Volcano Seismology

and a little infrasound

Greg Waite and Diana Roman

PASI: Magma Tectonic Interactions in the Americas, Leon Nicaragua

A few questions about magma-tectonic interactions volcano seismology can address?

Where is the magma?

Is the magma is moving?

Is the magma rich is gas?

What is the relationship between local and regional stress?

Are there variations over time?

Is a system is critical (ready to be triggered by some external stress)?

Outline

- The seismogram
- Seismometers
- Source and Path studies
  - Later talks will elaborate on these
- Volcanic earthquake classification
- Infrasound

The Seismogram: What we actually study

We study a distorted version of the true motion of the Earth in the seismogram

- seismogram or receiver (r) is a convolution (*) of the source (s), the Earth's response (g), and the seismometer's response(ϕ):

$$s(t) * g(t) * \phi(t) + noise = r(t)$$

- we can account for ϕ, and model g to derive s
  - source mechanism inversion

OR

- we can assume characteristics of s, account for ϕ to model g
  - e.g., seismic velocity tomography

Convolution

$$s(t) * g(t) * \phi(t) = r(t)$$

Convolution in the time domain is multiplication in the frequency domain

$$s(\omega)g(\omega)\phi(\omega) = r(\omega)$$

Which makes things like inverting for the source time function much simpler

$$s(\omega) = g^{-1}(\omega)\phi^{-1}(\omega)r(\omega)$$

The Receiver (seismometer)

- Mechanical transducer
- Band-limited
- A combination of instruments is required to record all frequencies of interest

<u>Seismic Frequencies (Hz)</u>

10^6 10^2 10 1 10^{-1} 10^{-2} 10^{-6}

--------- P and S waves ----------

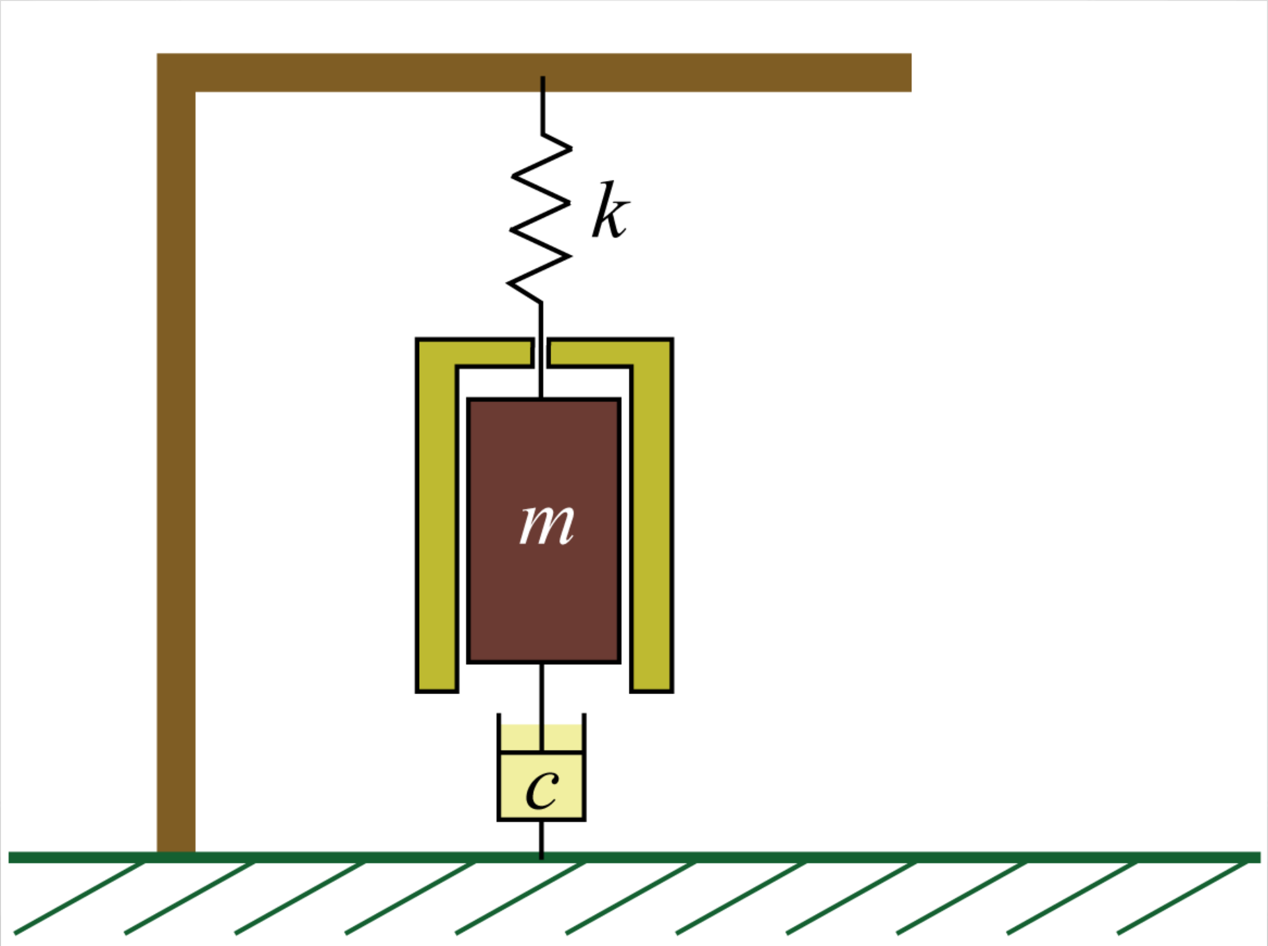
-surface waves-

<----- GPS -------------------------->

- free oscillations -

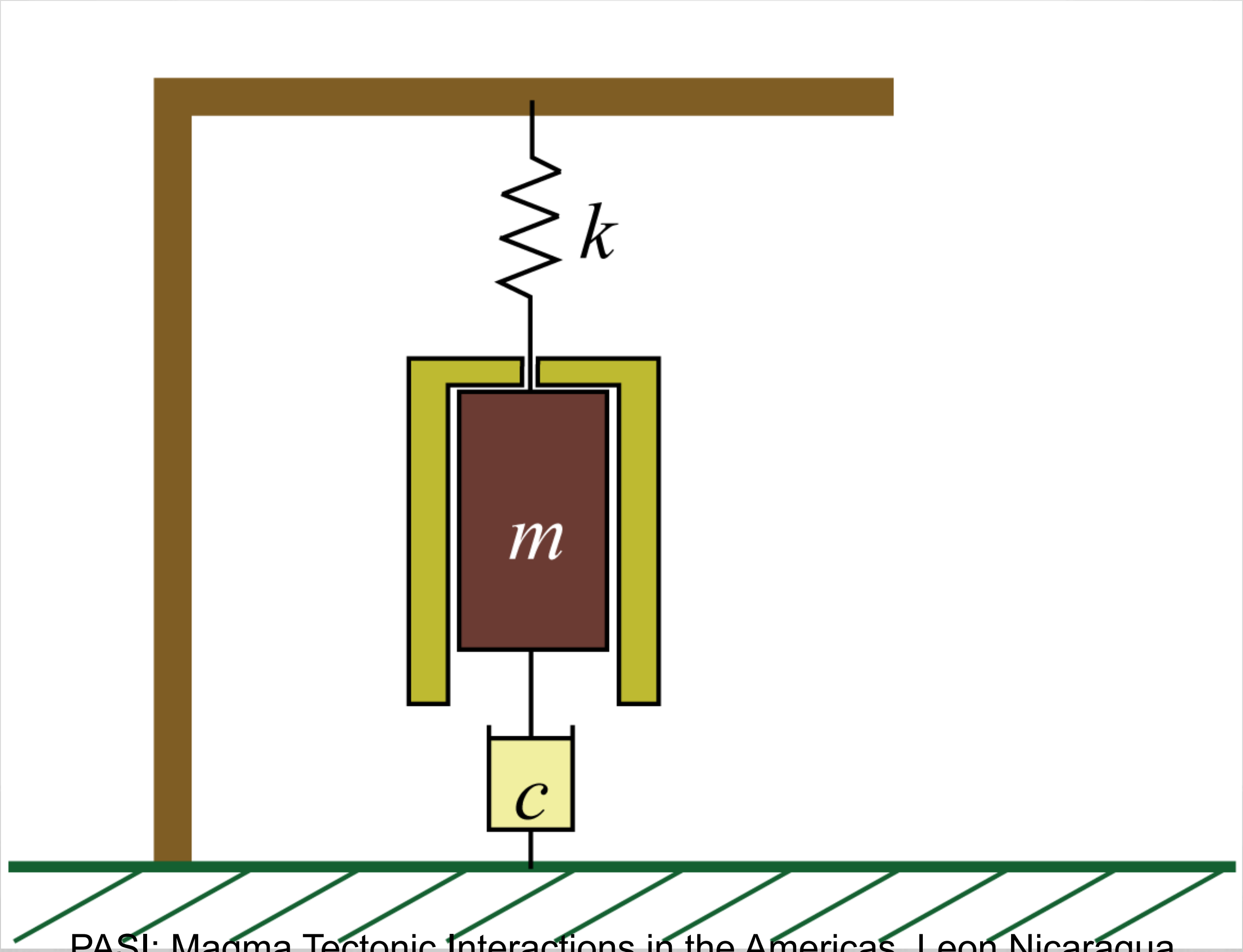
Seismometers

- Inertial seismometers work on the same basic principle
- A simple seismometer consists of an inertial mass (*m*), suspended by a spring with spring constant (*k*) and damping (*c*)



Seismometers

- When the ground moves, the frame of the seismometer moves, but the inertia of the mass keeps it in place (more or less) and it moves with respect to the frame



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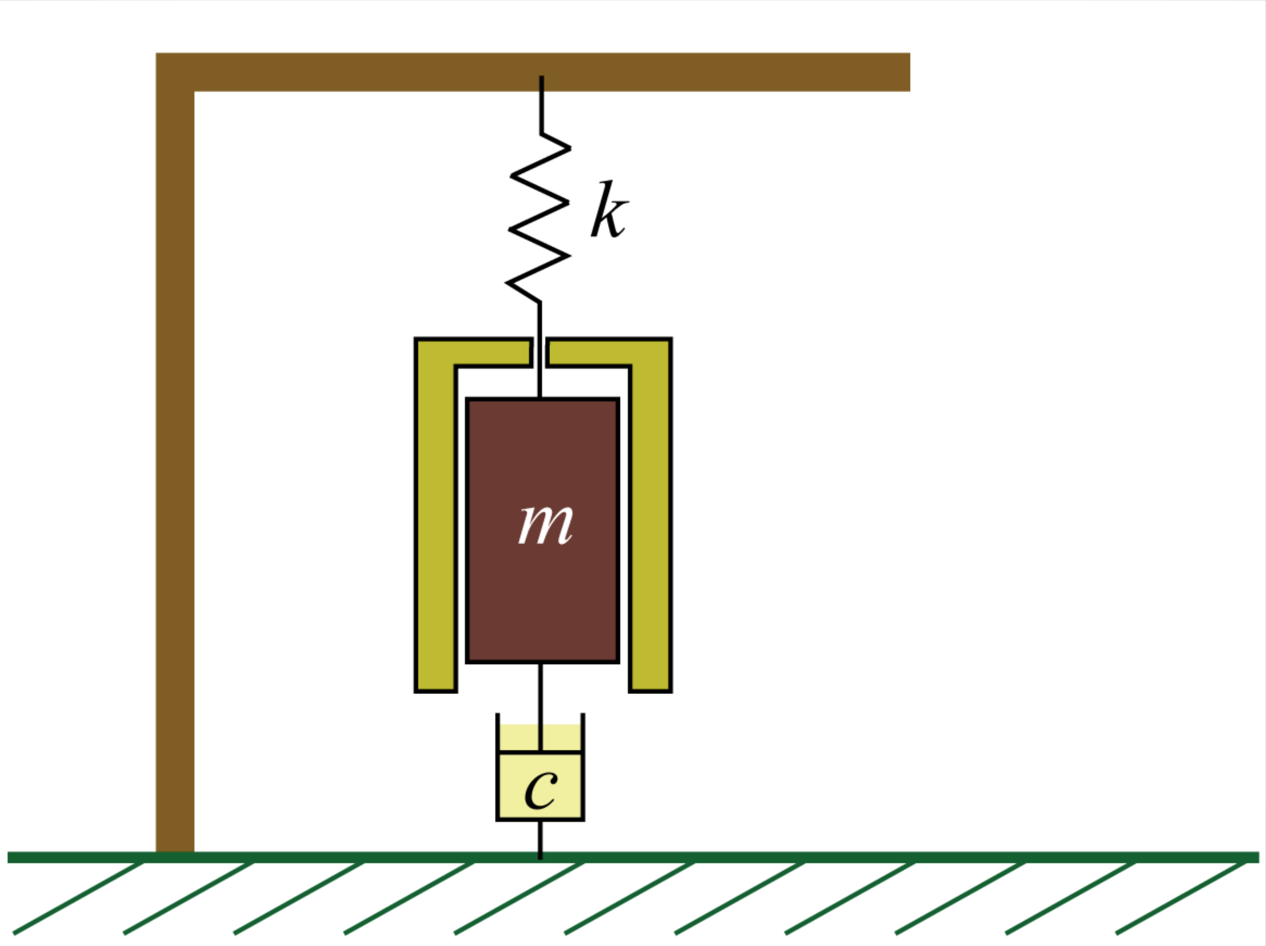

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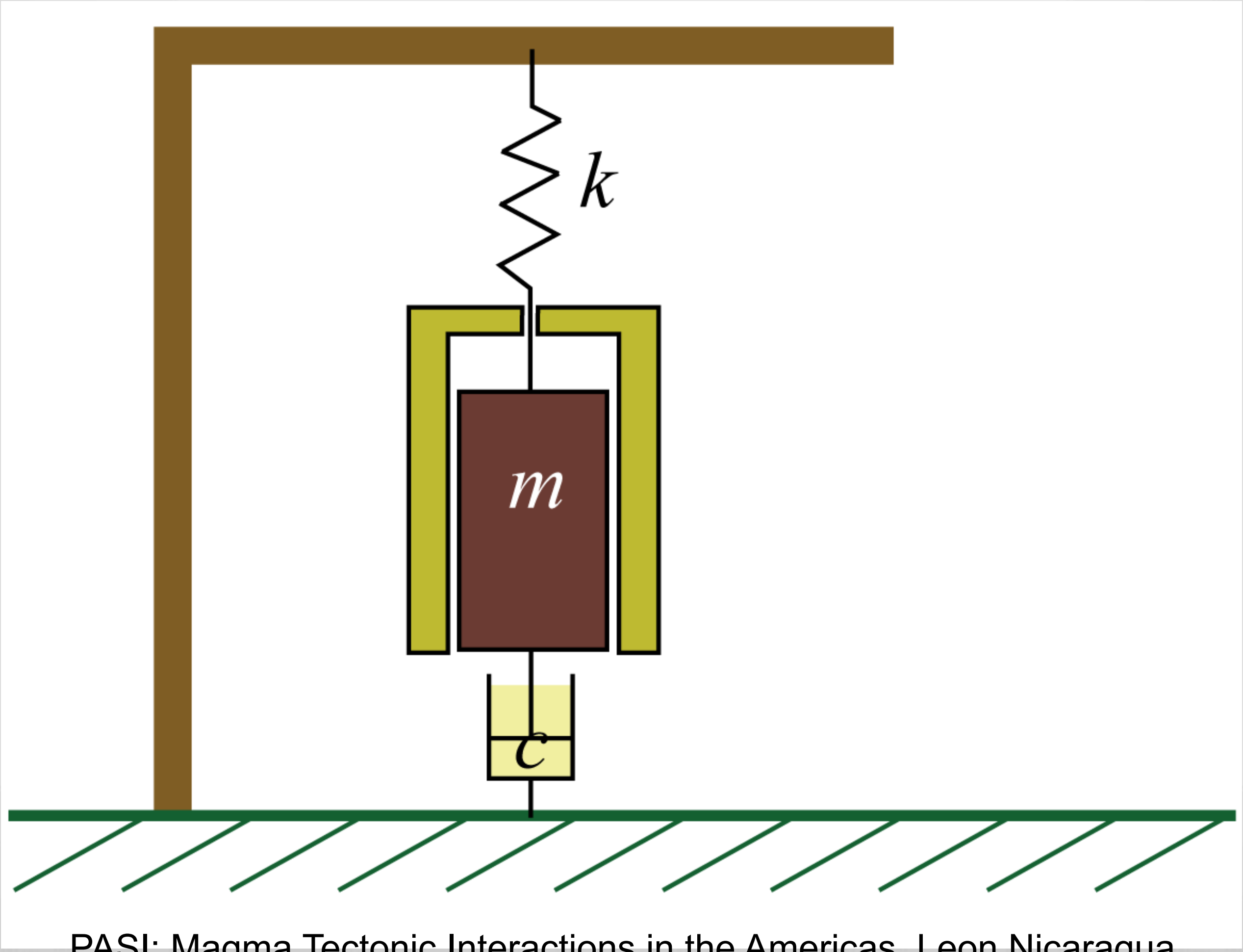

