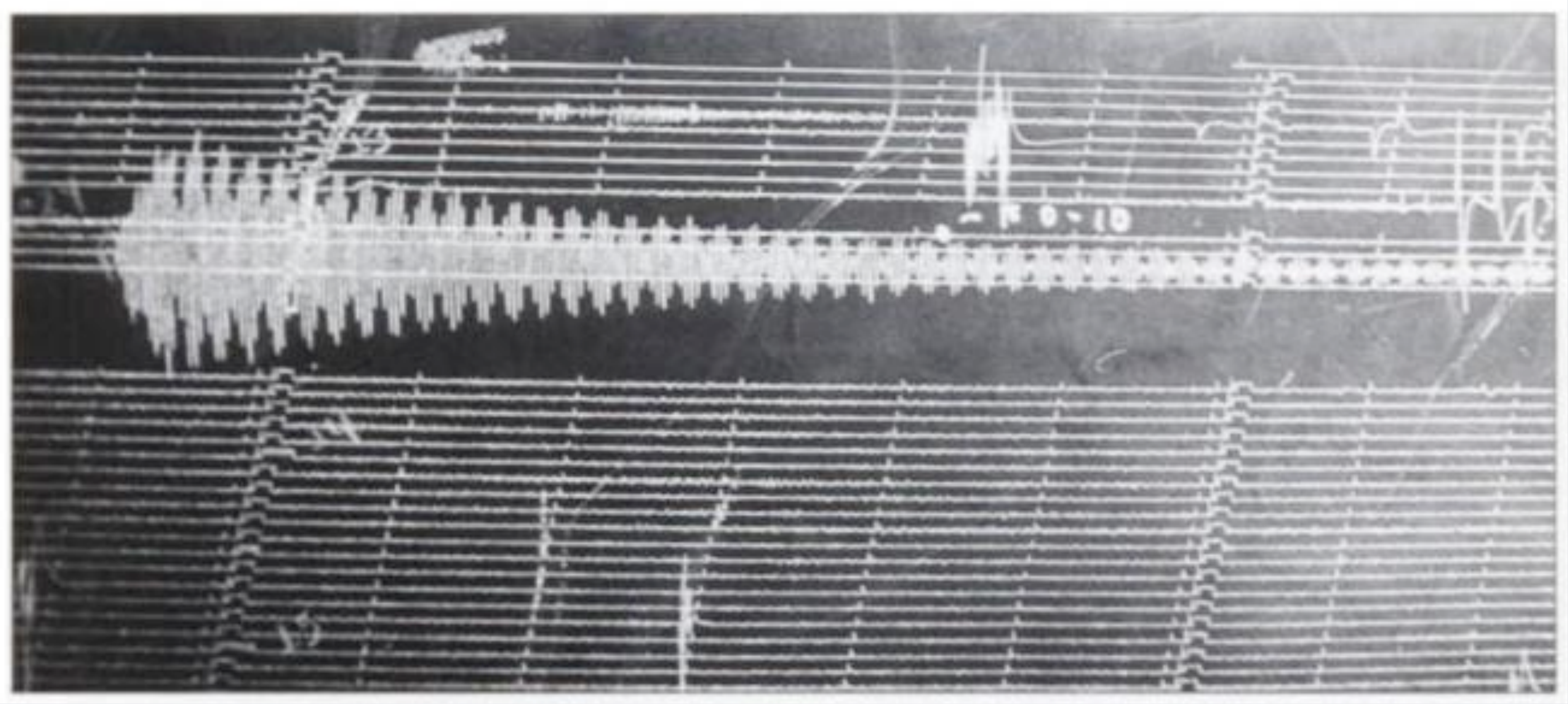


Low-frequency Volcanic Seismicity

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

Outline

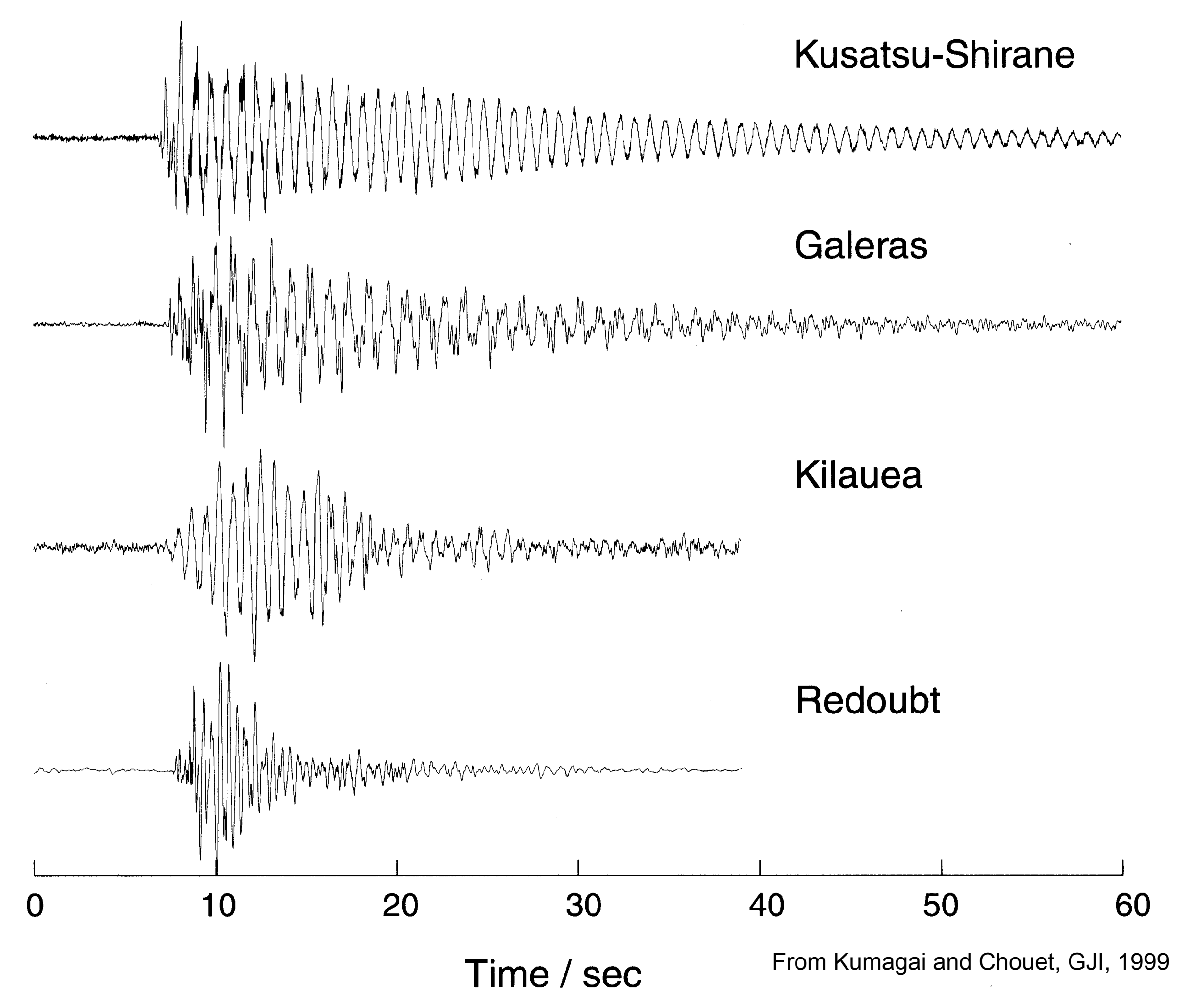
1. Pre-eruption earthquake swarms
    1. Characteristics and variability
    2. Use for eruption forecasting
2. Event classification and source characterization
    1. What are the causes of different signal types
    2. Path distortions
3. Emerging methodologies
    1. Ambient noise
    2. Ground tilt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

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
  - may occur in magmatic or hydrothermal system
- 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)

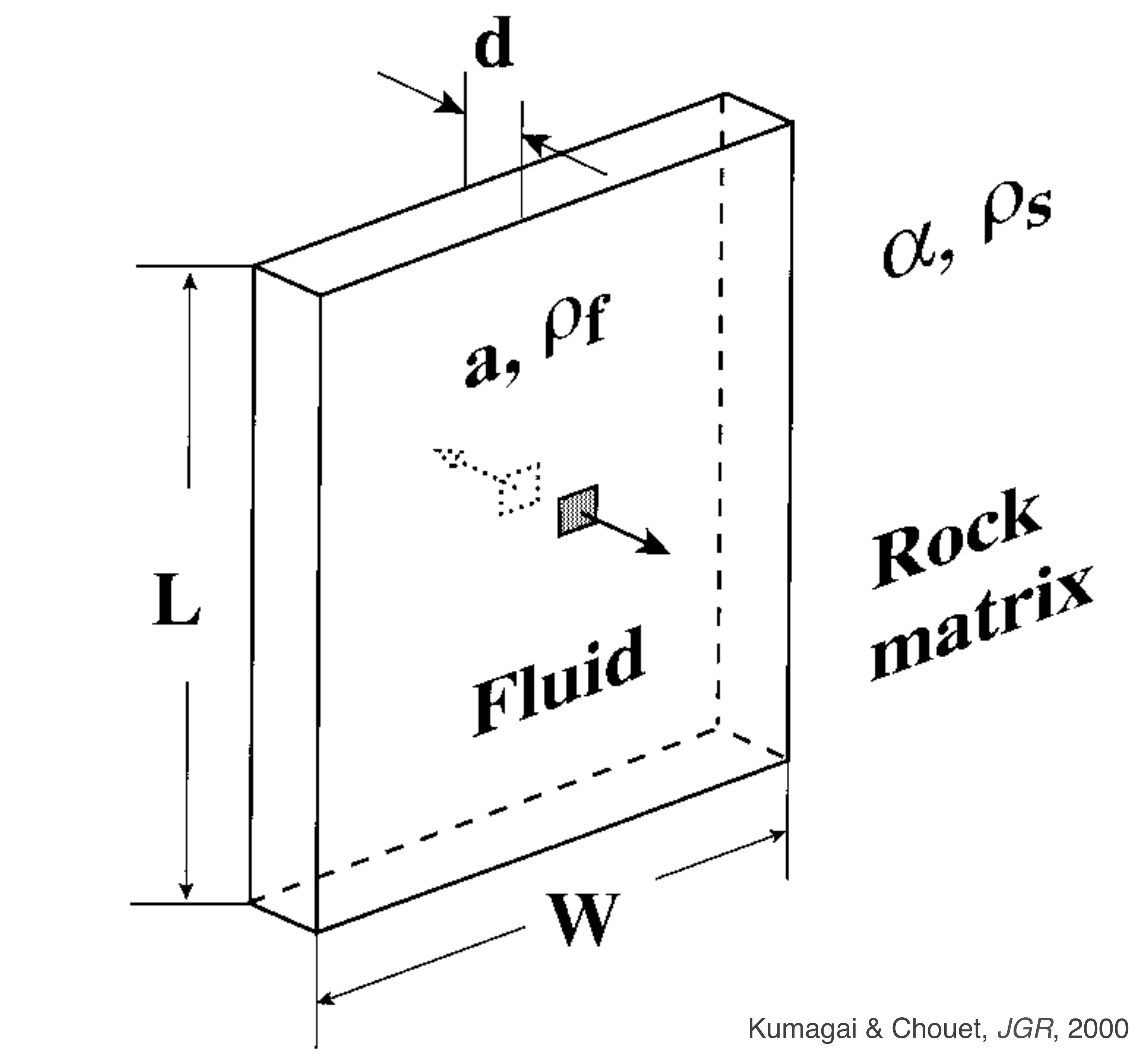


From Kumagai and Chouet, GJI, 1999

Crack Model

developed by Aki, Chouet and Ferrazzini among others

- 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

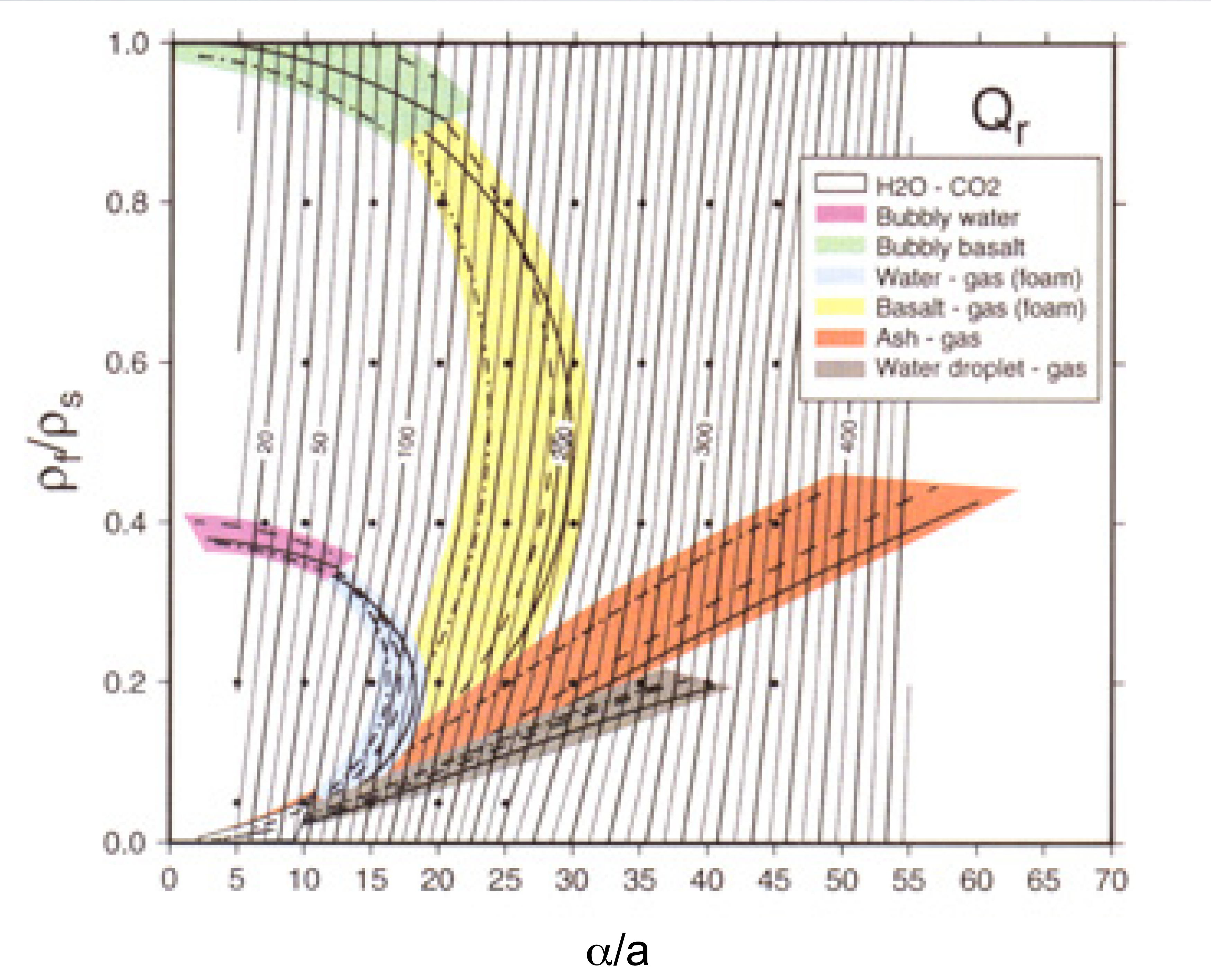
Crack Model

- 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)
  - multi-phase 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

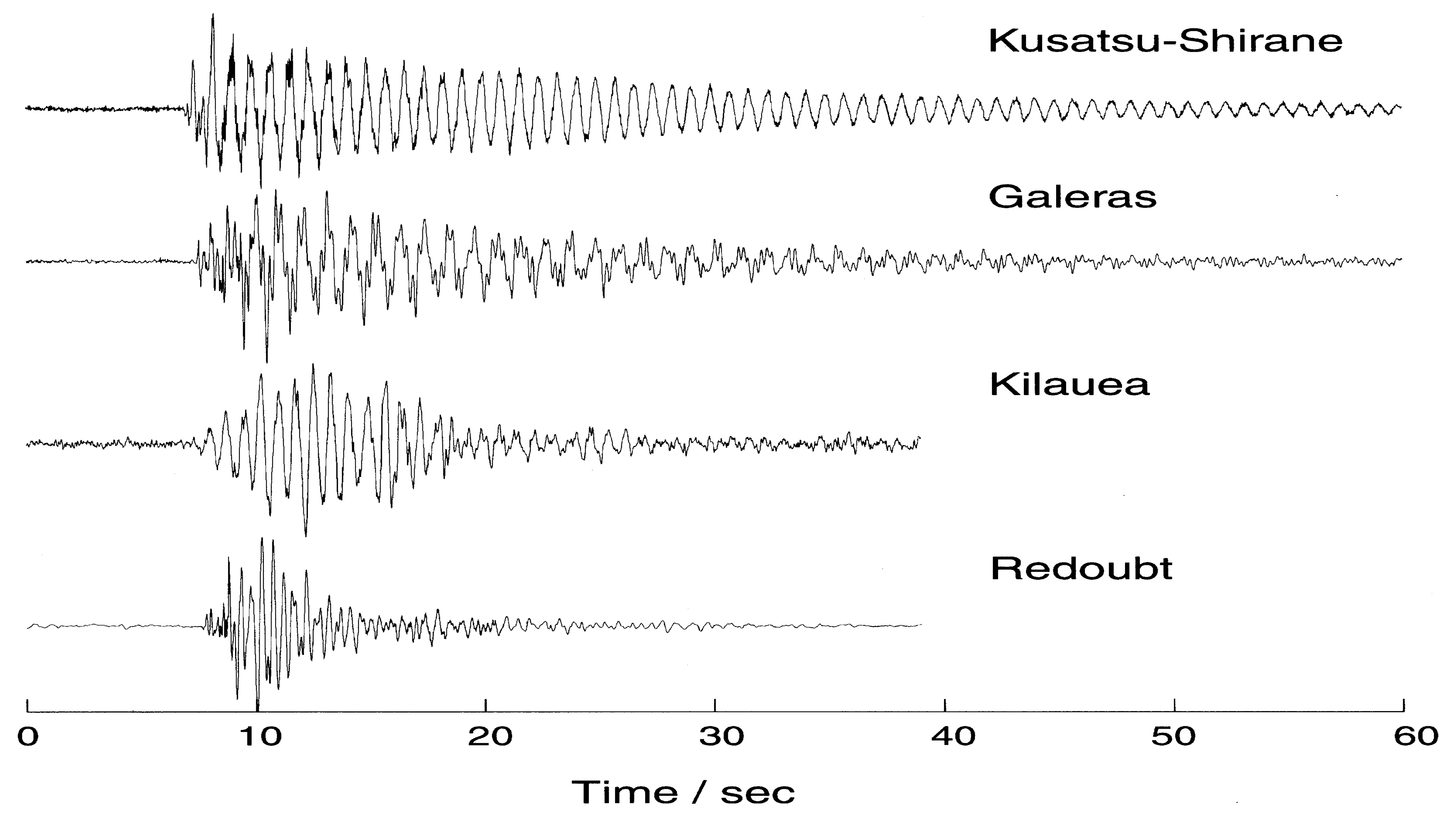
- Low Q$_r$ means the coda decays rapidly
- High Q$_r$ predicts long-duration codas

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: 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 of the wave 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

