Seismically Monitoring the Earth

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Acknowledgements and Outline

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Outline:

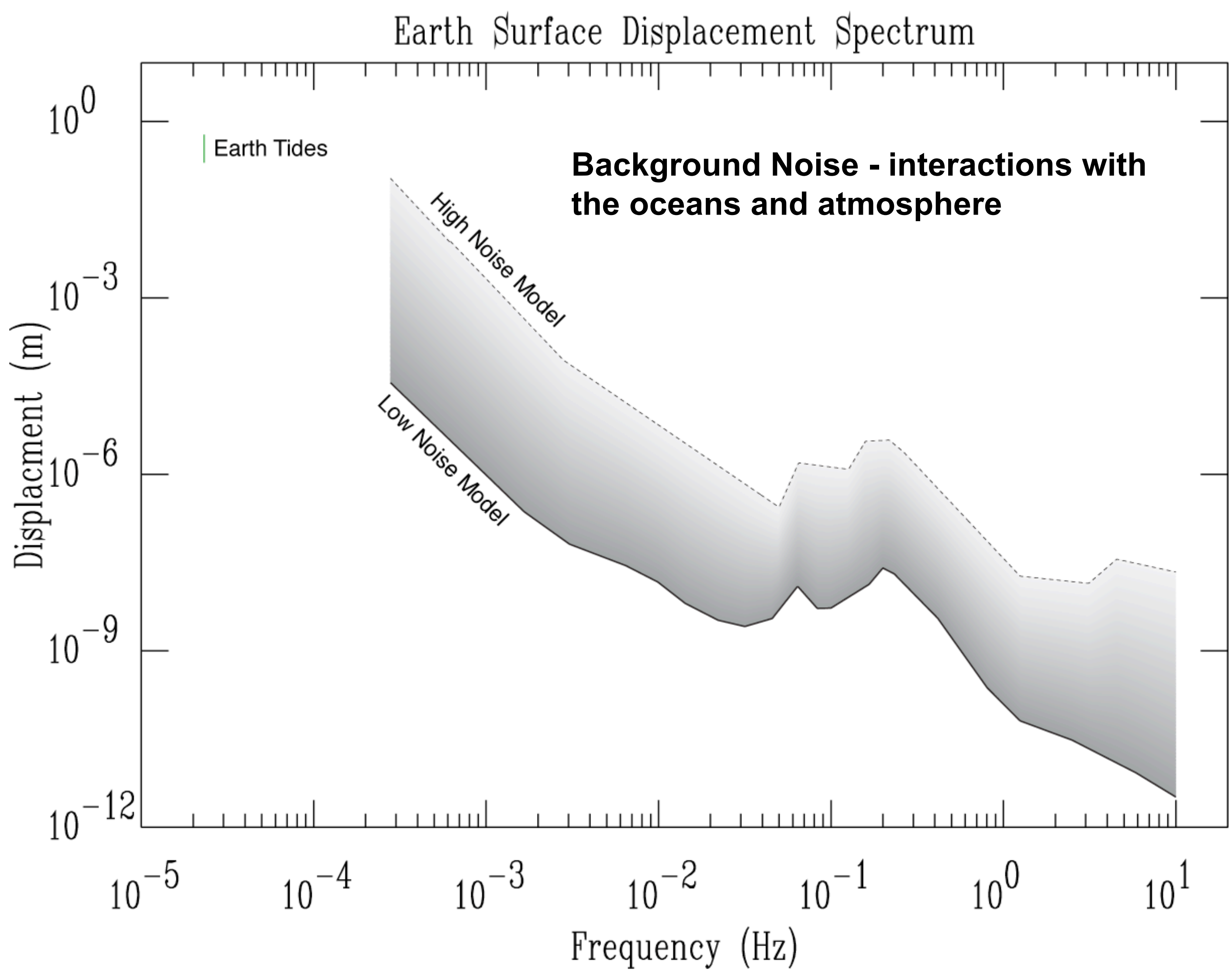
- Monitoring: What, Why, How
- 4 Areas of science underpinning monitoring
- 3 Grand Challenges

What is seismic monitoring?

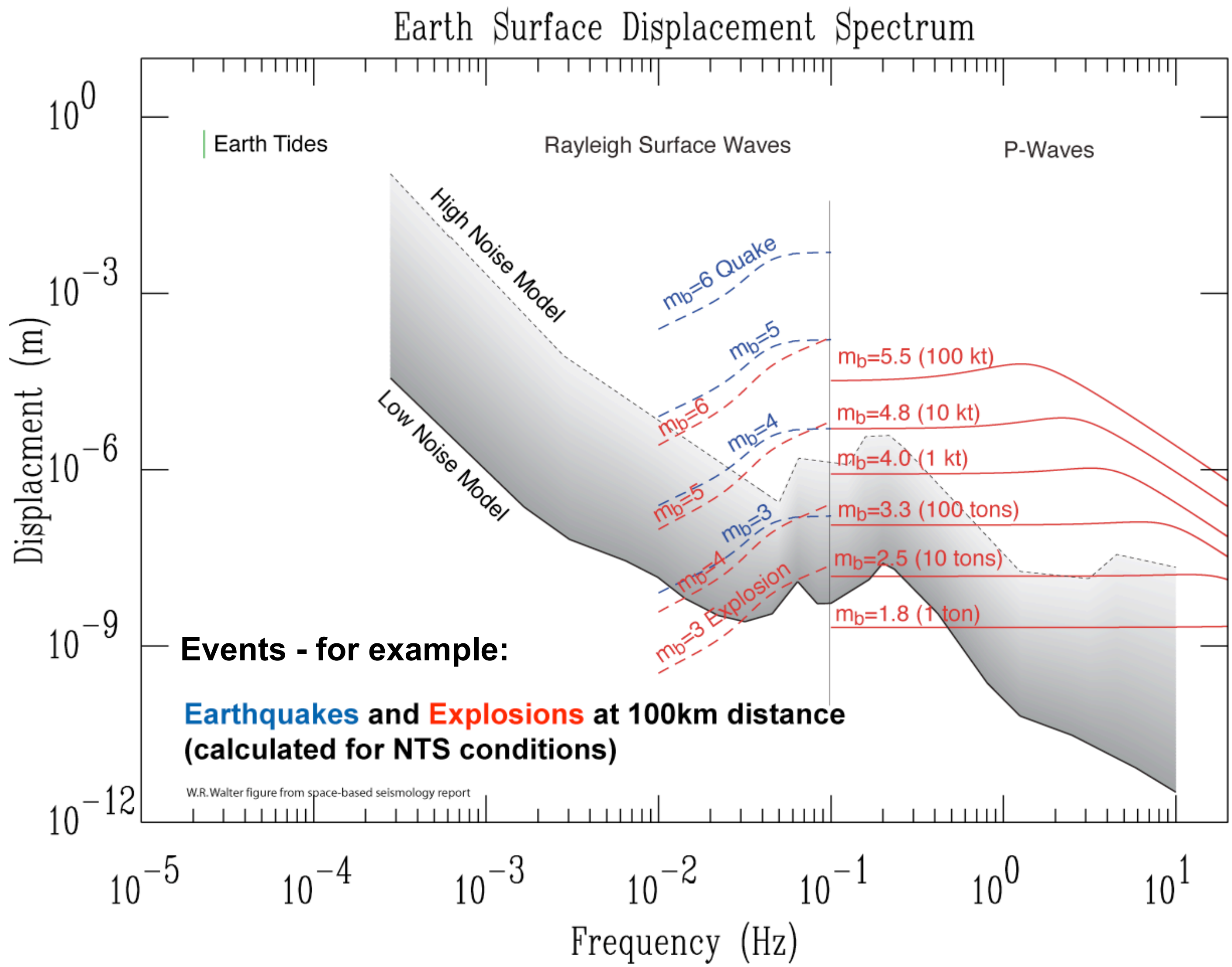
- **Applied Seismology**
- **Using observables to make inferences about Earth events**
- **Listening to the Earth**

Listening to the Earth
ParkeHarrison, Robert and Shana, b.1968/64
21st Journal of Contemporary Photography Vol. II, 1999
21.6 x 16.5 cm
Photogravure

Seismically listening to the Earth: What can we hear?



Seismically listening to the Earth: What can we hear?



Why are we listening/monitoring?

