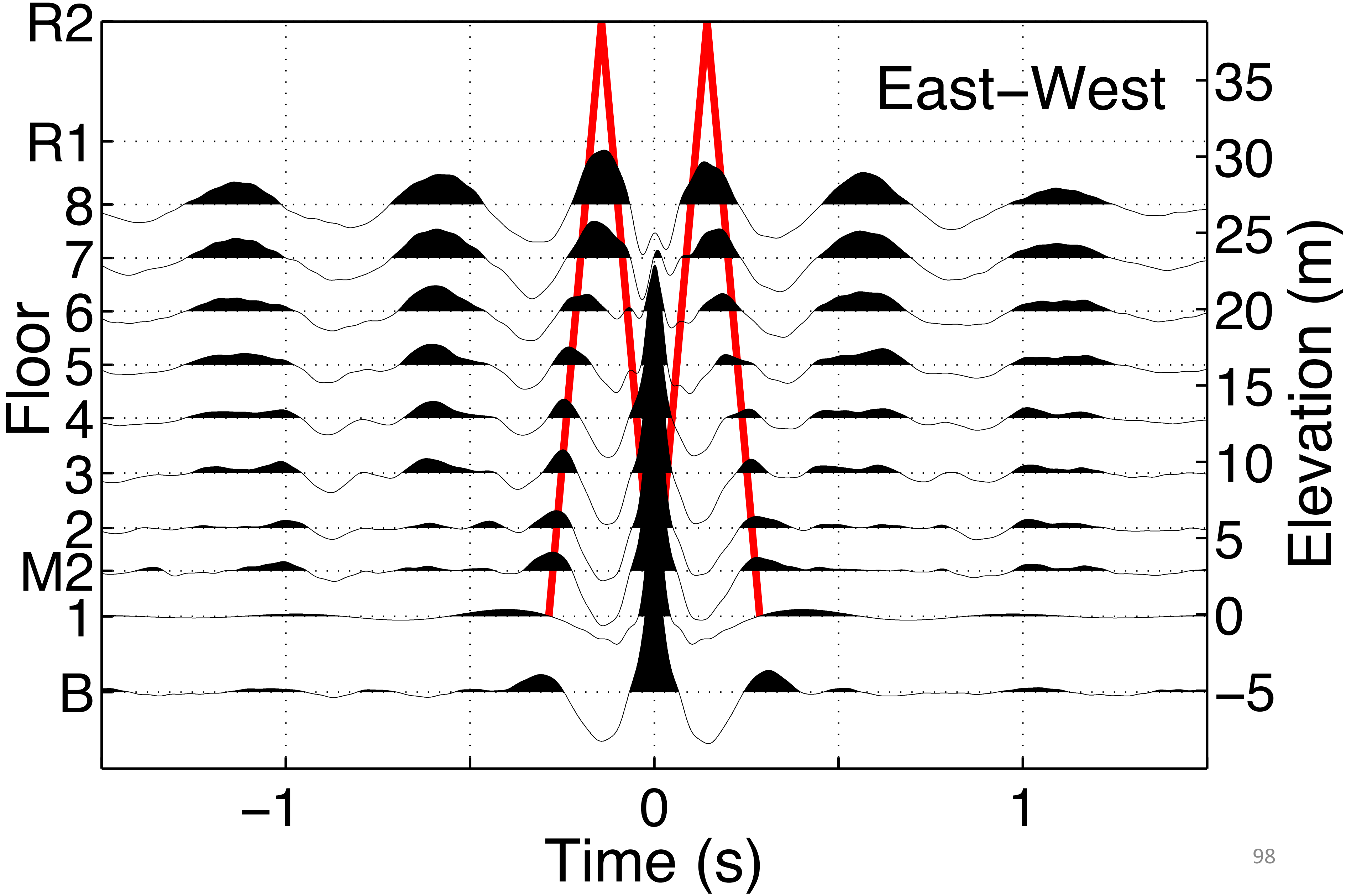


128°E
132°E
136°E
140°E
144°E
148°E
48°N
44°N
40°N
36°N
32°N
Before
After
Anisotropy change
Velocity change
I
II
III
IV
3 5 7 9
Magnitude
Anisotropy coefficient (%)
8
6
4
2
0
Earthquake depth (km)
100
75
50
25
0
Change in anisotropy coefficient (%)
40
20
0
-20
-40
Change in velocity (%)
10
5
0
-5
-10

