Seismo-acoustic signals of volcanic processes

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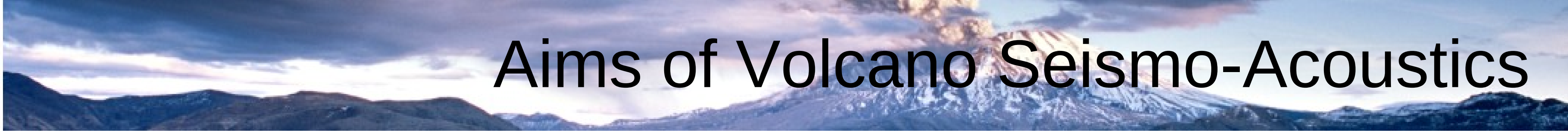
Lecture Outline:

- Introduction
- Volcano-seismic signals I – VTs
- Volcano-seismic signals II - LPs, VLPs, tremor
- Acoustic signals
- Future research directions

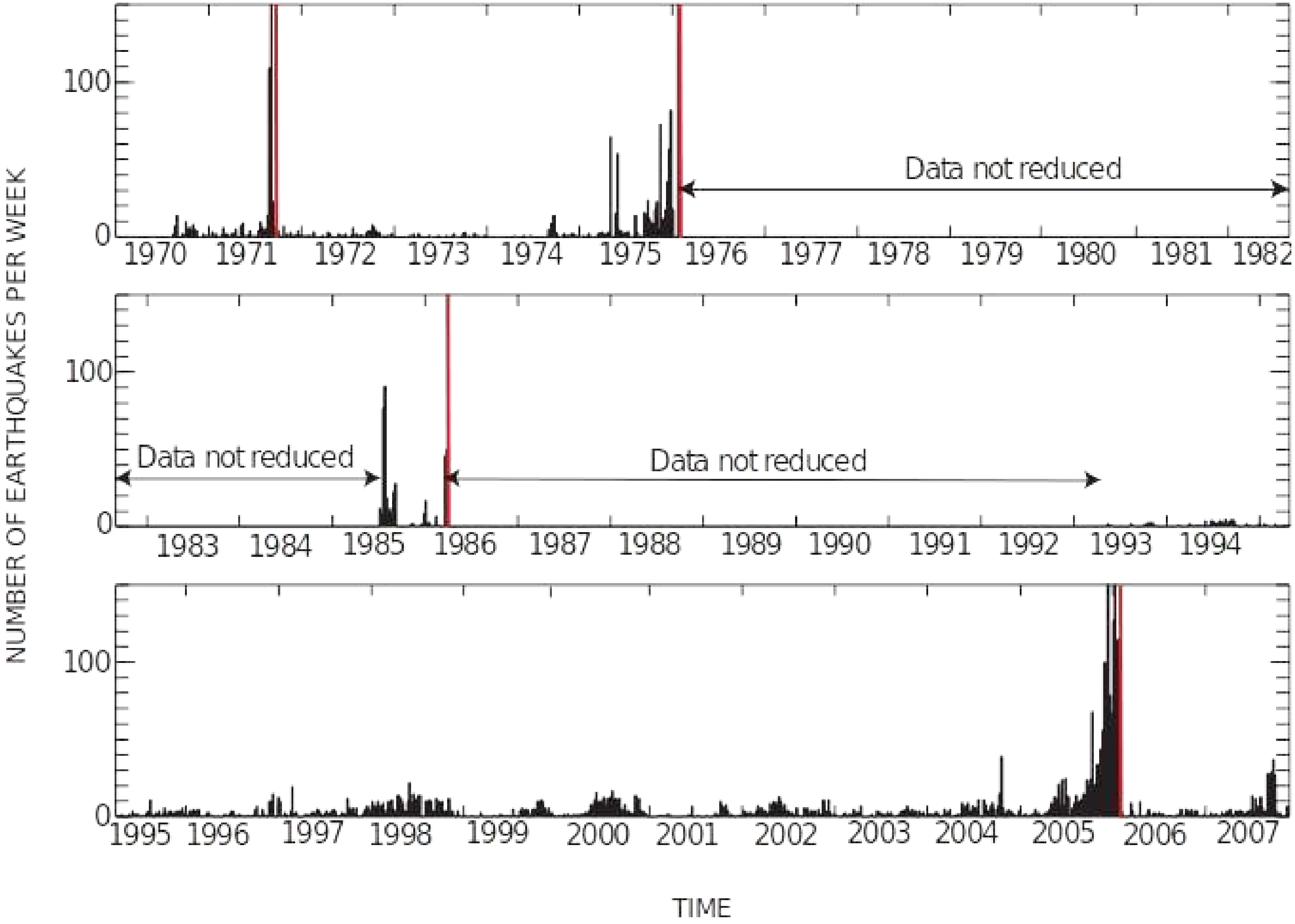


Aims of Volcano Seismo-Acoustics

- Volcanology perspective - understand volcanic processes from seismic/acoustic signals and patterns
- Seismology and acoustics perspective - understand seismic and acoustic source processes
- Monitoring and forecasting

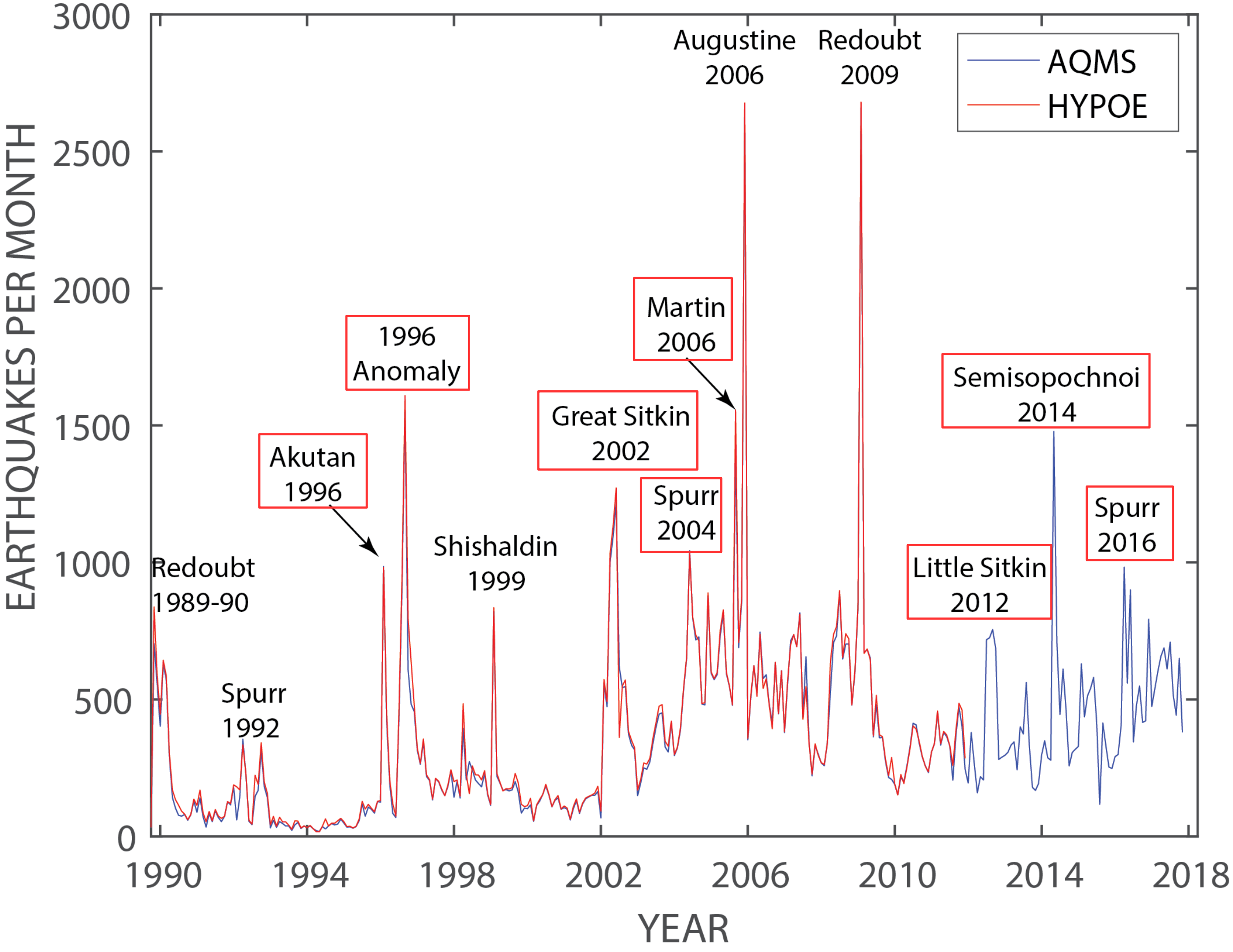
Paradigm I: Seismicity accompanies activity

- Seismicity at Augustine Volcano, Alaska, 1970-2007
  Red lines = eruptions



Power et al. 2010

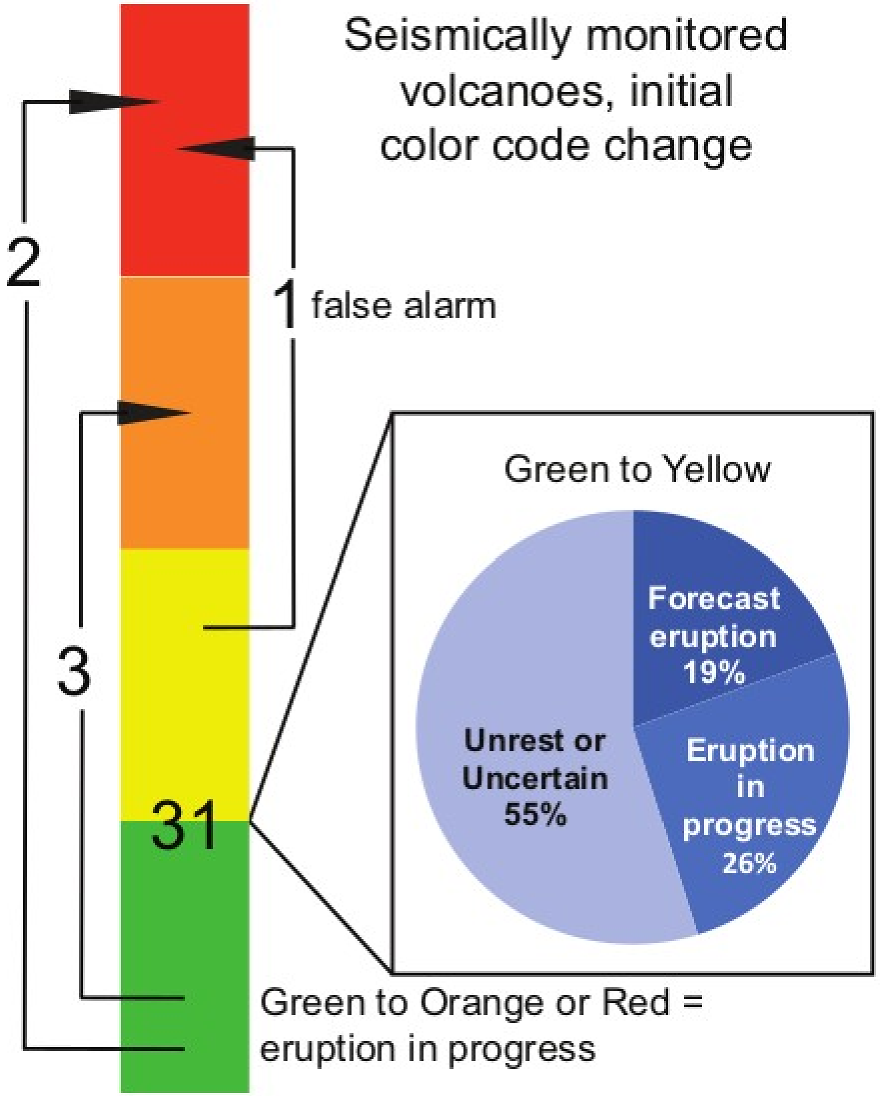
Paradigm I: Seismicity accompanies activity



After Power et al., 2019

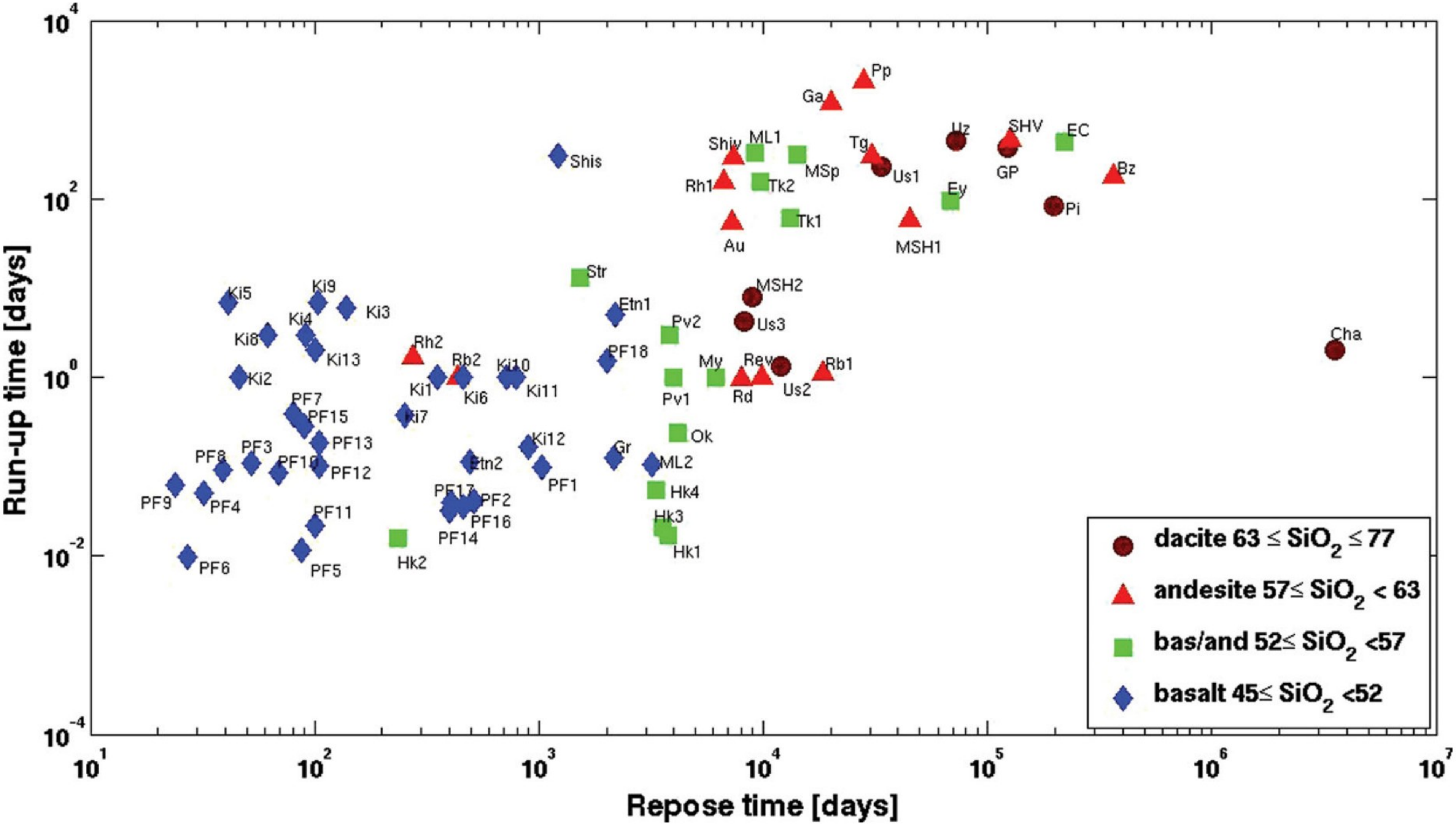
“Failed eruption” problem - see Moran et al. 2011

Paradigm I: Seismicity accompanies activity



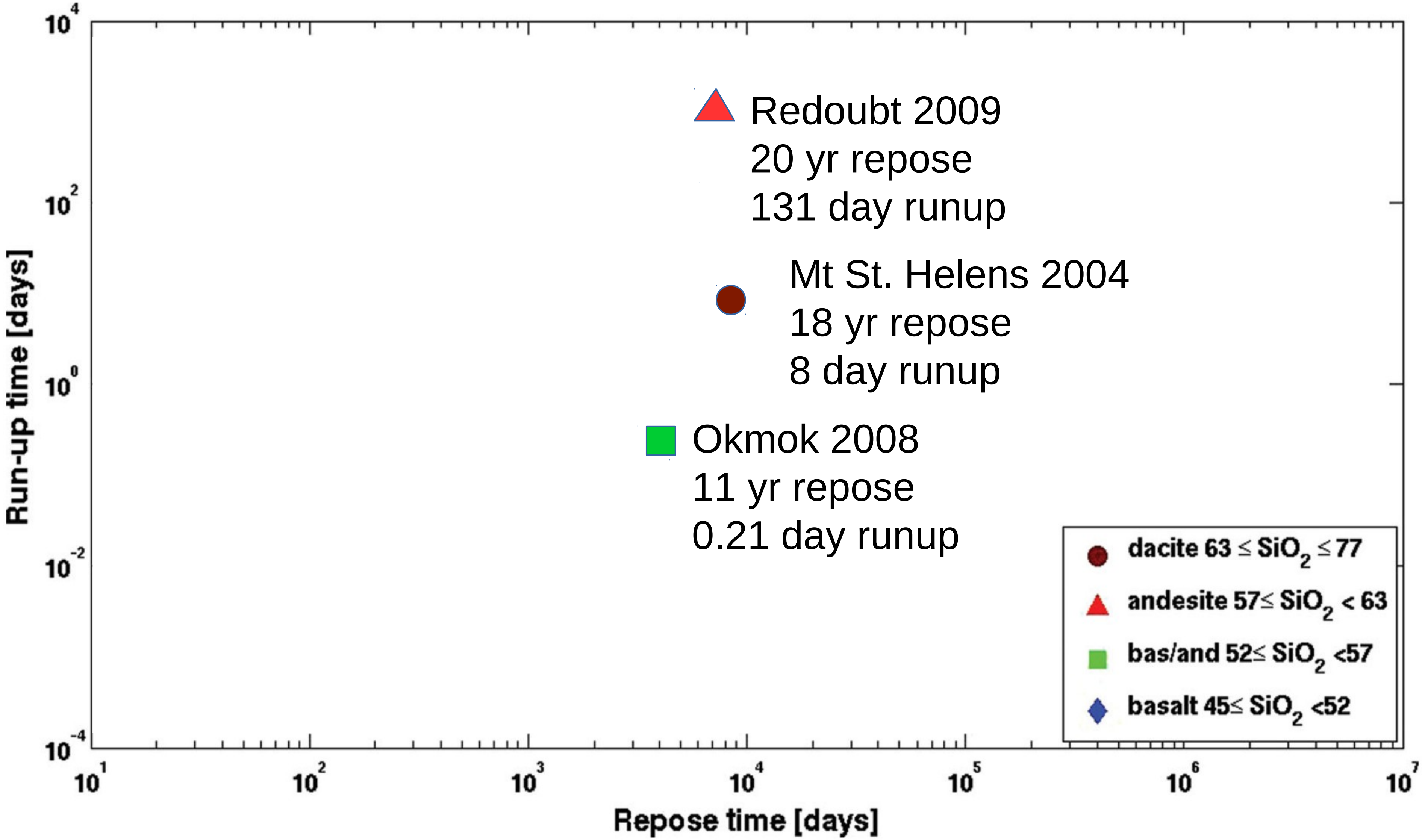
Cameron et al., 2018

Duration of Precursory Seismicity



Passarelli and Brodsky 2012 (GJI)

Duration of Precursory Seismicity



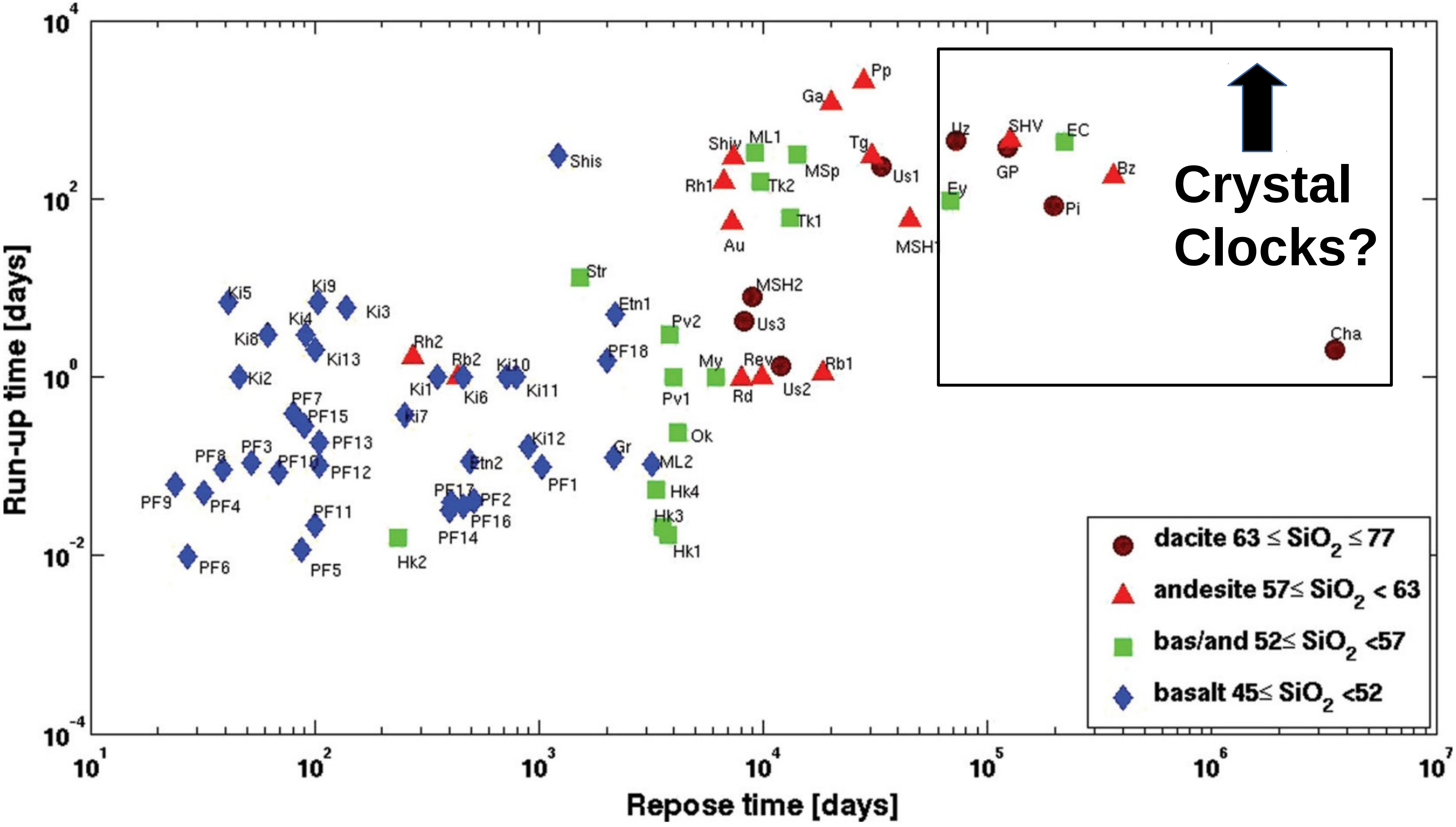
Redoubt 2009
20 yr repose
131 day runup

Mt St. Helens 2004
18 yr repose
8 day runup

Okmok 2008
11 yr repose
0.21 day runup

After Passarelli and Brodsky 2012 (GJI)

Duration of Precursory Seismicity



Crystal Clocks?

Passarelli and Brodsky 2012 (GJI)

Paradigm II: Seismic Event Classes

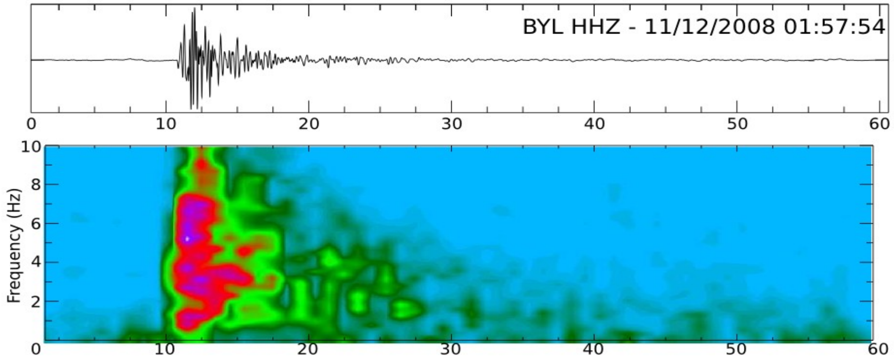
- Multiple processes produce seismic signals at volcanoes. The signals are (mostly/sometimes) distinctive and ultimately reflect the nature and underlying physics of the source process

- By looking for different event types, we can identify the processes occurring in a magmatic system and thus gain information about the state of the volcano

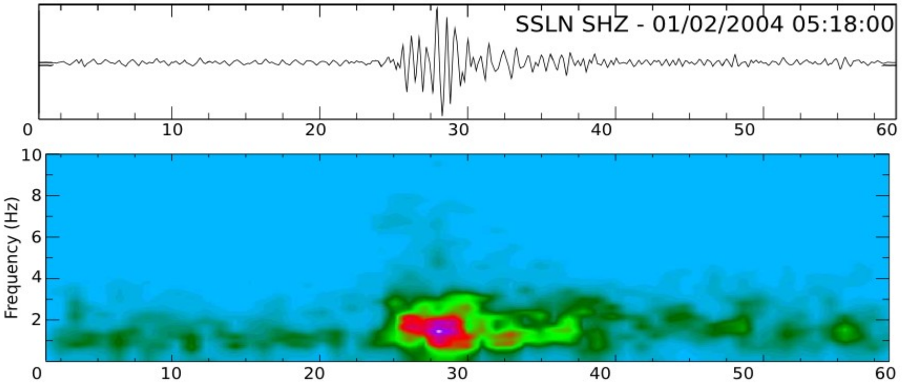
Paradigm II: Seismic Event Classes

- Distinguished by **frequency content** and shape/length

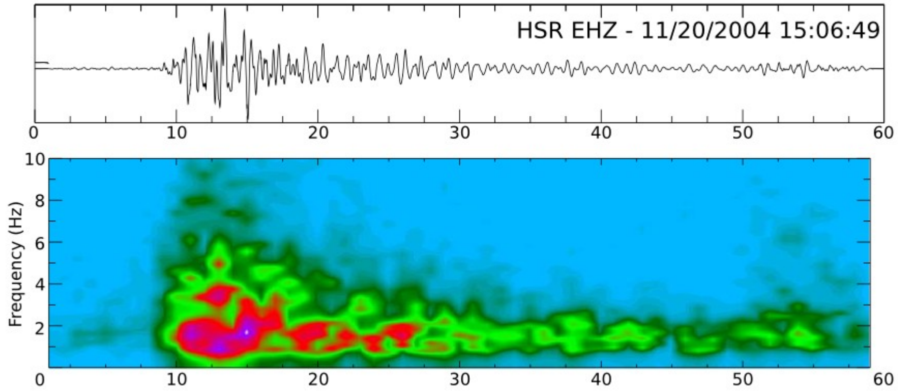
‘VT’ (volcano-tectonic) or ‘HF’ (high-frequency):



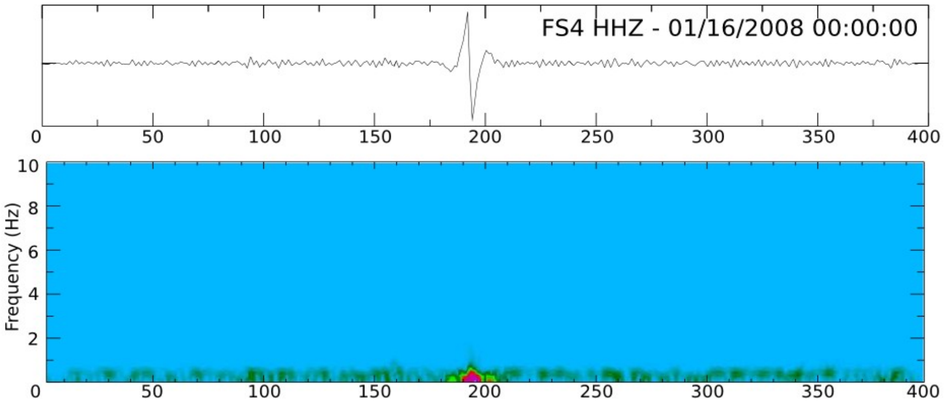
‘LP’ (long-period) or ‘LF’ (low-frequency):



Hybrid event:



‘VLP’ (very-long-period):

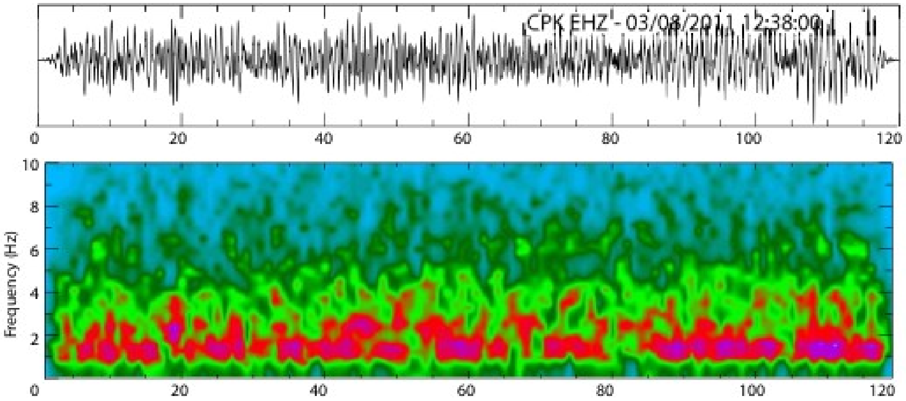


After McNutt and Roman 2015
see Minakami 1974, Lahr et al. 1994, Miller et al. 1998
for classification scheme descriptions

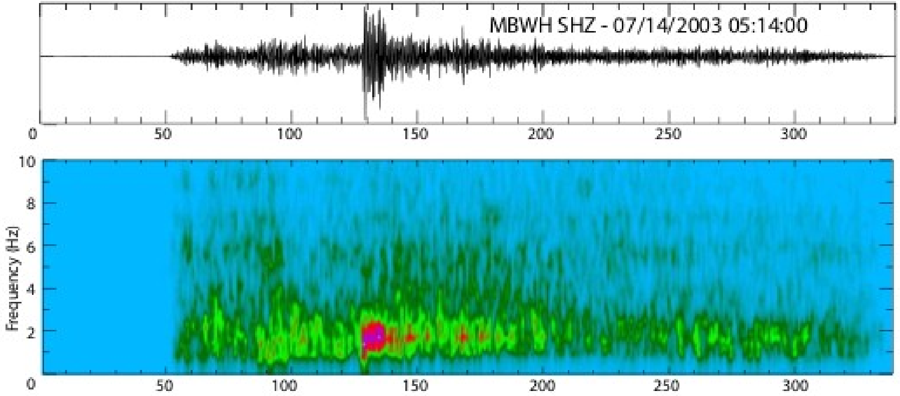
Paradigm II: Seismic Event Classes

- Distinguished by frequency content and **shape/length**

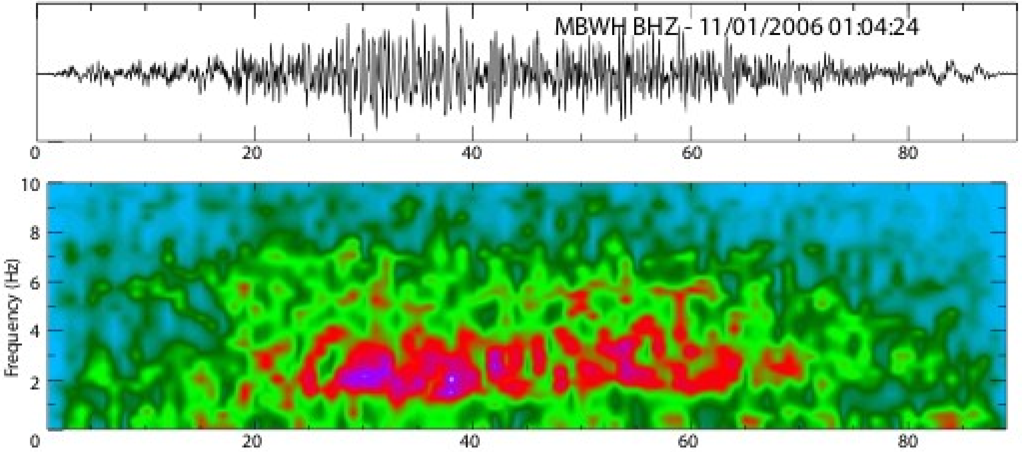
Volcanic tremor (can be harmonic or broadband):



Explosion with ground-coupled airwave:



Rockfall signal (note cigar shape):



After McNutt and Roman 2015

Event Classification Issues

Utility and appropriateness of a universal event classification scheme?

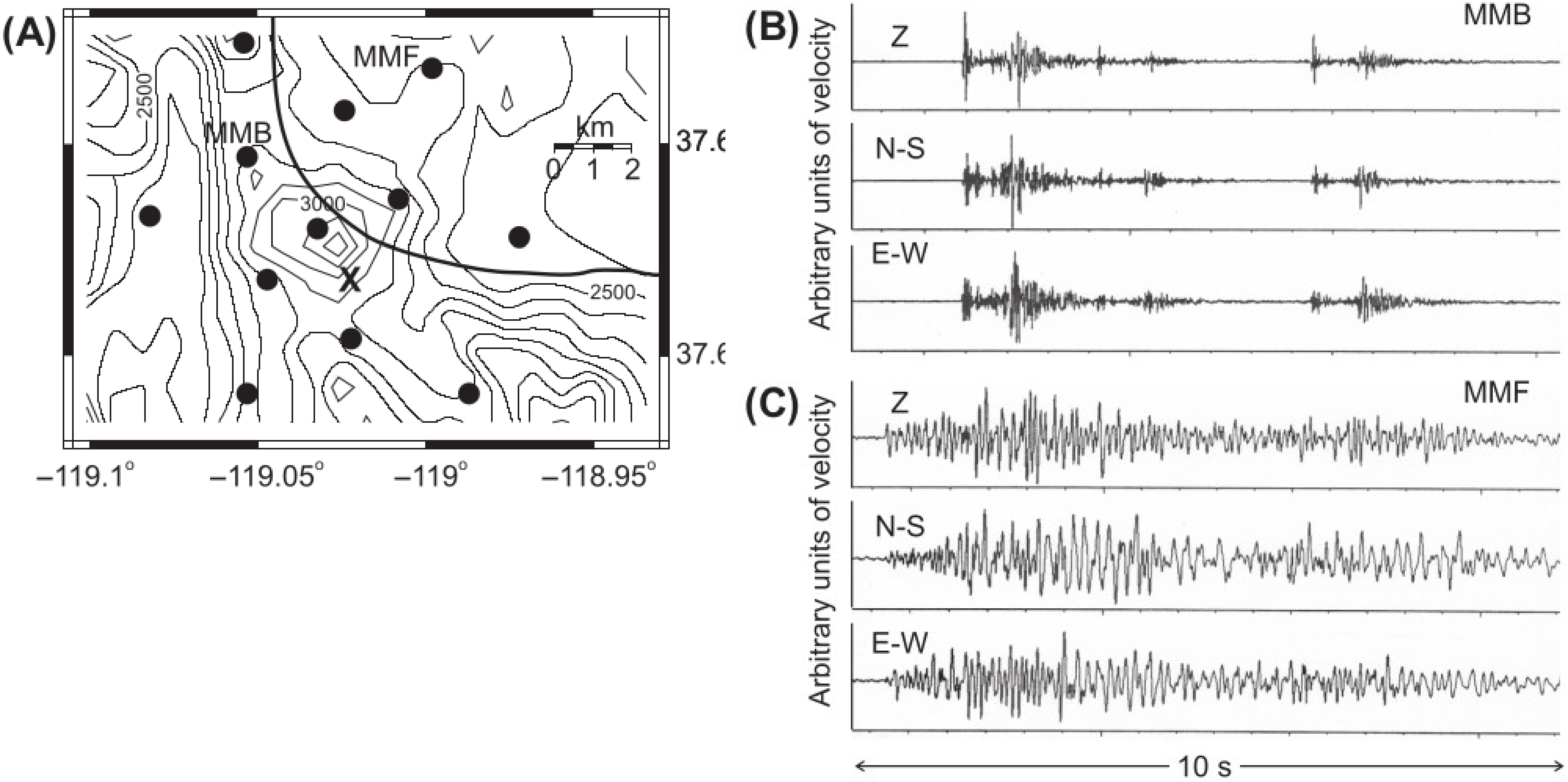
- Implies the existence of clearly distinct classes rather than a spectrum of event characteristics

- Implies that event classes are uniquely linked to a particular source process

- Implies that events do not interfere/interact with each other

Event Classification Issues

Station-to-station variations: Mammoth 1989



After Julian et al., 1998

Automated Event Detection/Classification

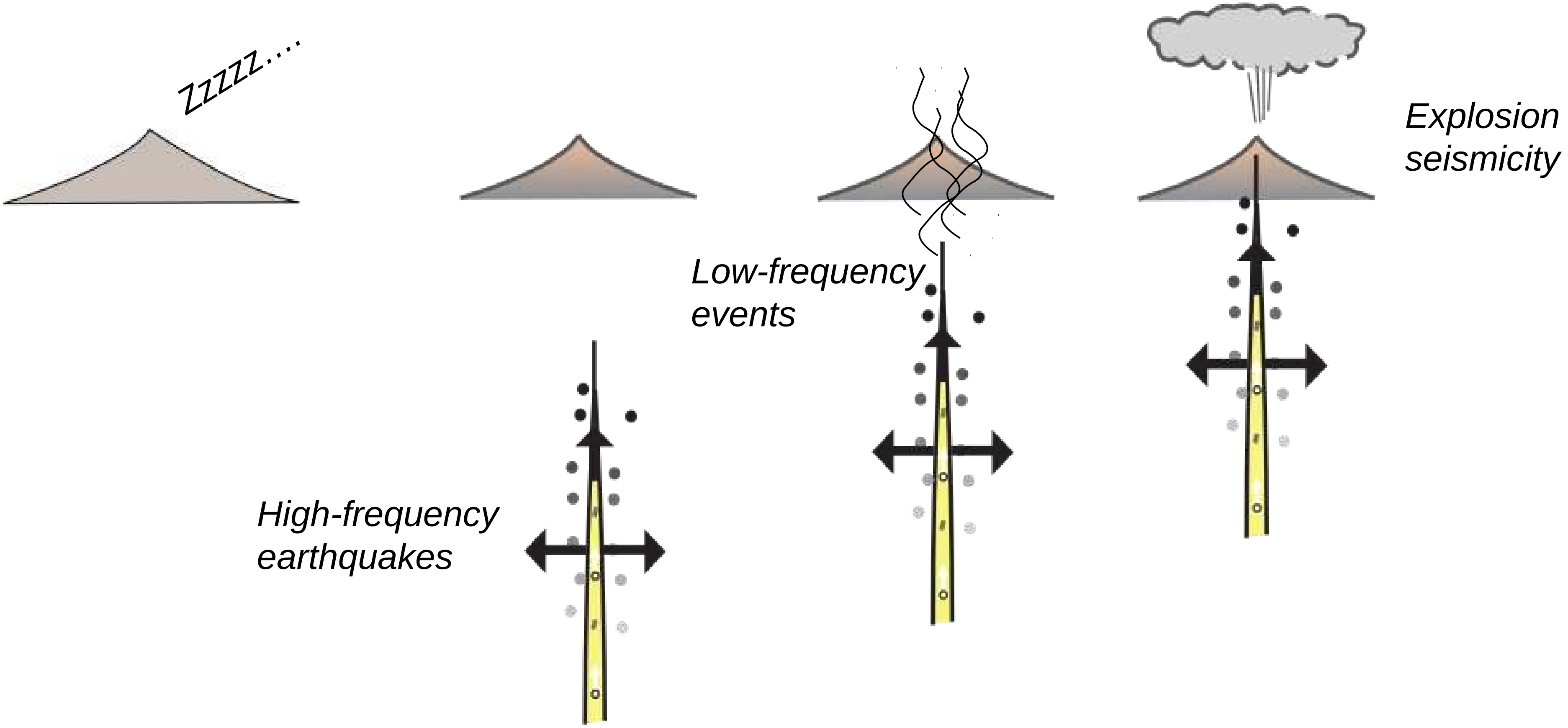
- Bueno et al. 2019, Seismol Res Lett
  https://github.com/srsudo/remos

- Malfante et al. 2018, IEEE Signal Proc Mag
  https://github.com/malfante/AAA

- Roman 2017, Geophys Res Lett
  https://github.com/dcroman/Tremometer
  (harmonic tremor detection)

- Wech and Creager 2008, Geophys Res Lett
  https://github.com/awech/AVO-alarms
  (broadband tremor detection)

Precursory Seismicity Patterns

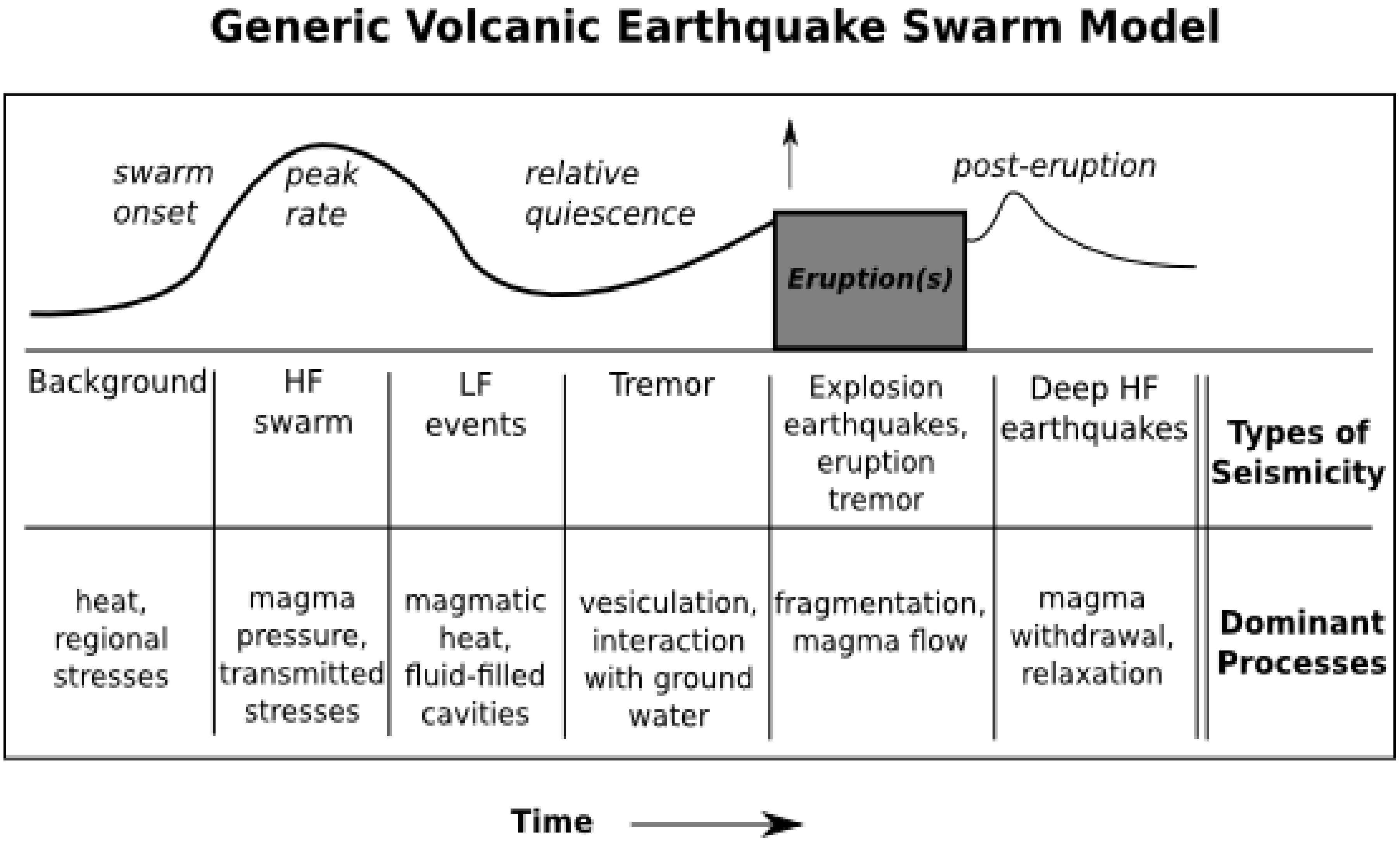


Explosion seismicity

Low-frequency events

High-frequency earthquakes

Precursory Seismicity Patterns

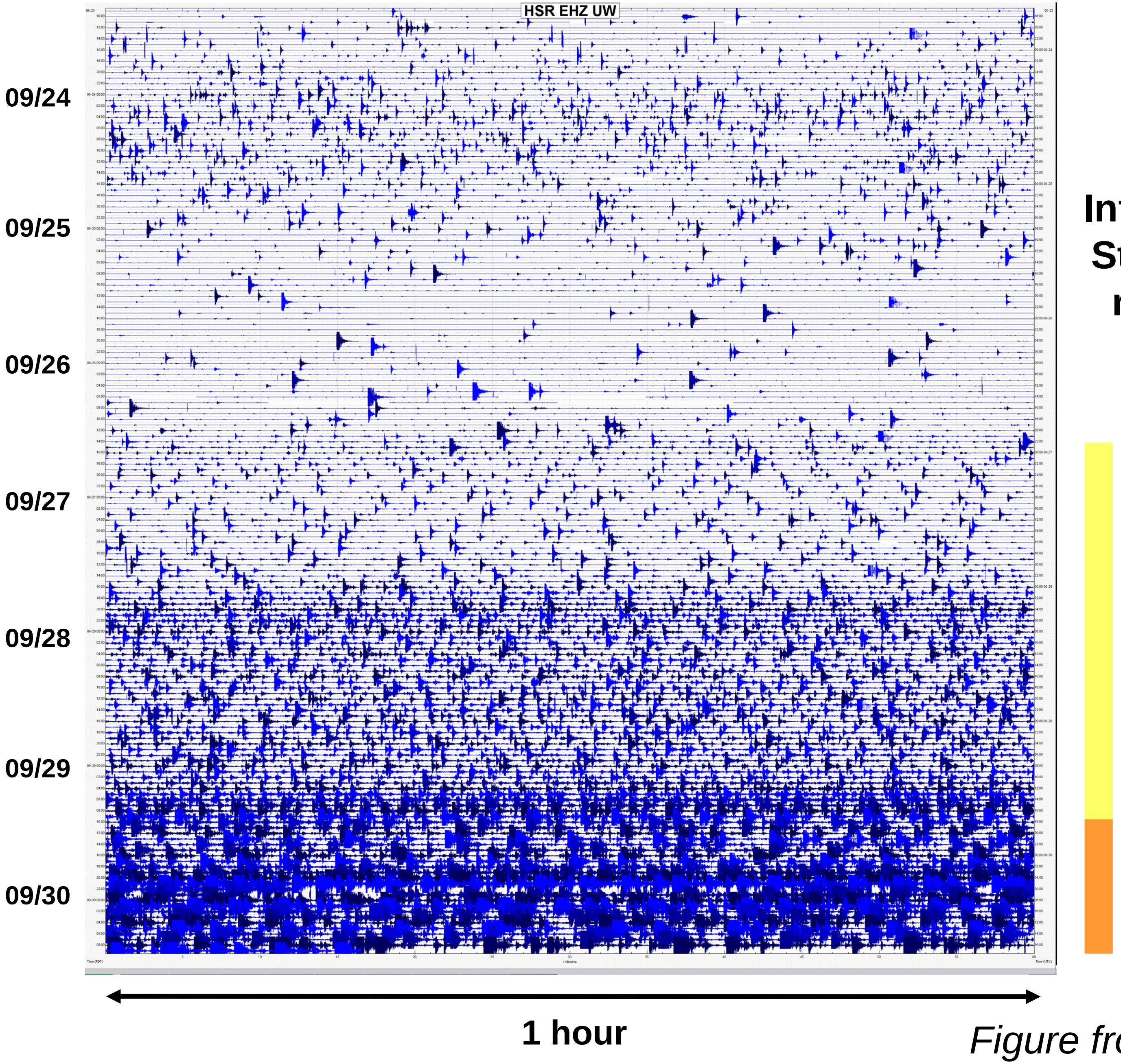


Generic Volcanic Earthquake Swarm Model

Background	HF swarm	LF events	Tremor	Explosion earthquakes, eruption tremor	Deep HF earthquakes	**Types of Seismicity**
heat, regional stresses	magma pressure, transmitted stresses	magmatic heat, fluid-filled cavities	vesiculation, interaction with ground water	fragmentation, magma flow	magma withdrawal, relaxation	**Dominant Processes**

McNutt and Benoit (1995)

Precursory Seismicity Patterns: MSH 2004



Information Statement released

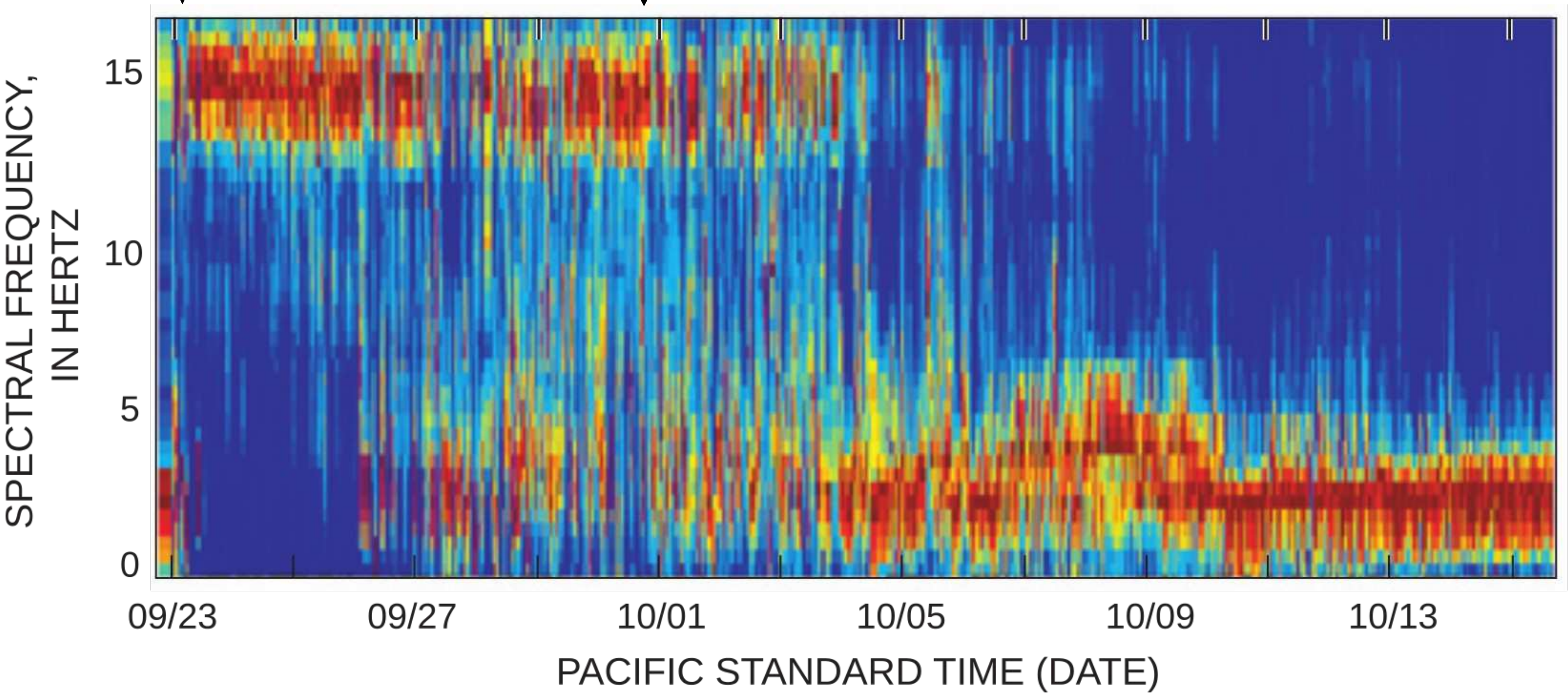
alert level changes

Figure from Seth Moran

Precursory Seismicity Patterns: MSH 2004

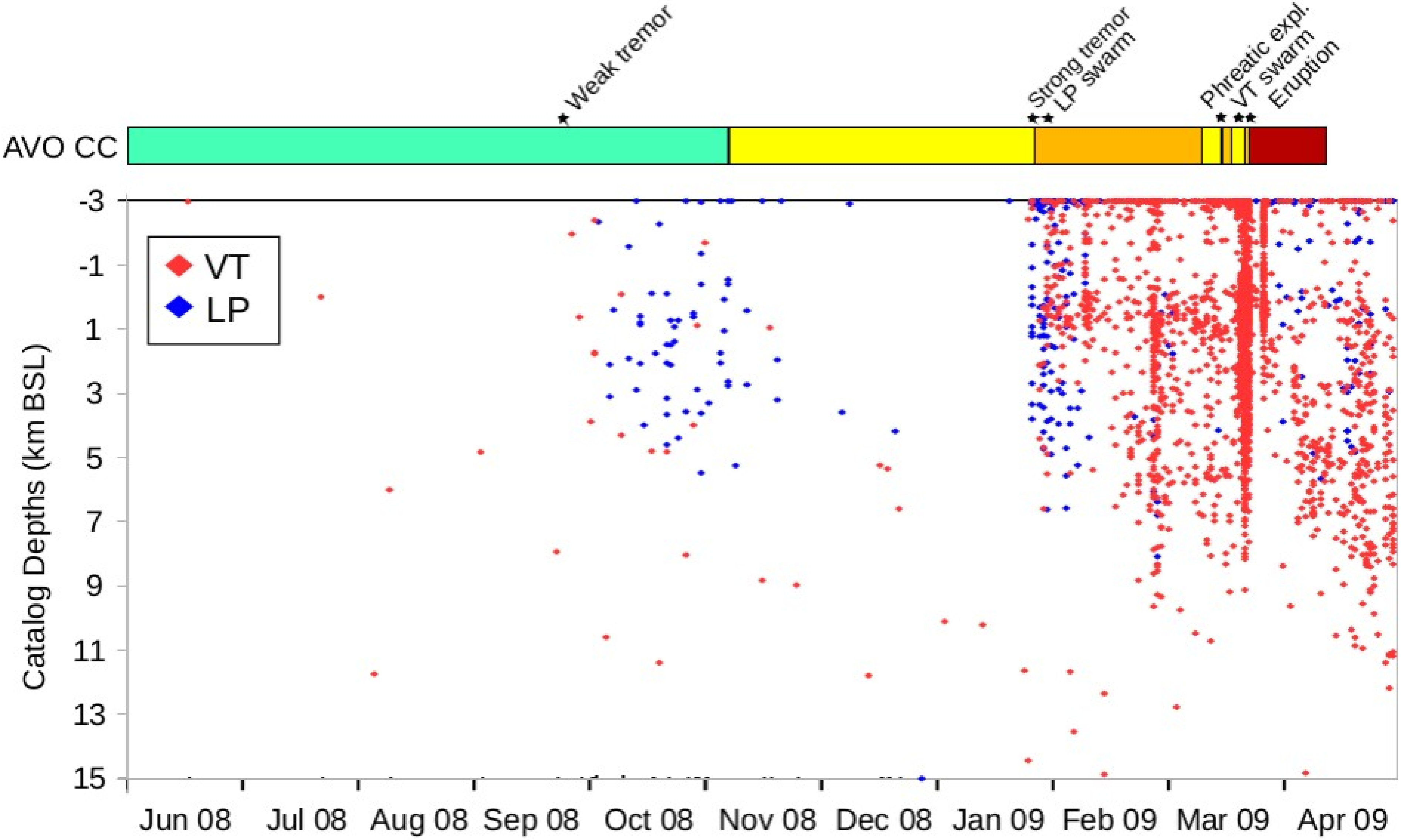
Onset of seismic unrest

Eruption Start



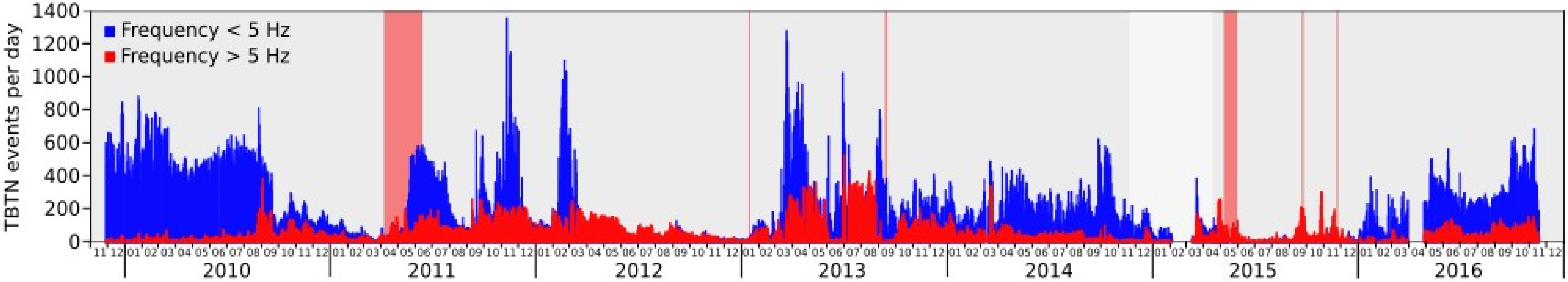
Moran et al., 2008

Precursory Seismicity Patterns: Redoubt 2009



After Roman and Gardine 2013
and Roman and Cashman 2018

Precursory (phreatic) Seismicity Patterns: Telica



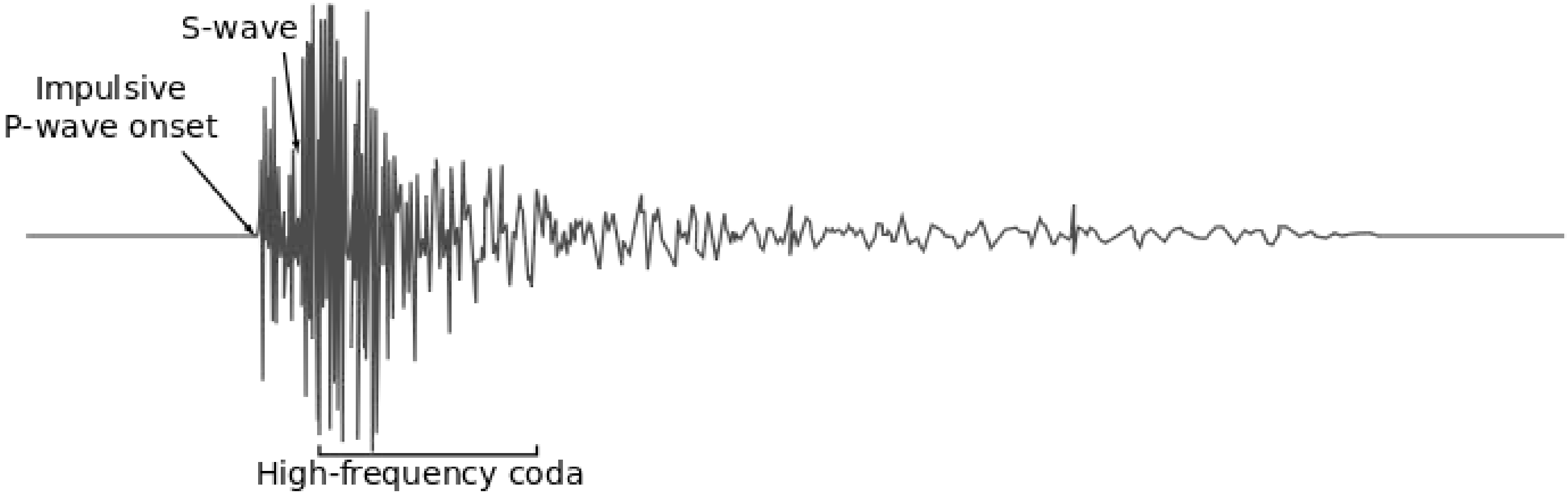
Geirsson et al., 2014
Rodgers et al., 2015
Roman et al., in review

VTs: Theory

Volcanotectonic (VT) (aka “HF”) earthquake:

- Clear high-frequency P and S waves, peak frequencies above 5 Hz, short coda

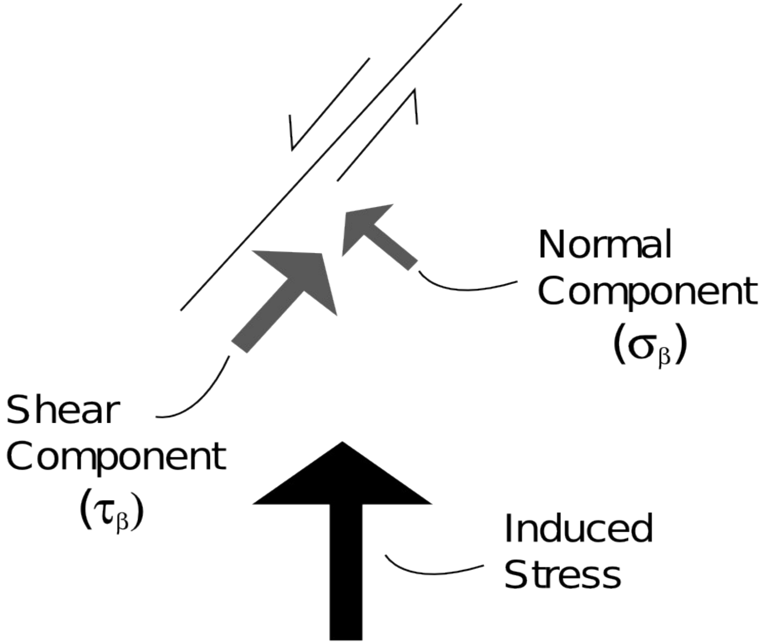
- Brittle response of host rock to processes in the magmatic system

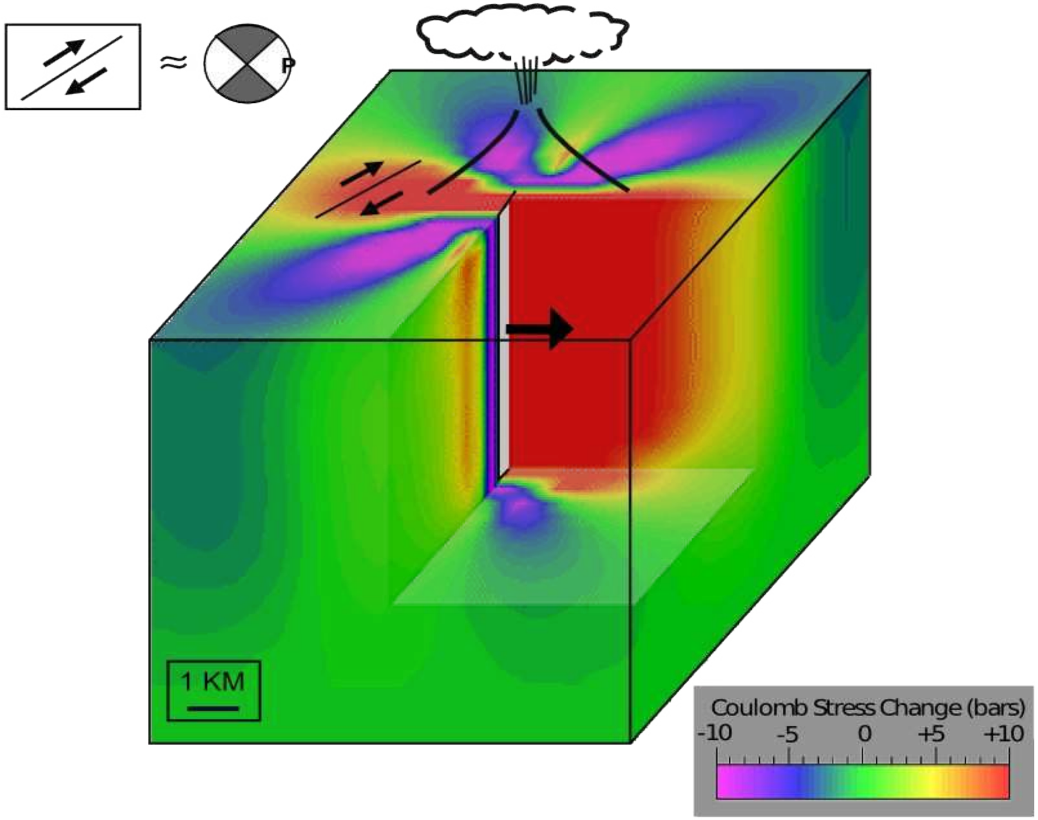


VTs: Theory

Coulomb stress change:

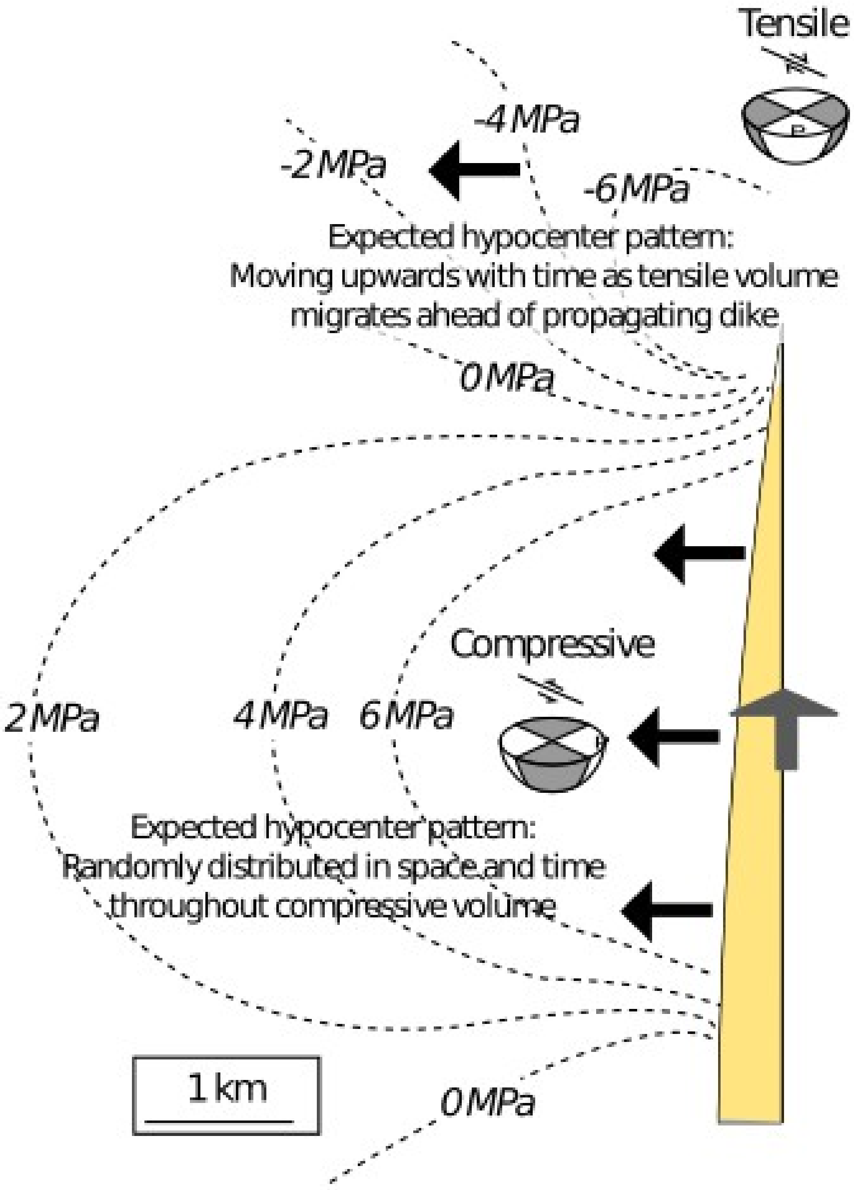
$$\Delta\sigma_f = \tau_\beta - \mu\,(\Delta\sigma_\beta - \Delta p)$$





See Toda et al., 2002; Segall et al. 2013;
Coulomb 3.3: https://earthquake.usgs.gov/research/software/coulomb/

Dike-induced stress regimes



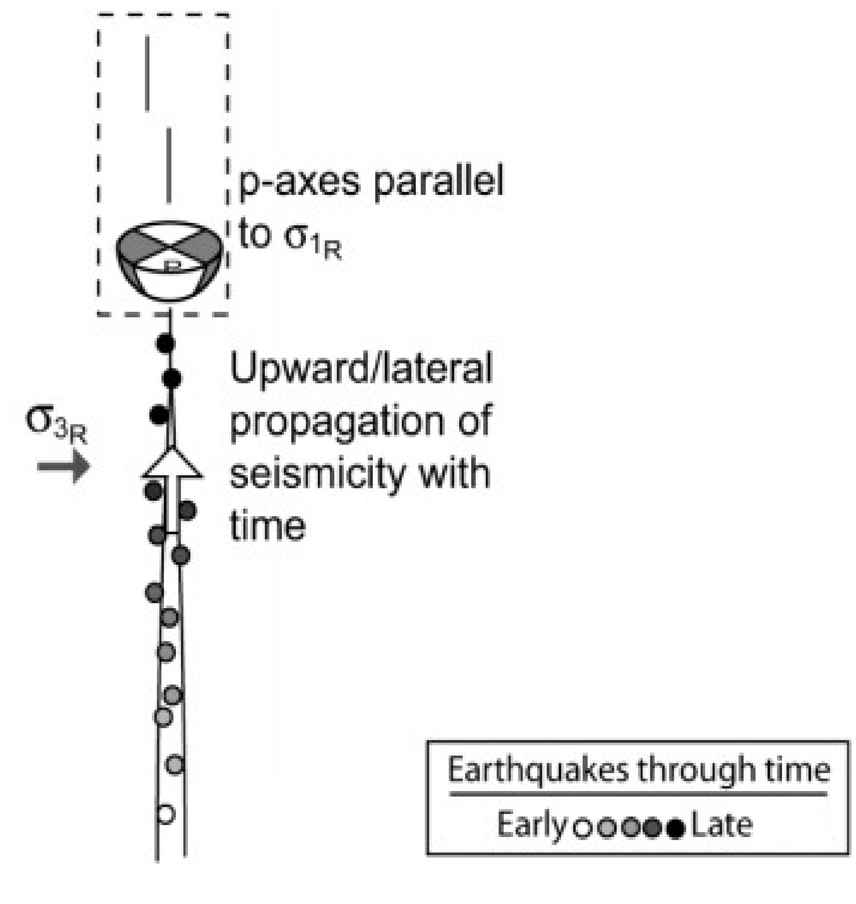
<u>Numerical models show
two induced stress regimes:</u>

- Compression in walls of dike (perpendicular to dike strike)
- Tension above propagating dike

