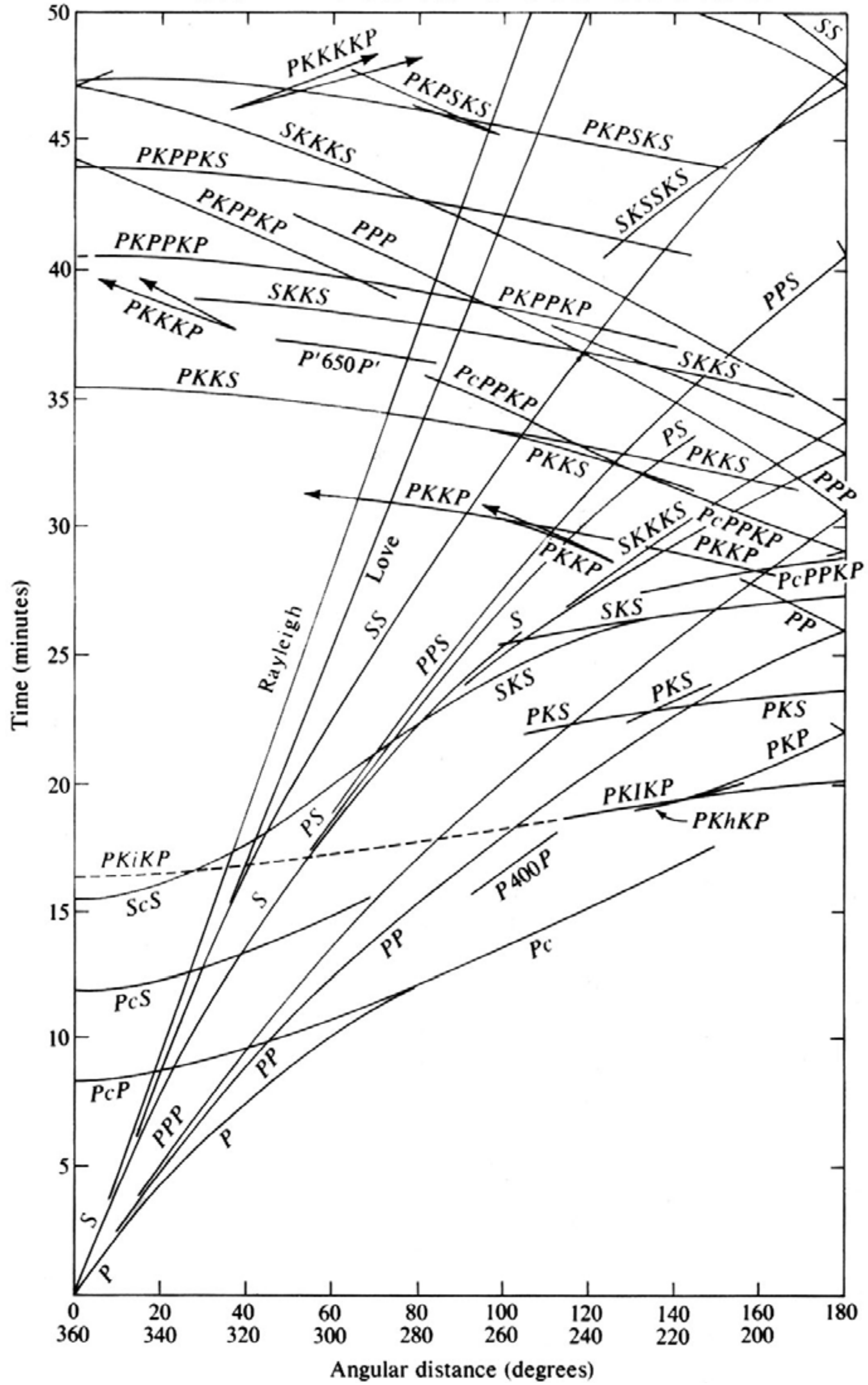
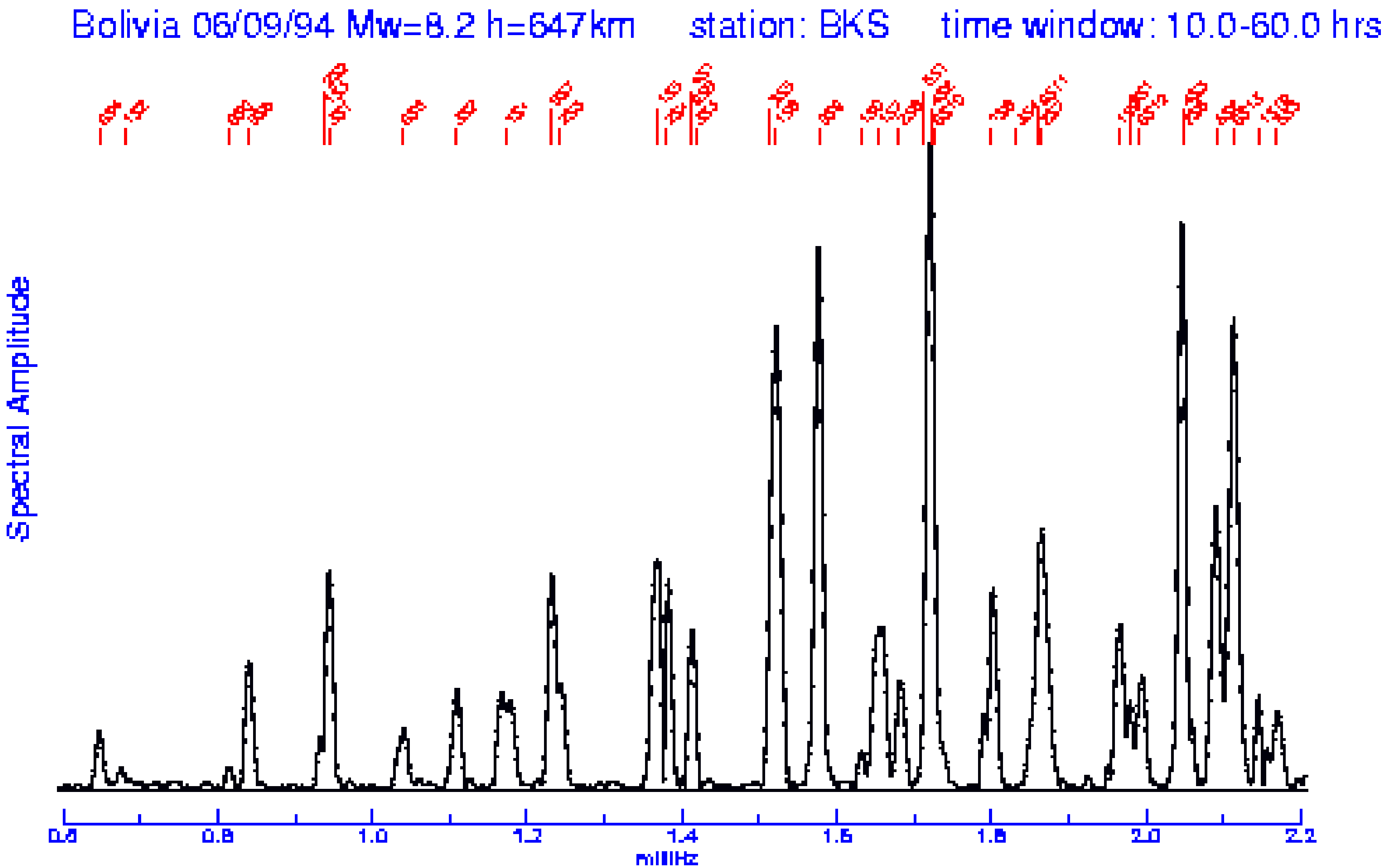
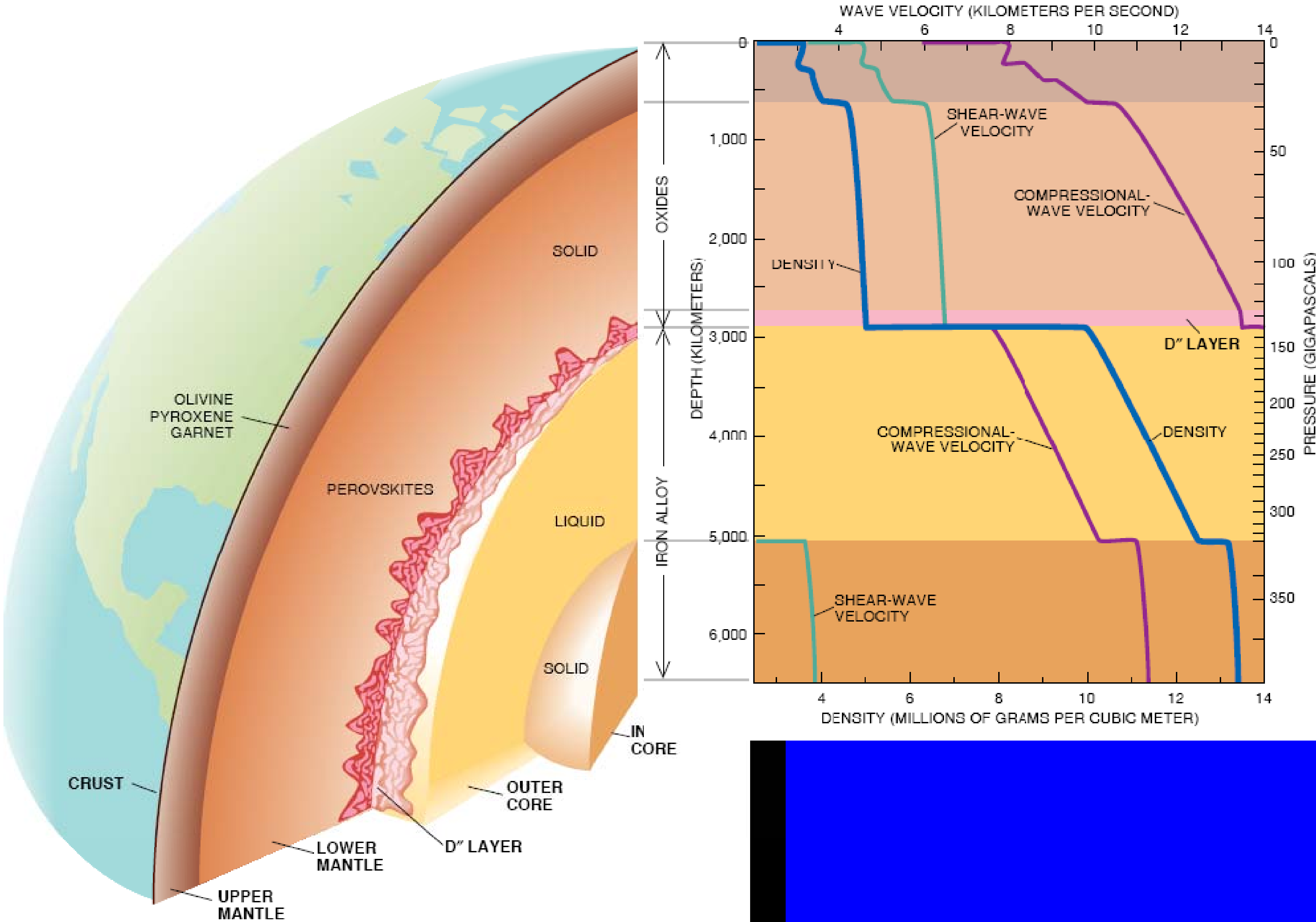
Planetary seismology: inspirations from recent Earth studies

Barbara Romanowicz
Berkeley Seismological Laboratory

Travel-Time Curves for a Surface Source




Bolivia 06/09/94 Mw=8.2 h=647km
station: BKS
time window: 10.0-60.0 hrs
Spectral Amplitude
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
milliHz



OLIVINE
PYROXENE
GARNET
PEROVSKITES
SOLID
LIQUID
SOLID
CRUST
UPPER
MANTLE
LOWER
MANTLE
D″ LAYER
OUTER
CORE
IN
CORE
OXIDES
IRON ALLOY
WAVE VELOCITY (KILOMETERS PER SECOND)
4
6
8
10
12
14
DEPTH (KILOMETERS)
0
1,000
2,000
3,000
4,000
5,000
6,000
PRESSURE (GIGAPASCALS)
0
50
100
150
200
250
300
350
SHEAR-WAVE
VELOCITY
COMPRESSIONAL-
WAVE VELOCITY
DENSITY
D″ LAYER
COMPRESSIONAL-
WAVE VELOCITY
DENSITY
SHEAR-WAVE
VELOCITY
DENSITY (MILLIONS OF GRAMS PER CUBIC METER)

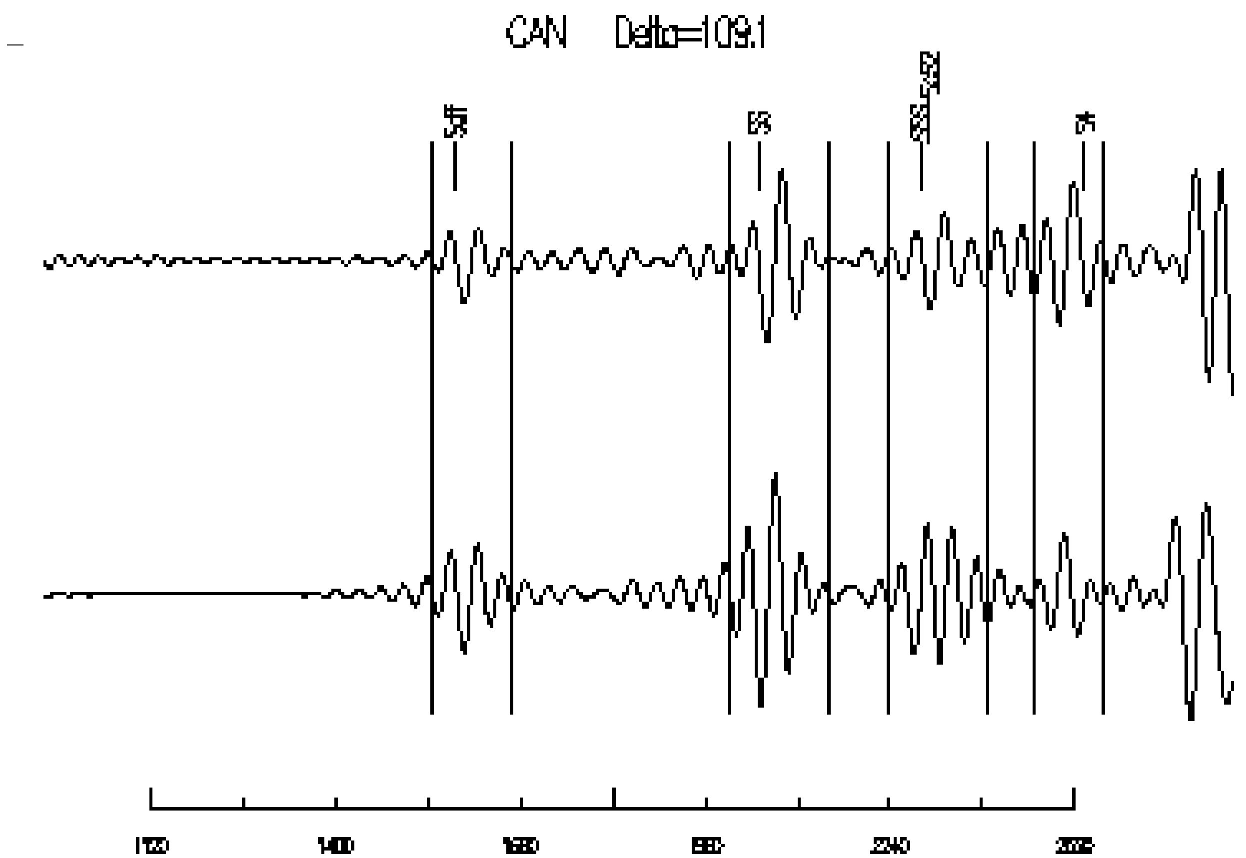
Solidity of the inner core

Mode	Mean period (s)	No. of observations	s.e.m. (s)	UTD124B′—Solid inner core: Comp. period	UTD124B′—Solid inner core: Rel. error (%)	Inner core energy: Compr.	Inner core energy: Shear	UTD124B′—Liquid inner core: Comp. period	UTD124B′—Liquid inner core: Rel. error (%)	5.08M: Comp. period	5.08M: Rel. error (%)
${}_1S_0$	613.57	11	0.236	614.59	0.17	0.181	0.000	607.39	−1.02	610.06	−0.57
${}_2S_0$	398.54	40	0.084	397.59	−0.24	0.206	0.001	392.31	−1.59	391.42	−1.81
${}_3S_0$	305.84	7	0.129	306.00	0.05	0.233	0.003	301.36	−1.48	301.84	−1.31
${}_4S_0$	243.59	12	0.067	243.80	0.09	0.192	0.007	241.11	−1.03	241.55	−0.84
${}_2S_2$	904.23	21	0.487	904.43	0.02	0.001	0.080	914.94	1.17	917.80	1.50
${}_5S_2$	397.36	11	0.157	397.03	−0.09	0.015	0.102	399.93	0.67	398.20	0.21
${}_6S_1$	348.41	21	0.046	348.23	−0.05	0.068	0.011	347.10	−0.38	347.38	−0.30
${}_7S_3$	281.37	11	0.113	281.59	0.08	0.004	0.022	282.77	0.50	283.34	0.70
${}_8S_1$	272.10	11	0.144	271.79	−0.11	0.115	0.052	271.00	−0.40	270.92	−0.43
	Nine modes—r.m.s.										

