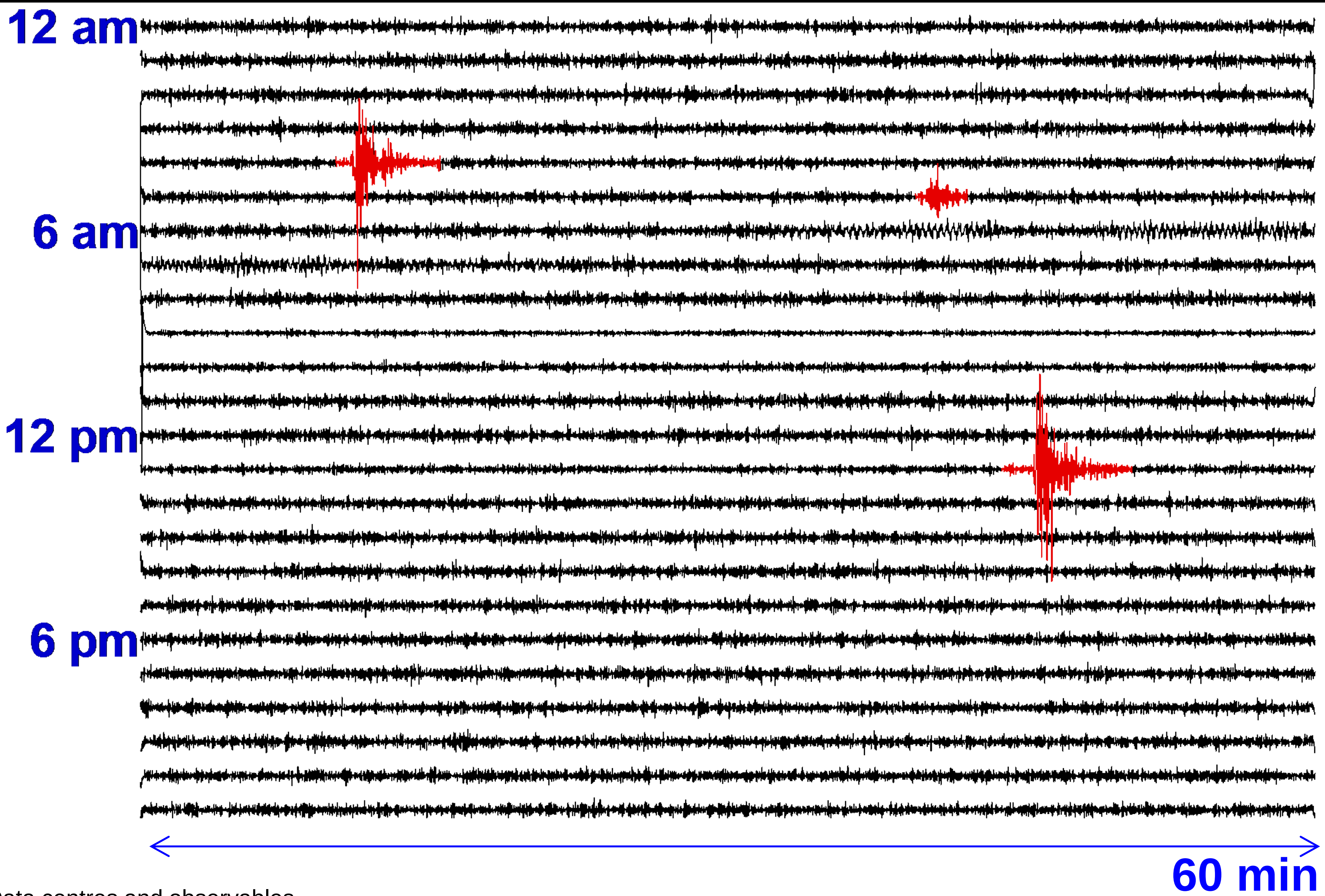
Data in seismology: networks, instruments, current problems

- Seismic networks, data centres, instruments
- Seismic observables and their interrelations

Earthquake service, seismic experiments, seismometer configurations, seismic network design

Earthquake / Noise

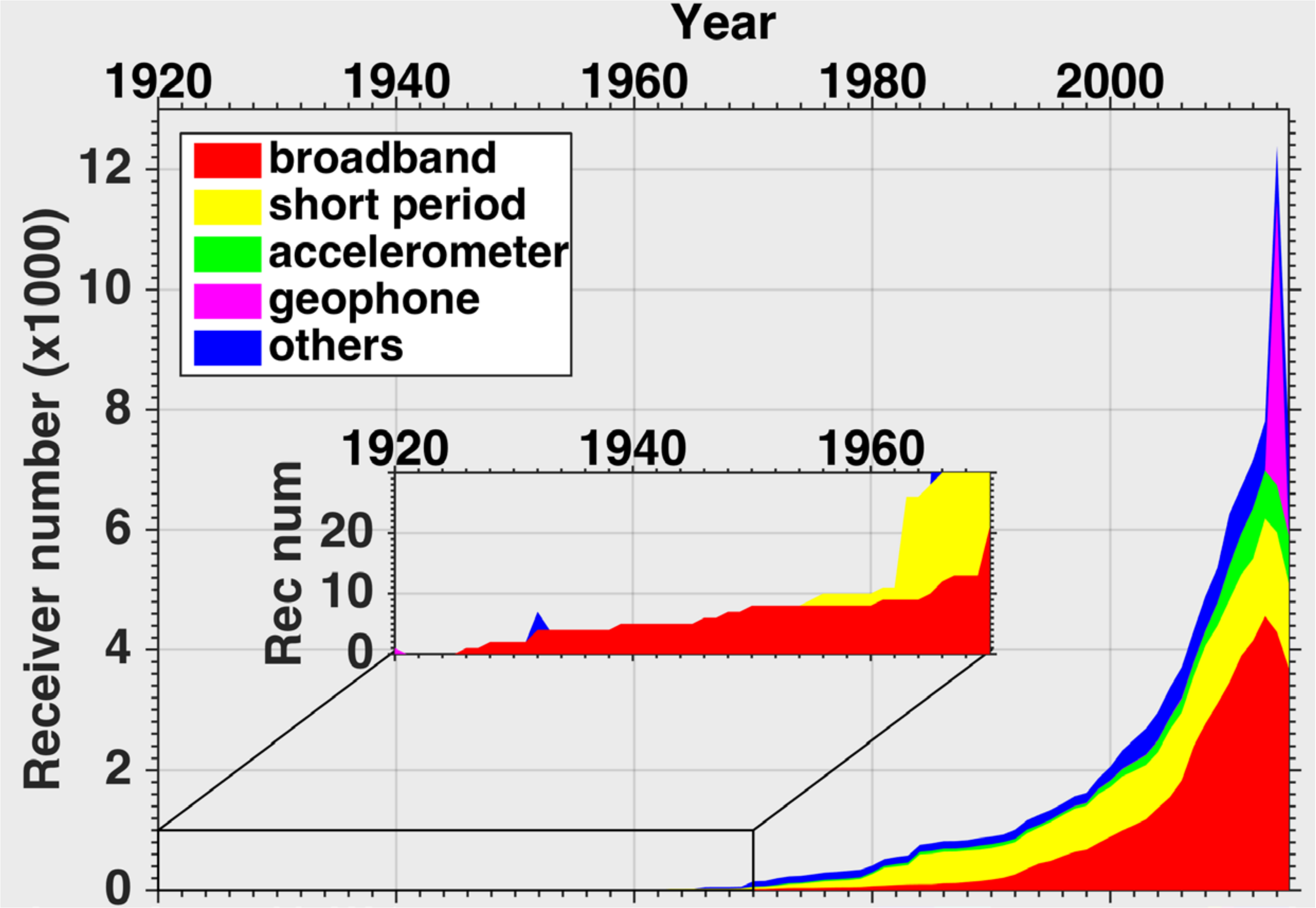


Seismic observables: Period ranges (order of magnitudes)

- Sound 0.001 – 0.01 s
- Earthquakes 0.01 – 100 s (surface waves, body waves)
- Eigenmodes of the Earth 1000 s
- Coseismic deformation 1 s – 1000 s
- Postseismic deformation +10000s
- Seismic exploration 0.001 - 0.1 s
- Laboratory signals 0.001 s – 0.000001 s

-> What are the consequences for sampling intervals, data volumes, etc.?

Seismometers



From Nakata

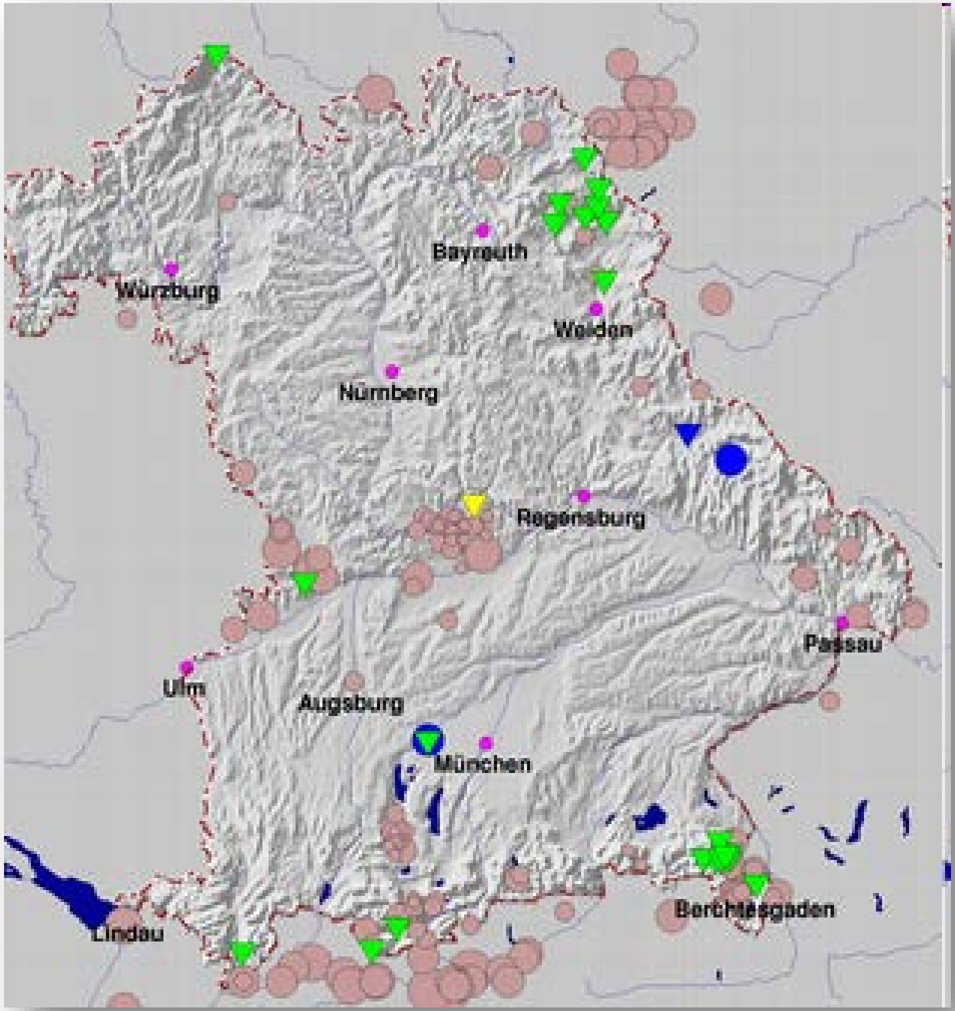
Passive vs. active experiments

- Passive
  - Natural sources (earthquakes, noise)
  - Long-term (weeks to decades)
  - Earthquake service
  - Volcano Monitoring
  - Global Tomography

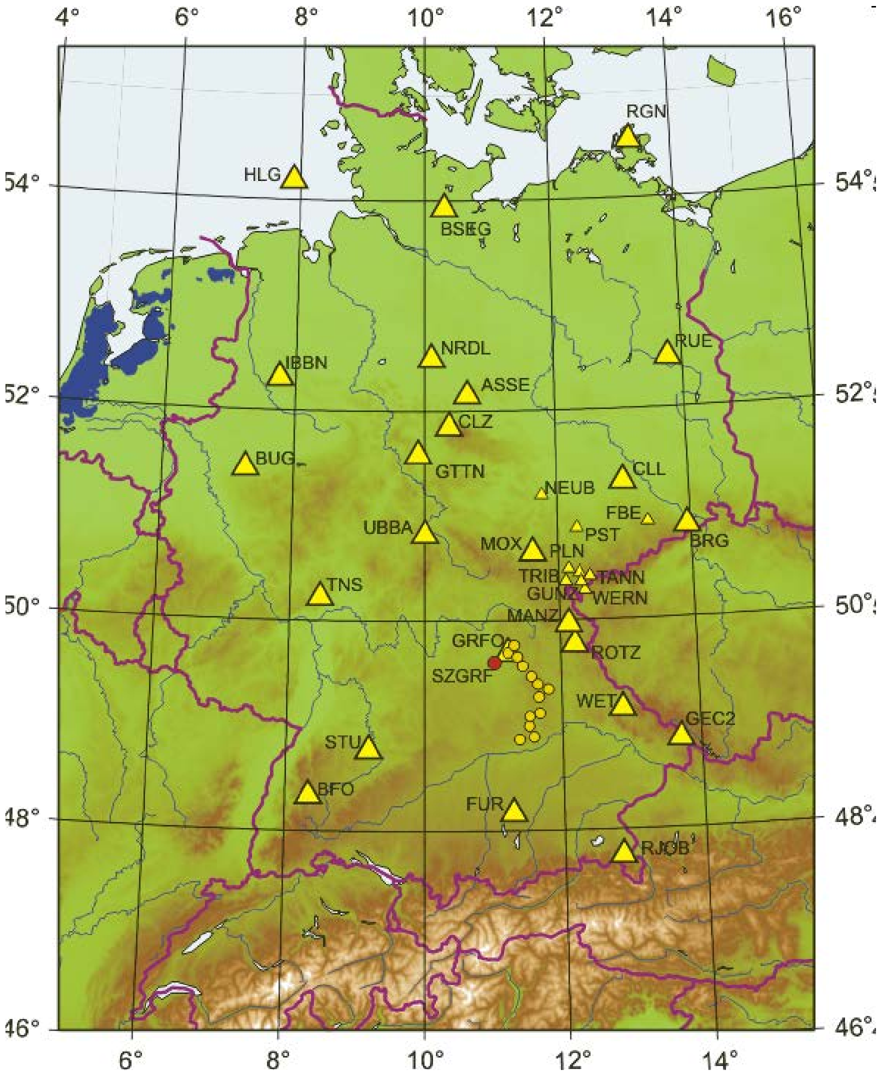
- Active
  - Man made sources (explosions, hammer, piezo, laser)
  - Crustal, near surface tomography
  - Hydrocarbon exploration
  - Reflection, refraction

Passive Experiments
(monitoring, earthquake service)