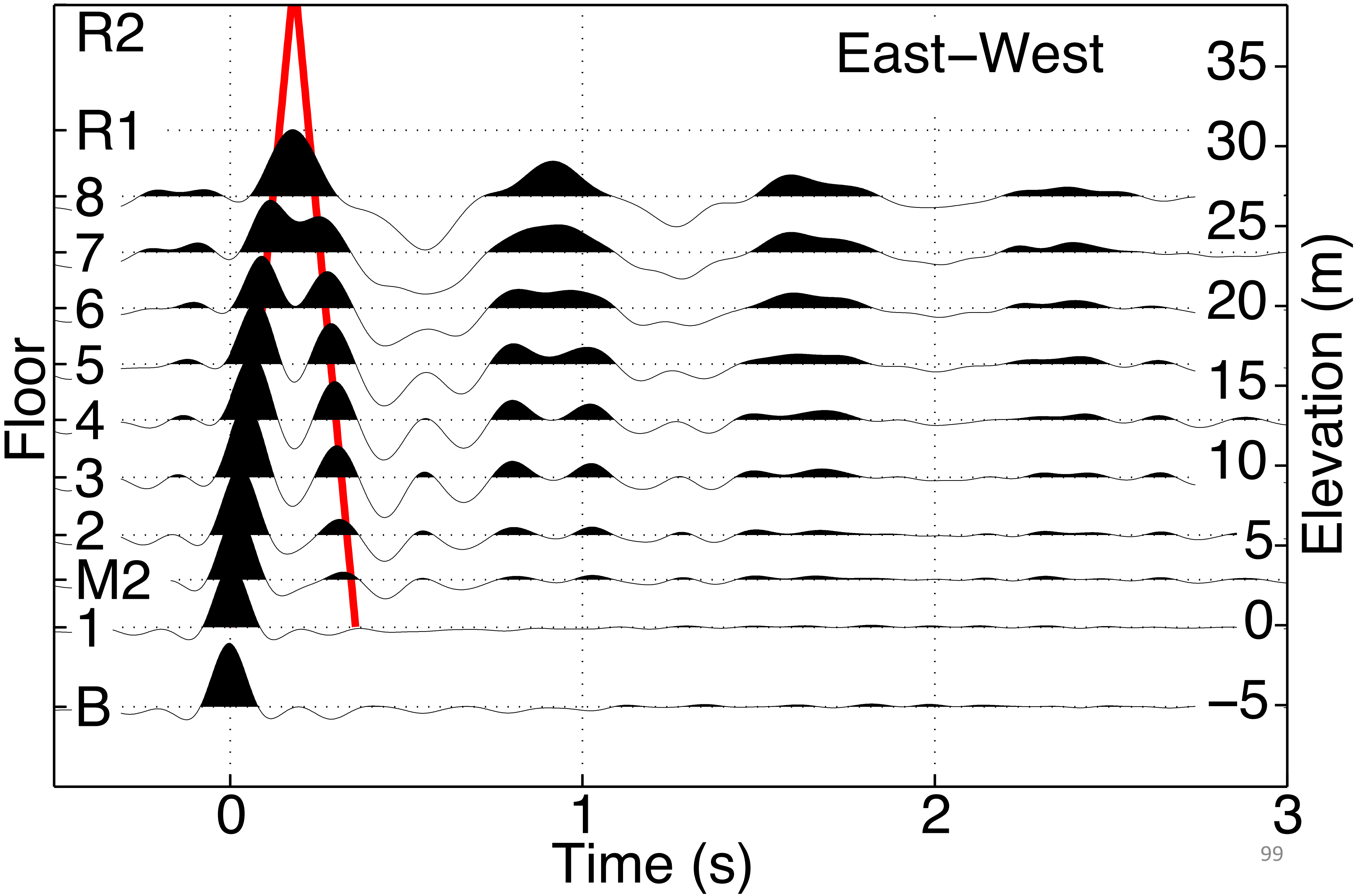
Ambient noise level



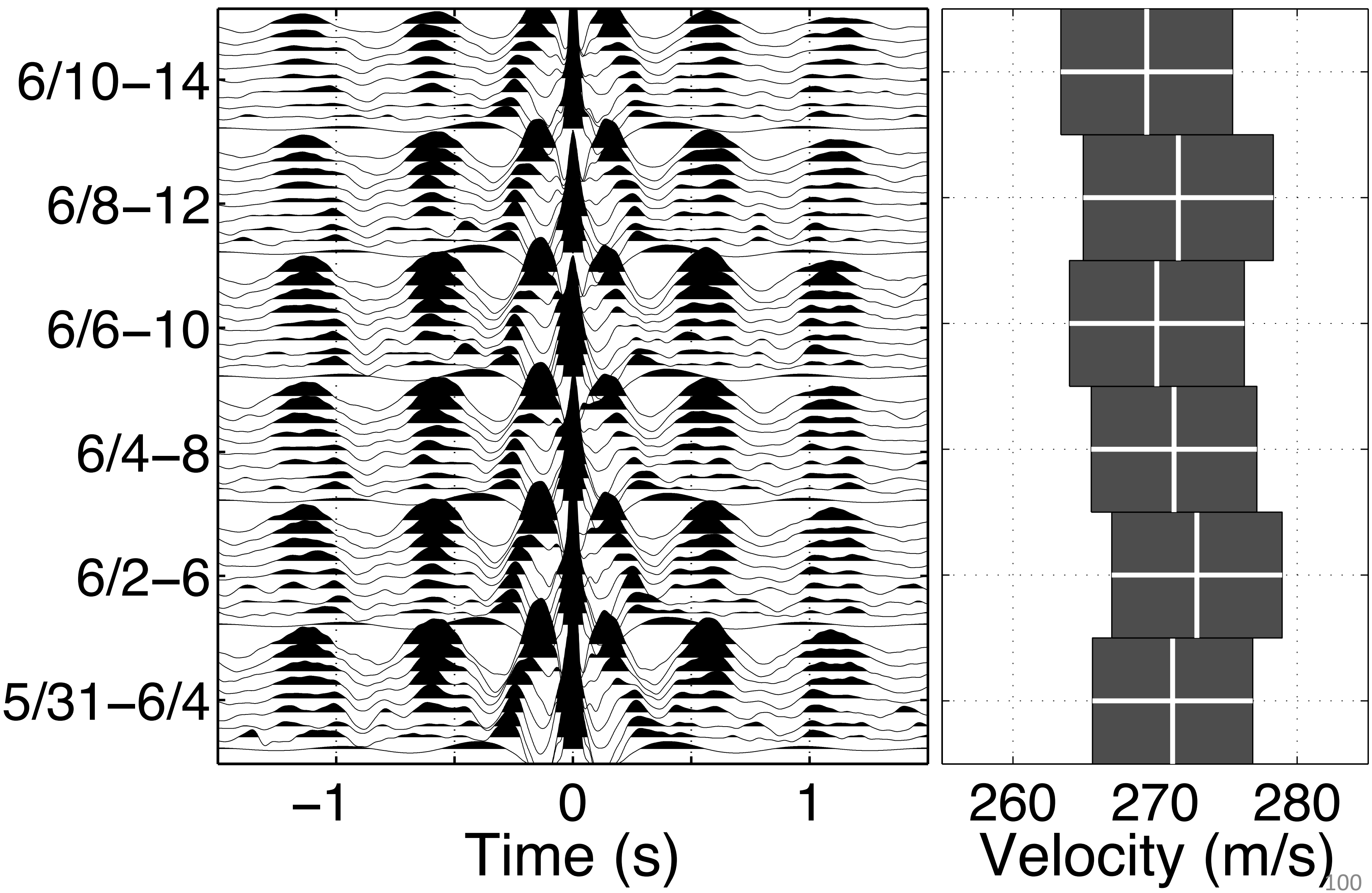
Ambient noise after deconvolution



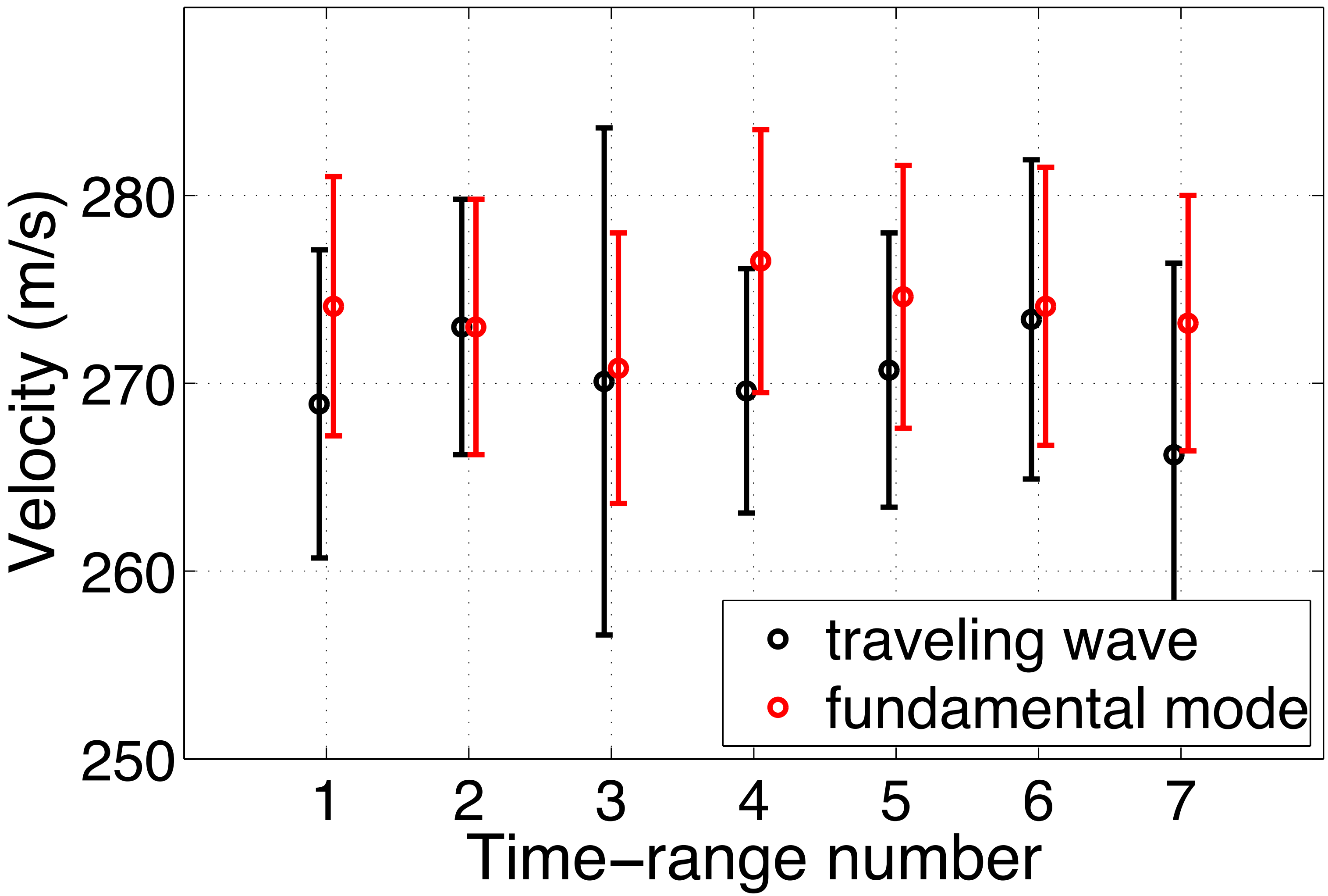
Earthquake after deconvolution