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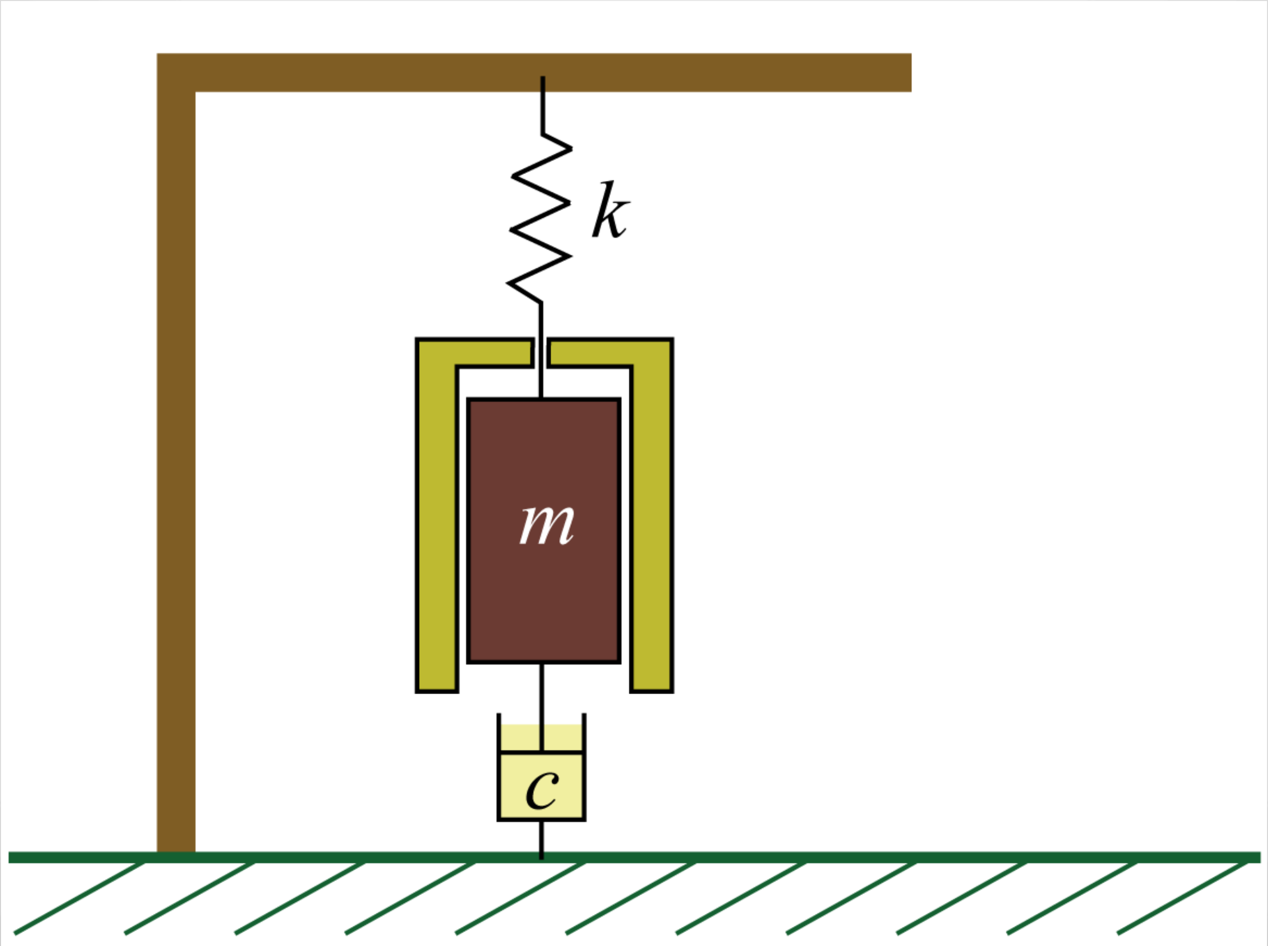

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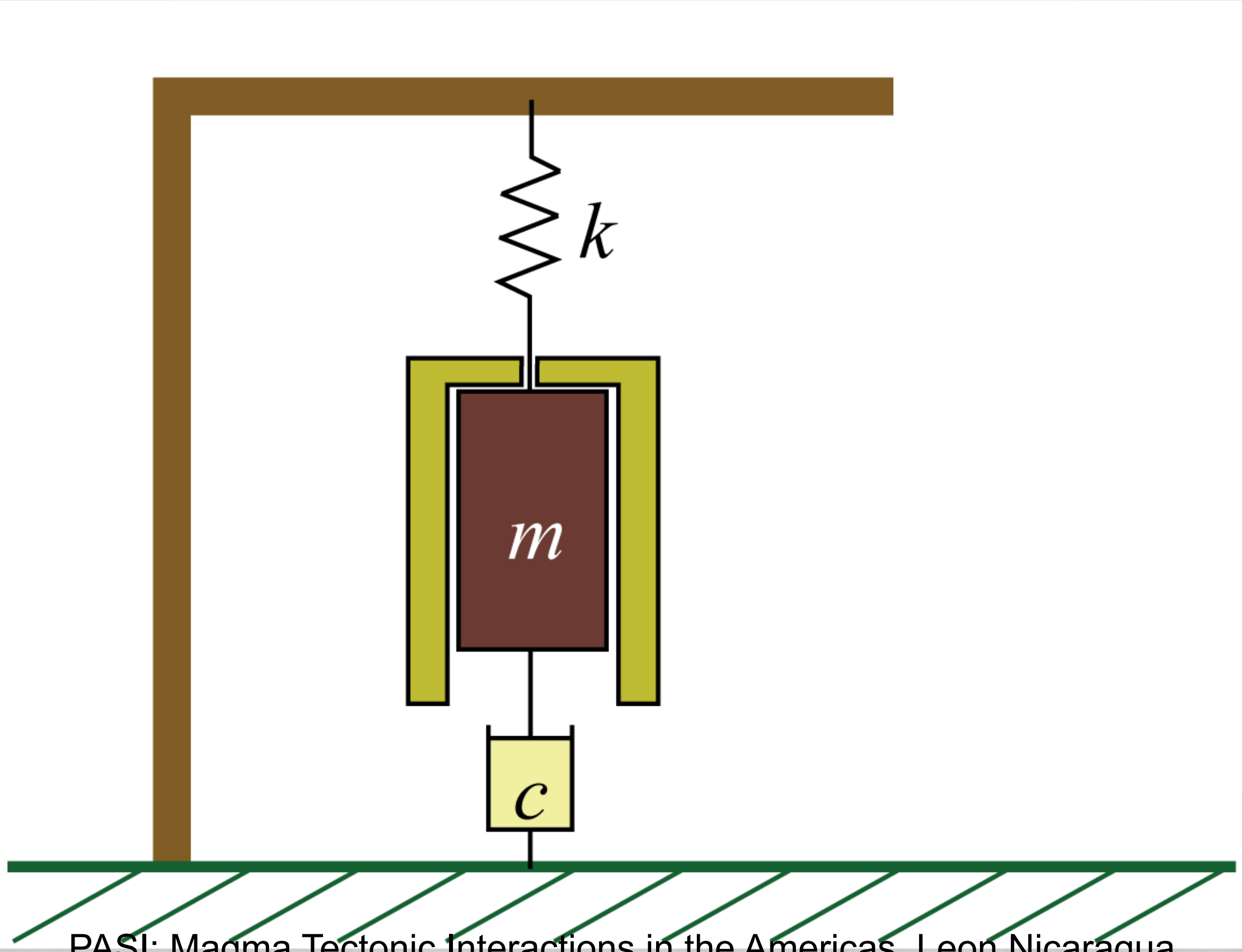

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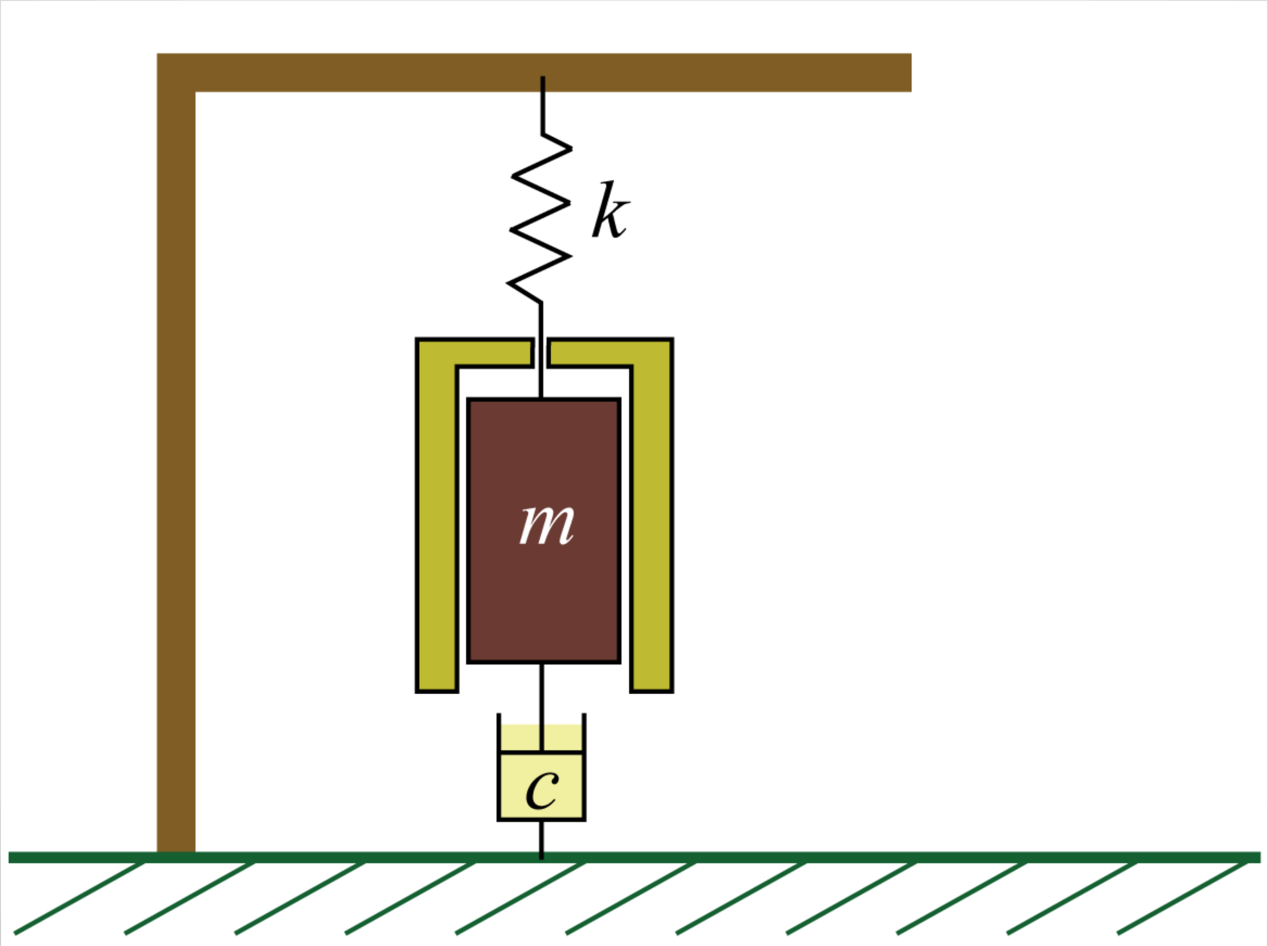

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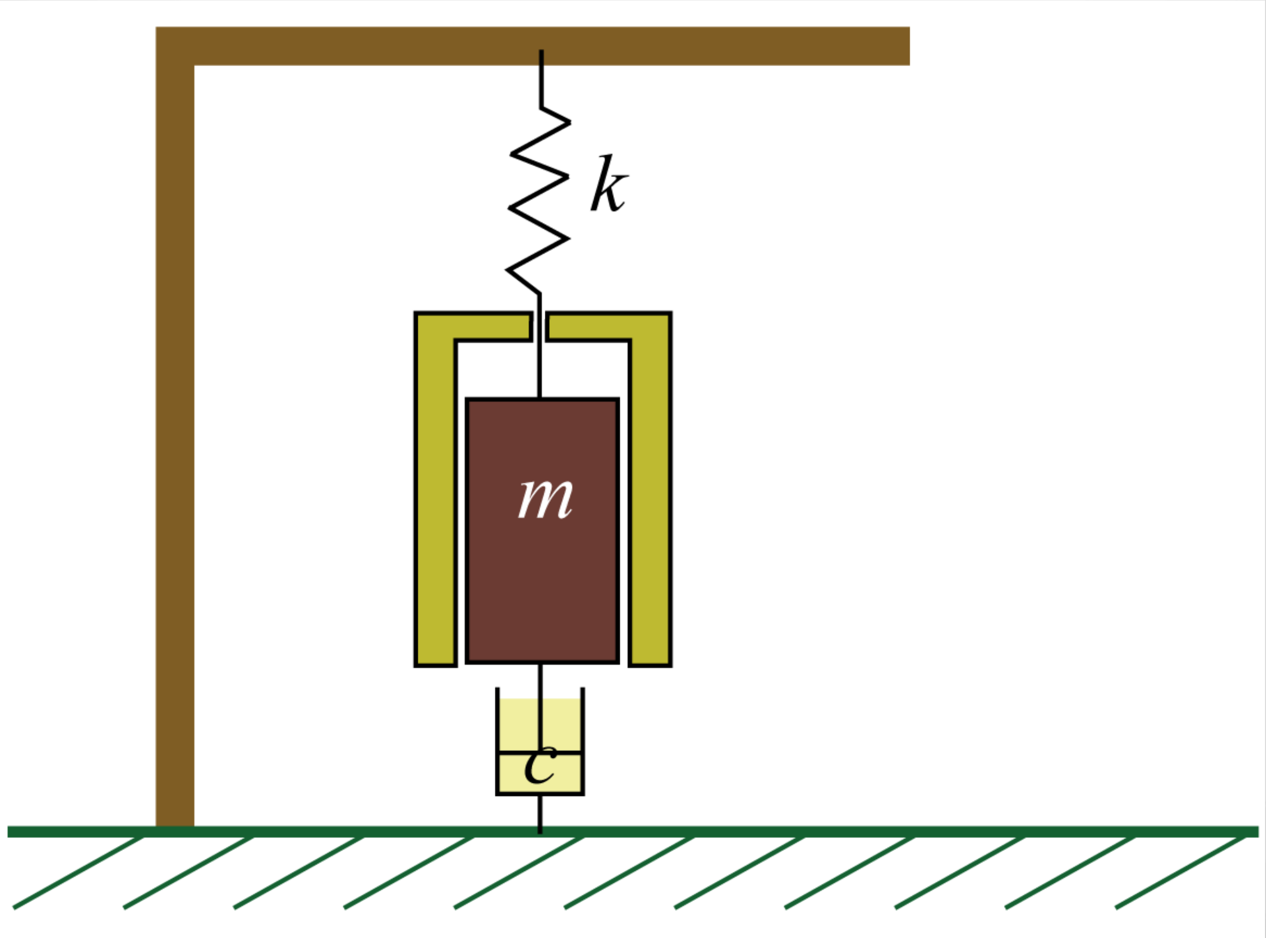