- 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

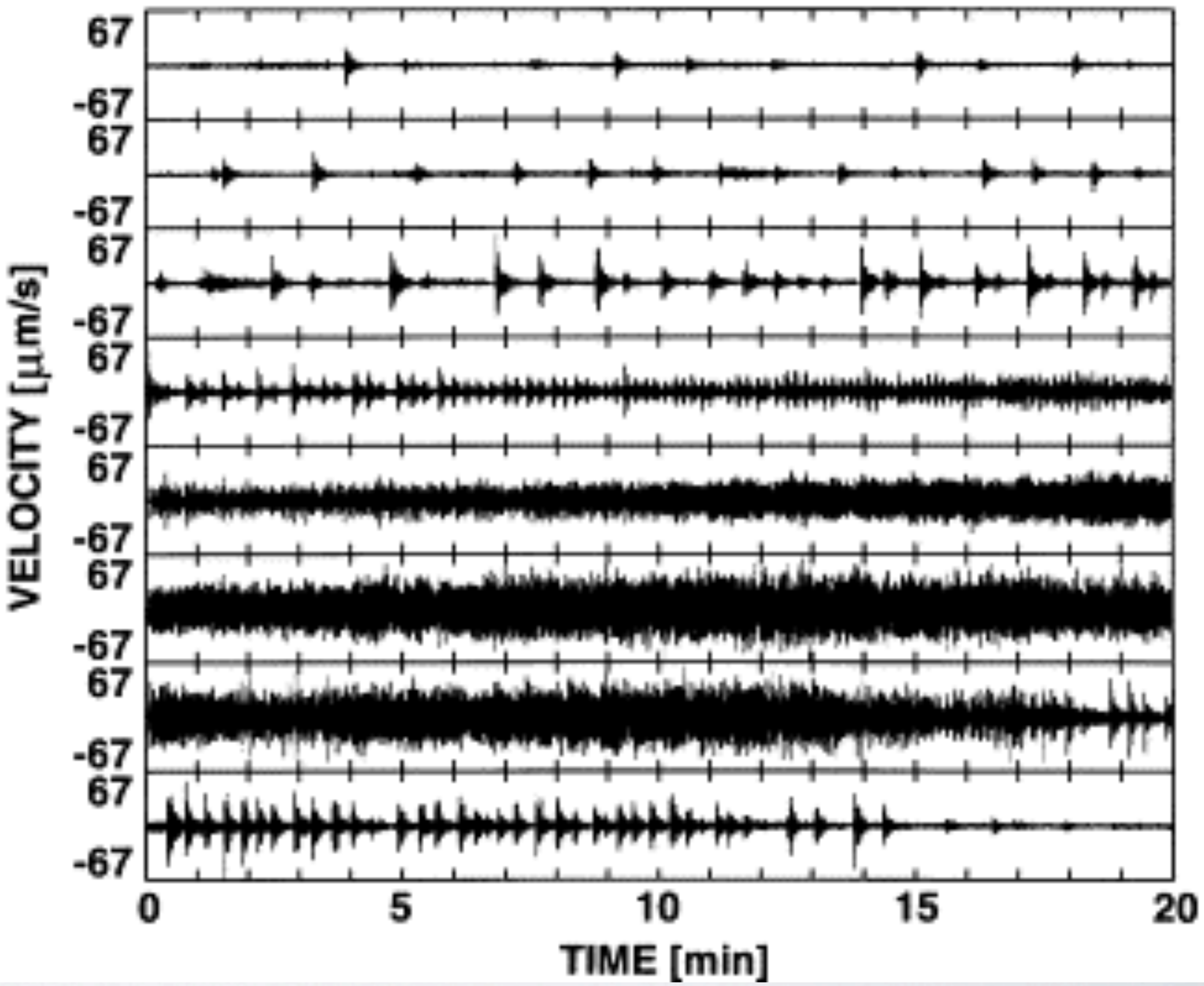
- At silicic volcanoes, a model involving resonance of fluid-filled cracks along the conduit margin may explain LP earthquakes

- 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

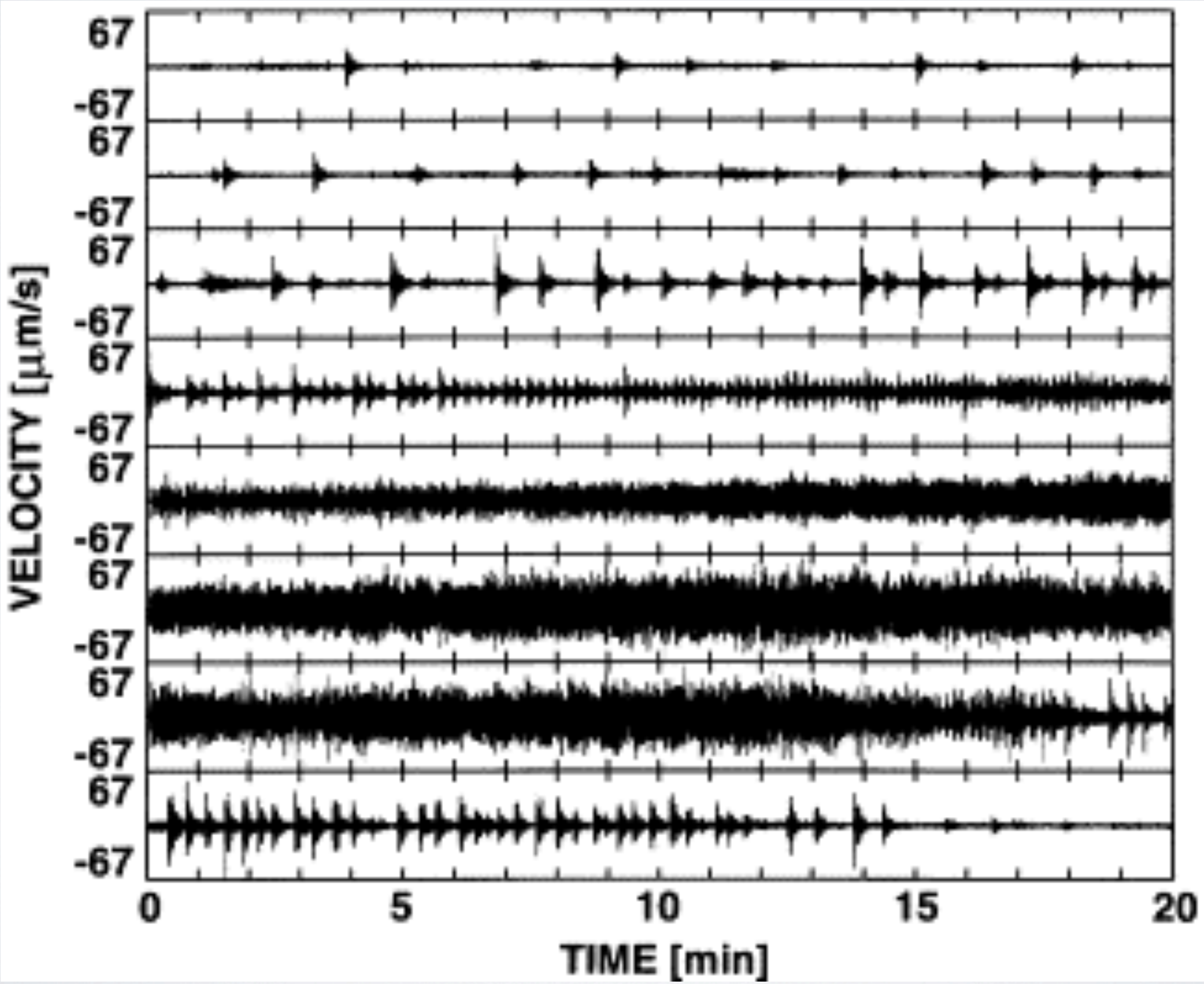
    - suggests a common source mechanism for LP and tremor activity



Neuberg et al., *JVGR*, 2000

Conduit Margin Fracture Resonance

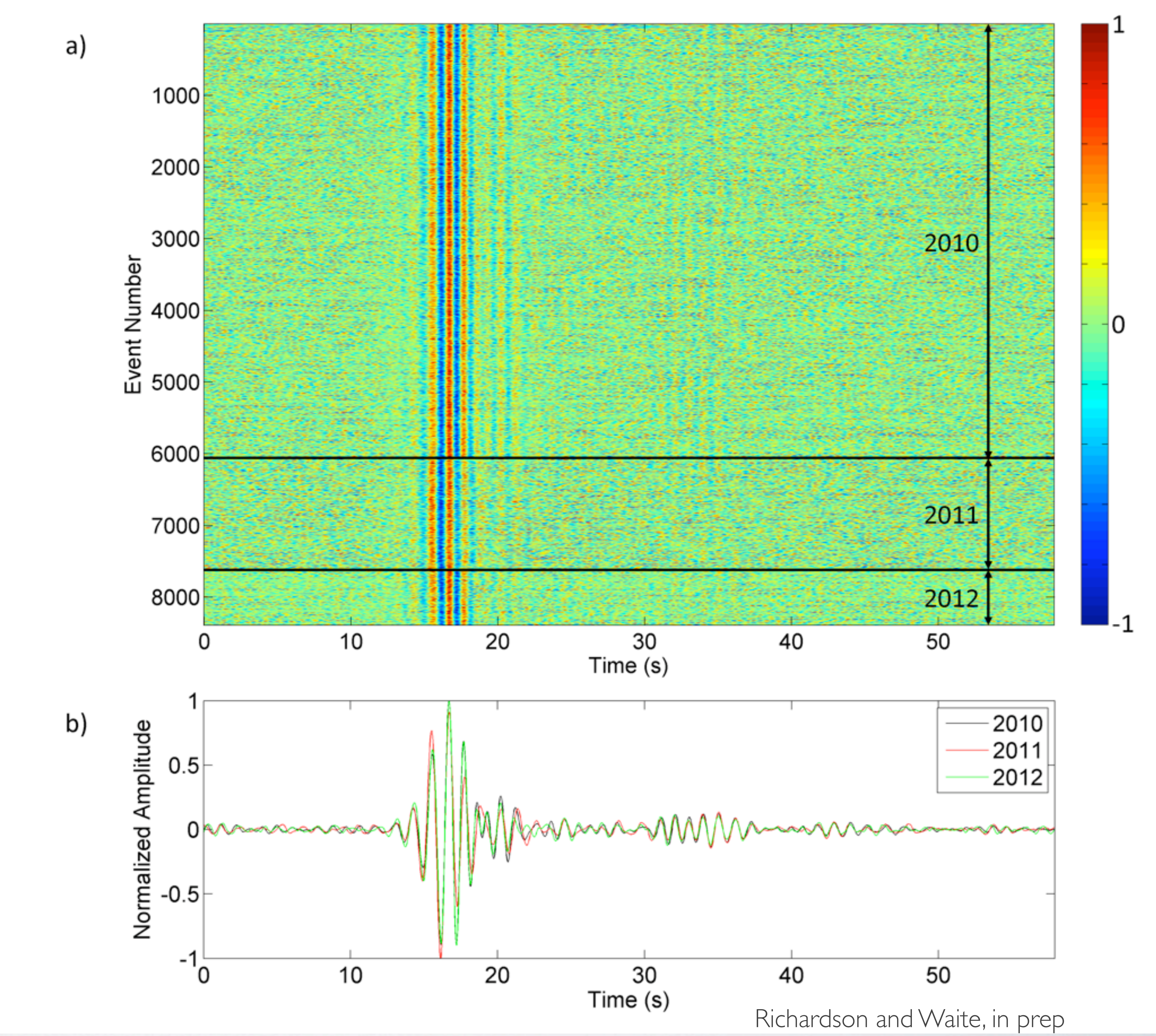
- Increased activity may indicate an increase in effusion rate



Neuberg et al., *JVGR*, 2000

Villarrica LPs and Tremor

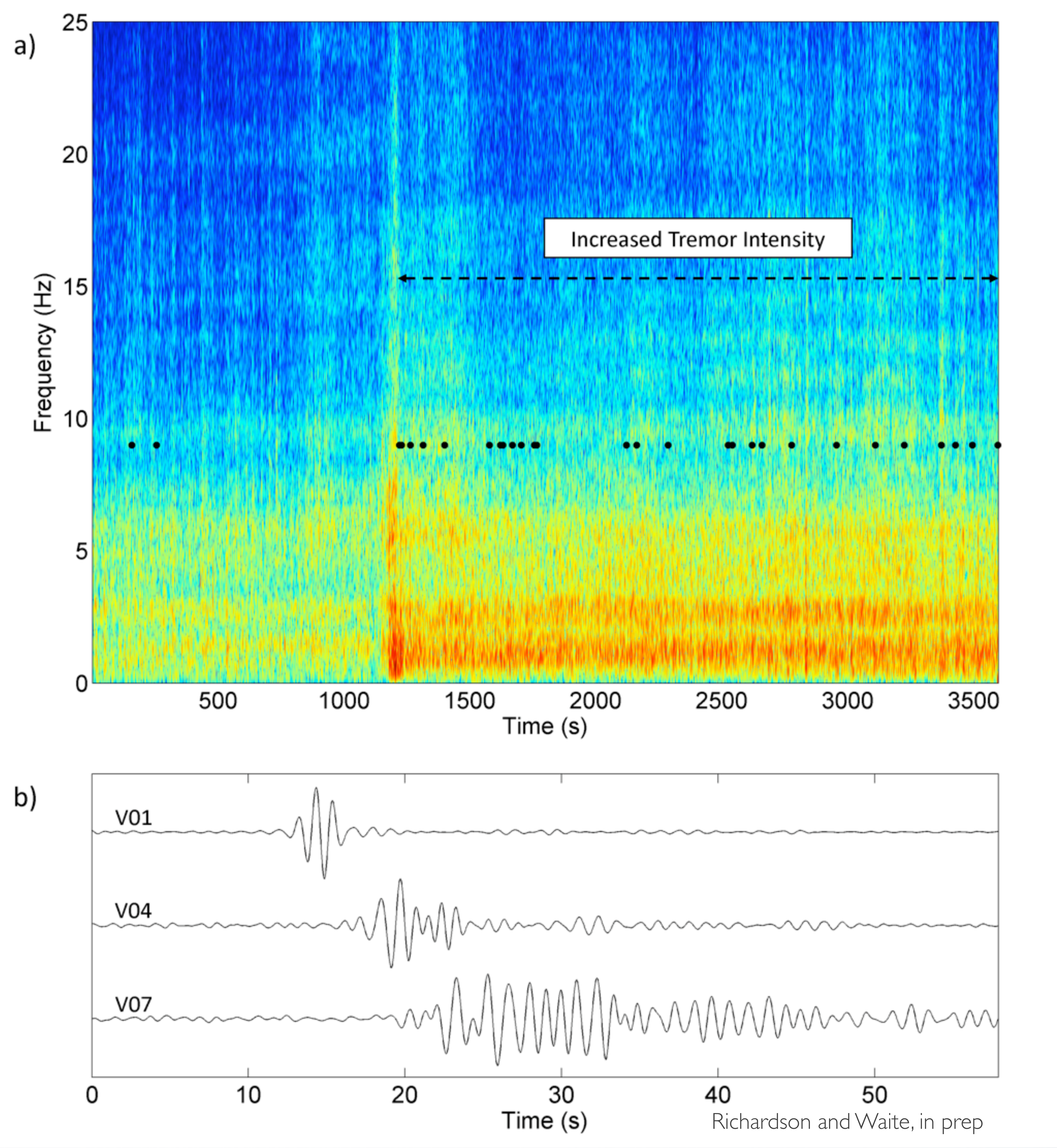
- weak seismic signal associated with bubble burst at the surface of the lava lake
- repeatable for years
- stack has high S/N