- Natural Hazard Response and Mitigation
  - Earthquakes
  - Tsunamis
  - Volcanoes
  - Other (e.g. rockfalls, landslides, bollides, glacier movement, etc,)

- Natural Resource Management (hydrocarbons, minerals, geothermal)
  - Exploration/Assesement
  - Extraction hazard and regulatory monitoring

- Nuclear Explosion Monitoring
  - Treaty Verification

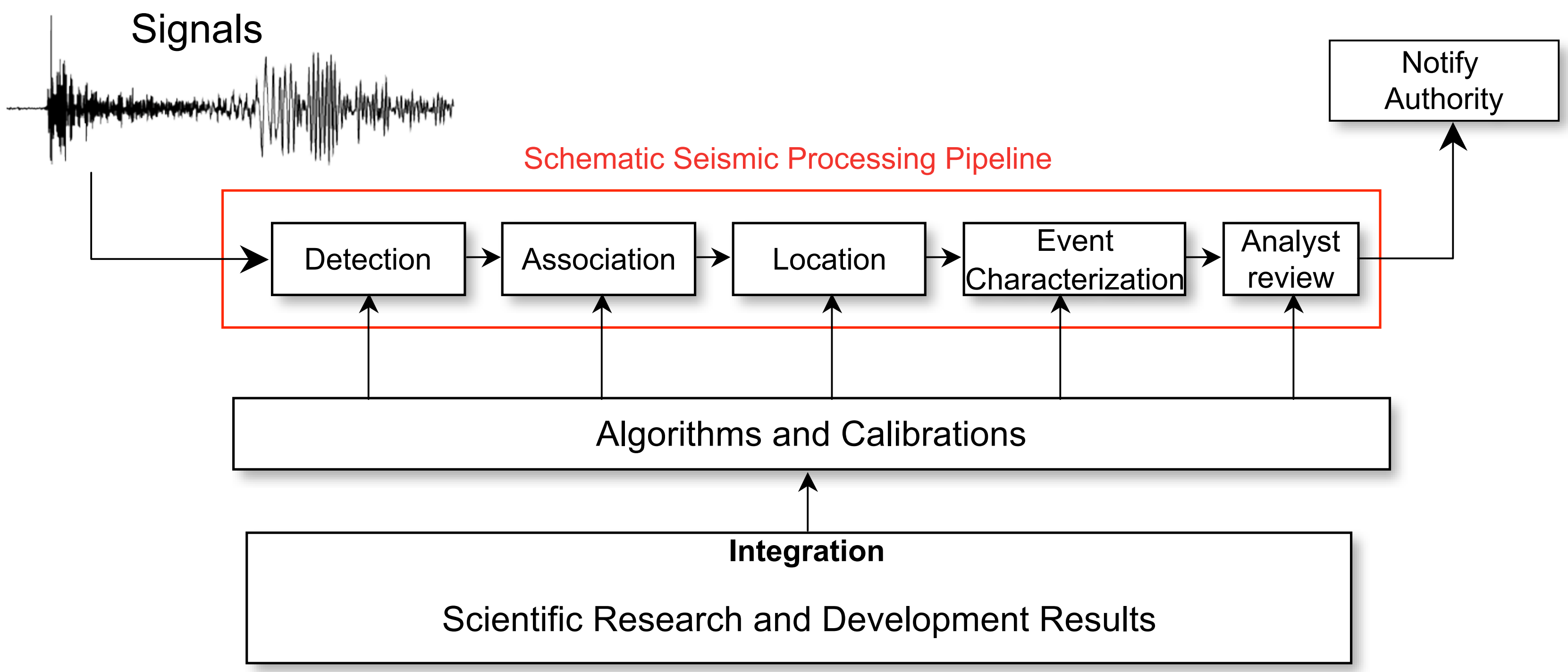
- Forensic Applications
  - Accidents (e.g. factory/gas line/munitions explosions)
  - Terrorism

- Military/Security Applications
  - Bomb damage assessment
  - Border/Facility monitoring (e.g. tunneling)

- Waste/Storage Management
  - Carbon Sequestration (e.g. 4D)
  - Nuclear (e.g. Yucca Mountain)

How do we monitor?

Real-time operational monitoring systems



This is where Seismological advances can dramatically improve monitoring:

- **Lowering thresholds and increasing throughput**
- **Improving accuracy and precision**
- **Identifying new kinds of sources**

How do we improve our monitoring capabilities?

Earth Monitoring Science

Source Physics

Sources
earthquake, explosion
mine blast, collapse,
volcano, accident,
bollide, etc.

↓

Source-Medium Interactions & Signal Generation

→

Signal Propagation

Solid Earth

Oceans

Atmosphere

Space

→

Sensors

Data collection
(seismic, infrasound, hydroacoustic, radionuclide, optical, EM, InSAR, radiation, etc.)

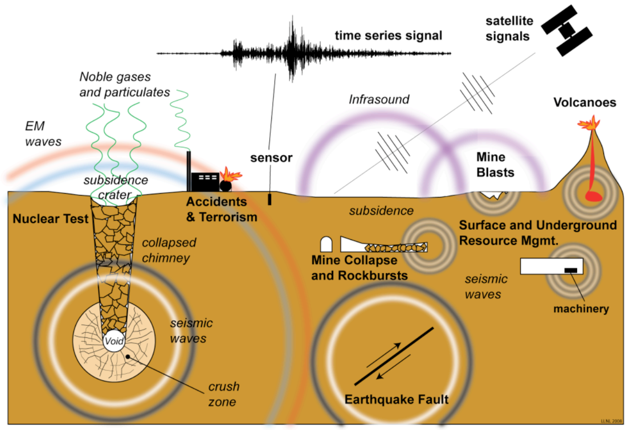
→

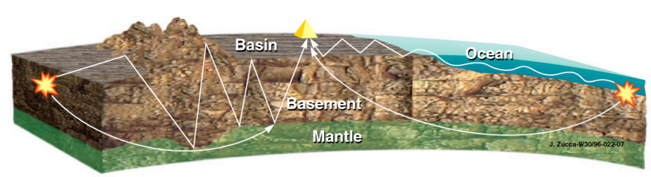
Signal Analysis

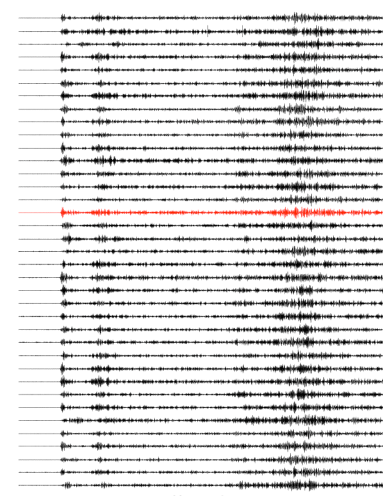
Signal Processing
(Measurements: times, amplitudes, spectra, full waveform, pulse shape, radionuclide, pressures, etc.

