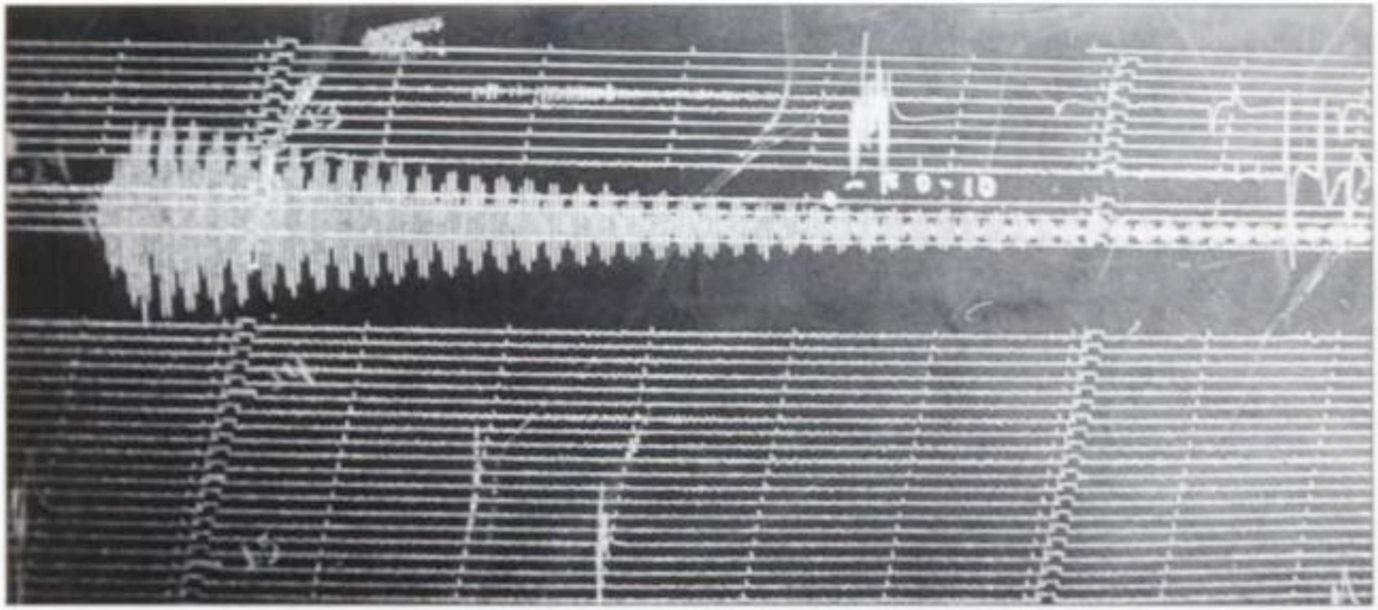


Volcanic Seismicity

Source processes and implications of VT, tremor, LP, VLP and tilt signals at volcanoes

MichiganTech

OUTLINE

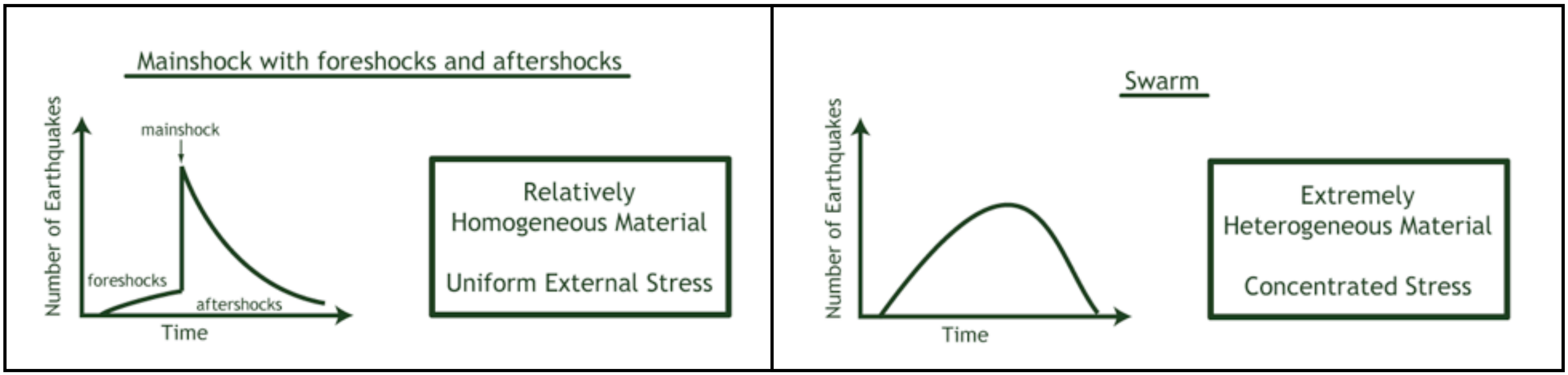
1. Pre-eruption earthquake swarms
   1.1. Characteristics and variability
   1.2. Use for eruption forecasting
2. Event classification and source characterization
   2.1. What are the causes of different signal types
   2.2. Path distortions
3. Emerging methodologies
   3.1. Ambient noise
   3.2. Ground tilt from seismometers

What is the Goal of Seismic Monitoring of Volcanoes?

- Eruption forecasting?
  - Look for patterns in activity that have been seen elsewhere?
  - Model the physics in the conduit using seismic (and complementary) data

ERUPTION FORECASTING

- Nearly every eruption is preceded by an increase in seismicity - an **earthquake swarm**



- Large main earthquake
- Predictable duration of aftershocks based on mainshock magnitude
- Foreshocks are atypical

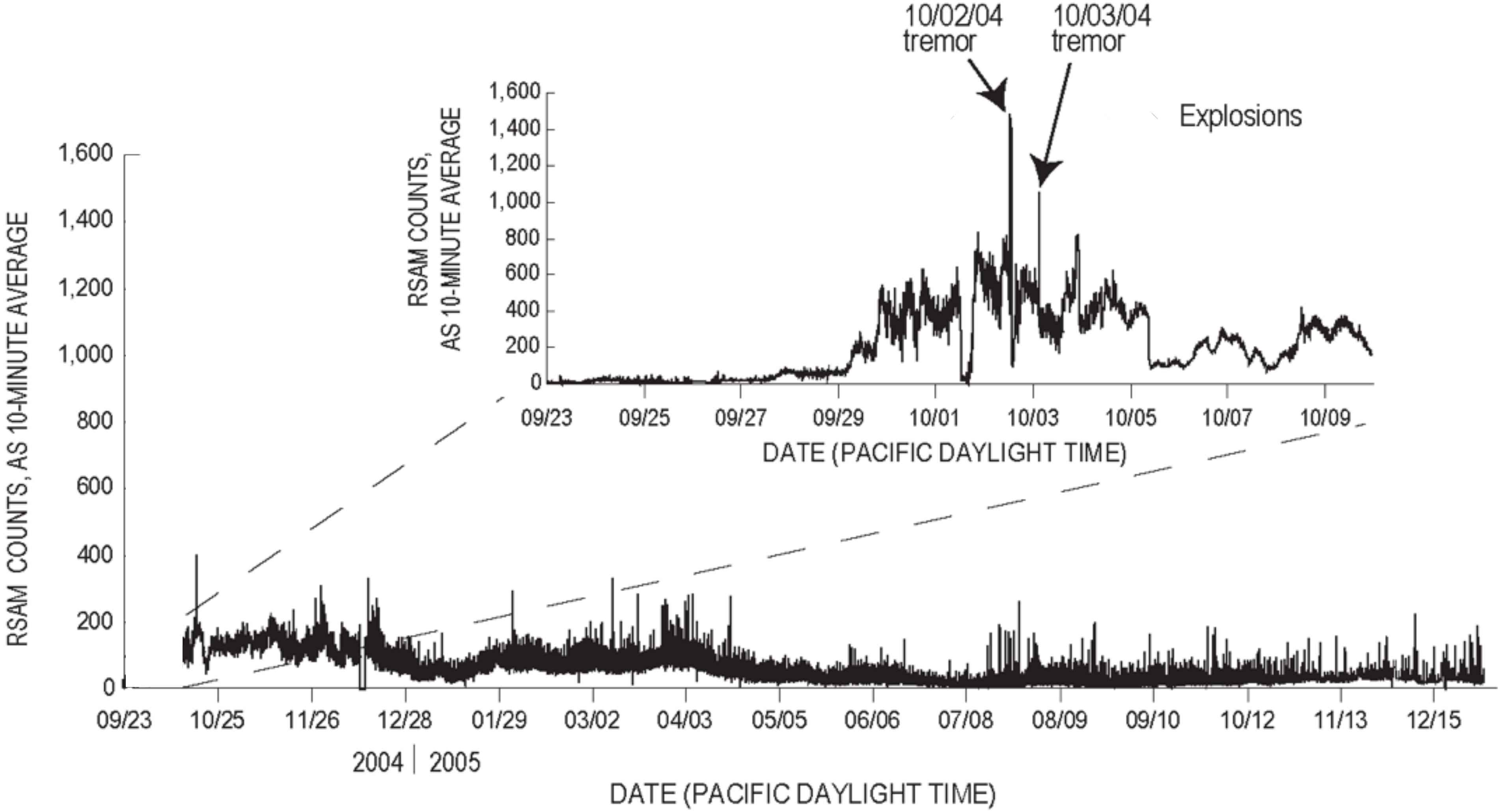
- No distinct mainshock
- Gradual increase and decay of activity
- Duration unpredictable (hours to years)

Mogi, 1963

ERUPTION FORECASTING

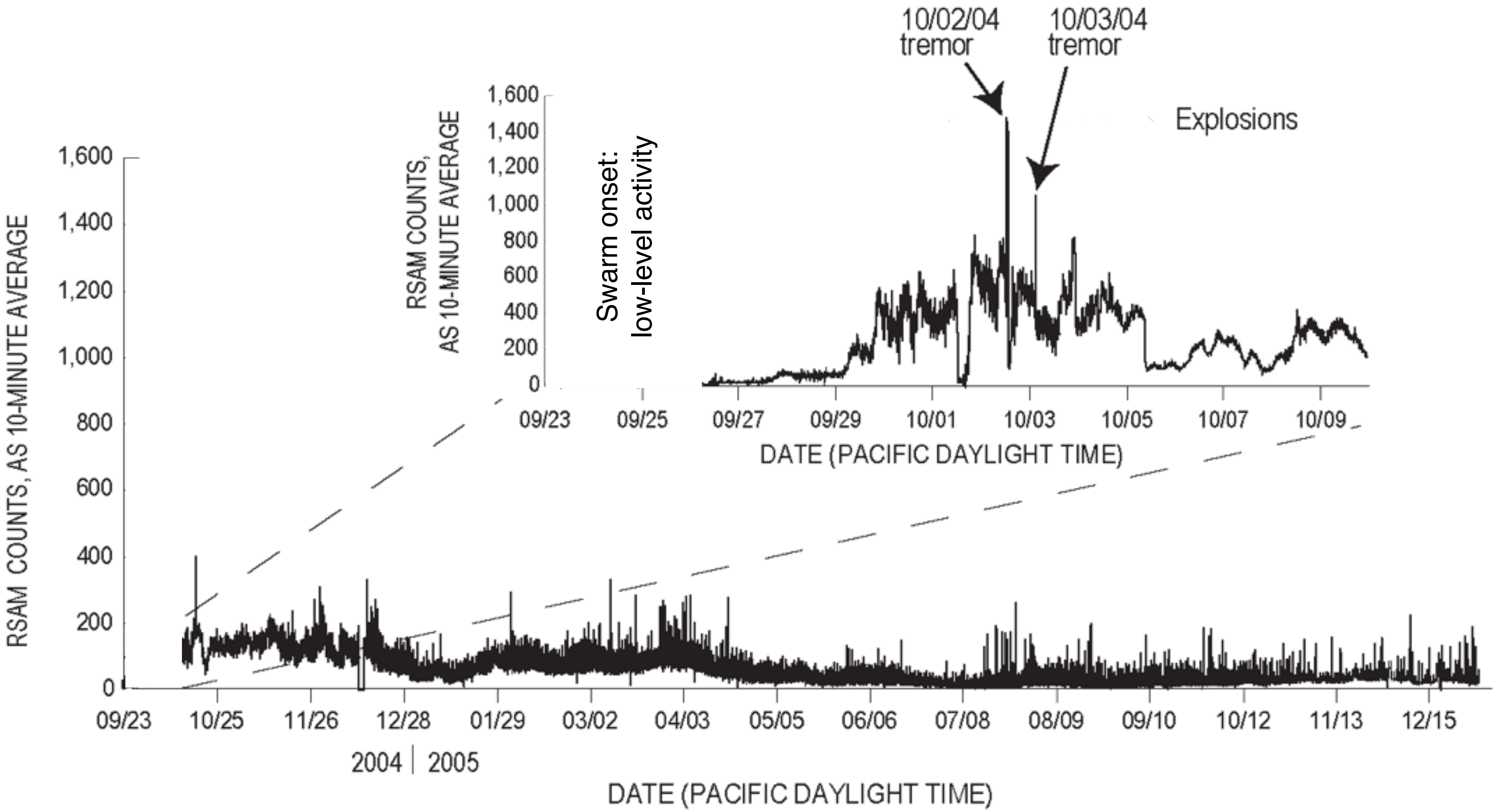
- Nearly every eruption is preceded by an increase in seismicity - an **earthquake swarm**
- Relatively simple analyses can inform about the likelihood of an eruption
  - Event counts (as in previous slide)
    - Track number of earthquakes per day
    - Measure magnitude and examine energy release over time
  - RSAM
    - average absolute amplitude over time (1 min, 10 min)
    - includes all types of signals (tremor, VT, LP earthquakes)
    - no need to count individual events (may not be possible!)

REAL-TIME SEISMIC AMPLITUDE MEASUREMENT (RSAM)



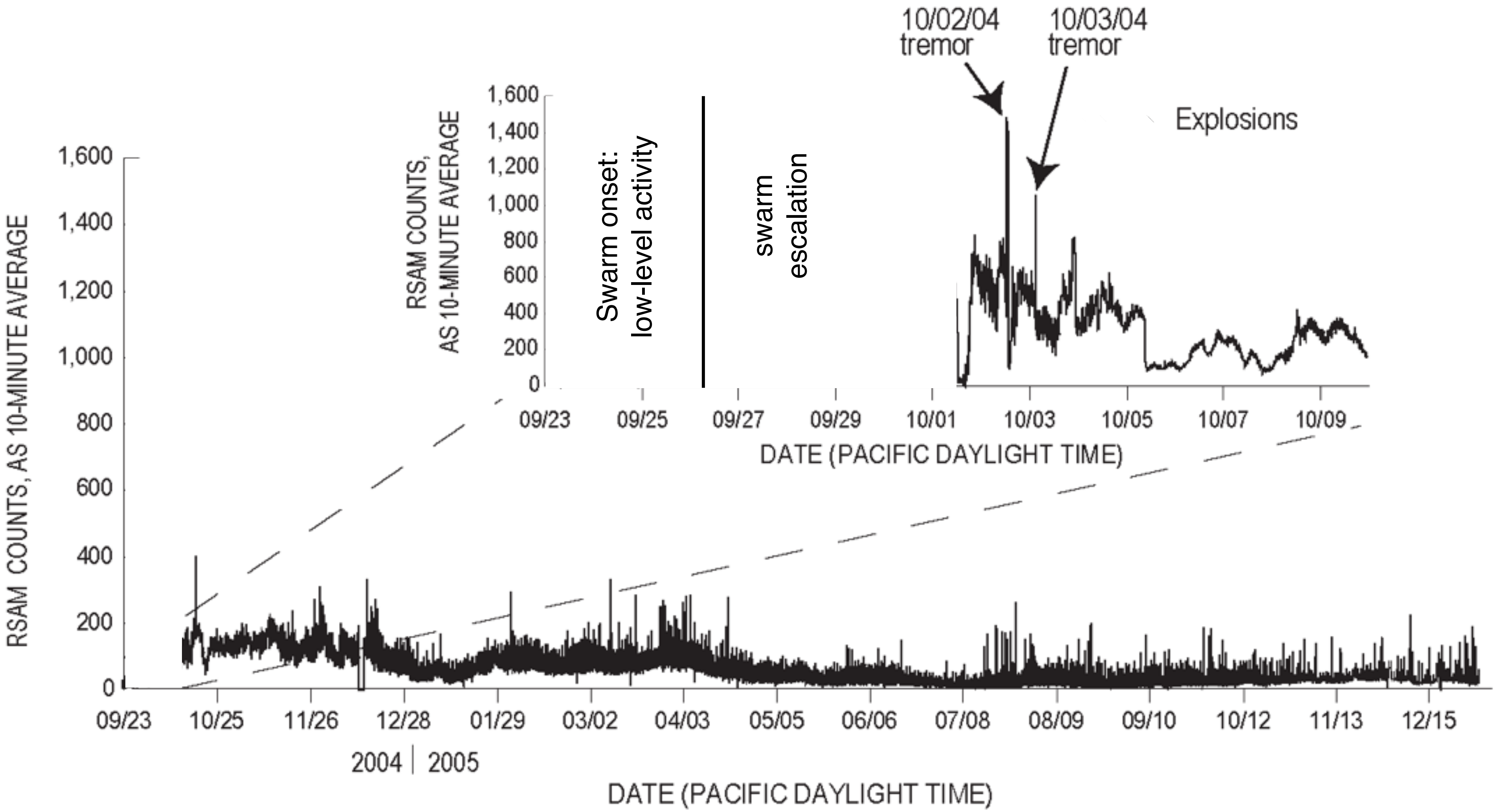
Moran et al., USGS, 2008

Real-time Seismic Amplitude Measurement (RSAM)



Moran et al., USGS, 2008

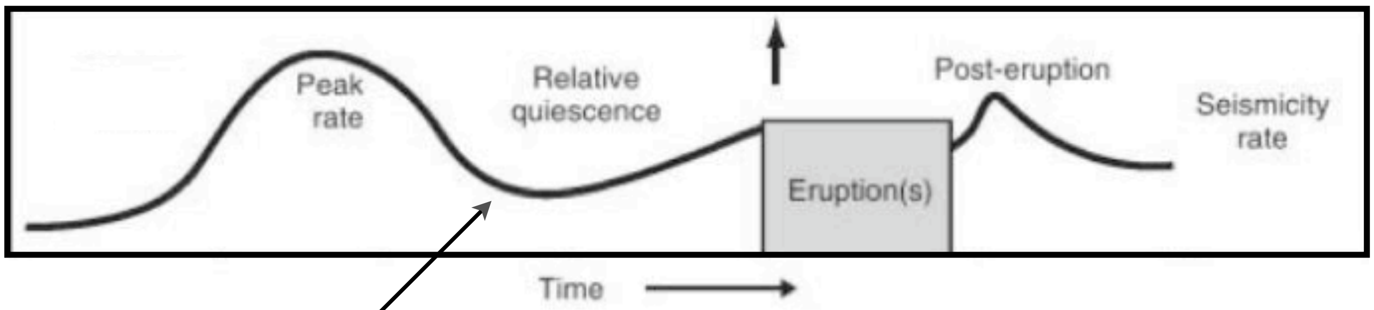
REAL-TIME SEISMIC AMPLITUDE MEASUREMENT (RSAM)



Moran et al., USGS, 2008

Generic Volcanic Earthquake Swarm Model

- Analysis of hundreds of pre-eruption earthquake sequences by McNutt and others suggested some common features



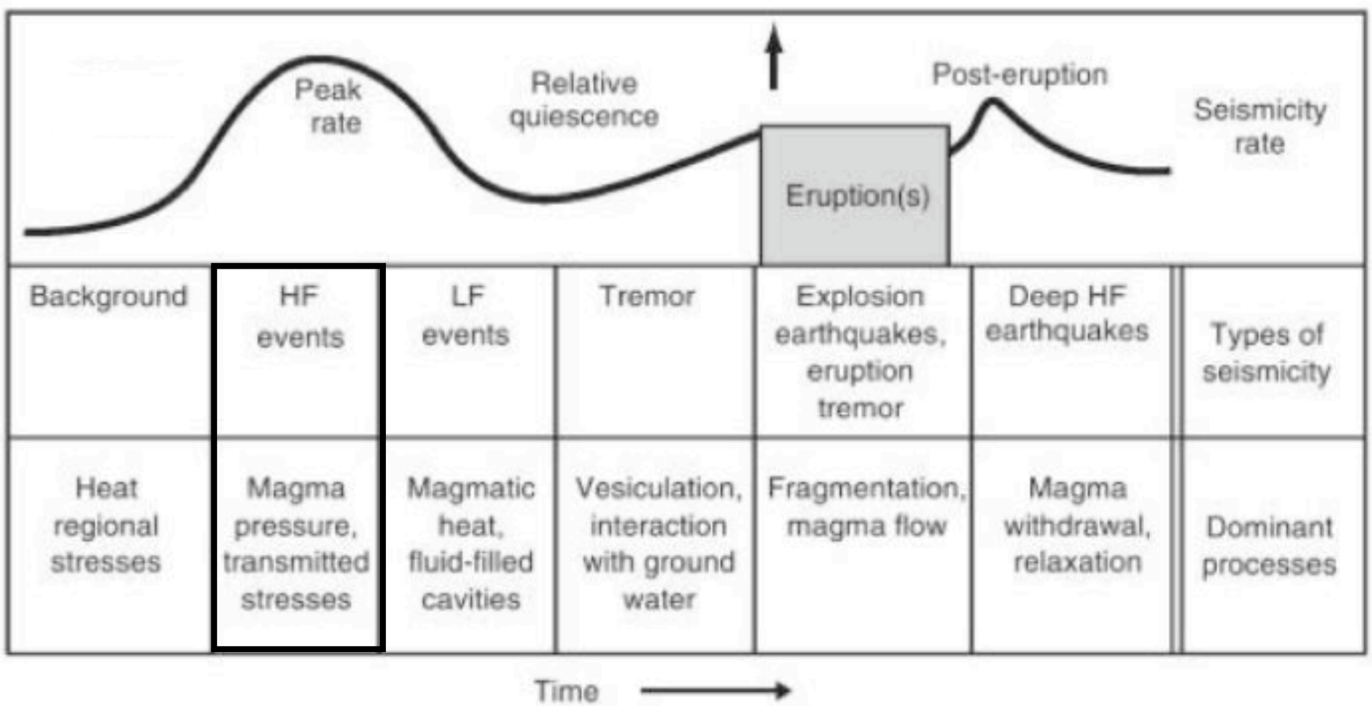
occurs about 1/4 of the time

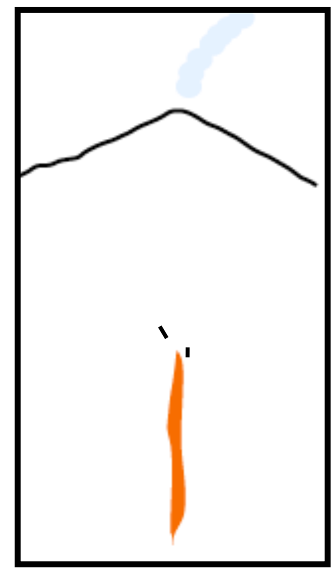
Benoit & McNutt, 1996

GENERIC VOLCANIC EARTHQUAKE SWARM MODEL

Shear fracture of host rock driven by
- Pressure increase in magmatic system
- Dike intrusion