Richardson and Waite, in prep

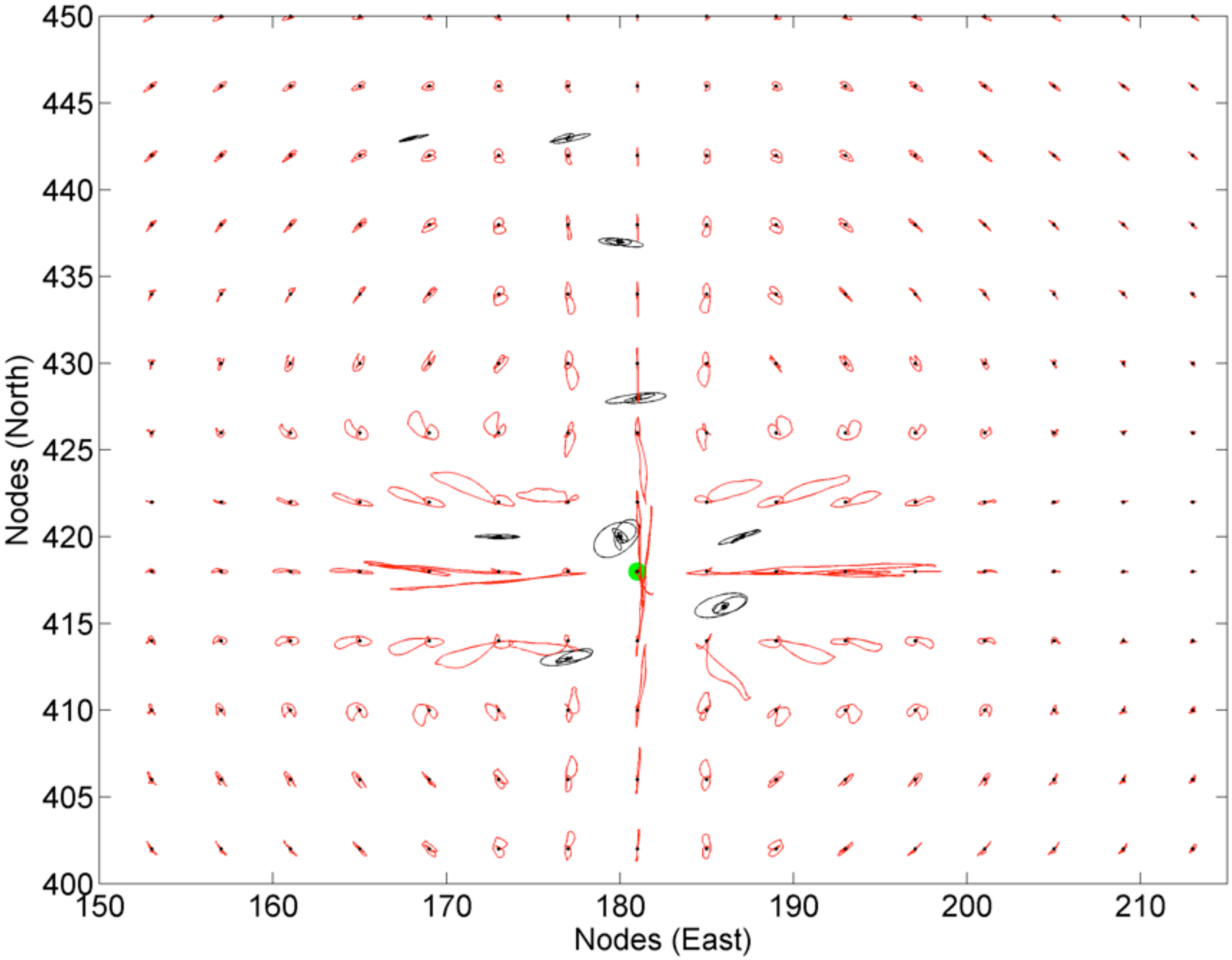
Villarric

- 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

a)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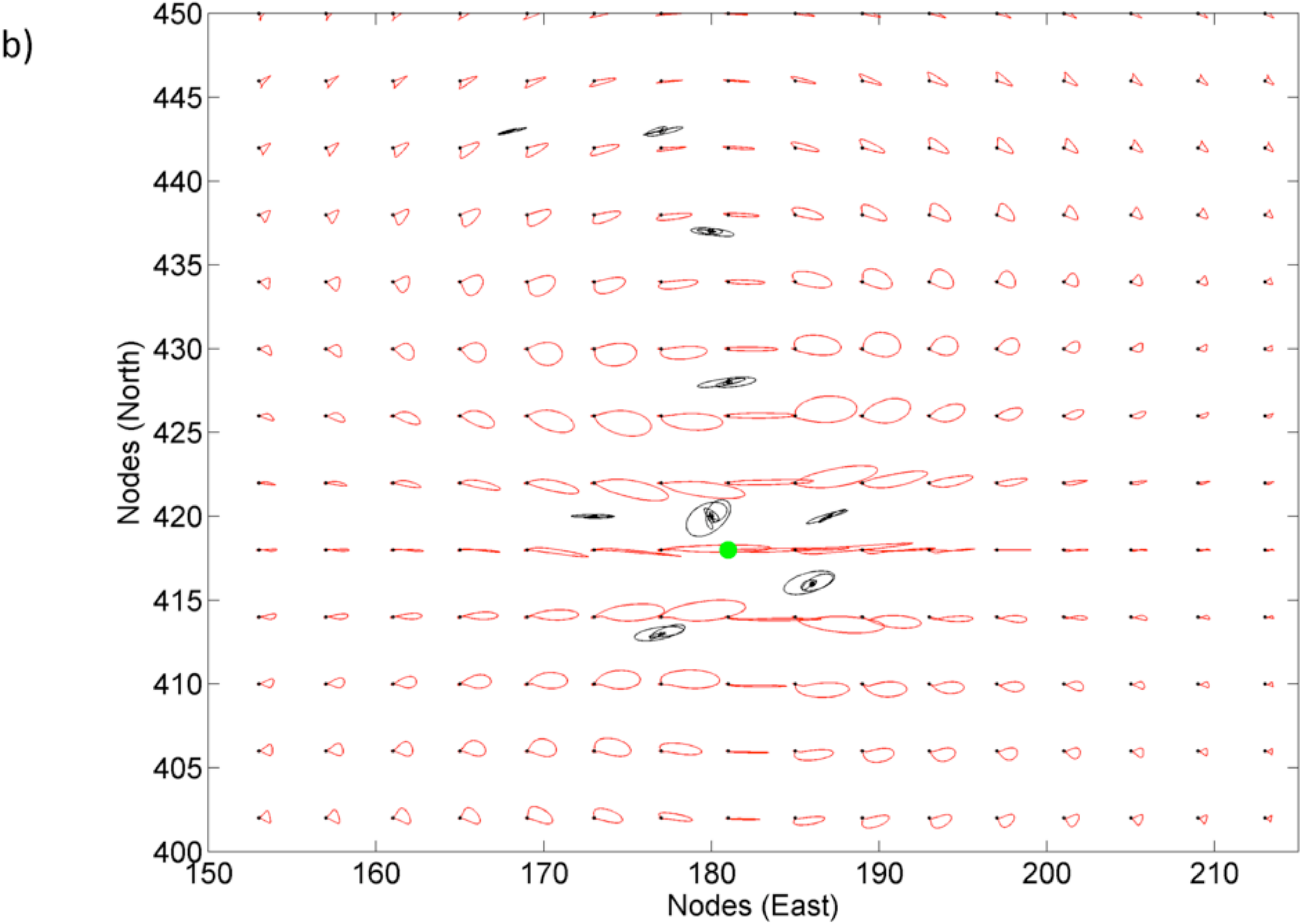
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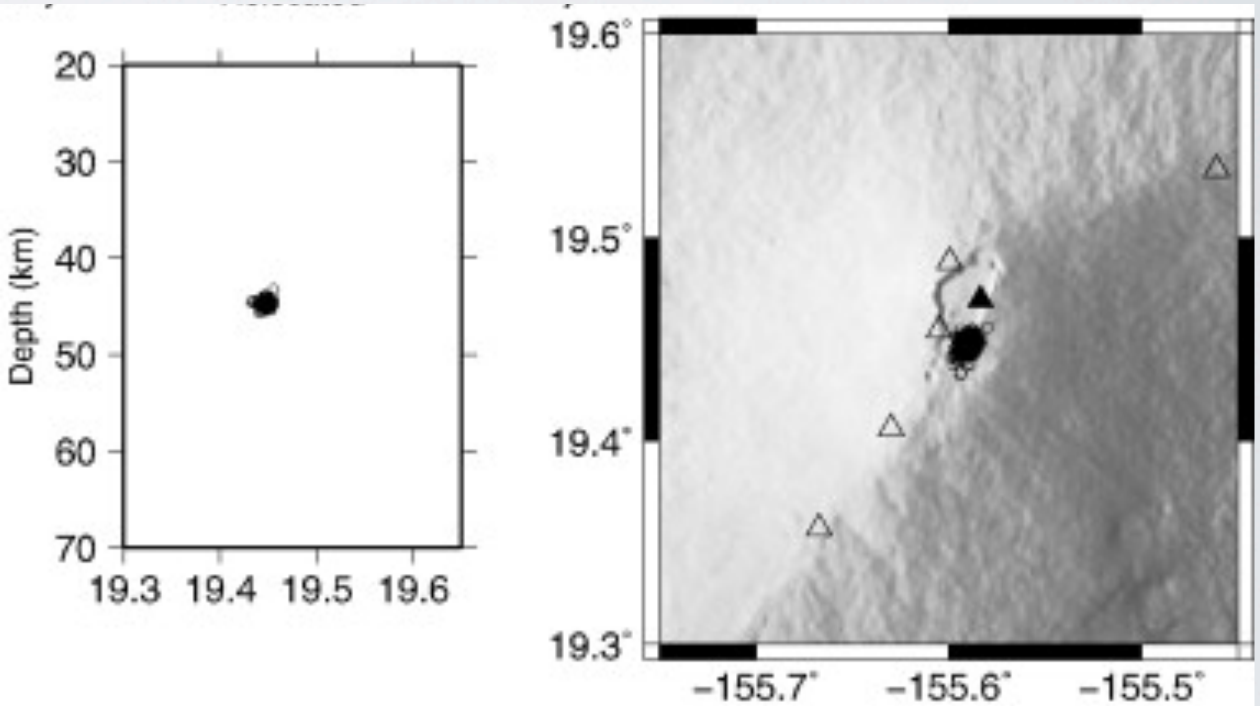
Nodes (East)


450

Deep LPs Beneath Mauna Loa

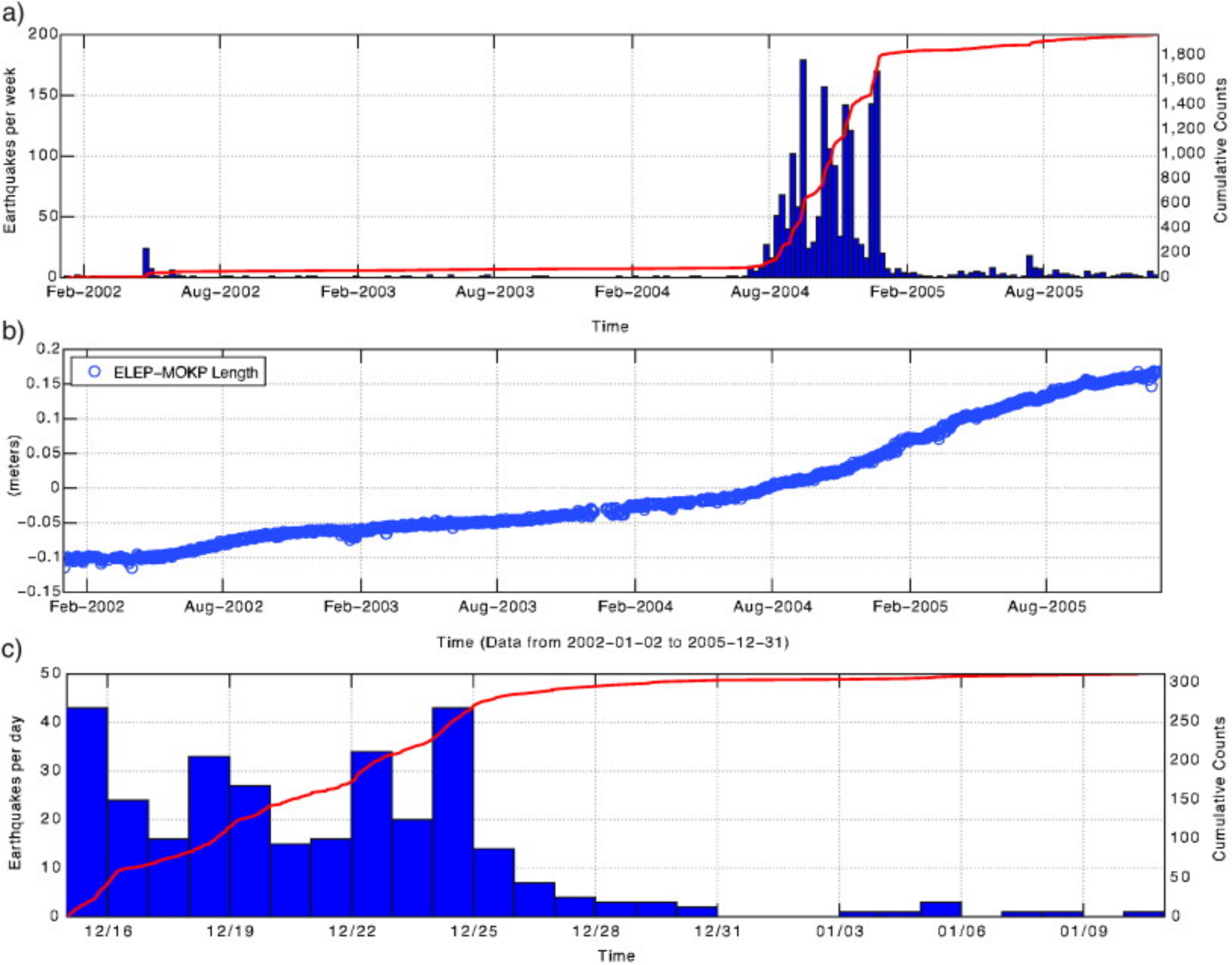
- Start of swarm preceded accelerated inflation of Mauna Loa in late 2004
- Located in the upper mantle
- Occurrence modulated by Sumatra M_W9.4
- P and S waves observed