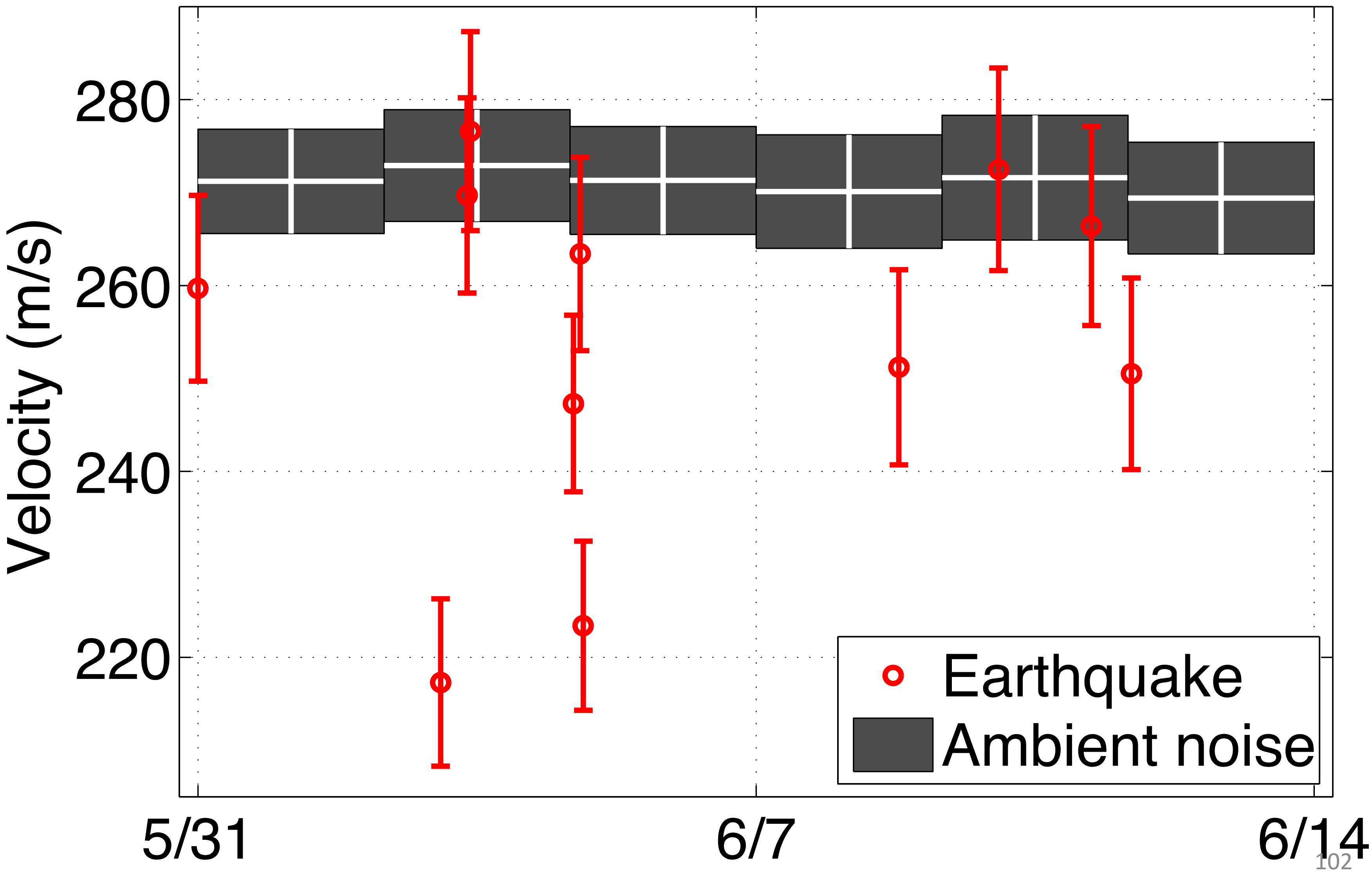
Response from noise



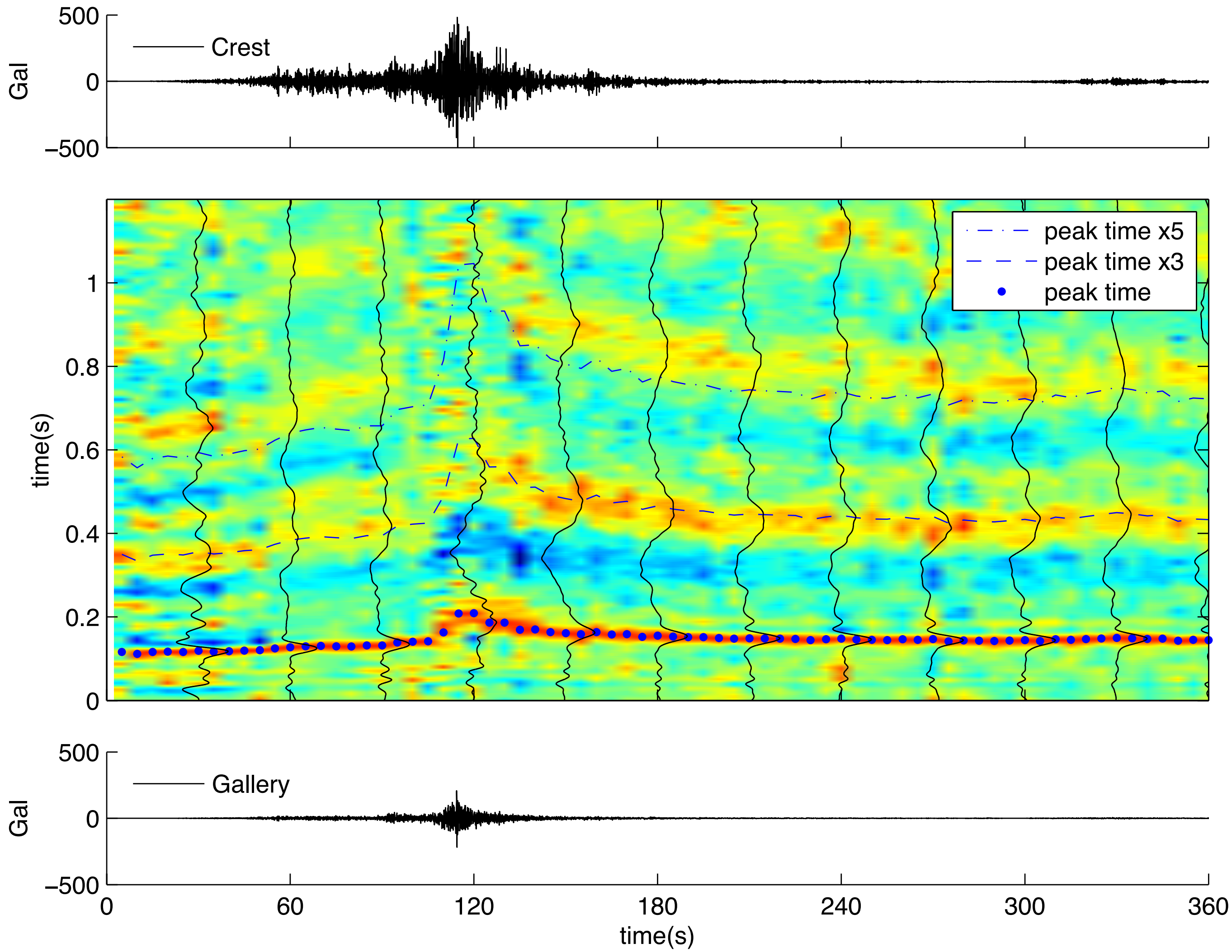
Shear velocity from ambient noise



Shear velocity from earthquakes and from noise