- Duration may reflect
  - Depth of magma chamber
  - Type of fluid intrusion
  - Temperature difference between host rock and magma
- Migration from shallow to deep sometimes seen

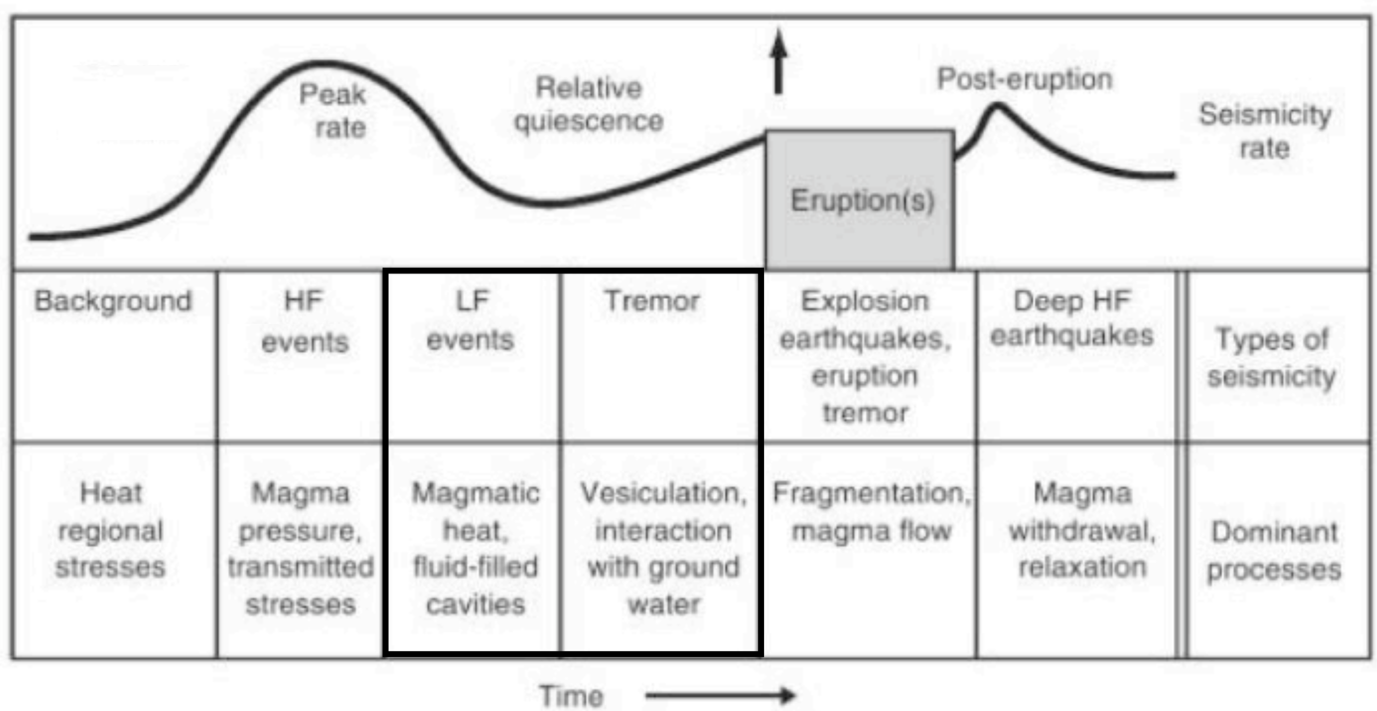


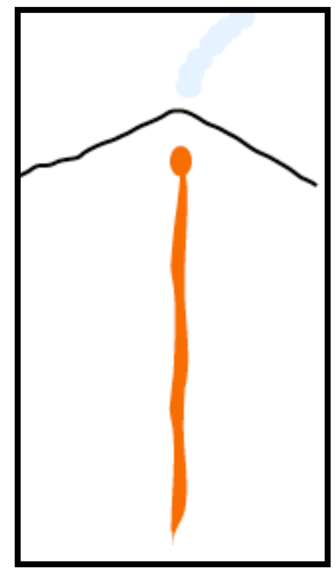


Benoit & McNutt, 1996

GENERIC VOLCANIC EARTHQUAKE SWARM MODEL

- Shallow intrusion
  - Gases exsolve from magma
  - Greater impedance between magma and host rock
- Magma may interact with ground waters
  - Steam may cause LF and tremor

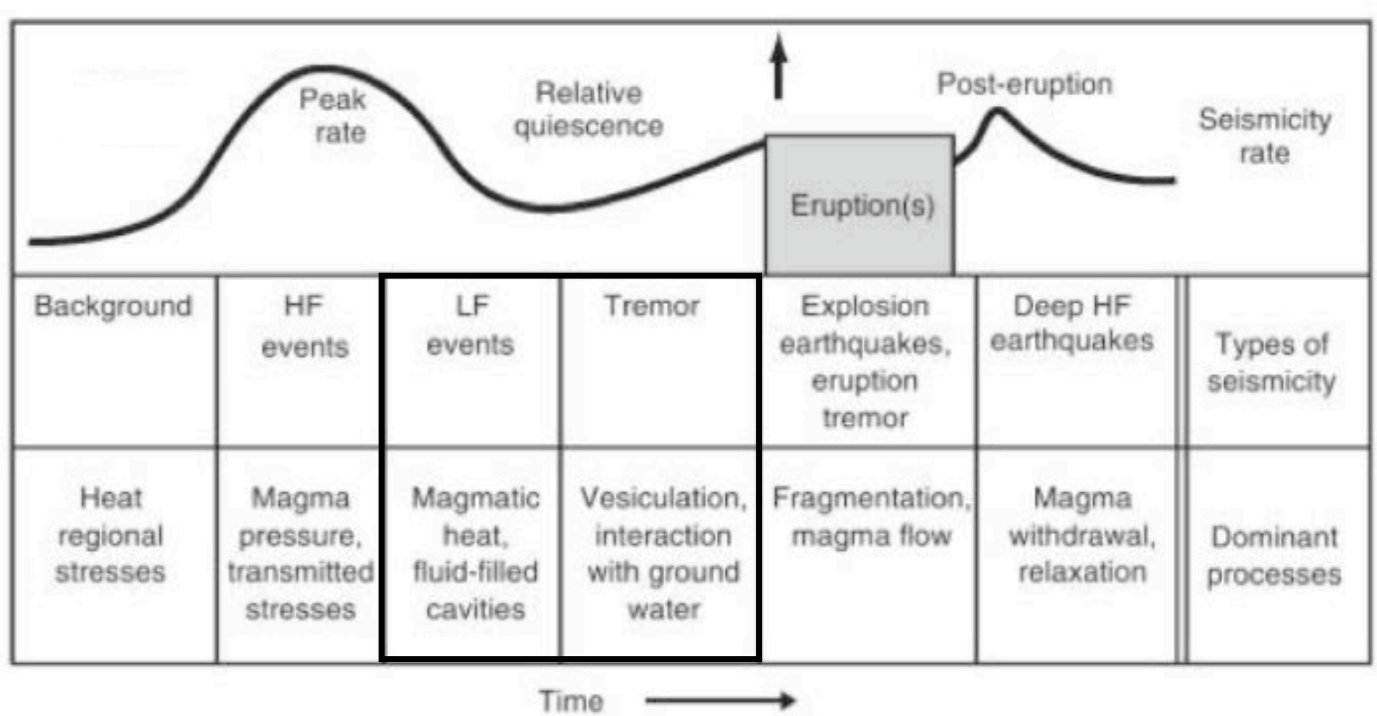


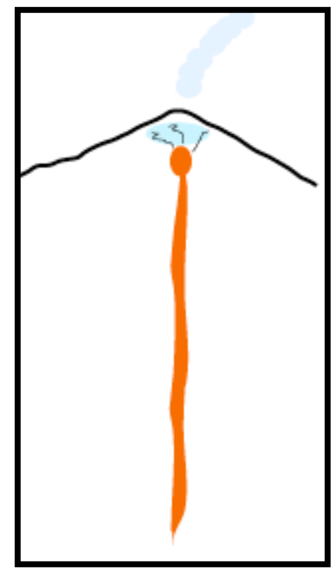


Benoit & McNutt, 1996

GENERIC VOLCANIC EARTHQUAKE SWARM MODEL

- Shallow intrusion
  - Gases exsolve from magma
  - Greater impedance between magma and host rock
- Magma may interact with ground waters
  - Steam may cause LF and tremor
- Relative quiescence
  - Gas venting to the surface through cracks
  - Temporary drop in pressure

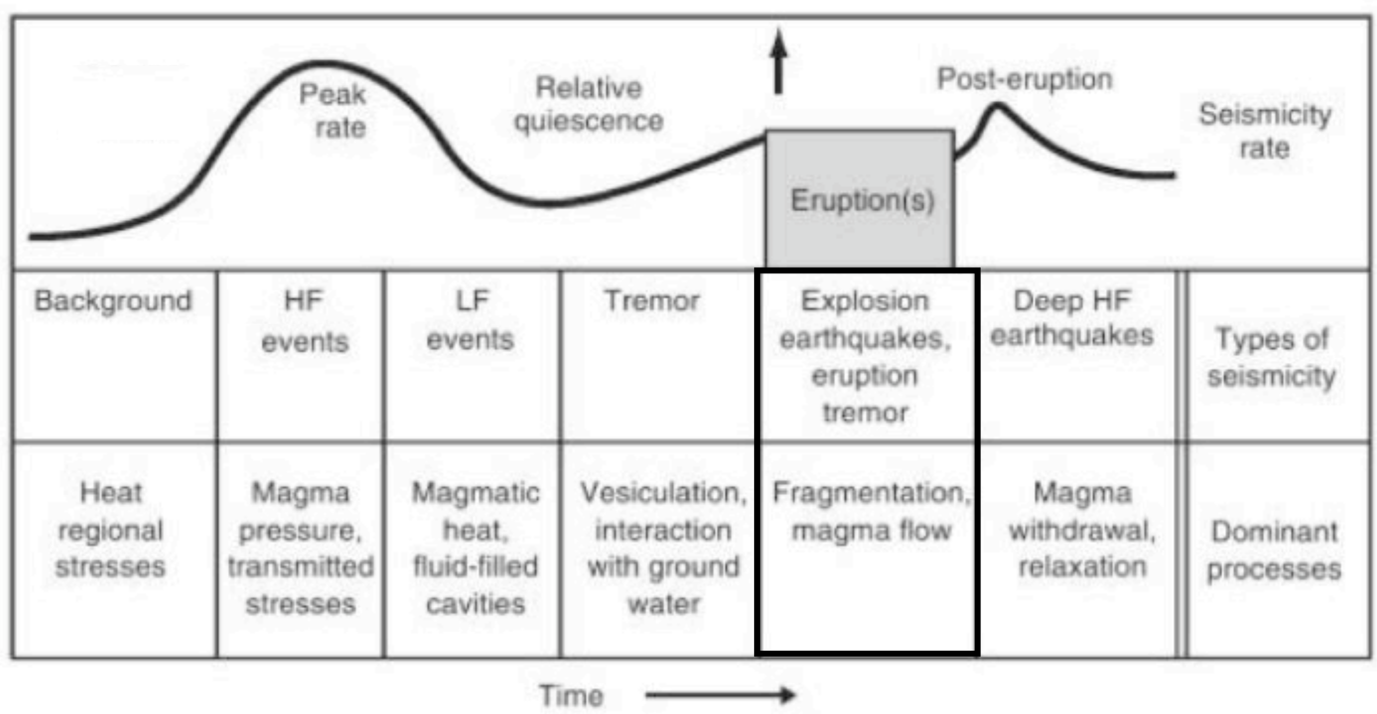


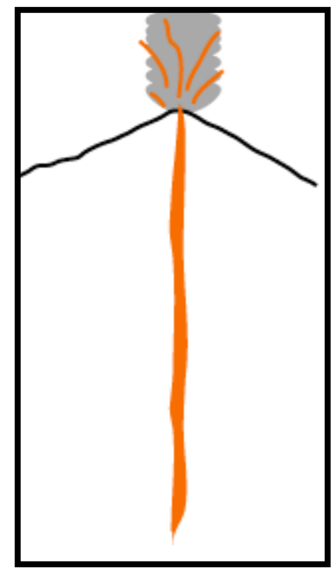


Benoit & McNutt, 1996

Generic Volcanic Earthquake Swarm Model

- Explosive eruption
  - Rapid pressure changes
  - Magma flow
- Broadband seismic signals
  - HF to VLP
  - Infrasound

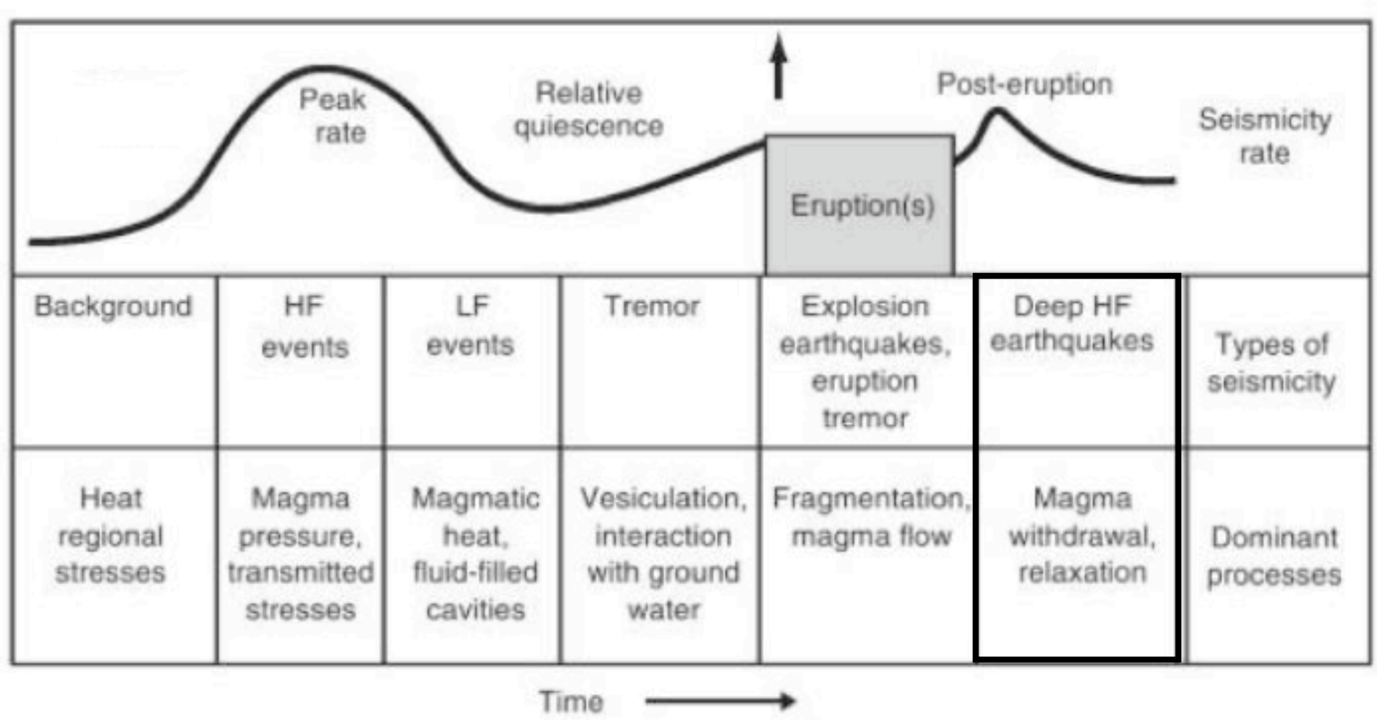


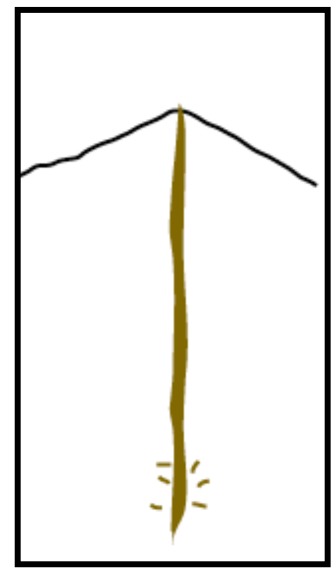


Benoit & McNutt, 1996

GENERIC VOLCANIC EARTHQUAKE SWARM MODEL

- Relaxation of the crust around the deep magma chamber causes earthquakes
  - may have different source mechanisms than pre-eruption events



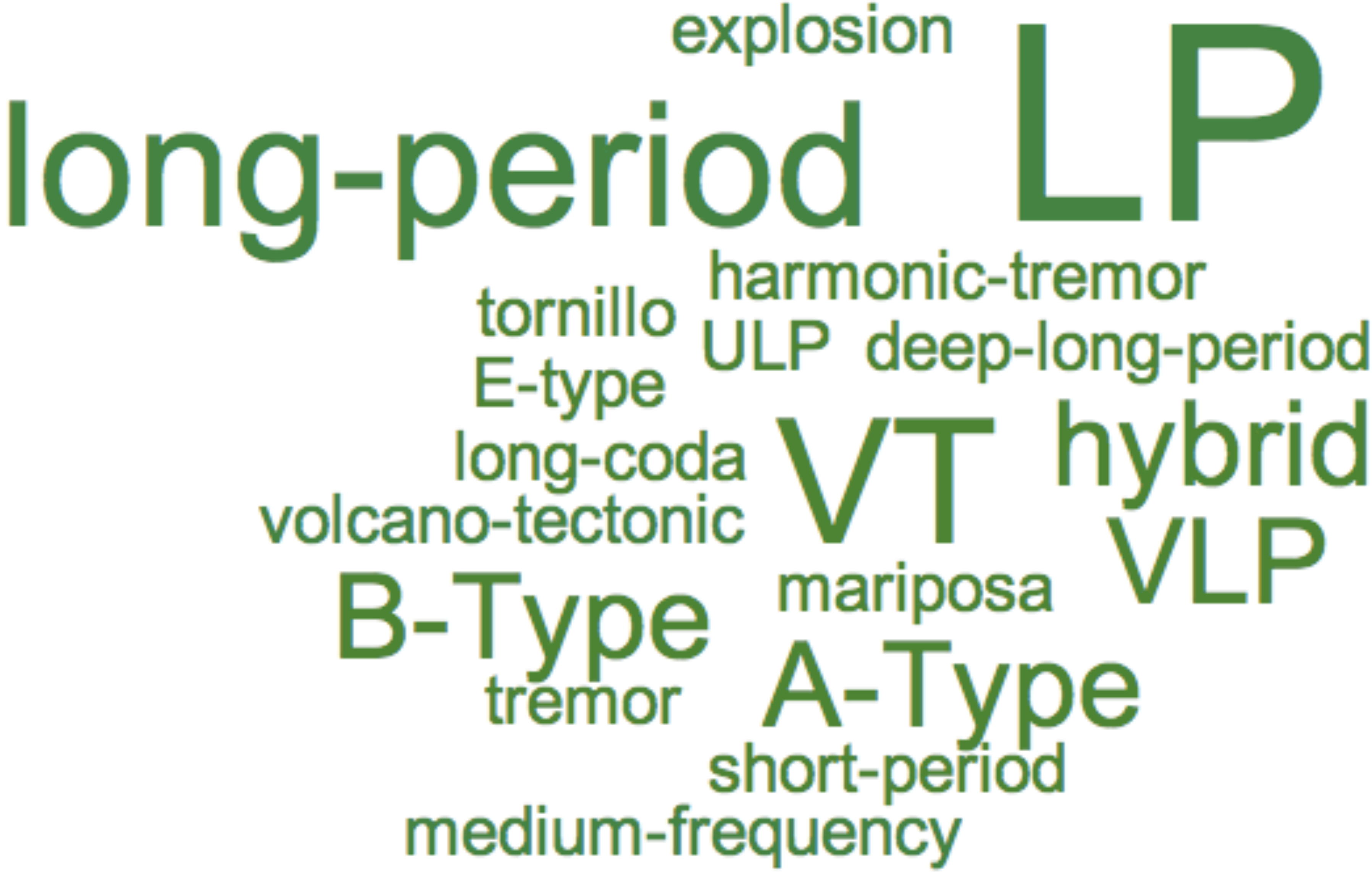


Benoit & McNutt, 1996

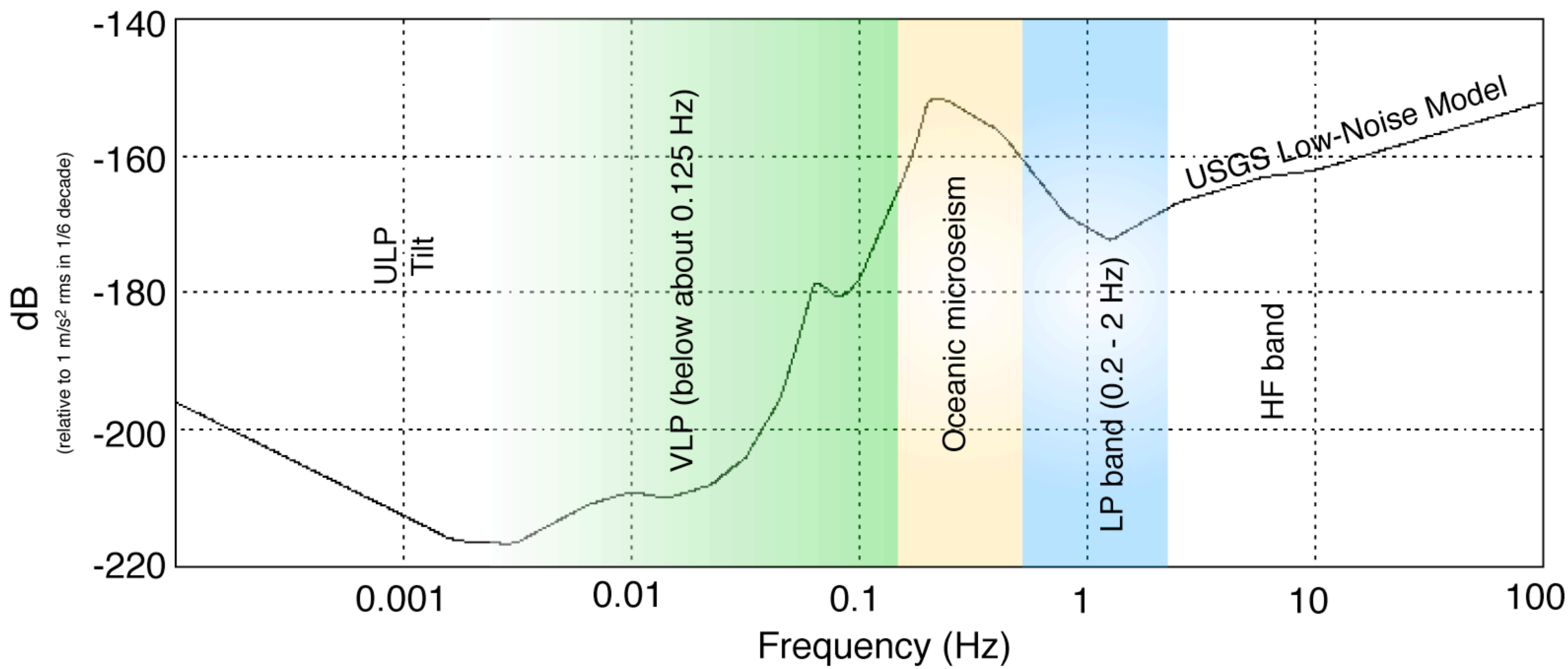
How to Improve Eruption Forecasting?