→ Vs-ic=3.517 km/s

Dziewonski and Gilbert, Nature 1971
Also Dziewonski, Science, 1971- radial modes

Waveform Tomography



observed

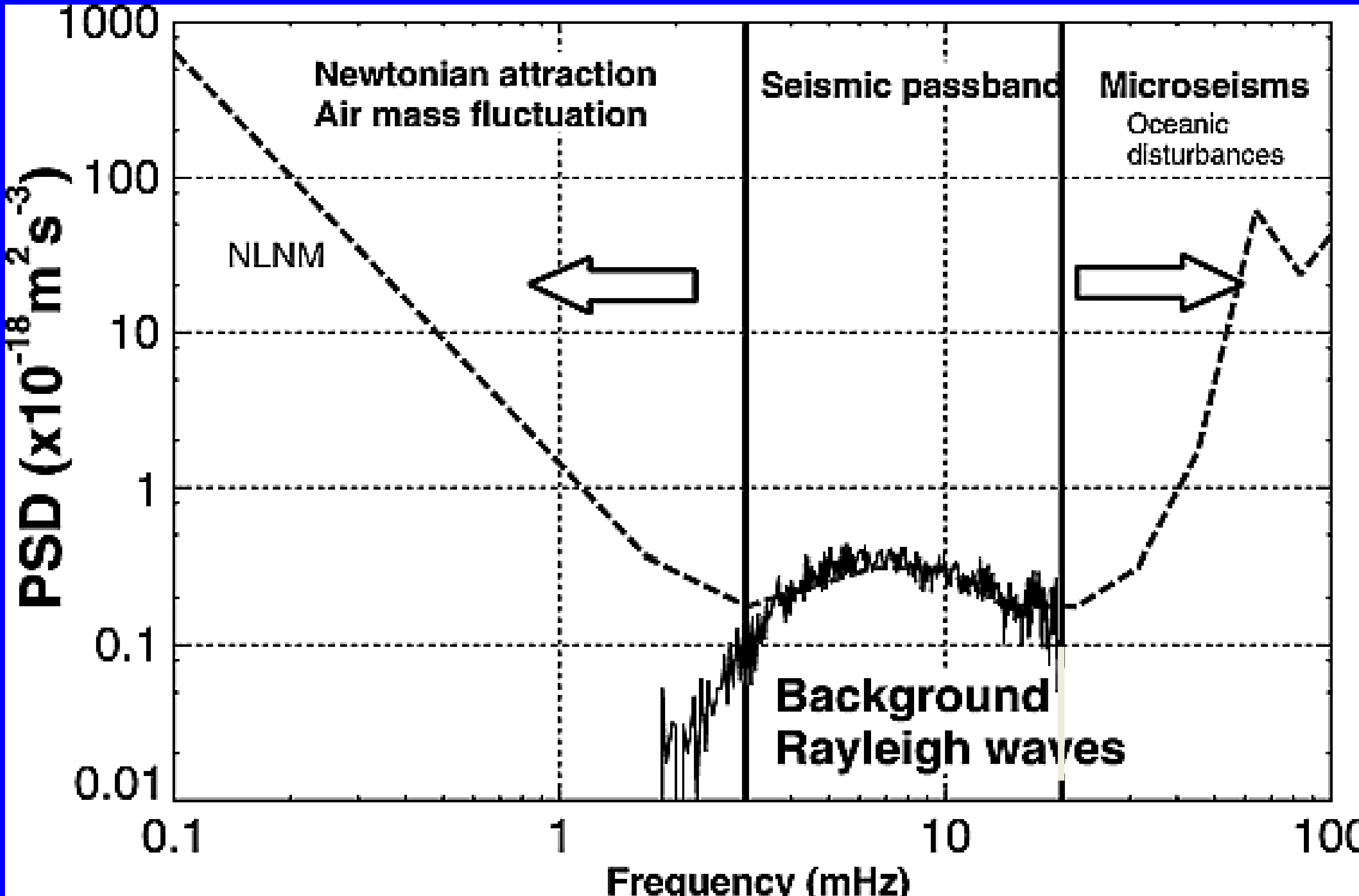
synthetic

- Different methods to compute synthetics including highly accurate 3D numerical ones
- Fast computers: many simulations

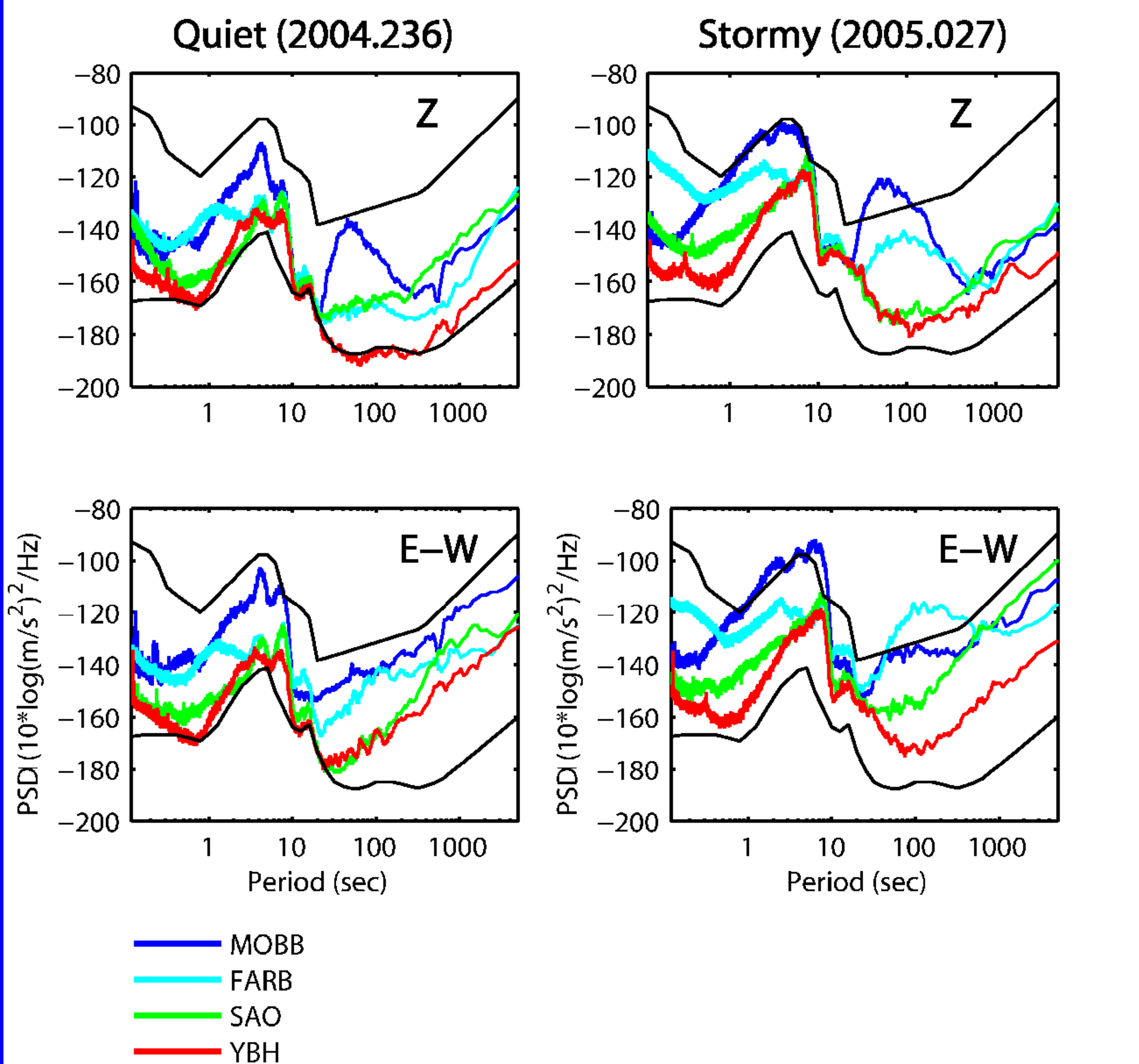
Without any quake-like events

- *Single broadband station:*
  - Single component (Z):
    - Seismic Noise PSD Spectrum
    - Hum from stacking of noise spectra-> free oscillation frequencies -> internal structure
  - Three components?
- *Two broadband stations:*
  - Single component (Z):
    - Noise correlation methodology
- *Array (3 or more stations):*
    - Noise source location

Seismic Noise Power Density Spectrum

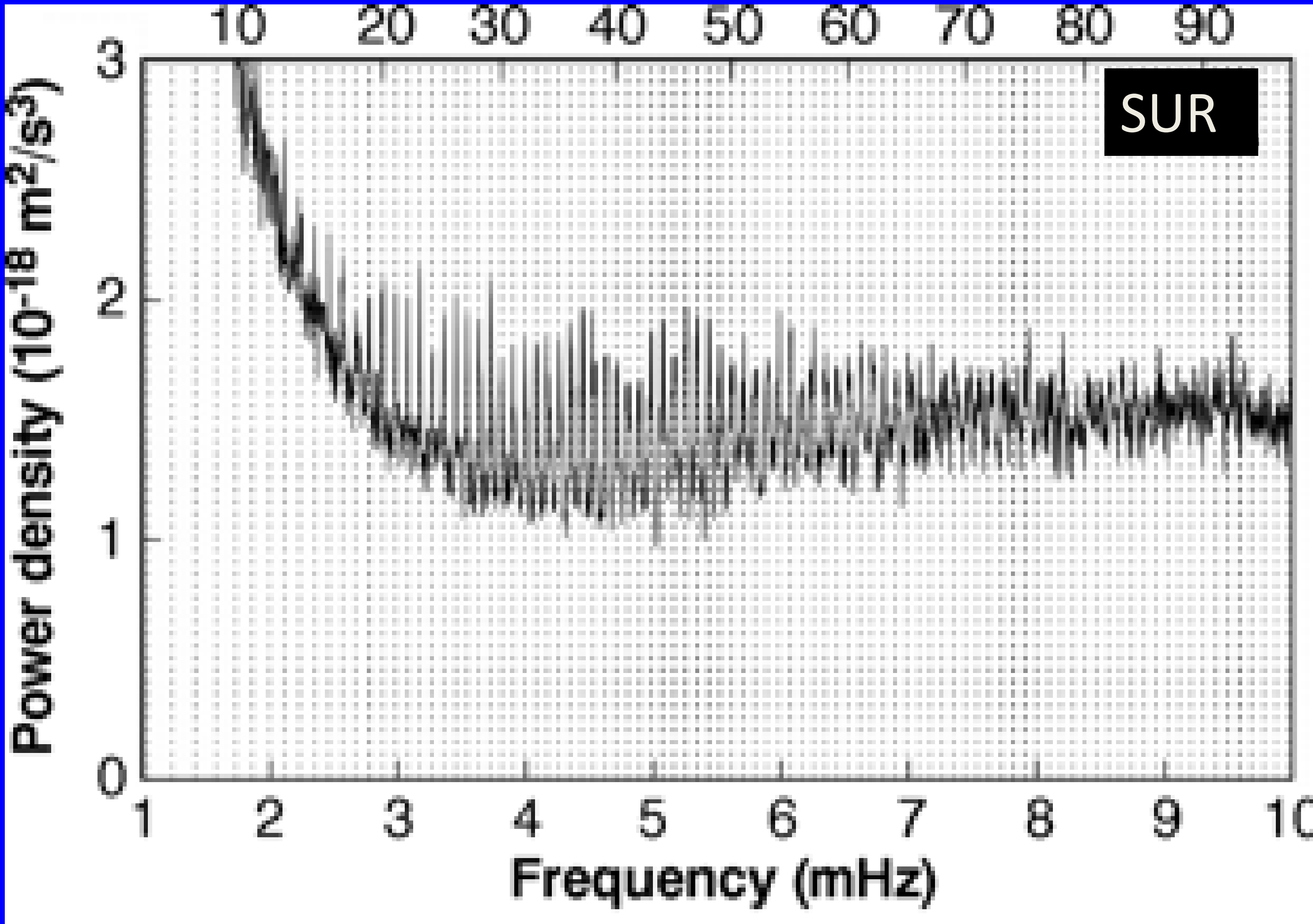


After Nishida et al., GRL, 2002

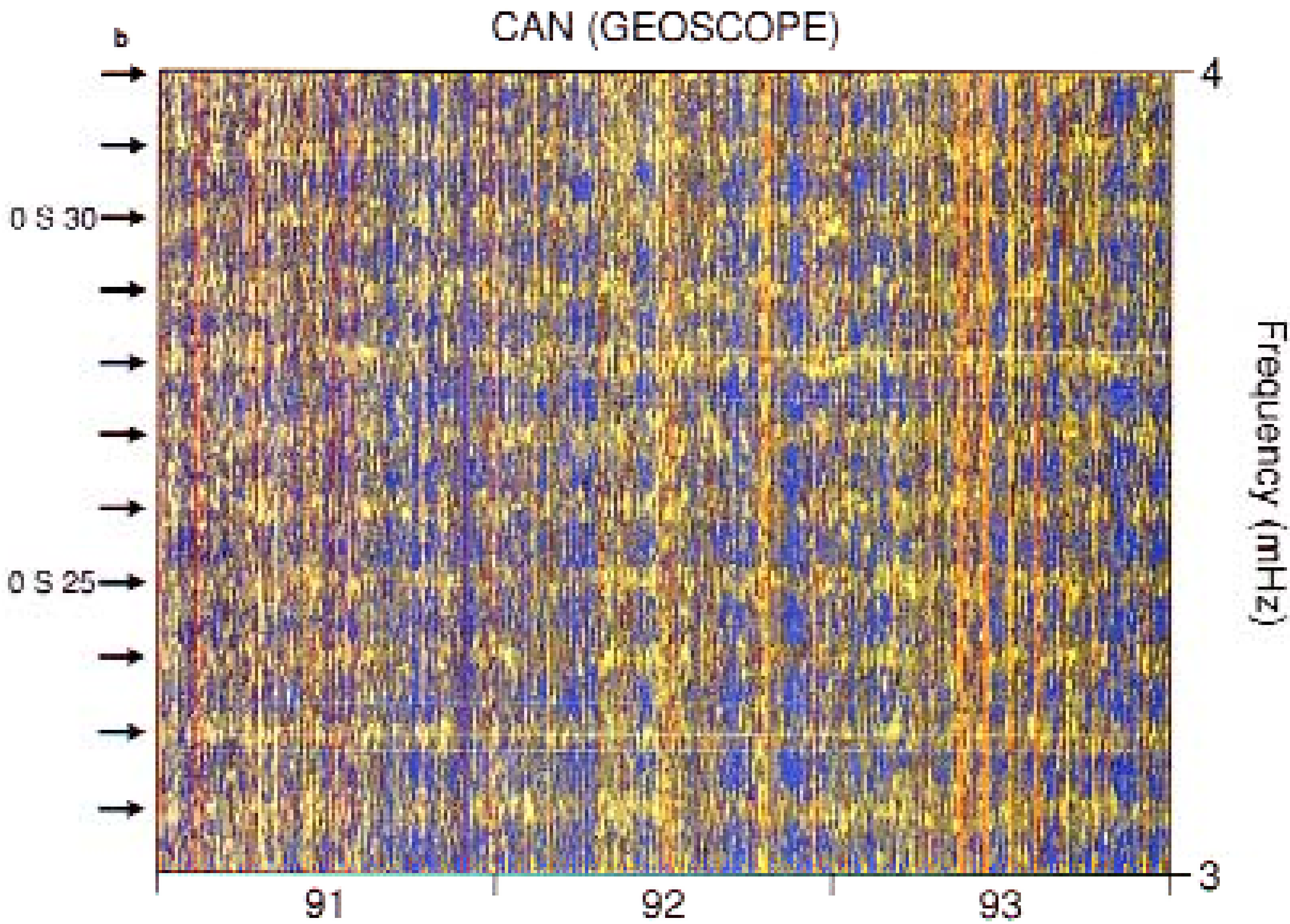


Quiet (2004.236)
Stormy (2005.027)
Z
E–W
PSD (10*log(m/s^2)^2/Hz)
Period (sec)
MOBB
FARB
SAO
YBH