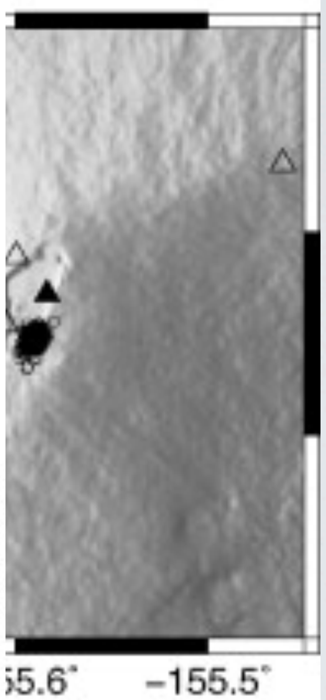


Okubo and Wolfe, JVGR, 2008

Deep LPs Beneath Mauna Loa

- Sta Loa in
  lat
- Loc
- Oc
- P a





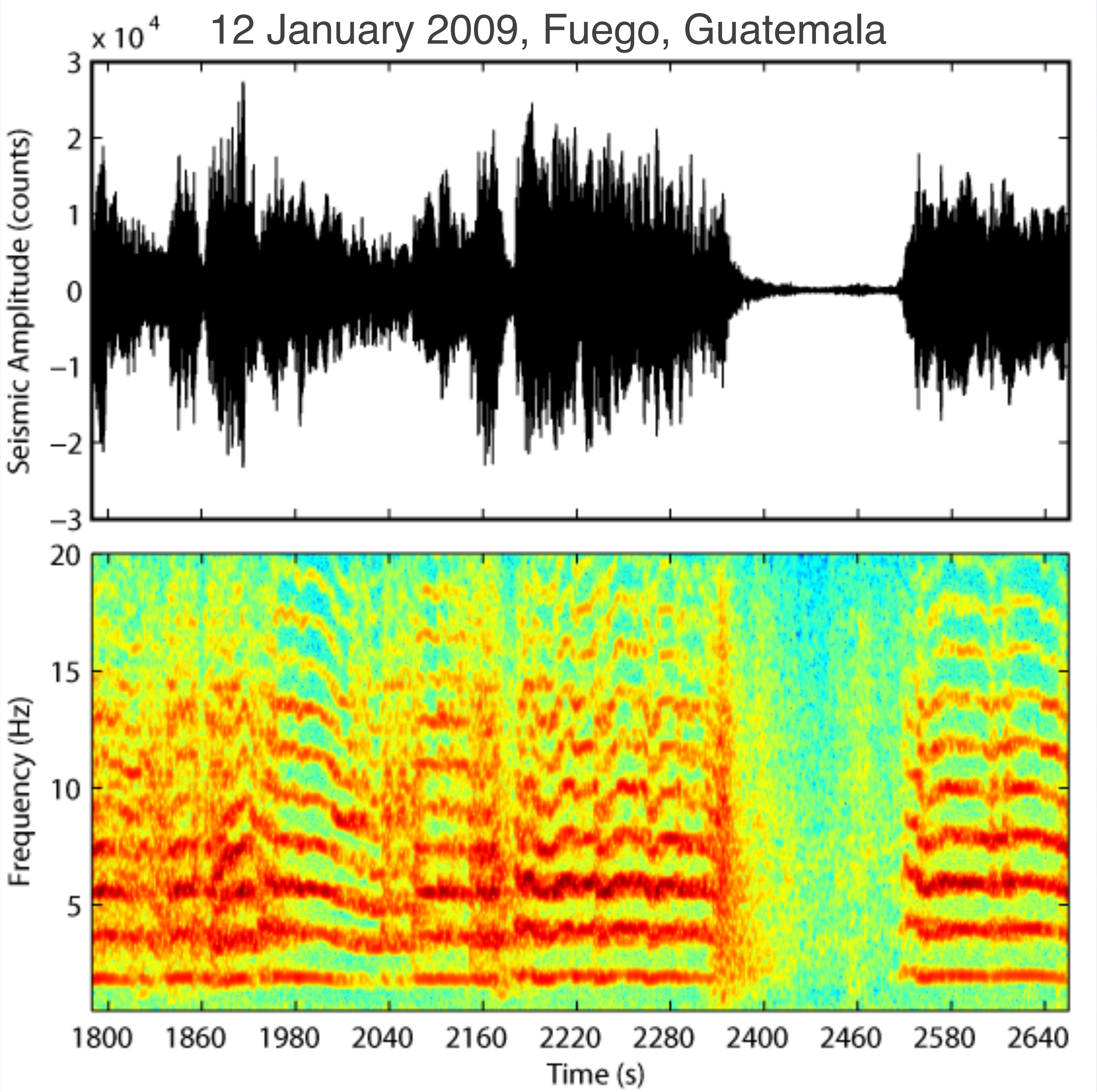
Okubo and Wolfe, JVGR, 2008

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

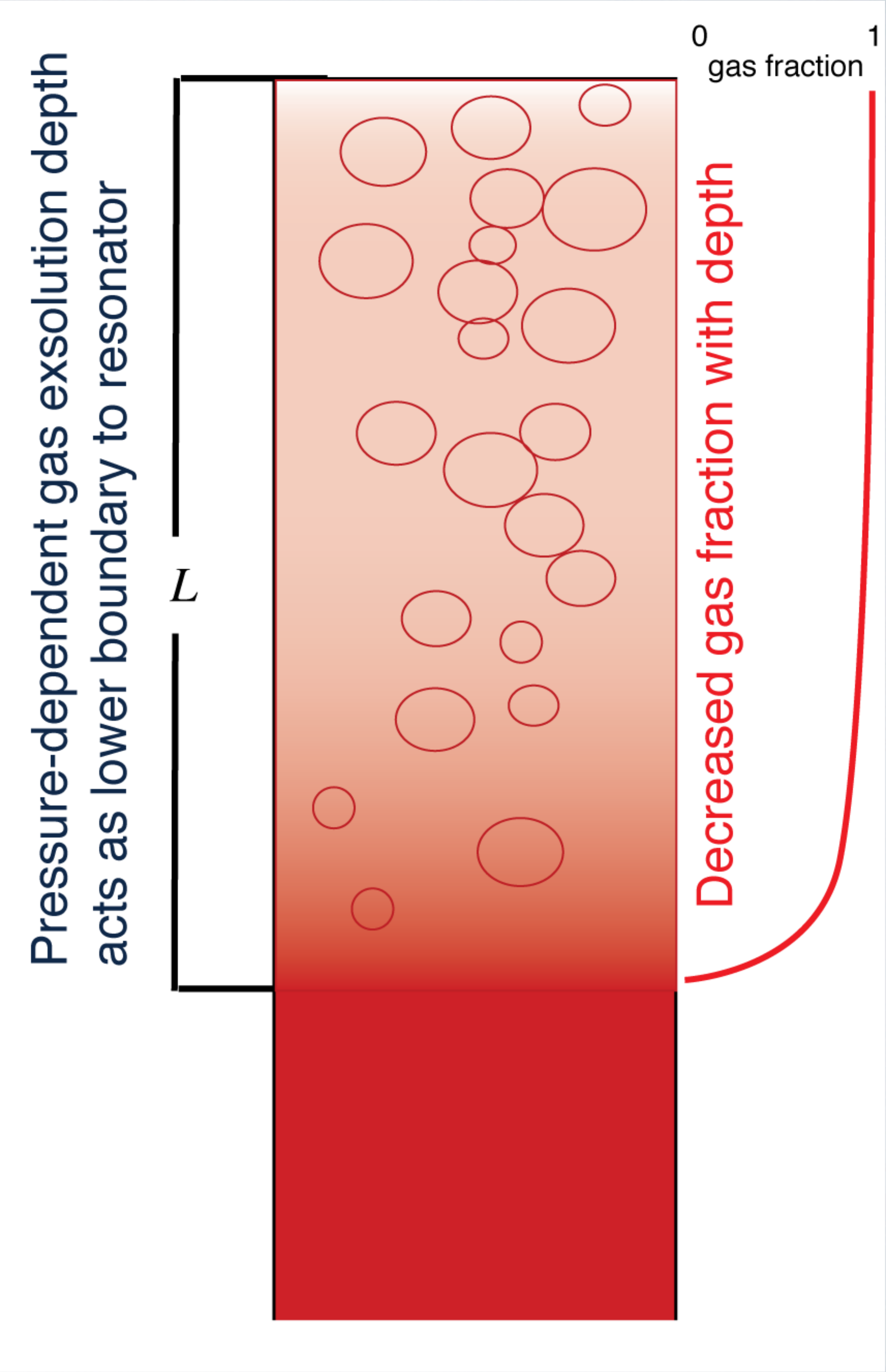
Harmonic Tremor

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

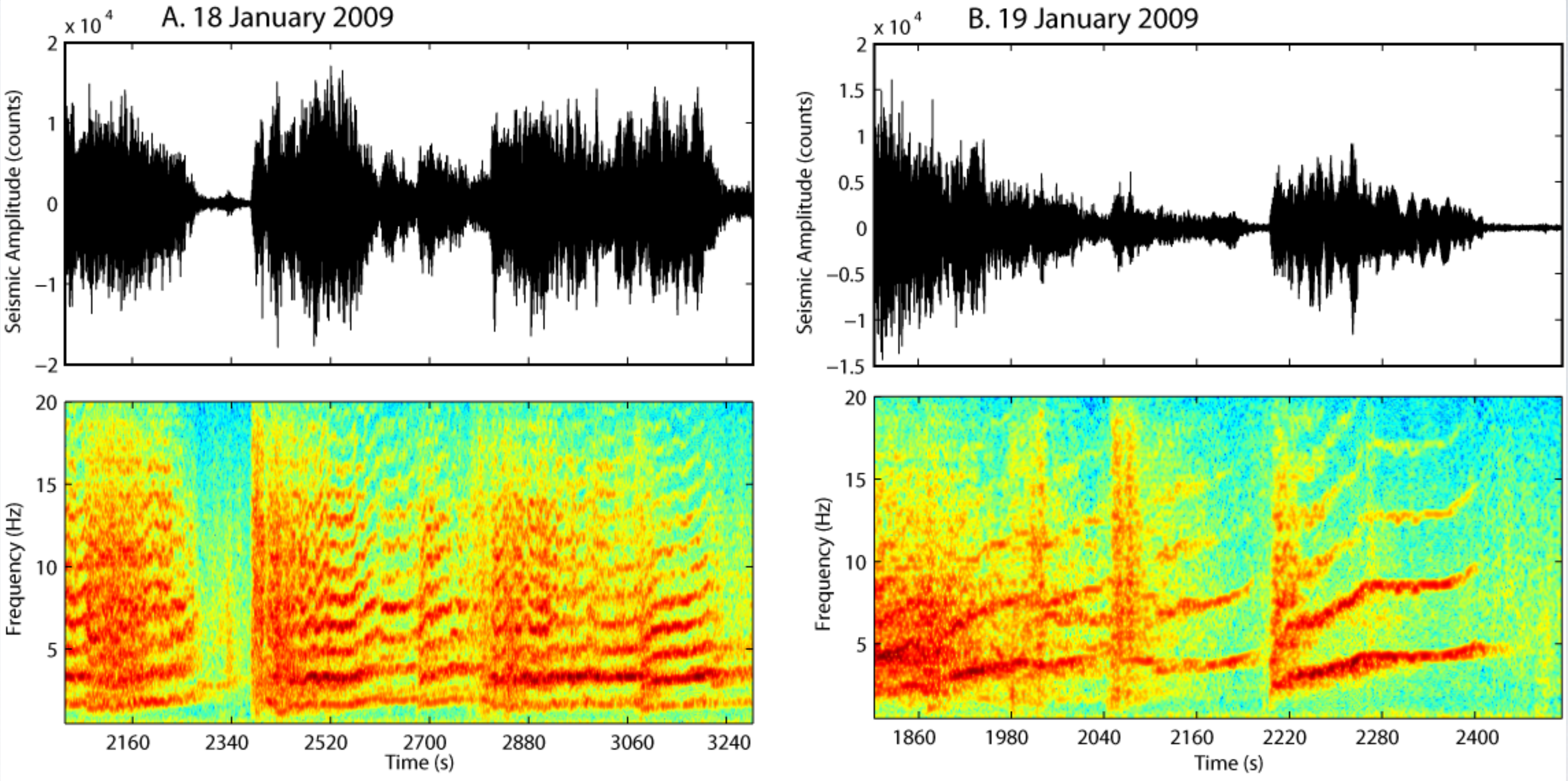

12 January 2009, Fuego, Guatemala

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



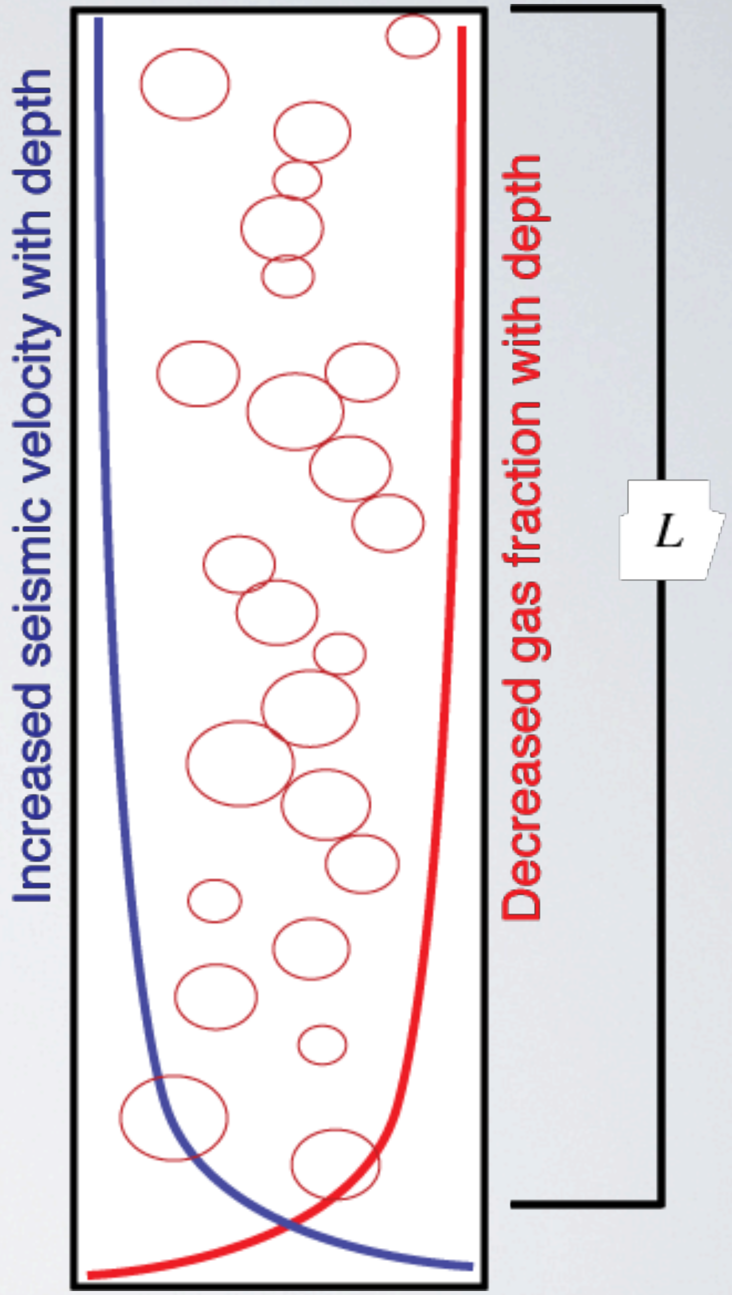
Harmonic Tremor Glide, Fuego Guatemala



- 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

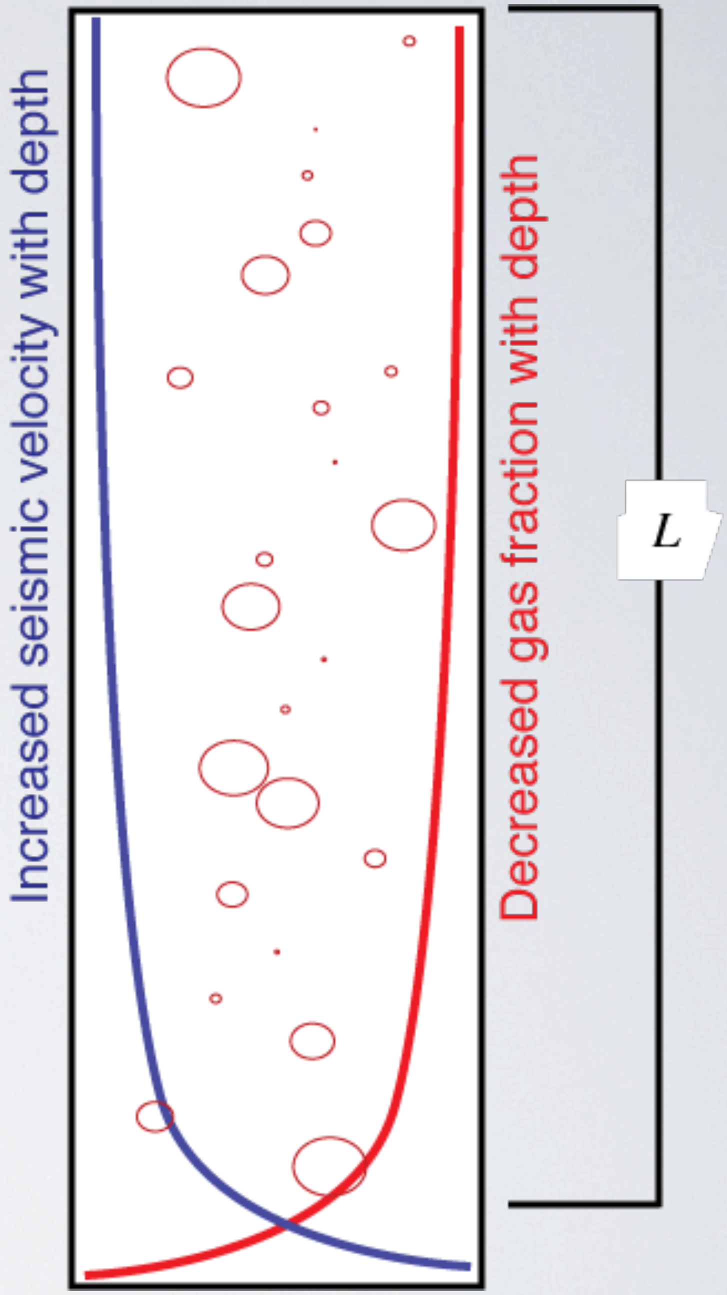
Model For Tremor Glide

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



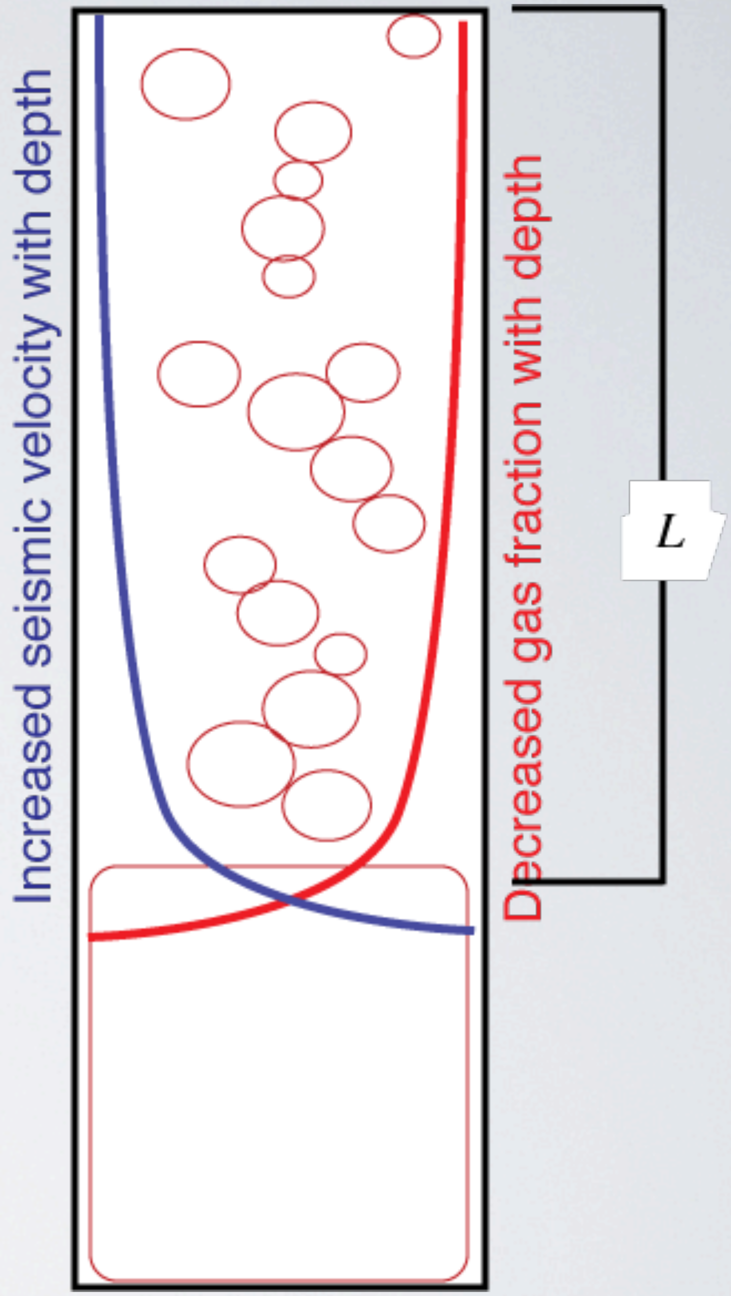
Model For Tremor Glide

- 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?

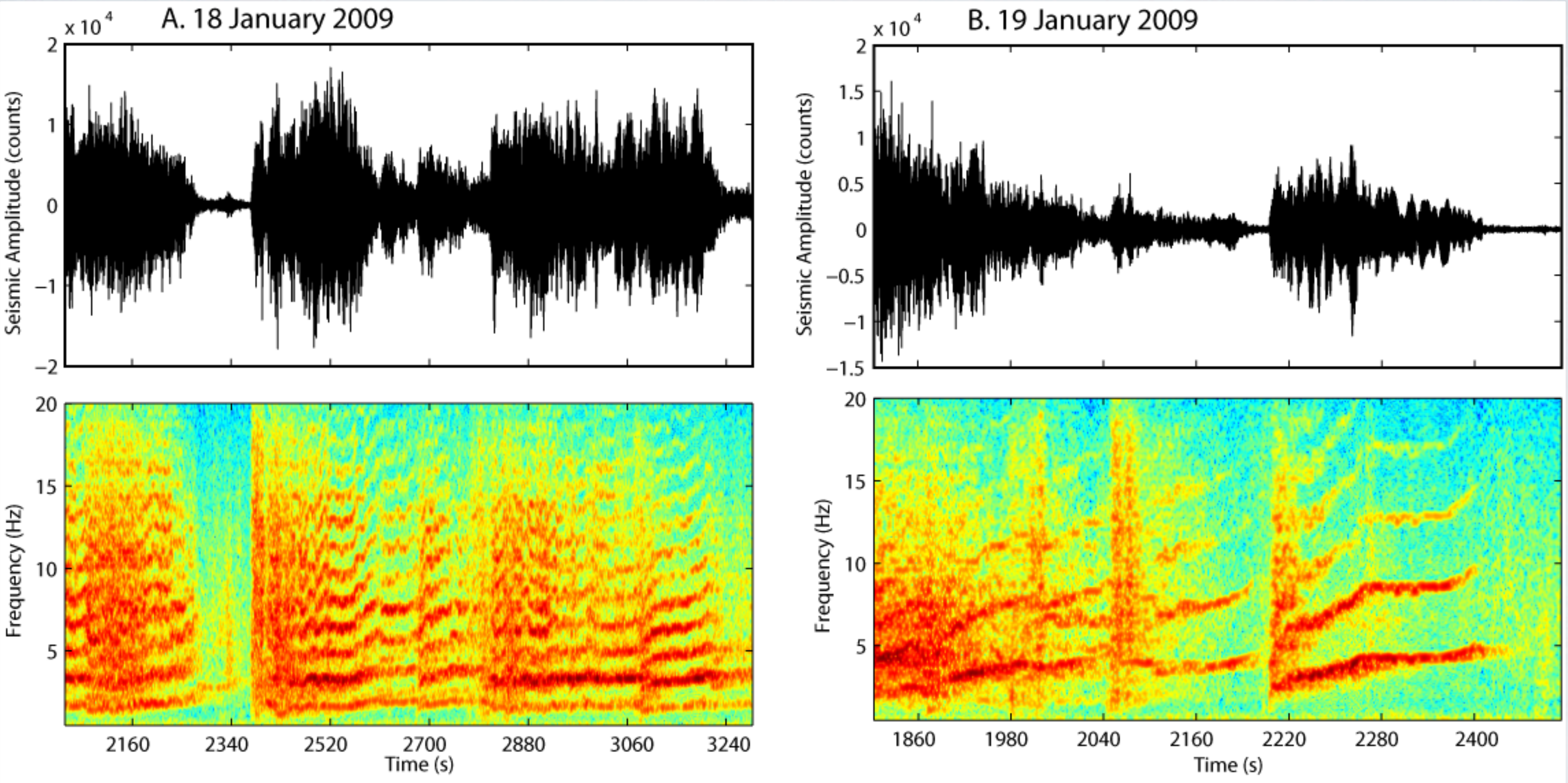


Model For Tremor Glide

- 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

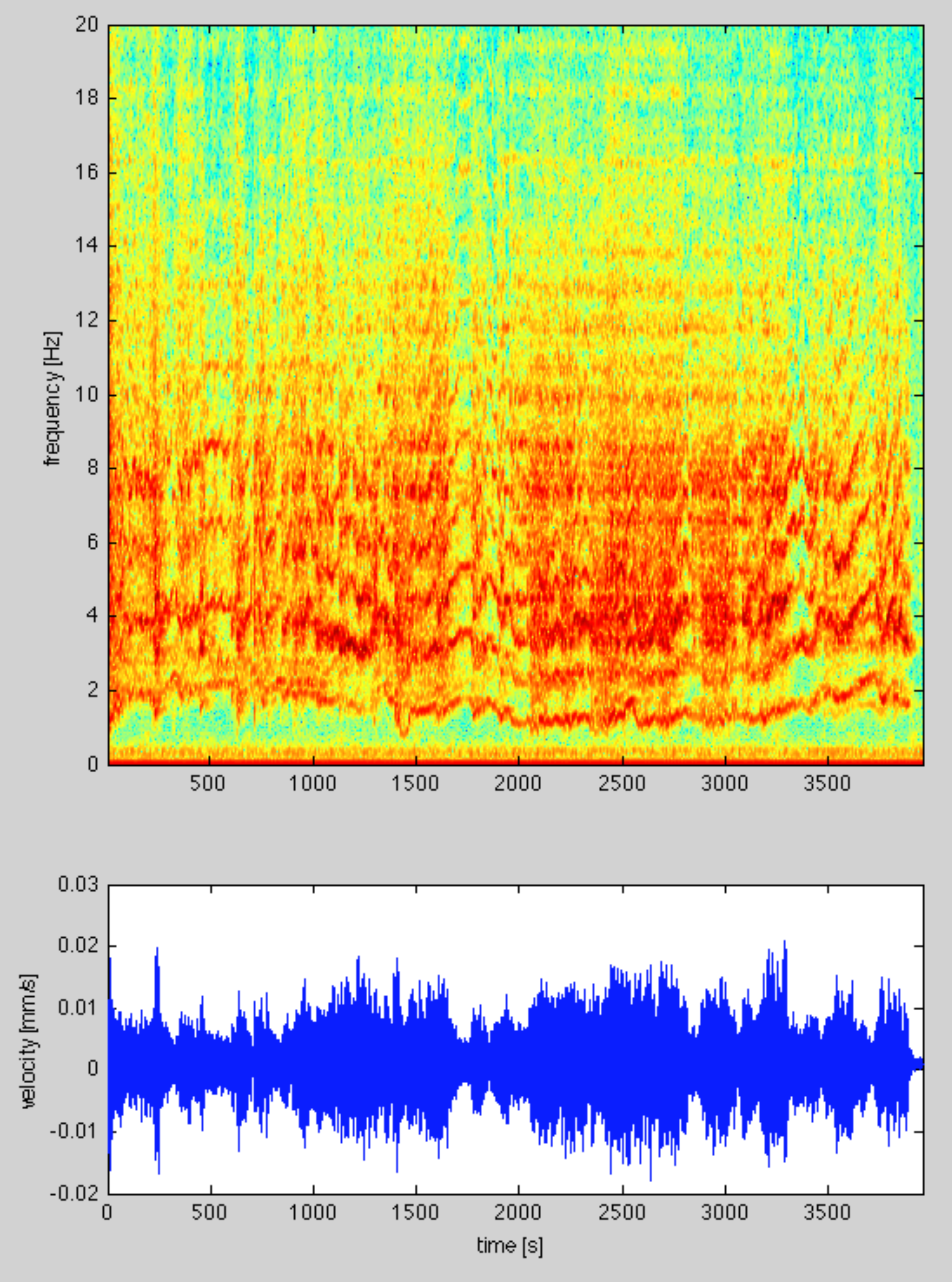


A Model for Harmonic Tremor Glide

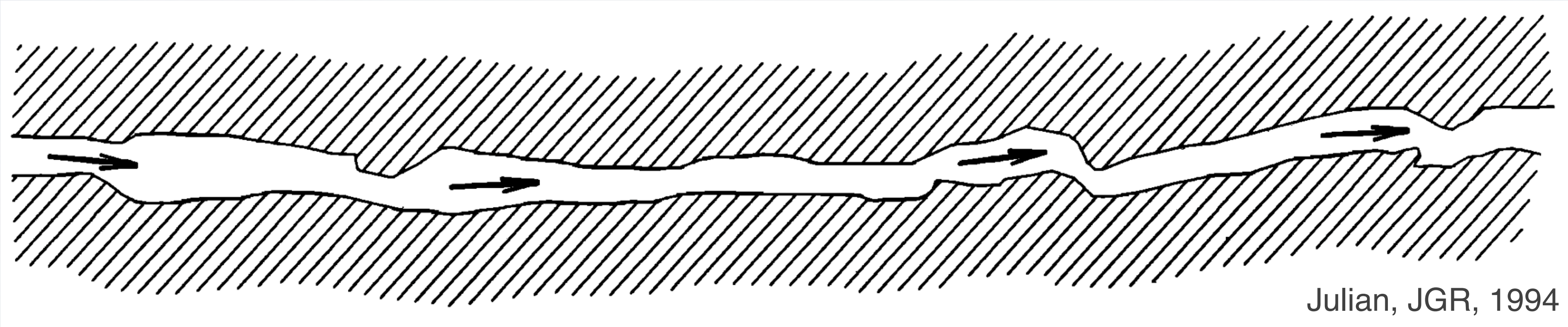


- Gliding could be due to shortening effective length of the conduit
  - For v=400 m/s and $f_0=2$, L=100 m => $f_0=4$, L=50 m
  - Implies mobile boundary migrates about 0.4 m/s
- If conduit is sealing, increased pressure could reduce L and increase v