- We need to understand what various types of signals can tell us about the state of the volcano
  - Classify earthquakes
  - Model the source mechanism
  - Include other types of data
    - gas emission
    - infrasound
    - ground tilt

Earthquake Classification

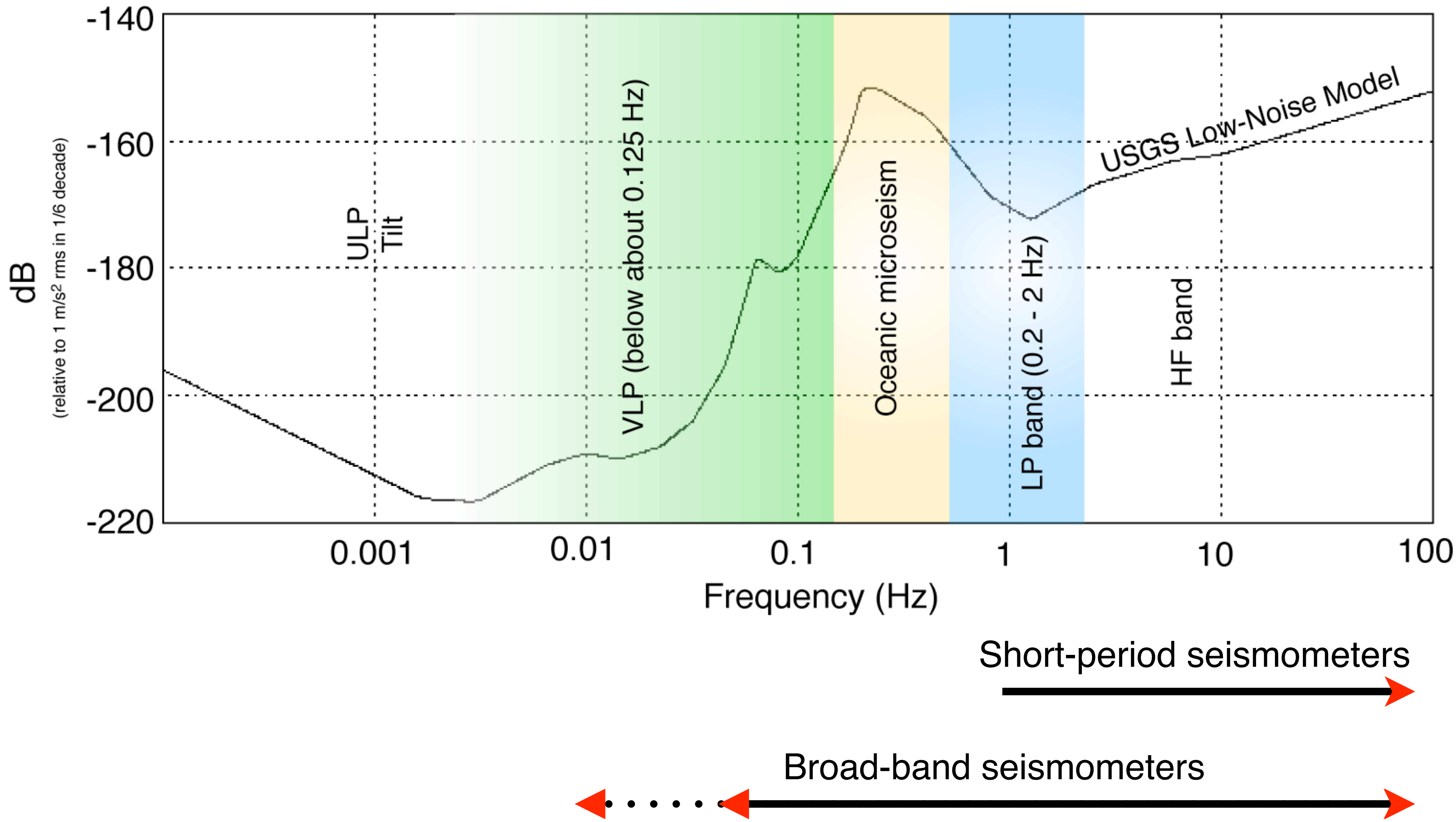


VOLCANO SEISMOLOGY CLASSIFICATION



- Primarily defined on the basis of the frequency content

Volcano Seismology Classification



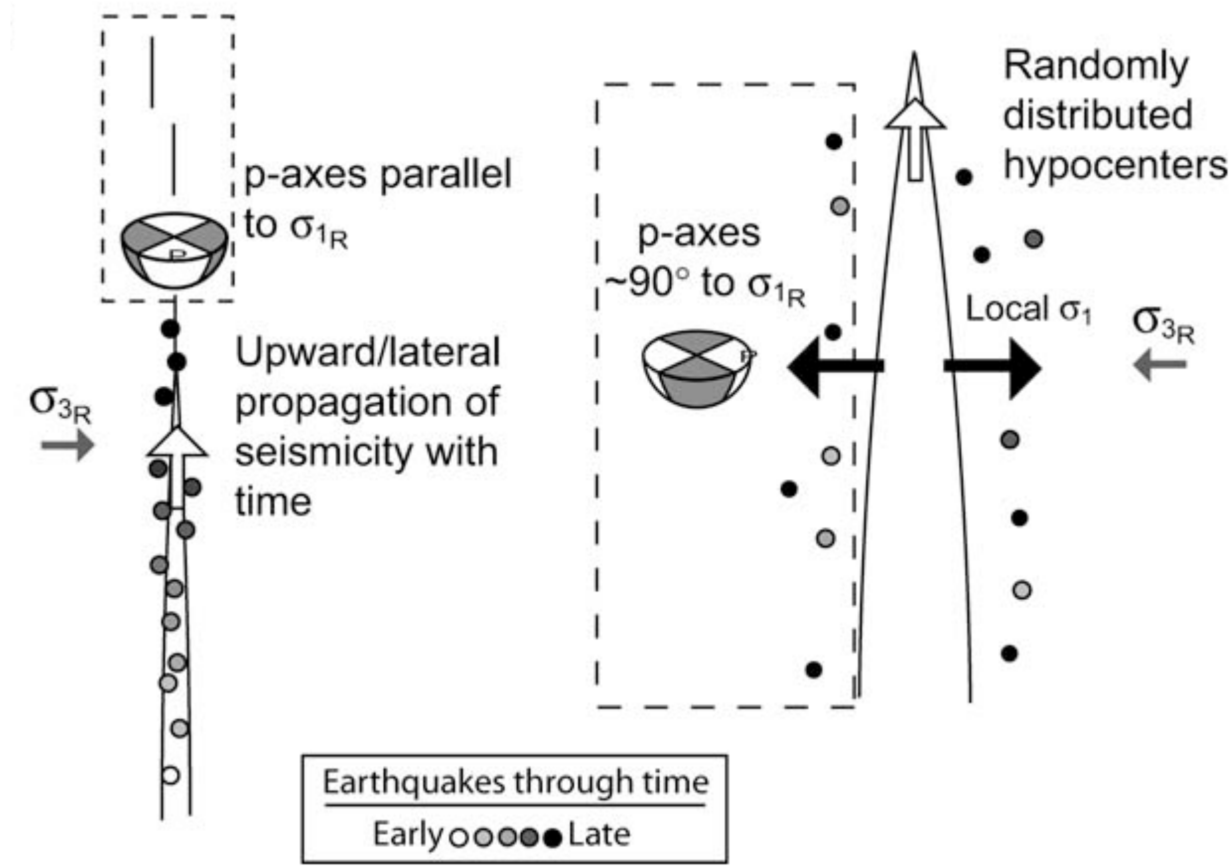
General Volcanic Earthquake Classification

- 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

Characteristics of HF (VT) Earthquakes

- Brittle-failure events
- Due to slip on a fault, just like typical earthquakes in non-volcanic areas
- Migration of activity used for tracking intrusions
- Typically small magnitude
  - large faults do not develop in the heterogeneous volcanic edifice
  - large *b* values
- Mechanisms can vary with time due to changing stresses
  - Have been used to infer dike intrusion

DIKE INTRUSION AND EARTHQUAKE MECHANISMS



- Mechanisms can vary with time due to changing stresses
  - Have been used to infer dike intrusion

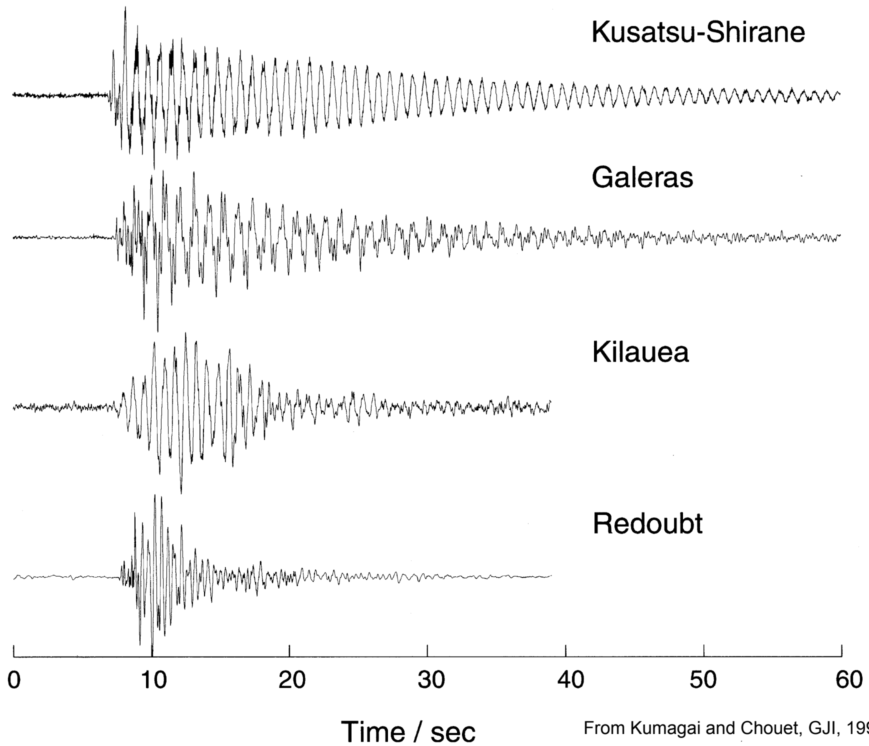
Roman & Cashman, Geology, 2006

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 distortions can cause events to look like LF events

LP (Long-Period) Earthquakes

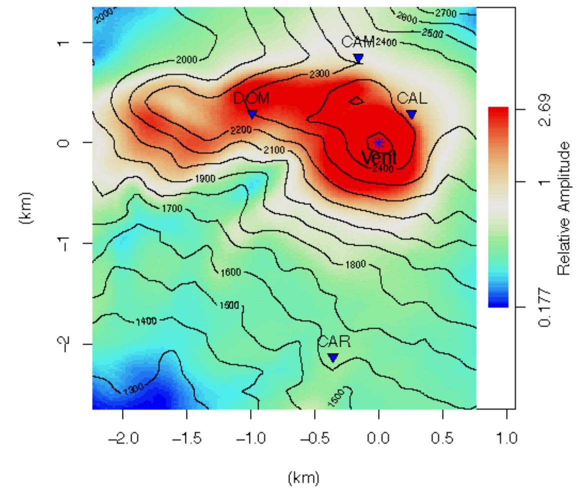
- Known by many names
  - LP, B-type, tornillo, ...
- Broadband *onset*
  - frequencies from .2 to 15 Hz
  - trigger
- Decaying, harmonic coda
  - frequencies .5 - 2 Hz
  - resonance
- Typically shallow (< 3 km), but can be very deep (upper mantle)



From Kumagai and Chouet, GJI, 1999

Path-Distorted LPs?

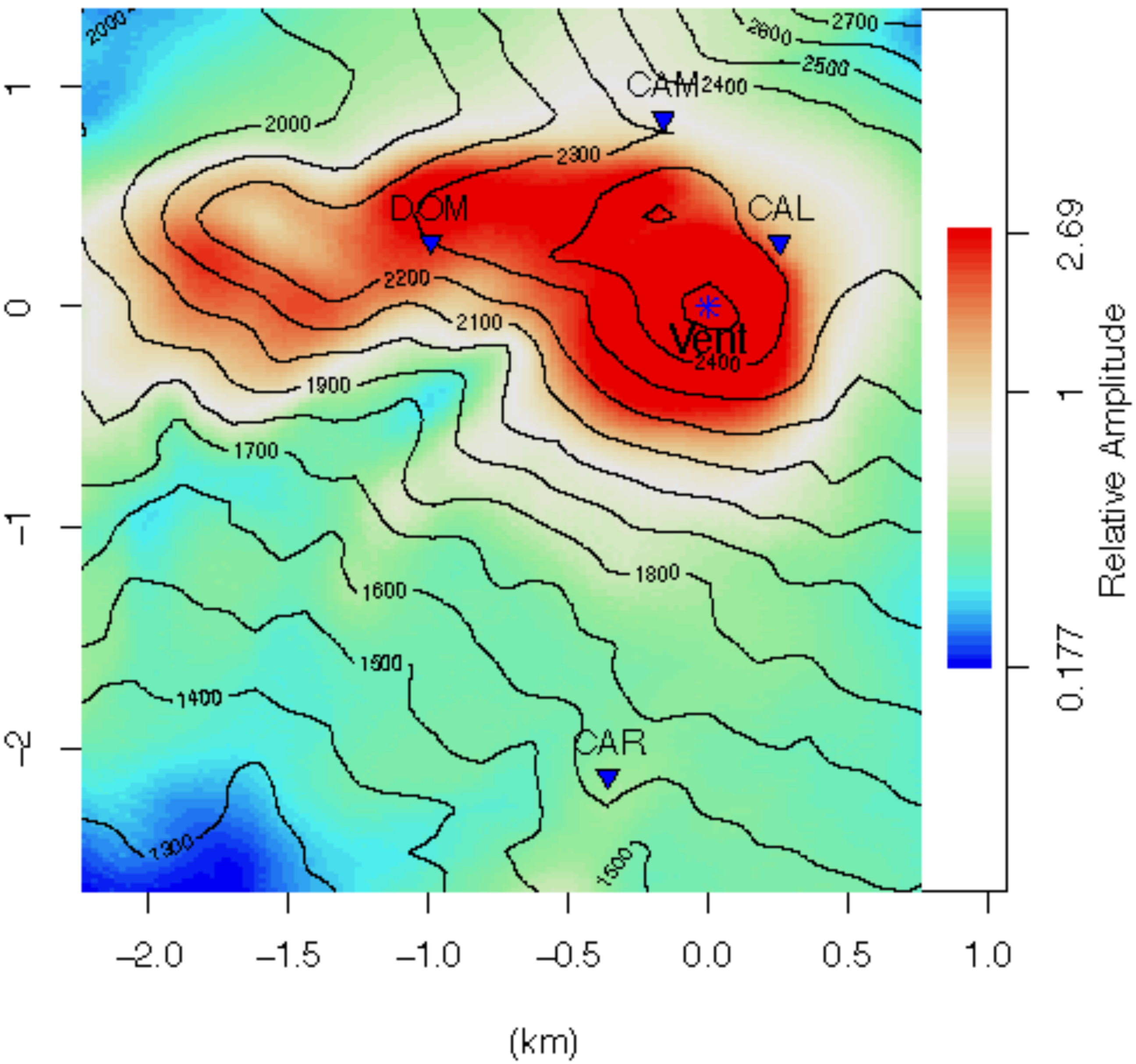
- Path can filter some frequencies and enhance others
- Shallow low-velocity layers can trap waves
  - prolongs the duration of the signal and may mimic LP coda characteristics
- Topography focusses and defocusses waves
  - Waves can be trapped beneath steep topographic features (hills and volcanic edifices)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



Anderson et al., BSSA, 2012

SYNTHETIC MODELING OF STRUCTURE

- Shallo
  - prol coda char
- Topog
  - Wav ures (hill
  - If ur ng for 10s



Anderson et al., BSSA, 2012

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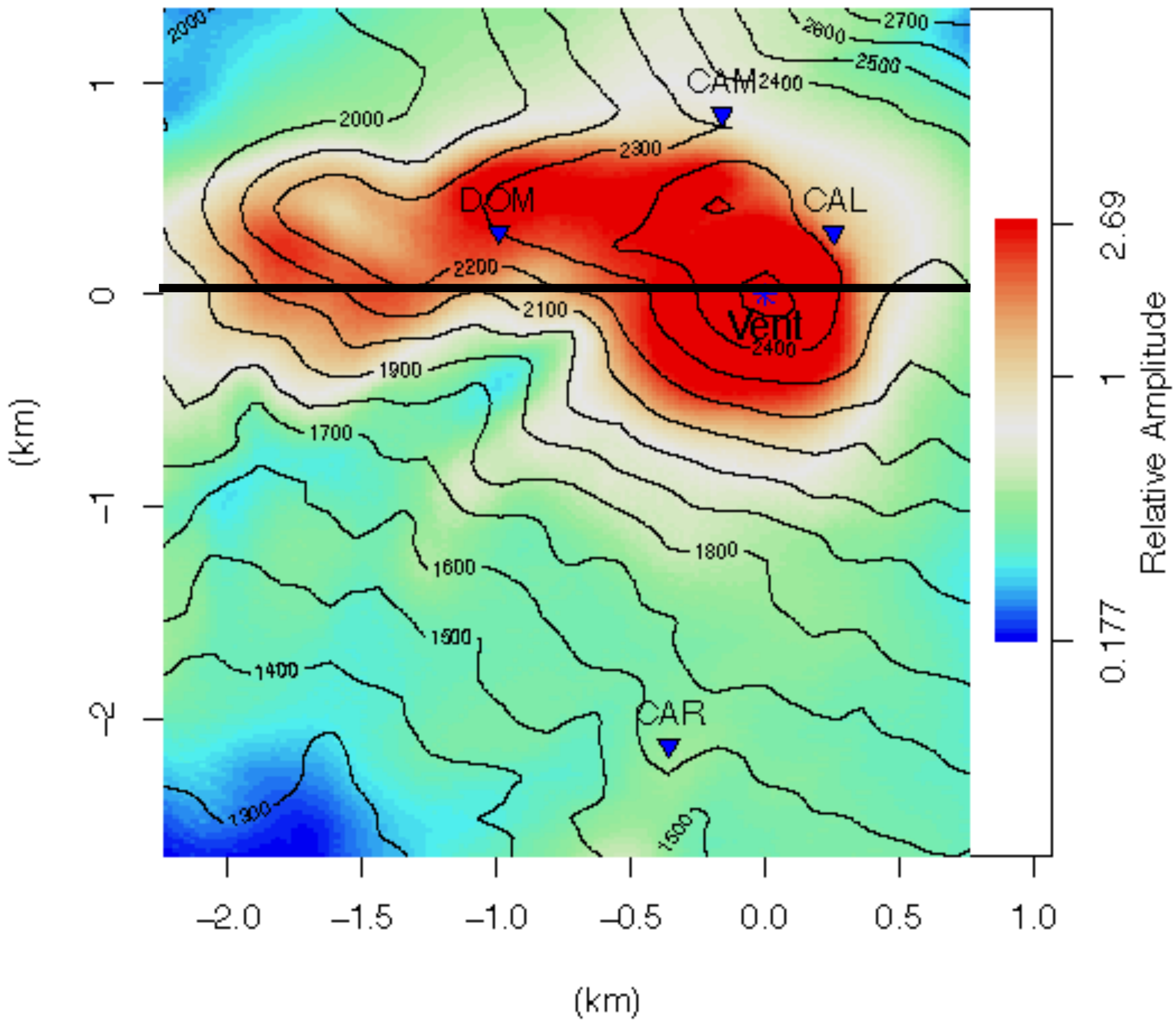
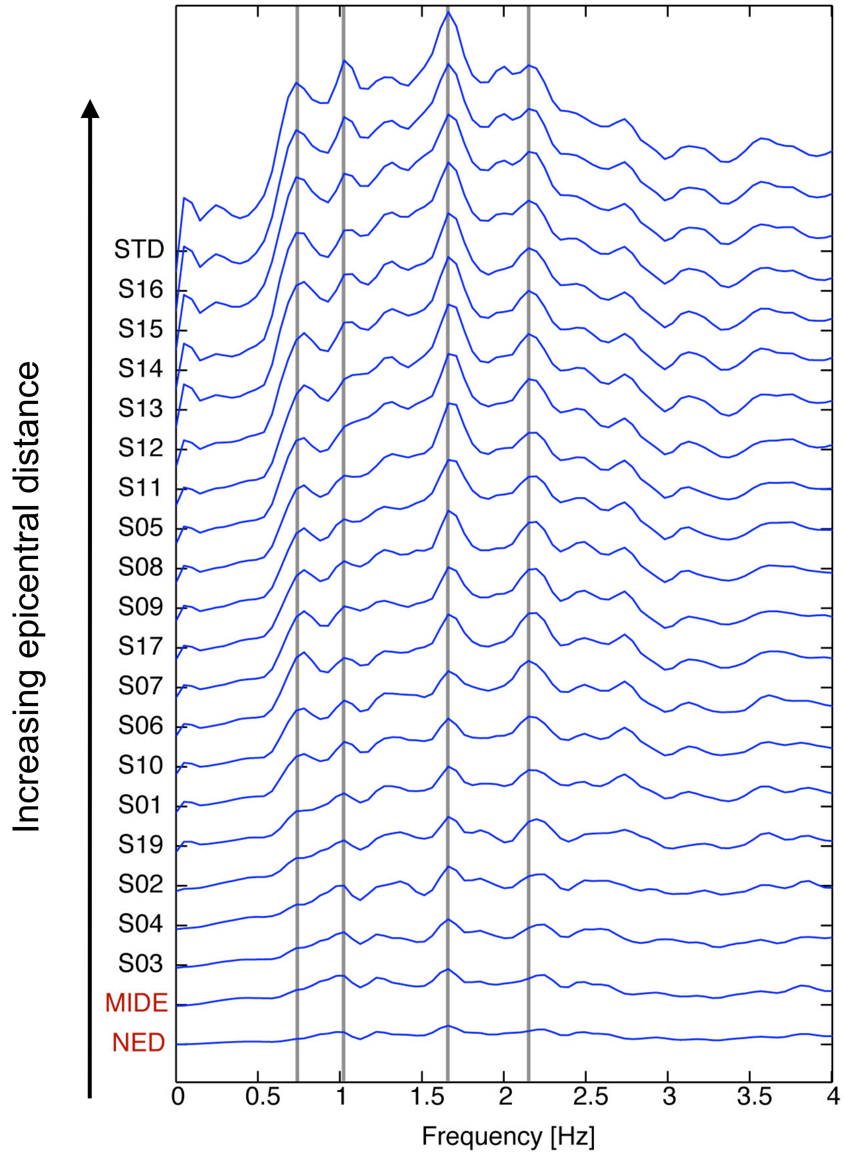