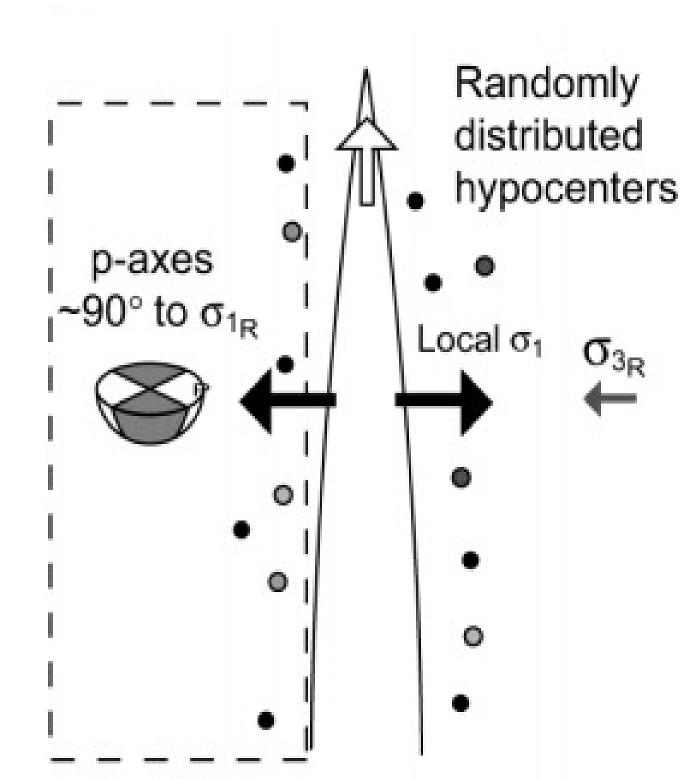
After Rubin and Pollard 1988

VTs: Theory

Low-viscosity magmas



High-viscosity magmas



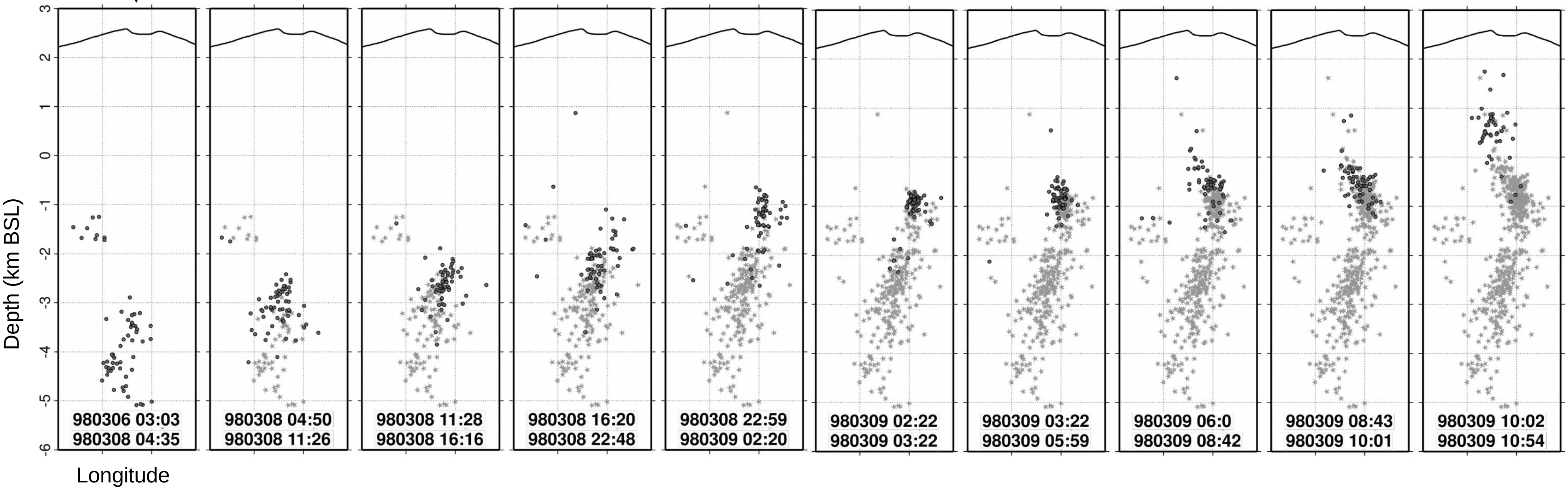
After Roman and Cashman (2006)

VTs: Low-Viscosity Magmas

Piton de la Fournaise, La Reunion - 1998

Onset of seismic unrest

Eruption Start

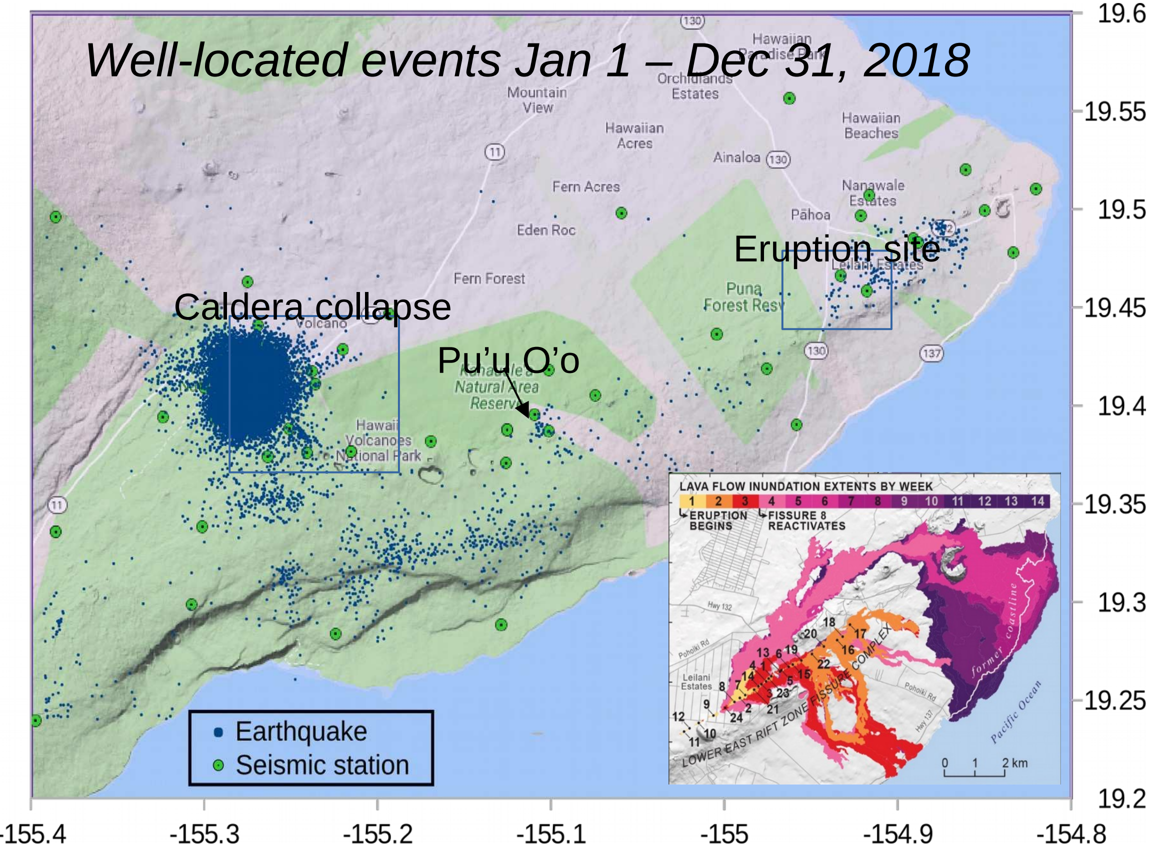


Time →

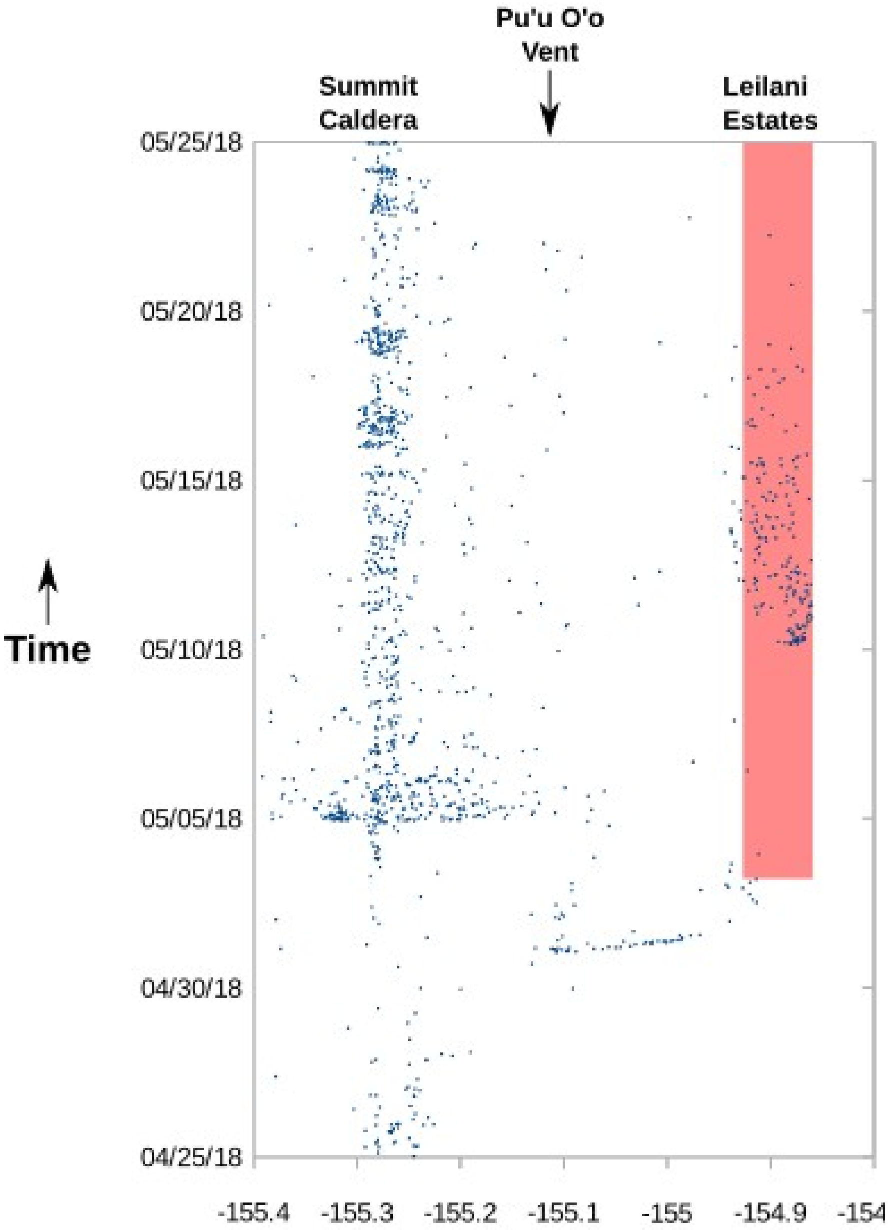
Battaglia et al., 2005

VTs: Low-Viscosity Magmas

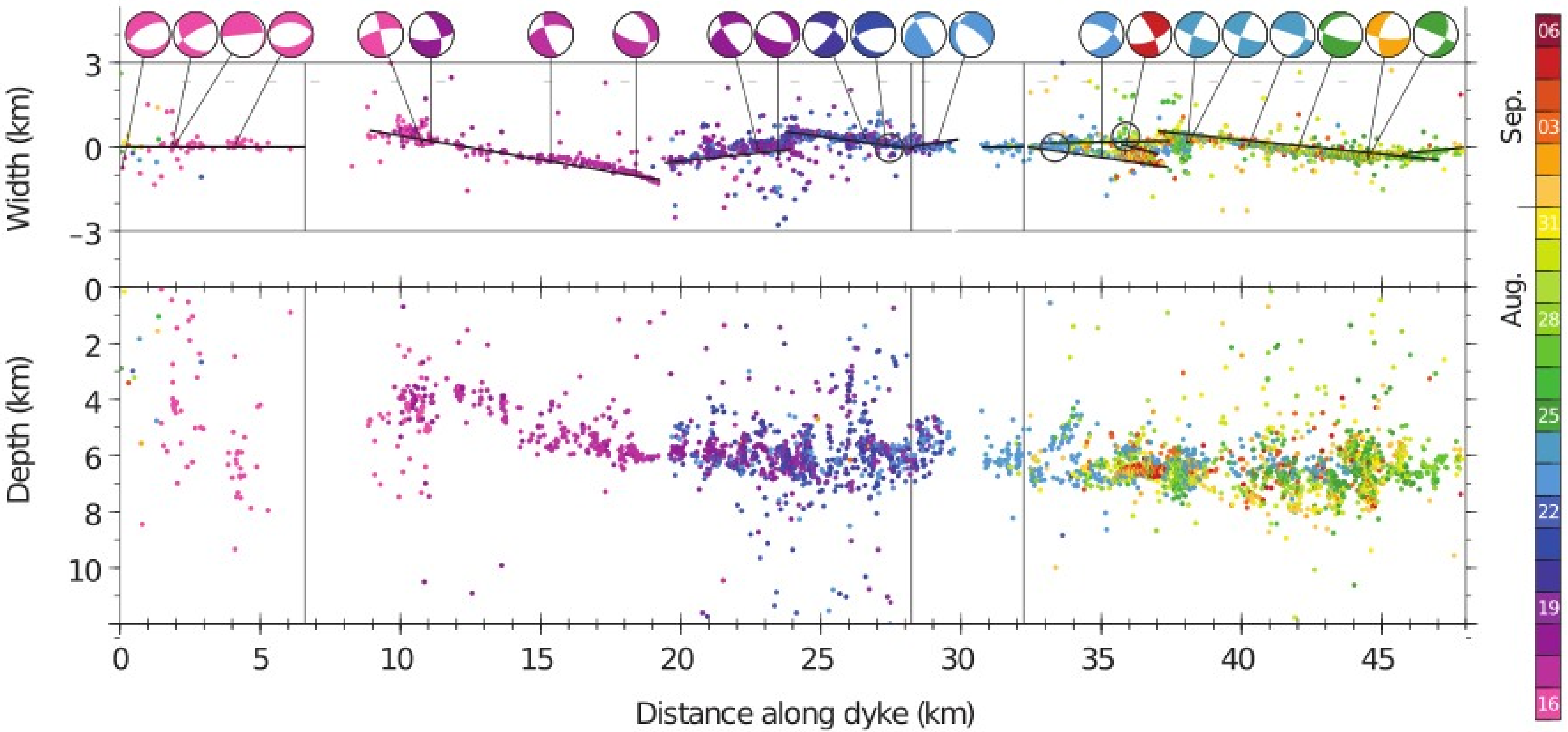
Kilauea, Hawai'i - 2018



Inset: Neal et al. (2018)



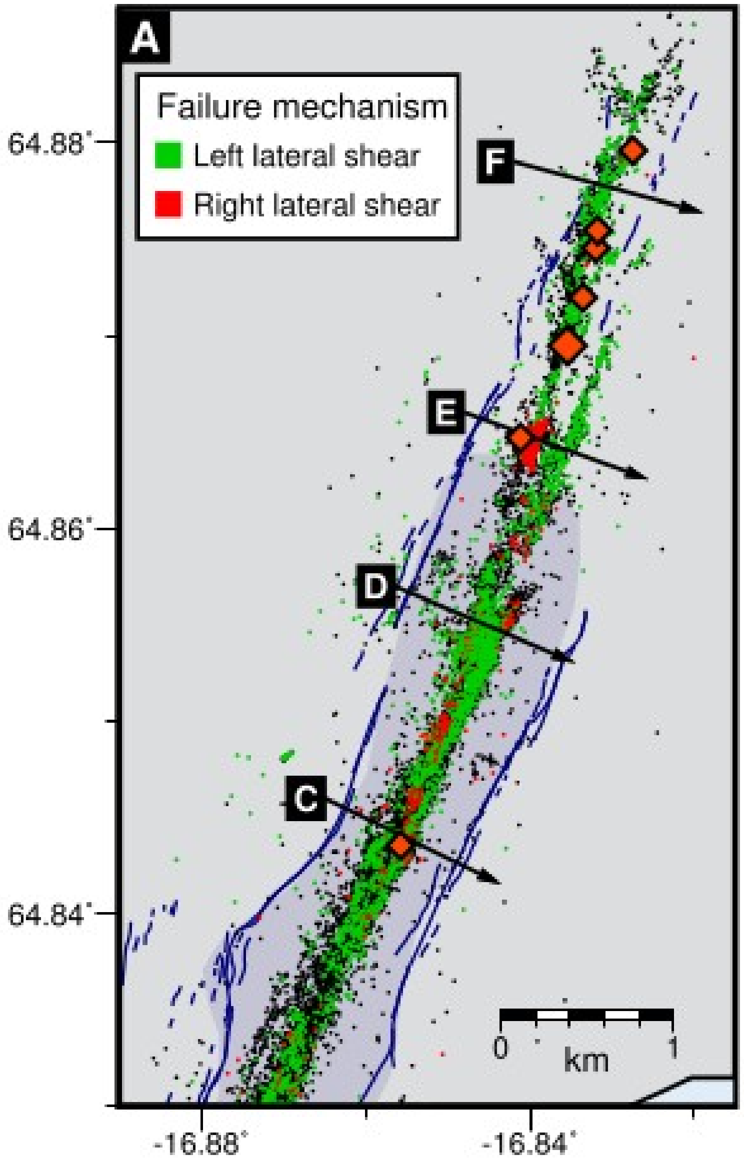
Holuhraun, Iceland - 2014

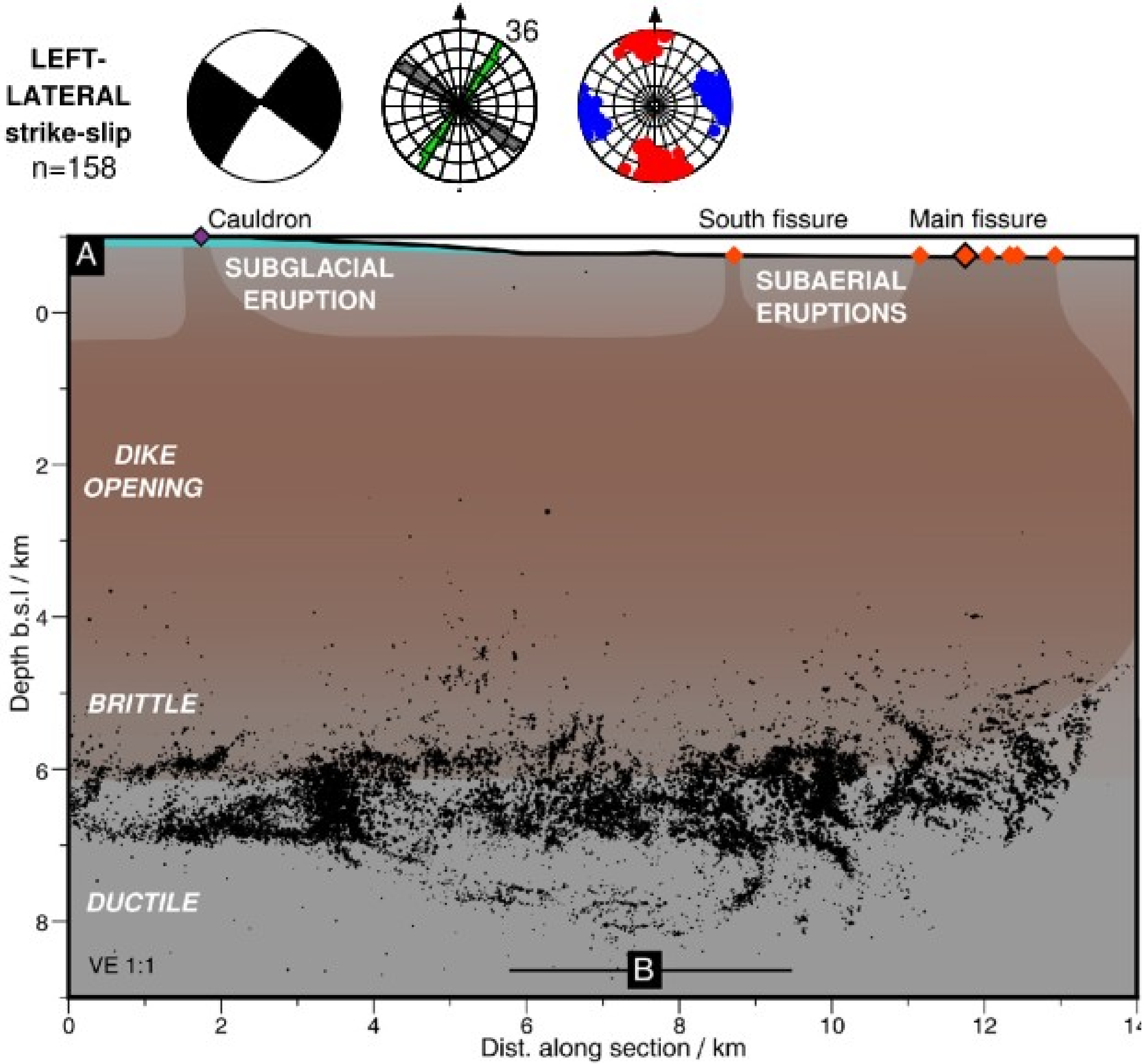


After Sigmundsson et al., 2015

VTs: Low-Viscosity Magmas

Holuhraun, Iceland - 2014

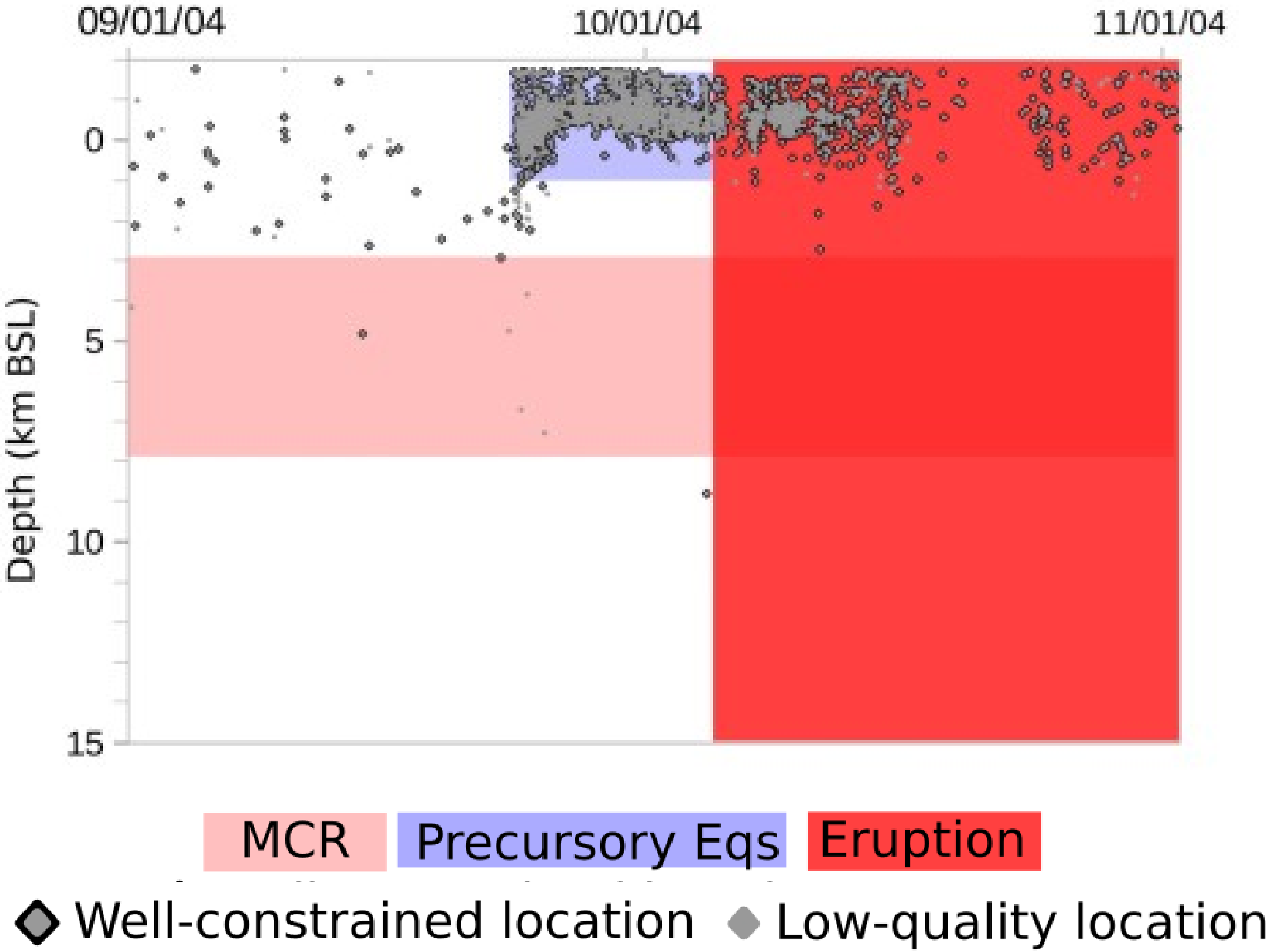




Agustsdottir et al., 2016; Woods et al., 2019

VTs: High-Viscosity Magmas

Mt. St. Helens, Washington - 2004

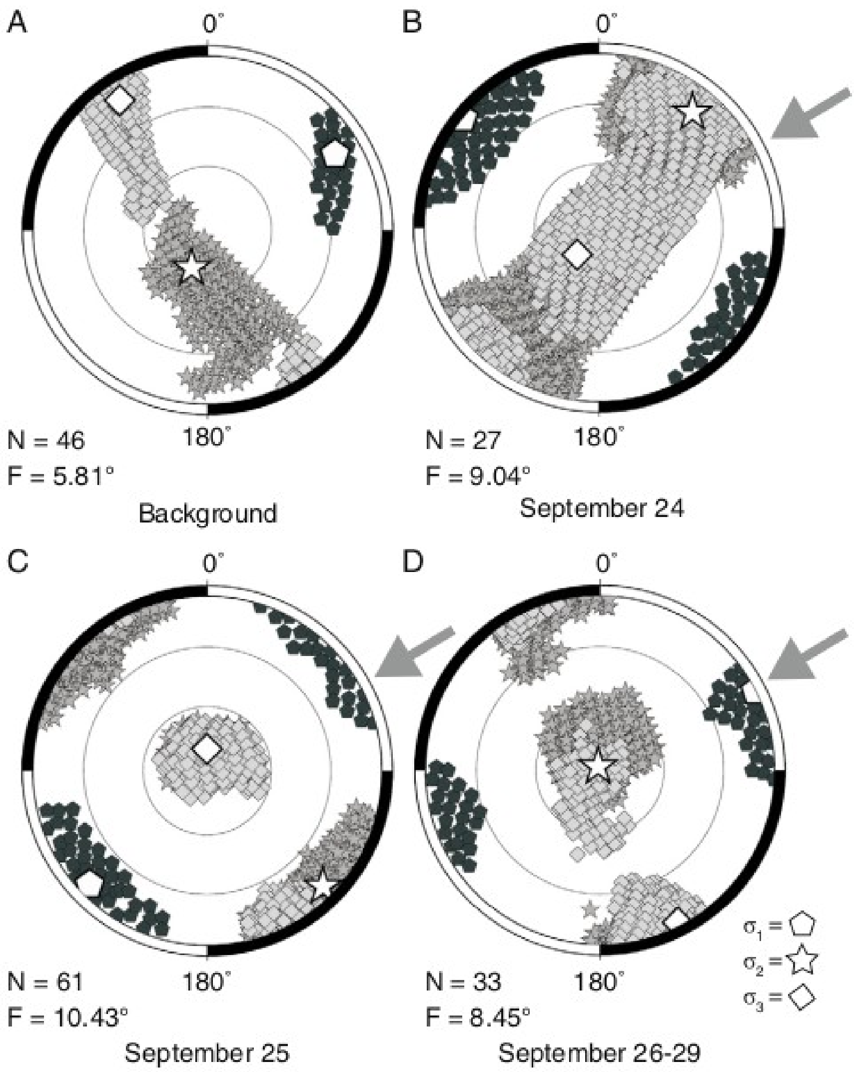


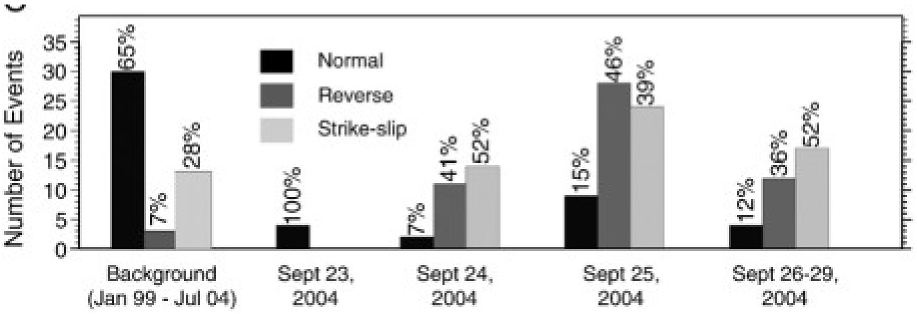
Roman and Cashman (2018)

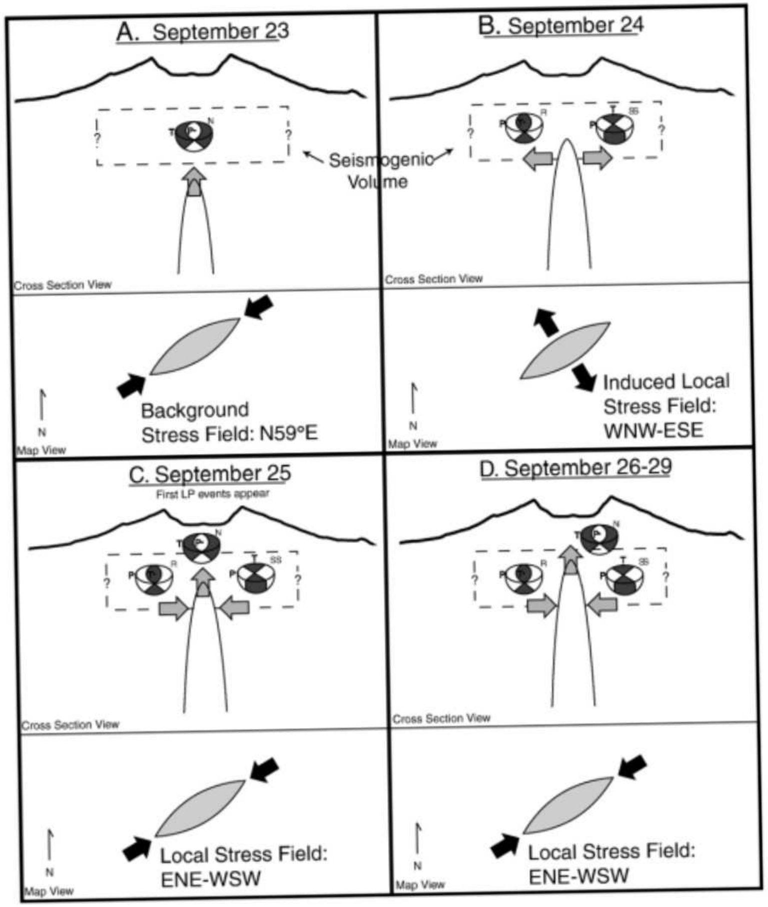
Seismic: Moran et al. 2008; Geodesy: Dzurisin et al. 2008; Petrology: Pallister et al. 2008

VTs: High-Viscosity Magmas

Mt. St. Helens, Washington - 2004

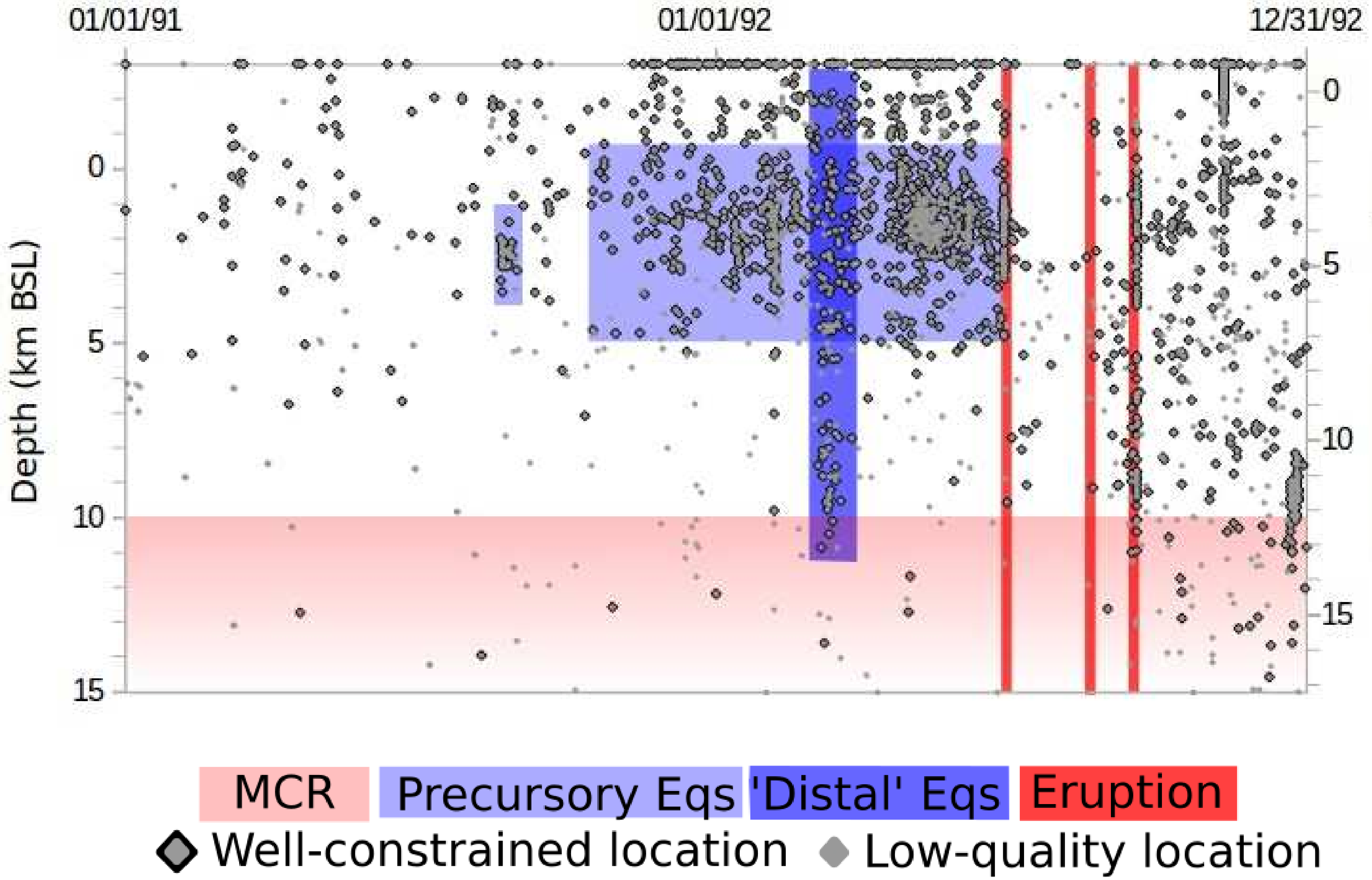






Lehto et al., 2010

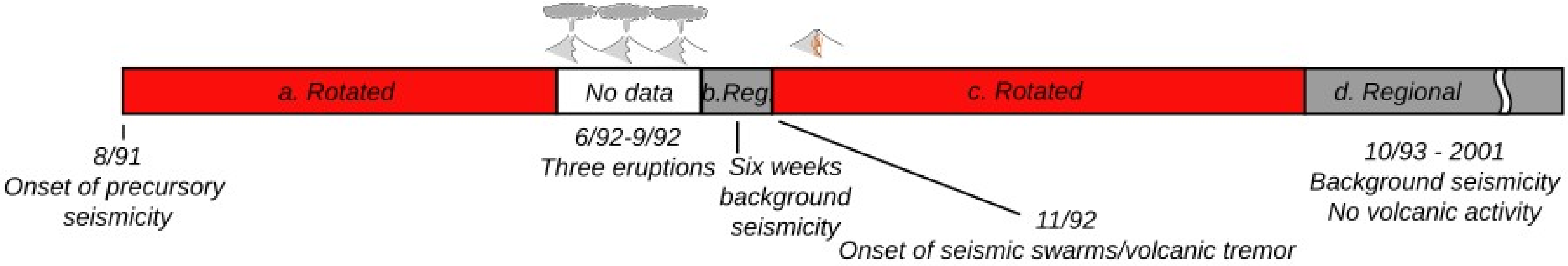
Mt. Spurr/Crater Peak, Alaska - 1992



Roman and Cashman (2018)
Seismic: Power et al. 1995; Petrology: Harbin et al. 1995 and Power et al. 2002

VTs: High-Viscosity Magmas

Mt. Spurr/Crater Peak, Alaska - 1992



a. Rotated | No data | b.Reg. | c. Rotated | d. Regional

8/91
Onset of precursory seismicity

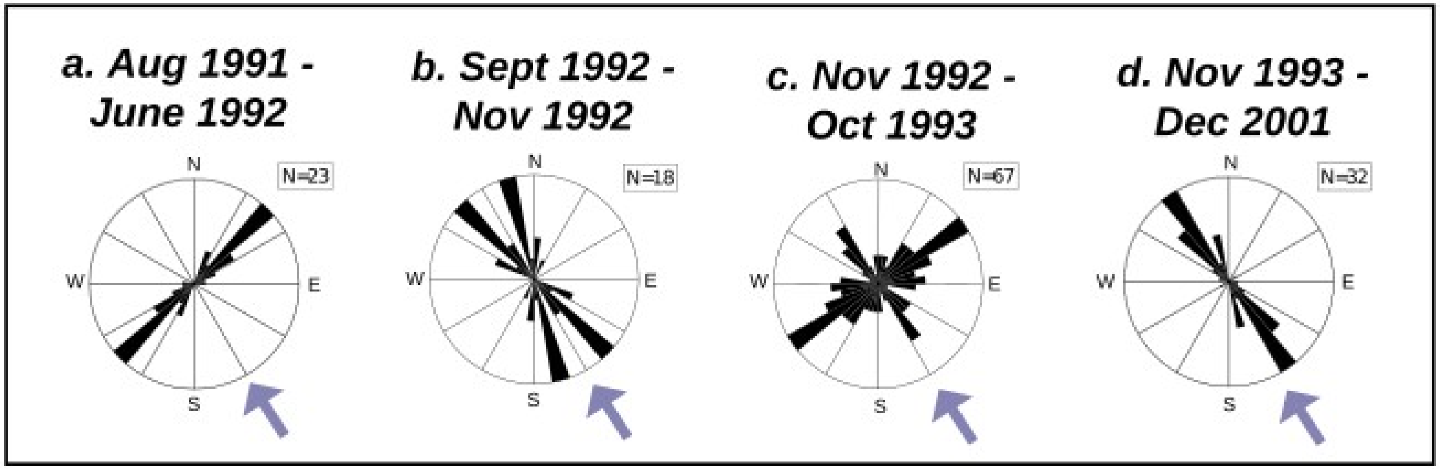
6/92-9/92
Three eruptions

Six weeks background seismicity

11/92
Onset of seismic swarms/volcanic tremor

10/93 - 2001
Background seismicity
No volcanic activity

Fault-plane solution P-Axis azimuths



a. Aug 1991 - June 1992

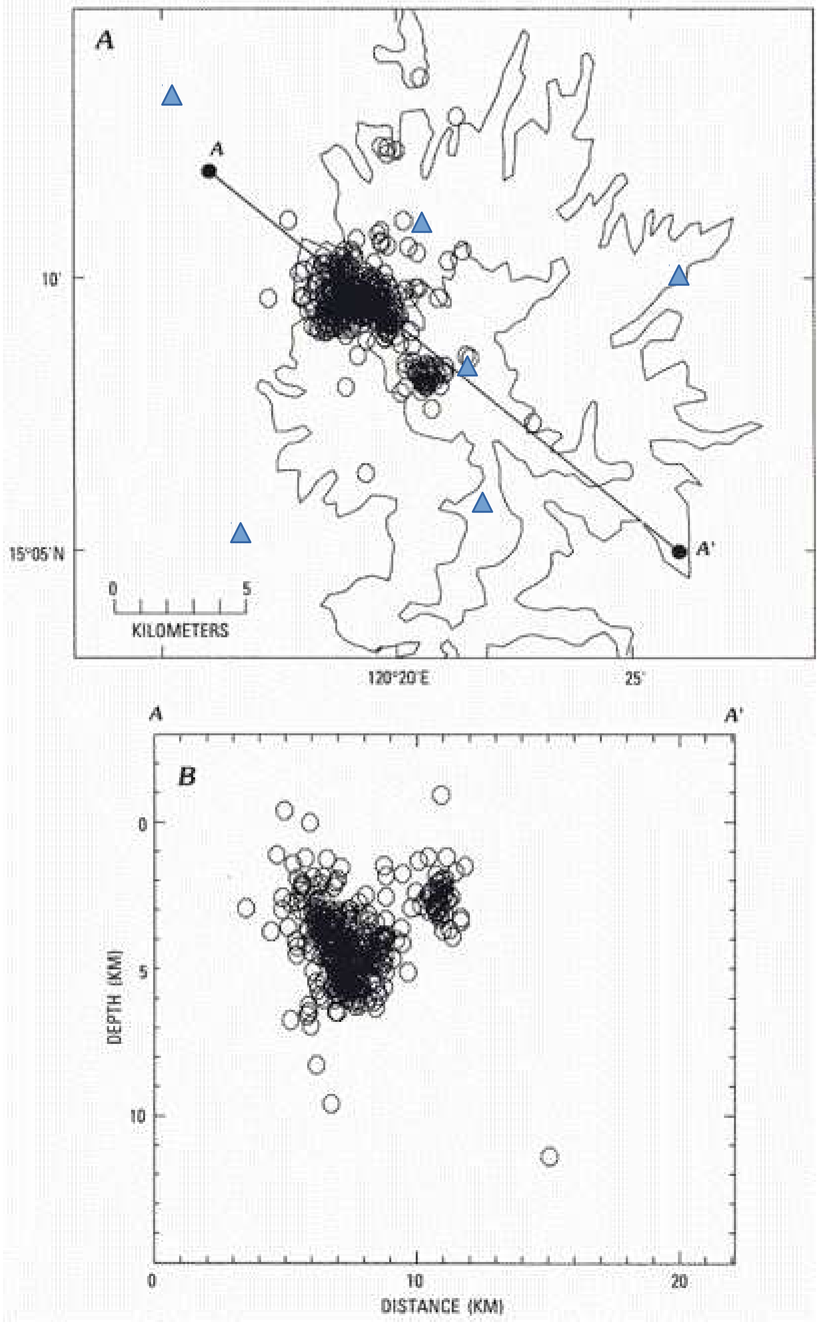
b. Sept 1992 - Nov 1992

c. Nov 1992 - Oct 1993

d. Nov 1993 - Dec 2001

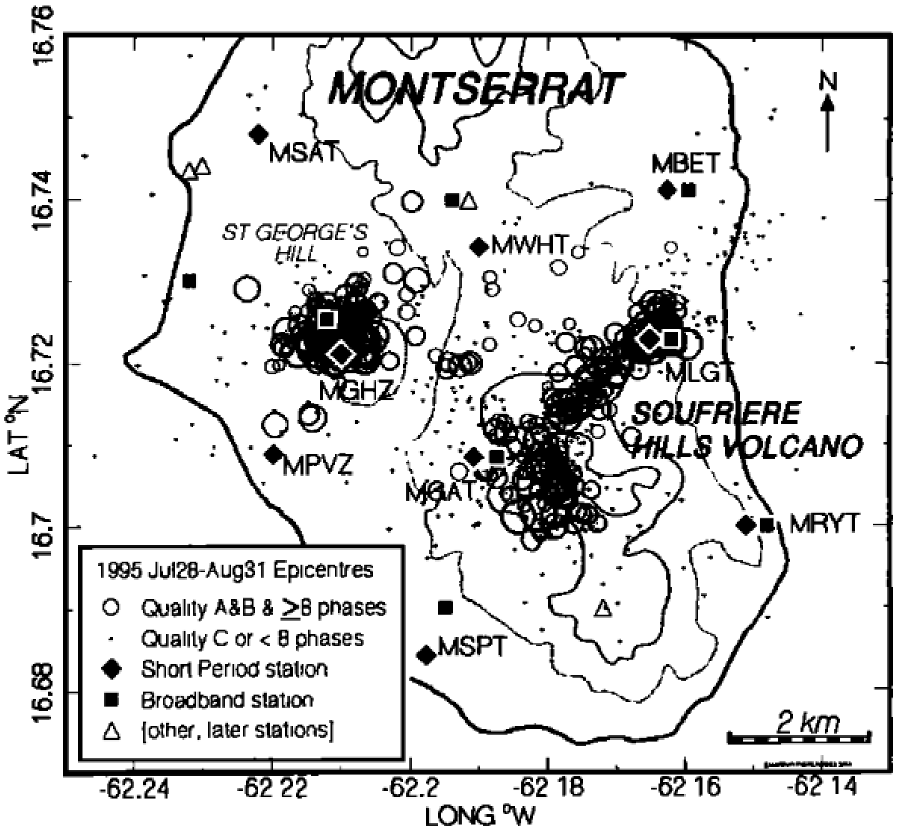
Roman et al. (2004)

Distal VT Earthquakes



Harlow et al., 1996

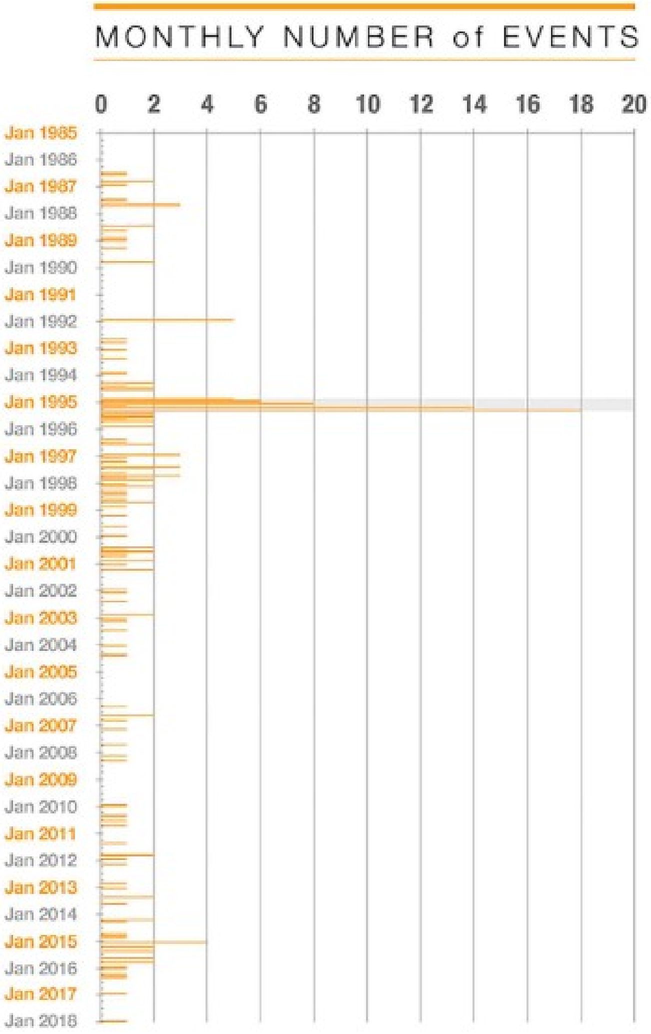
Left: Pinatubo 1991
Below: Soufriere Hills 1995

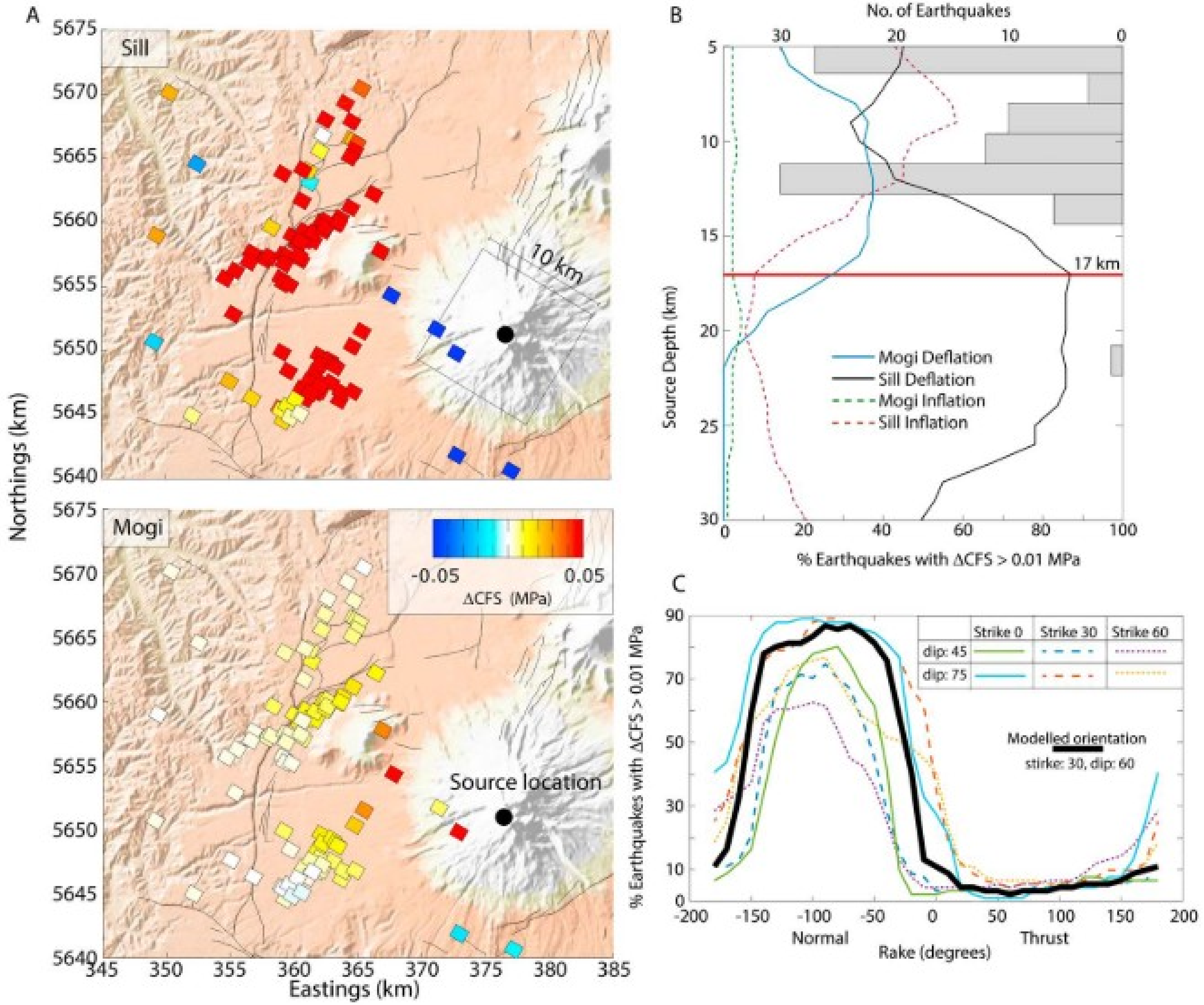


Aspinall et al., 1998

Distal VT Earthquakes

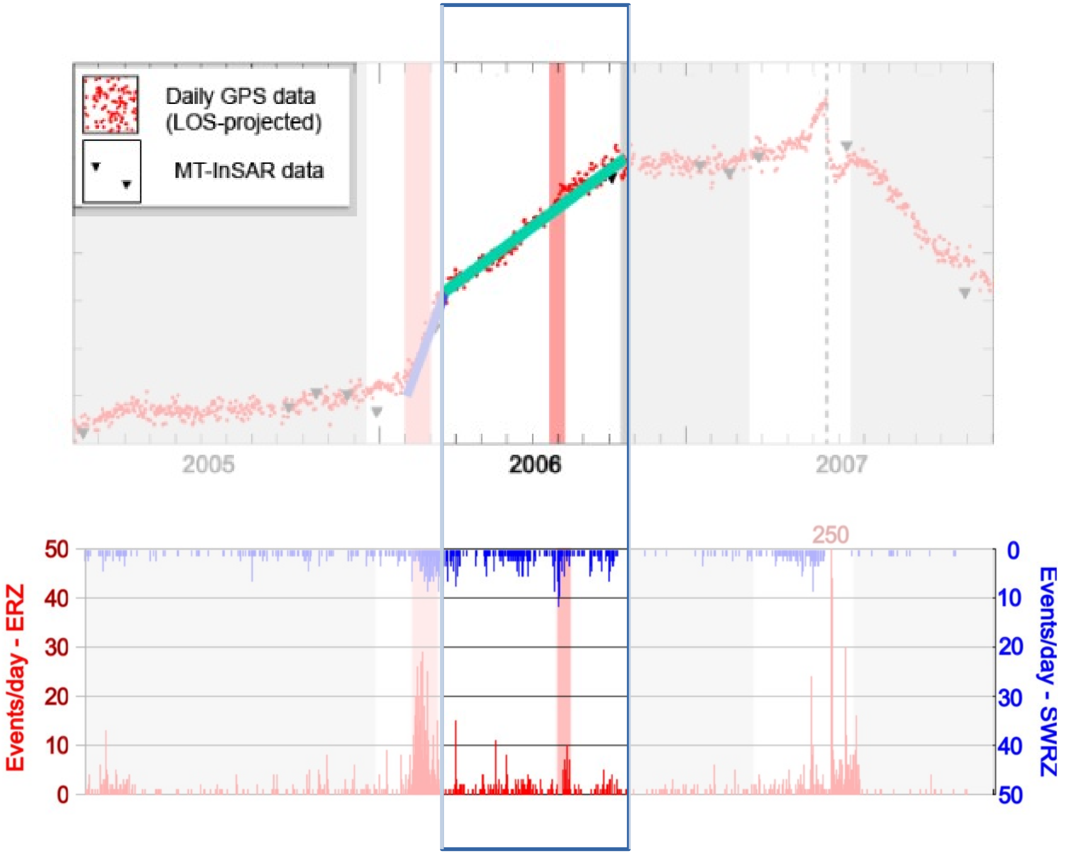
Ruapehu, New Zealand - 1995

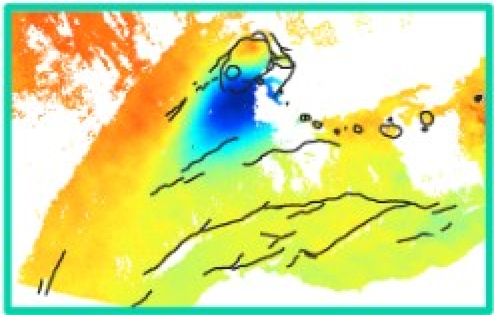


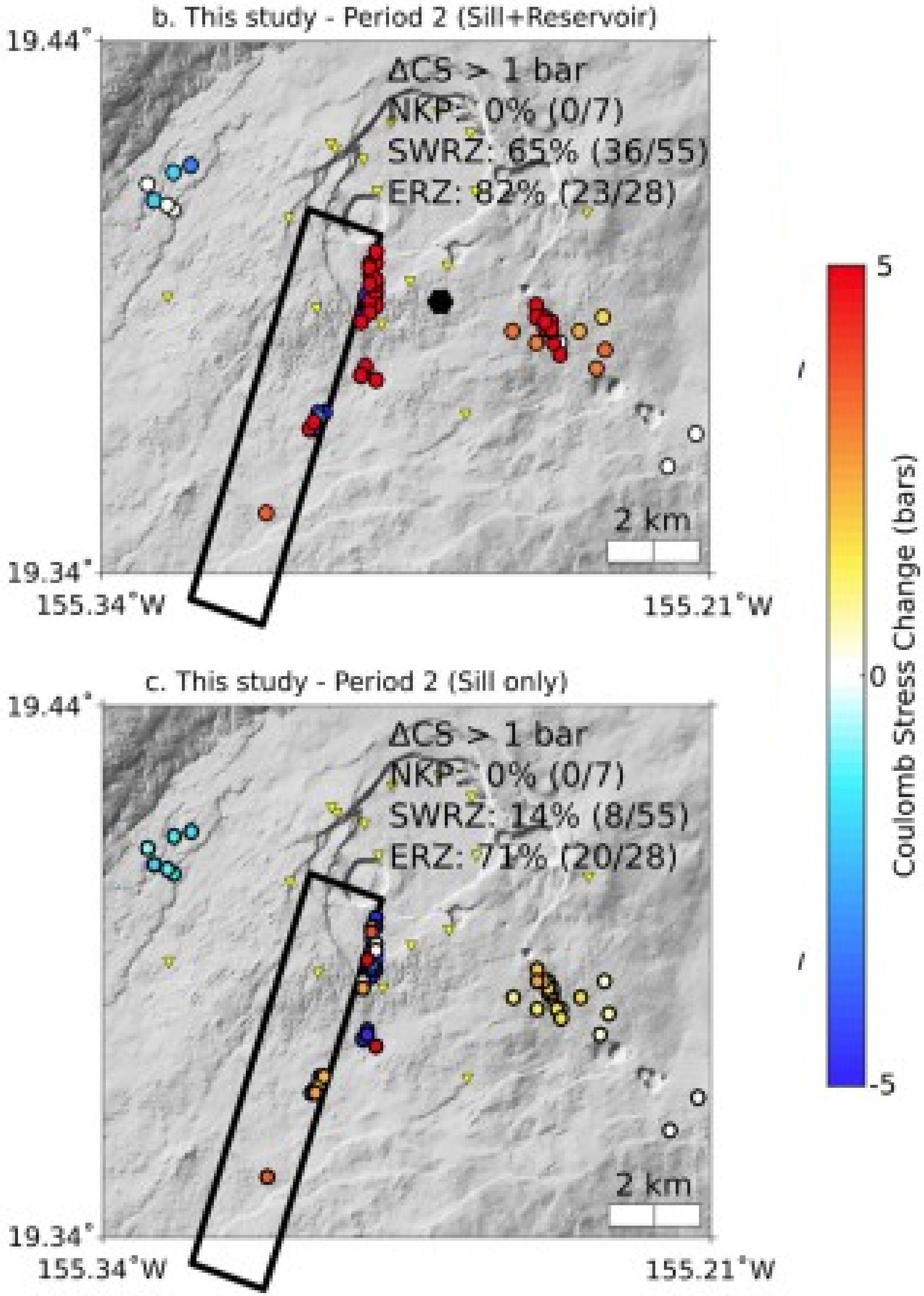


Hurst et al., 2018

Distal VT Earthquakes







Wauthier et al., 2016

Seismo-acoustic signals associated with volcanic processes II

Robin S. Matoza

Department of Earth Science; University of California, Santa Barbara

image: Tyson Fisher

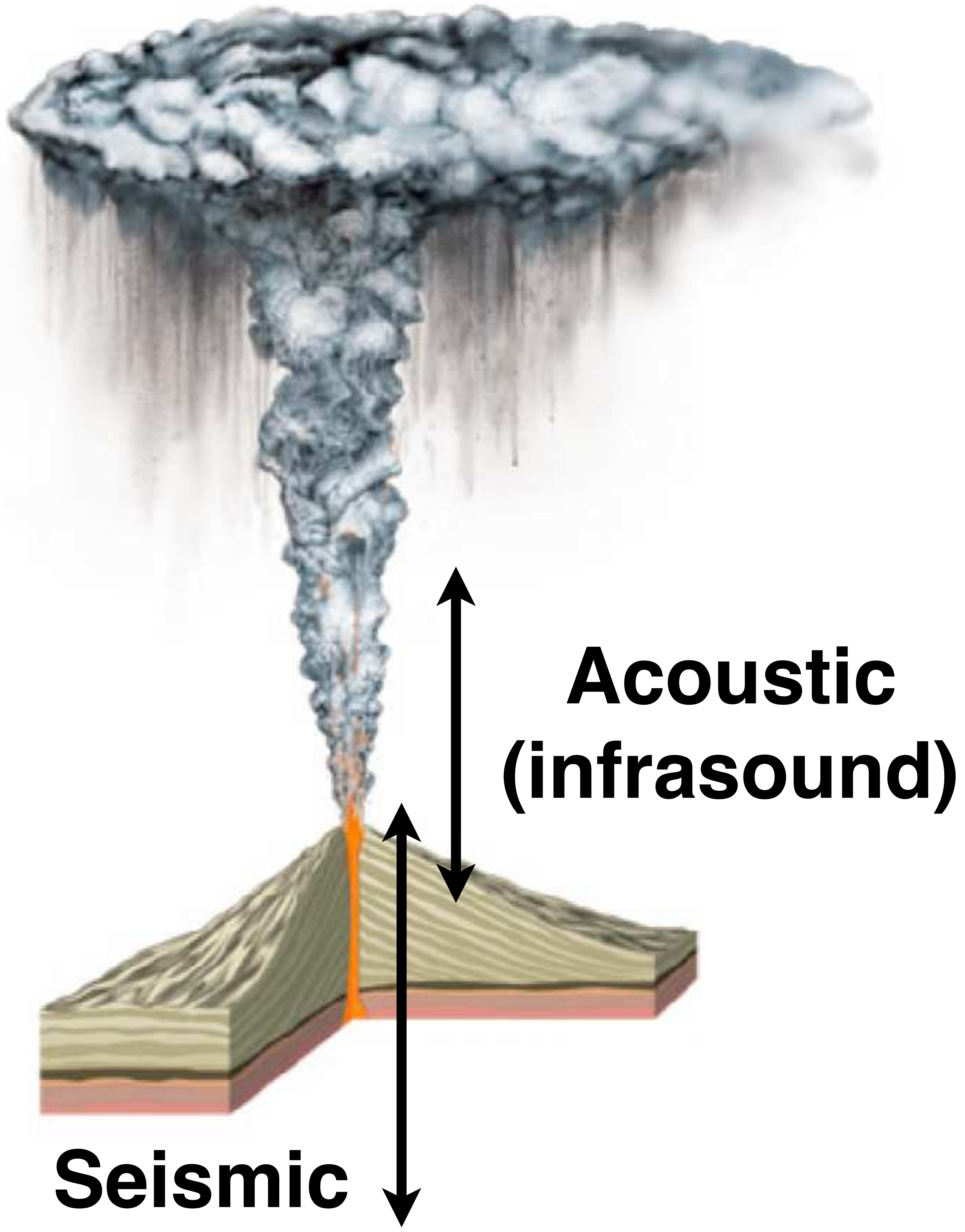
D. Fee

A. Austin

N. Key

A. Austin

Volcano seismology and acoustics



Acoustic

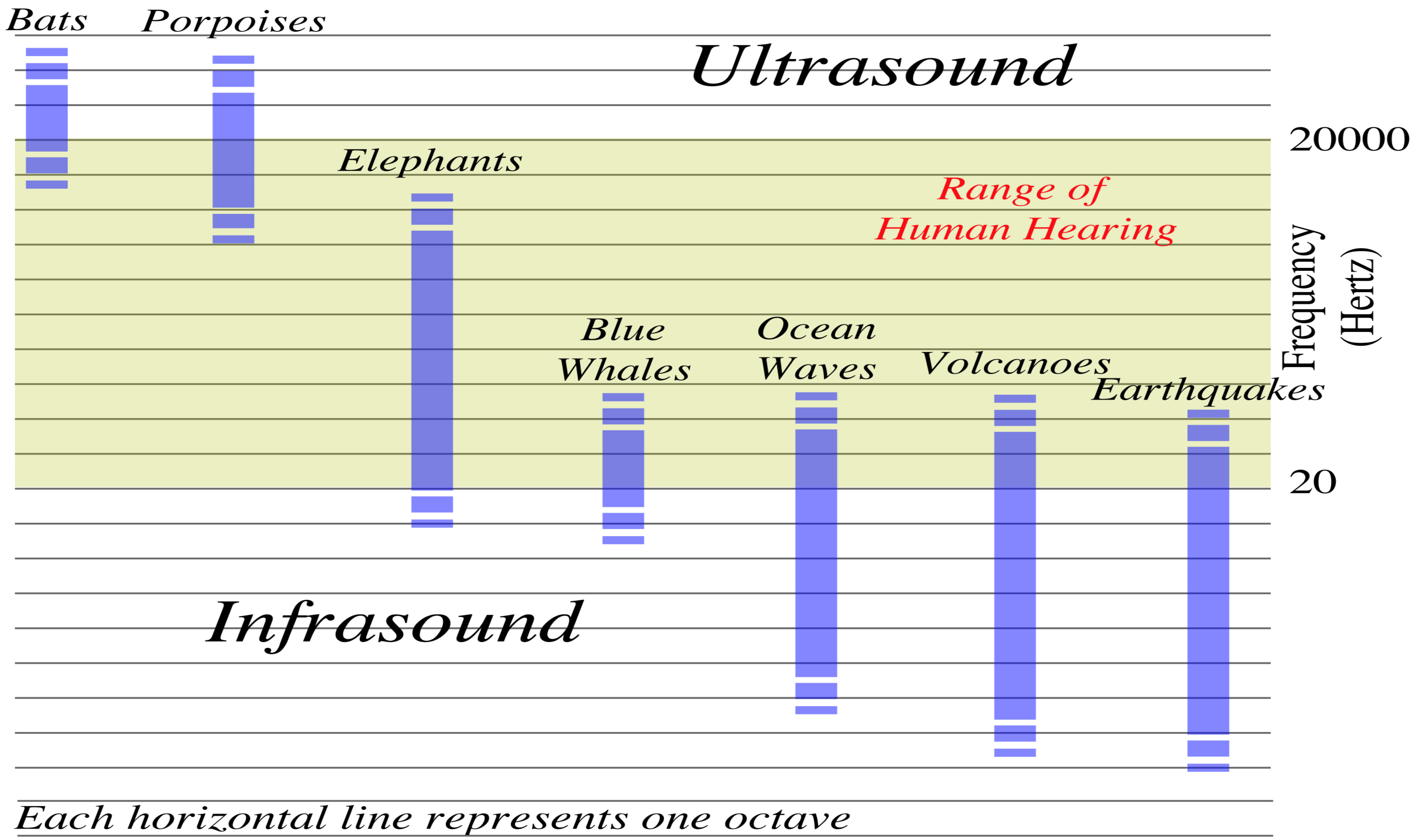
- Atmospheric acoustics (infrasound): ~0.01-20 Hz
- Variety of shallow and subaerial sources
- Explosive volcanism: powerful signals

Seismic

- Migration of fluid from mantle depths to surface
- Faulting & fluid transport in the solid earth
- Limited propagation < few hundred km

Infrasound

- Low-frequency acoustic waves below the 20 Hz human hearing threshold
- cf infrared



M. Hedlin

The acoustic cut-off frequency N_A is typically 3.3 mHz, and the Brunt-Väisälä frequency N is 2.9 mHz in the lower atmosphere.