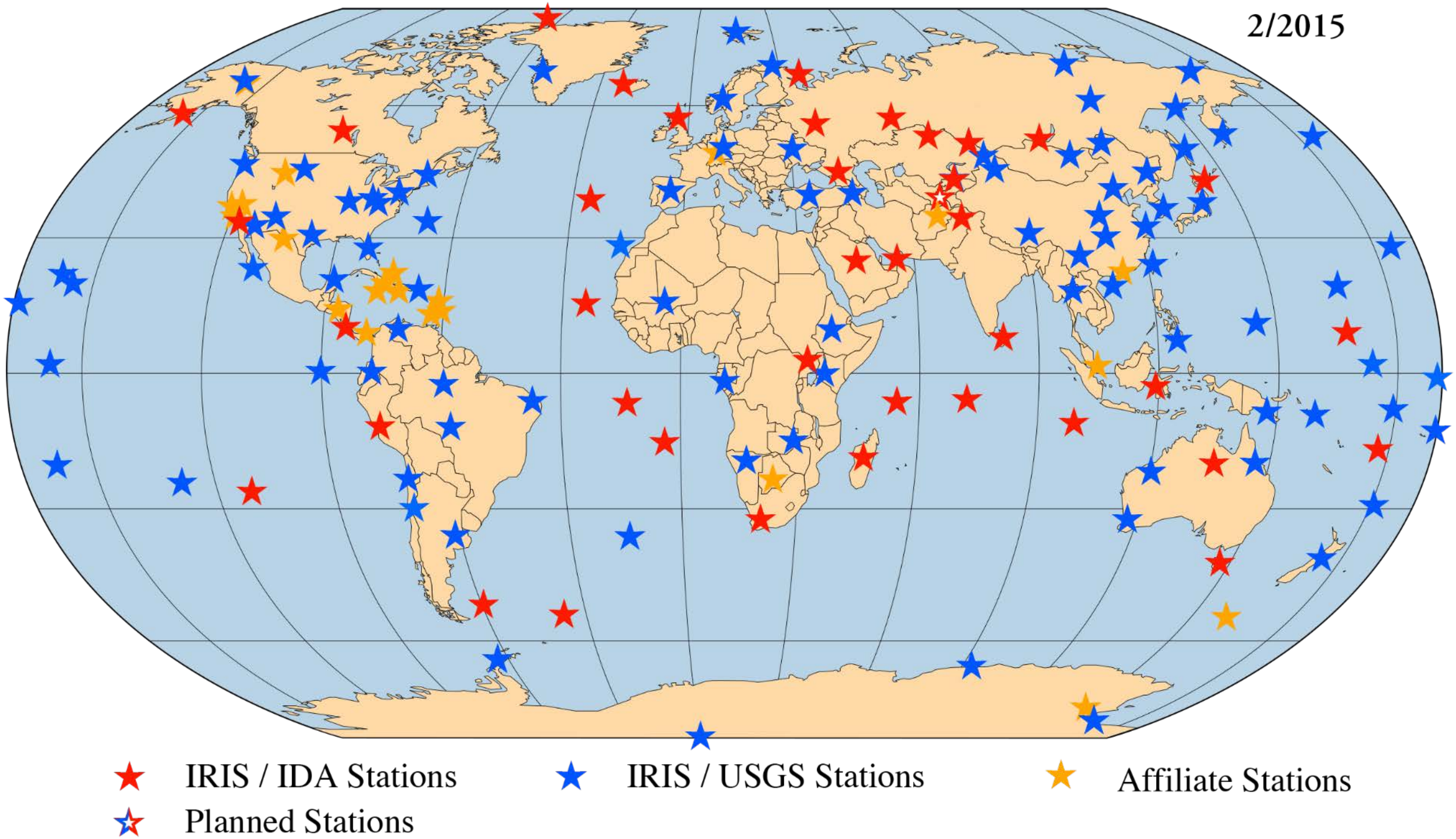
Local seismic networks



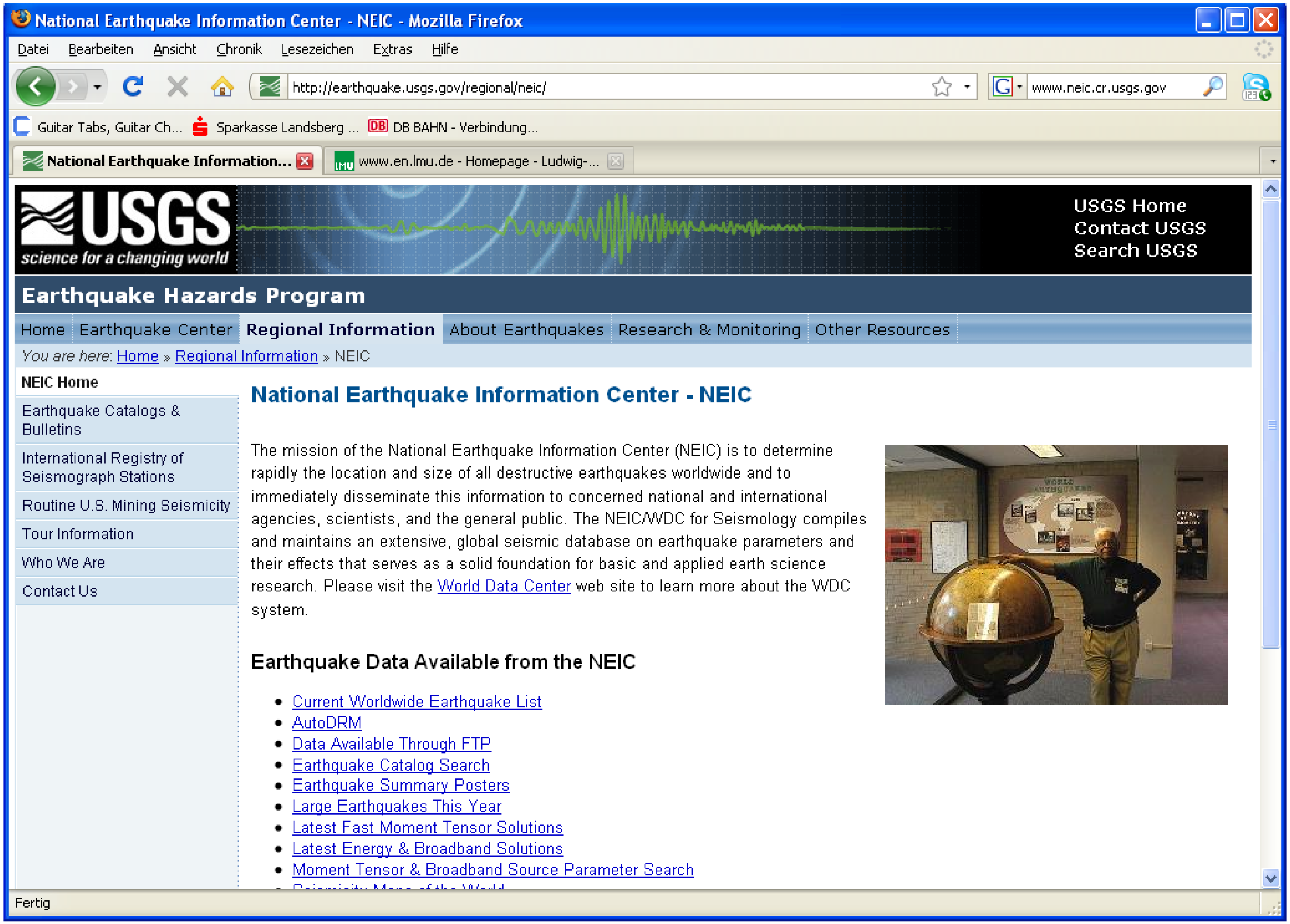
Regional seismic networks



Global seismic networks (FDSN)



Seismic data centres: NEIC



Detecting earthquakes – Earthquake service

Tasks:

- Determine origin time and location of earthquake
  - Hypocentre, epicentre
- Determine earthquake source mechanism
- Determine tsunami risk (where applicable)
- (near real time estimate) of seismic intensity (damage)
- Receive damage reports, create intensity maps
- Communicate to public, inform agencies
- Expert service (damage)

Was ging so völlig daneben?

Christchurch, Februar 2011

Tohoku-Oki, März 2011

Erdbeben und Tsunamis

- Erdbeben

P-Wellen ca. 6km/s

Oberflächenwellen ca 3km/s

Transmission von Information zum Datenzentrum mit nahezu Lichtgeschwindigkeit

- Tsunamis

Erzeugung abhängig von Herdmechanismus

Ausbreitungsgeschwindigkeit

$$c = \sqrt{gh}$$

g=9,81 m/s²

h Meerestiefe (m)

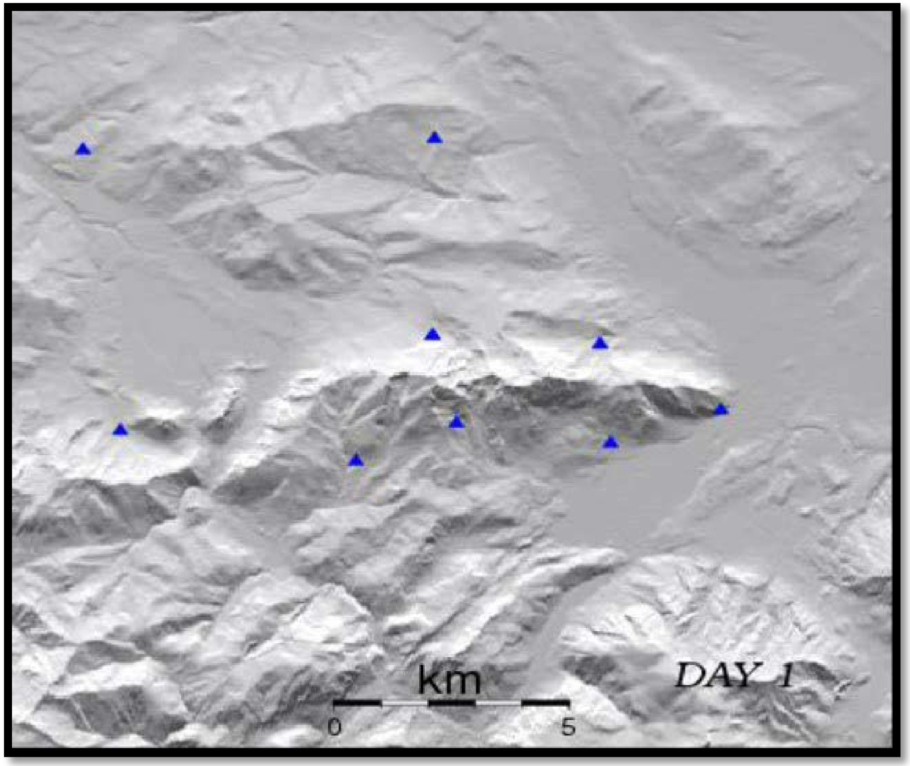
Typische Wellenlängen 100-500km

Passive Experiments

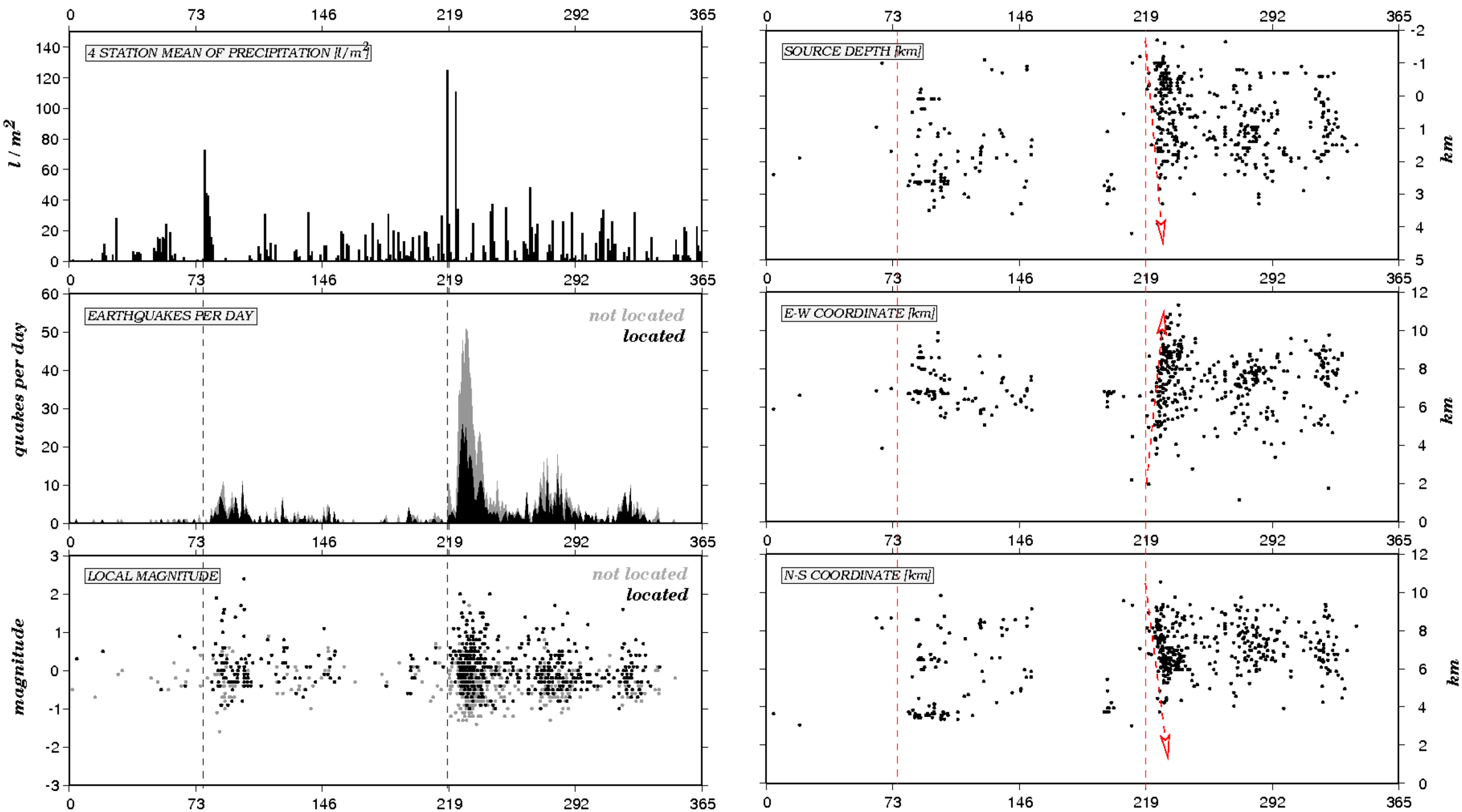
(campaign data, time-limited)

Seismizität 2002

... Die Regenfälle, die im August zum Hochwasser führten, hatten ihren Höhepunkt am Tag 218 ...

