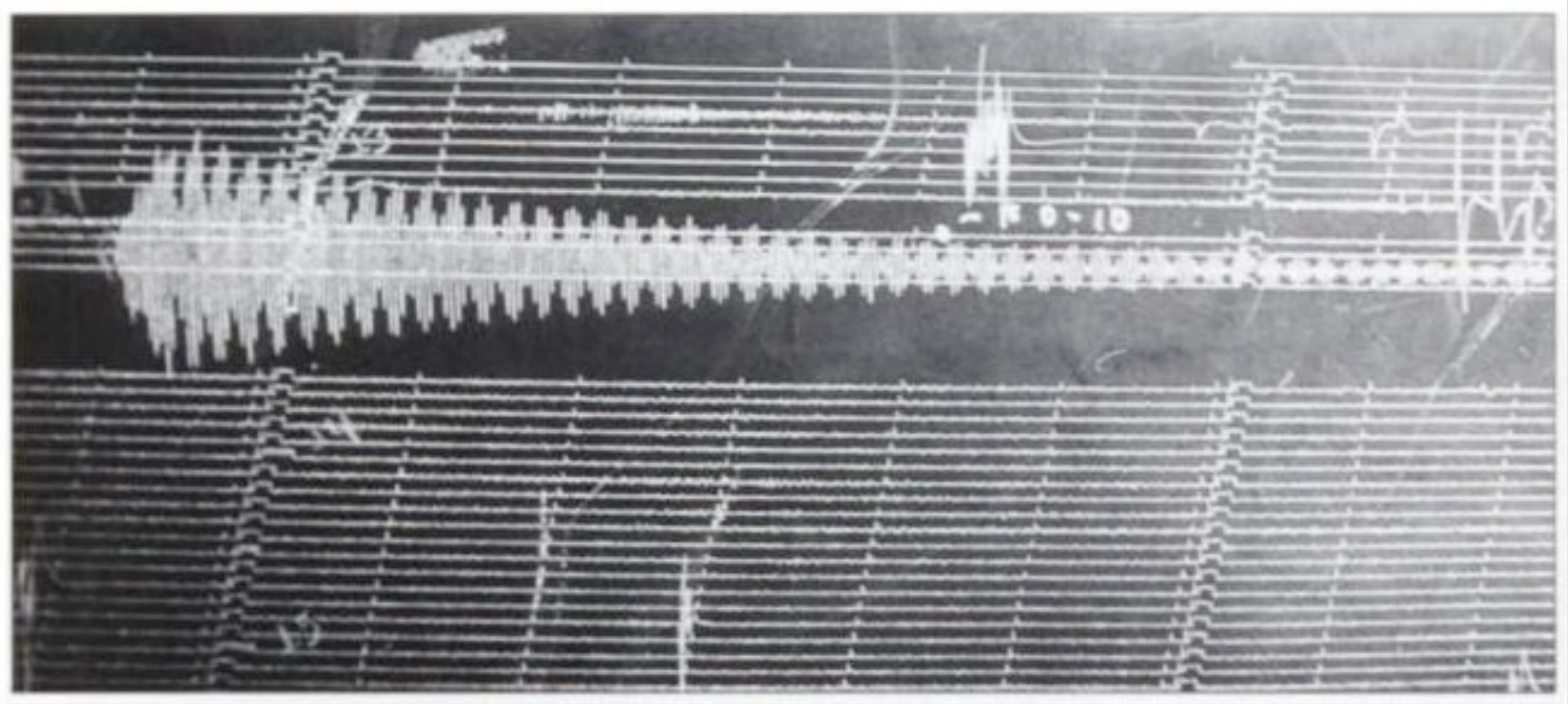
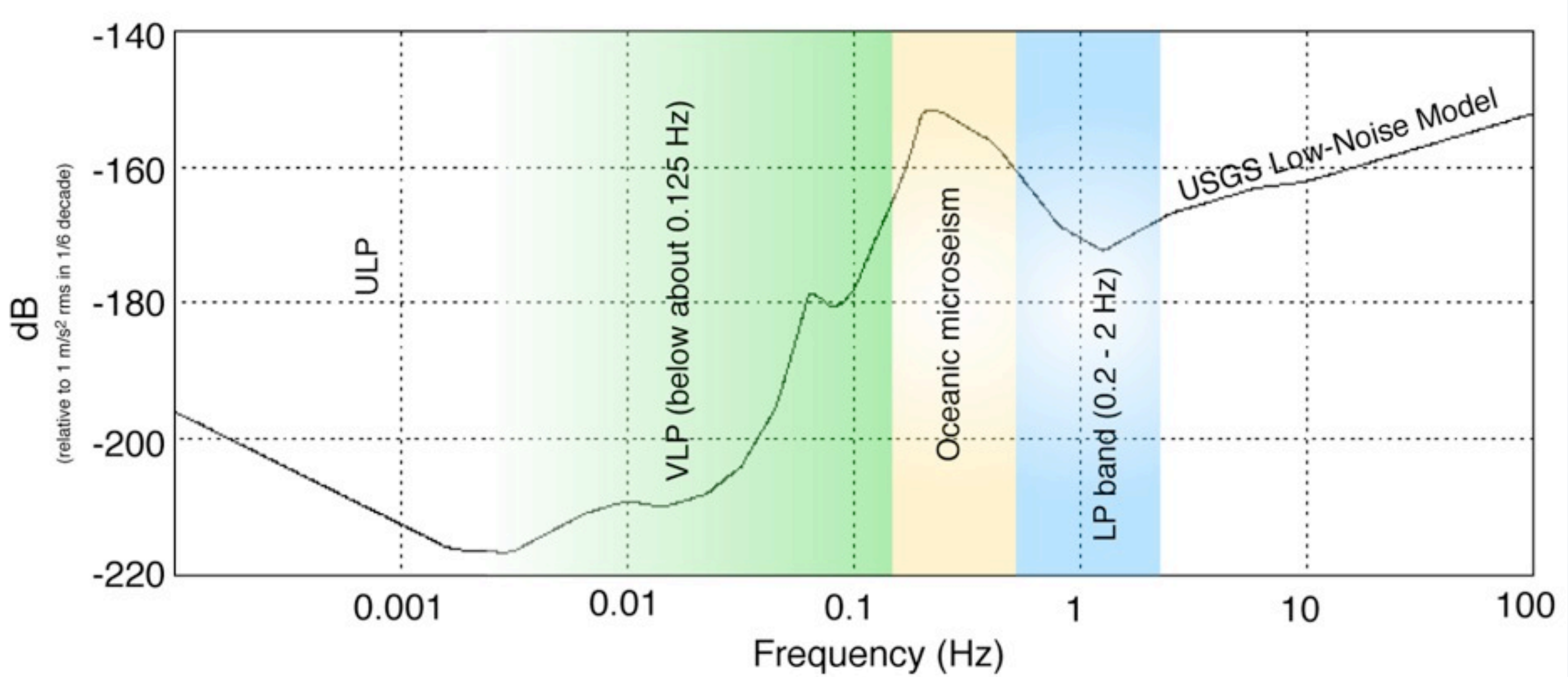


Low-Frequency Volcanic Seismicity

Source processes and implications of tremor, LP and VLP earthquakes at open-vent volcanoes

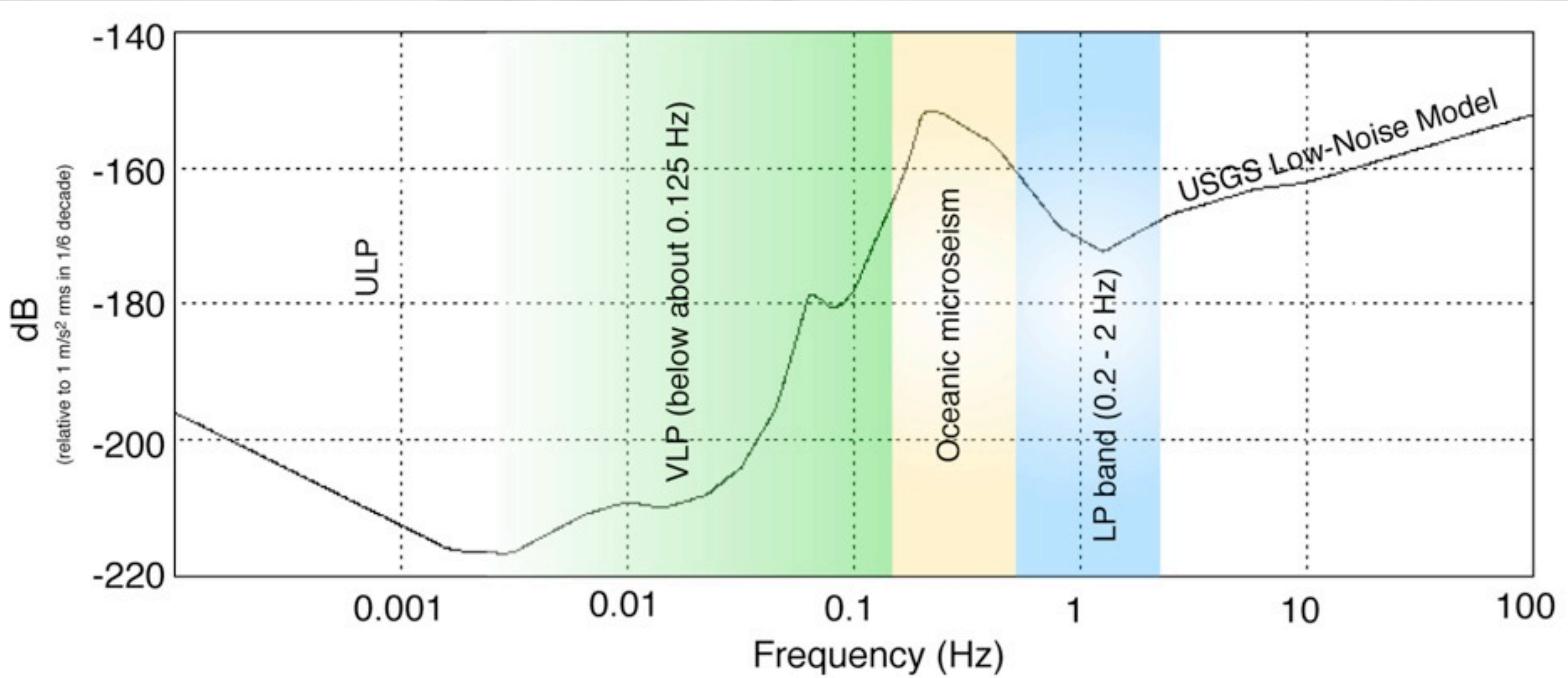
MichiganTech

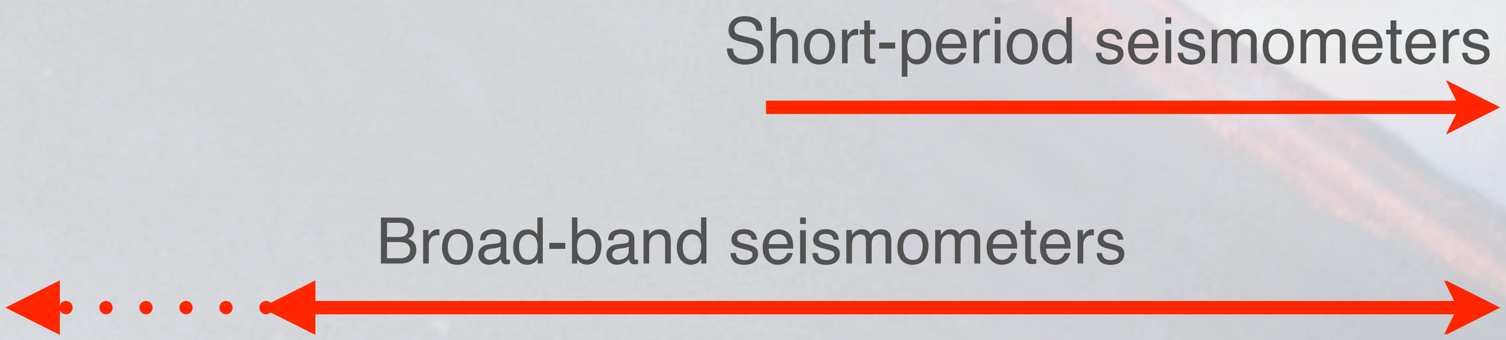
TREMOR, LP, AND VLP CHARACTERISTICS



- Primarily defined on the basis of the frequency content
- These all can be considered "low-frequency" seismicity

TREMOR, LP, AND VLP CHARACTERISTICS

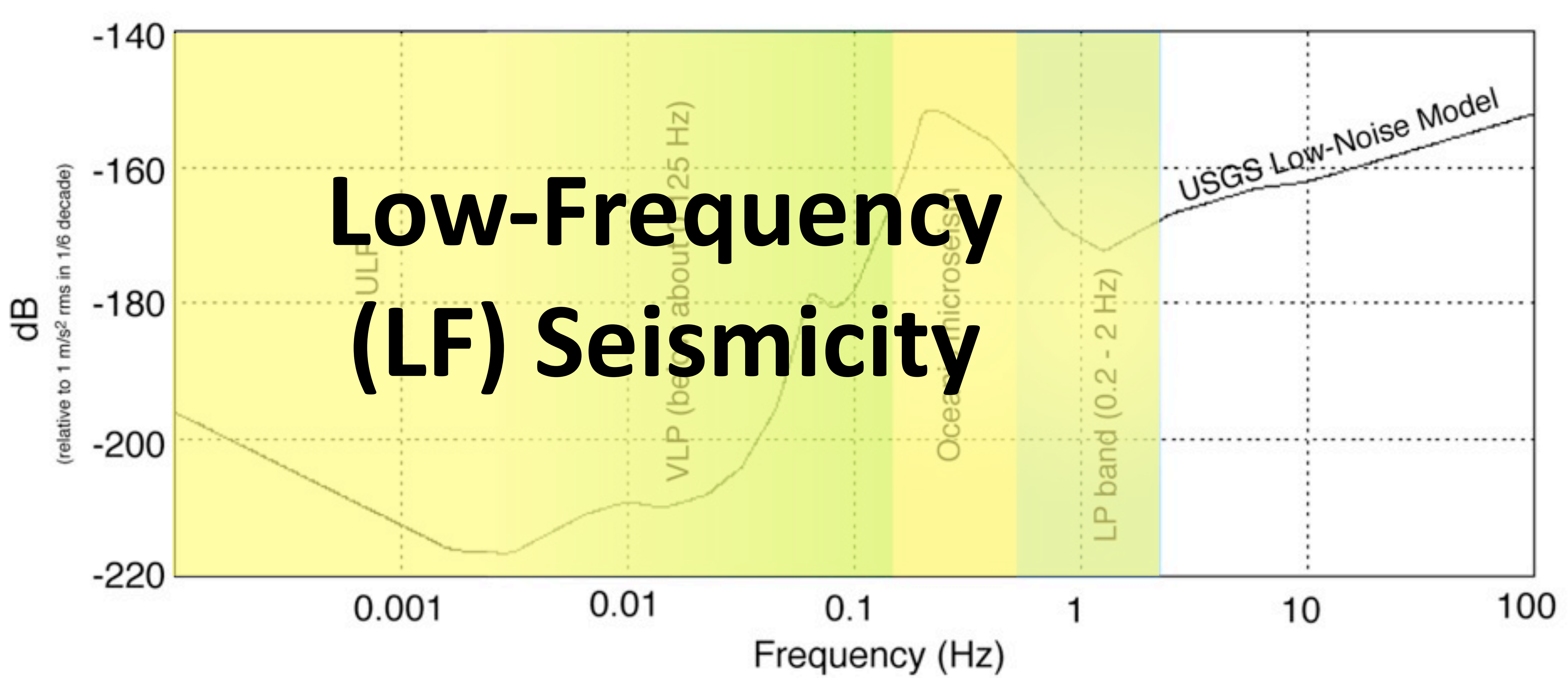




Short-period seismometers

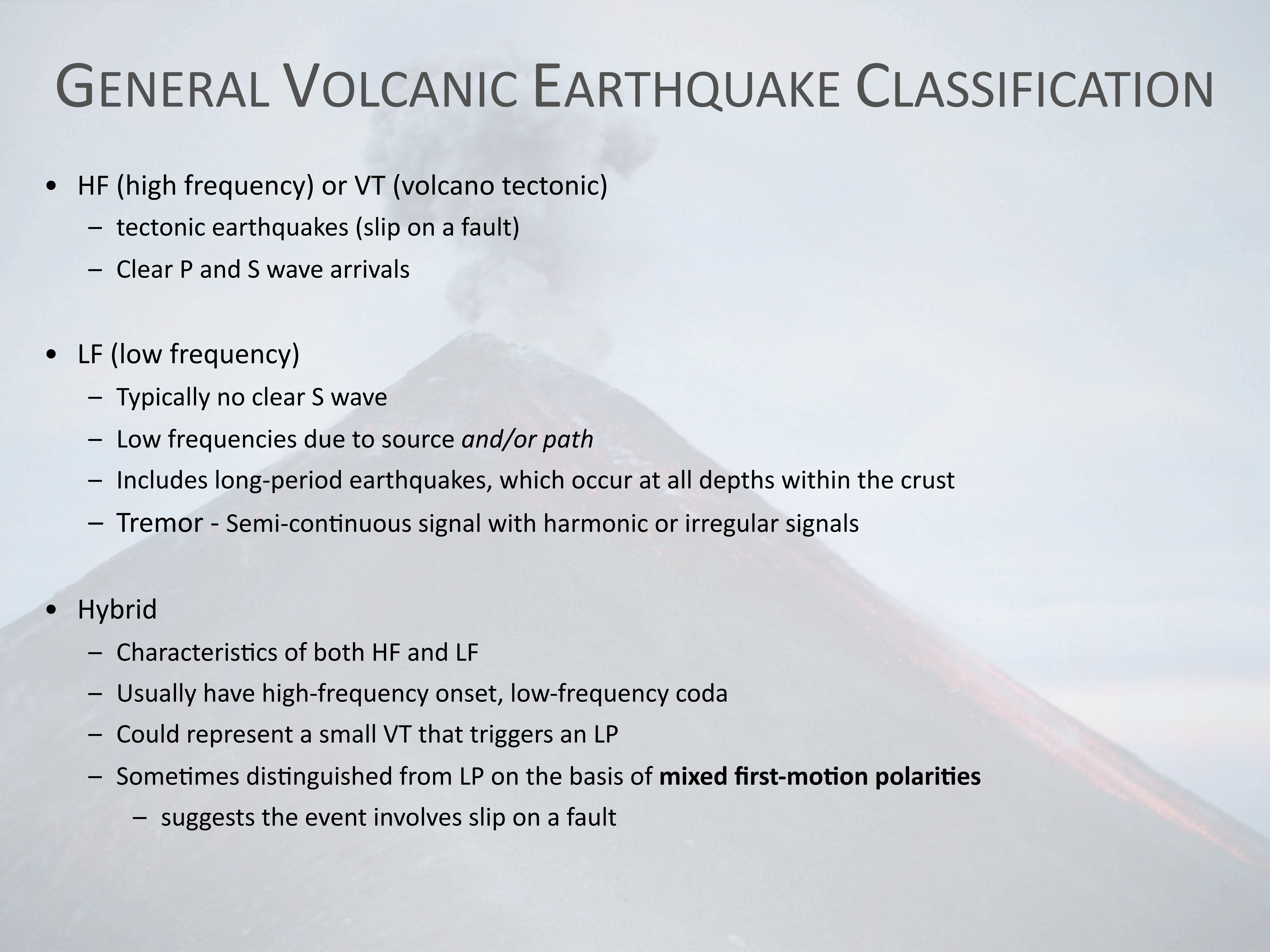
Broad-band seismometers

TREMOR, LP, AND VLP CHARACTERISTICS



Low-Frequency (LF) Seismicity

- Primarily defined on the basis of the frequency content
- These all can be considered "low-frequency" seismicity



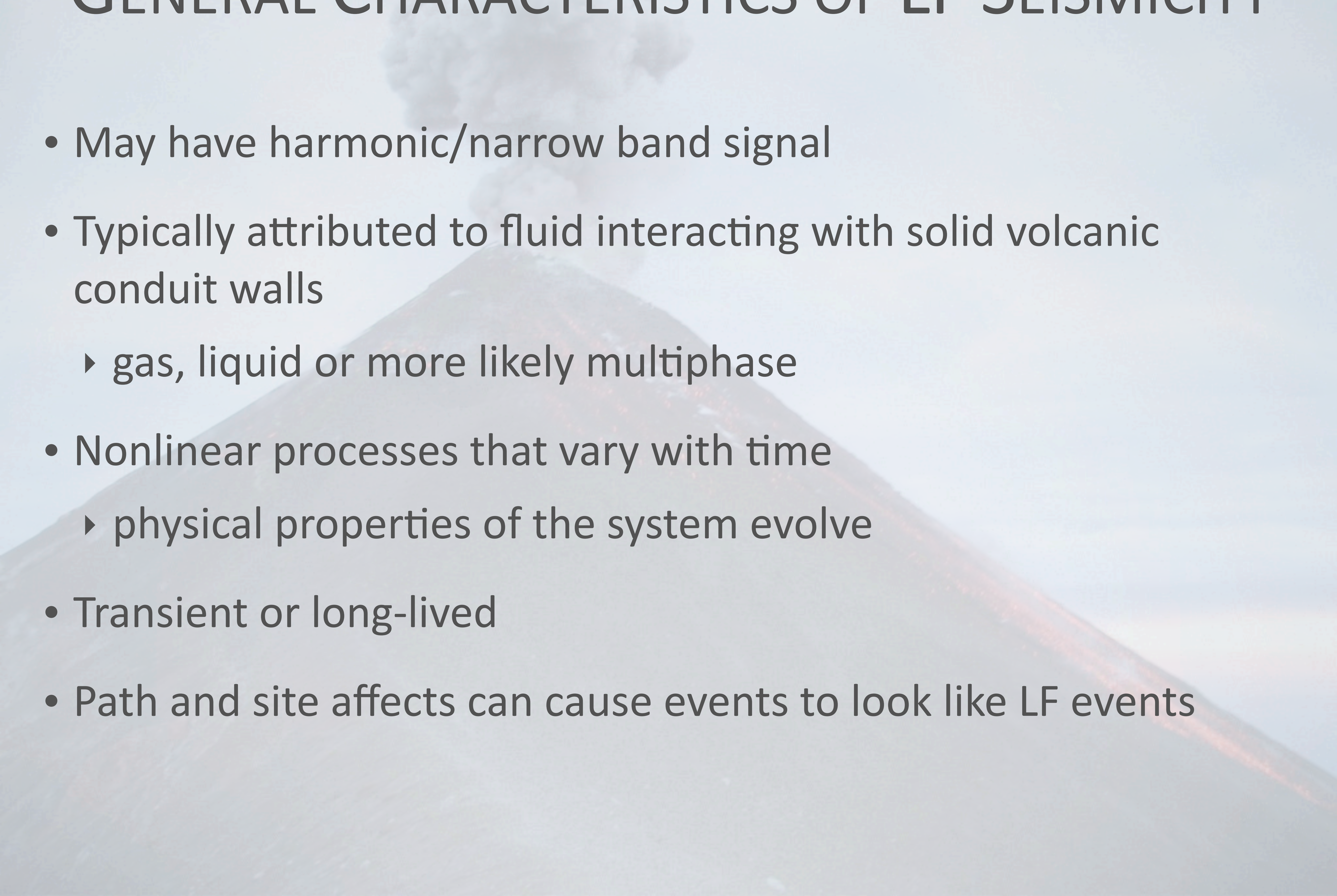
GENERAL VOLCANIC EARTHQUAKE CLASSIFICATION

