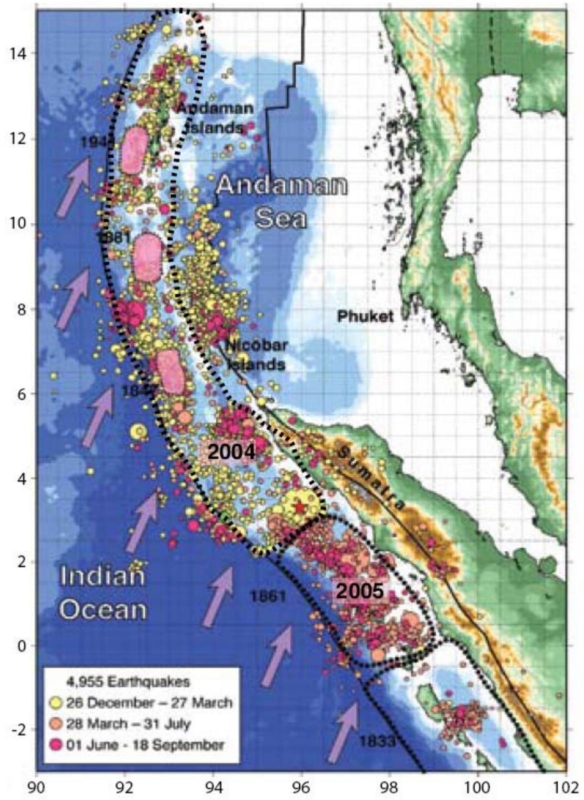
What are the key issues in seismology?

What scientific problems rely on the analysis of seismic waves?

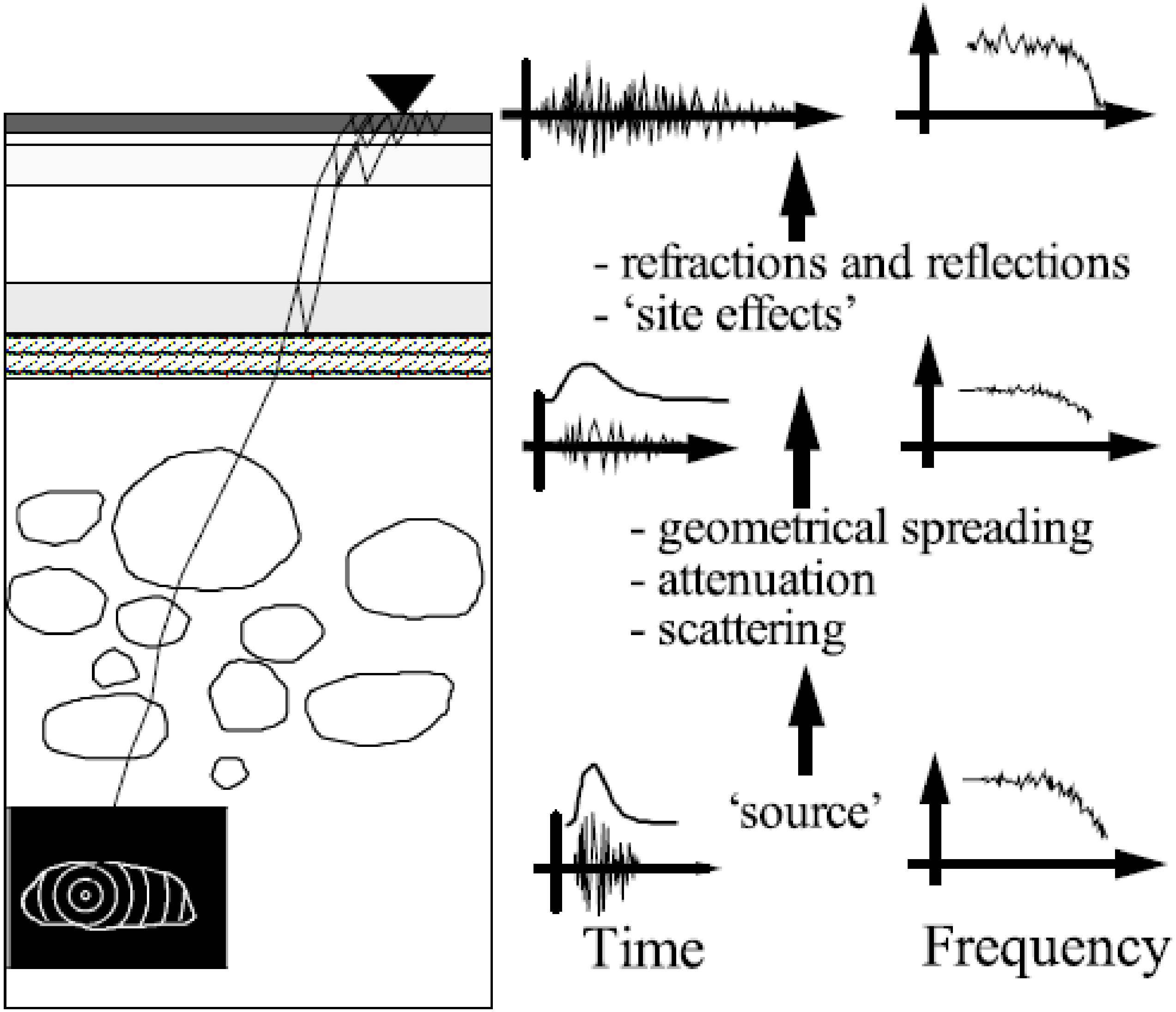
What methodologies are used?

What is the role of computations and data analysis?



Lay, T., ed. 2009. *Seismological Grand Challenges in Understanding Earth's Dynamic Systems*. Report to the National Science Foundation, IRIS Consortium, 76 pp.

Waves, Waves, Waves



… and seismometer recordings ….

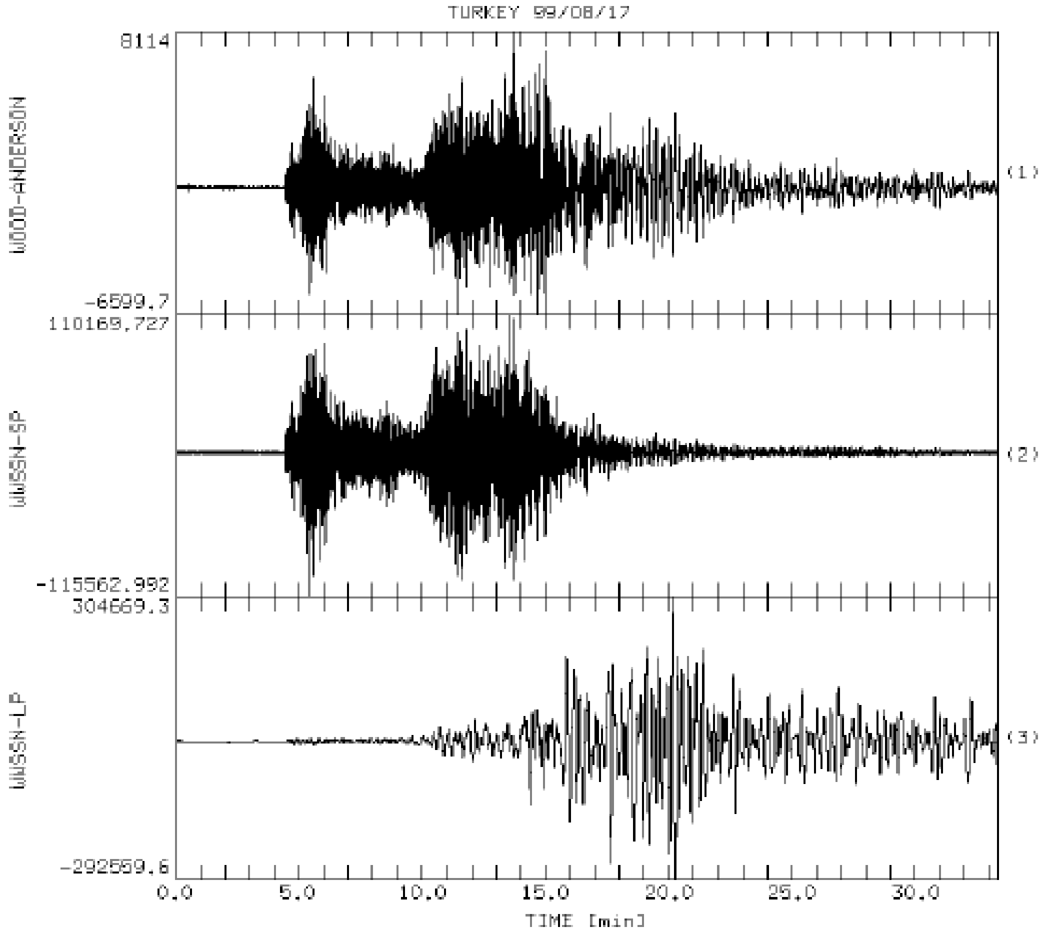


Fig. 1.2 Vertical component record of the Izmit earthquake in Turkey (1999/08/17) recorded at station MA13 of the University of Potsdam during a field experiment in Northern Norway. Shown from top to bottom are the vertical component records for a: Wood-Anderson, a WWSSN SP, and a WWSSN LP instrument simulation.

Seismology – Schematically

Seismic Source

Ruptures, crack propagation, physics of earthquakes, magnitude, faulting, seismic creep, radiation pattern, Earthquake precursors, aftershocks, fault planes, etc.

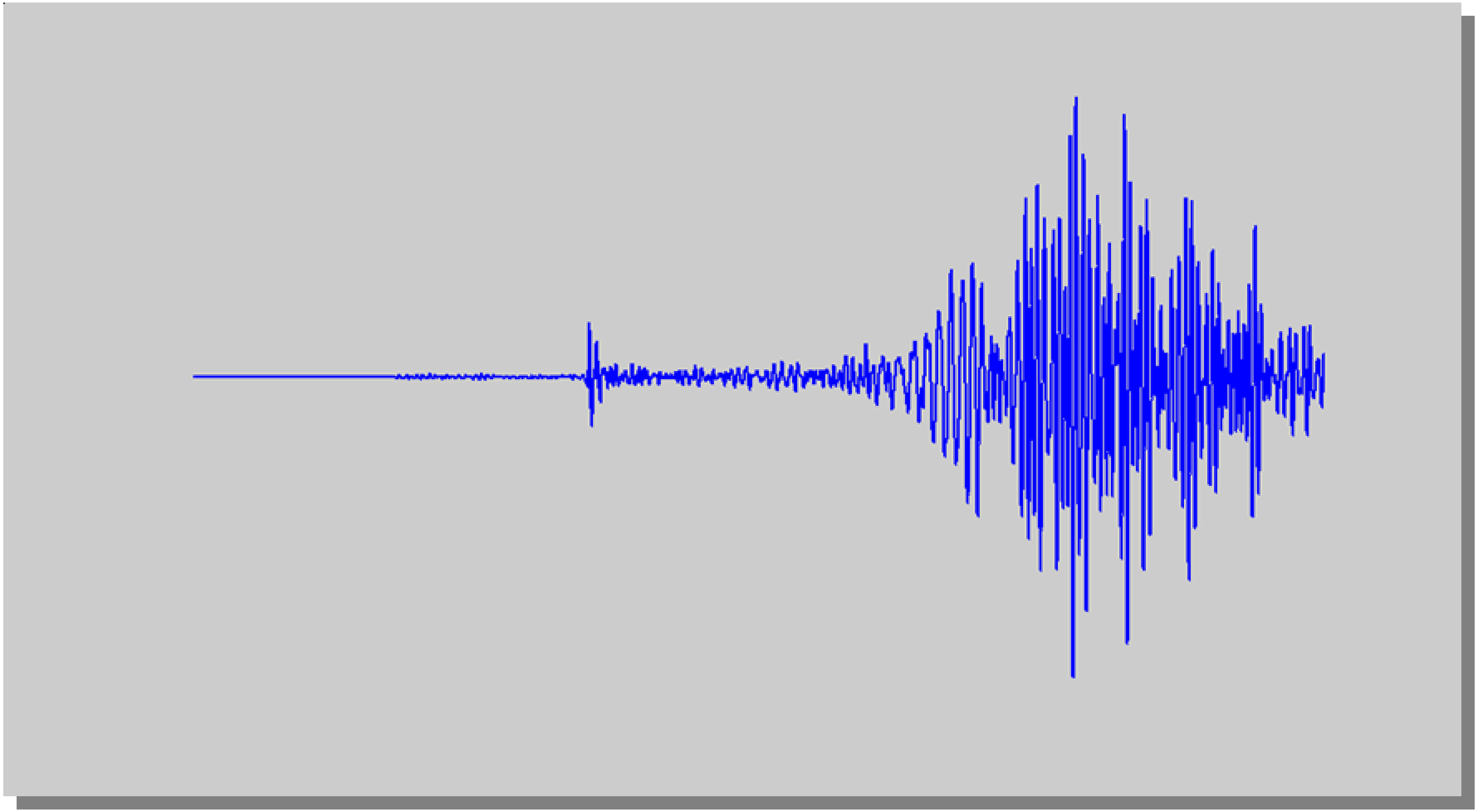
Seismometer

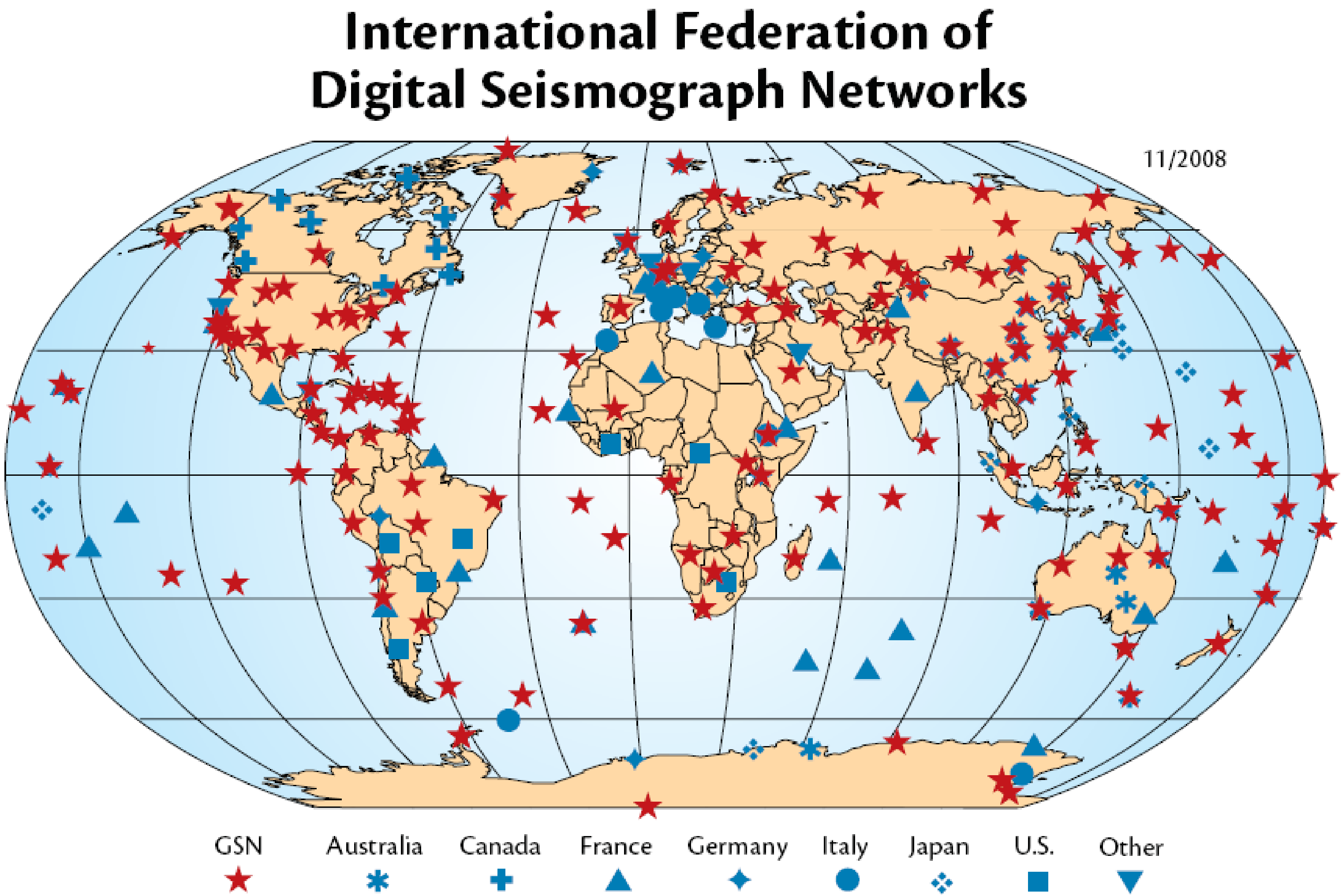
Filtering, (de)convolution, three components, spectrum, broadband, strong-motion, tilt, long-period, amplification, etc.

Propagation Effects

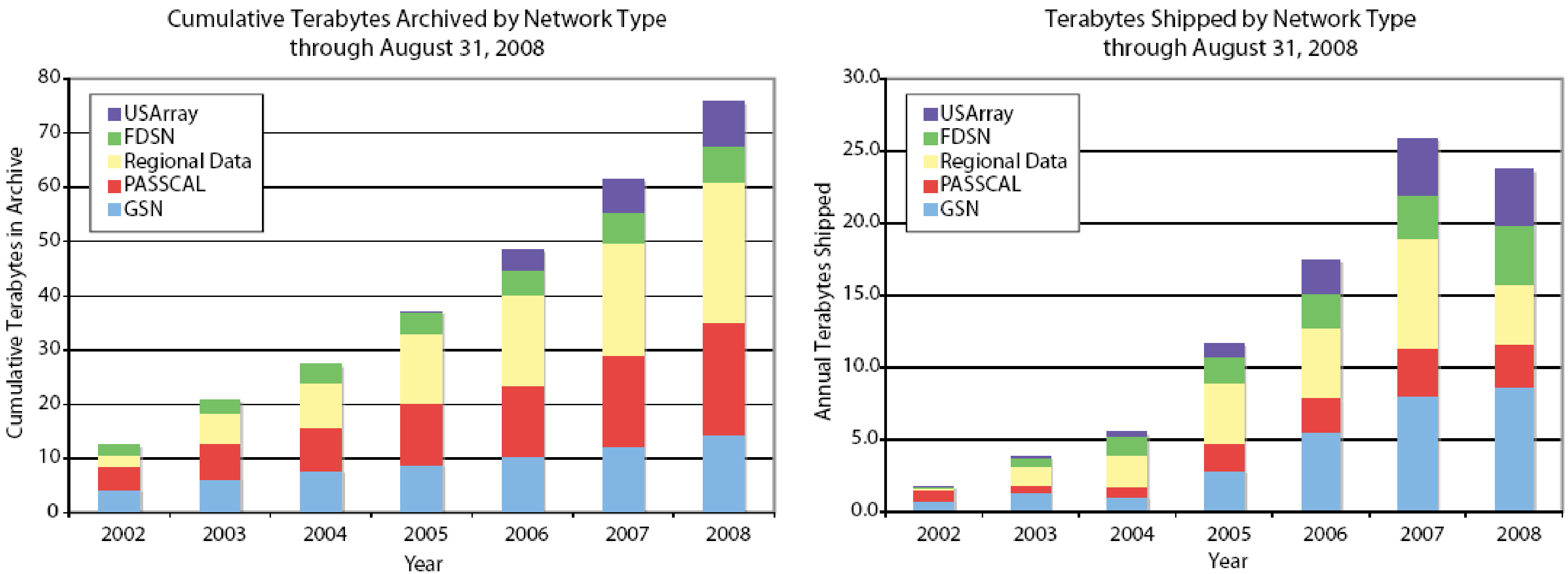
heterogeneities, scattering, attenuation, anisotropy, rays, body waves, surface waves, free oscillations, reflections, refractions, trapped waves, geometrical spreading, etc.