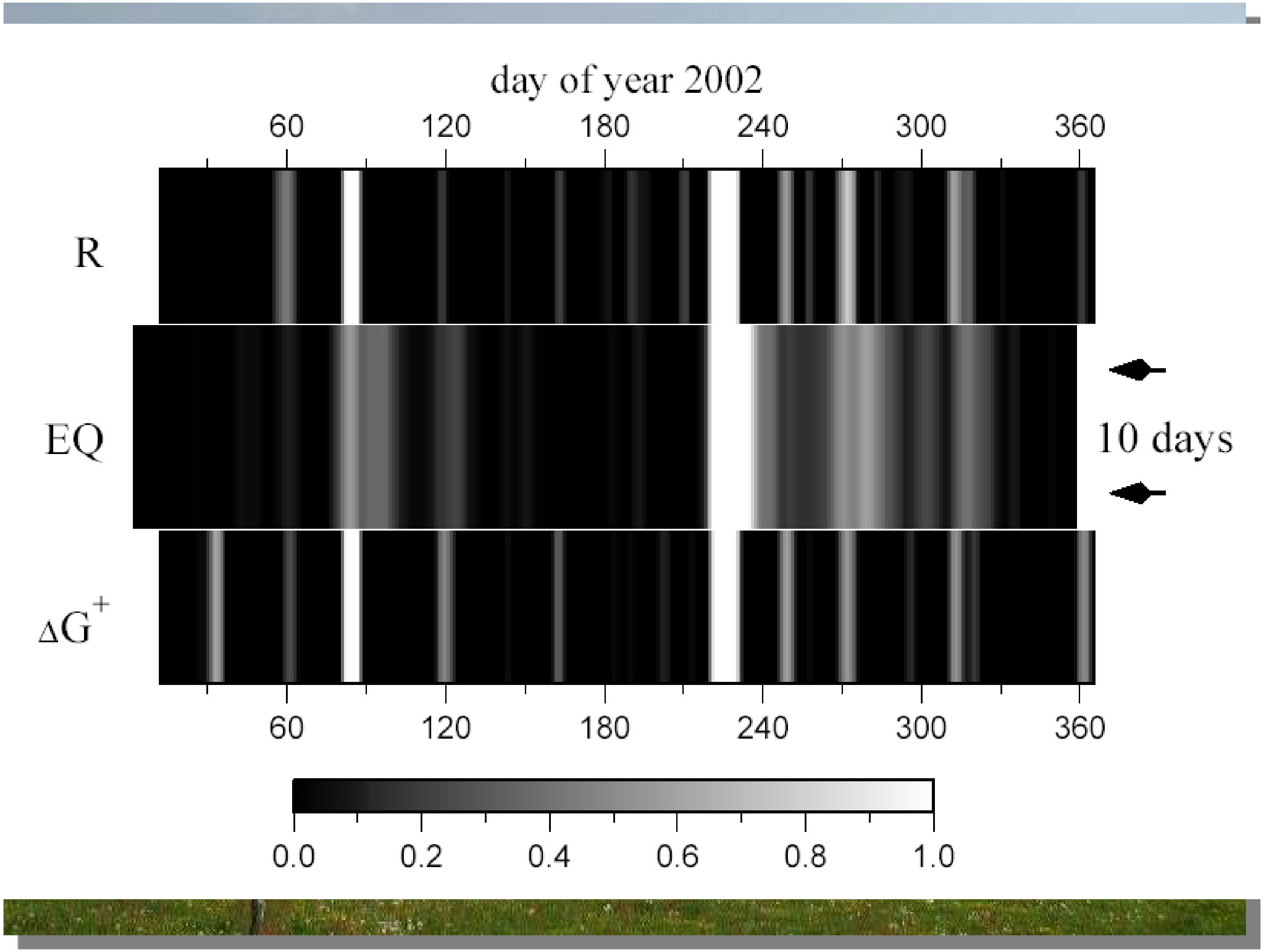


Observations

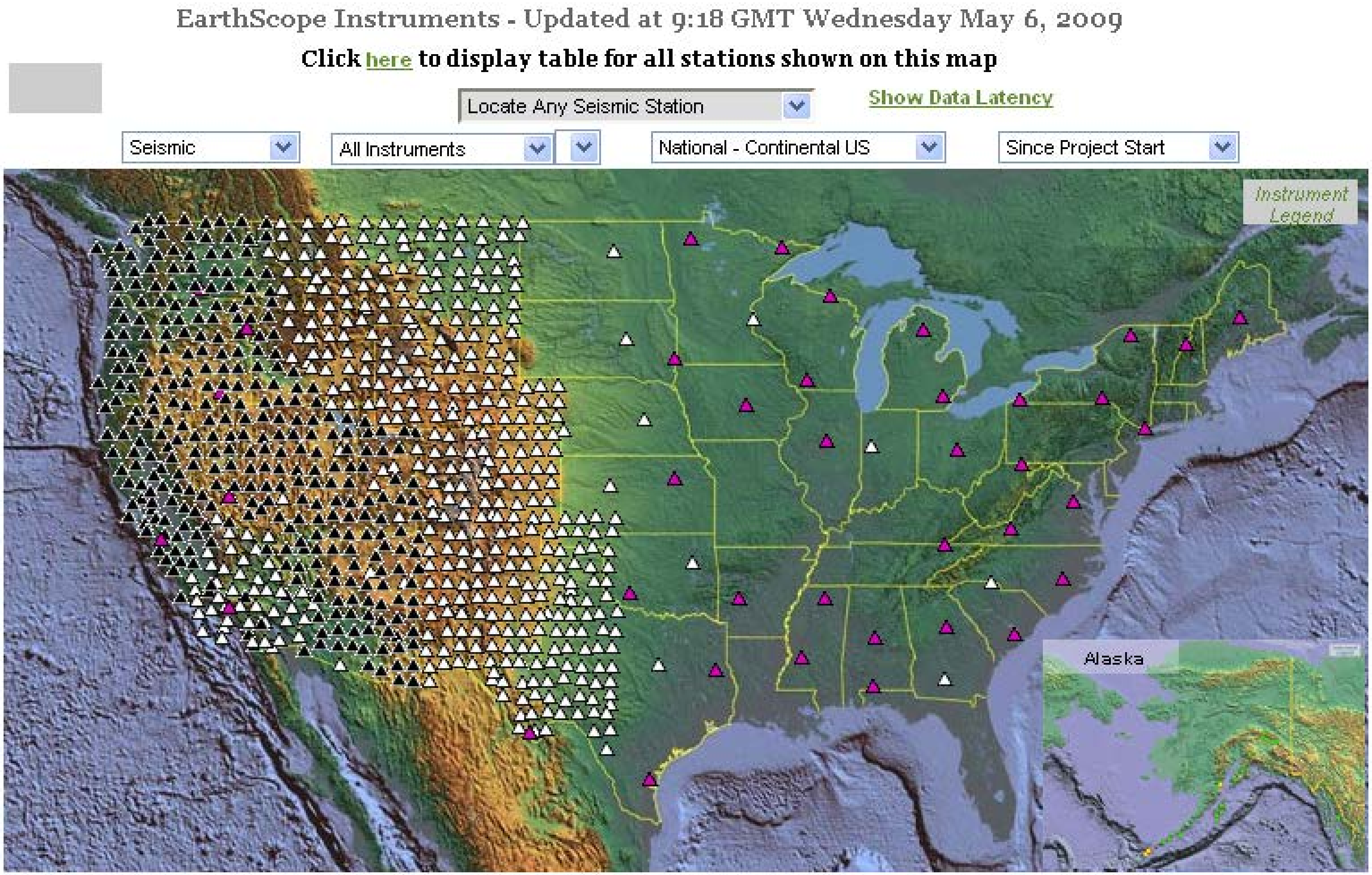


(Kraft et al., GJI, 2006)

Externer Einfluss auf Erdbeben?

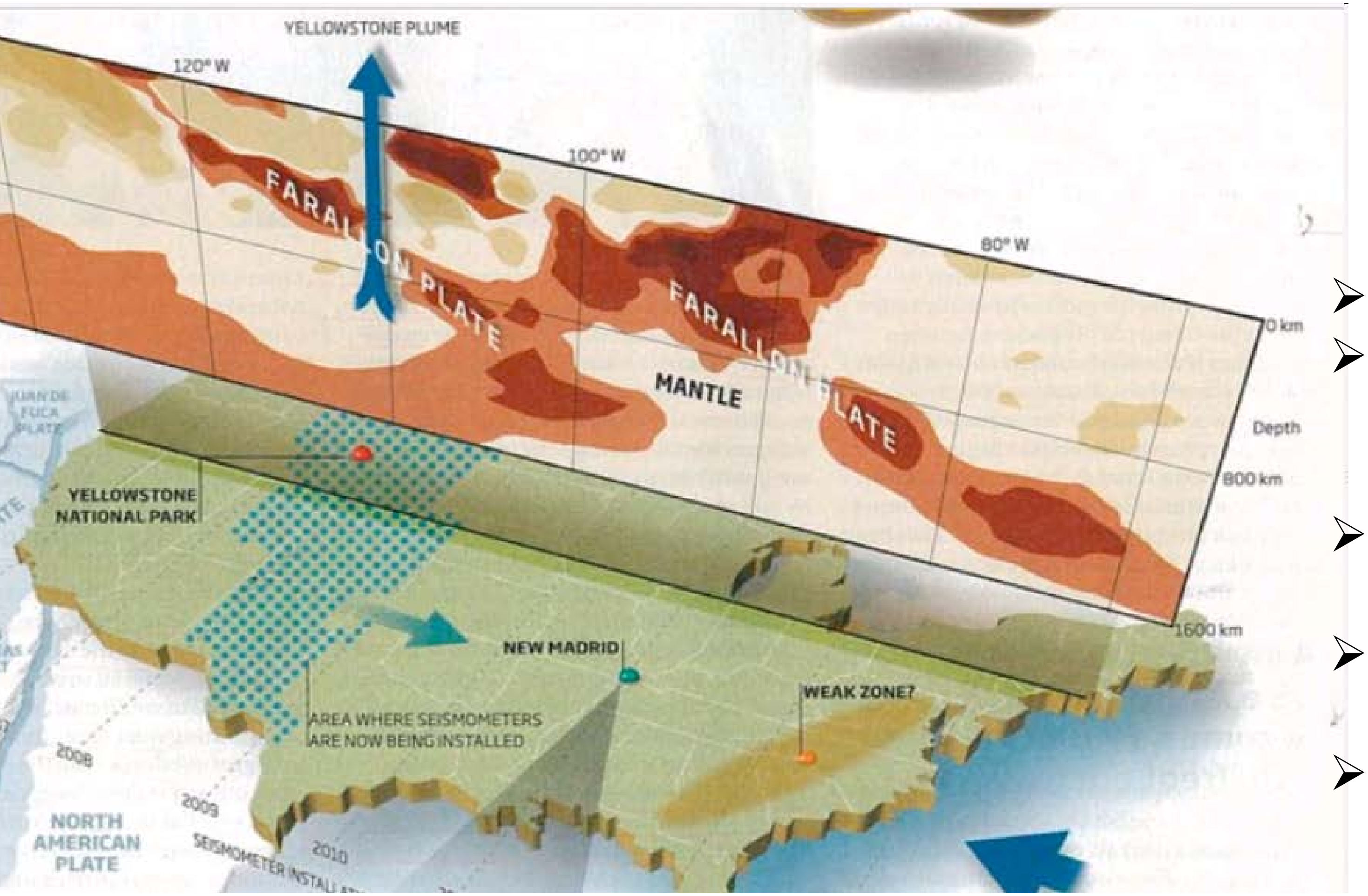


US Array – Big Foot



US Array - Observations

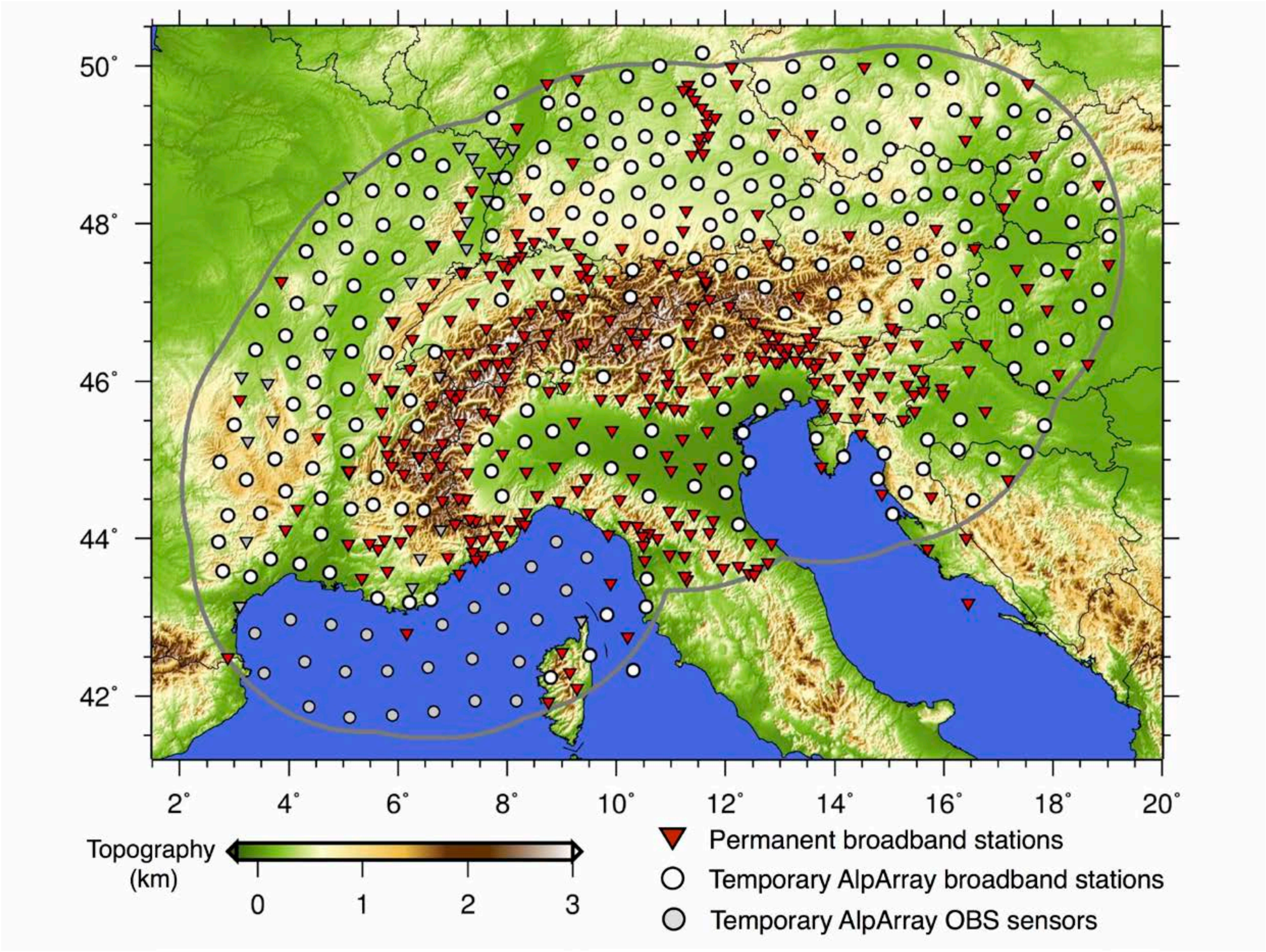
Science with US Array



- Fact or fiction?
- Significant geodynamic feature?
- Amplitude correct?
- Spatial scale correct?
- Depth correct?

From Sigloch et al.

Current Experiments: AlpArray



Goals with regional networks

- Tomography under the Alps
- Understanding alpine tectonics
- Montoring seismicity
- Investigating time-dependence
  - Deglaciation
  - External forcing (defrosting, rain)
- Ambient noise observations
- Seismic signals of rockfalls – passive monitoring

Tectonics Indian Ocean

Objectives

- Imaging upper and lower mantle structures beneath La Réunion hotspot

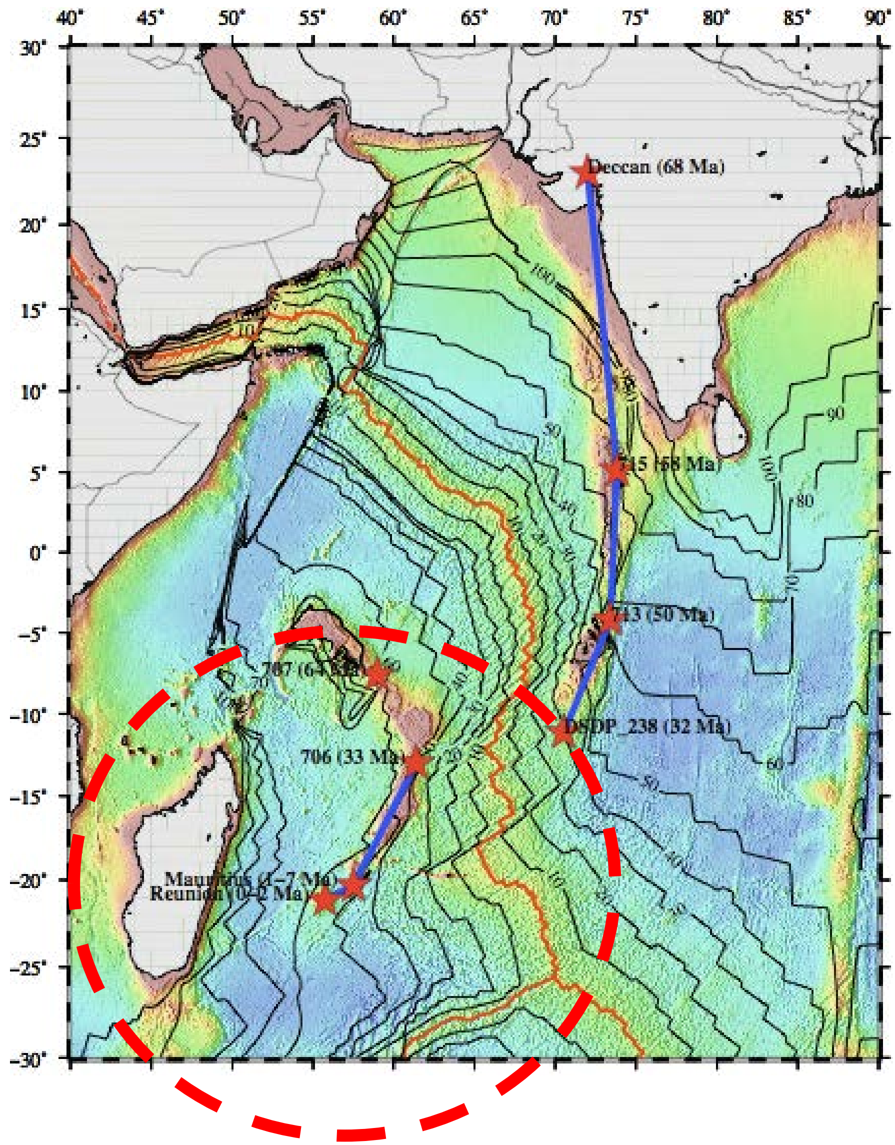
- Relationships with the south African superplume