- 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

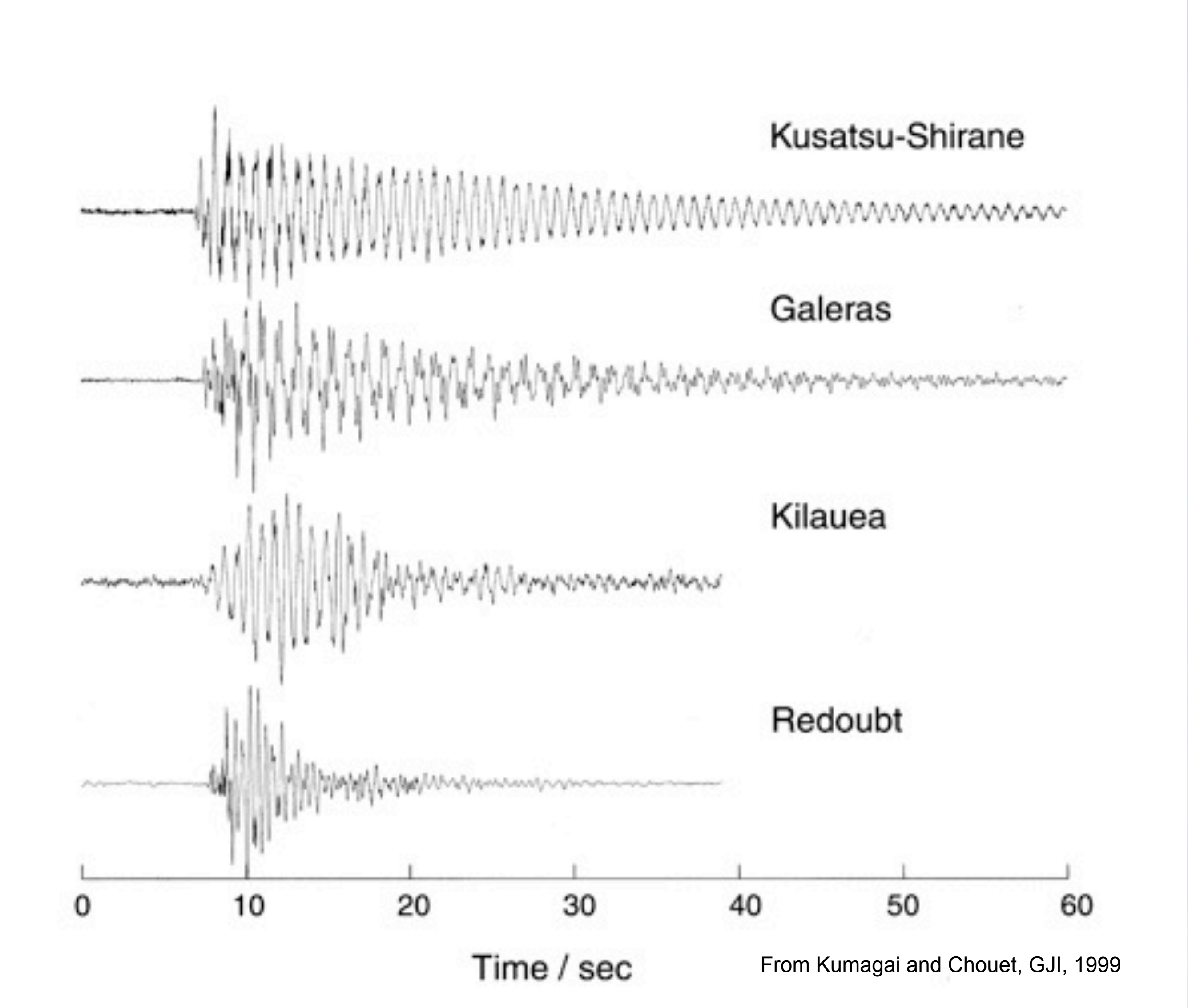
General Characteristics of LF Seismicity



- May have harmonic/narrow band signal
- Typically attributed to fluid interacting with solid volcanic conduit walls
    - gas, liquid or more likely multiphase
- Nonlinear processes that vary with time
    - physical properties of the system evolve
- Transient or long-lived
- Path and site affects can cause events to look like LF events

LP (Long-Period) Earthquakes

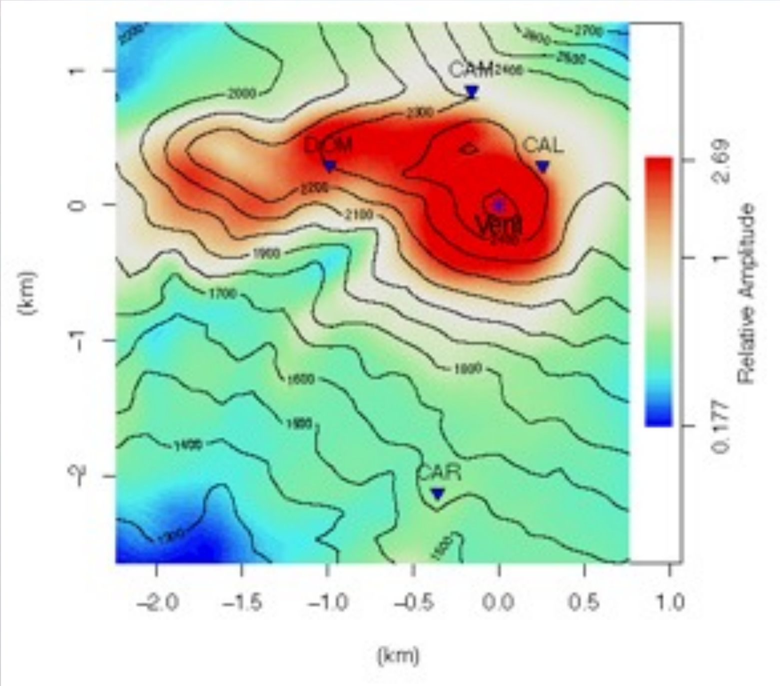
- Known by many names
  - LP, B-type, tornillo, ...
- Broadband onset
  - frequencies from .2 to 15 Hz
  - trigger
- Decaying, harmonic coda
  - frequencies .5 - 2 Hz
  - resonance
- Typically shallow, but can be very deep (upper mantle)



From Kumagai and Chouet, GJI, 1999

PATH-EFFECTED LPS?

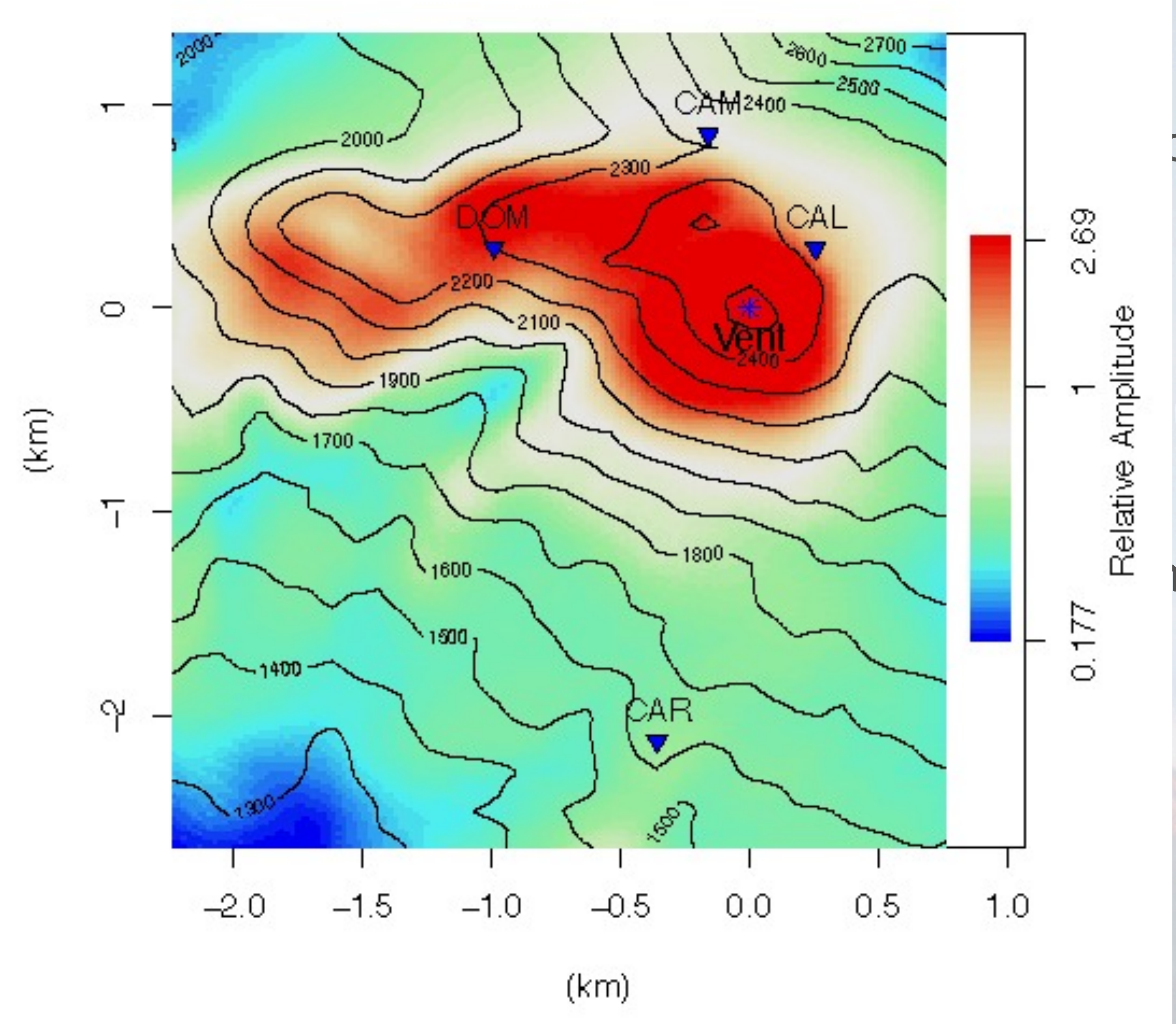
- Path can filter some frequencies and enhance others
- Shallow low-velocity layers can trap waves
  - prolongs the duration of the signal and may mimic LP coda characteristics
- Topography focusses and defocusses waves
  - Waves can be trapped beneath steep topographic features (hills and volcanic edifices)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



Anderson et al.,submitted to *G*^{3}, 2011

SYNTHETIC MODELING OF STRUCTURE

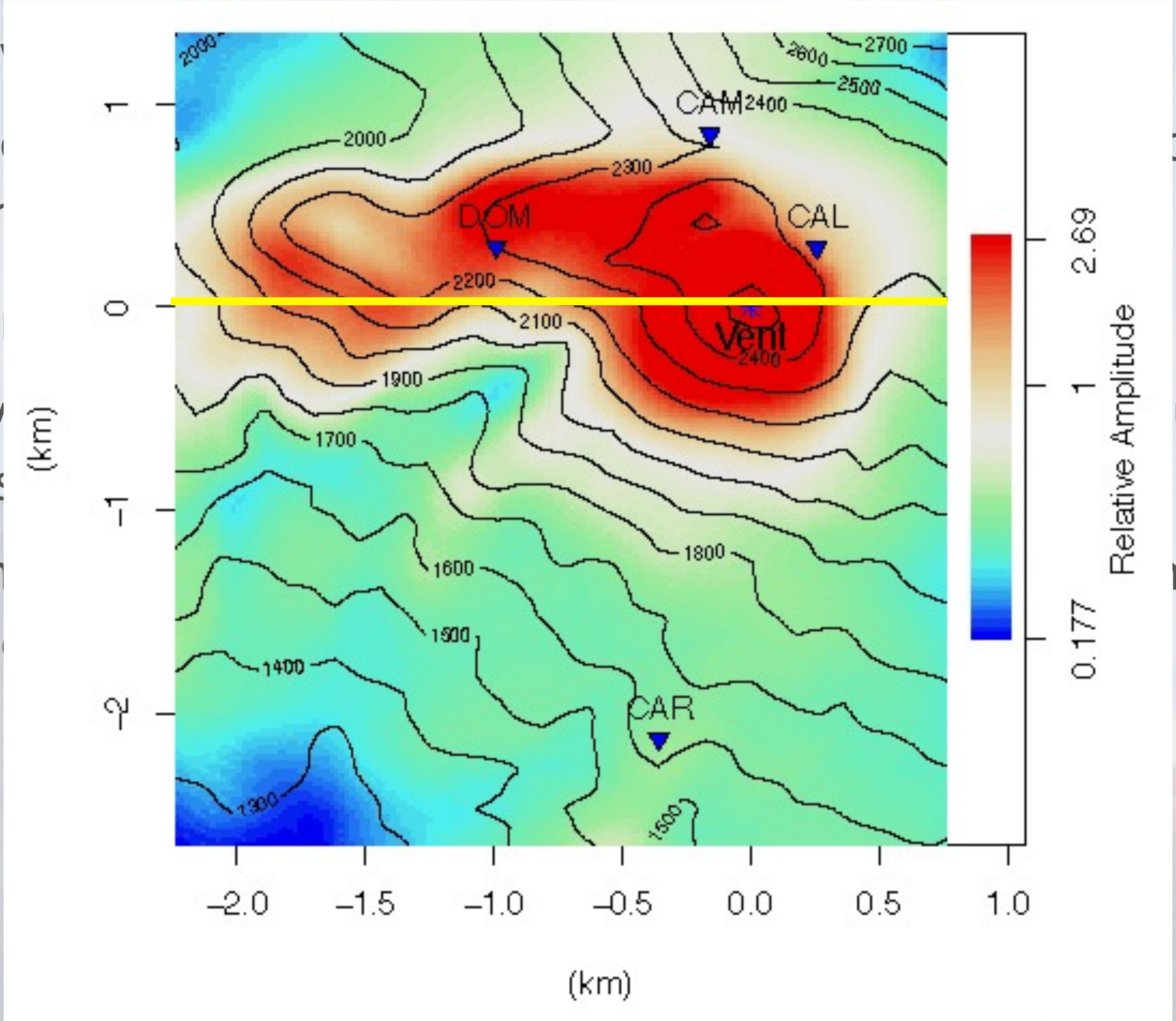
- Shallo
  - prol coda
    char
- Topog
  - Wav ures
    (hills
  - If un g for
    10s



Anderson et al.,submitted to *G^3*, 2011

SYNTHETIC MODELING OF STRUCTURE

- Shallo
  - prol coda
    char
- Topog
  - Wav ures
    (hills
  - If un g for
    10s



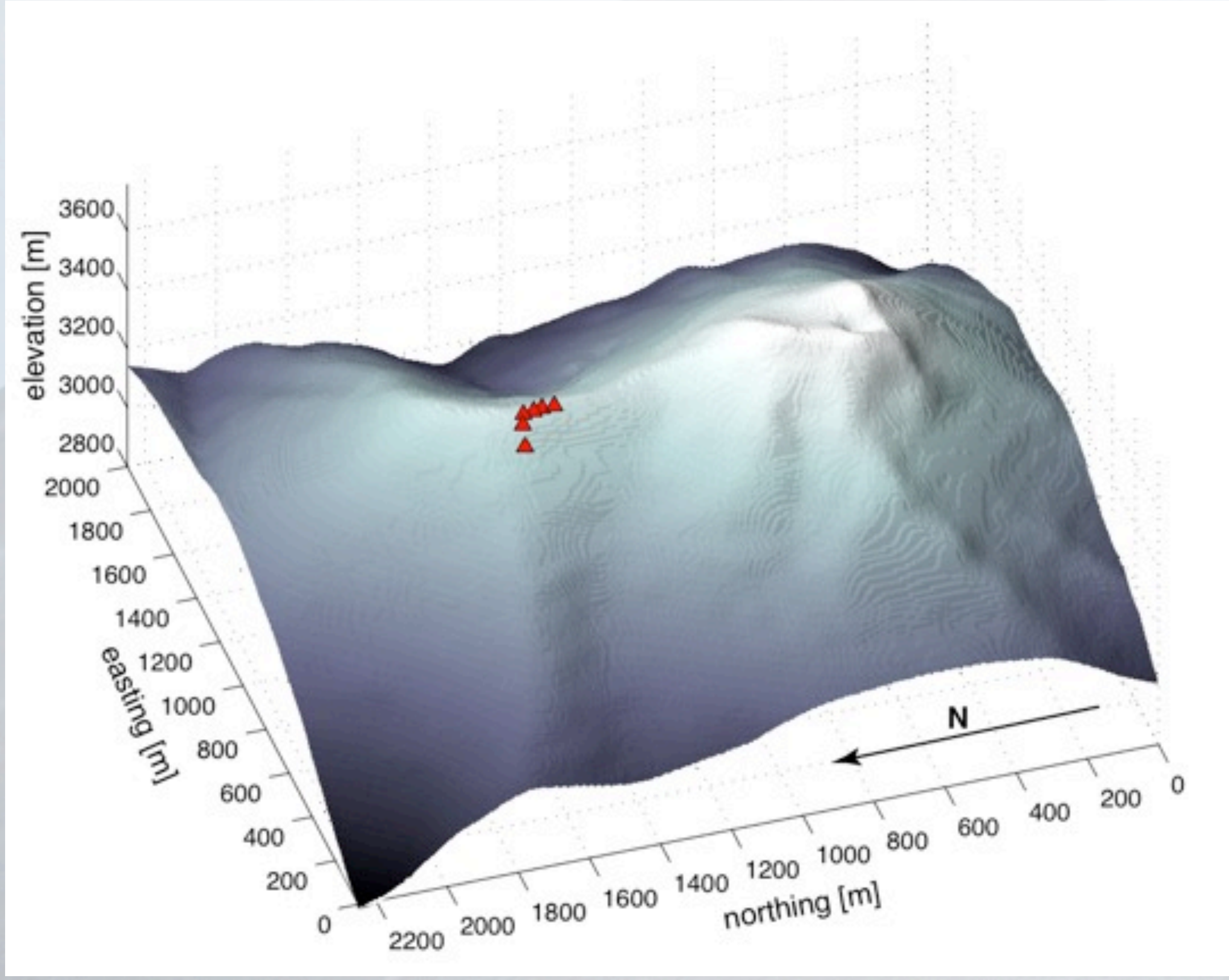
Anderson et al.,submitted to G^3, 2011

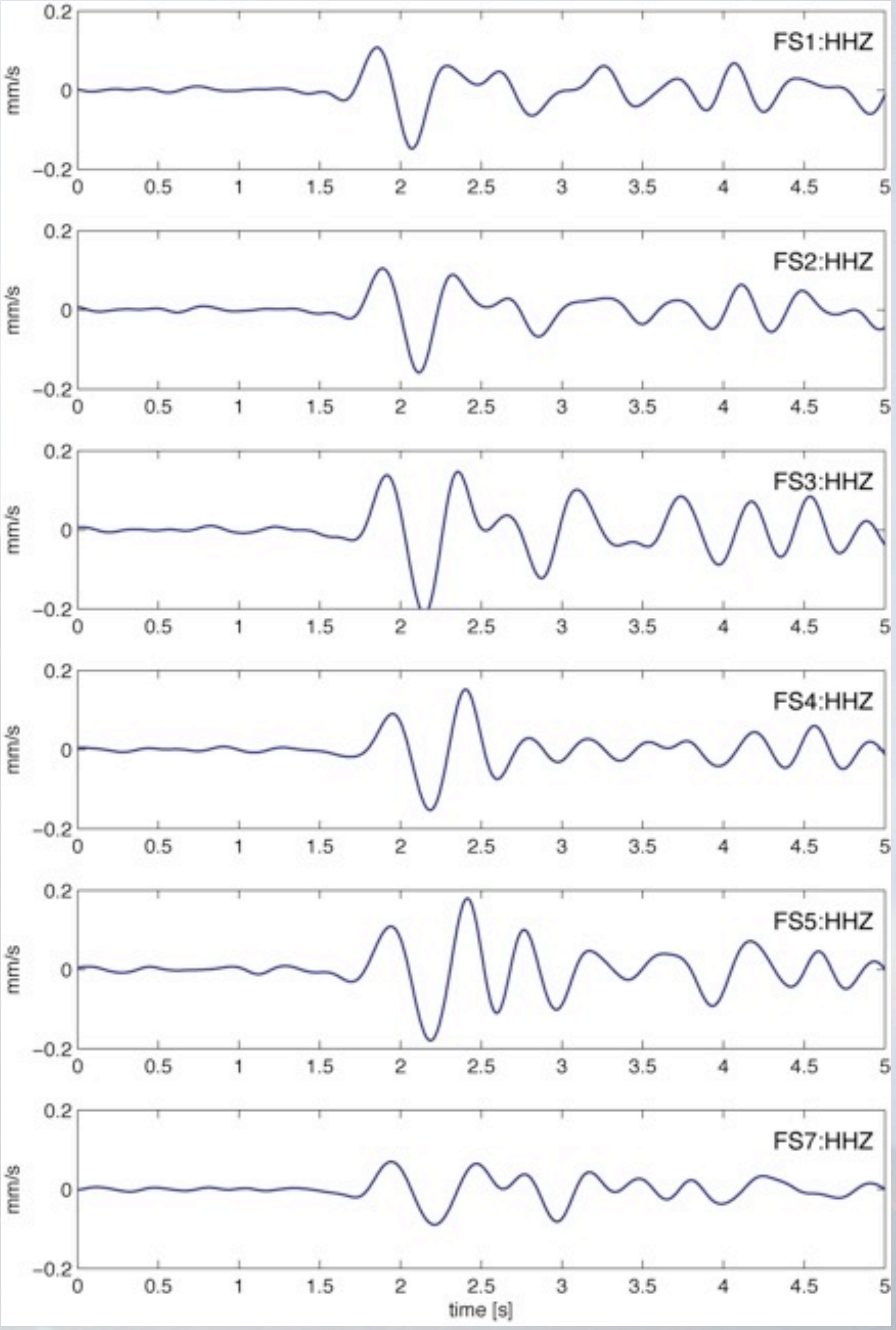
Anderson et al.,submitted to *G*^{3}, 2011

SOURCE VS. PATH AFFECTS

Fuego, Guatemala

- Topographic features greatly distort even a simple signal.

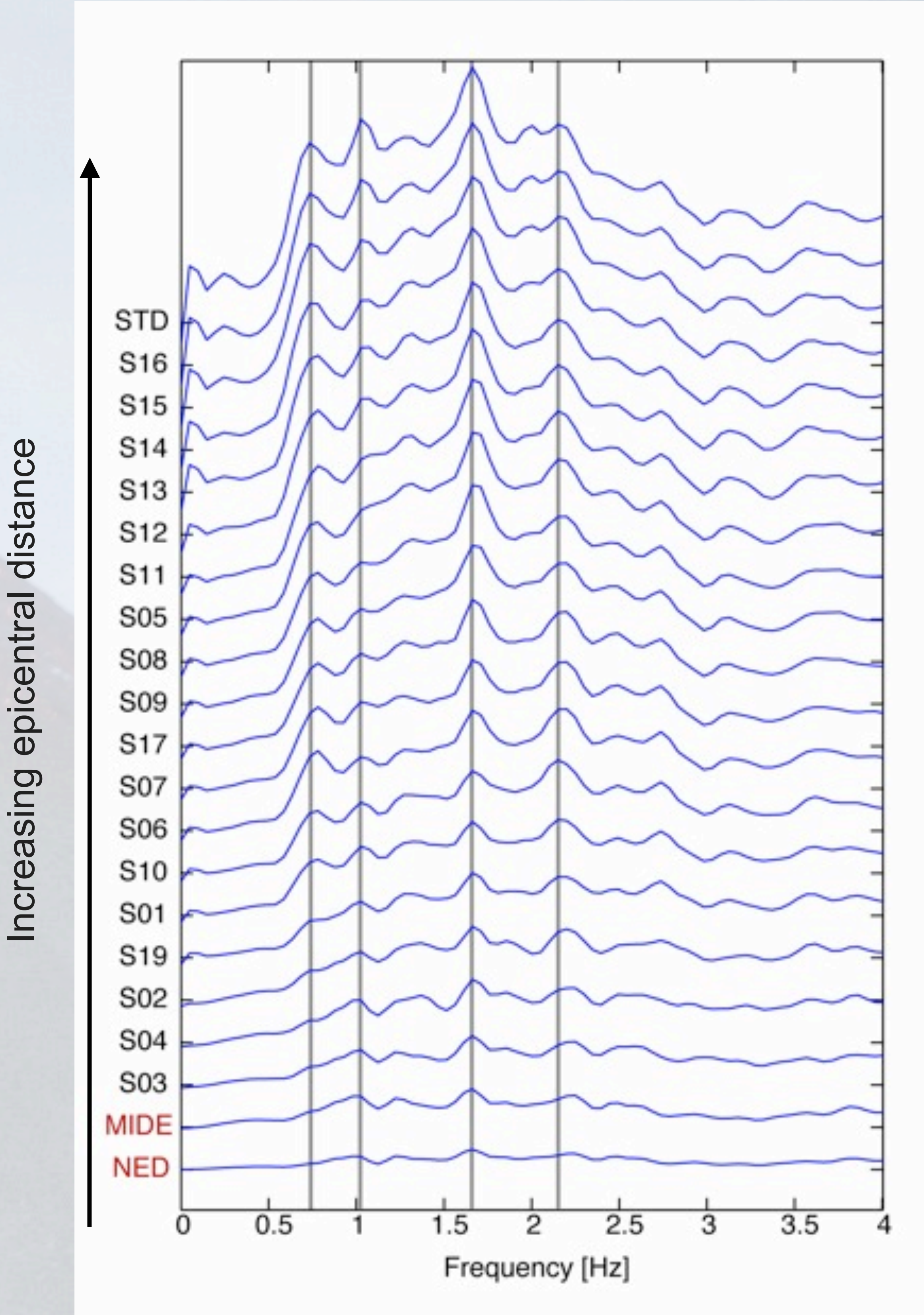




SOURCE VS. PATH AFFECTS

Mount St. Helens

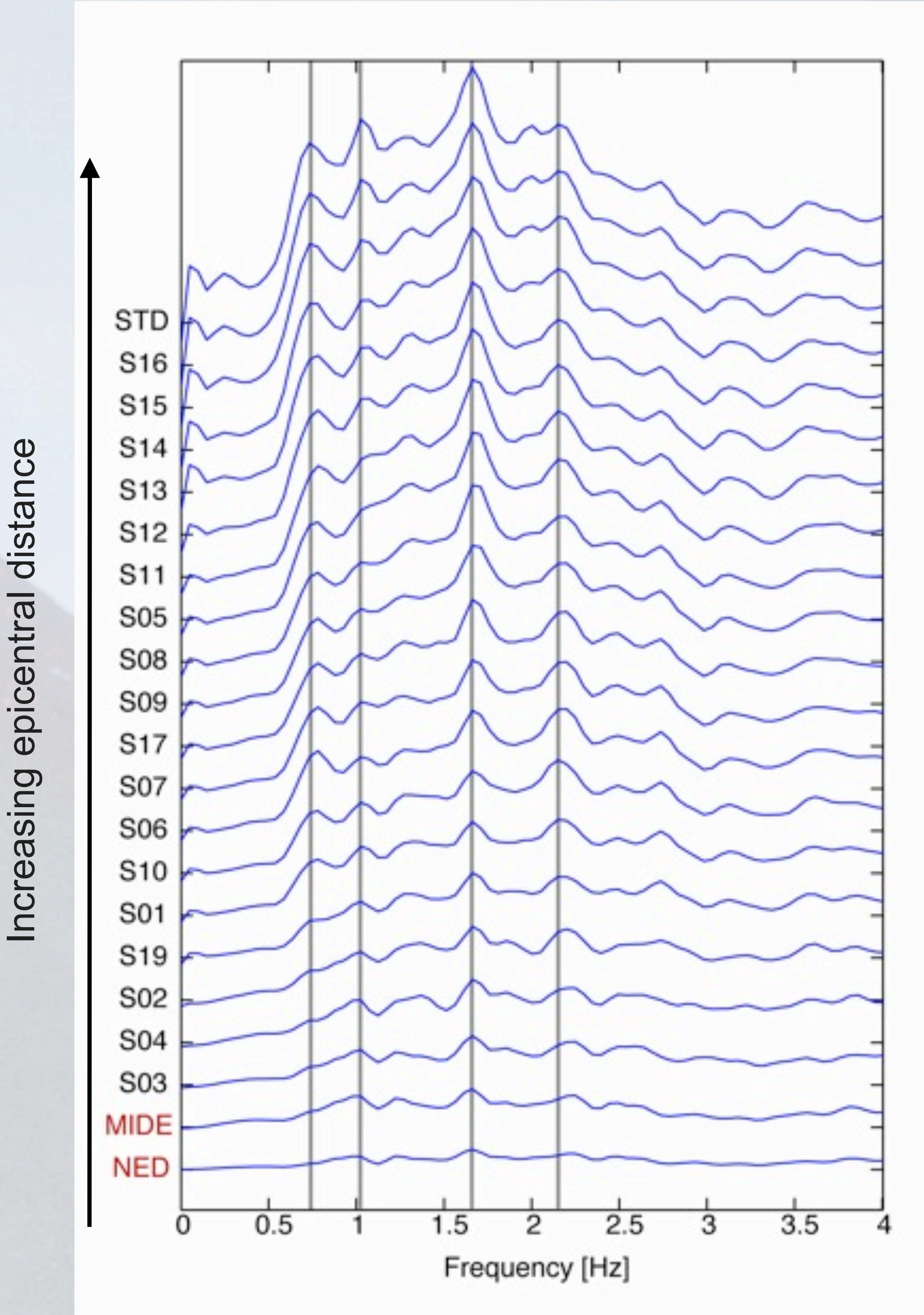
- Site affects are unlikely to be identical at all stations
  - Examine spectra of the coda for one event at all stations for similarity
  - Common spectral peaks at all azimuths are unlikely to be cause by site affects