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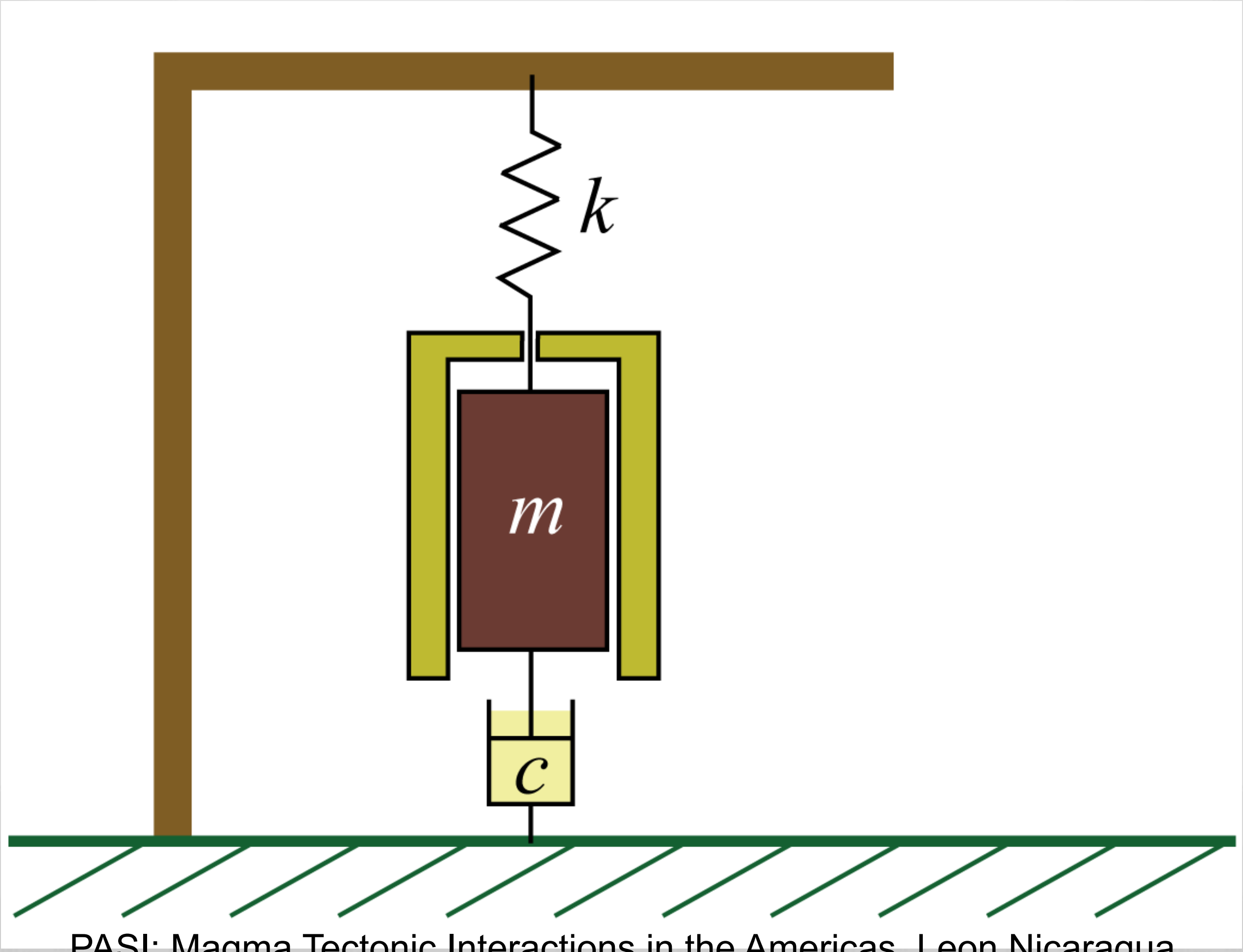
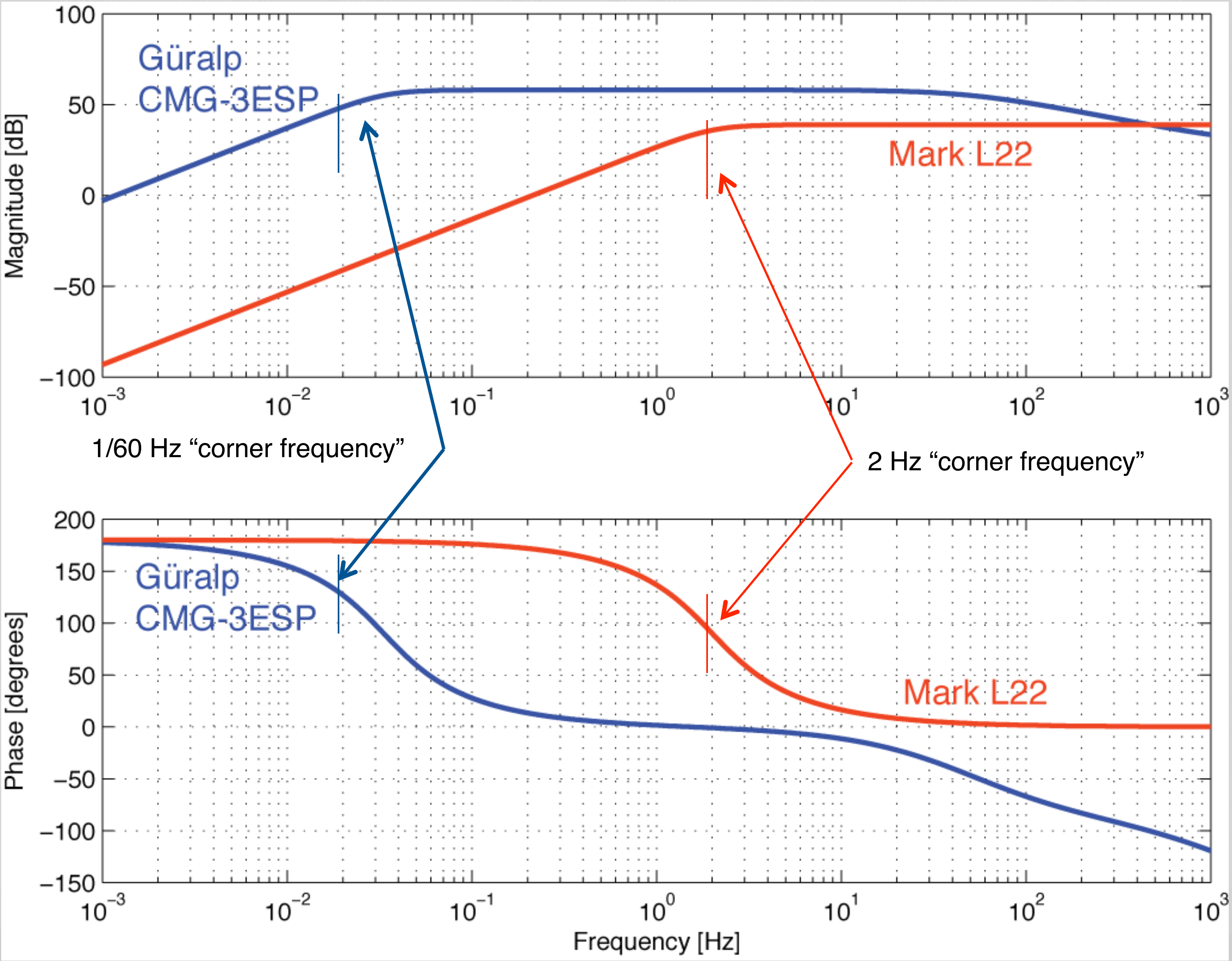


From Seismometer to Seismogram

- Output voltage is proportional to ground velocity (not the same as the seismic velocity of the medium) over a range of frequencies
- Analog voltage is digitized and recorded
- Frequency band of the seismometer depends on mass and spring constant
- “Broadband” seismometers use a force-balance feedback system where power is required to keep the mass fixed with respect to the frame – allows for wider dynamic range through a much lower corner frequency

Typical seismometer response functions



From Seismometer to Seismogram

Seismometers typically output **voltage**
Current is proportional to ground velocity
Sensitivity given in V/m/s, e.g., 2000 V/m/s for a Güralp-3ESP intermediate band sensor

Digitizer takes the input voltage (analog signal) and digitizes to **counts**
For a commonly used RefTek-130, the conversion from volts to counts is 6.29e5 counts/volt

So to get velocity from a digital record in counts:
divide by 6.29e5 and then divide by the sensitivity (2000 V/m/s)

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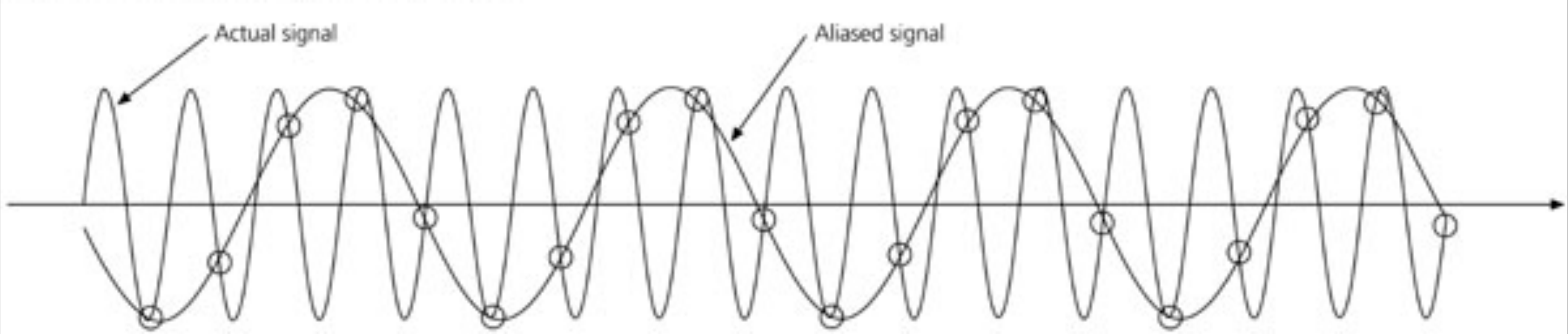
But this does not account for any phase shift!

Basic signal processing: aliasing

- Ground motion is continuous (analog)
- To examine digital data, we sample the continuous data
- Aliasing results from inadequate sample rate for the frequency of the signal



Stein & Wysession, 2003

Examples of path studies

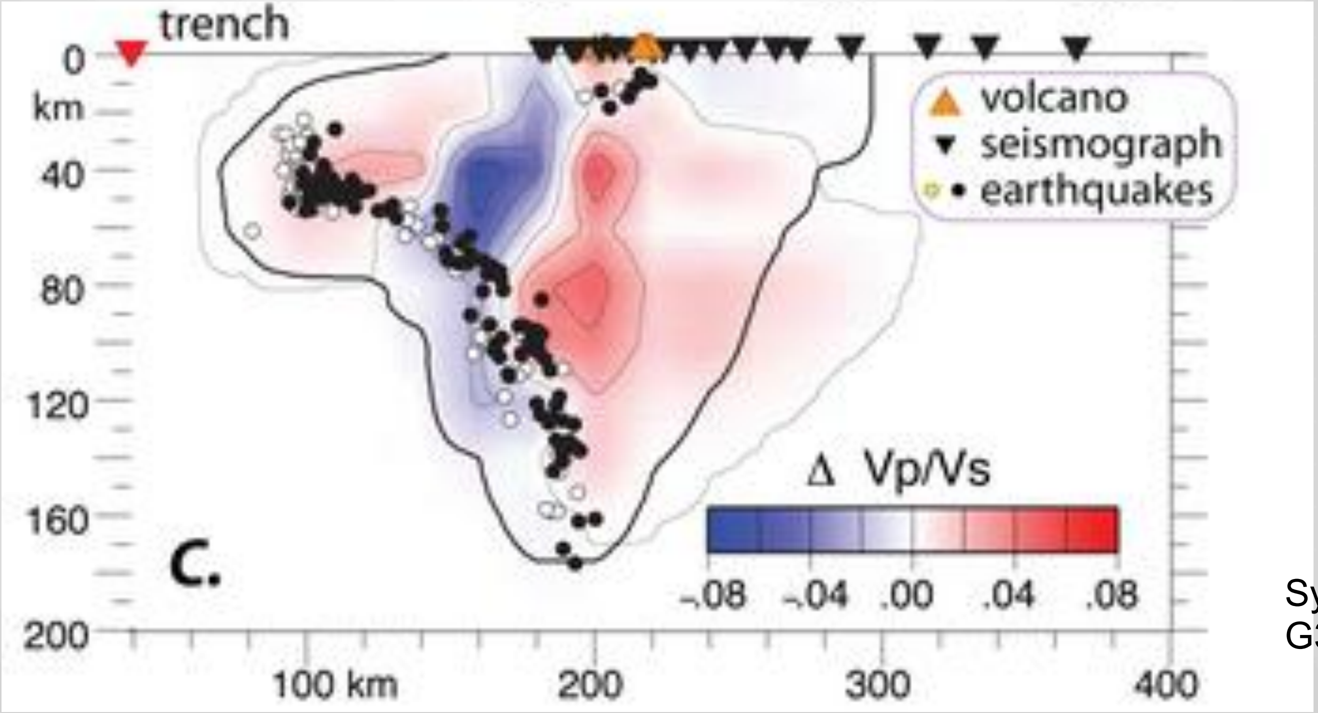
- Velocity tomography
  - Body wave
  - Surface wave
  - Ballistic or ambient noise
- Receiver functions
  - Use body wave conversions to infer depths and magnitudes of velocity contrasts
- Anisotropy
  - Multiple ways to model how seismic velocity varies with propagation direction

Seismic tomography

- Use of travel times from manmade or natural sources (earthquakes) mapped back into the Earth
- Critical for accurate earthquake locations
- Large portions of magmatic systems can be imaged
- Limited by
  - Network design
  - Source distribution
  - Wavelength

Regional scale seismic tomography

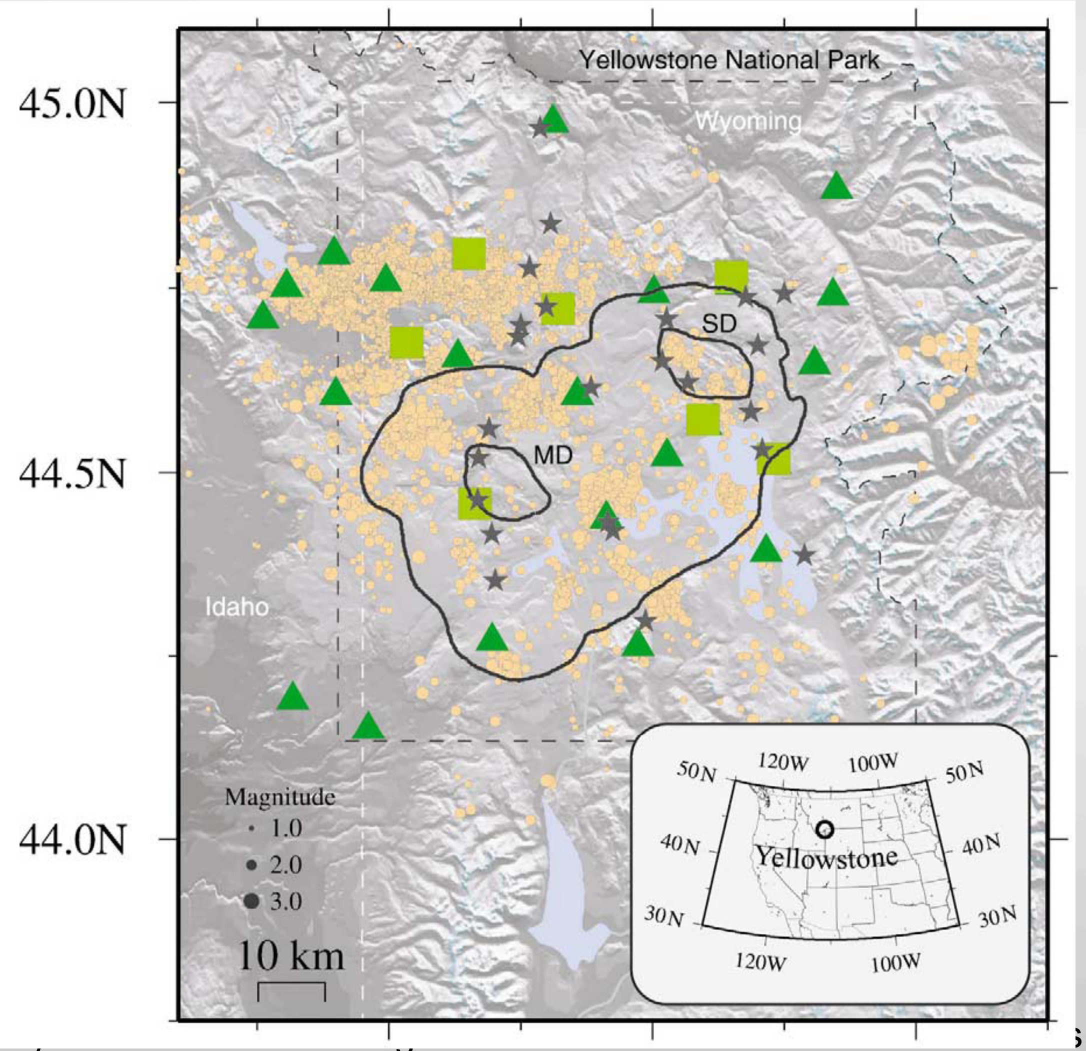
- Targets in the crust and upper mantle
- Use earthquakes and artificial sources
- Ratio of Vp to Vs particularly useful for finding fluids in the crust
  - Fluids have no shear strength, so Vs is zero (bulk Vs for fluid rich rock is low)
  - Vp/Vs is high for liquids, like magma