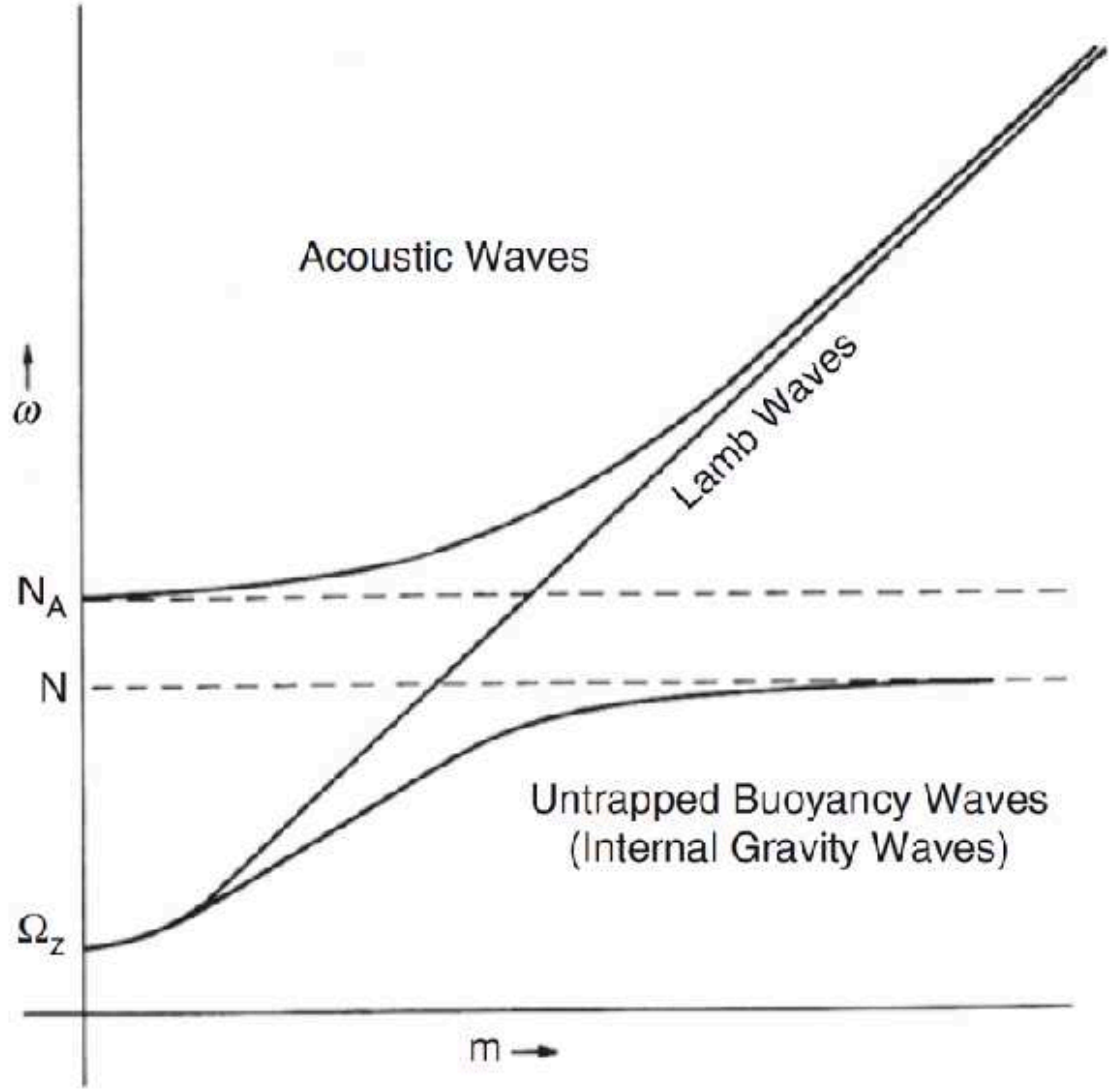
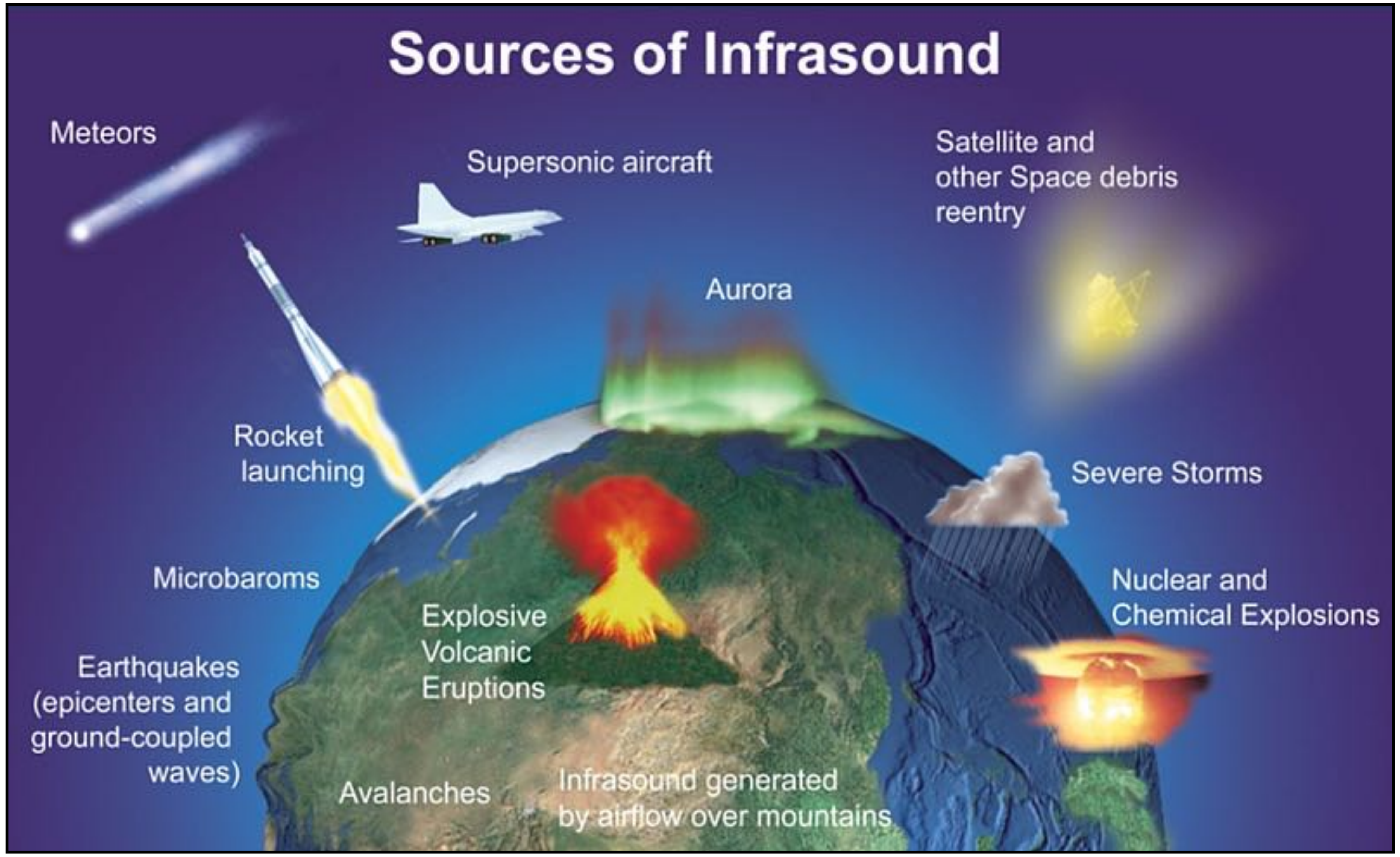


Fig. 1.1 Frequency ω vs. wavenumber m plot from Gossard and Hooke (1975). N_A is called the acoustic cut-off frequency, N the Brunt-Väisälä frequency, and Ω_z represents the angular frequency of the earth's rotation

Evers and Haak [2010] after *Gossard and Hooke* [1975]

Infrasound

- Large wavelengths (15 m ≤ λ ≤ 100 km), produced by large sources



CTBTO

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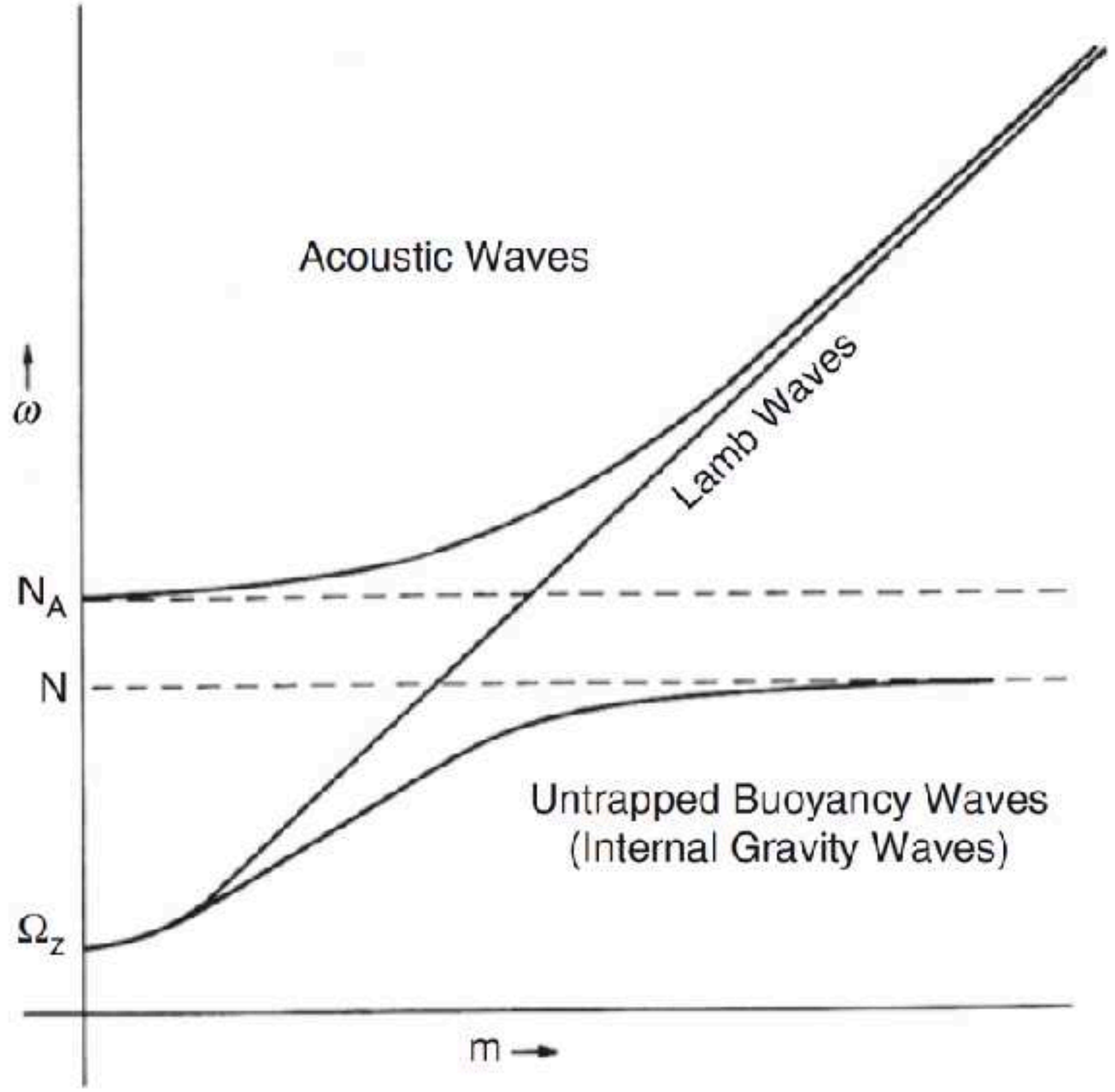

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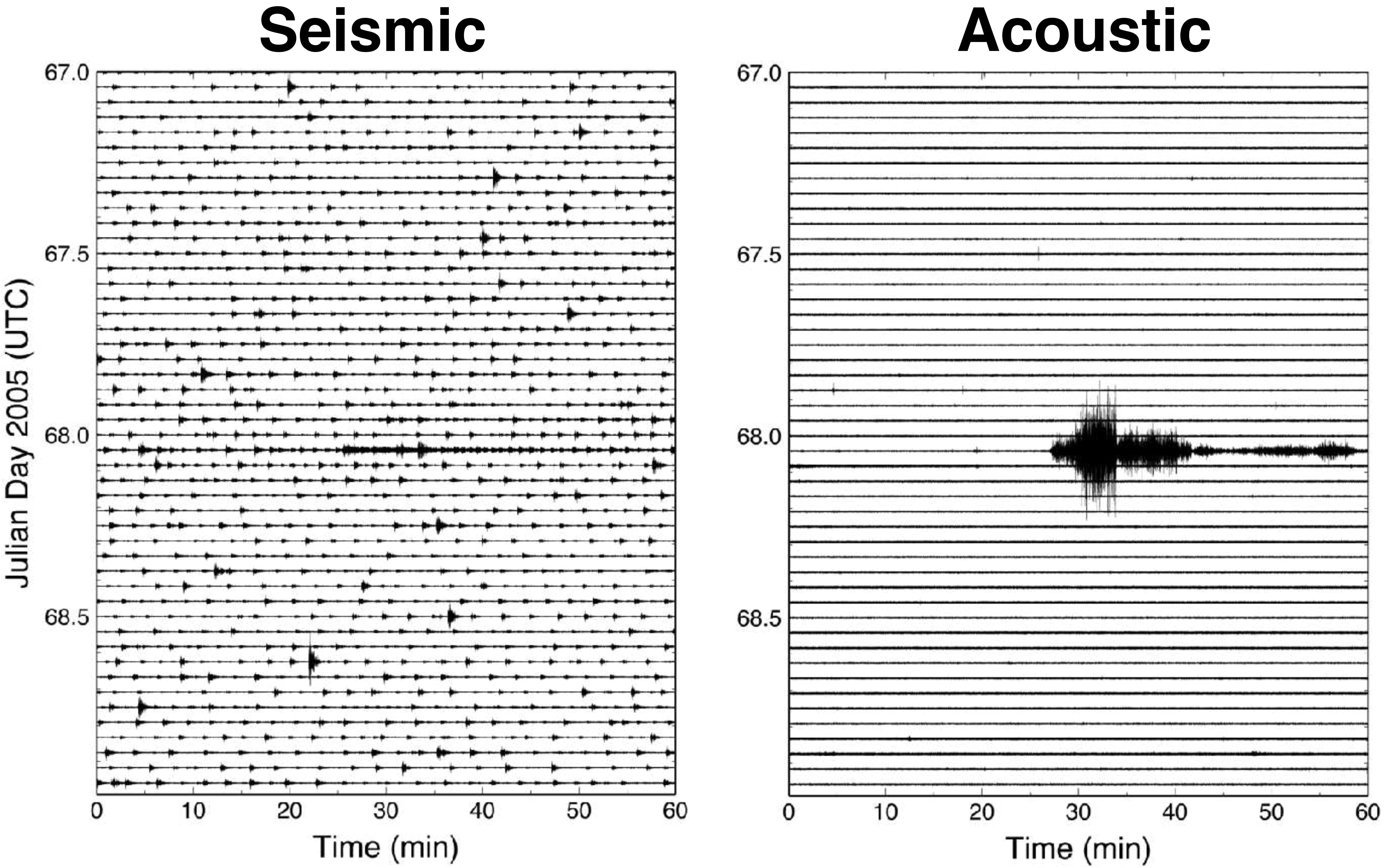
Evers and Haak [2010] after *Gossard and Hooke* [1975]

Phreatic explosion, Mount St. Helens, 8 March 2005

image: Tyson Fisher

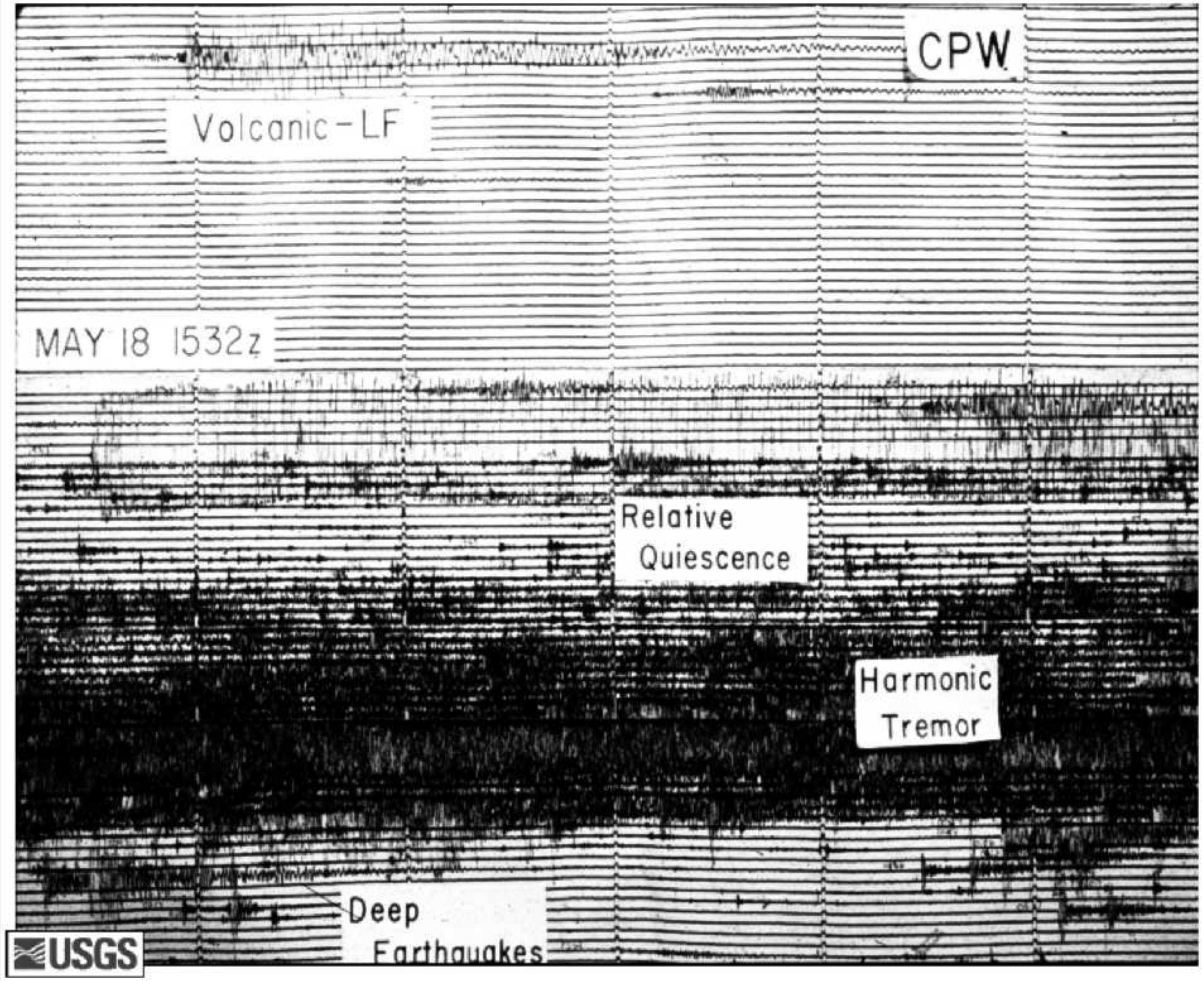
Phreatic explosion, Mount St. Helens, 8 March 2005



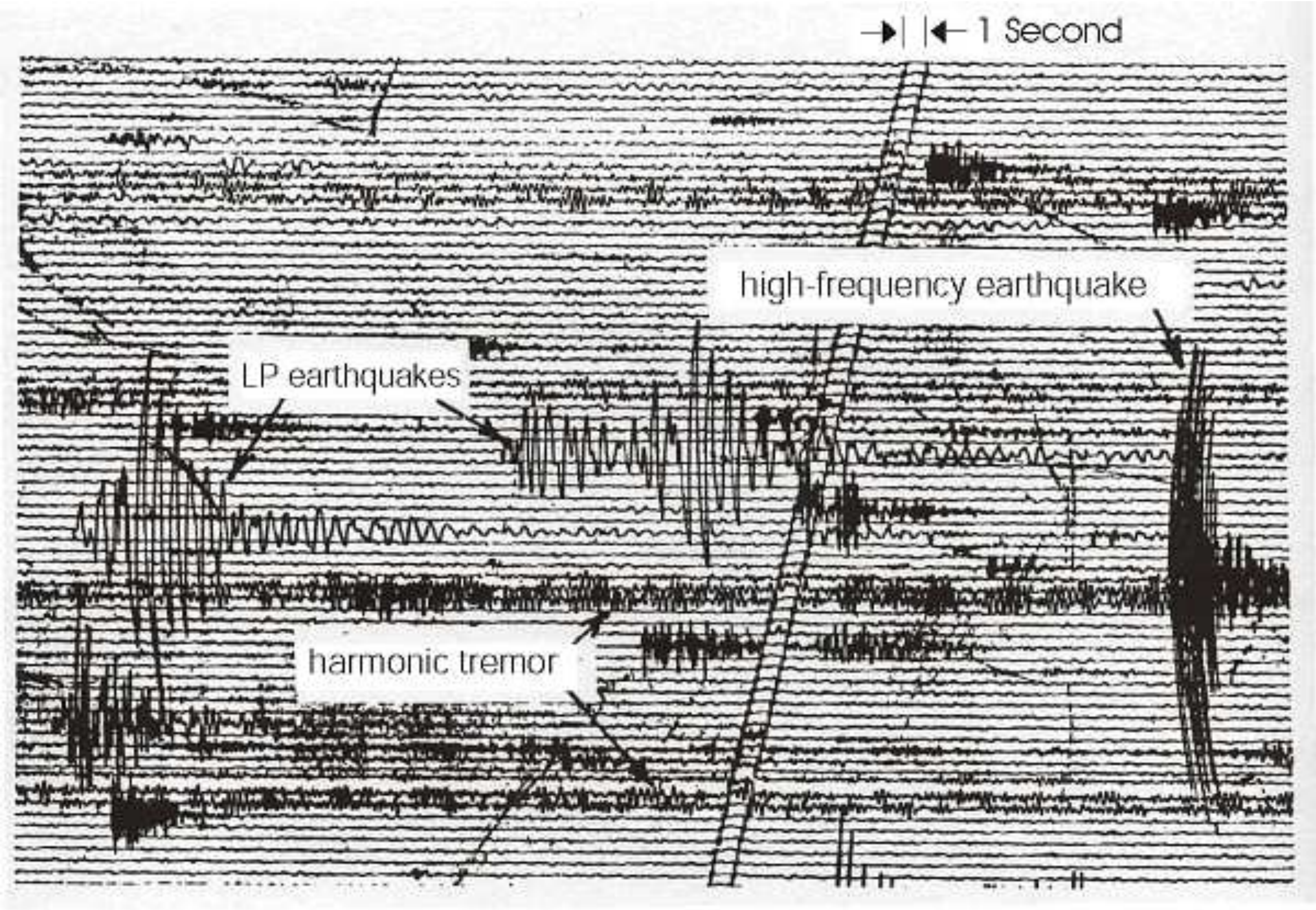
Matoza et al. [2007]

Volcano seismology: signal classification

Mount St. Helens, May 18, 1980, Station CPW, 70 miles to the northwest



- Classifications based on waveform and frequency content
- What you see depends on instrumentation
- Classifications based on physical mechanism



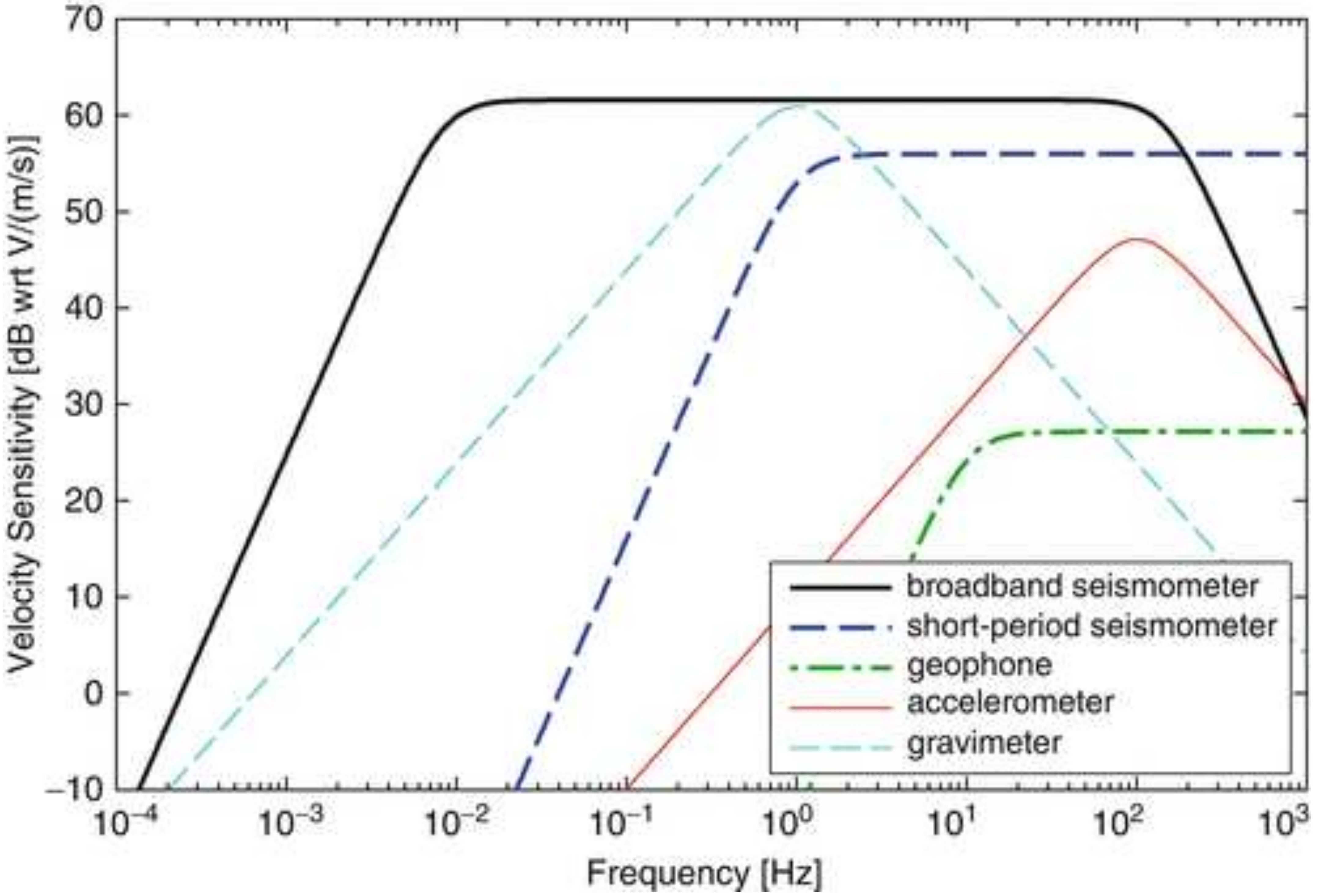
USGS

Volcano seismology: signal classification

Classification based on frequency content

Typically (but not always), the following definitions are used [*Ohminato et al.* 1998]:

	Period		Frequency
• Ultra-long-period (ULP)	**>100 s**	or	**<0.01 Hz**
• Very-long-period (VLP)	**2–100 s**	or	**0.01–0.5 Hz**
• Long-period (LP)	**0.2–2 s**	or	**0.5–5 Hz**
• Short-period (SP)	**0.05–0.2 s**	or	**5–20 Hz**

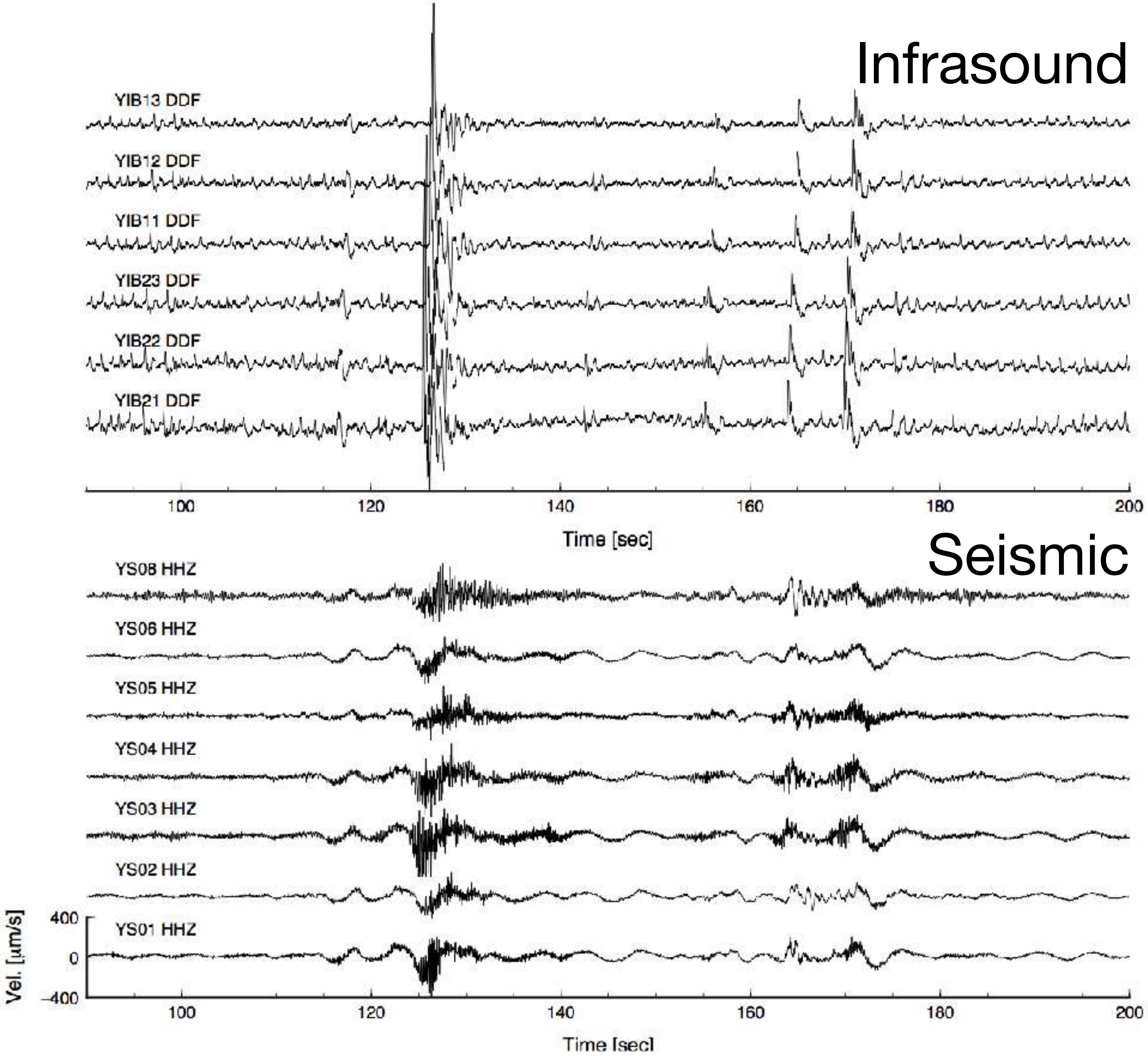


Ackerley [2015]
https://doi.org/10.1007/978-3-642-35344-4_172

- Strictly speaking, this terminology refers just to the band of the signal
- However, in general, different physical processes occur on different time and spatial scales
- Observed volcanic signals often do not fall neatly into these bands

The advent of broadband seismometry led to observations of new signals: VLPs and ULPs

VLPs: Strombolian gas slug ascent



Yasur, Vanuatu *Matoza et al.* [2018]

- Short-duration asymmetric explosion waveforms
- Near-continuous broadband infrasonic tremor consisting of repetitive positively skewed pulses

[*Marchetti et al.*, 2013; *Meier et al.*, 2016; *Spina et al.*, 2016]

- Numerous repetitive long-period (LP) events
- Underlain by very-long-period (VLP) signals with periods of ~10 s

[*Kremers et al.*, 2013; *Battaglia et al.*, 2012; 2016]

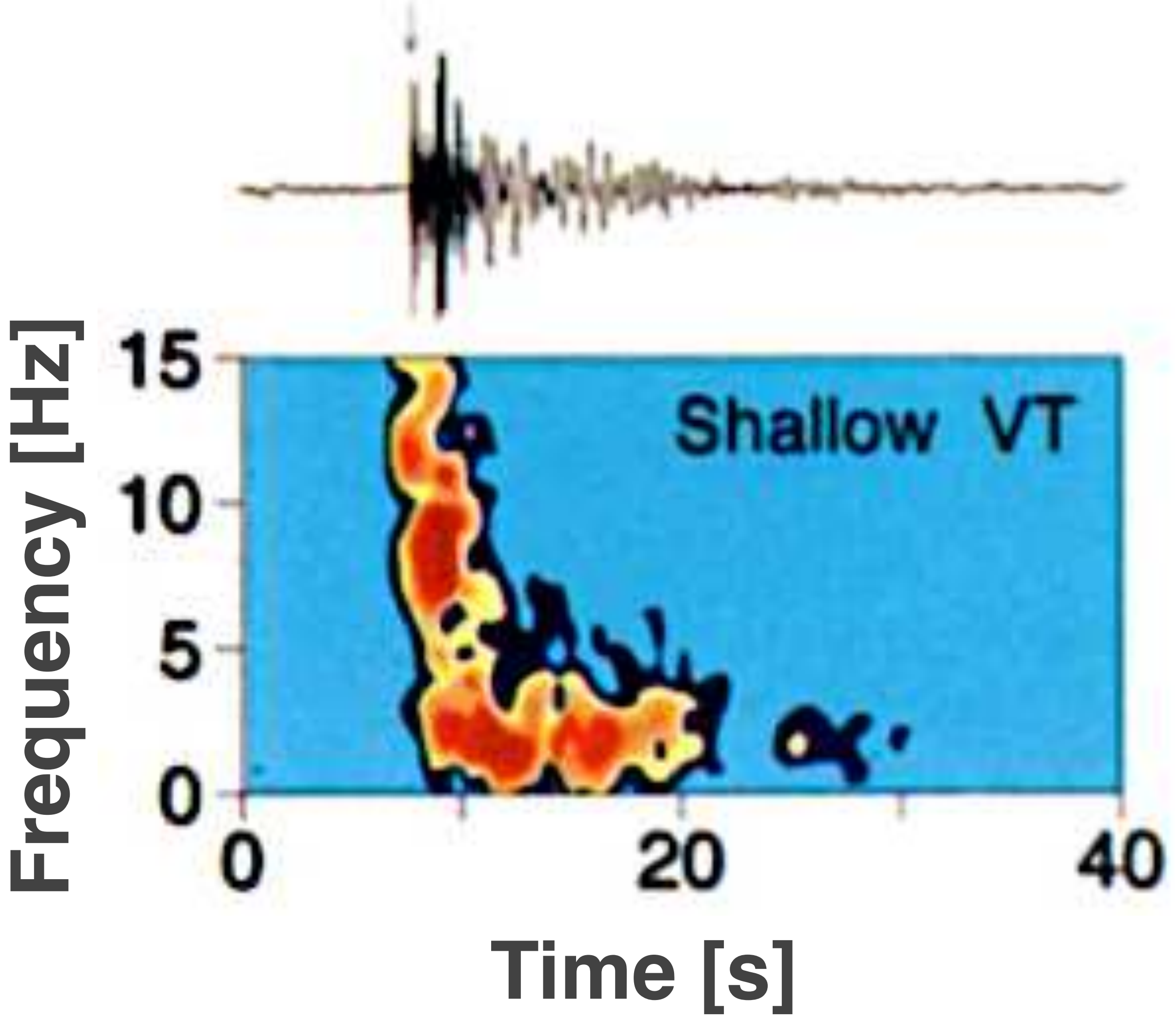
LP: 0.5–5 Hz (0.2–2 s period)
VLP: 0.01–0.5 Hz (2–100 s period)

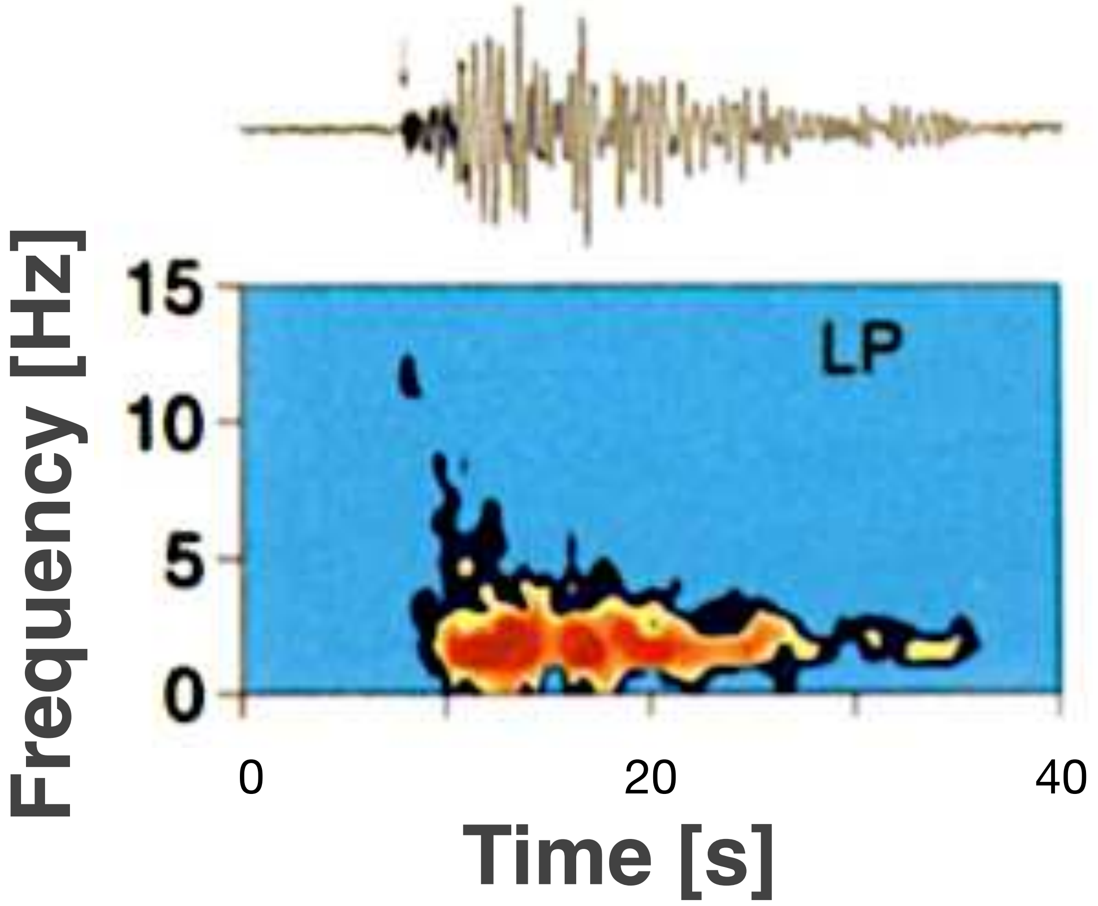
Volcano seismology: signal classification

Classification based on mechanism

1) **Volcano-tectonic (VT)**

2) **Long-period (LP)** [0.5-5 Hz]



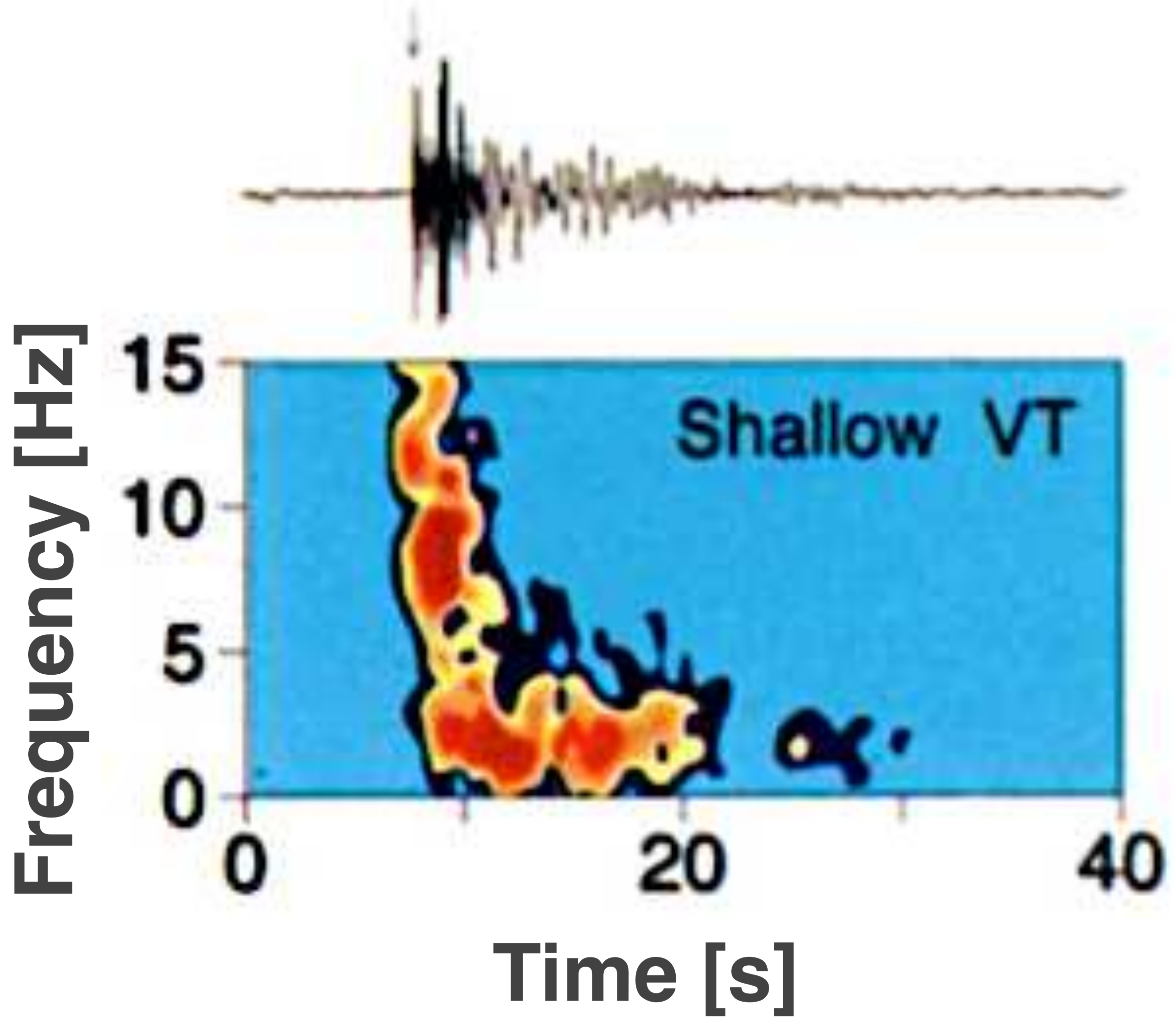


Chouet [1996]

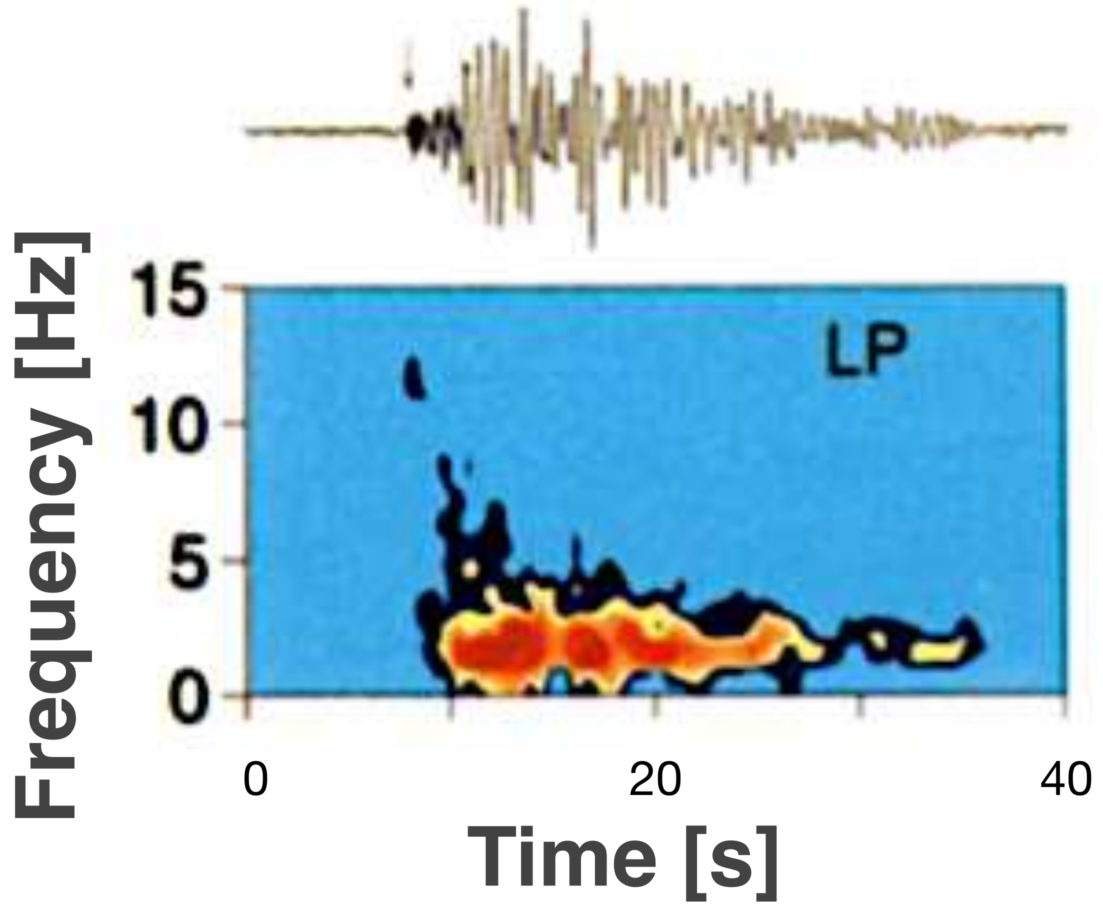
Volcano seismology: signal classification

Classification based on mechanism

1) **Volcano-tectonic (VT)**
   - Shear/tensile failure in brittle solid
   - e.g., intrusions, loading and deformation



2) **Long-period (LP)** [0.5-5 Hz]
   - Actively involve a fluid



Chouet [1996]

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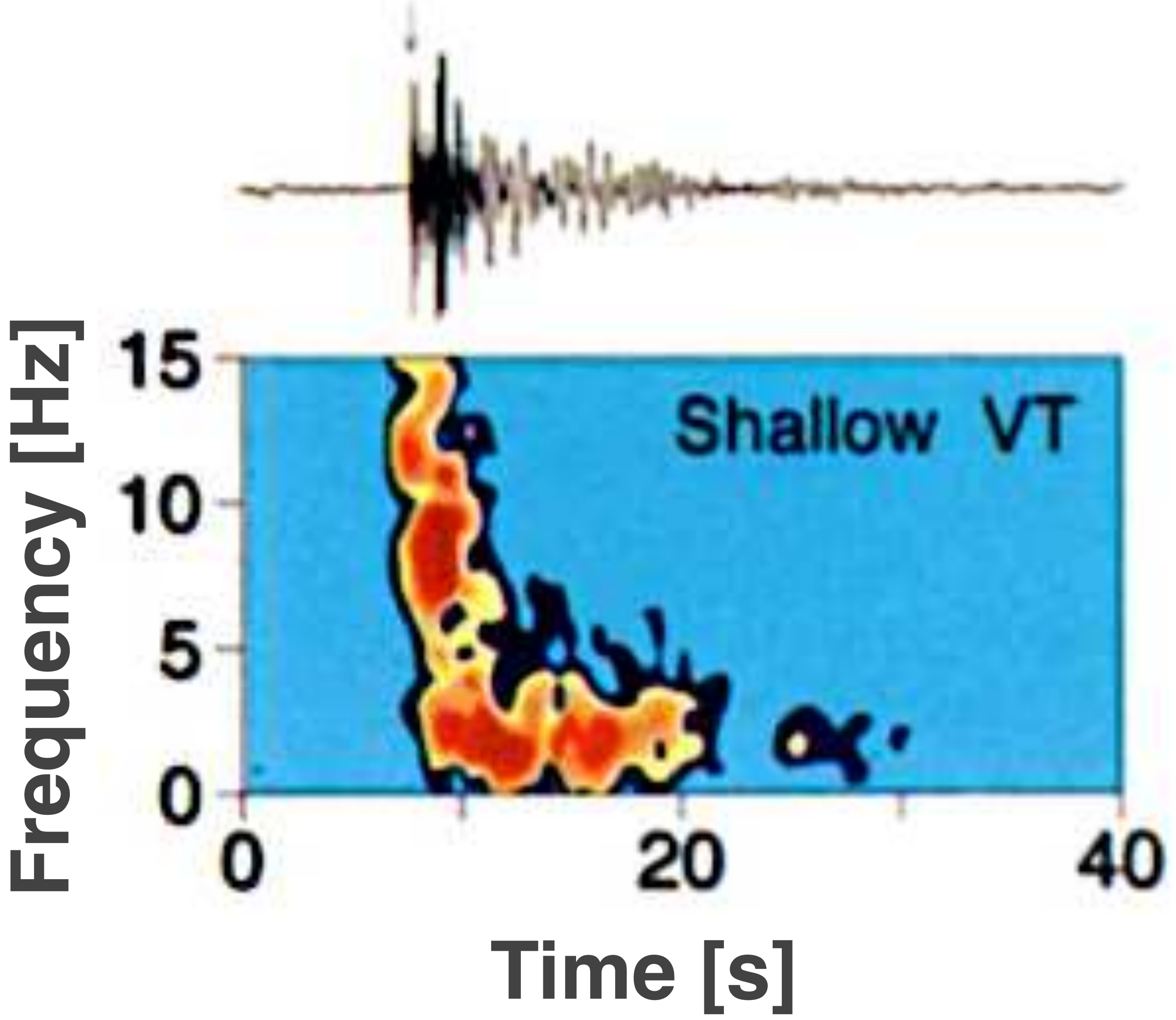

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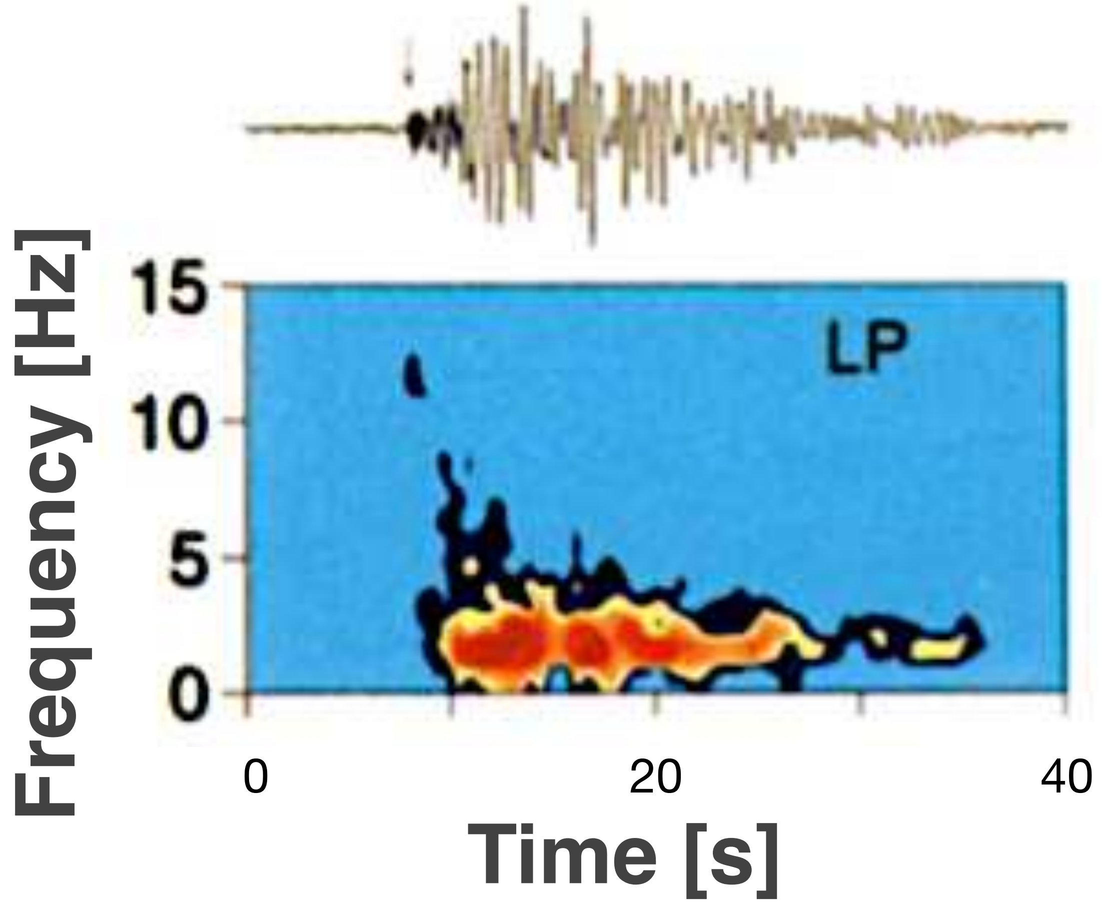
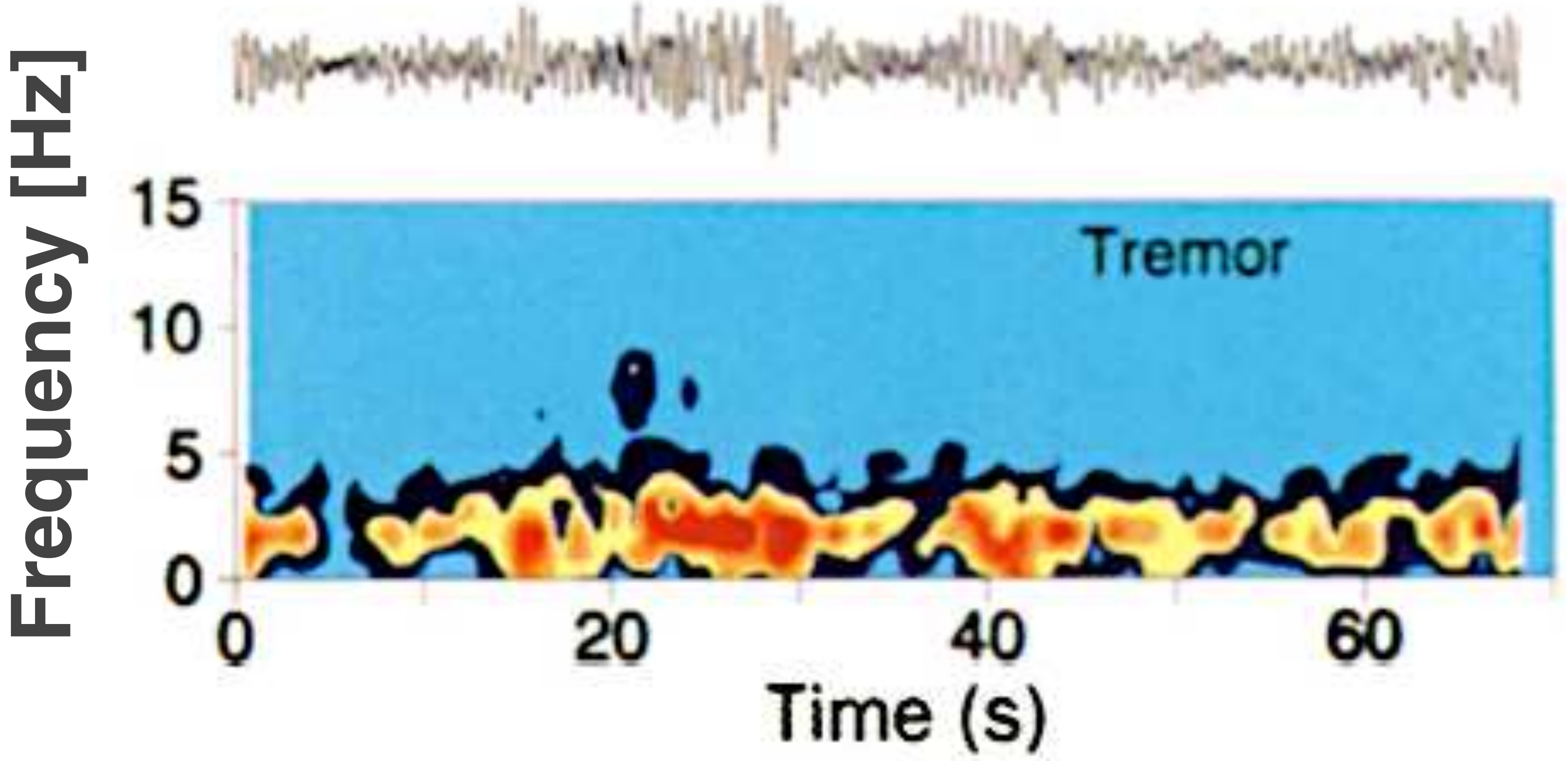




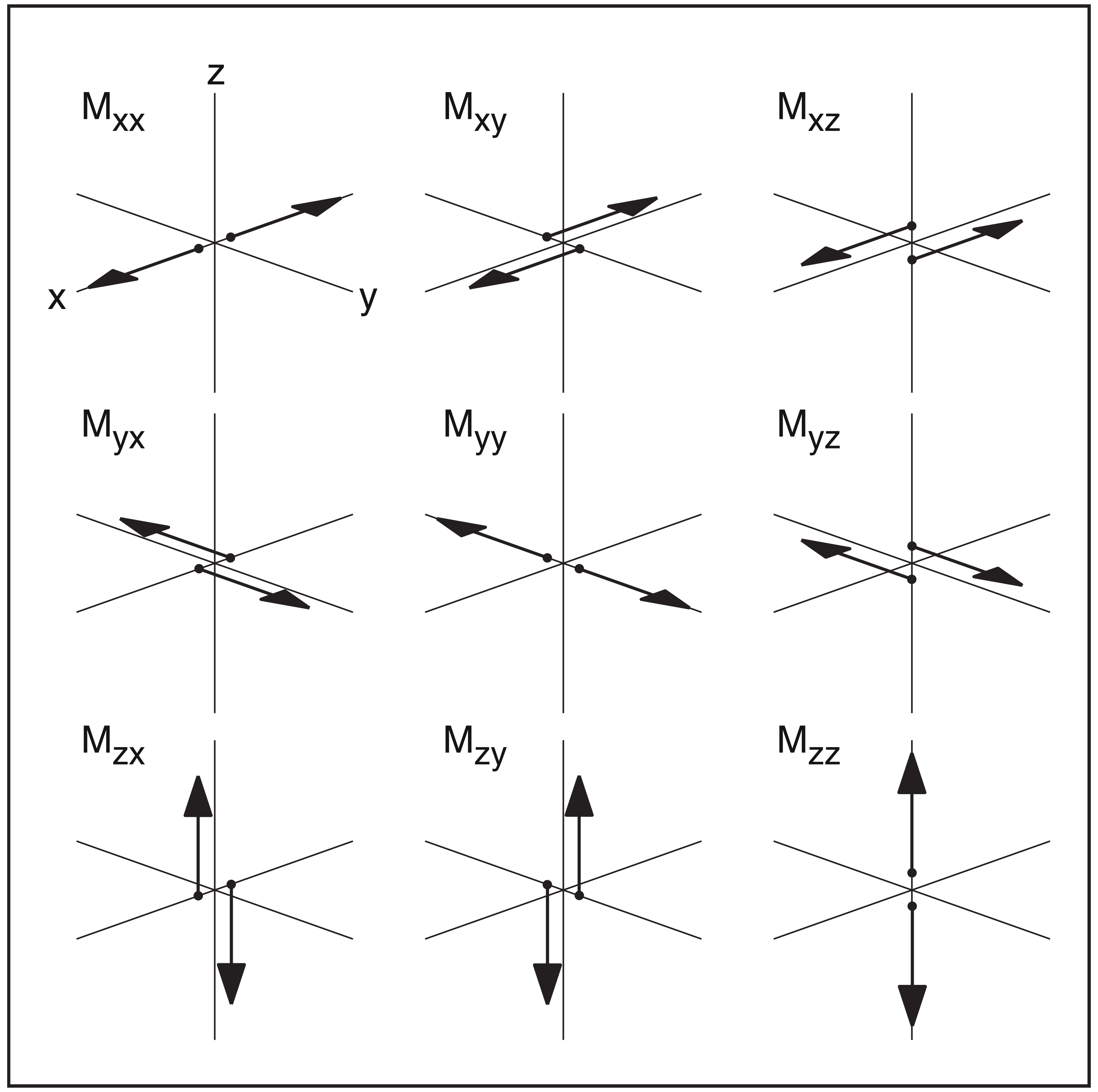
Chouet [1996]

Volcano-seismic sources

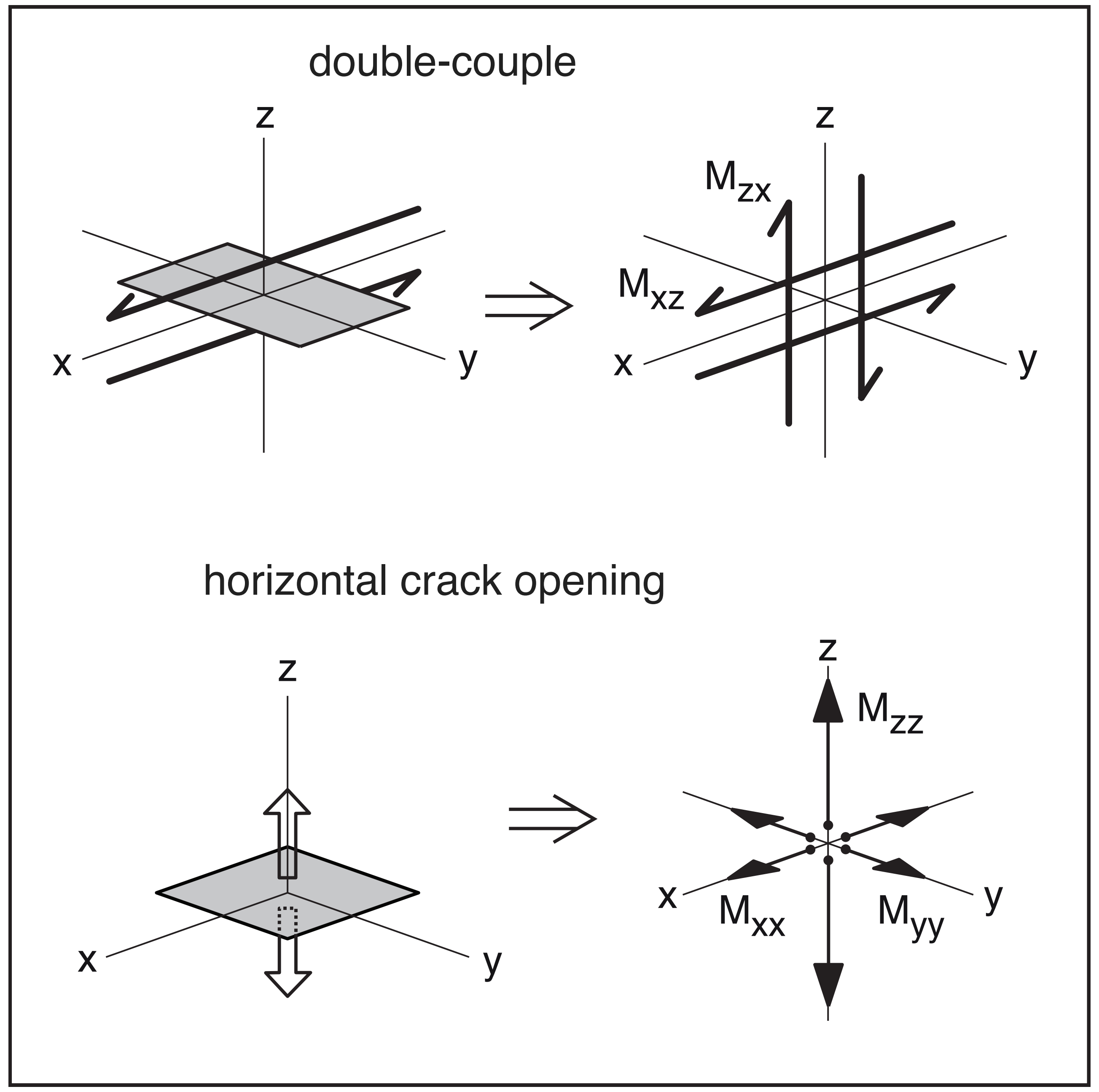
Moment-tensor **Single-force vector**

$$\mathbf{M} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}, \qquad \mathbf{F} = \begin{bmatrix} F_x \\ F_y \\ F_z \end{bmatrix}$$

Moment-tensor



- Represent arbitrary seismic source with equivalent point source: **moment-tensor** and **single-force vector**
- **Moment-tensor**: motion on generally orientated discontinuity (equivalent force couples)
- e.g., slip on a fracture or opening of a crack
- **Single forces**: mass advection



Chouet and Matoza [2013]

Volcanic tremor:

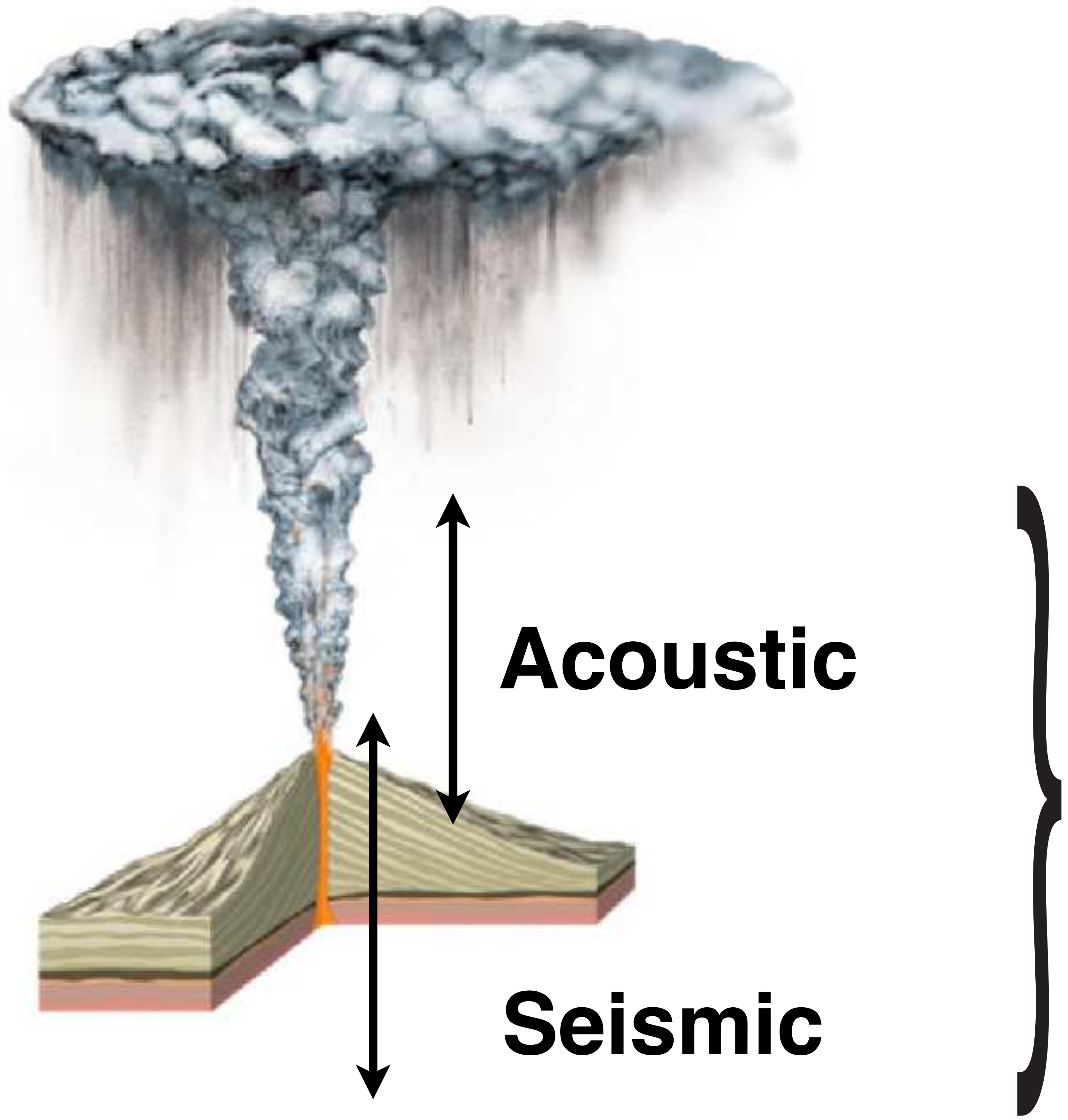
e.g., Luigi Palmieri 1856
“continuous tremor” at Vesuvius

Volcanic tremor:

e.g., Sakai et al. [1996]
infrasonic harmonic tremor at Sakurajima

e.g., Luigi Palmieri 1856
“continuous tremor” at Vesuvius

Volcanic tremor:



Acoustic

Seismic

“Seismo-acoustic”

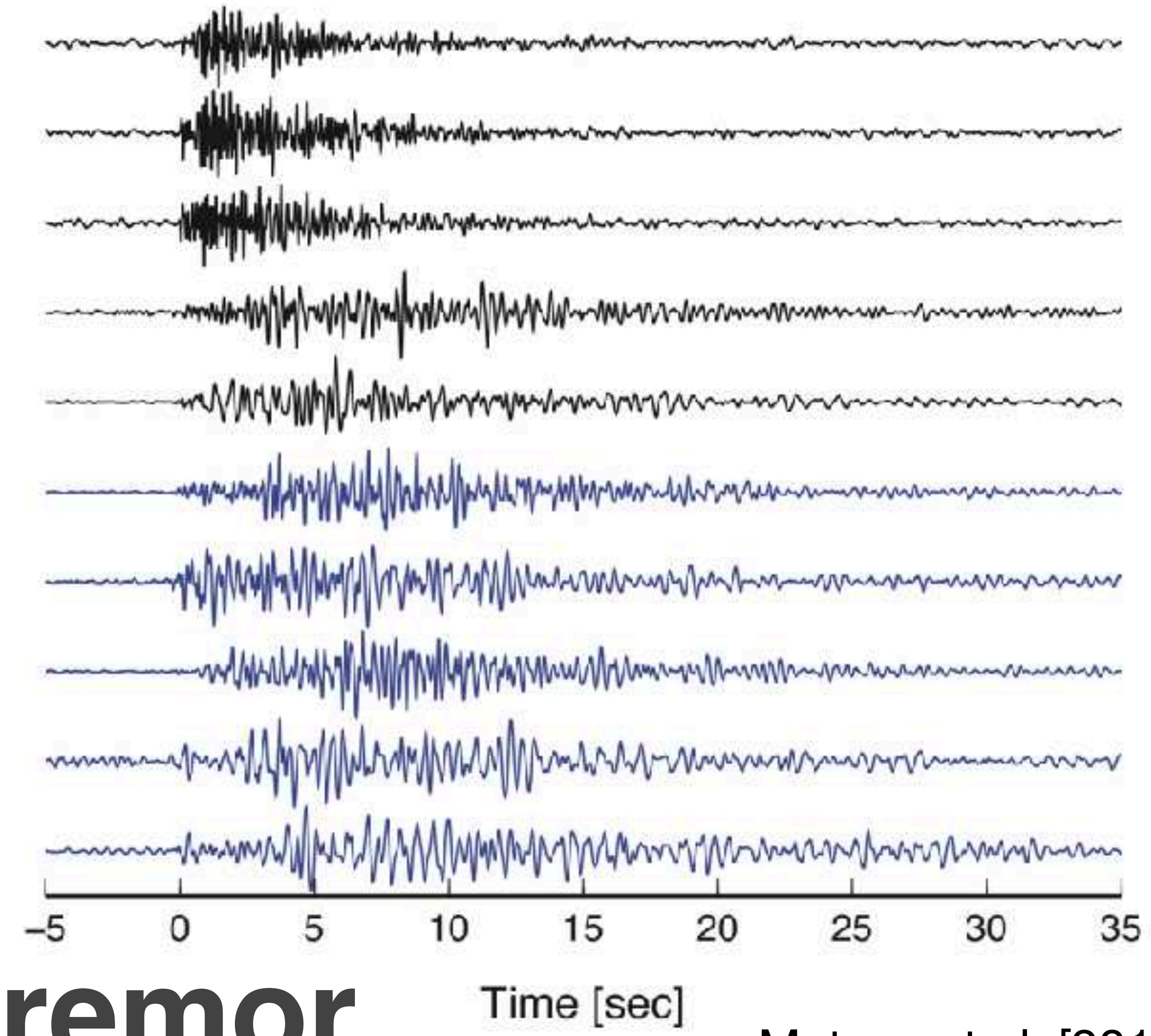
Volcanic tremor:

a catch-all term for *sustained* seismic and acoustic signals associated with a wide range of volcanic activity

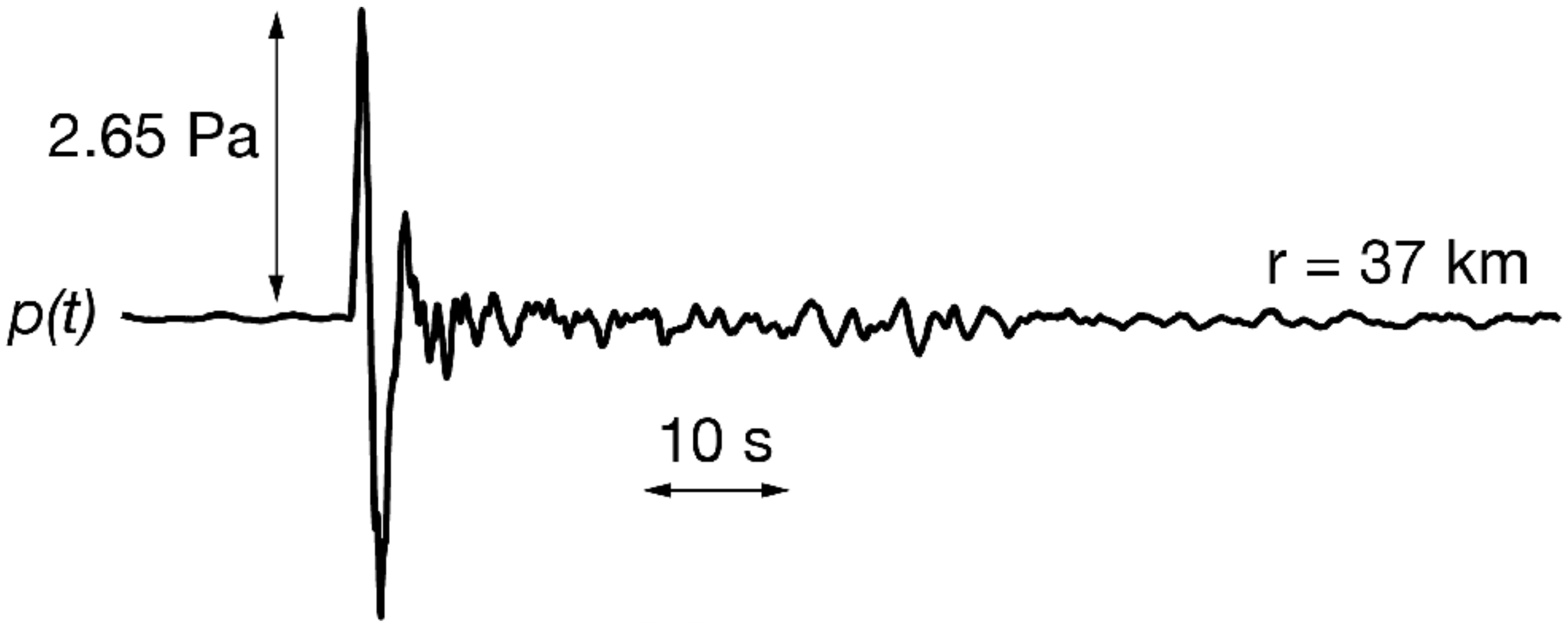
multifarious : many and of various types; having or occurring in great variety

Volcanic tremor:

a catch-all term for *sustained* seismic and acoustic signals associated with a wide range of volcanic activity



Not tremor

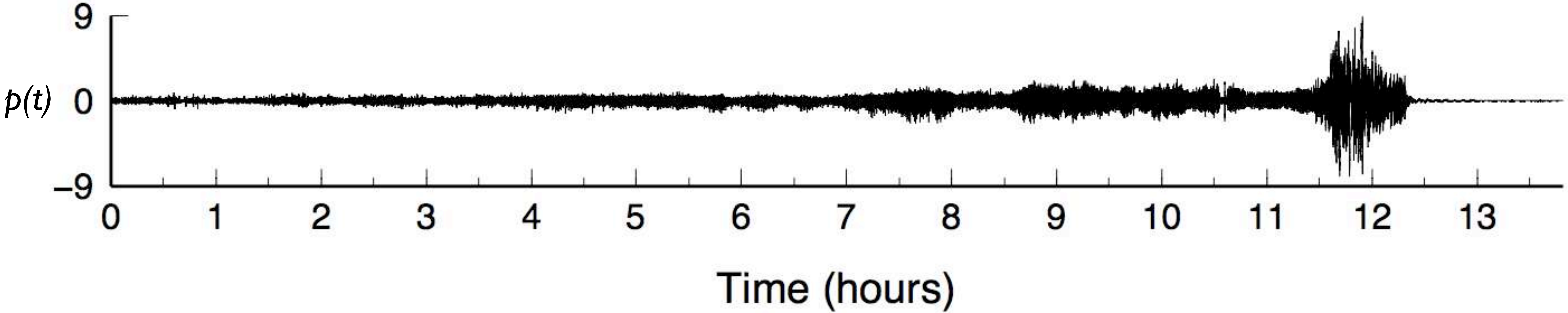


Not tremor

Matoza et al. [2014]

Volcanic tremor:

a catch-all term for *sustained* seismic and acoustic signals associated with a wide range of volcanic activity



Tremor

Volcanic tremor:

a catch-all term for *sustained* seismic and acoustic signals associated with a wide range of volcanic activity

- **Harmonic**
- **Monotonic/monochromatic**
- **Spasmodic**
- **Eruption**
- **Banded**
- **Tremor storm**

etc.? ...

e.g., Mcnutt [1992], Konstantinou and Schlindwein [2002]