SOURCE VS. PATH AFFECTS

Mount St. Helens

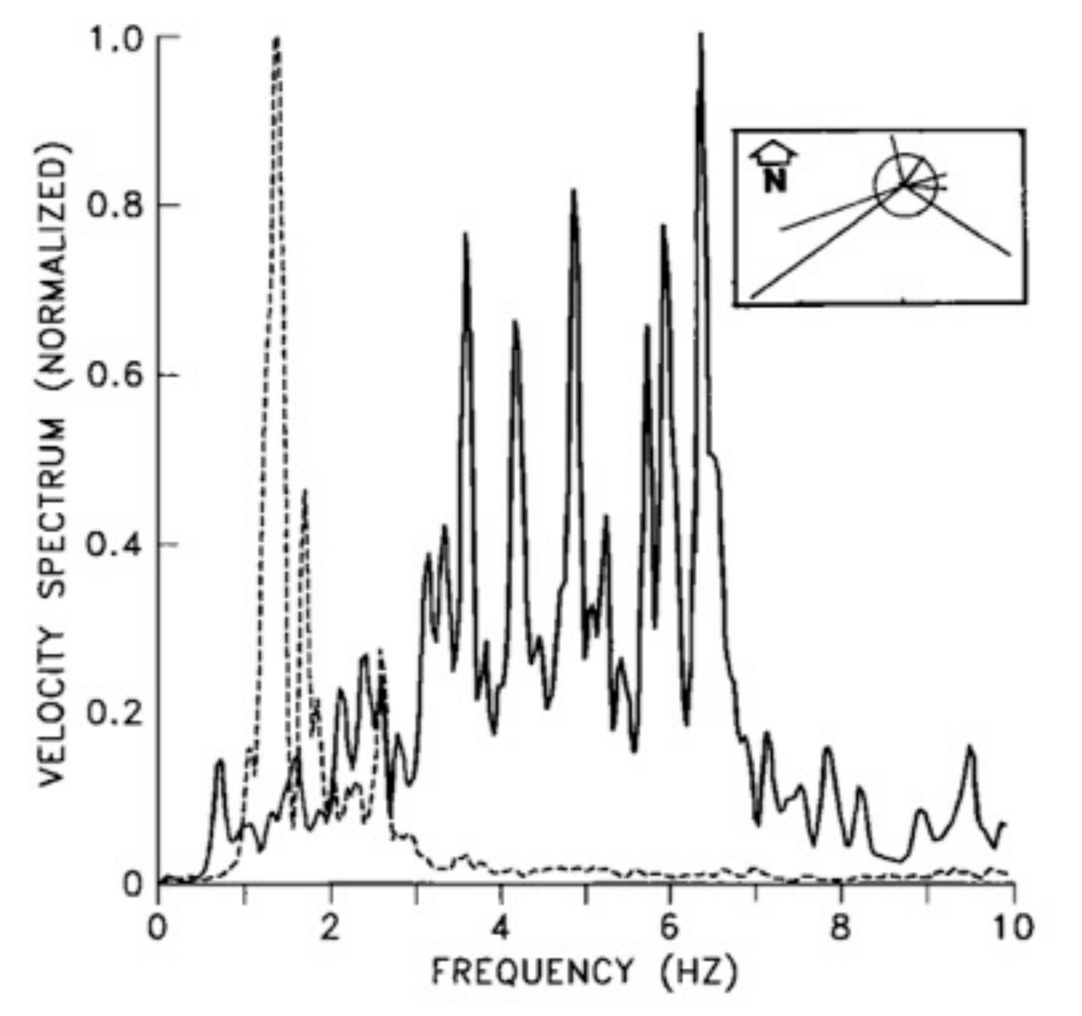
- Site affects are unlikely to be identical at all stations
  - Examine spectra of the coda for one event at all stations for similarity
  - Common spectral peaks at all azimuths are unlikely to be cause by site affects
- Caveat: crack model predicts variations in frequency content with azimuth



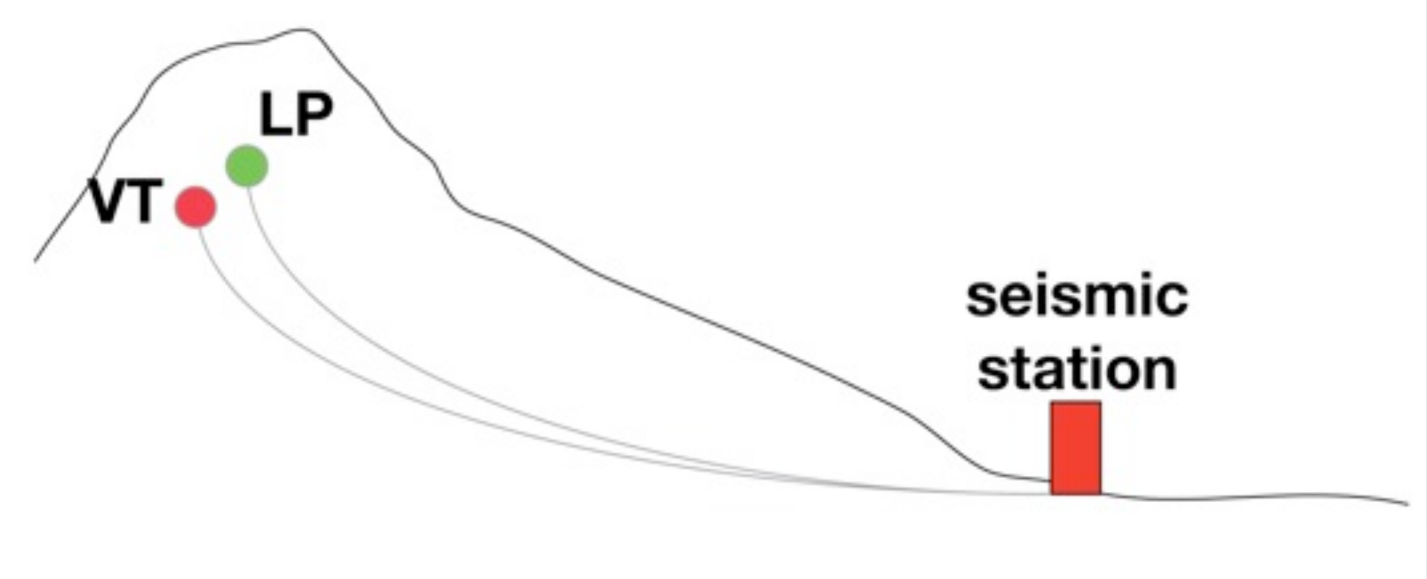
SOURCE VS. PATH AFFECTS

Difficult to identify for shallow events

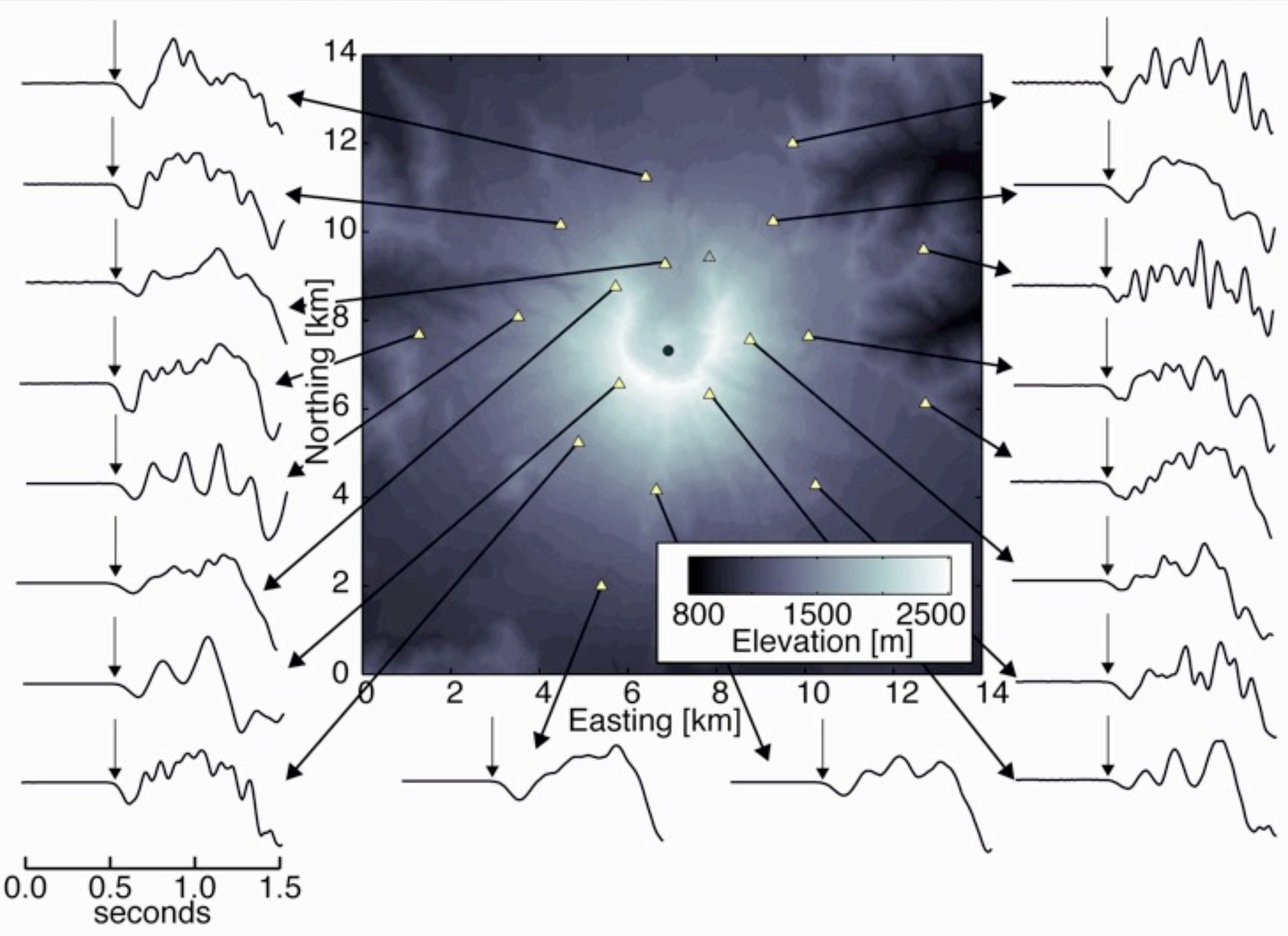
- One way to determine if LF signal is due to path or source is to examine different events (a VT and LP) that occur at about the same location
- Share the same path for most, so any differences attributed to source
- Mammoth Mountain example
  - Stacked spectra from 7 stations
  - Two events closely-spaced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



Pitt & Hill, *GRL*, 1994



LP SOURCE MECHANISM



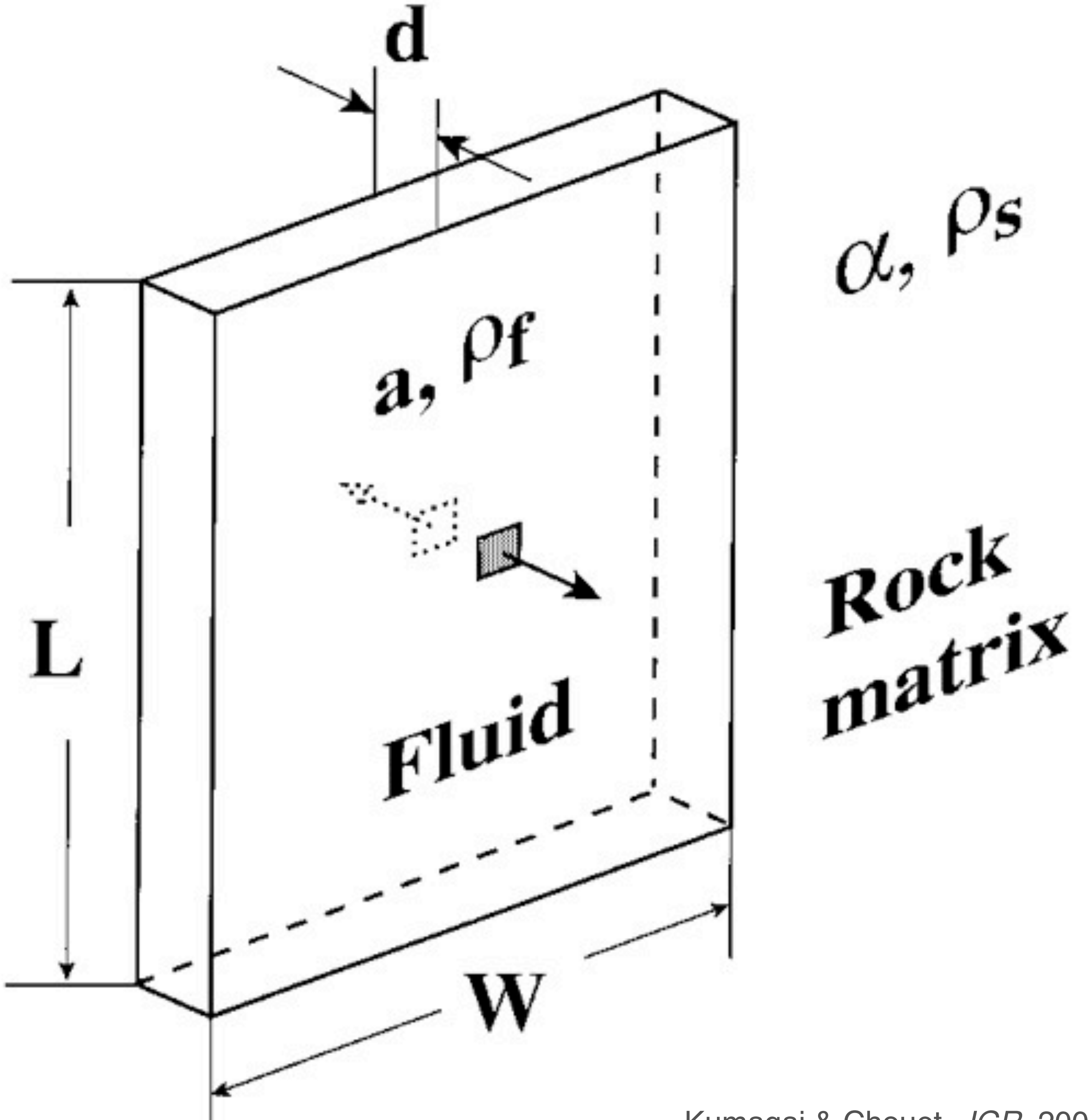
- In this example from Mount St. Helens, all the stations record the same dilatational first motion
- This cannot be a double-couple earthquake in which slip occurs along a planar fault

  but, can result from a volume decrease.

CRACK MODEL

championed by Bernard Chouet

- Large aspect ratio crack filled with magmatic or aqueous multiphase fluid
  - fluid velocity (a)
  - fluid density (ρ_f)
  - rock velocity (α)
  - rock density (ρ_s)
  - $Z = a\,\rho_f / \alpha\,\rho_s$

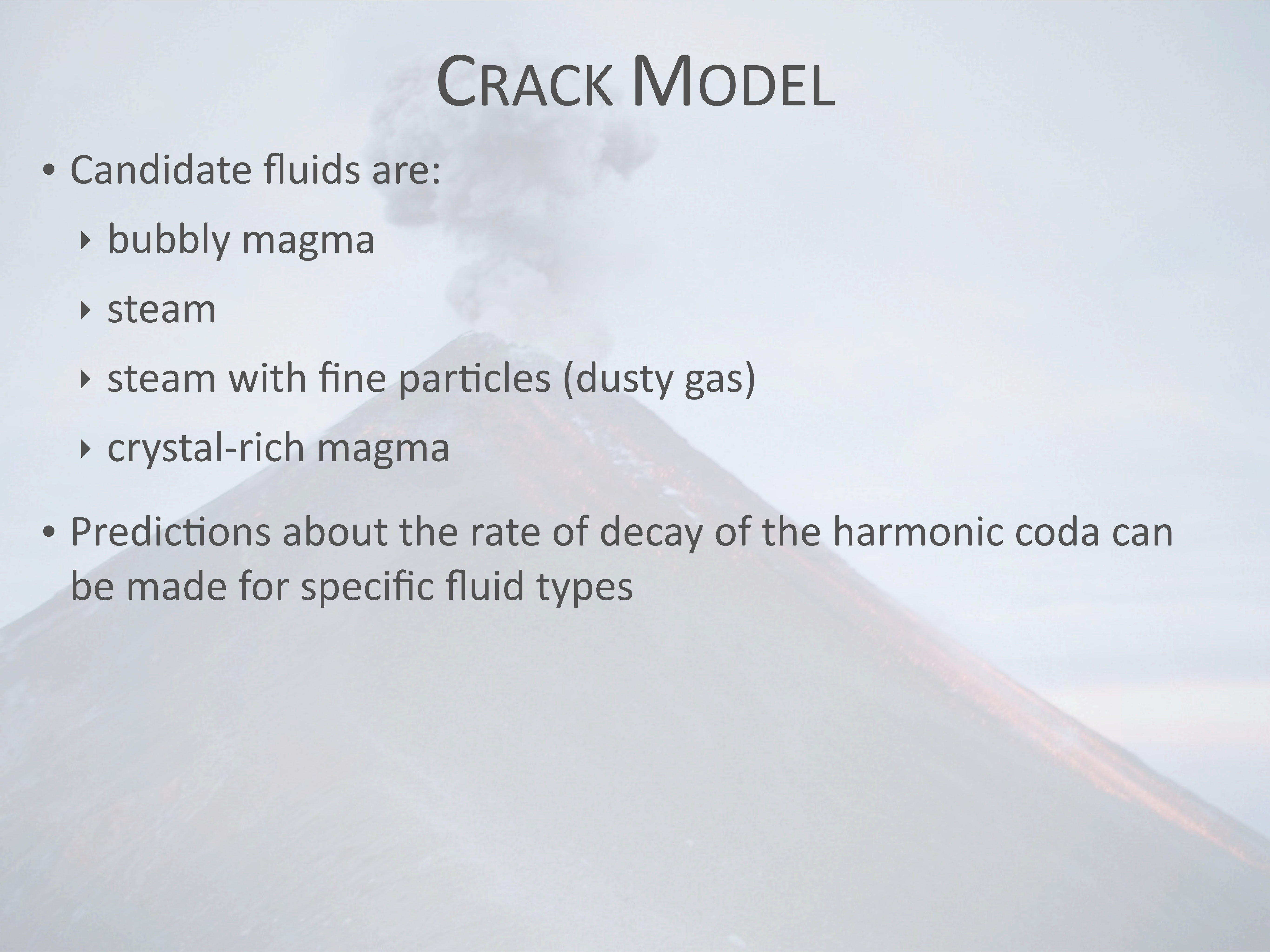


Kumagai & Chouet, *JGR*, 2000

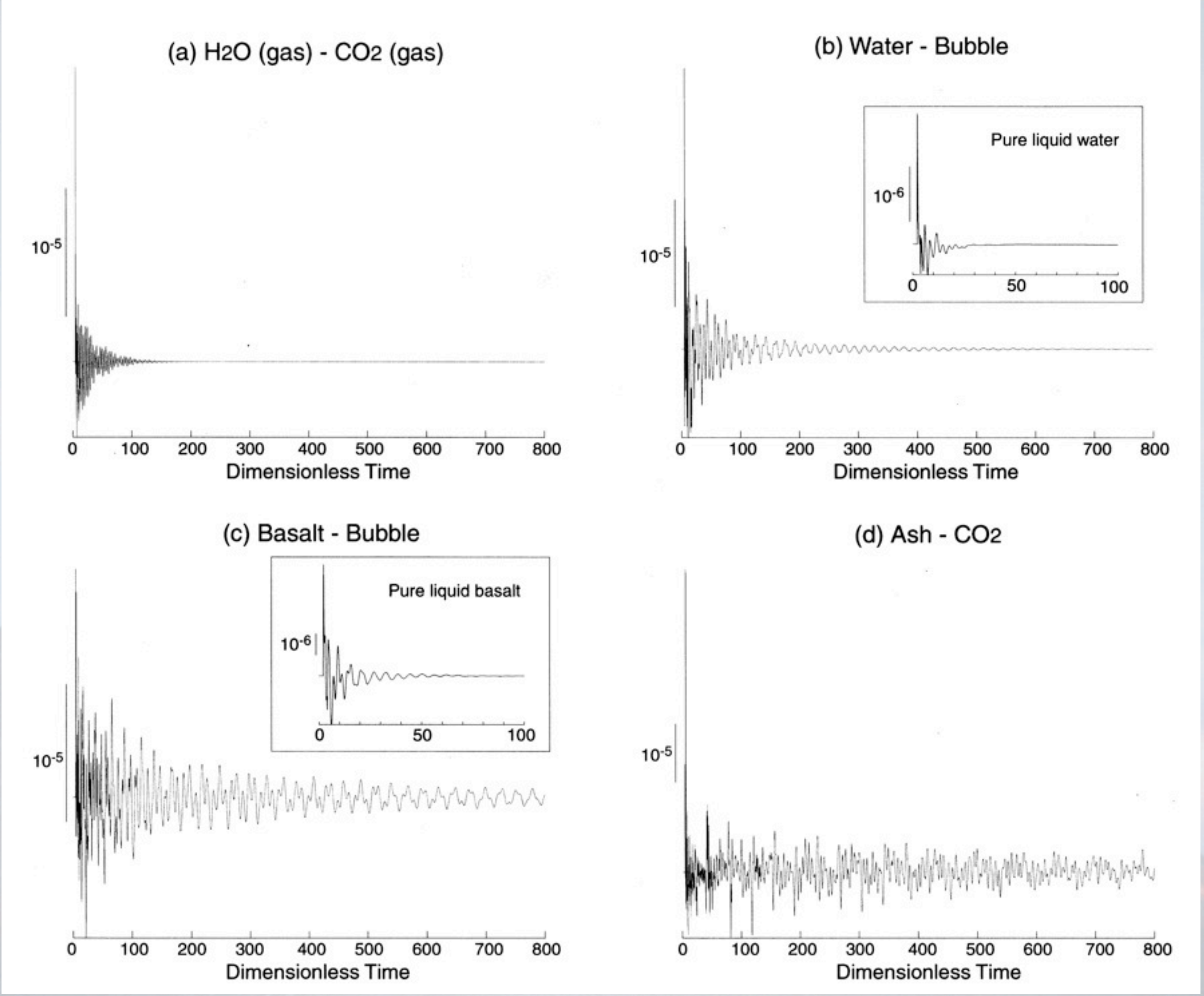
CRACK MODEL

- Large aspect ratio crack filled with magmatic or aqueous multiphase fluid
  - crack width and length on the order of 100s of m for crack width of 100s of cm
- Resonator due to large impedance contrast (Z) between solid crack walls and fluid
  - Z = fluid velocity X fluid density / rock velocity X rock density
  - Traps energy in the crack
  - **Large impedance contrast -> long duration coda**