Syracuse et al., G3, 2008

Local earthquake tomography

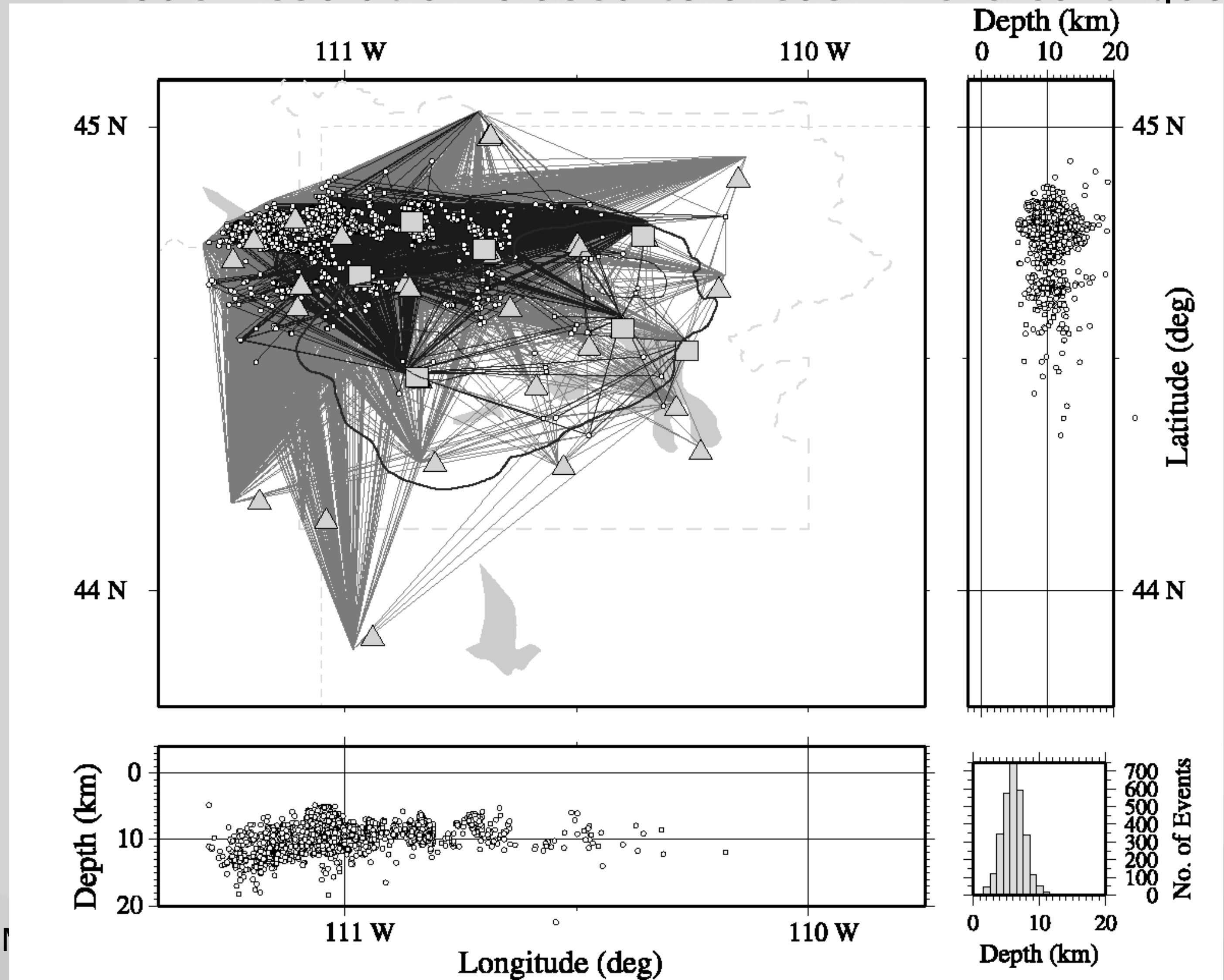
- Targets in the upper crust
- Models are biased to areas where earthquakes occur



Husen et al., JVGR, 2004

Local earthquake tomography

- Targets in the upper crust
- Model resolution biased to areas where earthquakes



Husen et al., JVGR, 2004

Challenges with seismic tomography

- Limited by
  - Network design
  - Source distribution
  - Wavelength

- Velocity tomography is *particularly challenging at volcanoes* where the targets are small and have low velocities
  - Diffraction affects mask evidence of low velocity layers
  - If size of anomaly is small, it won't be visible at the surface (wave front healing)

Path studies

- In the synthetic (Newberry) case, the secondary arrivals were modeled to identify the low-velocity zone
- In some cases, the anomalies may be large enough to be see with traveltime tomography, but the size and intensity (amount of velocity contrast) are underestimated

Volcanic Earthquake Classification

- Defined differently by observatories around the world
  - Different styles of eruption
  - Different types of earthquakes
  - Different recording geometry, instrumentation

- Seismograms are a convolution of the
  - Source process
  - Path effects
  - Seismometer
  - **Distinguishing between source and path effects is sometimes difficult**

Volcanic Earthquake Classification

- Minakami's classification was developed before digital seismographs (1950s)
- New analysis tools have been developed (computers) and new signals have been observed (e.g., very-long-period earthquakes) so that this classification must be adjusted
  - e.g., many observatories now use spectrograms to identify events

Why Classify Earthquakes?

Why Classify Earthquakes?

- If you can infer something about the source process, you have a better understanding of the likelihood of eruption, hazard, etc.

- Some prefer to classify events based on likely source process rather than simply how they look and/or where they occur w.r.t the volcano
  - This requires a lot of background work to compute source mechanisms for representative events
  - For some volcanic events, in particular, tremor, there may be multiple models that fit the data

Minakami's volcanic earthquake classification

- Minakami, T., 1960. Fundamental research for predicting volcanic eruptions (part 1). Earthquakes and crustal deformations originating from volcanic activities. Bull. Earthquake Res. Ins. 38, pp. 497–544.
- Based originally on volcanic earthquakes in Japan
- Has been used/adopted at other observatories
- A-type
  - Volcano tectonic earthquakes (slip on a fault, double-couple)
  - Clear P and S wave arrivals
  - Sometimes defined to be at depths 1-20 km below the volcanoes, but this is partly because of path effects in the shallow subsurface that can make tectonic events look strange
- B-type
  - No clear S wave
  - Defined to be very shallow (see above)
  - Generally have low frequencies due to source and/or path
  - May increase in number just before eruption
- Tremor
  - Semi-continuous signal with harmonic or irregular sine wave signals
  - Dominated by surface waves
- Explosion earthquakes
  - Accompany explosions!
  - Amplitude is related to energy release
  - Compressional first P on all stations
  - Ground-coupled air wave

Latter's volcanic earthquake classification

- Latter, J.H., 1979. Volcanological observations at Tongariro National Park, 2, Types and classification of volcanic earthquakes, 1976–1978. Rep. 150, N.Z. Dep. of Sci. and Ind. Res. Geophys. Div., Wellington, New Zealand, 60pp.
- Based originally on volcanic earthquakes in New Zealand, but adapted to other volcanoes
- Tectonic (A type)
  - Volcano tectonic earthquakes (slip on a fault, double-couple)
  - Clear P and S wave arrivals
- Volcanic (B type)
  - No clear S wave
  - Defined to be very shallow (see above)
  - Generally have low frequencies due to source and/or path
- Medium-frequency (C type)
  - Characteristics of both Tectonic and Volcanic
  - HF onset, LF coda
  - Sometimes called hybrid
- Volcanic tremor
  - Semi-continuous signal with harmonic or irregular sine wave signals
  - Dominated by surface waves
- Volcanic Explosion (E type)
  - Accompany explosions
  - Amplitude is related to energy release
  - Compressional first P on all stations
  - Ground-coupled air wave

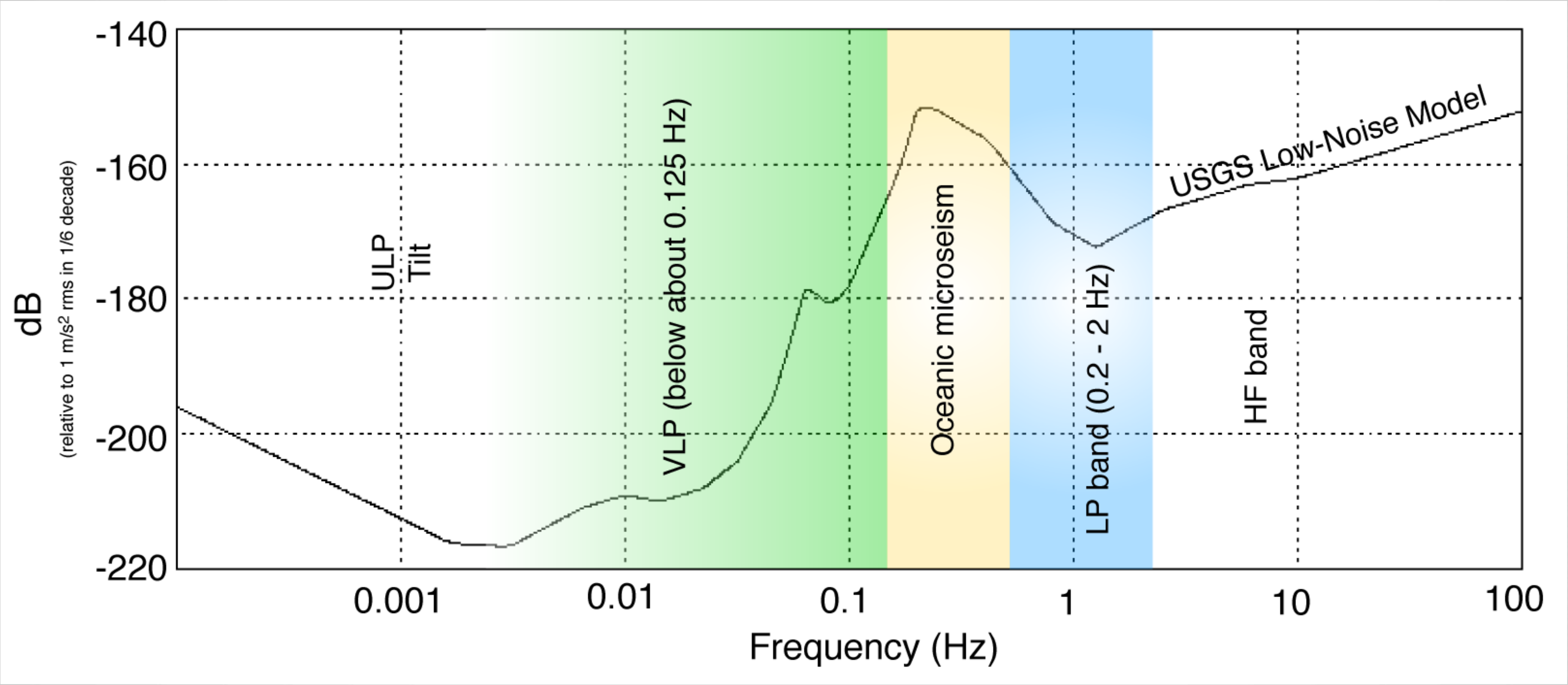
General classification (see, e.g., McNutt, 2005)

- HF (high frequency) or VT (volcano tectonic)
  - tectonic earthquakes (slip on a fault, double-couple)
  - Clear P and S wave arrivals
  - Basically the same as the A-type, but does not require specific depth interval beneath edifice
- Hybrid
  - Characteristics of both HF and LF
  - Usually have high-frequency onset, low-frequency coda
  - Some investigators define a hybrid as having mixed-modes (Chouet *et al*., 1994)
    - Compressional and dilatational 1st motions
  - Could represent a small VT that triggers an LP
  - Coda is not dispersive
- LF (low frequency)
  - No clear S wave
  - Low frequencies (0.5 - 4 Hz) due to source and/or path
  - Similar to B-type, but again, not depth specific
  - Includes long-period (LP) earthquakes, which occur at all depths within the crust
- Very-Long-Period
- Ultra-Long Period
- Tremor
- Explosion earthquakes

More general classifications (see, e.g., McNutt, 2005)

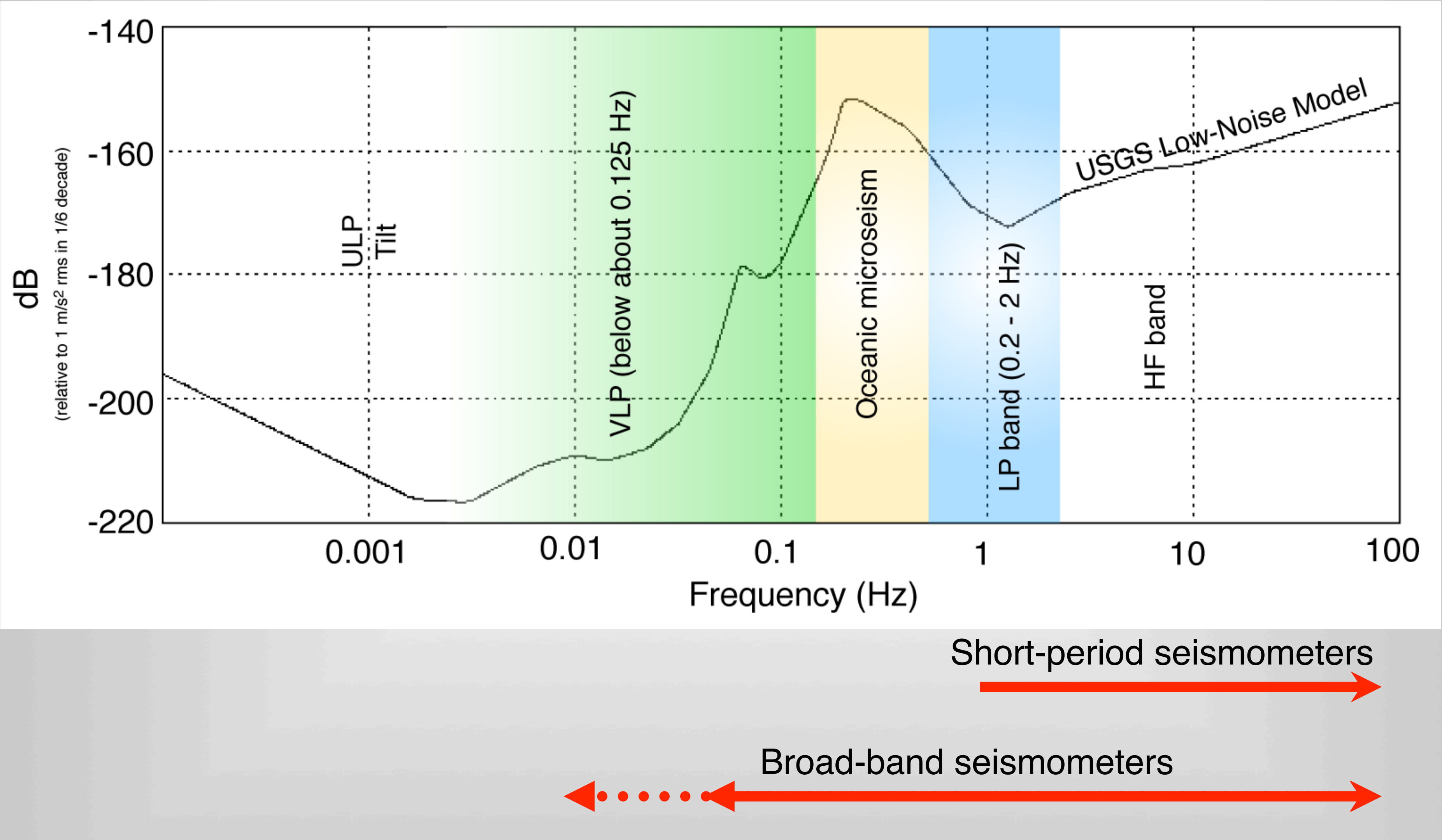
- HF (high frequency) or VT (volcano tectonic)
- Hybrid
- LF (low frequency)
- Very-Long-Period
  - Periods below LF down to instrument corner (30, 60, 120 s)
  - Involve mass exchange, frictional forces in conduits
- Ultra-Long Period
  - At periods below the instrument corner
  - Mostly ground rotation on horizontal components
- Tremor
  - Semi-continuous signal with harmonic or irregular sine wave signals
  - Dominated by surface waves
- Explosion earthquakes
  - Accompany explosions!
  - Amplitude is related to energy release
  - Compressional first P on all stations
  - Ground-coupled air wave