- Signature in the transition zone

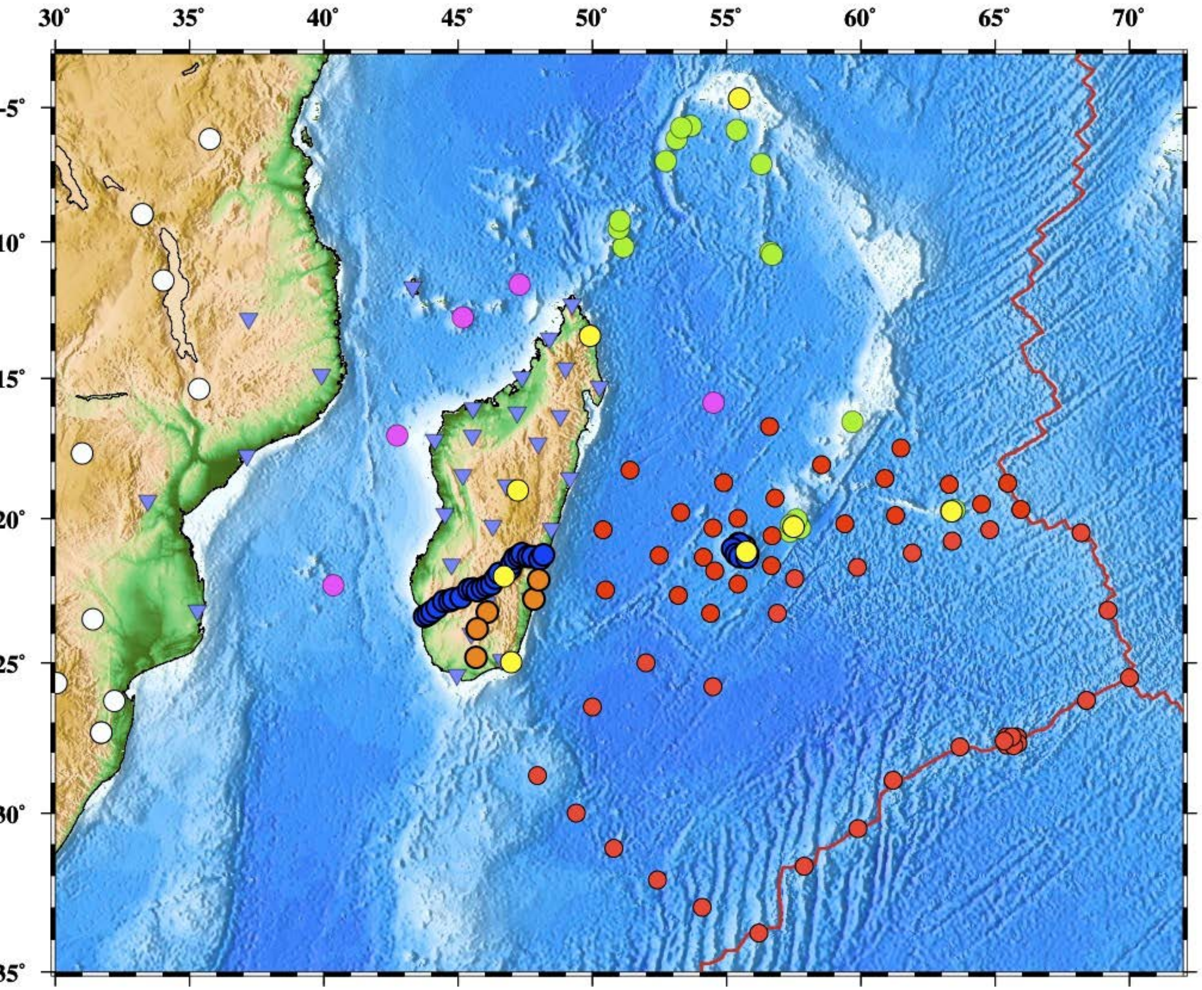
- Plume-lithosphere interactions, mantle flow, influence of pre-existing structures (ridges, transforms)

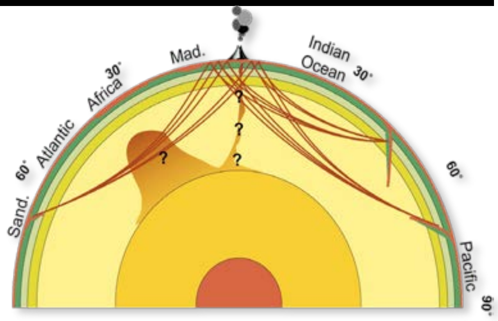
- Plume – ridge interaction – role of the Rodrigues ridge

- Plume signature with the surface observables (Bathymetry, gravimetry, magnetism).



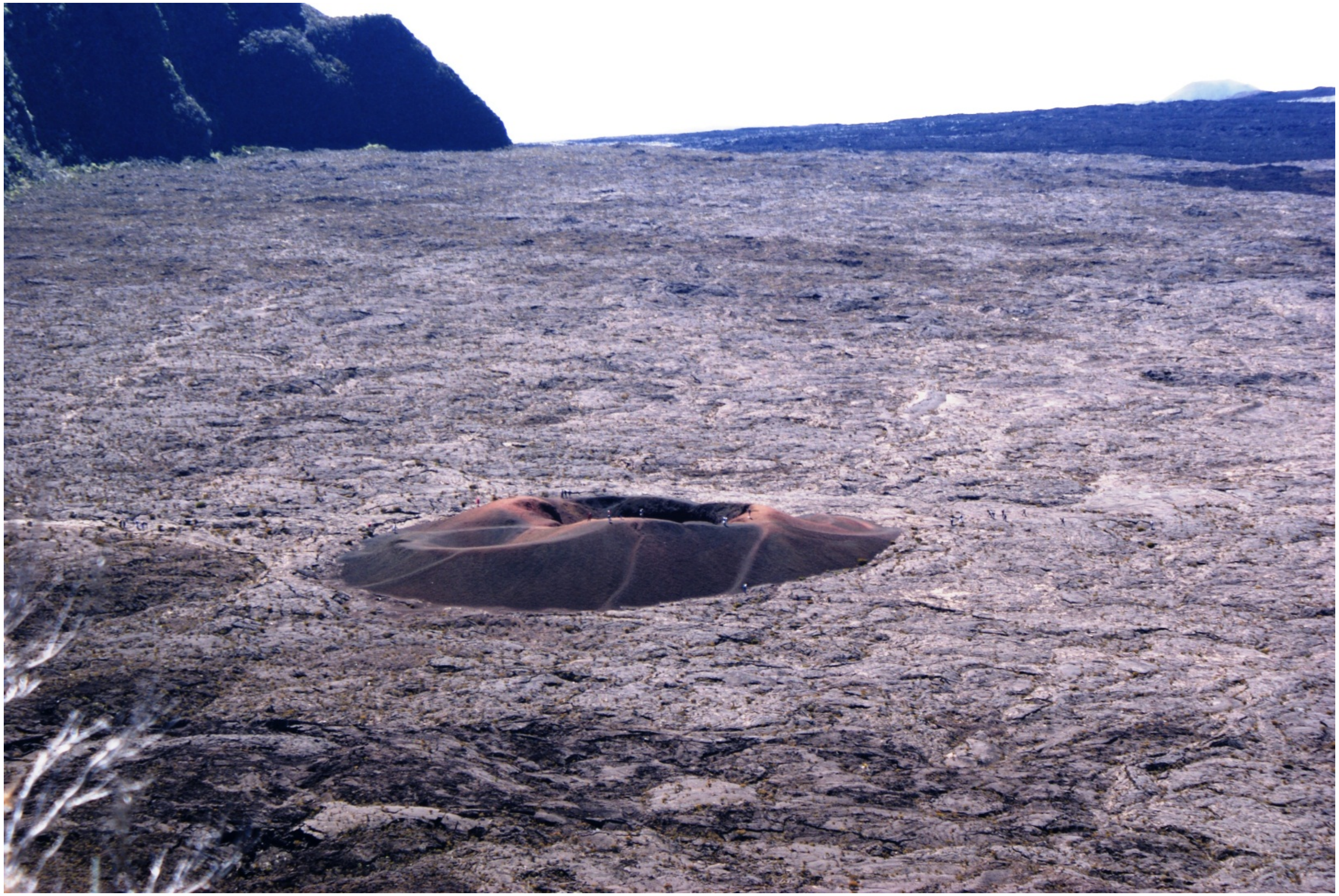
RHUM-RUM project





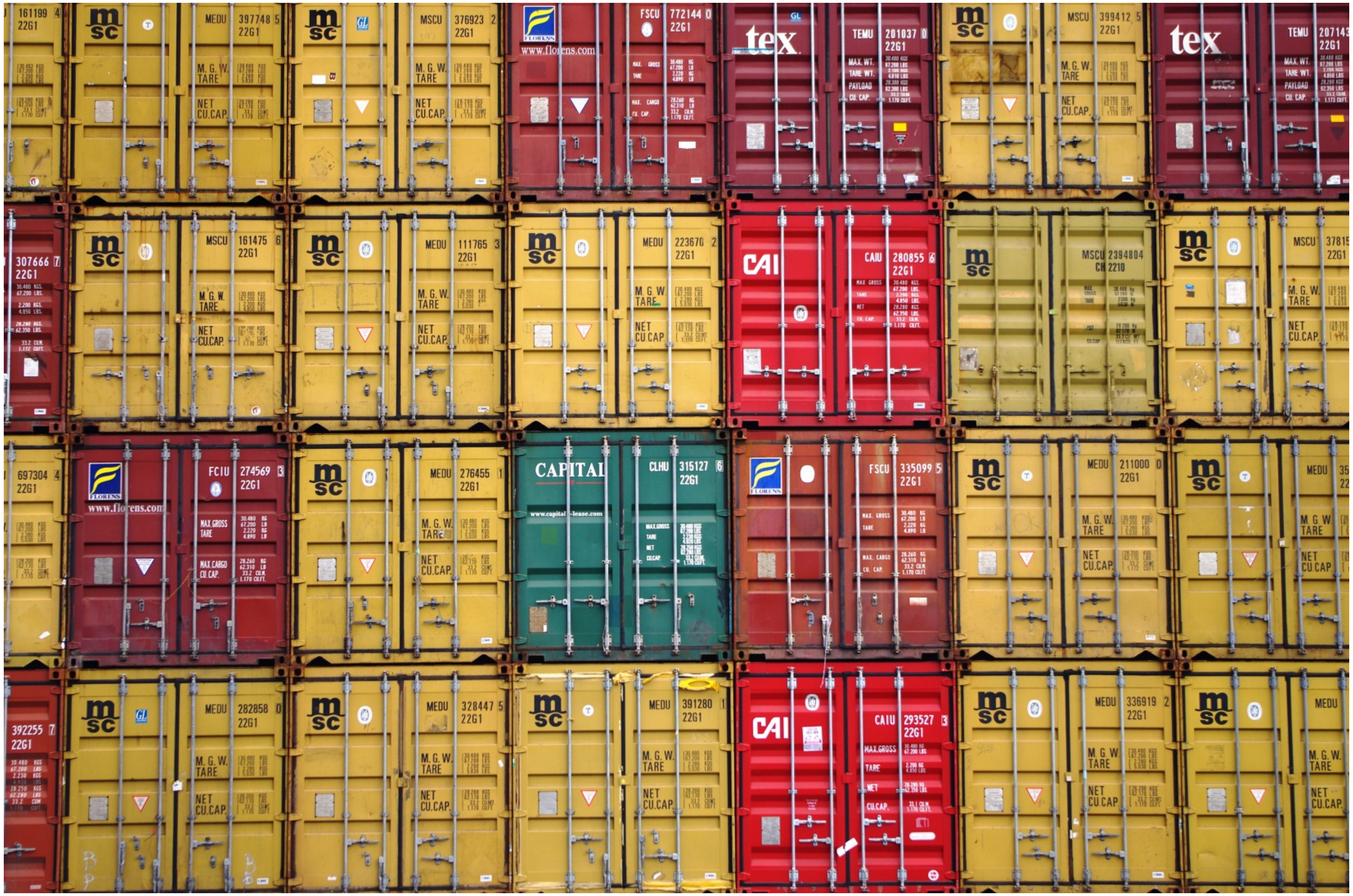
- 57 OBS RHUM-RUM
- Stations permanentes
- 12 stations DEPAS
- Seychelles – Mauritius - Rodrigue
- 25 stations GFZ Madagascar
- Stations AfricArray
- 5 stations RHUM Iles Eparses
- 30 stations US MACOMO
- 5 stations RHUM Madagascar

Lava lake 2007 La Reunion



Marion Dufresne

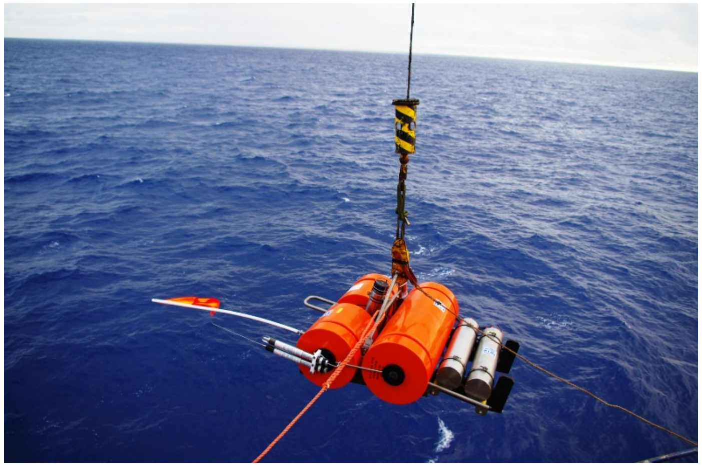
What we needed …



... but then ...

Ocean bottom seismometer experiments

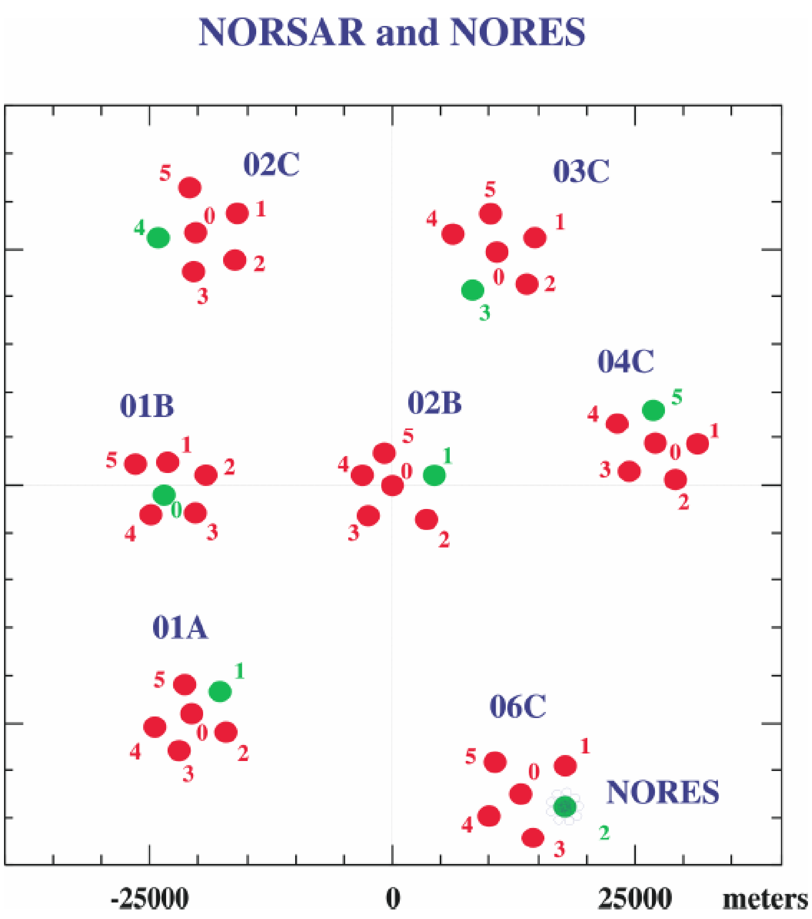
- OBS systems are expensive
- Risk of loss during experiment
- Ship time required – expensive
- Very noisy data (poor data quality)
- Special requirements for sensors (low power consumption)
- Timing problems (no GPS access at seafloor)
- National OBS pools available