A Moc nor Glide



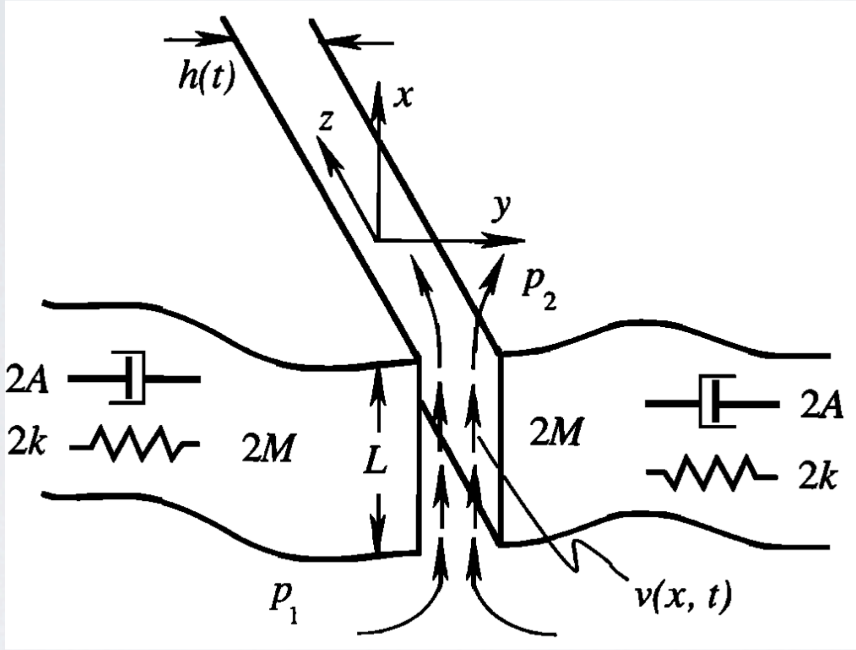
Tremor Due to Flow Instability



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:

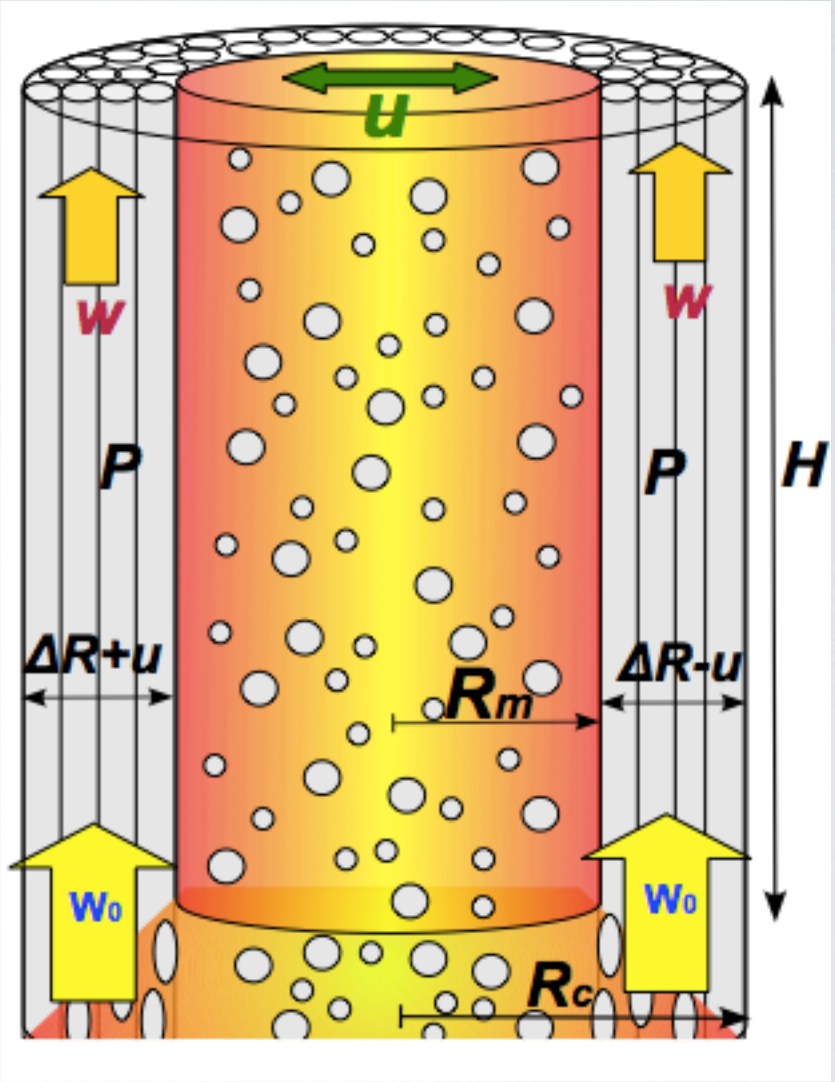
$$\frac{f_o^{\text{single}}}{f_o^{\text{cloud}}} \approx \beta^{1/6} N^{1/3}$$

(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

Magma Wagging

- New model for tremor in which oscillation of the magma column produces harmonic signal
- Relatively stiff magma acts as inverted pendulum
- Annulus of gas, and gas-filled cracks cushions the oscillating column
- Acceleration of extrusion rate prior to eruption may explain tremor glide



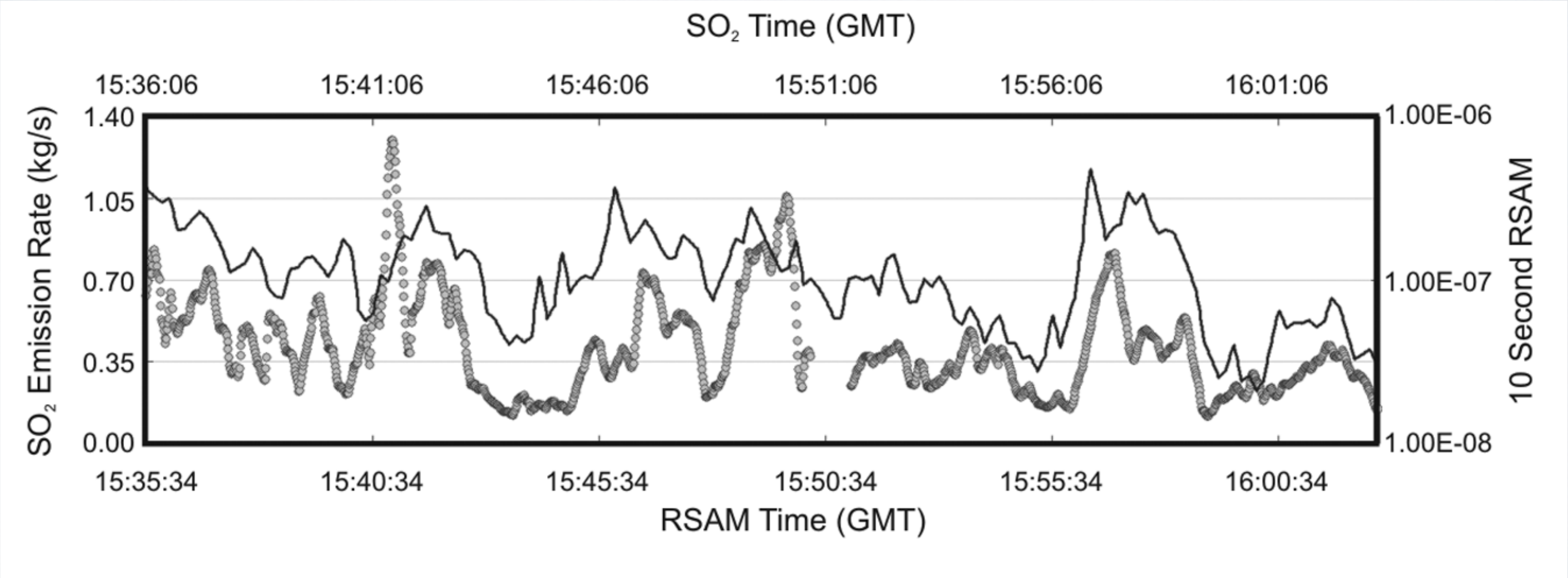
Jellinek & Bercovicic, Nature, 2011

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

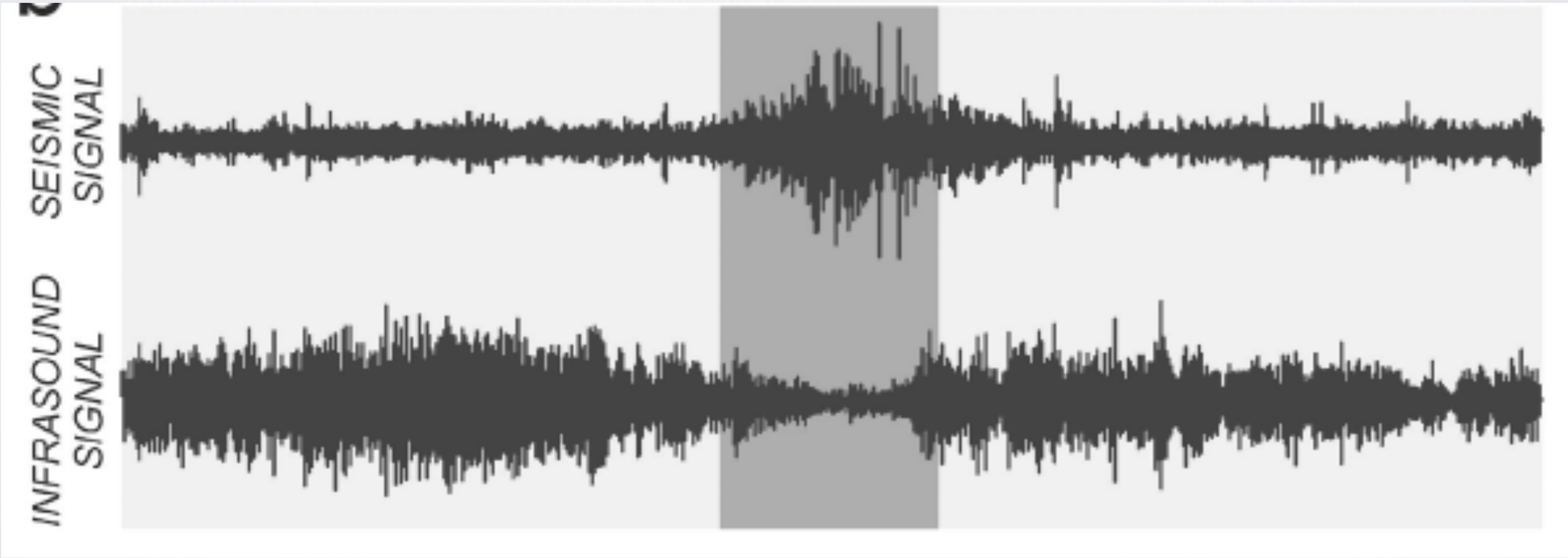
- Gas is involved with the tremor source in some cases



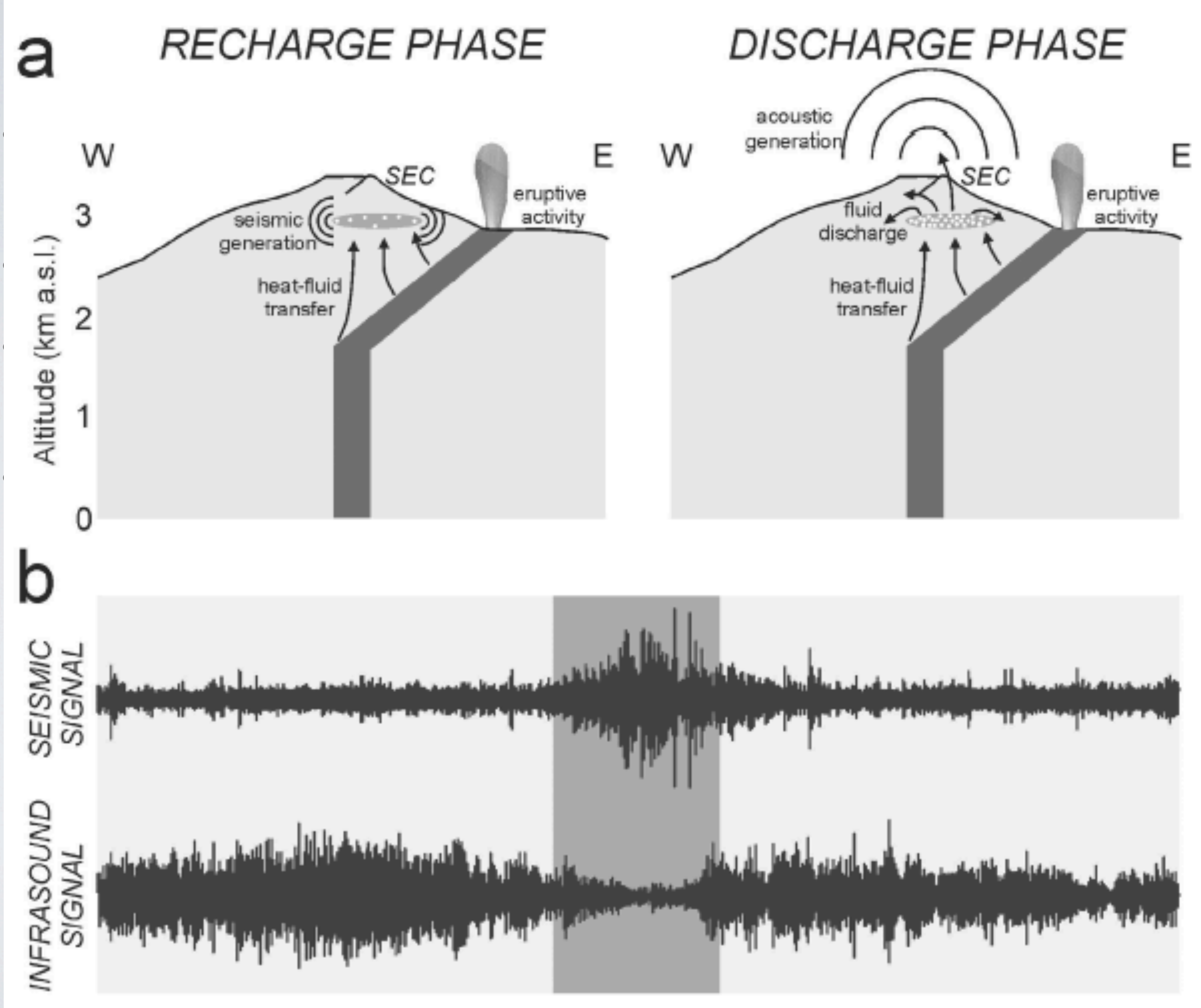
Nadeau et al., *GRL*, 2011

Banded Tremor

- Intermittent tremor that begins and ends at regular intervals
- Typically associated with hydrothermal activity
- Can be modeled similar to geysers (Ingebritsen and Rojstaczer, 1996)
- Relationship between acoustic and seismic suggests fluid discharge