Observed noise spectra stacks
437 days without earthquakes

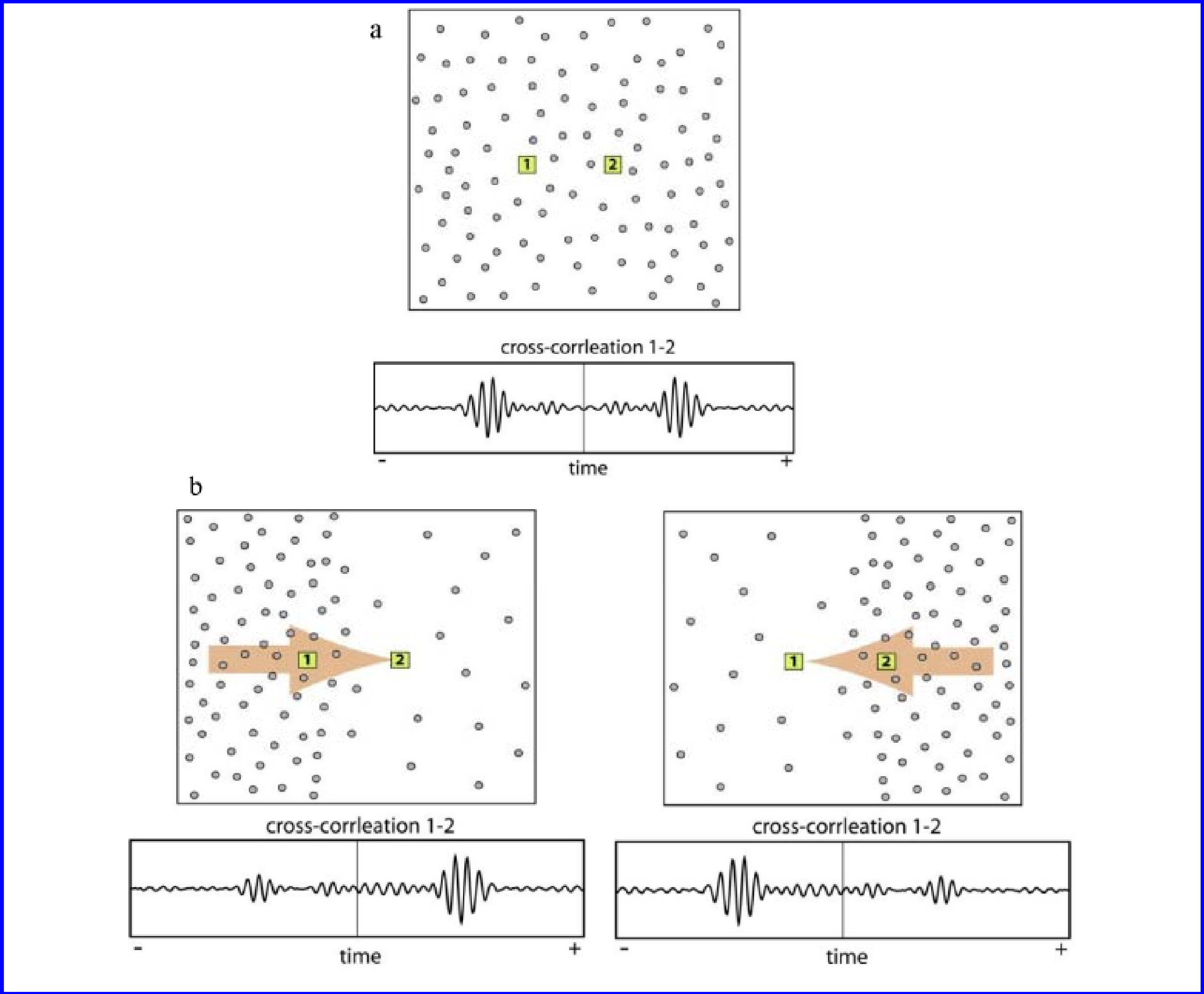


Suda et al., 1998

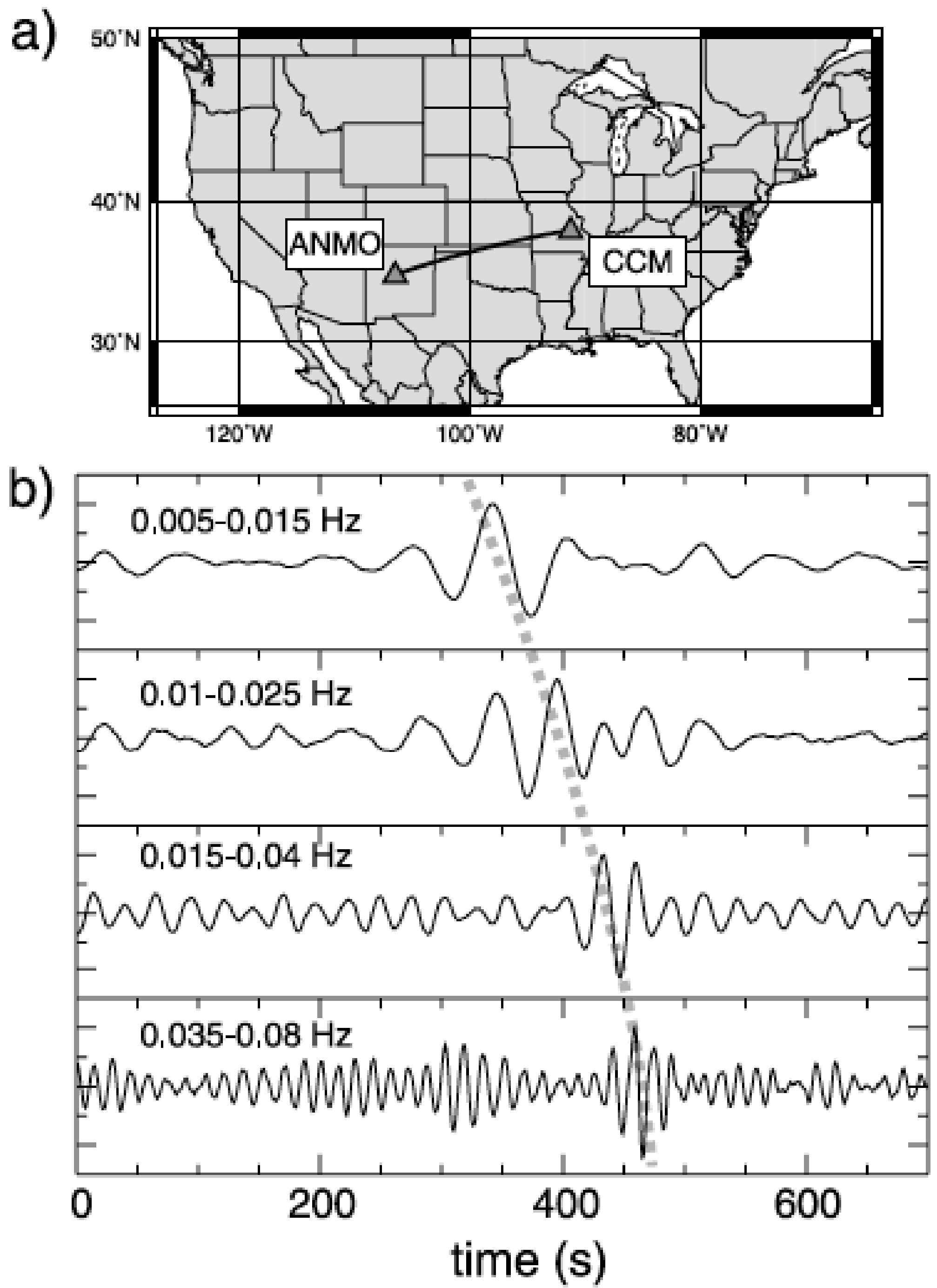


Tanimoto and Um, 1999

With two stations…

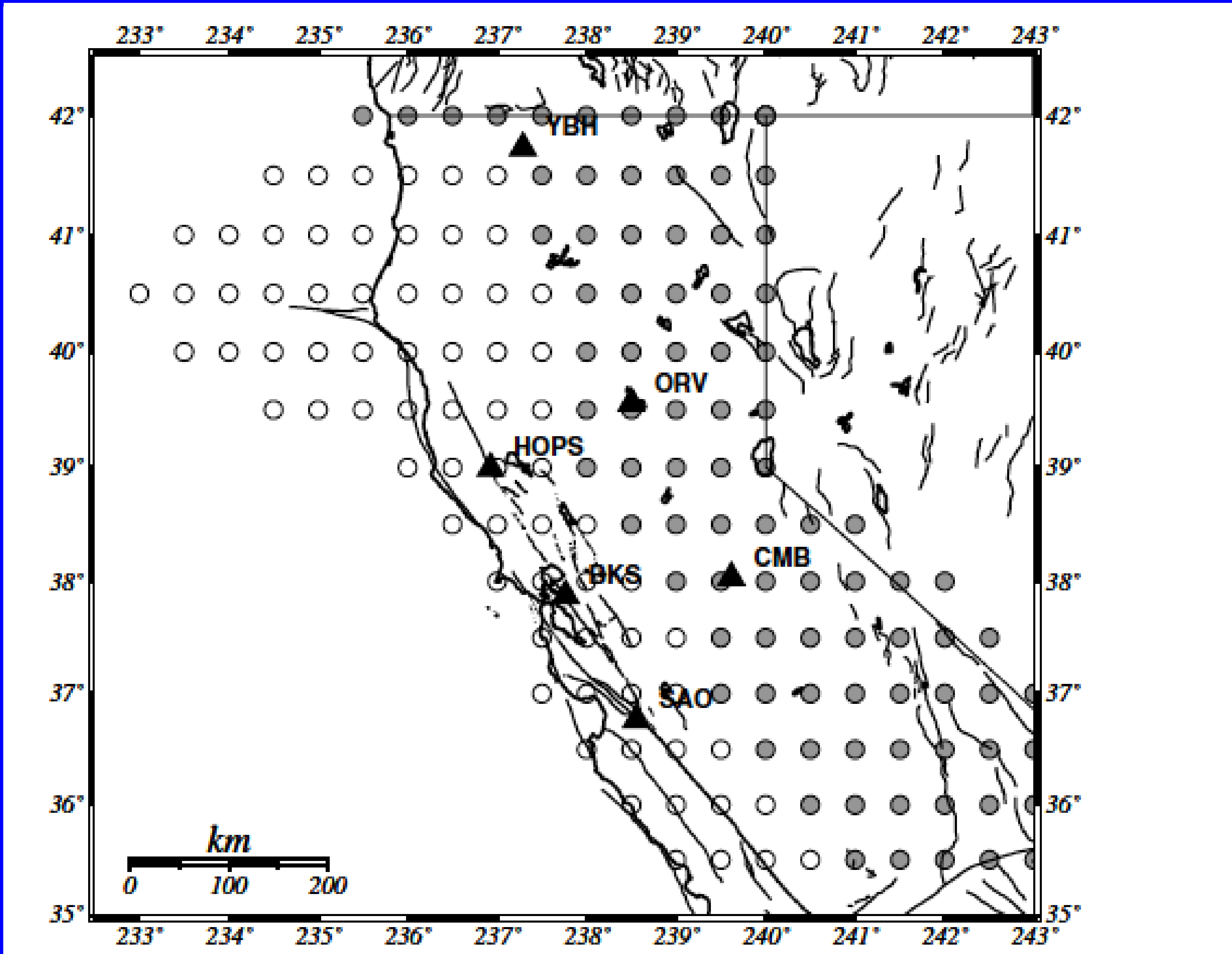


Stehly et al., 2006

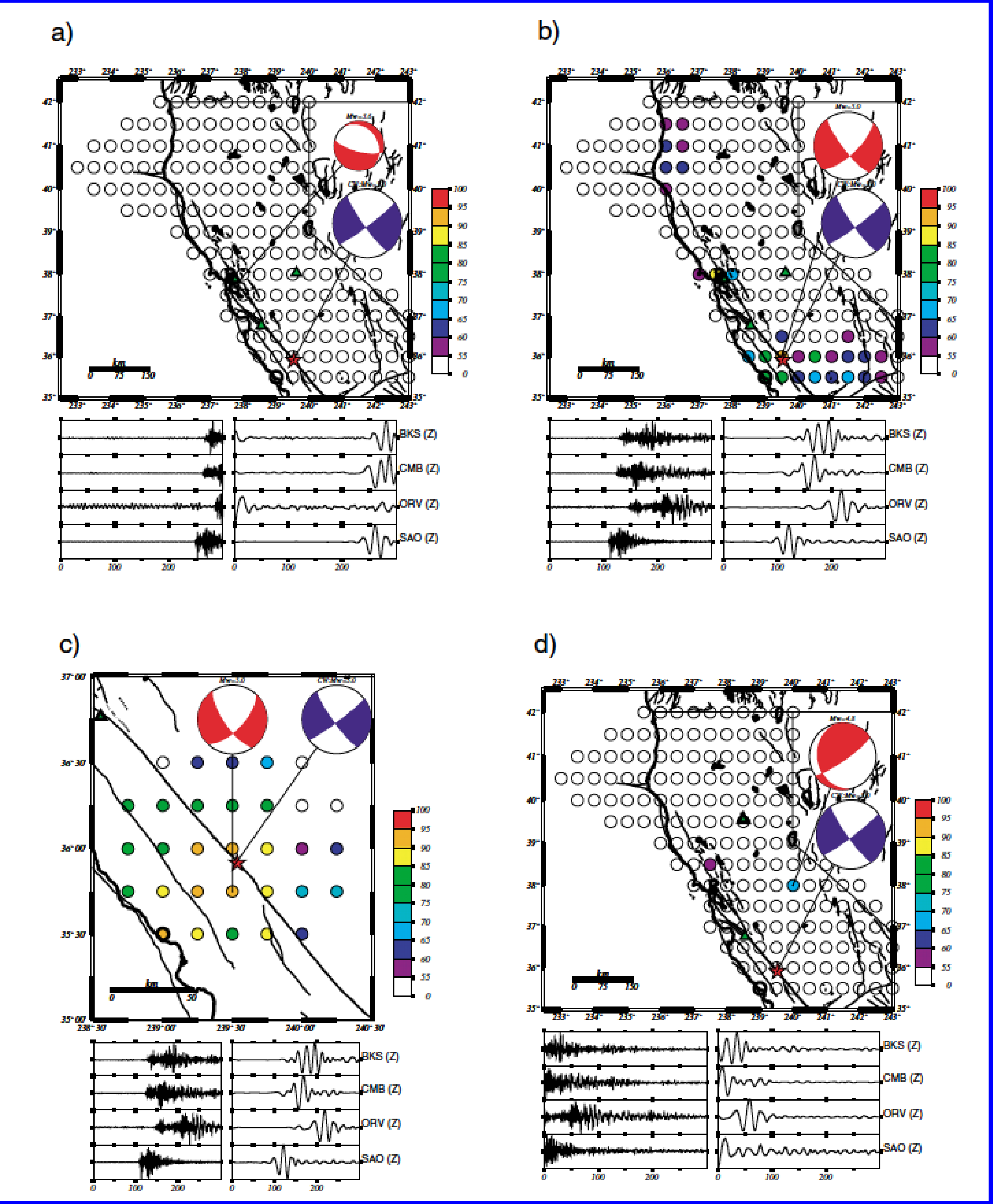


Shapiro and Campillo, 2004

Continuous wavefield monitoring



Parkfield
1997
M 4.7

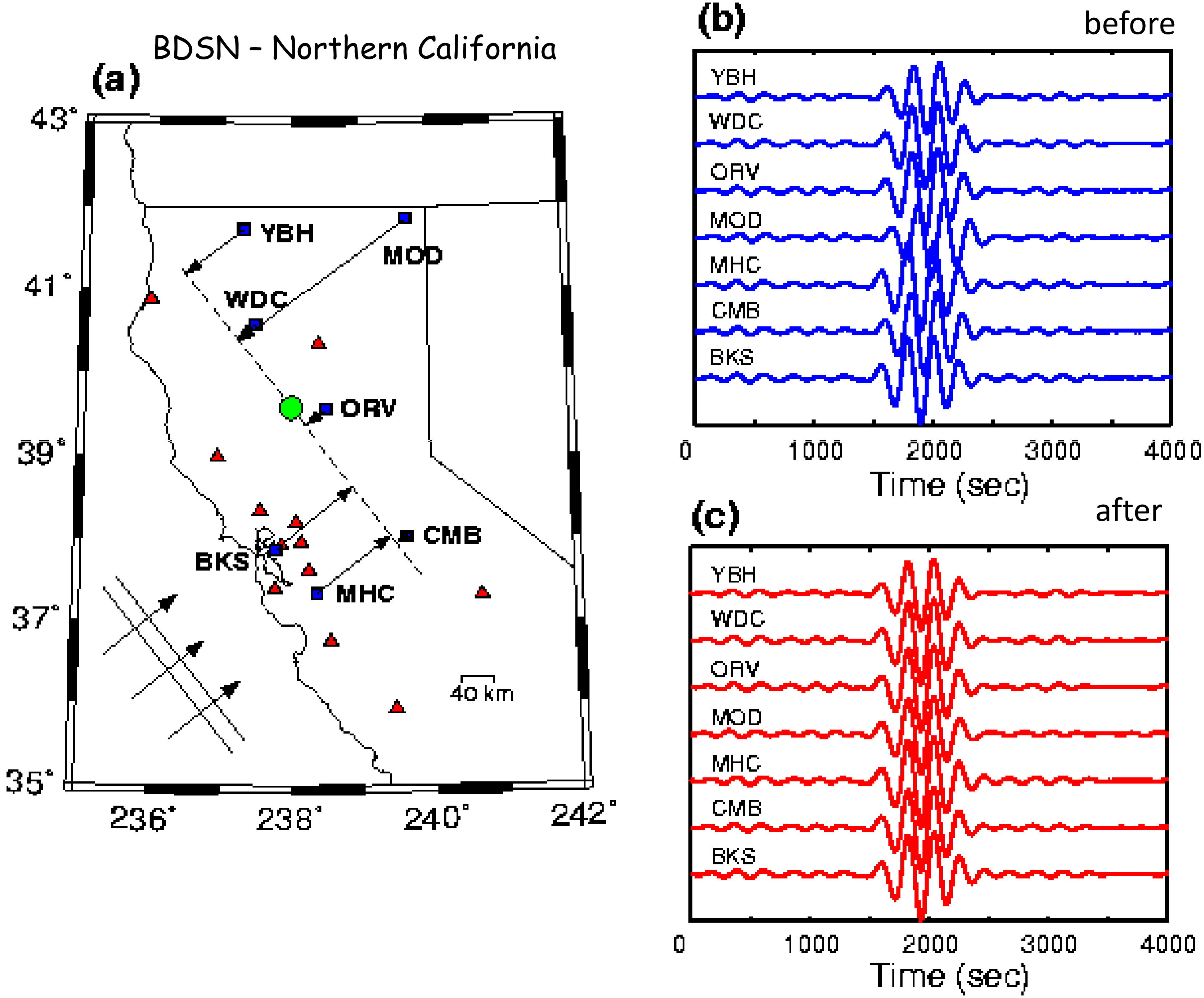


Tajima et al., 2002

Single 3 component versus 2 Z stations?