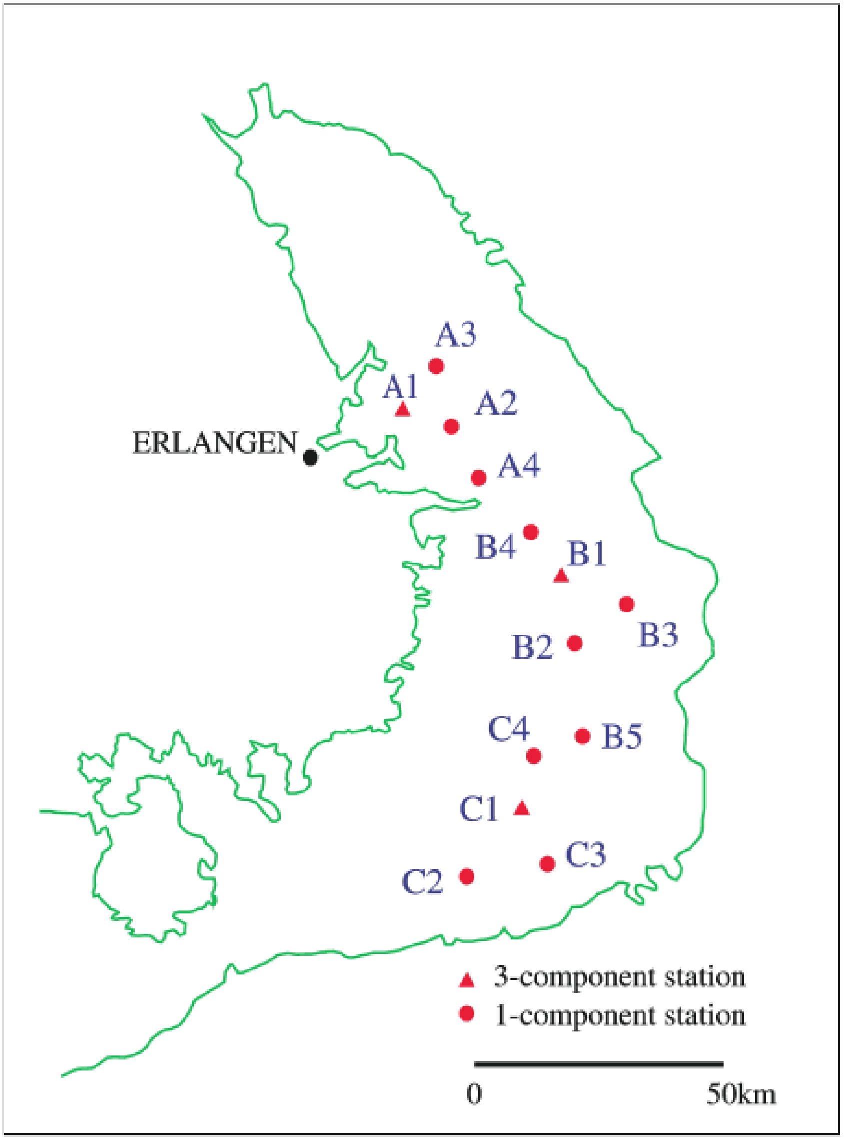


Passive Experiments

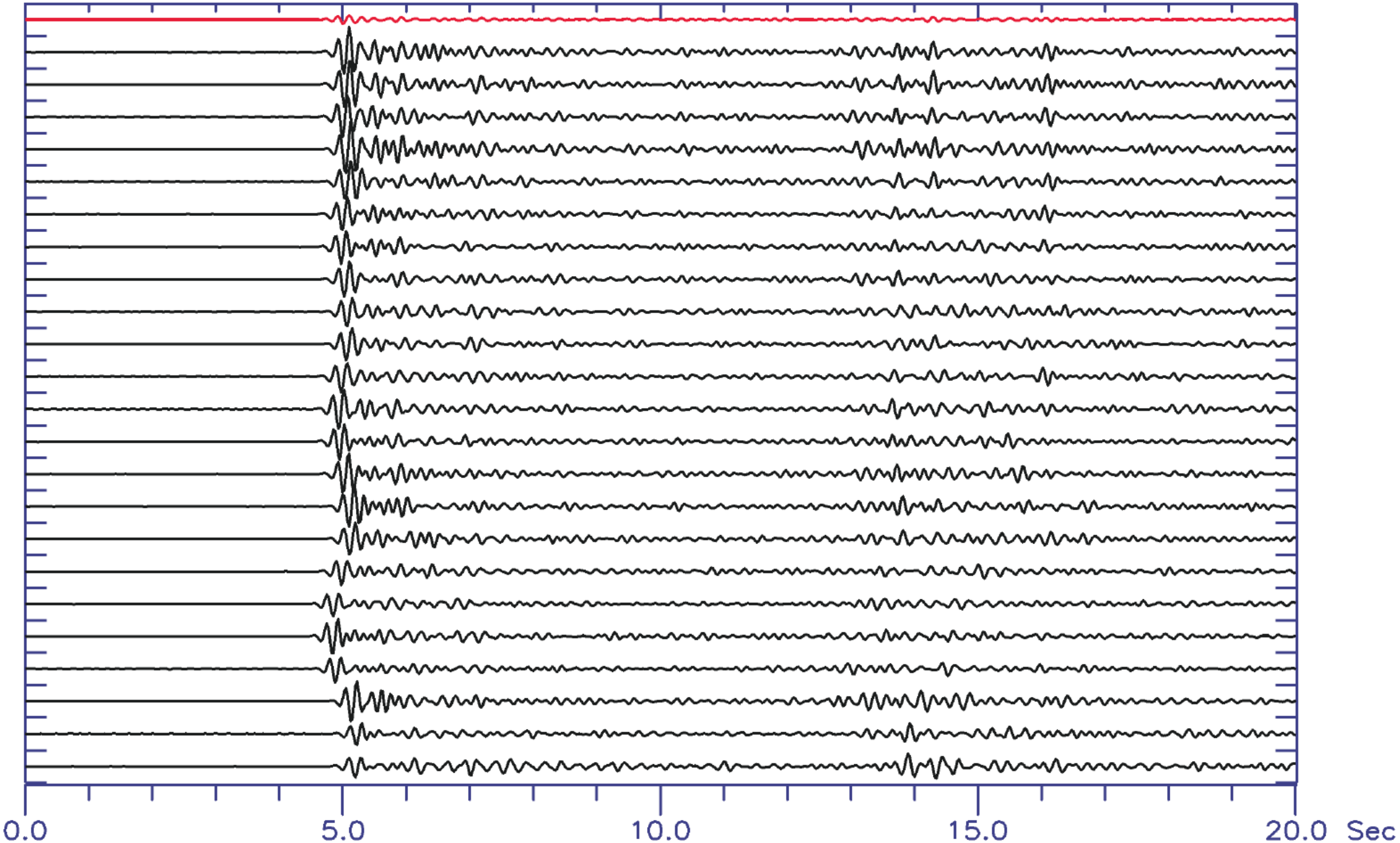
(small scale seismic arrays)

Seismic Arrays

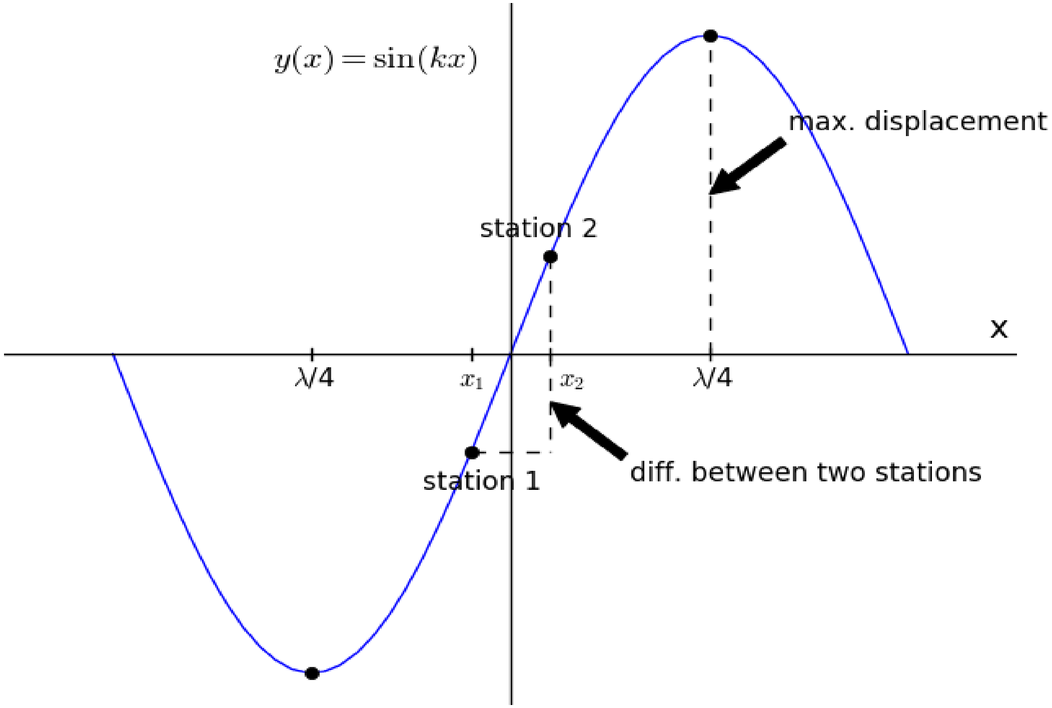




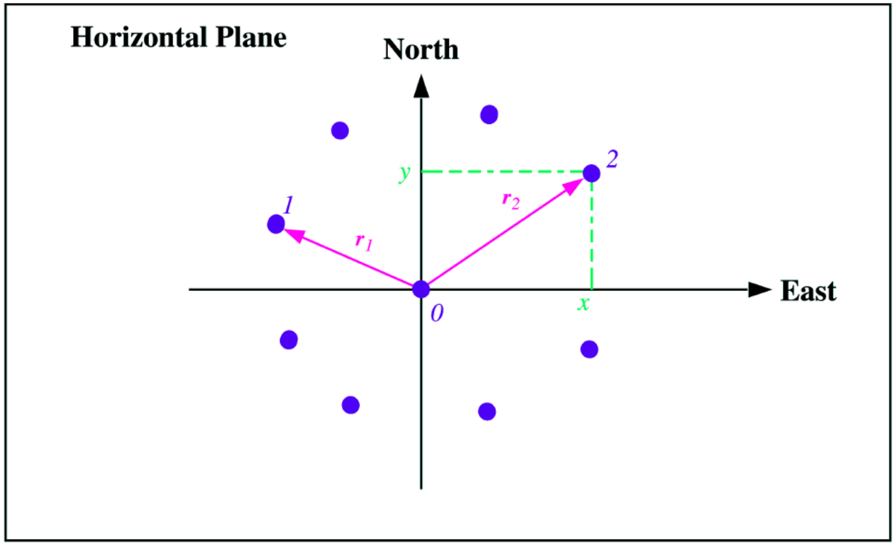
Array Data

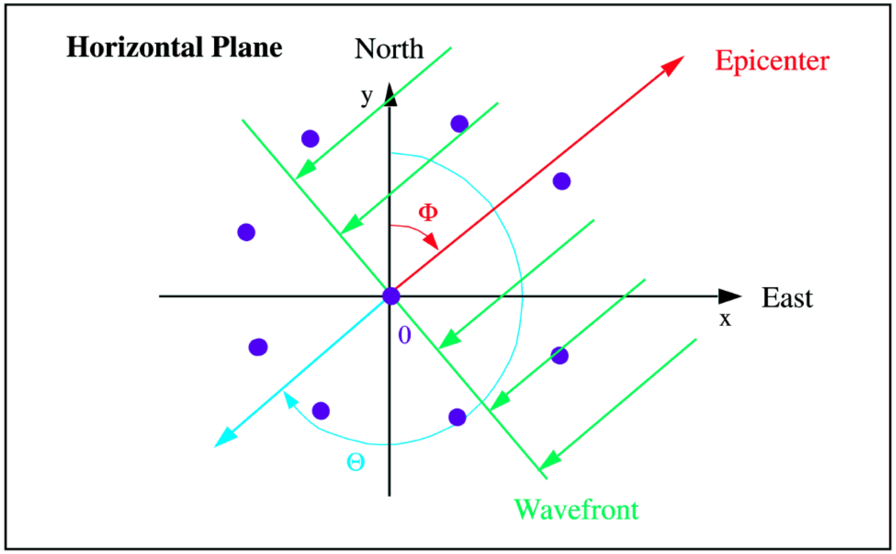


Estimating wavefield gradients



Benefits of seismic array

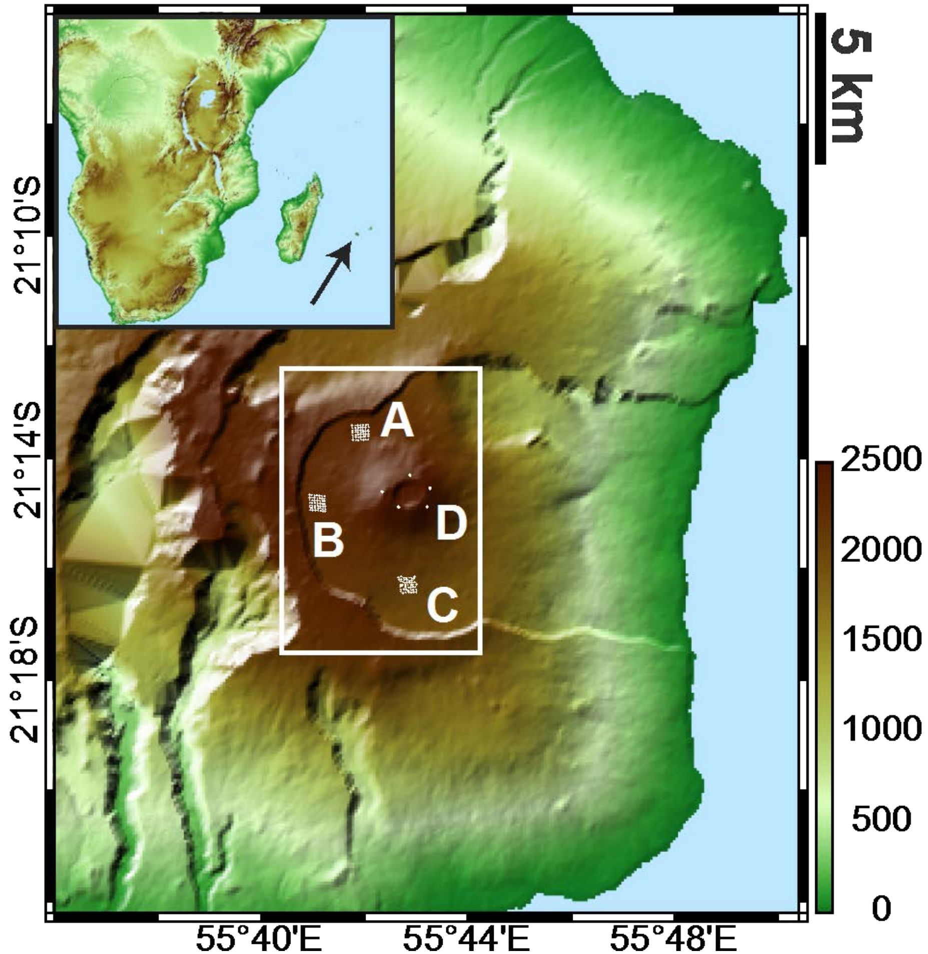


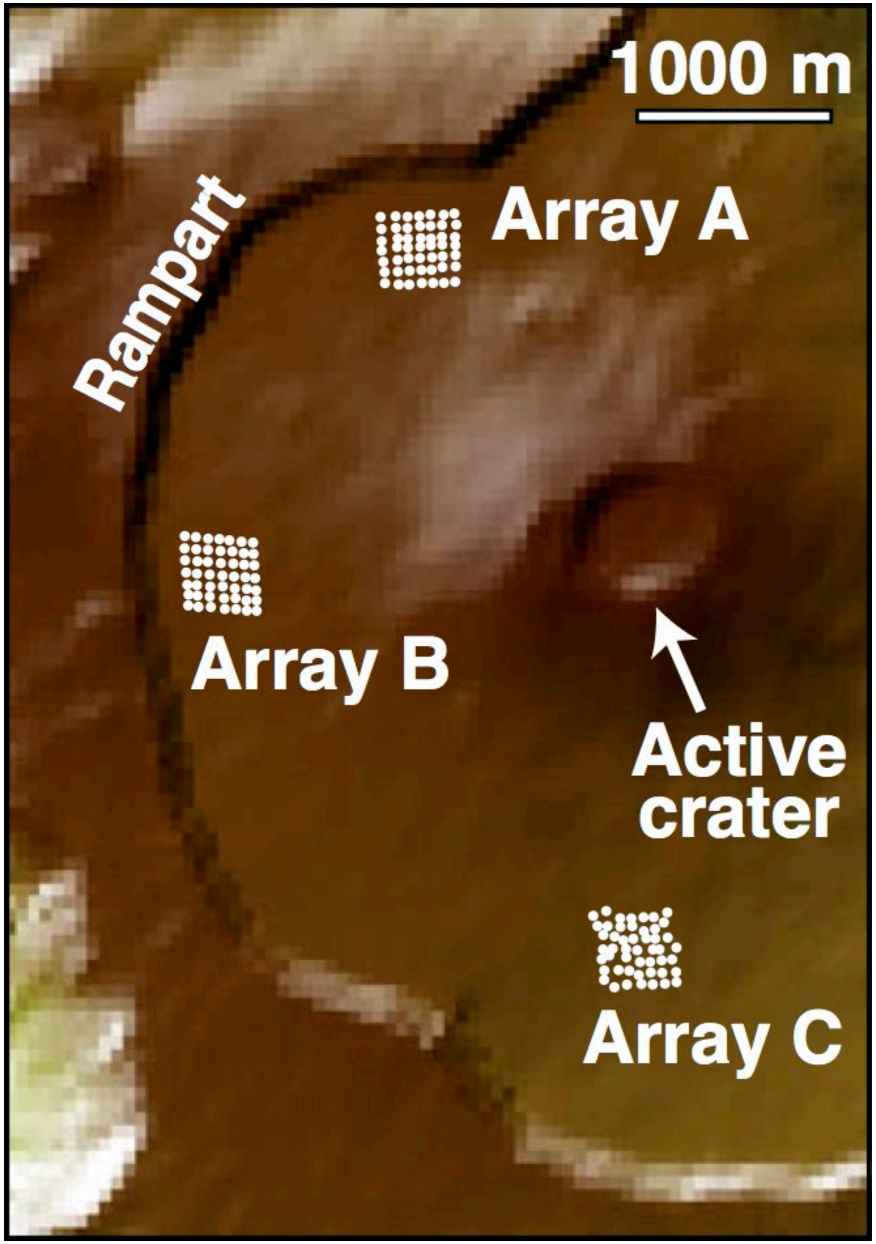


- Extract information about propagation direction
- Extract information about phase velocities
- Estimate the wavefield gradients (strain and rotation)
- Estimate incidence angles
- Separate P and S waves (Rayleigh and Love waves)