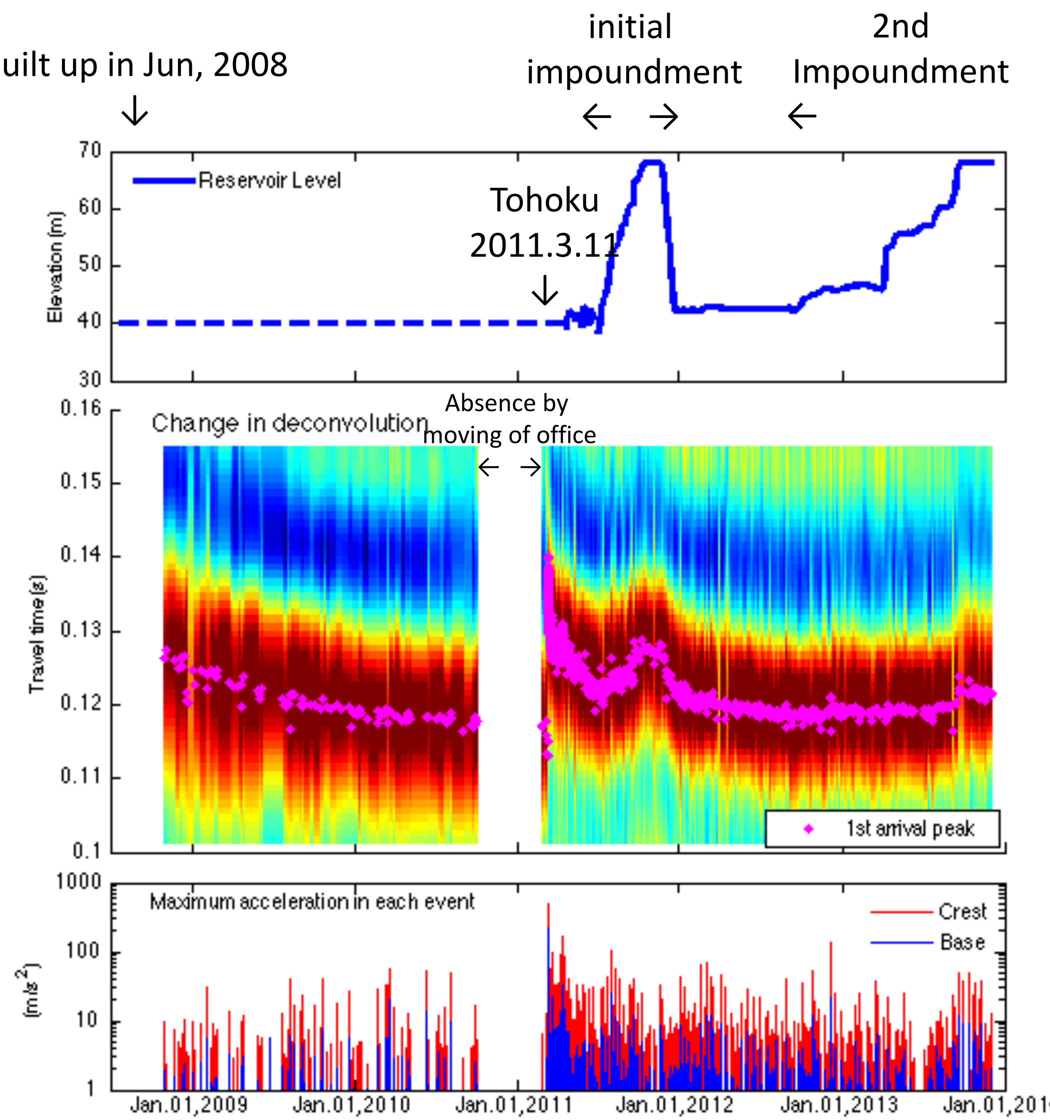


Change during Tohoku earthquake



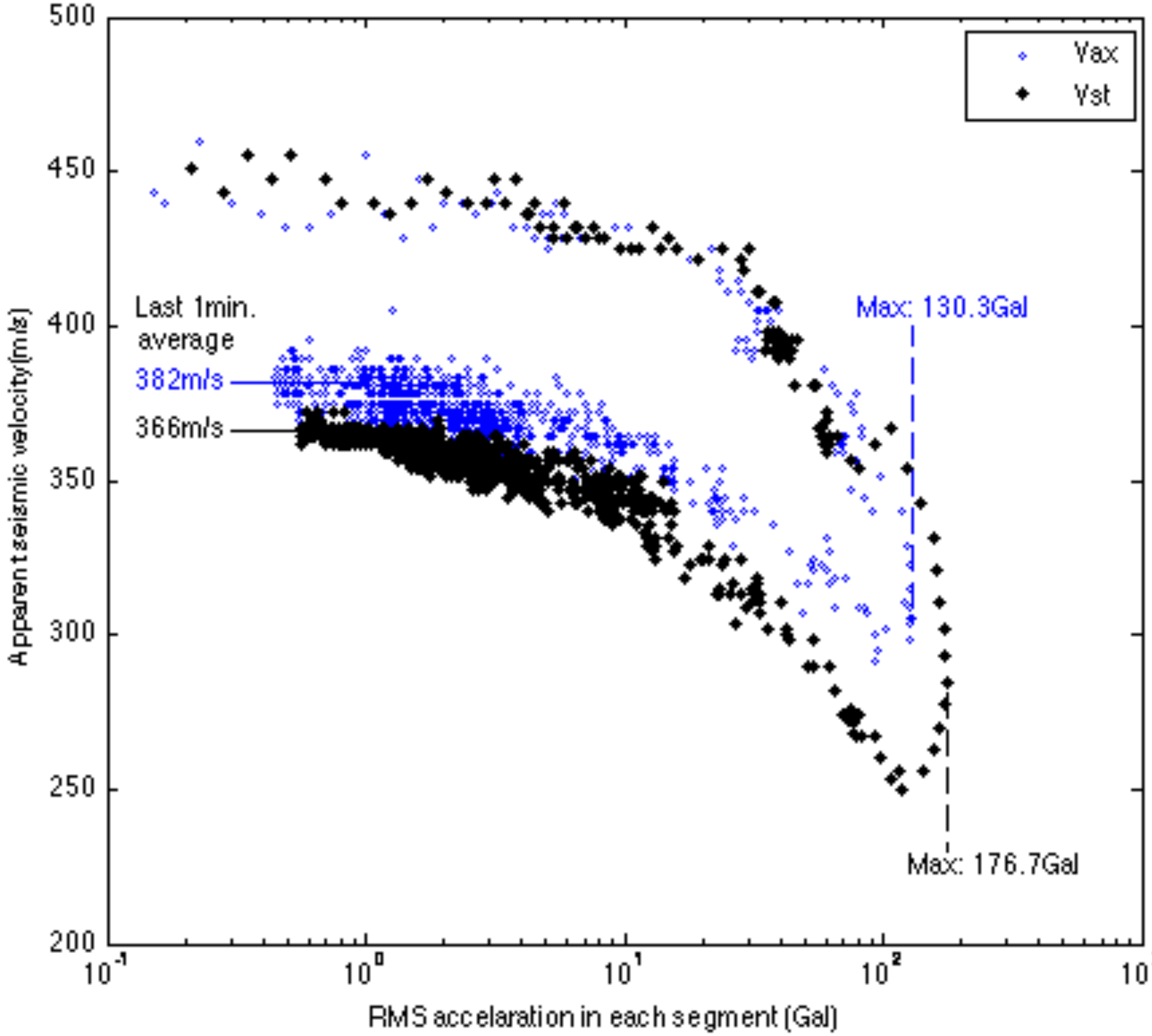
(a) Temporal change in deconvolution waveform of the stream direction during Tohoku-oki earthquake