Anderson et al., BSSA, 2012

SOURCE VS. PATH

Mount St. Helens

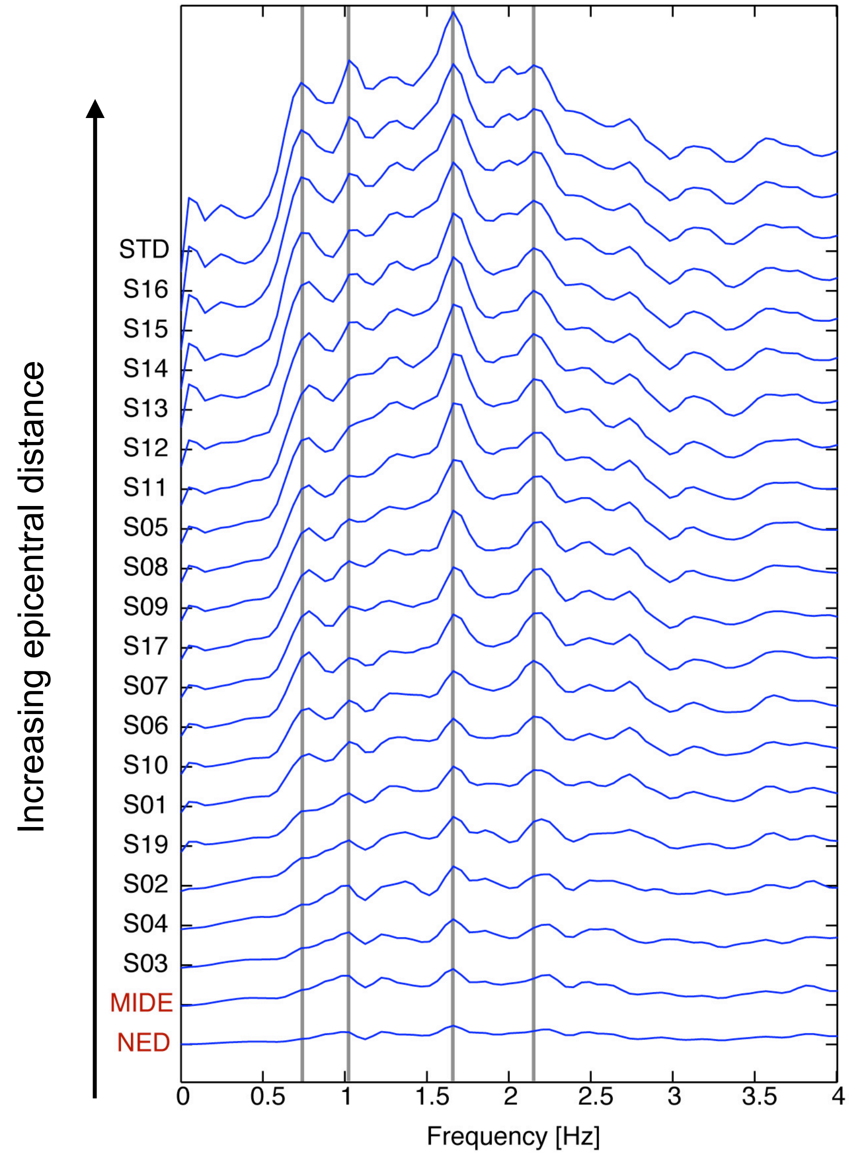
- Site affects are unlikely to be identical at all stations
  - Examine spectra of the coda for one event at all stations for similarity
  - Common spectral peaks at all azimuths are unlikely to be cause by site affects



SOURCE VS. PATH

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

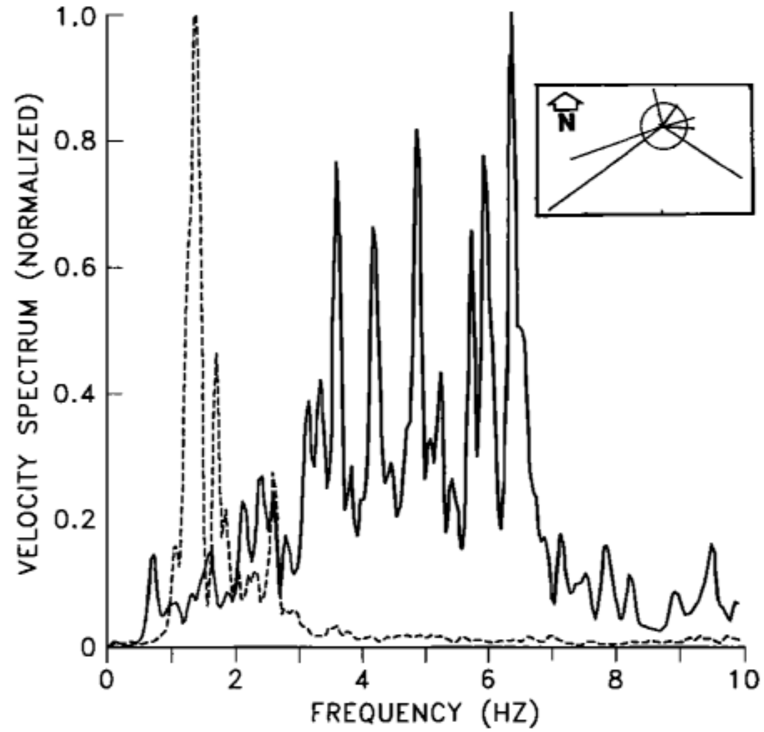


Waite et al., JGR, 2008

Source vs. Path

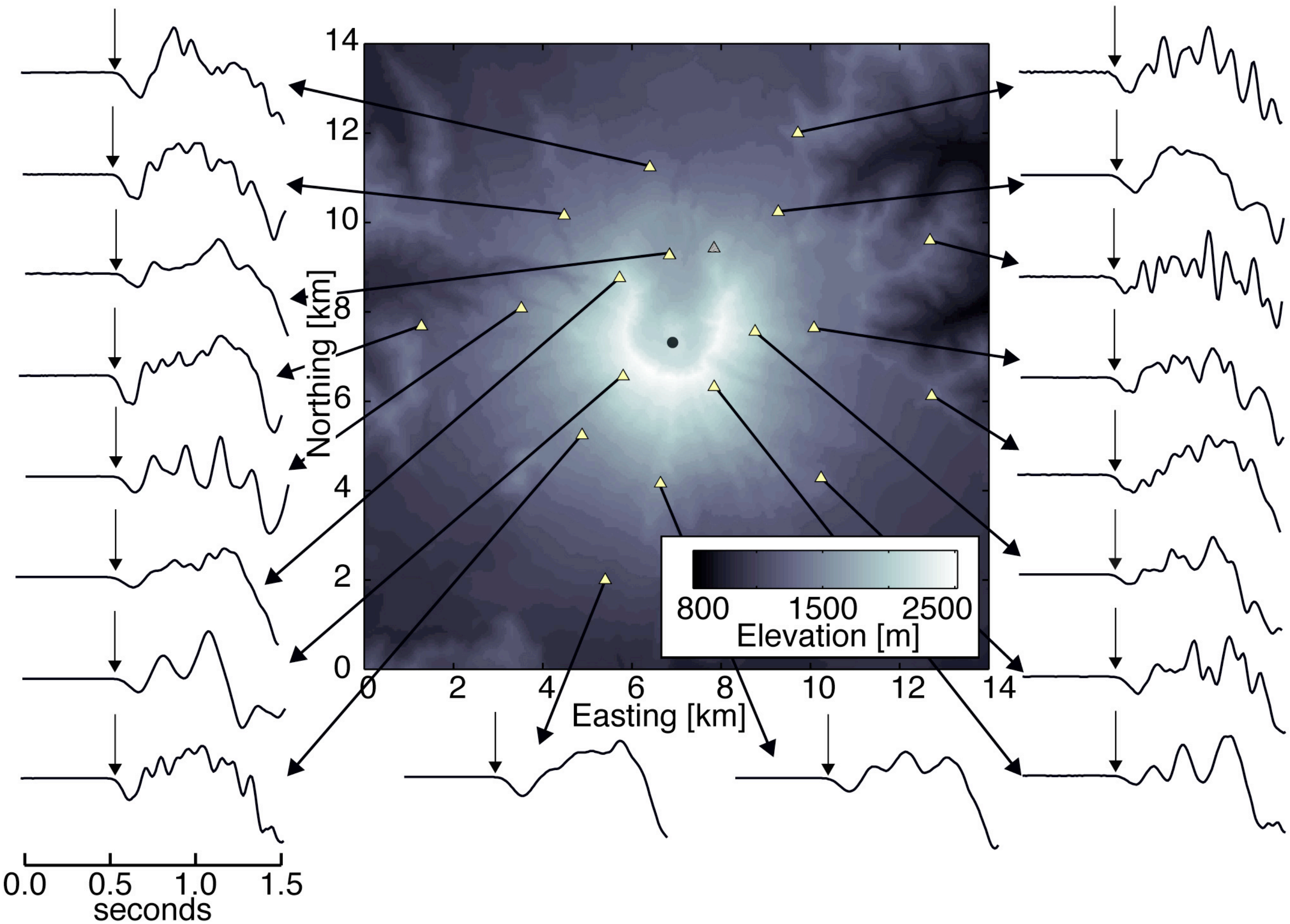
Difficult to identify for shallow events

- 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

LP Source Mechanism



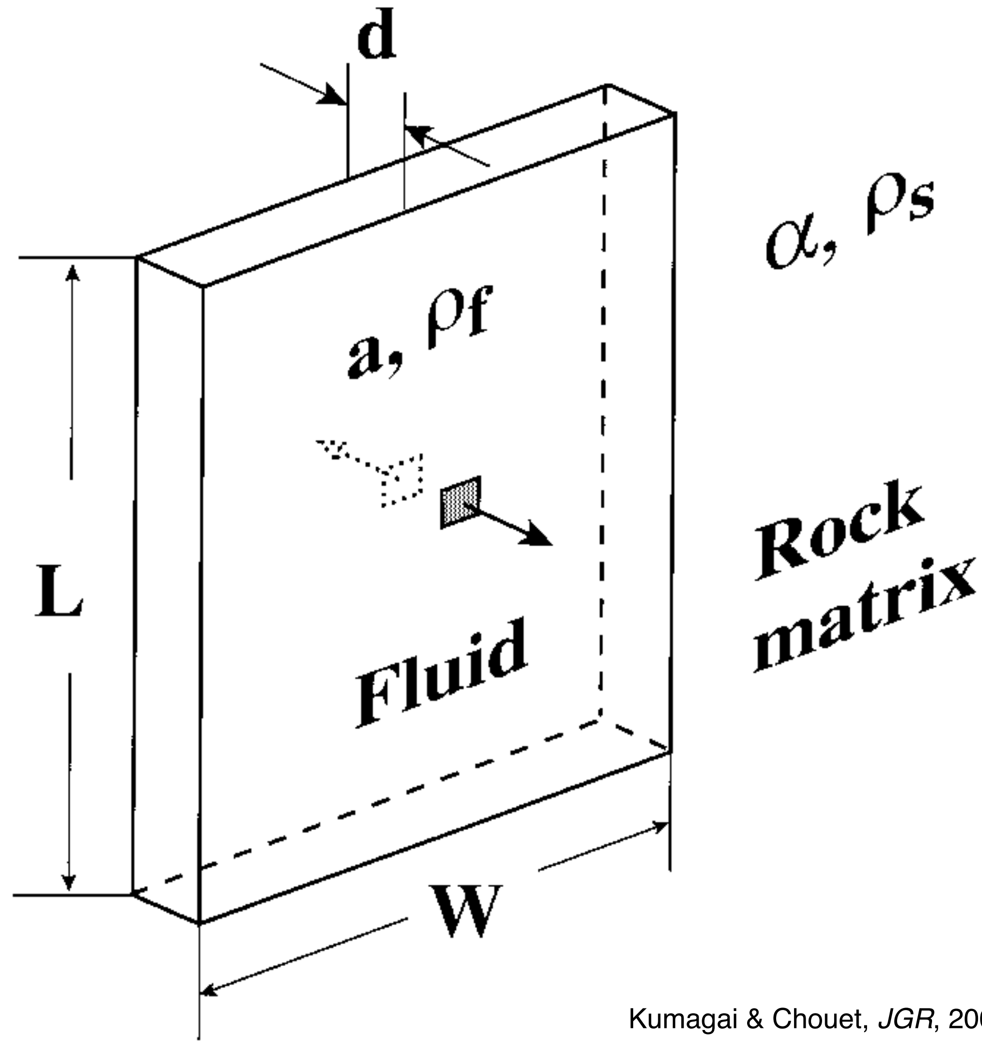
- In this example from Mount St. Helens, all the stations record the same dilatational first motion
- This cannot be a double-couple earthquake in which slip occurs along a planar fault but, can result from a volume decrease.

Waite et al., JGR, 2008

CRACK MODEL

developed 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

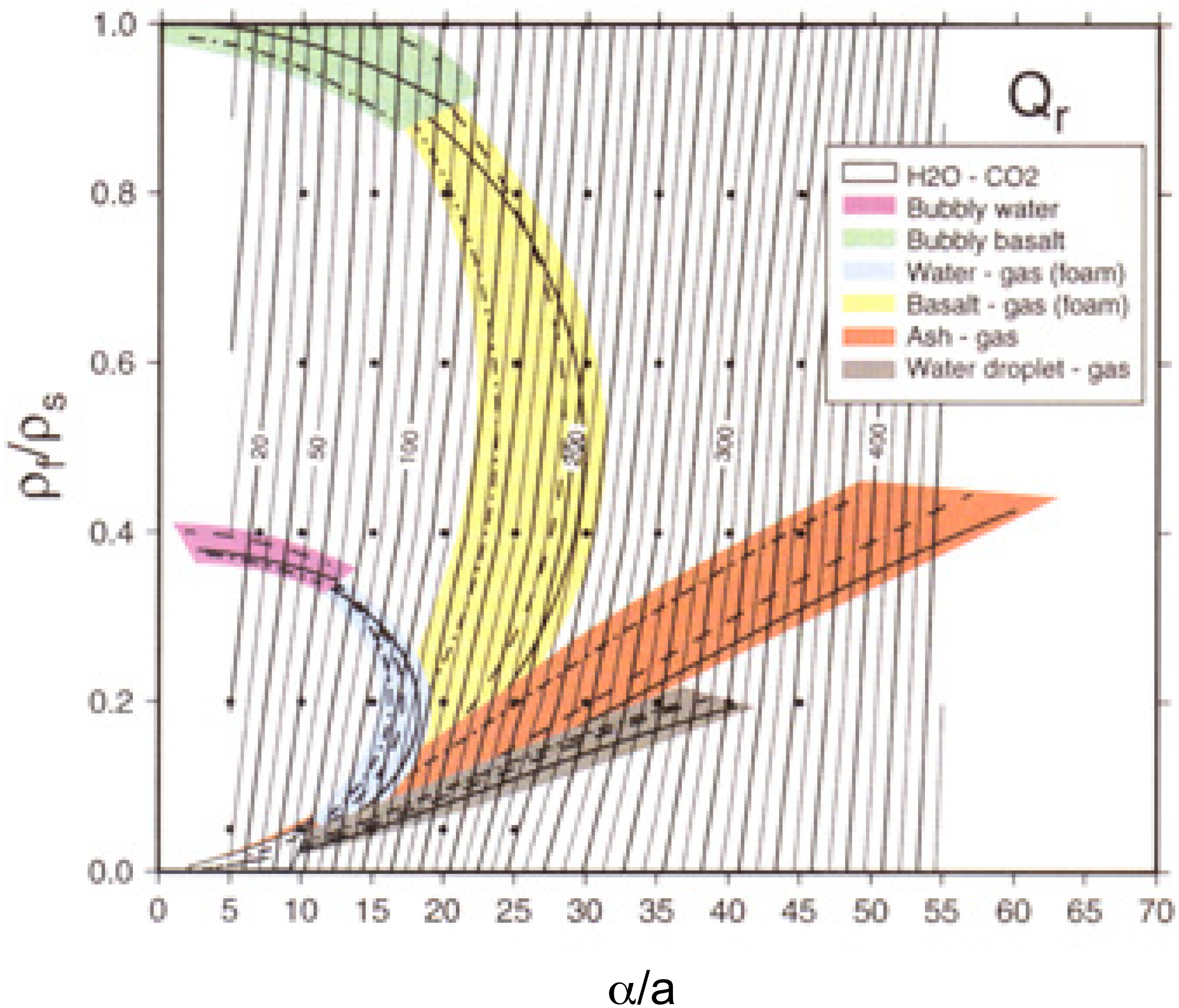
CRACK MODEL

- 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

CRACK MODEL



Q_r describes the signal attenuation due to radiation from the crack

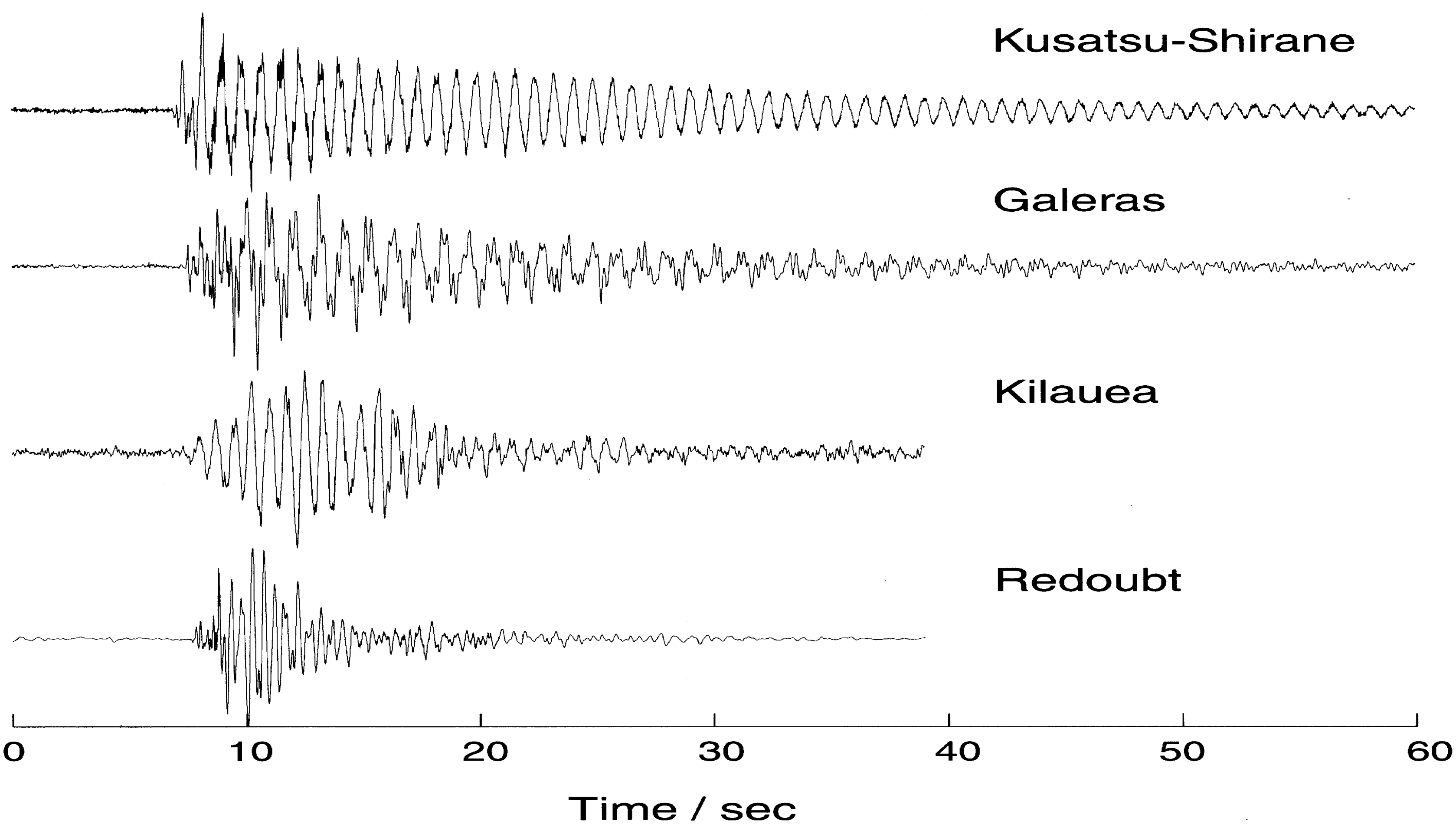
- Low Q_r means the coda decays rapidly
- High Q_r predicts long-duration codas

Kumagai & Chouet, *JGR*, 2000

- High Q_r (long coda) 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 (short coda) 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