Earthquake Classification



- Primarily defined on the basis of the frequency content

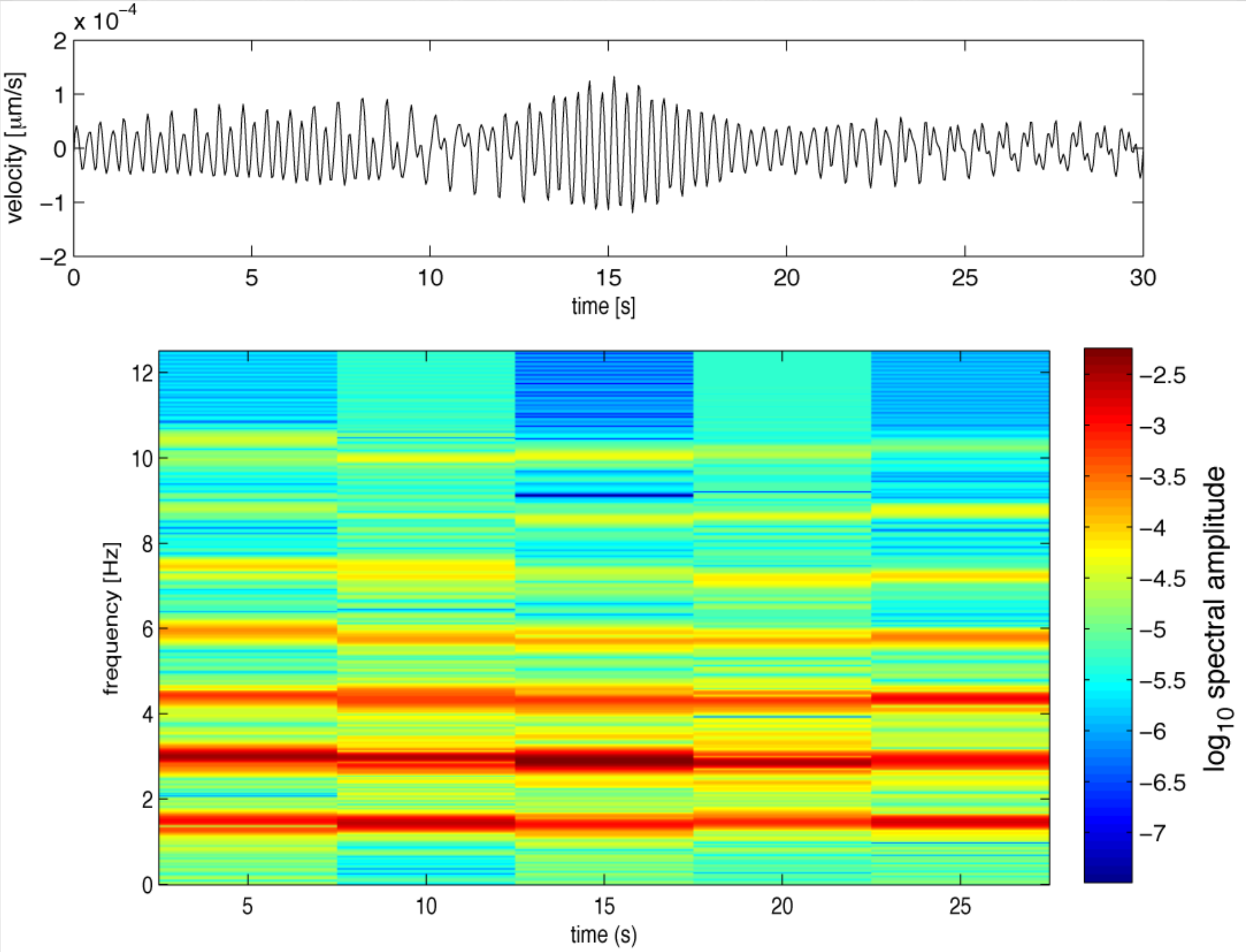
Earthquake Classification



General Volcanic Earthquake Classification

- Explosion
  - broadband, long-duration signals resulting from pressure release, fracture, magma flow
- HF (high frequency) or VT (volcano tectonic)
  - tectonic earthquakes (slip on a fault)
  - Clear P and S wave arrivals
- LF (low frequency)
  - Typically no clear S wave
  - Low frequencies due to source and/or path
  - Includes long-period earthquakes, which occur at all depths within the crust
  - Tremor - Semi-continuous signal with harmonic or irregular signals
- Hybrid
  - Characteristics of both HF and LF
  - Usually have high-frequency onset, low-frequency coda
  - Could represent a small VT that triggers an LP
  - Sometimes distinguished from LP on the basis of mixed first-motion polarities
    - suggests the event involves slip on a fault, start as a VT
- VLP (very-long-period)
  - involve volume changes, mass advection, drag forces

Example from Mt. Erebus



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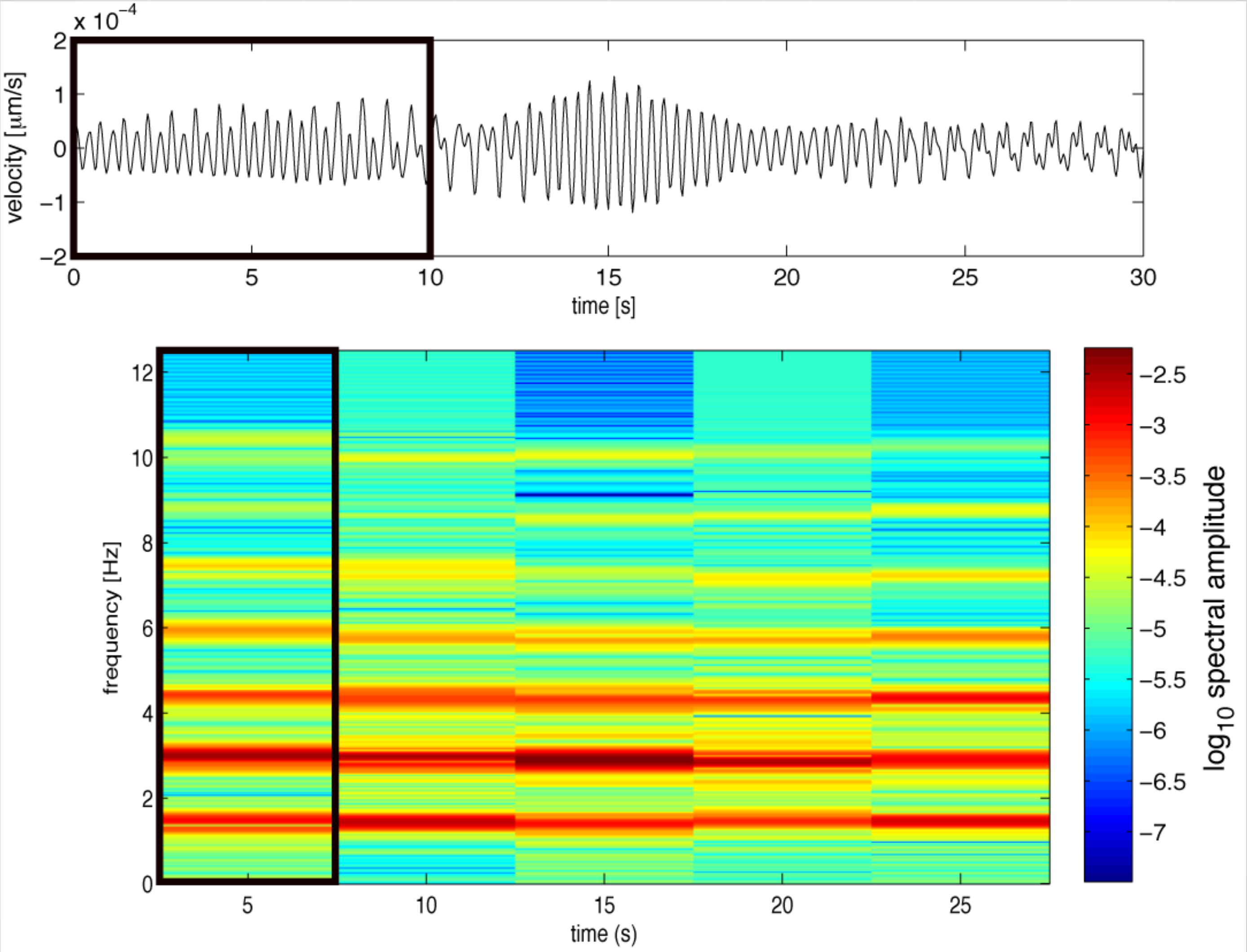

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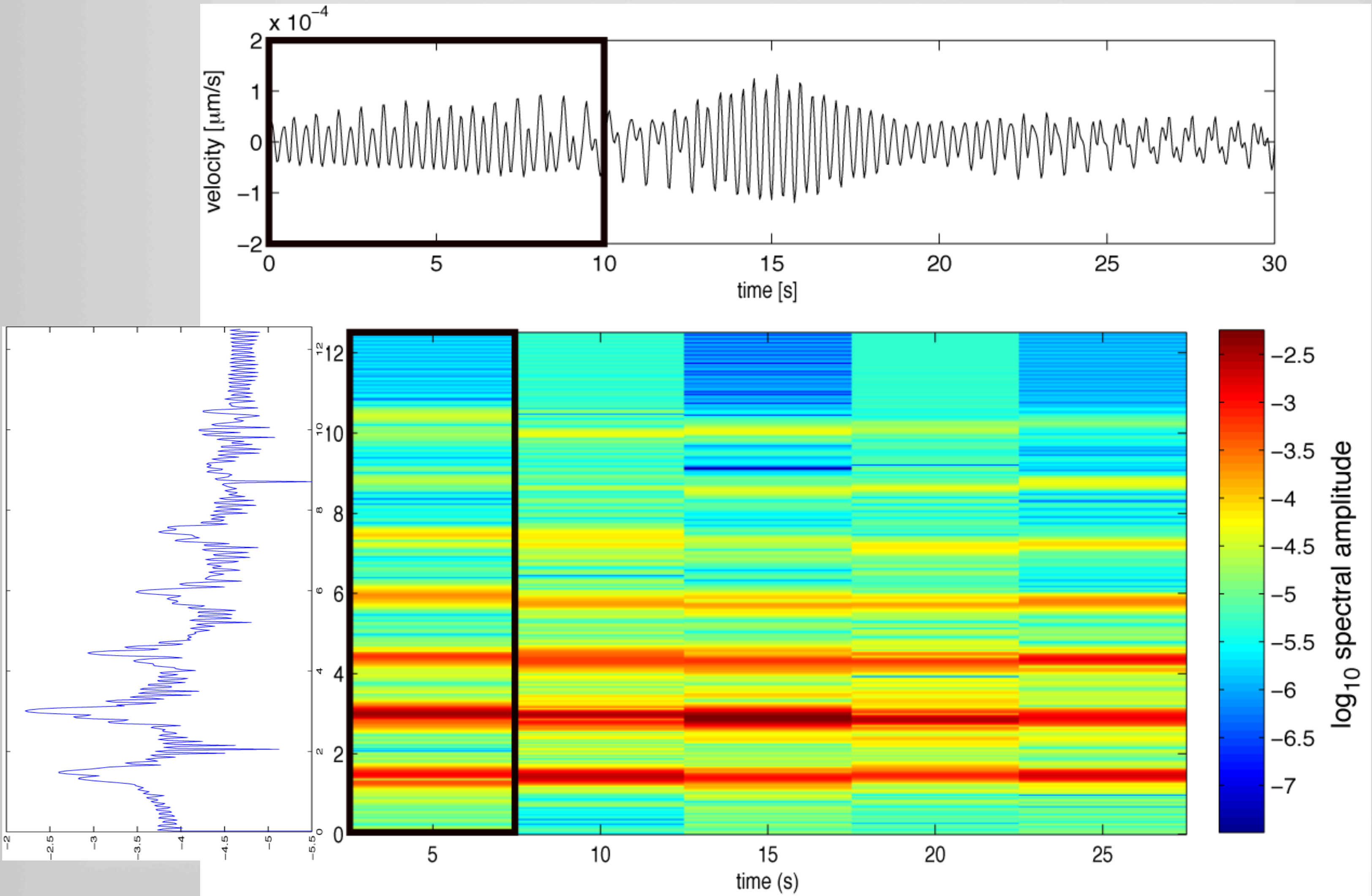