Long term change

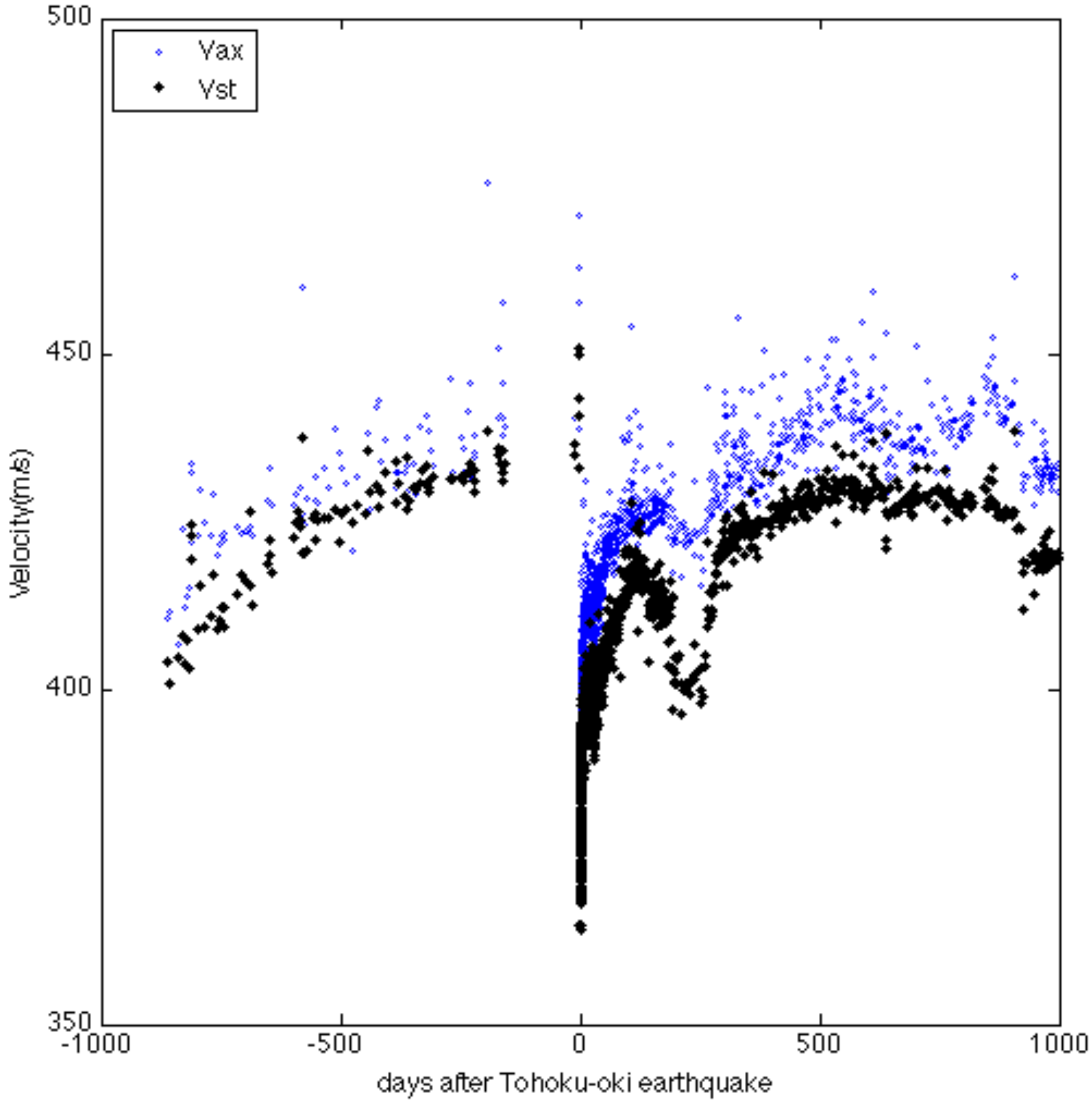


Long-term change in deconvolution waveform of the stream direction retrieved from late small coda waves of each earthquake events