CRACK MODEL

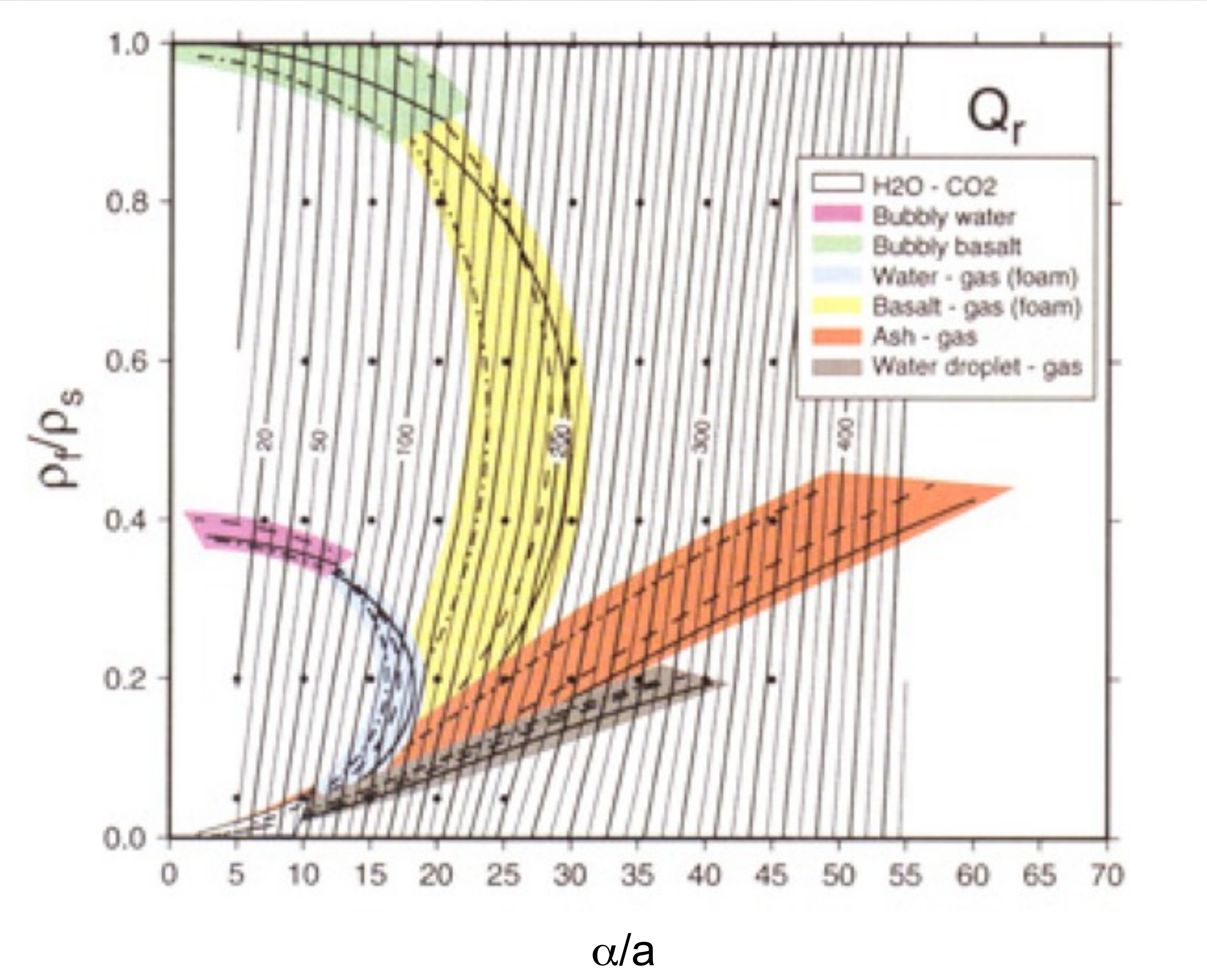


- Candidate fluids are:
  - bubbly magma
  - steam
  - steam with fine particles (dusty gas)
  - crystal-rich magma
- Predictions about the rate of decay of the harmonic coda can be made for specific fluid types



From Kumagai and Chouet, GJI, 1999

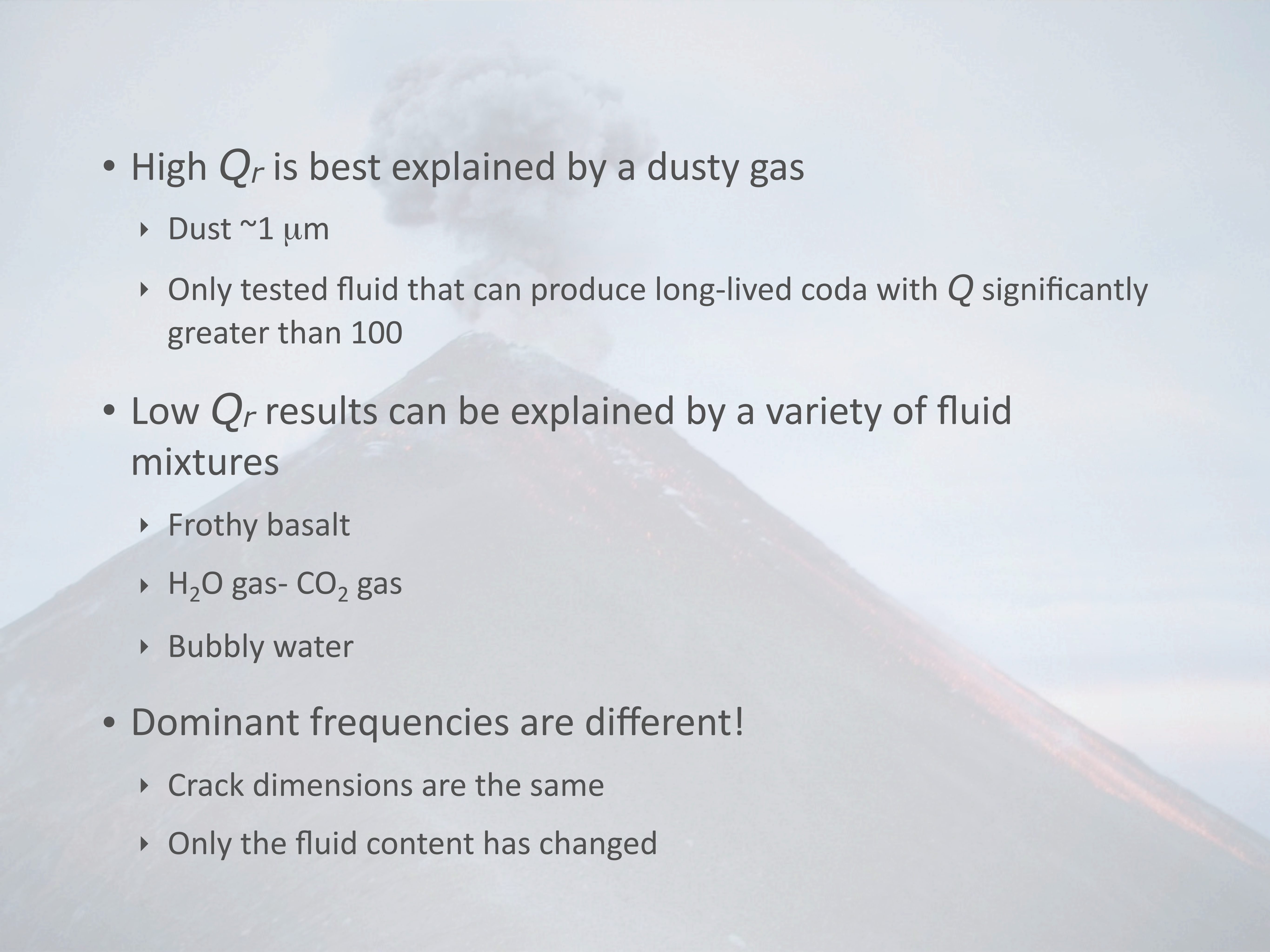
CRACK MODEL



Q_r describes the signal attenuation due to radiation from the crack

- Low Q_r means the coda decays rapidly
- High Q_r predicts long-duration codas

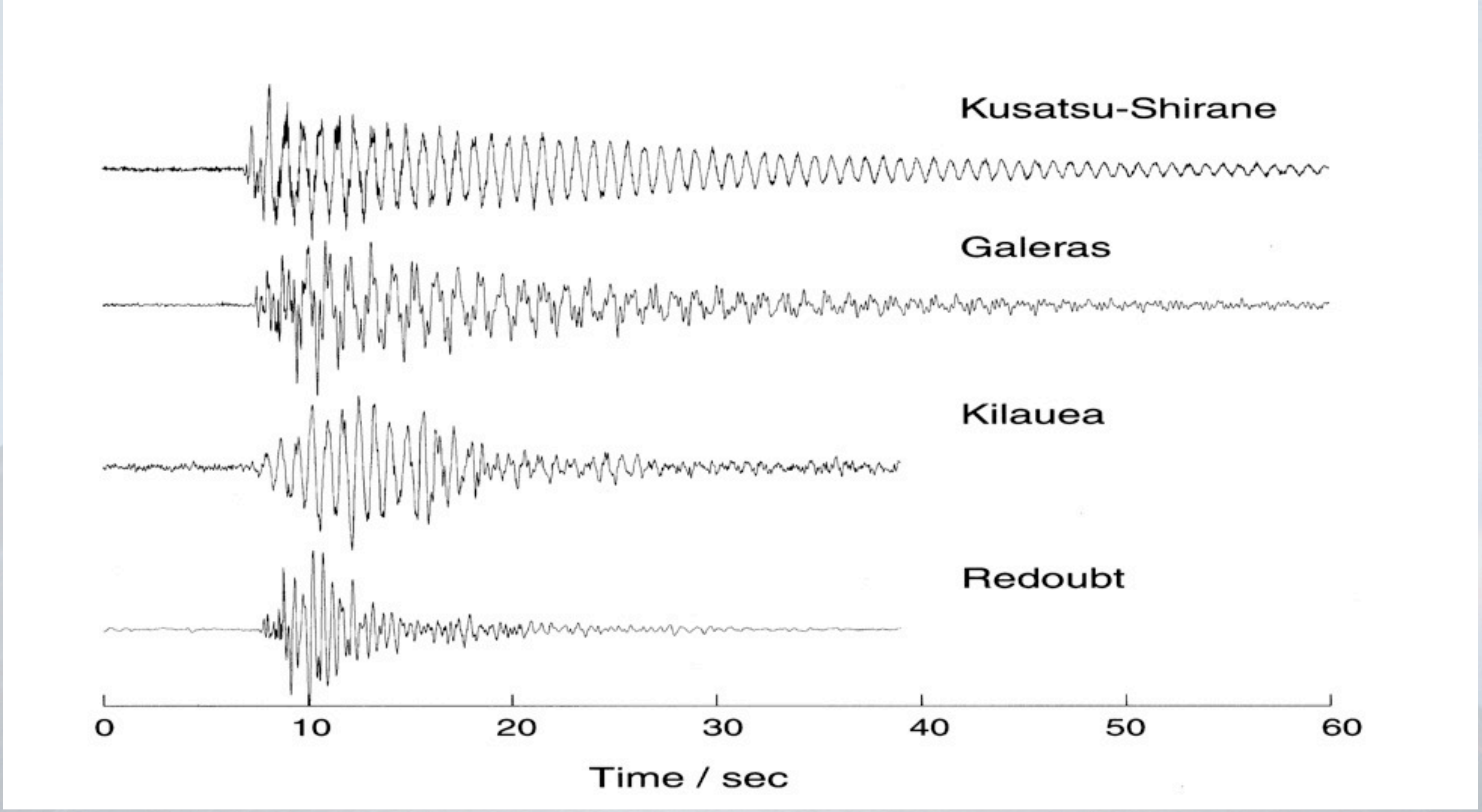
Kumagai & Chouet, *JGR*, 2000



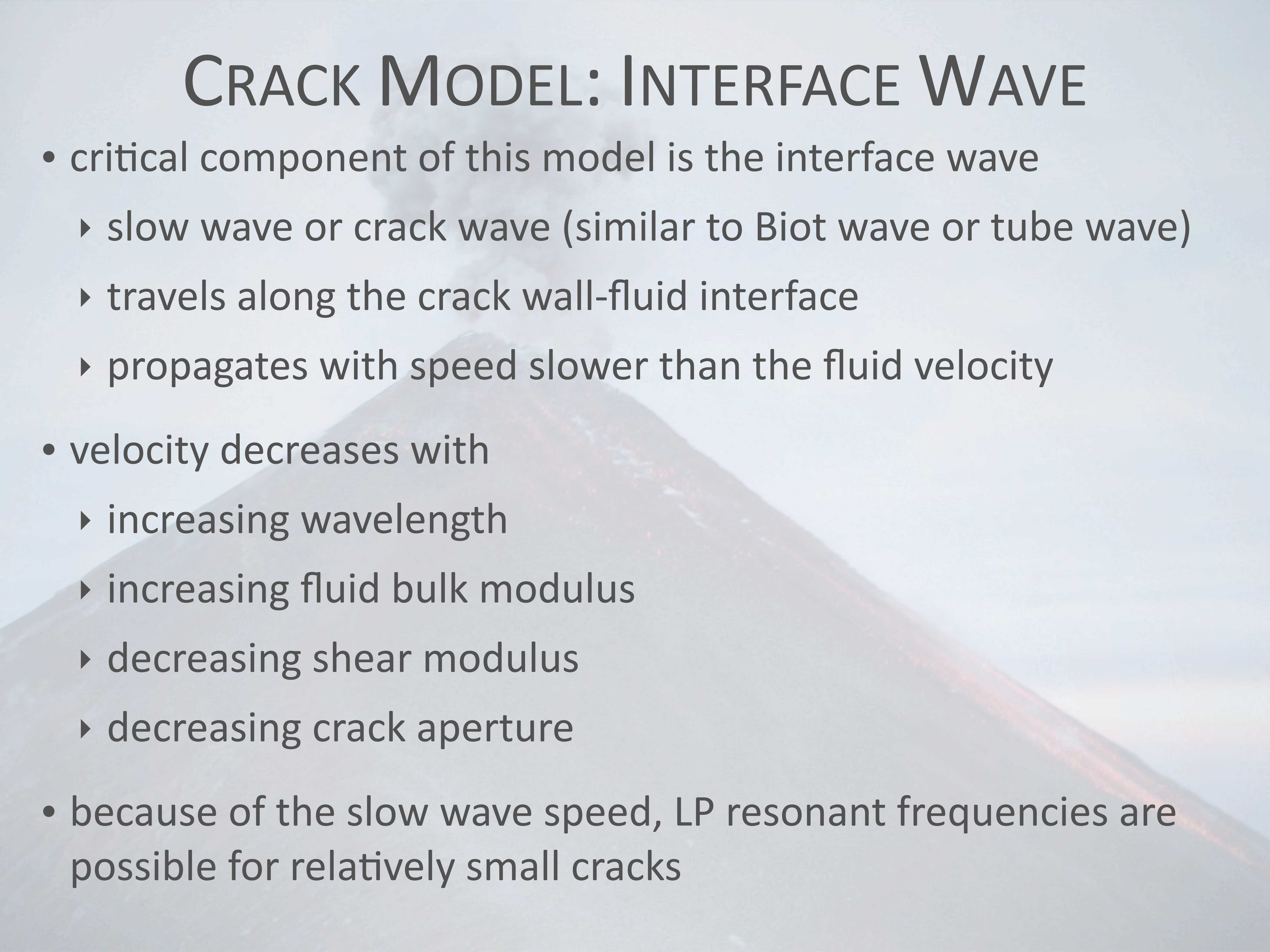
- High Q_r is best explained by a dusty gas
  - Dust ~1 μm
  - Only tested fluid that can produce long-lived coda with Q significantly greater than 100
- Low Q_r results can be explained by a variety of fluid mixtures
  - Frothy basalt
  - H_2O gas- CO_2 gas
  - Bubbly water
- Dominant frequencies are different!
  - Crack dimensions are the same
  - Only the fluid content has changed

CRACK MODEL

- Q_r varies from 10 at Redoubt to 1000 at Kusatsu-Shirane and Galeras



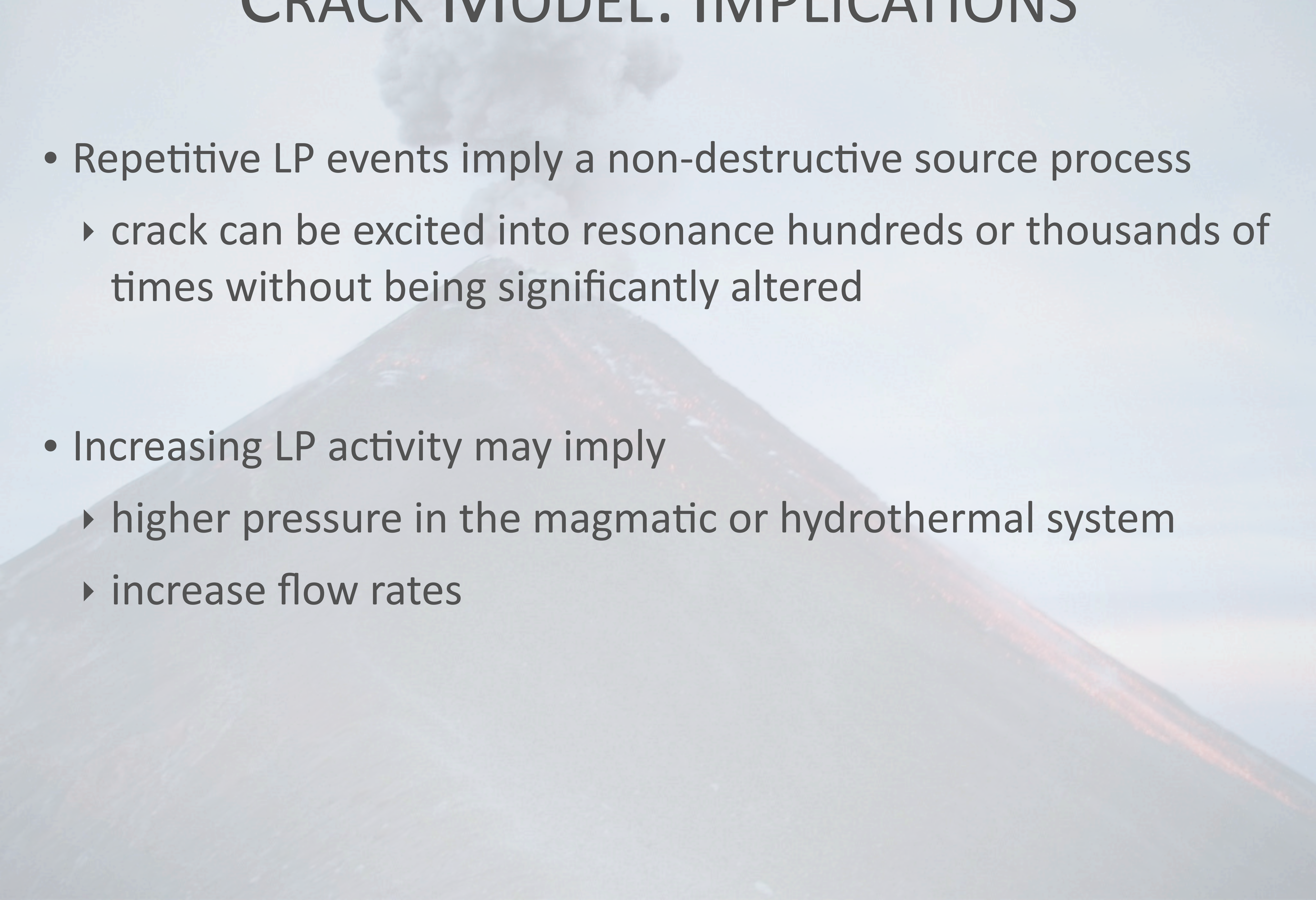
Kumagai and Chouet, GJI, 1999



CRACK MODEL: INTERFACE WAVE

- critical component of this model is the interface wave
  - slow wave or crack wave (similar to Biot wave or tube wave)
  - travels along the crack wall-fluid interface
  - propagates with speed slower than the fluid velocity
- velocity decreases with
  - increasing wavelength
  - increasing fluid bulk modulus
  - decreasing shear modulus
  - decreasing crack aperture
- because of the slow wave speed, LP resonant frequencies are possible for relatively small cracks

Crack Model: Implications



- Repetitive LP events imply a non-destructive source process
  - crack can be excited into resonance hundreds or thousands of times without being significantly altered
- Increasing LP activity may imply
  - higher pressure in the magmatic or hydrothermal system
  - increase flow rates

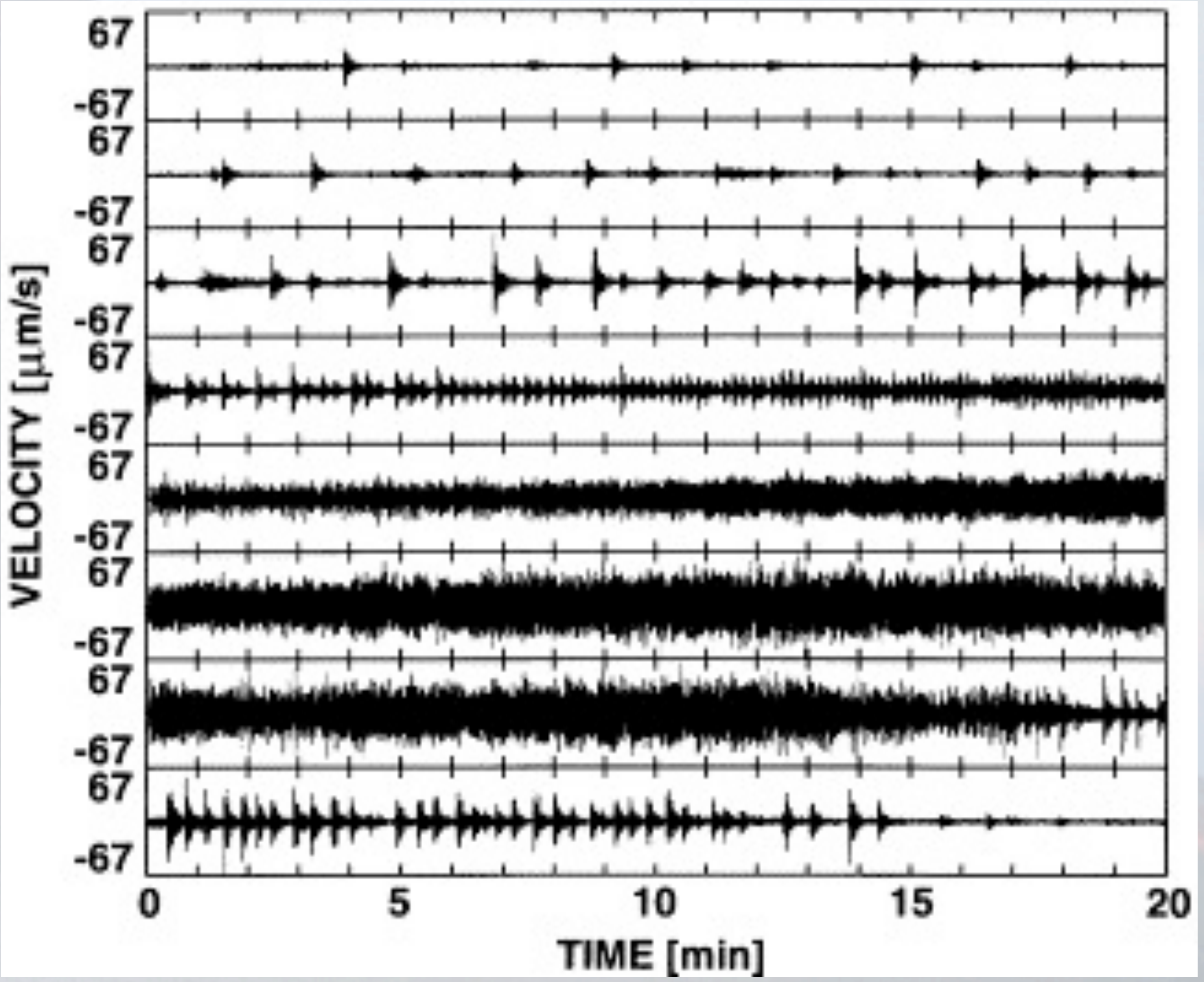
CONDUIT MARGIN FRACTURE RESONANCE

- At silicic volcanoes, a model involving resonance of fluid-filled cracks along the conduit margin may explain LP earthquakes