… and everything affects …



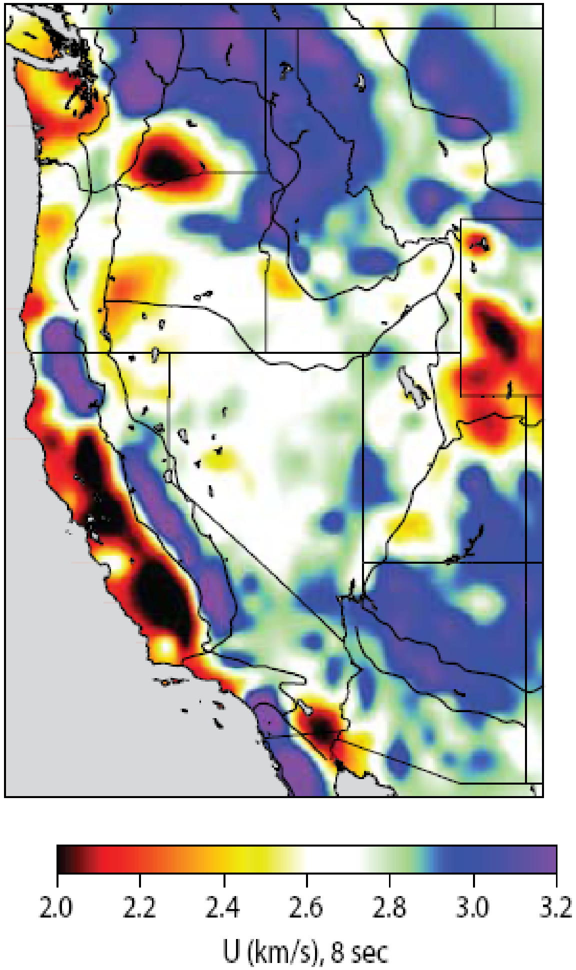

International Federation of
Digital Seismograph Networks
11/2008
GSN
Australia
Canada
France
Germany
Italy
Japan
U.S.
Other

Seismic Data Volumes



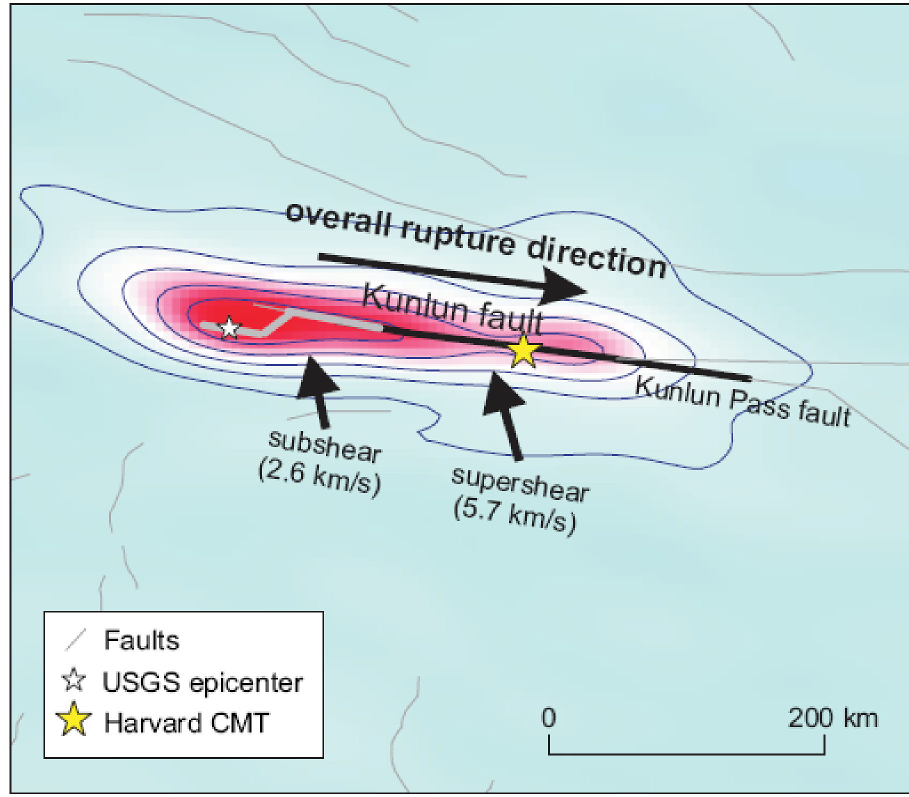
The cumulative volume of seismic data archived at the IRIS Data Management Center (left) for major seismic networks totals 81.3 terabytes as of August 2008. The annual number of terabytes shipped from the IRIS DMC (right) for the same seismic network types is twice as much data as new data arriving at the DMC, and will total more than 35 terabytes to end users in 2008. (Image courtesy of T. Ahern.)

A map showing variation of Rayleigh wave (a type of seismic surface wave) group velocity for 8 sec period vibrations derived from more than 60,000 measurements. By **cross correlating** up to three years of **continuous** data from 512 western U.S. stations, including the EarthScope USArray Transportable **Array** and regional **seismic networks**, inter-station propagation velocities for all available station pairs were recovered and **inverted** for regional velocity structure. Thick black lines define major tectonic province boundaries. (Image courtesy of M.P. Moschetti, M.H. Ritzwoller, and N.M. Shapiro.)



Earthquakes

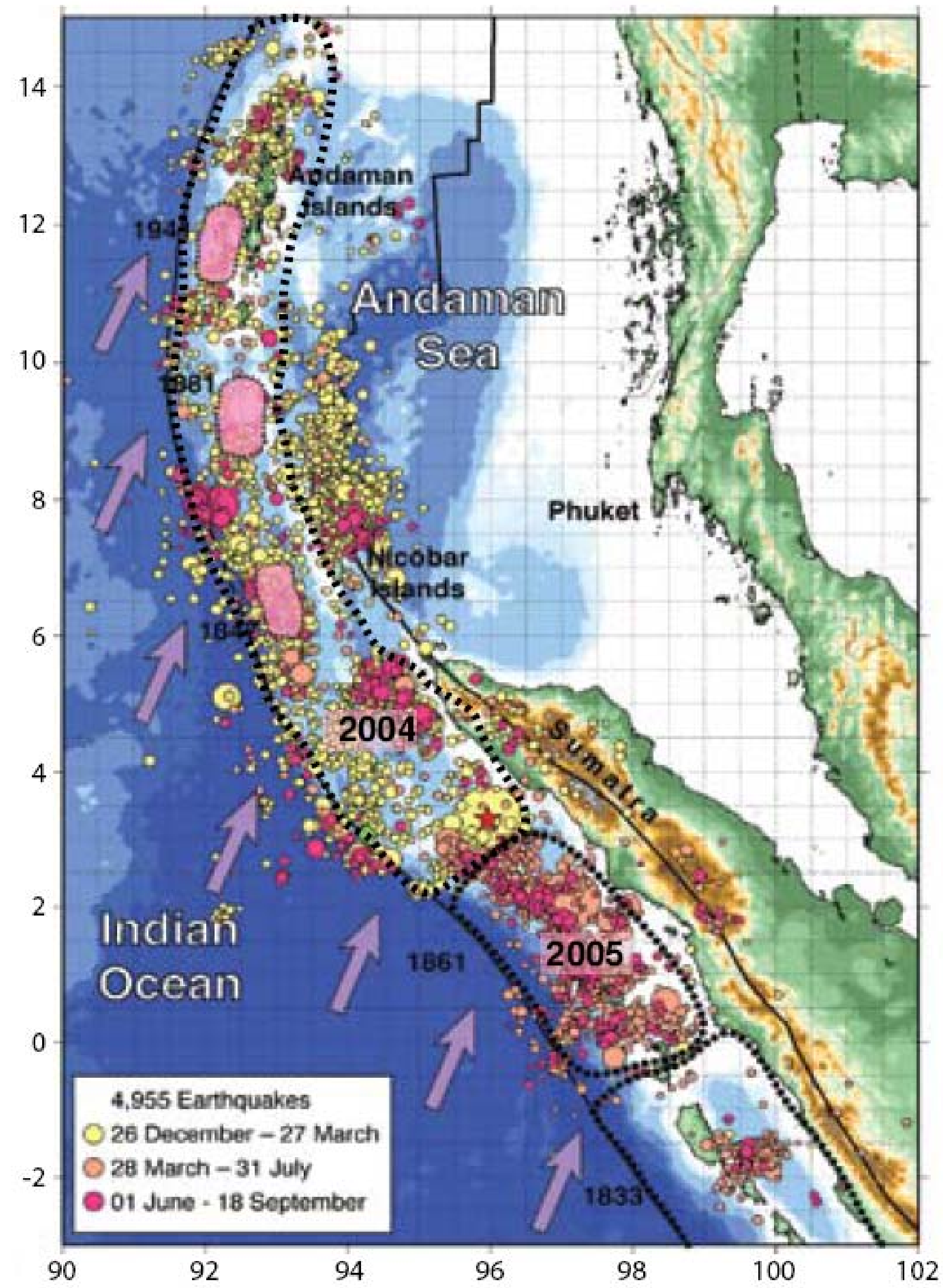
- Crack propagation
- Earthquake rupture
- Strong ground motion
- Directivity
- Source mechanism
- Finite sources



The 2001 Kokoxili (M_w 7.8) earthquake ruptured about 400 km of the Kunlun fault in northern Tibet and is one of the longest strike-slip events recorded by modern seismic networks. The contours indicate the intensity of high-frequency seismic radiation as imaged using back-projection of globally recorded P-waves, with the strongest regions plotted in red. Analysis shows that the rupture propagated at ~ 2.6 km/s for the first 120 km and then accelerated to ~ 5.7 km/s, a super-shear (faster than S-wave speed) velocity that continued for at least 290 km away from the epicenter. (Image courtesy of K.T. Walker and P.M. Shearer.)

Seismicity

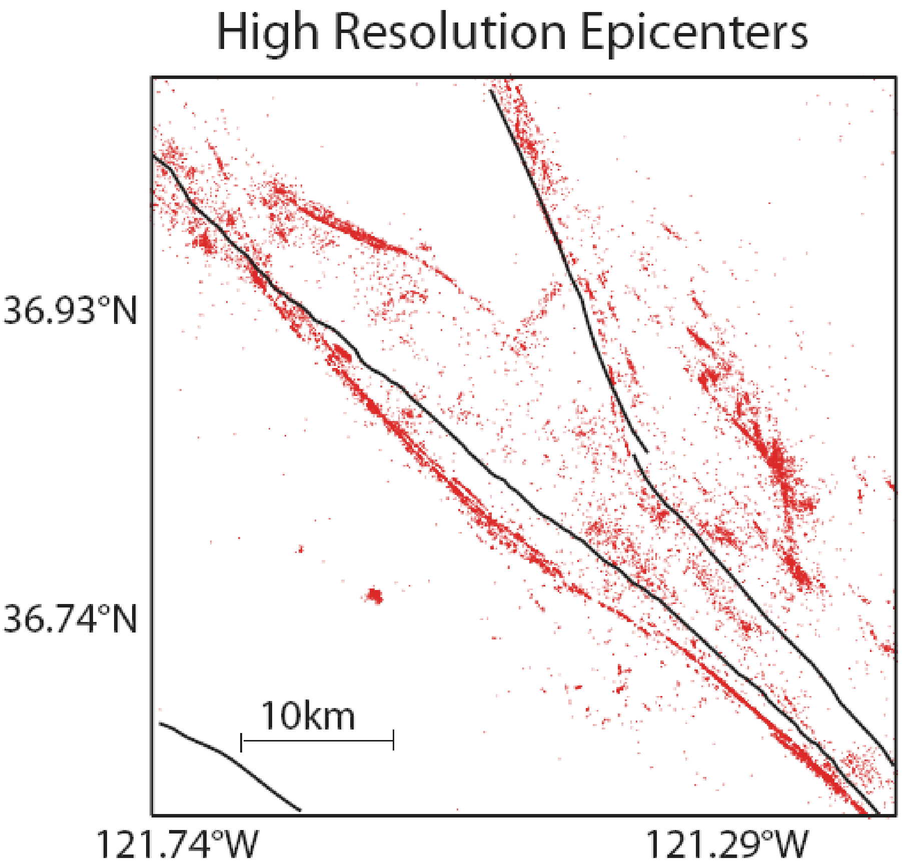
- Repeating earthquakes
- Seismic gaps
- Crustal deformation
- Seismic hazard
- Forecasting and prediction
- Stress transfer
- Tsunami generation

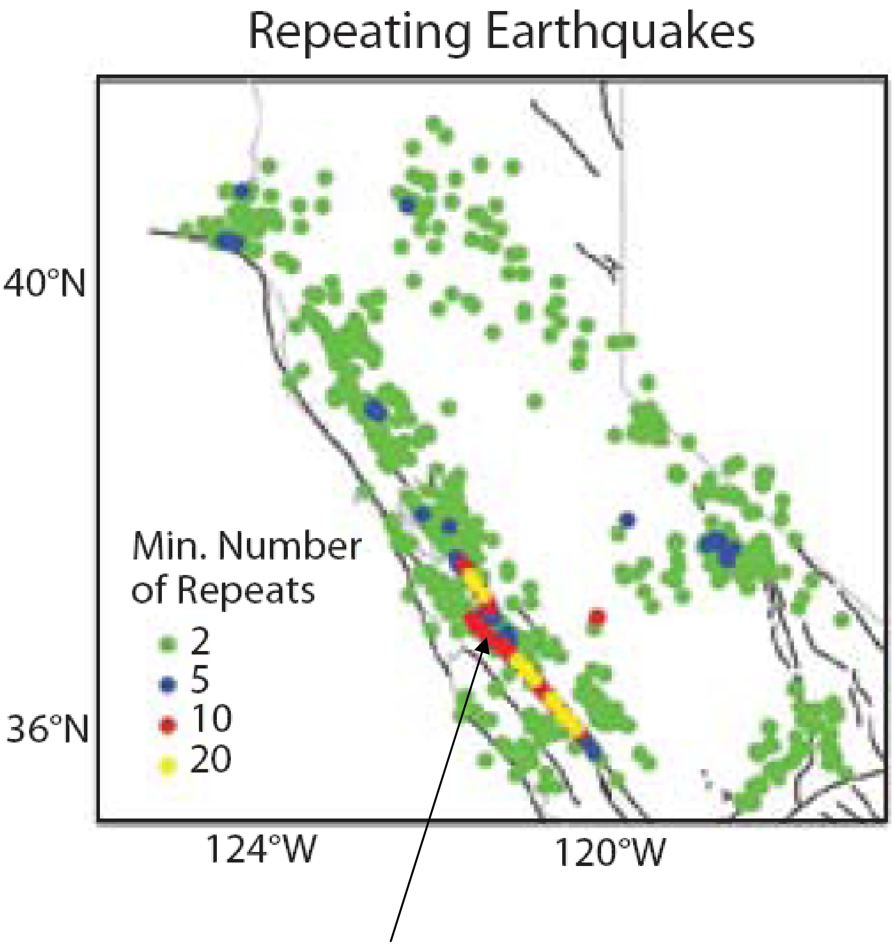


Grand Challenges

according to IRIS

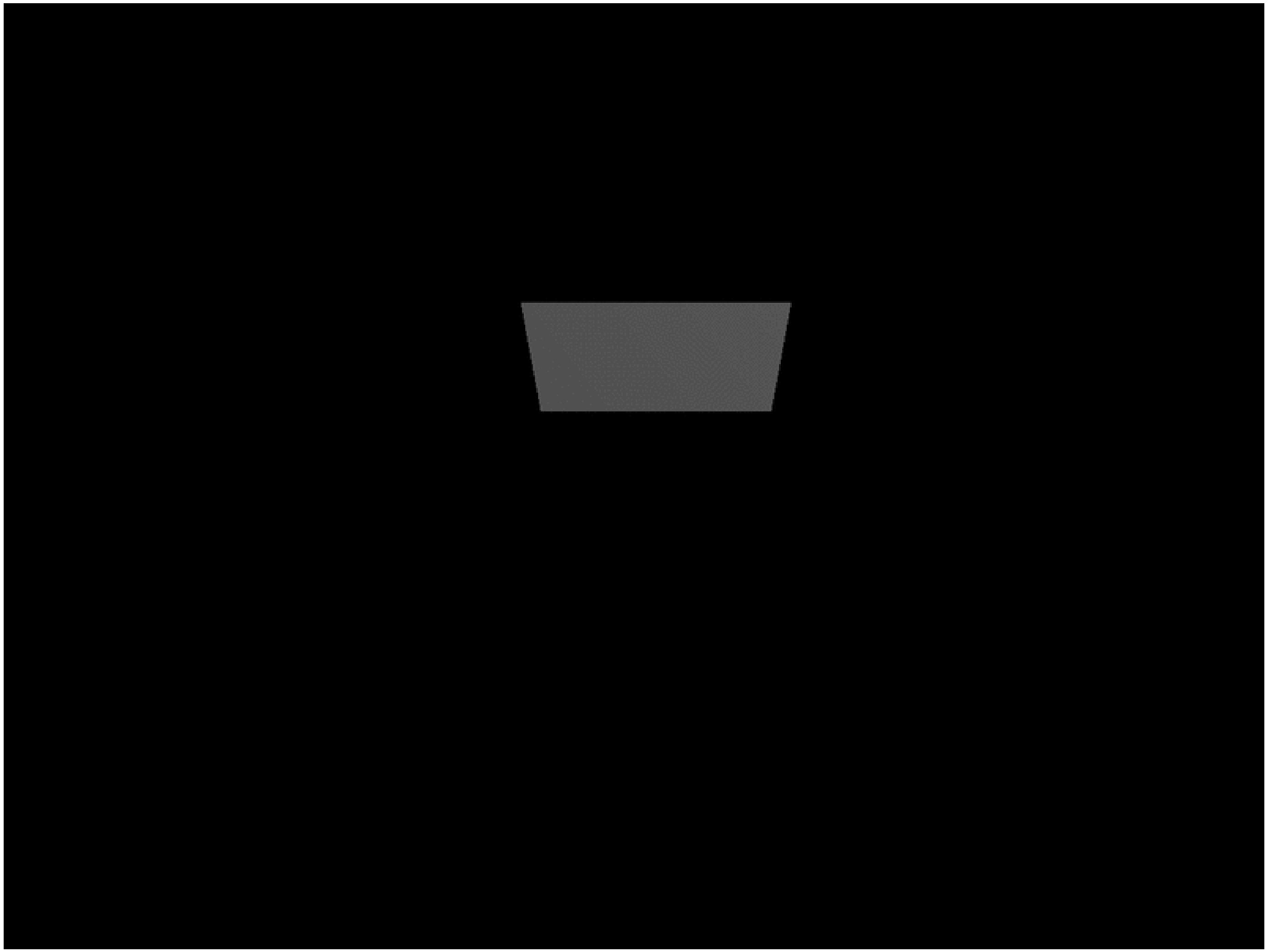
… what have those challenges to do with seismic data analysis ???