Cannata, et al. JGR, 2010

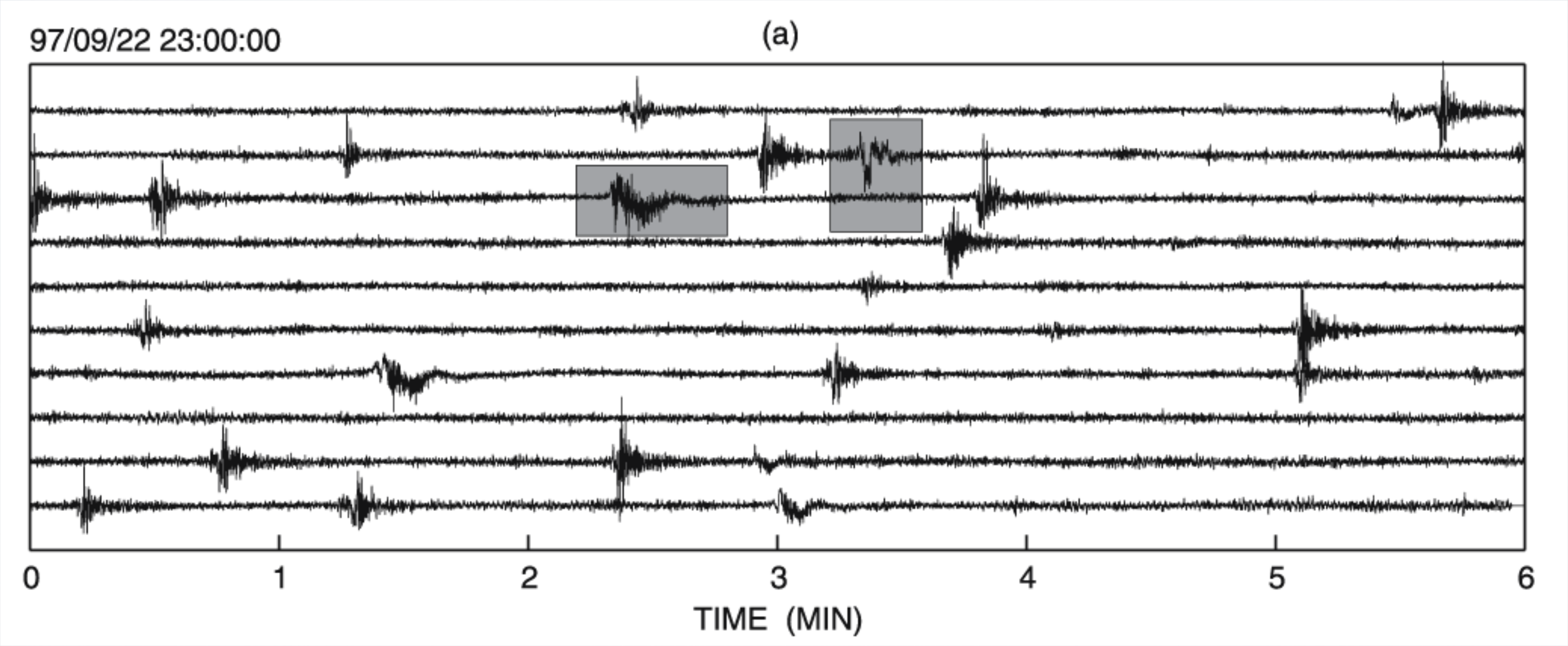


Cannata, et al. JGR, 2010

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

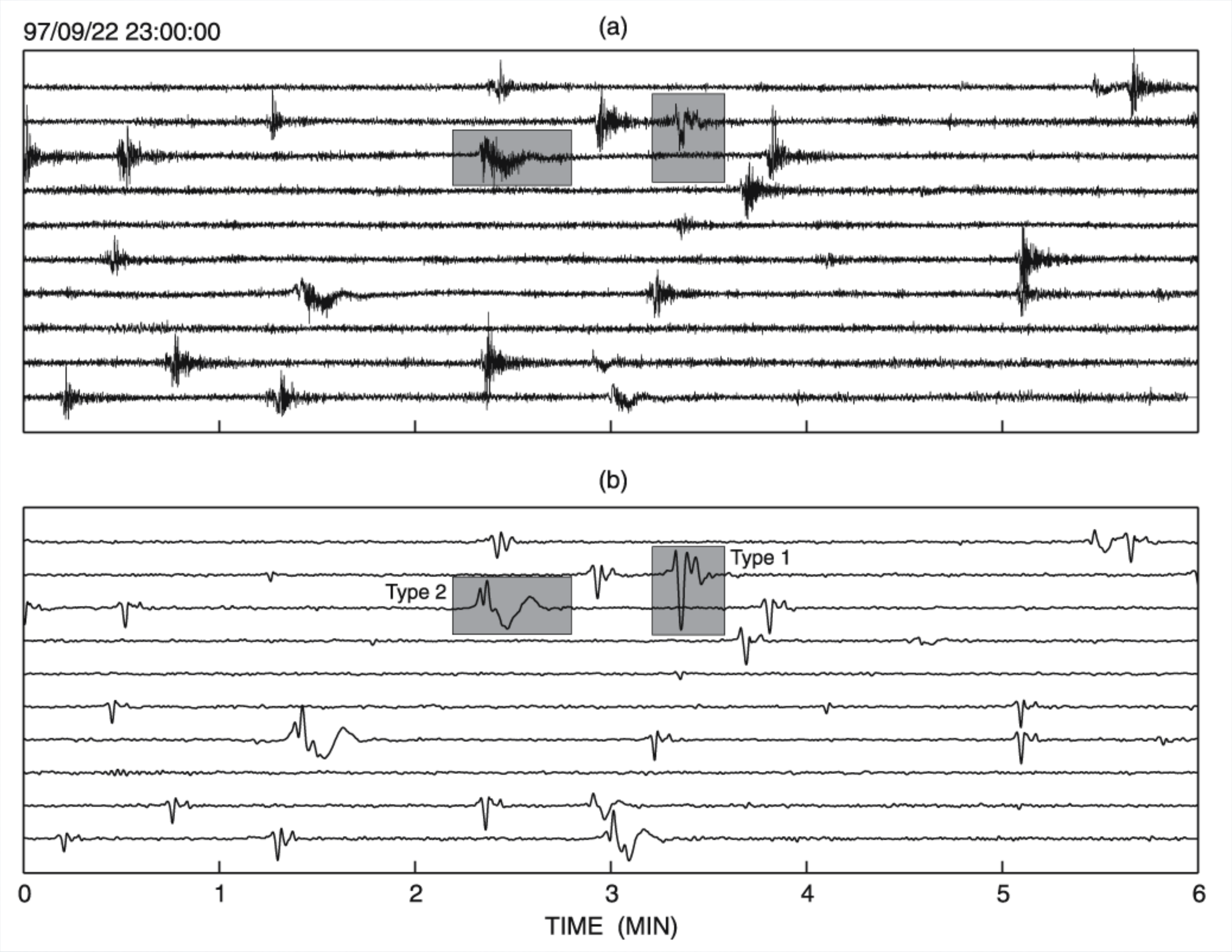
VLPs at Stromboli



- 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



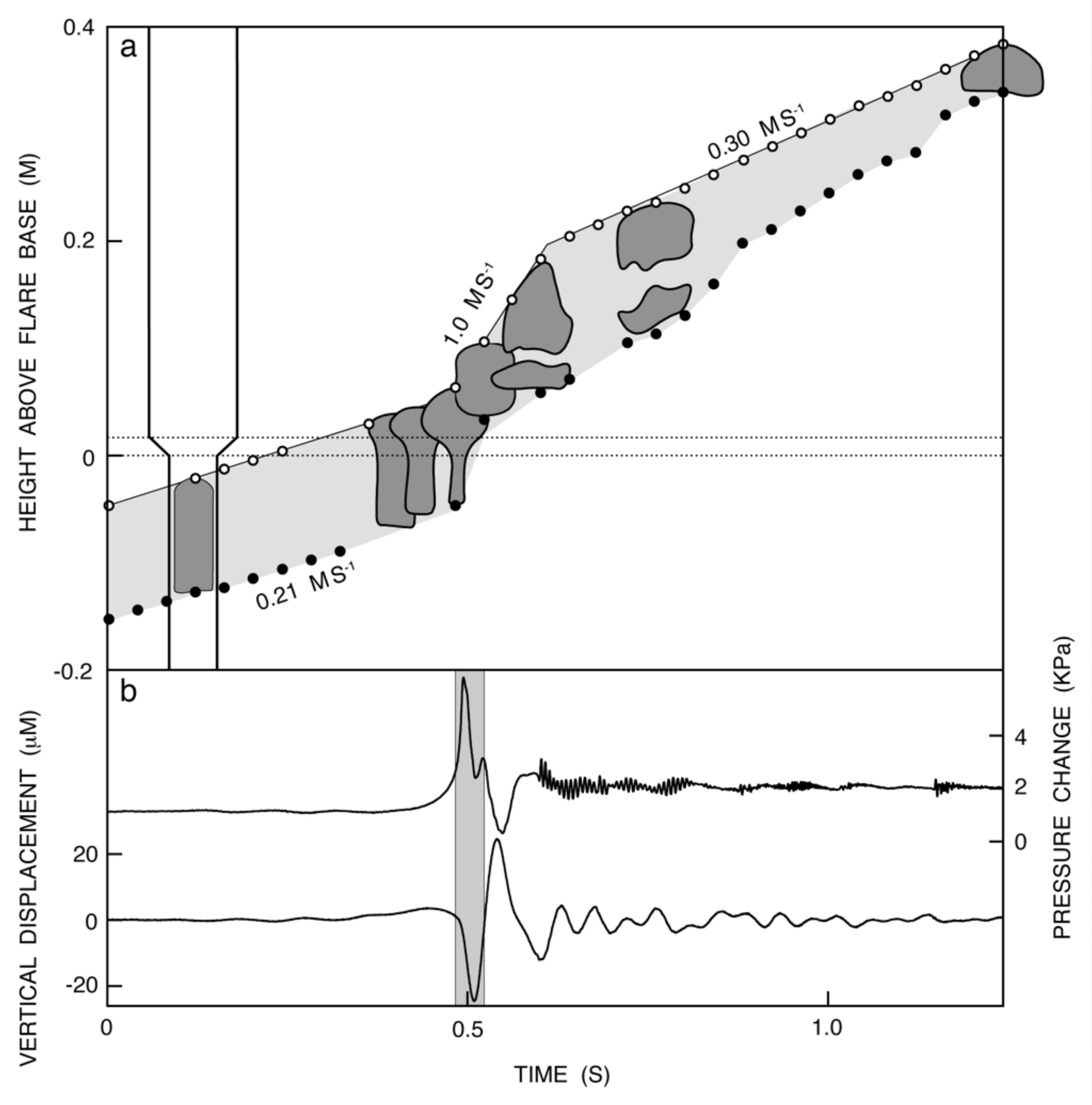
Chouet et al., *JGR*, 2003

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

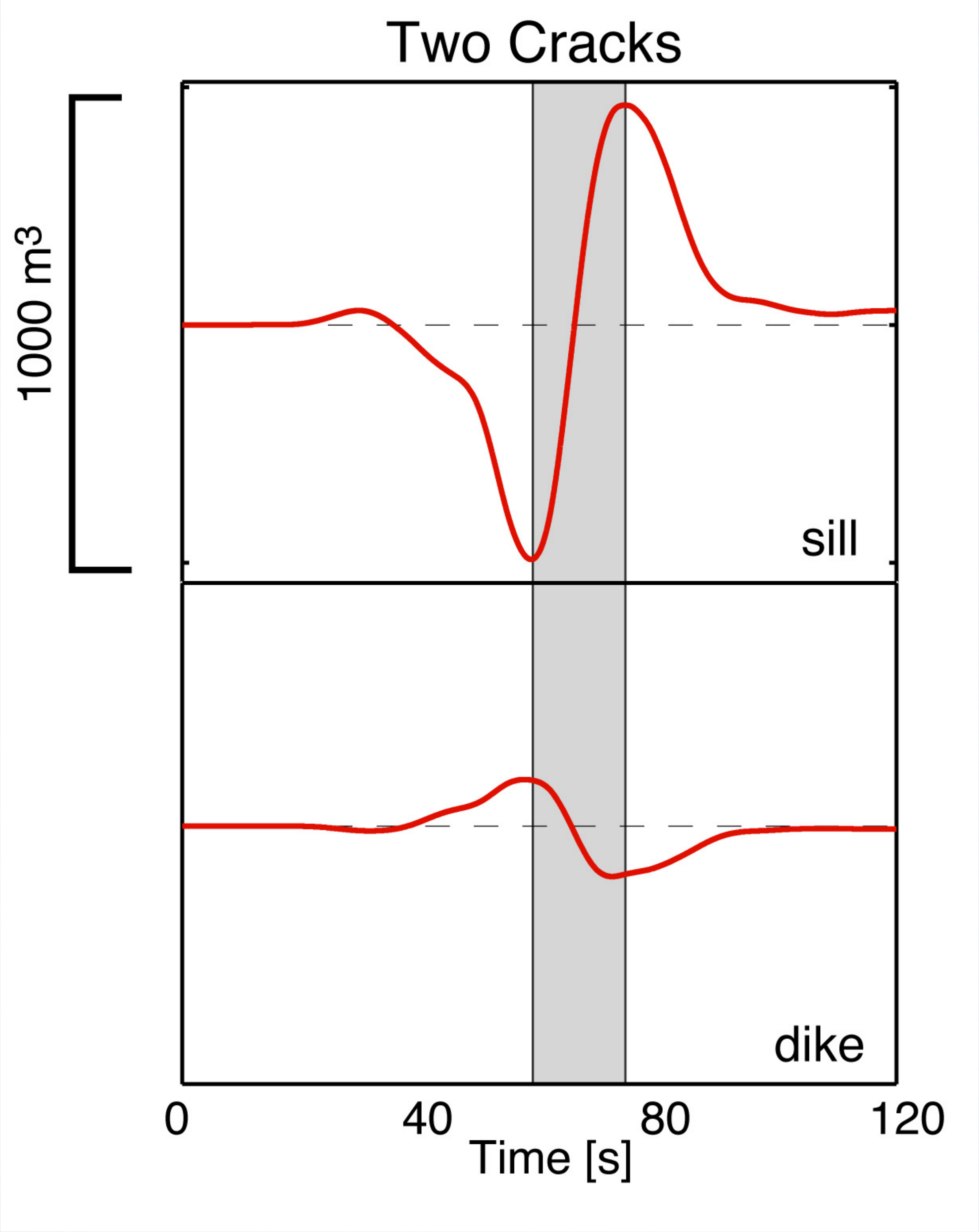
- Bubble accelerates through the flair in the tube
- Liquid annulus falling around the bubble also must accelerate
- Net result is a force (F=ma) that can be translated to the surrounding rock

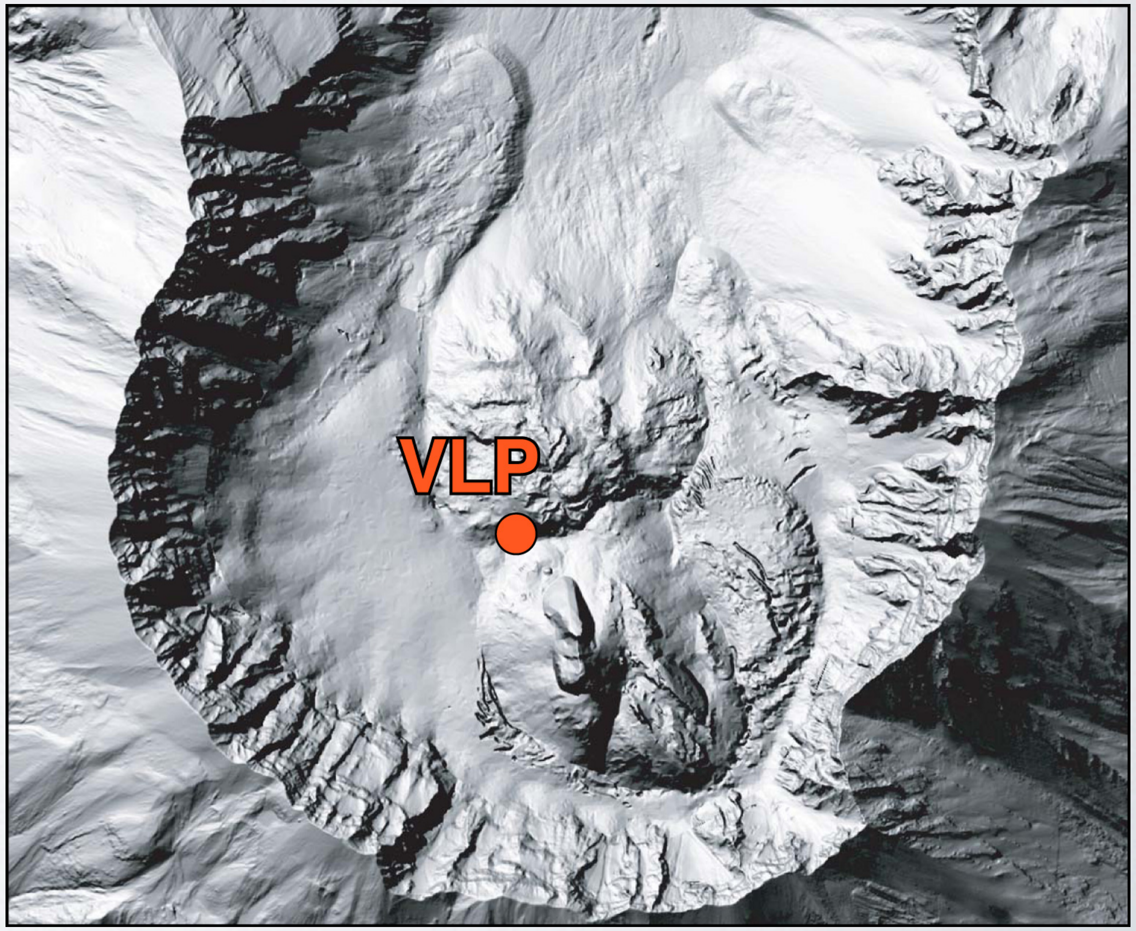


James et al, *JGR*, 2006

VLP Source-Time Function

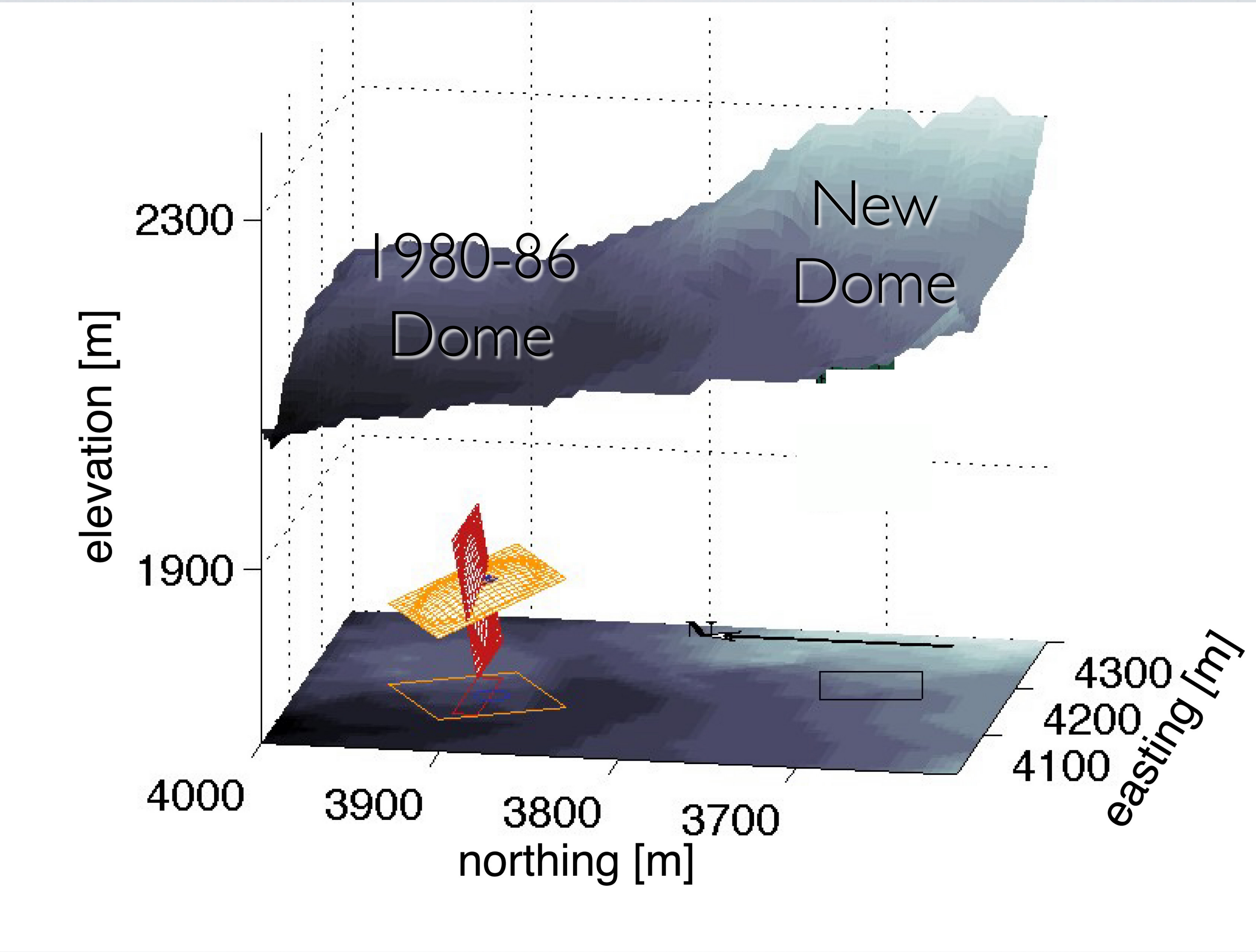
Mount St. Helens 2 July 2005 at 13:29 UTC