Spasmodic vs. harmonic tremor

Jagger/Omori: early 20th Century

Spasmodic tremor:
irregular vibrations

Harmonic tremor:
more rhythmic vibrations

Spasmodic vs. harmonic tremor

Jagger/Omori: early 20th Century

Spasmodic tremor:
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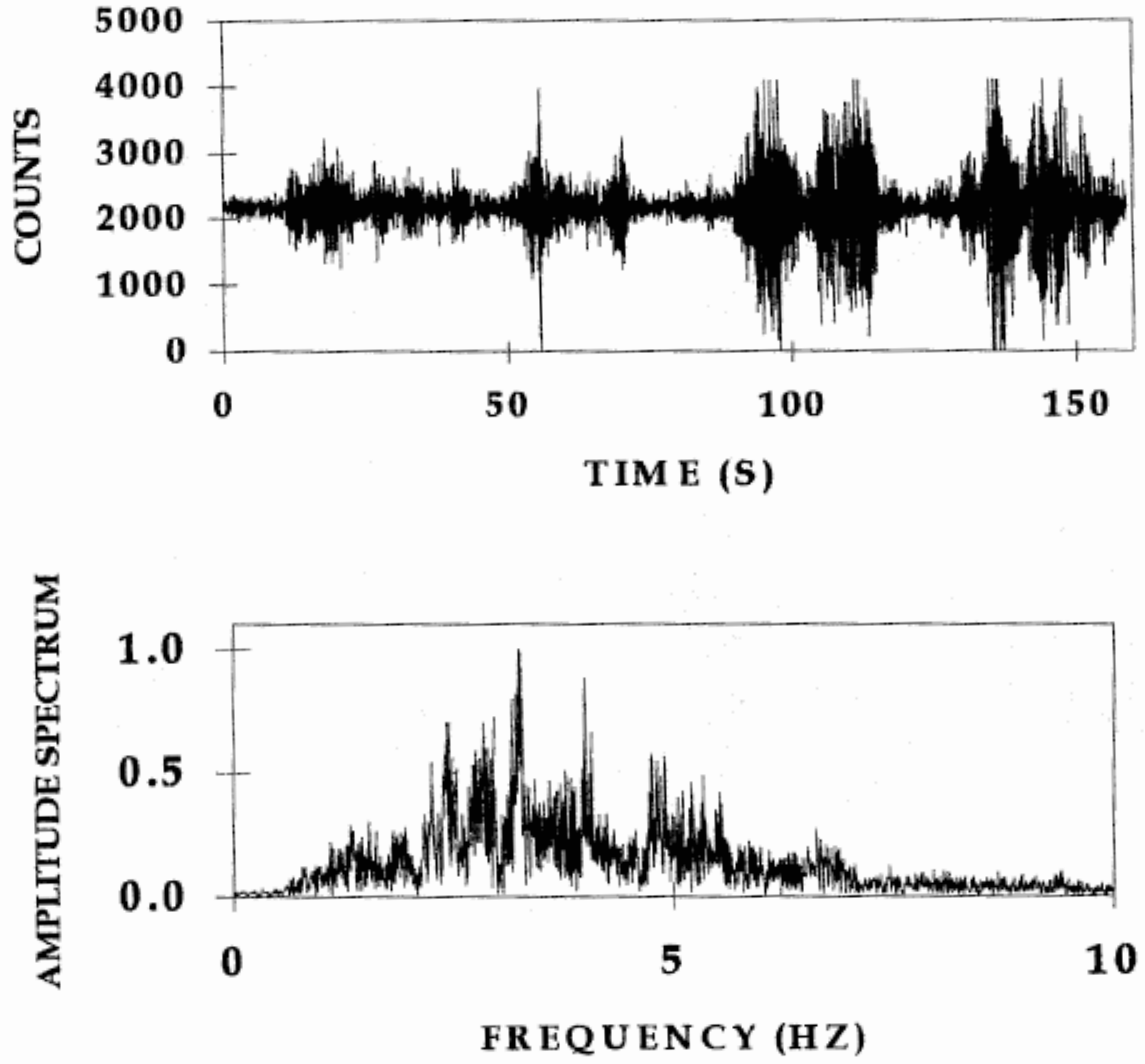
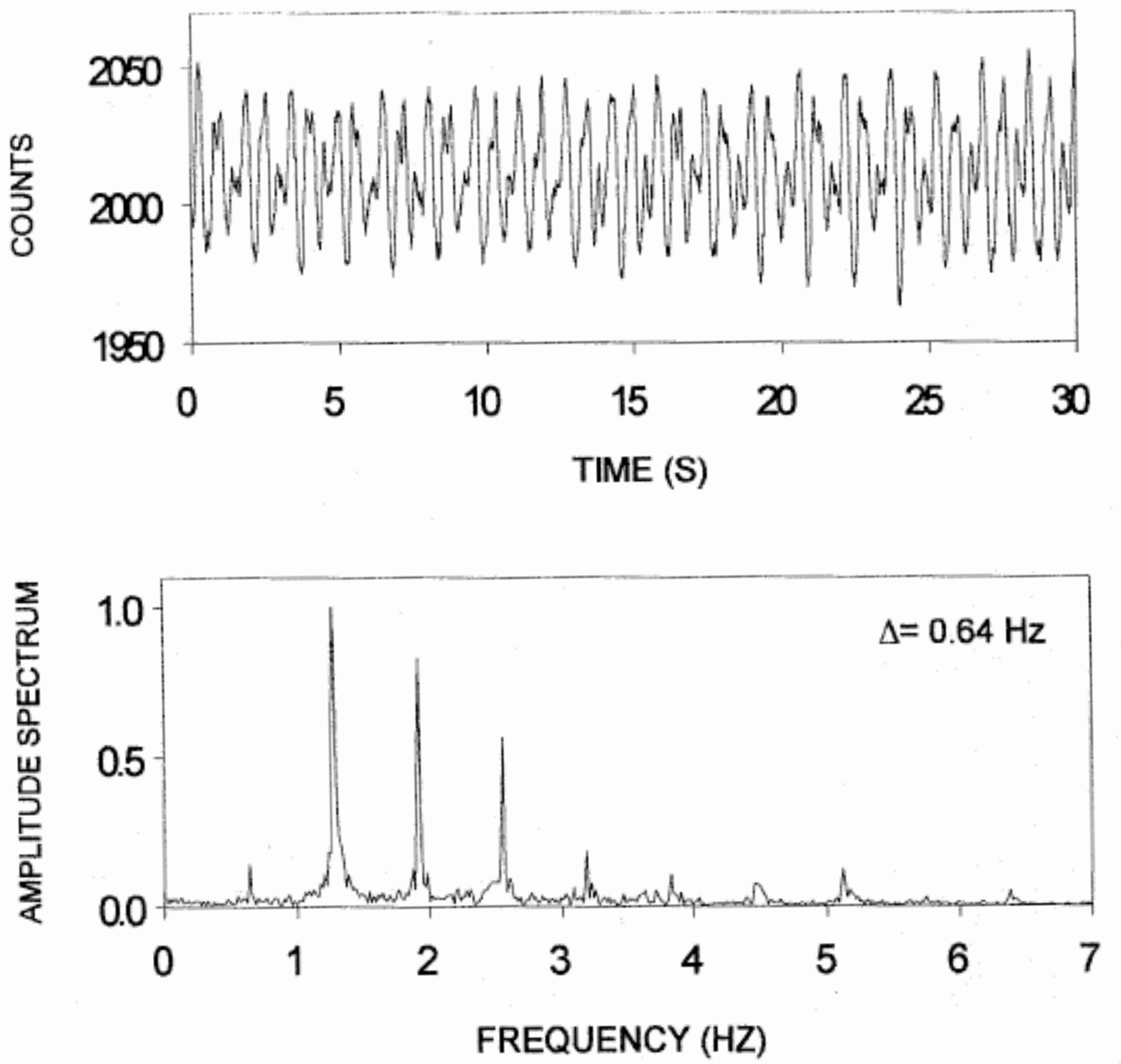
Harmonic tremor:
more rhythmic vibrations

Seismograms from Galeras, Colombia, Gil Cruz [1999]

Spasmodic tremor



Harmonic tremor



Spasmodic vs. harmonic tremor

Jagger/Omori: early 20th Century

Spasmodic tremor:
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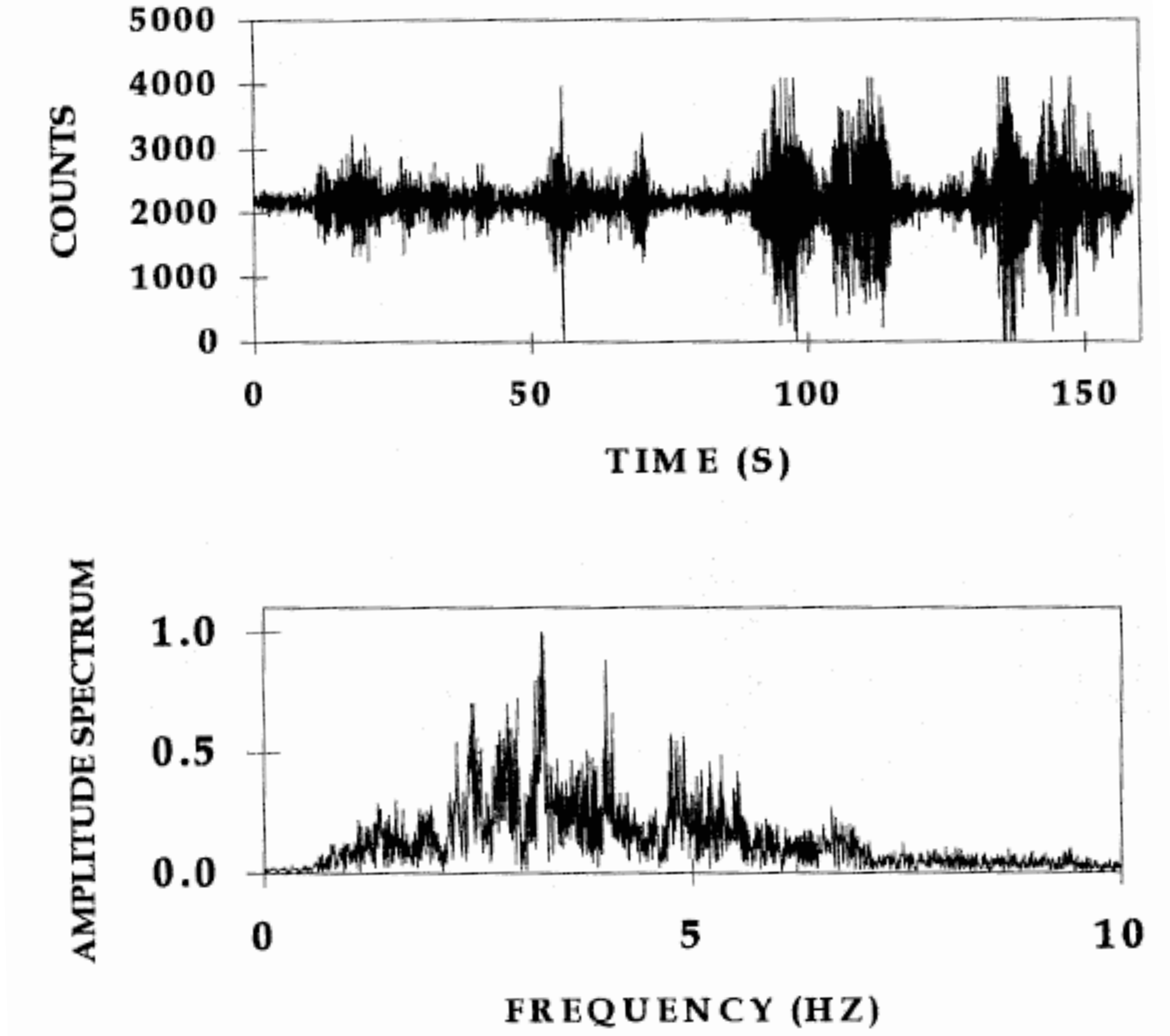
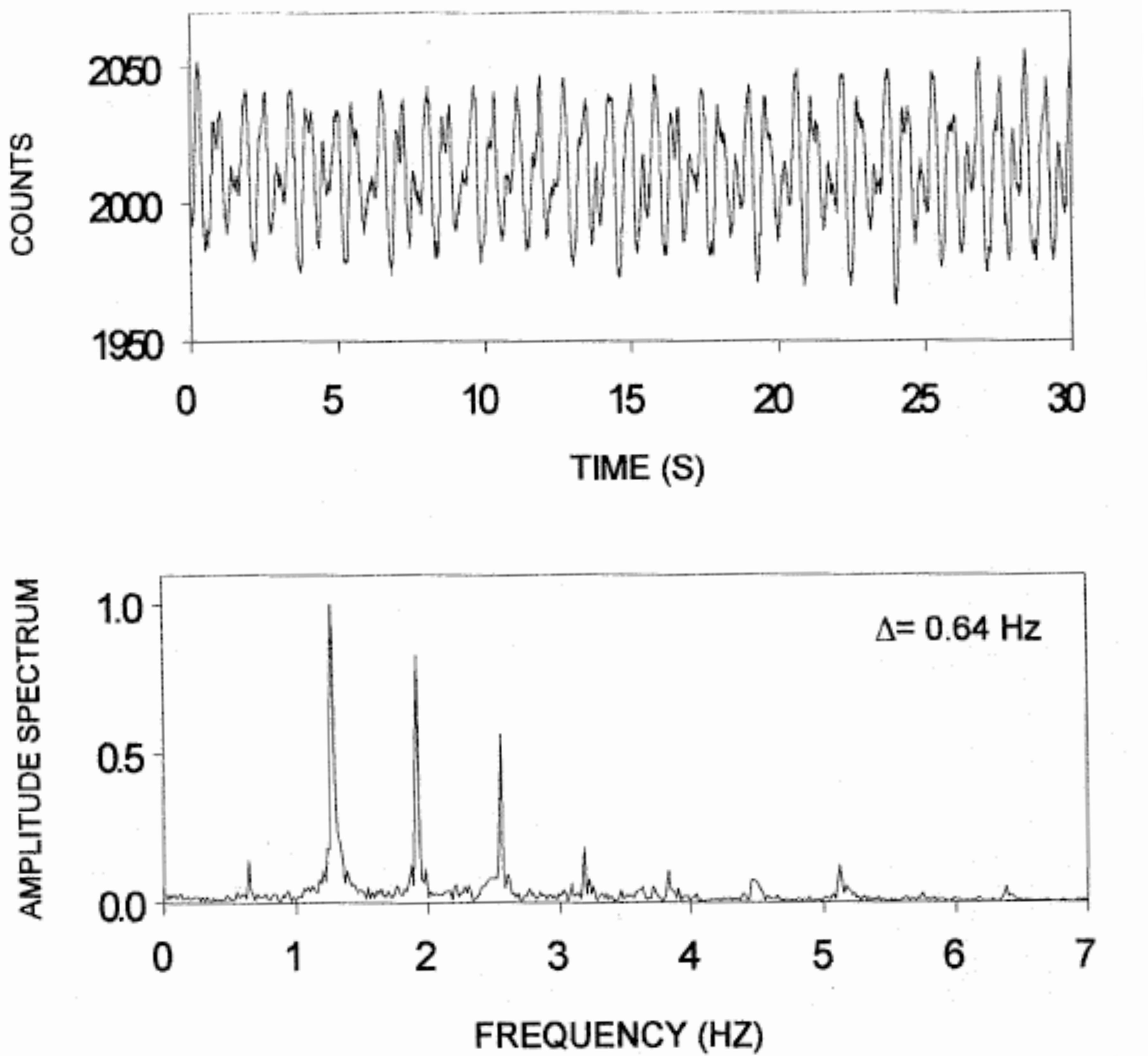
Harmonic tremor:
more rhythmic vibrations

Seismograms from Galeras, Colombia, Gil Cruz [1999]

Spasmodic tremor



Harmonic tremor



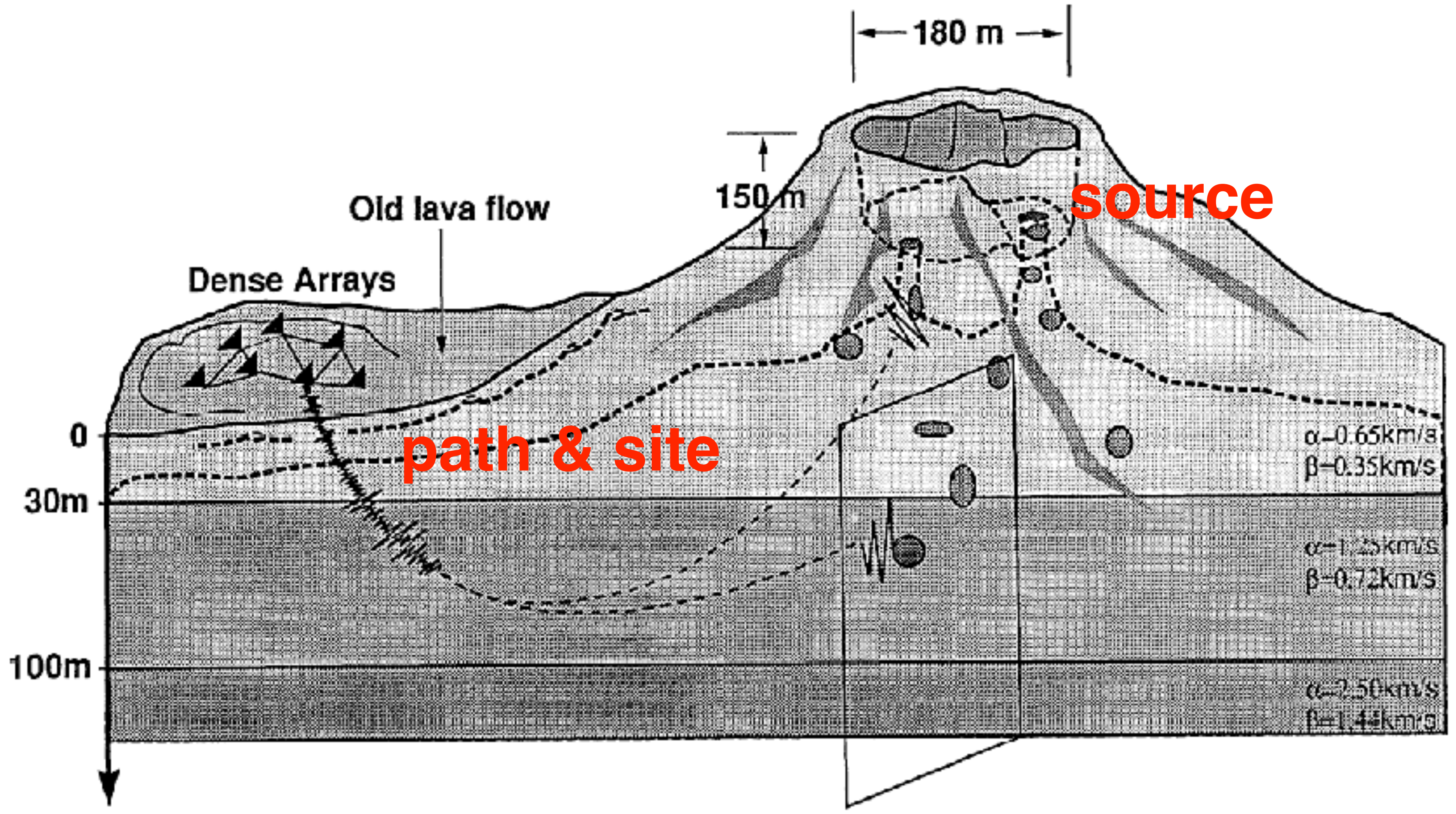
Seismic harmonic tremor: source vs. path effects

seismogram: $w(t) = s(t) * l(t) * g(t)$

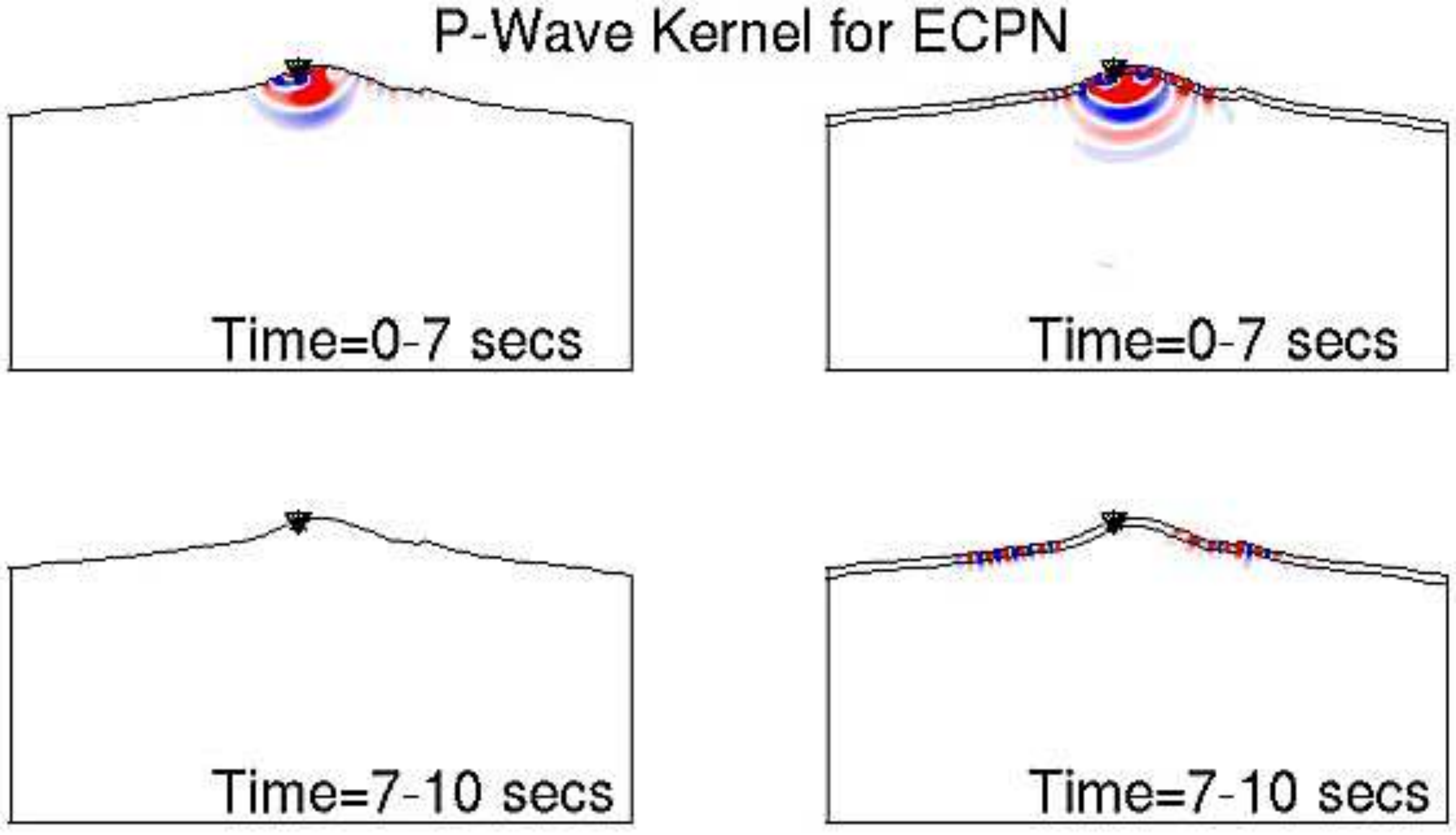
excitation/trigger

crack/conduit resonance

path & site effects



Goldstein and Chouet [1994]

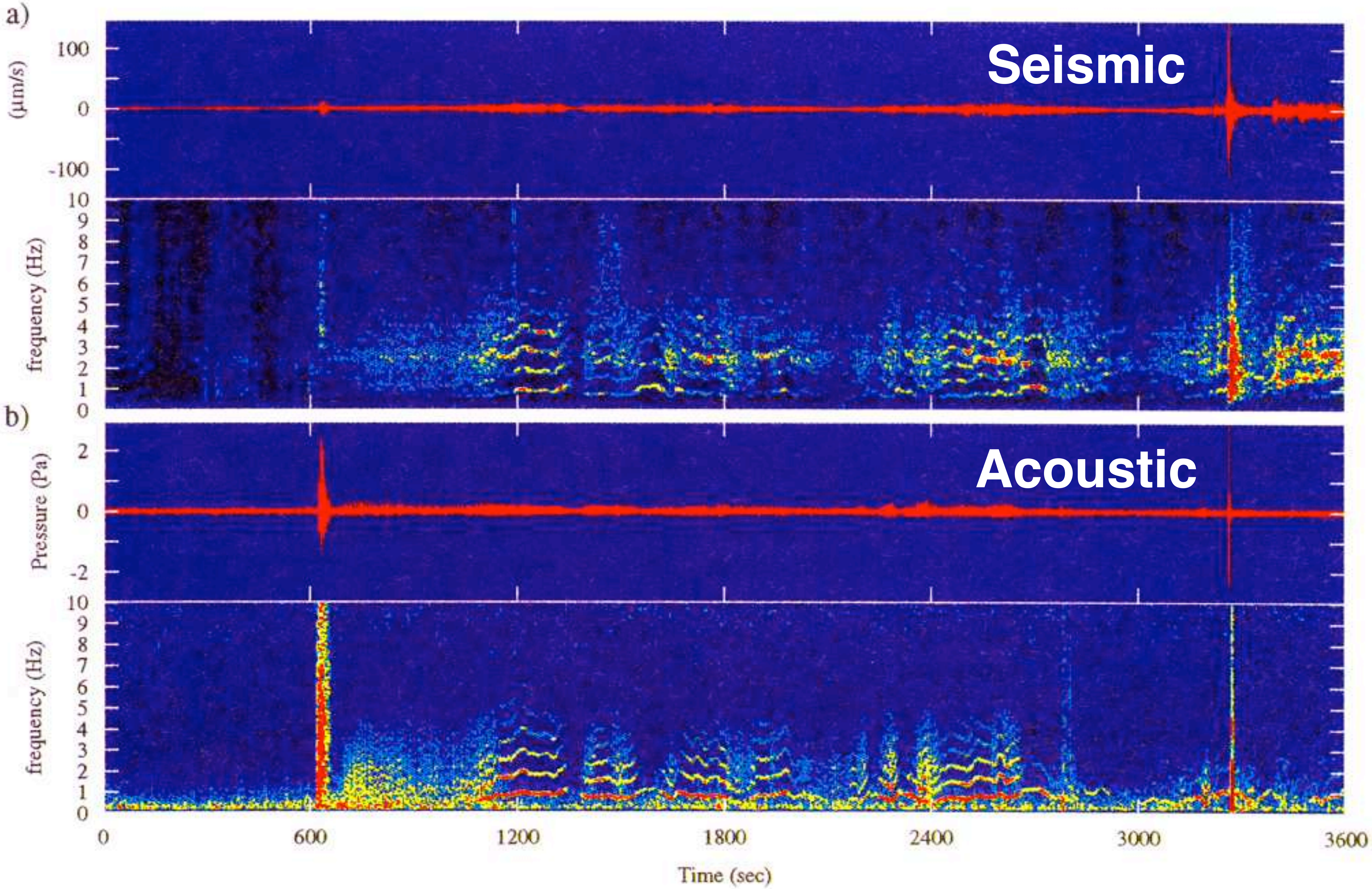


Homogeneous model

Near-surface layer model

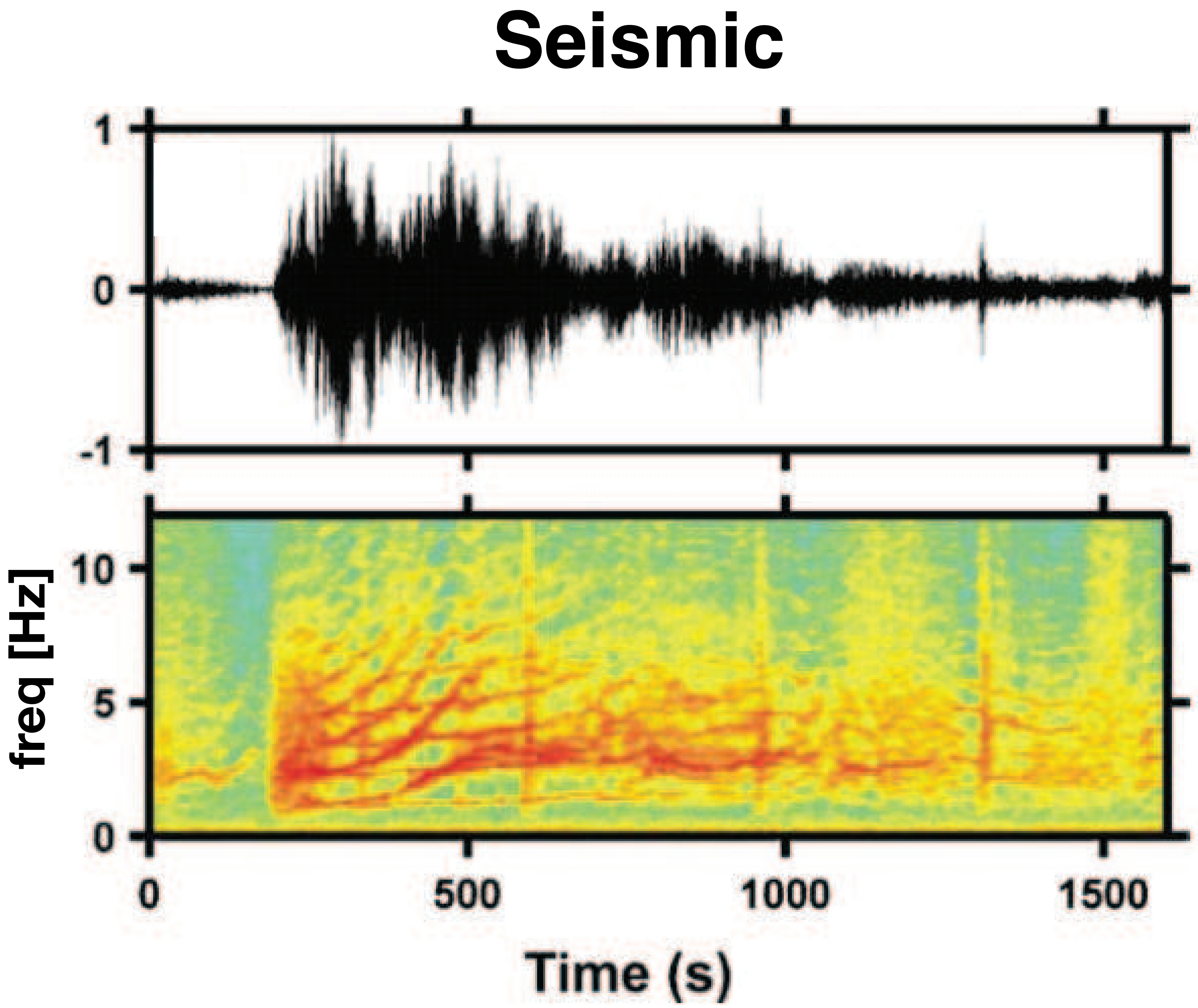
Bean et al. [2008]

Harmomic and monotonic tremor



Arenal, Costa Rica, Garces et al. [1998]

Harmomic and monotonic tremor



Arenal, Costa Rica, Lesage et al. [2006]

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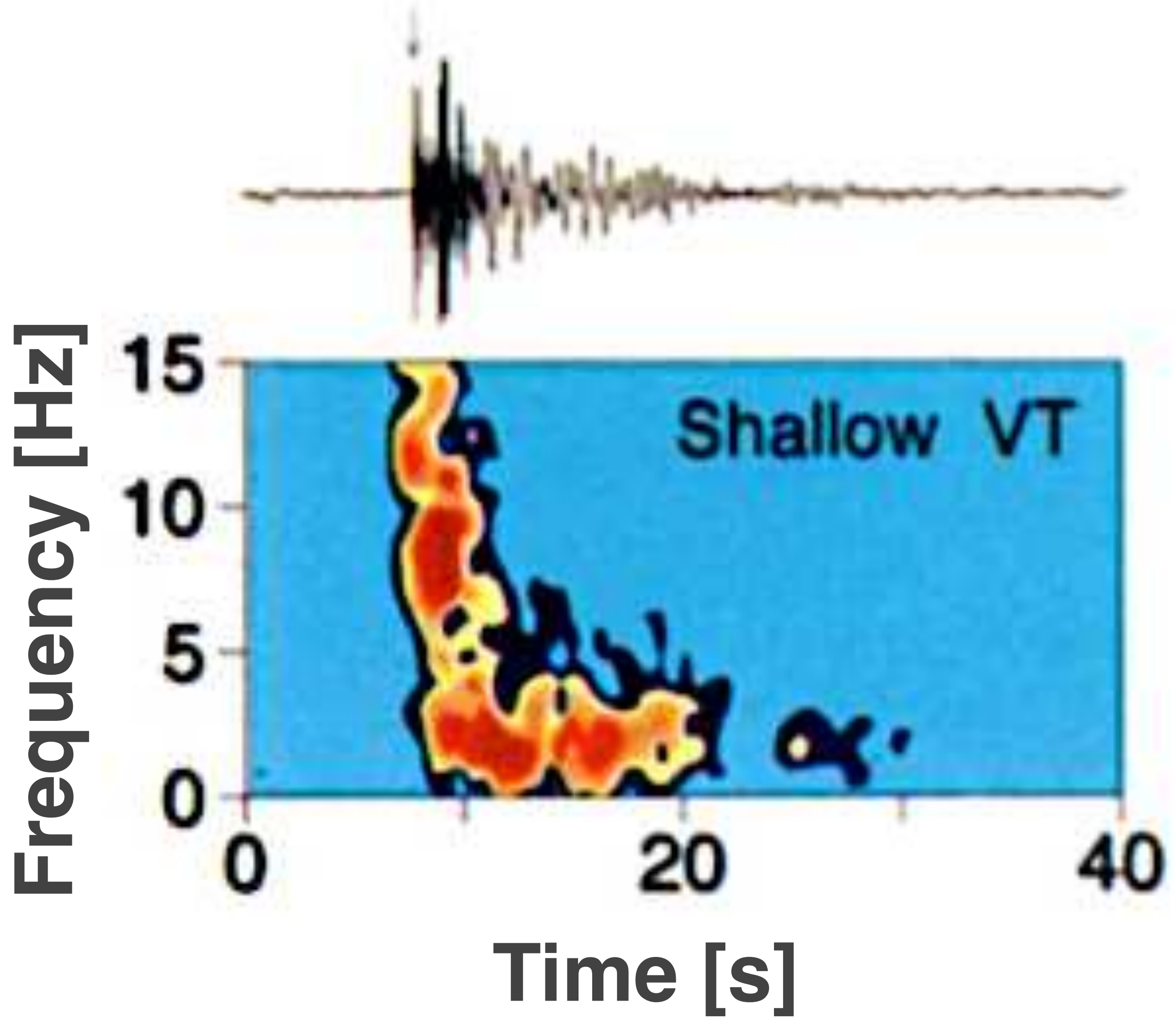

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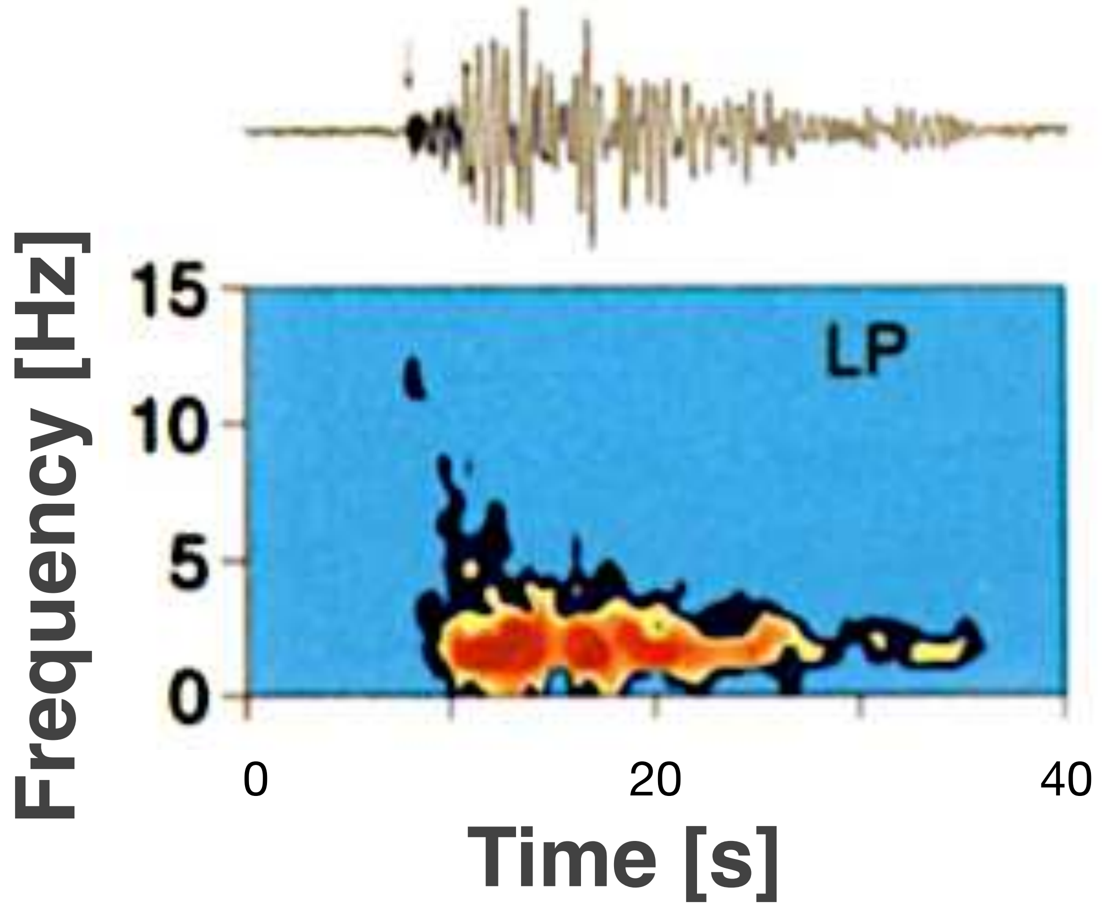
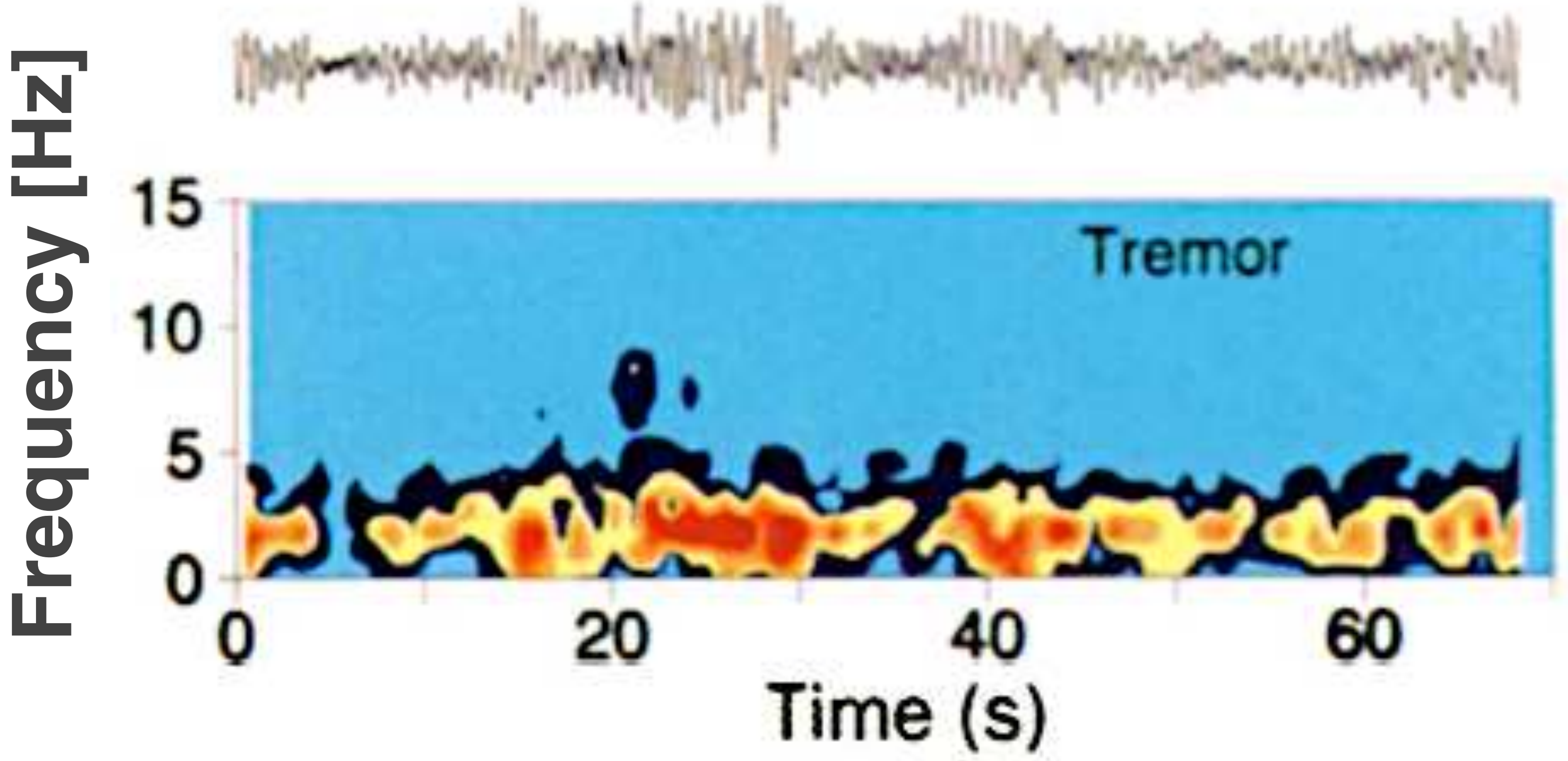
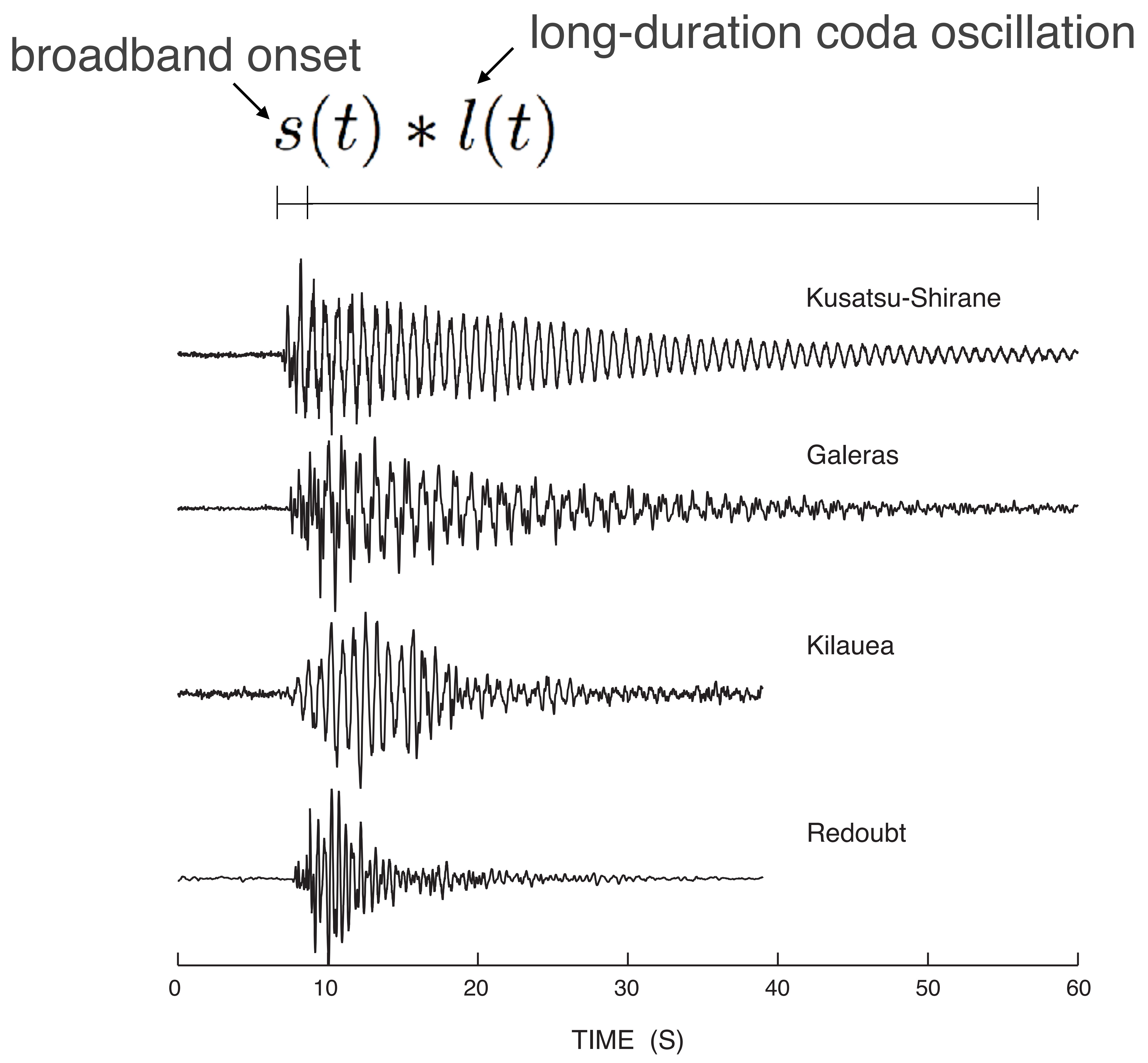




Chouet [1996]

Long-period (LP) events



LP events from volcanoes worldwide

Chouet and Matoza [2013]

LPs and tremor

Classification based on mechanism

- Individual LP events (transients) and certain types of tremor are closely linked
- LPs merge into tremor
- Collective term: long-period seismicity

[e.g., *Latter*, 1979; *Fehler*, 1983; *Neuberg*, 2011; *Hotovec et al.*, 2012]

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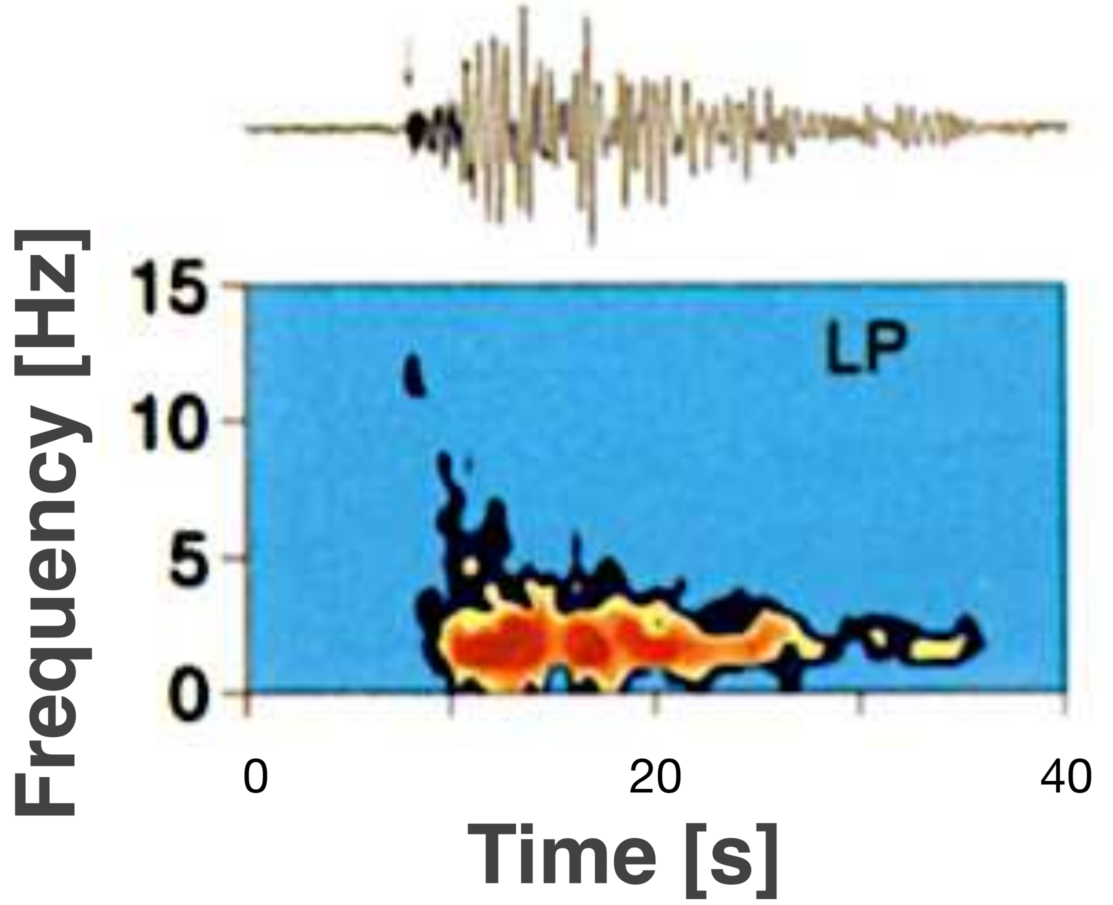

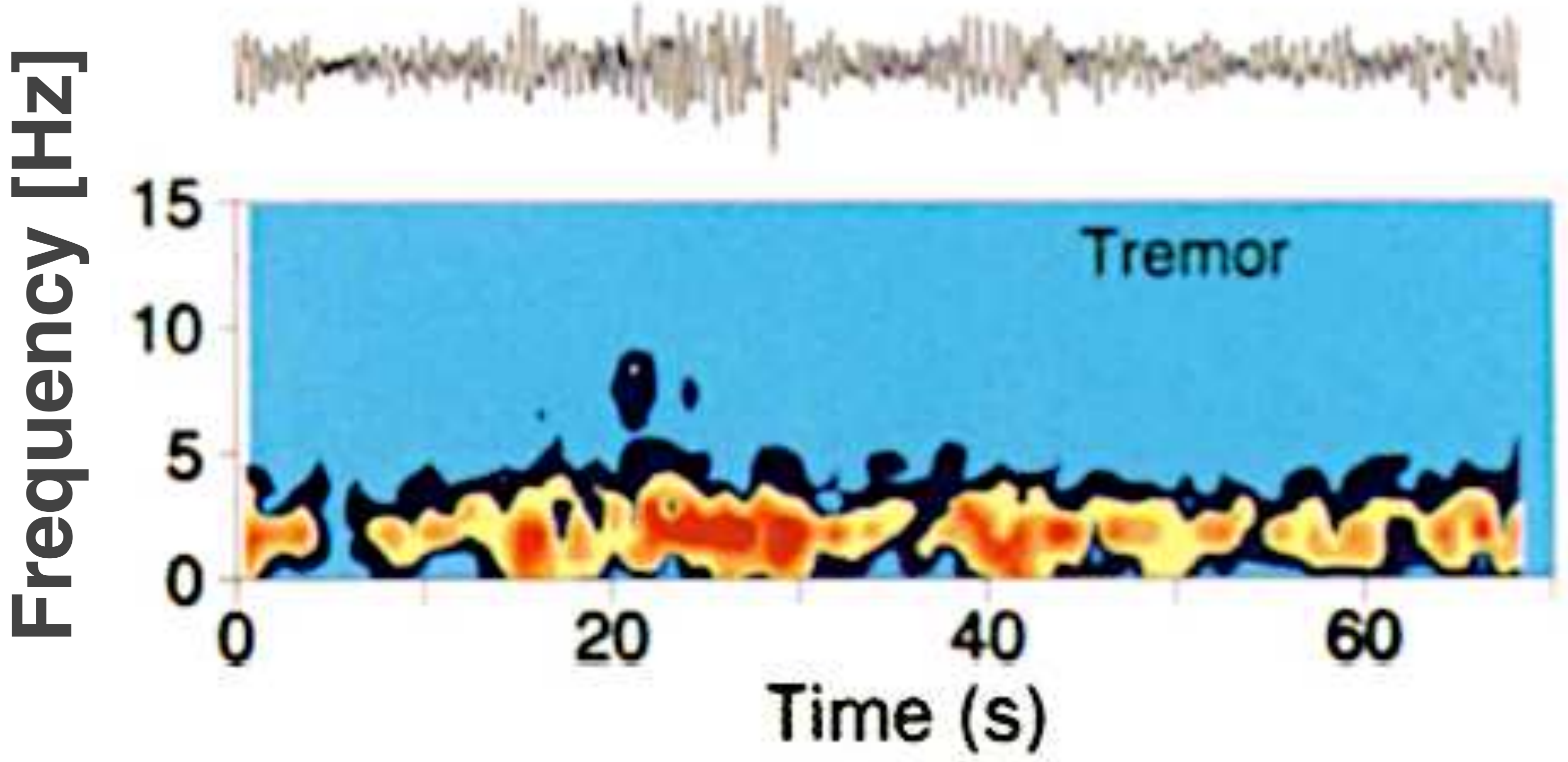

Chouet [1996]

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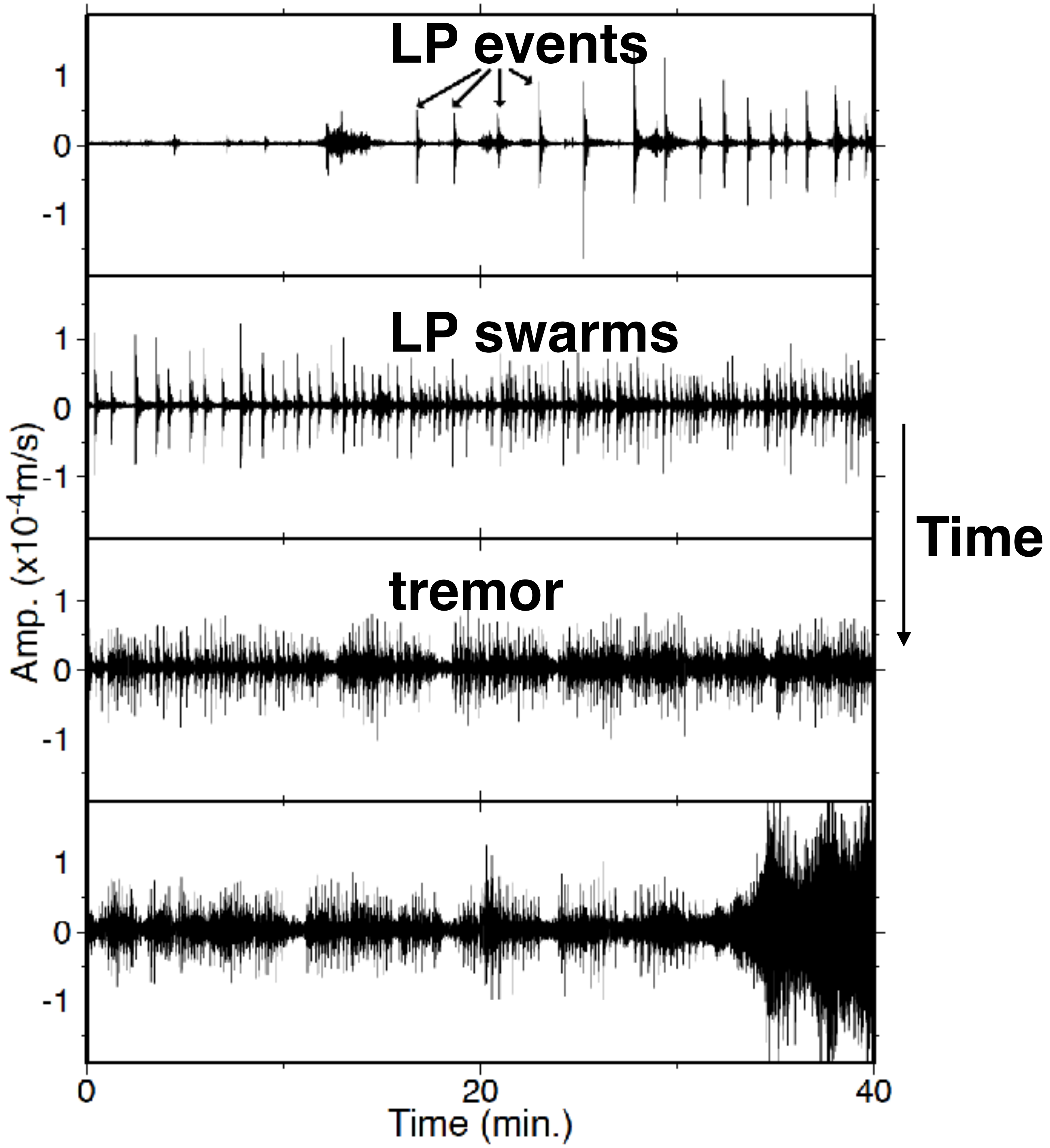

Soufrière Hills Volcano, Montserrat, June 25th 1997

[*Neuberg* 2000; *Green*, 2005]

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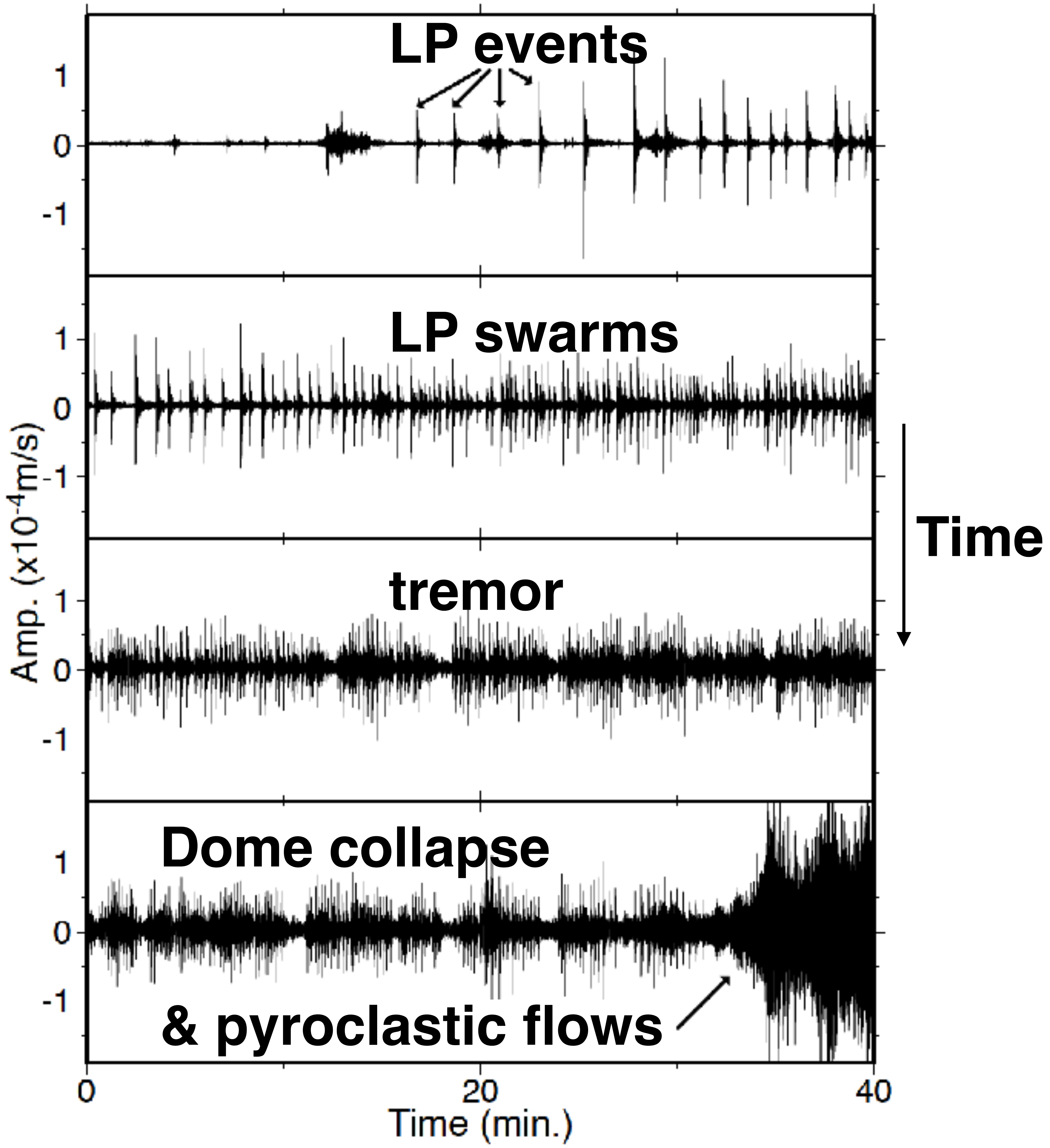
Paul Cole, MVO, 06/25/1997



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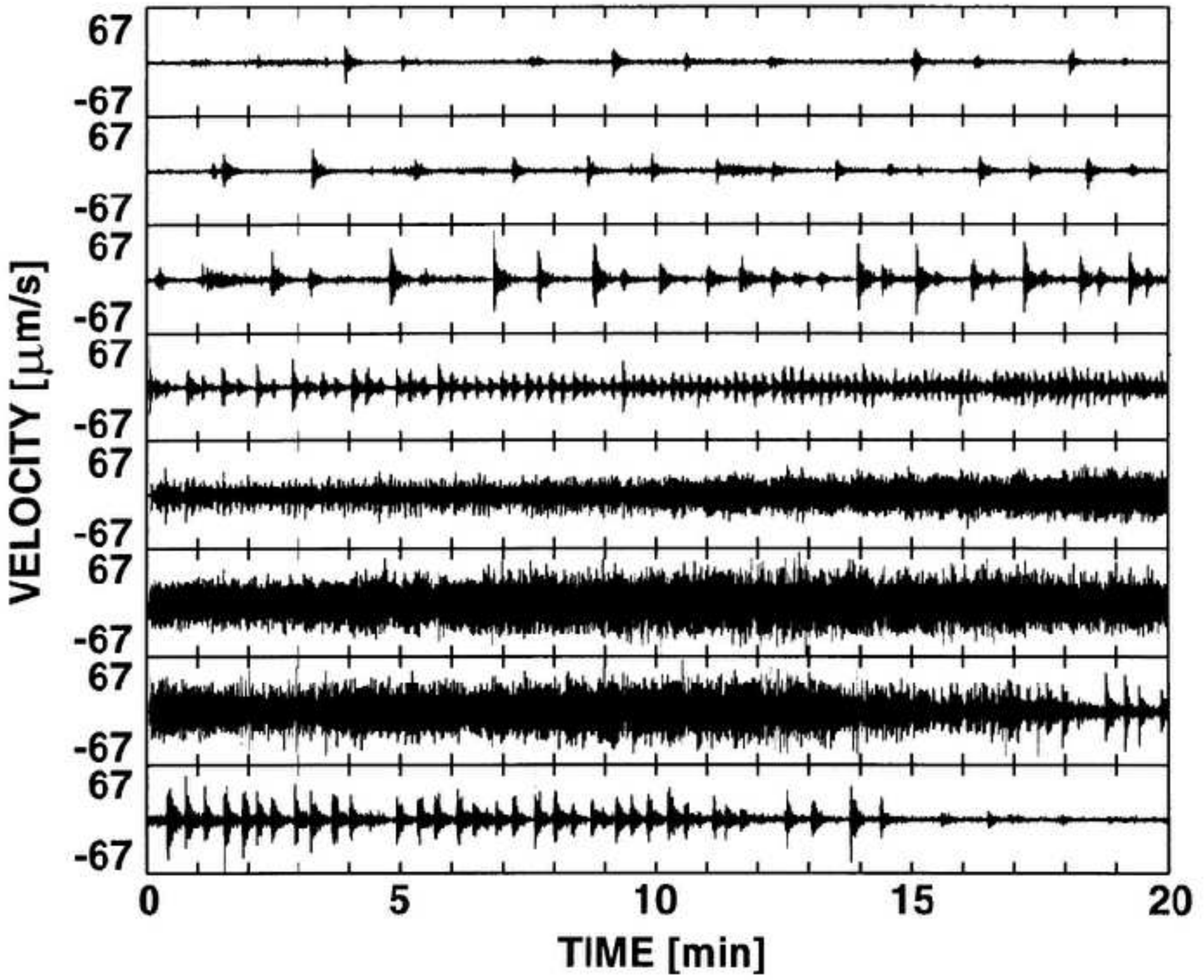
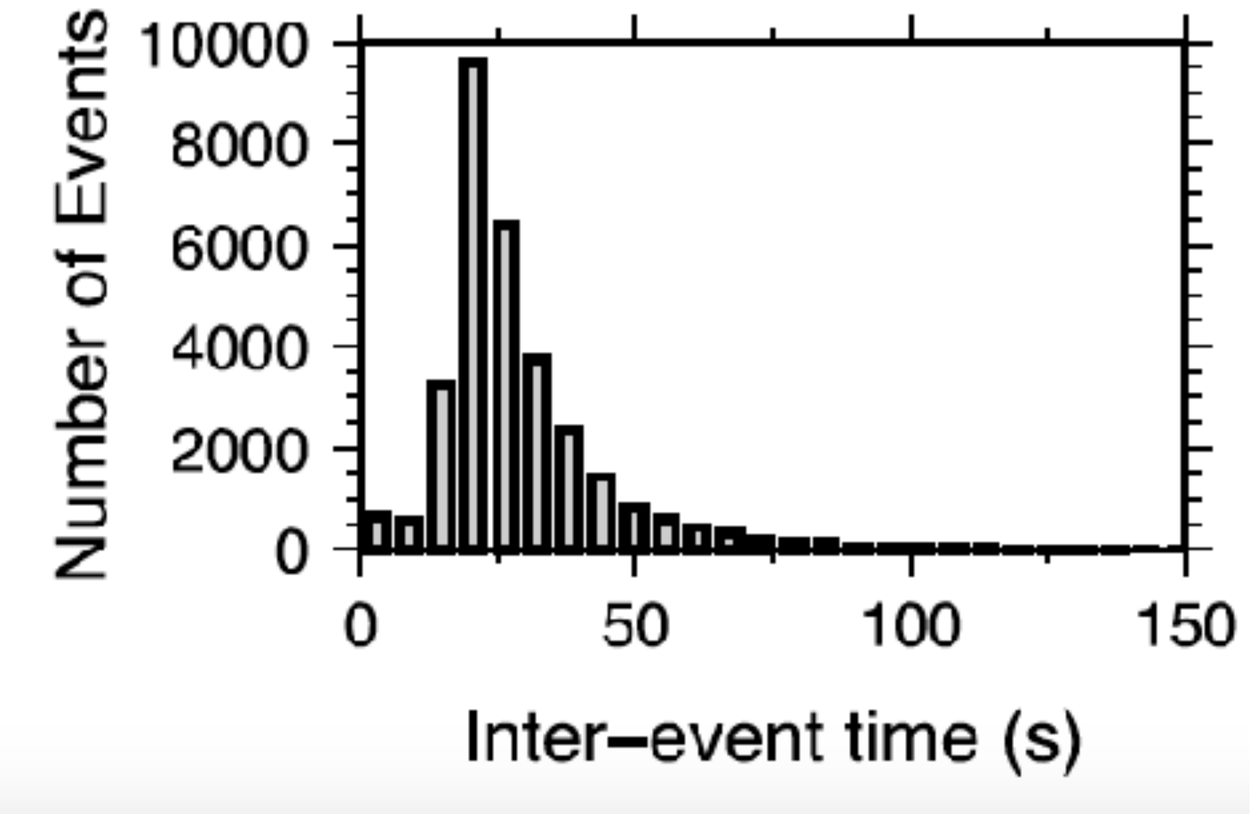


Soufrière Hills Volcano, Montserrat, February 12th 1997

[*Neuberg et al.,* 2000]

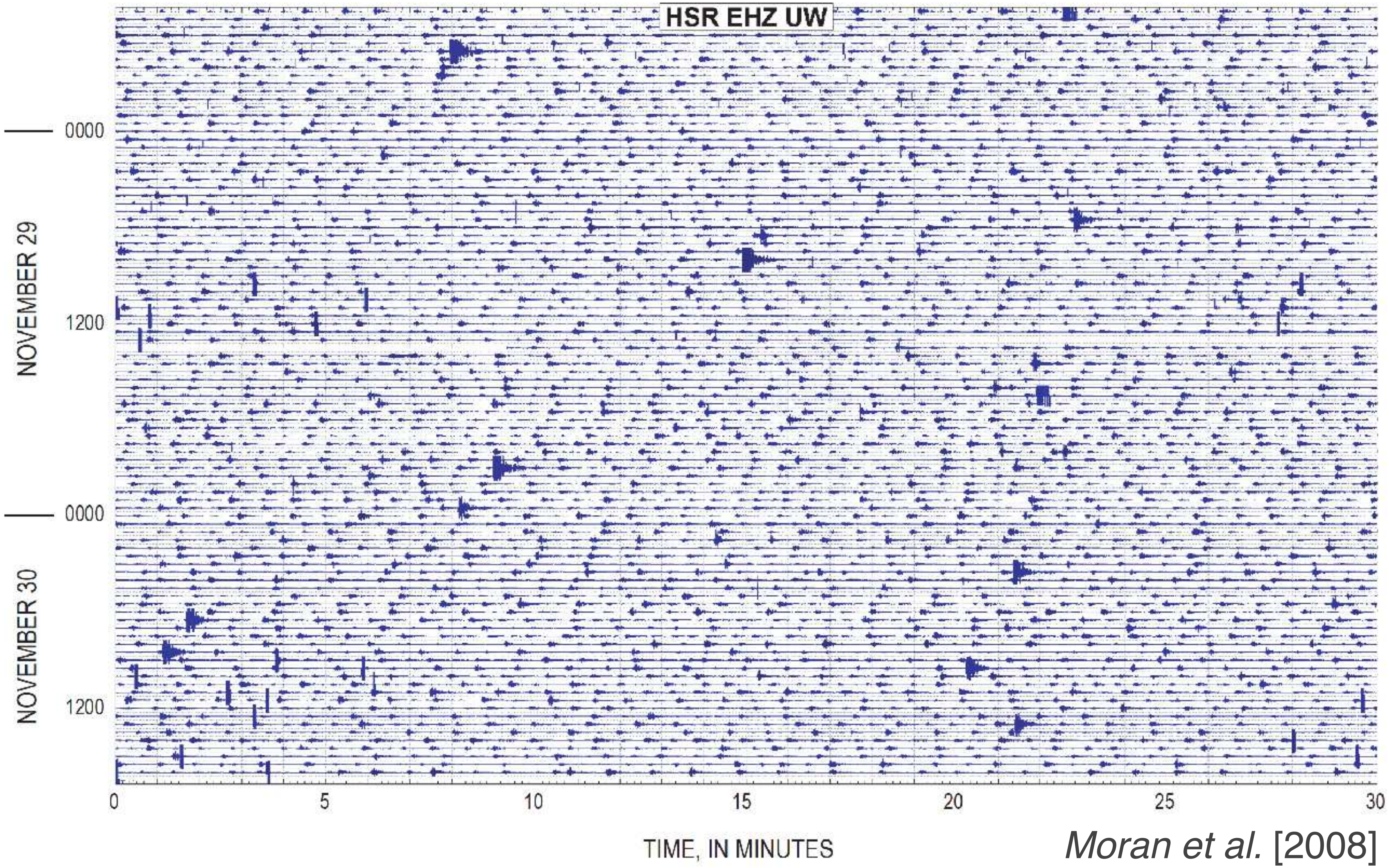
LPs and tremor

- Highly repetitive LPs with regular inter-event times ("drumbeats")
- May last for years in duration with slow evolution in event characteristics



Matoza and Chouet [2010]

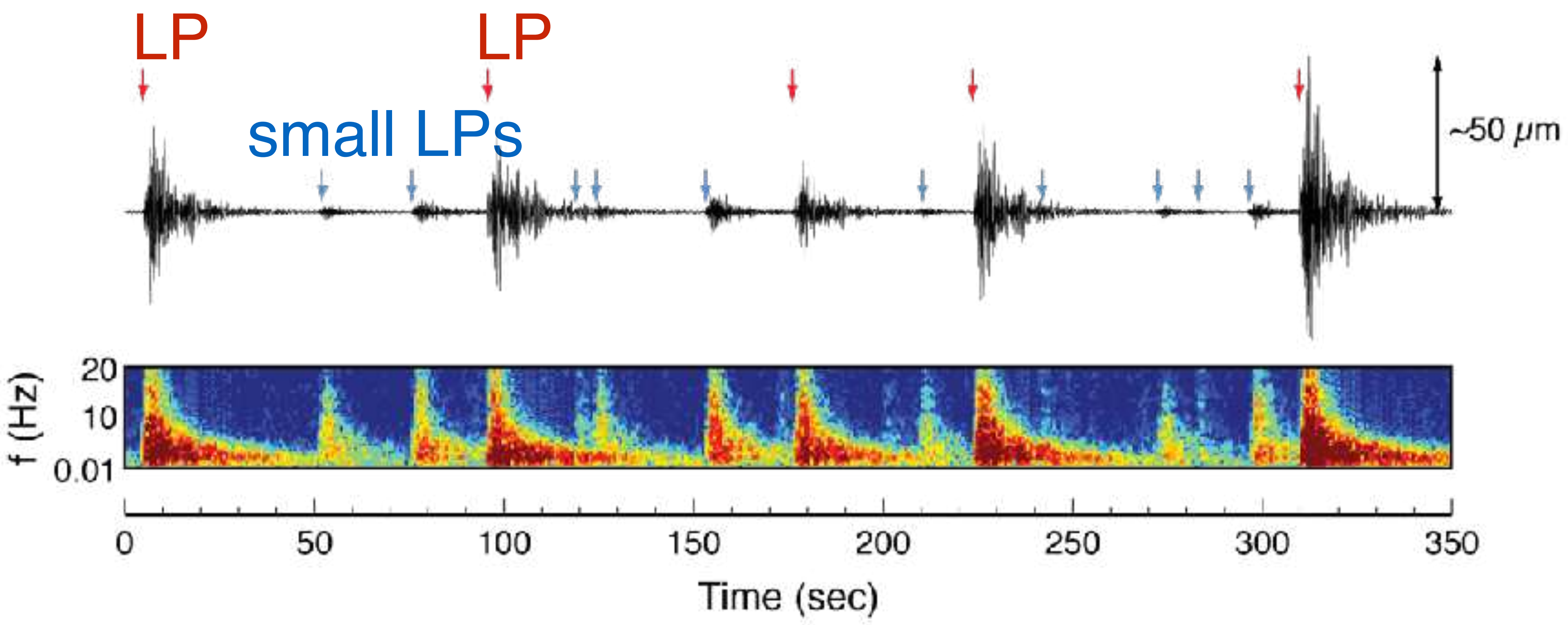
Mount St. Helens, WA November 2004; 48-hr seismogram ~2 km from summit