-> originally designed to improve detection and localization of nuclear tests

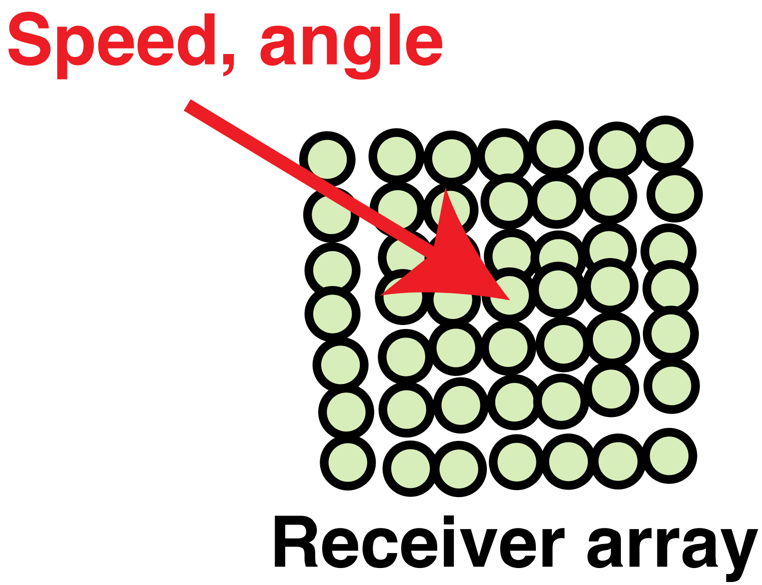
VolcArray

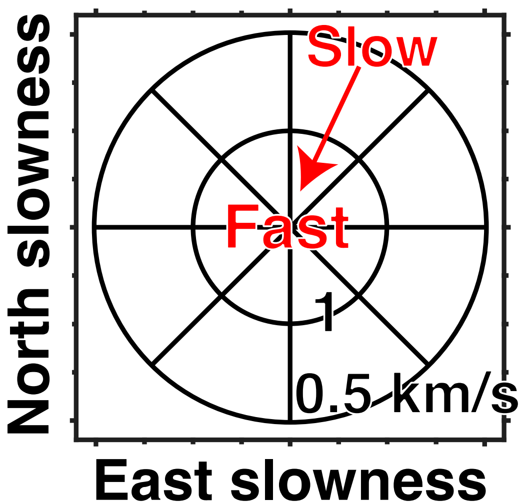


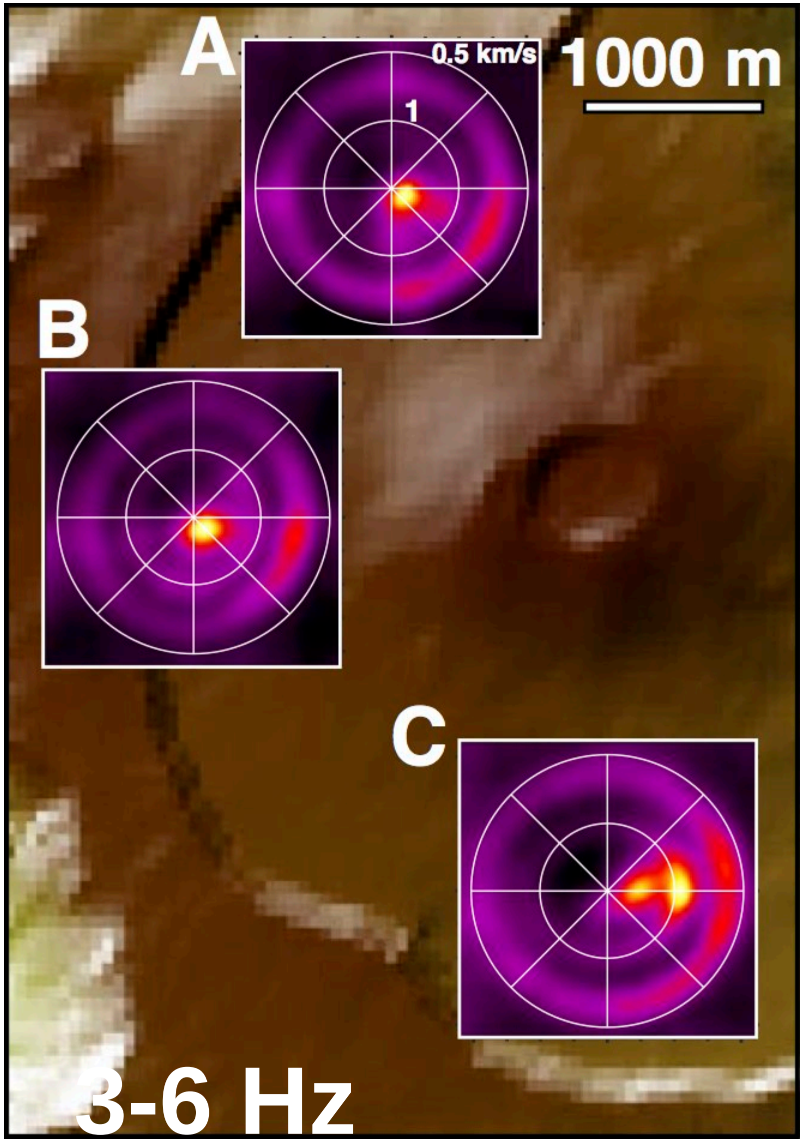


- **July, 2014 (30 days)**
- **150 station points (300 geophones, 10 Hz) Source: Nakata**

Beamforming







Seismic Arrays

- … are becoming and more popular
- AoA (Array of Array experiments are being proposed)
- Seismic sensors are becoming cheaper so large N experiments are the future
- For some areas this is difficult
  - Planets
  - Boreholes
  - Ocean floor