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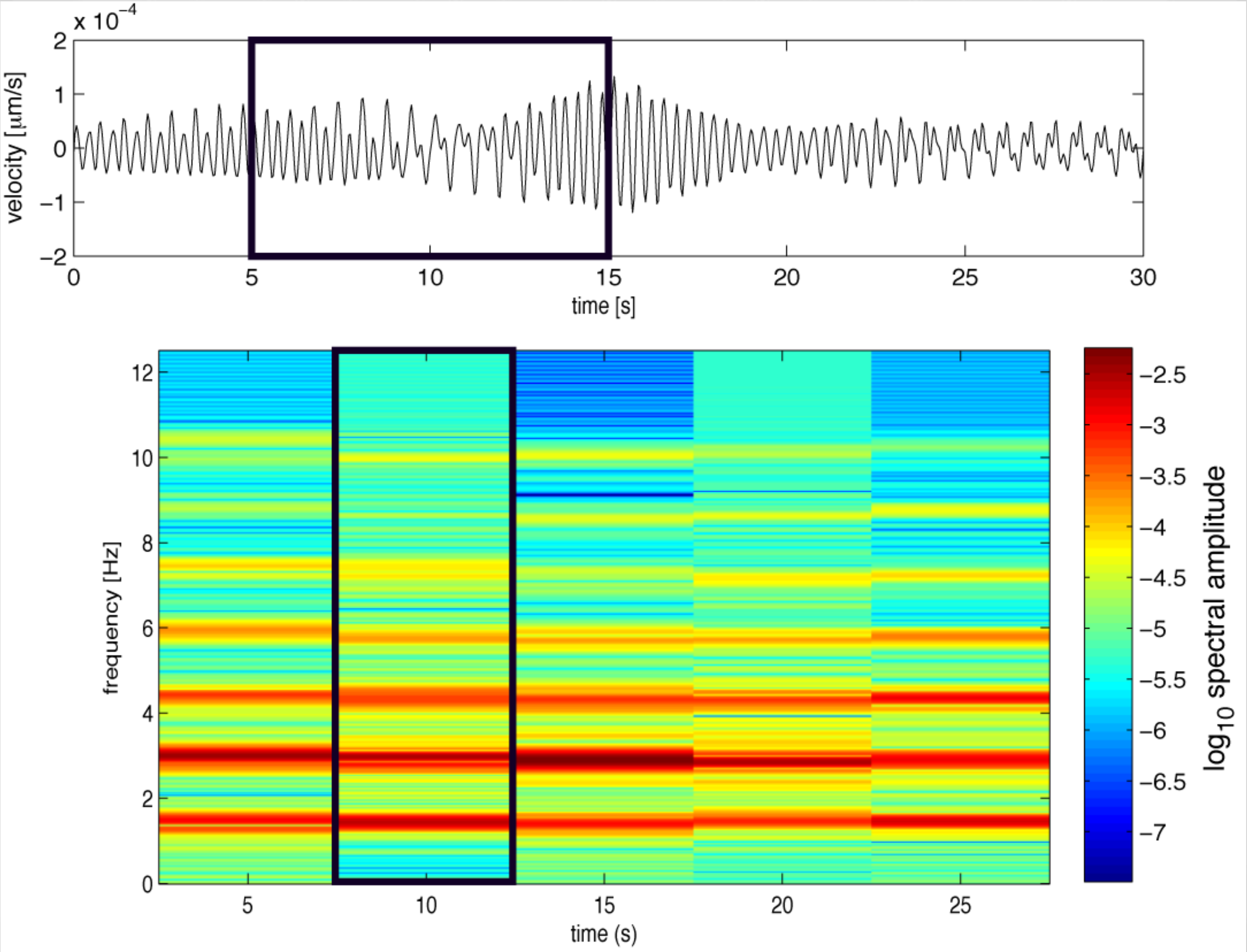
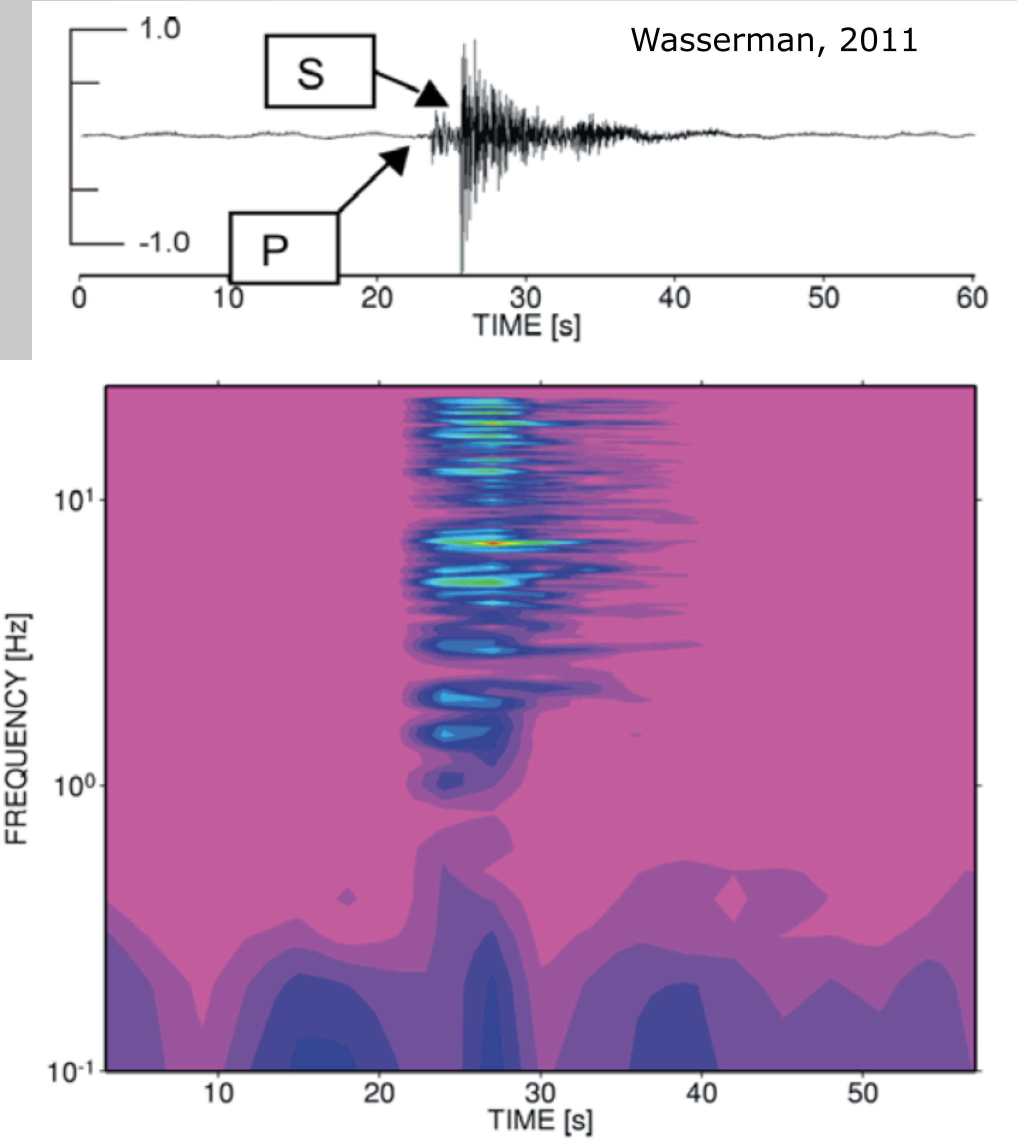
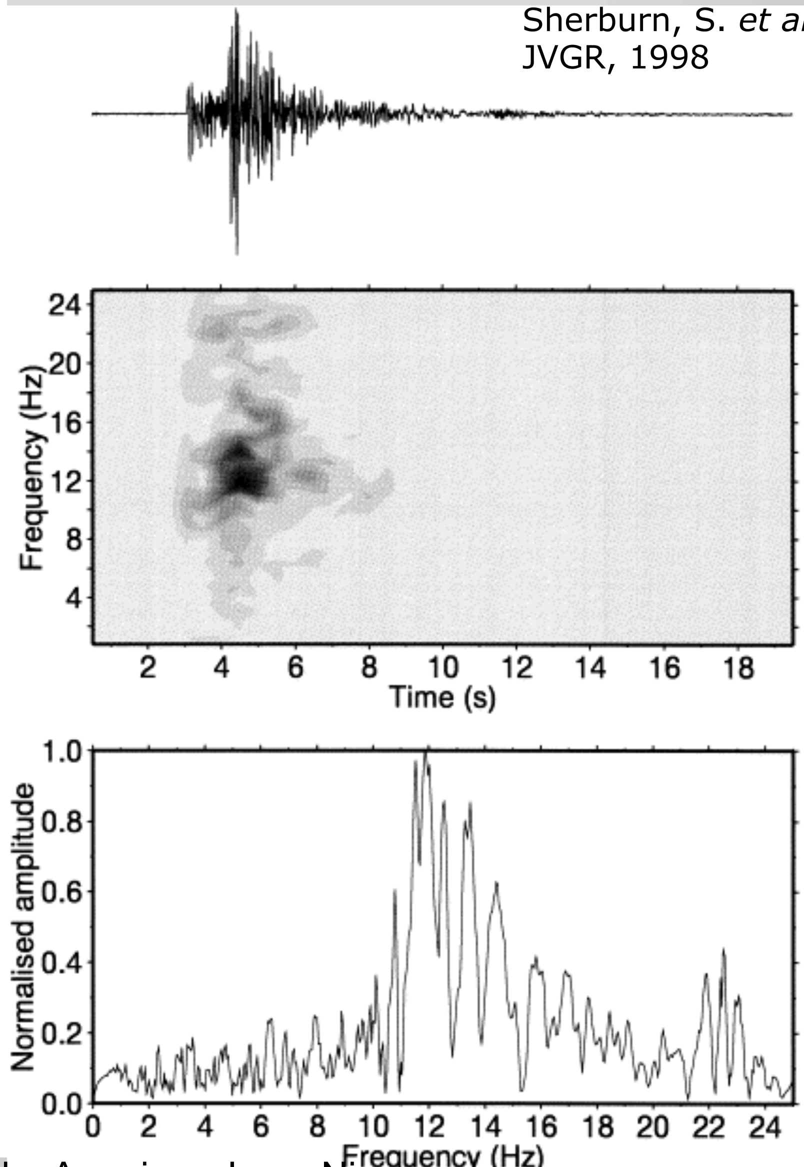
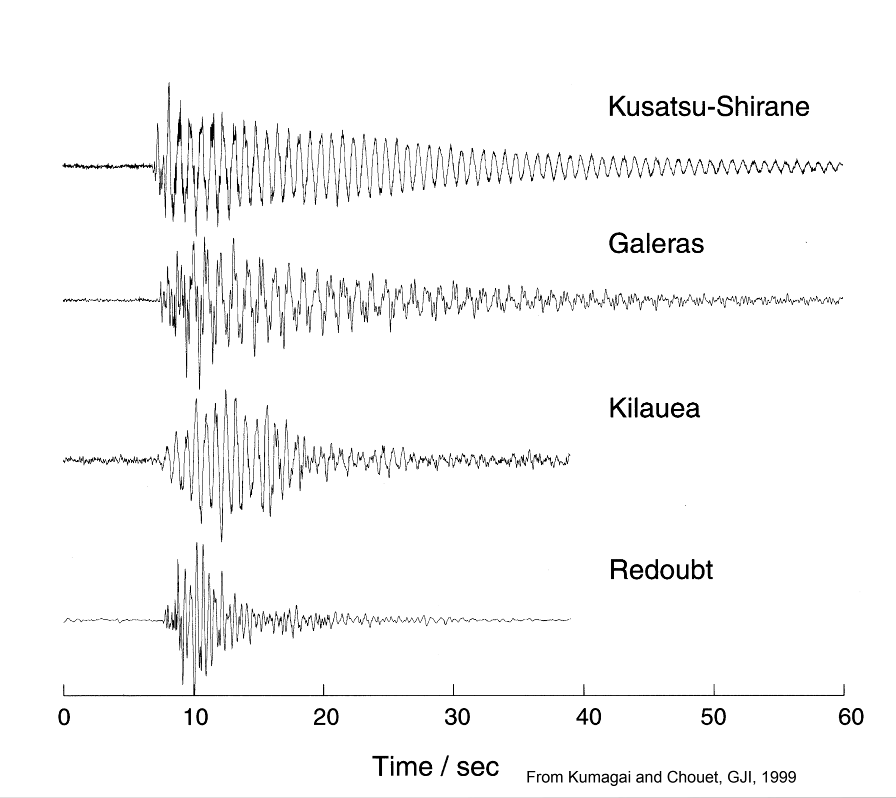


Volcano-tectonic events



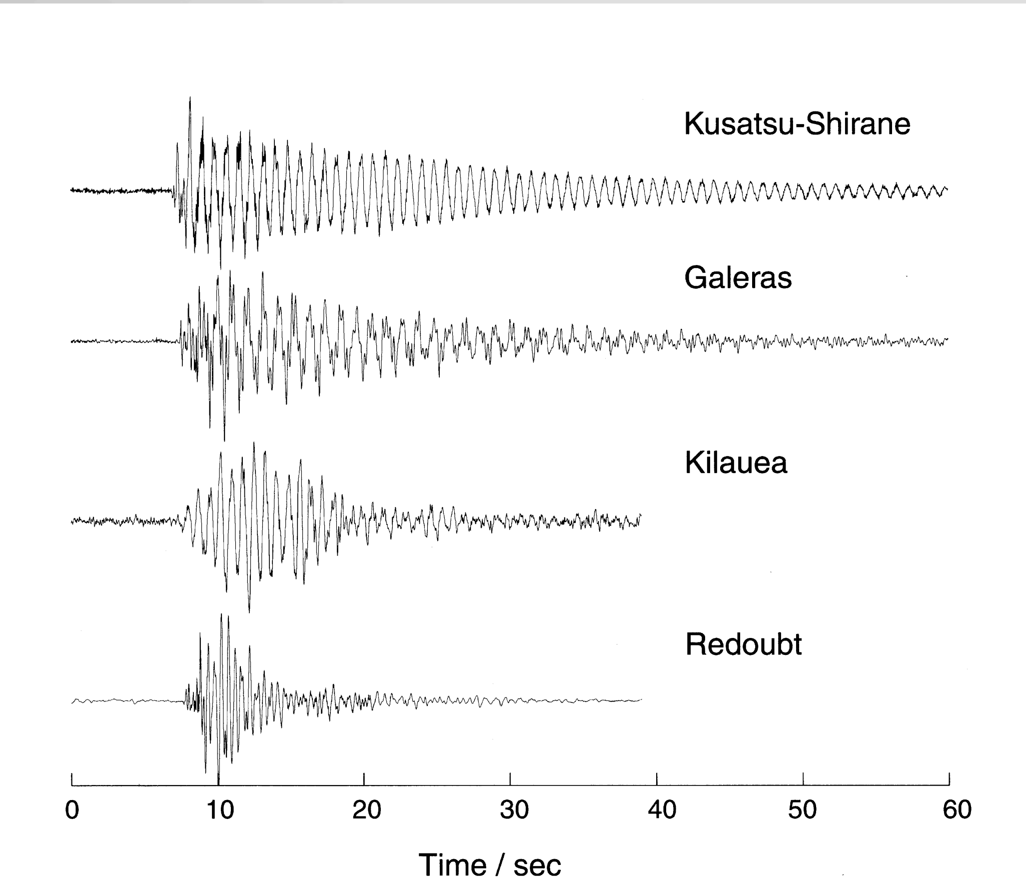


LP (Long-Period) Earthquakes

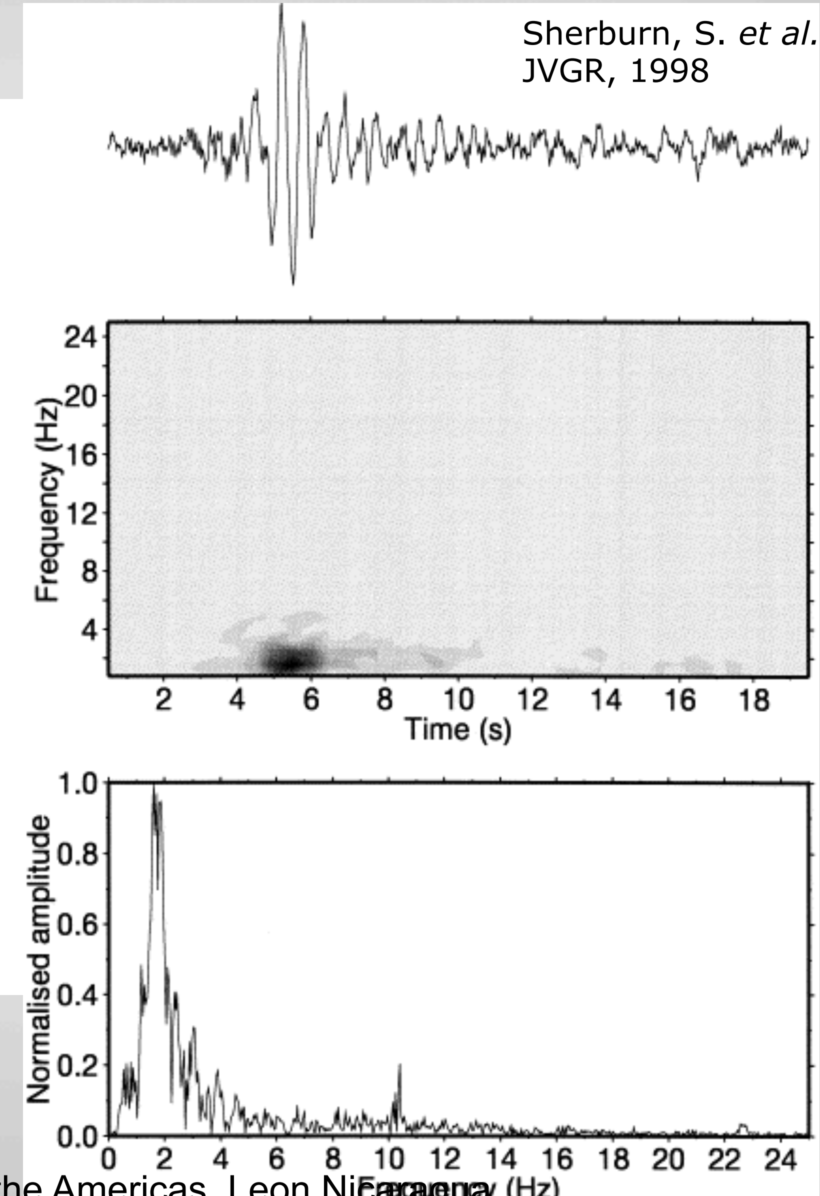


- Known by many names
  - LP, B-type, tornillo, ...
- Broadband onset
  - frequencies from .2 to 15 Hz
  - trigger
- Decaying, harmonic coda
  - frequencies .5 - 2 Hz
  - resonance
- Typically shallow (< 3 km), but can be very deep (upper mantle)