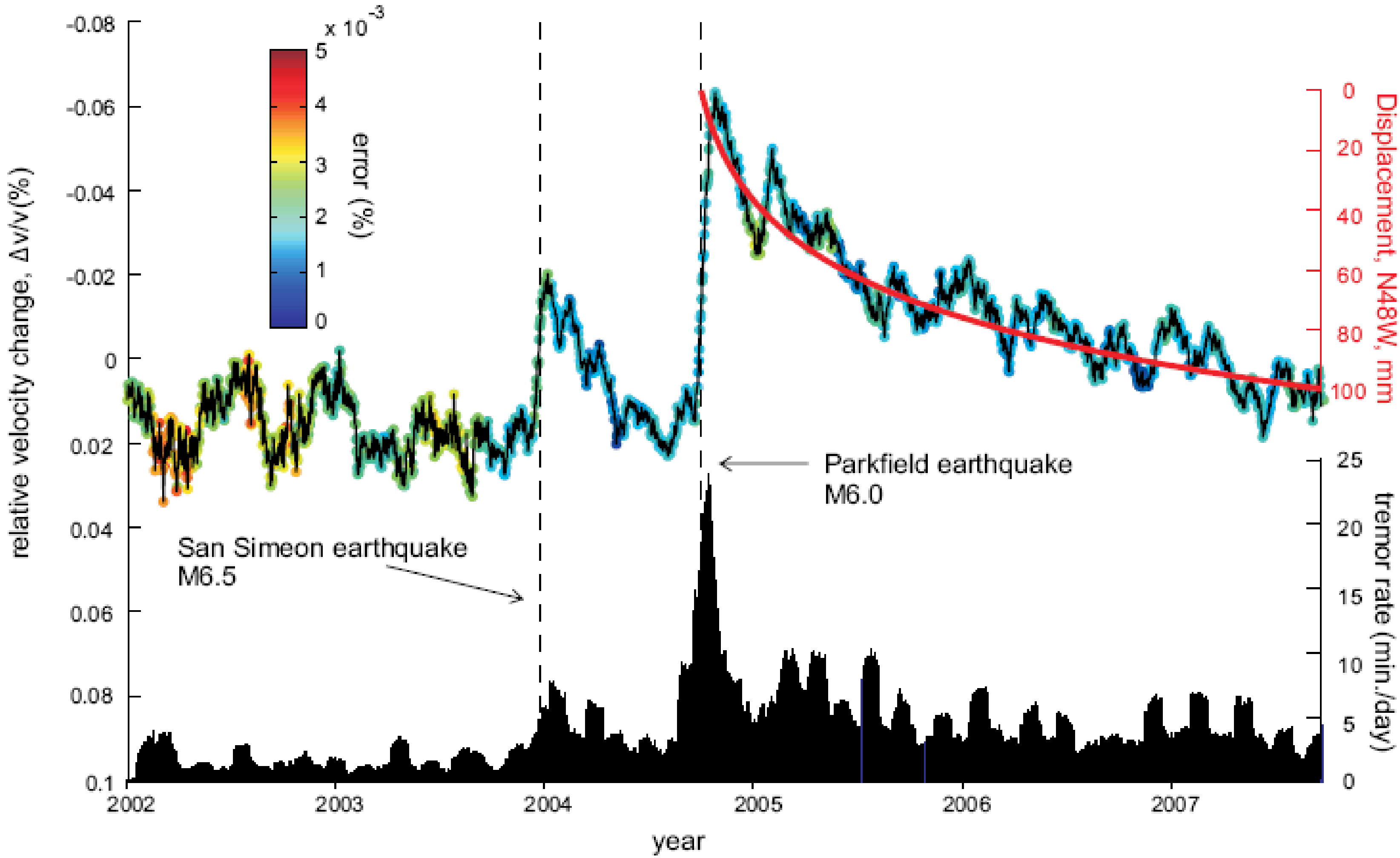


Hollister, California

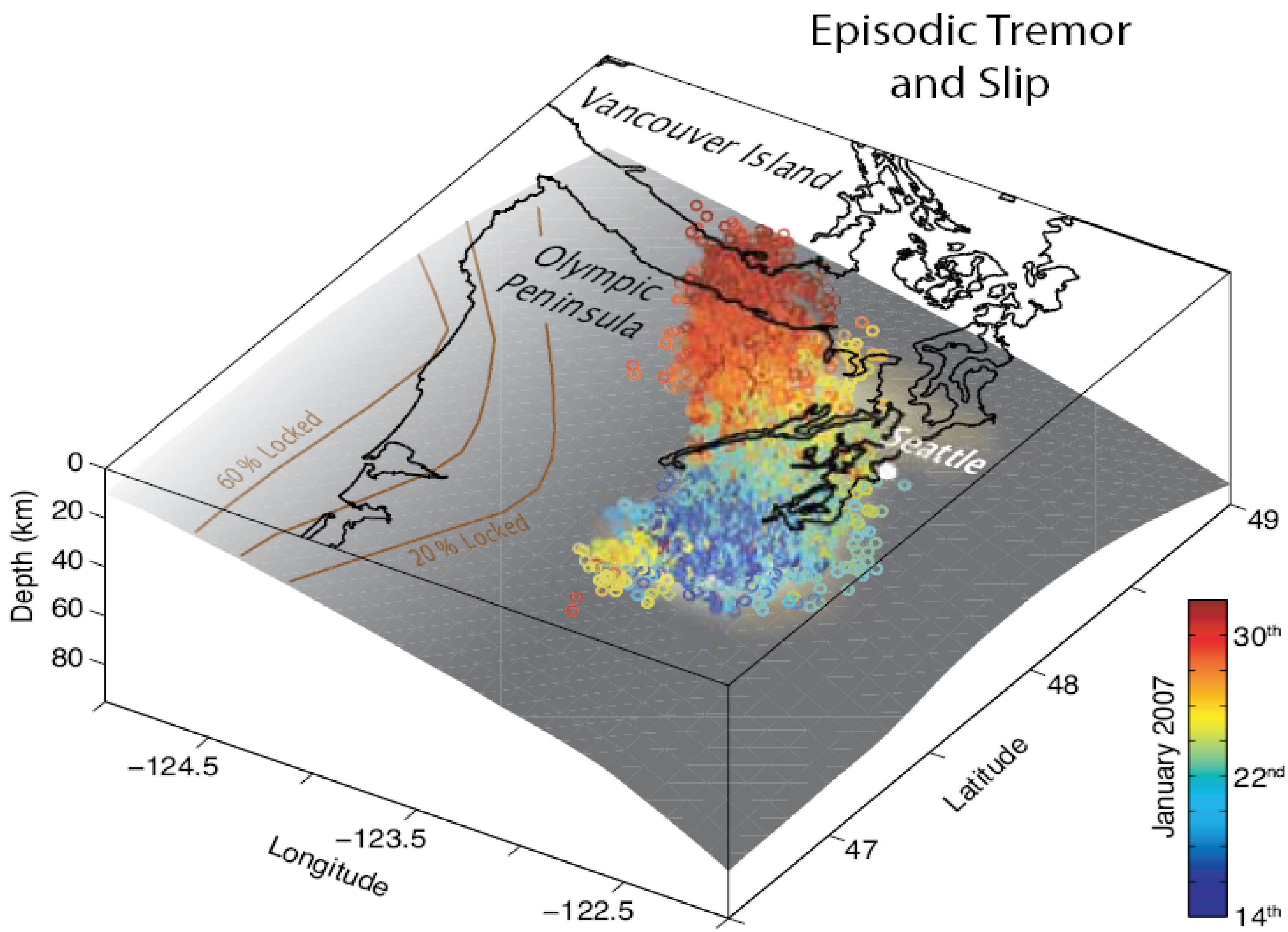
Rupture propagation



Temporal changes in seismic velocities



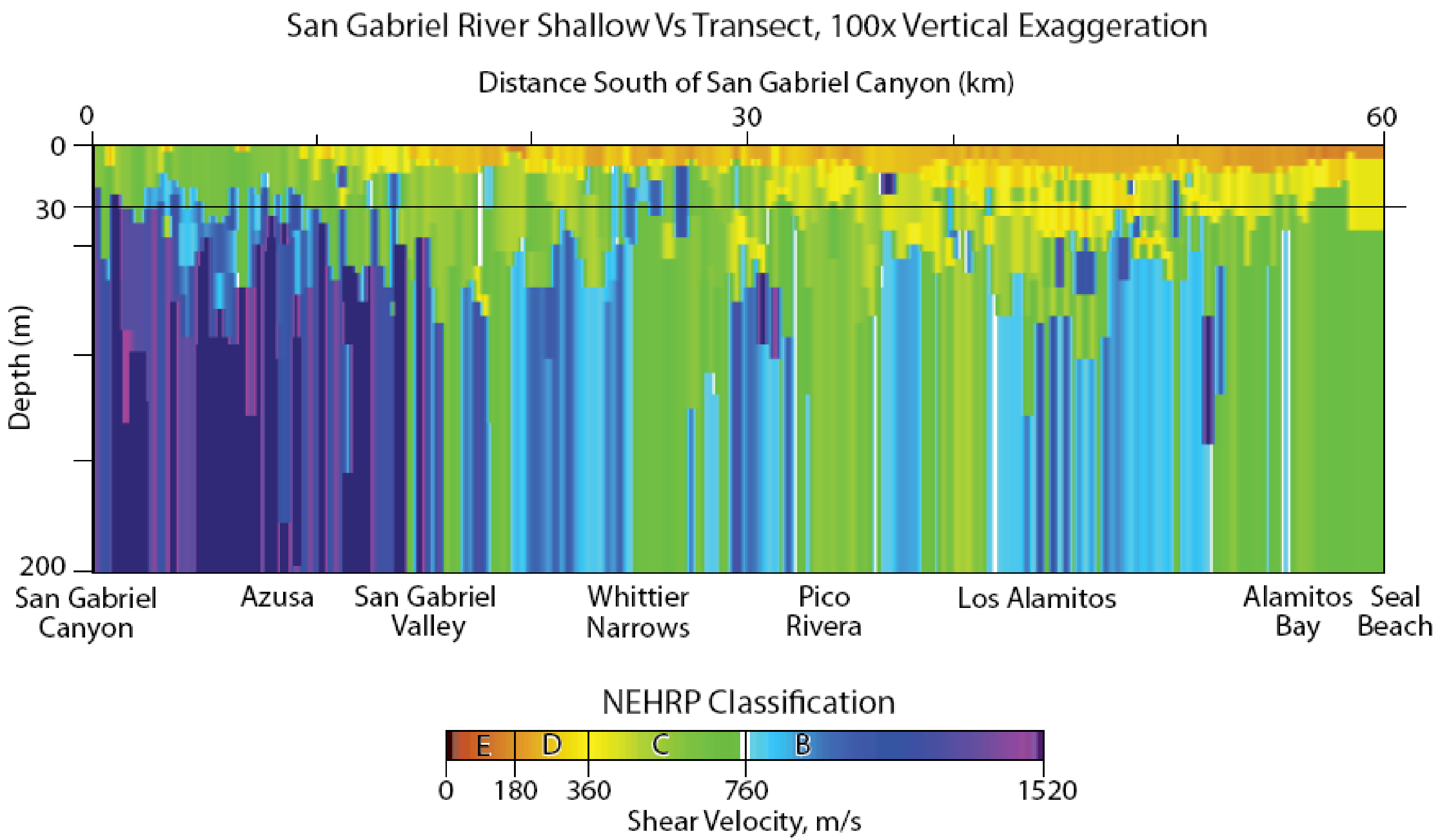
Non-volcanic tremors



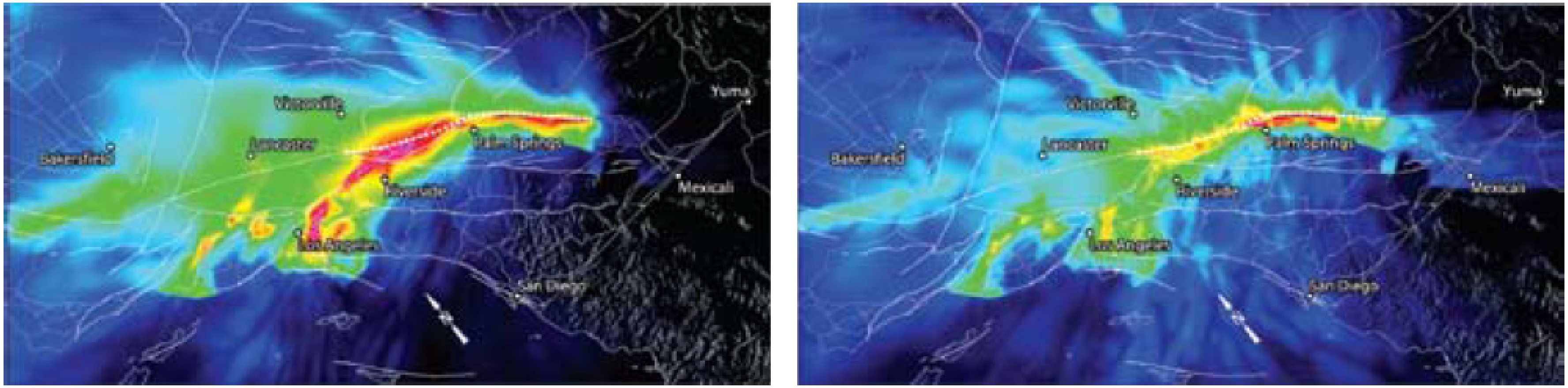
Issues

- Is there a preparatory stage for fault ruptures?
- How do ruptures stop?
- Are mechanisms of interplate and intraplate earthquakes different?
- Can tremor be used for forecasting large earthquakes

… information on these topics related to frequency content in seismograms (spectra) …

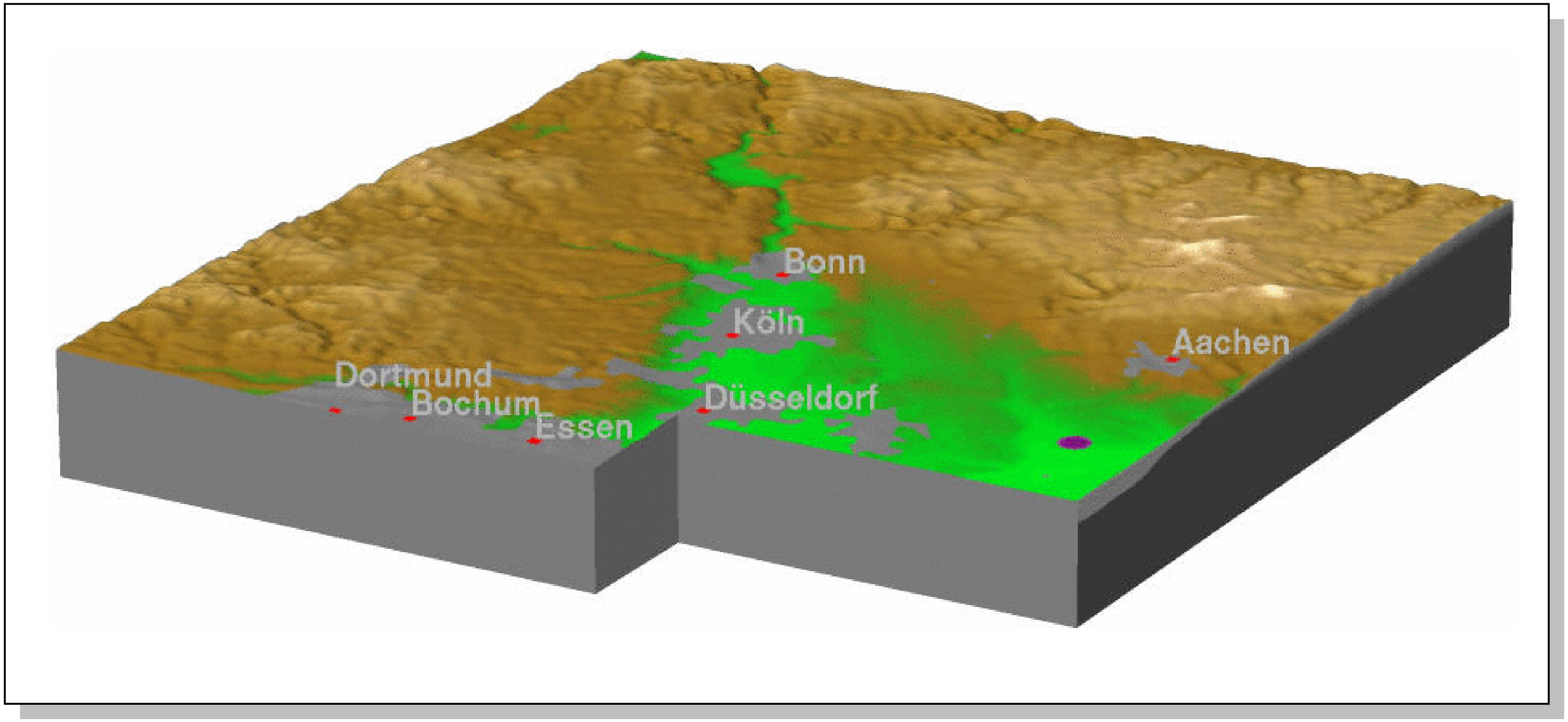

San Gabriel River Shallow Vs Transect, 100x Vertical Exaggeration
Distance South of San Gabriel Canyon (km)
0
30
60
Depth (m)
0
30
200
San Gabriel Canyon
Azusa
San Gabriel Valley
Whittier Narrows
Pico Rivera
Los Alamitos
Alamitos Bay
Seal Beach
NEHRP Classification
E
D
C
B
0
180
360
760
1520
Shear Velocity, m/s