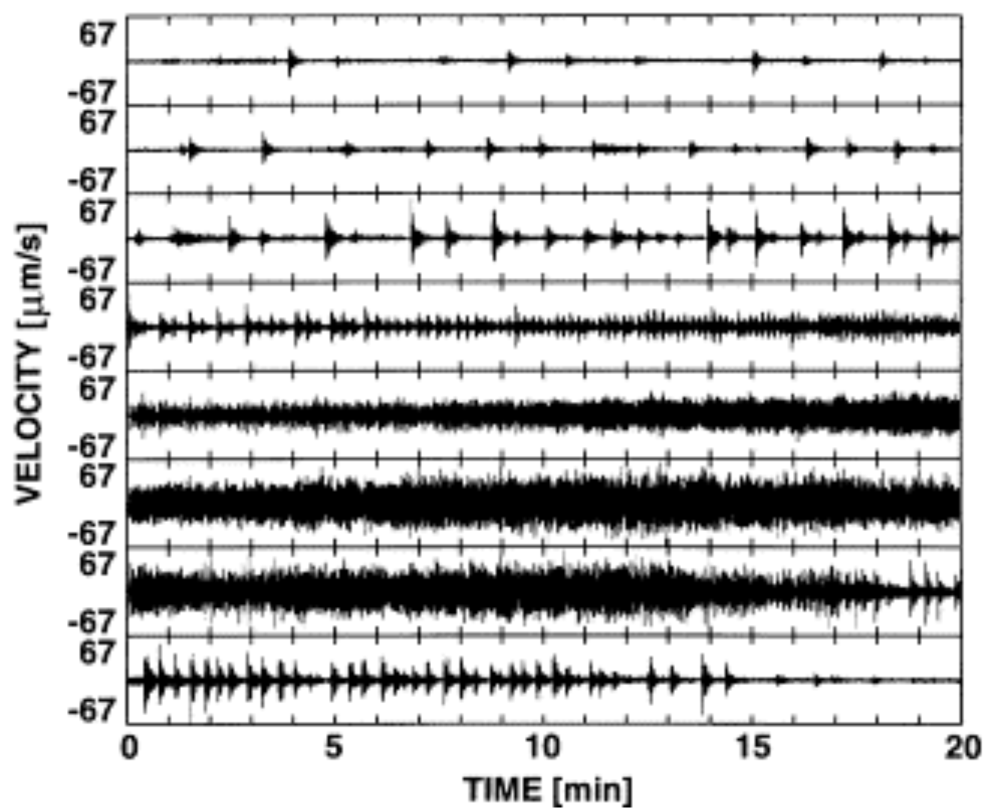
Kumagai and Chouet, GJI, 1999

Crack Model: Implications

- Because of the slow wave speed (slower than acoustic velocity of the fluid), LP resonant frequencies are possible for relatively small cracks
- 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

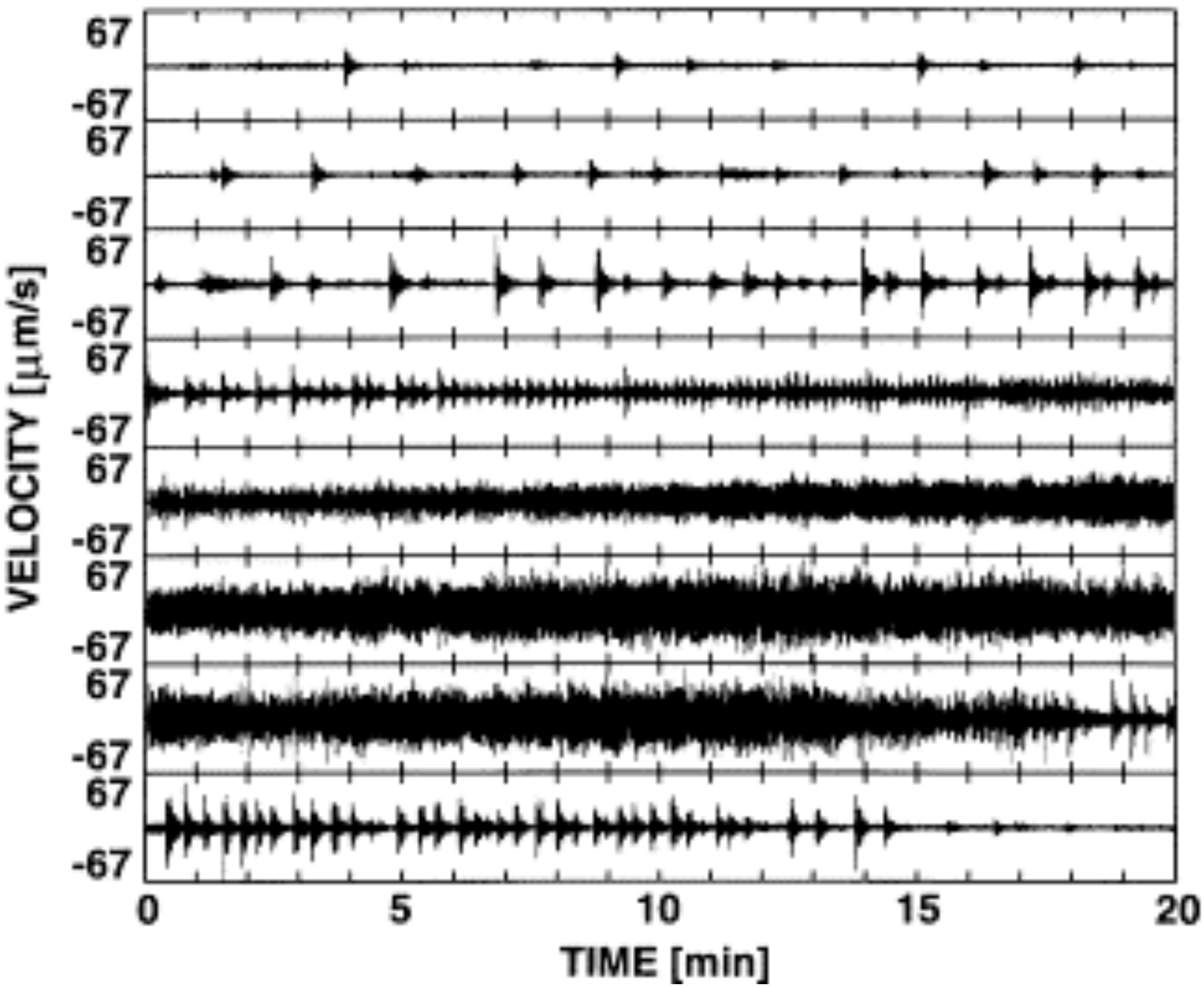
- At silicic volcanoes, a model involving resonance of fluid-filled cracks along the conduit margin may explain LP earthquakes
- Large strains at margin cause brittle failure in hot rock
- Pressure changes can trigger resonance in system of interconnected cracks
- LP events may increase in frequency and merge into tremor
  - suggests a common source mechanism for LP and tremor activity



Neuberg et al., *JVGR*, 2000

Conduit Margin Fracture Resonance

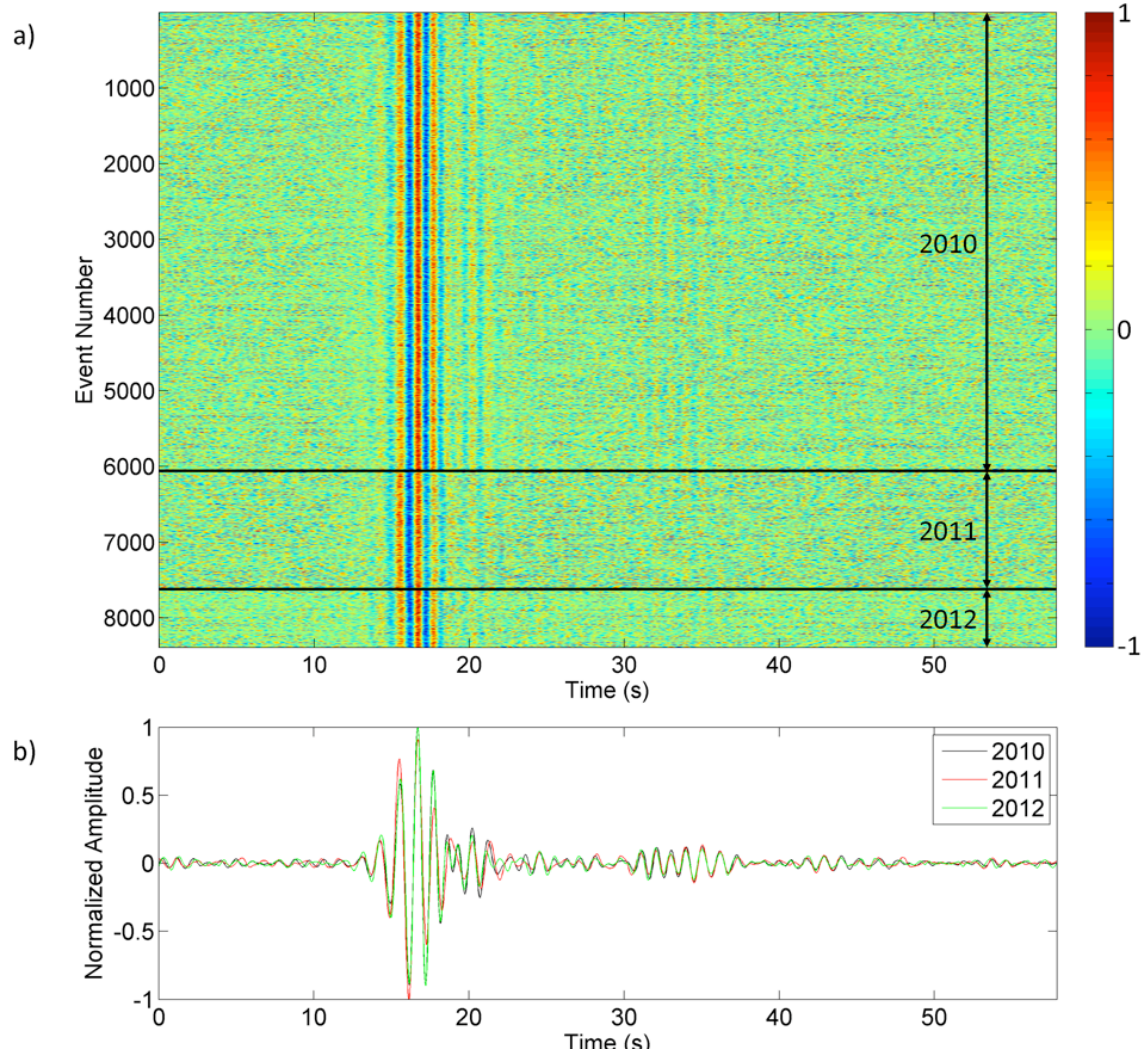
- Increased activity may indicate an increase in effusion rate



Neuberg et al., *JVGR*, 2000

VILLARRICA LPS AND TREMOR

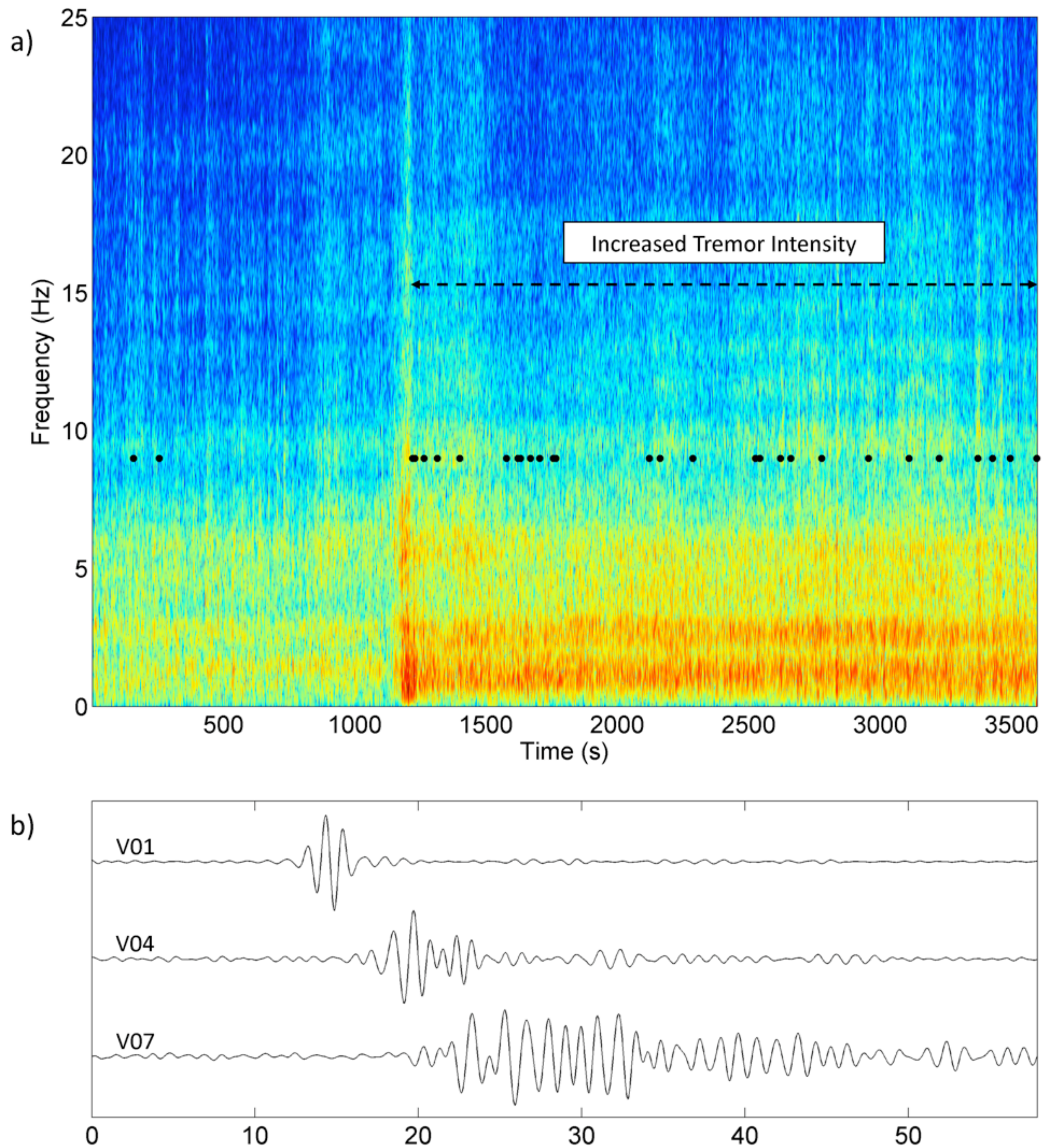
- weak seismic signal associated with bubble burst at the surface of the lava lake
- repeatable for years
- stack has high S/N



Richardson and Waite, in prep

VILLARR

- As with Soufriere Hills, tremor seems to have the same mechanism as the LPs
- The LP coda grows with increased distance from the source