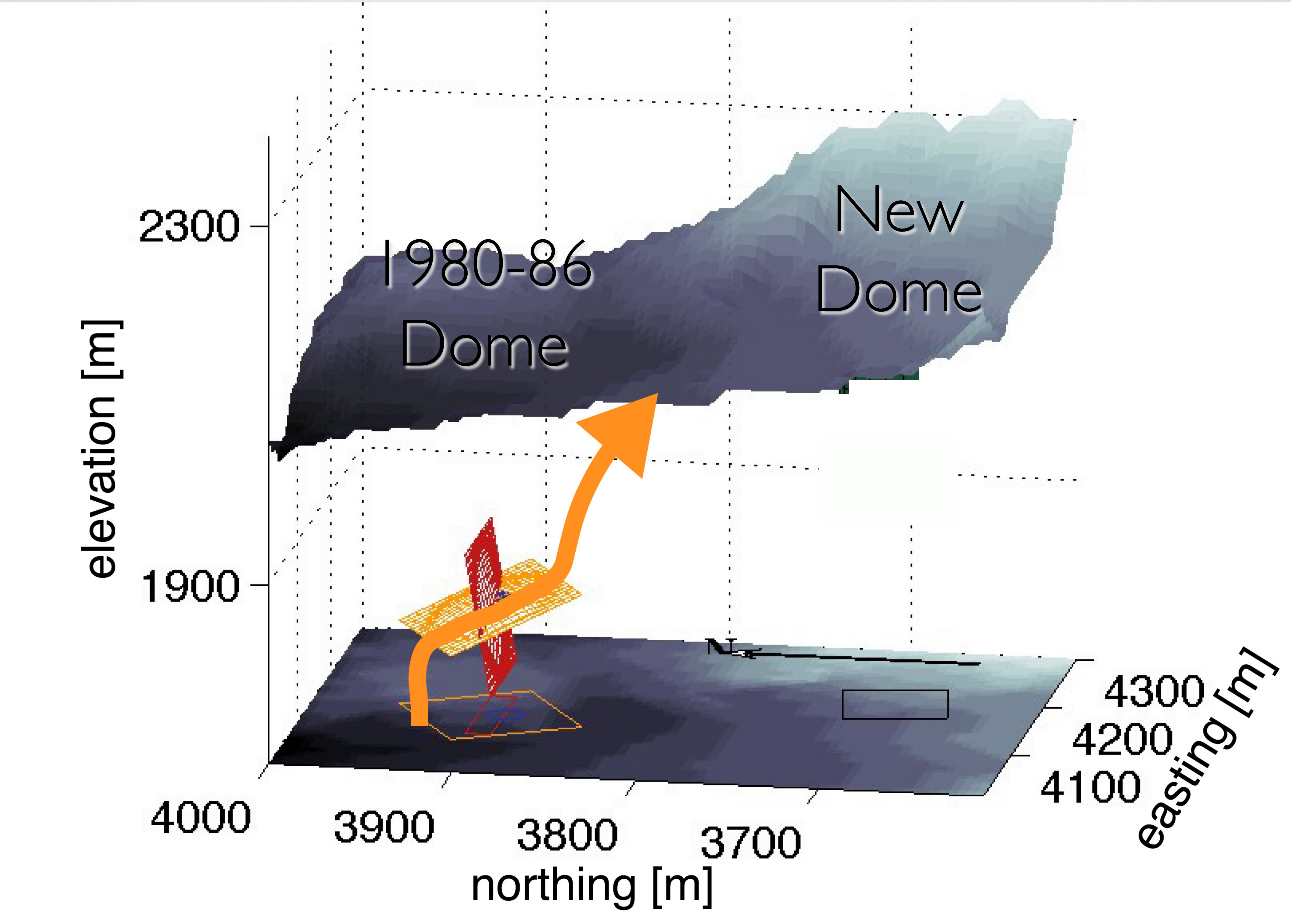
Perspective View of Two Cracks

Mount St. Helens

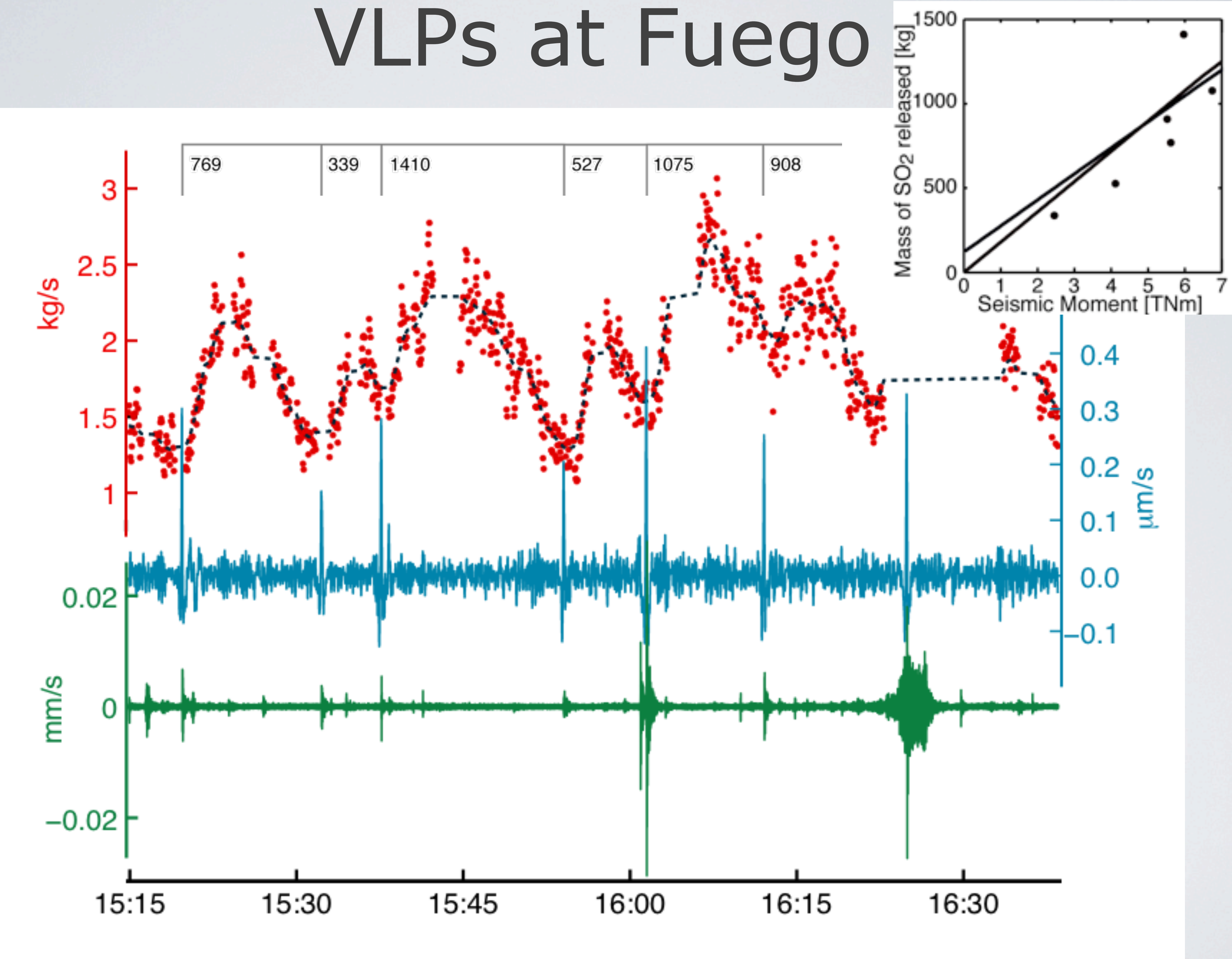


Perspective View of Two Cracks

Mount St. Helens



VLPs at Fuego



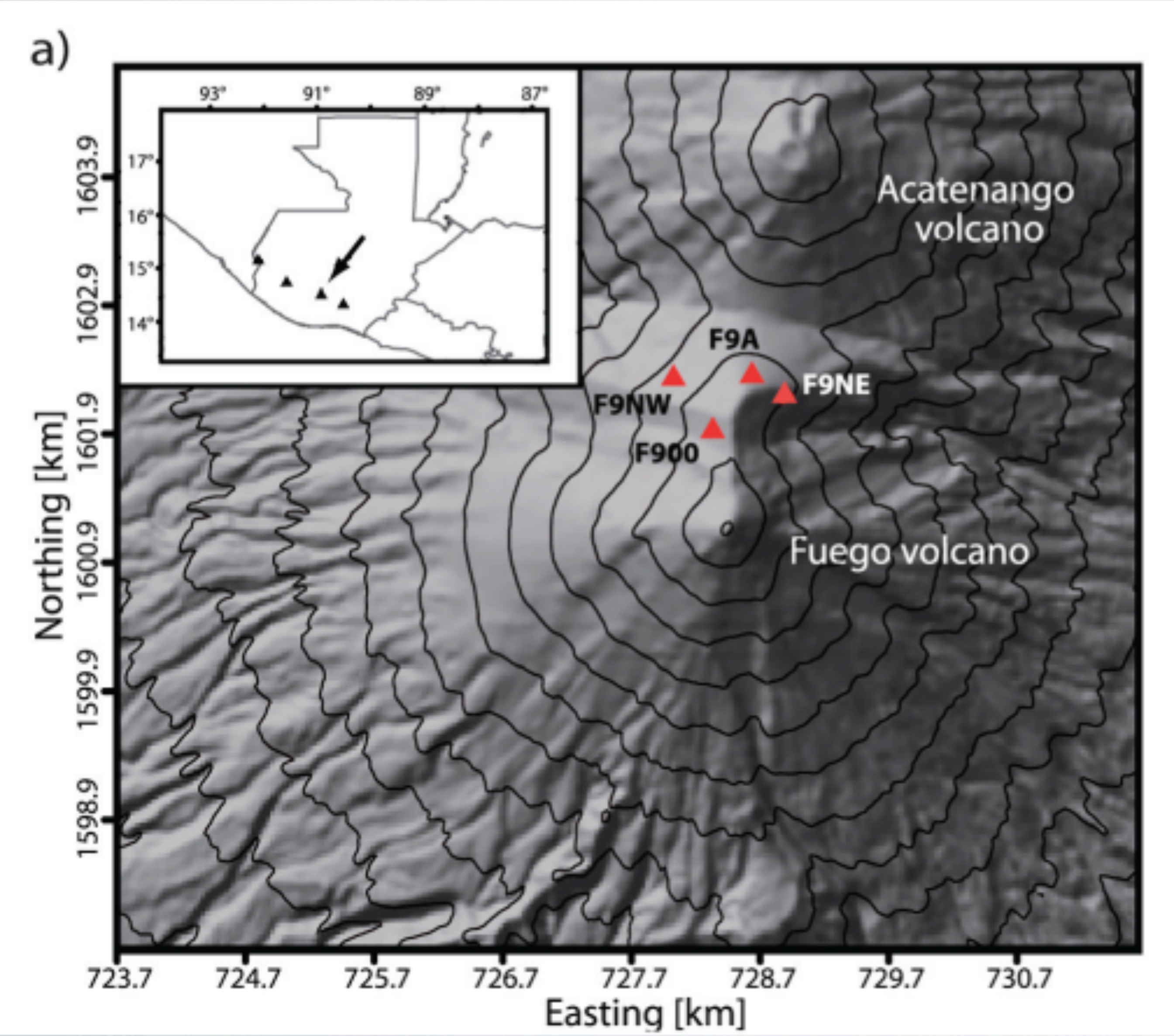
Waite et al, *JGR*, 2013

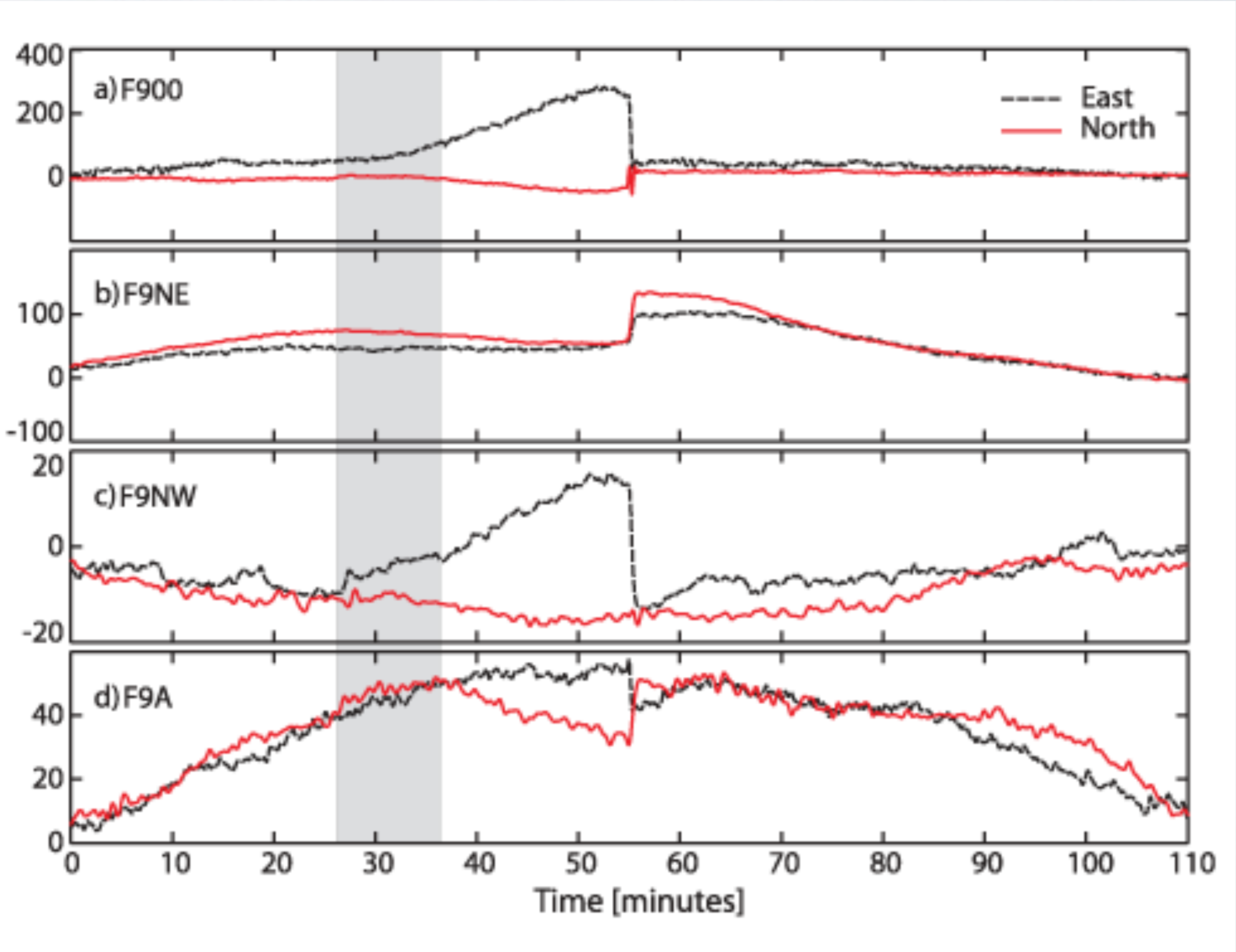
Tilt from Seismometers

- 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

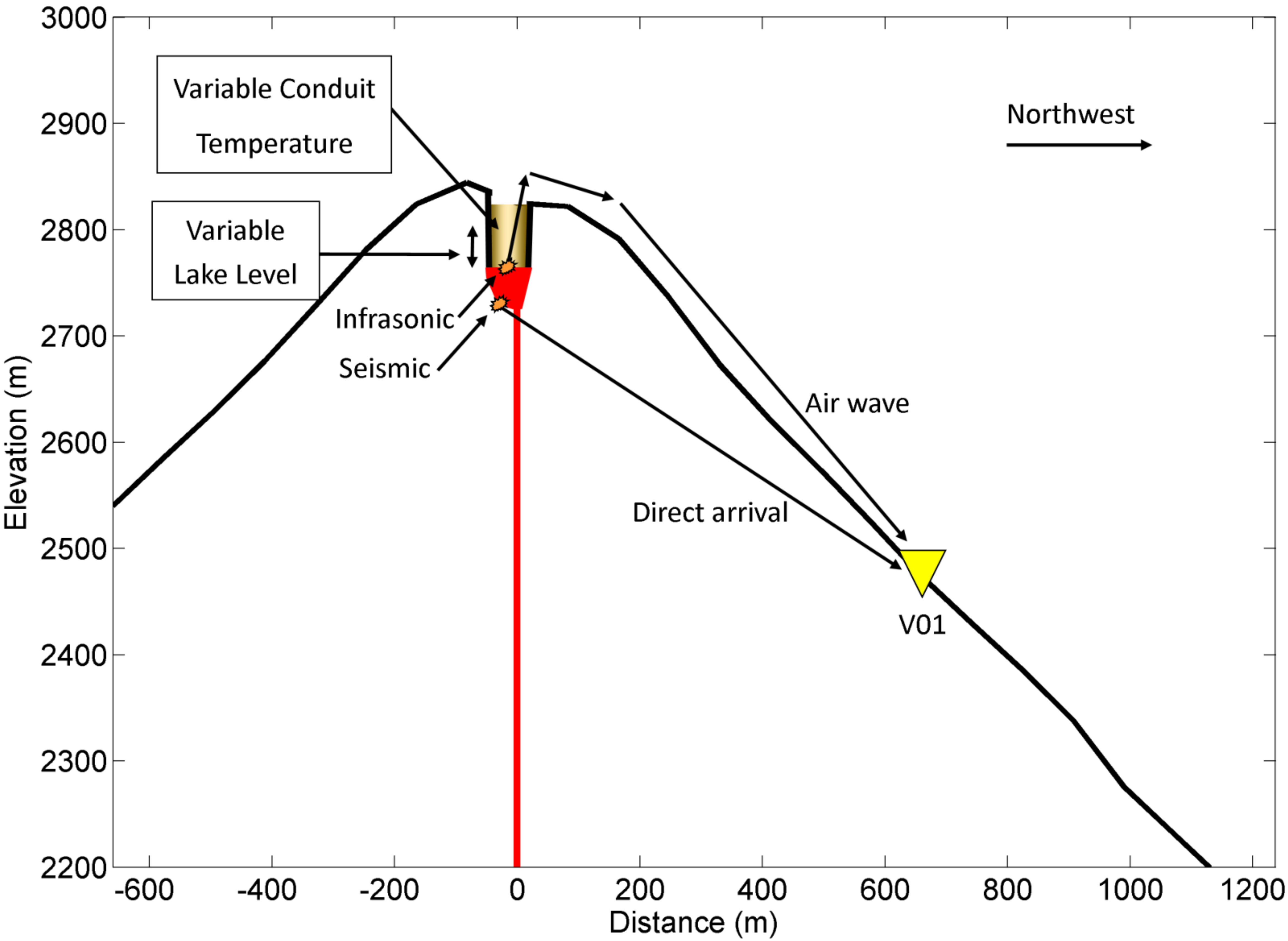




Lyons *et al*, GRL, 2012

Summary

- Models for low-frequency seismicity offer insight into magma (or other fluid) composition
  - No one model can universally explain a particular type of LF event
  - Particularly useful for understanding "critical systems"
- Integration with other data is a powerful means to constrain modeling
  - Infrasound
  - Gas emission