Earthquake scenario simulations



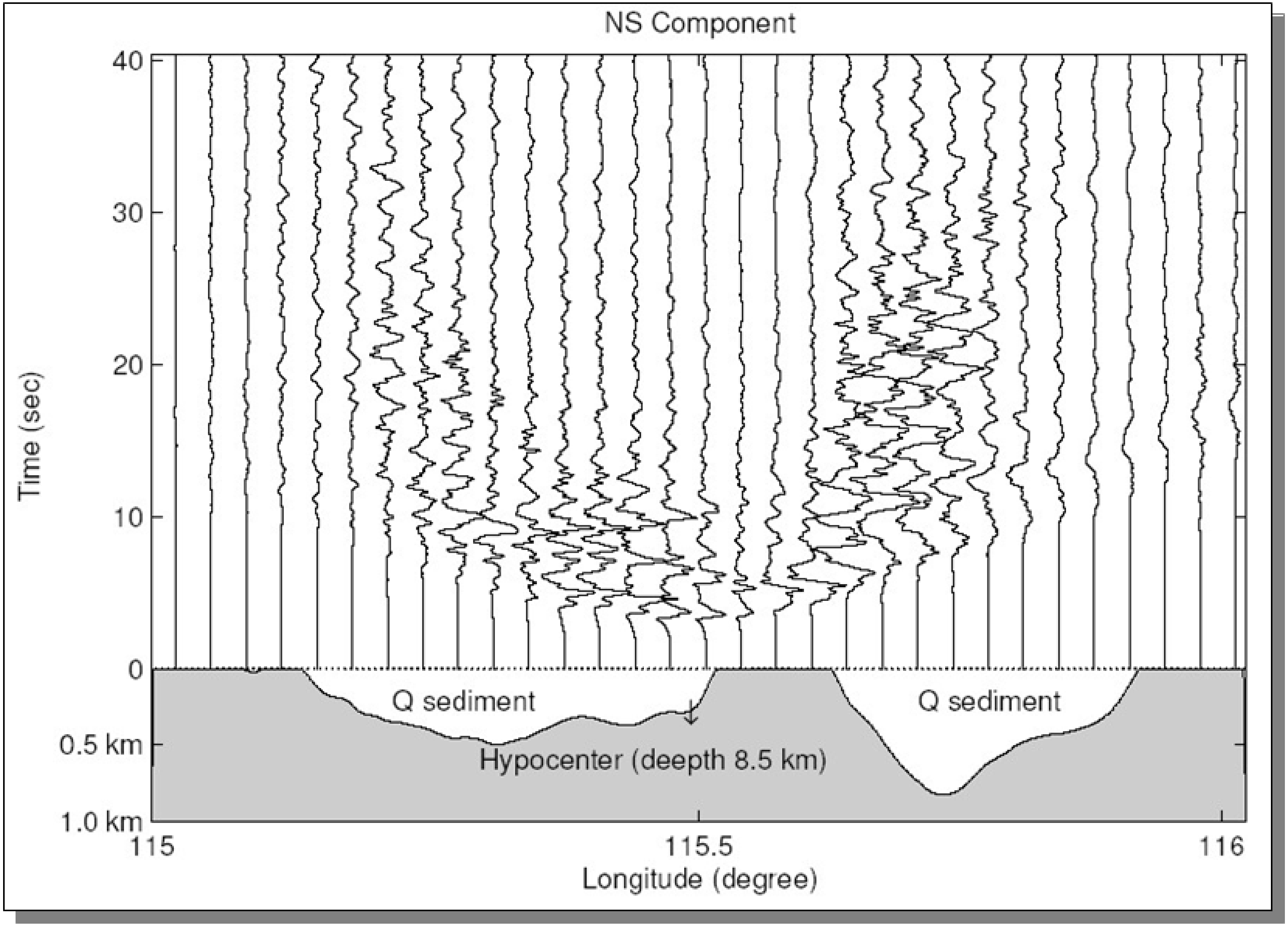
Ground motion intensities (warm colors correspond to high intensities) for a simulated M 7.7 earthquake with SE to NW rupture on a 200-km section of the San Andreas Fault. Strong rupture directivity and intensity amplification occur due to funneling of seismic waves through sedimentary basins south of the San Bernardino and San Gabriel Mountains. The simulation to the left assumes a kinematic (space-time history of slip being prescribed) rupture model, while the one on the right uses a dynamic (physics-based) rupture. The difference in the predicted intensities in this highly populated region underscores the importance of properly characterizing source processes in such simulations. (Image modified from K.B. Olsen, S.M. Day, J.B. Minster, Y. Cui, A. Chourasia, D. Okaya, P. Maechling, and T. Jordan, 2008. TeraShake2: Spontaneous rupture simulation of Mw 7.7 earthquakes on the Southern San Andreas Fault, *Bulletin of the Seismological Society of America*, 98(3):1162–1185, ©Seismological Society of America)

Earthquake scenario simulations

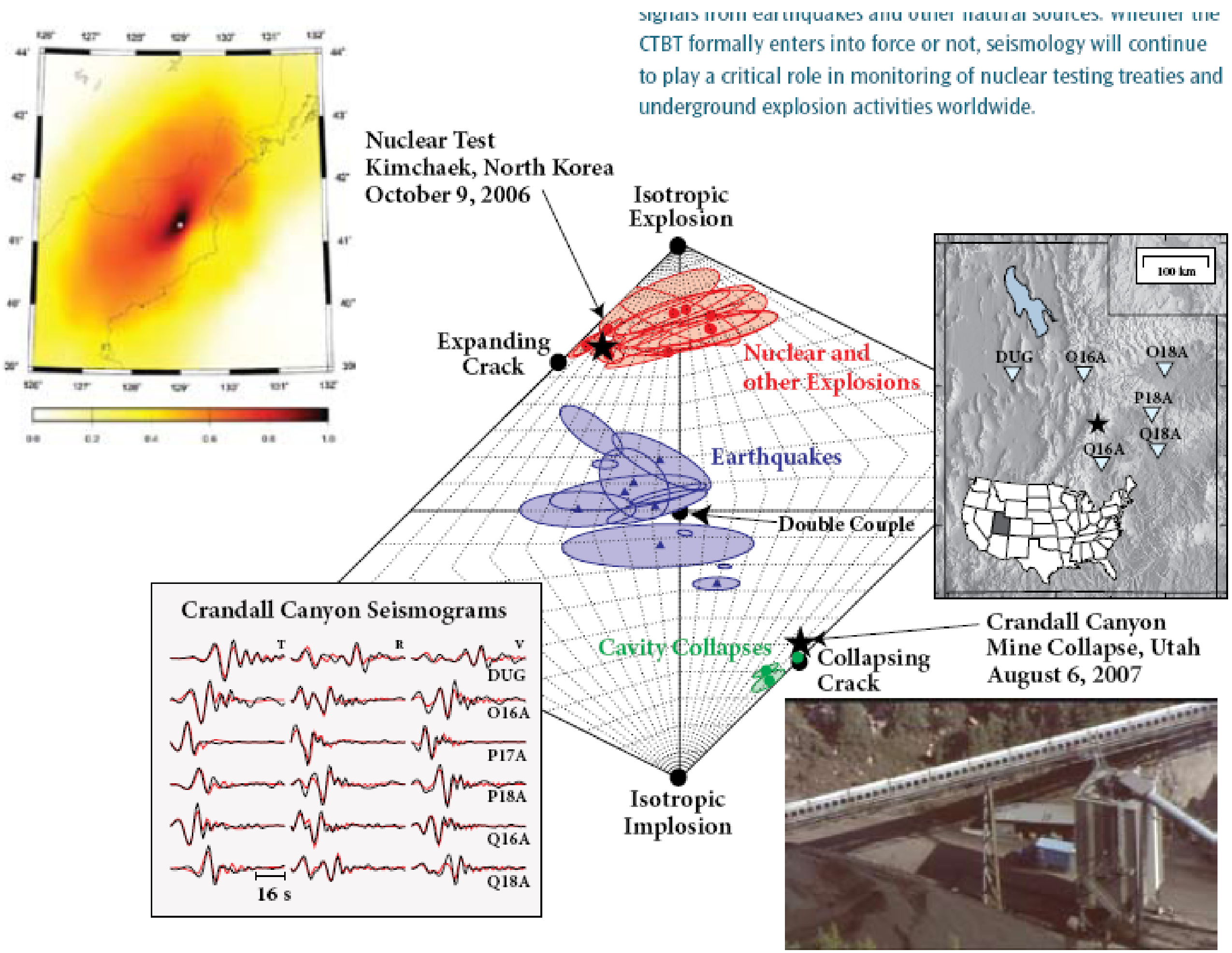


… large scale parallel simulations and analysis of synthetic seismograms

Basin effects, amplification, Rhine Graben, Germany



Source characterization



Issues

- How can the acute heterogeneity in the near surface best be imaged and its material properties constrained in diverse applications?
- How can time-dependent properties of shallow aquifers best be characterized to monitor water and contaminant transport?
- What is the resolution of seismological techniques to identify and locate unexploded ordinance, tunnels, buried landfills, and other human-made subsurface hazards?

What is the Relationship Between Stress and Strain in the Lithosphere?

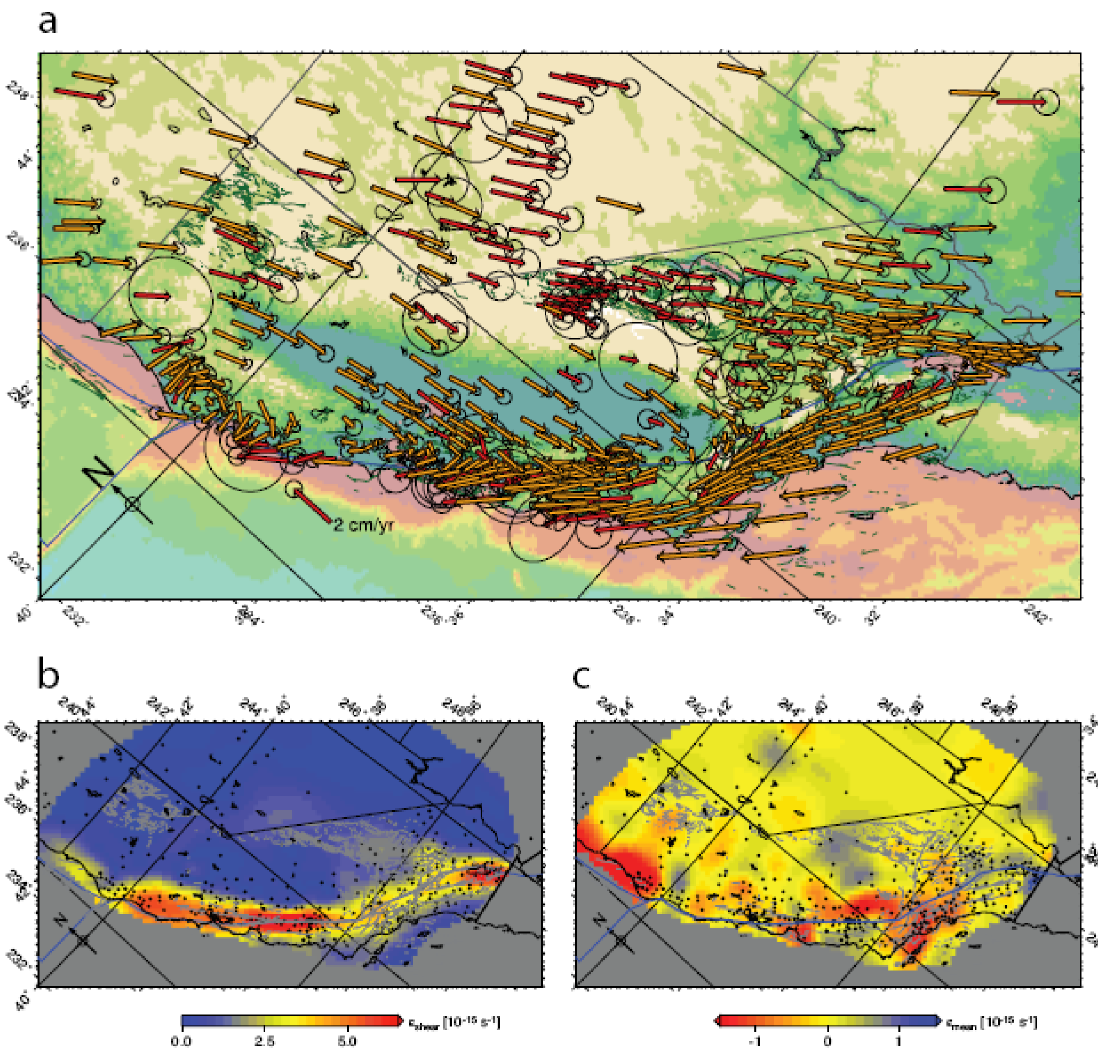
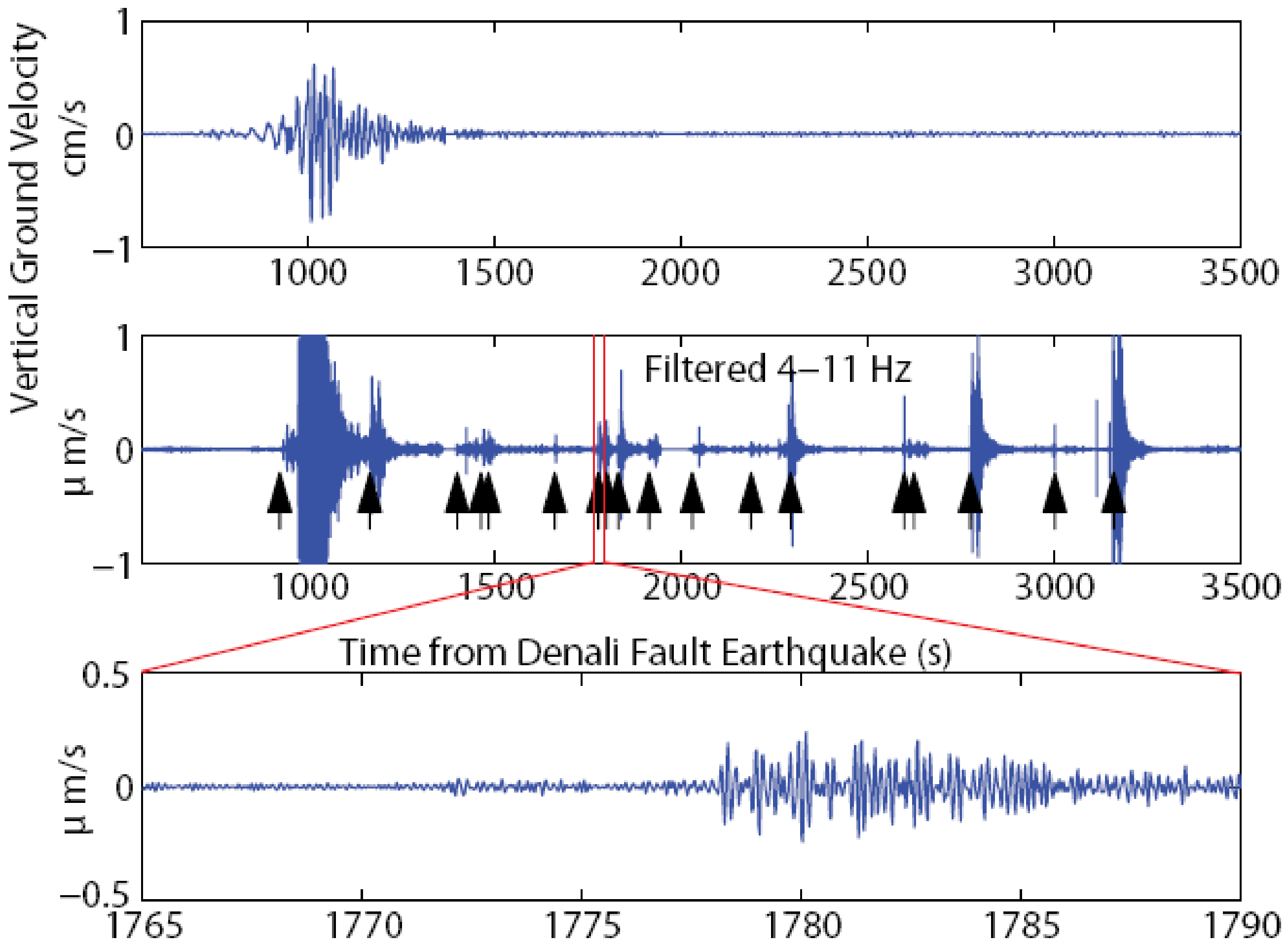


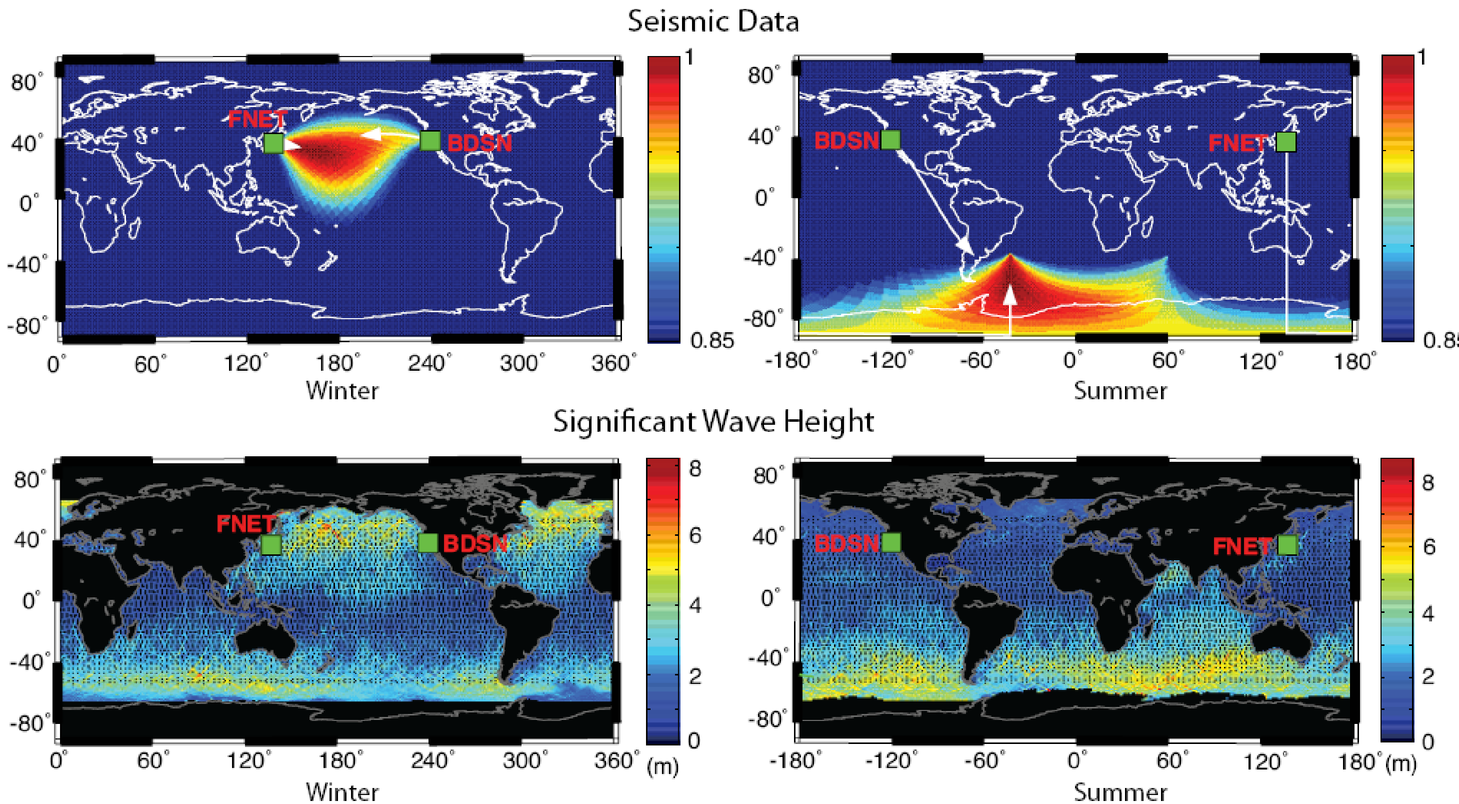
Plate boundary deformations, involving (a) surface velocities, (b) shear strains, and (c) mean strains, quantified here for the San Andreas system by geodetic measurements, provide a framework for stress accumulation and release, but the overall driving process and resulting earthquake stresses are not well understood. (Image modified from J.P. Platt, B.J.P. Kaus, and T.W. Becker, 2008. The mechanics of continental transforms: An alternative approach with applications to the San Andreas system and the tectonics of California, *Earth and Planetary Science Letters*, 274:380–391, doi:10.1016/j.epsl.2008.07.052.)