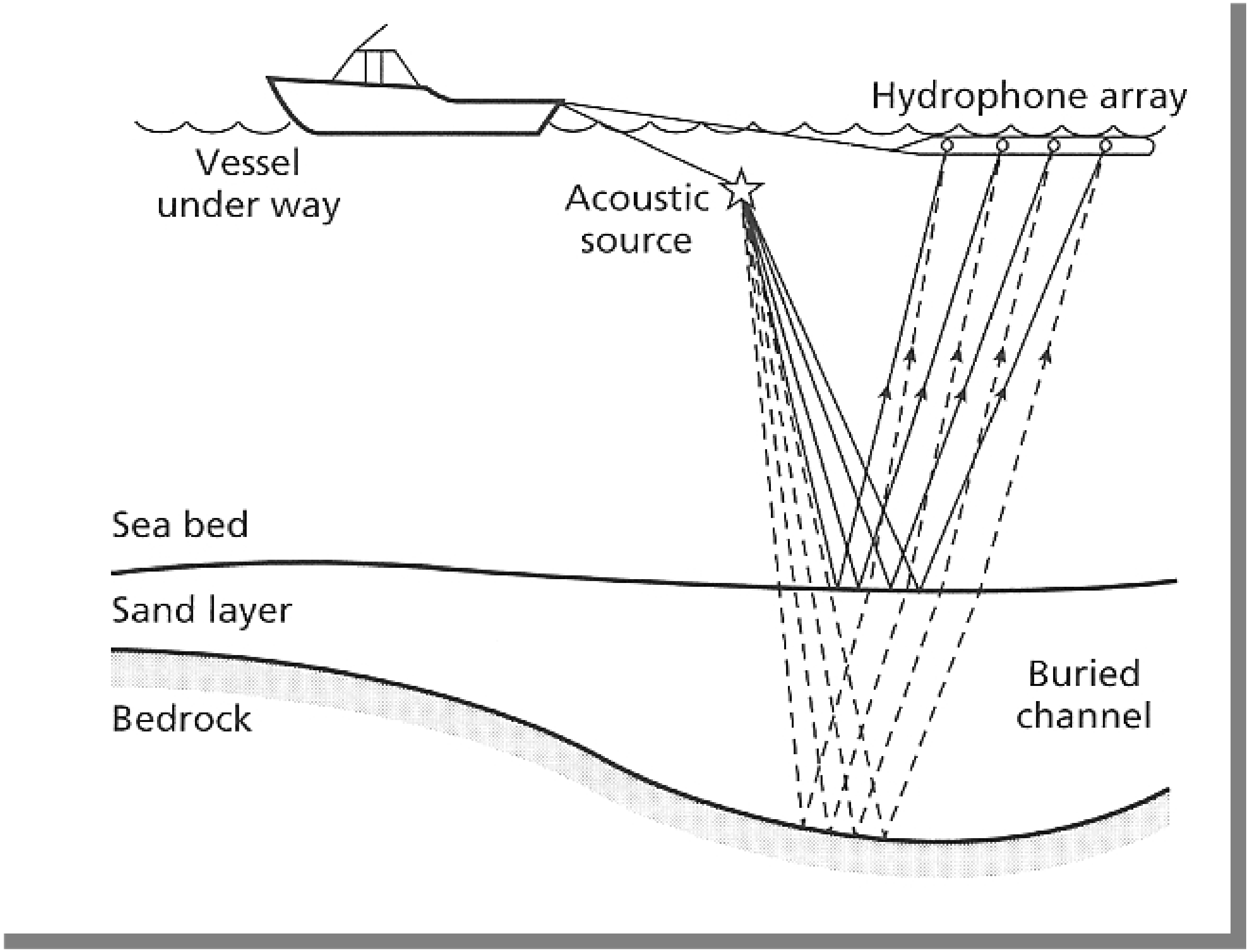
Active Experiments

Explosions

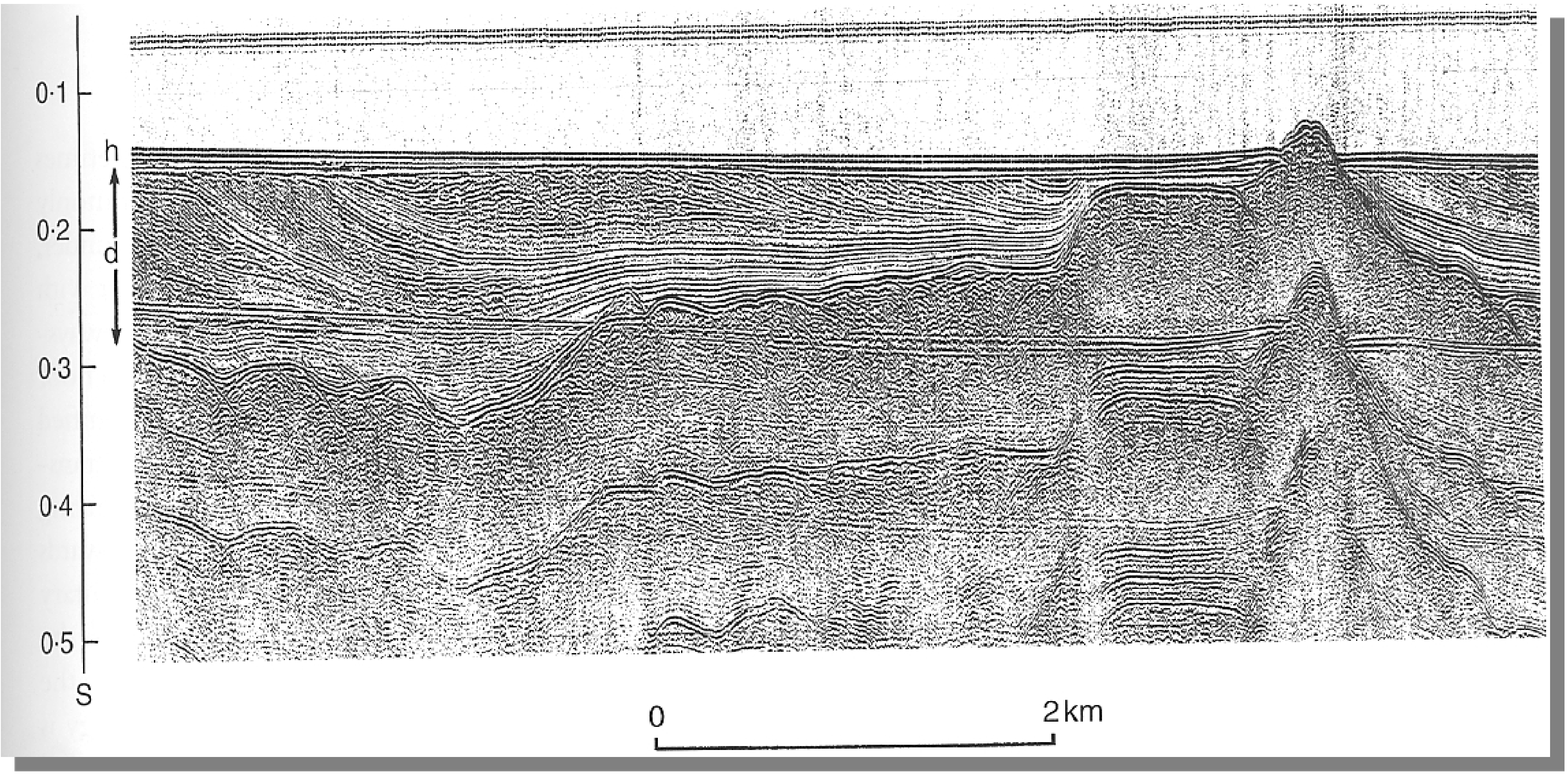
Vibrator trucks

Hammer

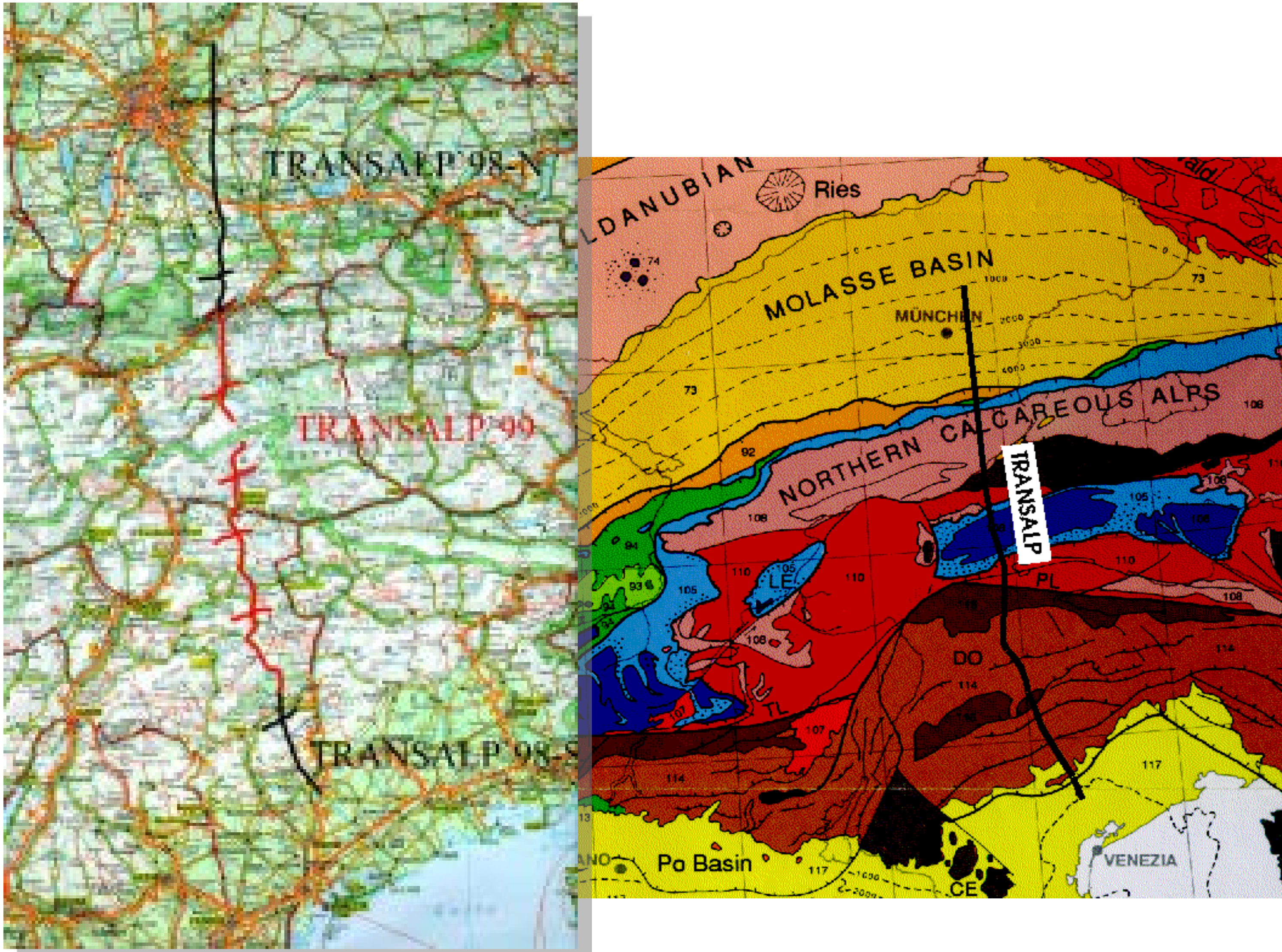
Marine Reflexionsseismik



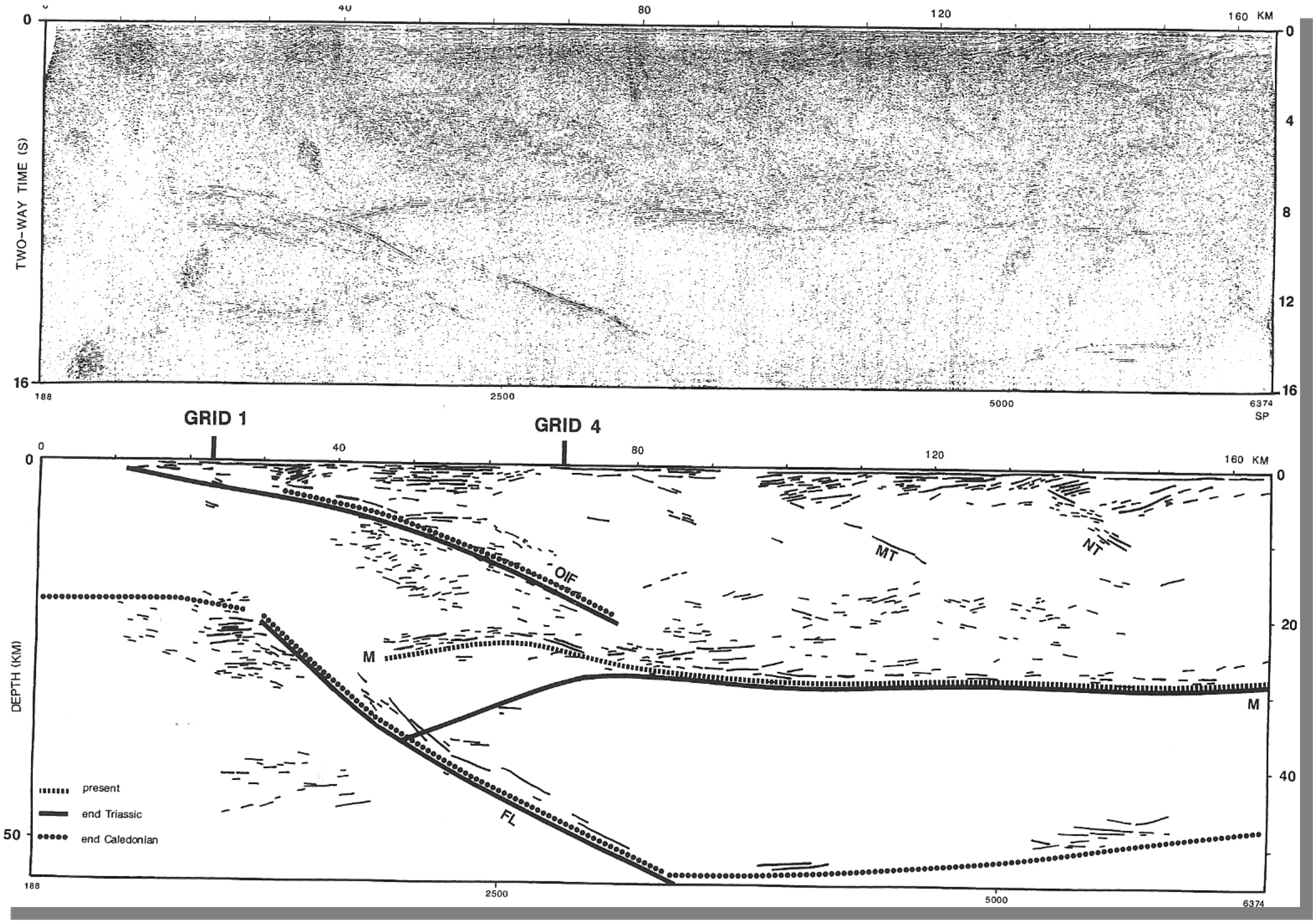
Reflexions Seismogramme



Transalp


TRANSALP'98-N
TRANSALP'99
TRANSALP'98-S
Ries
MOLASSE BASIN
MÜNCHEN
NORTHERN CALCAREOUS ALPS
TRANSALP
LE
PL
DO
TL
Po Basin
CE
VENEZIA

Tiefen Migrationen



Reservoir lifetime monitoring: Valhall

Experiment to be repeated annualy:

- 50,000+ shots
- 2300+ OBC [hydrophones]
- O(Tbyte) of Data
- Typical (even small) experimental setup
- Seemingly gigantic simulation/inversion task in 3D (full waveform inversion)

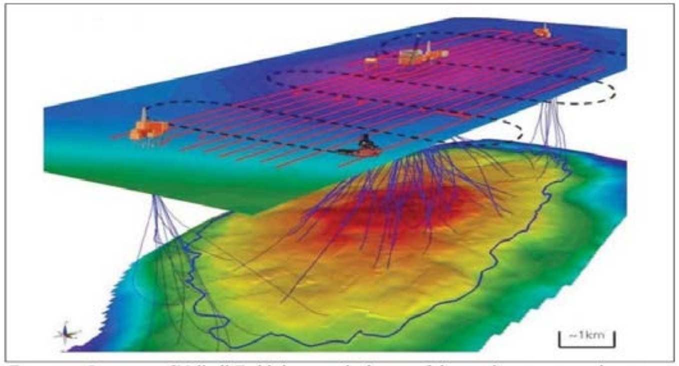
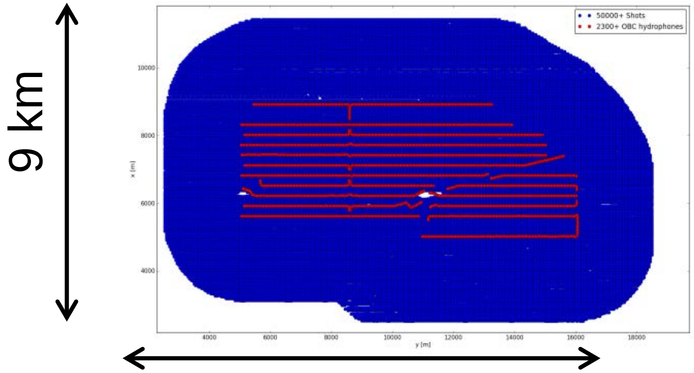


Figure 1. Overview of Valhall Field showing the layout of the geophone array at the sea floor (red lines), the top of the reservoir, the outline of the field (dark blue line), and the wells (thin blue lines).

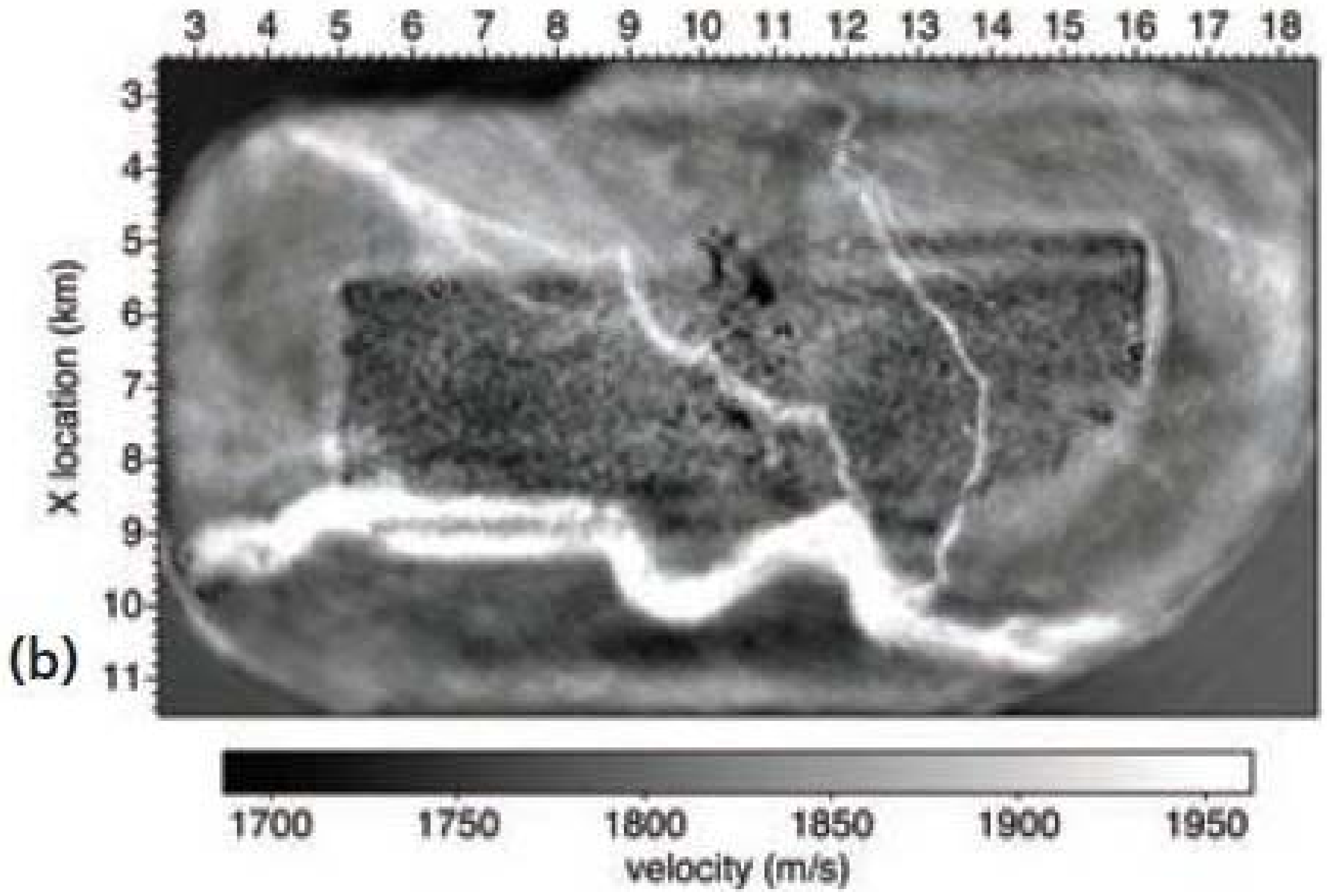
Gestel et al. (2008), TLE



16 km

- Sources
- Receivers

Thue future: full waveform inversion



Sirgue et al. (2010)

Seismic Observables

translation

strain

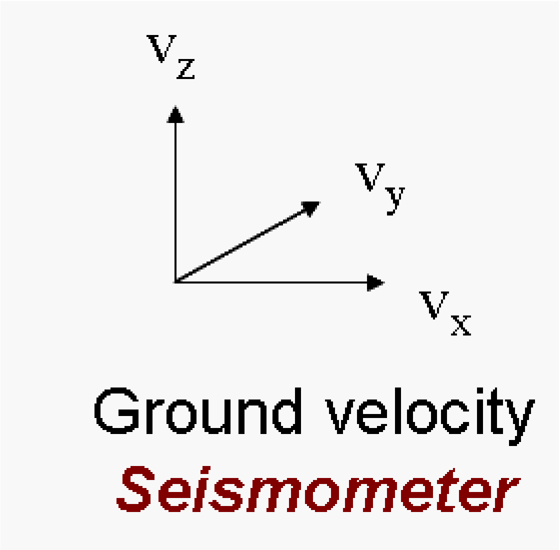
Rotation (tilt)

Seismic observables: *translations*

Translational motions are deformations in the direction of three orthogonal axes. Deformations are usually denoted by **u** with the appropriate connection to the strain tensor (explained below).

Each of the orthogonal motion components can be measured as displacement u, velocity v, or acceleration a.

The use of these three variations of the same motion type will be explained below.

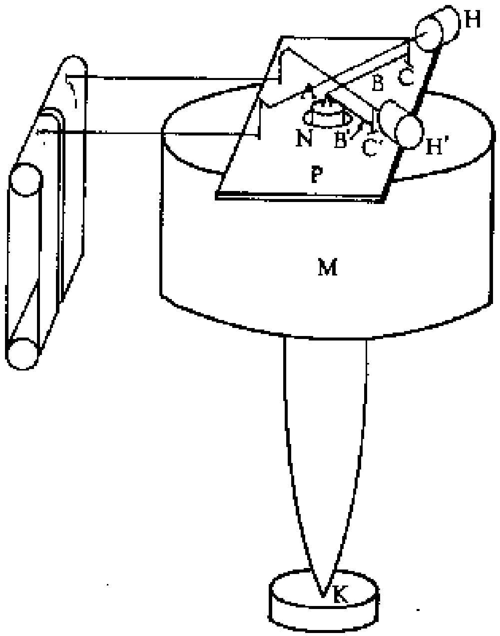


Seismic observables: *translations - displacements*

Displacements are measured as „differential“ motion around a reference point (e.g., a pendulum). The first seismometers were pure (mostly horizontal) displacement sensors. Measureable *co-seismic* displacements range from *microns to dozens of meters* (e.g.,Great Andaman earthquake).

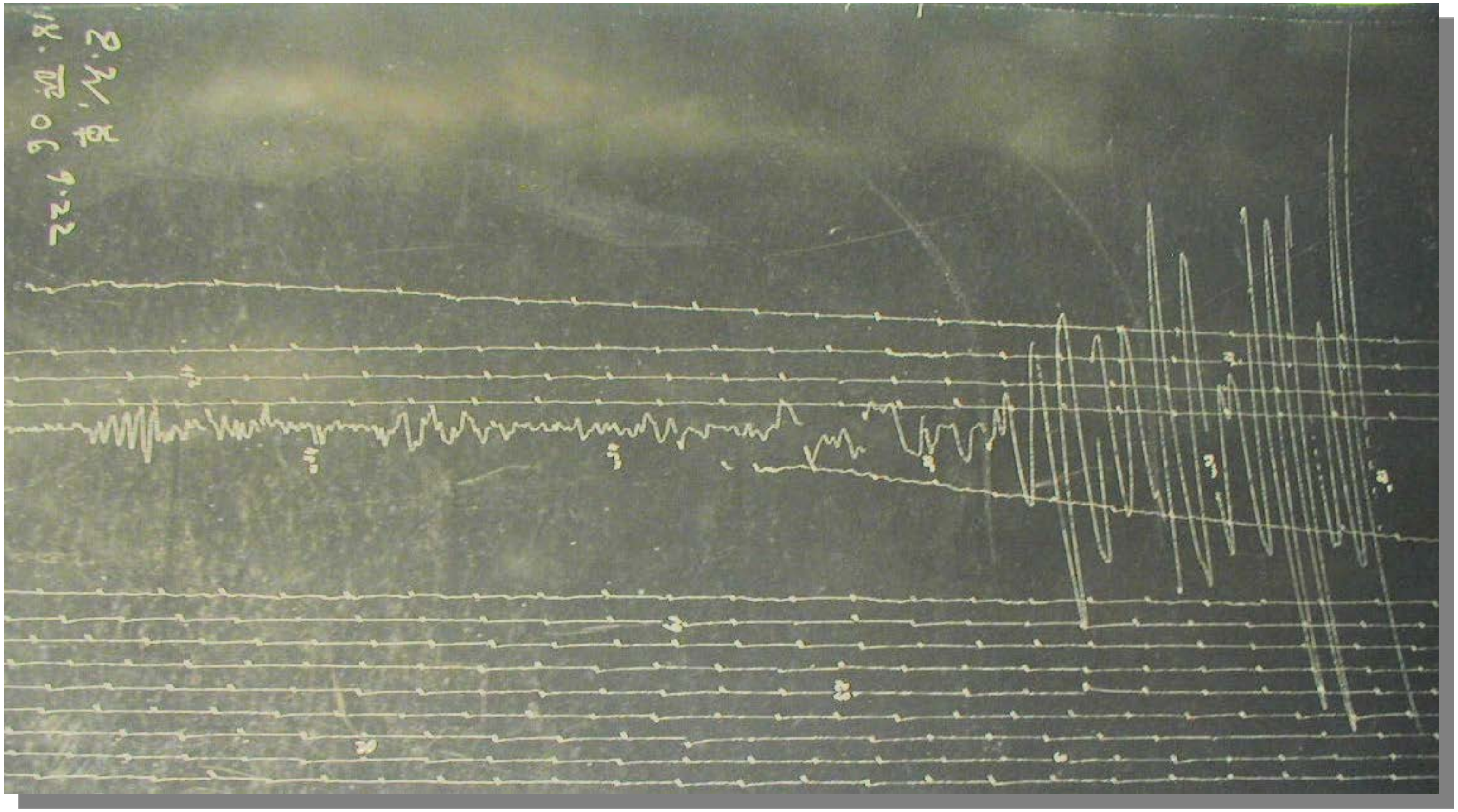
Horiztonal displacement sensor (ca. 1905). Amplitude of ground deformation is mechanically amplified by a factor of 200.