↓

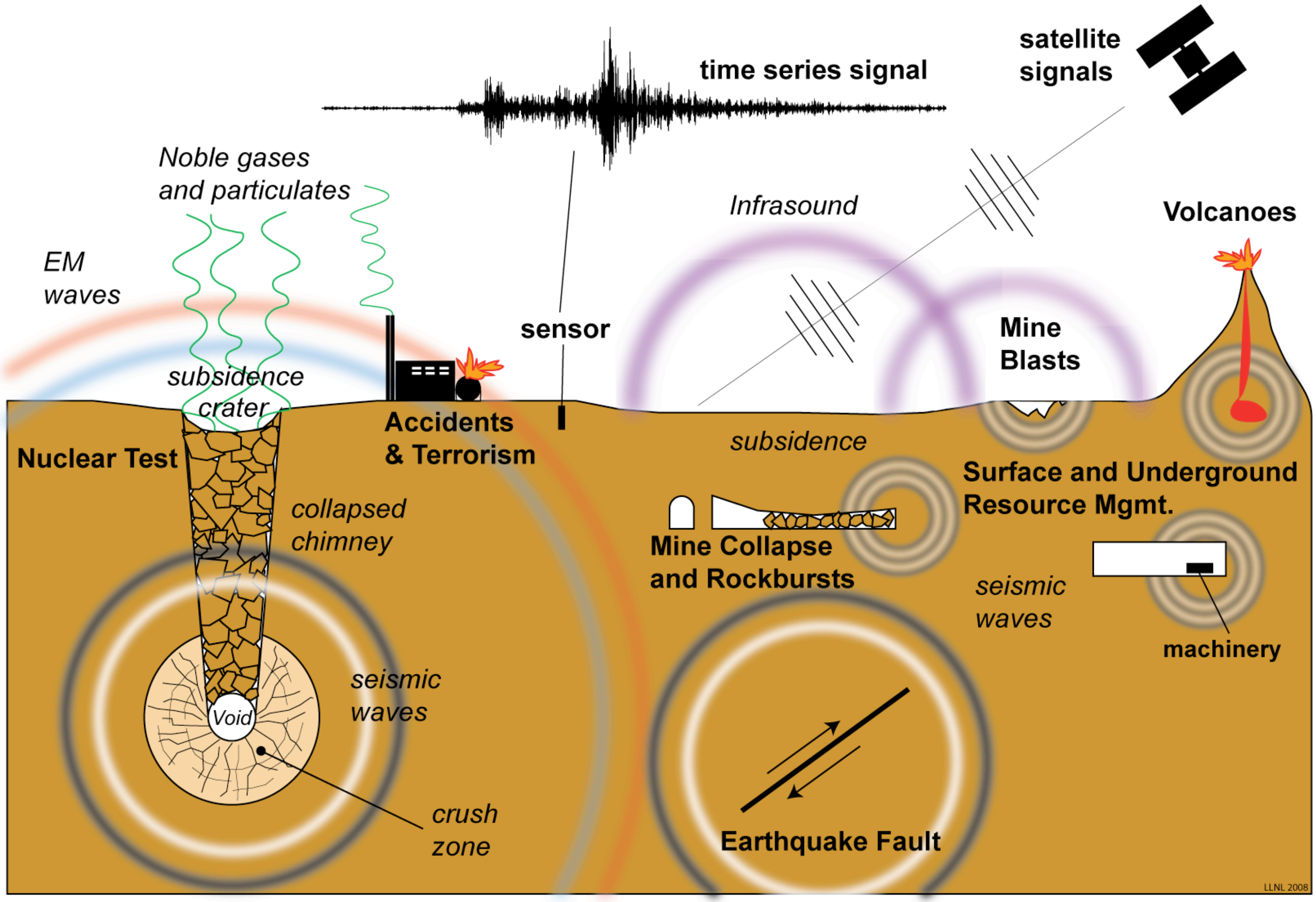
Results and Context
(Where, What, Why and Confidence in results)







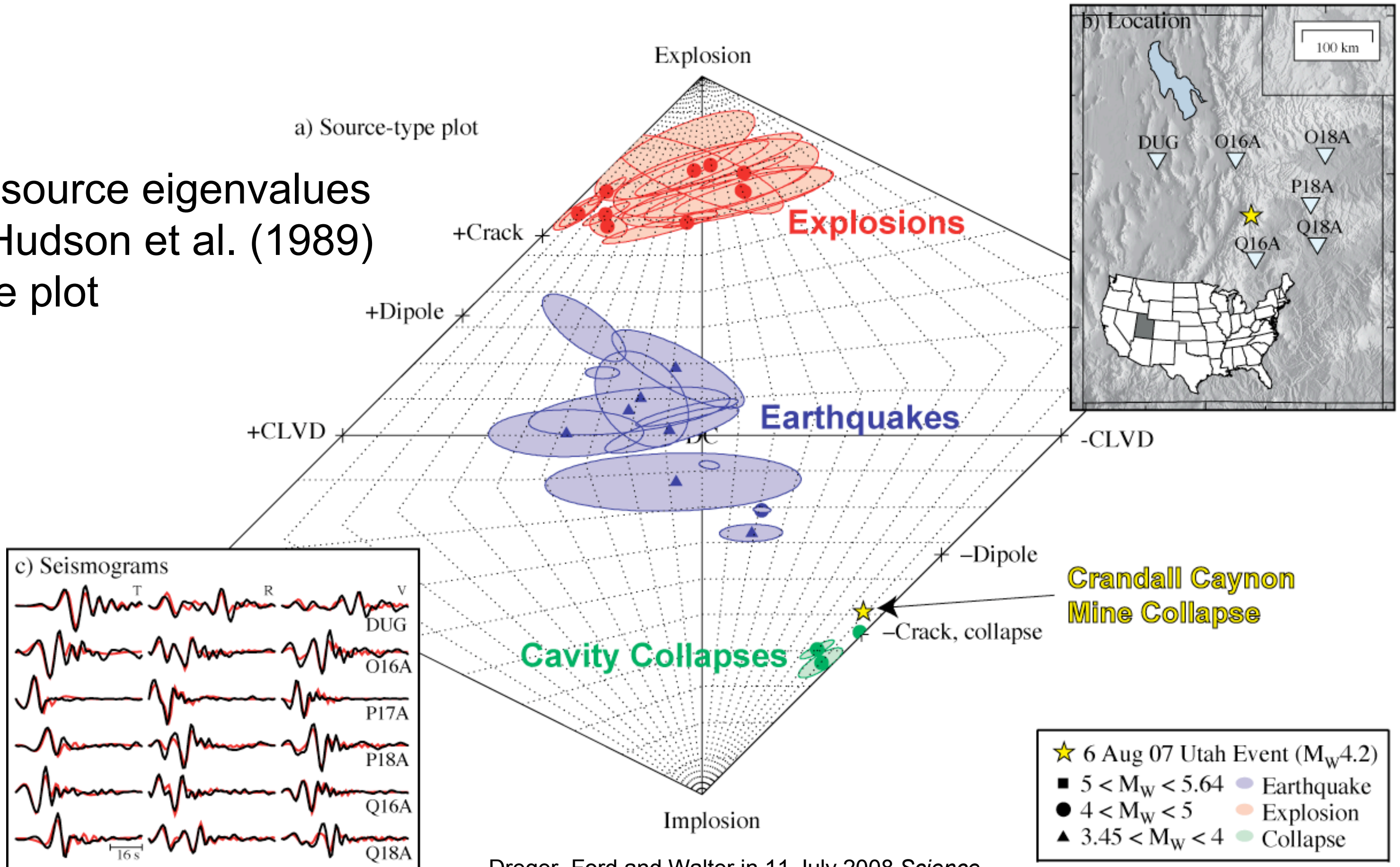
In Source Physics we must understand how target and background sources generate signals



Example: moment tensor full waveform modeling at intermediate periods can separate source types

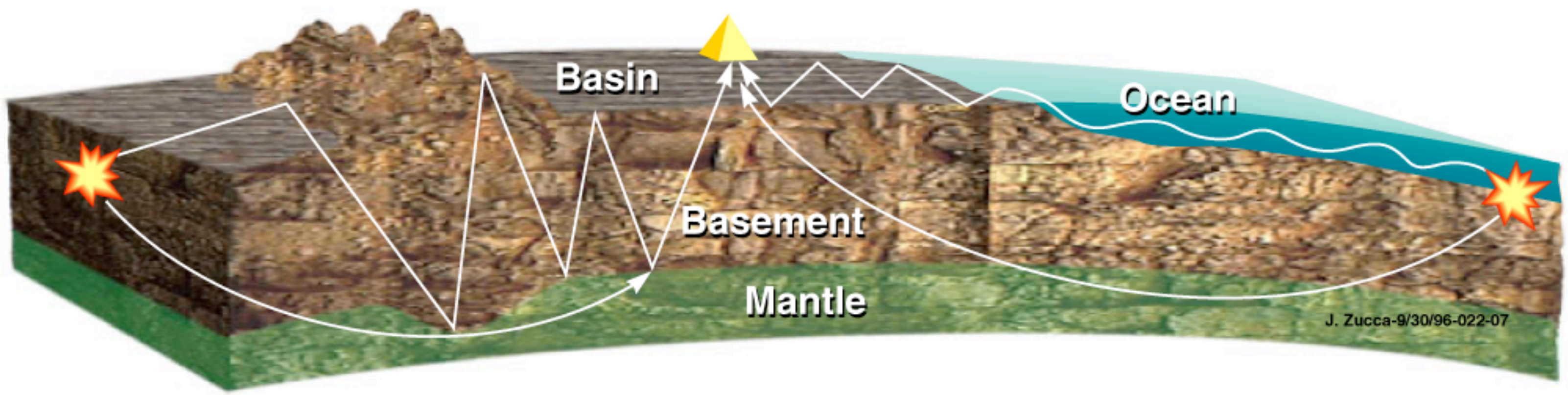
Moment tensor full waveform 1-D modeling identifies the seismic signal associated with the August 2007 Crandall Mountain coal mine accident as due to a cavity collapse