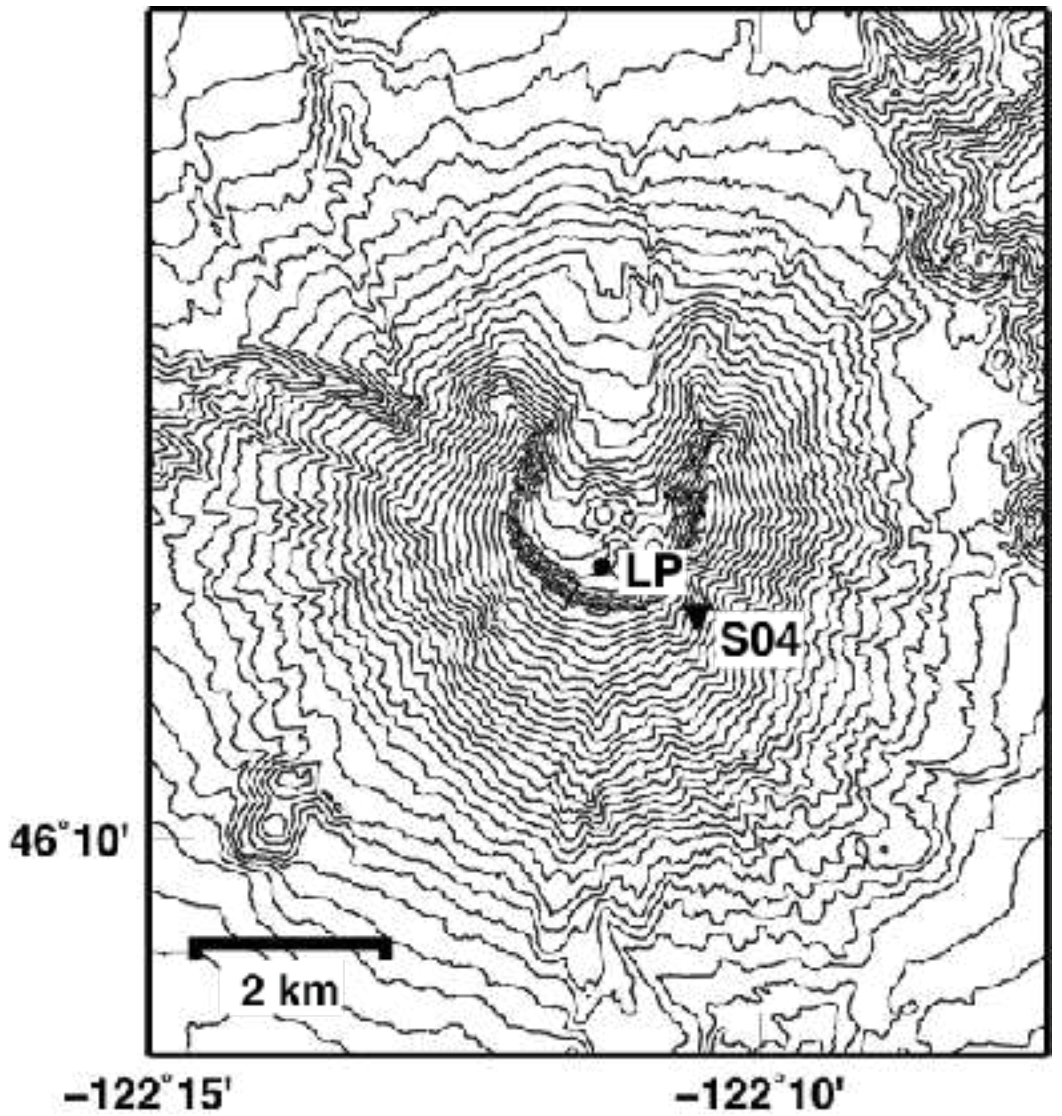


Moran et al. [2008]

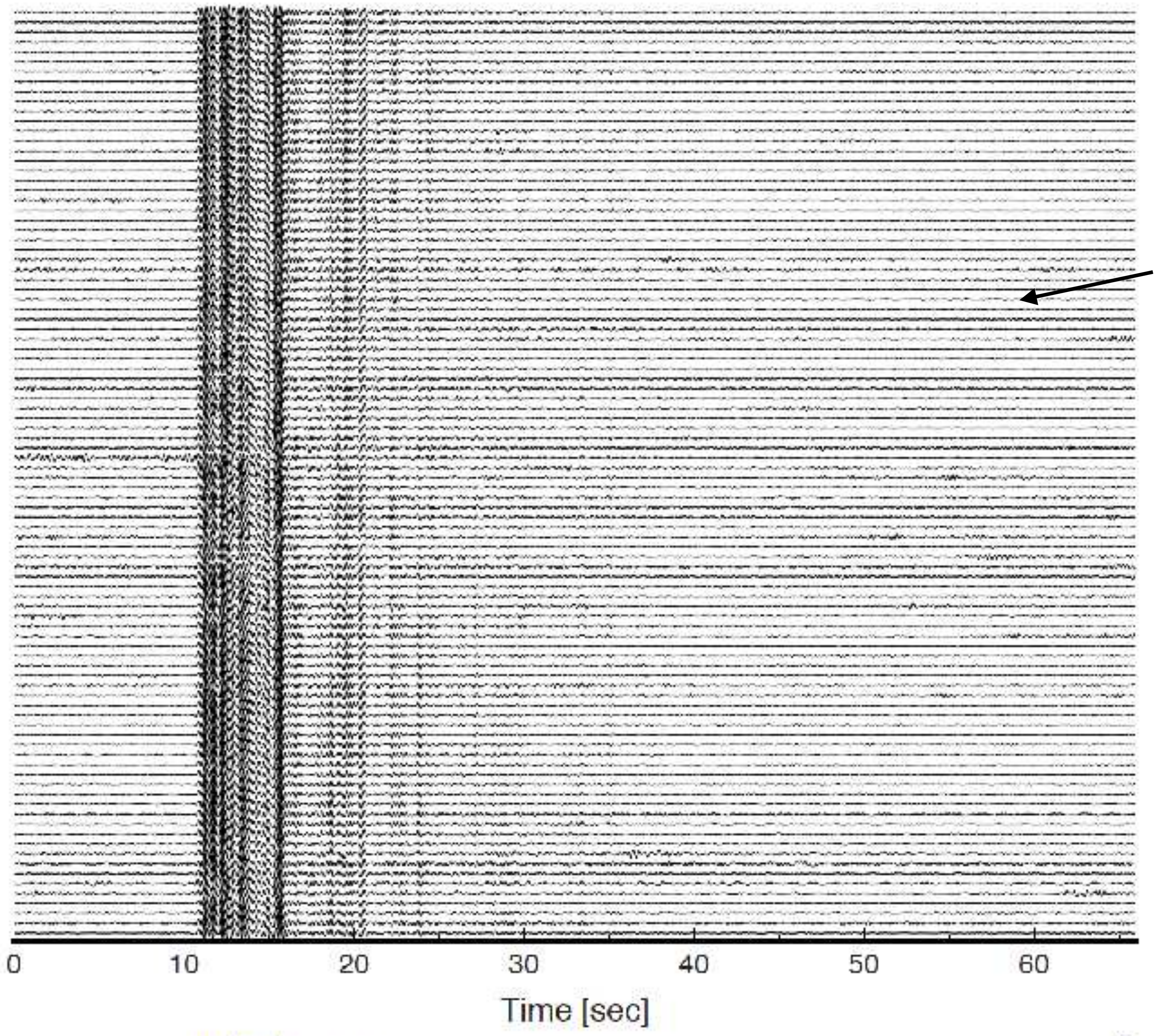
LP events: repetitive waveforms

S04 HHZ
distance 1.1 km

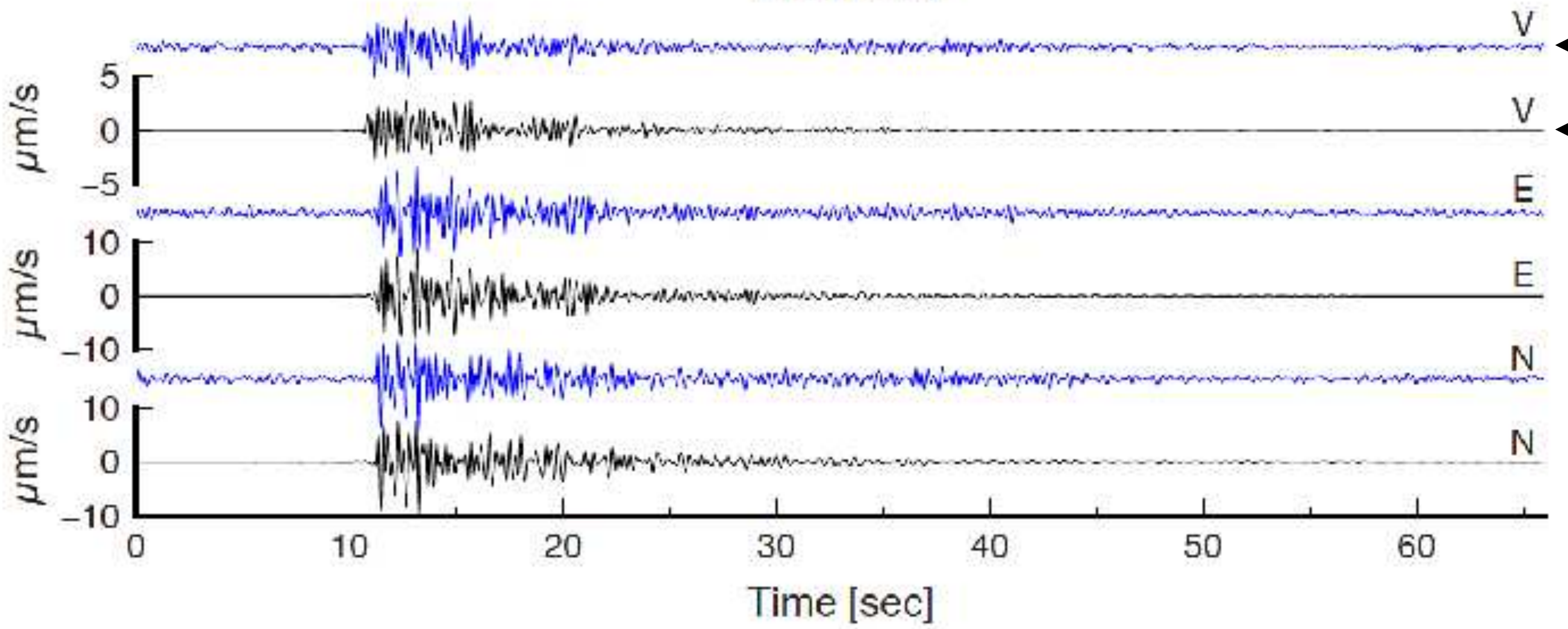




Small LP events at Mount St. Helens



2-hr mean
stacks



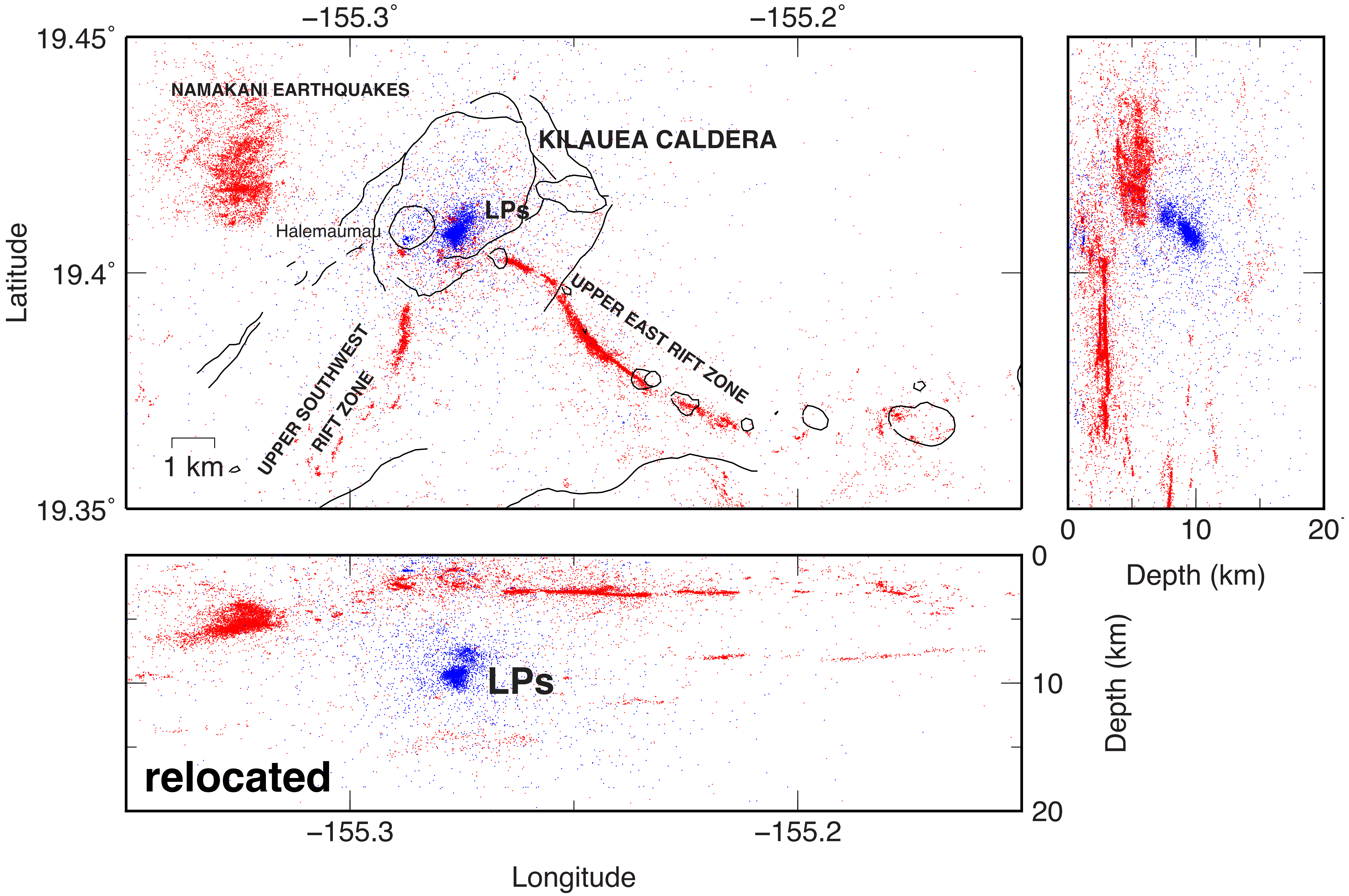
Seed event

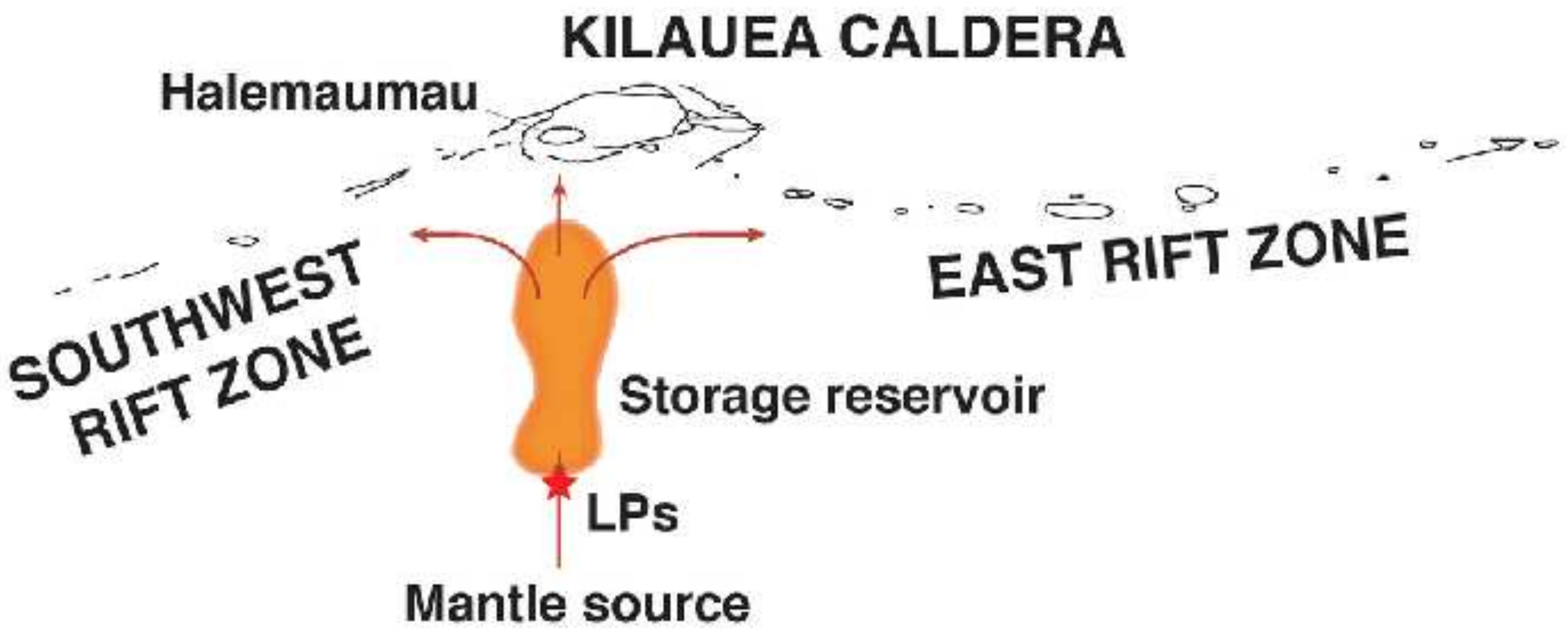
Final stack

Matoza et al. [2015]

LP events: stable source locations

- LP source location remarkably stable from 1986 to 2009: structurally controlled





Matoza et al. [2014]

LPs as the impulse response of the resonant tremor system

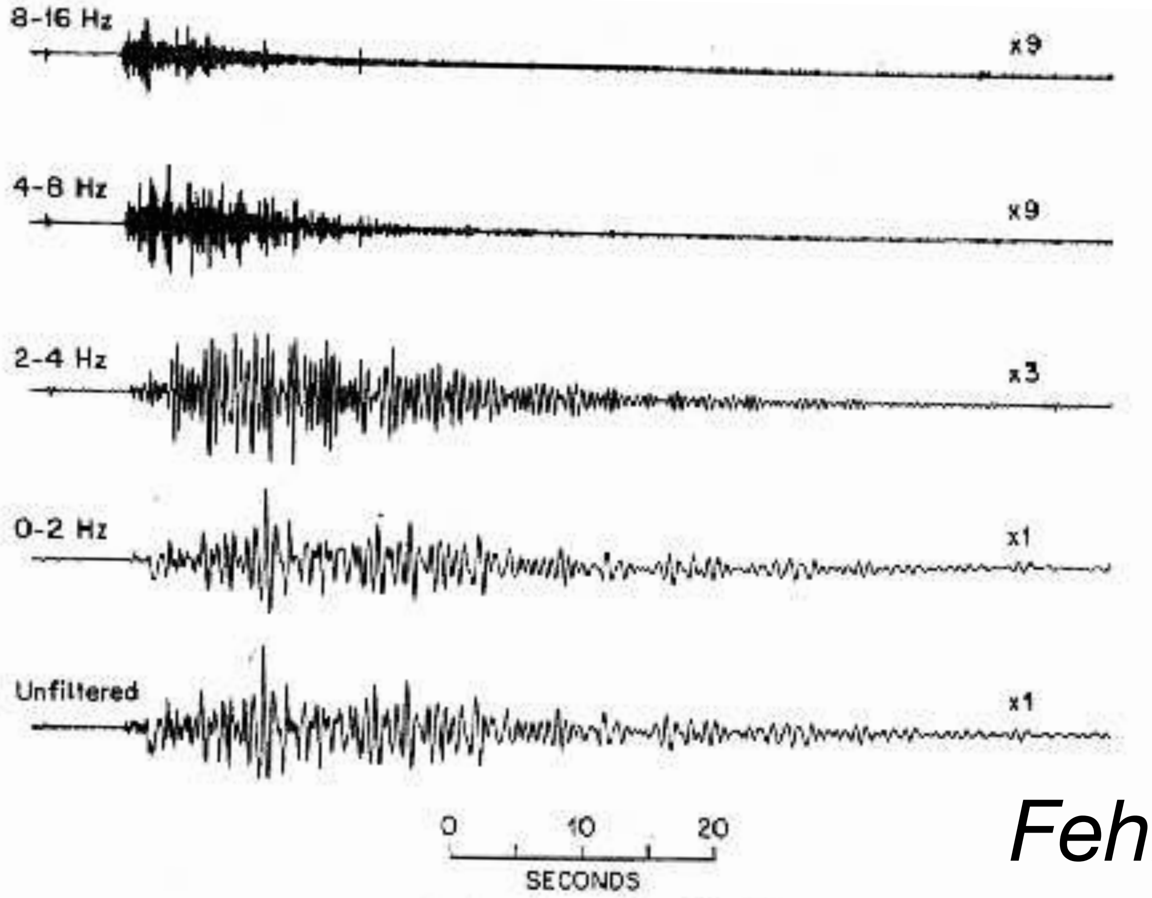
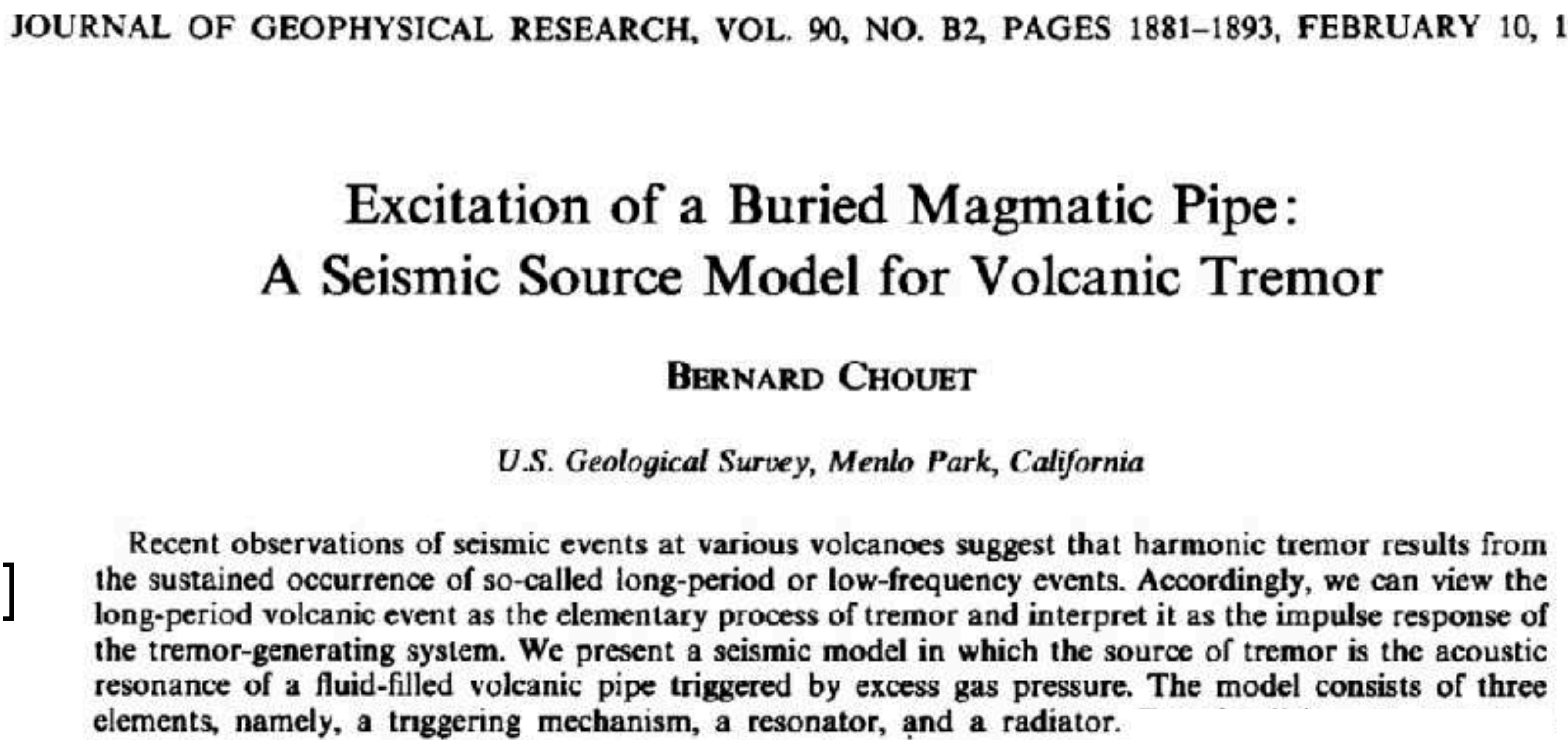


Fig. 9. Waveform of a typical long-period earthquake recorded at Mount St. Helens in October 1980 (lower trace). Upper traces show the result when the waveform is filtered with a band pass filter. The passband of the filter is labeled next to each trace. Note that some of the filtered traces have been magnified compared to the original traces.

Fehler [1983]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 90, NO. B2, PAGES 1881–1893, FEBRUARY 10, 1

Excitation of a Buried Magmatic Pipe: A Seismic Source Model for Volcanic Tremor

Bernard Chouet

U.S. Geological Survey, Menlo Park, California

Recent observations of seismic events at various volcanoes suggest that harmonic tremor results from the sustained occurrence of so-called long-period or low-frequency events. Accordingly, we can view the long-period volcanic event as the elementary process of tremor and interpret it as the impulse response of the tremor-generating system. We present a seismic model in which the source of tremor is the acoustic resonance of a fluid-filled volcanic pipe triggered by excess gas pressure. The model consists of three elements, namely, a triggering mechanism, a resonator, and a radiator.

Chouet [1985]

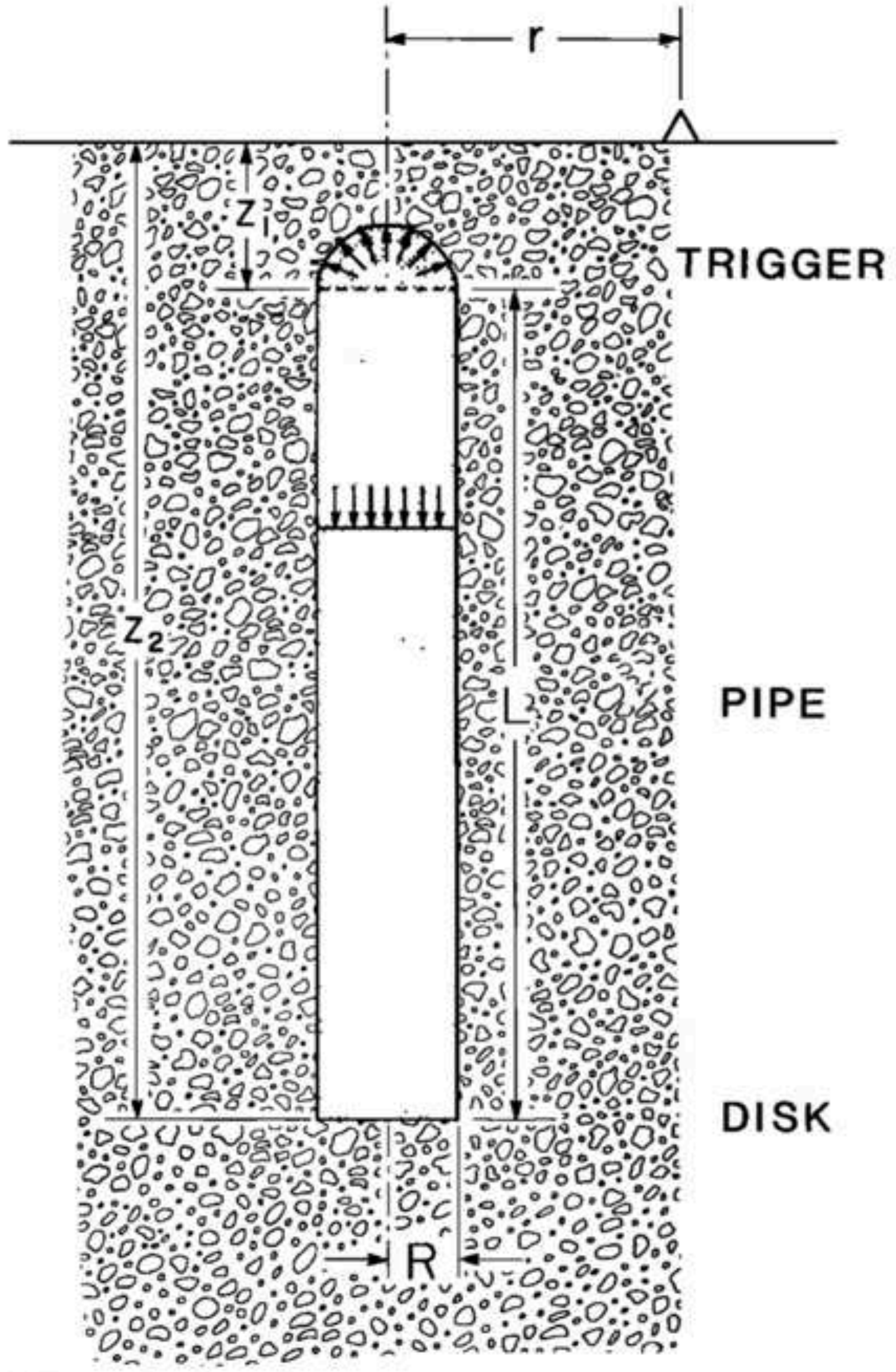


Fig. 1. Configuration of the source, medium, and receiver used in the computation of the ground motion produced by the excitation of a fluid-filled pipe. The composite source consists of a vertical conduit of radius *R* and length *L* capped by a hemisphere and shut by a horizontal disk at the bottom. The pipe is filled with a liquid while the hemispherical cap contains a gas. The depth to the pipe inlet is z_1, and the receiver is located at the epicentral distance *r*.

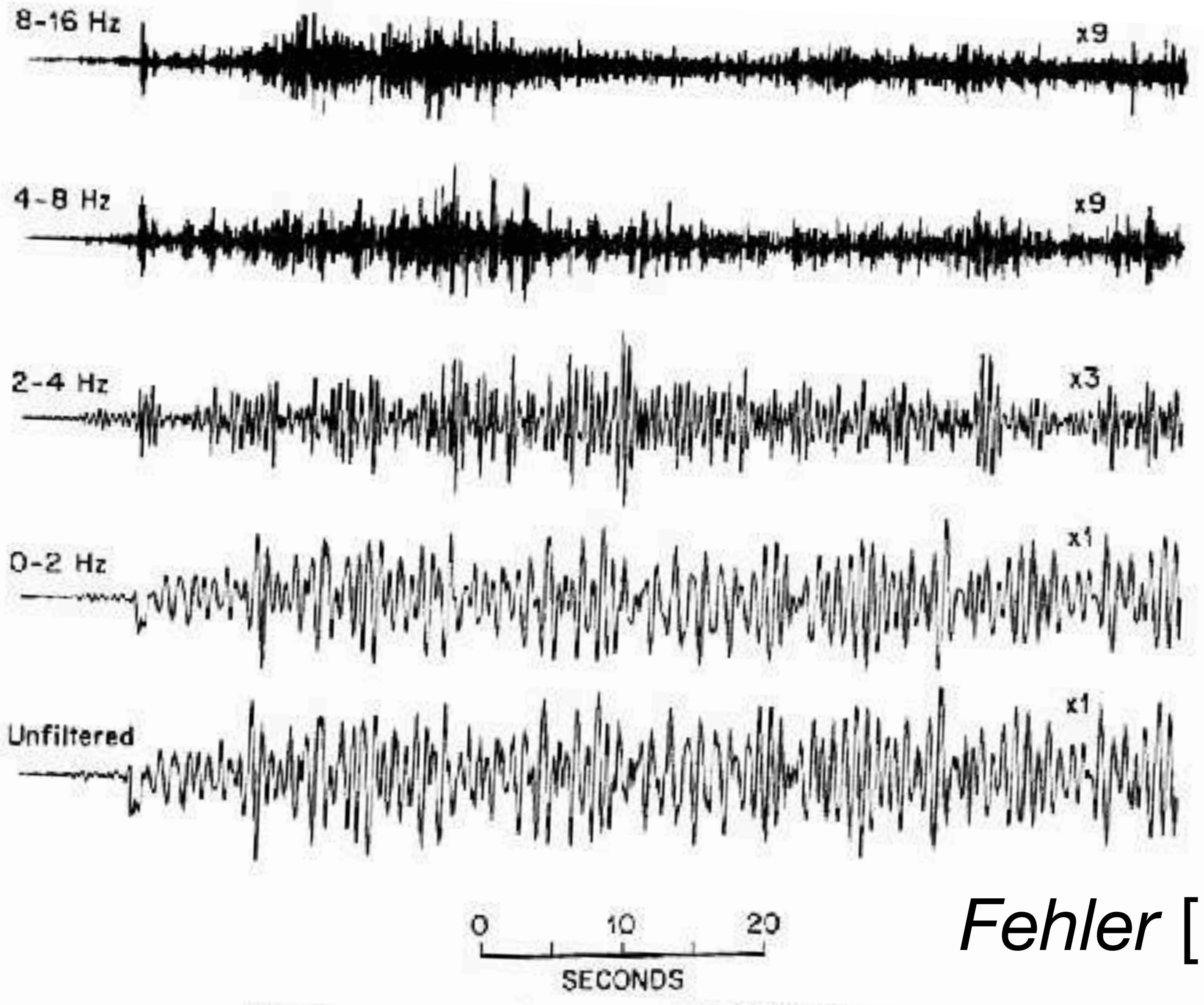
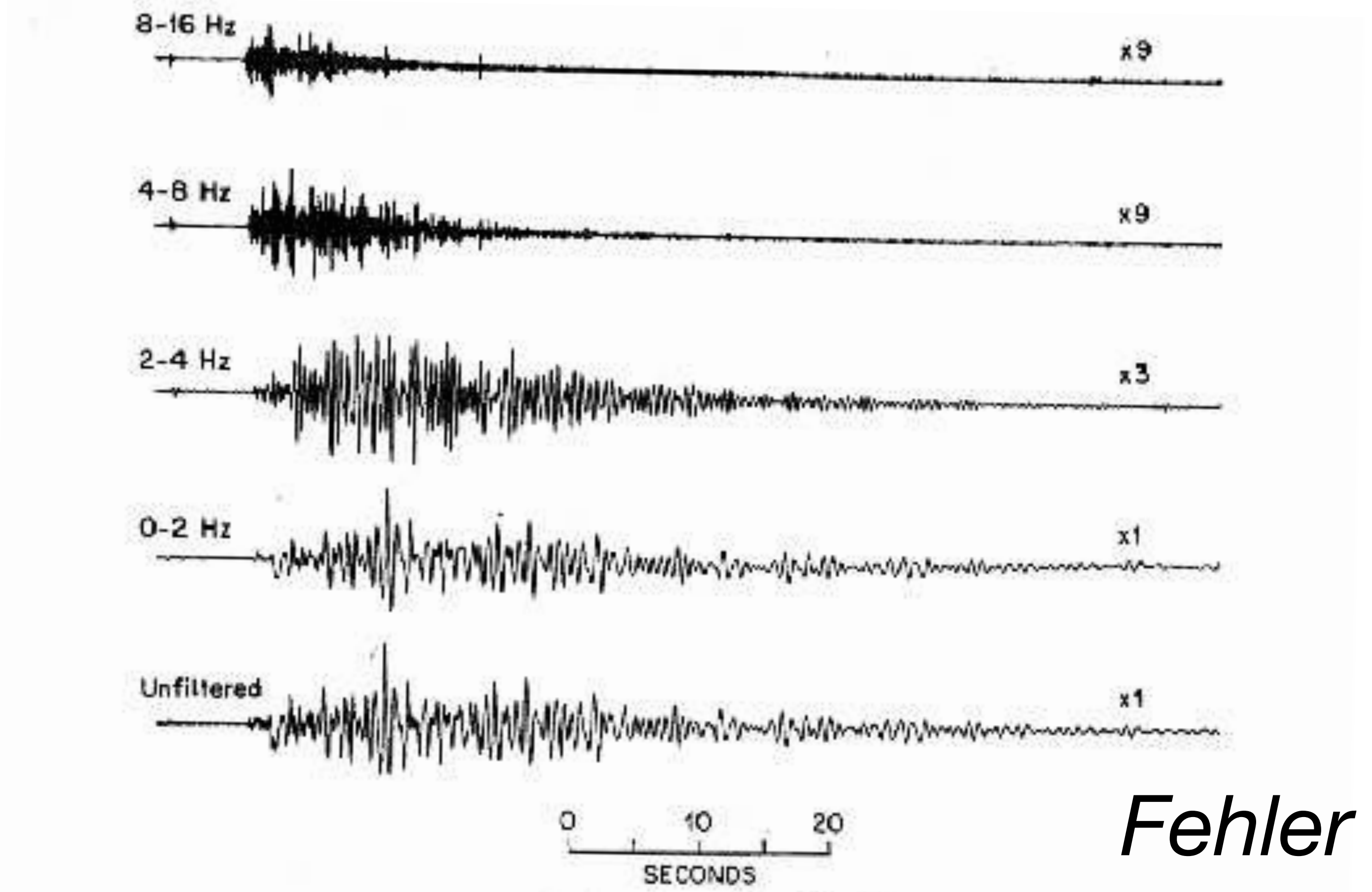


Fig. 10. Waveform of a tremor event and filtered traces.

Fehler [1983]

see also *Jousset et al.* [2003]; finite-difference solution of conduit resonance

LPs as the impulse response of the resonant tremor system



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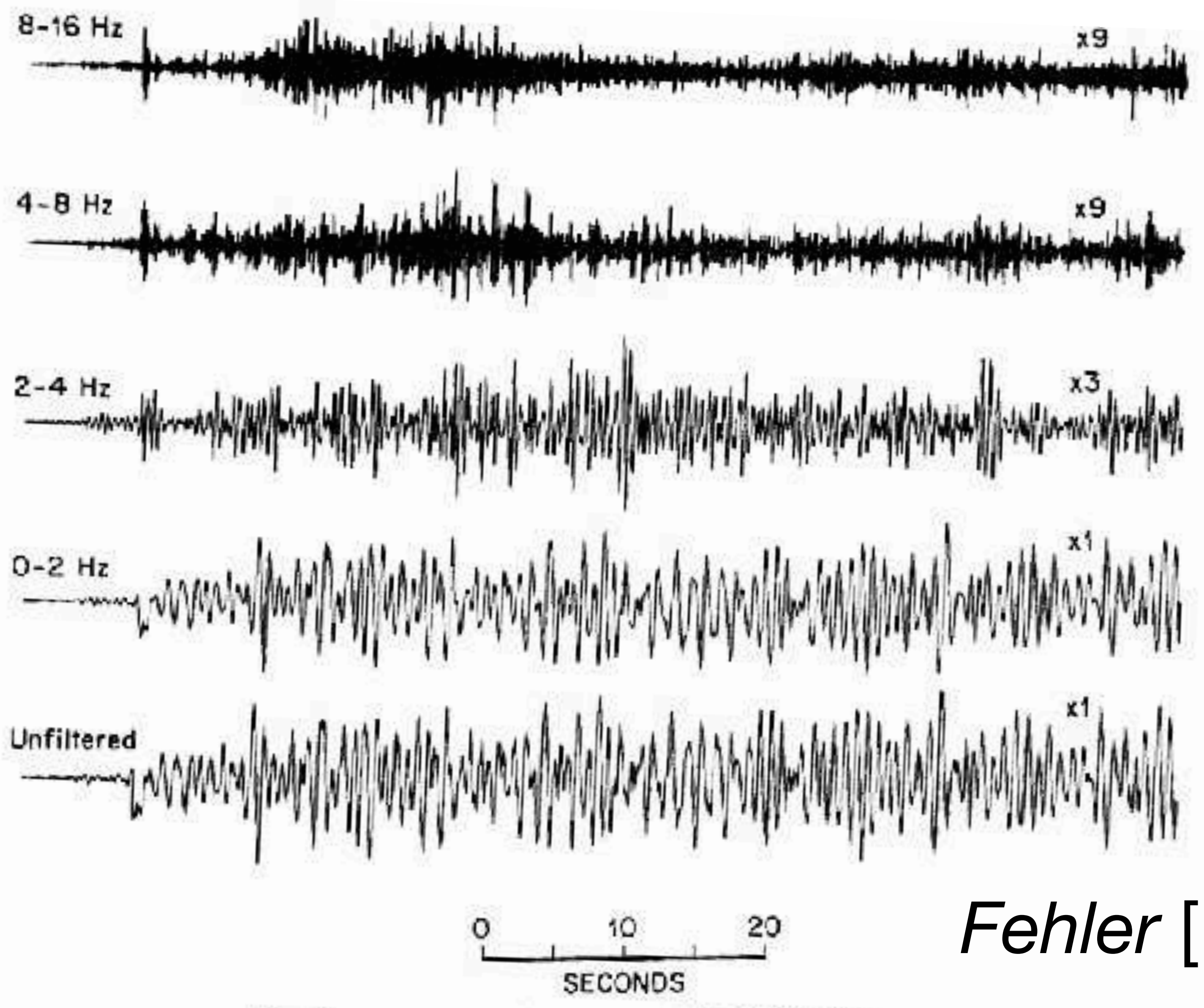
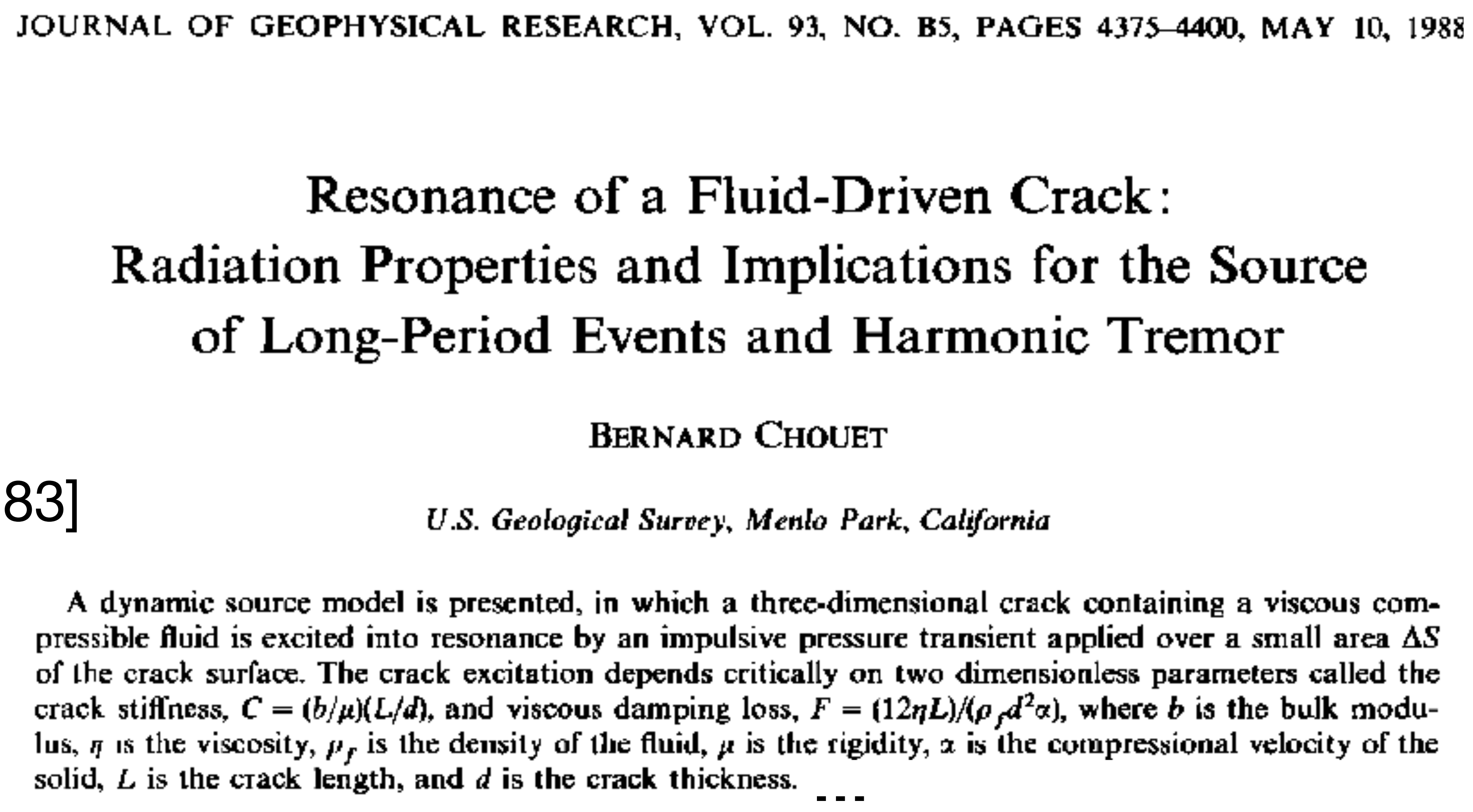


Fig. 10. Waveform of a tremor event and filtered traces.

Fehler [1983]



JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 93, NO. B5, PAGES 4375–4400, MAY 10, 1988

Resonance of a Fluid-Driven Crack: Radiation Properties and Implications for the Source of Long-Period Events and Harmonic Tremor

BERNARD CHOUET

U.S. Geological Survey, Menlo Park, California

A dynamic source model is presented, in which a three-dimensional crack containing a viscous compressible fluid is excited into resonance by an impulsive pressure transient applied over a small area ΔS of the crack surface. The crack excitation depends critically on two dimensionless parameters called the crack stiffness, $C = (b/\mu)(L/d)$, and viscous damping loss, $F = (12\eta L)/(\rho_f d^2 \alpha)$, where b is the bulk modulus, η is the viscosity, ρ_f is the density of the fluid, μ is the rigidity, α is the compressional velocity of the solid, L is the crack length, and d is the crack thickness. ...

Chouet [1988]

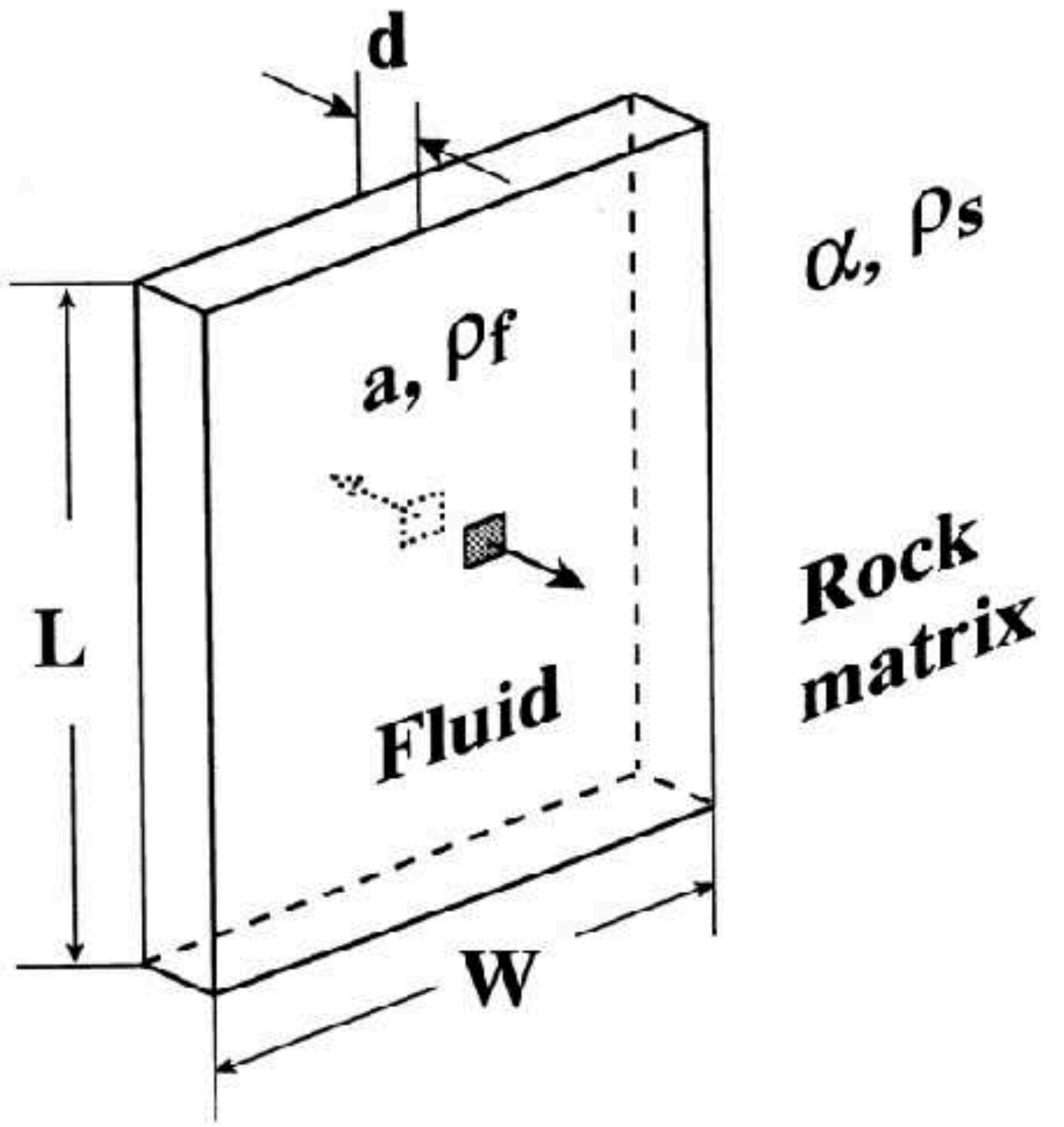


Figure 1. Geometry of the crack model. L, W, and d are the length, width, and aperture of the crack, respectively; a is the sound speed of the fluid in the crack and α is the P wave velocity of the rock matrix, and ρ_f and ρ_s are the densities of the fluid and rock matrix, respectively. We use $W/L = 0.5$, $L/d = 10^4$, and a step increase in pressure applied at the center of the crack as the crack excitation throughout this study.

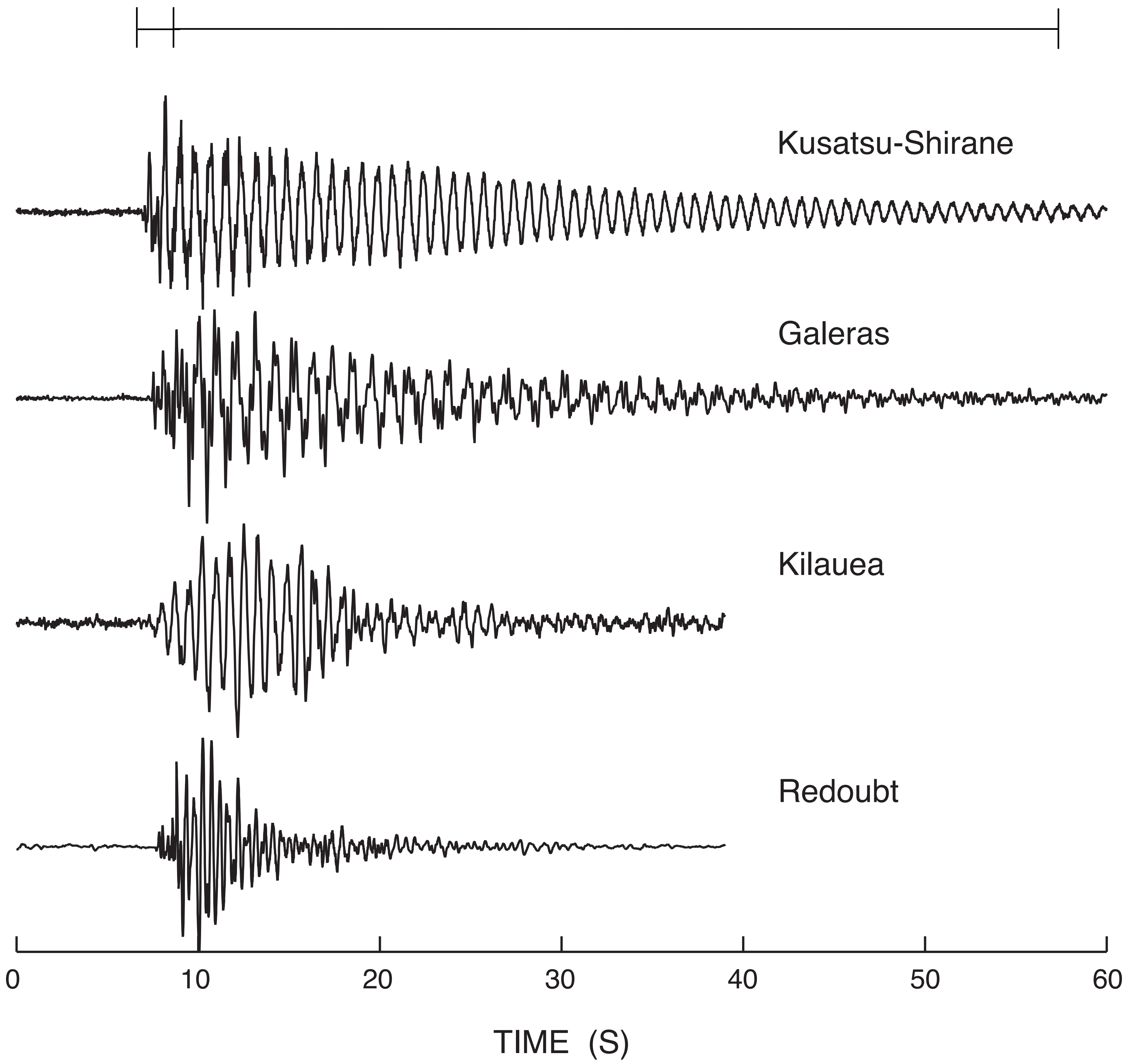
figure: *Kumagai and Chouet* [2000]

LPs: the fluid-driven crack model

broadband onset

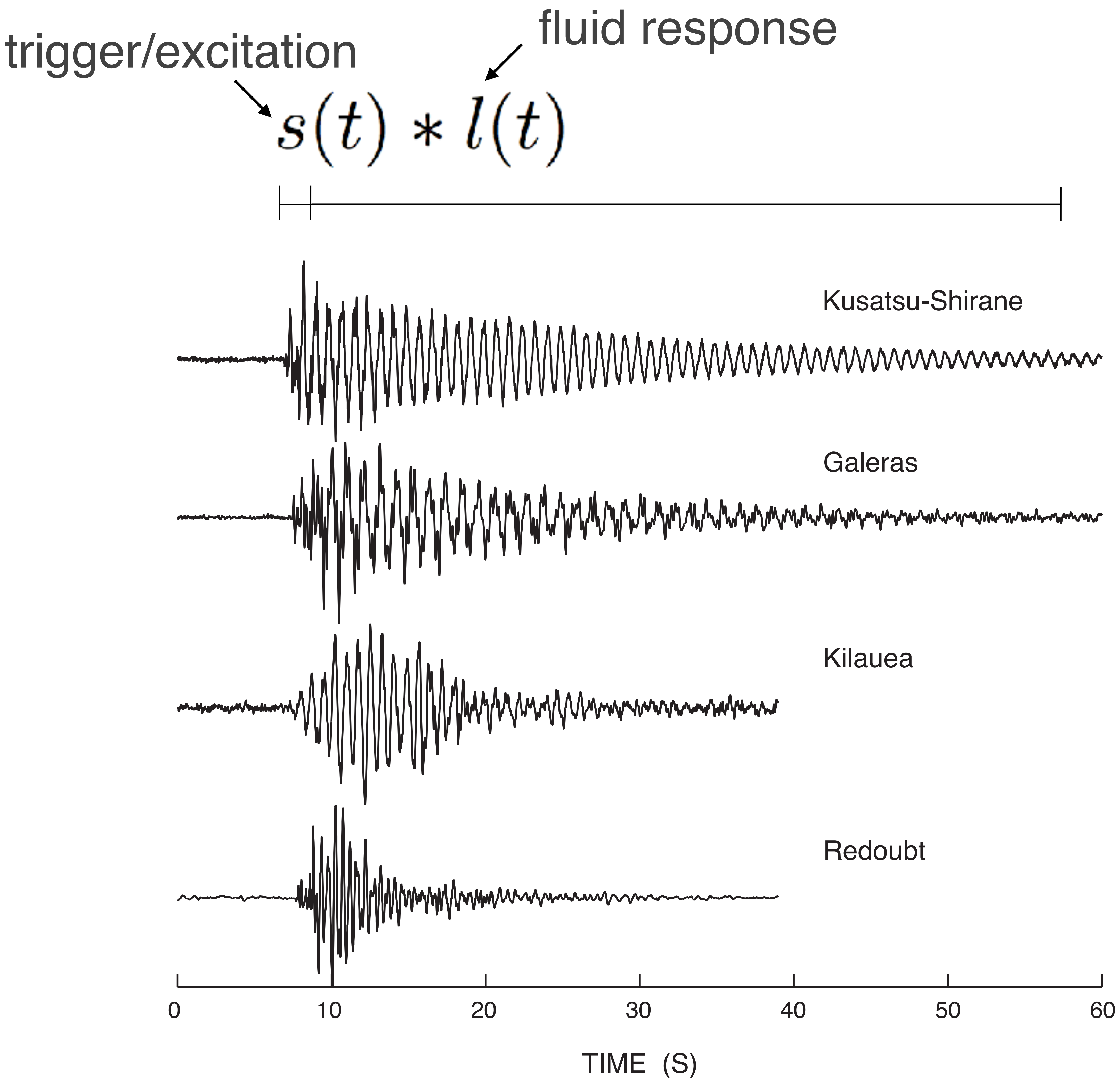
long-duration coda oscillation

$$s(t) * l(t)$$



Chouet and Matoza [2013]

LPs: the fluid-driven crack model



- Impulsive trigger: discrete LP event
- Sustained trigger: tremor

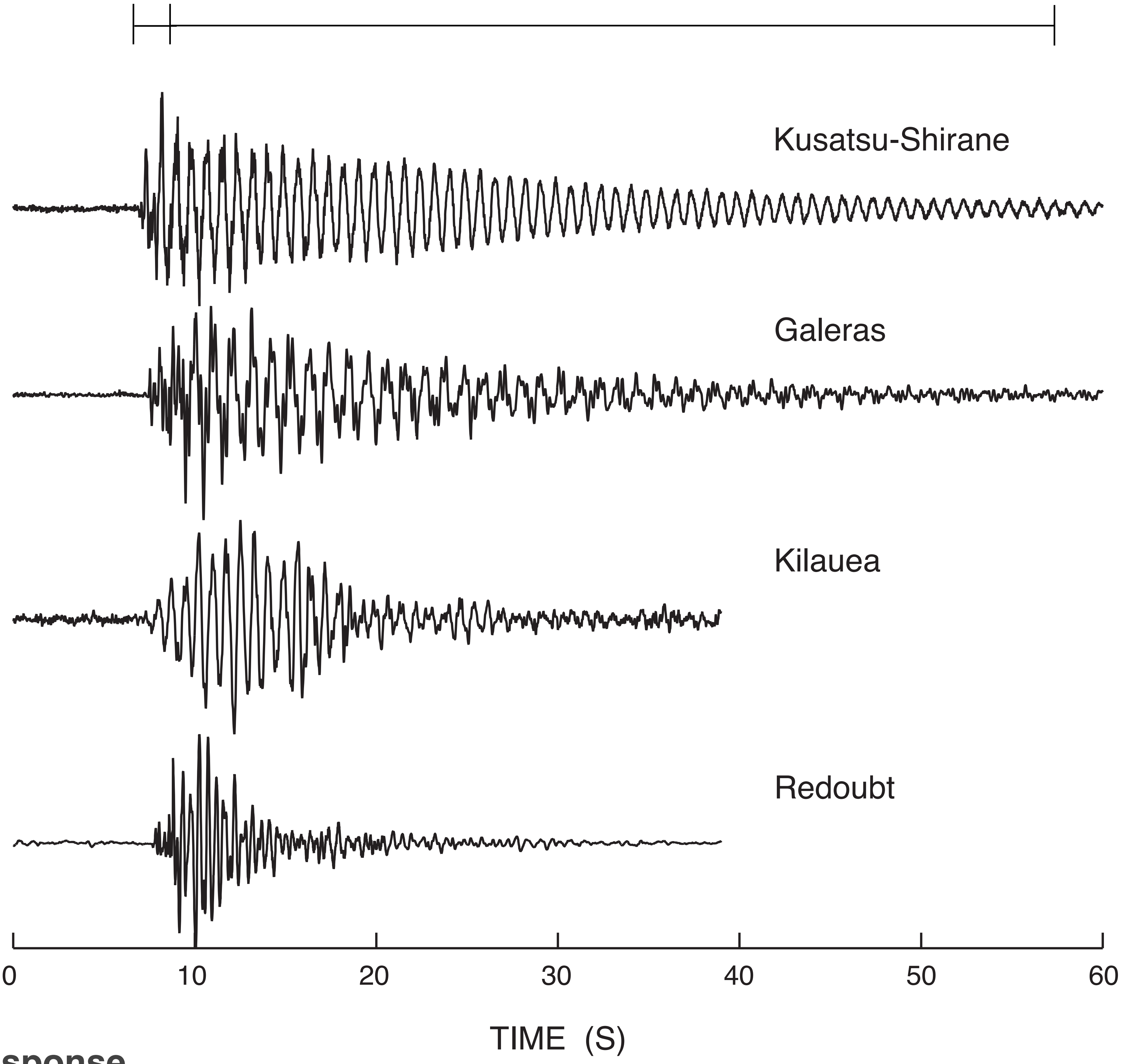
Chouet and Matoza [2013]

LPs: the fluid-driven crack model

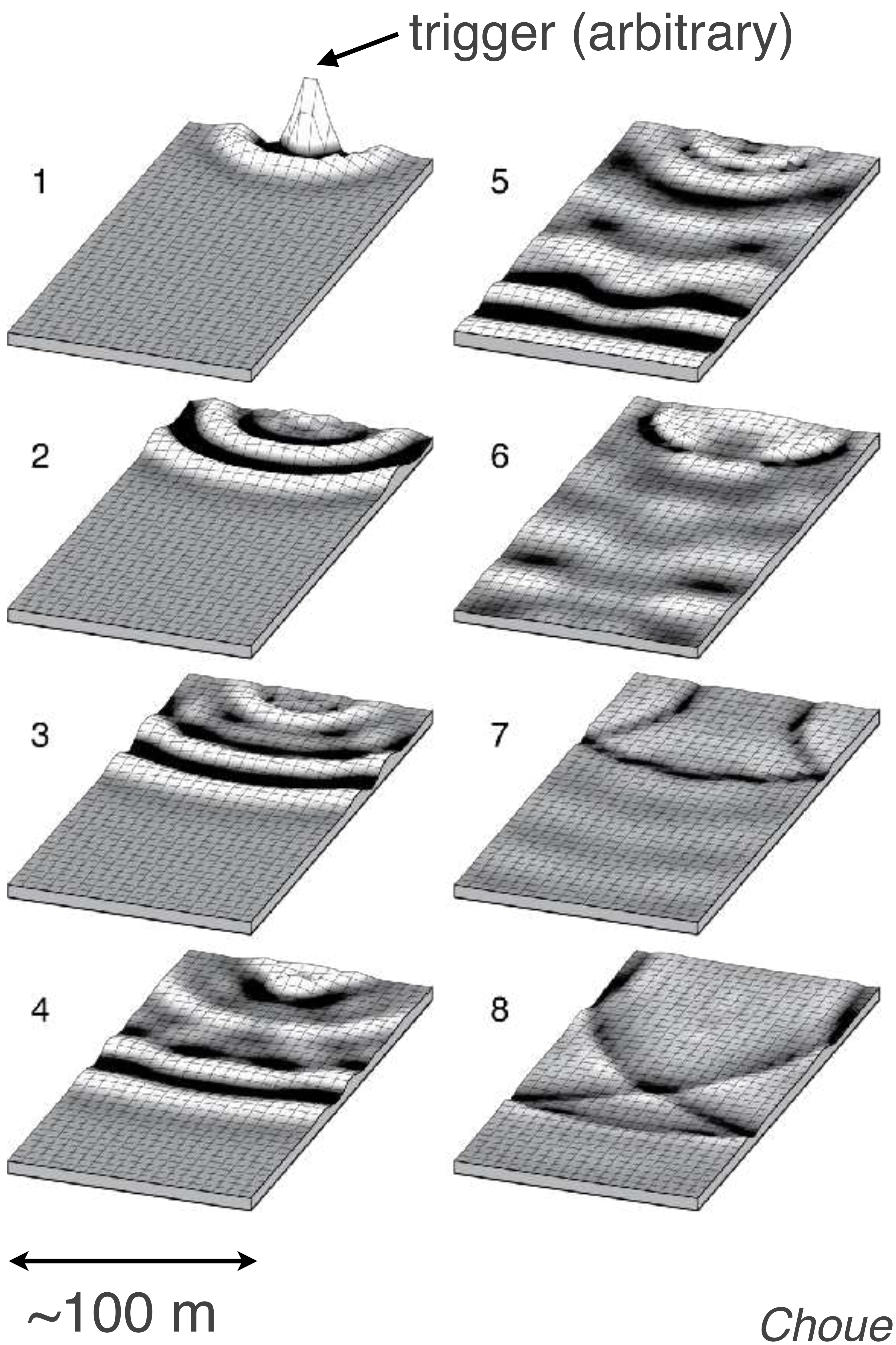
trigger/excitation

fluid response

$$s(t) * l(t)$$



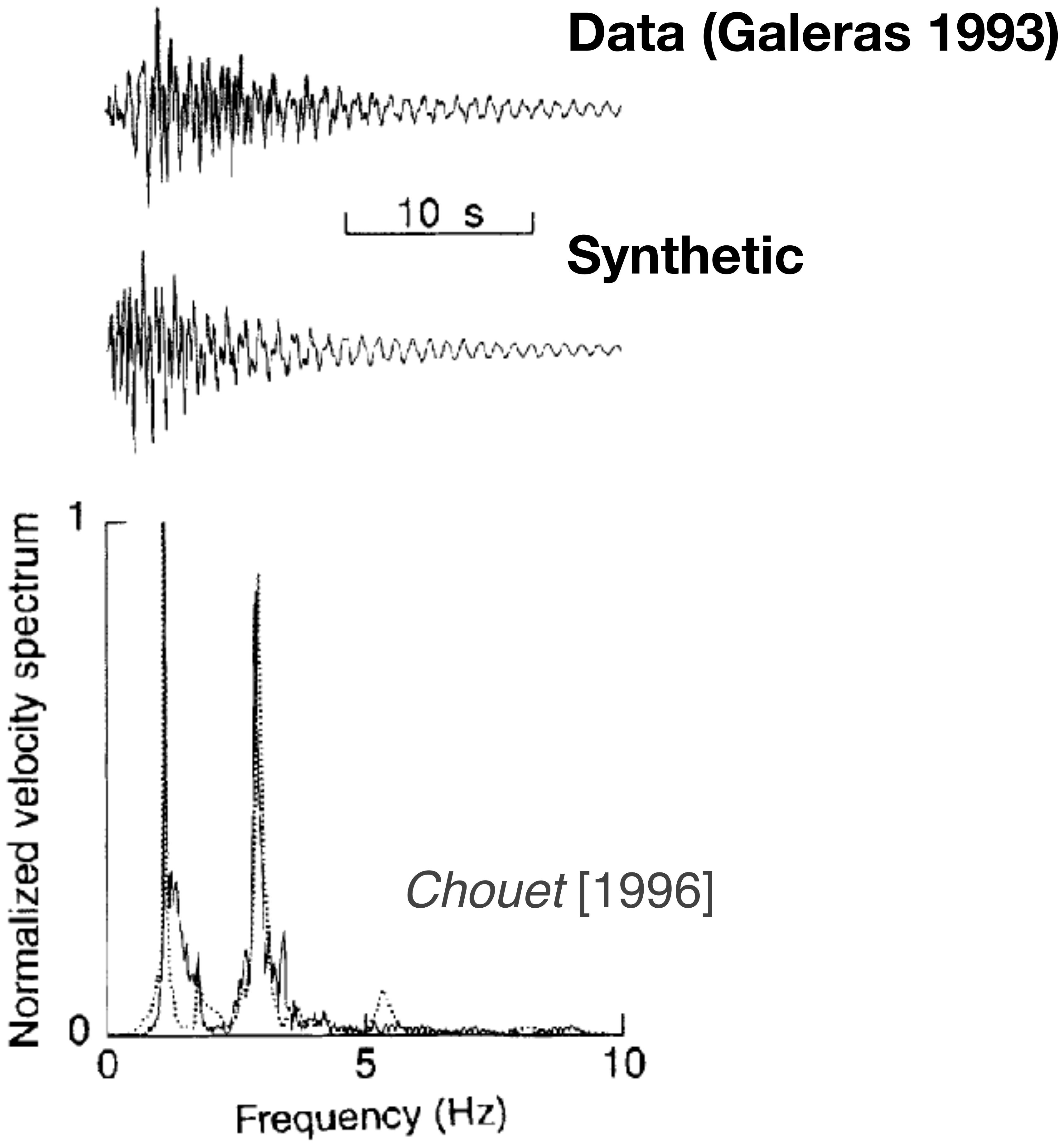
Resonant response
- Fluid-filled crack or conduit
- Bubbly magma, water, steam, dusty gas



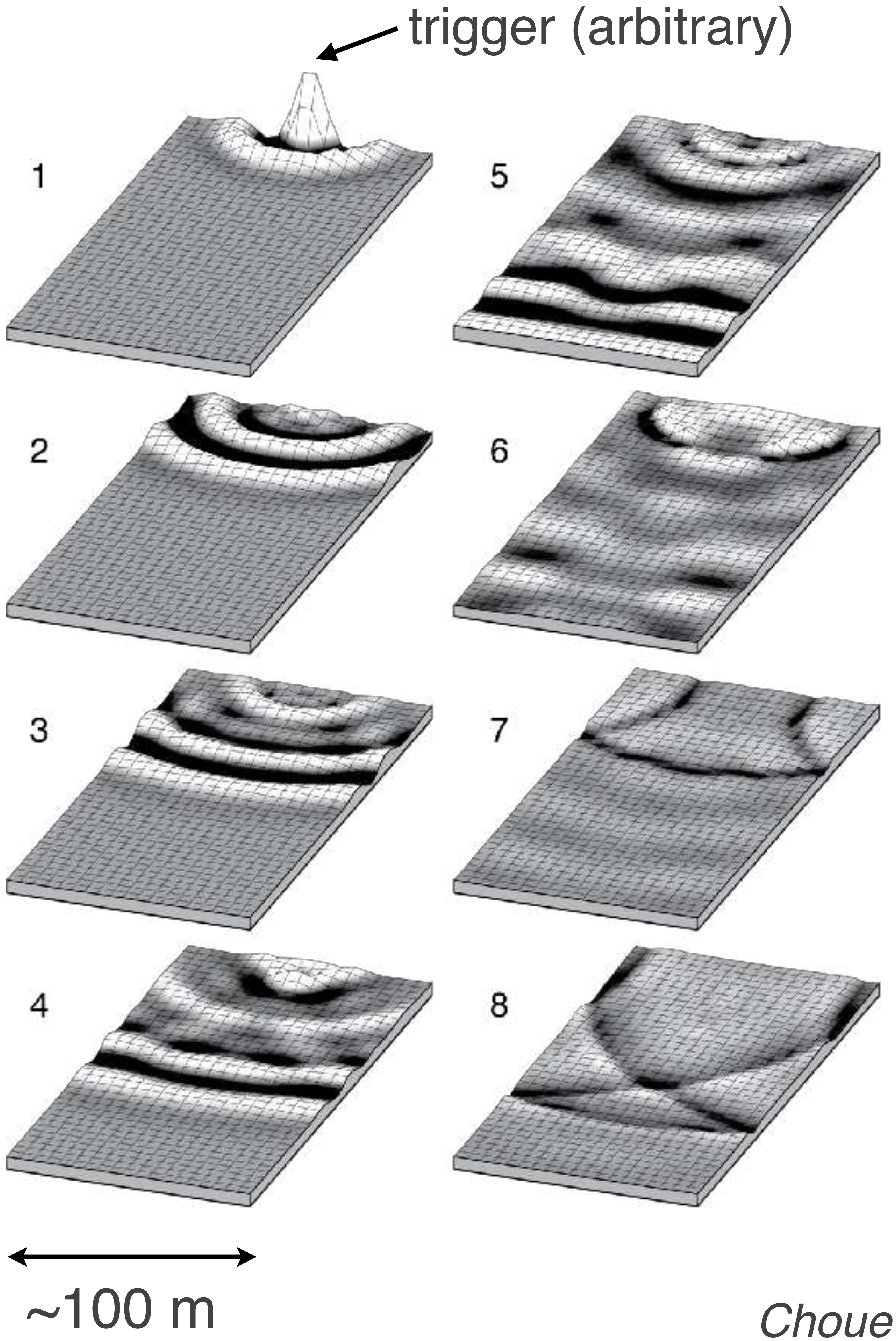
"Crack waves"
Solid-fluid interface waves; fluid-filled crack in elastic solid