- Large strains at margin cause brittle failure in hot rock

- Pressure changes can trigger resonance in system of interconnected cracks

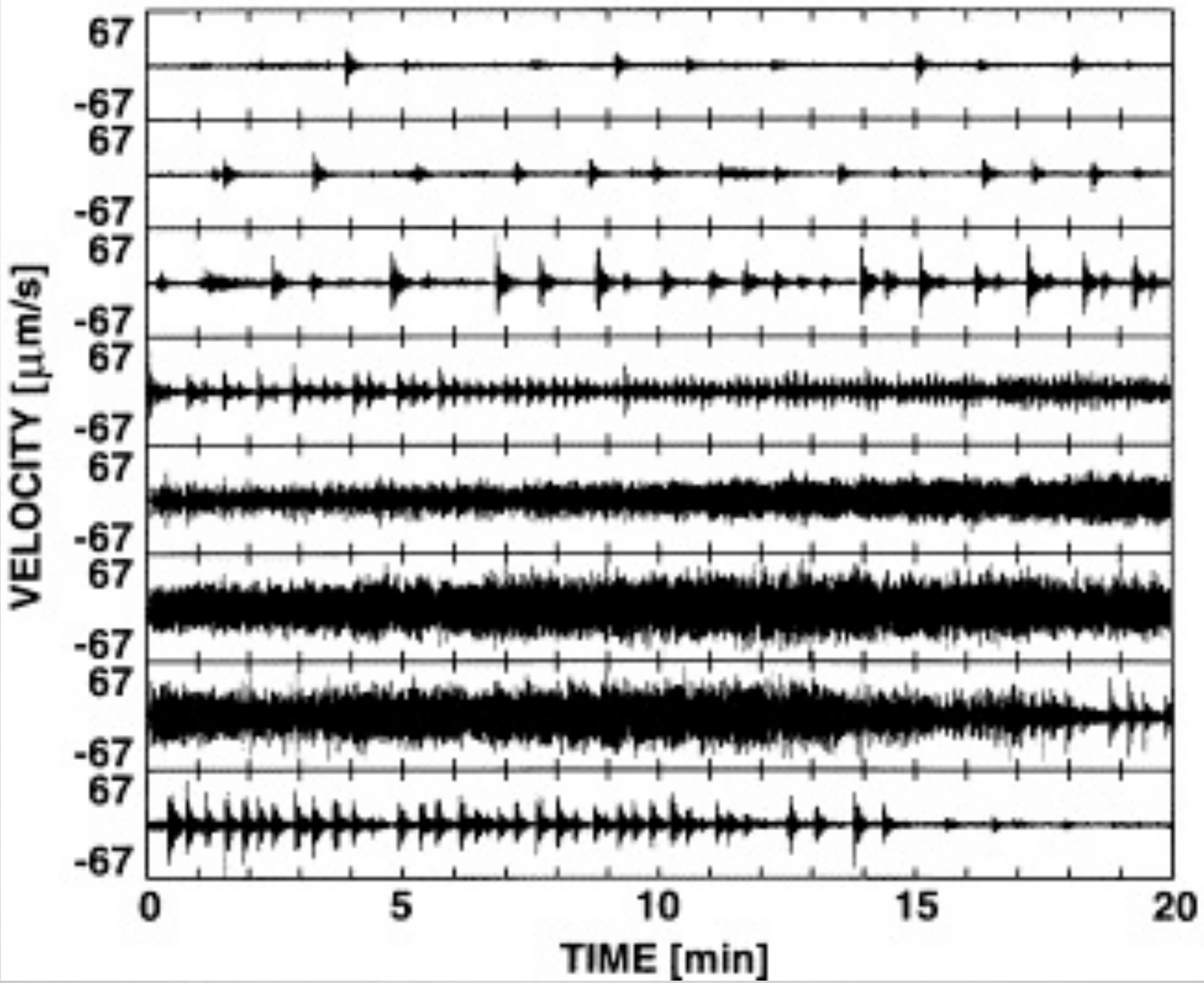
- LP events may increase in frequency and merge into tremor
  - suggests a common source mechanism for LP and tremor activity



Neuberg et al., *JVGR*, 2000

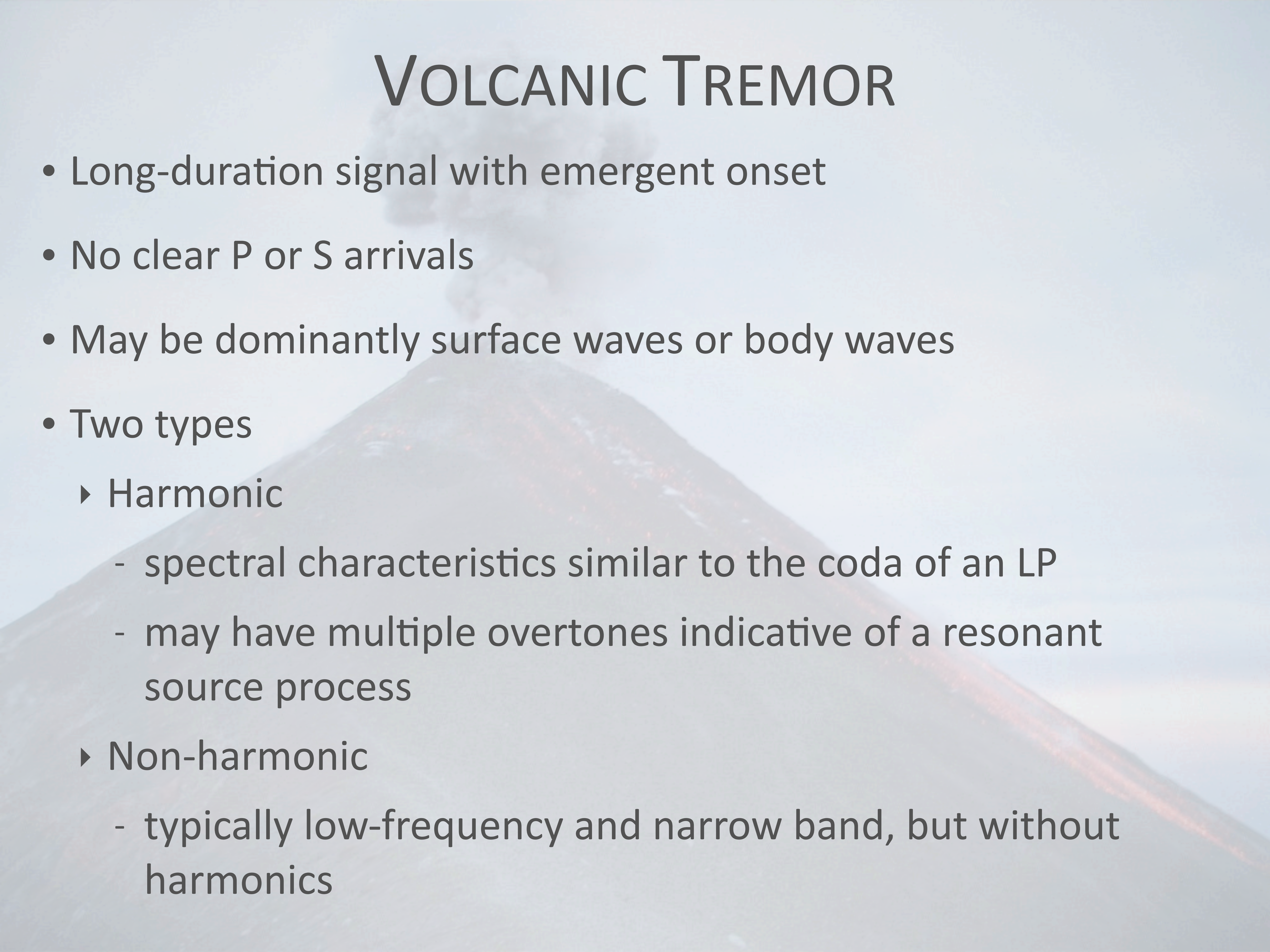
CONDUIT MARGIN FRACTURE RESONANCE

- Increased activity may indicate an increase in effusion rate



Neuberg et al., *JVGR*, 2000

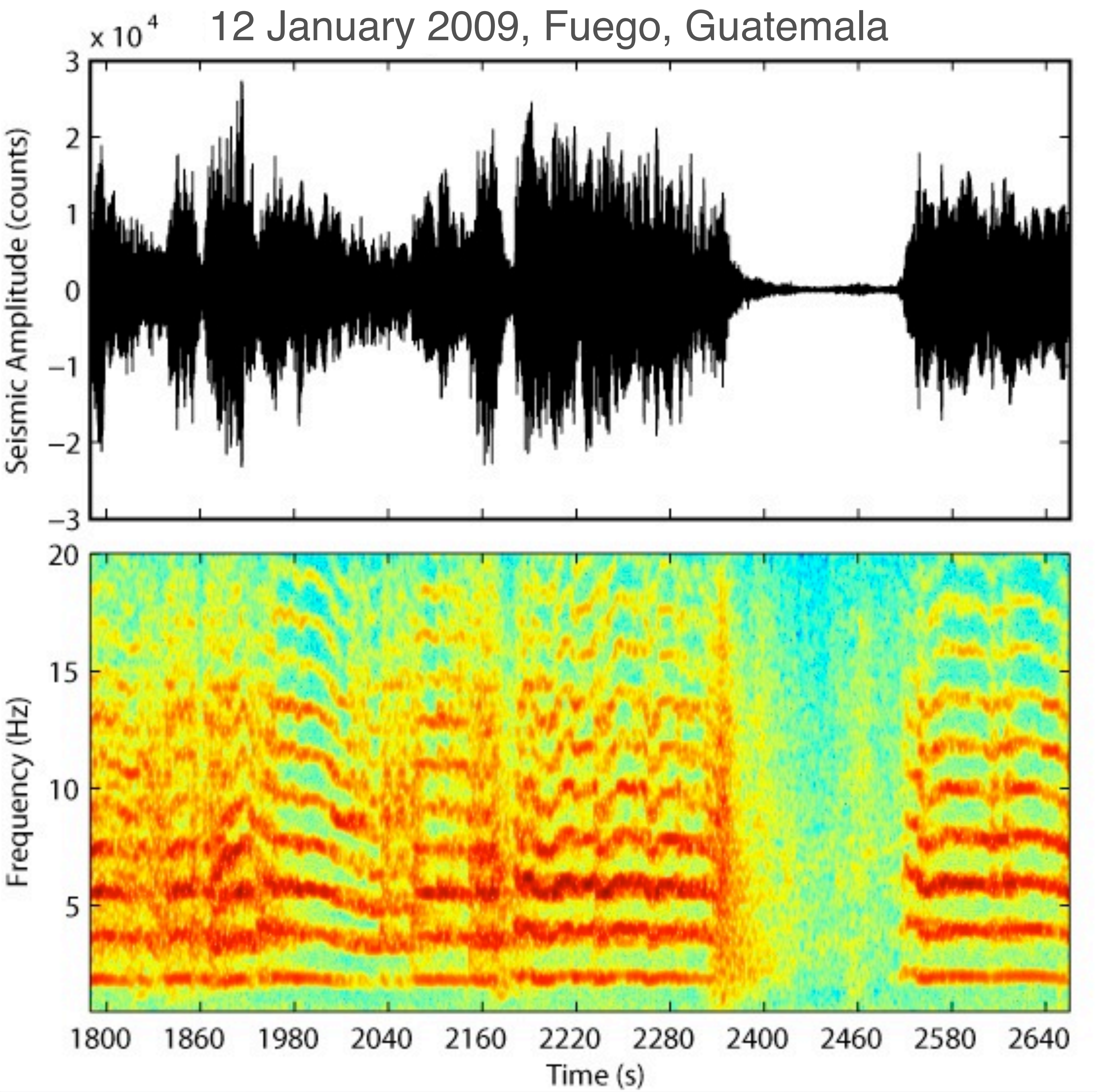
VOLCANIC TREMOR



- Long-duration signal with emergent onset
- No clear P or S arrivals
- May be dominantly surface waves or body waves
- Two types
  - Harmonic
    - spectral characteristics similar to the coda of an LP
    - may have multiple overtones indicative of a resonant source process
  - Non-harmonic
    - typically low-frequency and narrow band, but without harmonics

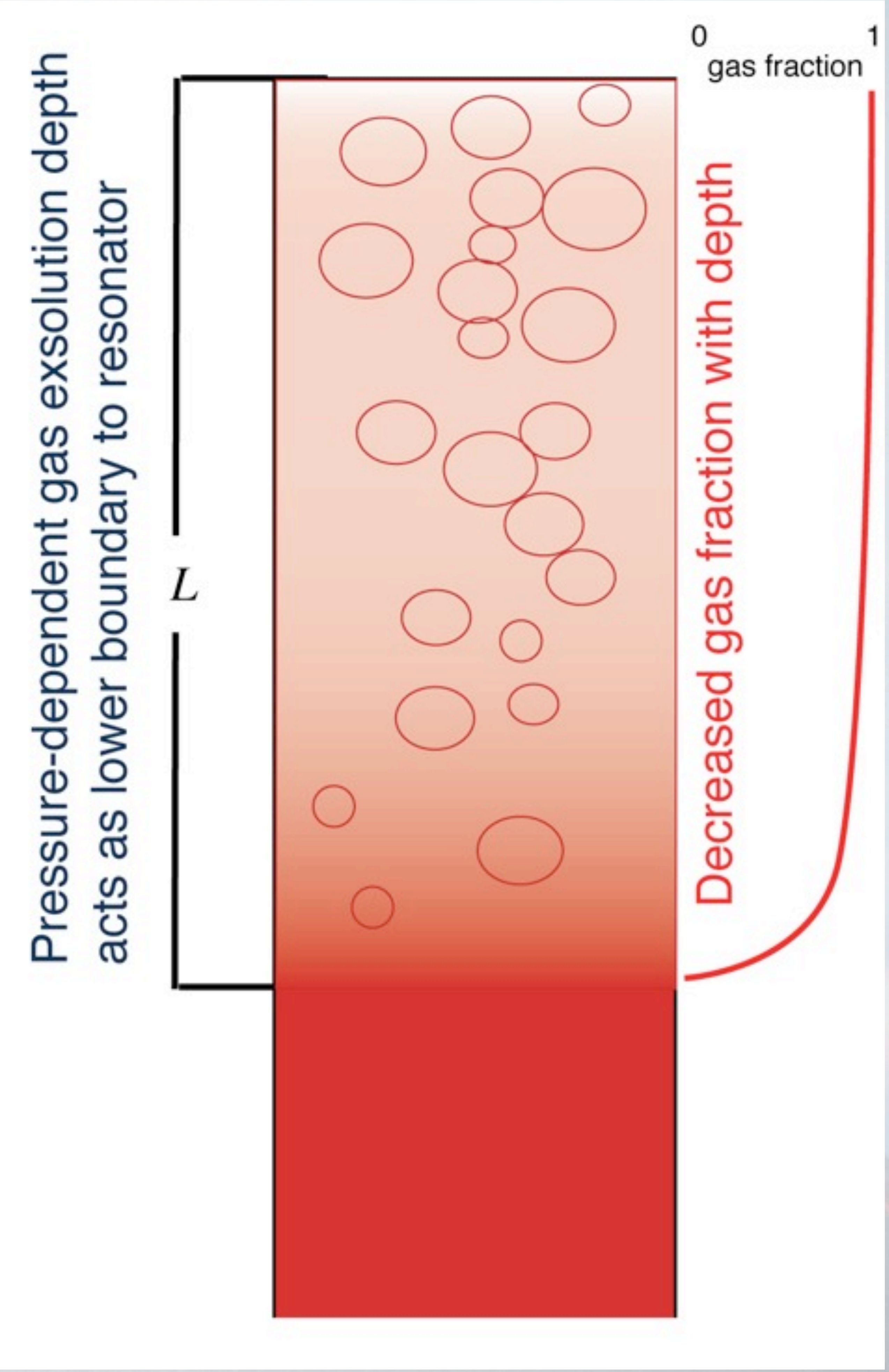
HARMONIC TREMOR

- Narrow-band, long-duration signal
- 1 or more (>10) harmonic overtones of the fundamental frequency, f_0

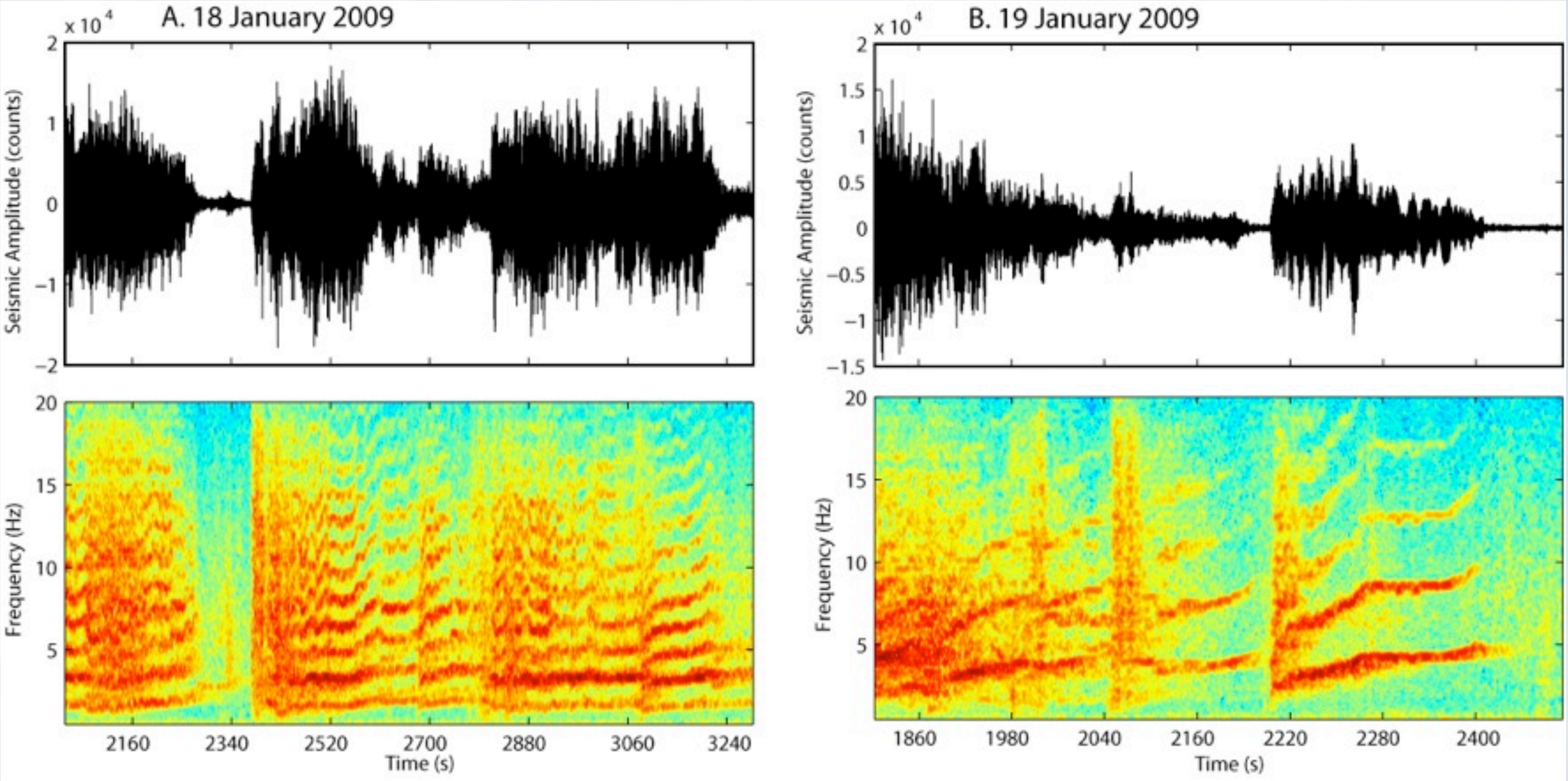

12 January 2009, Fuego, Guatemala

HARMONIC TREMOR

- A simple harmonic resonator (organ pipe) model:
  - $f_0 = v/2L$ (Hagerty, 2000)
    - where v is the speed of the interface wave
    - L is the length of the resonator
- nonlinear change in density at gas exsolution front acts as lower boundary

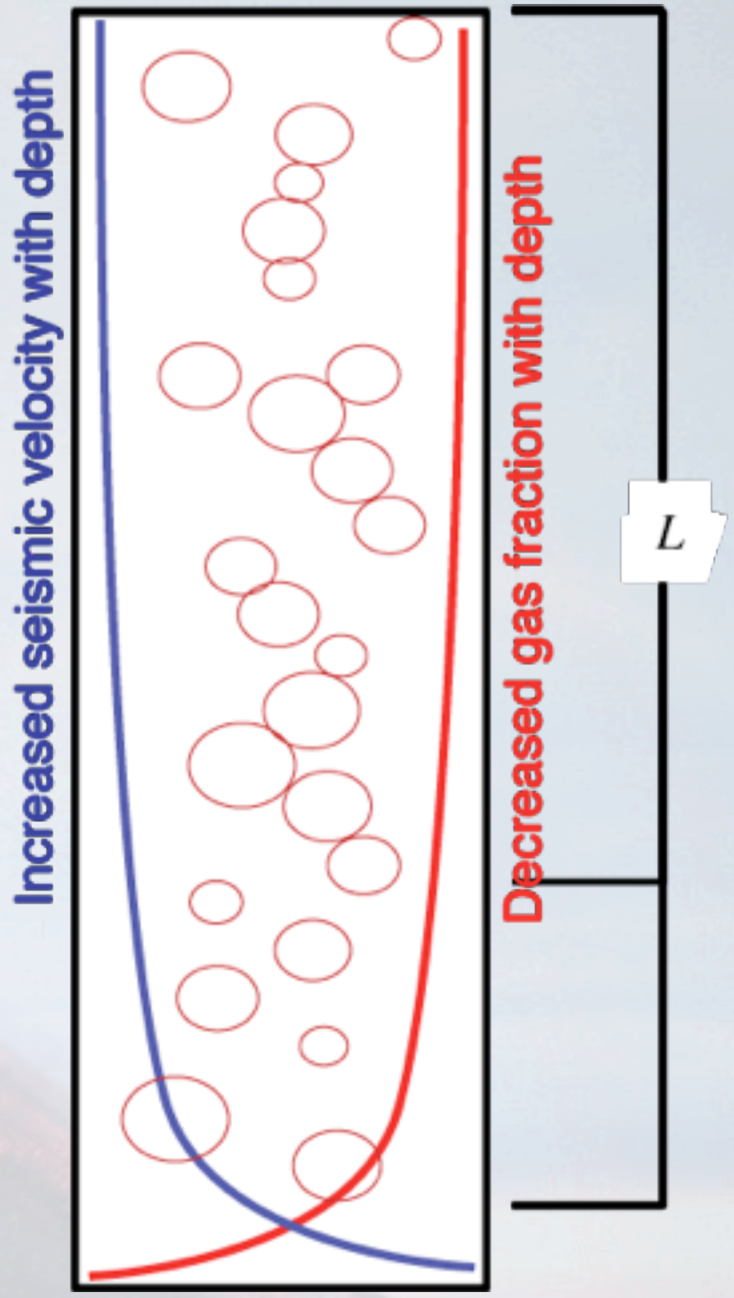


HARMONIC TREMOR GLIDE, FUEGO GUATEMALA



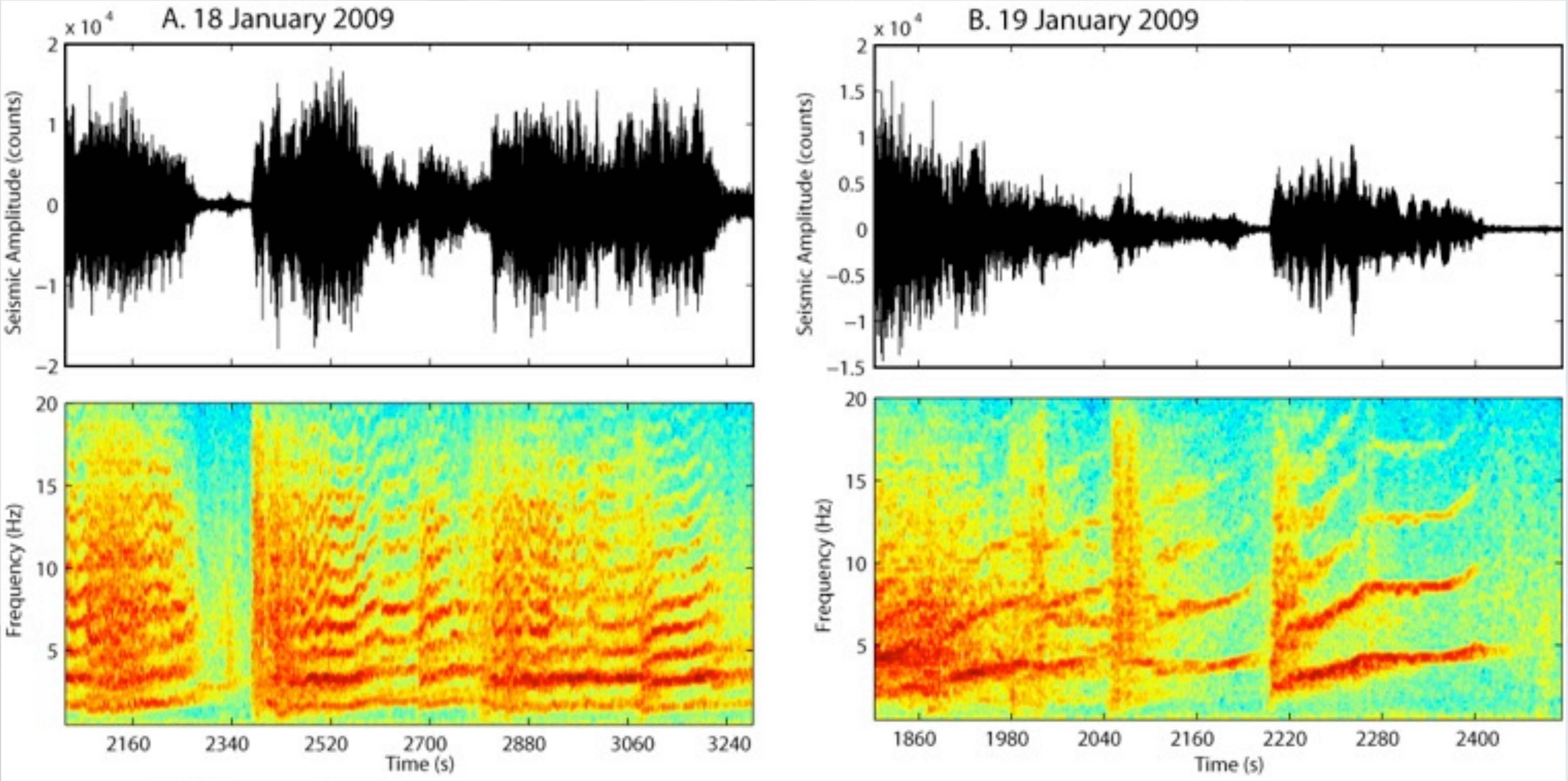
- Harmonic tremor with up to 10 harmonics
- Tremor typically glided upward just prior to an explosion over 1-2 minutes
- Fundamental frequency from 2 - 4 Hz
- Amplitude decayed as frequency increased