Point-source eigenvalues on a Hudson et al. (1989) source plot

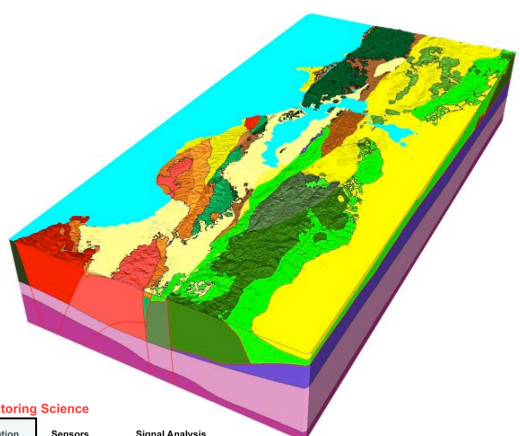


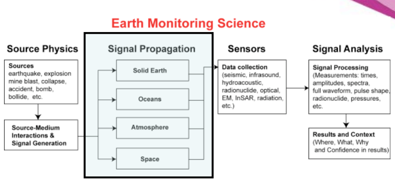
Dreger, Ford and Walter in 11 July 2008 *Science*

In Signal Propagation we must understand and predict the media's effect over a wide frequency range



Development of accurate 3D models





Brocher et al, 2006

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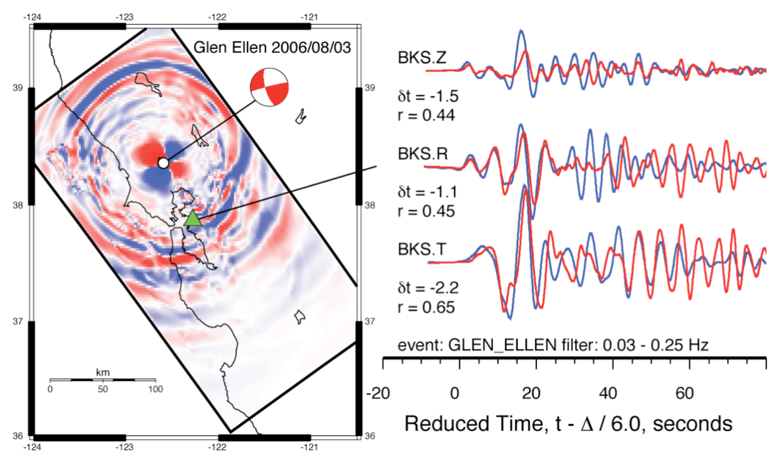
Development of 3D computational capability

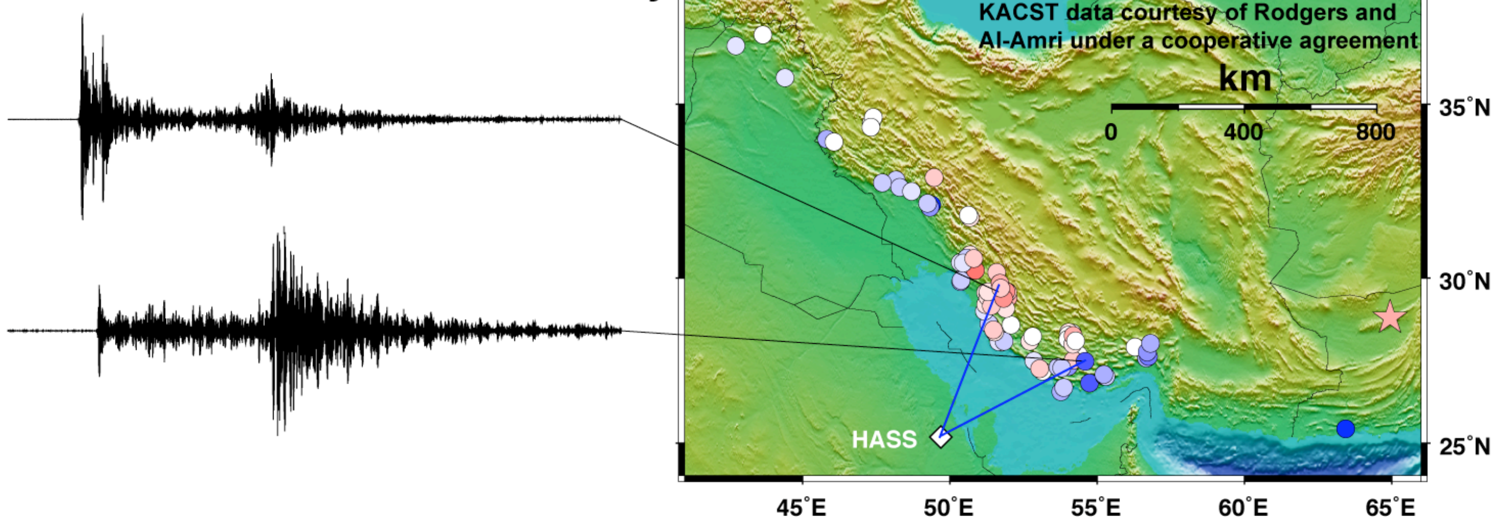


Rodgers et al, 2008

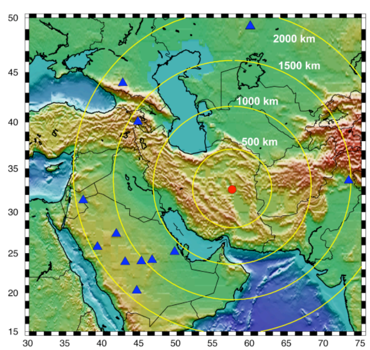
Example: 3D wavefield calculations will help explain and predict complex observations

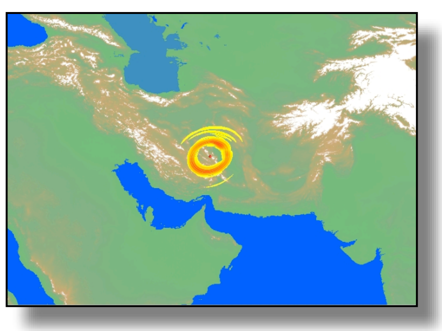
Example of large 6-8 Hz Pn/Sn variation in the Middle East