Chouet and Matoza [2013]

LPs: the fluid-driven crack model



Chouet [1996]



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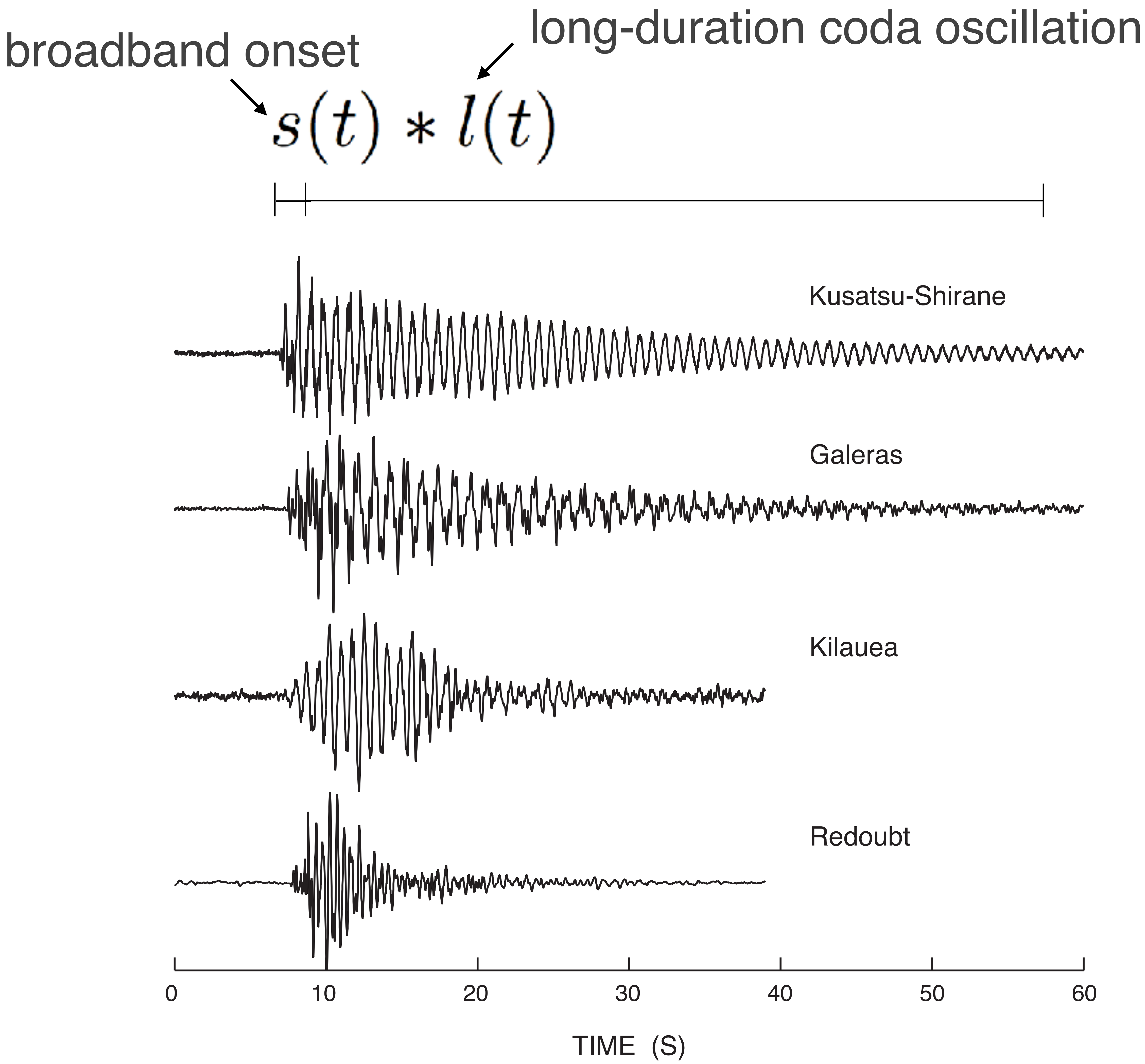


broadband onset

long-duration coda oscillation

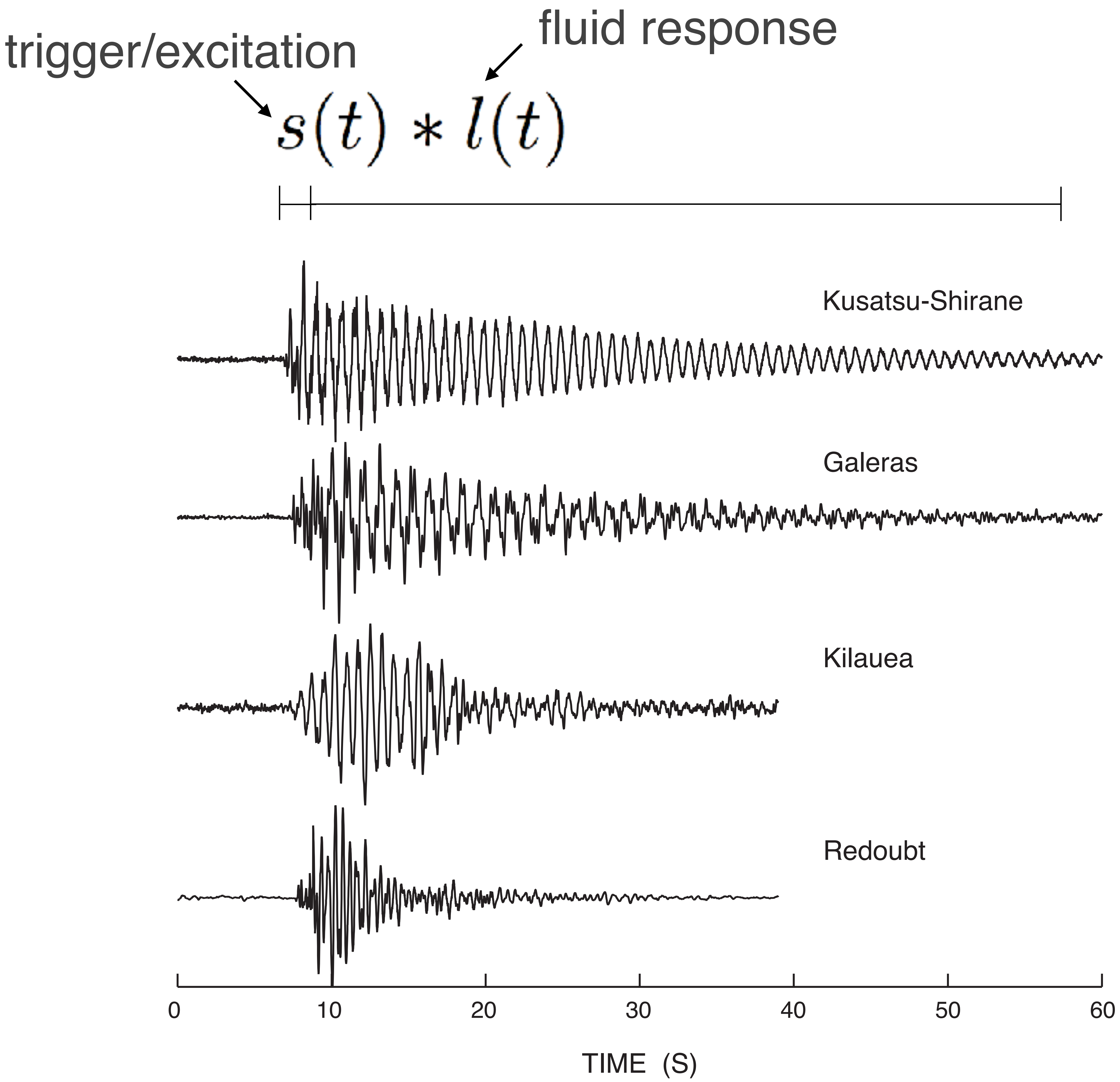
$$s(t) * l(t)$$

The trigger mechanism

- What excites the resonance?
- Impulsive trigger: discrete LP event
- Sustained trigger: tremor

Chouet and Matoza [2013]

LPs: the fluid-driven crack model



trigger/excitation

fluid response

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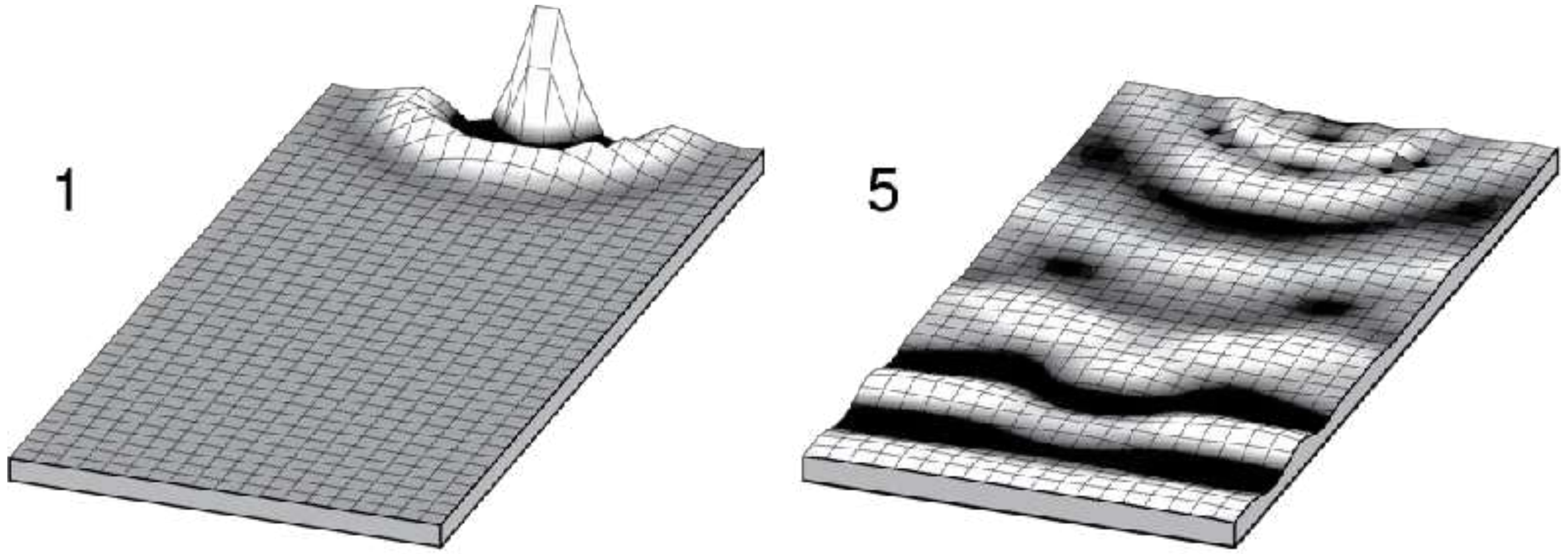
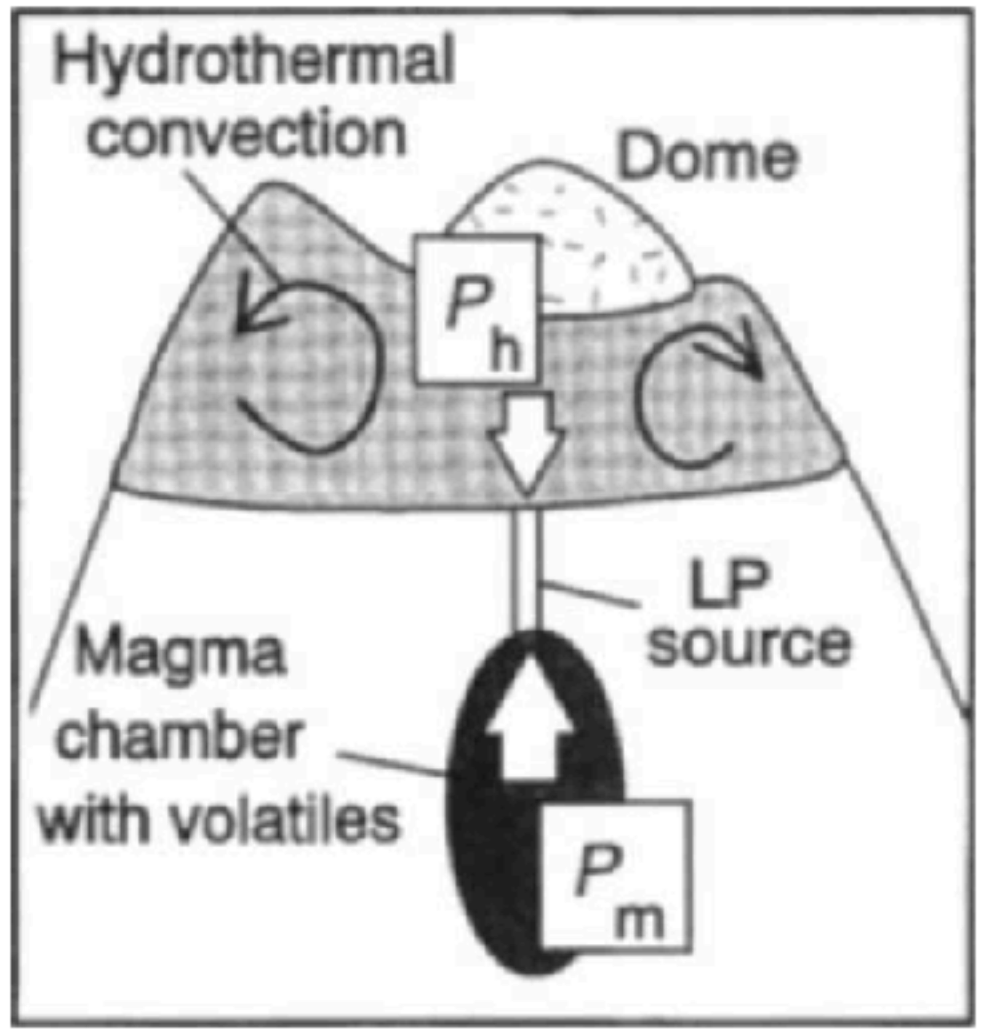


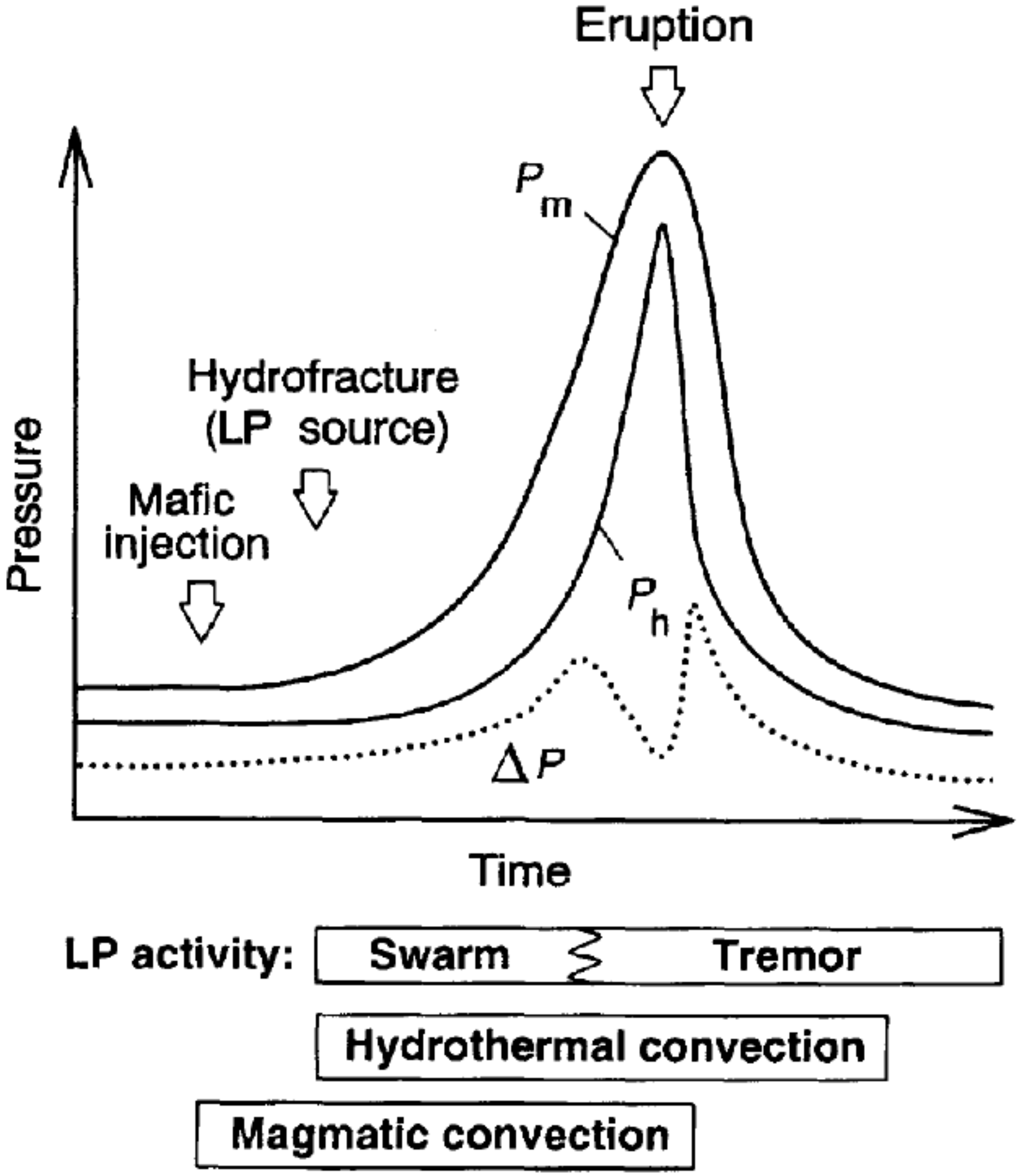
arbitrary pressure step function

Chouet and Matoza [2013]

LPs: the fluid-driven crack model

- Interpretation: shallow LP seismicity results from the pressure-induced disruption of a shallow hydrothermal region
- “can accordingly be a useful indicator of impending eruption”

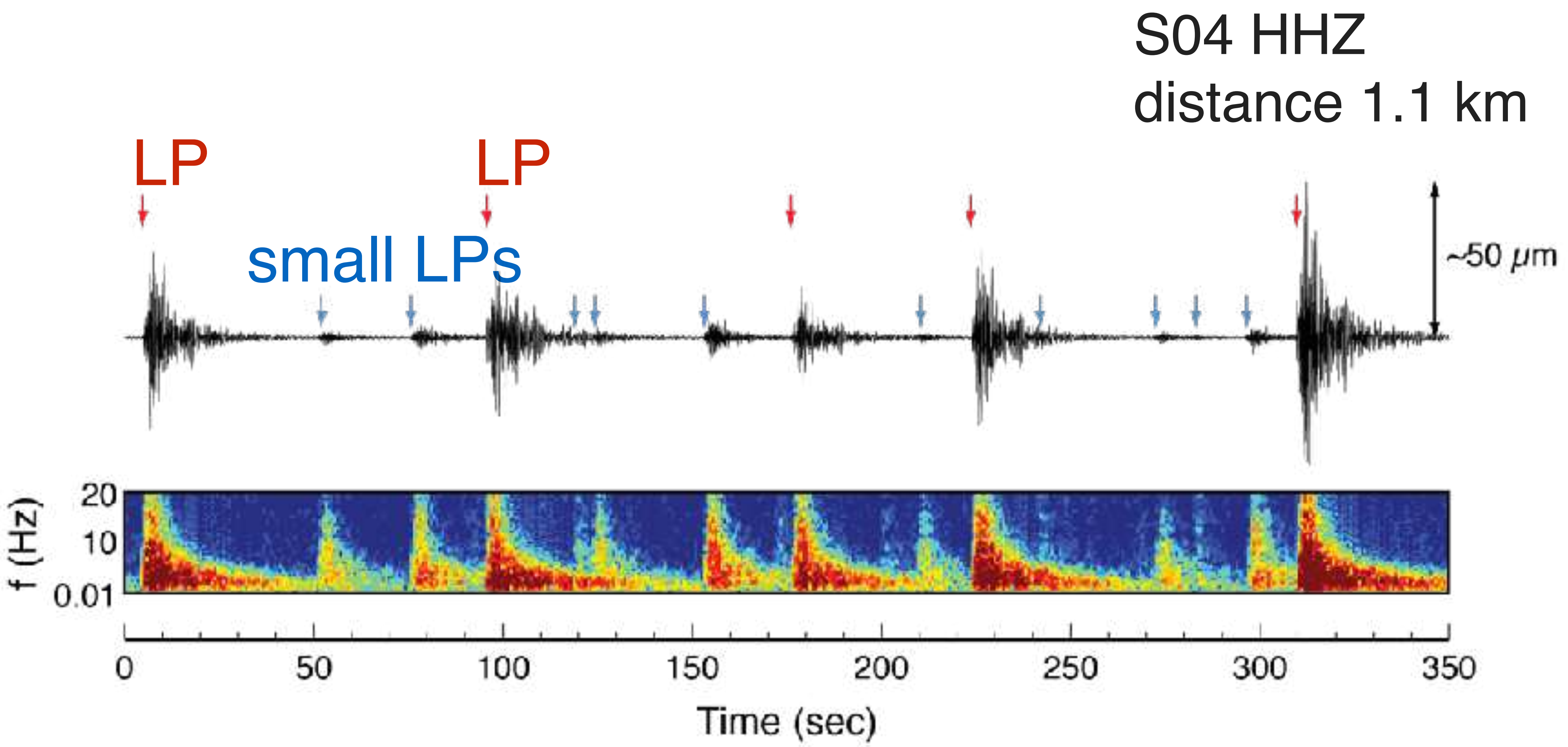




Chouet [1996]

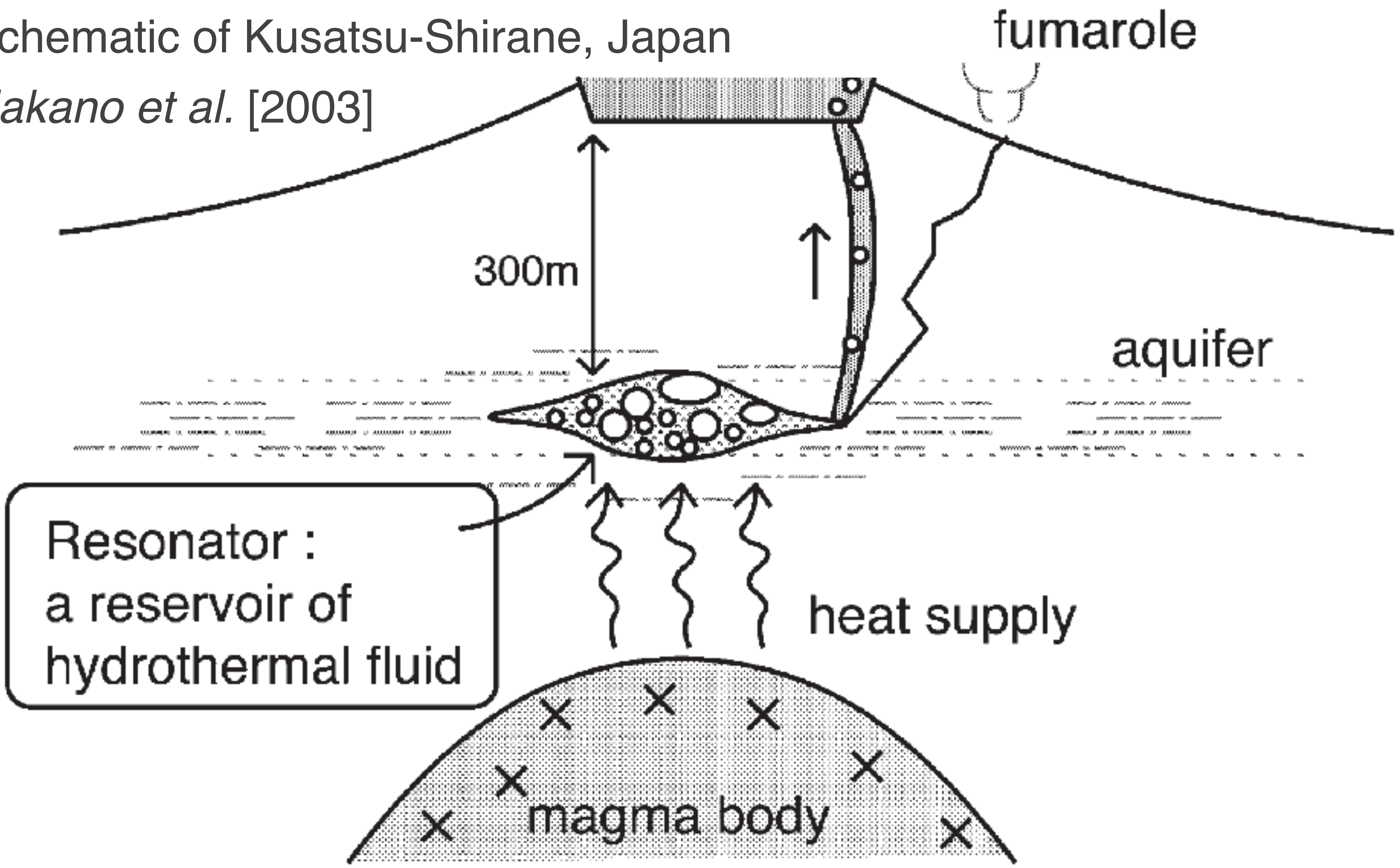
LPs: trigger mechanism in magmatic-hydrothermal systems

Cyclic recharge-collapse of a hydrothermal crack



Schematic of Kusatsu-Shirane, Japan

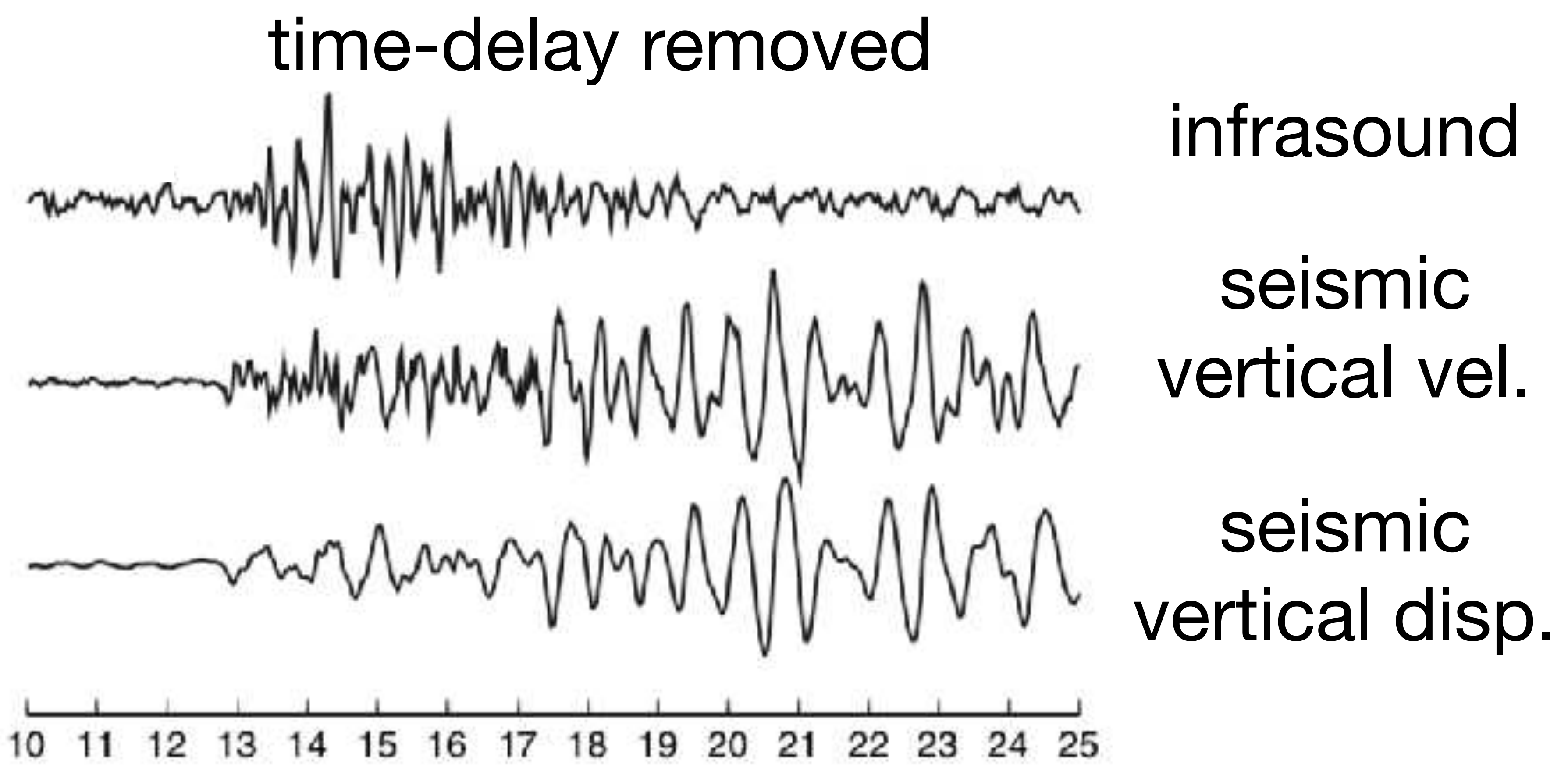
Nakano et al. [2003]

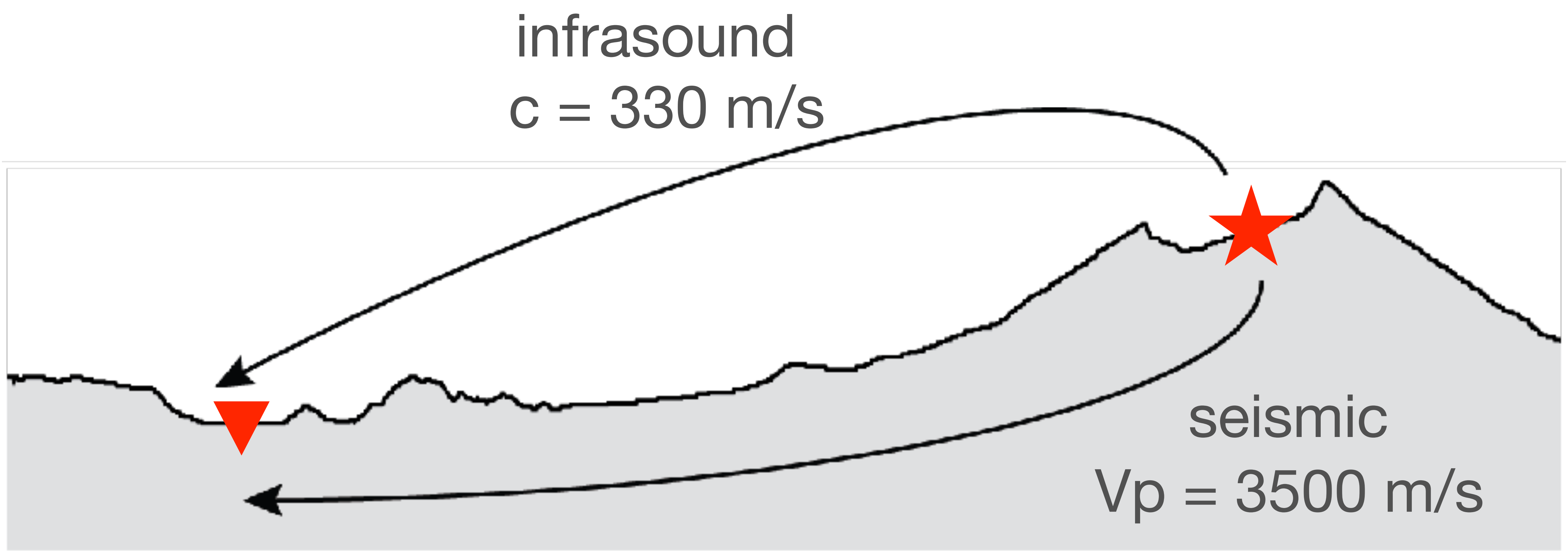


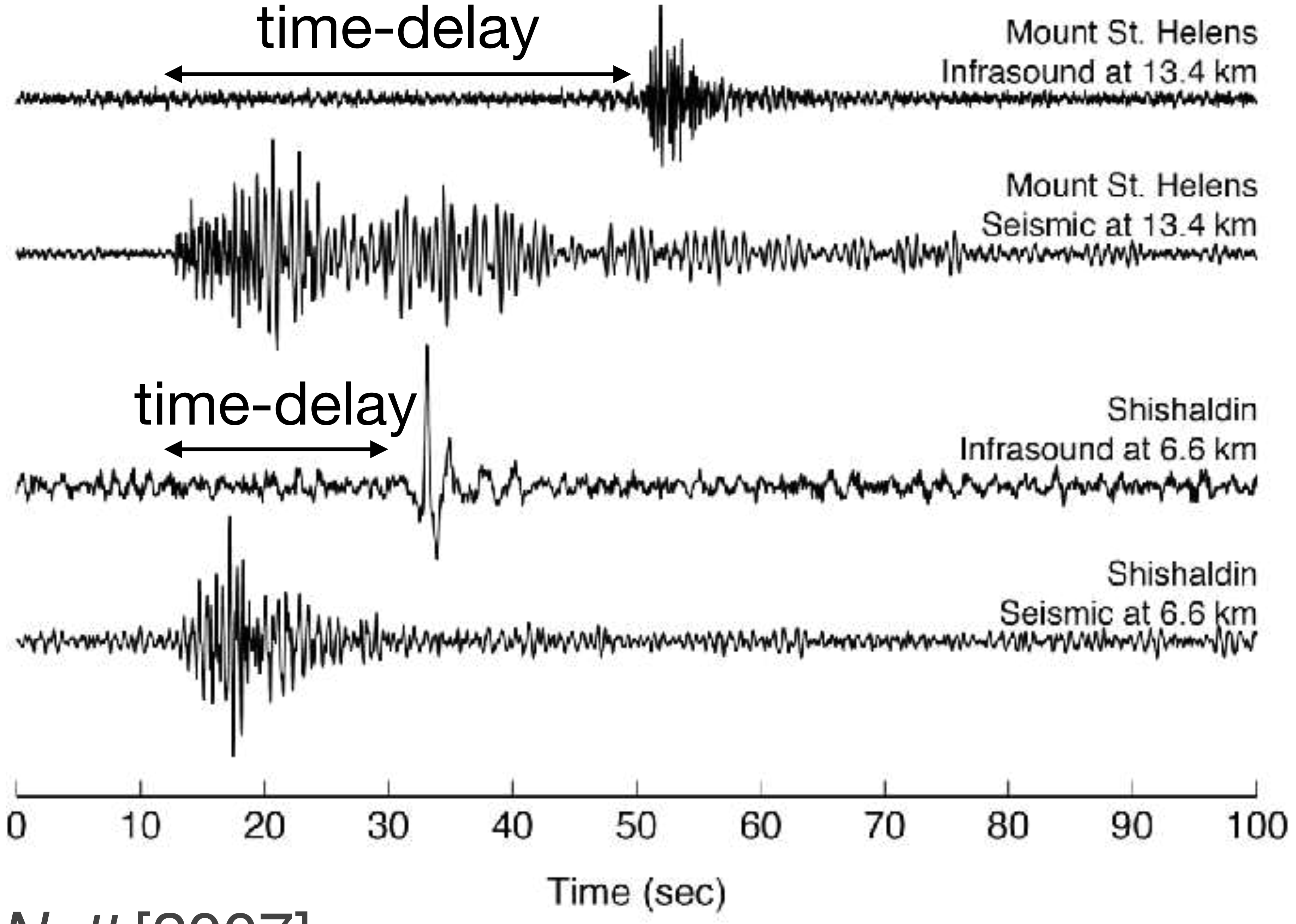
e.g., *Ohminato* [2006]*; Waite et al.* [2008]; *Matoza et al.* [2009]; *Matoza and Chouet* [2010]; *Maeda et al.* [2013]

LPs: infrasonic pulse associated with trigger

- Broadband infrasonic pulse arrives time-delayed from seismic LP arrival
- Captures a record of the “trigger” portion of the LP waveform



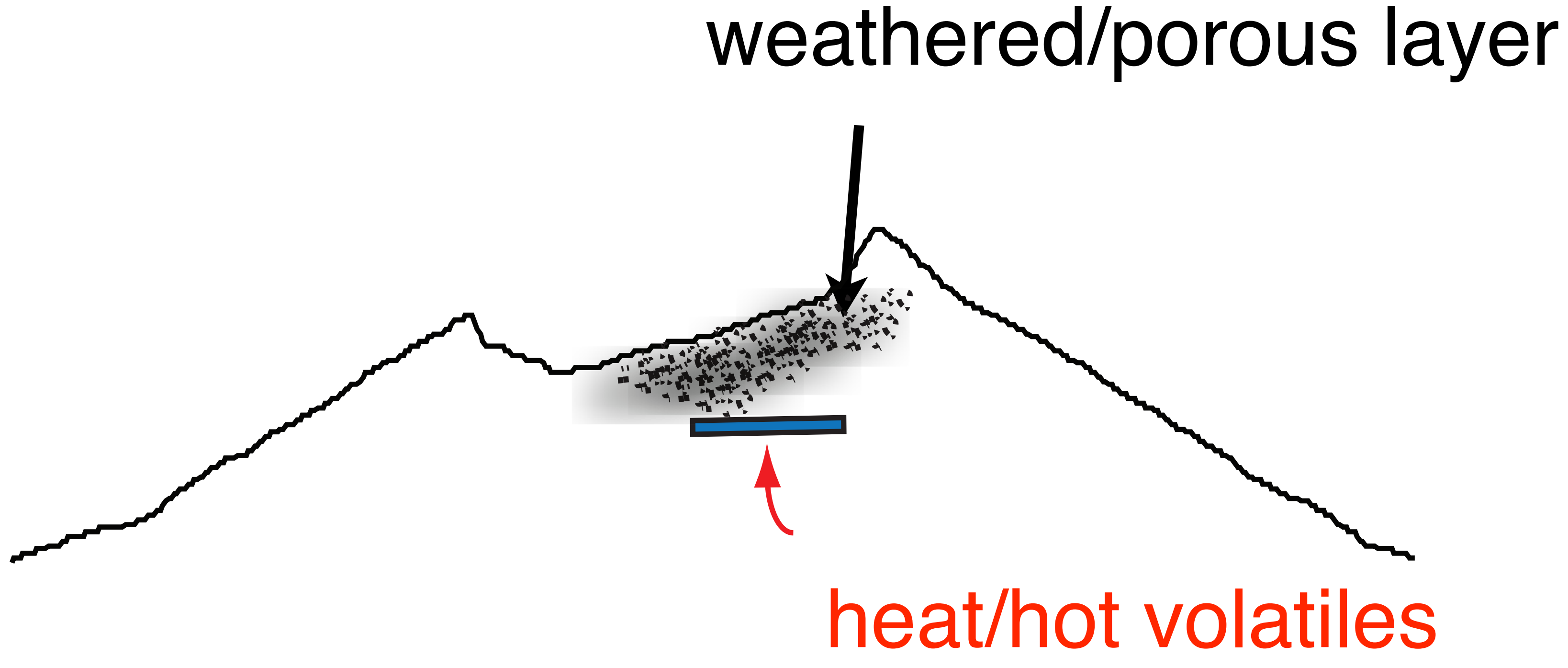




Matoza et al. [2009]; see also *Yamasato* [1998]; *Petersen and McNutt* [2007]

LPs: infrasonic pulse associated with trigger

- Heating from magmatic activity
- Pressure rises in hydrothermal crack



Waite et al. [2008]; *Matoza et al.* [2009]

LPs: infrasonic pulse associated with trigger

- Heating from magmatic activity
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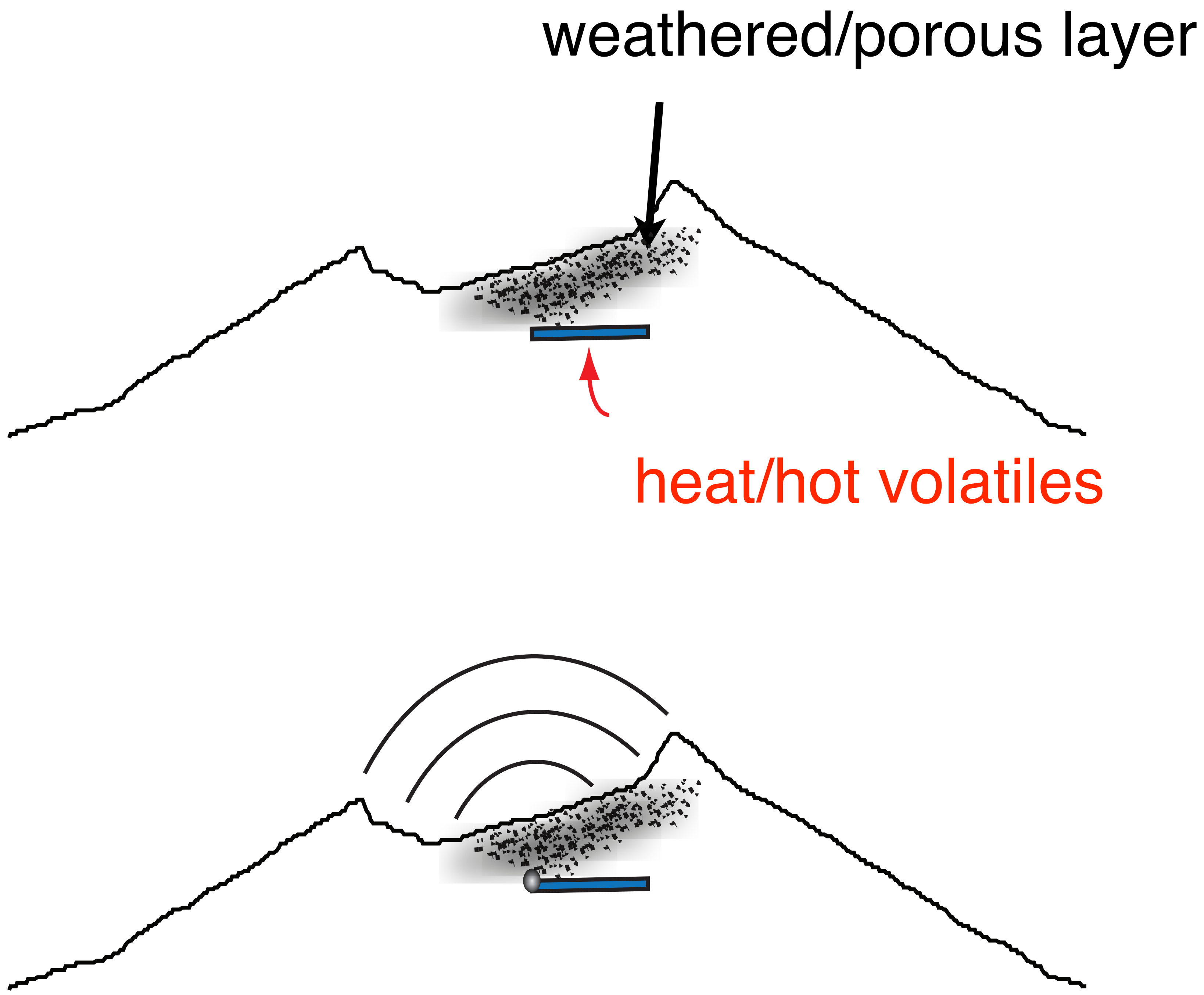
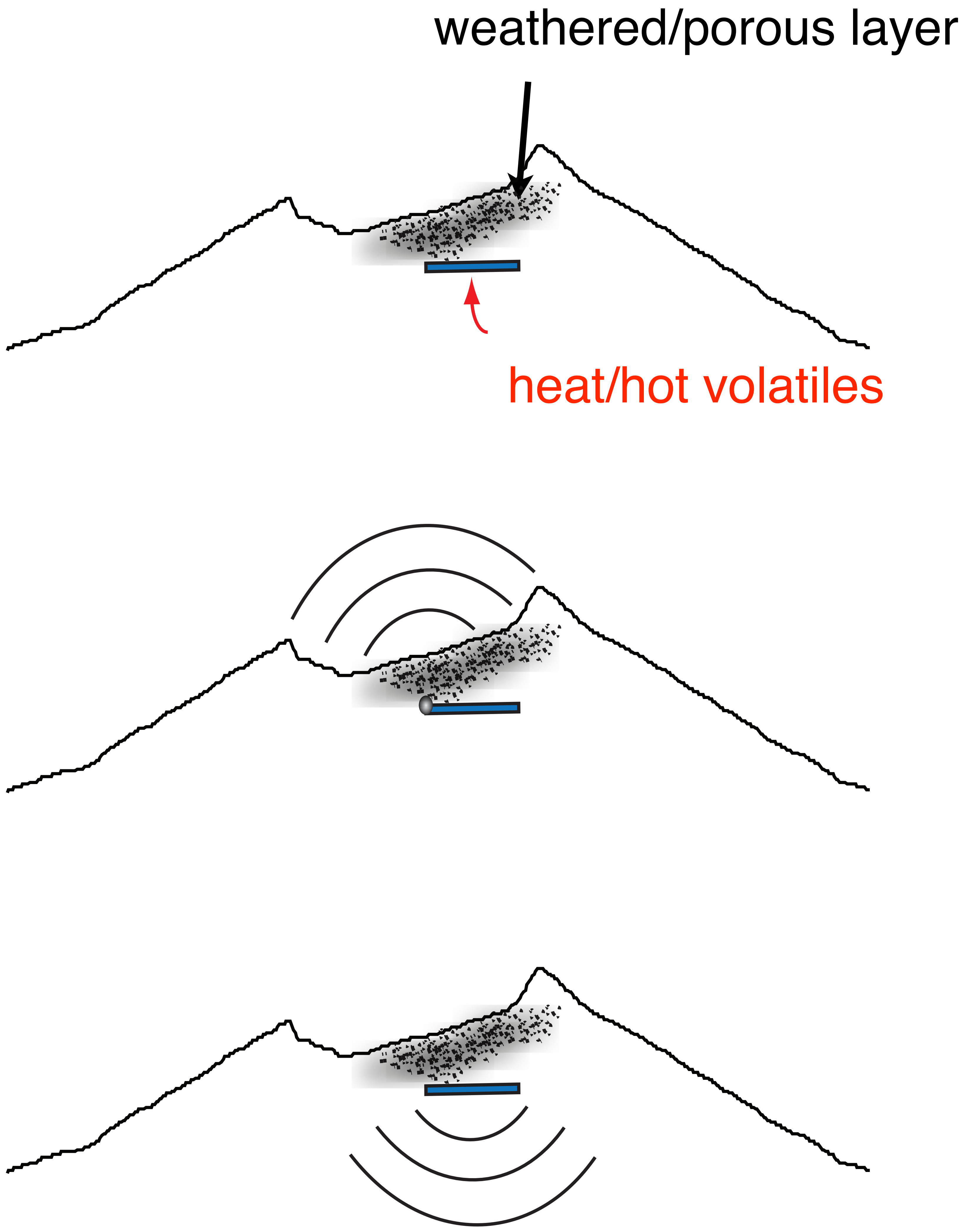
- Reach threshold for rupture of “valve” sealing crack
- Pressure release: infrasound signal



Waite et al. [2008]; *Matoza et al.* [2009]

LPs: infrasonic pulse associated with trigger

- Heating from magmatic activity
- Pressure rises in hydrothermal crack
- Reach threshold for rupture of “valve” sealing crack
- Pressure release: infrasound signal
- Collapse of crack: imaged in seismic waveform inversion
- Resonance of crack: LP coda
- Re-sealing of “valve”, cyclic recharge, periodic “drumbeats”

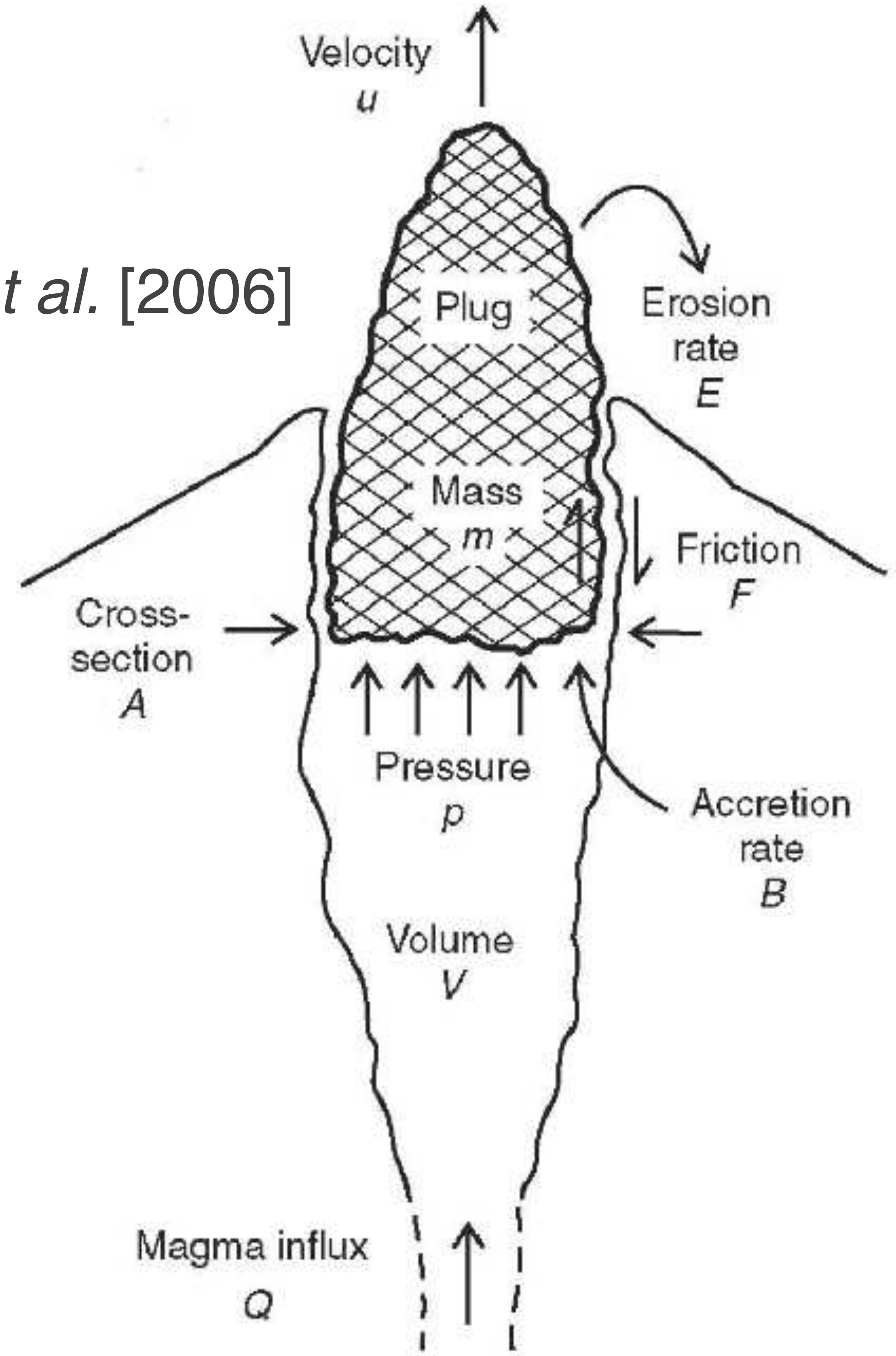


Waite et al. [2008]; *Matoza et al.* [2009]

Mount St. Helens 2004–2008 eruption

Solid extrusion, plug stick-slip

Iverson et al. [2006]



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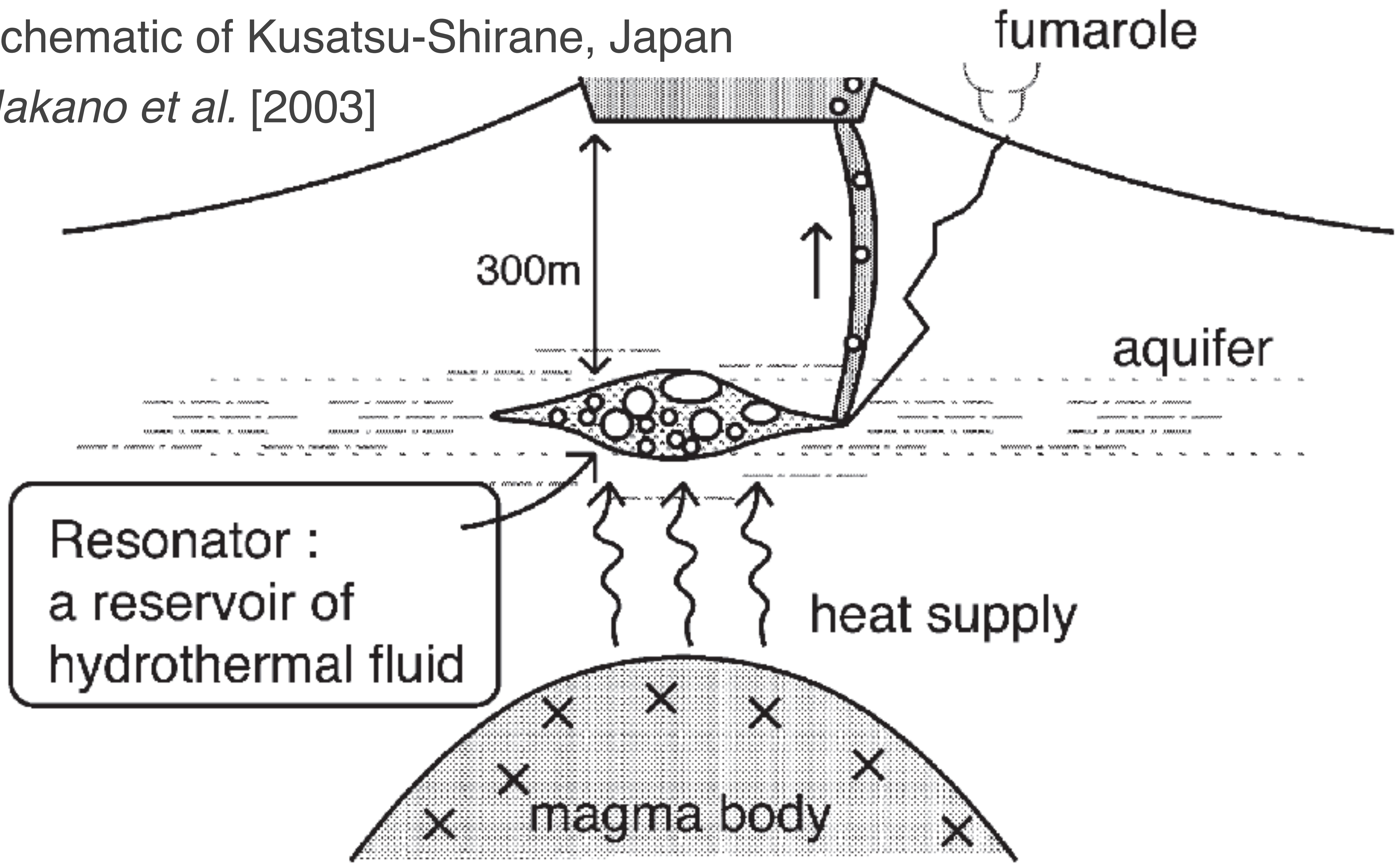

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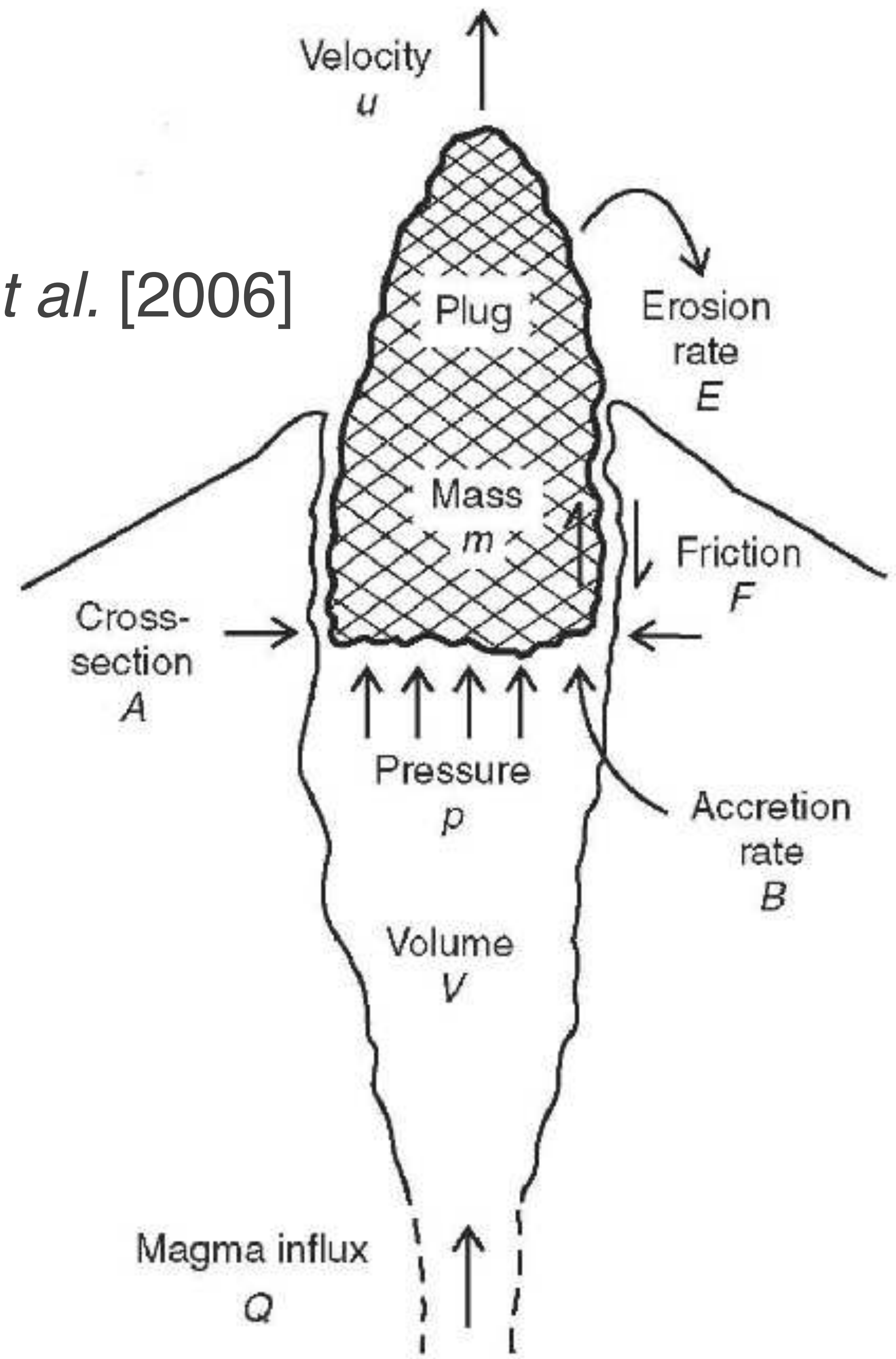


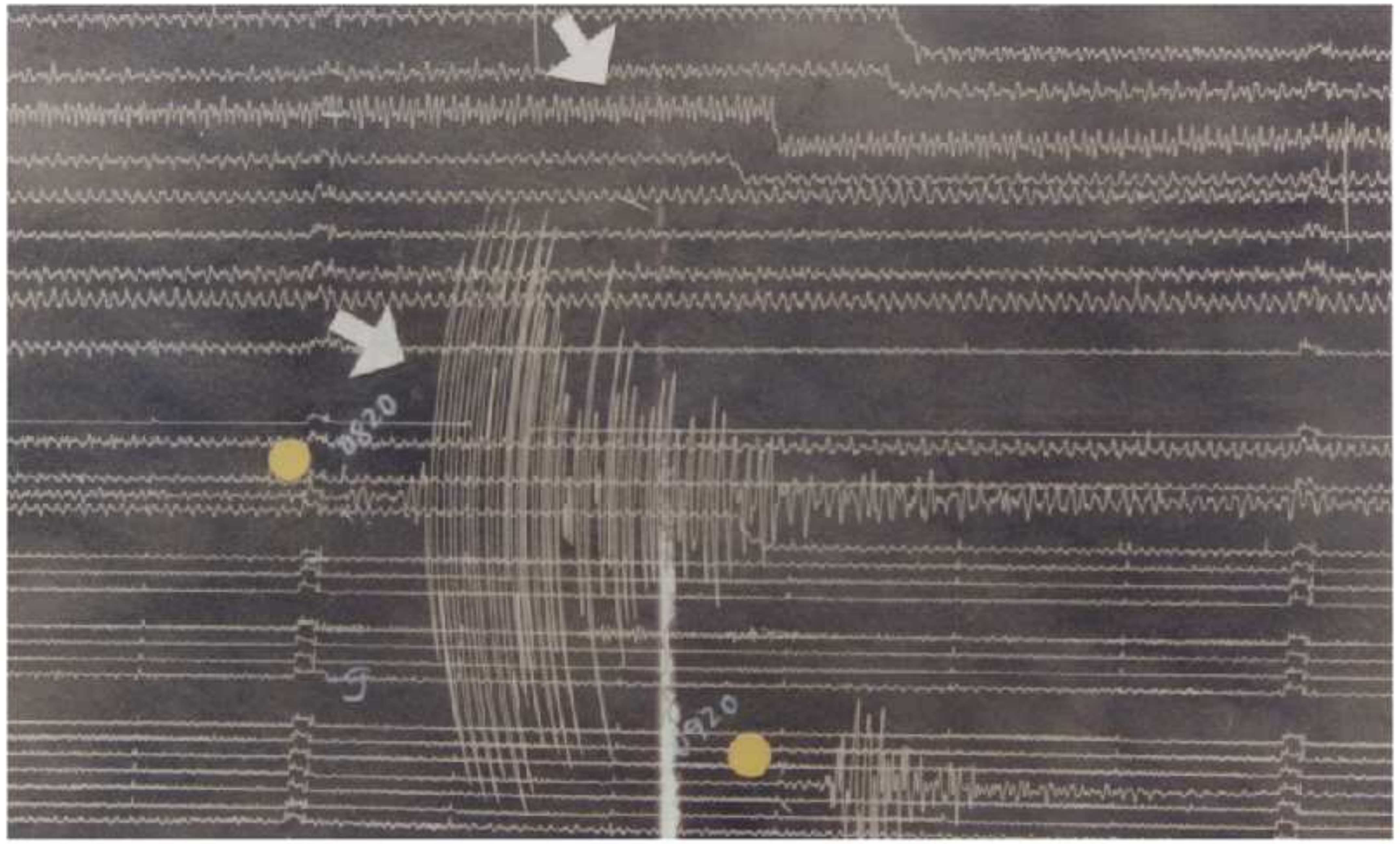
Slickensides, soft gauge 1-3 m thick

J.S. Pallister, USGS

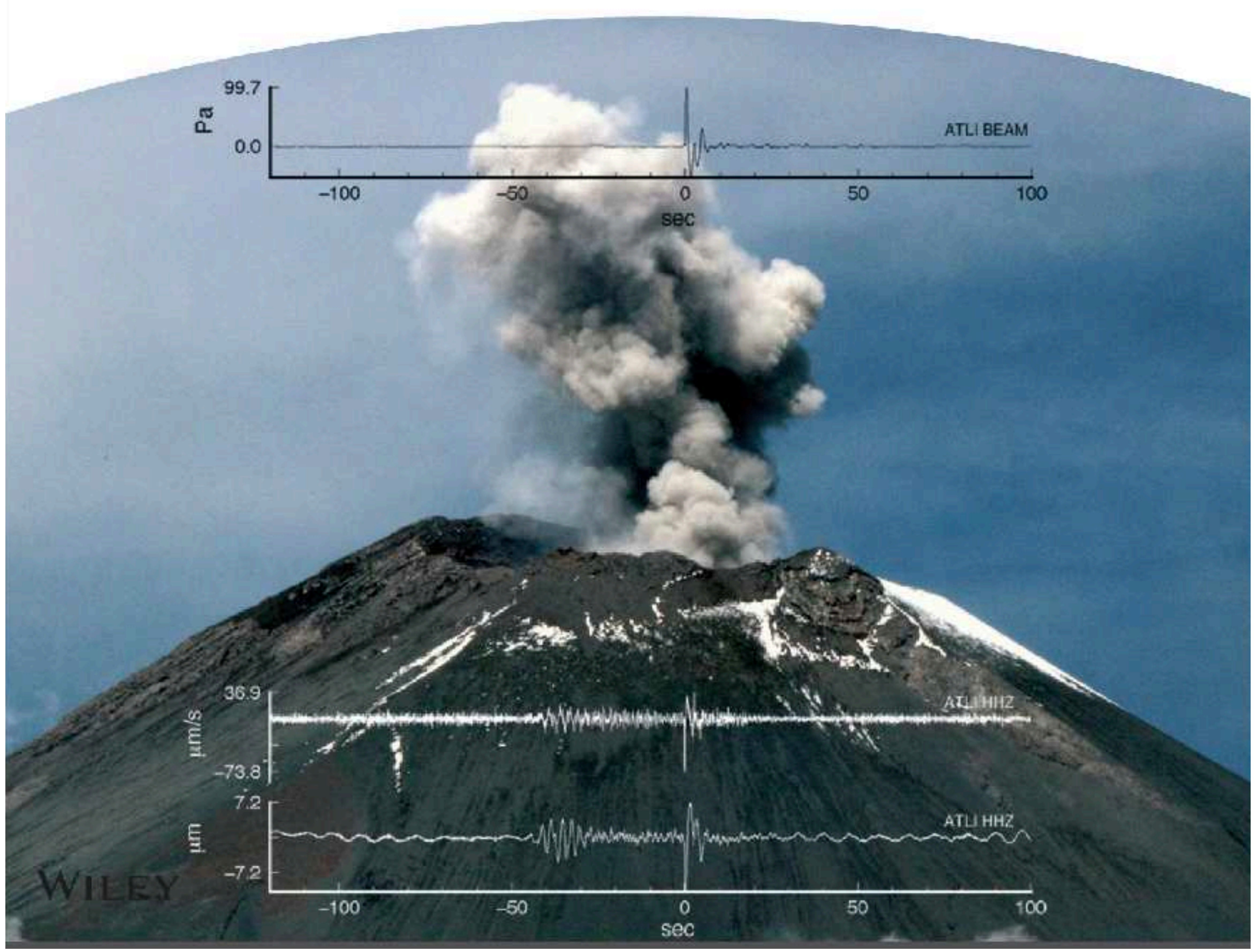
e.g., *Iverson et al.* [2006]; *Harrington and Brodsky* [2007];
Iverson [2008]; *Kendrick et al.* [2014]

Magmatic degassing

Galeras, Colombia, 1991



Popocatépetl, Mexico, 2017

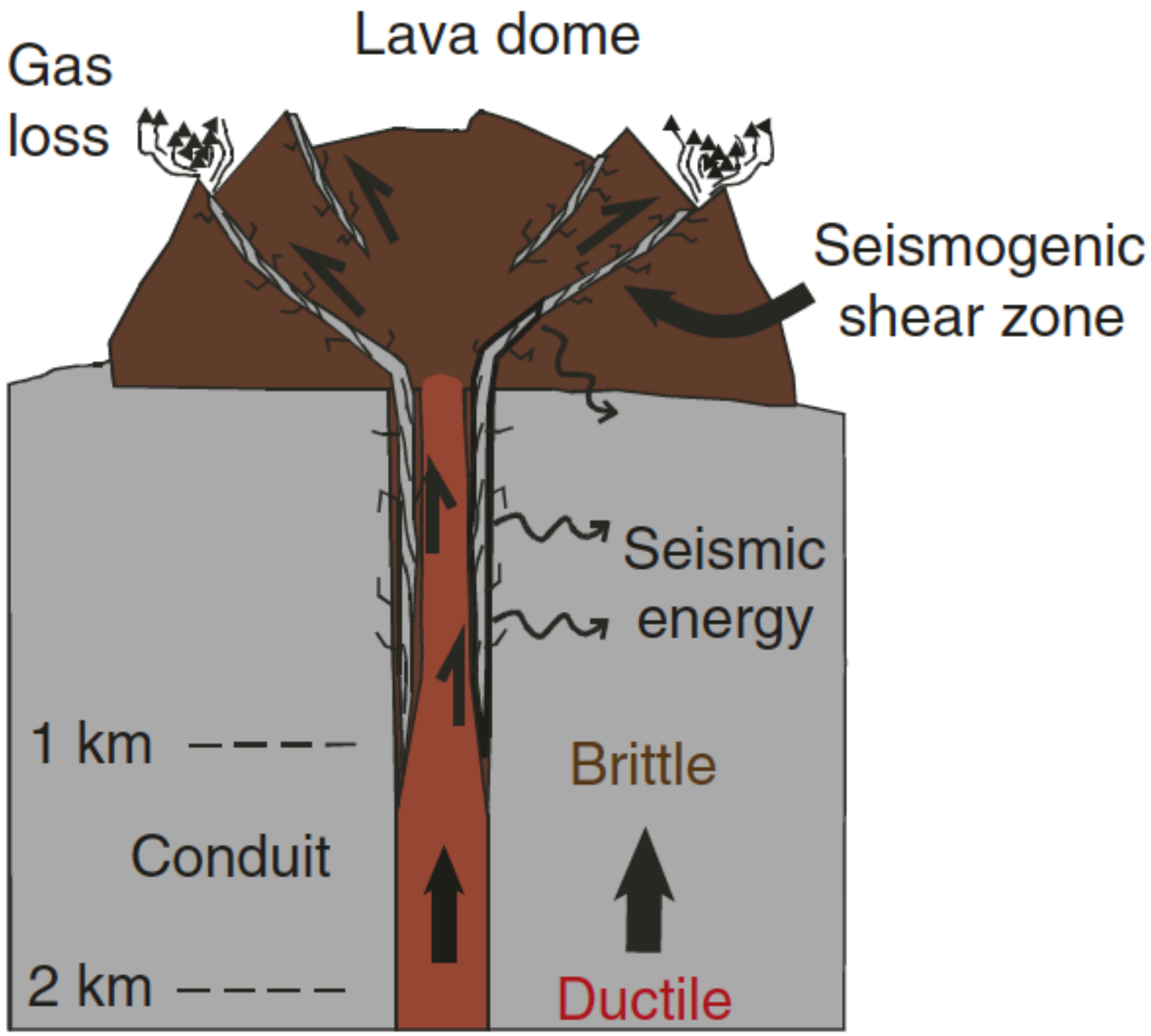


Matoza et al. [2019]