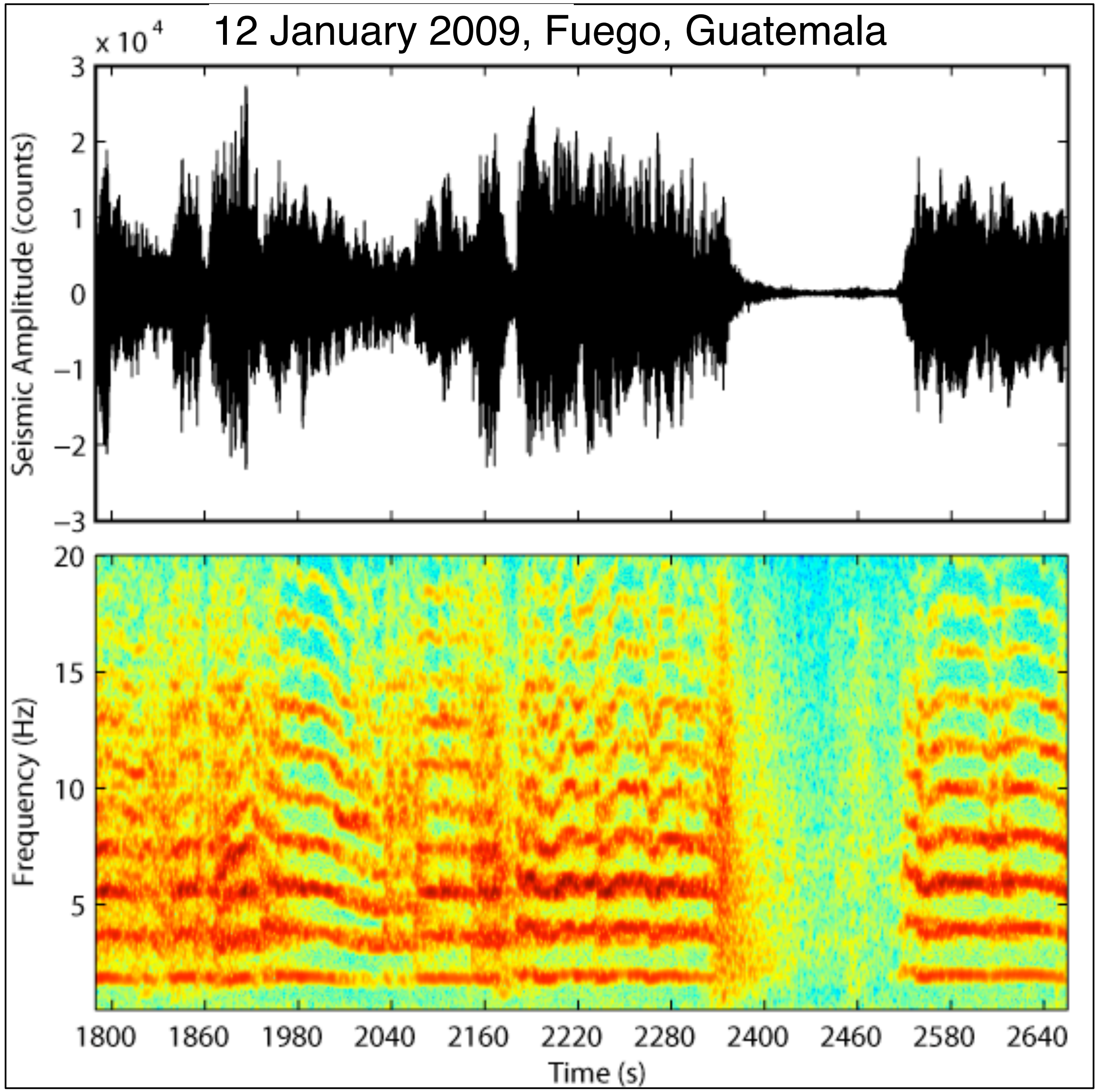
Richardson and Waite, in prep

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

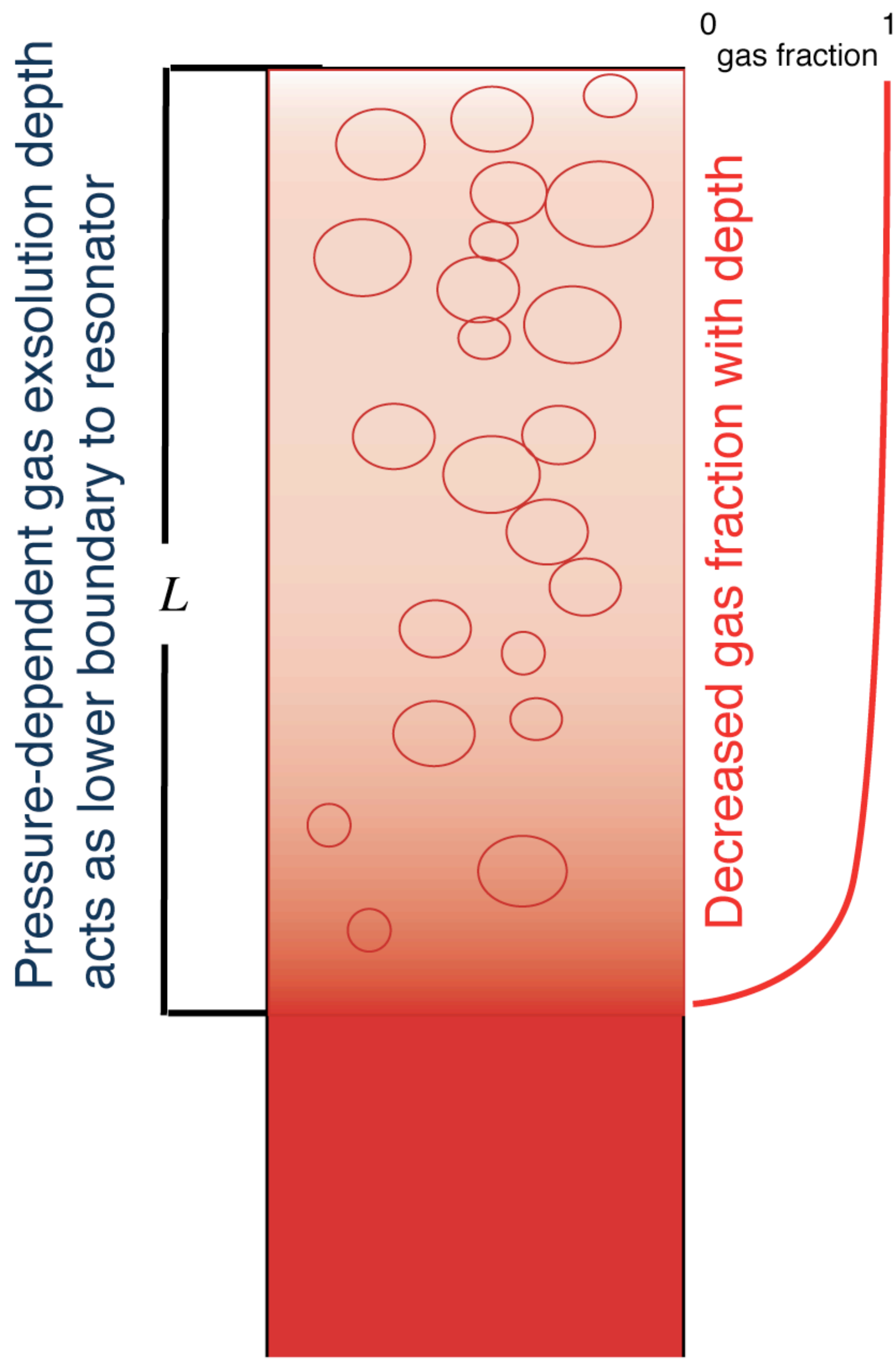
HARMONIC TREMOR

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

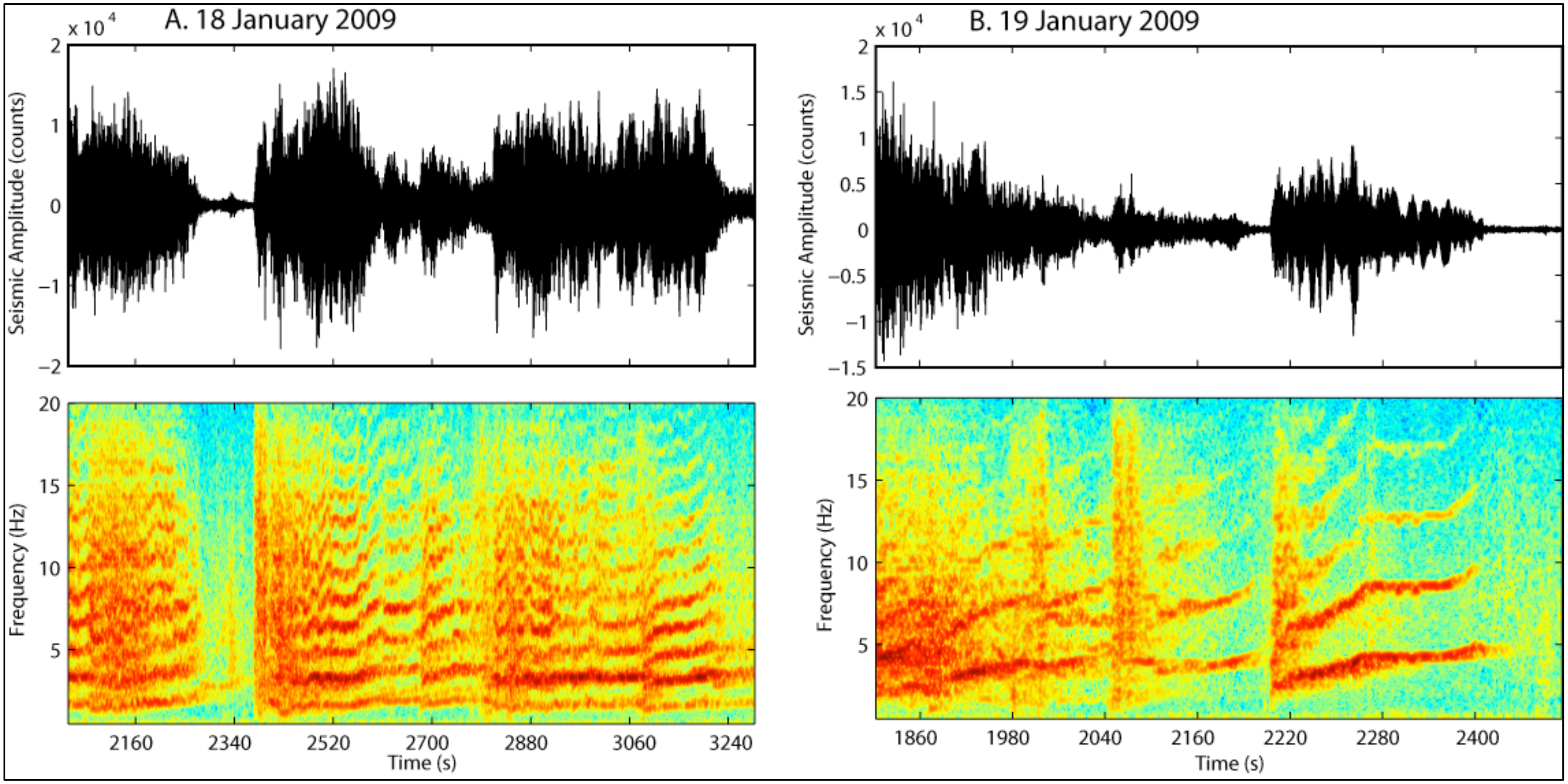


HARMONIC TREMOR

- 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



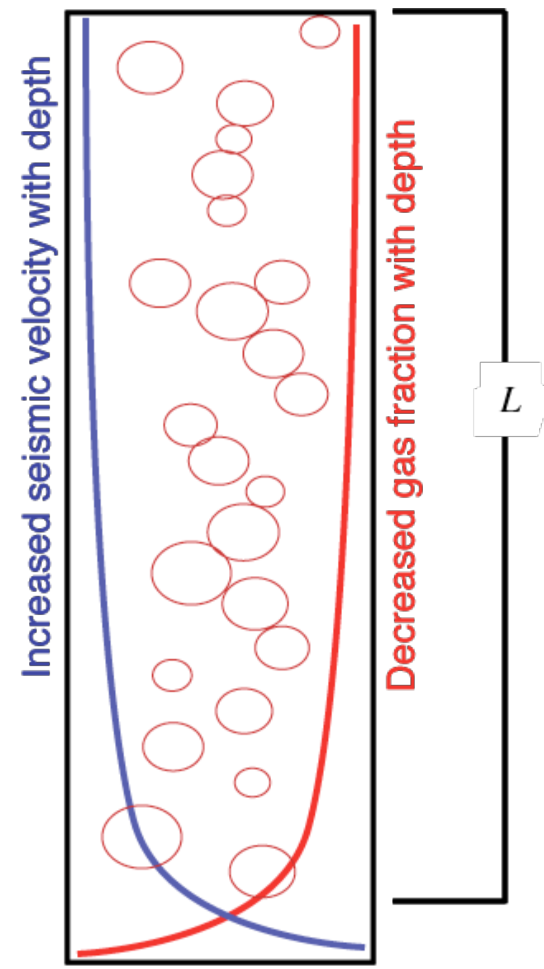
Harmonic Tremor Glide, Fuego Guatemala



- 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

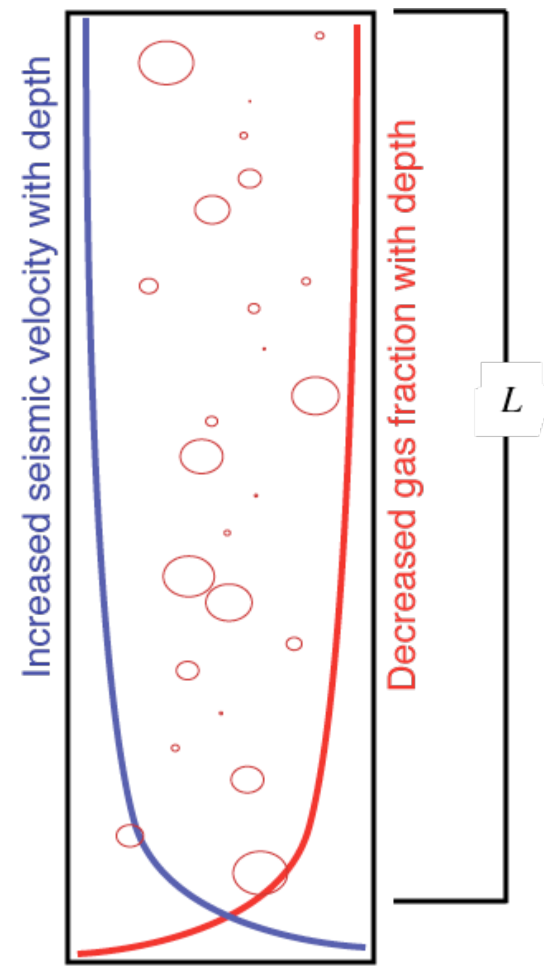
Model For Tremor Glide

- harmonics that are integer multiples of a fundamental frequency, f_0, suggest a column with matched boundary conditions (closed-closed or open-open)
- $f_0 = v/2L$



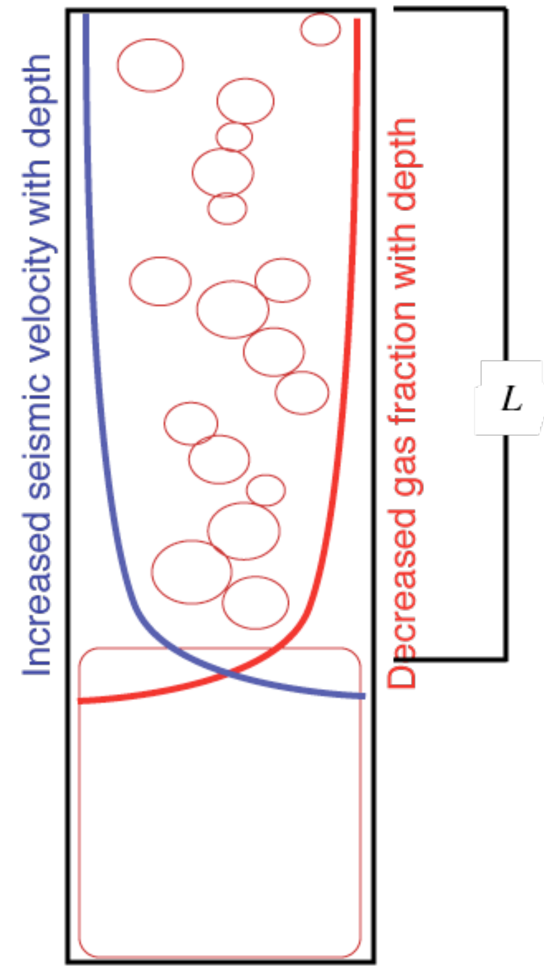
Model For Tremor Glide

- 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?

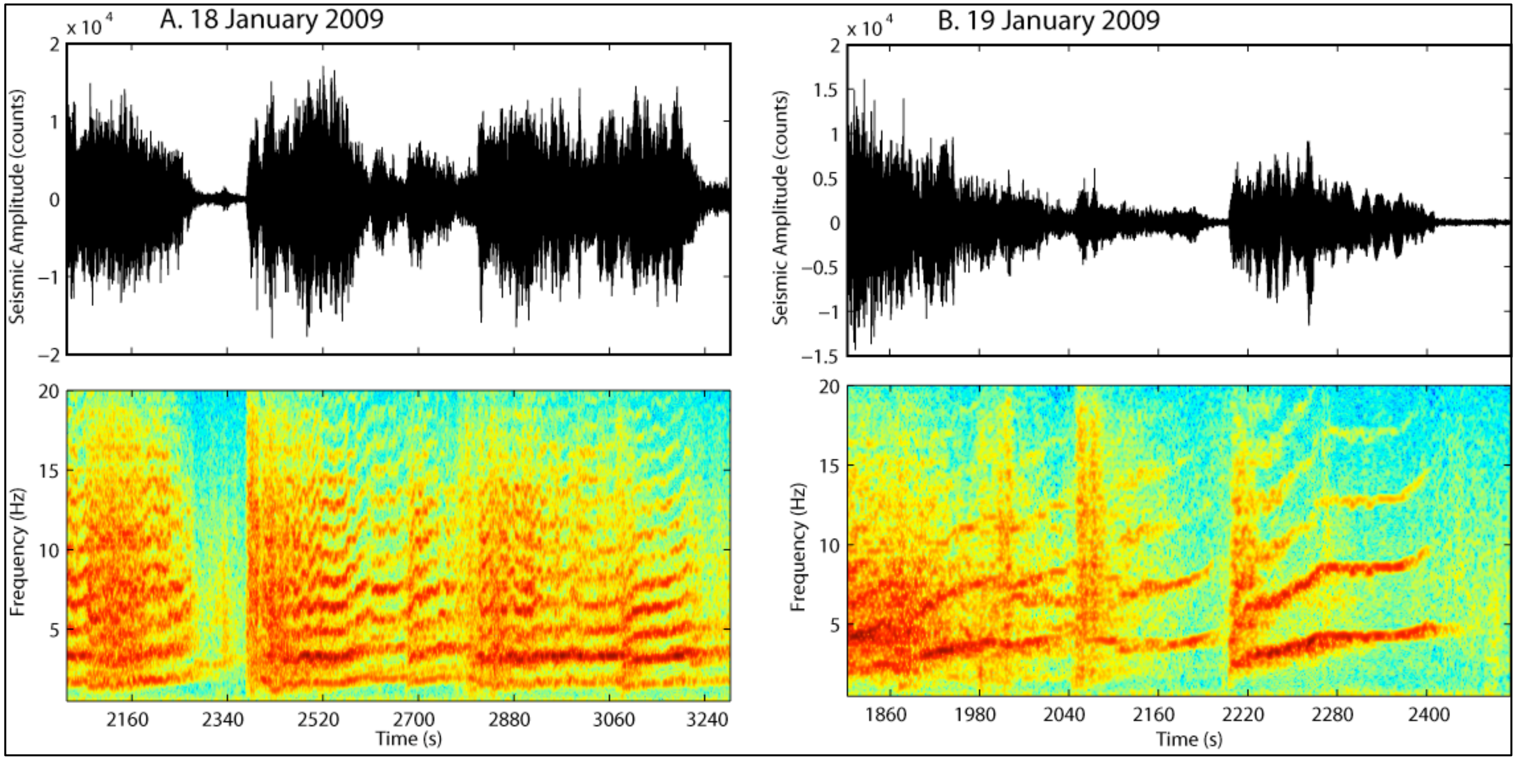


Model For Tremor Glide

- 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

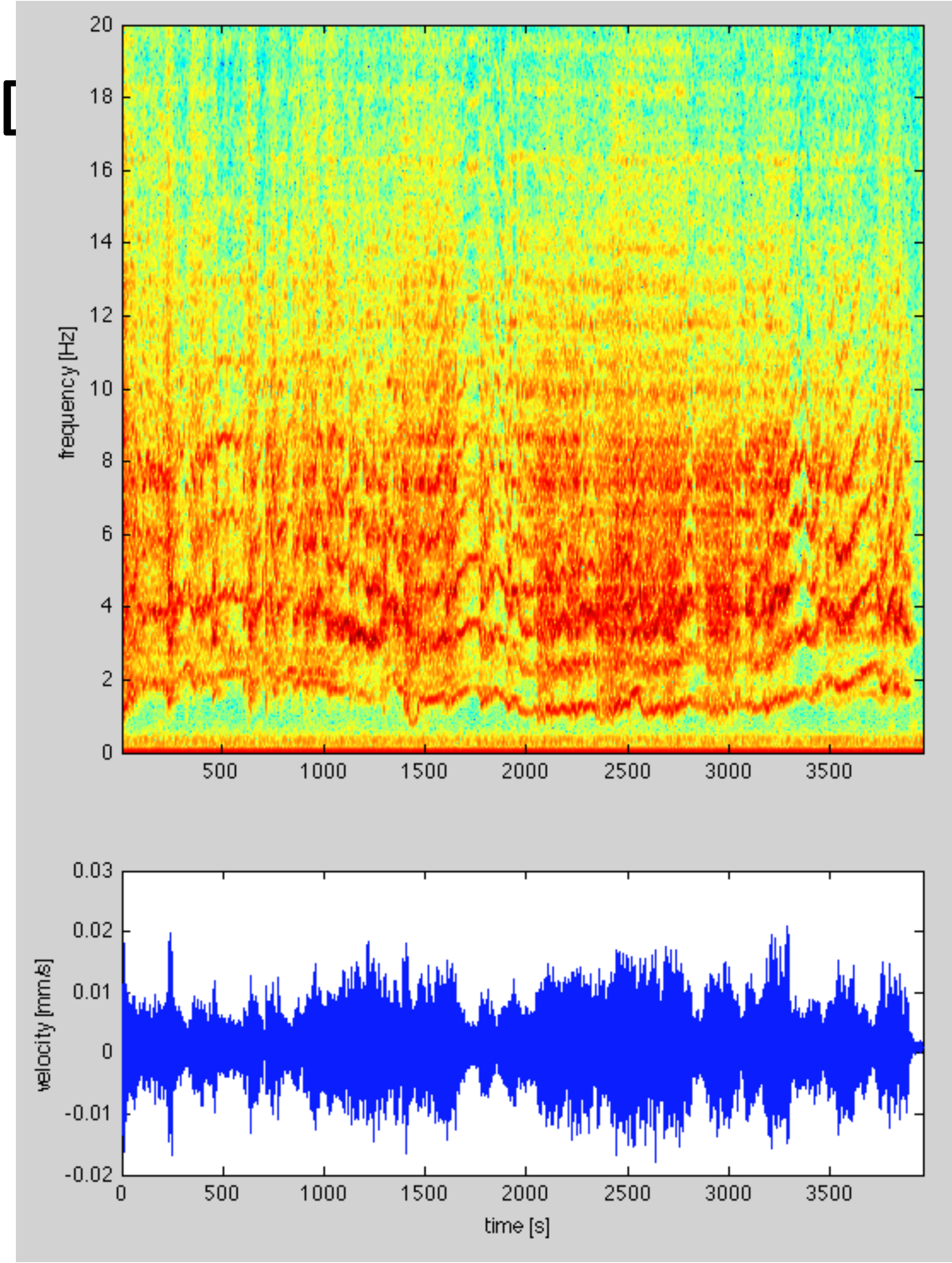


A Model for Harmonic Tremor Glide

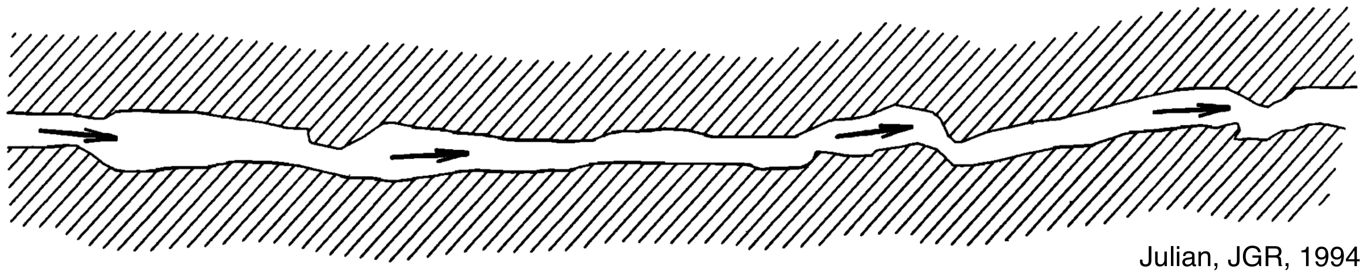


- Gliding could be due to shortening effective length of the conduit
  - For v=400 m/s and f_0=2, L=100 m => f_0=4, L=50 m
  - Implies mobile boundary migrates about 0.4 m/s
- If conduit is sealing, increased pressure could reduce L and increase v

A MOD… …MOR GLIDE



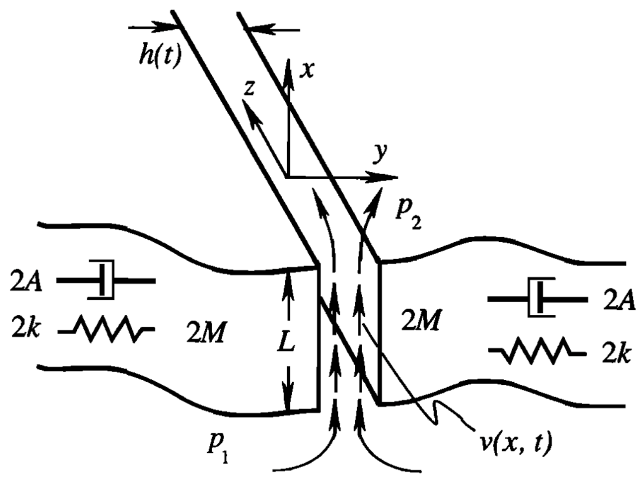
TREMOR DUE TO FLOW INSTABILITY



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 FLOW INSTABILITY



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 number 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)

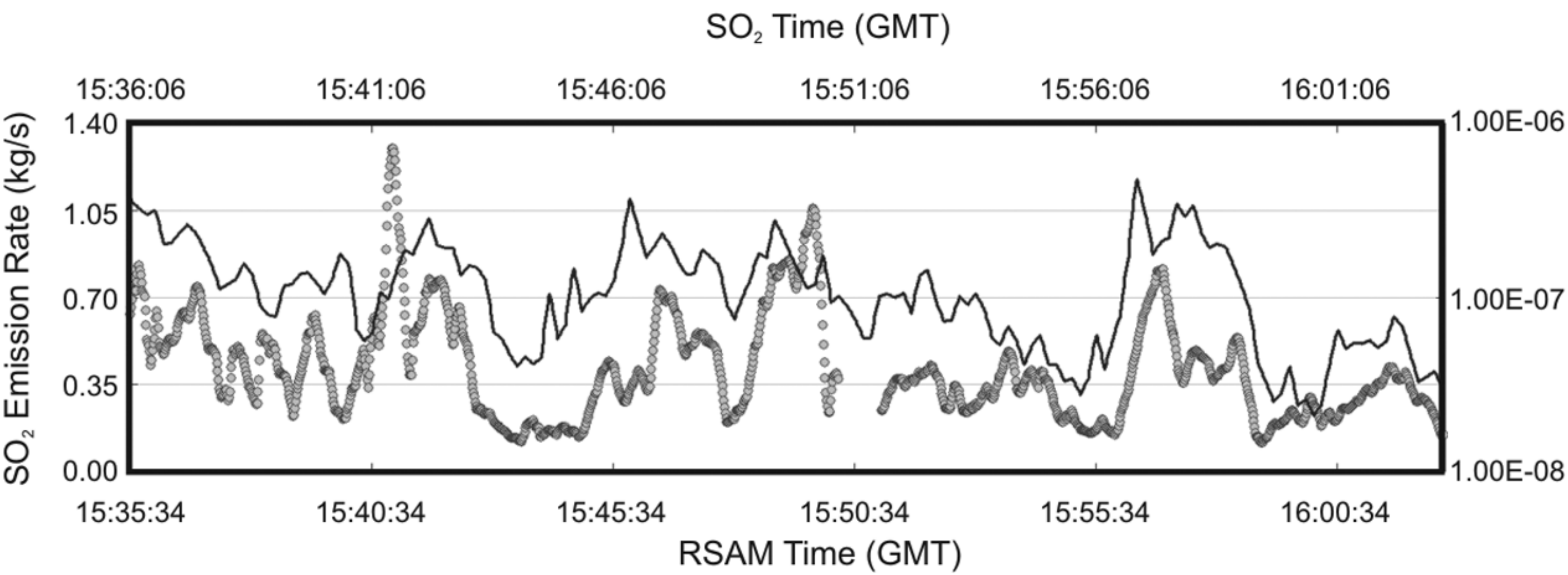
- Example,
  - for r = 1 mm, f_o^{single} ~ 10,000 Hz
  - If $N = 10^{12}$, f_o^{cloud} ~ 2 Hz

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 switch between harmonic and non-harmonic tremor as condition change