MODEL FOR TREMOR GLIDE



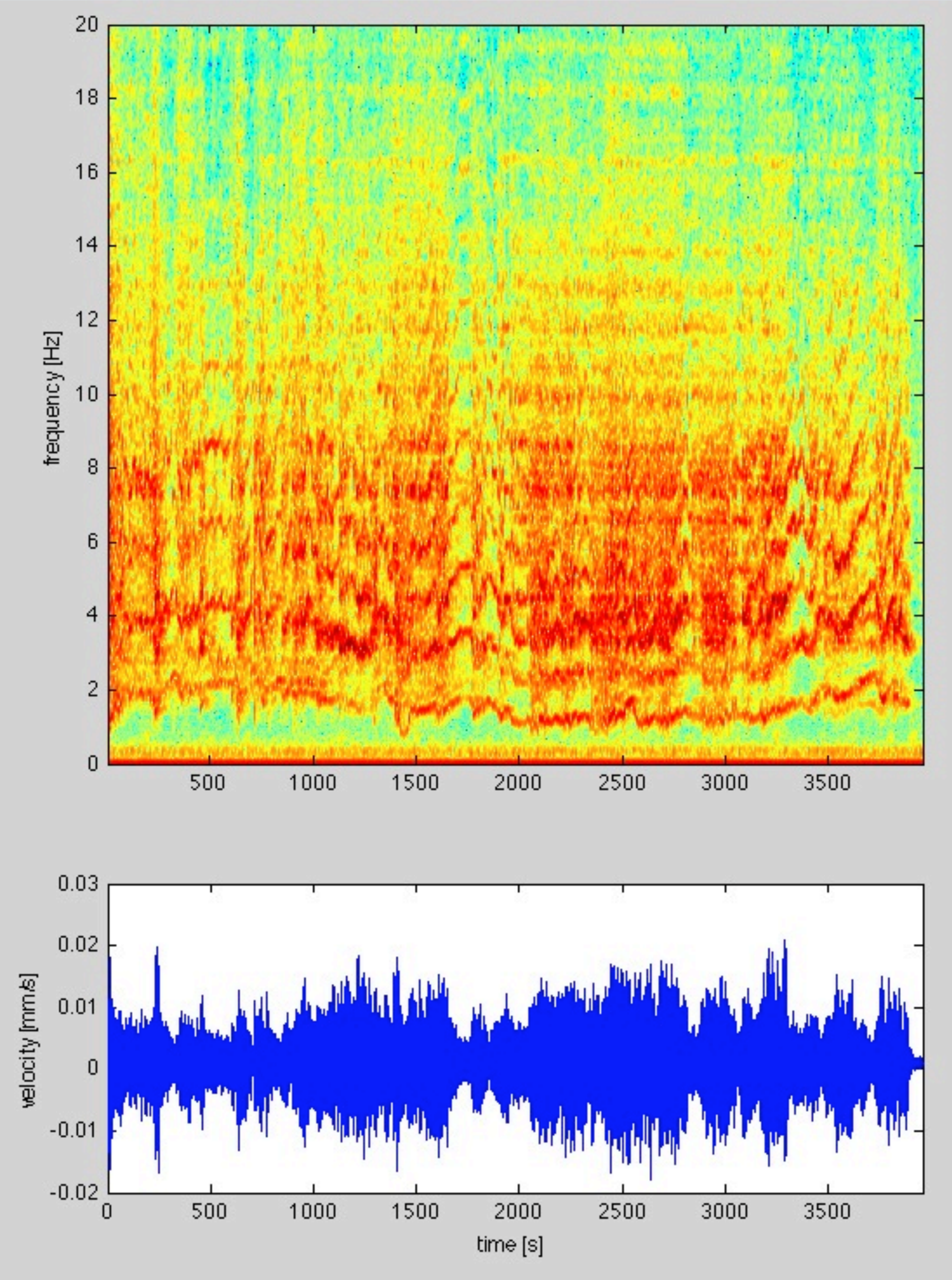
- harmonics that are integer multiples of a fundamental frequency, f_0, suggest a column with matched boundary conditions (closed-closed or open-open)
- $f_0 = v/2L$
- for fixed L, increased f_0 implies increased v
  - rapid dissolution of existing bubbles?
- for fixed v, increased f_0 implies decreased L
  - pressurization of the magma due to sealing could cause exsolution front to migrate upward

A MODEL FOR HARMONIC TREMOR GLIDE

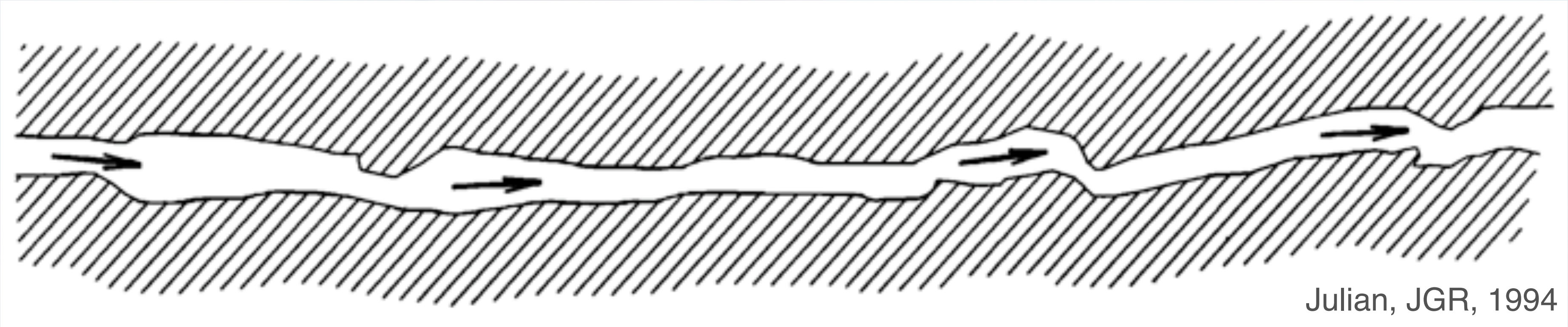


- Gliding could be due to shortening effective length of the conduit
  - For v=400 m/s and f_0=2, L=100 m => f_0=4, L=50 m
  - Implies mobile boundary migrates about 0.4 m/s
- If conduit is sealing, increased pressure could reduce L and increase v

A MOD MOR GLIDE

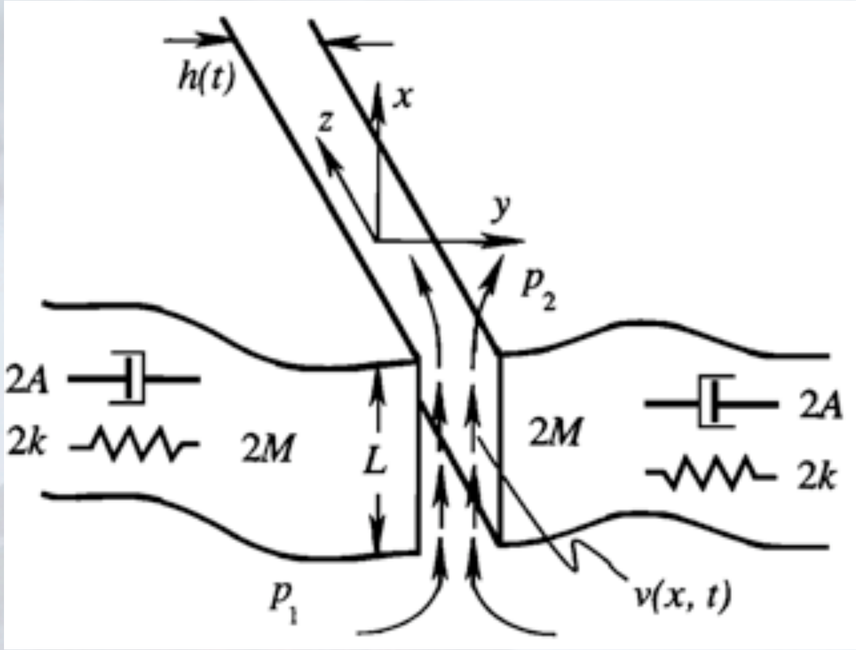


TREMOR DUE TO UNSTABLE FLOW


Julian, JGR, 1994

- Rapid fluid flow through a constriction in the conduit can excite harmonic tremor
  - Consider the sound made by the slow release of air from a balloon
  - May work for liquid or gas
- Modeled for an incompressible, Newtonian fluid and elastic crack

TREMOR DUE TO UNSTABLE FLOW



Julian, JGR, 1994

- Modeled for an incompressible, Newtonian fluid and elastic crack (Julian, *JGR*, 1994)
    - Pressure difference ($p_1 > p_2$) drives fluid through the constriction
    - walls close due to reduced pressure (Bernoulli effect)
    - narrower constriction reduces flow rate
    - walls open back up due to decreased flow velocity

Some Bubble-Related Tremor Models

- Single bubble oscillation
  - frequency of oscillation depends on radius, r, and fluid pressure, P, and density, ρ:

$$f_o^{\text{single}} = \frac{1}{2\pi}\sqrt{\frac{3P}{\rho r^2}}$$

(van Wijngaarden, 1972)

- Bubble cloud oscillation
  - depends on gas fraction, β, dimension of bubble cloud, L:

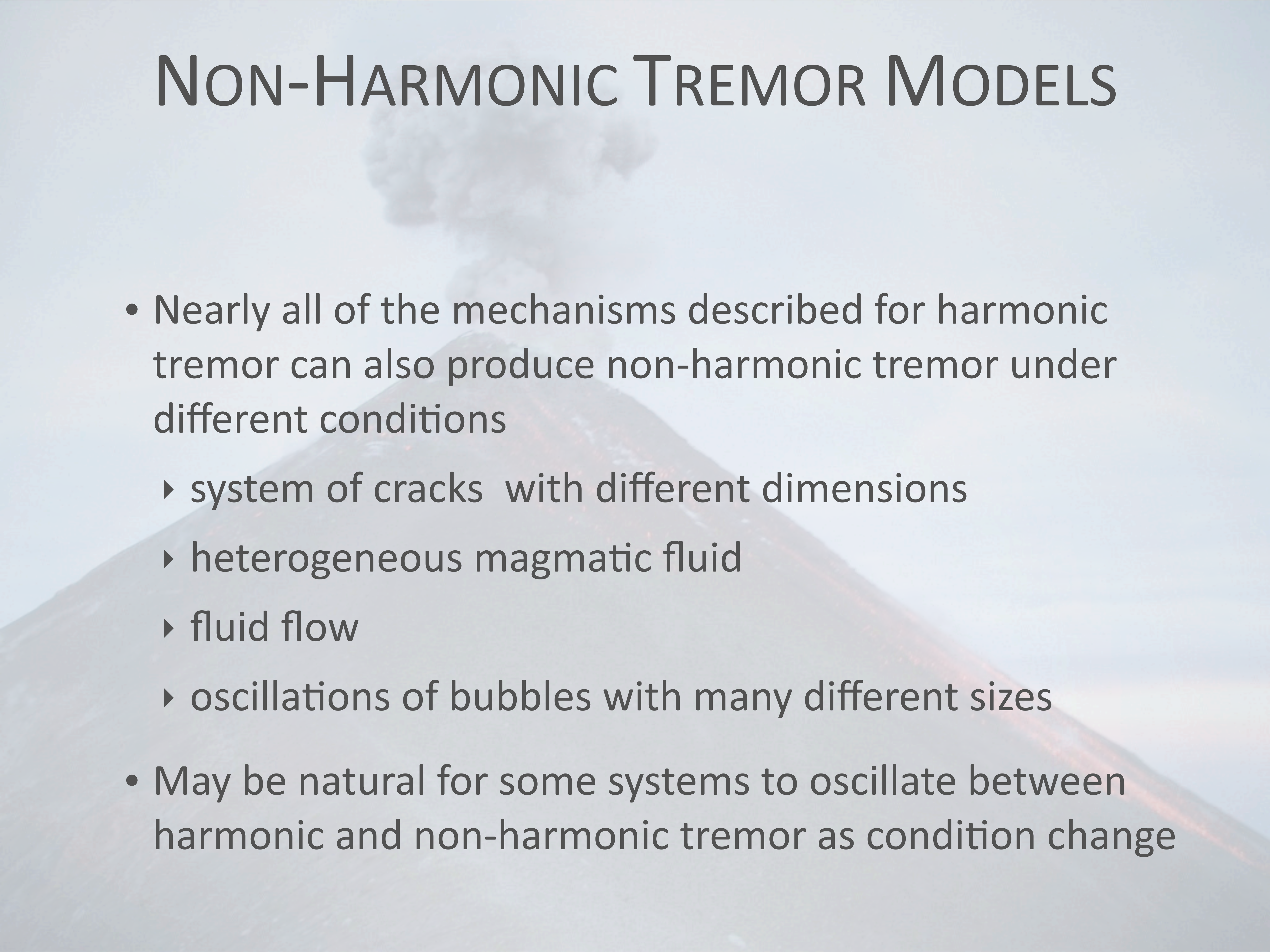
$$f_o^{\text{cloud}} \approx \frac{1}{2L}\sqrt{\frac{P}{\rho\beta}}$$

- Increased numbers of bubbles, N, lowers the frequency:

$$\frac{f_o^{\text{single}}}{f_o^{\text{cloud}}} \approx \beta^{1/6} N^{1/3}$$

(van Wijngaarden, 1972;
Chouet, 1996)

- Example,
  - for r = 1 mm, f_o^{single} ~ 10,000 Hz
  - If N =10^{12}, f_o^{cloud} ~ 2 Hz

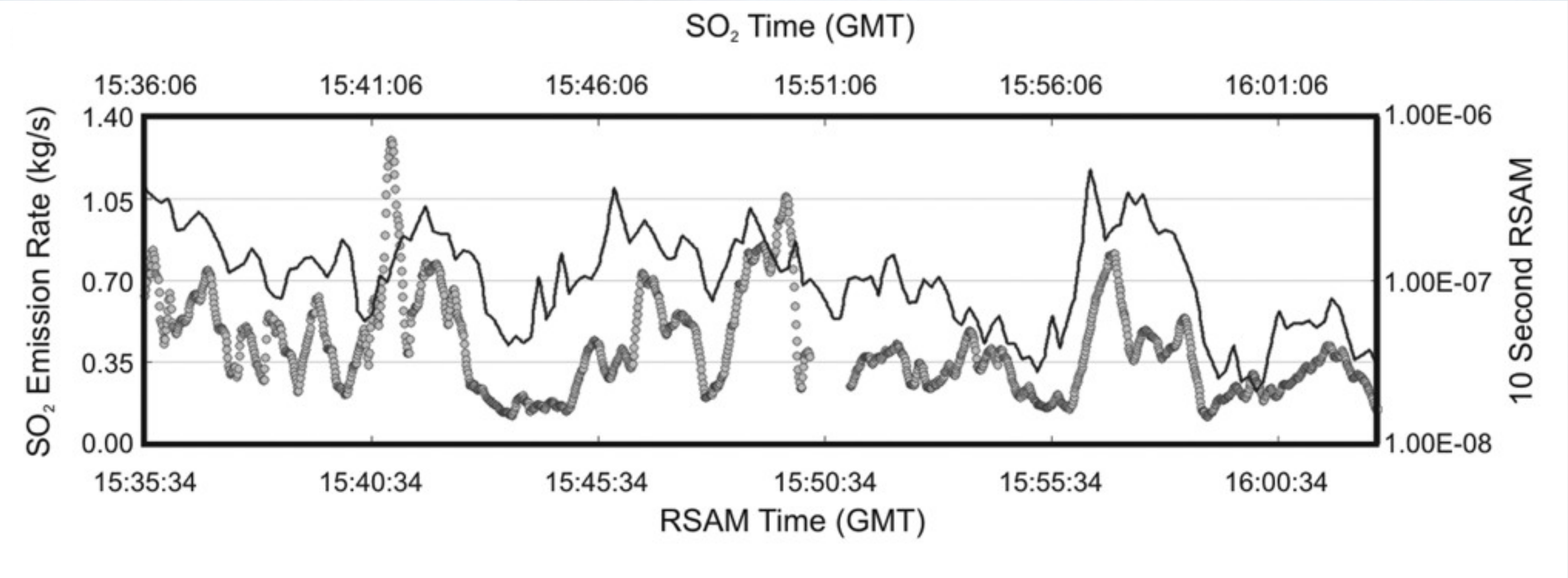


Non-Harmonic Tremor Models

- Nearly all of the mechanisms described for harmonic tremor can also produce non-harmonic tremor under different conditions
    - system of cracks with different dimensions
    - heterogeneous magmatic fluid
    - fluid flow
    - oscillations of bubbles with many different sizes
- May be natural for some systems to oscillate between harmonic and non-harmonic tremor as condition change

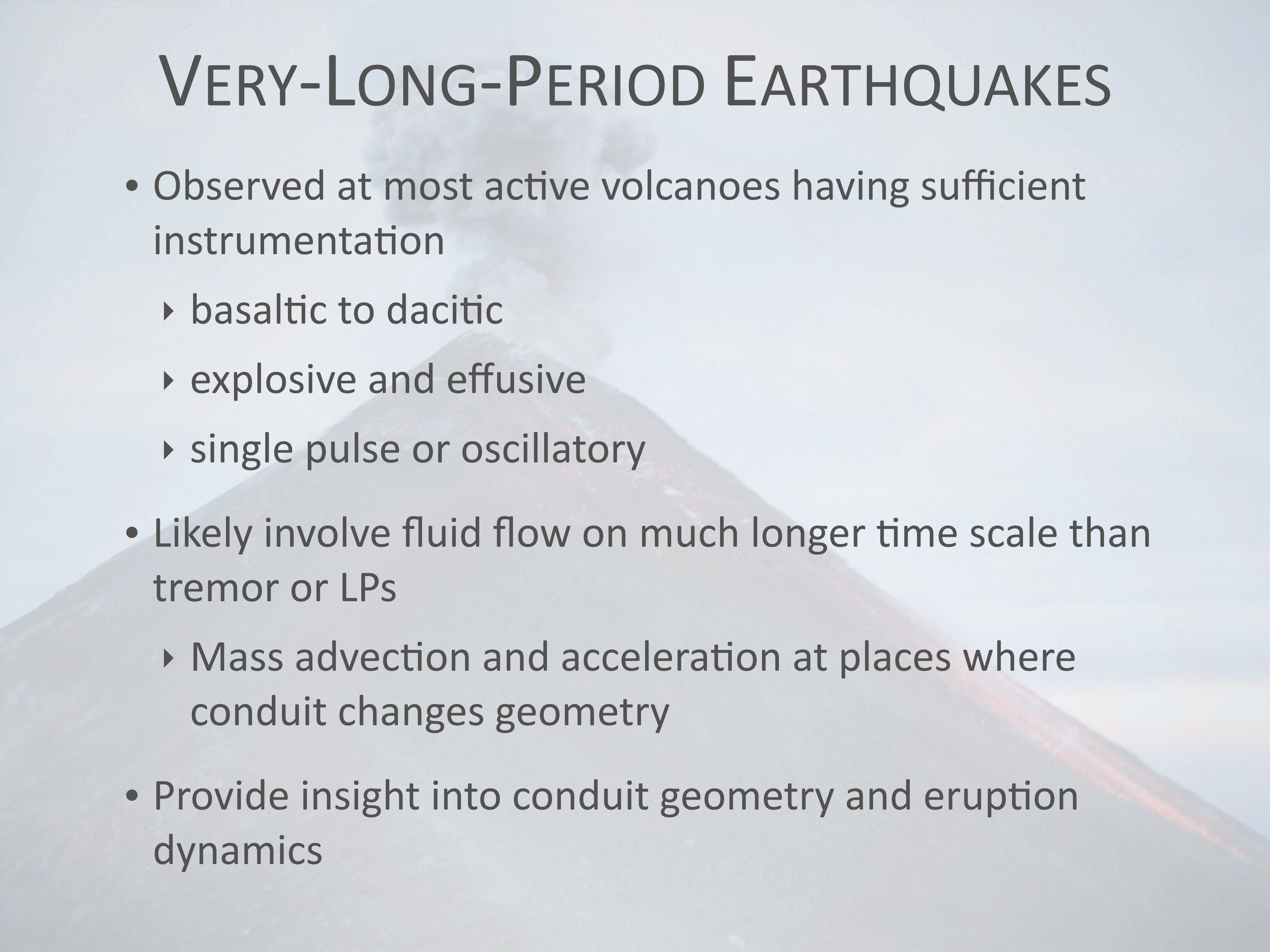
NON-HARMONIC TREMOR MODELS

- Gas is involved with the tremor source in some cases



Nadeau et al., *GRL*, 2011

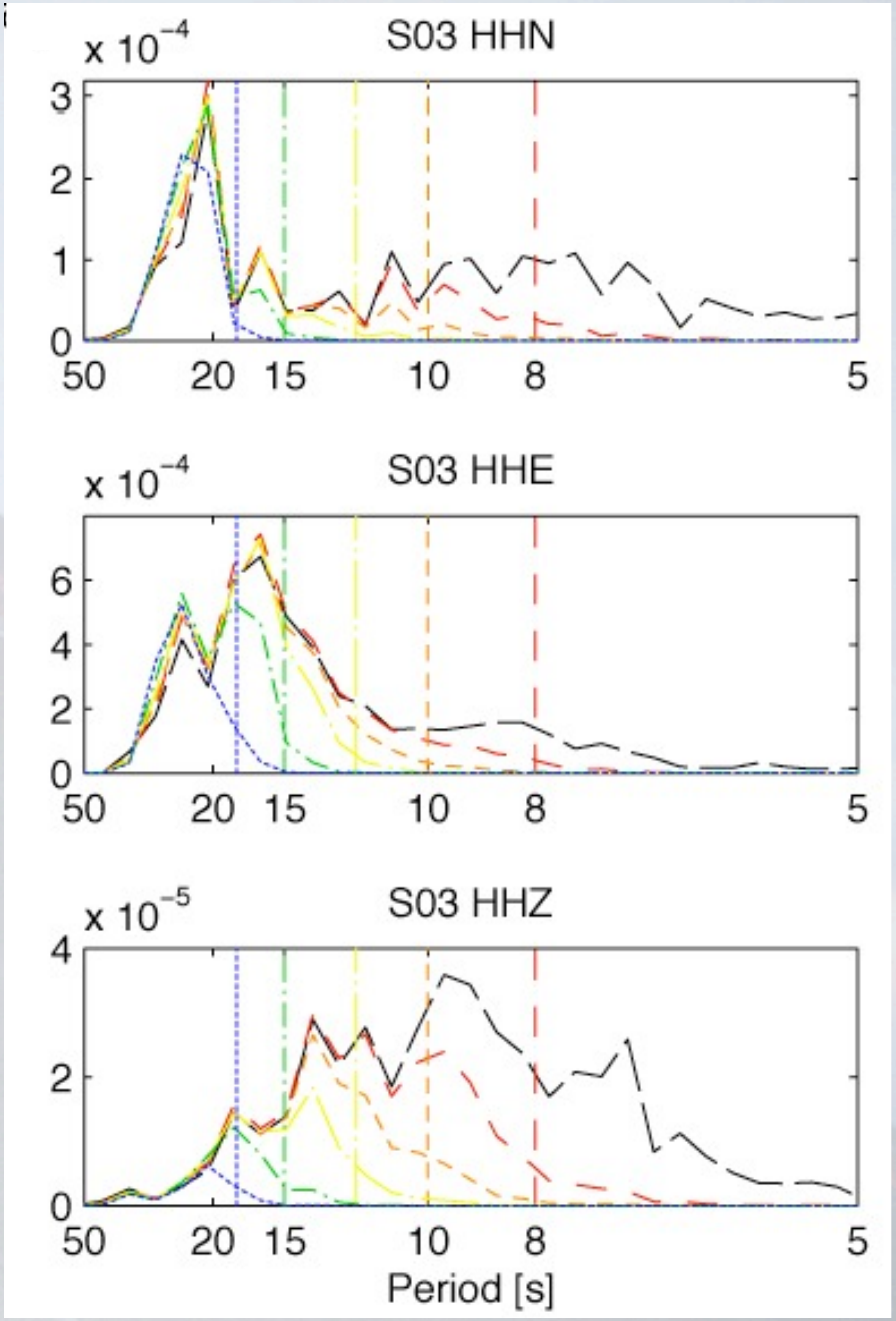
VERY-LONG-PERIOD EARTHQUAKES



- Observed at most active volcanoes having sufficient instrumentation
  - basaltic to dacitic
  - explosive and effusive
  - single pulse or oscillatory
- Likely involve fluid flow on much longer time scale than tremor or LPs
  - Mass advection and acceleration at places where conduit changes geometry
- Provide insight into conduit geometry and eruption dynamics