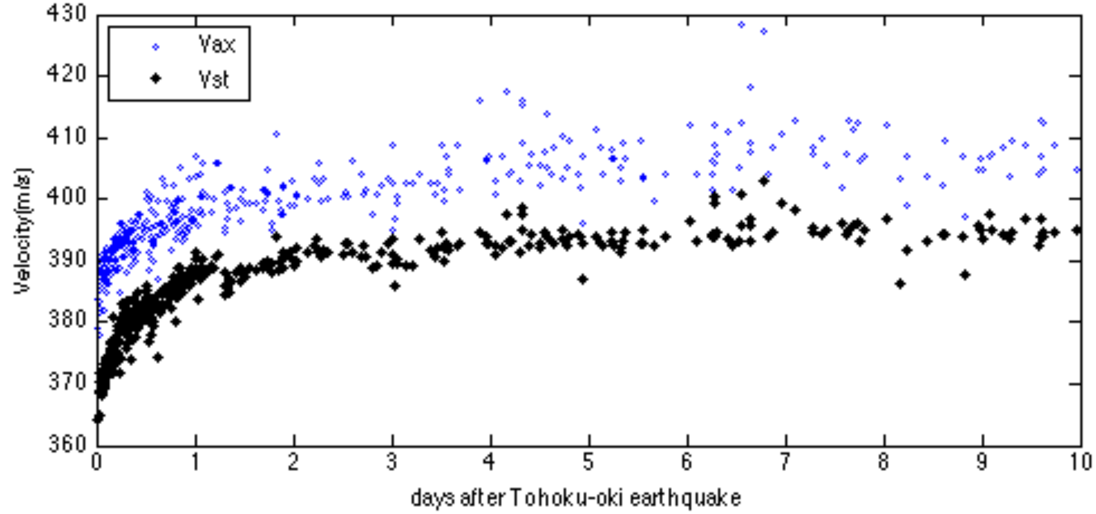
Change during Tohoku earthquake

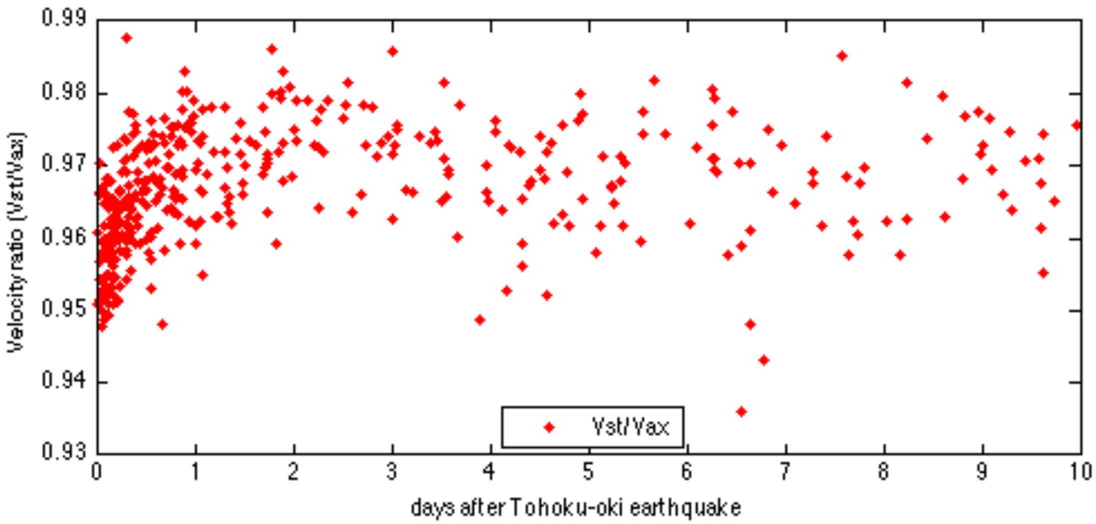


(a) Temporal change in apparent seismic velocity between crest and basement estimated by deconvolution waveform of the stream directionduring Tohoku-oki earthquake. We can find the difference in the direction caused by shaking restricted by the abut