NON-HARMONIC TREMOR MODELS

- Gas is involved with the tremor source in some cases



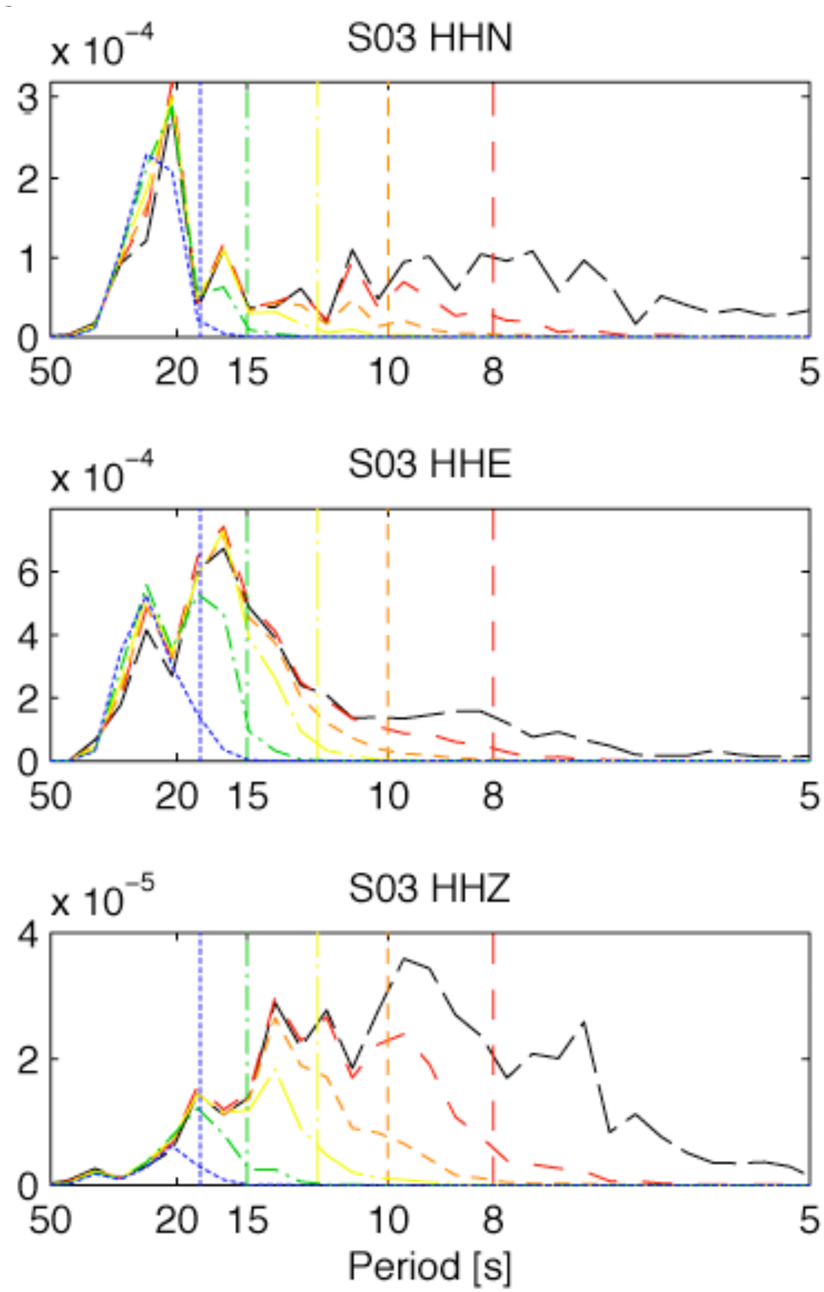
Nadeau et al., *GRL*, 2011

Very-Long-Period Earthquakes

- Observed at many 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

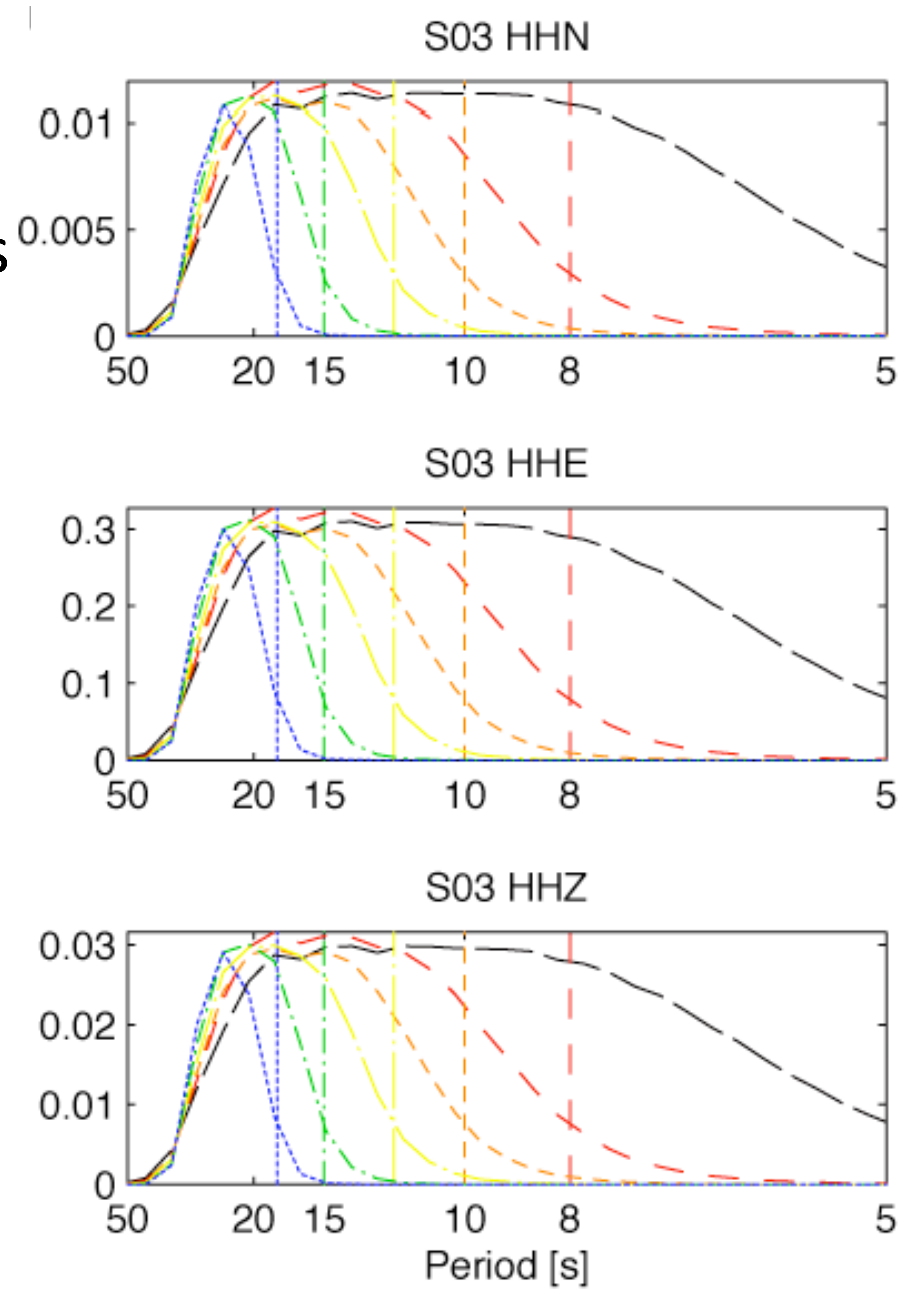
VERY-LONG-PERIOD EARTHQUAKES

- 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 filter independent

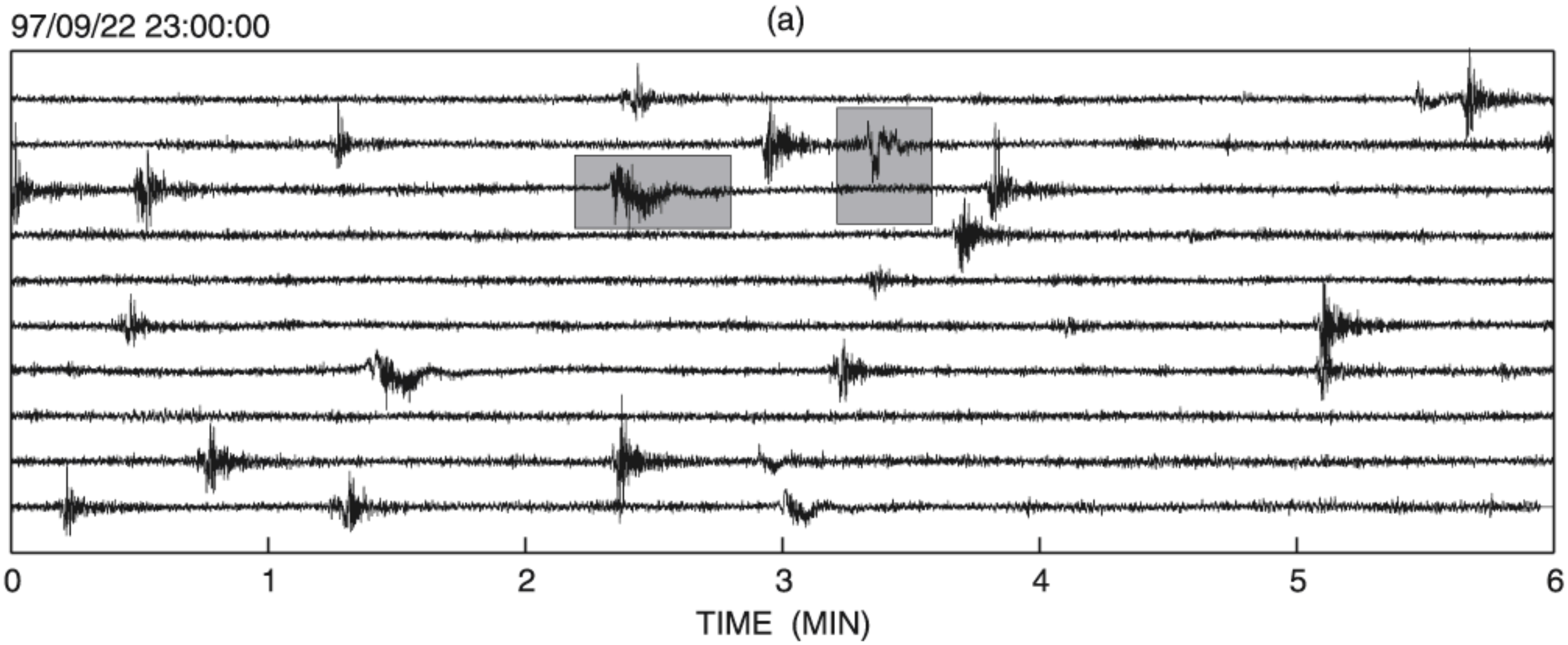


Very-Long-Period Earthquakes

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



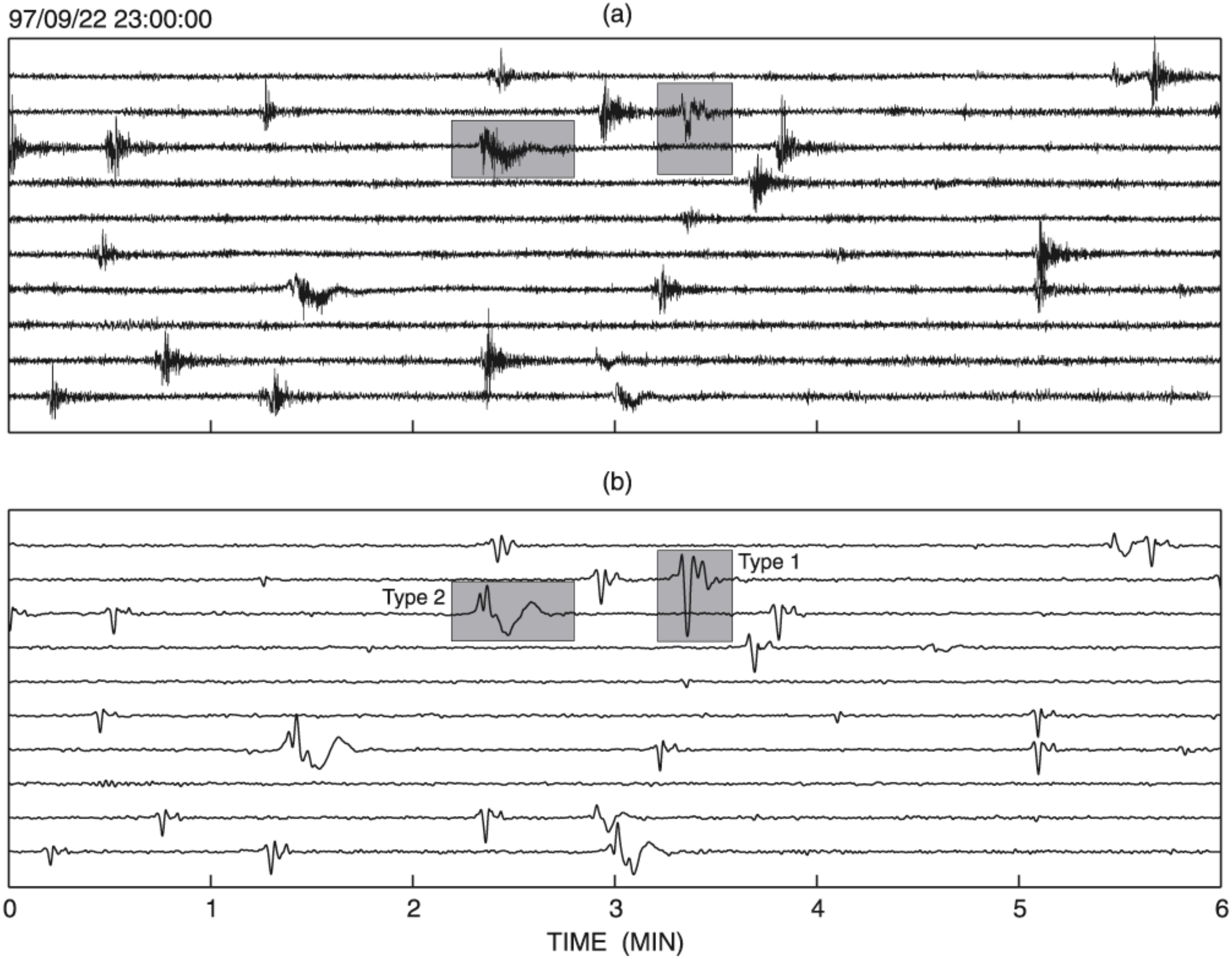
VLPs at Stromboli



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

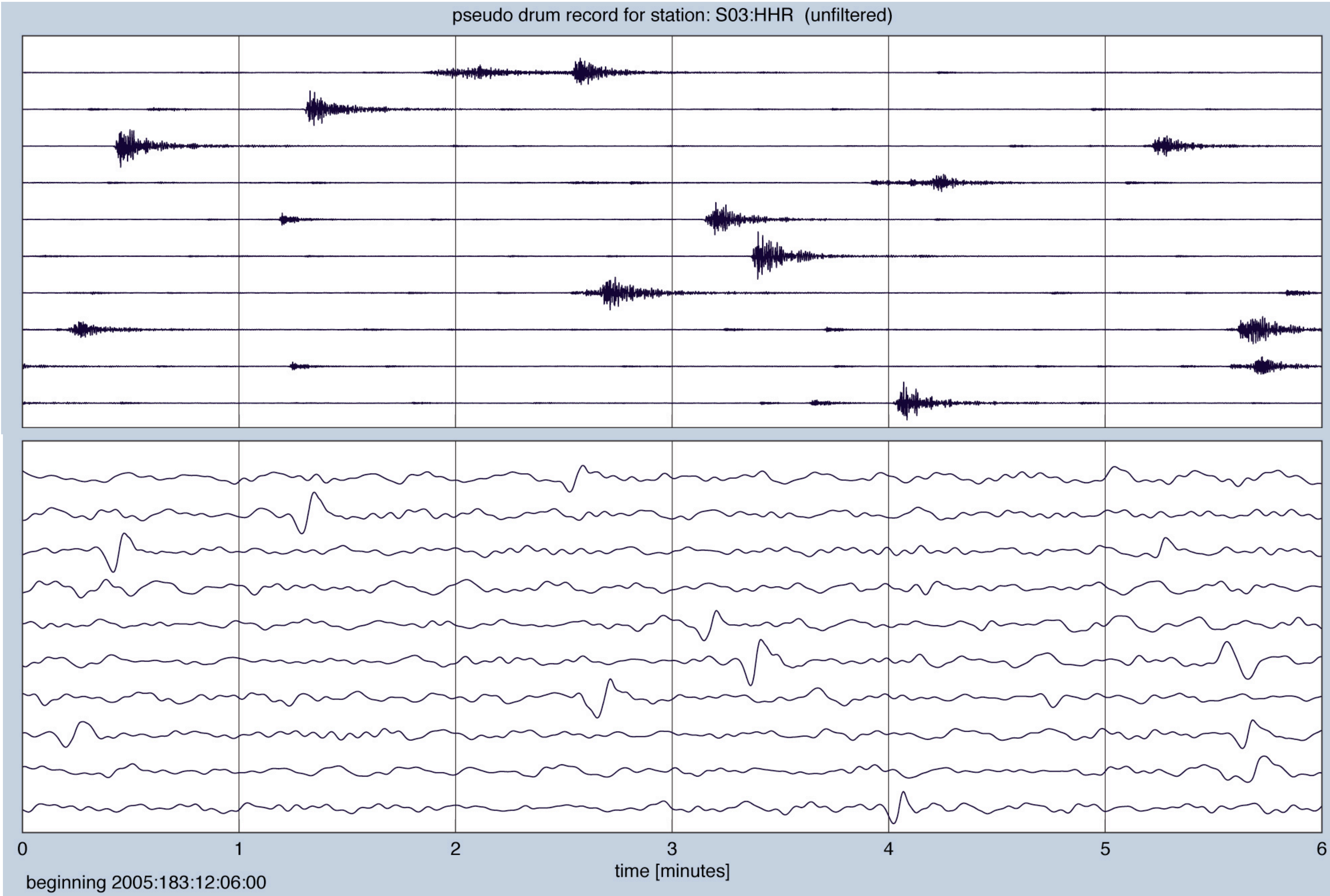
Chouet et al., *JGR*, 2003

VLPs at Stromboli



Chouet et al., *JGR*, 2003

VLPs at Mount St. Helens



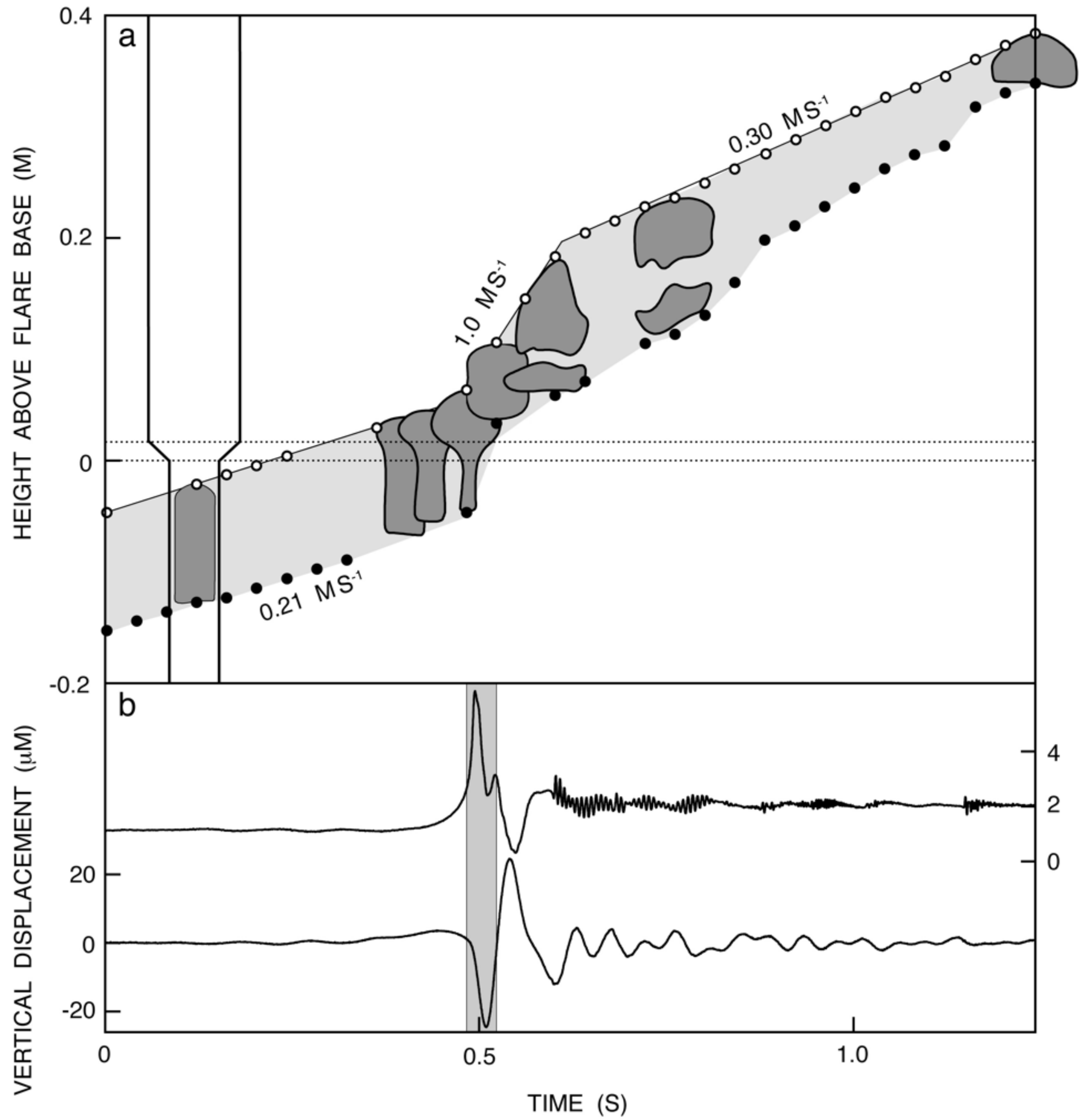
Waite et al., *JGR*, 2008

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

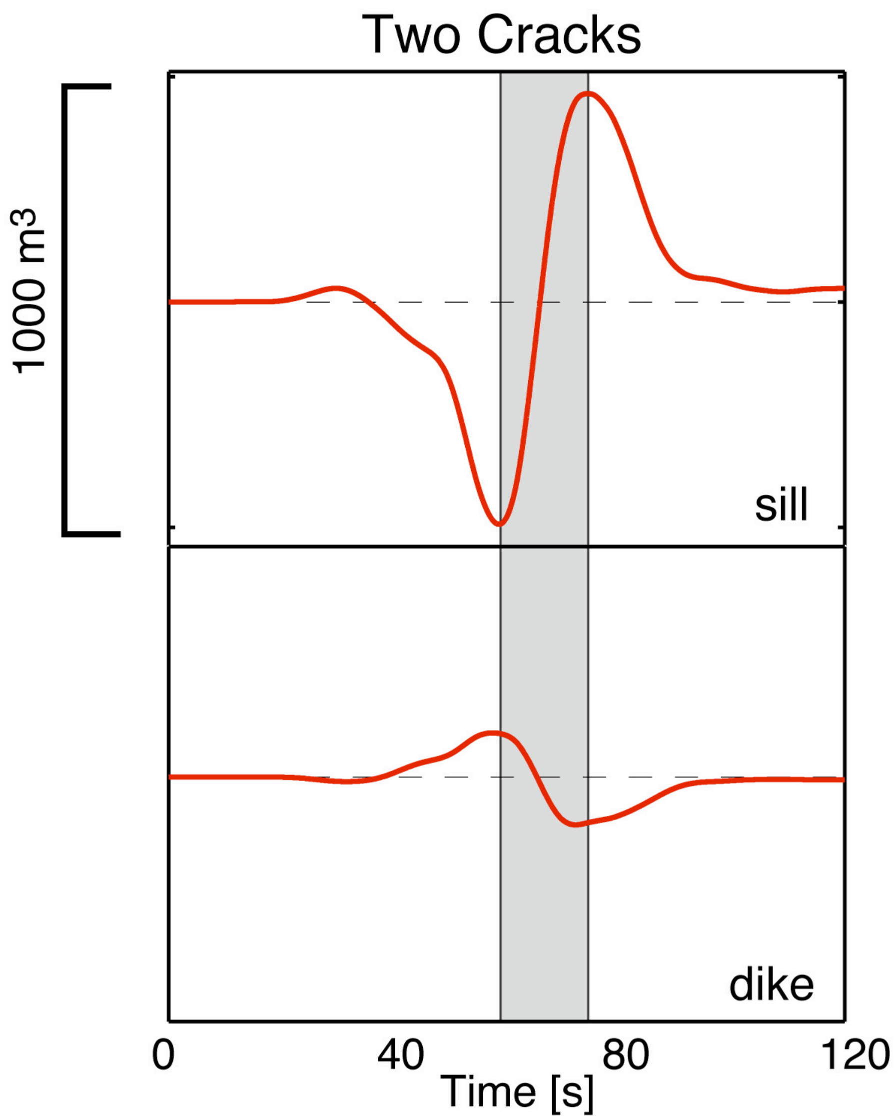
- Bubble accelerates through the flair in the tube
- Liquid annulus falling around the bubble also must accelerate
- Net result is a force (F=ma) that can be translated to the surrounding rock