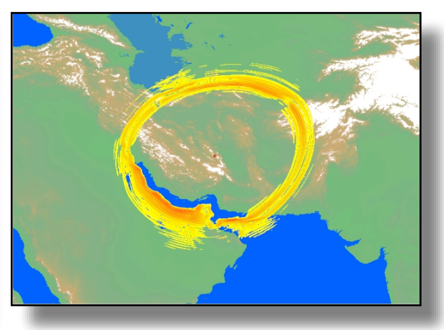
Two mb~4.5 events about 550 km away

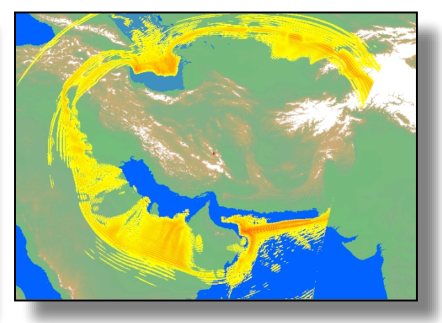


February 2005 Kerman earthquake simulations by A. Rodgers et al. on BlueGene/L

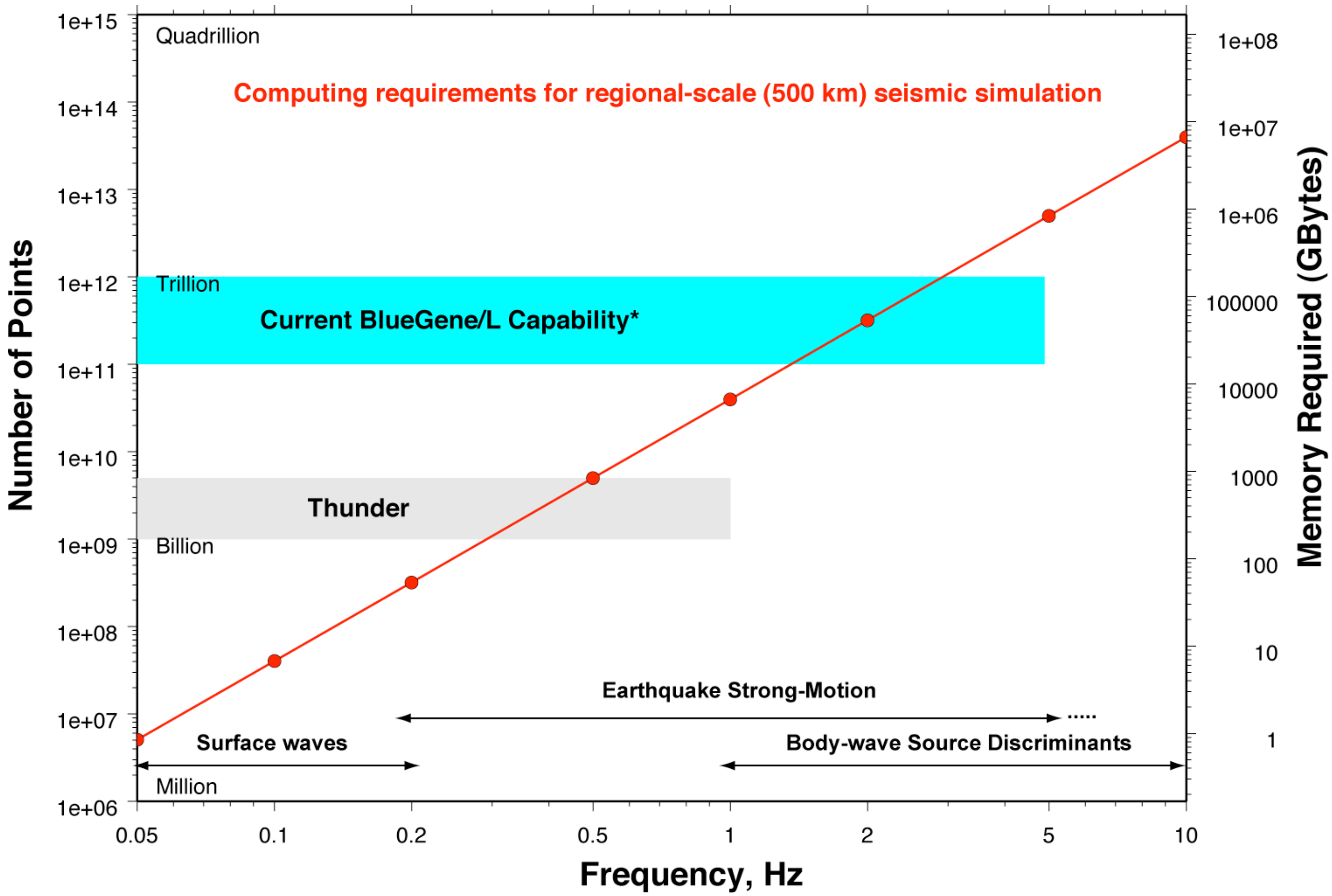








Example: 3D wavefield calculations are becoming more feasible



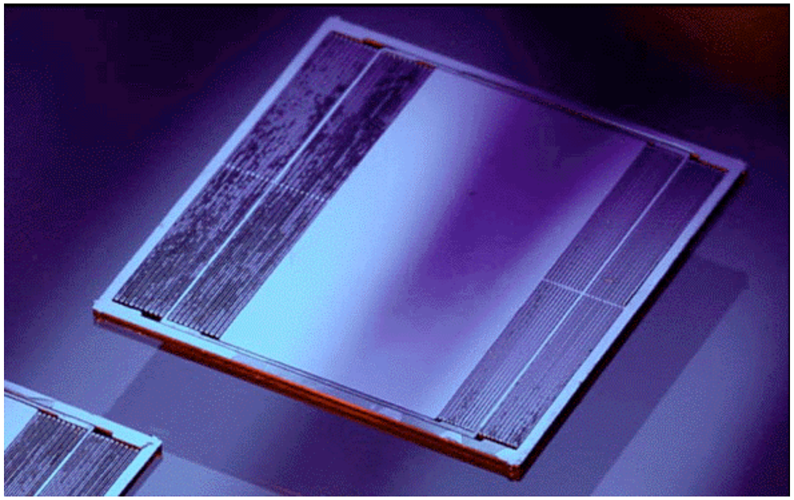
For Sensors we want to improve sensitivity, and lower power requirements and device costs

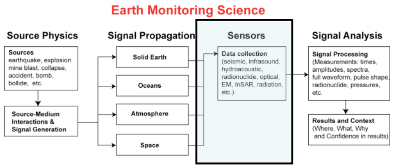
Current Sensors

Future Sensors

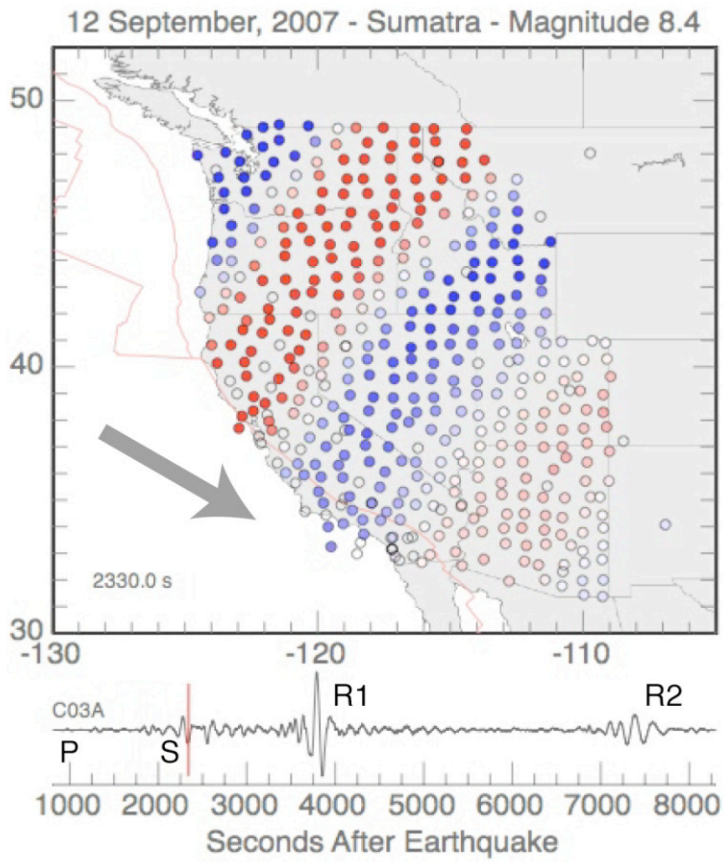
Imperial College Prototype MEMS seismometer

(AFRL BAA FA8718-06-C-0011)



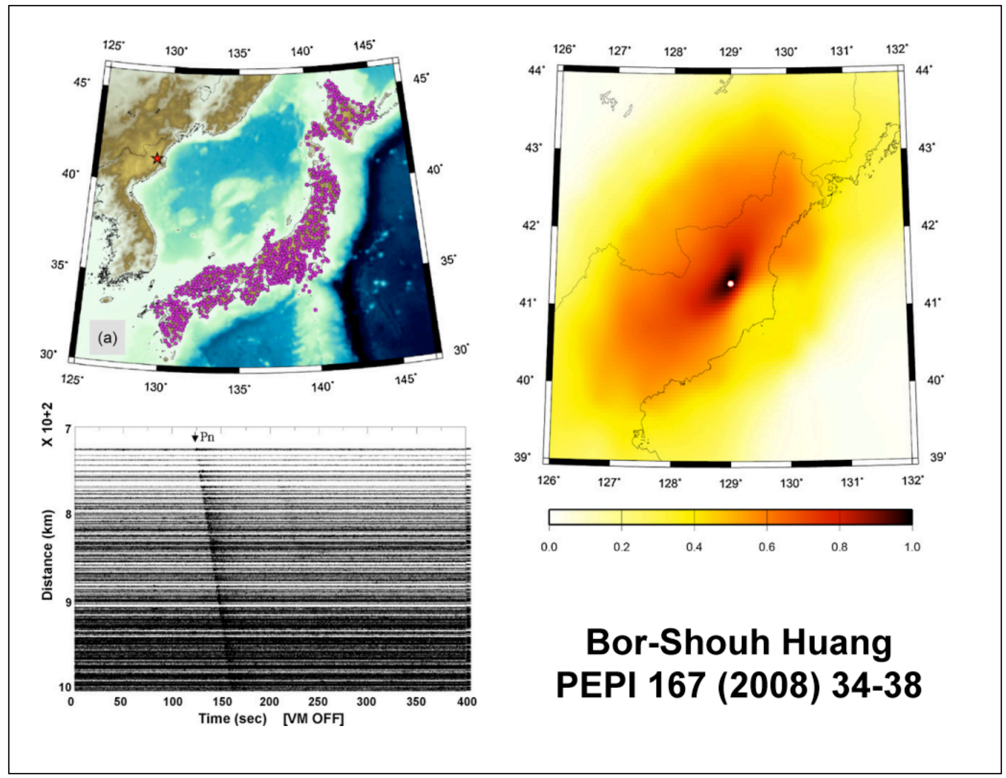


Dense sensor deployments allow non-aliased wavefeld sampling and new kinds of processing