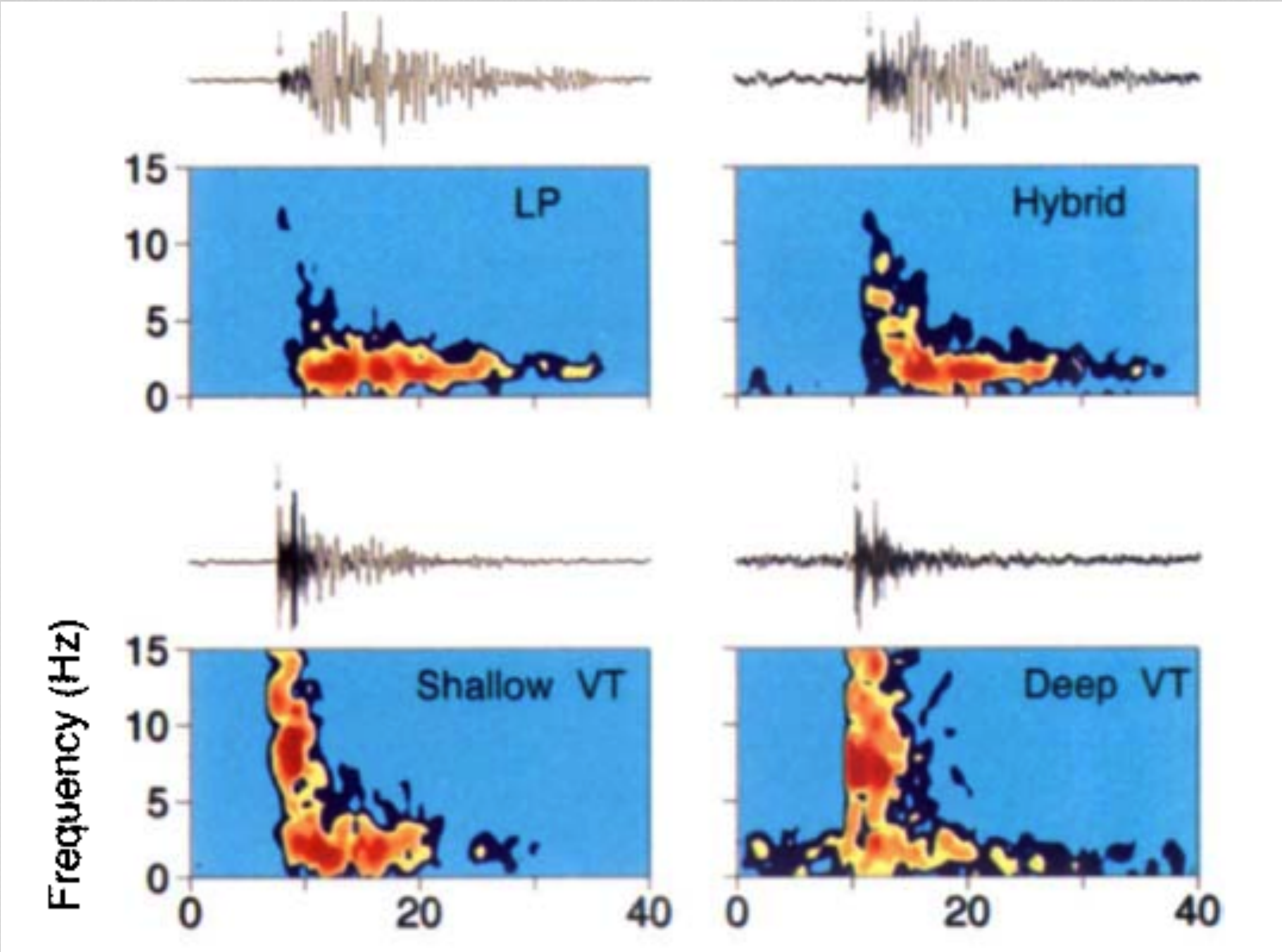
Long-period earthquakes



Kumagai and Chouet, GJI, 1999

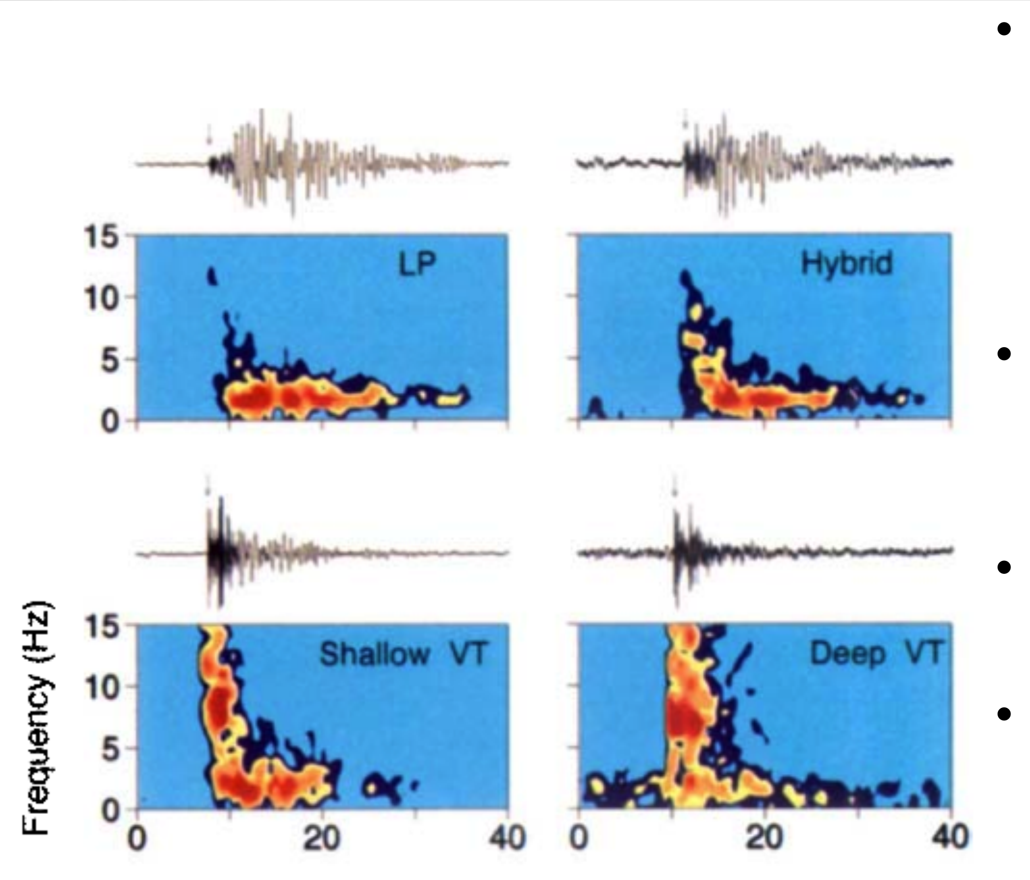


Sherburn, S. *et al.*, JVGR, 1998



Chouet, Nature, 1996

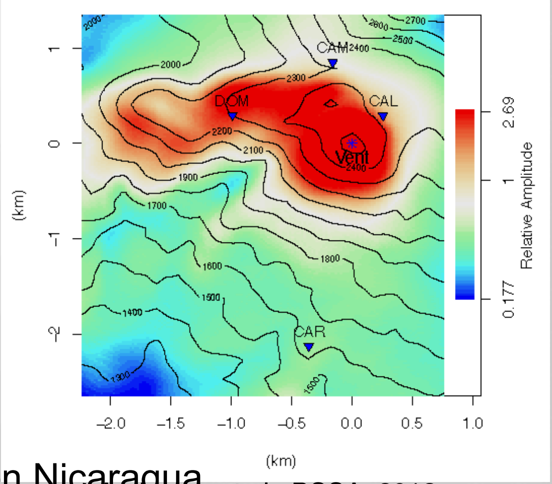
Summary of volcanic earthquakes



- Waveforms and spectrograms from Redoubt
  - LP, hybrid and shallow VT occurred 1.4-1.7 km below crater
- LP
  - Dominant f=1.5Hz
  - Broadband onset
- Hybrid (mixed 1st motions)
  - Non-dispersive coda
- Shallow VT
  - Broadband body waves
  - Dispersive coda not obvious
- Deep VT
  - Shorter coda (less efficient at generating surface waves)

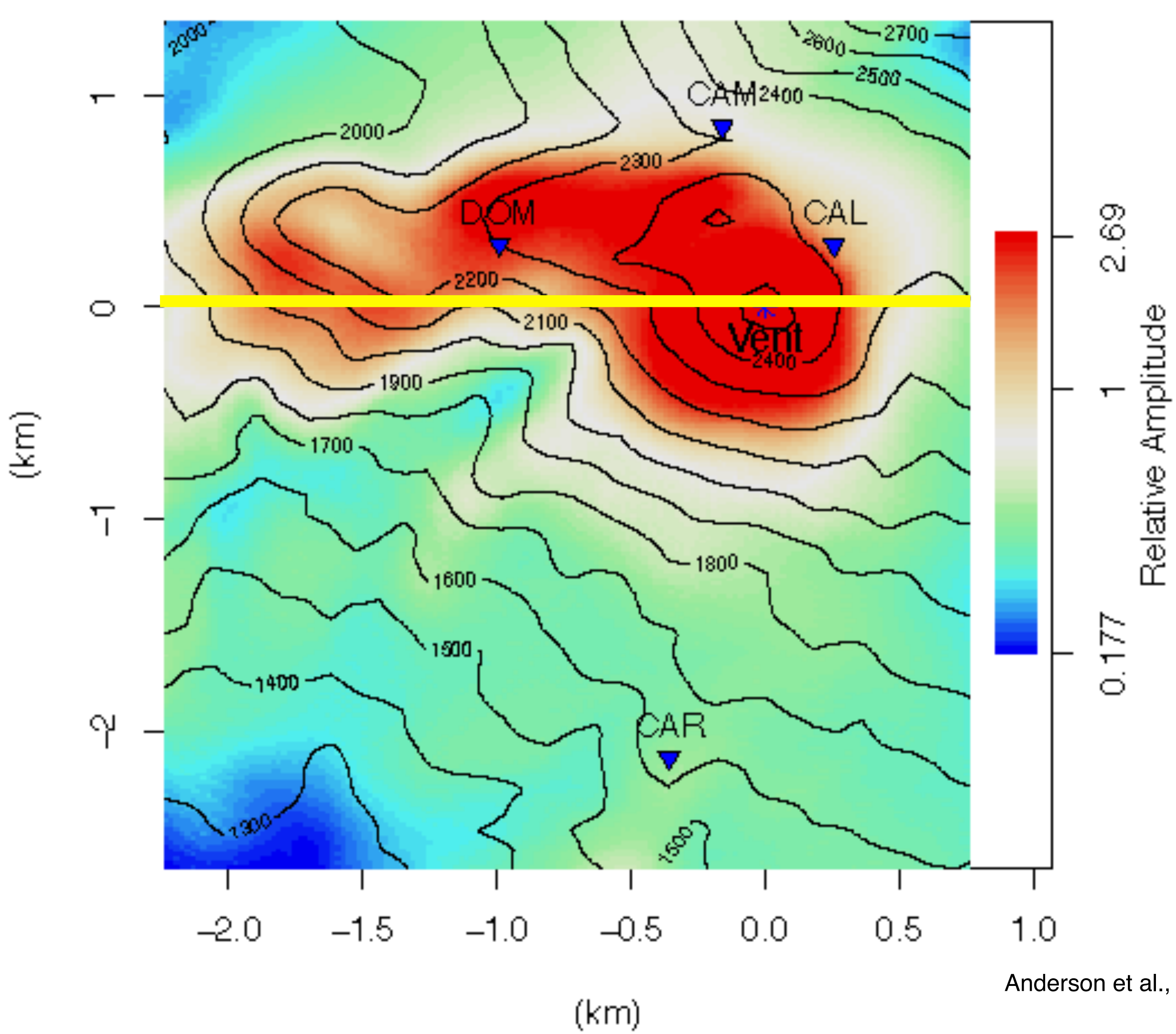
Path-Distorted LPs?

- Path can filter some frequencies and enhance others
- Shallow low-velocity layers can trap waves
  - prolongs the duration of the signal and may mimic LP coda characteristics
- Topography focuses and defocuses waves
  - Waves can be trapped beneath steep topographic features (hills and volcanic edifices)
  - If underlain by strong reflective layer, the signal can ring for 10s of seconds



Anderson et al., BSSA, 2012

Santiaguito Example



Anderson et al., BSSA, 2012

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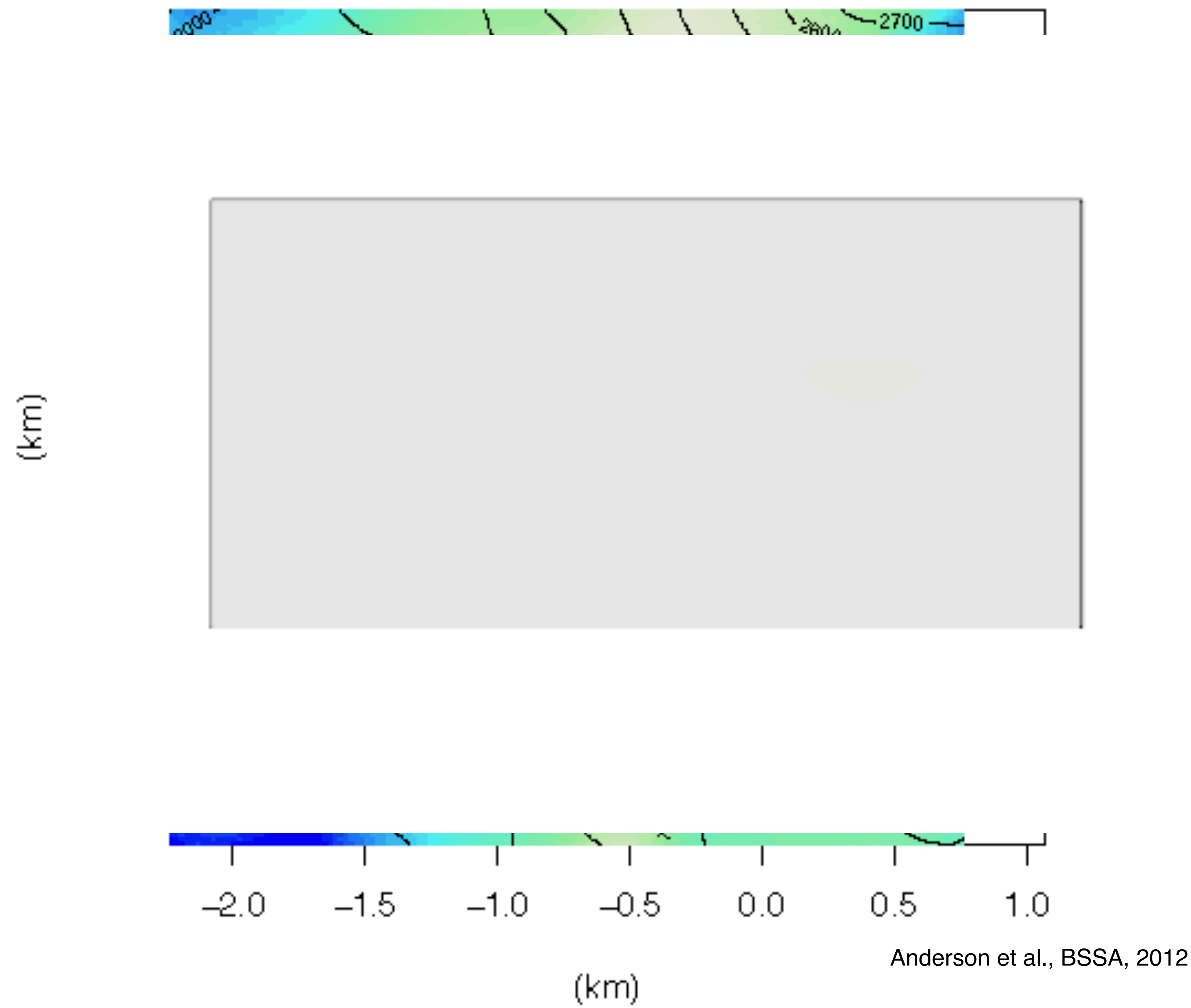
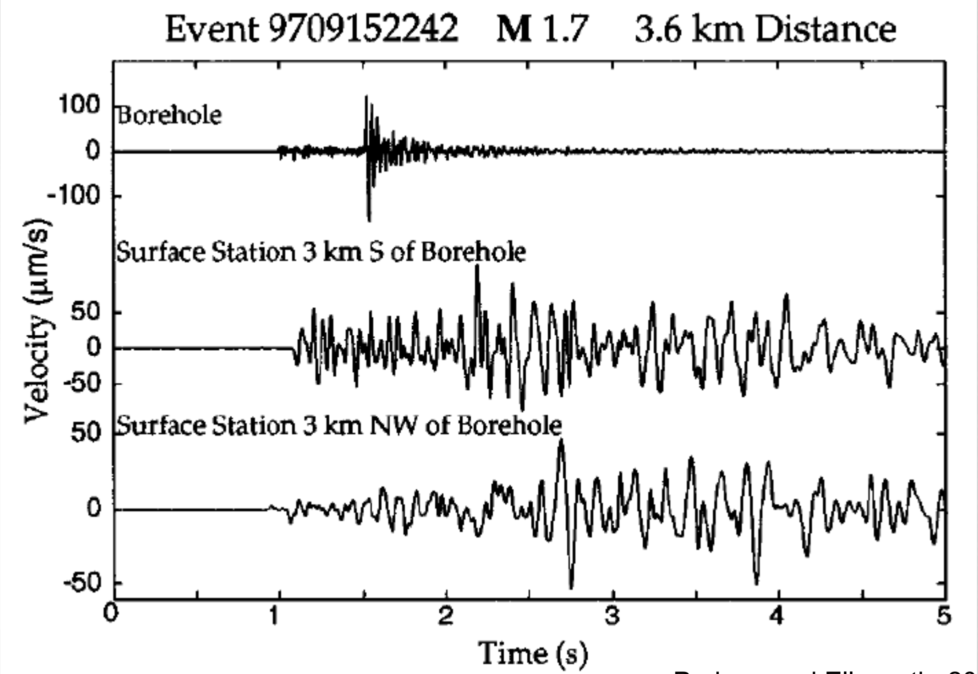


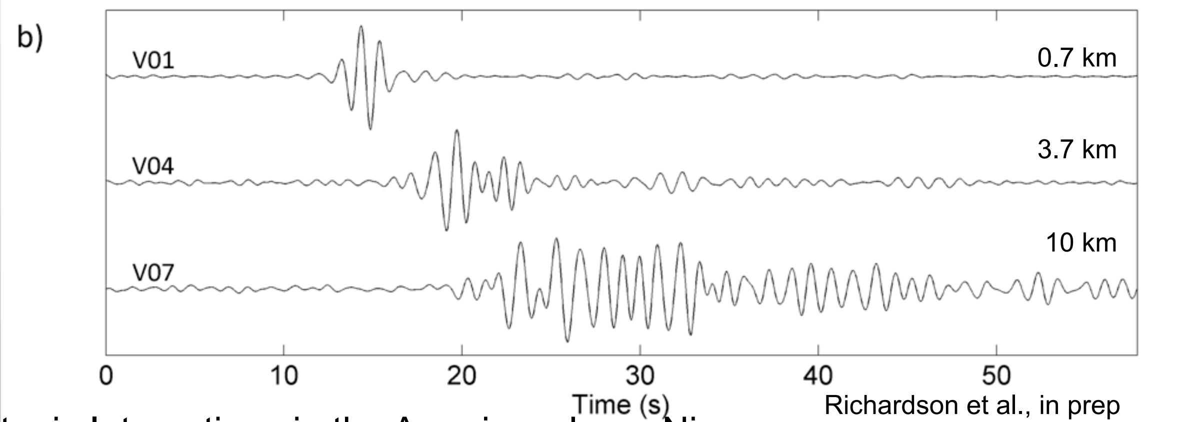
Anderson et al., BSSA, 2012

LP path affects

- The LP coda grows with increased distance from the source
- Evidence that coda is largely a result of scattering *in some cases*, rather than an extended source process
- This scattering can be used to model structure