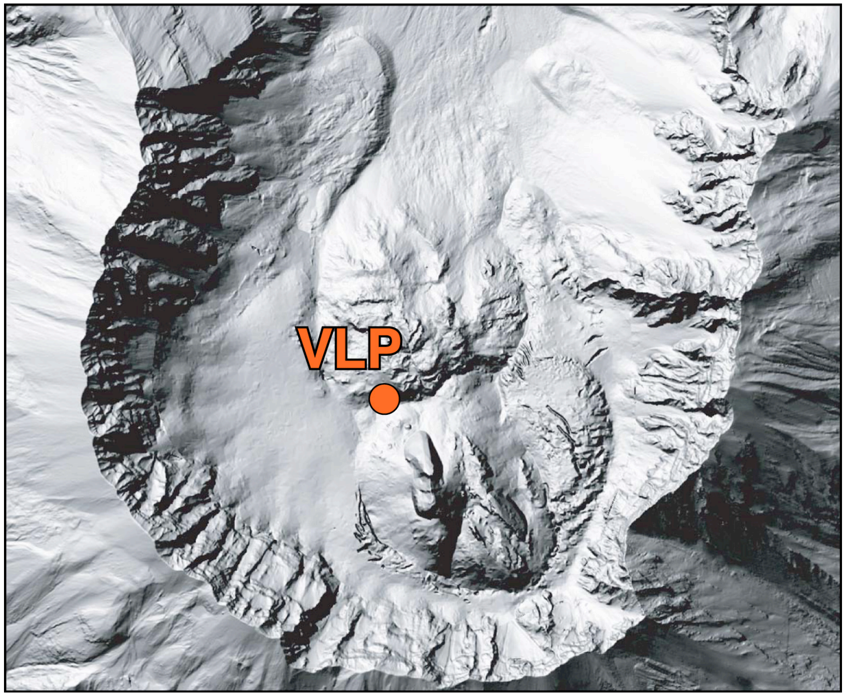


James et al, *JGR*, 2006

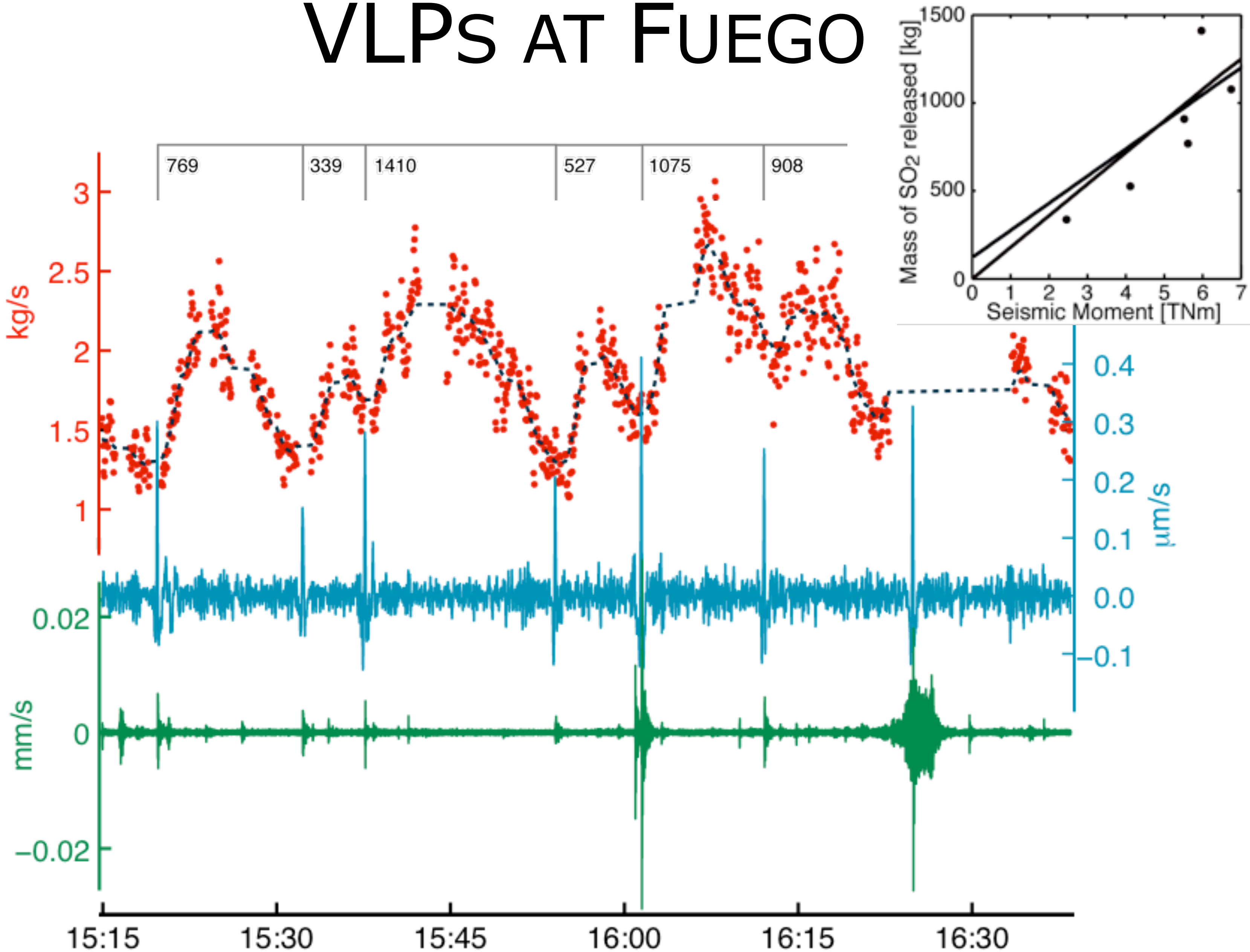
VLP Source-Time Function

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





VLPs at Fuego



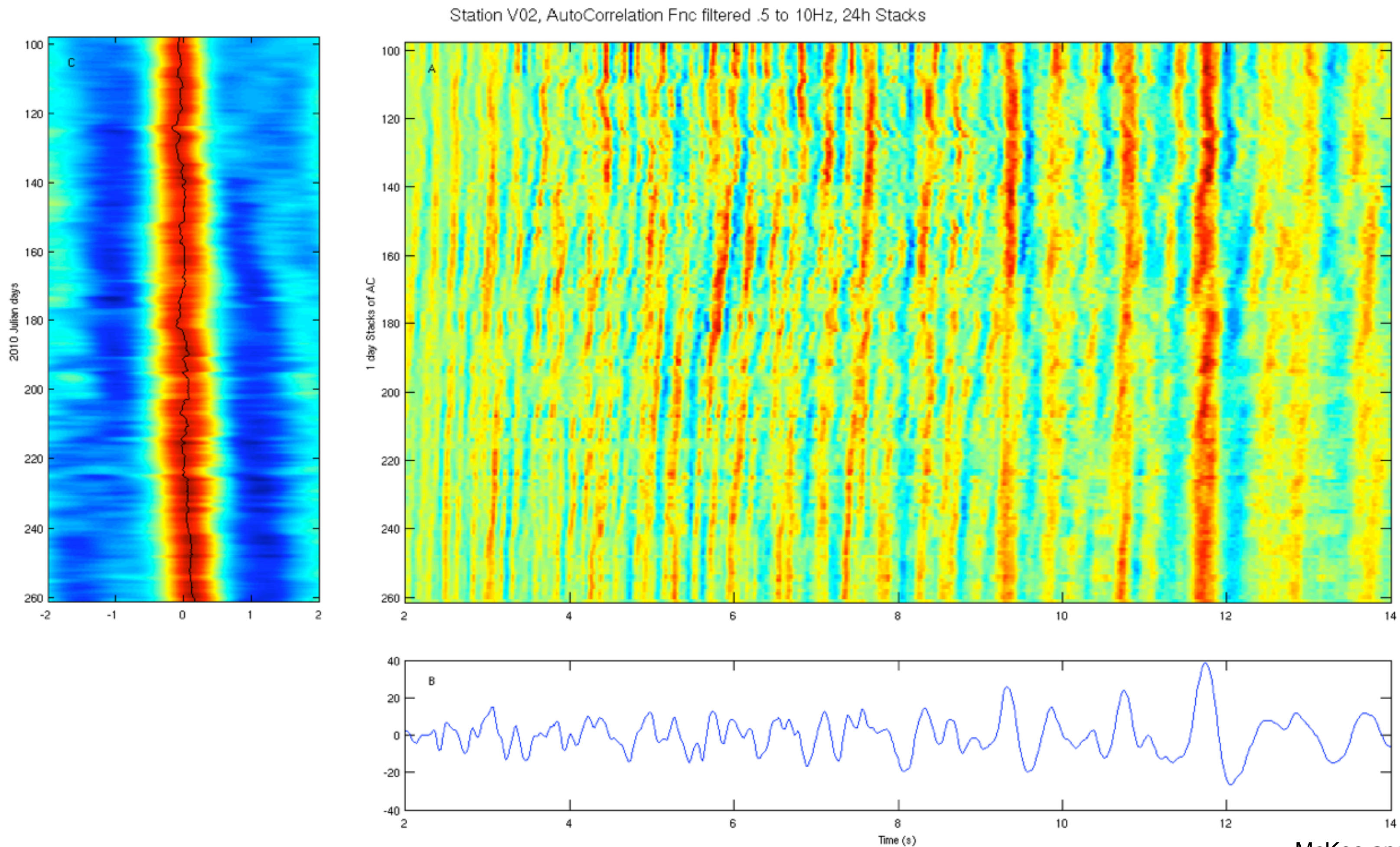
Waite et al, *JGR*, in review

SIGNAL FROM NOISE

- Studies in many settings are demonstrating that information can be extracted from ambient seismic noise
- Seismic waves scatter off of heterogeneities and result in many waves traveling in many directions
- By examining the signals from long recordings at station pairs or single stations, it is possible to model the scattering features in the medium
- Subtle changes in this over time may indicate changes in seismic velocities due to
  - pressure, temperature, etc.

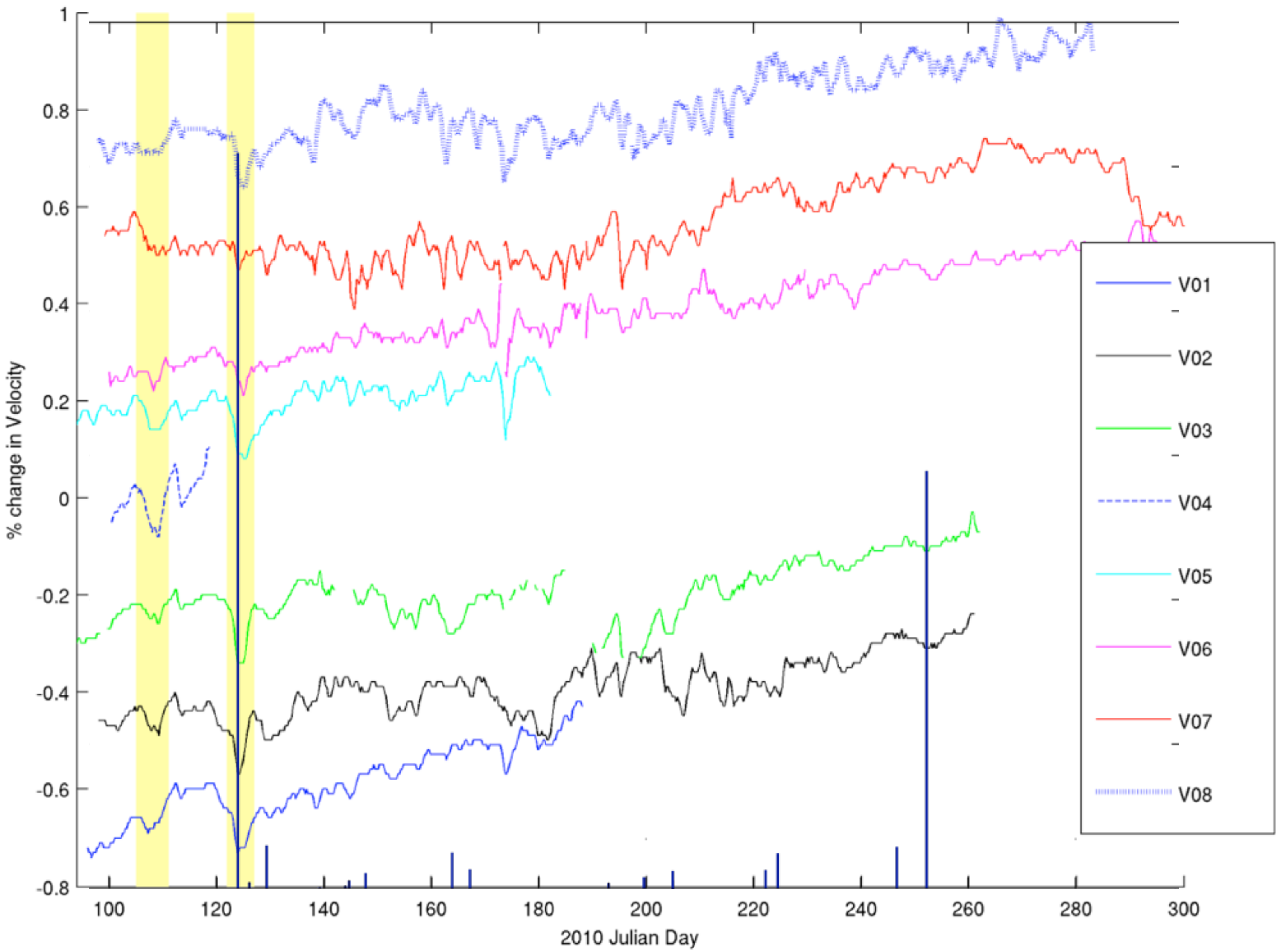
VILLARRICA AMBIENT NOISE

- Auto-correlated hour-long traces after removing large signals from earthquakes, etc.
  - correlation function varies over time



McKee and Waite, in prep

VILLARRICA AMBIENT NOISE



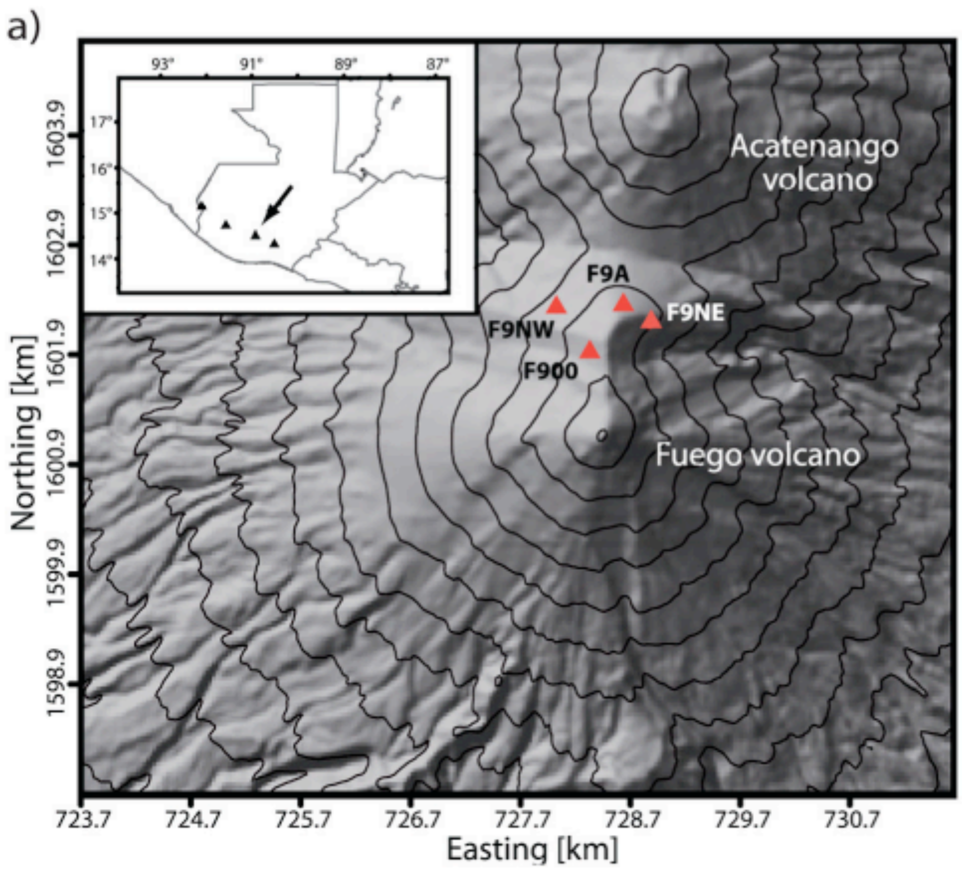
McKee and Waite, in prep

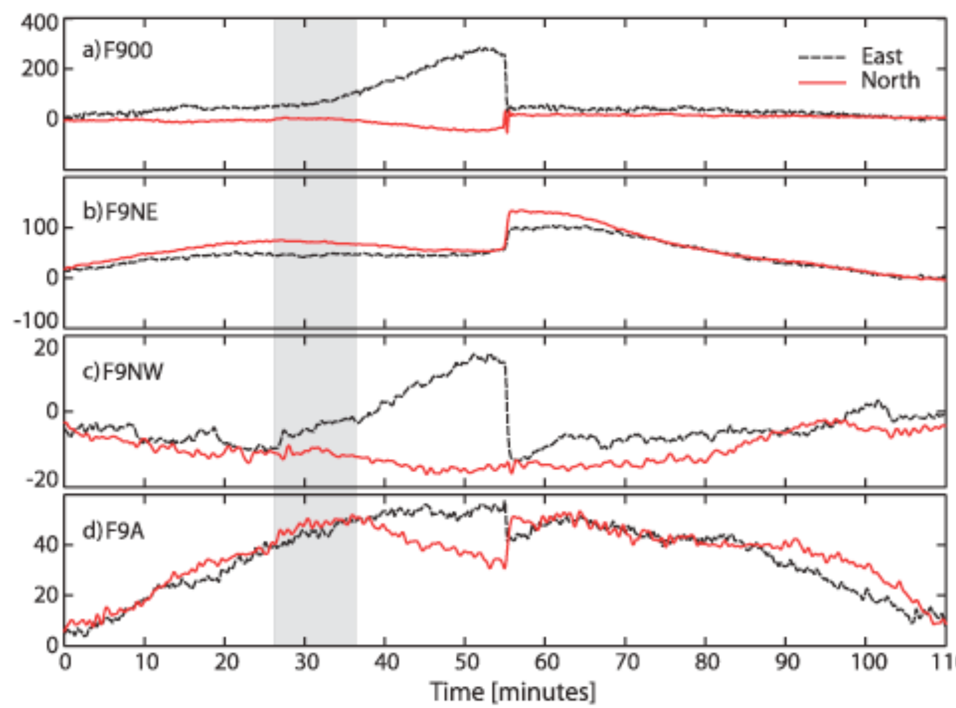
TILT FROM SEISMOMETERS

- the horizontal channels of seismometers respond to ground tilt because it accelerates the masses
  - vertical channels are less affected
- for very low frequencies, ground tilt signal dominates
- must be observed in the near field (< 2 km)
- examples from Soufriere Hills [Voight et al.,1999], Merapi [Voight et al., 2000], Anatahan [Wiens et al., 2005], Stromboli [Genco and Ripepe, 2010], Meakan-dake [Aoyama and Oshima, 2008], Santiaguito [Johnson et al., 2009; Sanderson et al., 2010], Fuego [Lyons et al., 2012]

ULPs at Fuego

- small explosions occurred approximately once per hour
- each explosion was preceded by a tilt signal observed on all stations within 2 km of the vent





Lyons *et al*, GRL, 2012

Summary

- Relatively simple measures of seismicity have been used successfully to predict many eruptions
- Research on different types of volcano seismic signals has helped to improve understanding of the processes involved at different preeruptive stages
- Integration with other data is a powerful new tool for understanding the physical processes
- New techniques have the potential to increase the warning time before eruptions

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PASSCAL Instrument Center

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