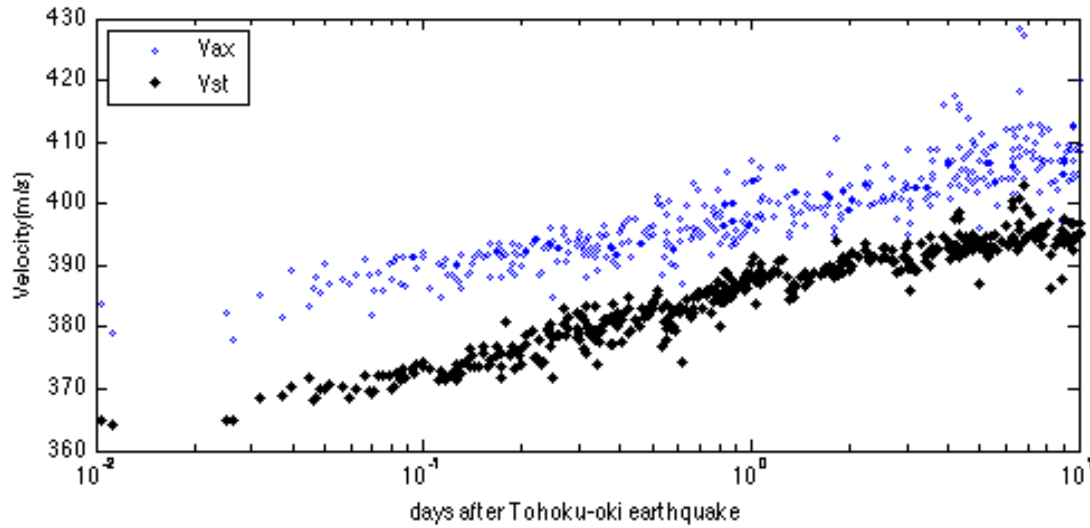


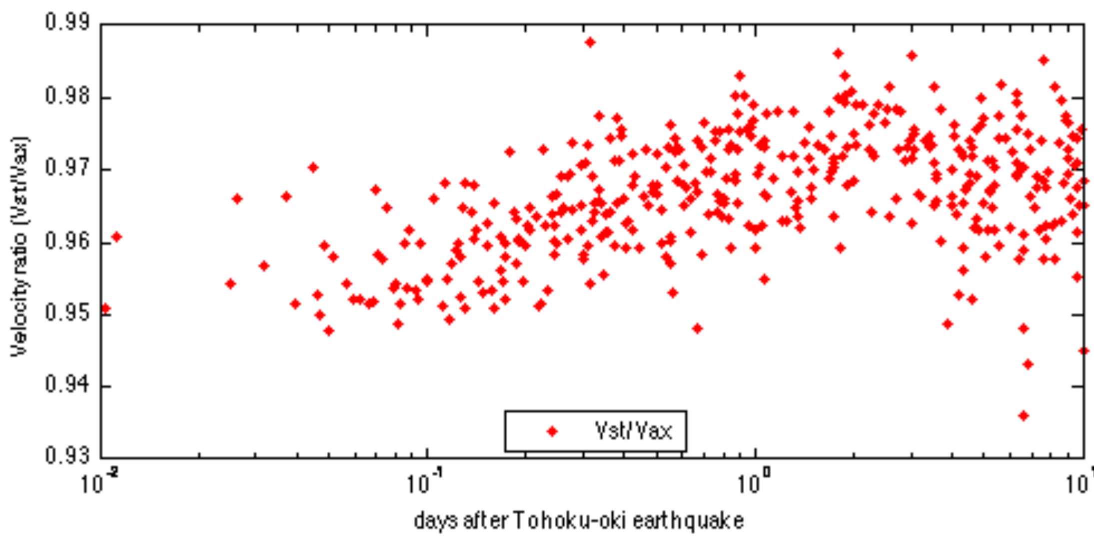
(a) Long-term change in seismic apparent velocity estimated by deconvolution of the 2 horizontal direction retrieved from late coda waves of each earthquake events





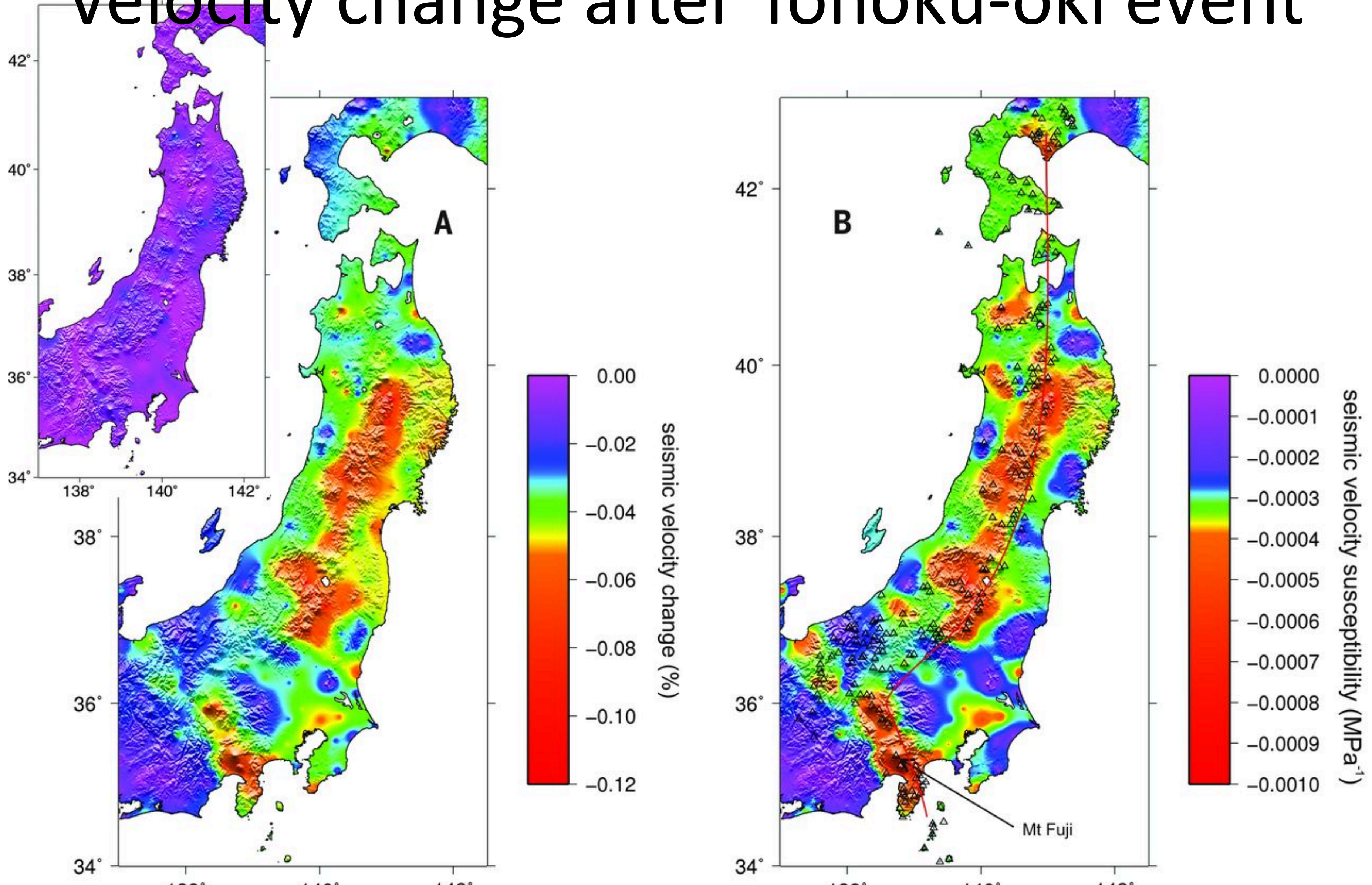
(b) Change in seismic apparent velocity in the 2 directions and its anisotropy estimated by deconvolution retrieved from late coda waves of each earthquake events 10 days after Tohoku earthquake





Change in seismic apparent velocity in the 2 directions and its anisotropy estimated by deconvolution retrieved from late coda waves of each earthquake events 10 days after Tohoku earthquake (in logarithmic time scale)