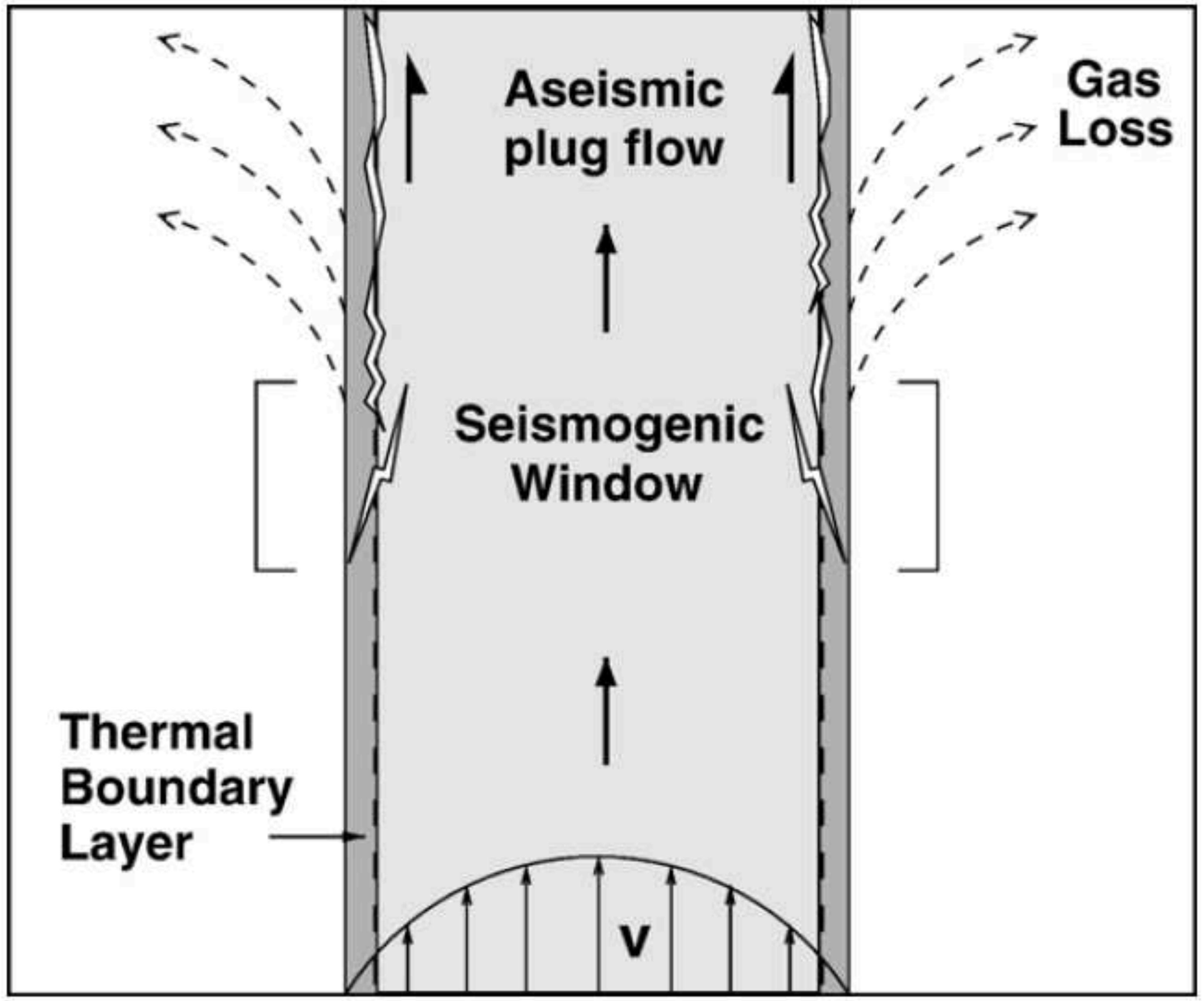
[*Gil Cruz and Chouet*, 1997]

Brittle failure of melt

- Brittle failure of melt in the glass transition
- Multiplets: repeated fracture and heal or ascent through a limited seismogenic window



Tuffen et al. [2008]



Neuberg et al. [2006]

Seismo-acoustic signals associated with volcanic processes III

Robin S. Matoza

Department of Earth Science; University of California, Santa Barbara

image: Tyson Fisher

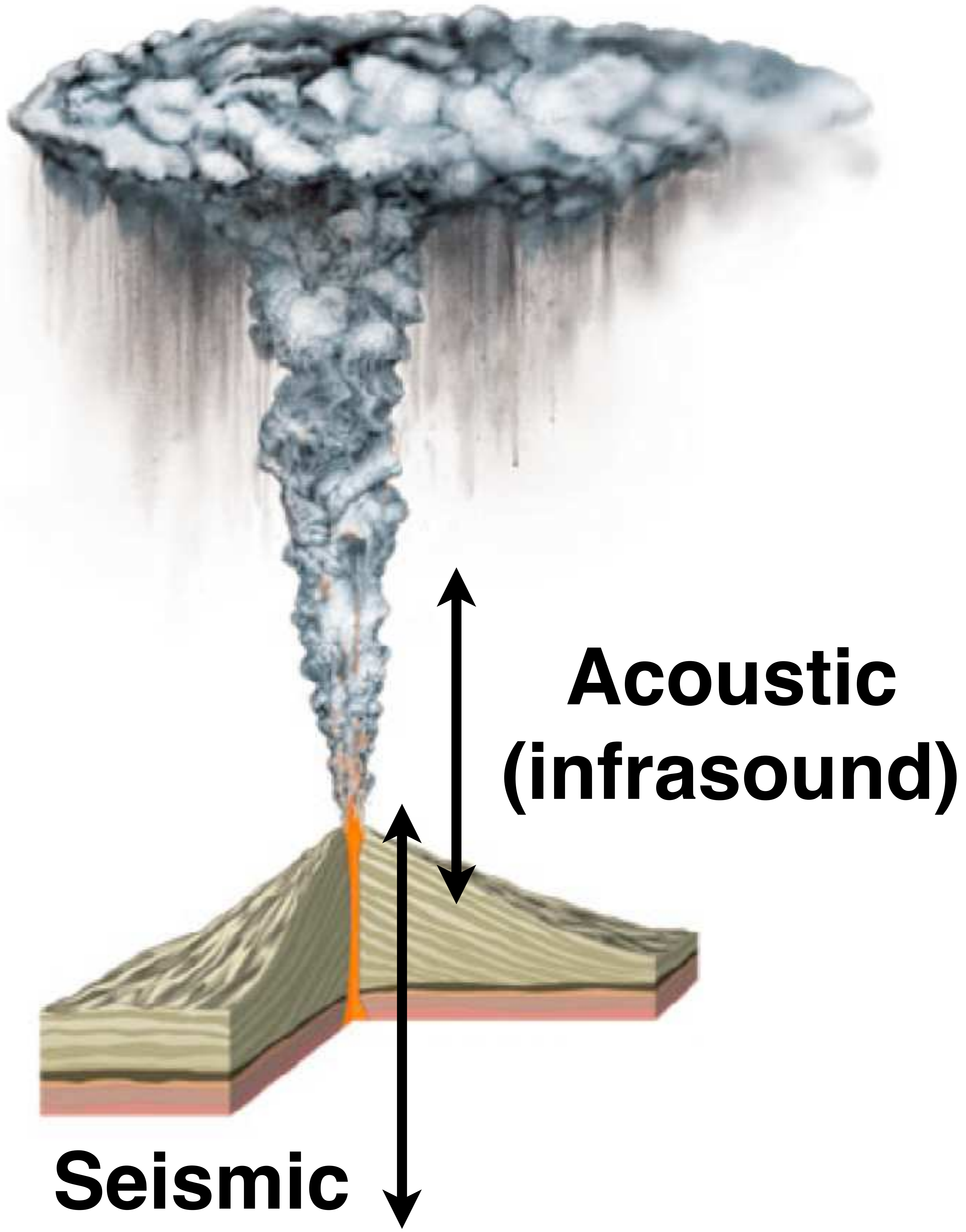
D. Fee

A. Austin

N. Key

A. Austin

Volcano seismology and acoustics



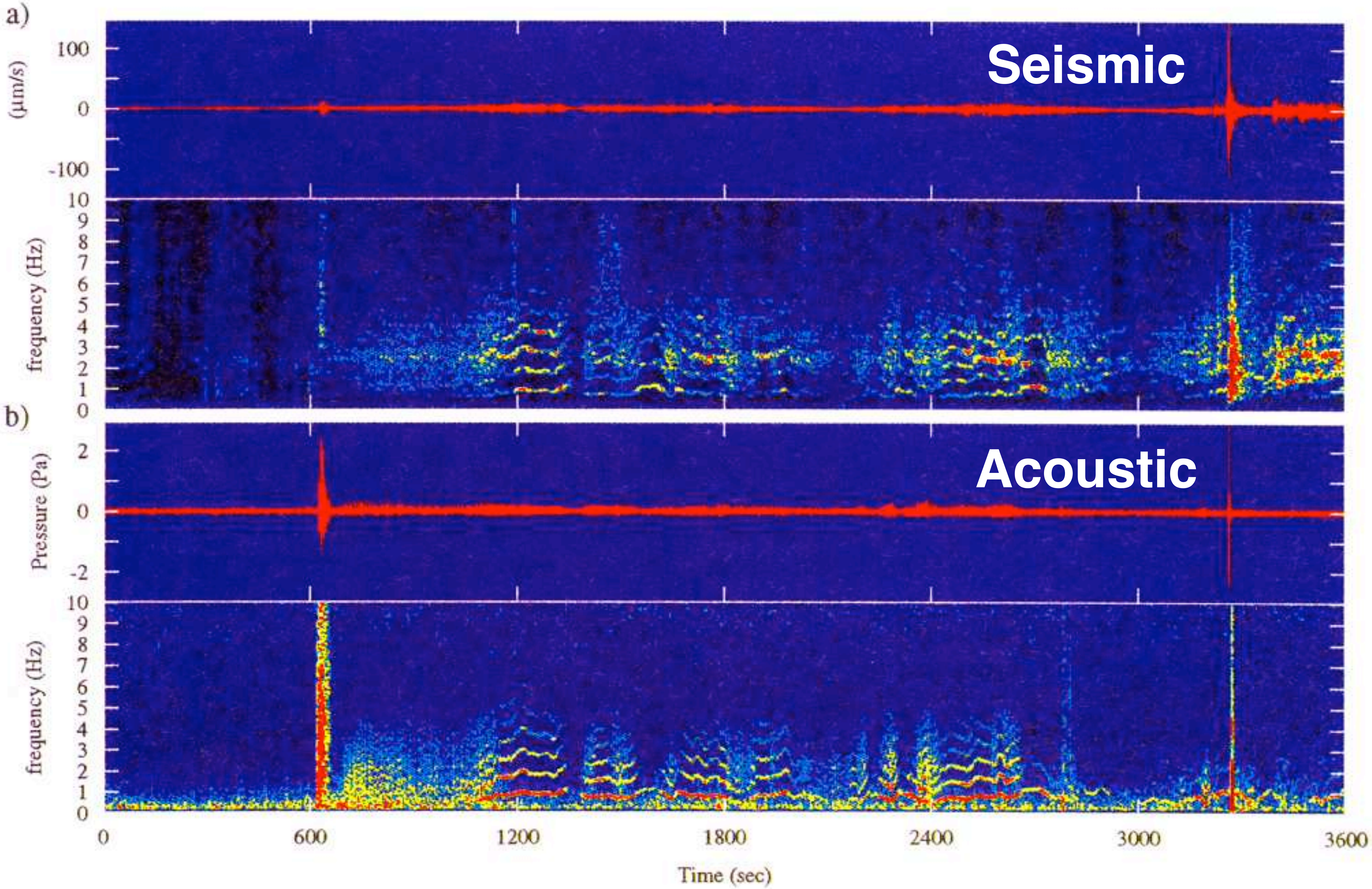
Acoustic

- Atmospheric acoustics (infrasound): ~0.01-20 Hz
- Variety of shallow and subaerial sources
- Explosive volcanism: powerful signals

Seismic

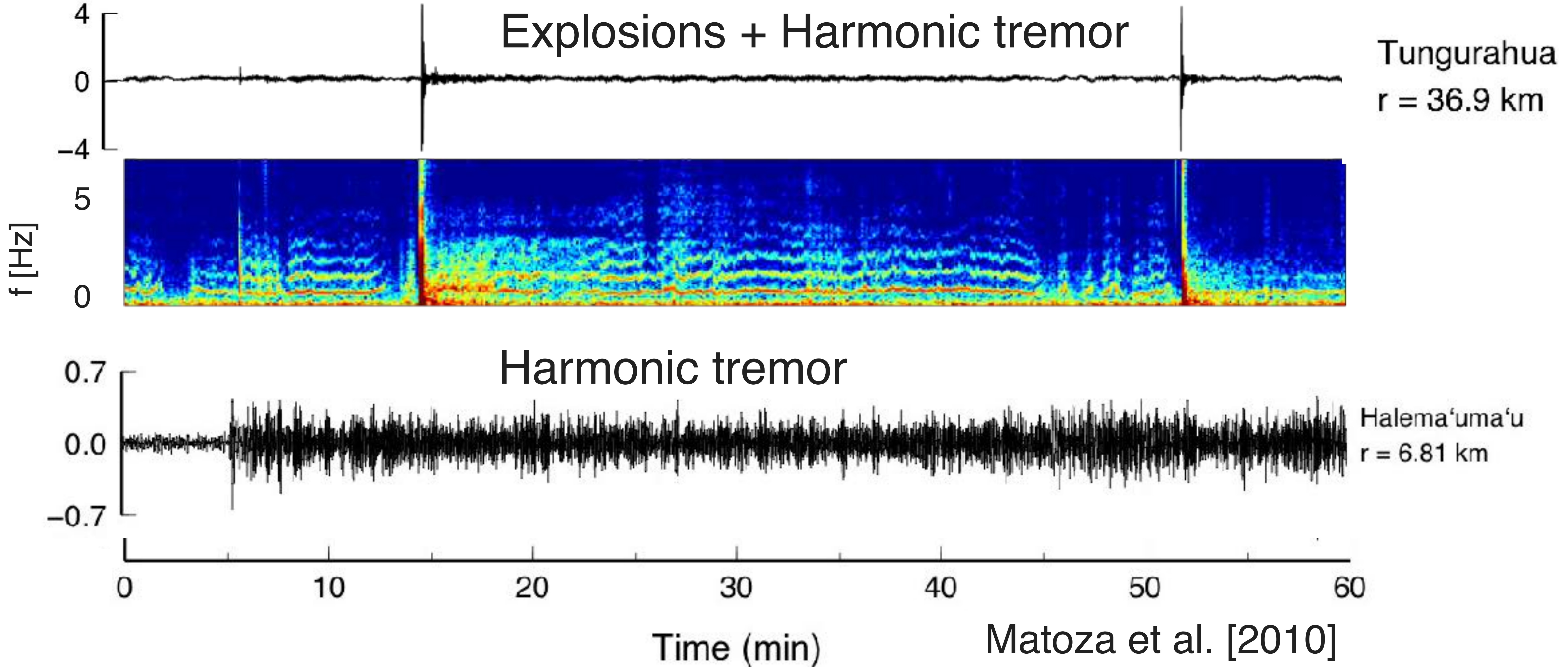
- Migration of fluid from mantle depths to surface
- Faulting & fluid transport in the solid earth
- Limited propagation < few hundred km

Harmomic and monotonic tremor

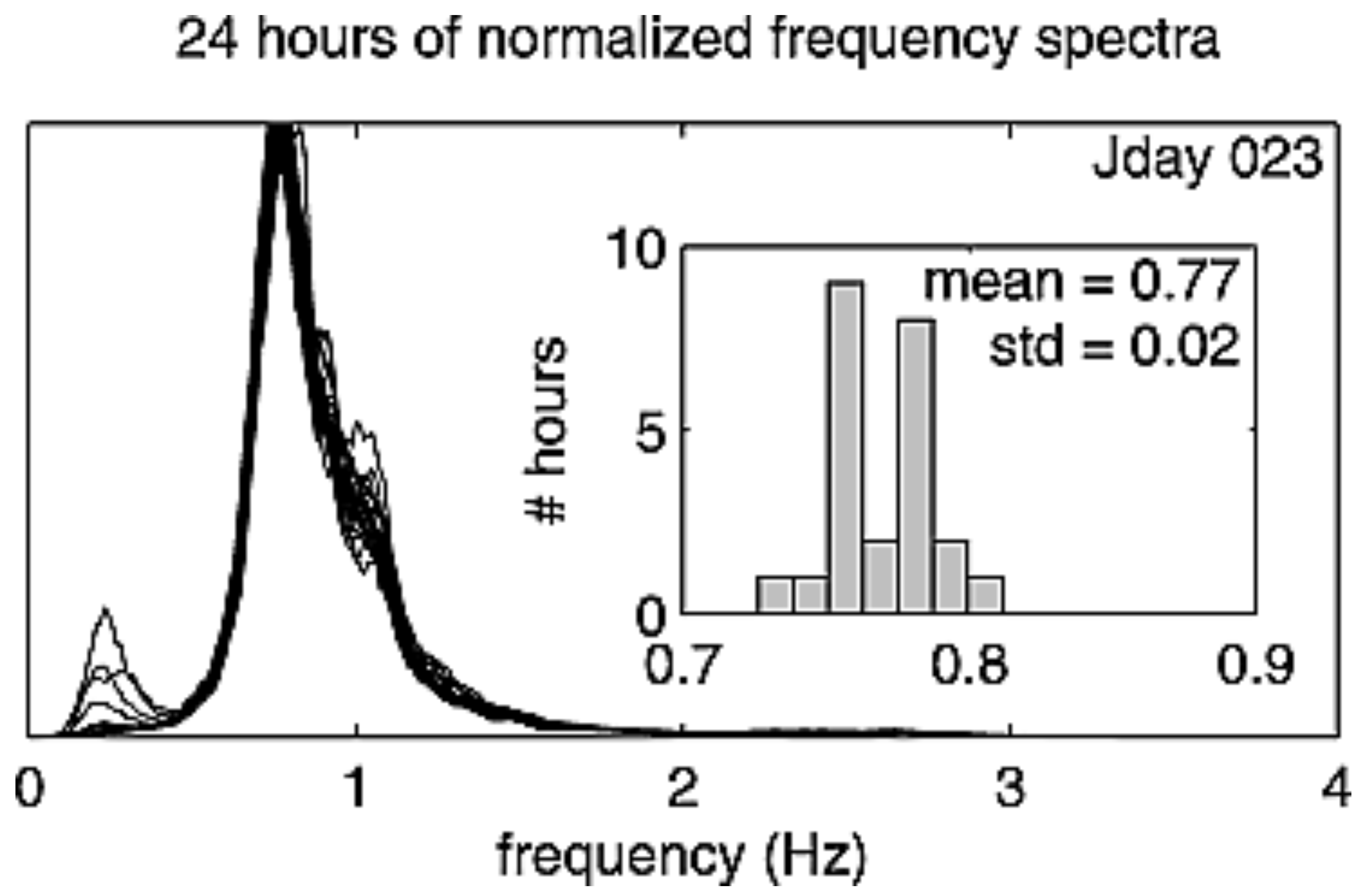


Arenal, Costa Rica, Garces et al. [1998]

Harmomic and monotonic tremor



Matoza et al. [2010]



Tungurahua
image: El Comercio / Ecuador / GDA

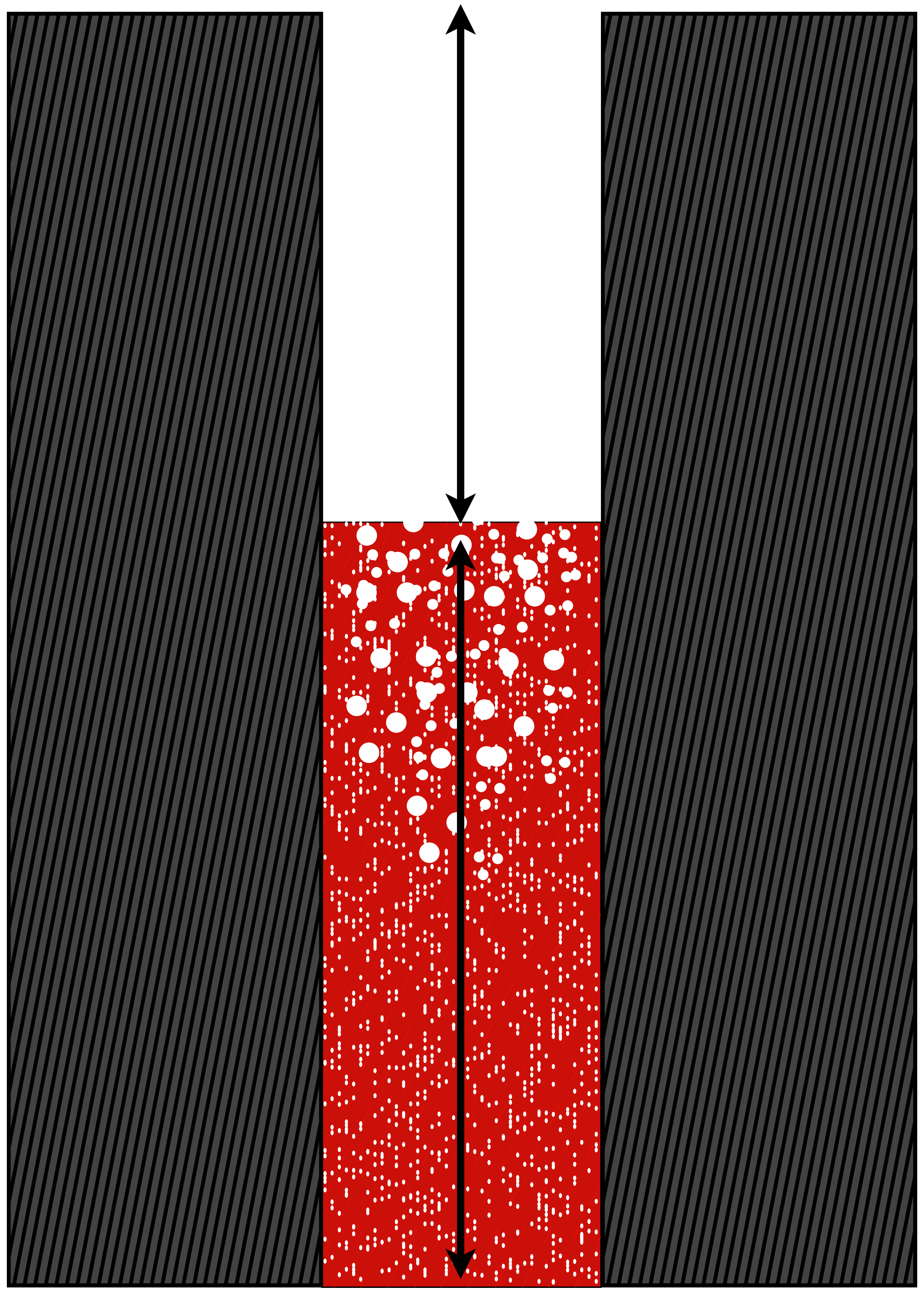
Pu`u O`o: Bubbly flow/degassing/ helmholtz resonance

Villarrica

Goto and Johnson [2011]

Acoustic harmonic tremor: Conduit resonance

Shallow conduit resonance



gas/steam or air

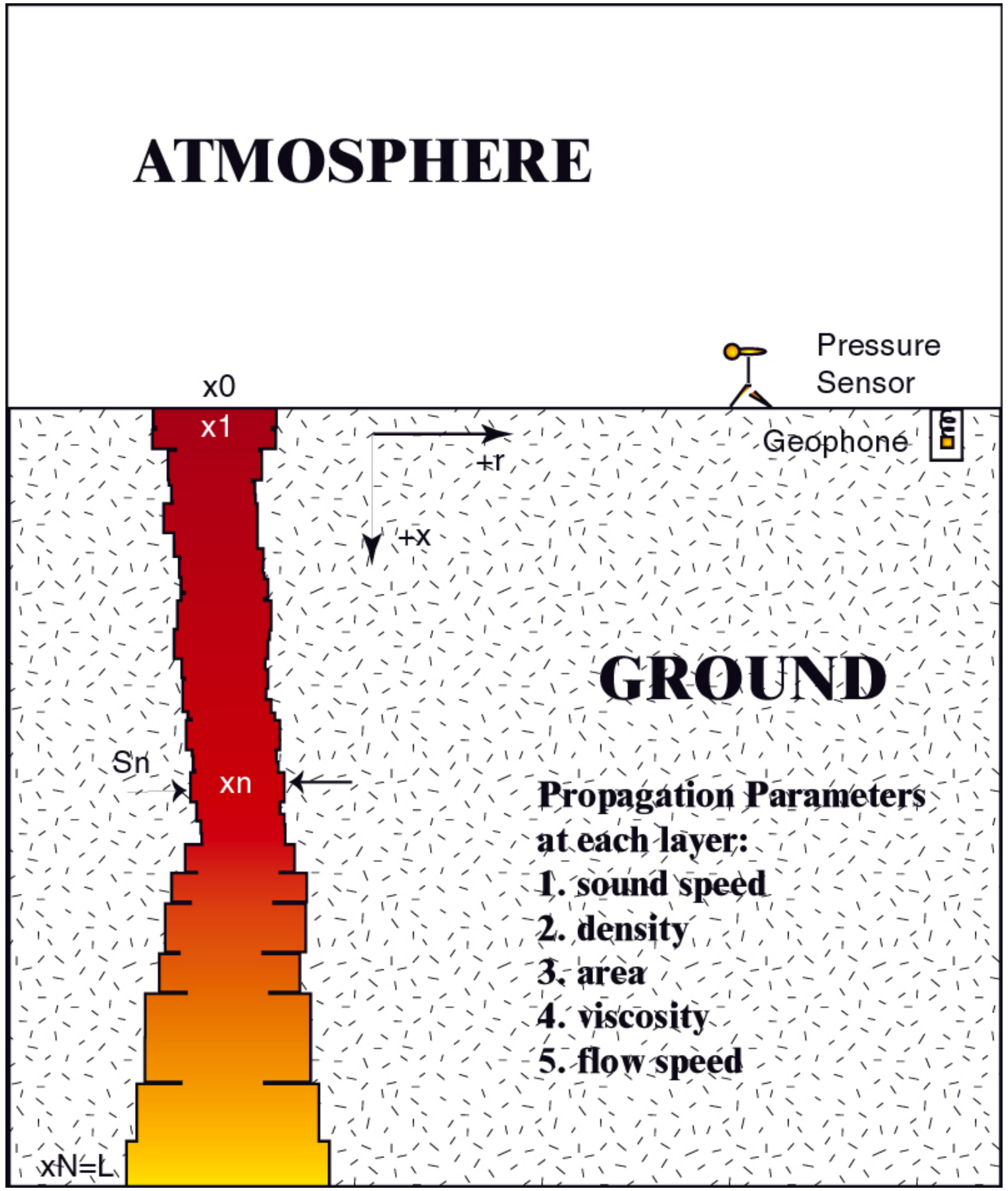
magma

Acoustic harmonic tremor: Conduit resonance

Shallow conduit resonance

Analytic solution for airborne sound from a resonant magma conduit

From: Buckingham and Garces [1996]
to: Garces [2000]



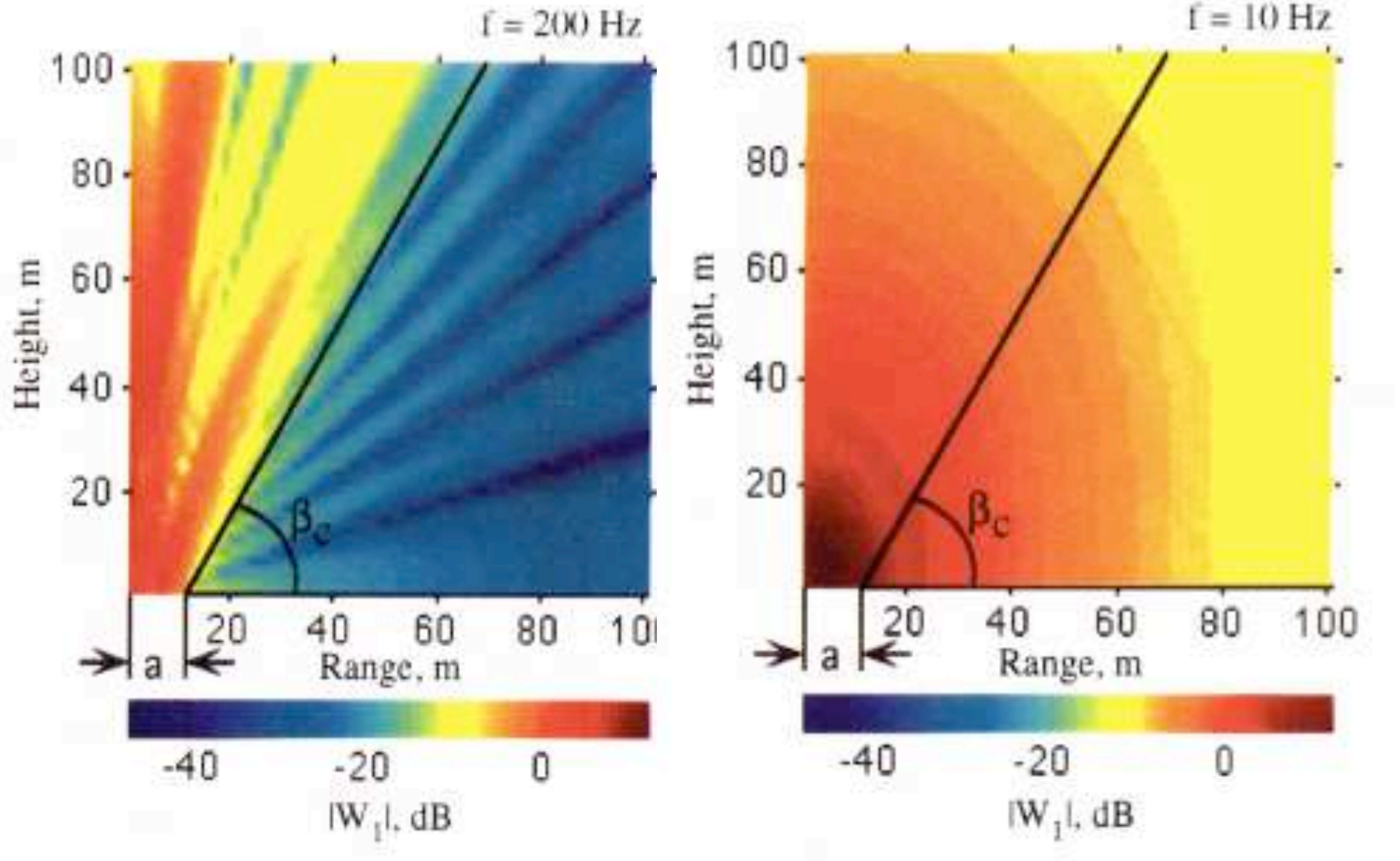
Garces [2000]

Acoustic harmonic tremor: Conduit resonance

Shallow conduit resonance

Key question #1: how does sound couple from the magma conduit into the air?

1. Diaphragm-like motion of the magma surface [Buckingham and Garces, 1995]



Acoustic harmonic tremor: Conduit resonance

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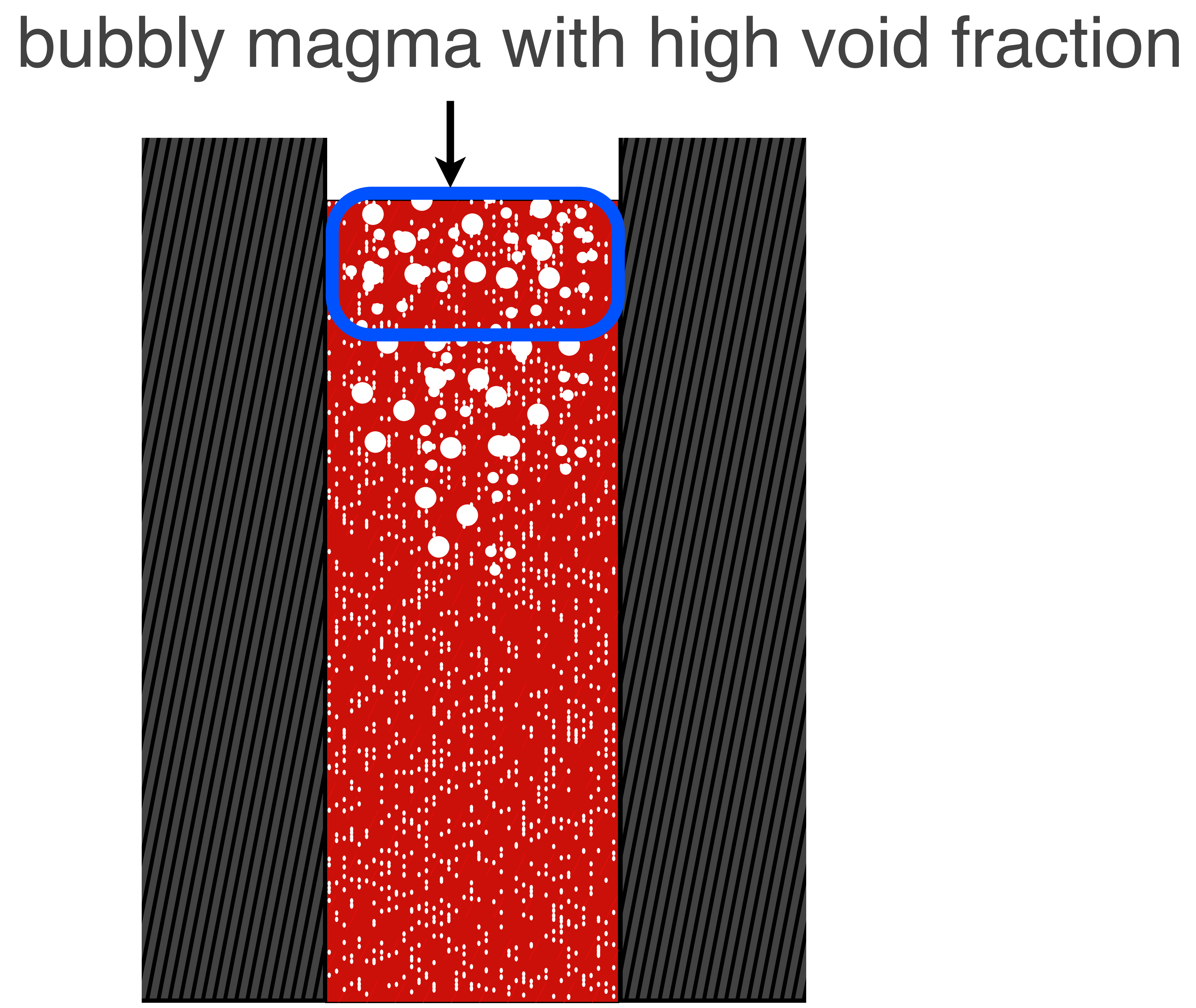

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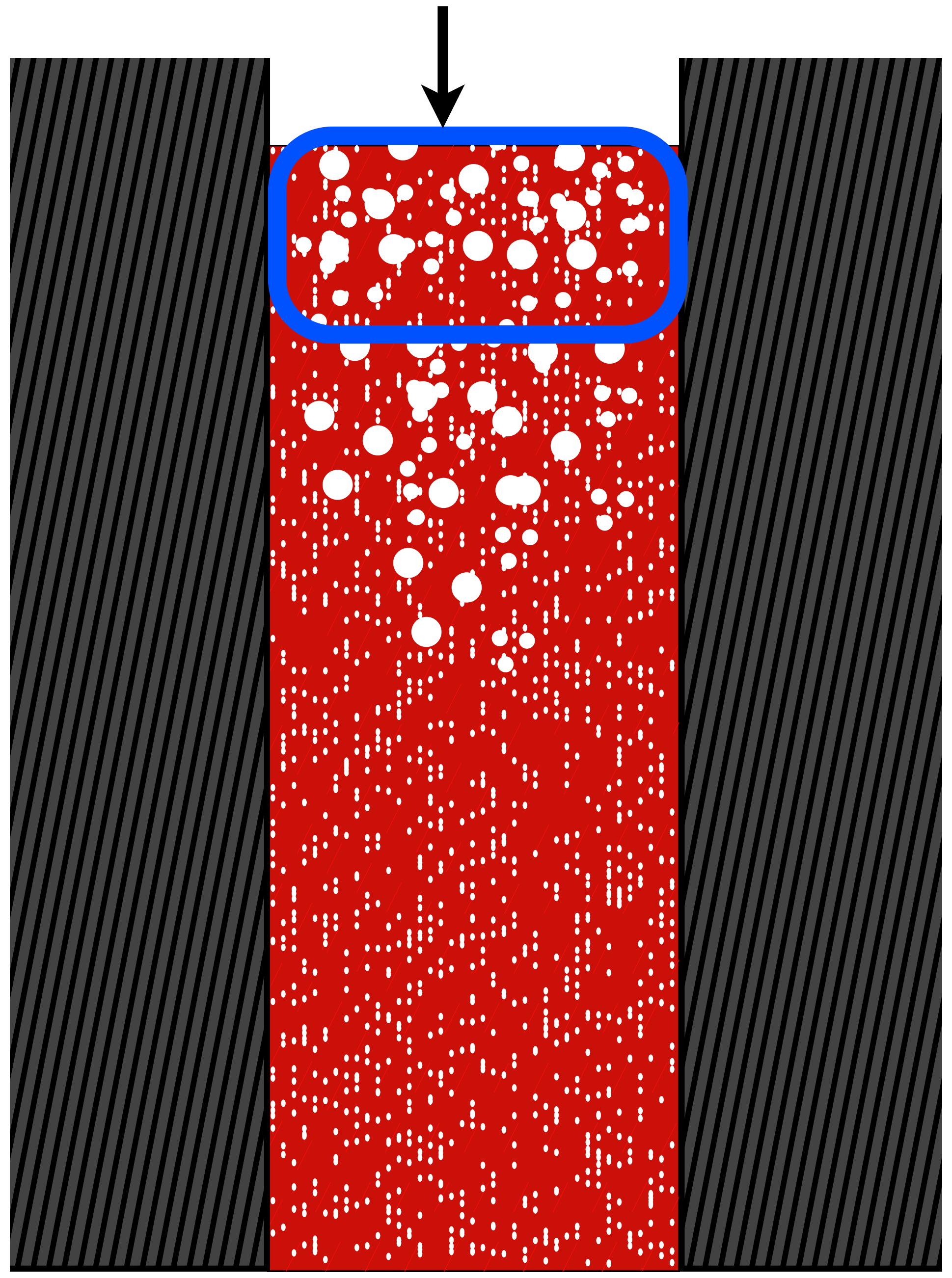

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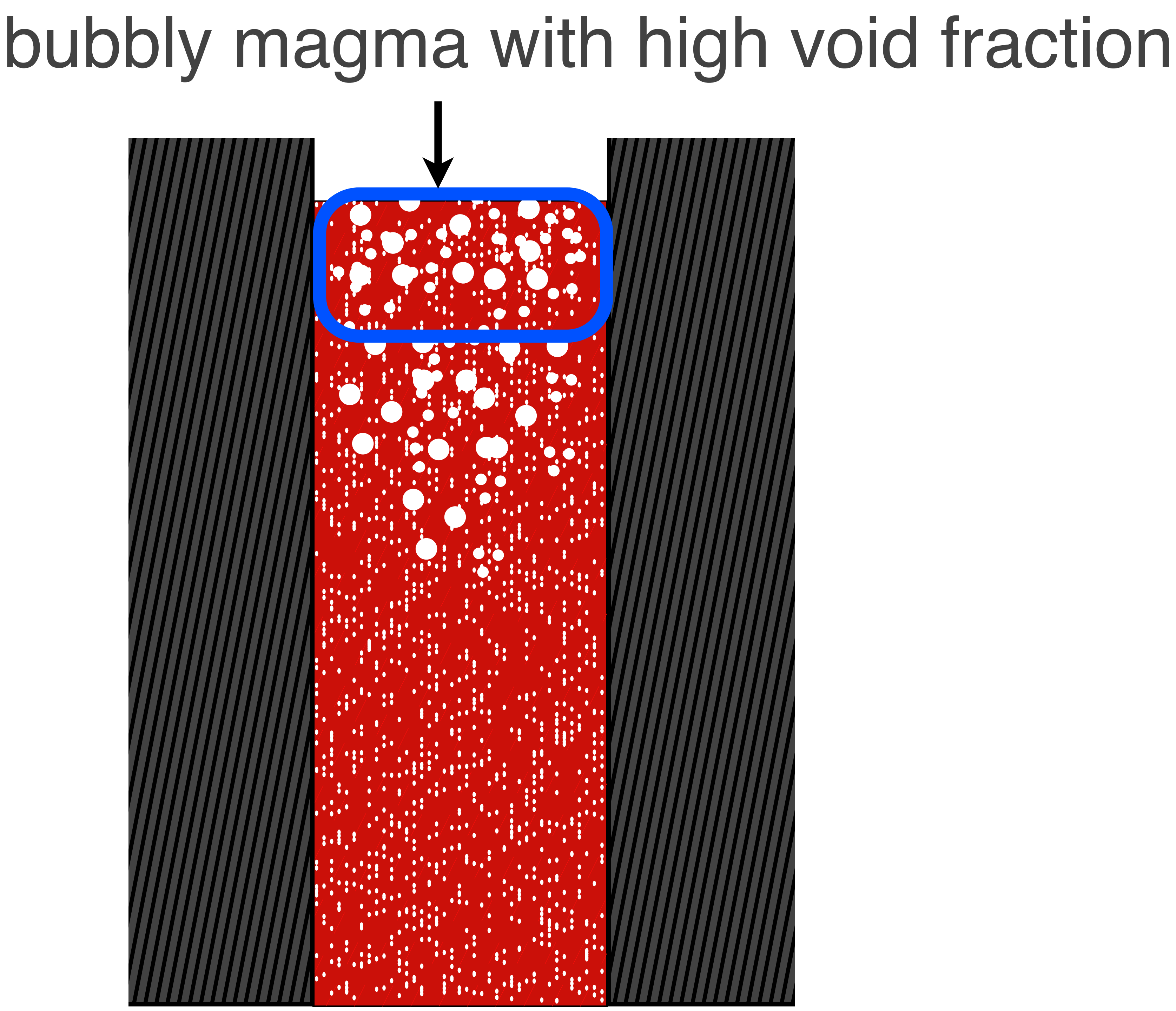
4. "Anomalous transparency" of the magma-air interface at infrasonic frequencies [Matoza et al., 2010, Godin 2006, 2007]



Acoustic harmonic tremor: Conduit resonance

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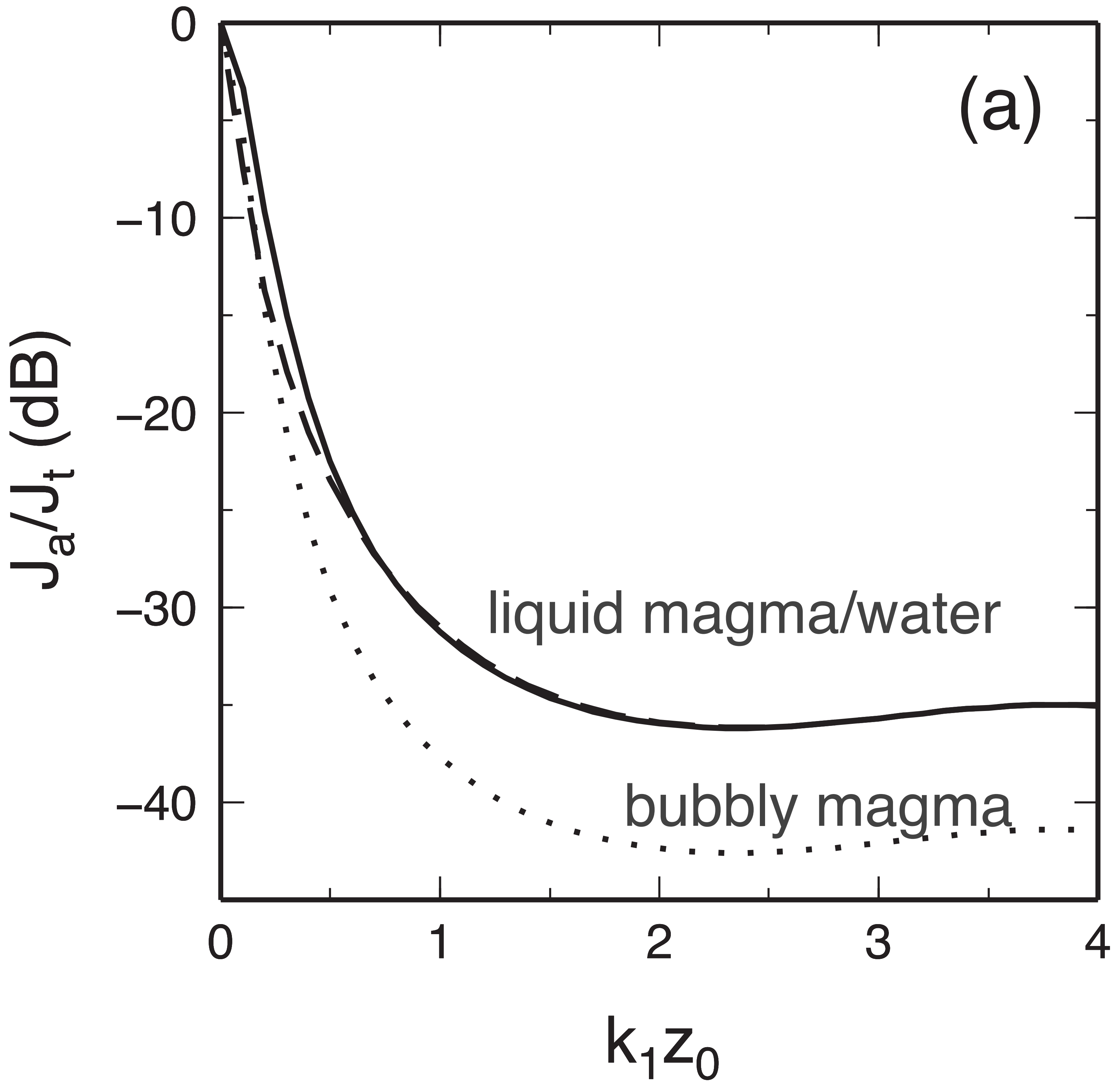
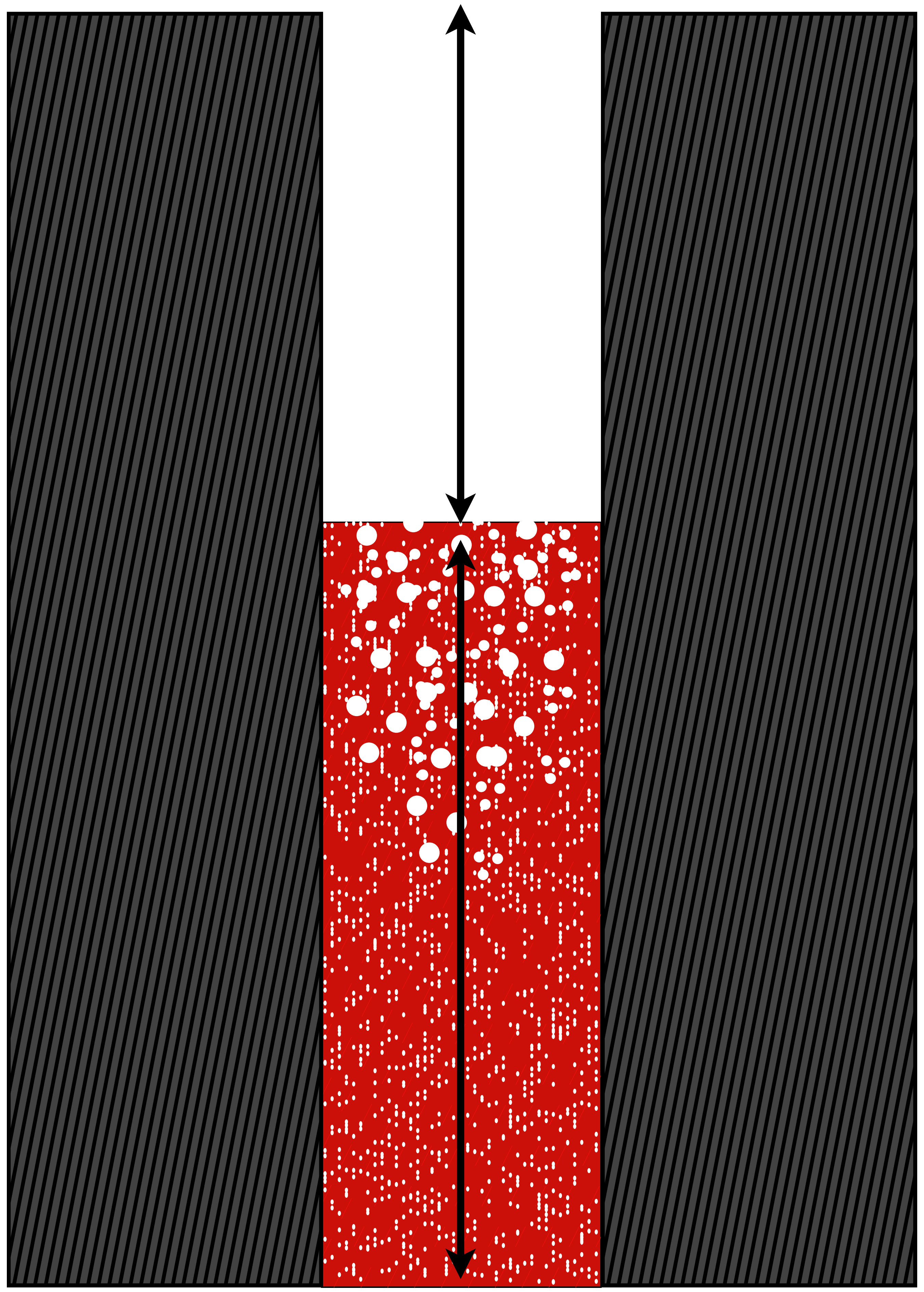


Upper few tens of meters couple well into atmosphere

Matoza et al. [2010]

Acoustic harmonic tremor: Conduit resonance

Shallow conduit resonance



gas/steam or air

magma

Helmholtz resonance: e.g., Halema`uma`u

Helmholtz resonance of a conduit/cavity

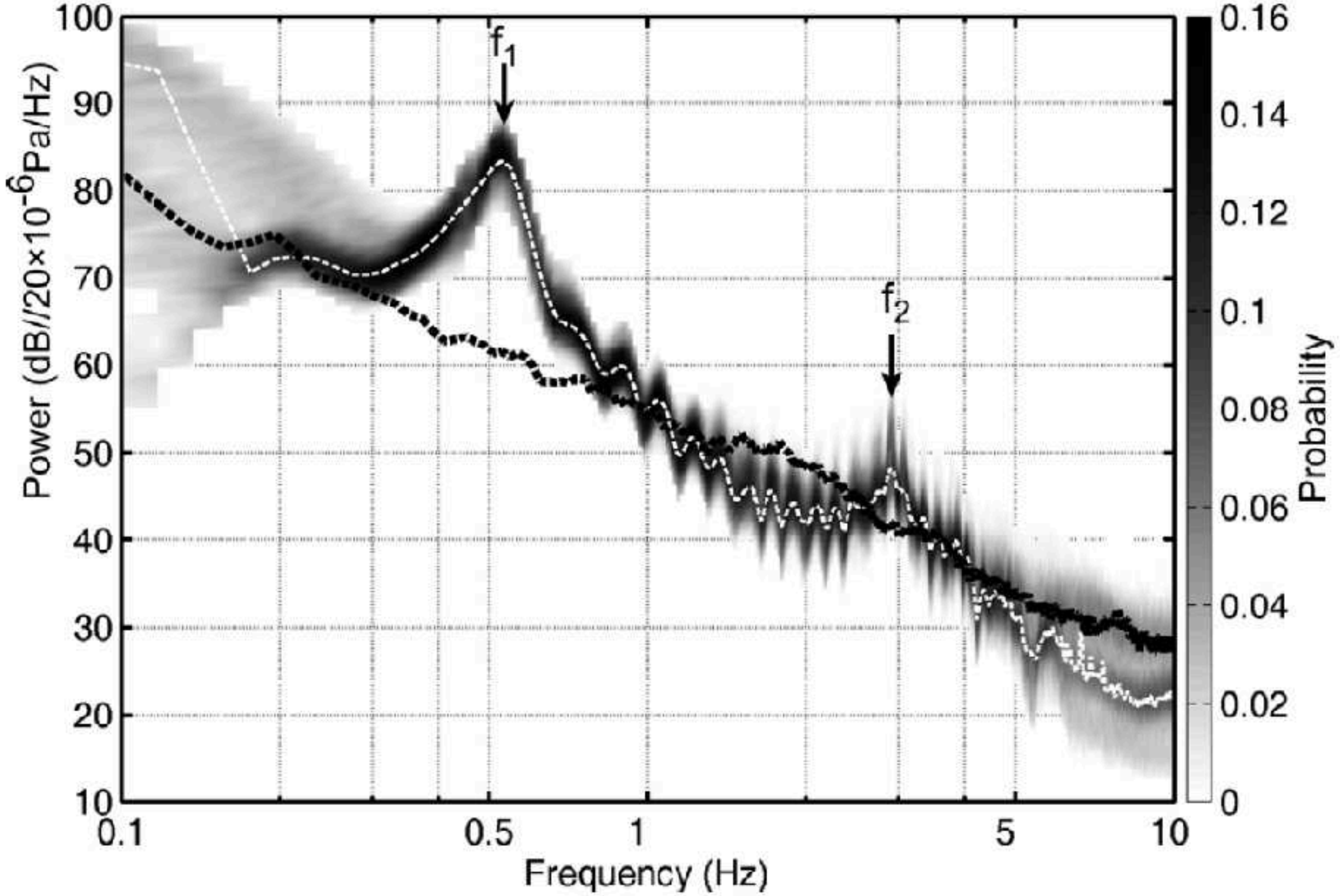
For wavelengths larger than the dimensions of the volume:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S_a}{L_H V}}$$

cross-sectional area of neck

effective neck length

cavity volume



Fee et al. [2010]

Helmholtz resonance: e.g., Halema`uma`u

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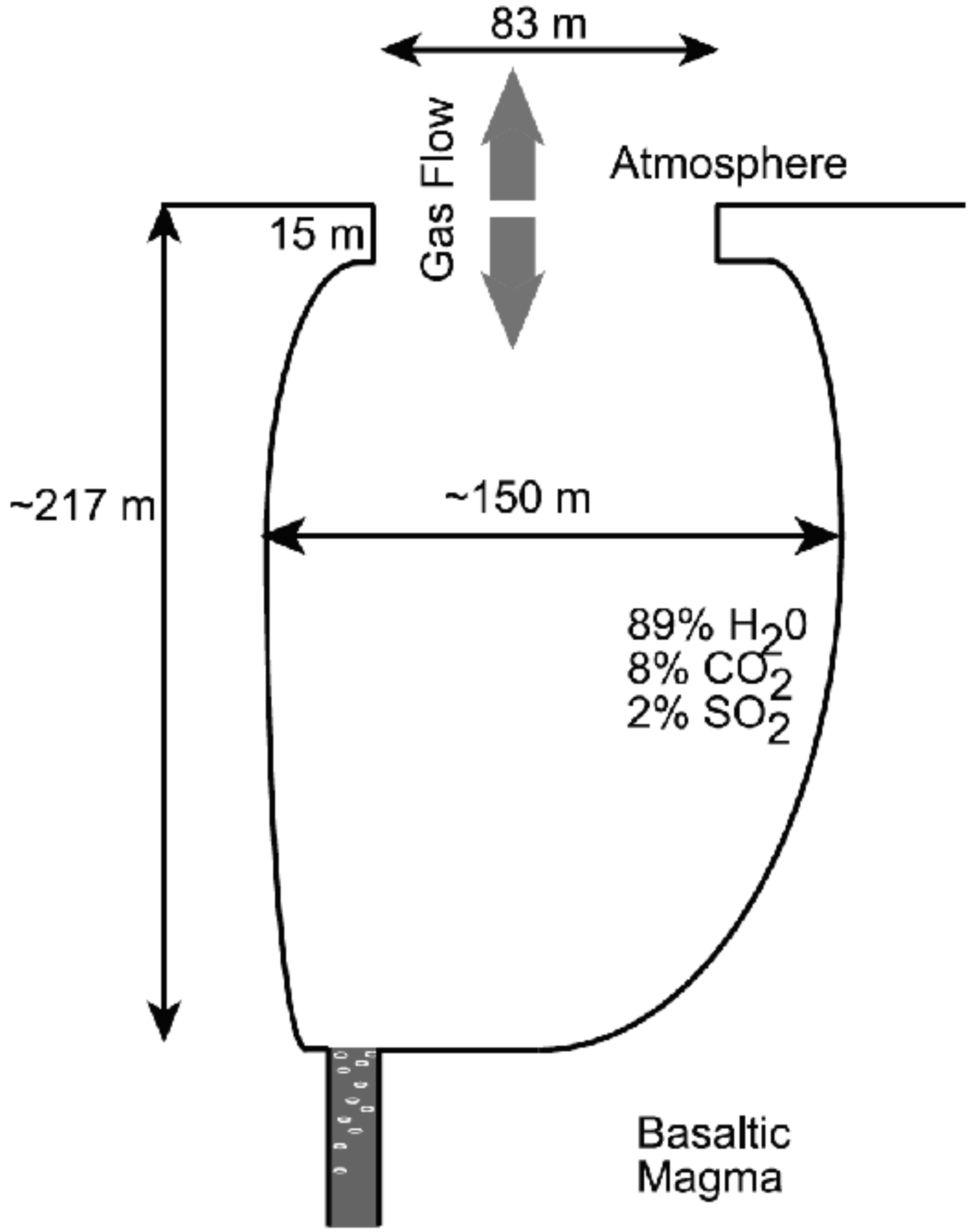


Fee et al. [2010]

For wavelengths larger than the dimensions of the volume:

$$f_H = \frac{c}{2\pi}\sqrt{\frac{S_a}{L_H V}}$$

S_a ← cross-sectional area of neck

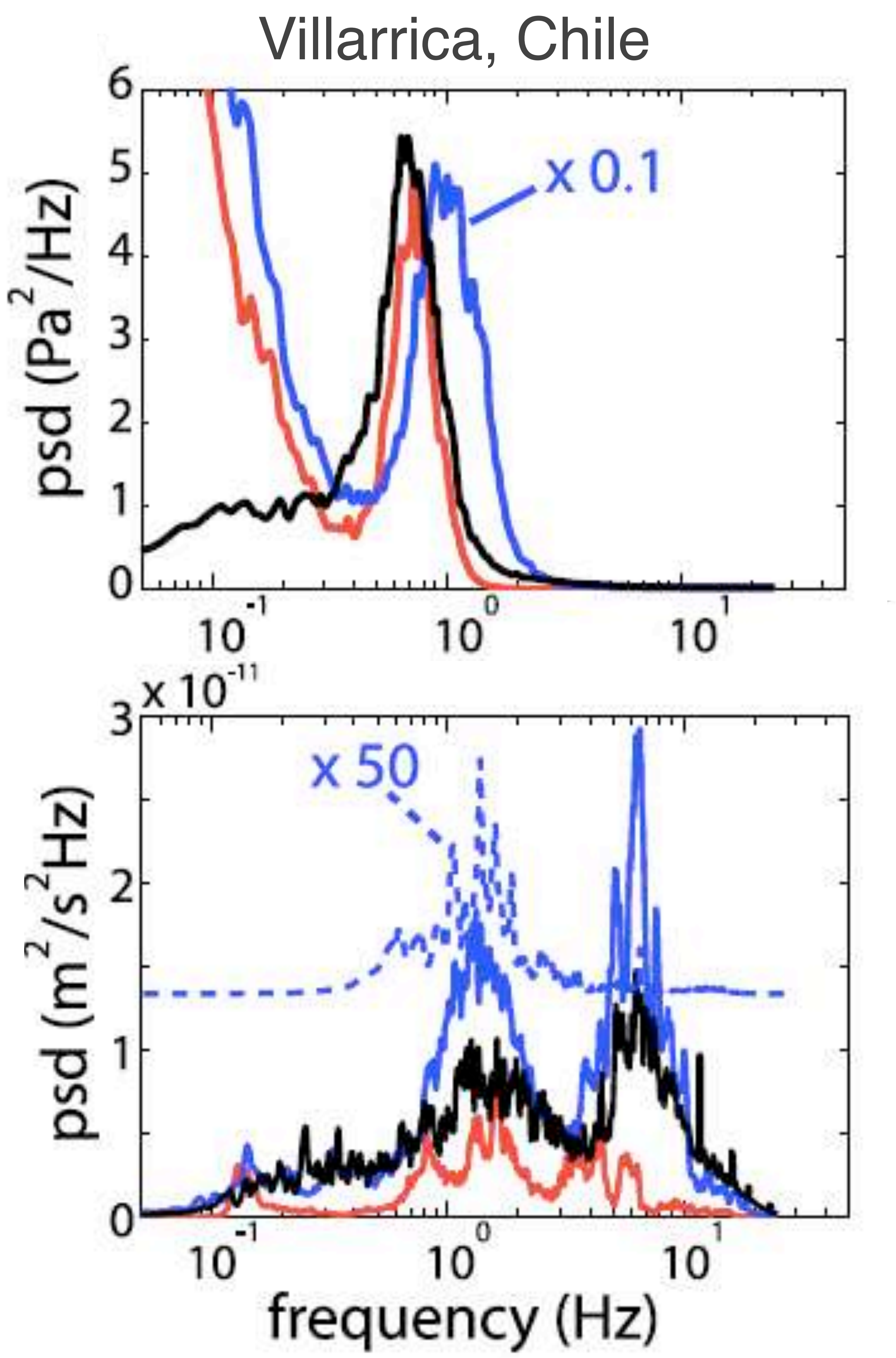
L_H: effective neck length

V: cavity volume

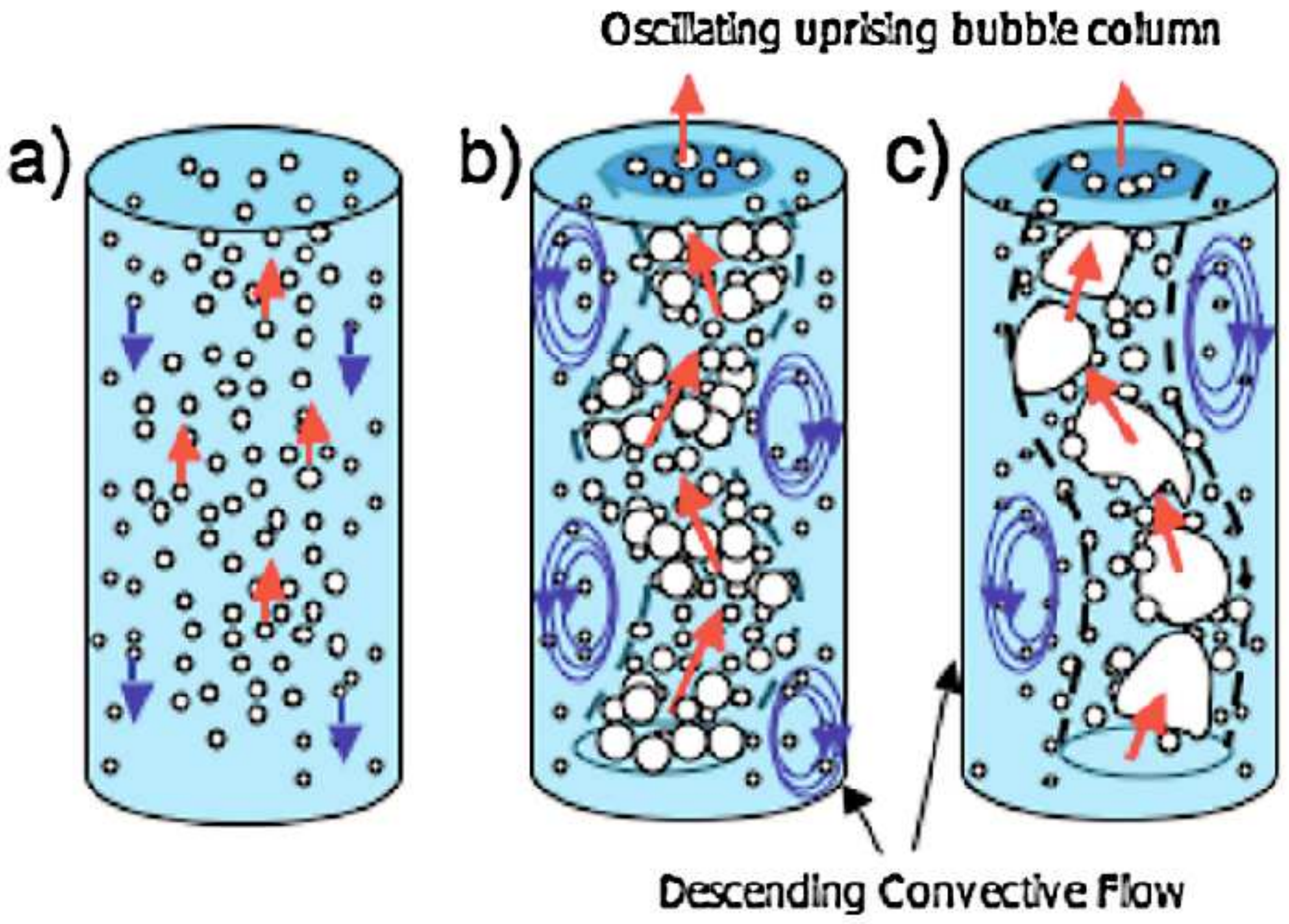
Acoustic harmonic tremor: Conduit resonance

Shallow conduit resonance

Key question #2: what drives the oscillation?