VERY-LONG-PERIOD EARTHQUAKES

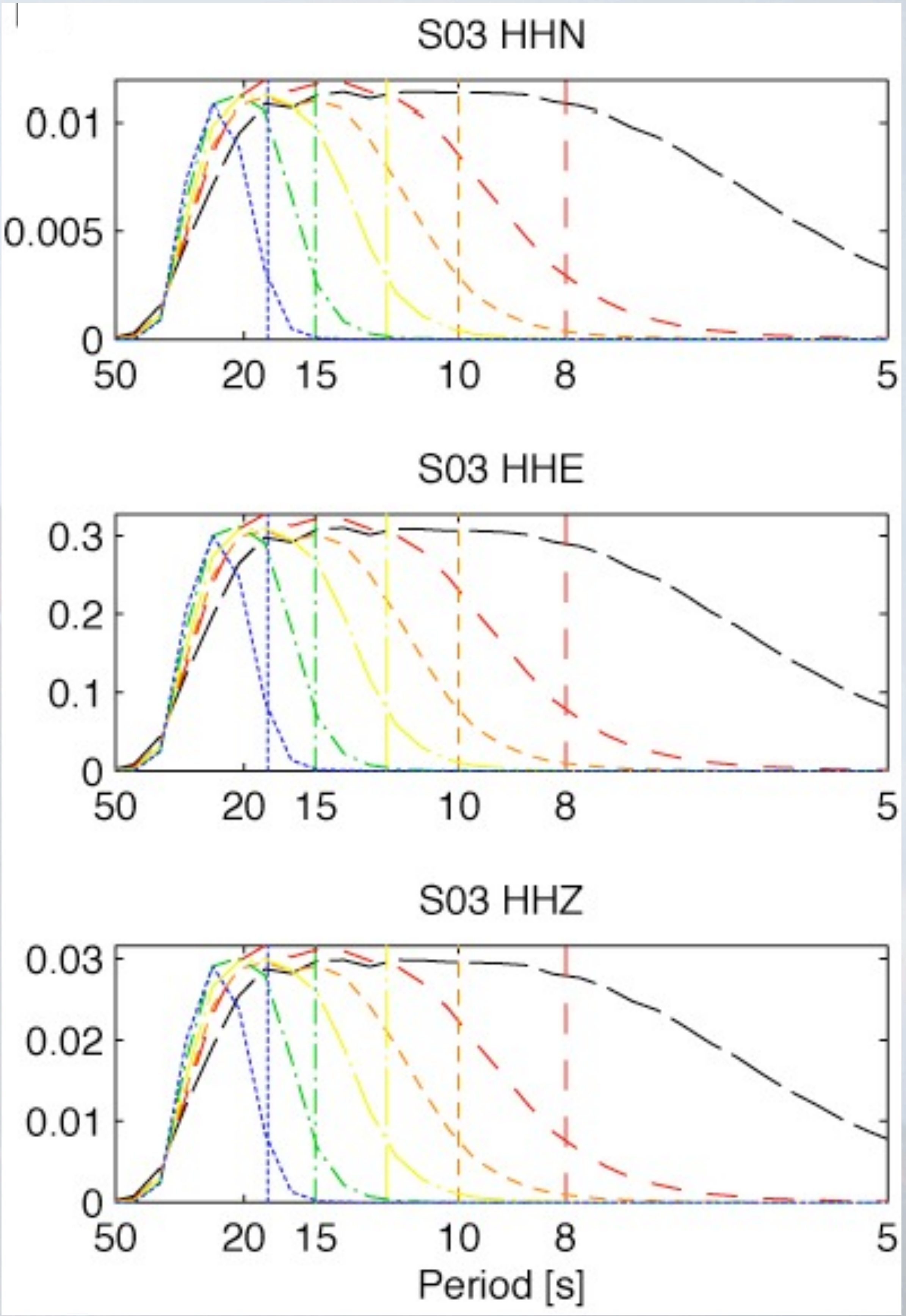
- Easy to identify
  - Use a low-pass or band-pass filter to remove the frequencies above the VLP range
  - If VLP signal is real, it will be largely frequency independent



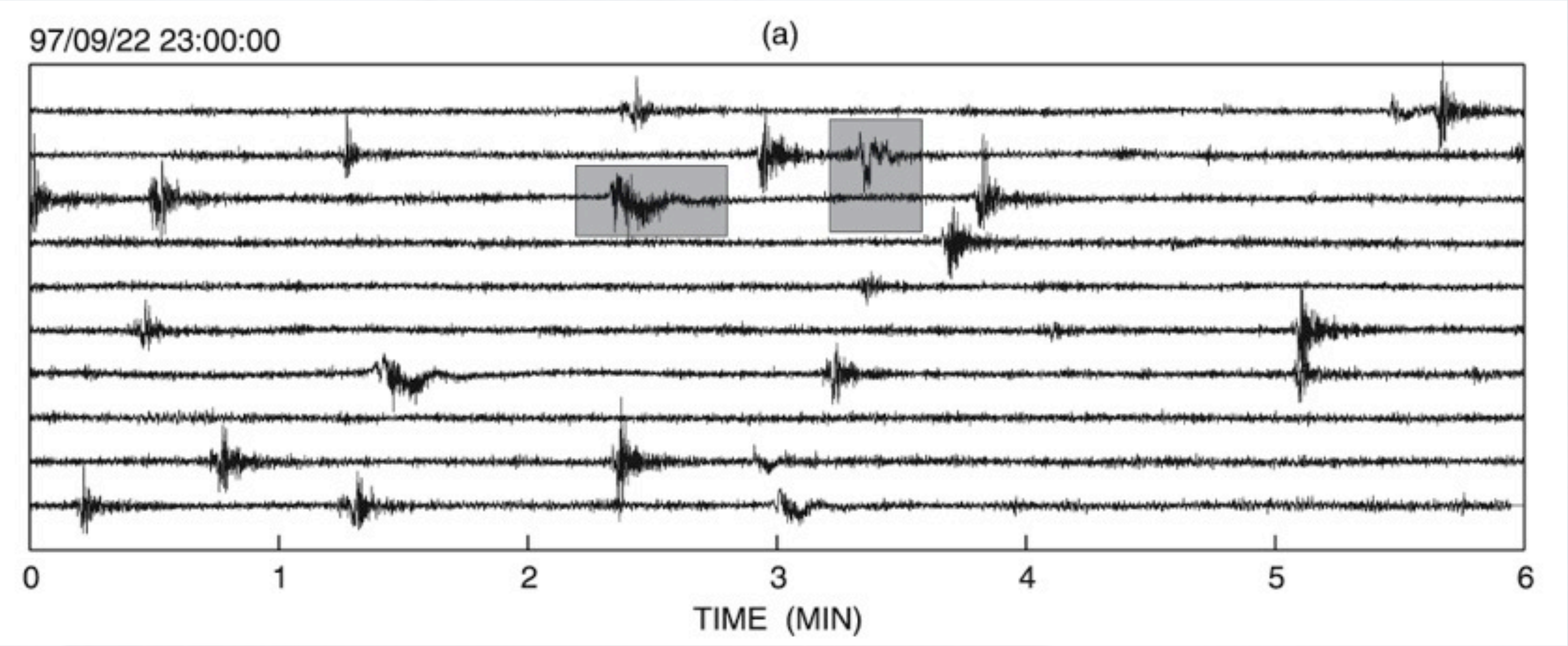
VERY-LONG-PERIOD EARTHQUAKES

- Easy to identify
  - Use a low-pass or band-pass filter to remove the frequencies above the VLP range
  - If VLP signal is real, it will be largely frequency independent

- Pitfalls
  - step-response will look like VLP when filtered
  - tilt can look like VLP signal



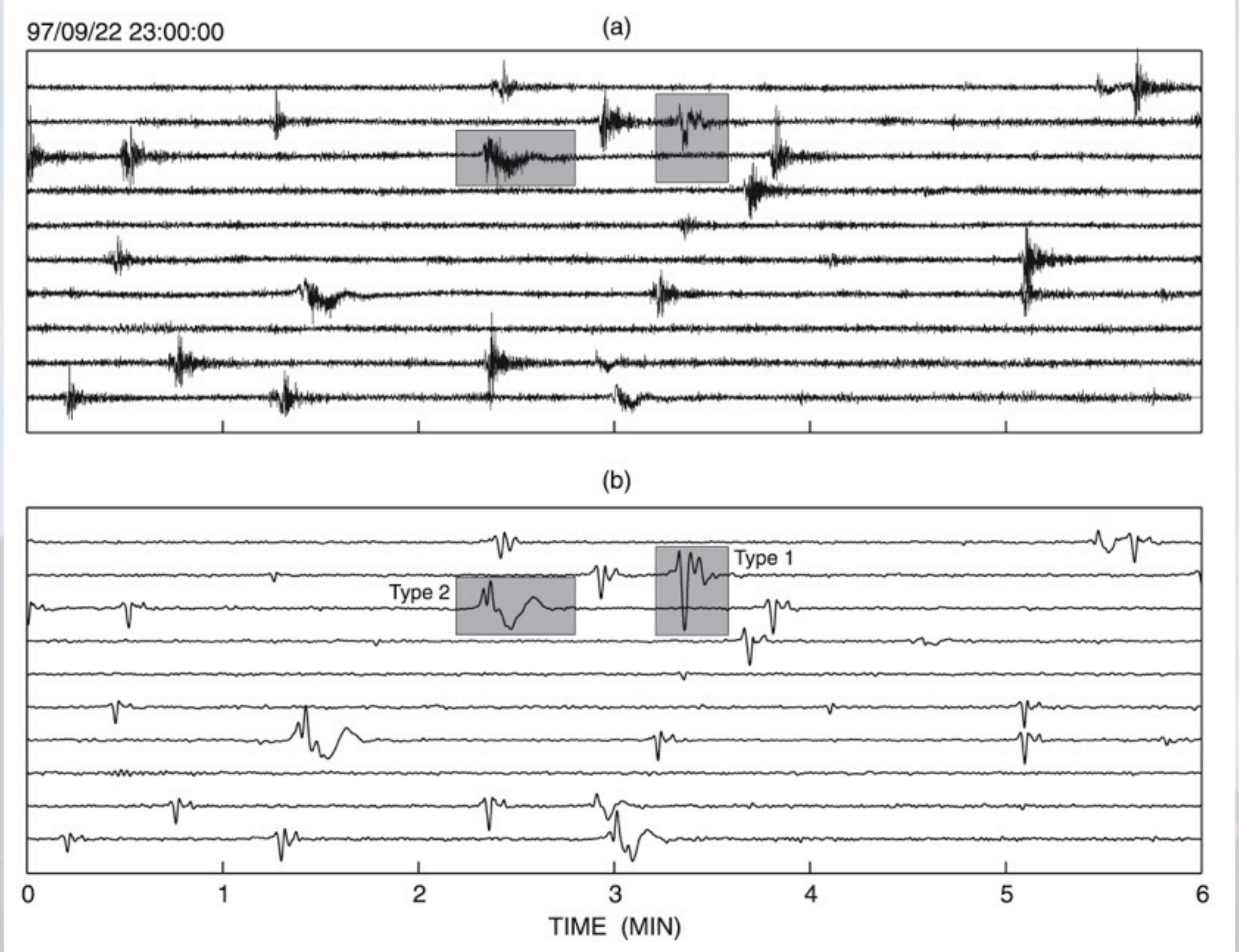
VLPs at Stromboli



- Broadband signals associated with strombolian explosions at Stromboli
- Two types associated with two different vents
- Clearly have a VLP component

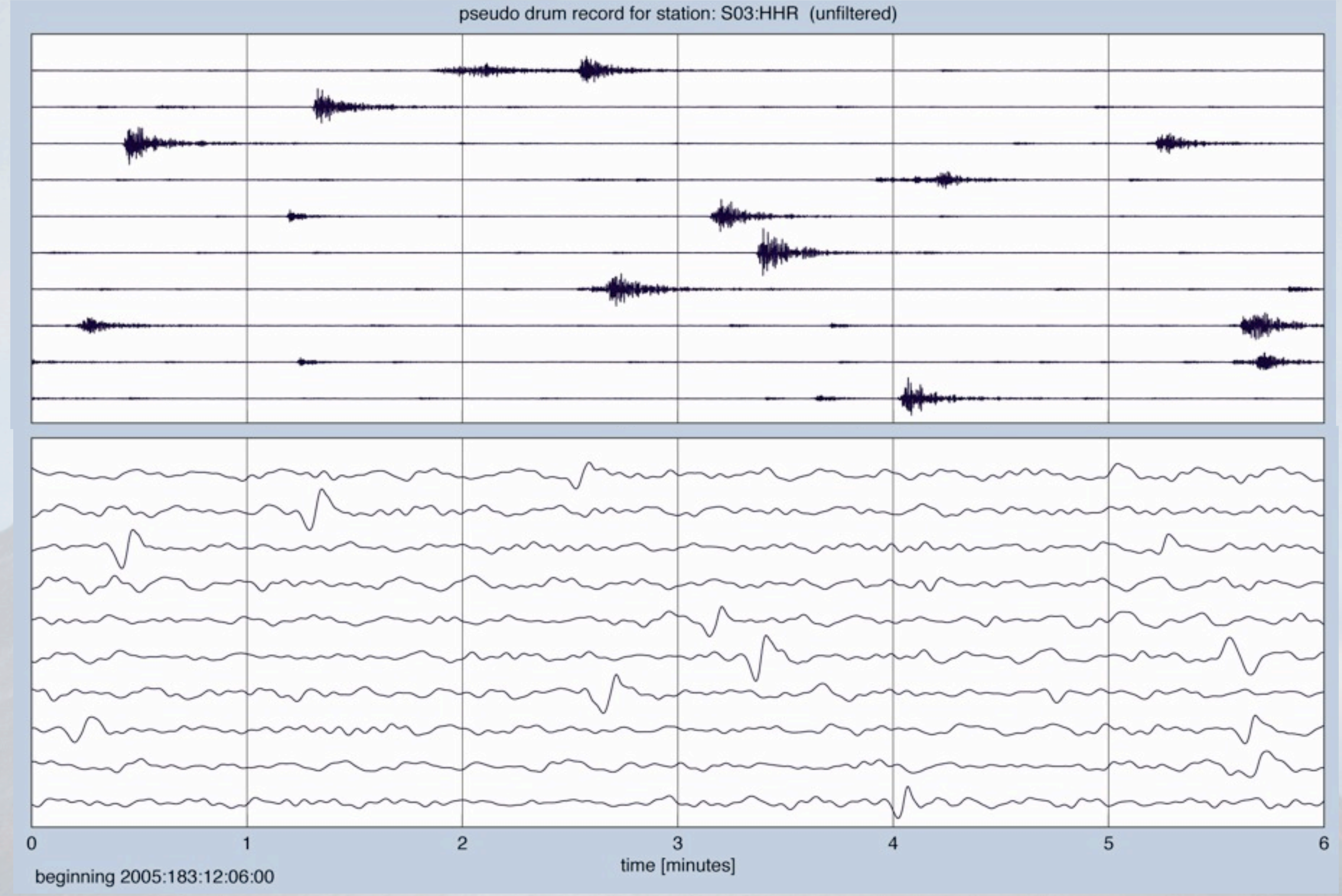
Chouet et al., *JGR*, 2003

VLPs at Stromboli

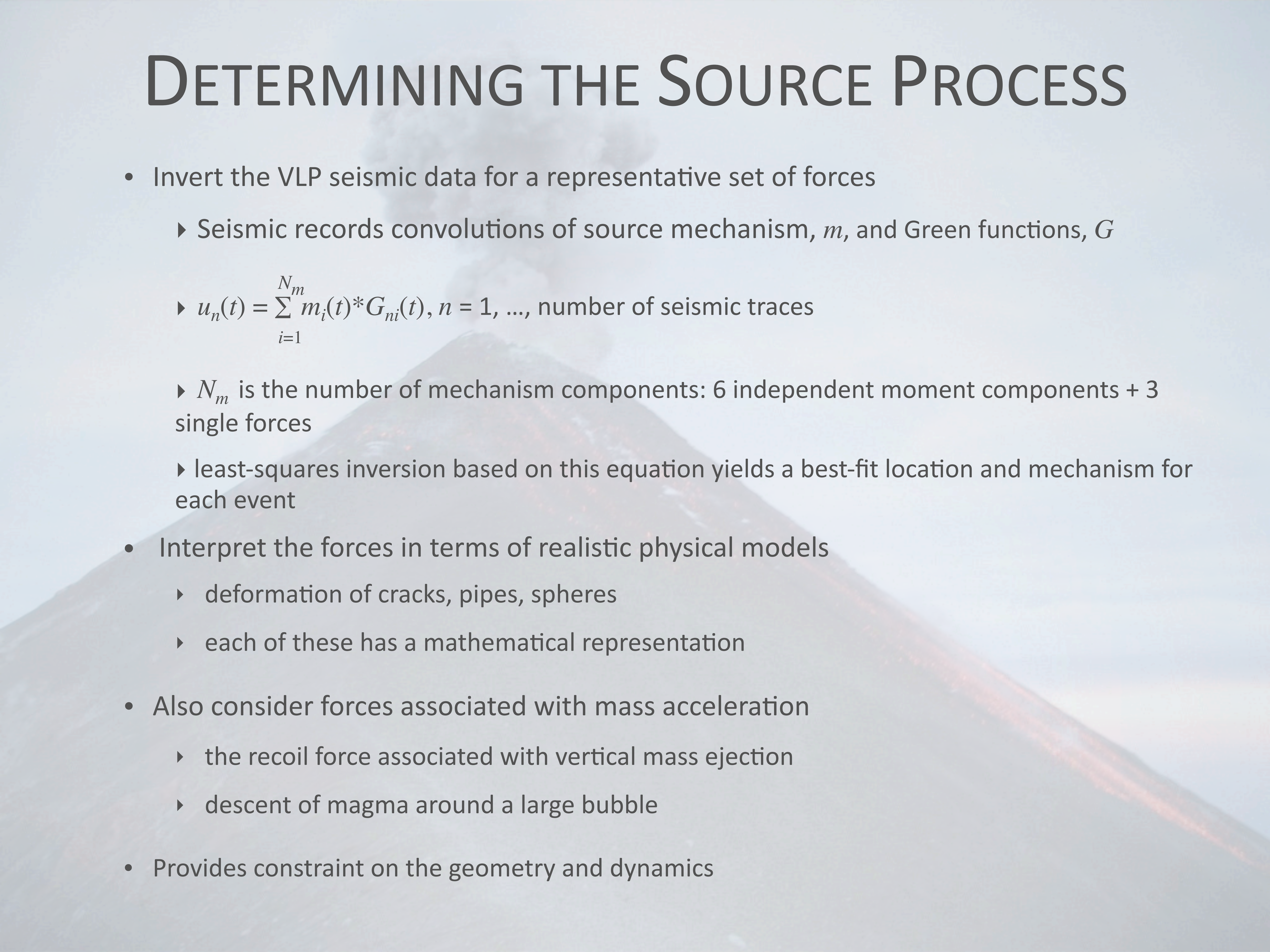


Chouet et al., *JGR*, 2003

VLPs at Mount St. Helens



Waite et al., *JGR*, 2003

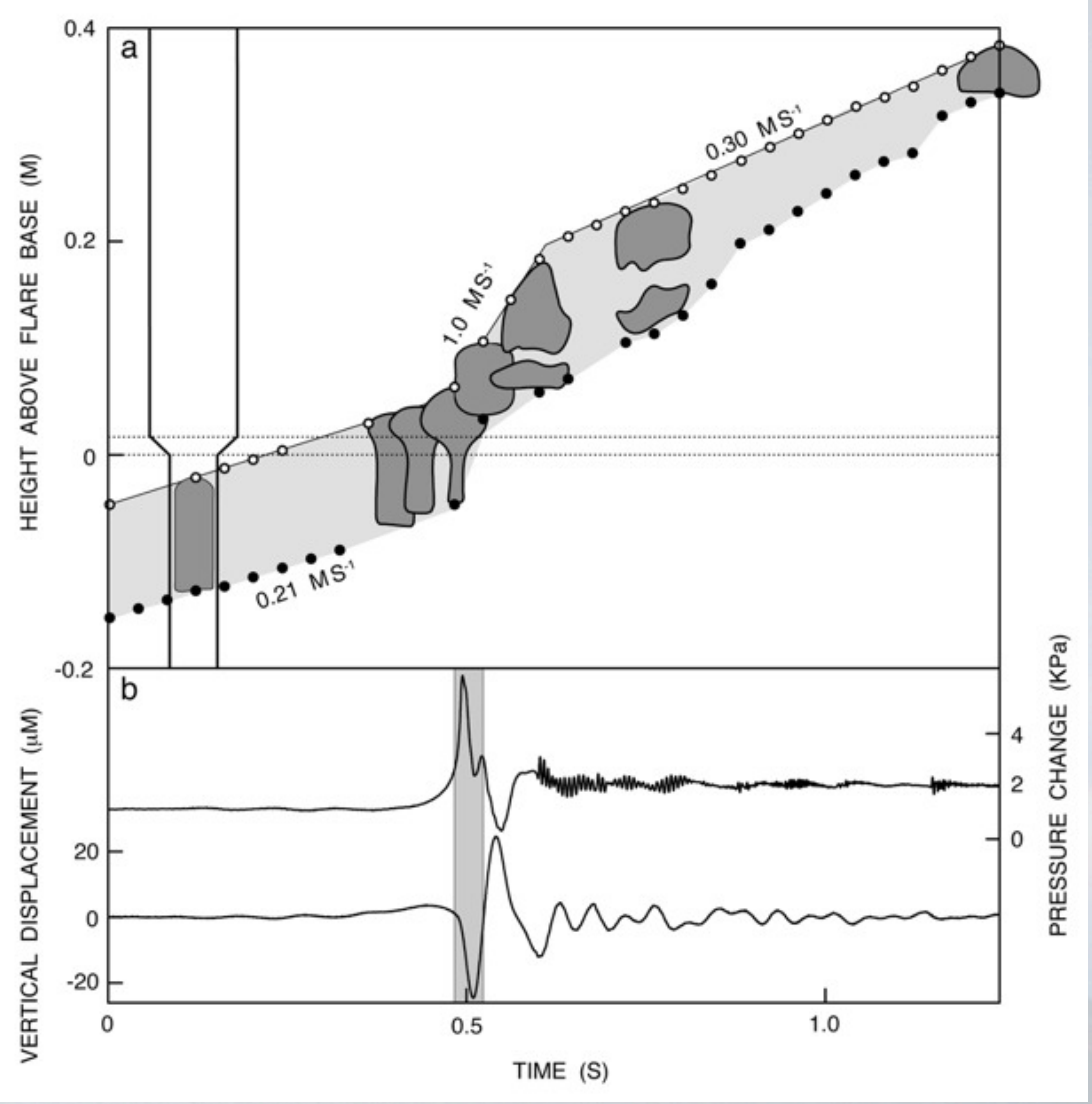


DETERMINING THE SOURCE PROCESS

- Invert the VLP seismic data for a representative set of forces
  - Seismic records convolutions of source mechanism, m, and Green functions, G
  - $u_n(t) = \sum_{i=1}^{N_m} m_i(t) * G_{ni}(t)$, n = 1, …, number of seismic traces
  - N_m is the number of mechanism components: 6 independent moment components + 3 single forces
  - least-squares inversion based on this equation yields a best-fit location and mechanism for each event
- Interpret the forces in terms of realistic physical models
  - deformation of cracks, pipes, spheres
  - each of these has a mathematical representation
- Also consider forces associated with mass acceleration
  - the recoil force associated with vertical mass ejection
  - descent of magma around a large bubble
- Provides constraint on the geometry and dynamics