Variable Conduit Temperature
Variable Lake Level
Infrasonic
Seismic
Northwest
Air wave
Direct arrival
V01
Elevation (m)
Distance (m)
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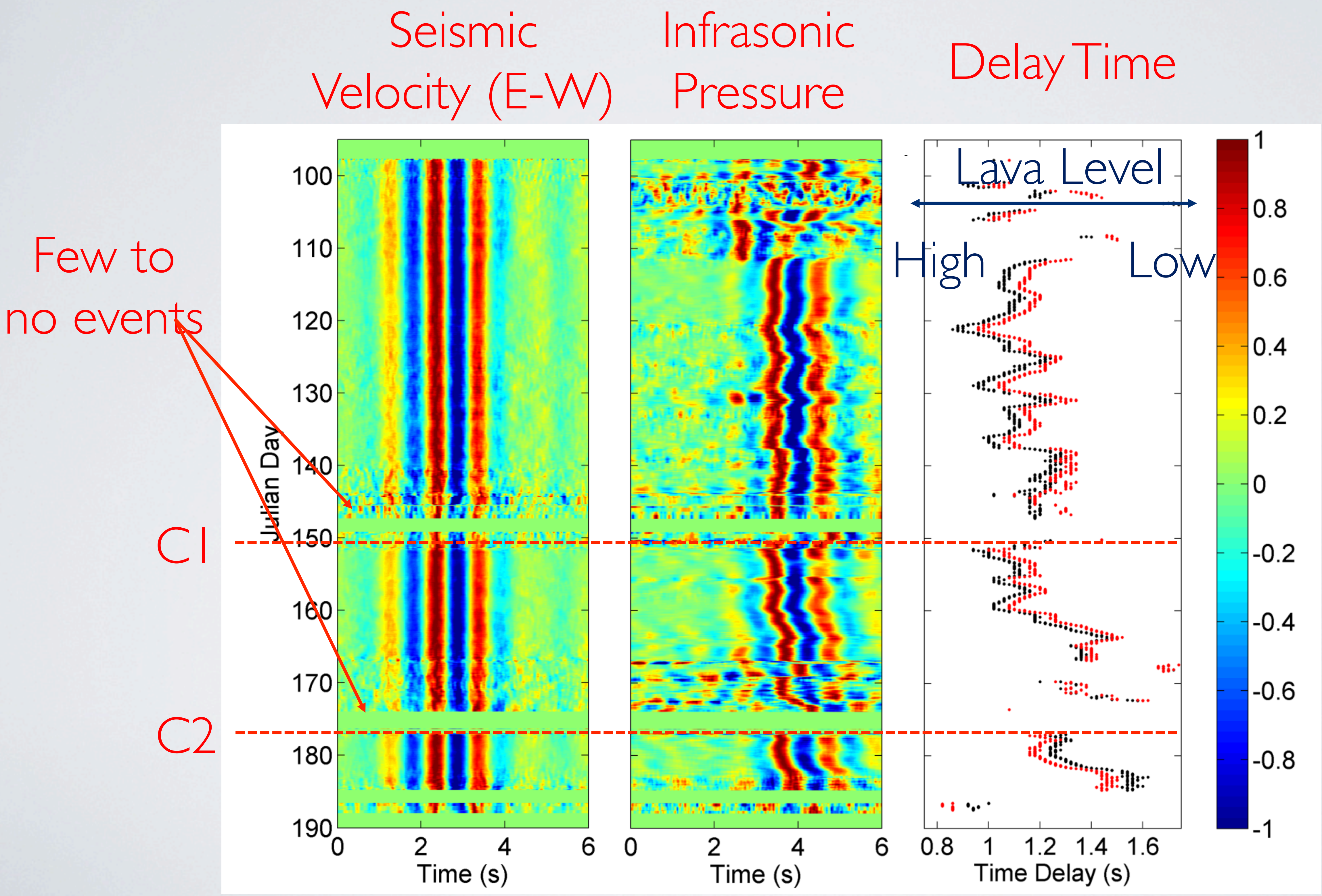
2900
2800
2700
2600
2500
2400
2300
2200
-600
-400
-200
0
200
400
600
800
1000
1200

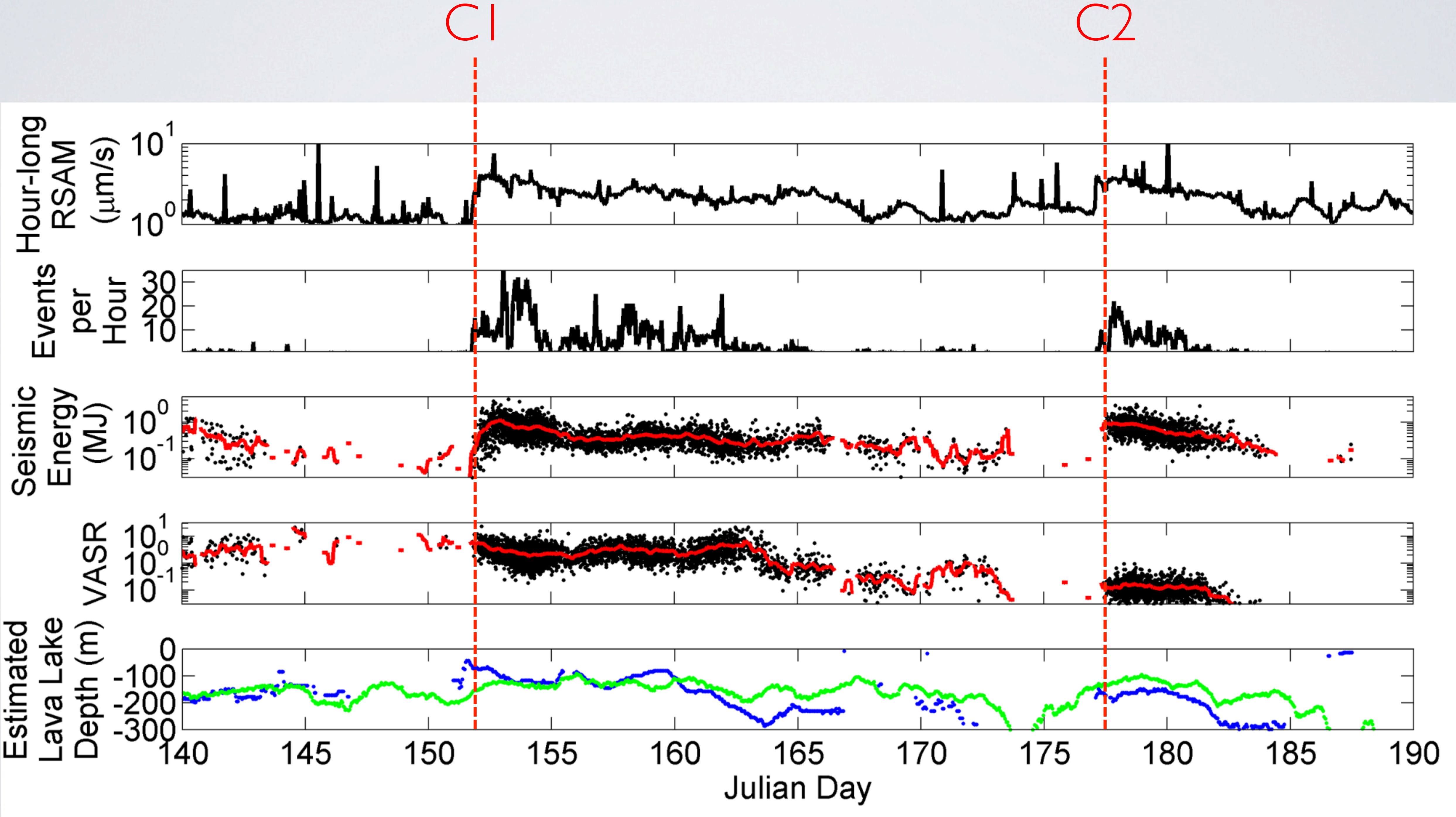
Seismic-Infrasound Delays



Using a repetitive event to infer changes in the lava lake

- Two cycles start with elevated: seismic amplitudes, event frequency, seismic energies, VASR, and lava lake

- C1 and C2 reflect deeper processes in magmatic system: High gas flux, larger gas bubbles, and higher magma column



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PASSCAL Instrument Center

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Using a repetitive event to infer changes in the lava lake

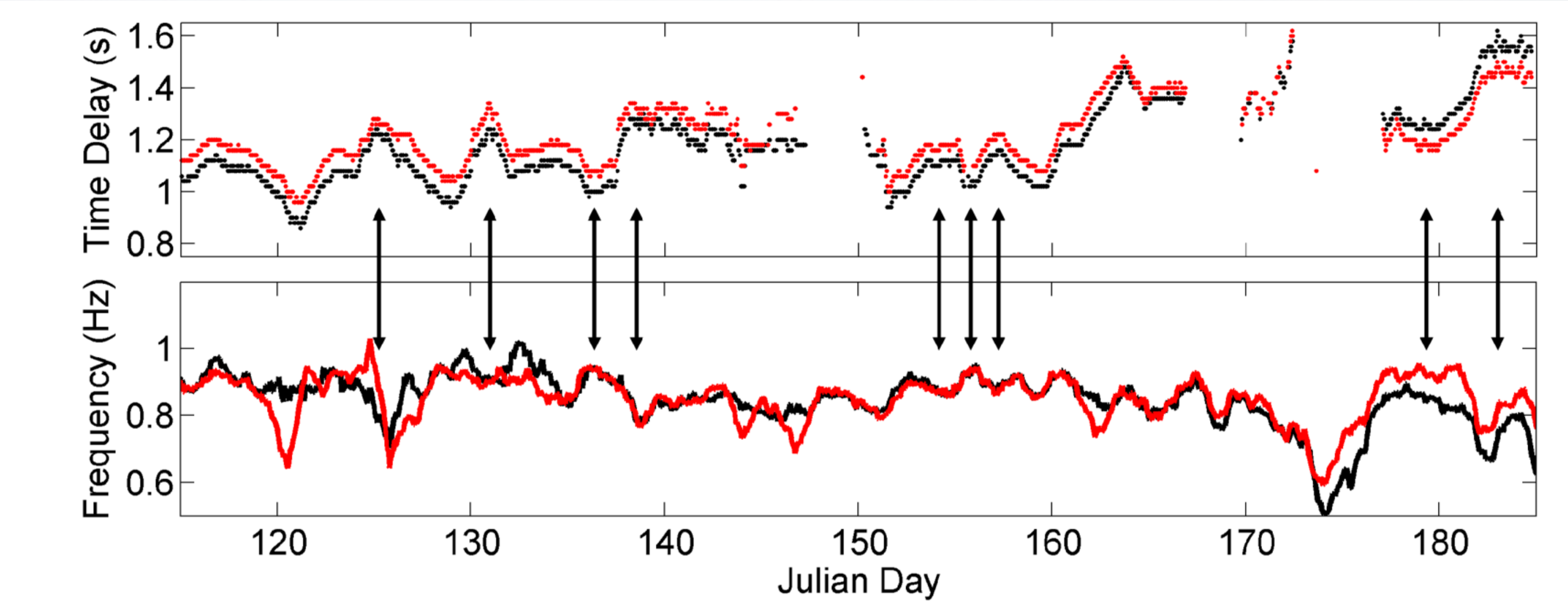
- Relationship between time delay and infrasonic tremor frequency:
  Large delays ~= low frequency

- Infrasonic tremor previously proposed as Helmholtz resonance or coupled two-phase flow

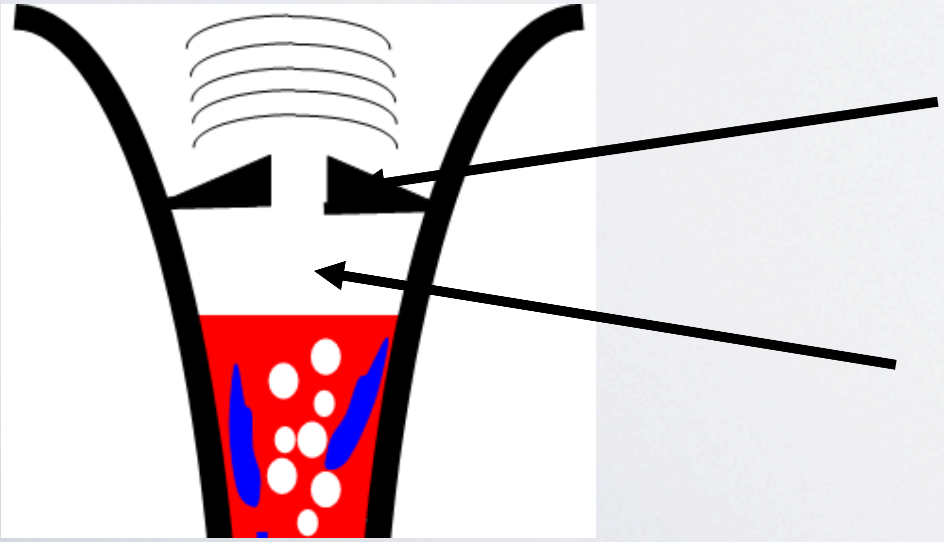
Low

Lava Level ↕

High



Helmholtz Cavity



Spatter Roof

Frequency: function of cavity dimensions, opening size, and sound speed

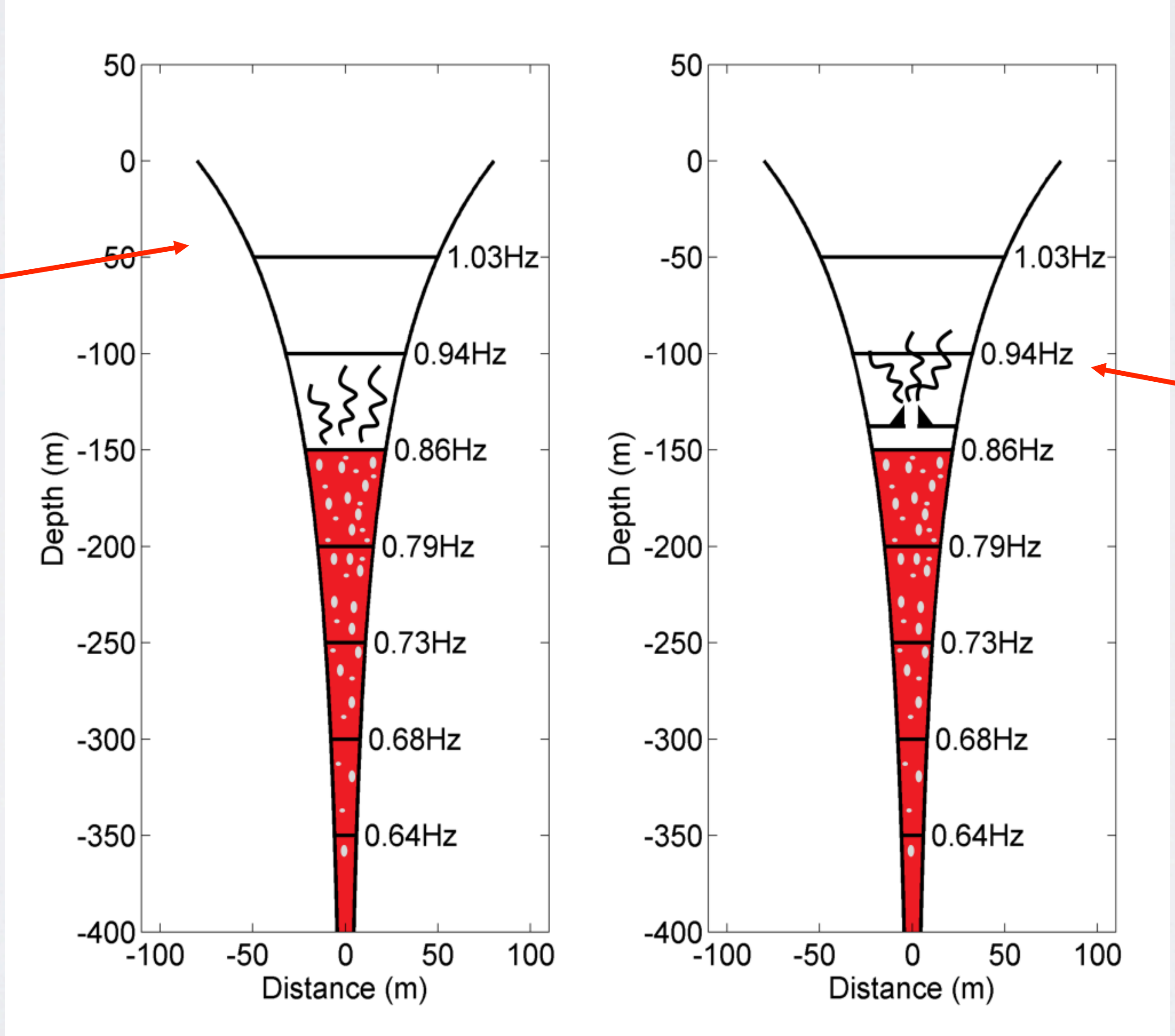
Using a repetitive event to infer changes in the lava lake

- Persistent infrasonic tremor from Helmholtz cavity would require a permanent spatter roof
  - Spatter roof would be destroyed by rising or falling lava
- Propose a new model using crater/shaft geometry as Bessel horn resonator
  - Non-integer higher-order harmonics (no harmonics observed)

Open

Spatter Roof

Approximate Crater Geometry

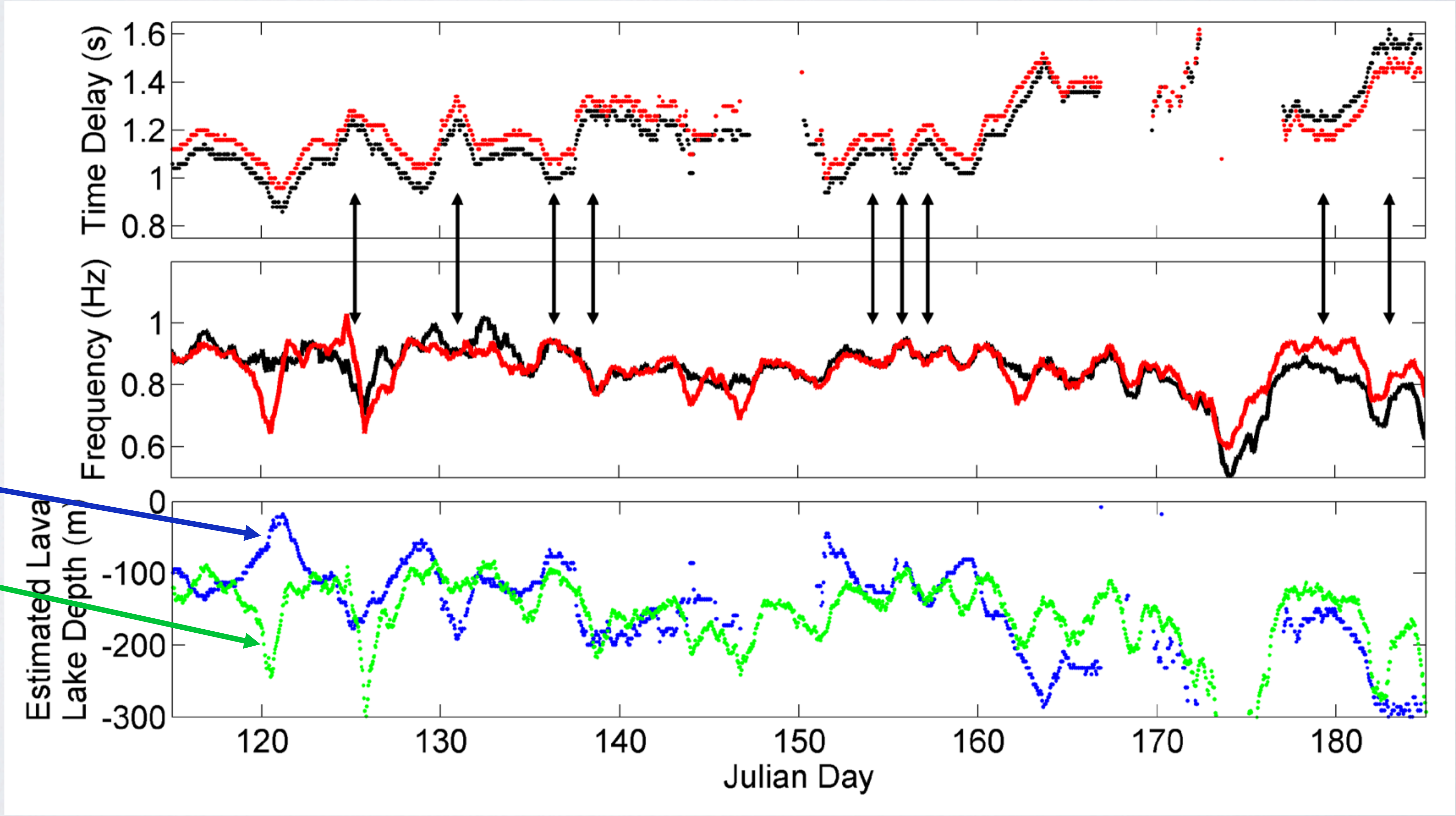


First Harmonic Frequencies

Using a repetitive event to infer changes in the lava lake

- Calculate predicted lava lake depth:
  - Fix delay times to general lava lake observations
  - Plot corresponding Bessel horn depths based on reported conduit dimensions and infrasonic tremor frequency

- Reasonable agreement between independent methods



Low

Lava Level

High

Delay times

Infrasonic Tremor