Remote triggering



Issues

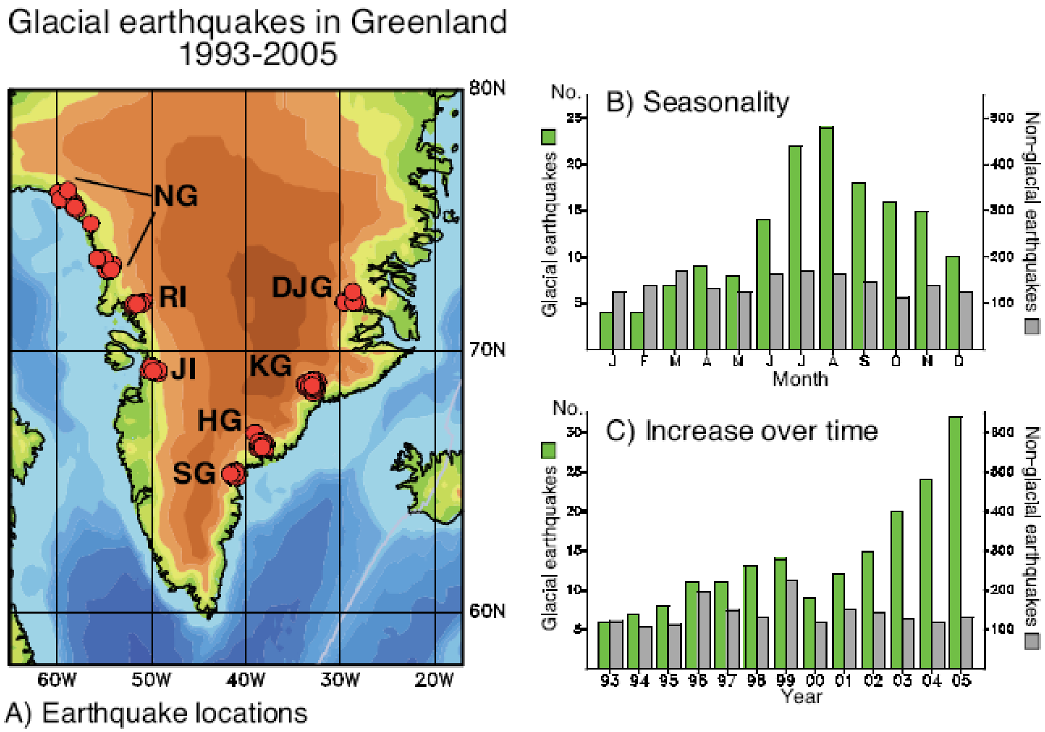
- What is the state of stress on active faults and how does it vary in space and time?
- How do pore fluids influence the stress environment in fault zones?
- What is the relative importance of static (elastic) versus dynamic (vibrational) stress changes for earthquake triggering?
- On what time- and spatial scale do earthquake „communicate“?



Comparison of seasonal variations in the distribution of long period "hum" sources (top) from array analysis using very broadband seismograph (STS-1) recordings, and significant wave height in the oceans (bottom) from satellite observations. Hum sources (the color bar indicates areas generating hum with amplitudes larger than 85% of the maximum) track the location of the strongest winter storms. Top left: averages for the winter months (January to March and October to December). Top right: averages for the summer months (April to September). Bottom: averaged images from Topex/Poseidon for the month of January (left) and July (right). (Reprinted by permission from Macmillan Publishers Ltd: J. Rhie and B. Romanowicz, 2004. Excitation of Earth's incessant free oscillations by atmosphere-ocean-seafloor coupling, *Nature*, 431:552–556, doi:10.1038/nature02942, ©2004.)

Glacial earthquakes

… detected by careful data analysis



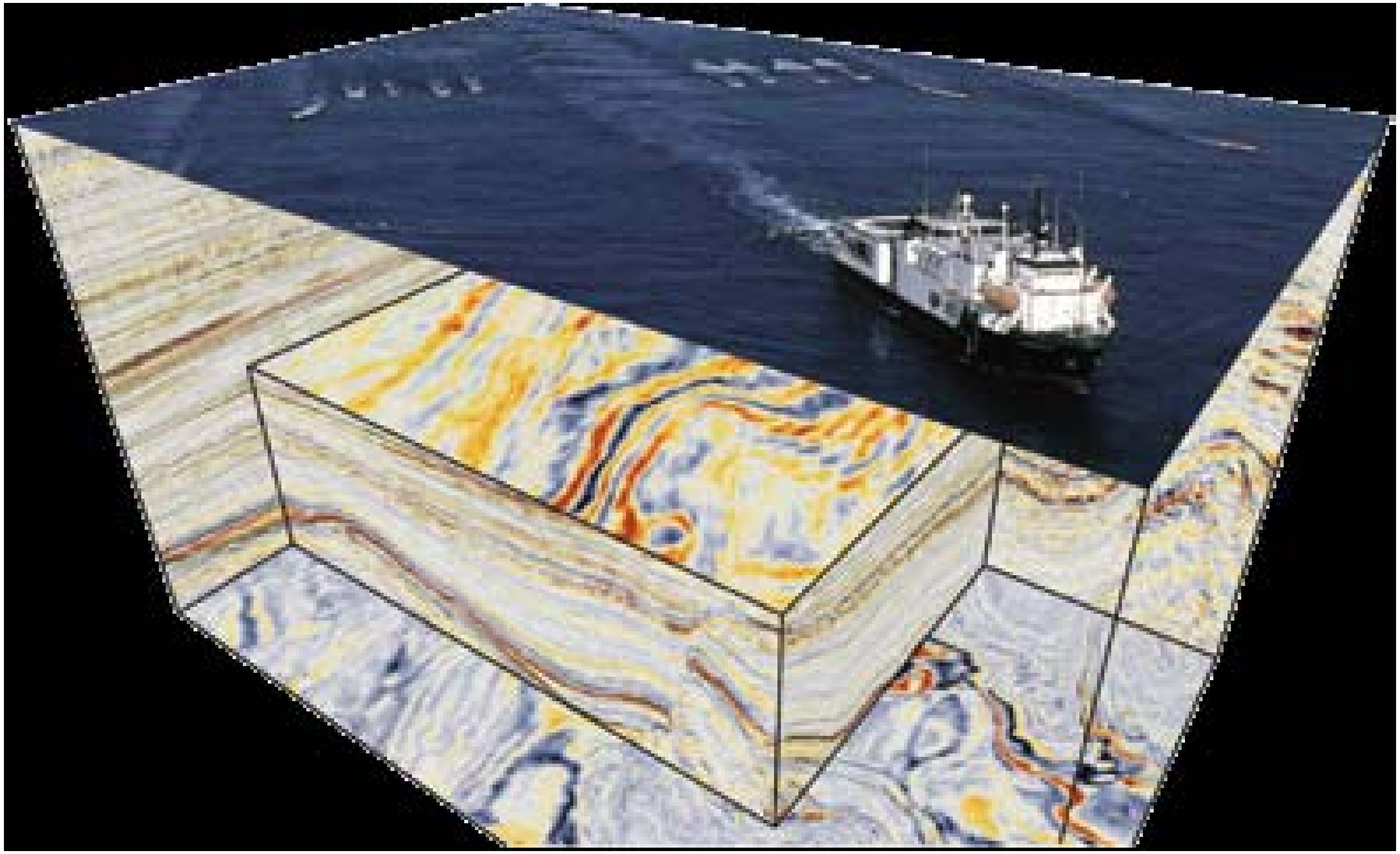
Example of novel glaciological signals studied with seismology. Seismically identified and located long-period glacial events detected with the GSN are associated with major outlet glaciers in Greenland, showing seasonality and annual variability. (Image from G. Ekström, M. Nettles and V.C. Tsai, 2006. Seasonality and increasing frequency of Greenland glacial earthquakes, *Science*, 311(5768):1756–1758, doi:10.1126/science.1122112. Reprinted with permission from AAAS.)

Issues

- How are Earth's normal modes excited by phenomena in the atmosphere and ocean?
- How do ocean wave and other seismic background noise variations track climate change?
- How can seismic and infrasound data best be used to study tornadic storm systems and tornado touch downs?

… analysing long-period information in seismograms … coherent energy in seismic networks … array processing …

Where are Water and Hydrocarbons Hidden Beneath the Surface?

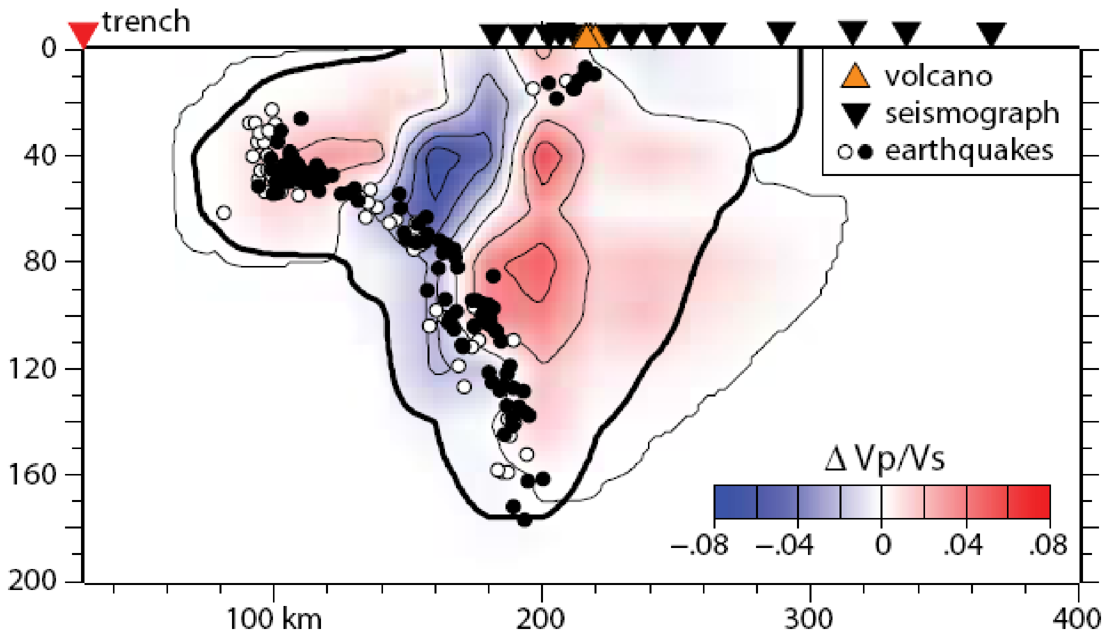


Issues

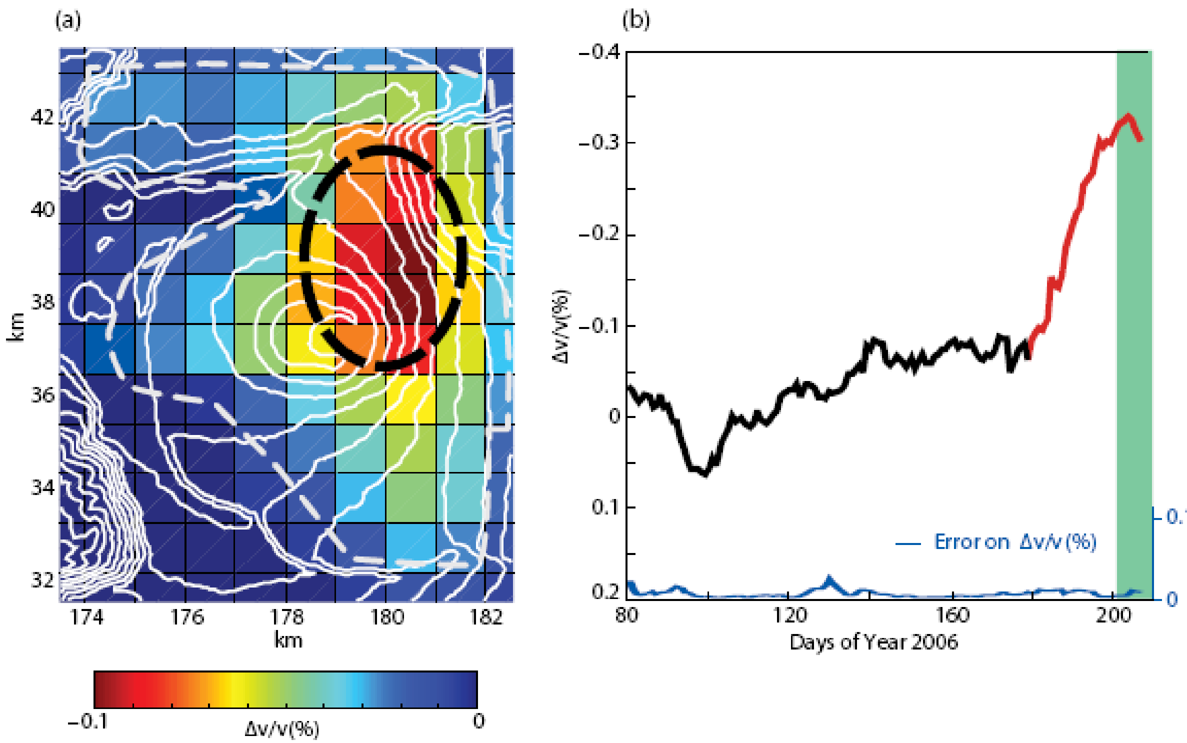
How can we improve the detection, characterization, and production of hydrocarbon resources including detecting deep deposits beneath salt, finding small-scale pockets in incompletel extracted reservoirs, and monitoring porosity, permeability, and fluid flow at high resolution?

How do magmas ascend and erupt?

Volcanoes and seismicity

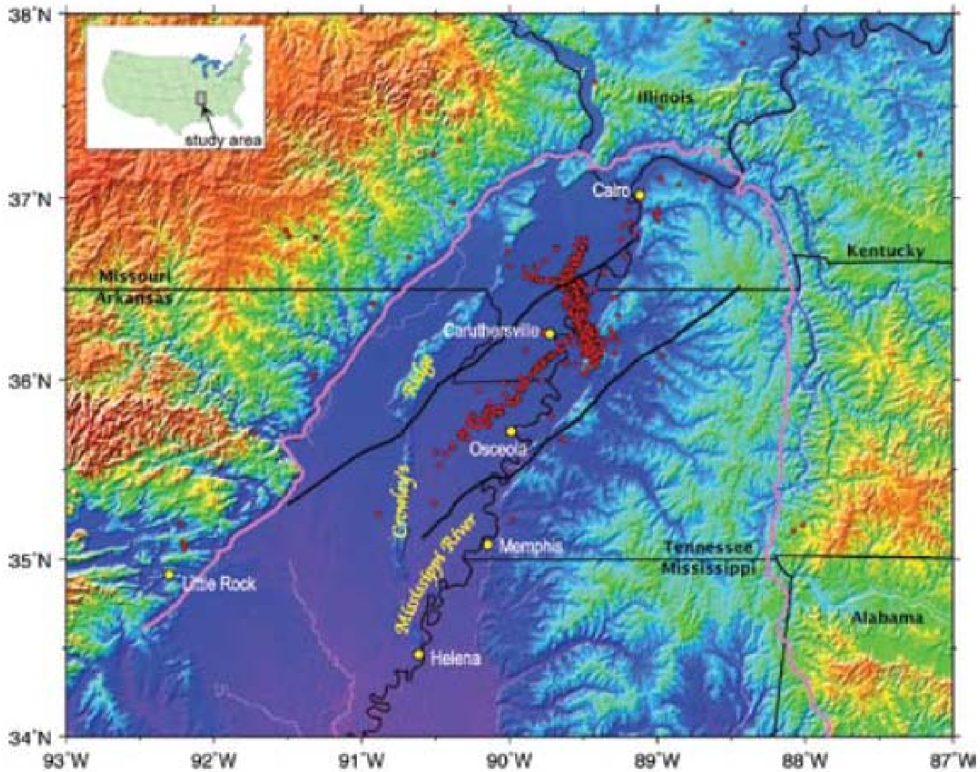


Tomographic image of the ratio between P velocity and S velocity in a subduction zone beneath Nicaragua. The highest ratio (darkest red area) indicates the presence of melts rising from near the subducted oceanic plate. The sinking plate is indicated by earthquakes extending to depths of 175 km. Fluids released from the sinking plate lower the melting temperature of material in the mantle wedge, resulting in partial melting and ascent of magmas to the volcanic arc. (Image from E.M. Syracuse, G.A. Abers, K.M. Fischer, L.G. MacKenzie, C.A. Rychert, J.M. Protti, V. Gonzalez, and W. Strauch, 2008. Seismic tomography and earthquake locations in the Nicaraguan and Costa Rican upper mantle, *Geochemistry, Geophysics, Geosystems,* 9, Q07S08, doi:10.1029/2008GC001963.)