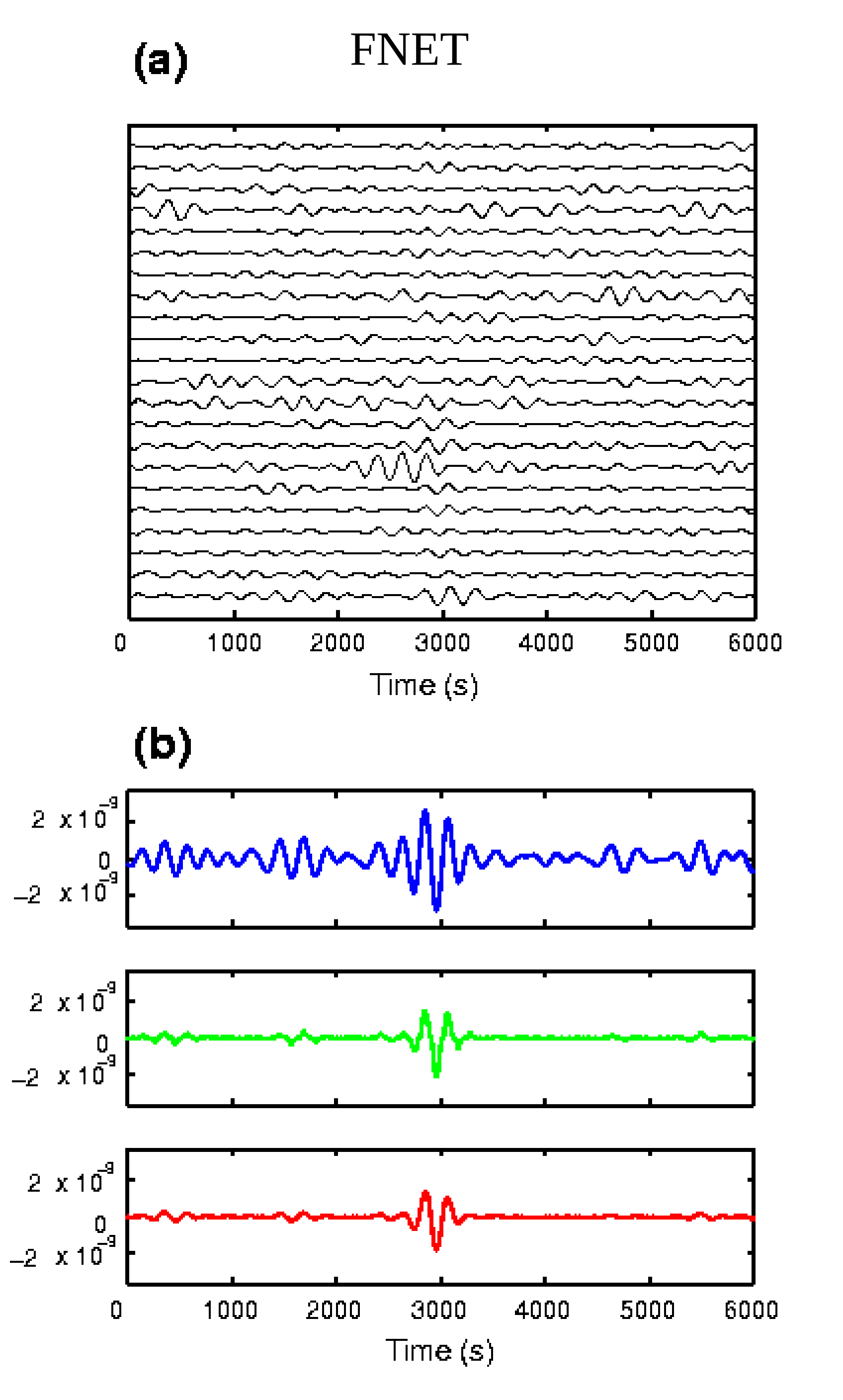
- Two Z stations !!
  - Noise spectra
  - Hum
  - Noise correlations
  - Robustness/redundancy

More than two stations (regional array)