Ammon and Lay 2007

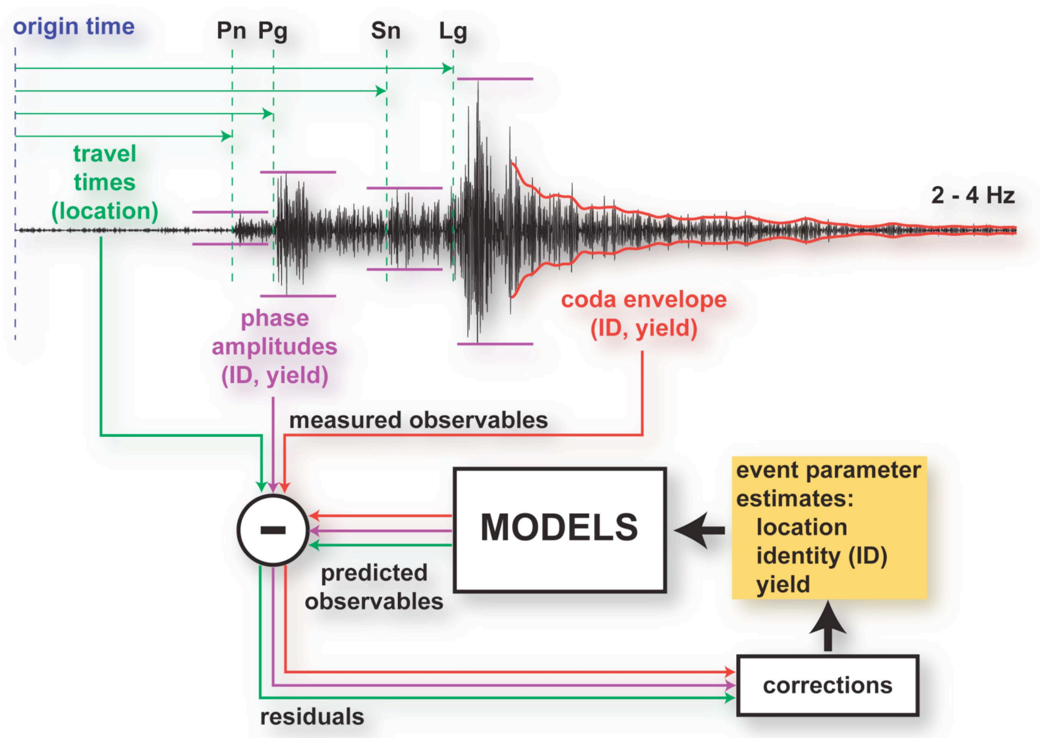
Hi-Net Location of 2006 North Korean test

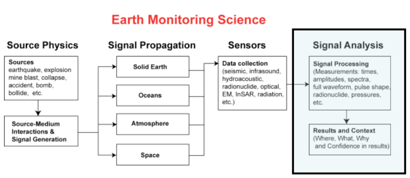


Similar to Ishii et al 2005

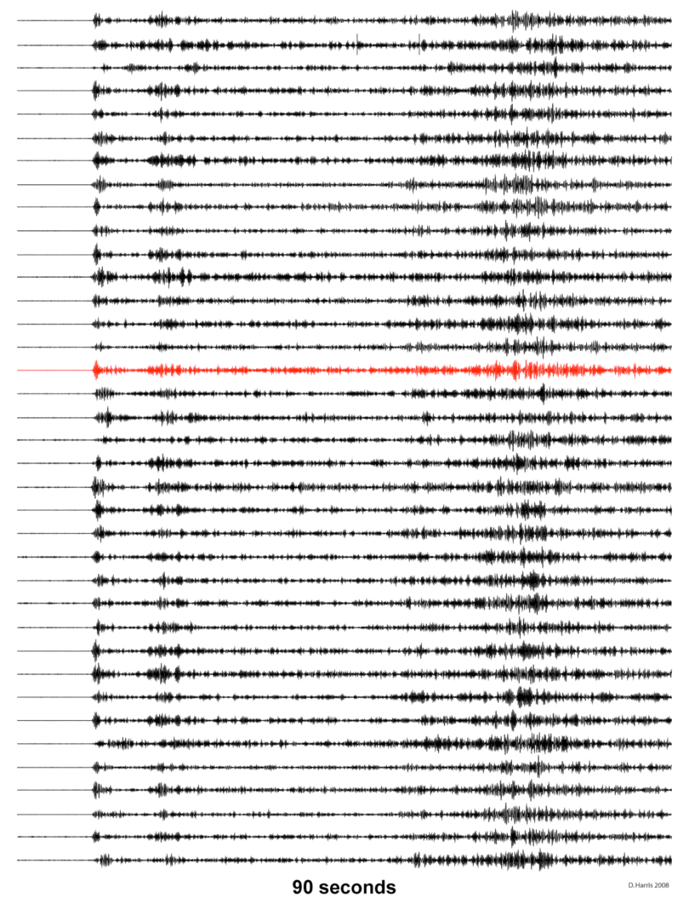
In Signal Analysis we want to exploit all available signal within the context of empirical and model data

Current Practice



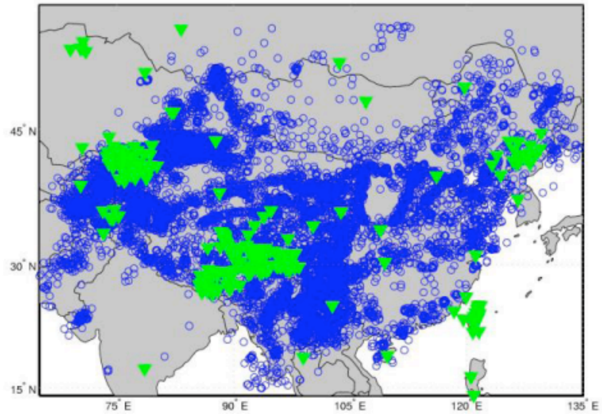


Future Practice

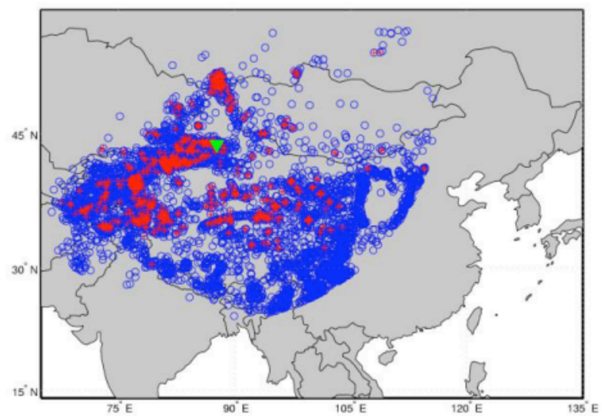


Cross-correlation and matched-field examples

18,886 events (BLUE) at 363 stations (GREEN).