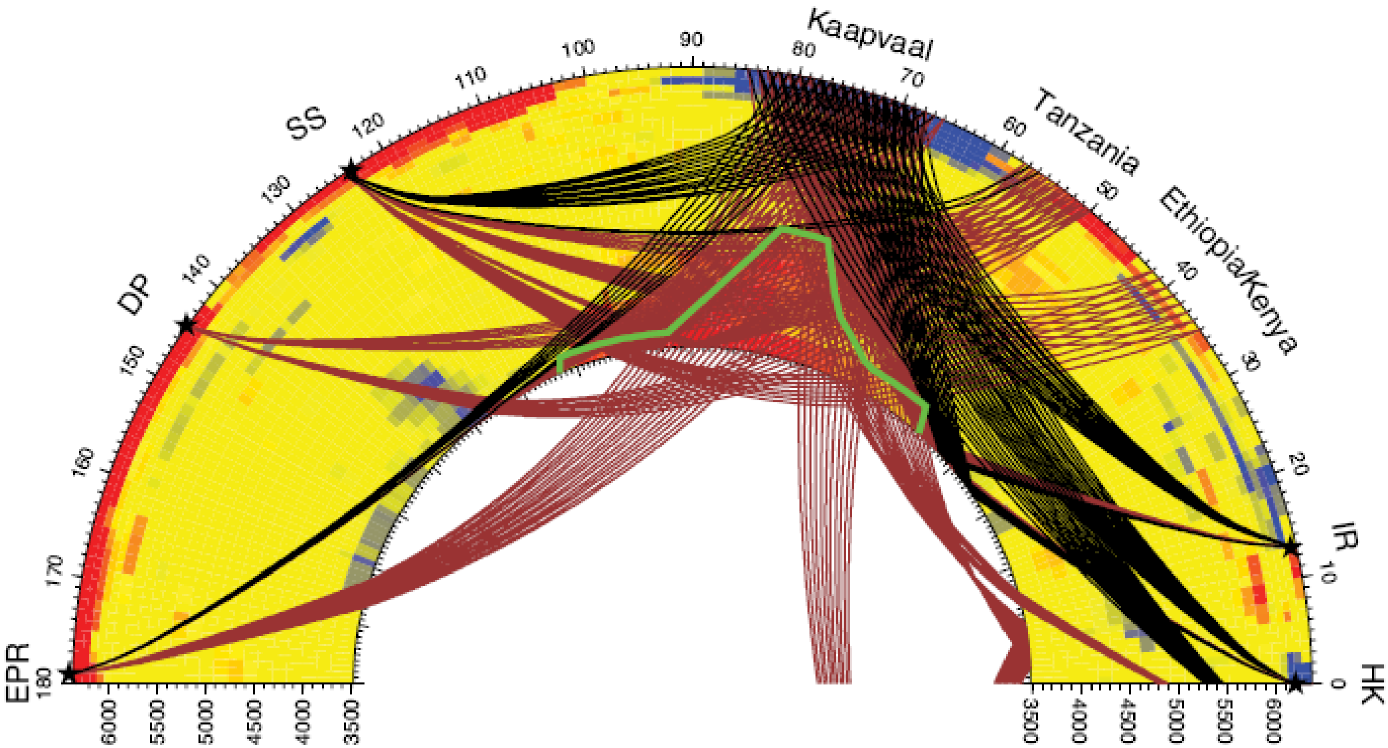
(a) Map of the cumulative changes in seismic velocity that had occurred just before the September 1999 eruption of Piton de la Fournaise volcano, Réunion. White dashed line shows the limit of coverage. Solid white lines are topographic contours. Black dashed oval is a region of normally high velocity thought to be an effect of solidified dikes associated with the zone of magma injection. For this small eruption, the high-velocity regions decreased in velocity; the maximum change was about 0.1%. (b) Velocity changes before a larger eruption in July 2006 reached about 0.3% shown by the red curve. Green shaded area indicates period of eruption. (Reprinted with permission from Macmillan Publishers Ltd.: F. Brenguier, N.M. Shapiro, M. Campillo, V. Ferrazzini, Z. Duputel, O. Coutant, and A. Nercessian, 2008. Towards forecasting volcanic eruptions using seismic noise, *Nature Geoscience*, 1:126–130, doi:10.1038/ngeo104, ©2008.)

Intraplate earthquakes



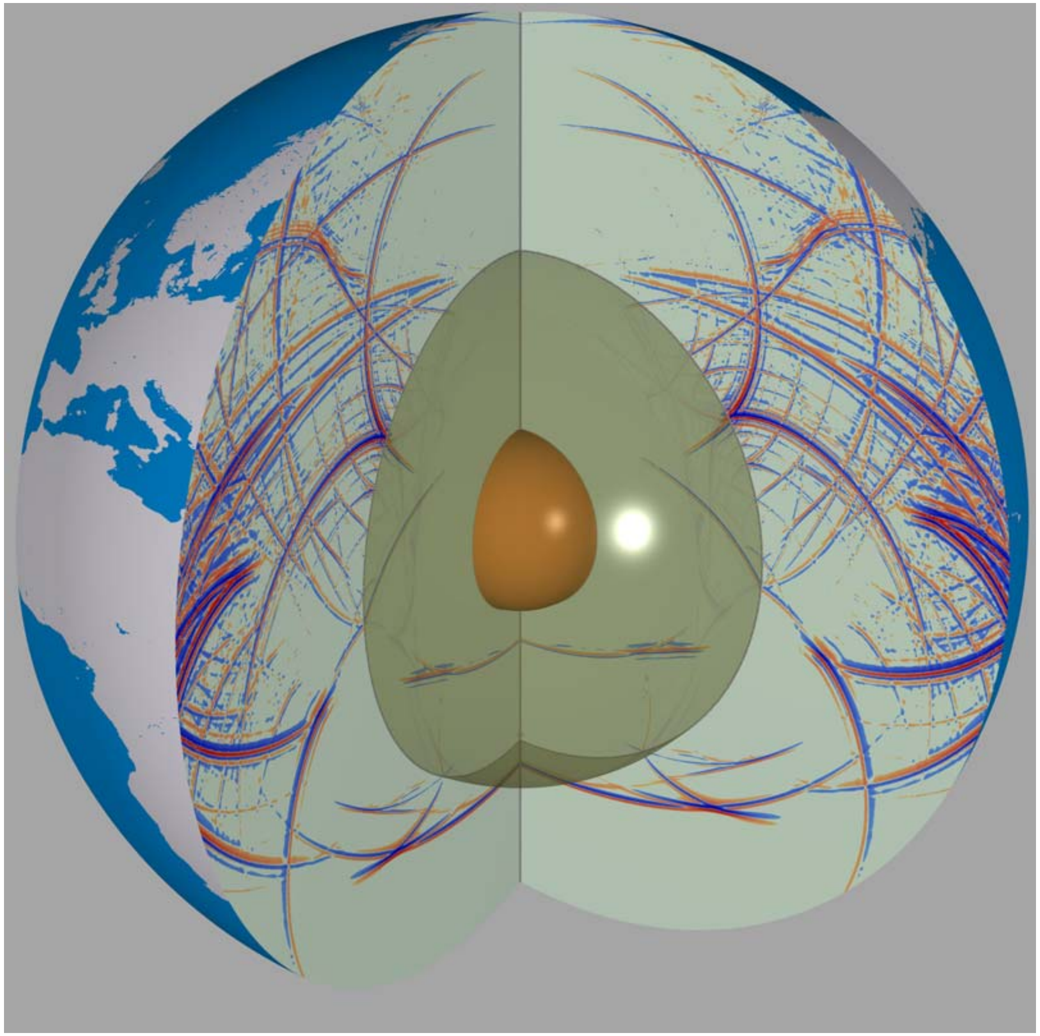
Intraplate seismicity of the New Madrid seismic zone in the central USA superimposed on a topography map with warmer colors indicating higher elevations. The red circles are earthquake locations from local seismic network analyses. The magenta line shows the boundary of the Mississippi embayment structure that, geologically, is an incursion of the Gulf of Mexico coastal plain. Thick black lines show the approximate boundary of the Reelfoot Rift zone, an ancient (approximately 500 million year old) rift that has been subsequently covered by recent Mississippi embayment sediments. Ancient faults of the Reelfoot Rift have presumably been reactivated to form the complex fault structures seen in the distribution of earthquakes. This region has experienced at least four series of large earthquakes over the past 2500 years, including three with magnitudes of 7.0, 7.2, and 7.5 in 1811–1812. (Image courtesy of M.B.Magnani.)

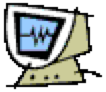
Global tomography

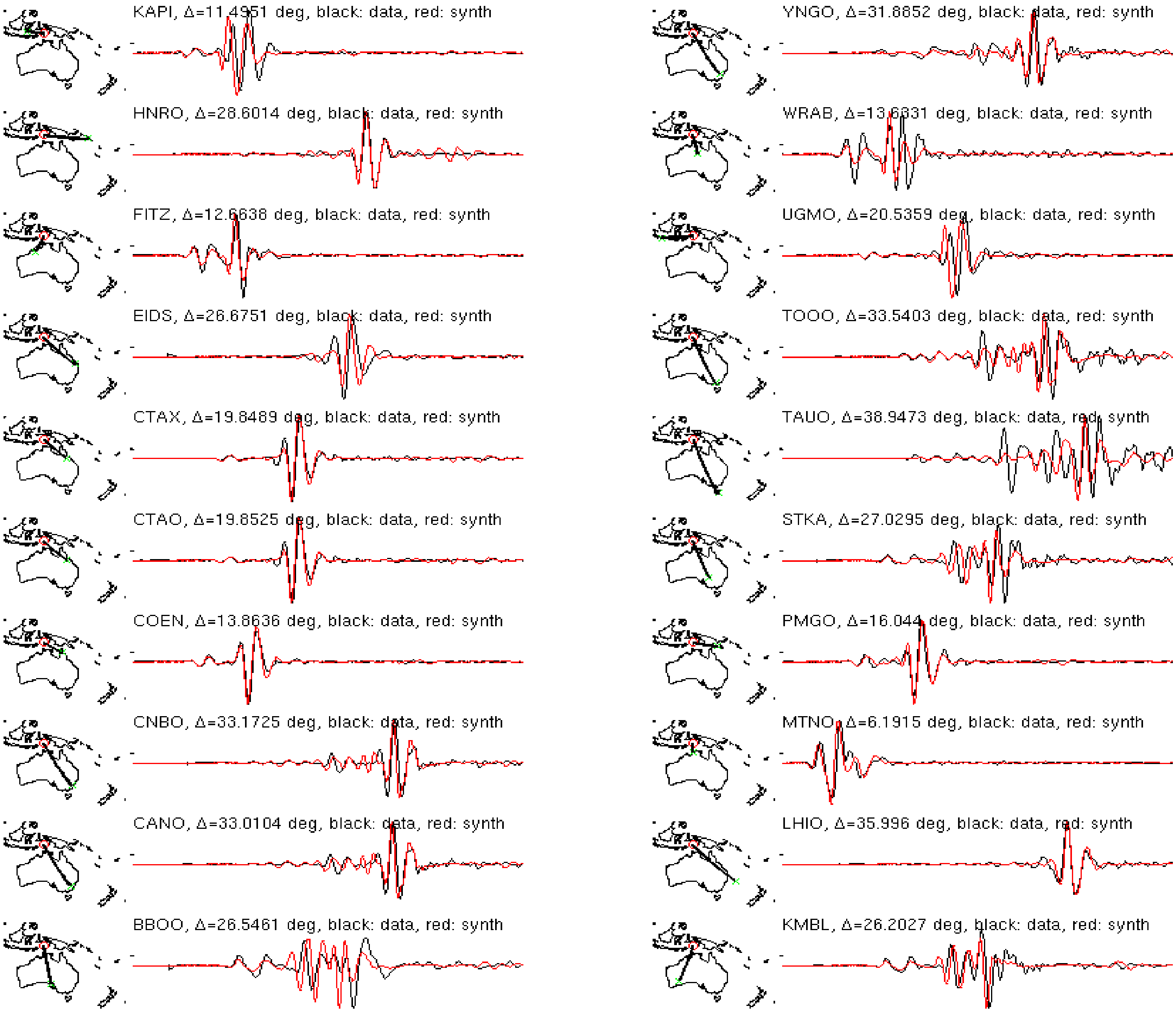


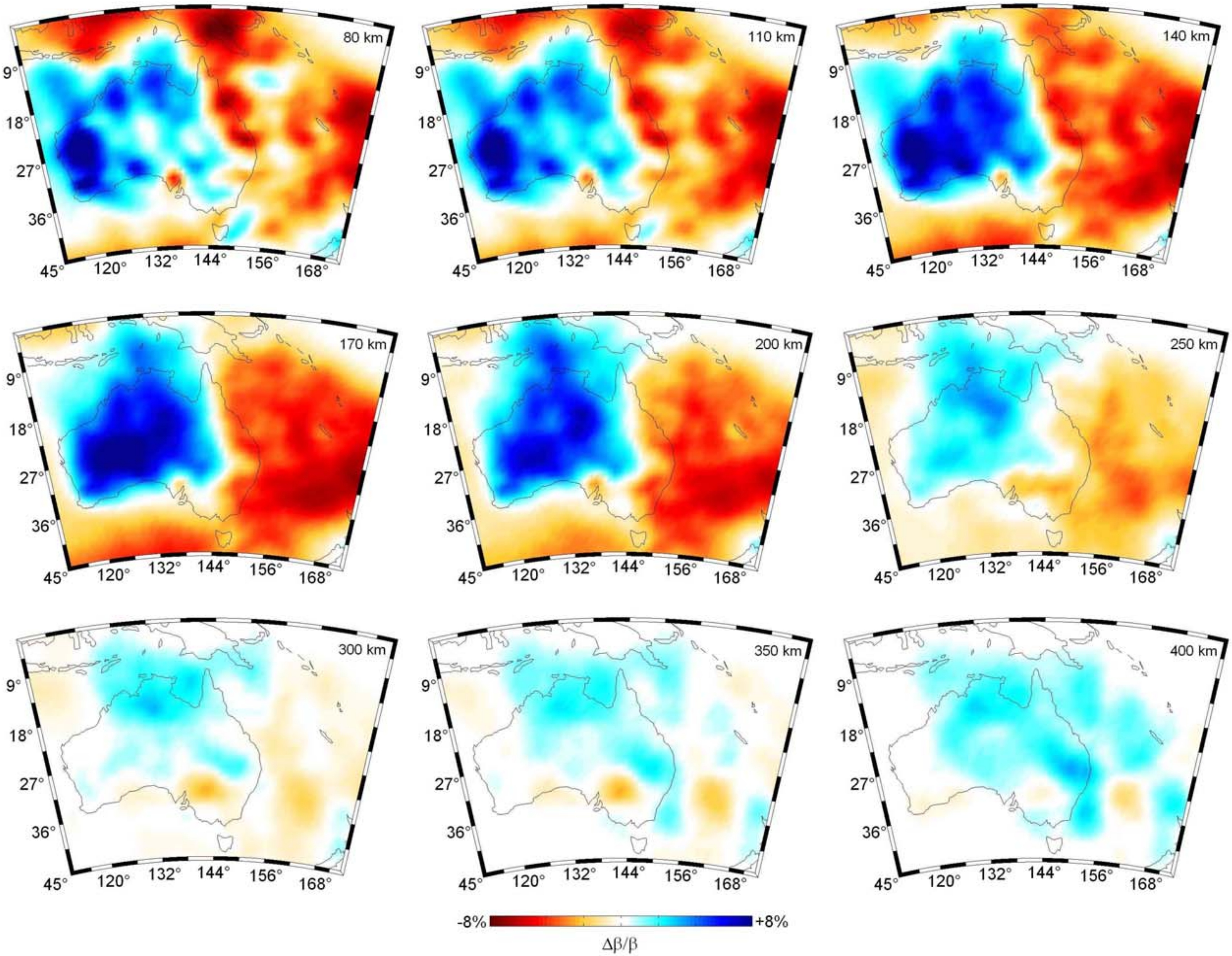
Cross section through the mantle showing how ray paths for diverse seismic phases from various source regions constrain the extent of the large, low-shear velocity province beneath Africa, which is bounded by the green outline. S-wave velocities within the province are about 3% lower than in the surrounding lower mantle. The structure extends upward more than 1000 km above the core-mantle boundary. (Image from Y. Wang and L. Wen, 2007. Geometry and P and S velocity structure of the "African Anomaly," *Journal of Geophysical Research*, 112, B05313, doi:10.1029/2006JB004483.)