Rhie and Romanowicz, 2004

Jan 2, 2000
Mw 5.8
$\Delta = 36.31^{o}$



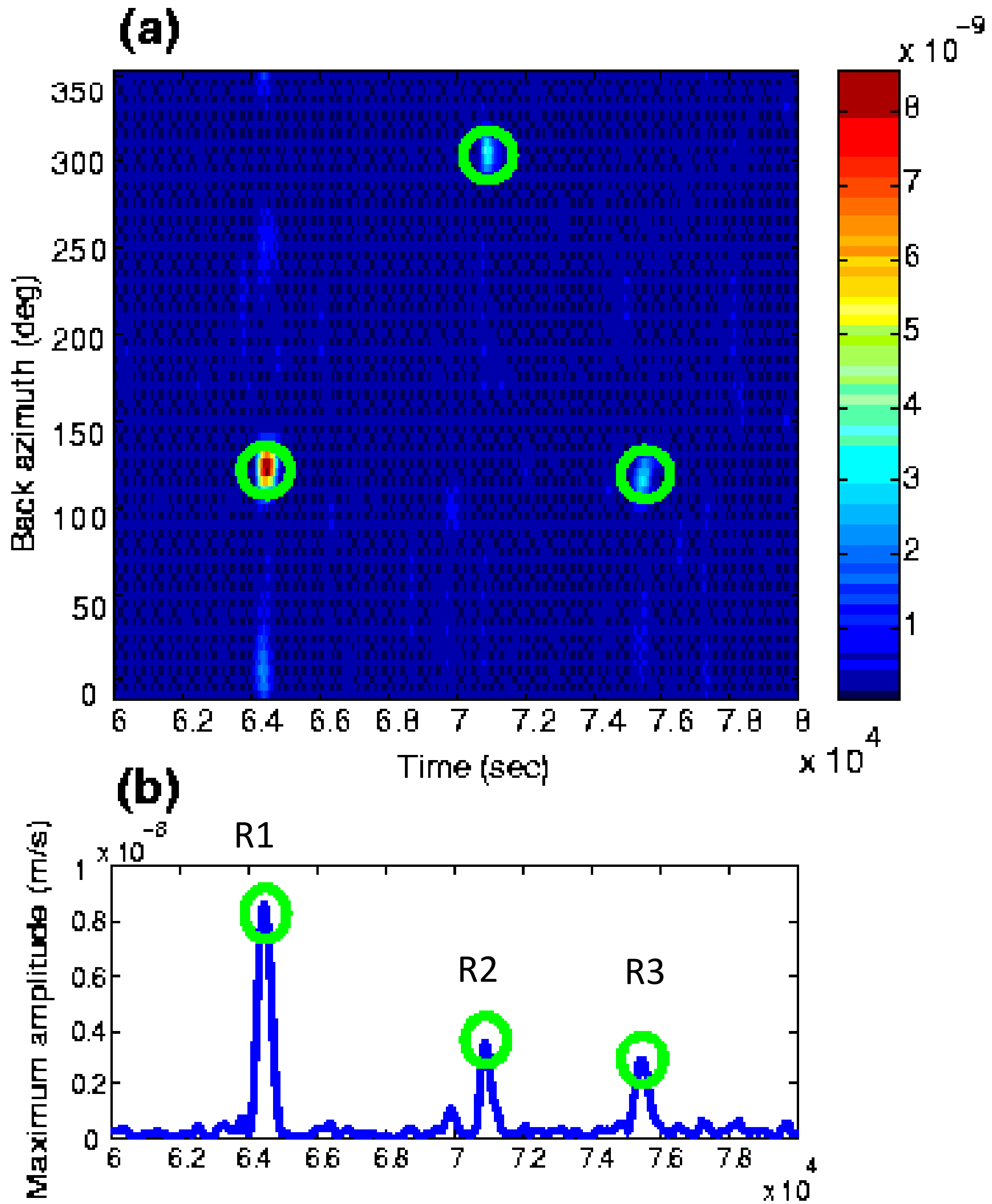
Straight stack

3rd root stack

Phase Weighted Stack

Stack Amplitude as a function of time and azimuth, FNET

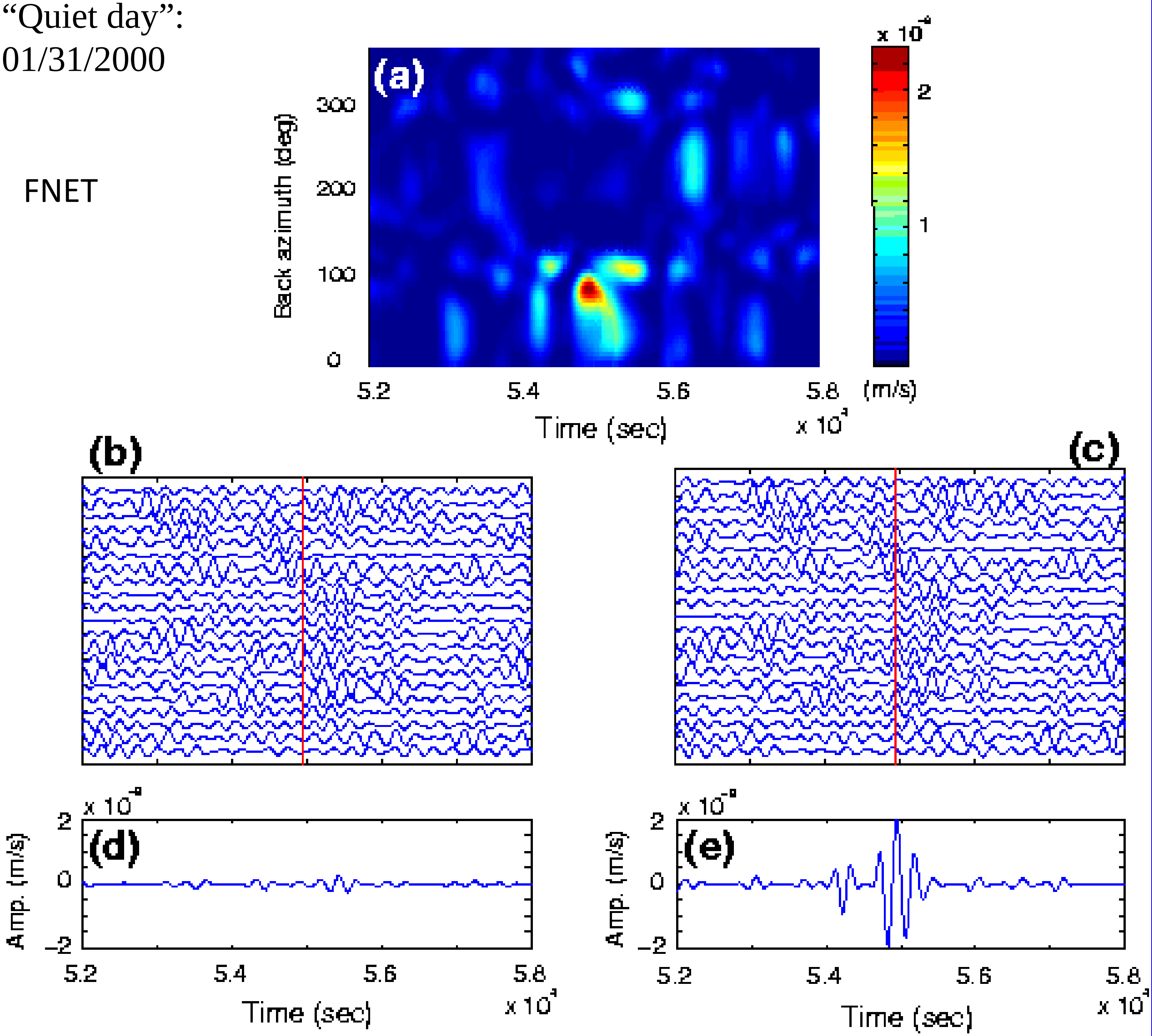
01/02/2000
Mw 5.7
Δ = 74.17°



T = 240 s

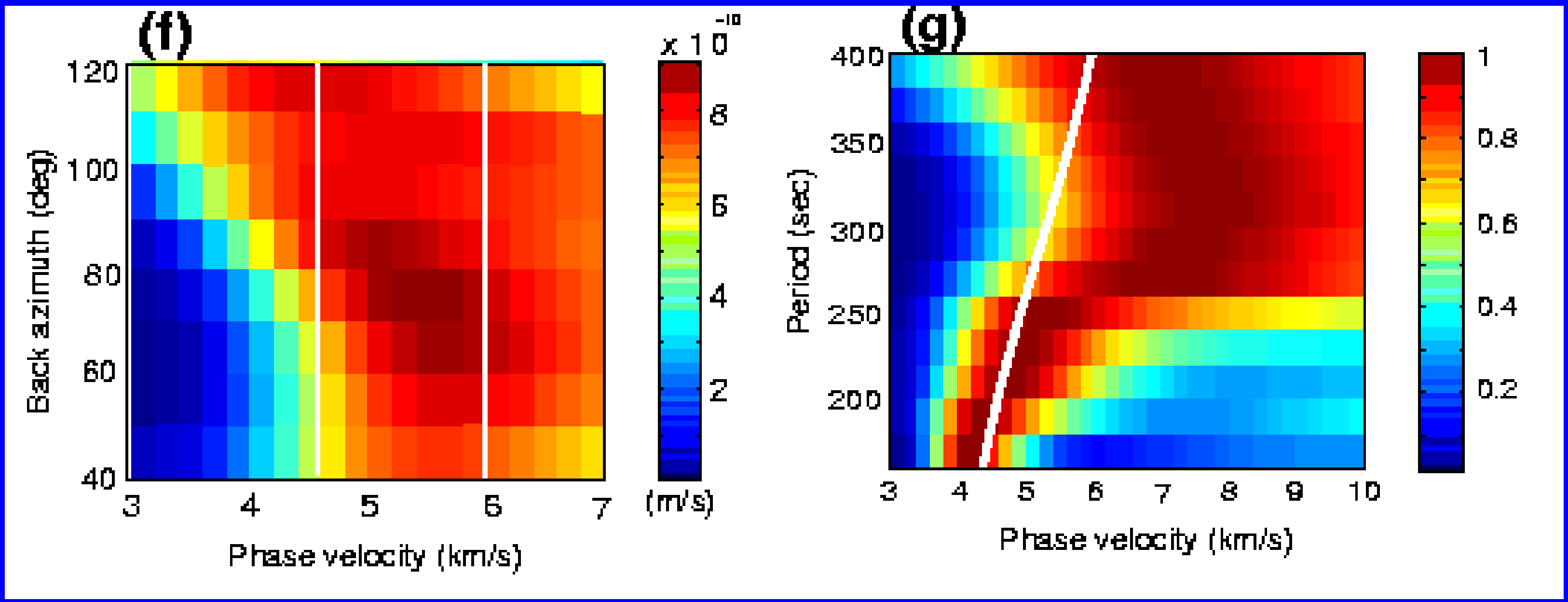
“Quiet day”:
01/31/2000

FNET



F-NET: search for maximum stack amplitude

Day 2000.031 time interval: 54,500-55,500 sec



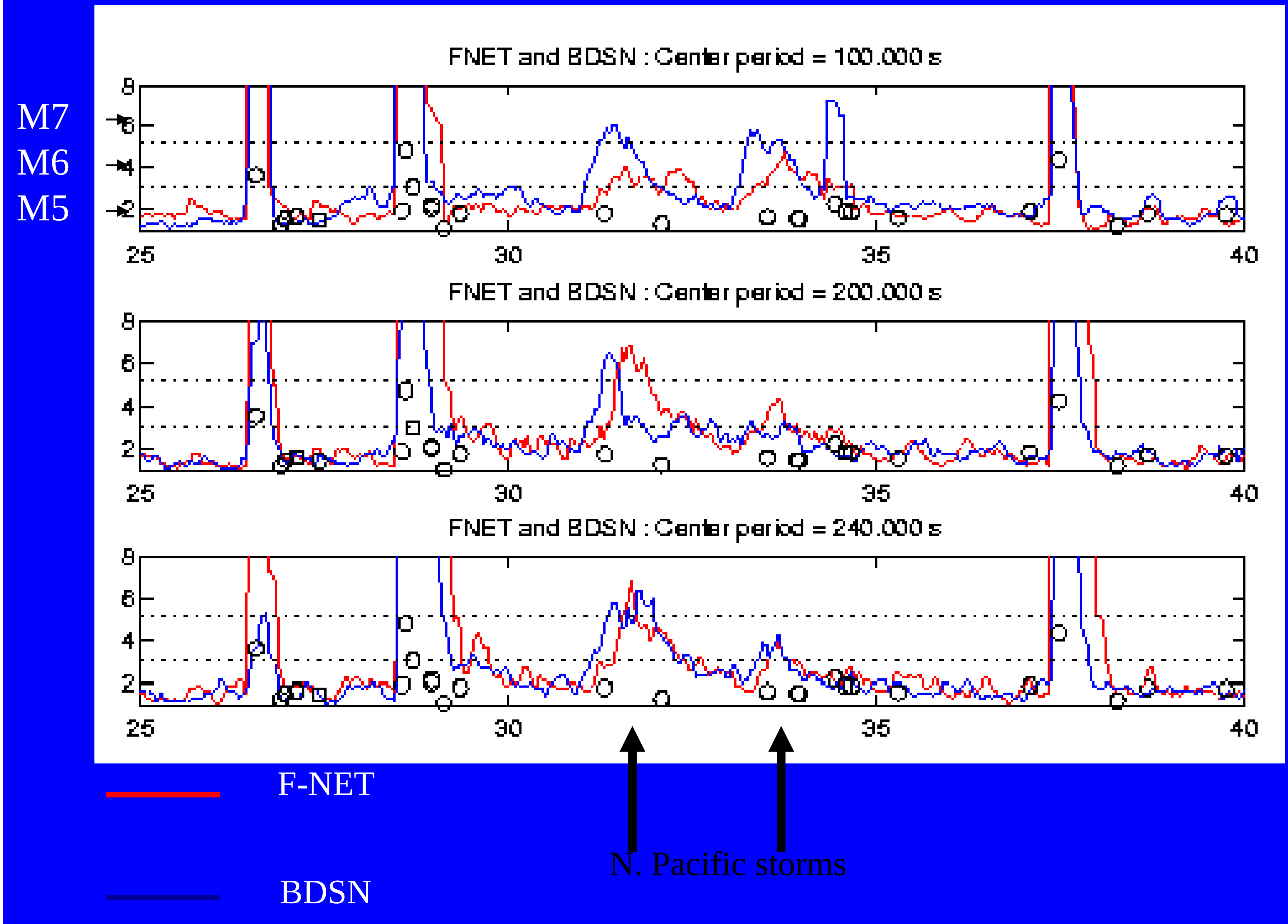
Back-Azimuth/
phase velocity

Period/phase velocity

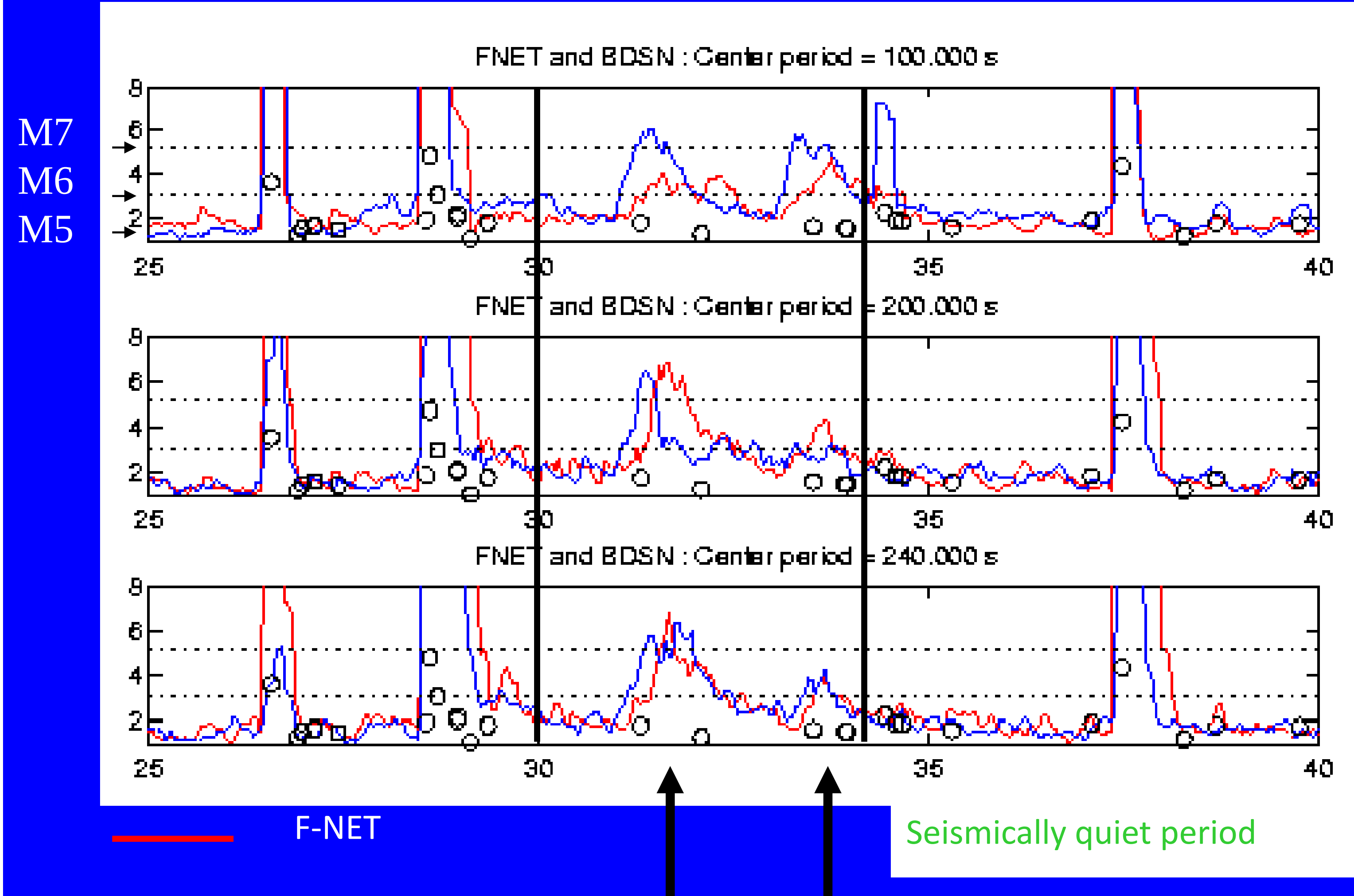
PREM model

Rhie and Romanowicz, Nature, 2004

Jan. 2000: 6-hour moving averages - stacks at FNET and BDSN



Jan. 2000: 6-hour moving averages - stacks at FNET and BDSN



F-NET

BDSN

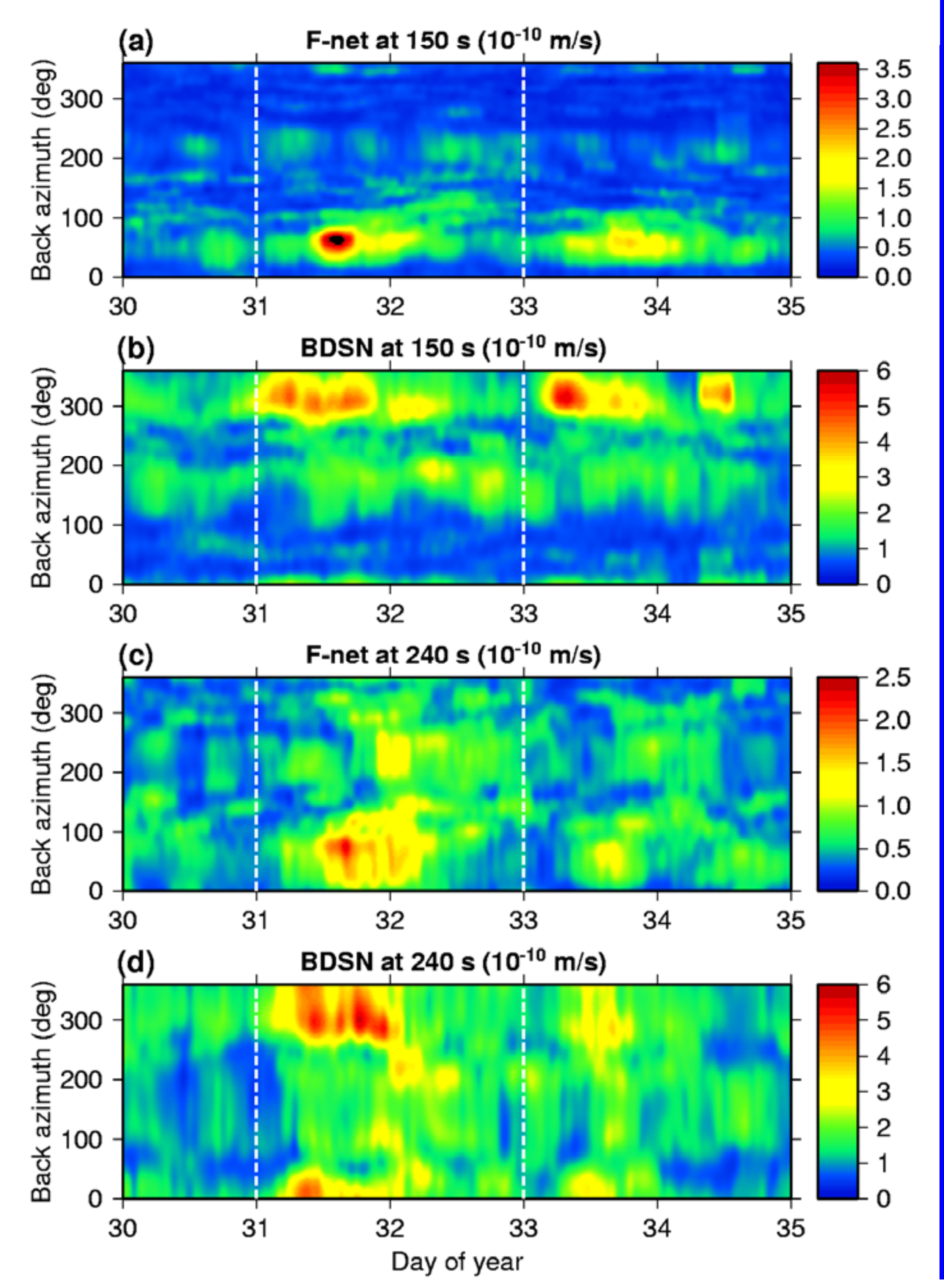
N. Pacific storms

Seismically quiet period

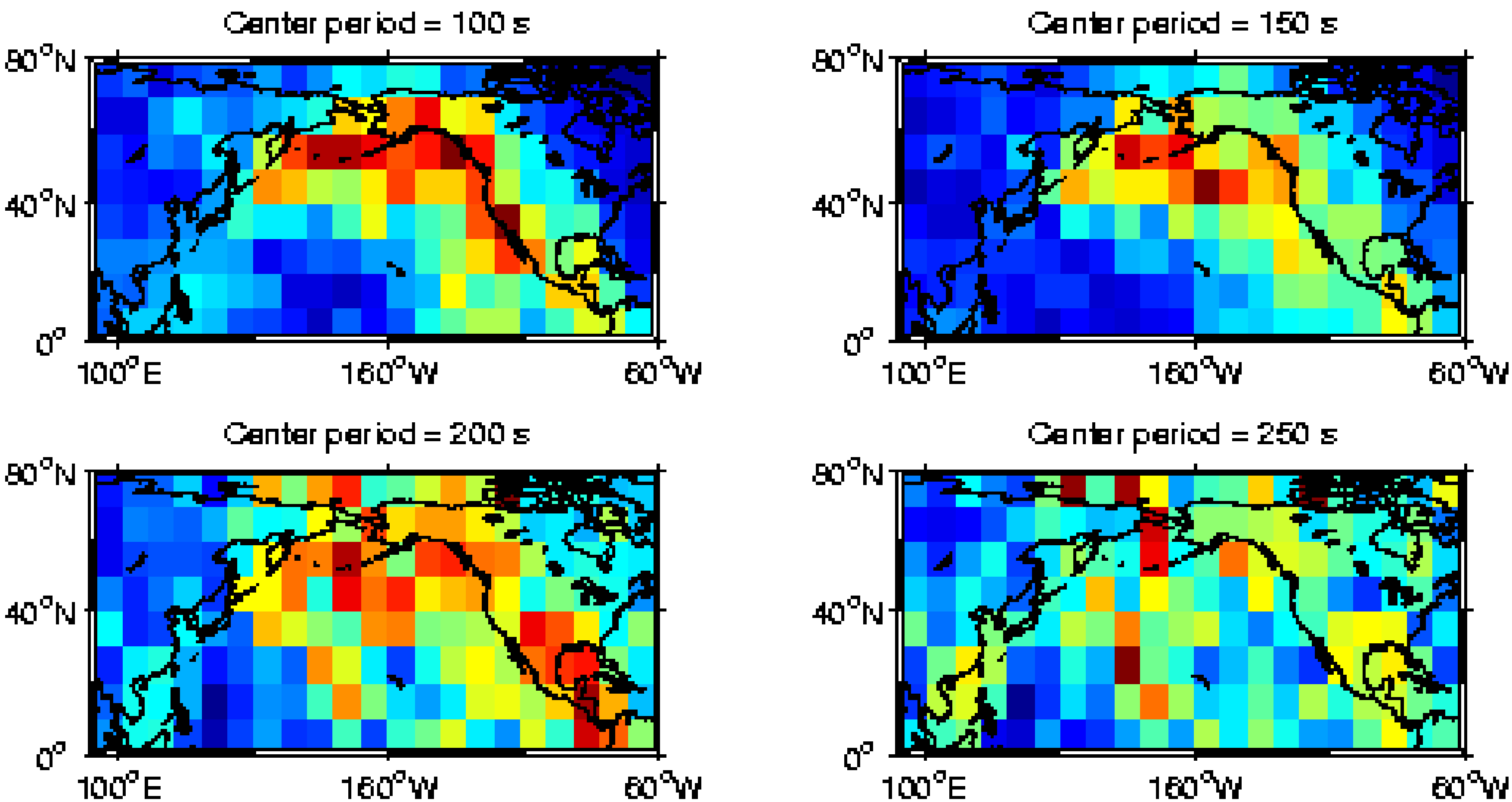
Rhie and Romanowicz, G-cubed, 2006

Days 2000/030.5 to 2000.034

3h running average
with 30mn shift



Grid search for source locations, maximizing stack amplitudes at F-NET, BDSN and 10 stations in Europe

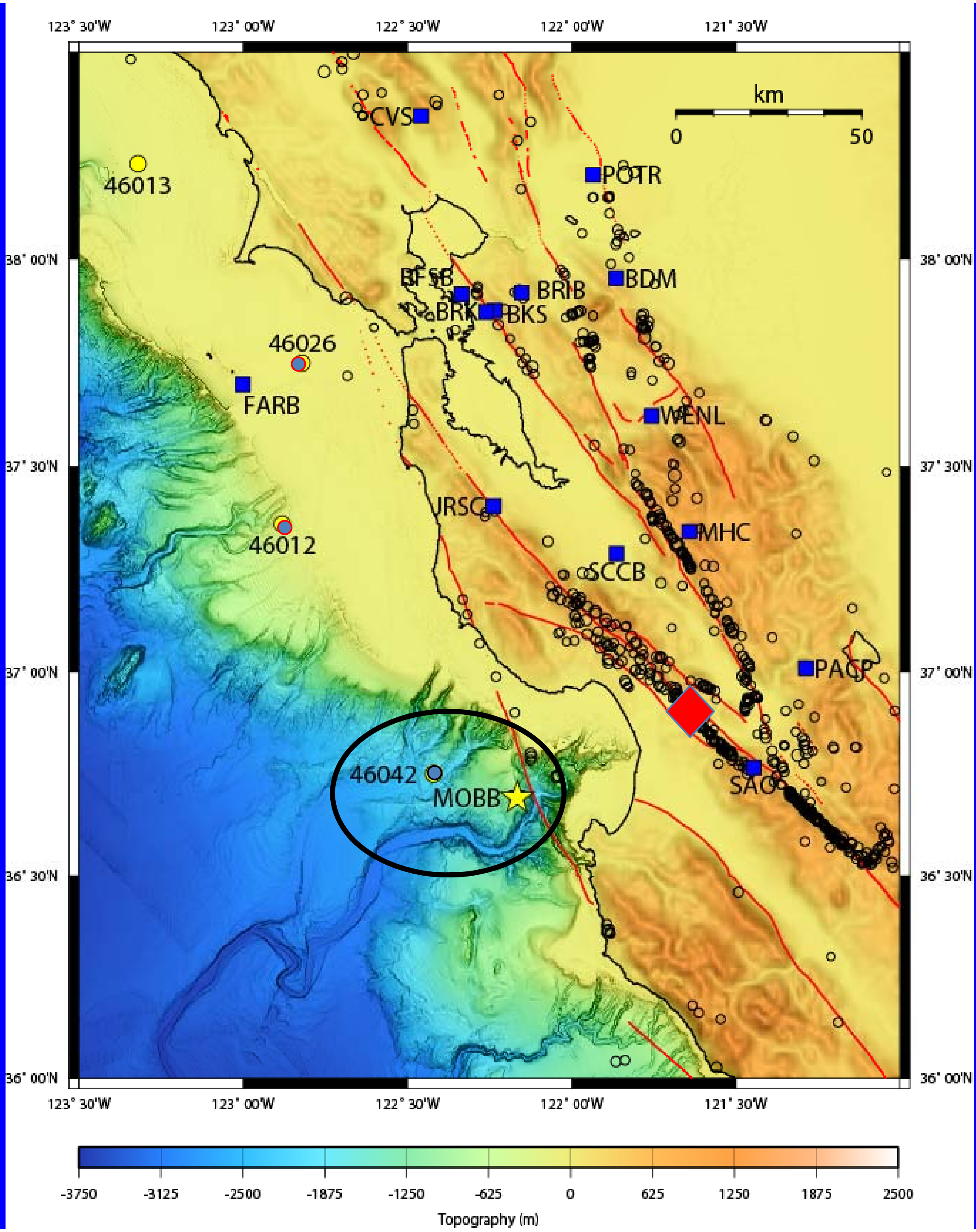


Time interval: 6 hours on 2000.031

With at least one large enough "quake" recorded

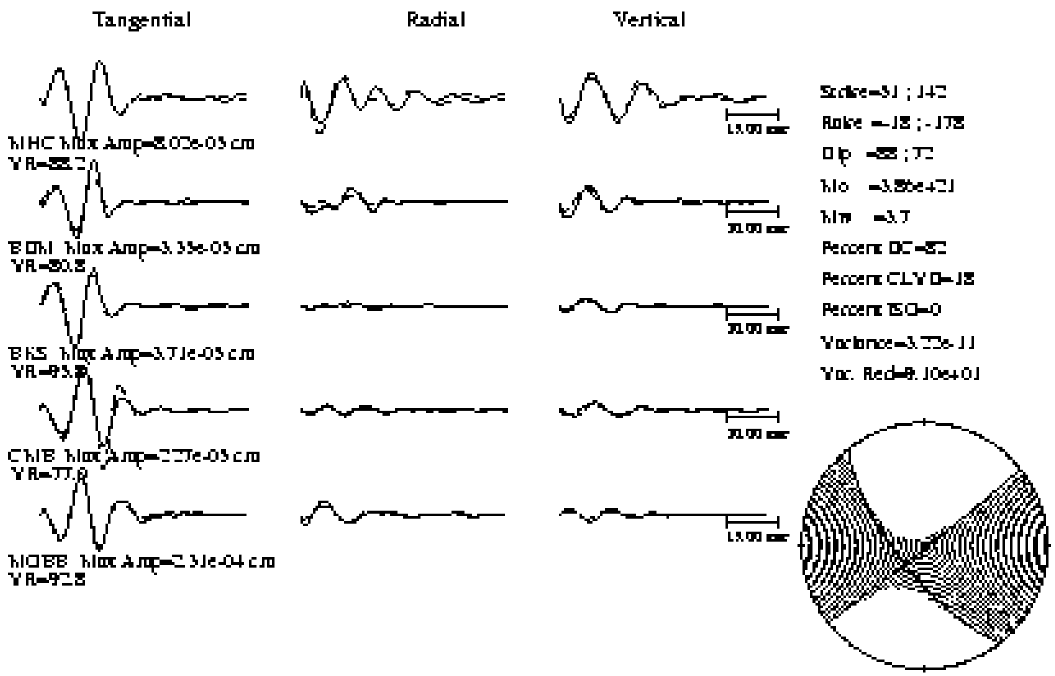
- Single station
- Two stations
- Regional array ($N \geq 3$)
- Global network ($N \geq 3$)