Today displacements are measured using GPS sensors.



Seismic observables: *translations - displacements*

Data example: the San Francisco earthquake 1906, recorded in Munich



Seismic observables: *translations - velocities*

Most seismometers today record *ground velocity.* The reason is that seismometers are based on an electro-mechanic principle. An electric current is generated when a coil moves in a magetic field. The electric current is proportional to ground velocity v.

Velocity is the time derivative of displacement. They are in the range of μm/s to m/s.

$$v(x,t) = \partial_t u(x,t) = \dot{u}(x,t)$$

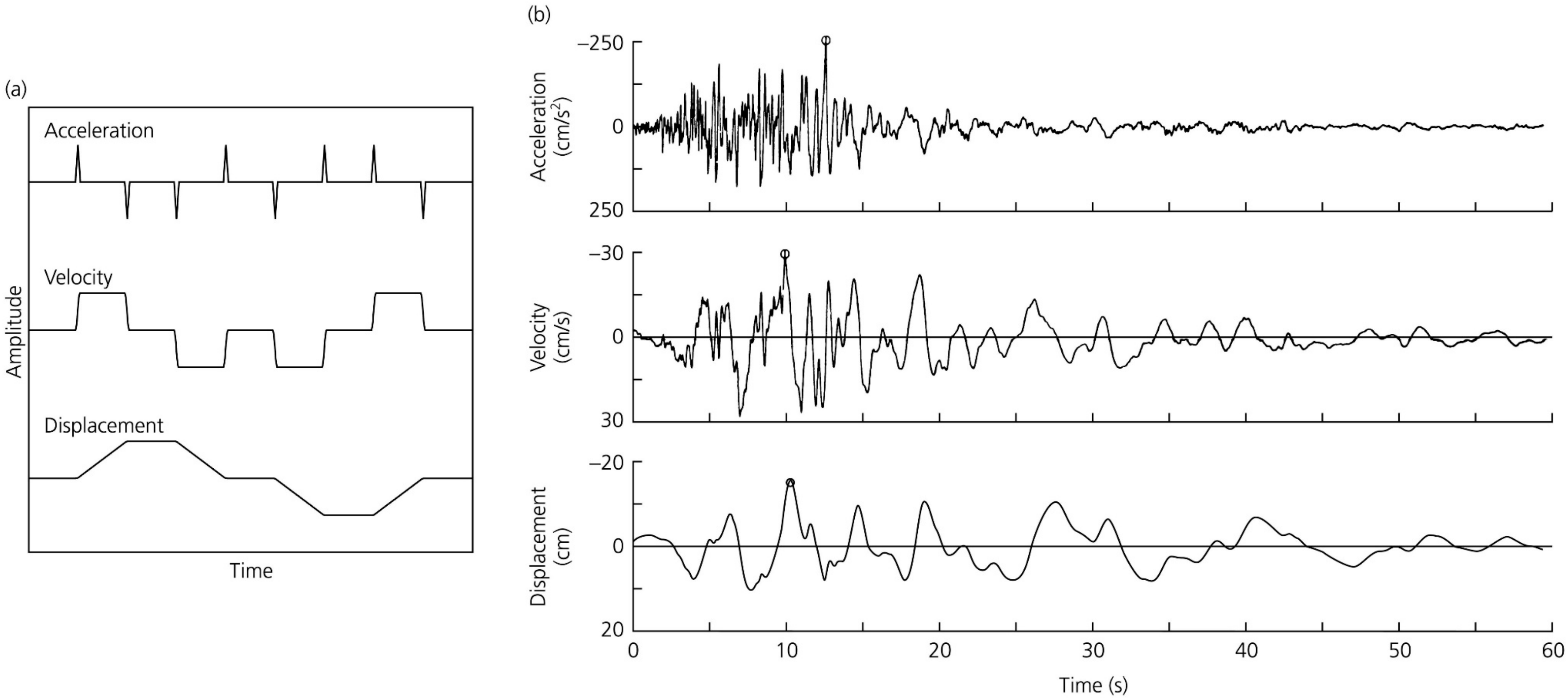
Seismic observables: *translations - accelerations*

Strong motions (those getting close to or exceeding Earth's gravitational acceleration) can only be measured with accelerometers. Accelerometers are used in earthquake engineering, near earthquake studies, airplanes, laptops, ipods, etc. The largest acceleration ever measured for an earthquake induced ground motion was 40 m/s^2 (four times gravity, see *Science* 31 October 2008: Vol. 322. no. 5902, pp. 727 – 730)

$$a(x,t) = \partial_t^2 u(x,t) = \ddot{u}(x,t)$$

Displacement, Velocity, Acceleration

Figure 6.6-14: Relation between displacement, velocity, and acceleration in the time domain.



Translational Measurements

- Displacement (m)
  - Old seismometers
  - GPS sensors
- Velocity (m/s)
  - Almost all weak-motion sensors today
  - Geophones in Exploration
- Acceleration (m/s^2)
  - Strong motion (close to earthquakes)
  - Engineering, navigation
  - Laptops, smartphones

Seismic observables: *strain*

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Strain is a tensor that contains 6 independent linear combinations of the spatial derivatives of the displacement field. Strain is a purely geometrical quantity and has no dimensions.

Measurement of differential deformations involves a spatial scale (the length of the measurement tube).

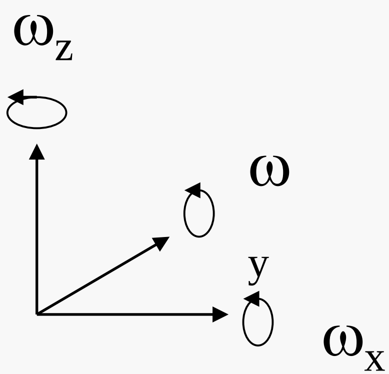
What is the meaning of the various elements of the strain tensor?

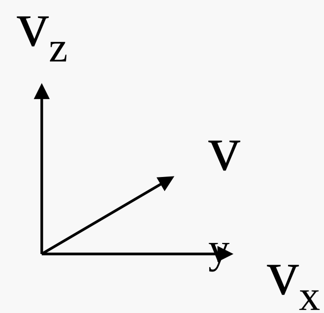
Seismic observables: *strain*

Strain components (2-D)

$$\varepsilon_{ij} = \begin{bmatrix} \dfrac{\partial u_x}{\partial x} & \dfrac{1}{2}\left(\dfrac{\partial u_x}{\partial y} + \dfrac{\partial u_y}{\partial x}\right) \\ \dfrac{1}{2}\left(\dfrac{\partial u_x}{\partial y} + \dfrac{\partial u_y}{\partial x}\right) & \dfrac{\partial u_y}{\partial y} \end{bmatrix}$$

$$\begin{pmatrix}\omega_x\\ \omega_y\\ \omega_z\end{pmatrix} = \frac{1}{2}\nabla\times\underline{\mathbf{v}} = \frac{1}{2}\begin{pmatrix}\partial_y v_z - \partial_z v_y\\ \partial_z v_x - \partial_x v_z\\ \partial_x v_y - \partial_y v_x\end{pmatrix}$$





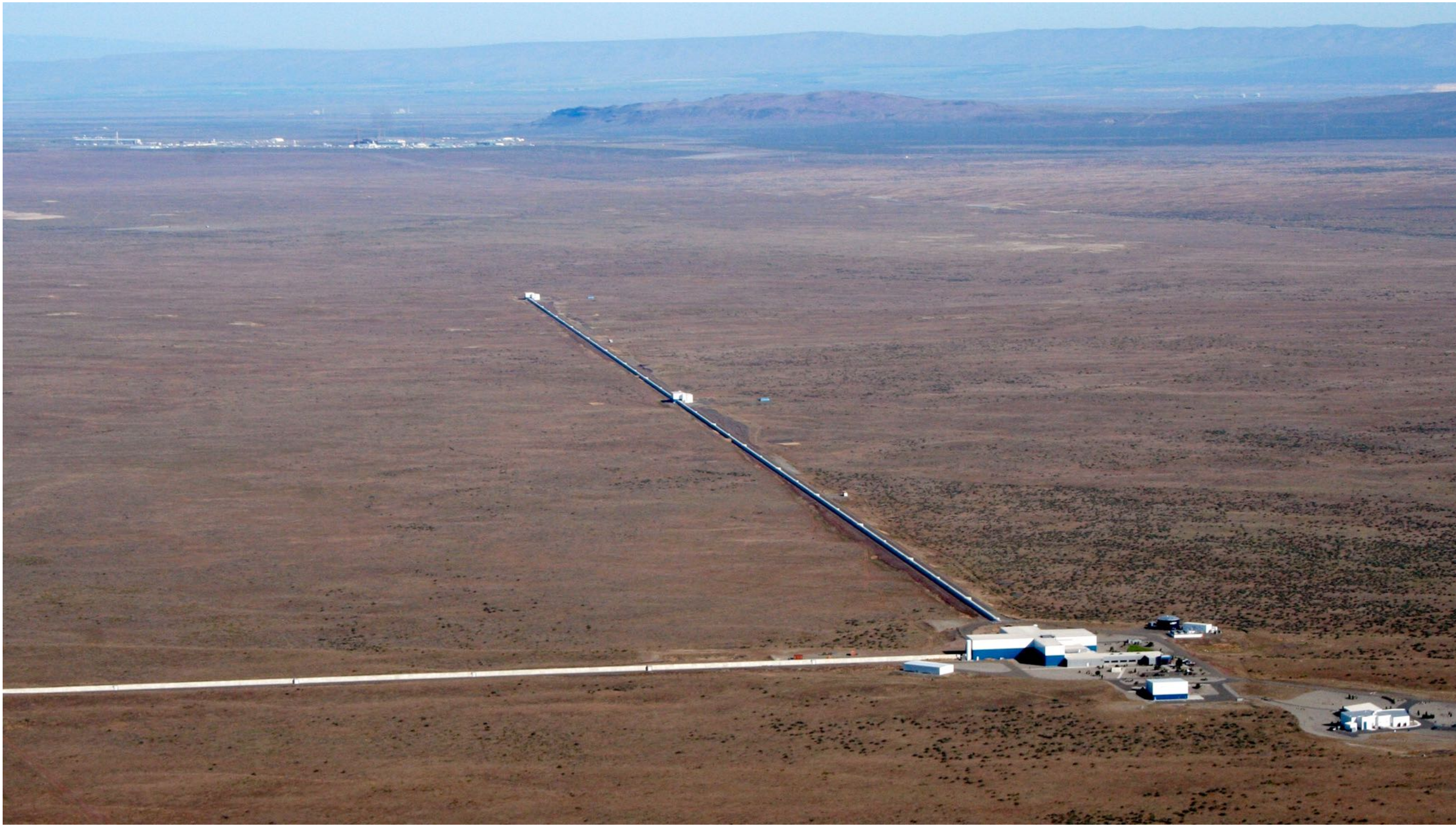
Rotation rate

Rotation sensor

Ground velocity

Seismometer

LIGO – strainmeter



Seismic observables: *rotations*

- Rotation is a vectorial quantity with three independent components
- At the Earth‘s surface rotation and tilt are the same
- Rotational motion amplitudes are expected in the range of 10^{-9} – 10^{-3} rad/s
- Rotations are only now being recorded
- Rotations are likely to contribute to structural damage

Seismic observables: *tilt*

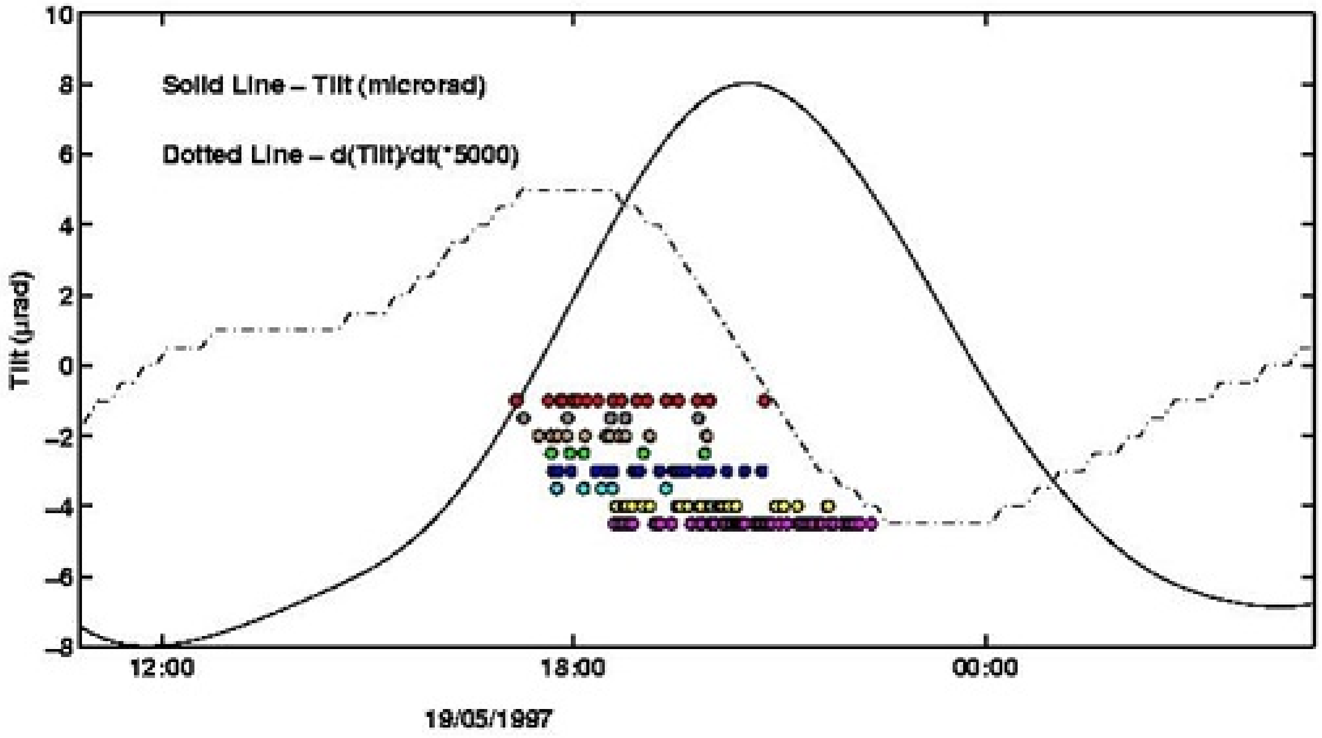
Tilt is the angle of the surface normal to the local vertical. In other words, it is rotation around two horizontal axes. Any P, SV or Rayleigh wave type in layered isotropic media leads to tilt at the Earth‘s free surface. In 3-D anisotropic media all parts of the seismic wave field may produce tilts.

$$\Theta(x,t) = \partial_x u_z$$

Other causes of tilt:

- Earth tides
- Atmospheric pressure changes
- Soil deformation (water content)
- Temperature effects
- Mass movements (lawn mower, trucks, land slides)

Tilt signals at volcanoes



Tilt cycle (solid line) and seismicity (dots) on Montserrat, West Indies. The tilt signal goes through an inflection point (maximum/minimum of tilt derivative w.r.t. time, dotted line) as soon as seismicity starts, and again when seismicity ceases, indicating that part of the shear stress that causes the tilt is reduced by seismic slip at the conduit wall during magma ascent. (Source: J. Neuberg)

Summary: Observables

- Translations are the most fundamental and most widely observed quantity (standard seismometers)
- Translation sensors are sensitive to rotations!
- Tilt measurements are sensitive to translations!
- Really we should be measuring all 12 quantities at each point (cool things can be done with collocated observations of translation, strains and rotations)