Global wave propagation

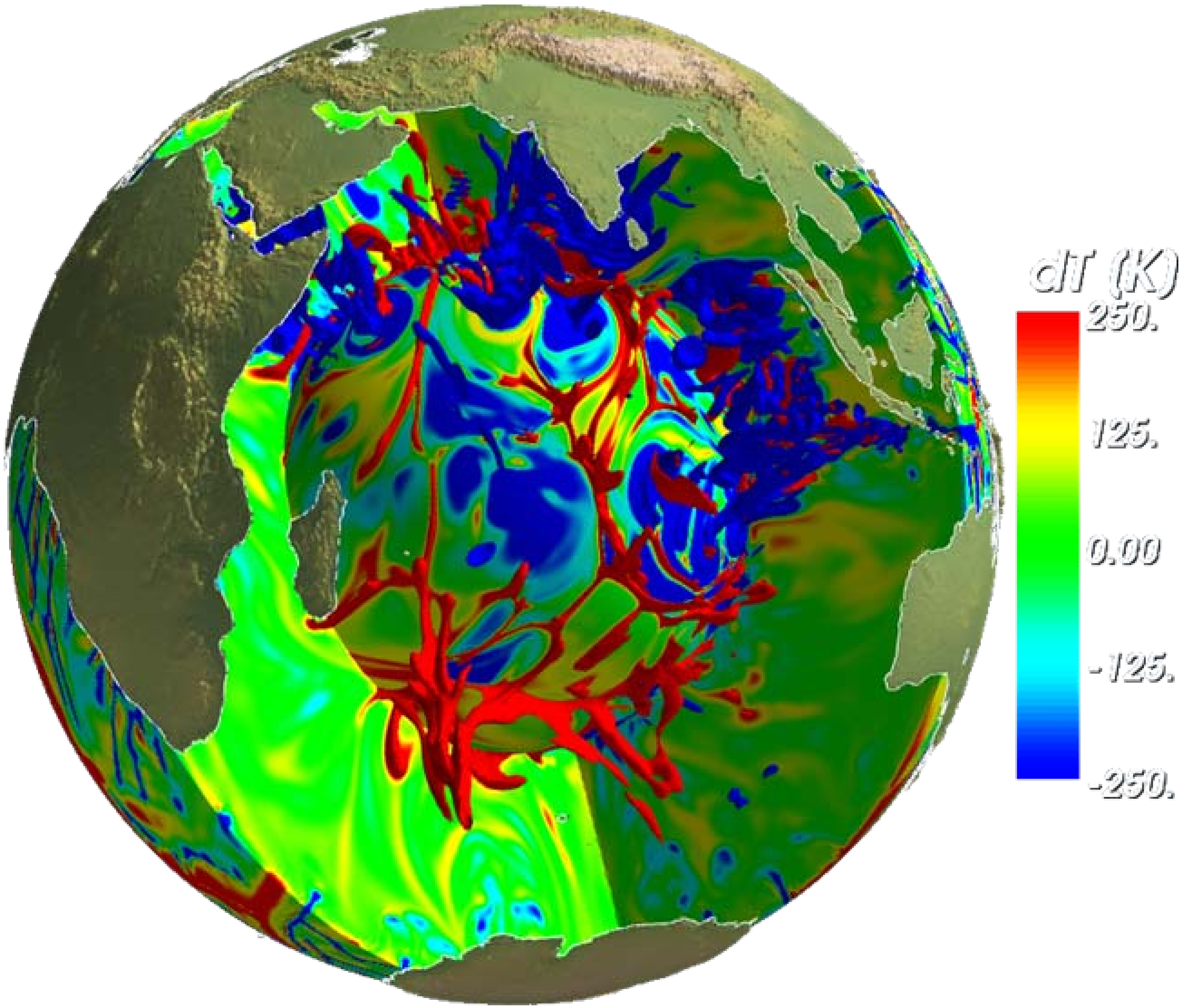





KAPI, Δ=11.4951 deg, black: data, red: synth
HNRO, Δ=28.6014 deg, black: data, red: synth
FITZ, Δ=12.6638 deg, black: data, red: synth
EIDS, Δ=26.6751 deg, black: data, red: synth
CTAX, Δ=19.8489 deg, black: data, red: synth
CTAO, Δ=19.8525 deg, black: data, red: synth
COEN, Δ=13.8636 deg, black: data, red: synth
CNBO, Δ=33.1725 deg, black: data, red: synth
CANO, Δ=33.0104 deg, black: data, red: synth
BBOO, Δ=26.5461 deg, black: data, red: synth
YNGO, Δ=31.8852 deg, black: data, red: synth
WRAB, Δ=13.6331 deg, black: data, red: synth
UGMO, Δ=20.5359 deg, black: data, red: synth
TOOO, Δ=33.5403 deg, black: data, red: synth
TAUO, Δ=38.9473 deg, black: data, red: synth
STKA, Δ=27.0295 deg, black: data, red: synth
PMGO, Δ=16.044 deg, black: data, red: synth
MTNO, Δ=6.1915 deg, black: data, red: synth
LHIO, Δ=35.996 deg, black: data, red: synth
KMBL, Δ=26.2027 deg, black: data, red: synth


80 km
110 km
140 km
170 km
200 km
250 km
300 km
350 km
400 km
9°
18°
27°
36°
45°
120°
132°
144°
156°
168°
-8%
+8%
Δβ/β

Mantle convection



Issues

- What are the scales of heterogeneity in the global mantle convection system, and what are the chemical, thermal, and mineralogical causes of the multiscale heterogeneity?
- Are there large thermal plumes in the mantle, and are they related to surface hotspots?
- What are the nature and cause of deep mantle anisotropy?

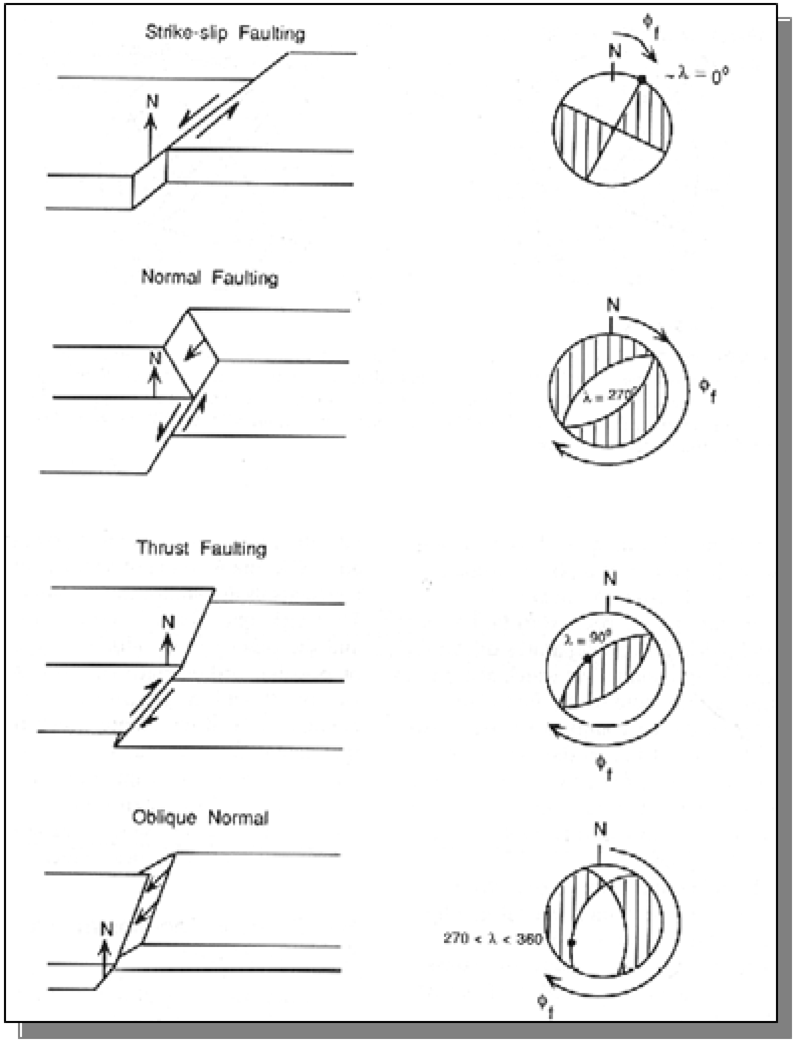
Summary

- Many of the fundamental question in Earth Sciences rest on results from the **analysis of seismograms**
- Seismology is a **data-rich** science, so (automated) processing of seismograms is essential
- The two key goals of seismic data analysis are the understanding of (1) the **seismic source** and (2) the **Earth‘s structure**
- Achieving both goals requires several **data processing** steps and a theory for **data fitting (inversion)**
- A recent – fundamentally new development – is the use of seismic noise and **correlation techniques** to do tomography and to detect temporal changes of Earth‘s structure -> **passive imaging**

Appendix:
The seismology primer
(qualitative)

- Earthquakes and seismic sources
- Seismic waves
- Fundamental spectral analysis

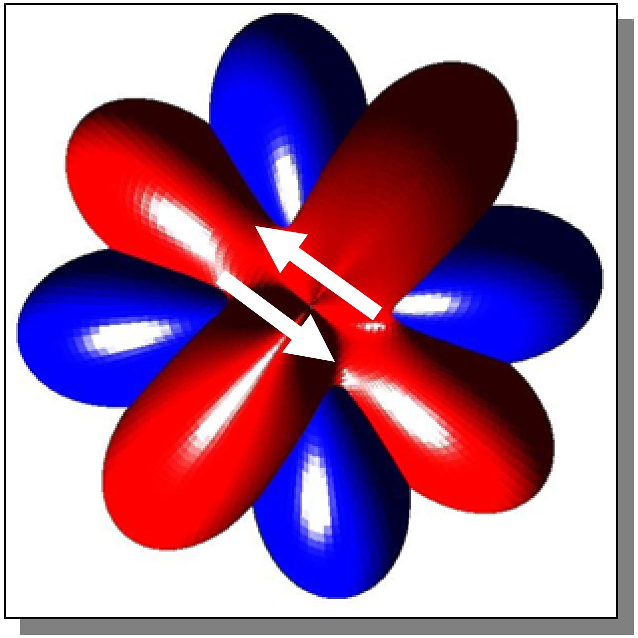
Source mechanisms

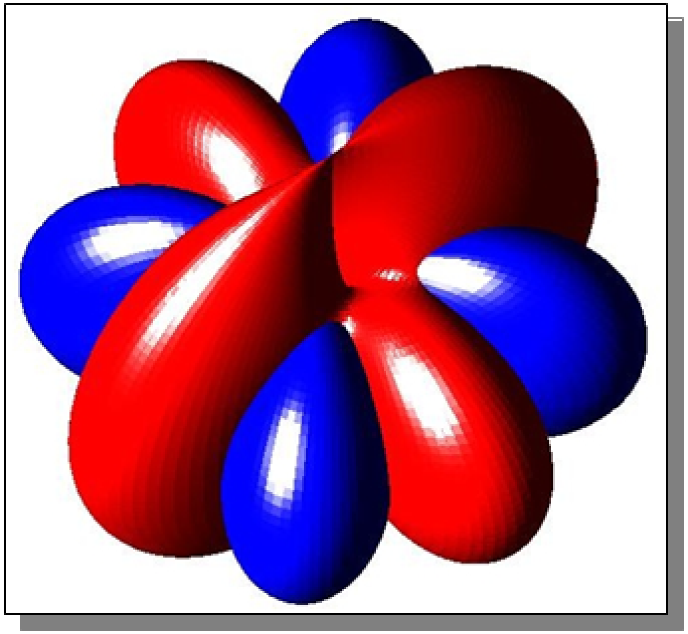


Basic fault types and their appearance in the focal mechanisms. Dark regions indicate compressional P-wave motion.

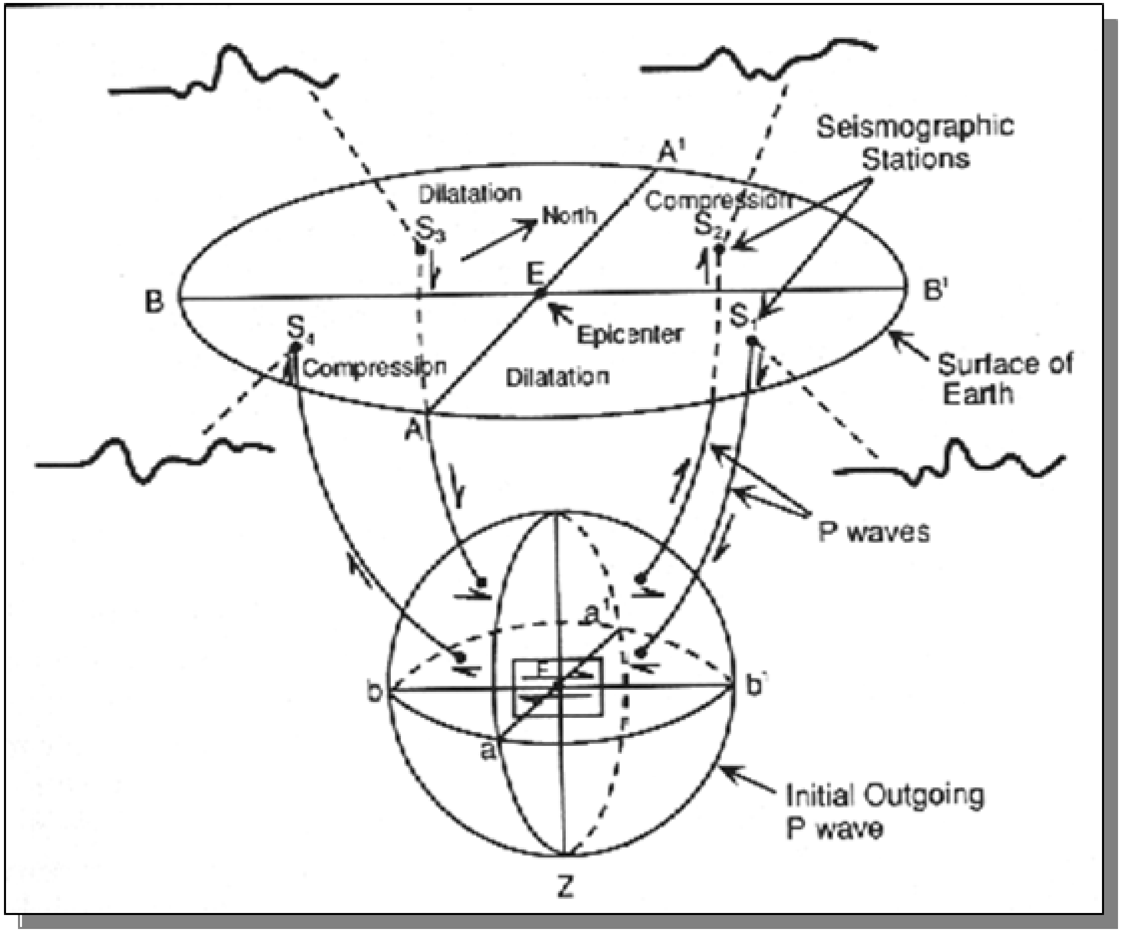
Radiation patterns of a double couple point sources

Far field P – blue
Far field S - red





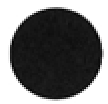
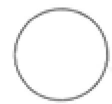
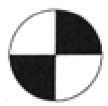
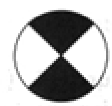
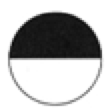
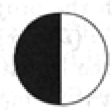
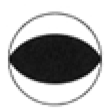
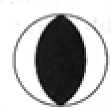
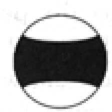
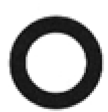
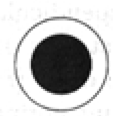
Radiation from shear dislocation



First motion of P waves at seismometers in various directions.

The polarities of the observed motion is used to determine the point source characteristics.

Beachballs and moment tensor

Moment Tensor	Beachball	Moment Tensor	Beachball
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&1\\0&1&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&1&0\\0&0&-1\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&1\\0&0&0\\1&0&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&0&0\\0&0&-1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$	

explosion - implosion

vertical strike slip fault

vertical dip slip fault

45° dip thrust fault

compensated linear vector dipoles

Magnitude Scales – Richter and others

Local Magnitude M_L

M_L = log A – log A_0 -log A_0 from tables or

M_L = log A + 0.003R + 0.7 R distance in km, A in mm

Domain: R < 600km

Surface wave magnitude M_S

M_S = log(A /T)+1.66 logD + 3.3 T=18-22s, D=20-160°, h < 50km

Body wave magnitude M_b

M_b = log(A /T)+Q(D,h) T=0.1-3.0s

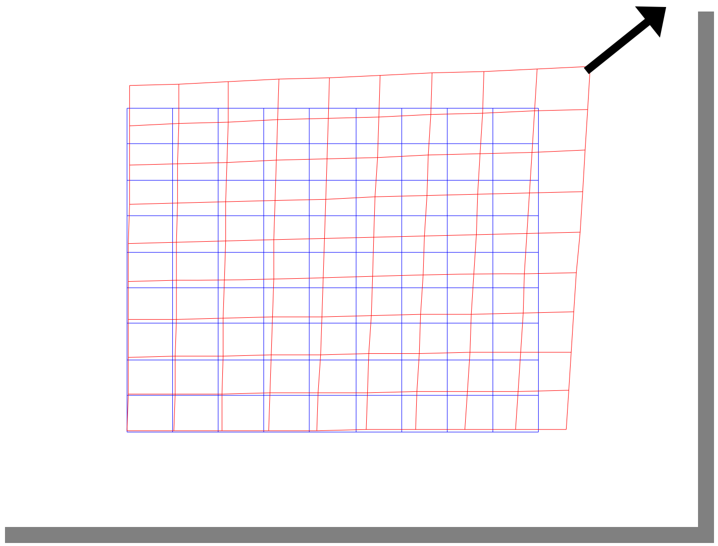
Moment magnitude M_w

M_w = 2/3 log M_0 – 10.7 M_0 scalar Moment

Stress and strain

To first order the Earth's crust deforms like an elastic body when the deformation (strain) is small.

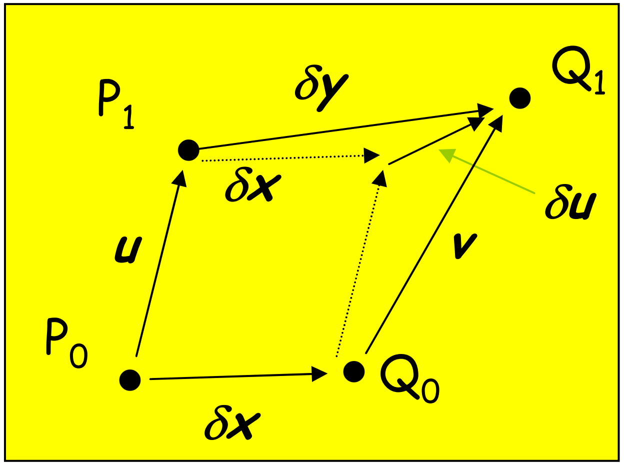
In other words, if the force that causes the deformation is stopped the rock will go back to its original form.



The change in shape (i.e., the deformation) is called strain, the forces that cause this strain are called stresses.

Linear Elasticity

The relative displacement in the unstrained state is u(r). The relative displacement in the strained state is v=u(r+ δx).