Monterey
bay
Ocean
Bottom
Broadband
seismic
station



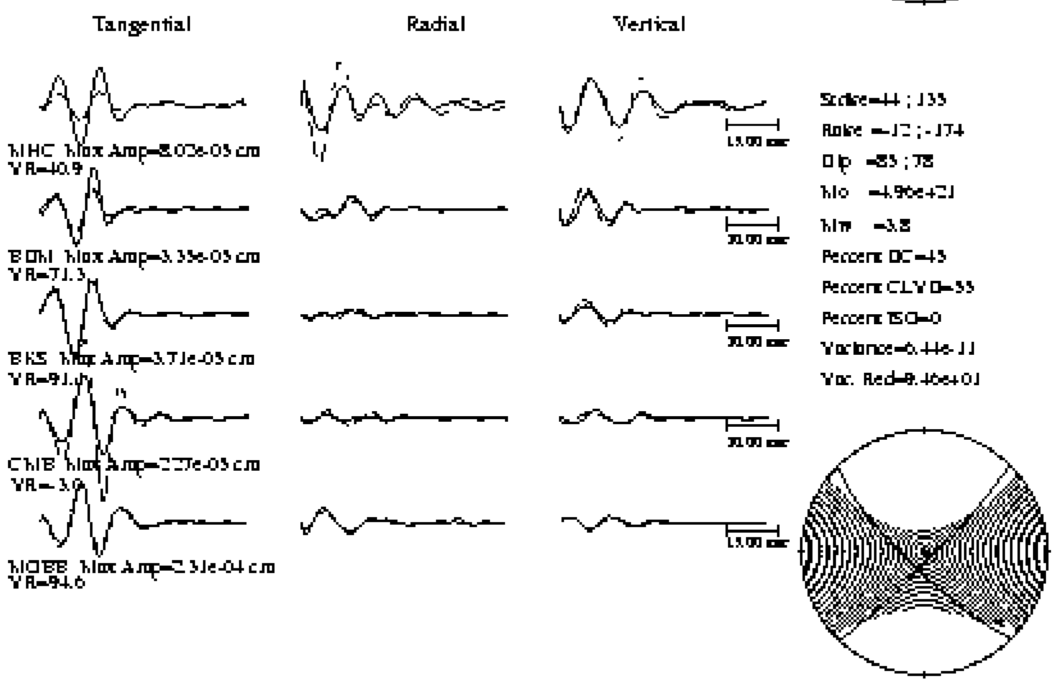
MBARI/
UCB

San Andreas
04/23/02
Mw 3.7
D = 53.4 km



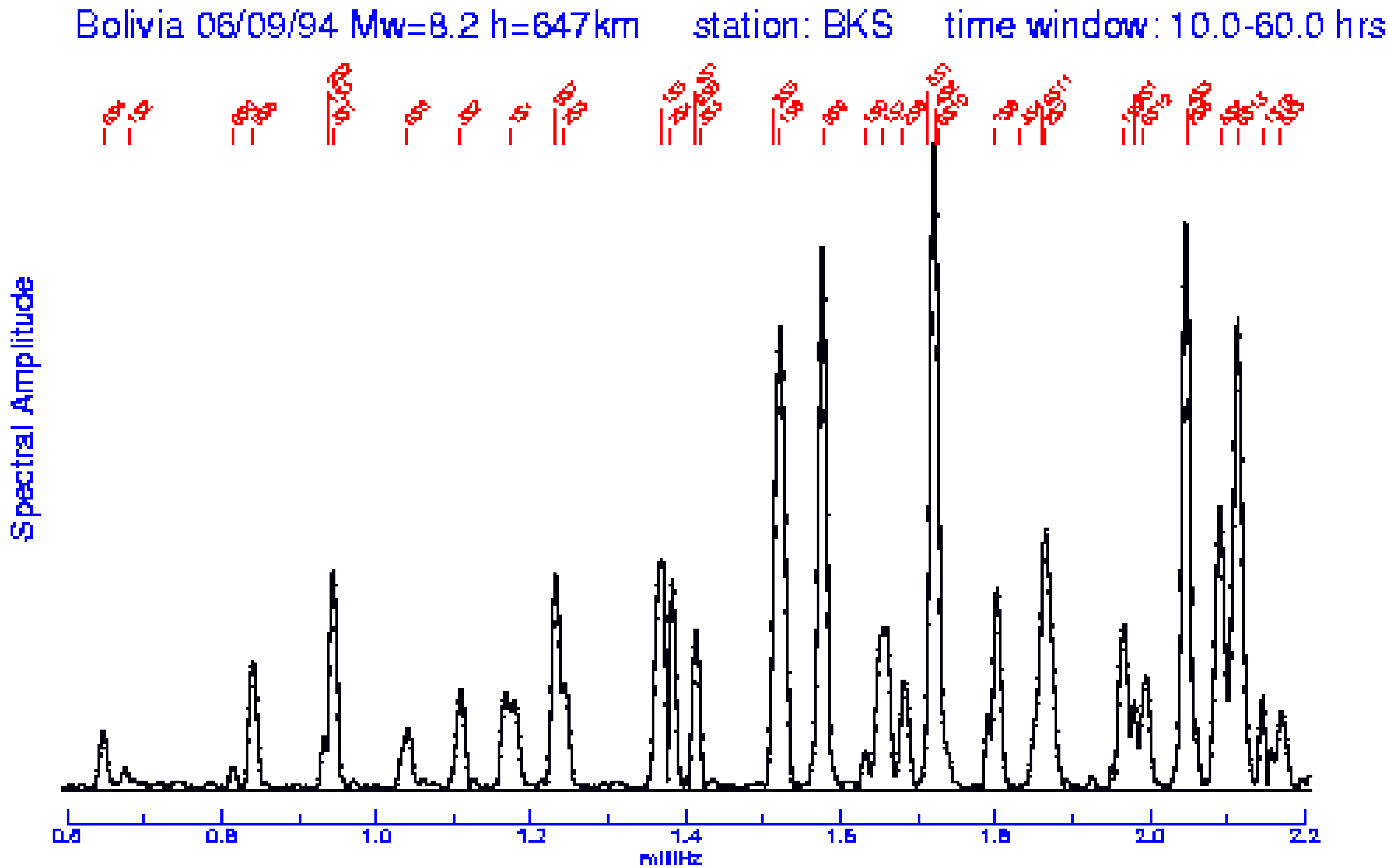
A)

Moment tensor
Solution with 5
BDSN stations



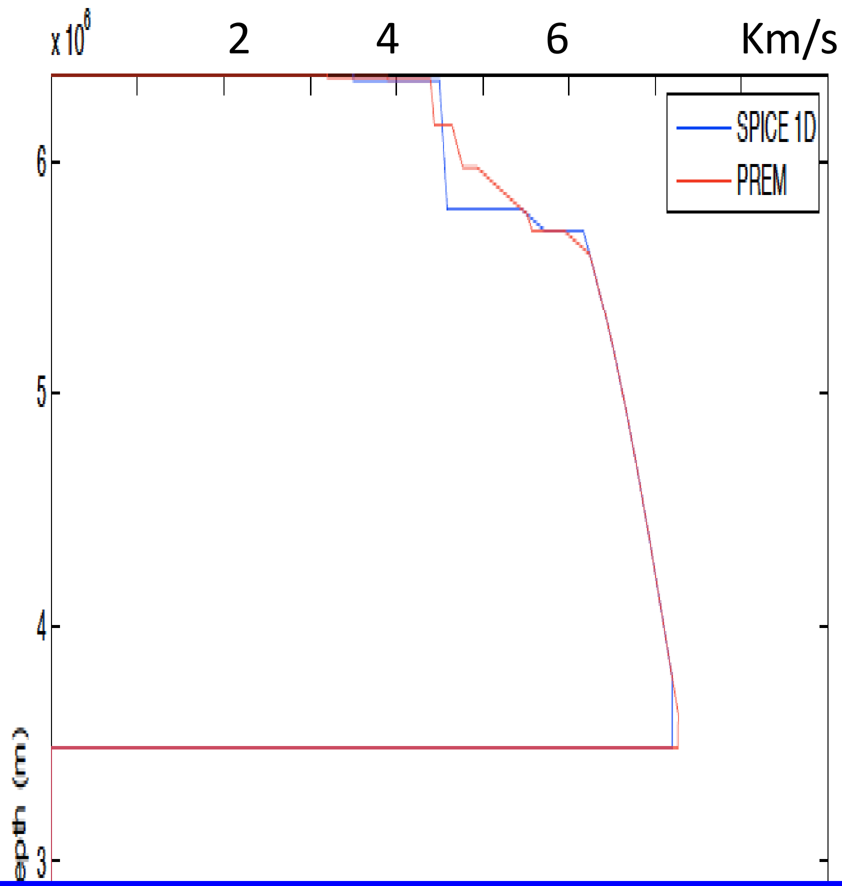
B)

Moment tensor
Solution using
Only MOBB

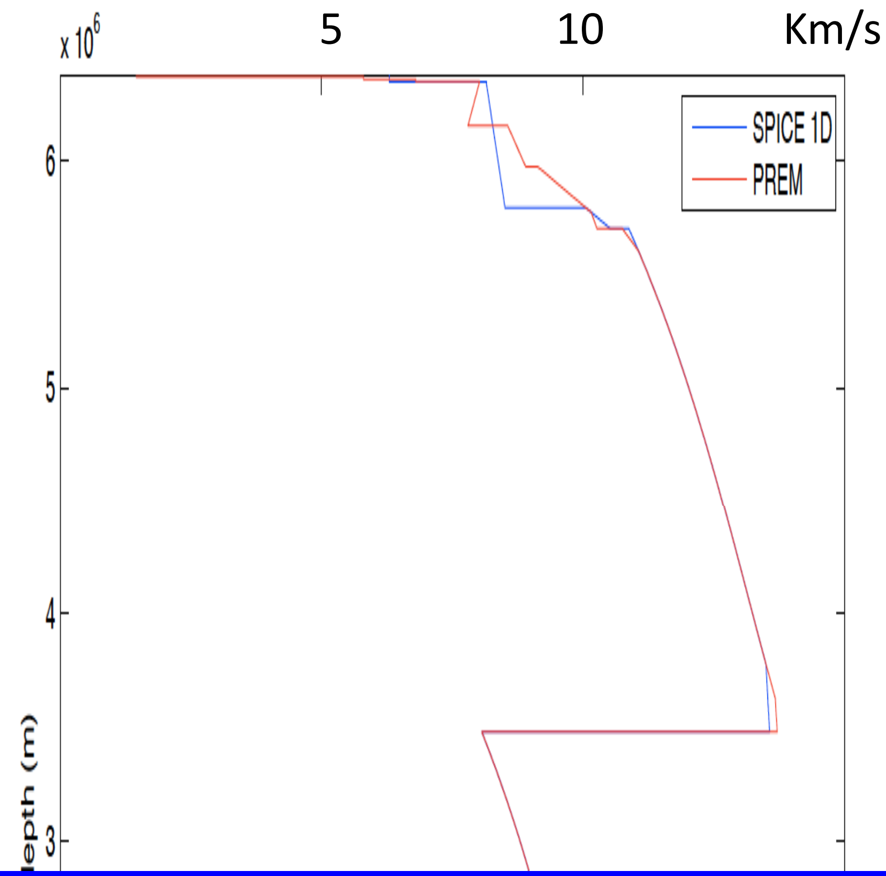


Bolivia 06/09/94 Mw=8.2 h=647km
station: BKS
time window: 10.0-60.0 hrs
Spectral Amplitude
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
milliHz