VERY-LONG-PERIOD EARTHQUAKE ANALOG

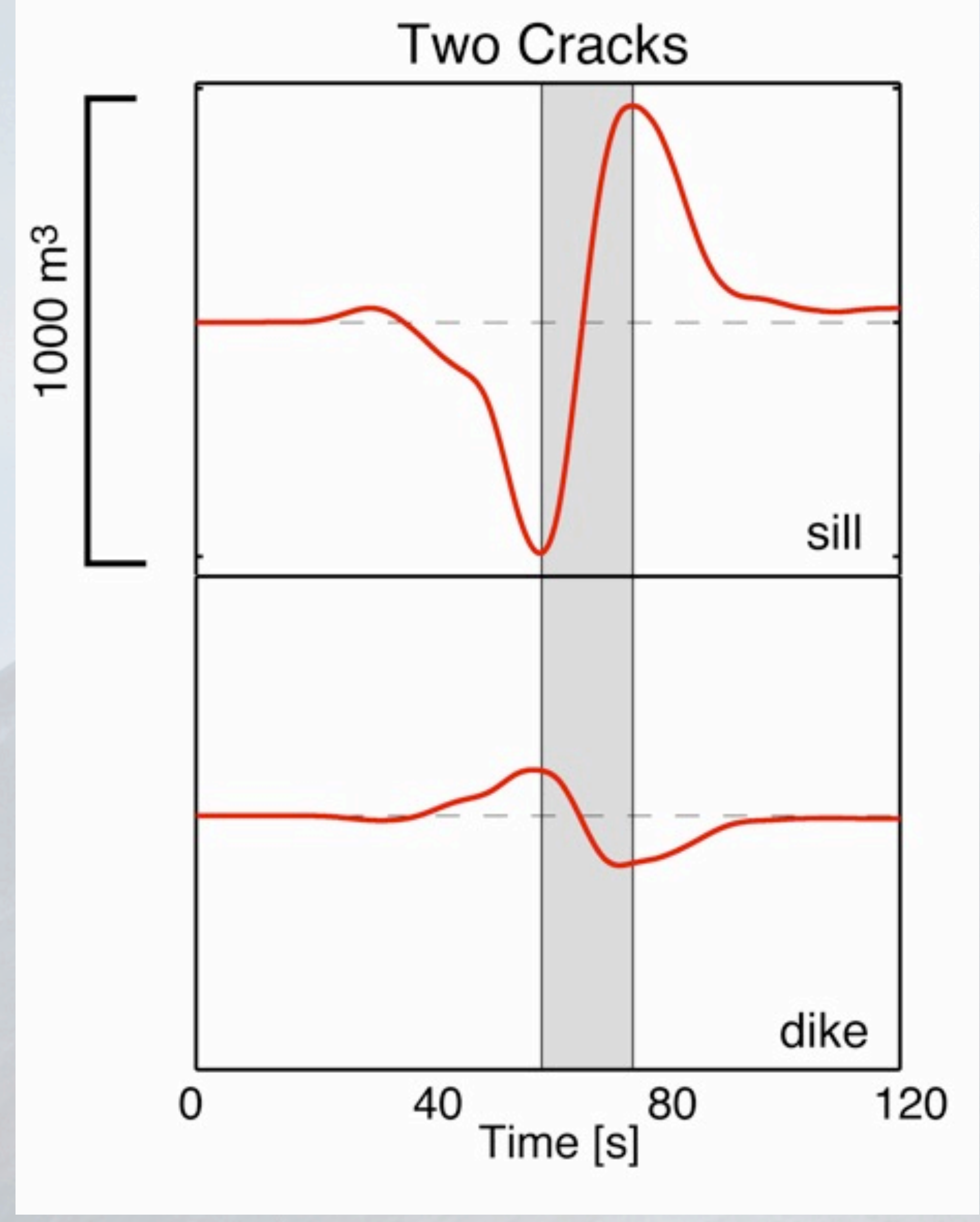
- Bubble accelerates through the flair in the tube
- Liquid annulus falling around the bubble also must accelerate
- Net result is a force (F=ma) that can be translated to the surrounding rock

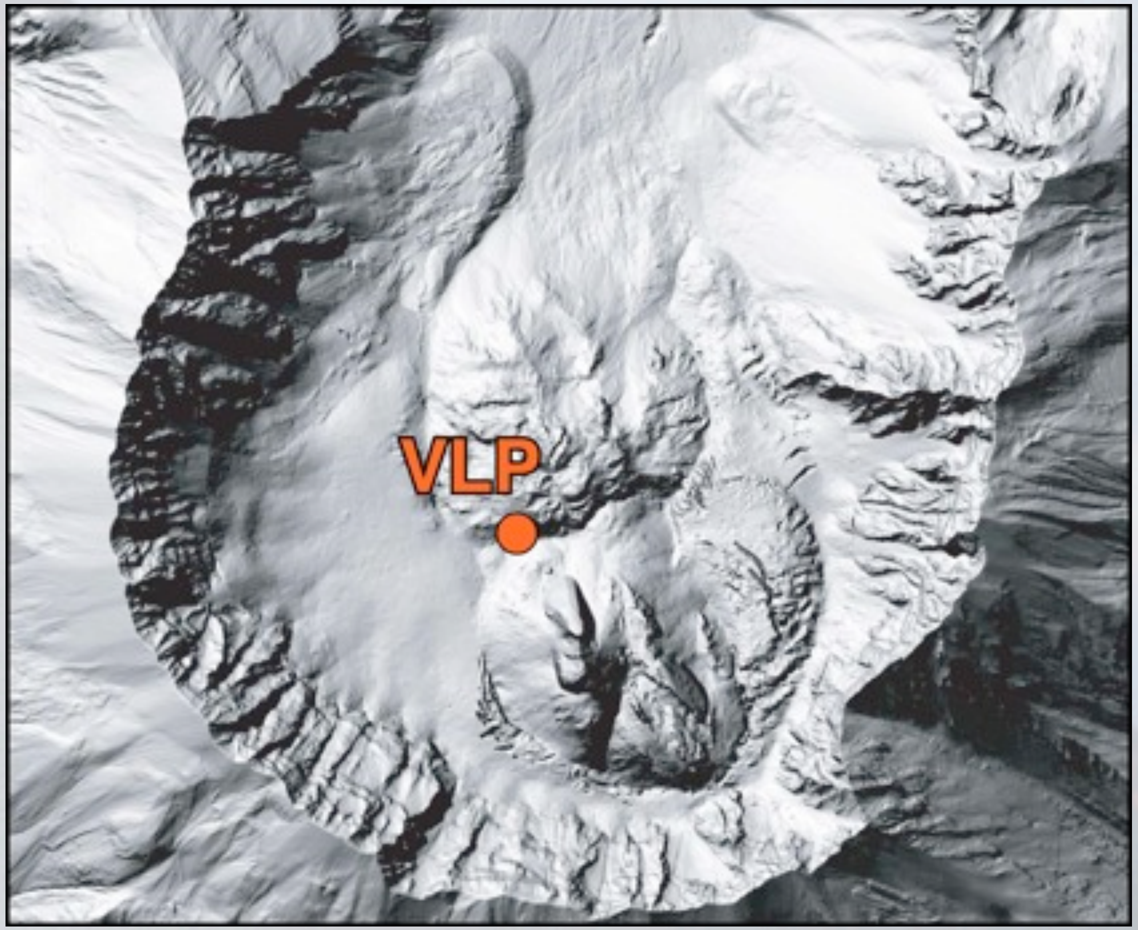


James et al, *JGR*, 2006

VLP SOURCE-TIME FUNCTION

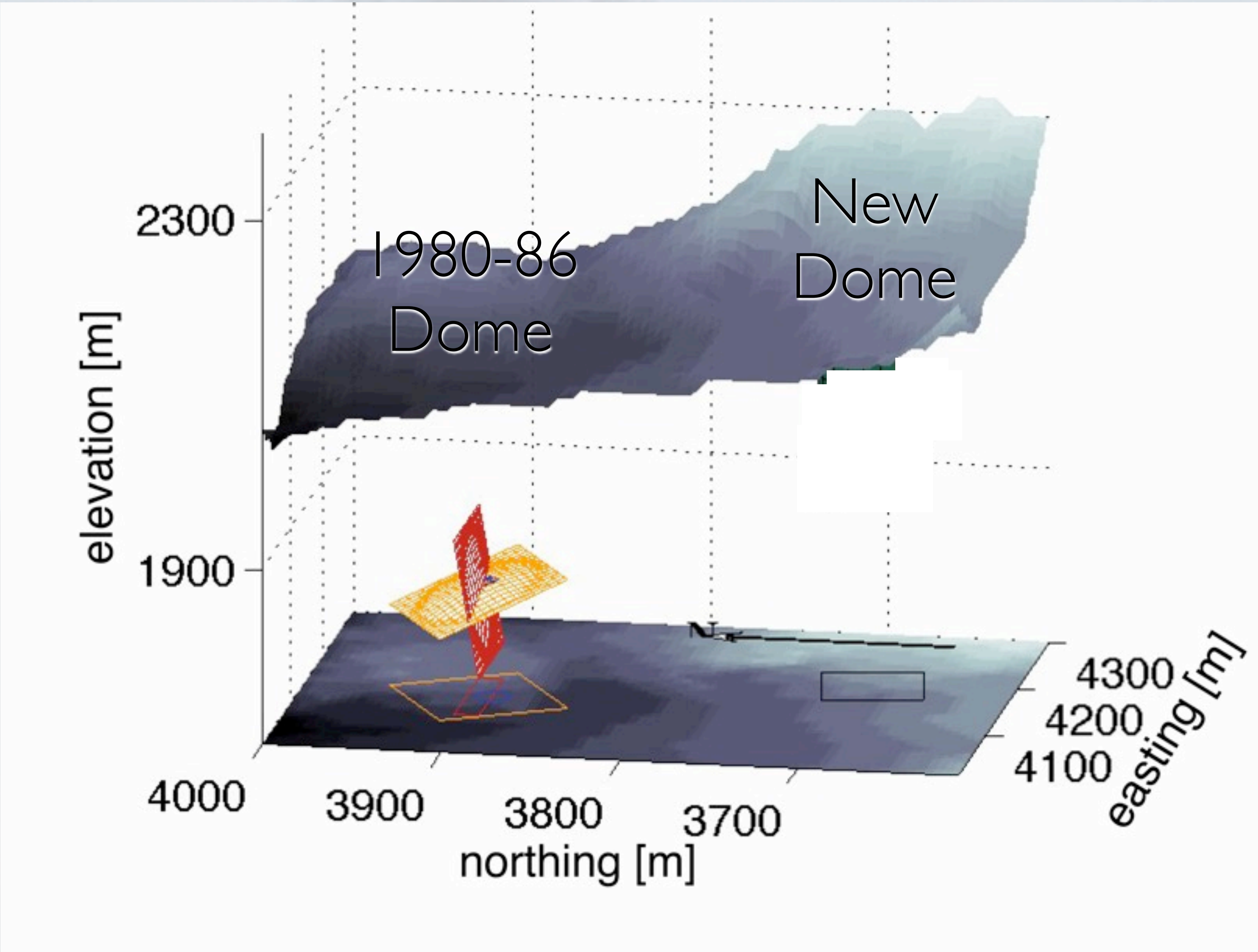
Mount St. Helens 2 July 2005 at 13:29 UTC





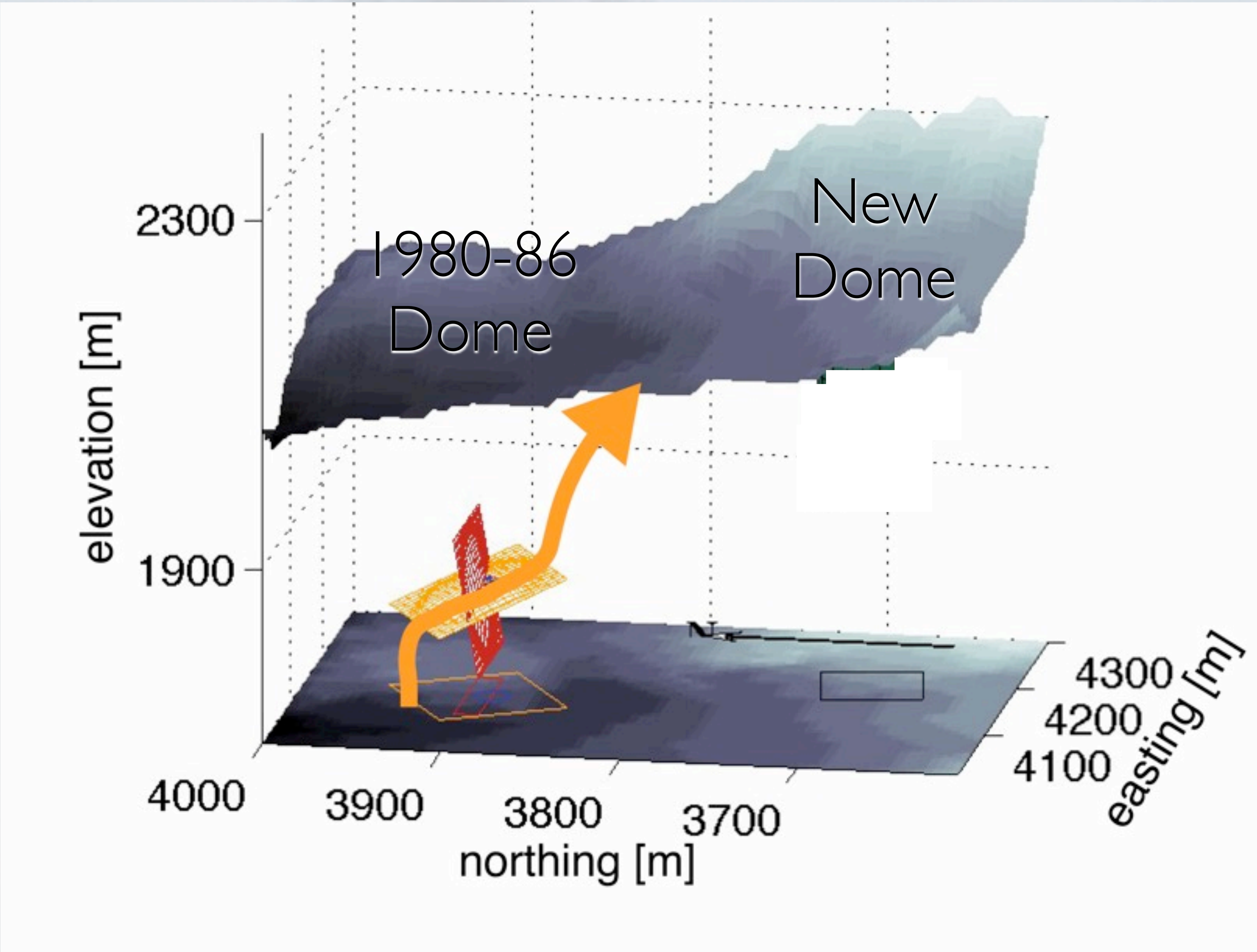
PERSPECTIVE VIEW OF TWO CRACKS

Mount St. Helens

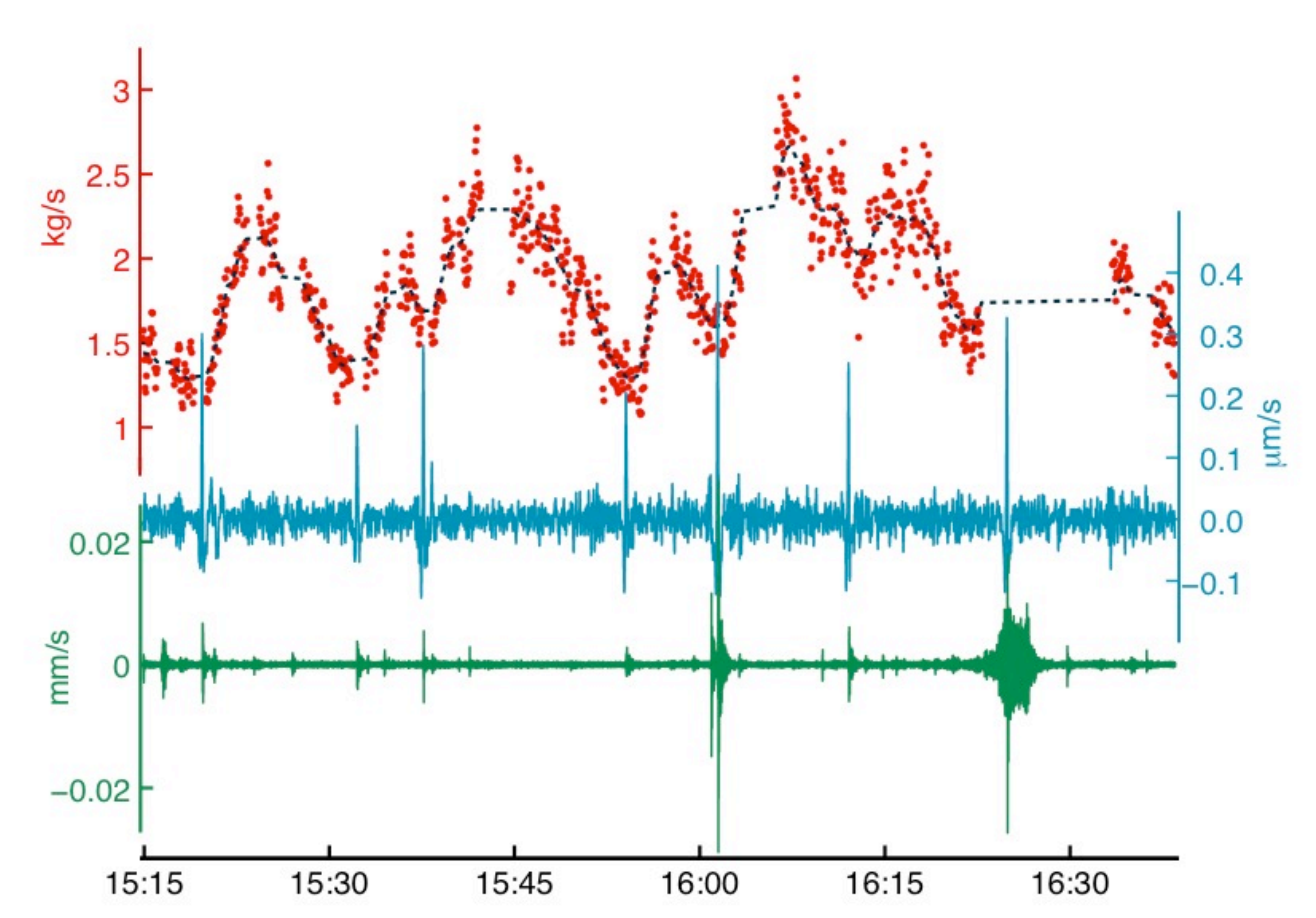


PERSPECTIVE VIEW OF TWO CRACKS

Mount St. Helens



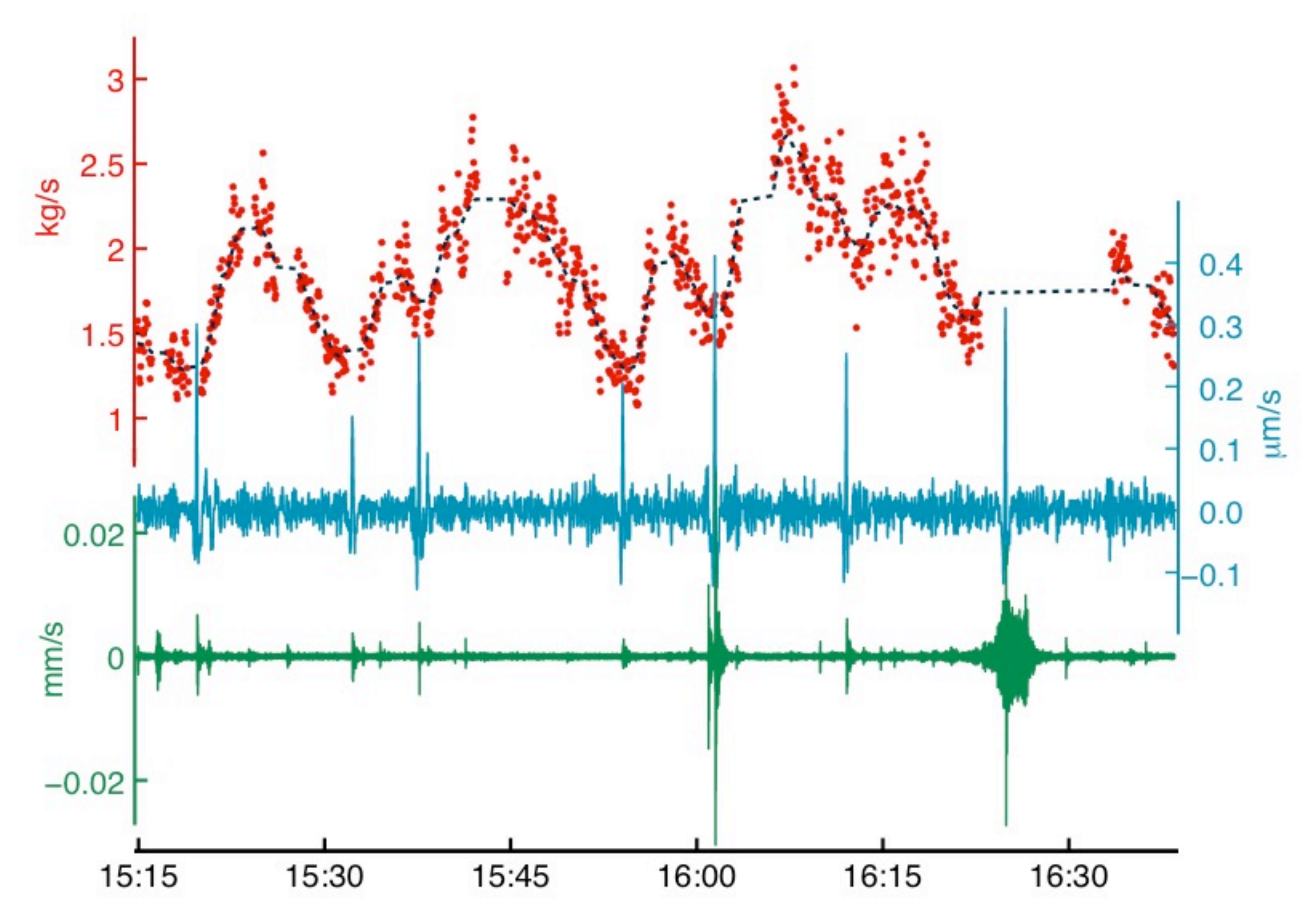
VLPs at Fuego

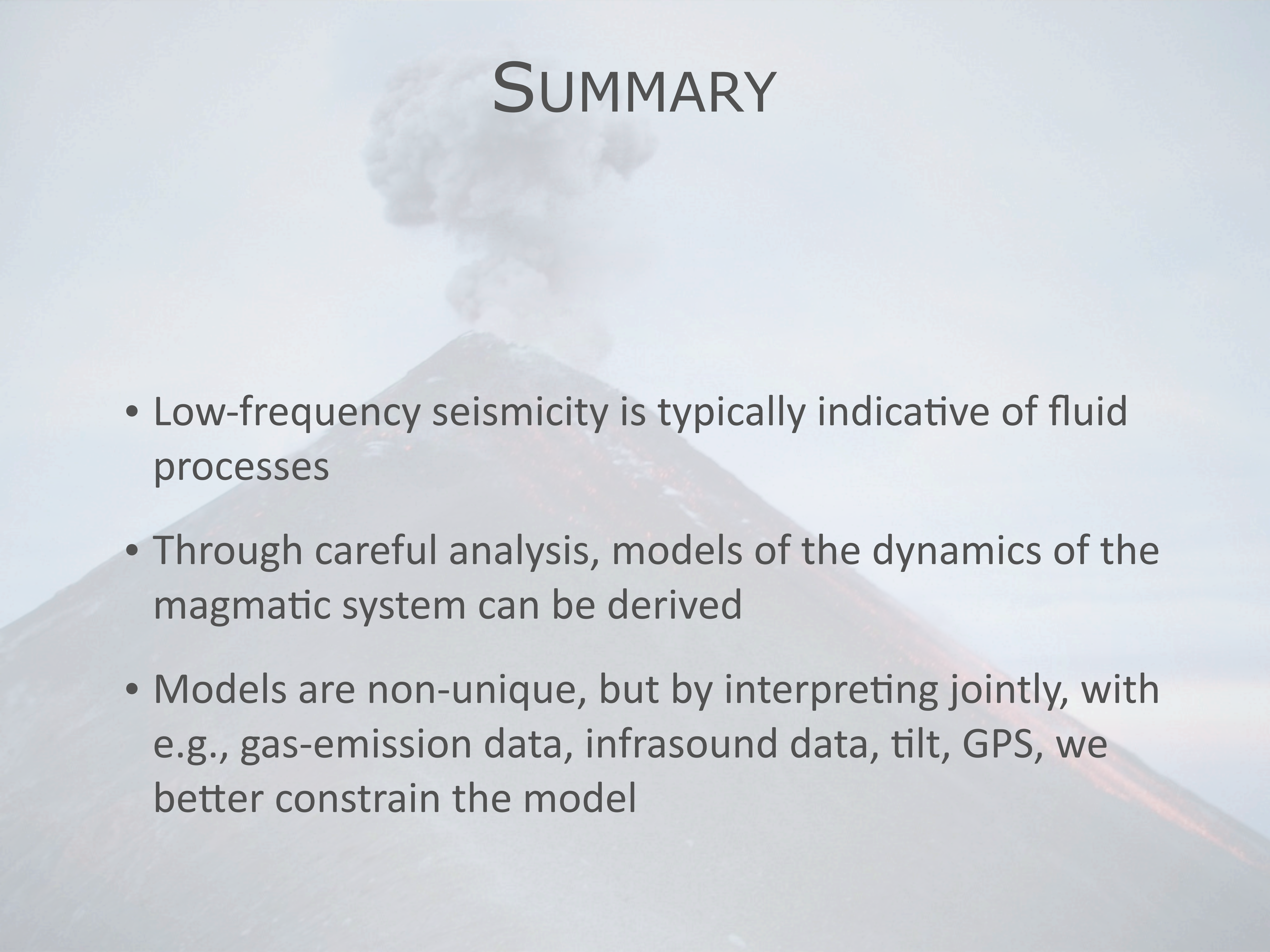


VLPS AT FUEGO

Photo by Gustavo Chigna, INSIVUMEH, March 2008

VLPs at Fuego





SUMMARY

- Low-frequency seismicity is typically indicative of fluid processes
- Through careful analysis, models of the dynamics of the magmatic system can be derived
- Models are non-unique, but by interpreting jointly, with e.g., gas-emission data, infrasound data, tilt, GPS, we better constrain the model

ACKNOWLEDGEMENTS

John Lyons, Patricia Nadeau, José Luis Palma, Josh Richardson, Bill Rose, MTU; Bernard Chouet, Phil Dawson, Seth Moran, Haruhisu Nakamchi, Joel Robinson, USGS; Gustavo Chigna, INSIVUMEH; Jeff Johnson, NMT; Jonathan Lees, Jake Anderson, UNC
PASSCAL Instrument Center
Funding from National Science Foundation, USGS