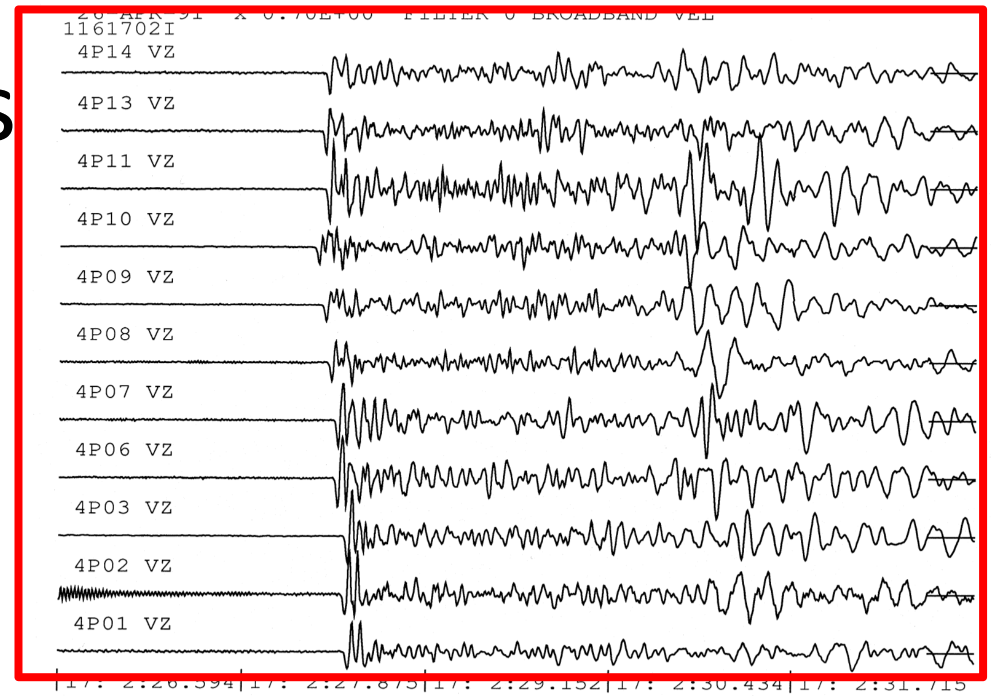
Velocity change after Tohoku-oki event

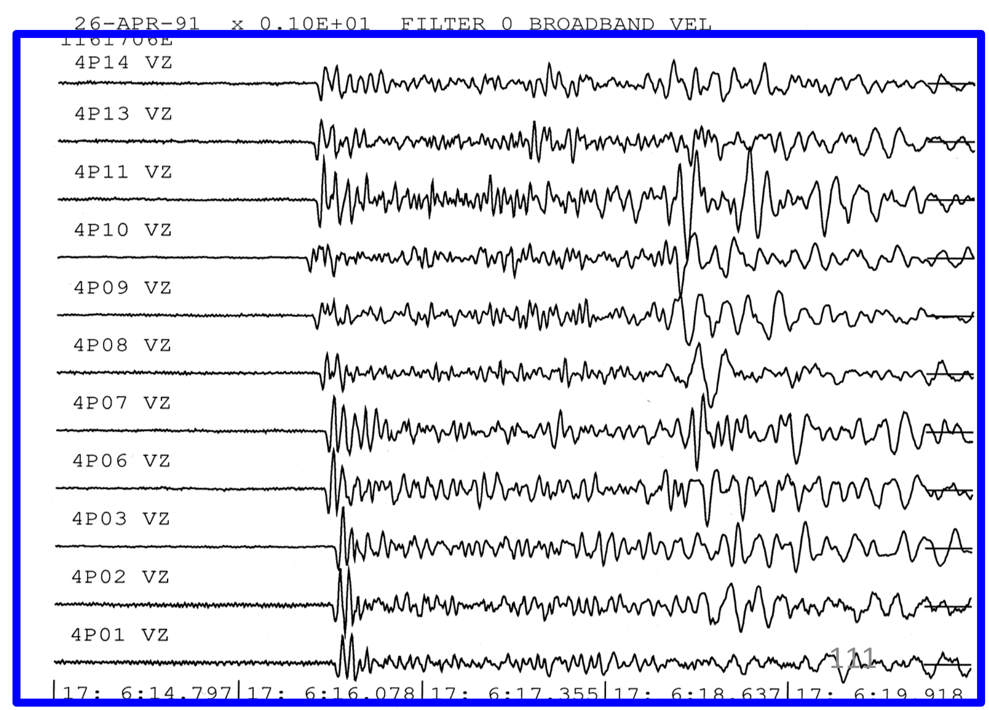


(Brenguier et al., Science, 345, 80-82, 2014)

How it started …

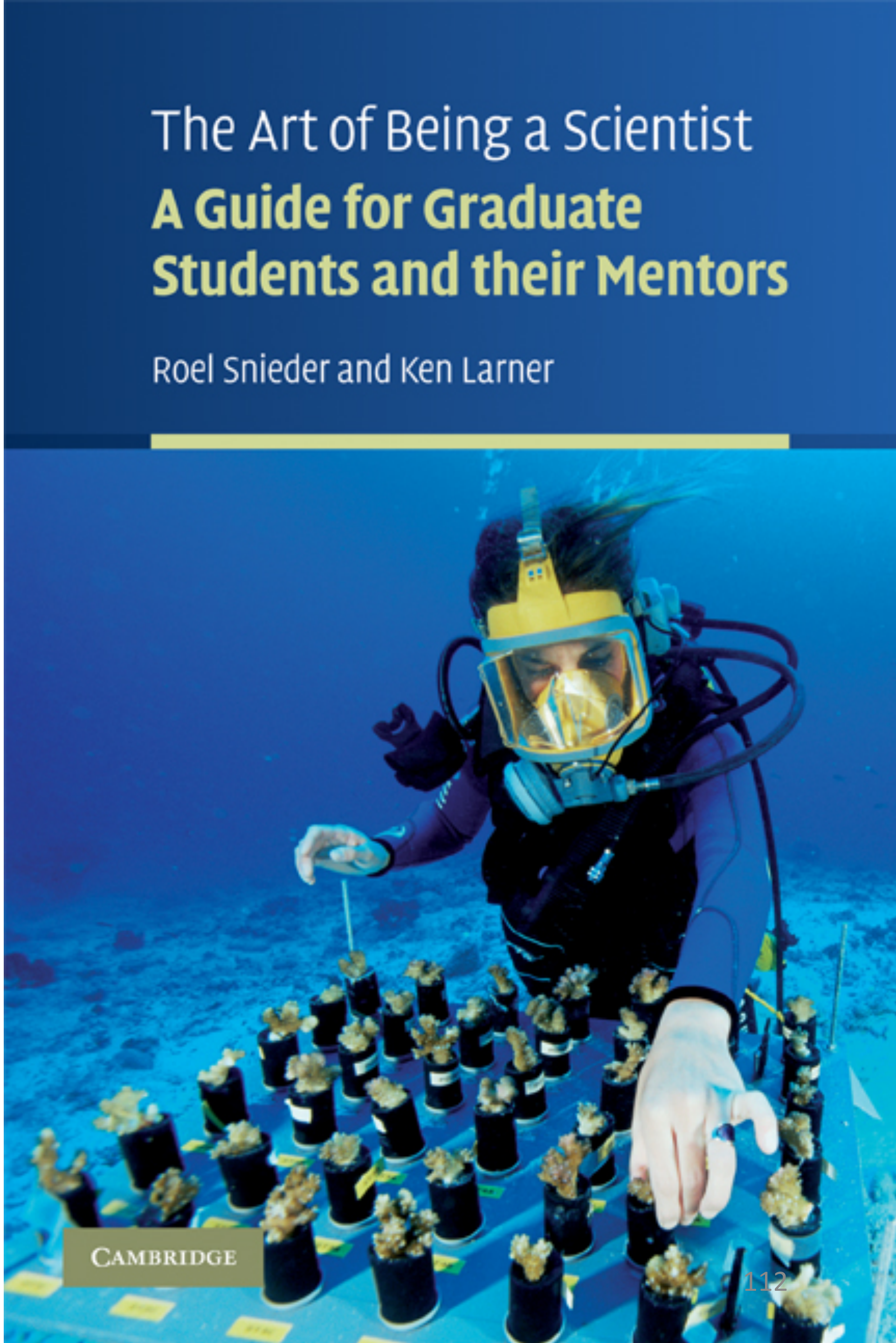
Earthquake doublets





The Art of Science

Thursday April 21, 1330-1500
Room 2.61



Thank you!