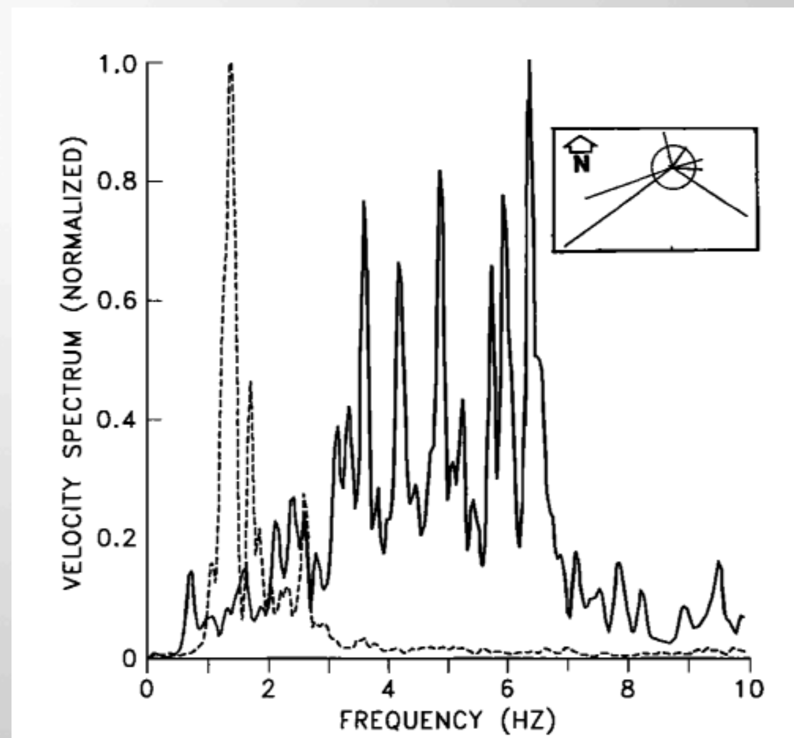
Prejean and Ellsworth, 2001

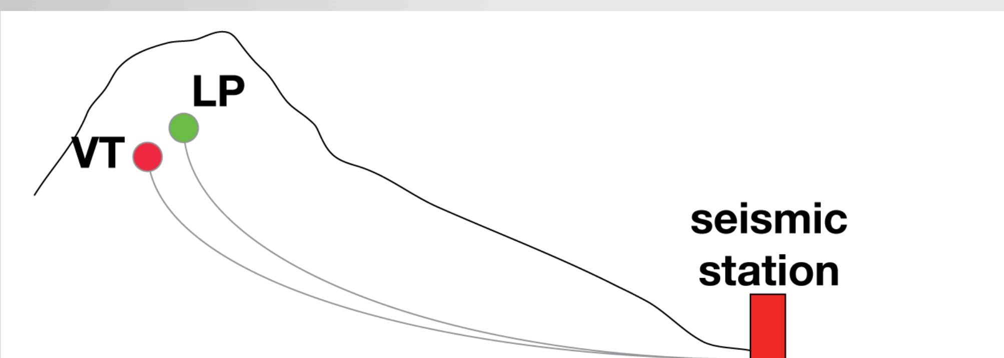


Richardson et al., in prep

Source vs. Path

- Difficult to identify for shallow events
  - One way to determine if LF signal is due to path or source is to examine different events (a VT and LP) that occur at about the same location
  - Share the same path for most, so any differences attributed to source
  - Mammoth Mountain example
    - Stacked spectra from 7 stations
    - Two events closely-spaced
    - Differences unlikely to be path-only



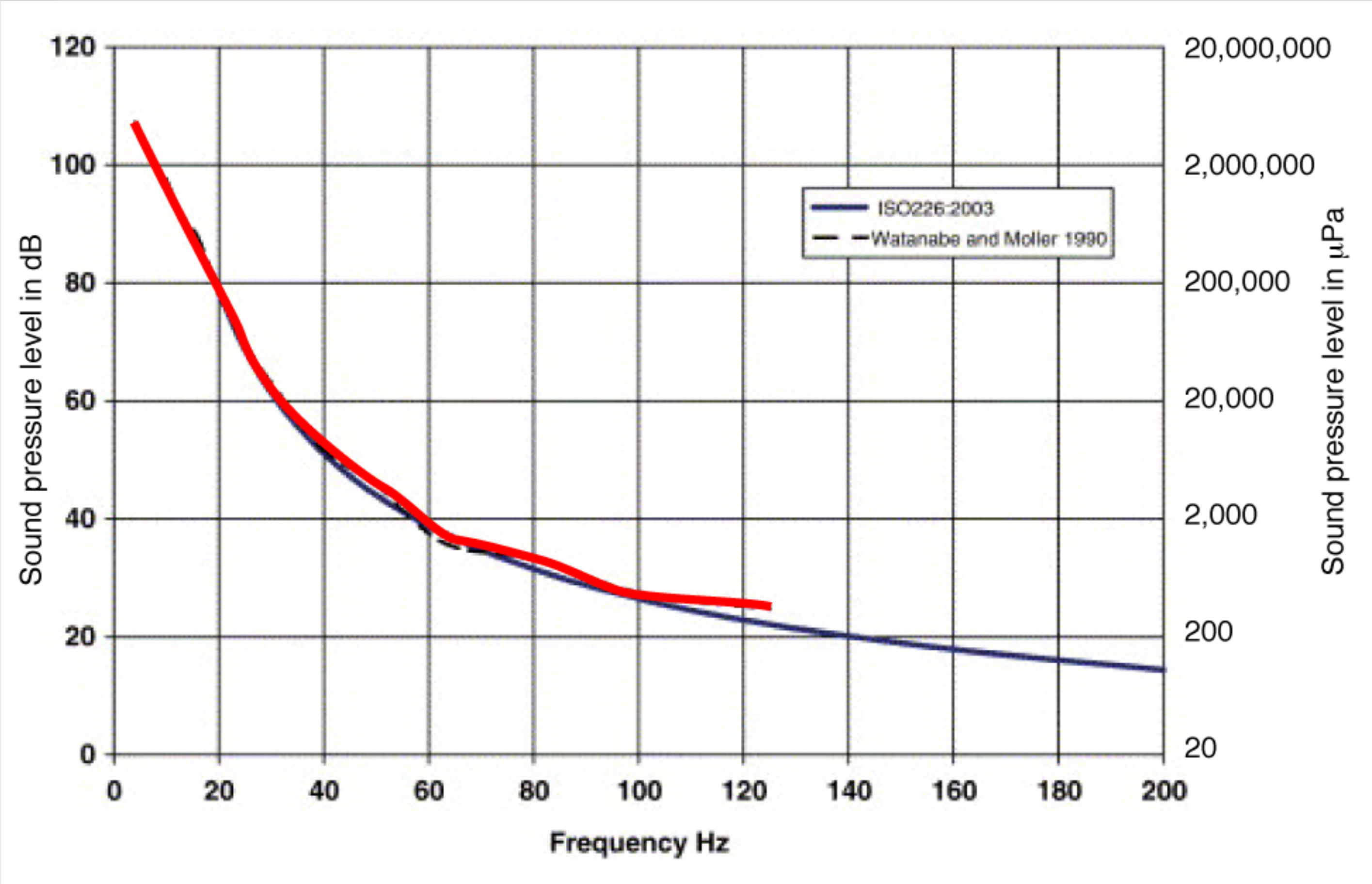


Pitt & Hill, *GRL*, 1994

What is *infra*sound

- Atmospheric pressure wave at frequencies below audible,
  - ~20 Hz or 17 m wavelength and down to ~100 s period
  - Roughly the same frequency range as seismology
  - Measured by pressure variations (instead of ground velocity)
- Most volcanic acoustic emission is near infrasound from about 0.5 - 20 Hz (or 17-680 m)

Frequency and the threshold of human hearing



Leventhall, *Progress. Biophys. Molec. Bio.*, 2007

Sources of infrasound

- Anything that displaces air
- Volcanoes
- Earthquakes
  - Shaking of the microphone up and down changes the pressure very slightly
  - Ground motion from earthquake (surface waves) generate pressure fluctuation by displacing air
- Snow avalanches
- Calving icebergs
- Bolides (meteors)
- Wind
  - e.g., Turbulent flow over mountains
- Ocean waves and storms
  - Breaking waves
  - Microbaroms – 3-8 seconds
- Explosions – CTBT

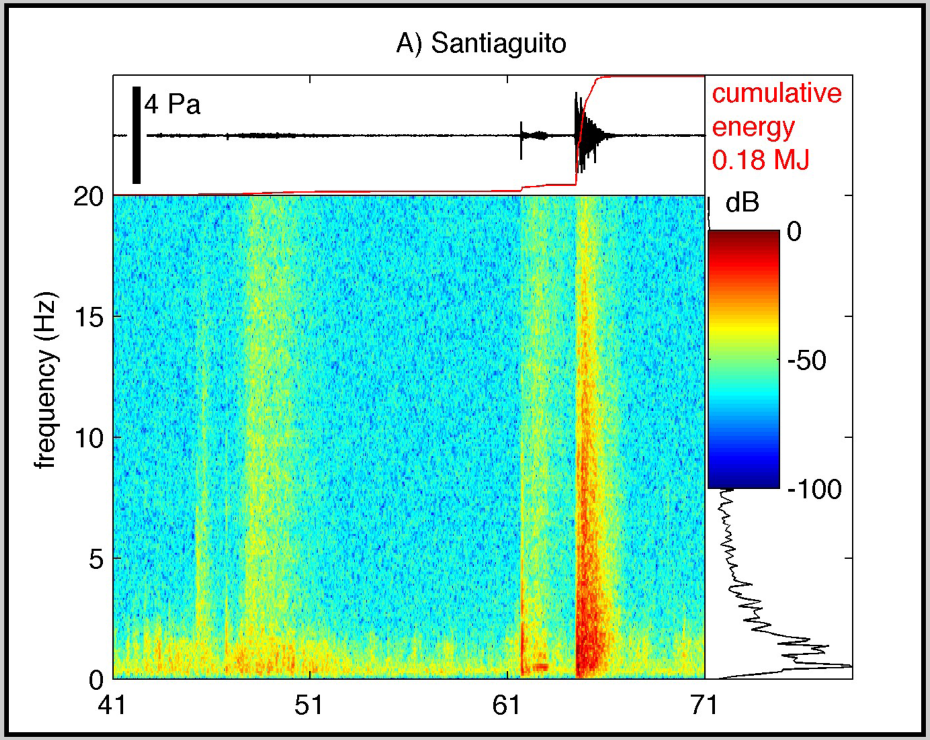
Infrasound recordings

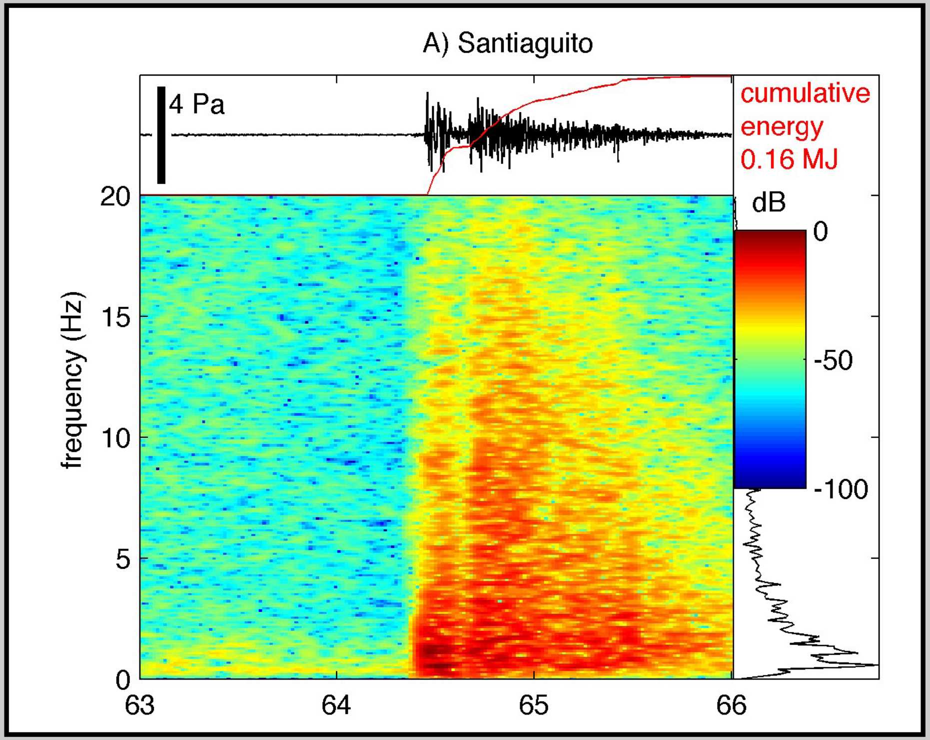
- Time histories of excess pressure ΔP
  - 1-1000 Pa
  - Atmospheric pressure 10^5 Pa
  - Can be treated as linear elastic waves (like seismic waves) rather than nonlinear shock waves
- Acoustic energy scales with ΔP^2
  - For hemispherically radiated infrasound

$$E_a = \frac{2\pi r^2}{\rho_a c} \int \Delta P^2 dt$$

c = 343 m/s, ρ_a = 1.20 kg/m^3 at 20ºC

Example volcanic infrasound





Santiaguito (Guatemala) - pyroclastic-laden eruptions with buoyant plumes up to ~1.2 km. Only about 100 Watts of acoustic power is associated with time averaged Santiaguito eruptive behavior and is dominated by explosive events. Up to 3000 Watts is generated during eruption.

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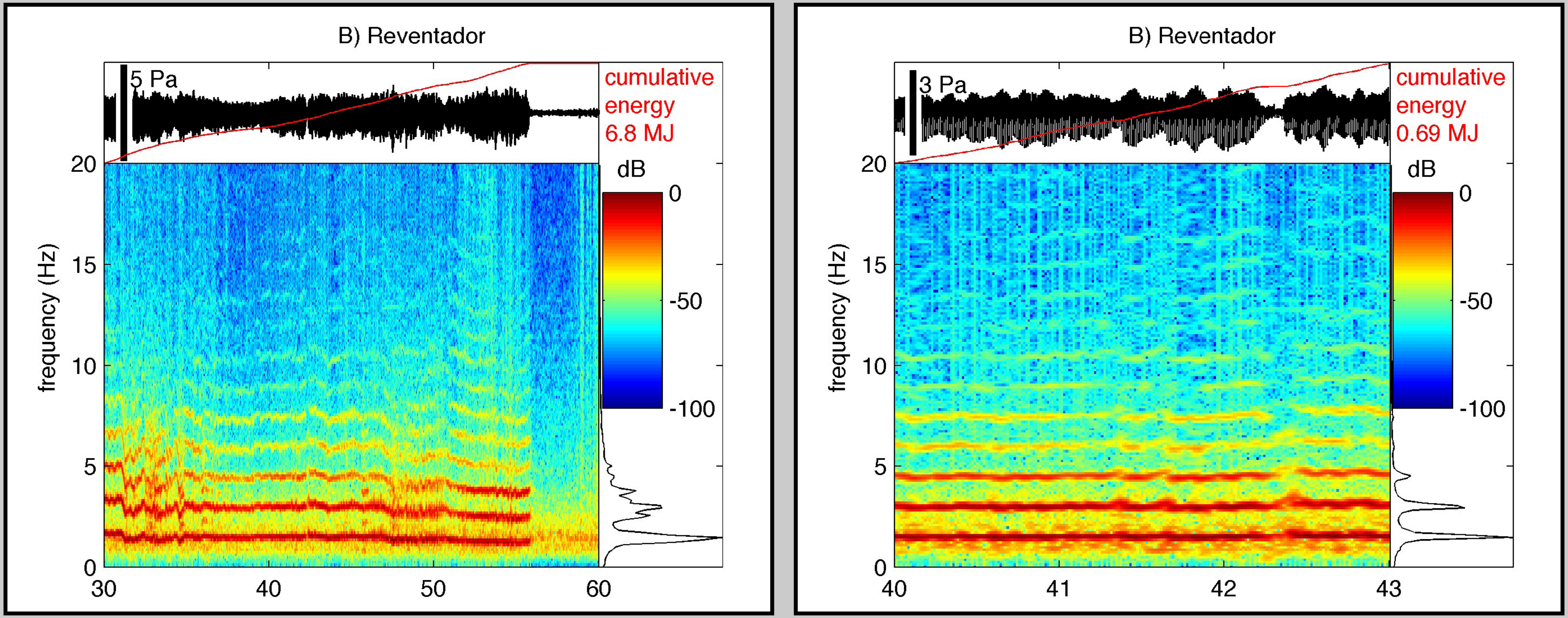
Example volcanic infrasound



Reventador (Ecuador) - continuous degassing giving rise to ~500-m-high vapor plume. Infrasound is dominated by harmonic tremor ('chugging'), which produces consistent levels of sound and sound power (~4000 Watts) until shutting off.

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Infrasound summary

- Relatively simply path at close distances -> velocity is constant
- Relatively slow speed permits accurate locations
  - Pick errors are less significant compared with seismic wave pick errors
    - 10 ms error on P wave at 3.4 km/s translates to 34 m location error
    - 10 ms error on acoustic arrival at 340 m/s is only 3.4 m
- Noise (e.g., wind) can be surpressed by beam forming

Seismic summary

- What you see on the seismogram is a convolution of multiple filters
  - both the path and source are important
- Earthquake classification is largely based on event frequency content
  - Multiple stations critical for determining path vs. source
  - Short-period vertical instruments are adequate

Is our current classification system useful?