So finally we arrive at expressing the relative displacement due to strain:

$\delta u = u(r + \delta x) - u(r)$

We now apply Taylor's theorem in 3-D to arrive at:

$$\boxed{\delta u_i = \frac{\partial u_i}{\partial x_k} \delta x_k}$$

Stress-strain relation

The relation between stress and strain in general is described by the tensor of elastic constants c_{ijkl}

$$\boxed{\sigma_{ij} = c_{ijkl}\varepsilon_{kl}}$$

Generalised Hooke's Law

From the symmetry of the stress and strain tensor and a thermodynamic condition if follows that the maximum number if independent constants of c_{ijkl} is 21. In an isotropic body, where the properties do not depend on direction the relation reduces to

$$\boxed{\sigma_{ij} = \lambda\Theta\delta_{ij} + 2\mu\varepsilon_{ij}}$$

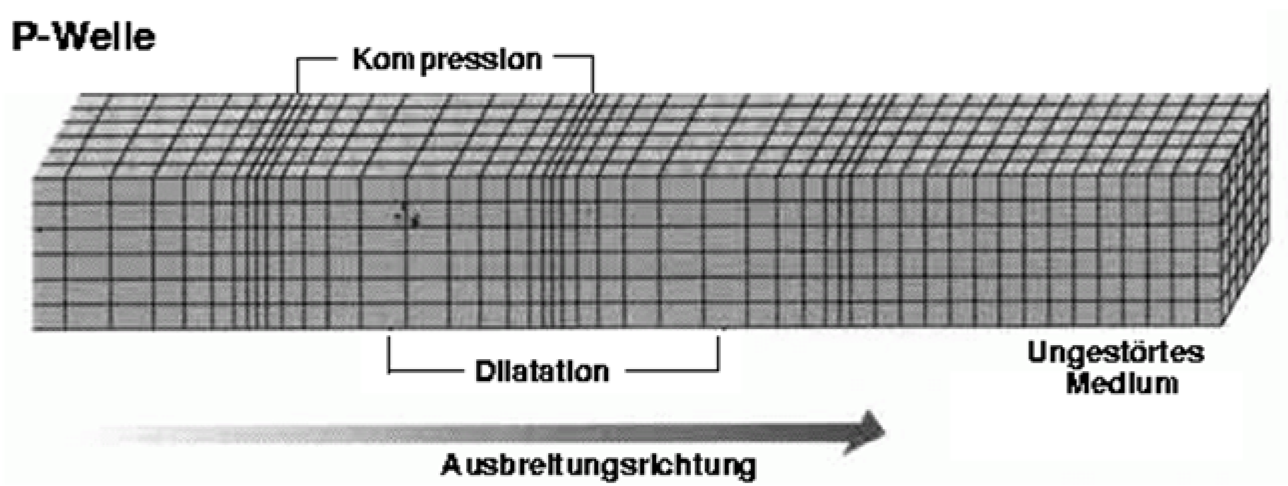
Hooke's Law

where l and m are the Lame parameters, q is the dilatation and d_{ij} is the Kronecker delta.

$$\Theta\delta_{ij} = \varepsilon_{kk}\delta_{ij} = \left(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}\right)\delta_{ij}$$

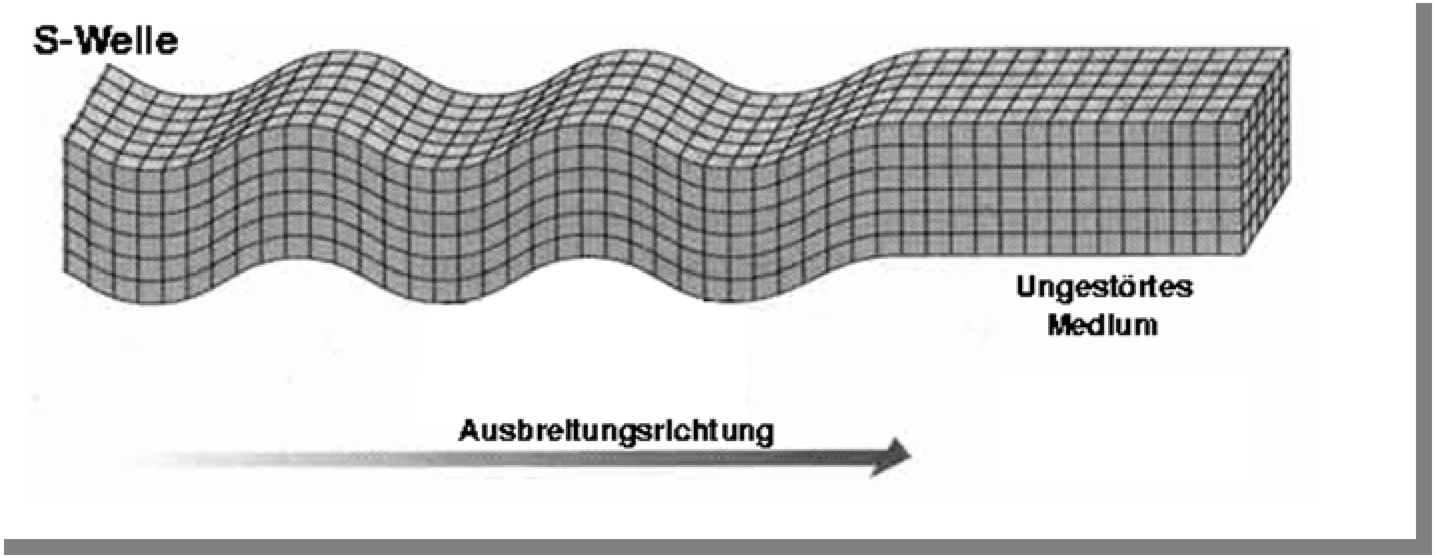
Seismic wave types
P - waves

P – primary waves – compressional waves – longitudinal waves



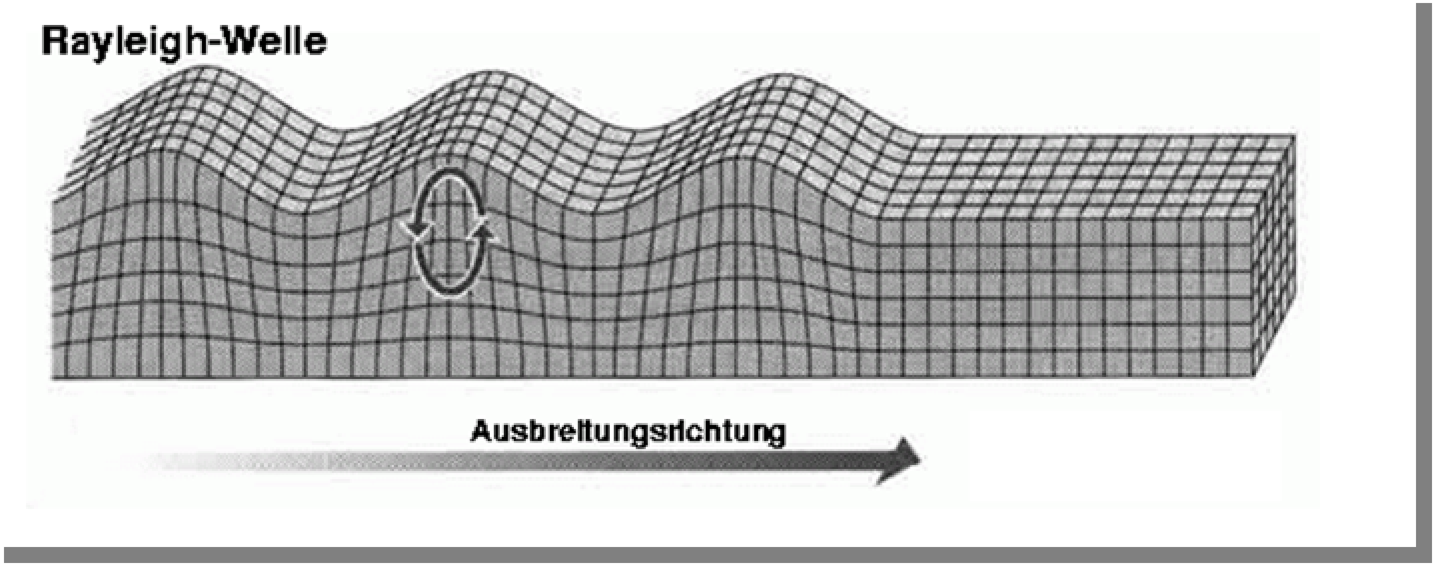
Seismic wave types
S - waves

S – waves – secondary waves – shear waves – transverse waves



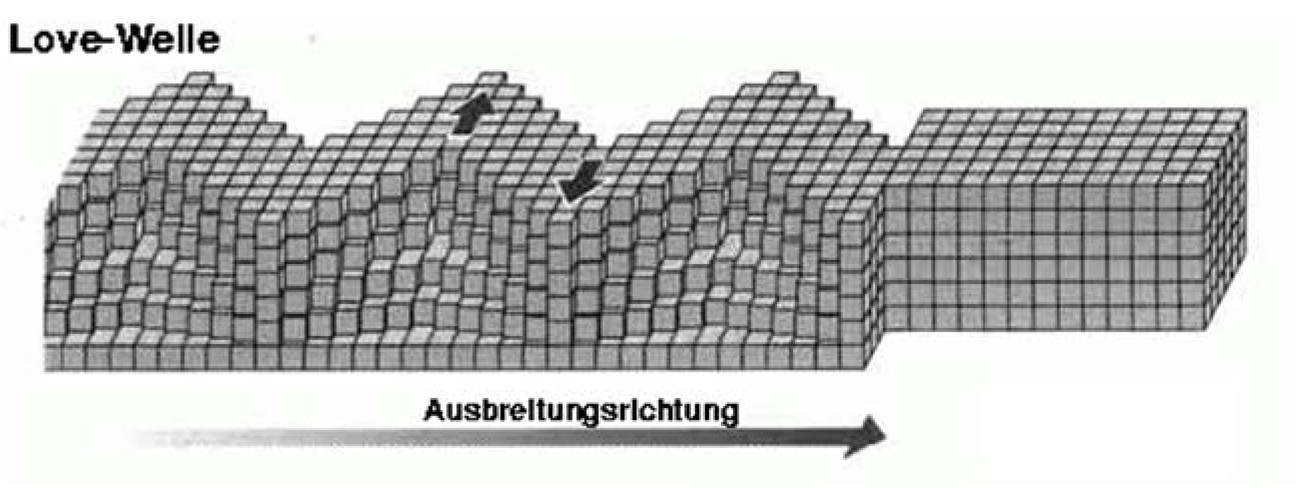
Rayleigh waves

Rayleigh waves – polarized in the plane through source and receiver – superposition of P and SV waves



Seismic wave types
Love waves

Love waves – transversely polarized – superposition of SH waves in layered media



Seismic wave velocities

Seismic wave velocities strongly depend on

- rock type (sediment, igneous, metamorphic, volcanic)
- porosity
- pressure and temperature
- pore space content (gas, liquid)

$$v = \sqrt{\frac{ElasticModuli}{Density}}$$

P-waves

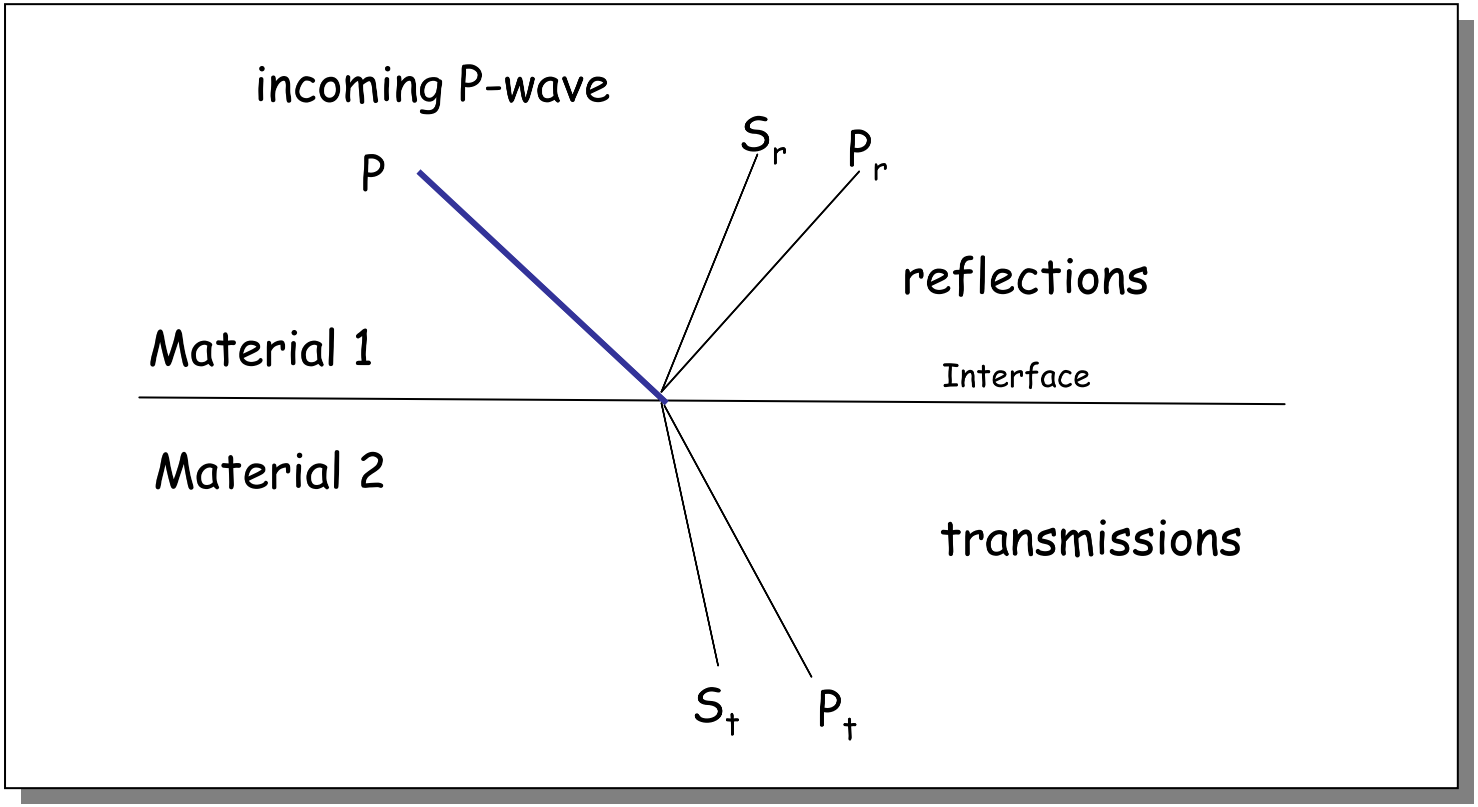
$$v_p = \sqrt{\frac{\lambda + 2\mu}{\rho}}$$

S-waves

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

Reflection and transmission at boundaries
oblique incidence - conversion

P waves can be converted to S waves and vice versa. This creates a quite complex behavior of wave amplitudes and wave forms at interfaces. This behavior can be used to constrain the properties of the material interface.



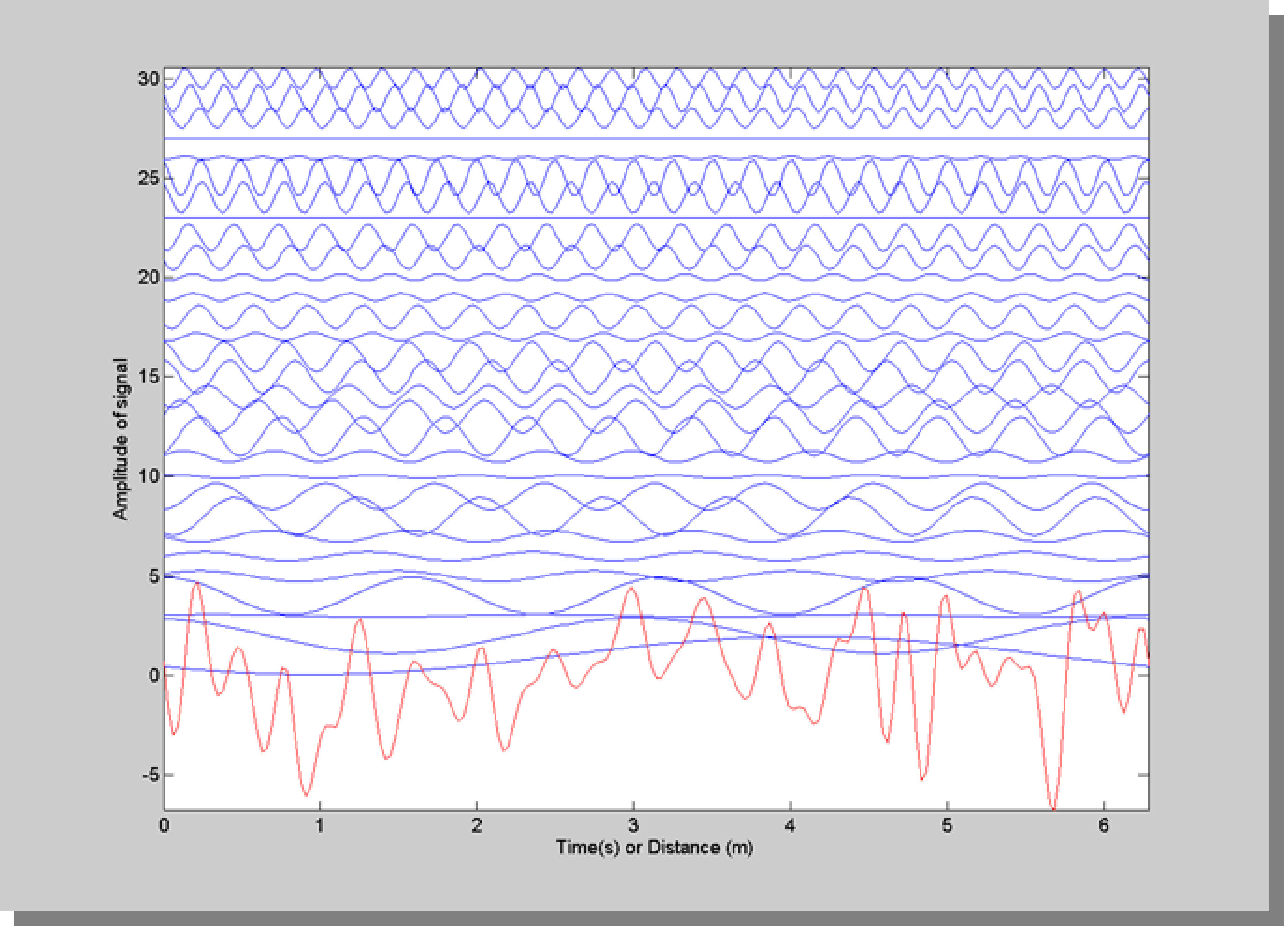
Harmonic Analyis – Spectral Synthesis

At the heart of spectral analyis is an extremely powerful concept, that is one of the most important theorems in mathematical physics:

> Any arbitrary periodic signal can be obtained by superposition of harmonic (sinusoidal) signals.

Furthermore: the representation of physical systems in time and space or in frequency and wavenumber domain is equivalent! There is no loss of information when going from one space to the other and back.

Spectral synthesis



The red trace is the sum of all blue traces!

Amplitude spectrum

Phase spectrum

Fourier space

Physical space