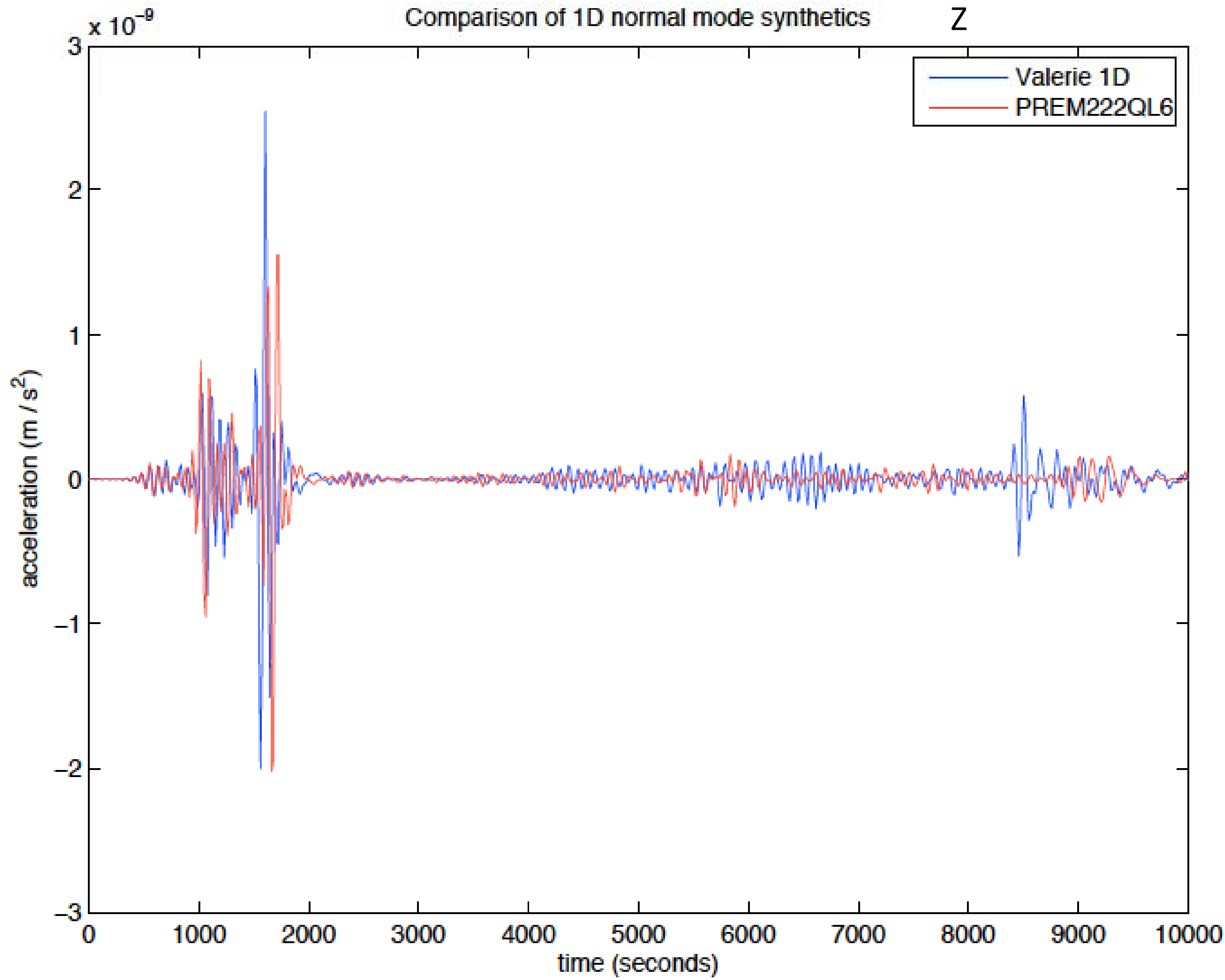
Waveform modelling techniques


x 10^6
2
4
6
Km/s
6
5
4
3
Depth (m)
SPICE 1D
PREM

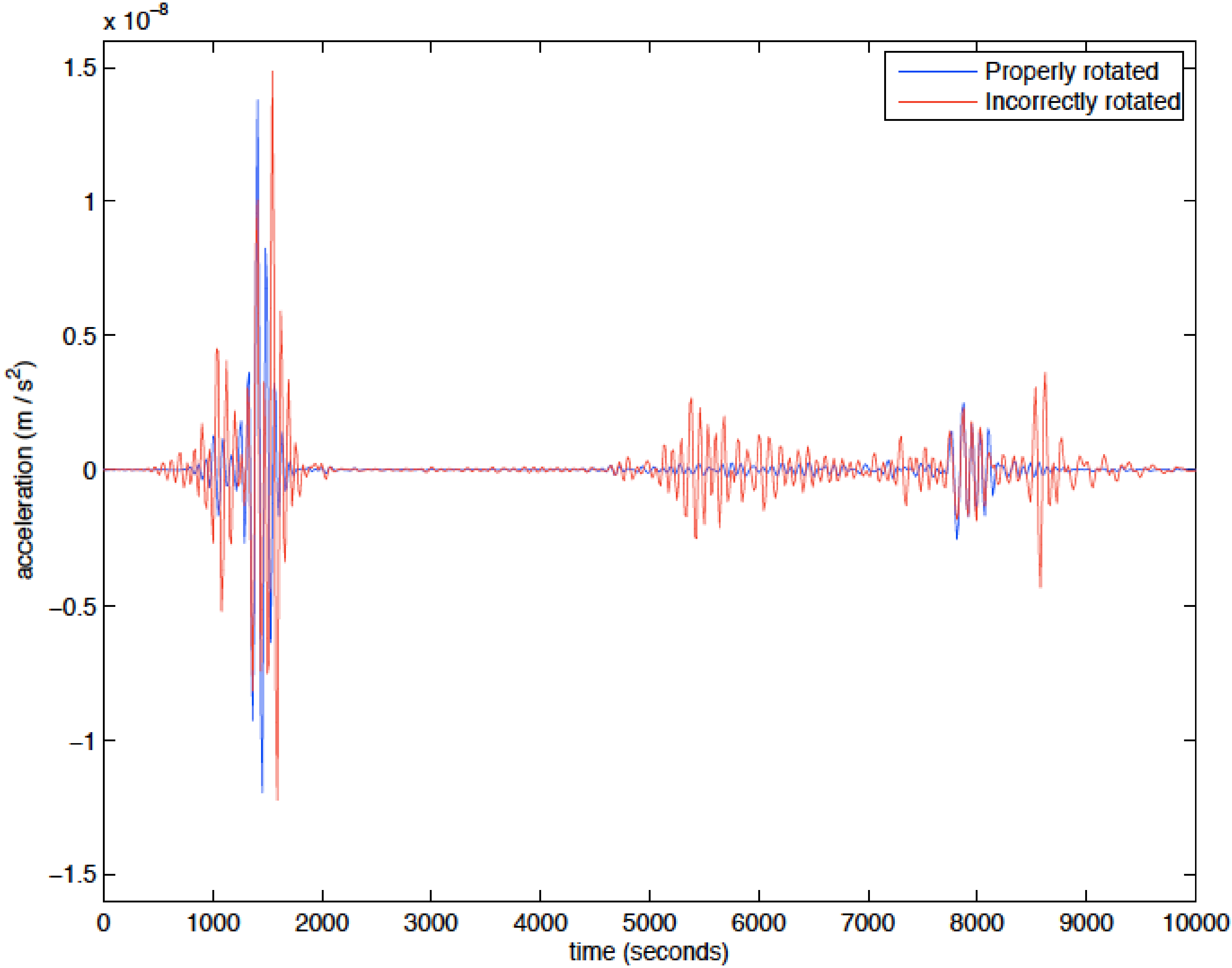
Vs


x 10^6
5
10
Km/s
6
5
4
3
Depth (m)
SPICE 1D
PREM

Vp



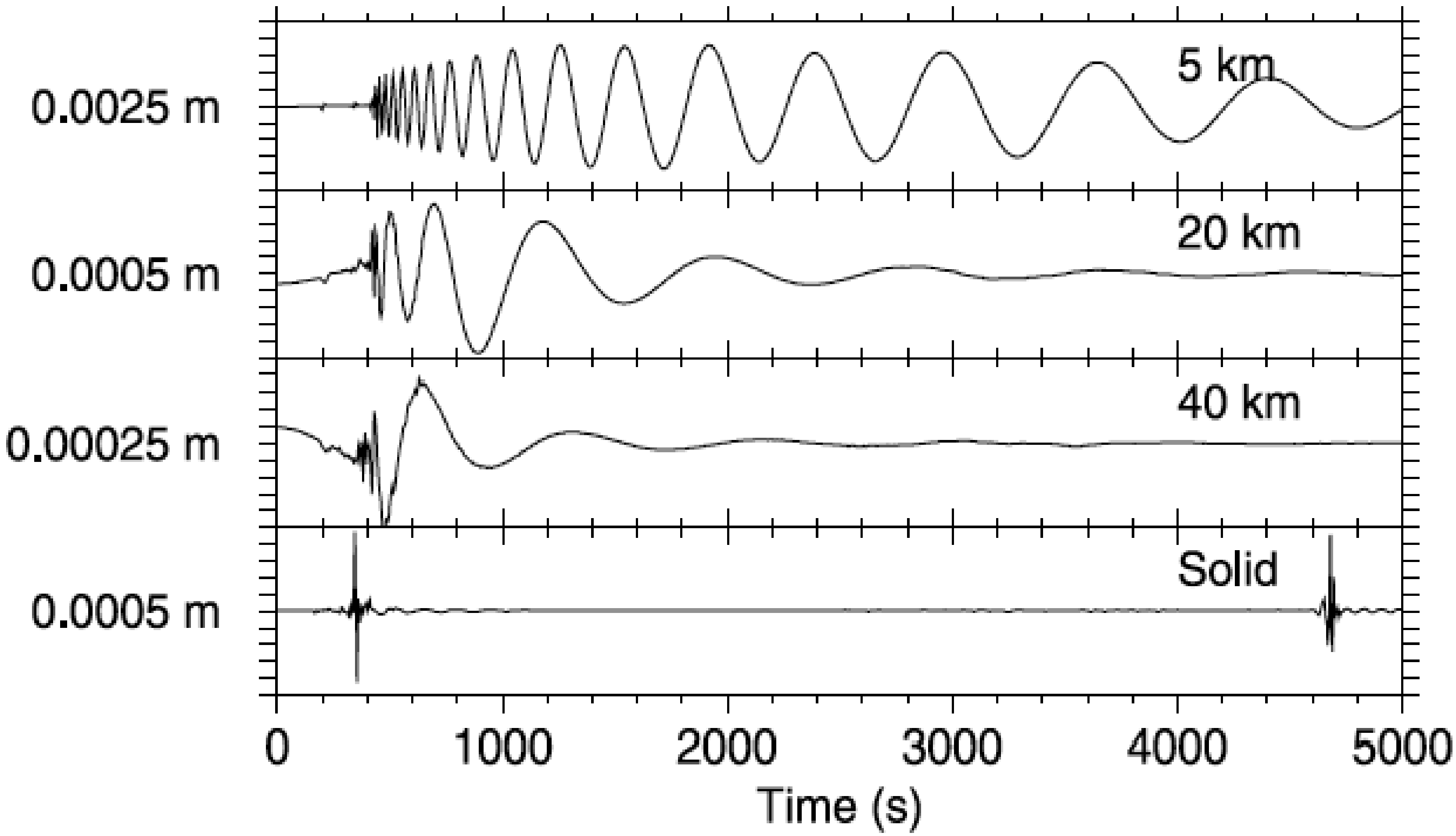
Comparison of 1D normal mode synthetics
Z
x 10^-9
Valerie 1D
PREM222QL6
acceleration (m / s^2)
time (seconds)
3
2
1
0
−1
−2
−3
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000


x 10^-8
1.5
1
0.5
0
−0.5
−1
−1.5
acceleration (m / s^2)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
time (seconds)
Properly rotated
Incorrectly rotated

Synthetic seismograms on Europa as a function of ice shell thickness

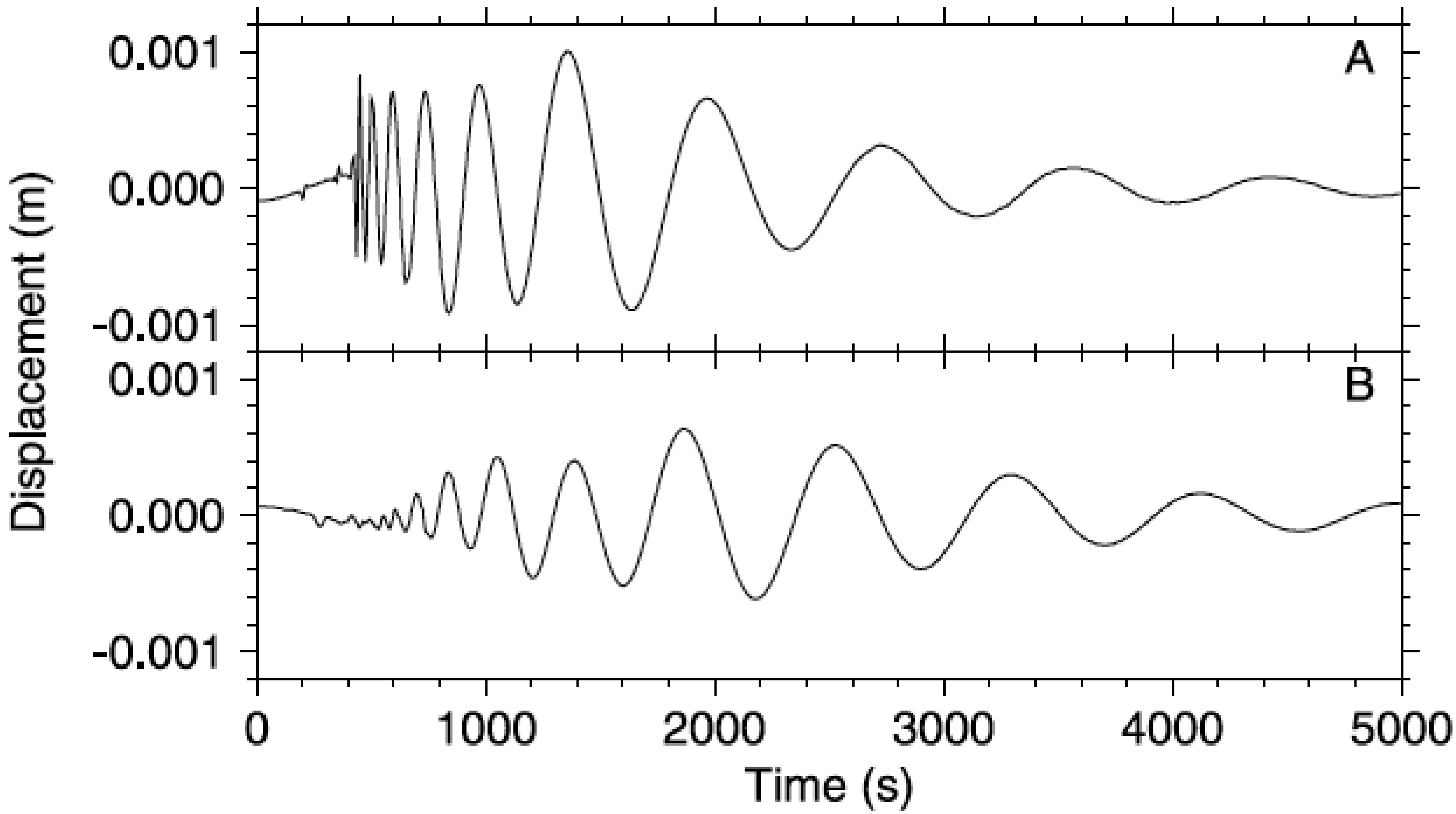
Mw =5.0 normal fault distance 20 deg –depth = 300m

Δ = 680 km

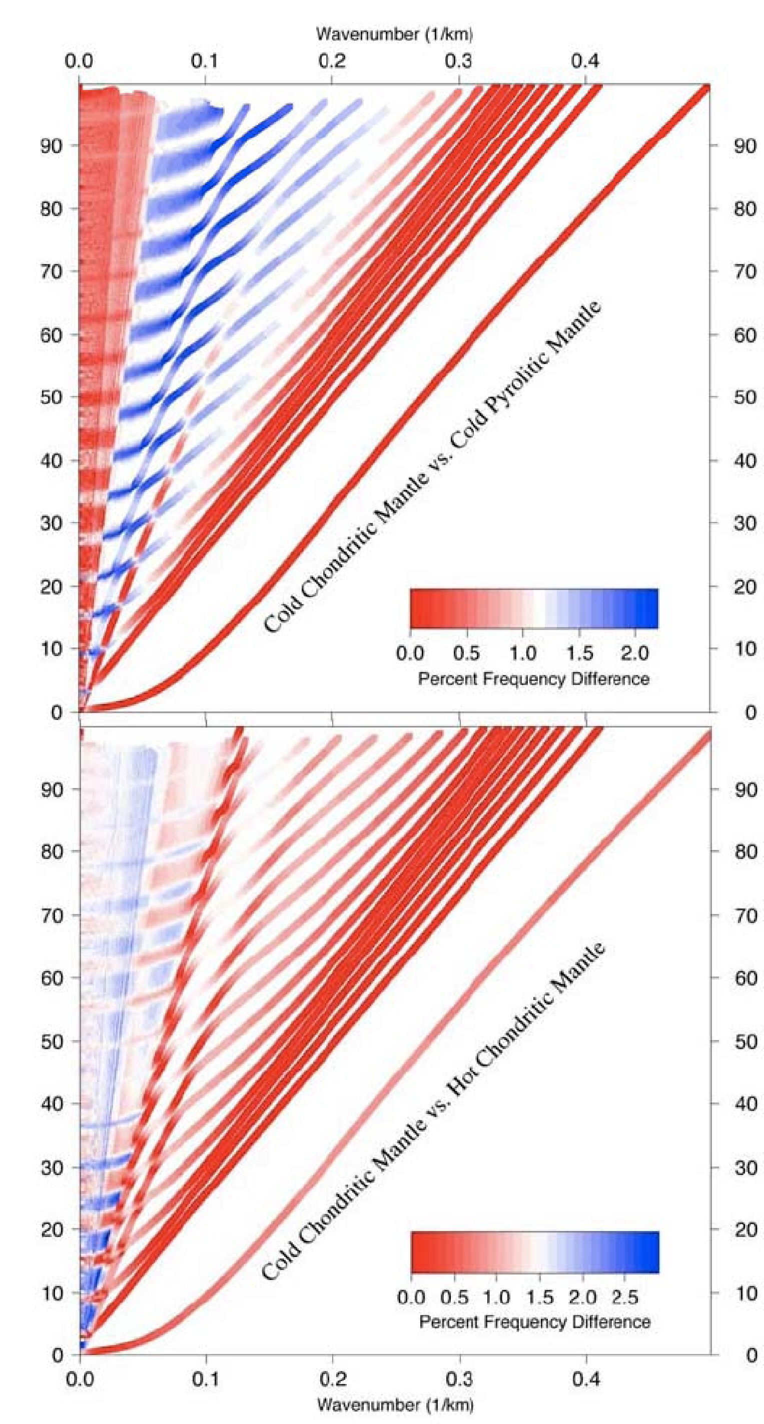


Panning et al., 2006

High versus low attenuation



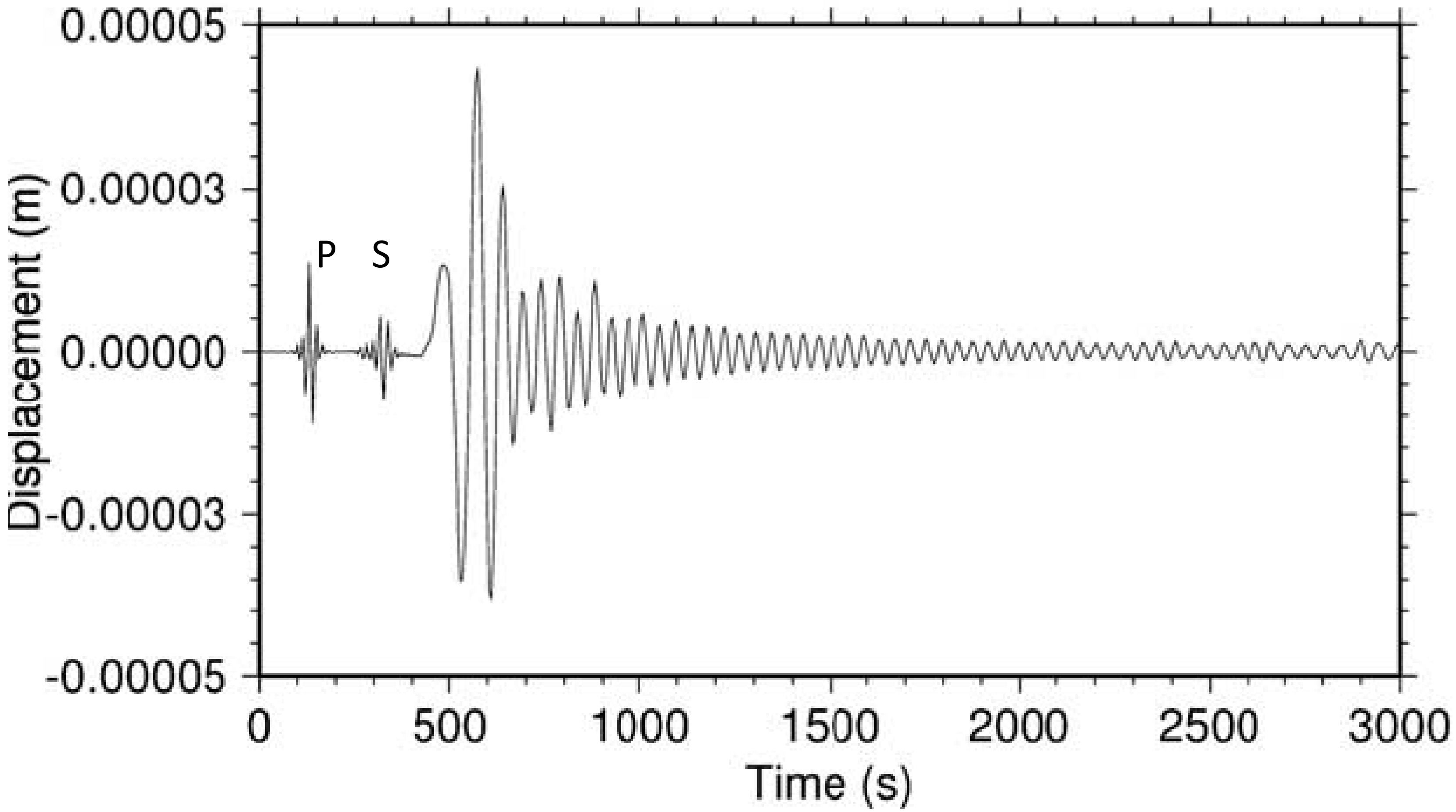
Panning et al., 2006



Panning et al., 2006

Observation from orbiter: Moving source analysis

Observation point starts 410 km east of the source at the event origin time and moves North with an apparent surface velocity of 1.4 km/s calculated in the high Q 5 km thick ice shell model