17% (RED) correlate (CC> 0.5) with at least one other event at station WMQ



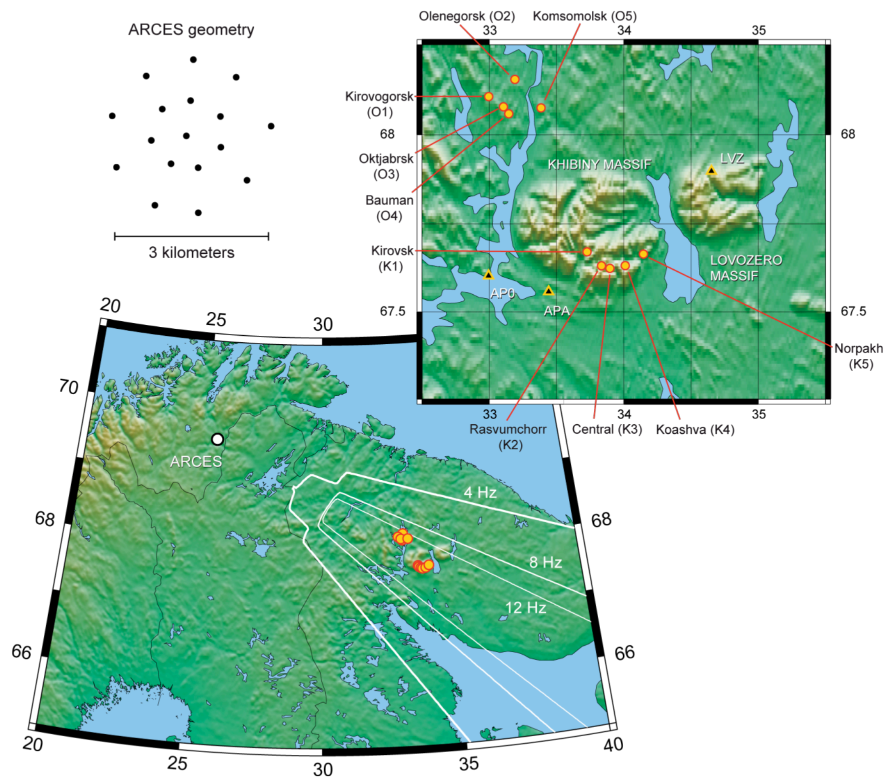
Schaff and Waldhauser, 2007

Matched Field is “adaptive optics” for seismology

- Data processed coherently in space, but not in frequency

– Distinguishes closely-spaced sources heretofore inseparable

– Works where waveform correlation methods fail



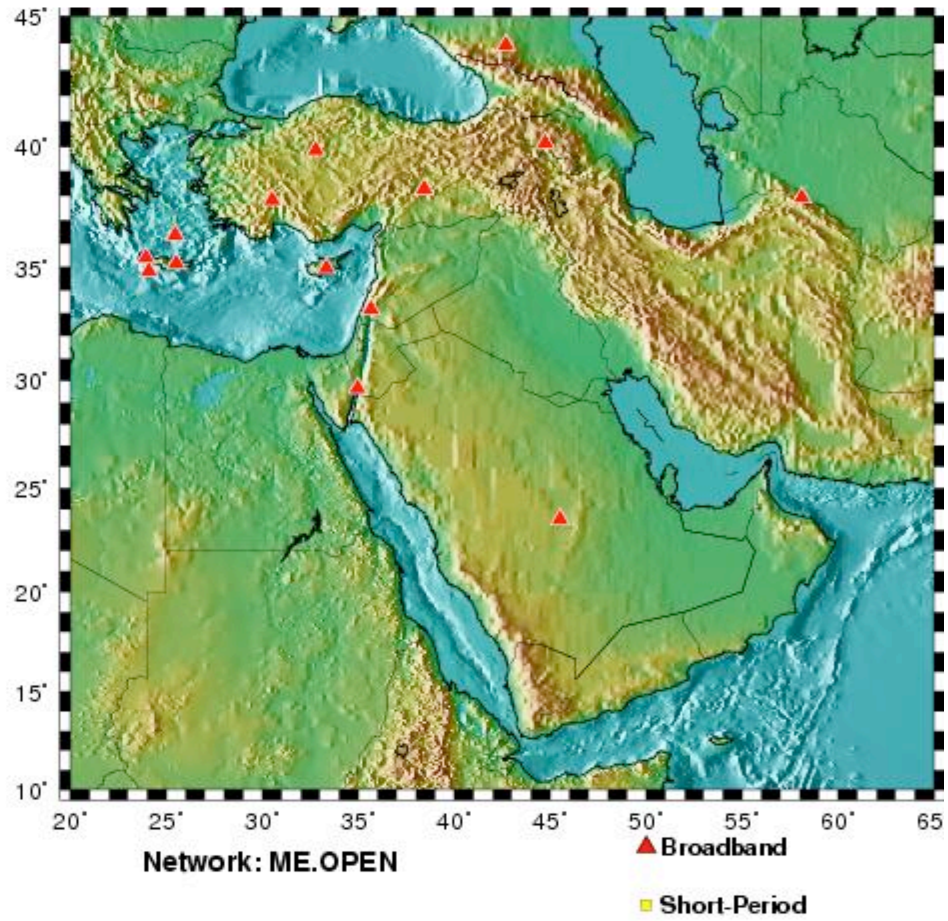
Harris et al., 2008

Grand Challenge 1: More Data

Seismology is a data-driven science: We need to increase the available data by orders of magnitude

Middle East Example:

- Currently existing and openly available



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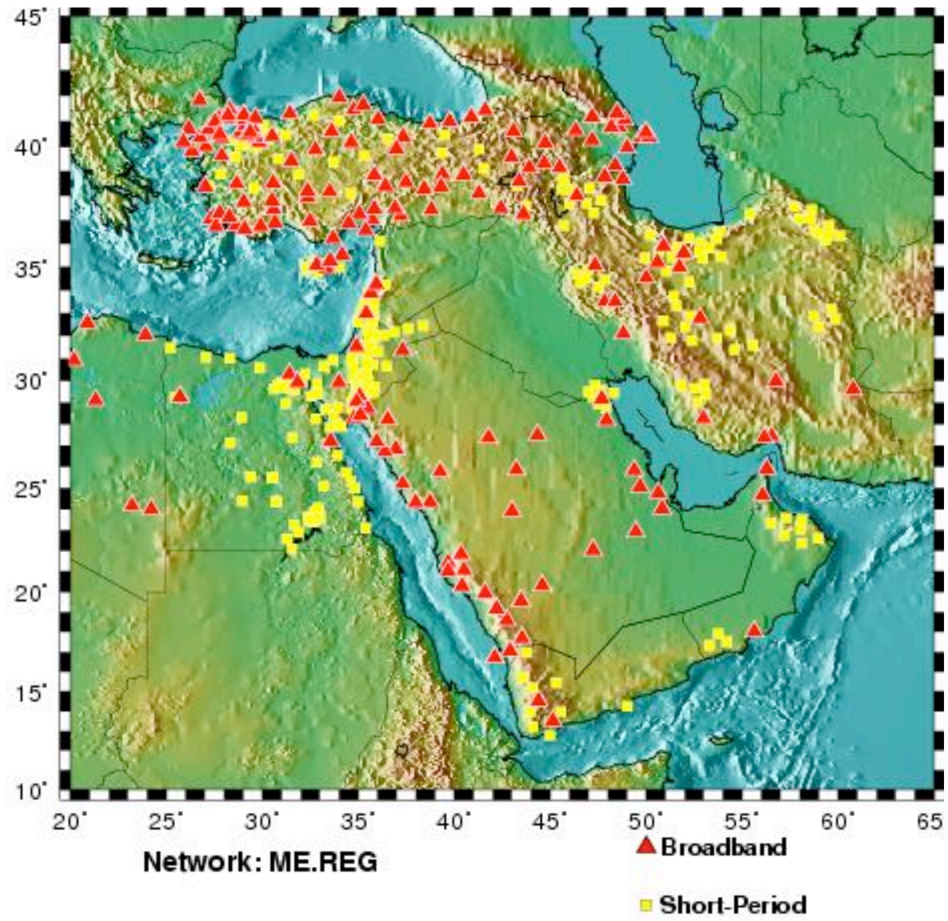
Middle East Example:

- **Currently existing and openly available**

- **National Networks not all openly available**

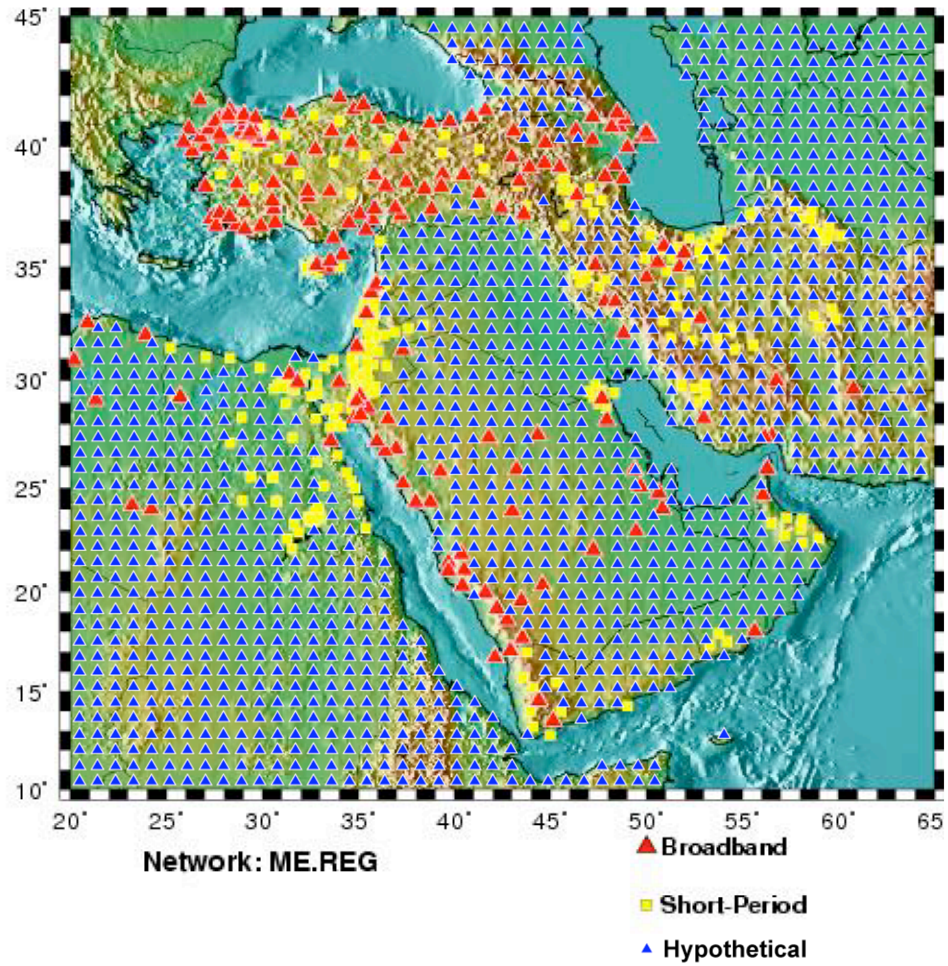


Grand Challenge 1: More Data

Seismology is a data-driven science: We need to increase the available data by orders of magnitude

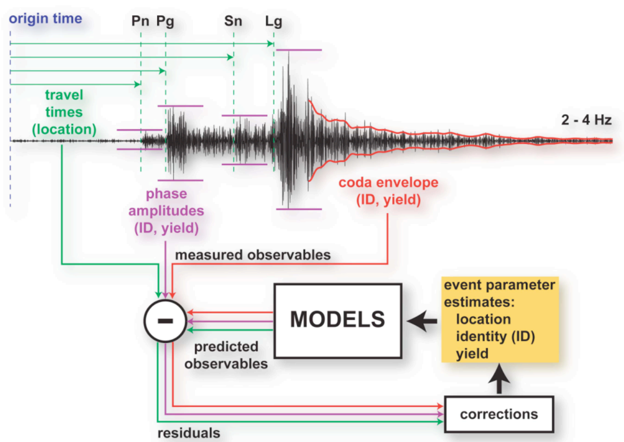
Middle East Example:

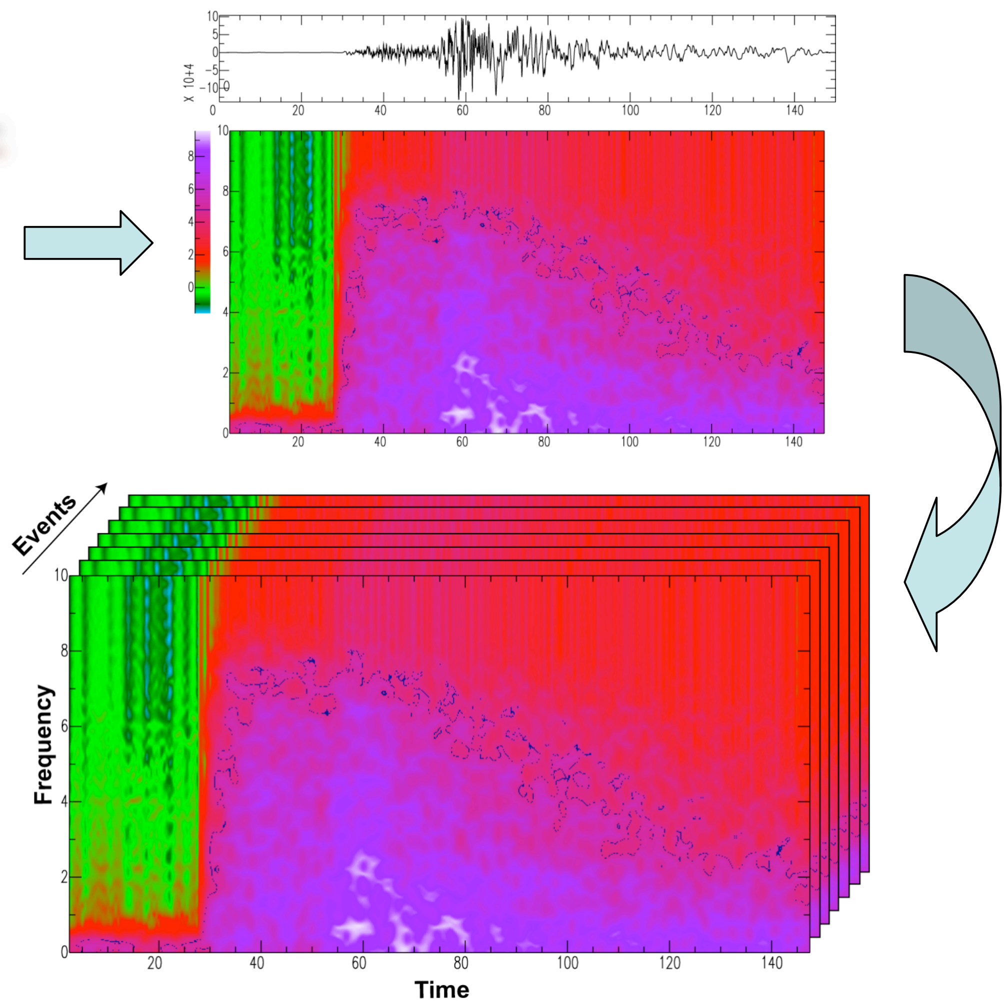
- Currently existing and openly available
- National Networks not all openly available
- Future Possibilities:
  - Eurasia Array
  - Africa Array
  - …



Grand Challenge 2: Better data exploitation

With nearly all the world's continuous seismology data online, what new kinds of processing/analysis should we be doing?





Goals: Use all time-bandwidth available and compare to all empirical and model data

Grand Challenge 3: Putting it all together

How do we meld many disparate/conflicting results into a single global reference model for the Earth?

In principle this is just multi-set inversion but how to do it practice?

Grand Challenge 3: Putting it all together

How do we meld many disparate/conflicting results into a single global reference model for the Earth?

One suggestion - Take a page from the Climate Modelers: DOE Office of Science sponsored PCMDI: "Program for Climate Model Diagnosis and Intercomparison"

How about a TERRA Program: "Testing Earth Realizations and Reconciling Anomalies?

Summary

- **Monitoring is ultimately advanced by its ability to predict the observables (noise and events)**
  - **Source Physics**
  - **Signal Propagation**
  - **Sensors**
  - **Signal Analysis**

- **The long-range goal is end-to-end prediction capability across the full spectrum of observable seismic amplitudes and frequencies**

- **Some Grand Challenges:**
  - **How do we expand worldwide data?**
    - National Networks
    - New deployments
  - **How do most effectively process the seismic data we observe?**
    - empirical+model based full time-bandwidth processing
  - **How do we create a 3-D Earth Reference Model for Monitoring?**
    - Something like a TERRA Program to evaluate and reconcile models