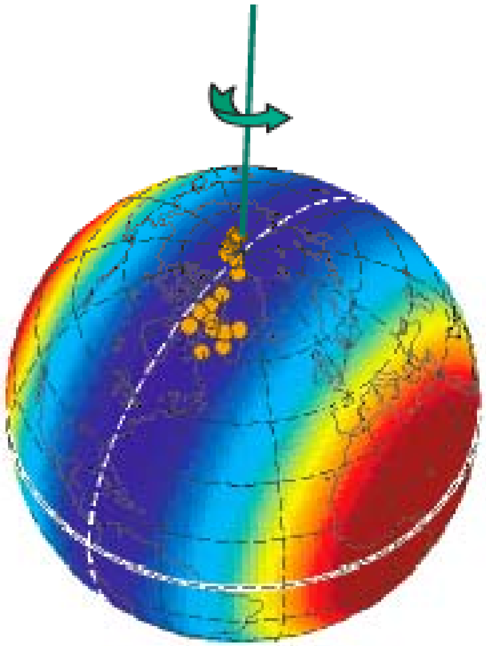


Panning et al., 2006

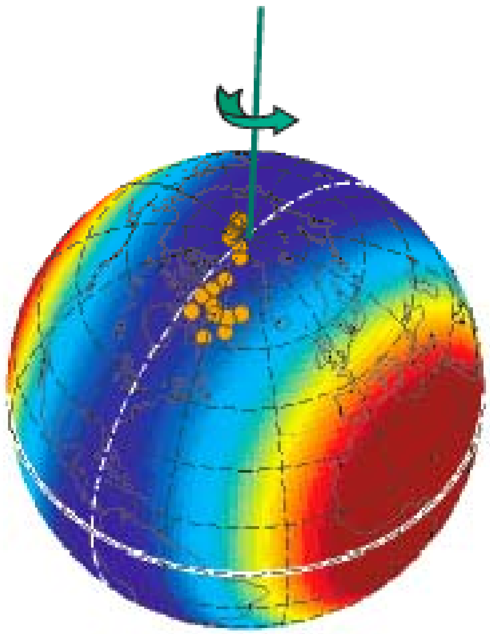
Several stations: lateral heterogeneity

"Degree 2" structure

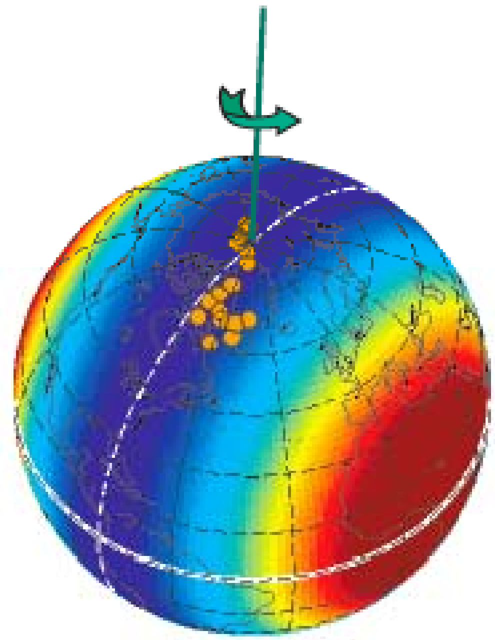
S362ANI



SAW24B16



S20RTS



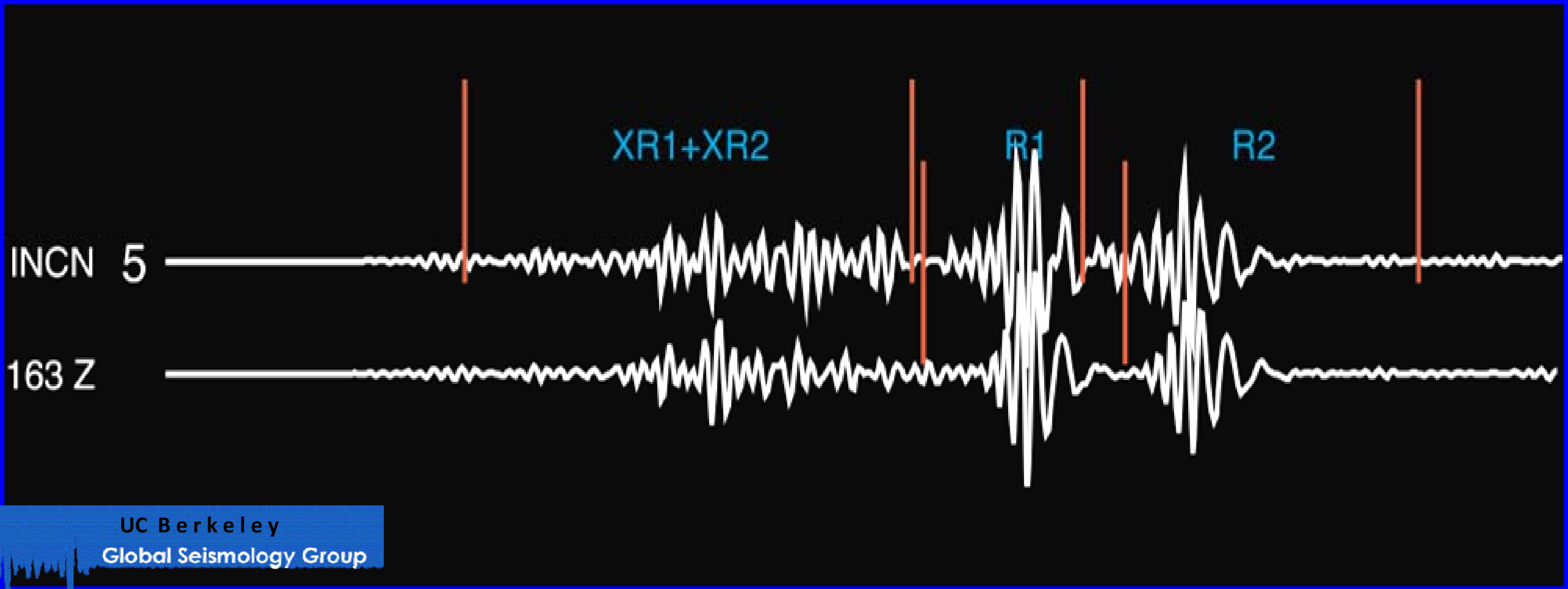
Dziewonski et al., submitted

Full Waveform Tomography

- Long period (30s-400s) 3- component seismic waveforms

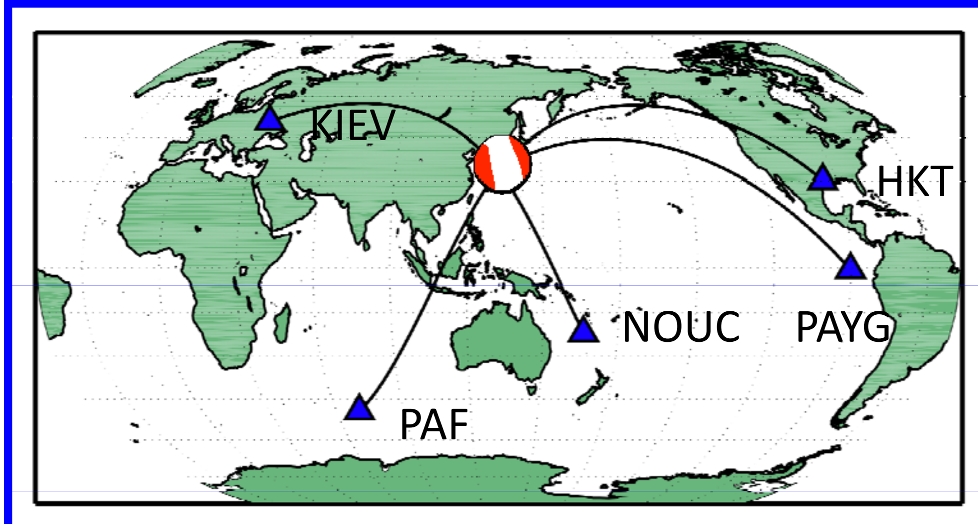
- Subdivided into wavepackets and compared in time domain to synthetics (mode asymptotics-→ SEM).

- $u(\underline{x},t) = G(m)$ → $du = A\, dm$
  - $A = \partial u/\partial m$ contains Fréchet derivatives of G



UC Berkeley
Global Seismology Group

Vertical Component Fits

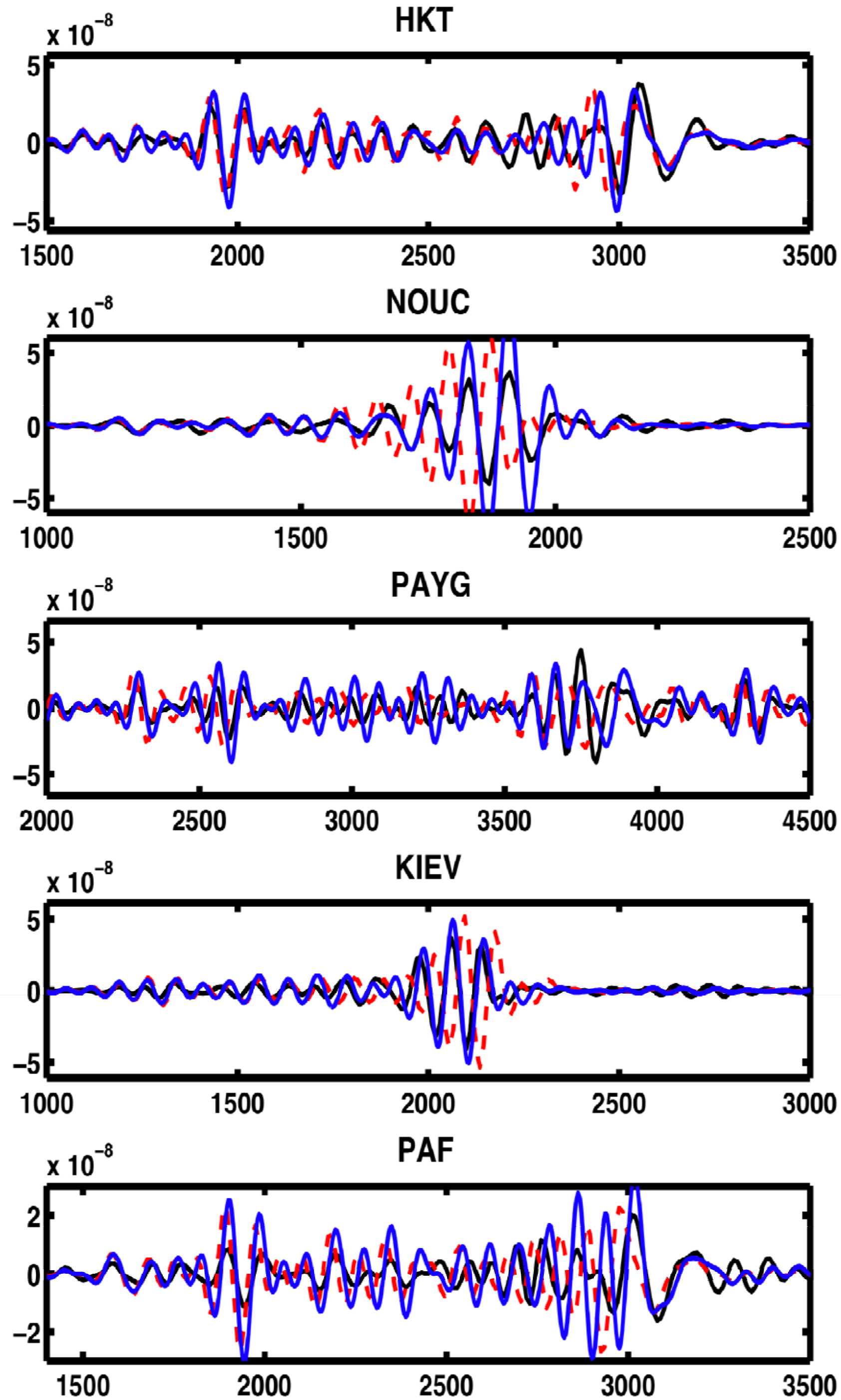


Starting Model

3rd iteration Model

Data

Courtesy of Ved Lekic, BSL



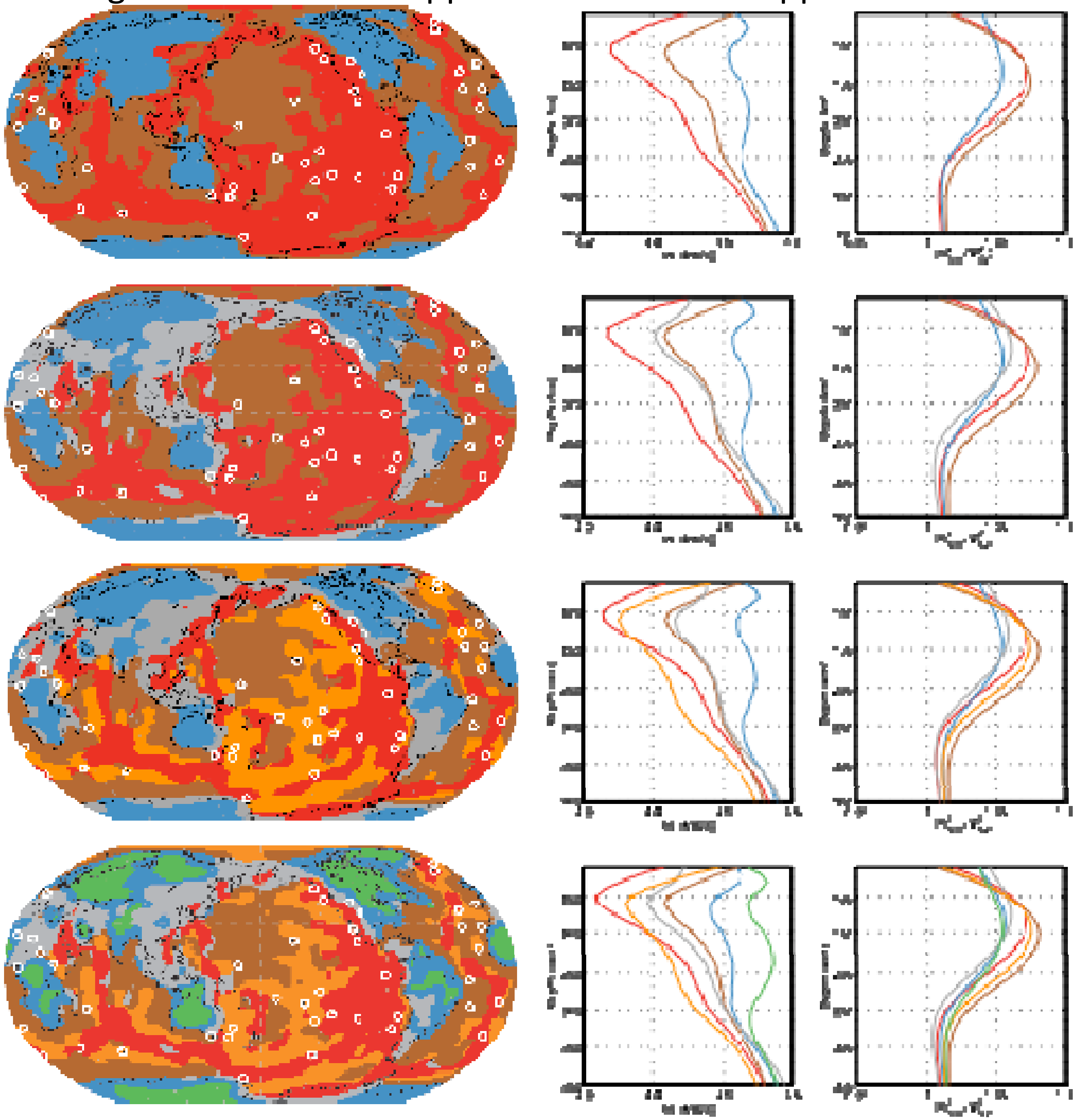
K-means clustering with N clusters – applied to SEM based upper mantle model

N=3

N=4

N=5

N=6



Lekic, 2009 Thesis