1. Bubble cloud oscillation [Chouet, 1996; Matoza et al. 2010]
2. Density-driven oscillations of the bubble column [Ripepe et al. 2010]



Ripepe et al. [2010] after Mudde [2005]

Pu`u O`o seismic and infrasonic tremor

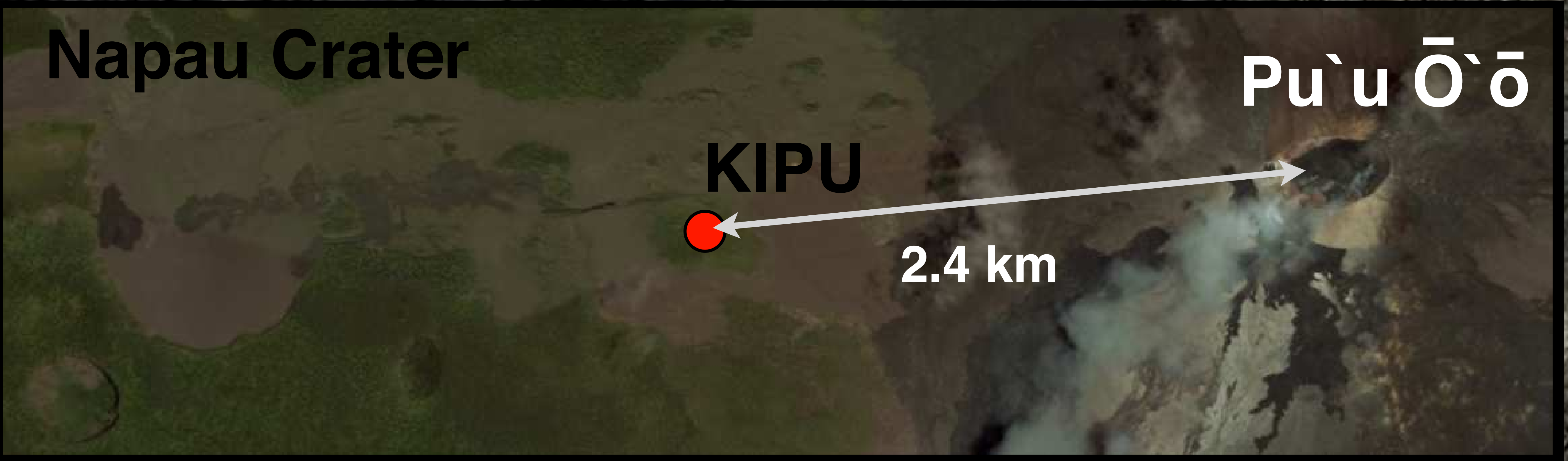
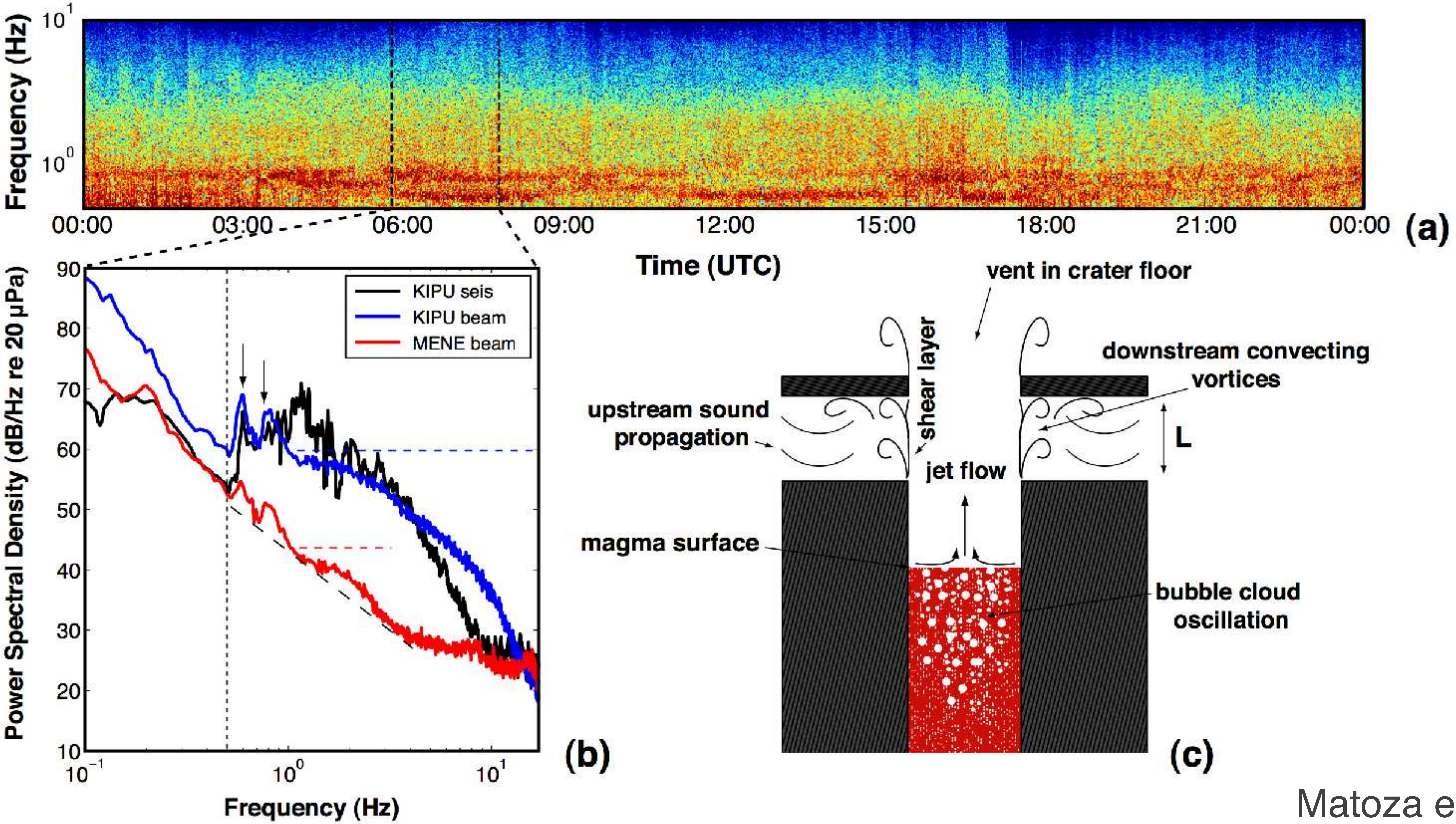


image: HVO/USGS

Pu`u O`o seismic and infrasonic tremor



Matoza et al. [2010]

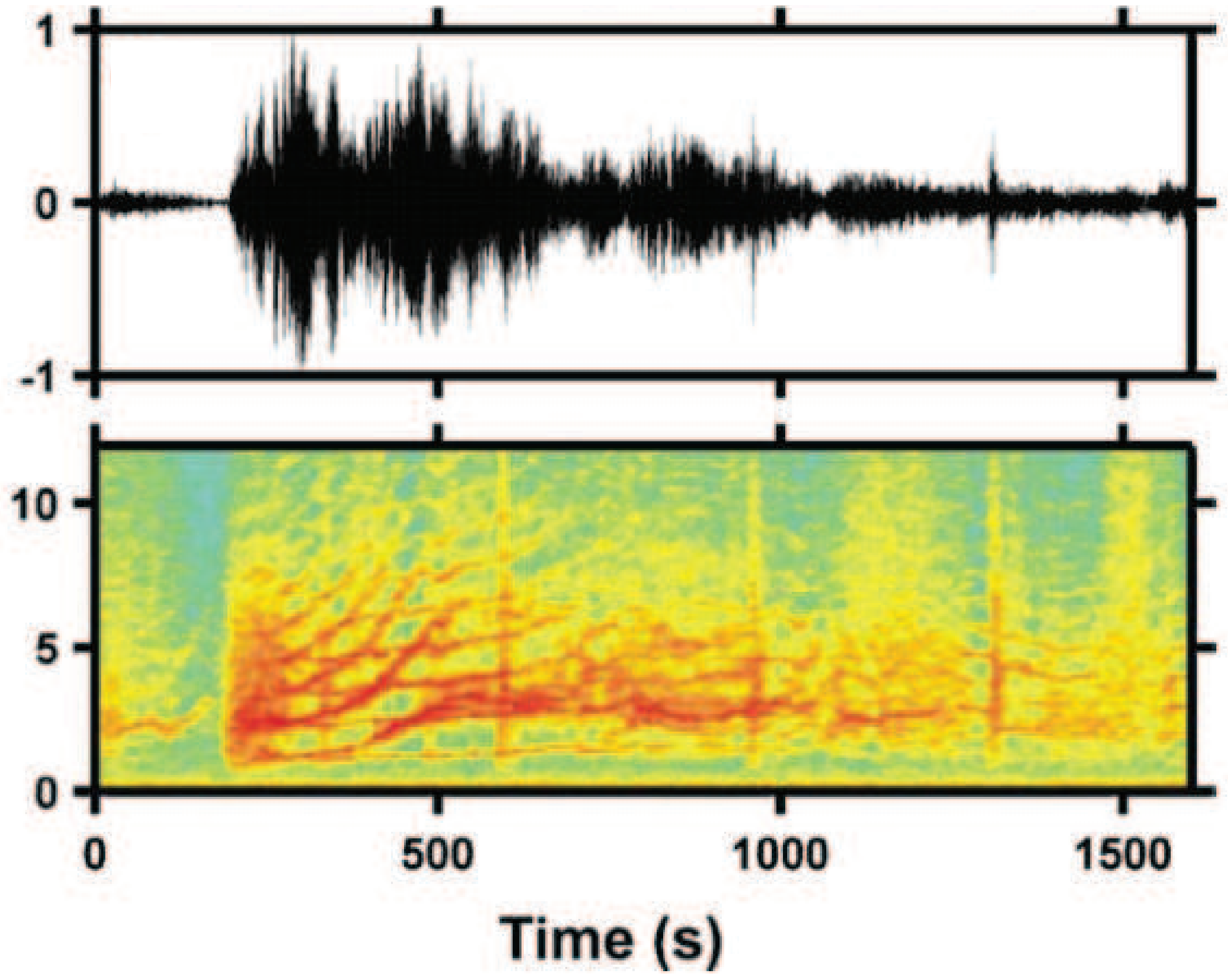
Seismo-acoustic harmonic tremor

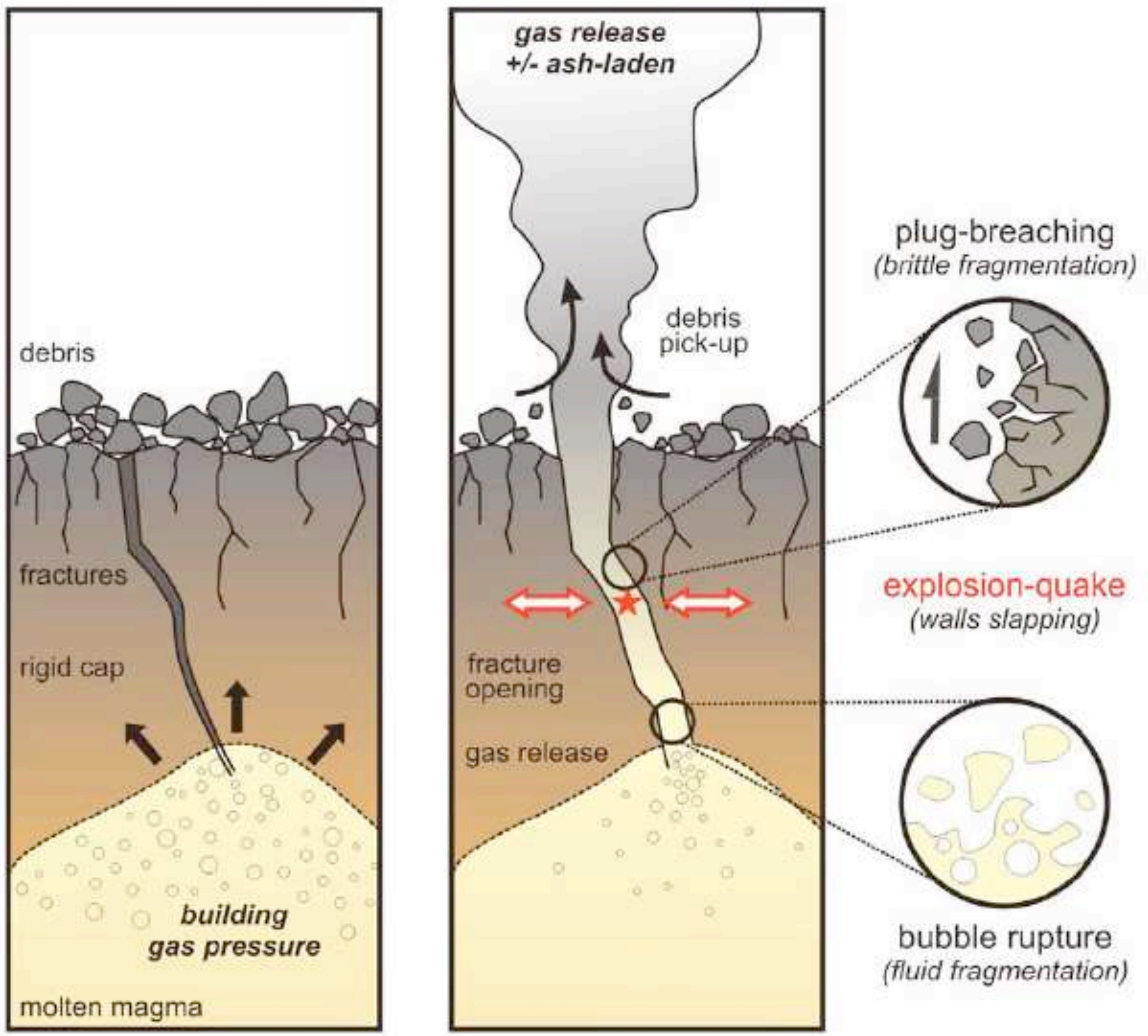
Degassing through sealed caps

e.g.,
Gil Cruz and Chouet [1997]
Hellweg [2000]
Johnson and Lees [2000]
Lesage et al. [2006]
Valade et al. [2012]
Girona et al. [2019]

...can be coupled with and controlled by upper conduit/cavity resonance

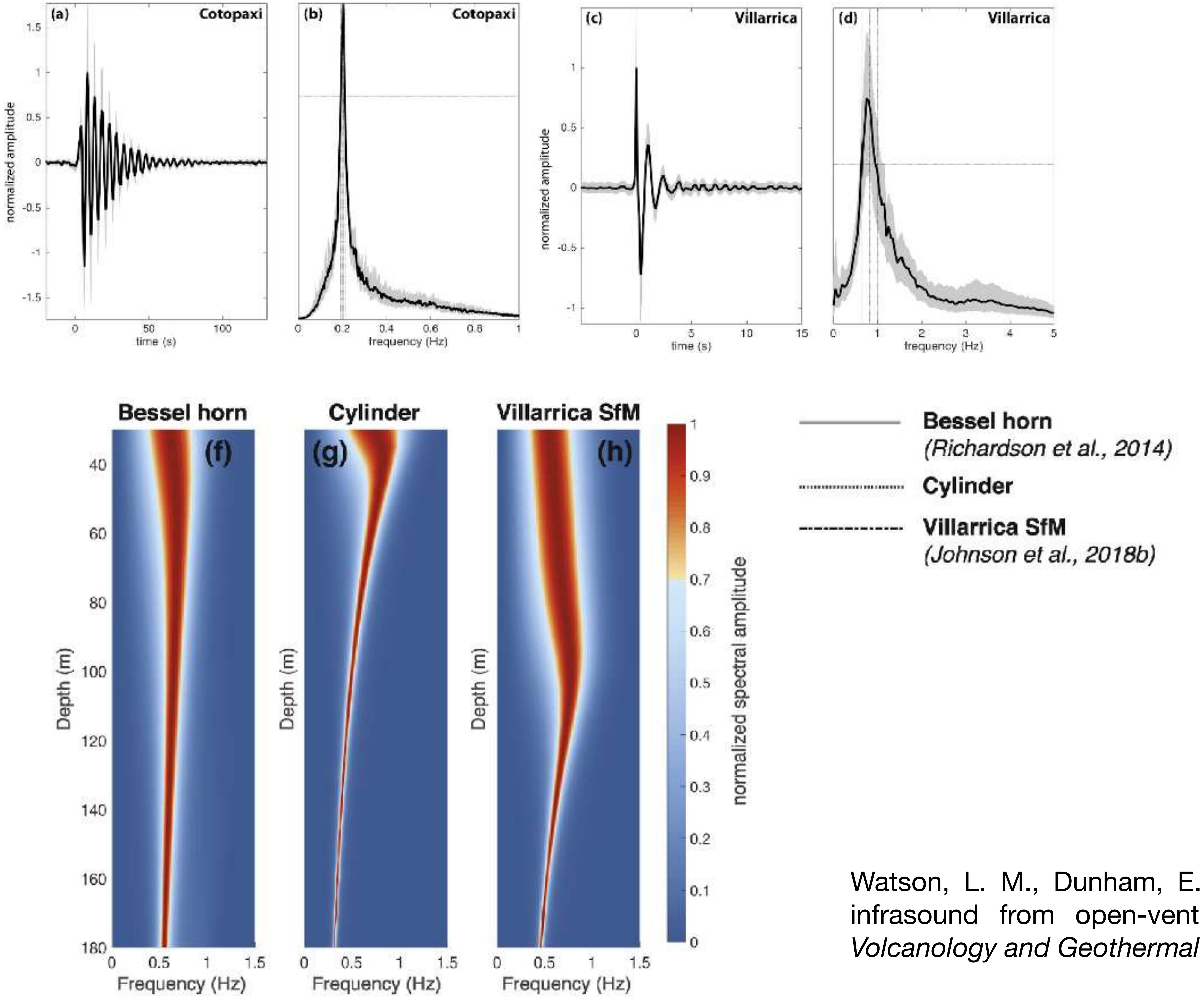
Hagerty et al. [2000]
Lesage et al. [2006]
Matoza et al. [2010]

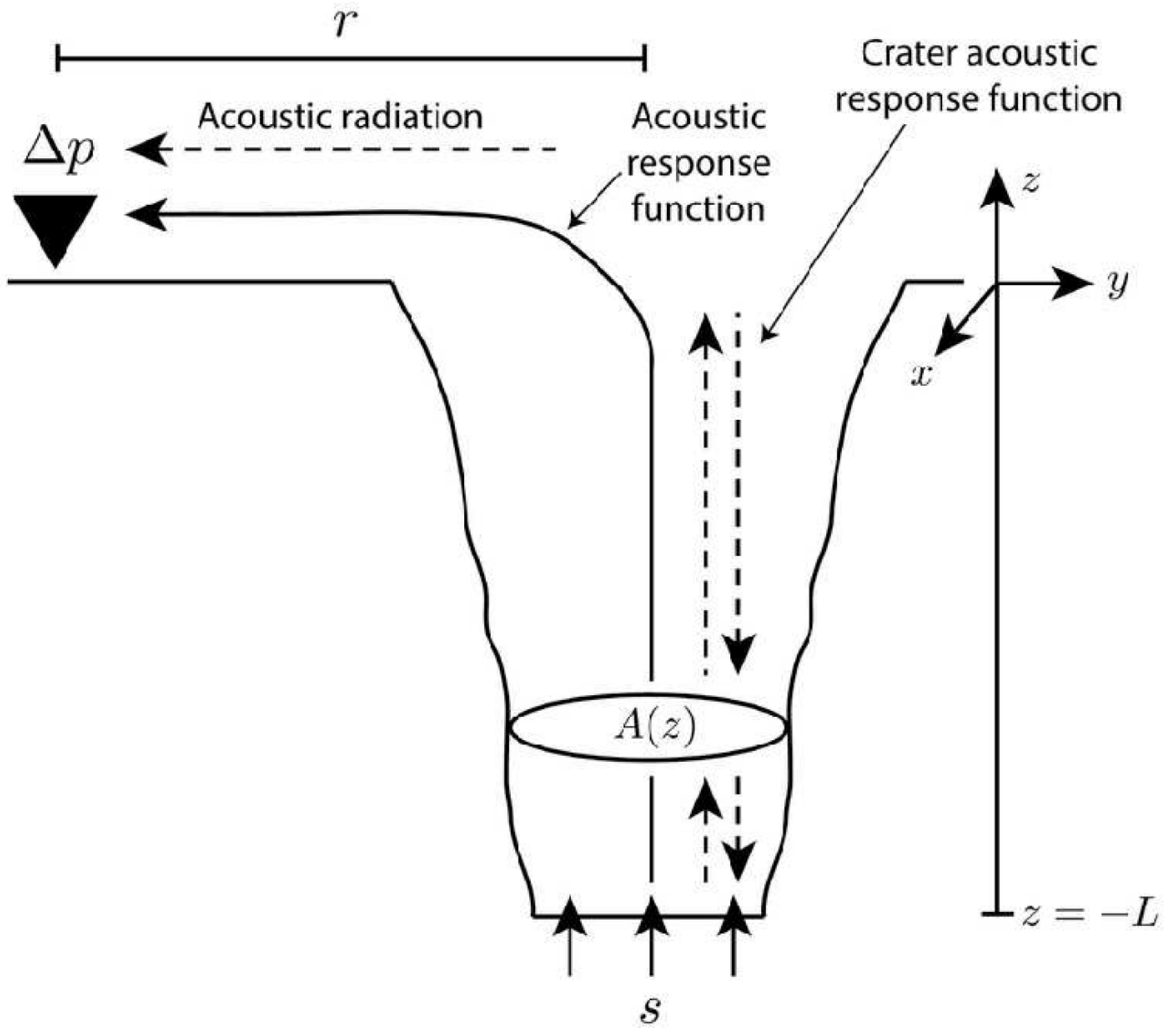




Valade et al. [2012]

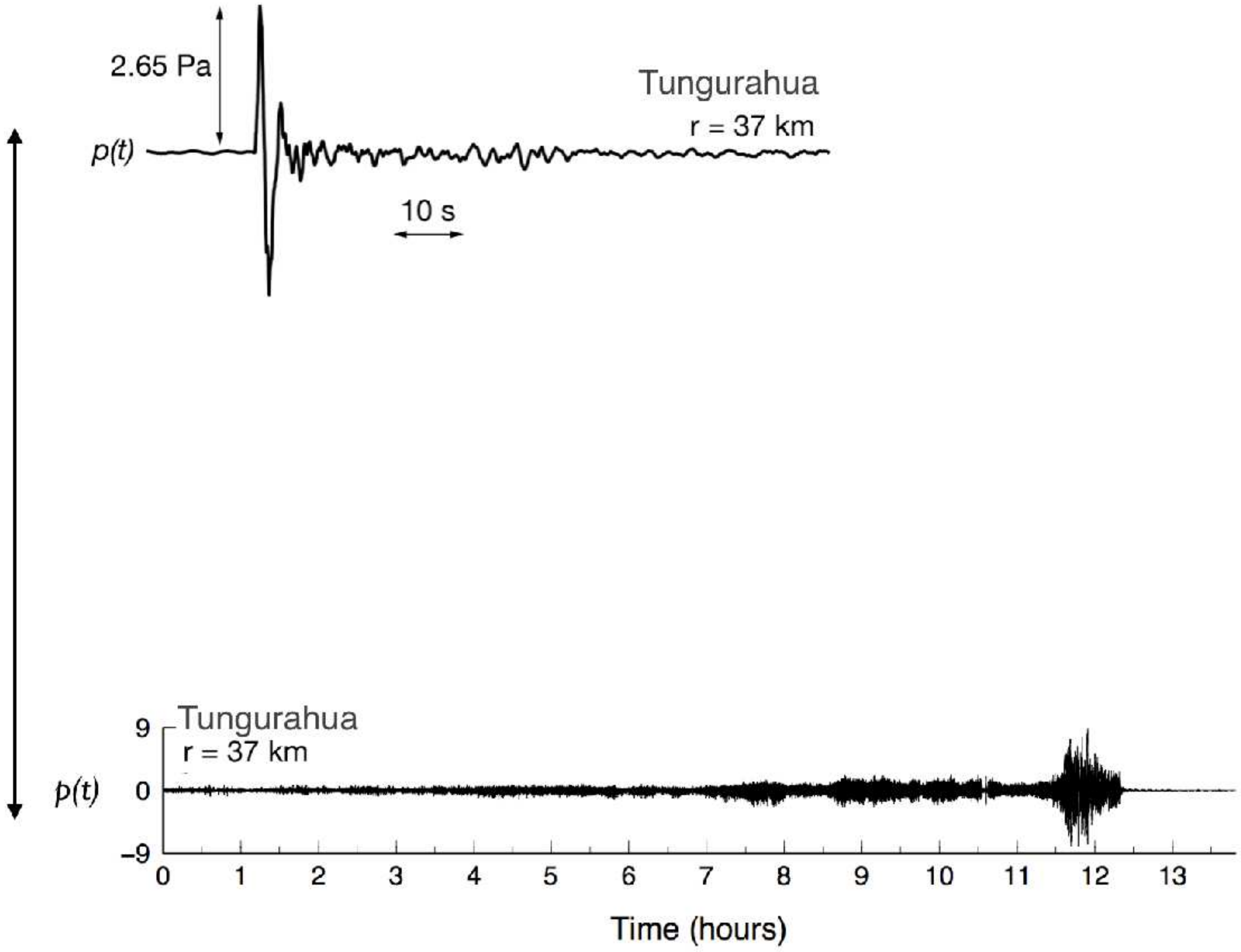
Crater resonance





Watson, L. M., Dunham, E. M., & Johnson, J. B. (2019). Simulation and inversion of harmonic infrasound from open-vent volcanoes using an efficient quasi-1D crater model. *Journal of Volcanology and Geothermal Research, 380, 64-79*

Explosive volcanism: source processes



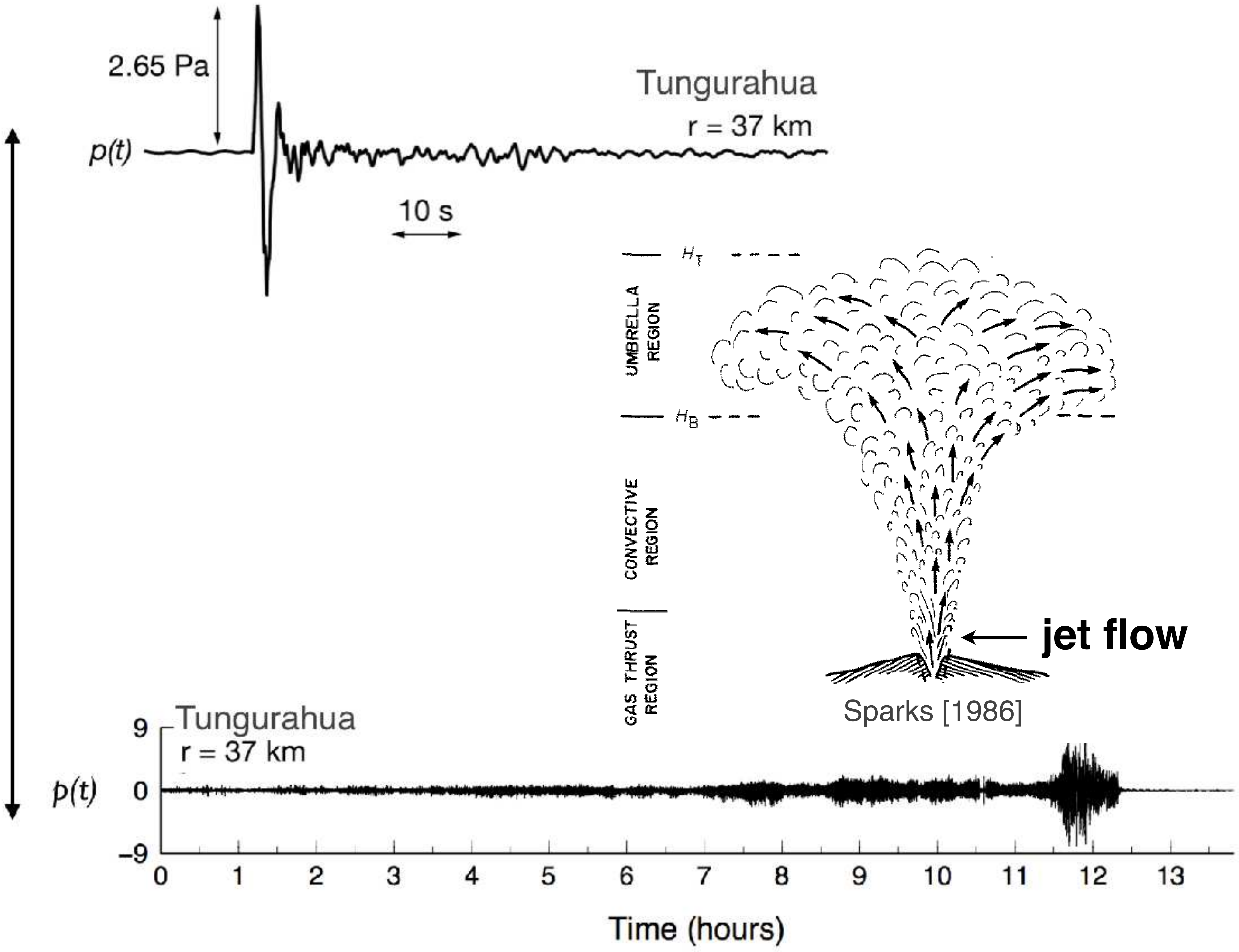
“Explosions” or blast-waves

e.g., Johnson et al. [2003], Marchetti et al. [2013]

Volcanic jet-noise

Matoza et al. [2009, 2013]
Fee et al. [2010, 2013]

Explosive volcanism: source processes



Sparks [1986]

“Explosions” or blast-waves

e.g., Johnson et al. [2003], Marchetti et al. [2013]

Volcanic jet-noise

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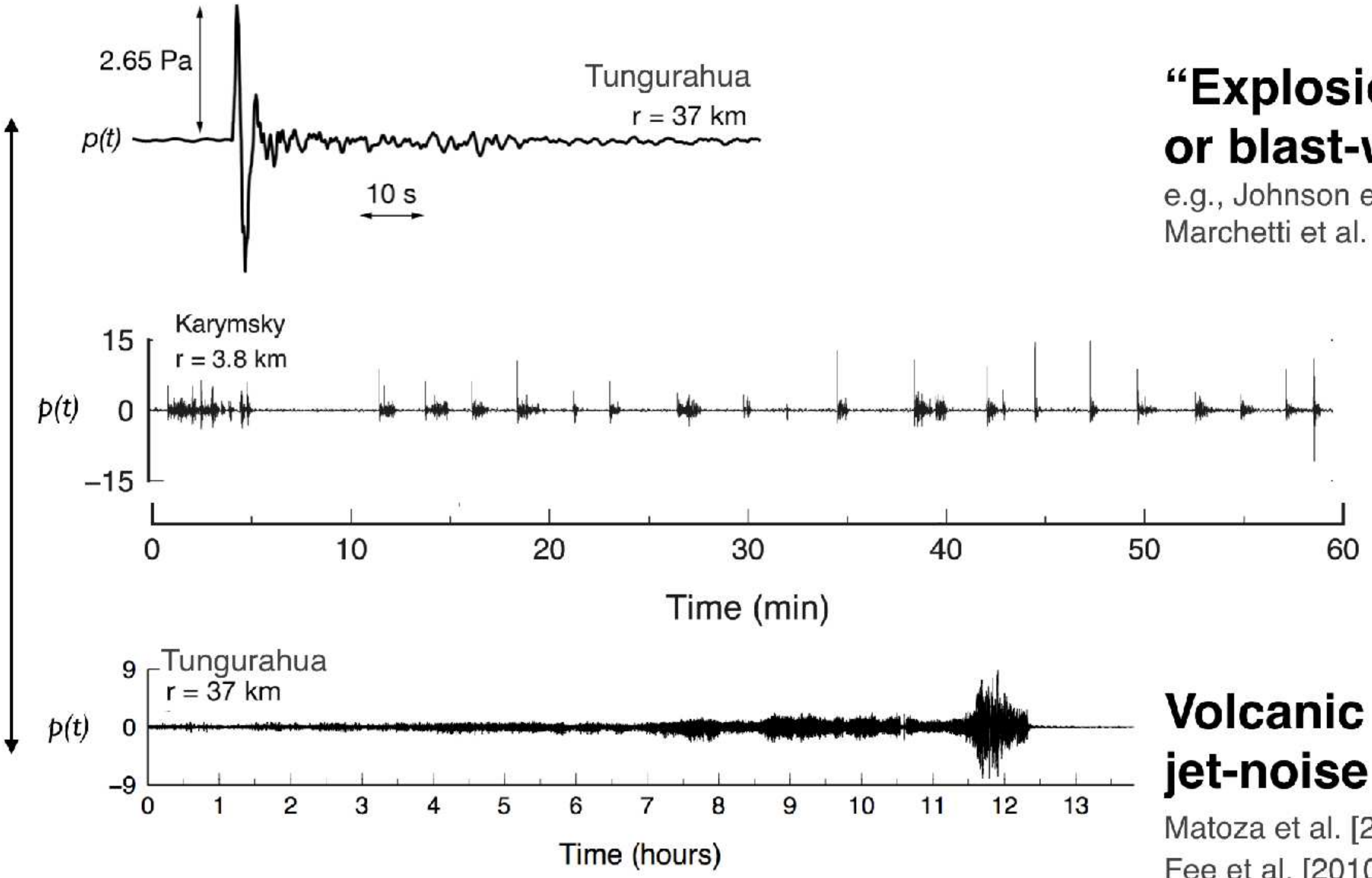
Explosive volcanism: source processes



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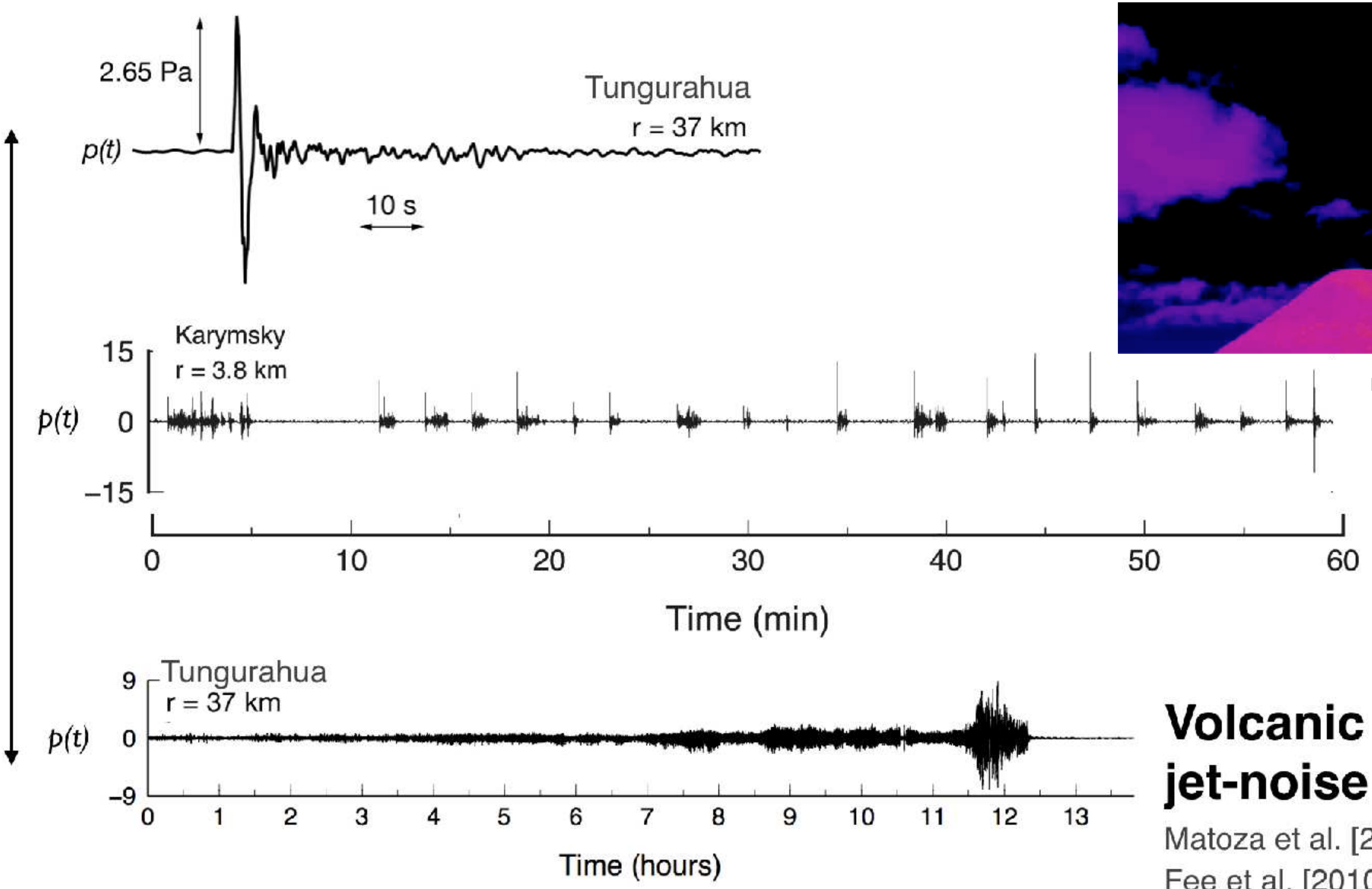
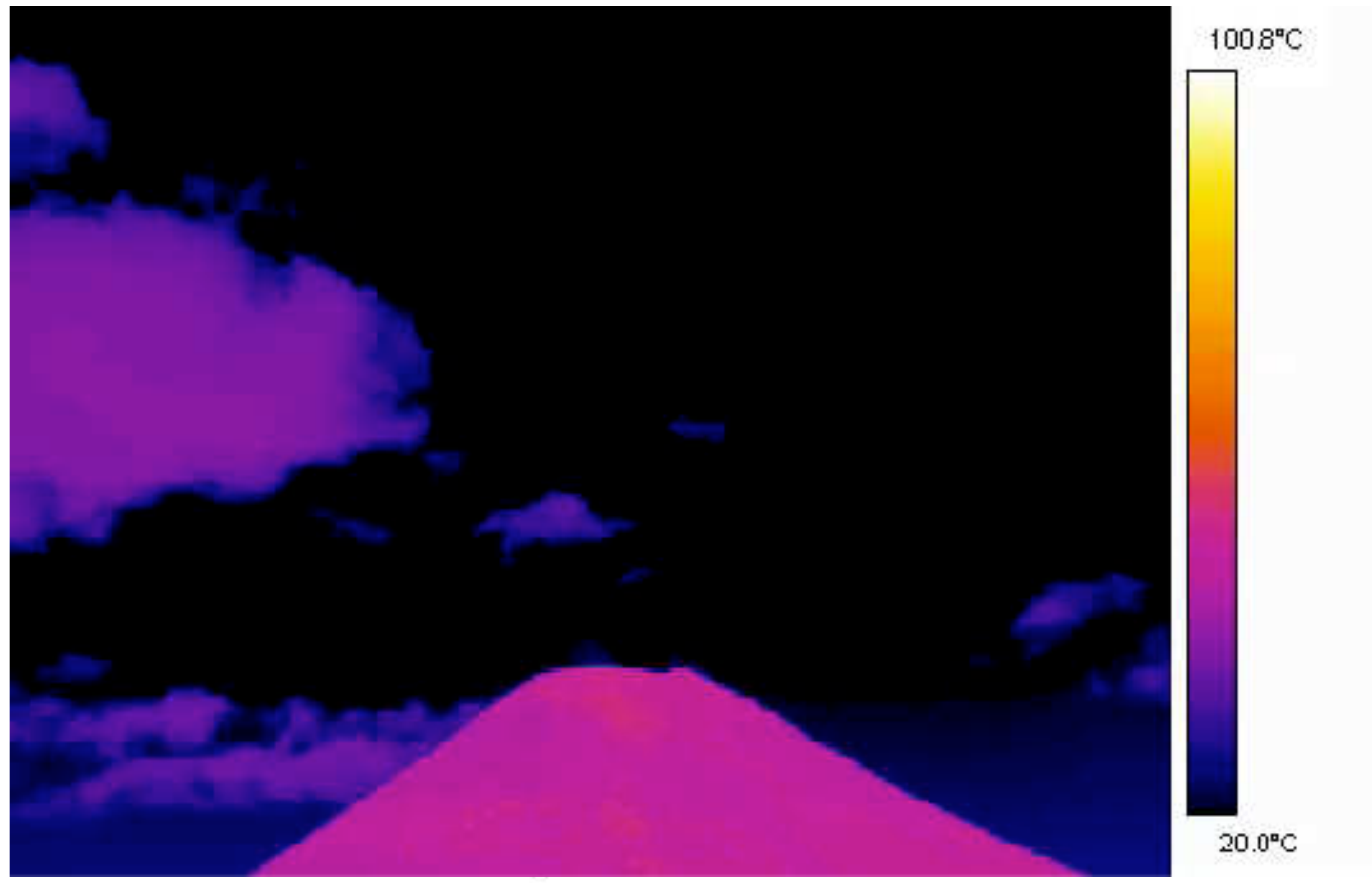




movie: David Fee, UAF

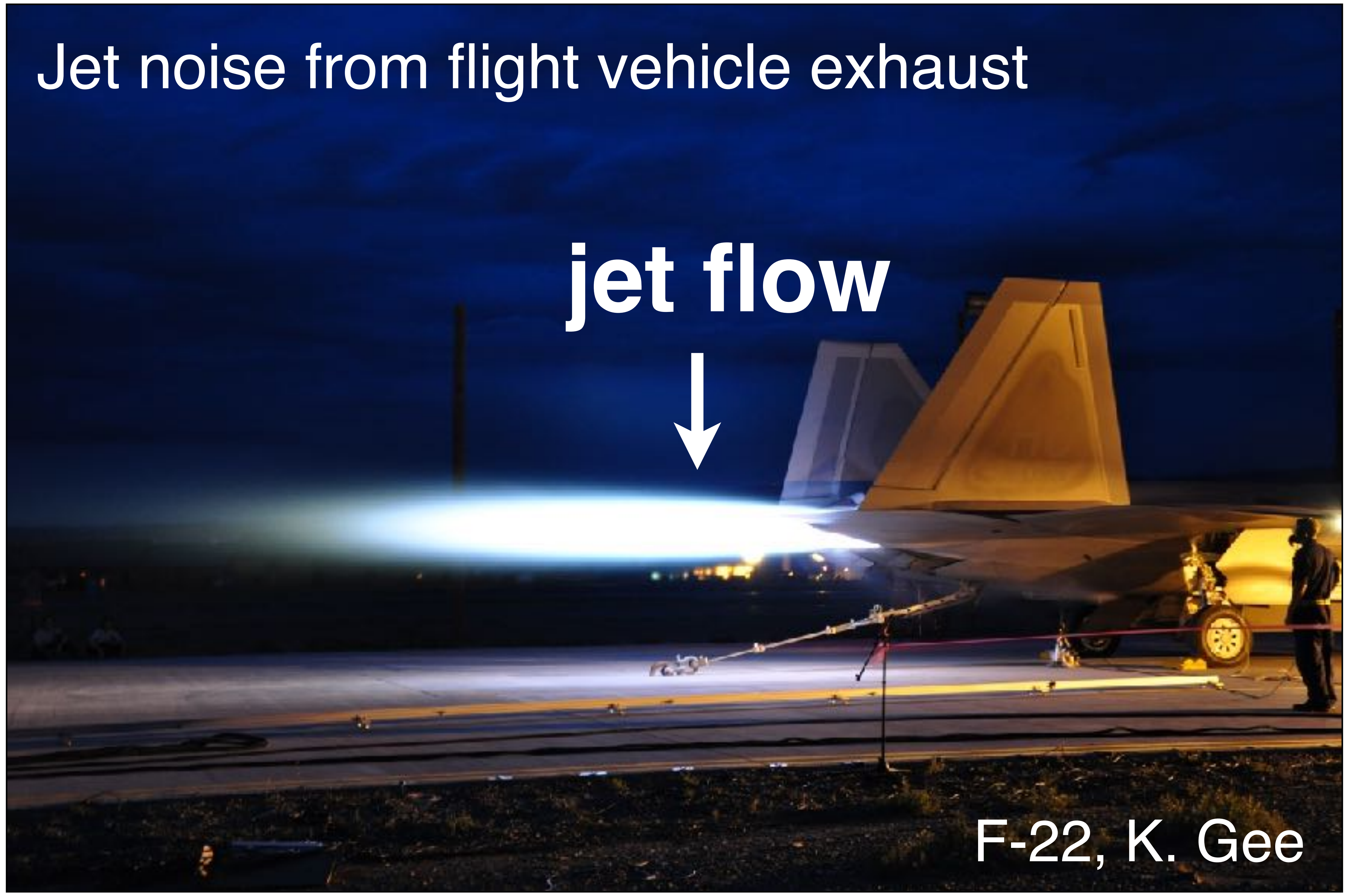
Volcanic jet-noise

Matoza et al. [2009, 2013]
Fee et al. [2010, 2013]

Infrasonic volcanic jet noise

- Noise from the exhaust flow of jet engines and rockets
- Studied for noise and vibration control in mechanical and aerospace engineering

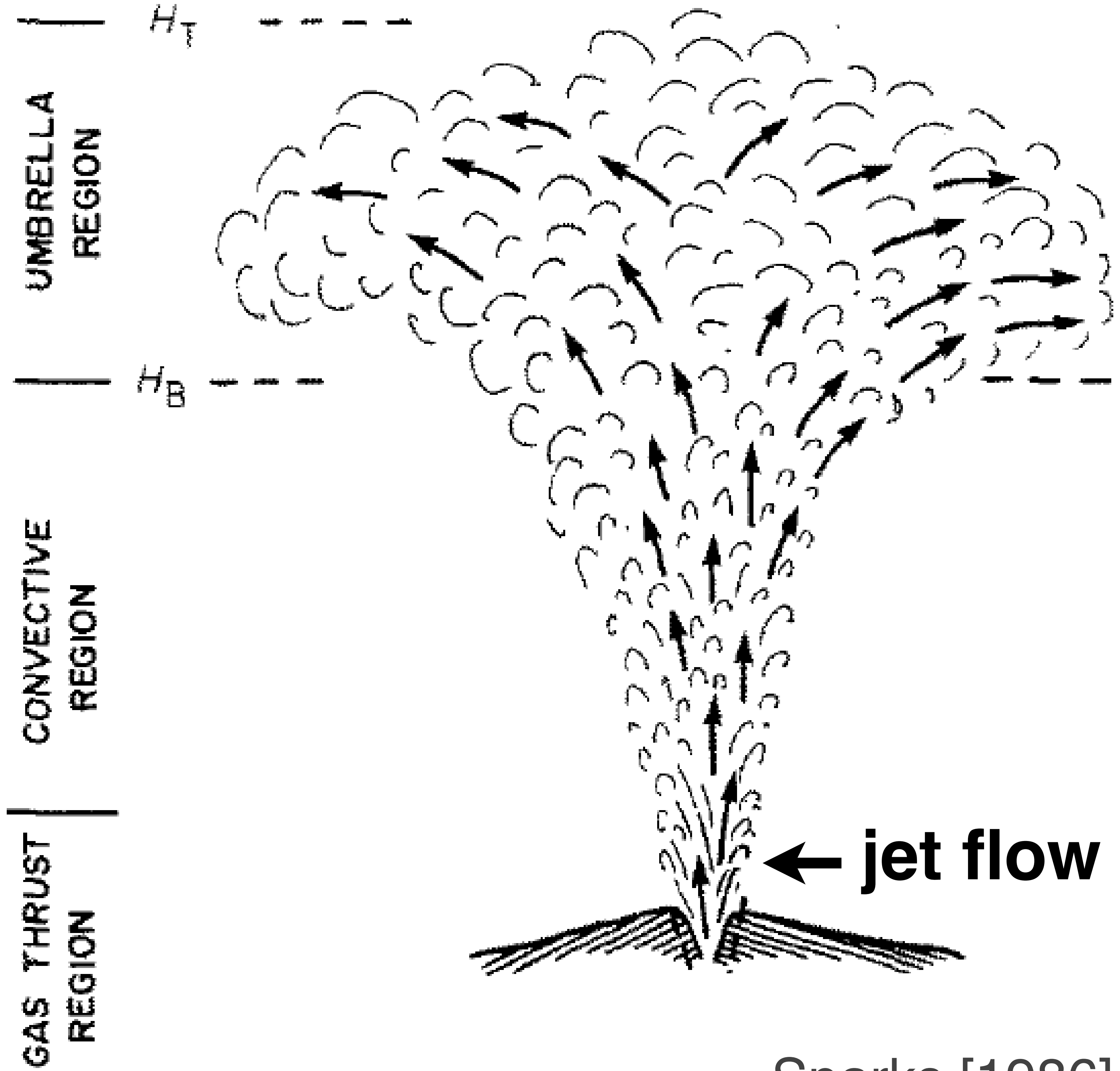
Jet noise from flight vehicle exhaust



F-22, K. Gee

- **Hypothesis:** noise-generation mechanisms scale up to volcanic length-scales *Matoza et al.* [2009; 2013]; *Fee et al.* [2013]

Natural large-scale jet flow (gas-thrust)



Sparks [1986]

Infrasonic volcanic jet noise

— eruption signal

- - - ambient noise

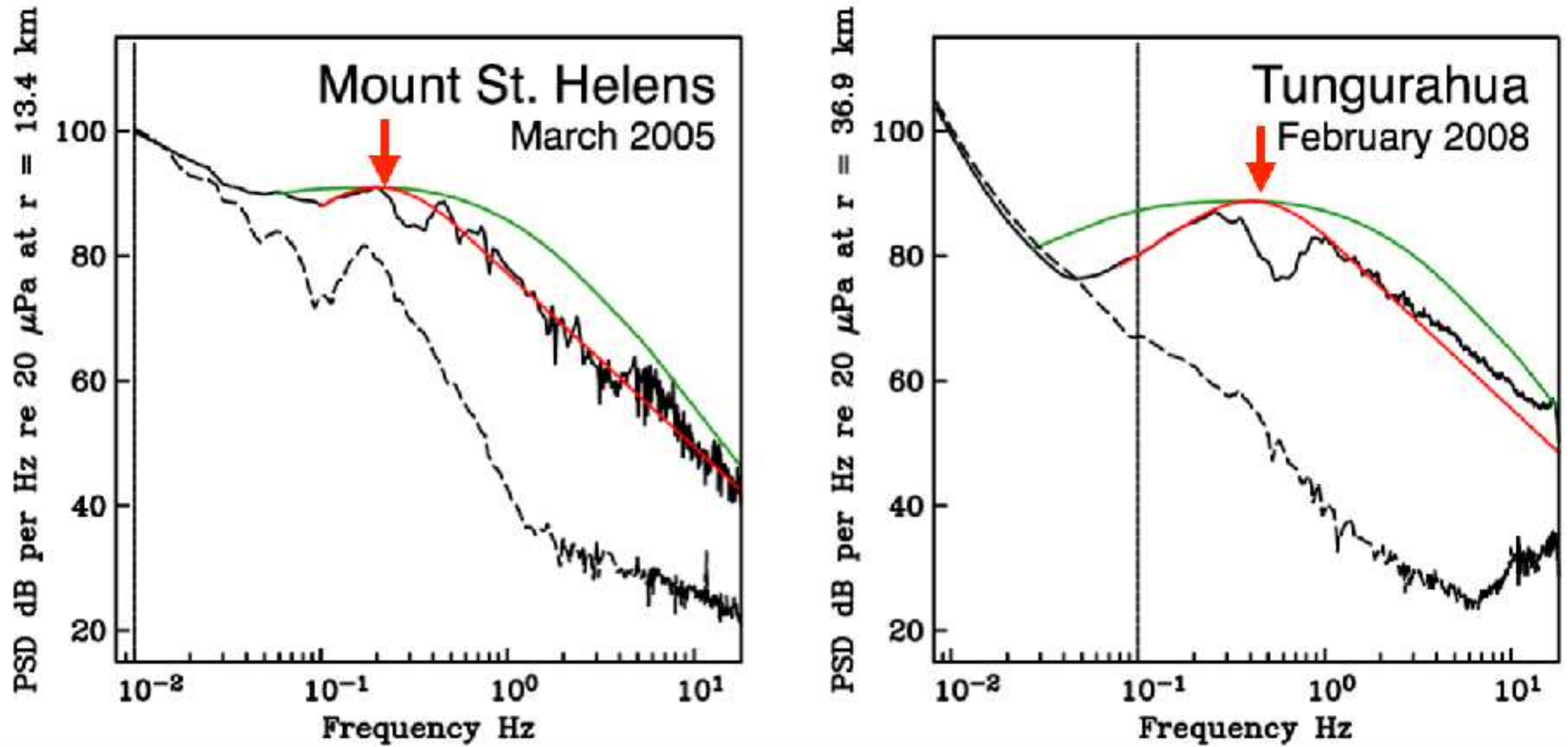
— LST } Empirical fits to thousands of lab experiments
— FST

Tam et al. [1996]

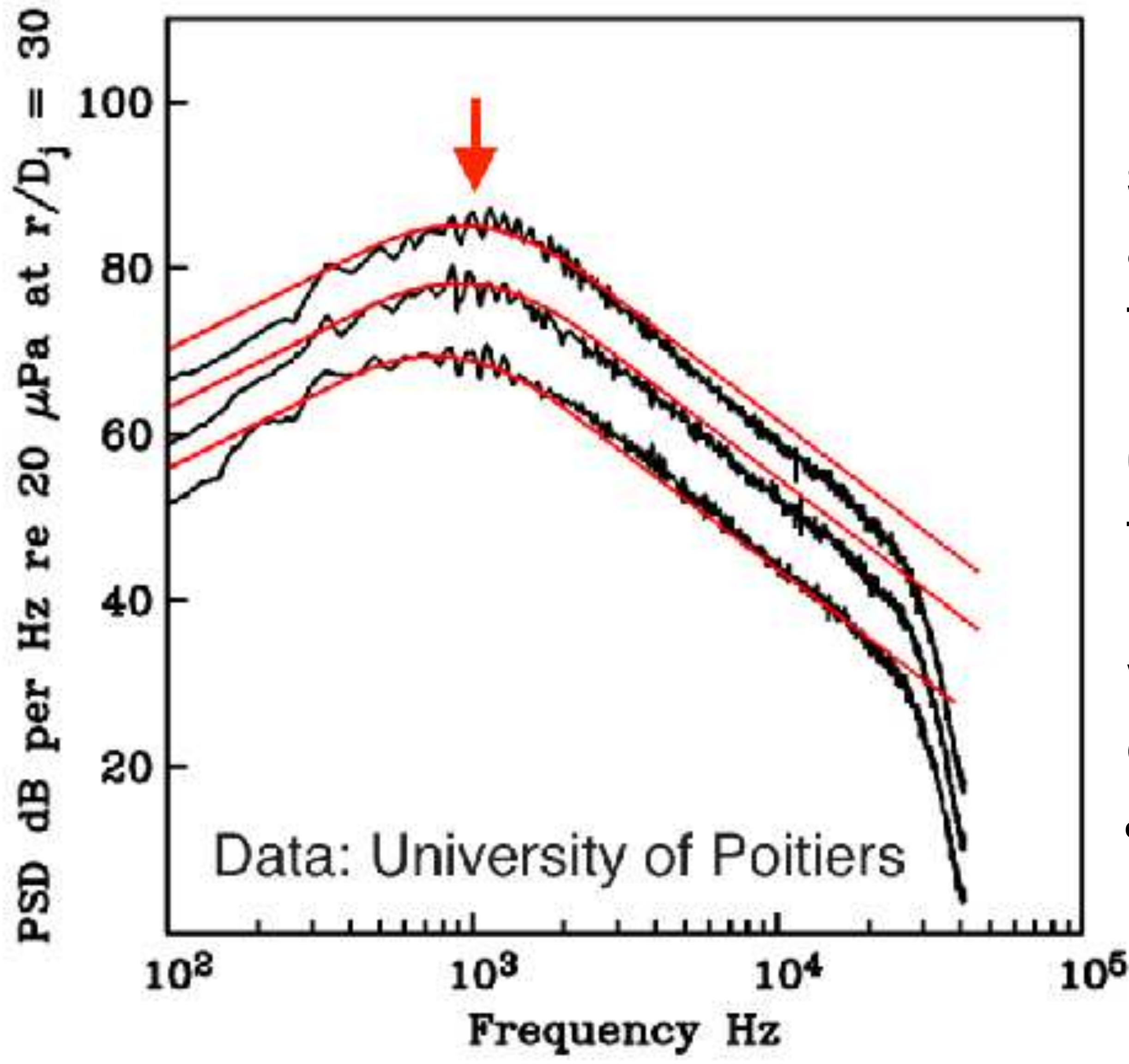
- Noise generation mechanisms appear to scale

$$St = \frac{f D_j}{U_j}$$

Volcano infrasound data



Laboratory jet noise data



Fits of the LST similarity spectrum (red) to acoustic data (black) from 3 laboratory jets: Mach numbers 0.60, 0.75, 0.9; with temperature ratios of 1.0, and r/D$_j$ = 30, where r = 1.5 m, D$_j$ = 5 cm. Data from *Koenig et al.*, [2010, 2011].

Limitations of fit:

- Spectral notch
- High-frequency roll-off

Matoza et al. [2009]

Hypotheses

Volcanic jet noise likely deviates from pure-air laboratory jets because of, e.g.,

1. Multiphase flow (e.g., tephra particles)
2. Nozzle/crater geometry and roughness
3. High-temperature and density effects
4. Buoyancy effects

image: P.A. Ramon, IG-EPN

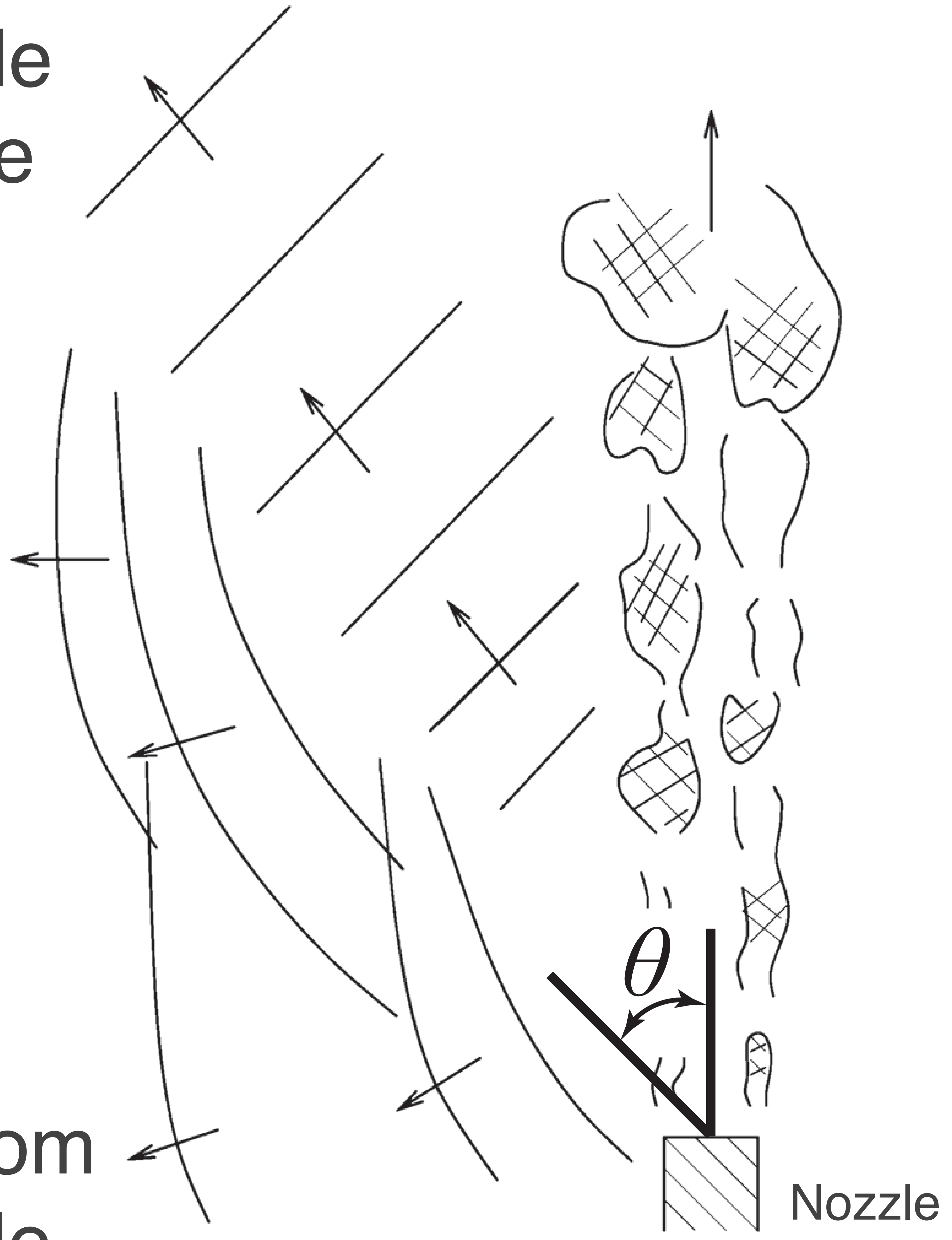
Tungurahua Volcano, Ecuador

image: C. Waythomas AVO/USGS

Redoubt Volcano, AK

Jet noise directionality

- Known that jet noise is **highly directional** (does not radiate sound equally in all directions)



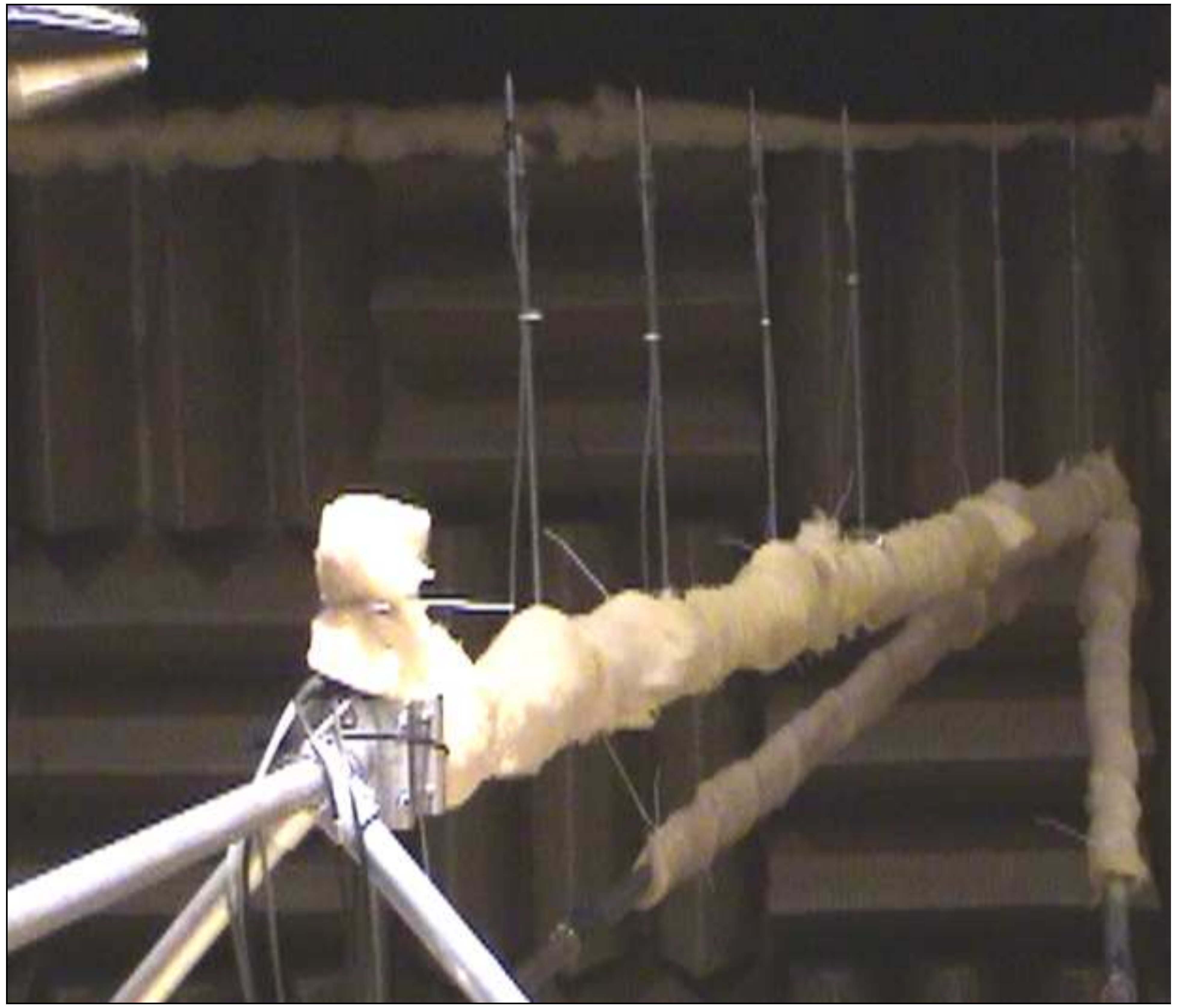
Noise from large-scale turbulence

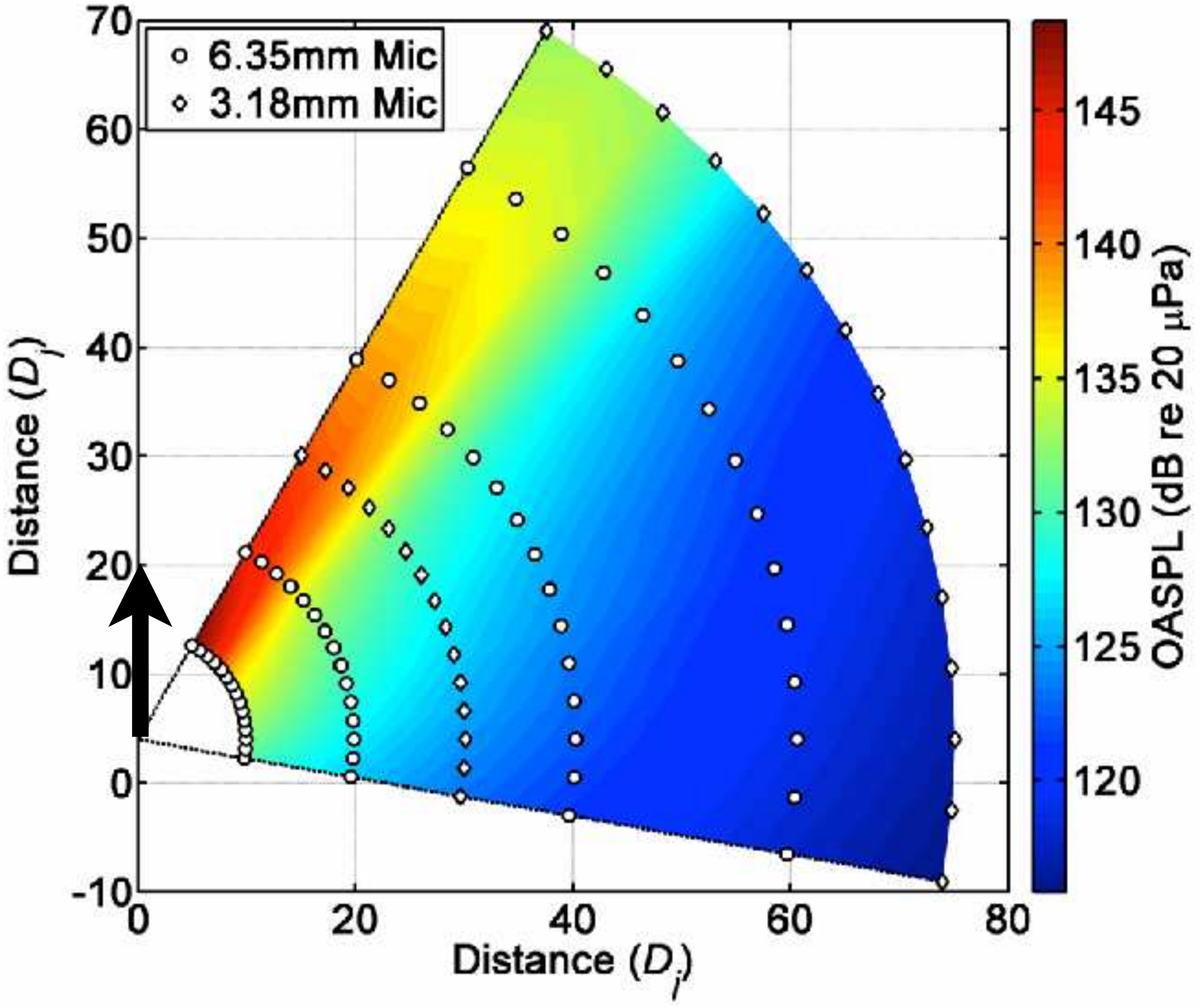
Noise from fine-scale turbulence

Tam et al., [2008]

Consequences of jet noise directionality

1. Acoustic power $\overline{\Pi}$ estimates require sampling of jet directionality





Laboratory study of jet noise [Gee et al. 2010]

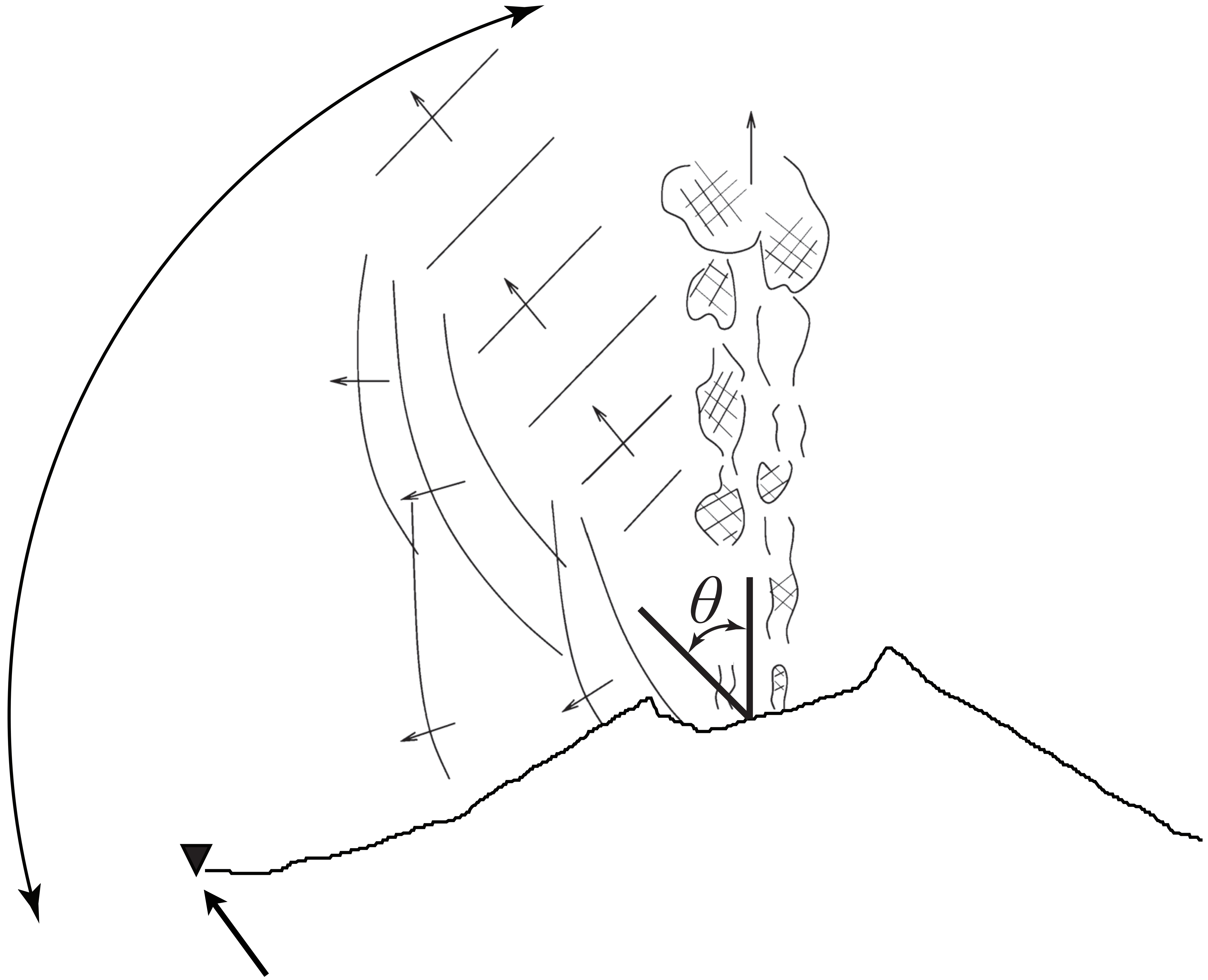
Consequences of jet noise directionality

1. Acoustic power $\overline{\Pi}$ estimates require sampling of jet directionality

Field study of jet noise from a large solid rocket motor [Gee et al. 2013]

Consequences of jet noise directionality

1. Acoustic power $\overline{\Pi}$ estimates require sampling of jet directionality

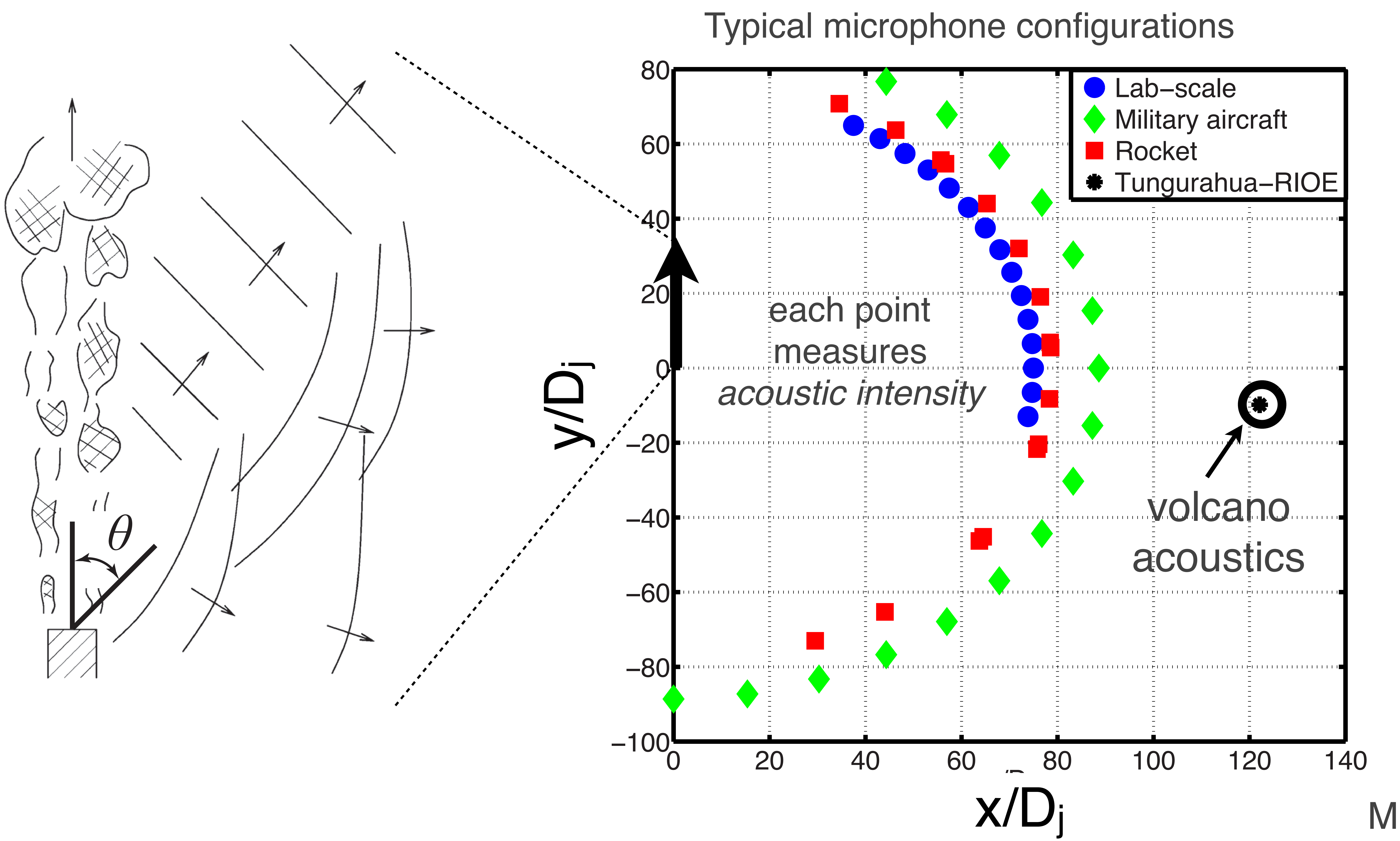


Infrasound sensor

Matoza et al. [2013]

Consequences of jet noise directionality

2. Acoustic *intensity* should be used instead (power per unit area)



Typical microphone configurations

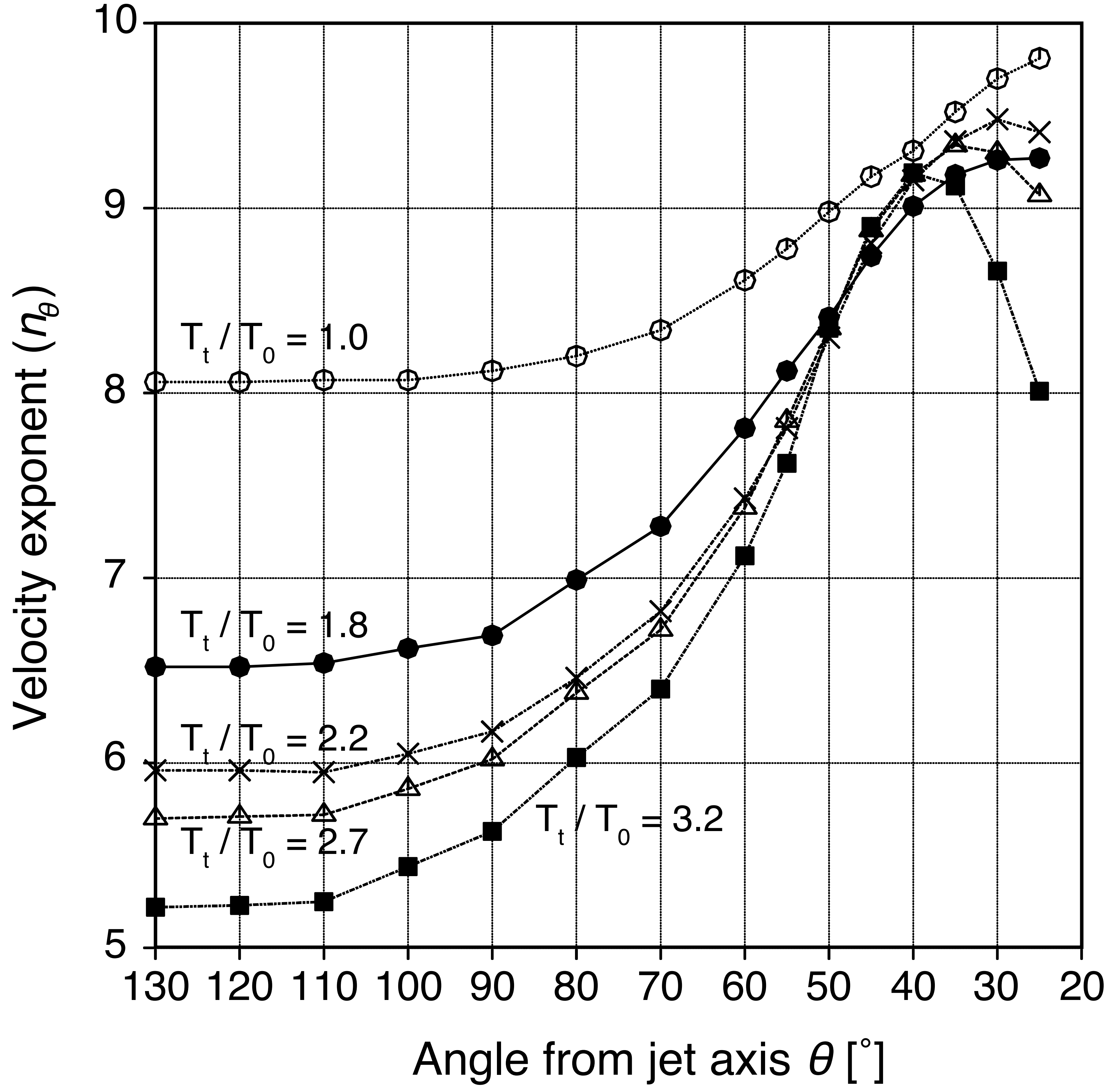
each point measures *acoustic intensity*

volcano acoustics

Matoza et al. [2013]

Acoustic intensity (power per unit area)

Results from pure-air jet noise studies:



Viswanathan [2006]

acoustic intensity

velocity

$$\overline{I}_\theta \propto \left(\frac{V_j}{c}\right)^{n_\theta}$$

$$n_\theta = n_\theta\left(\theta, \frac{T_t}{T_0}\right)$$

Velocity exponent is a non-linear function of:

1) Angle from the jet axis

2) Temperature

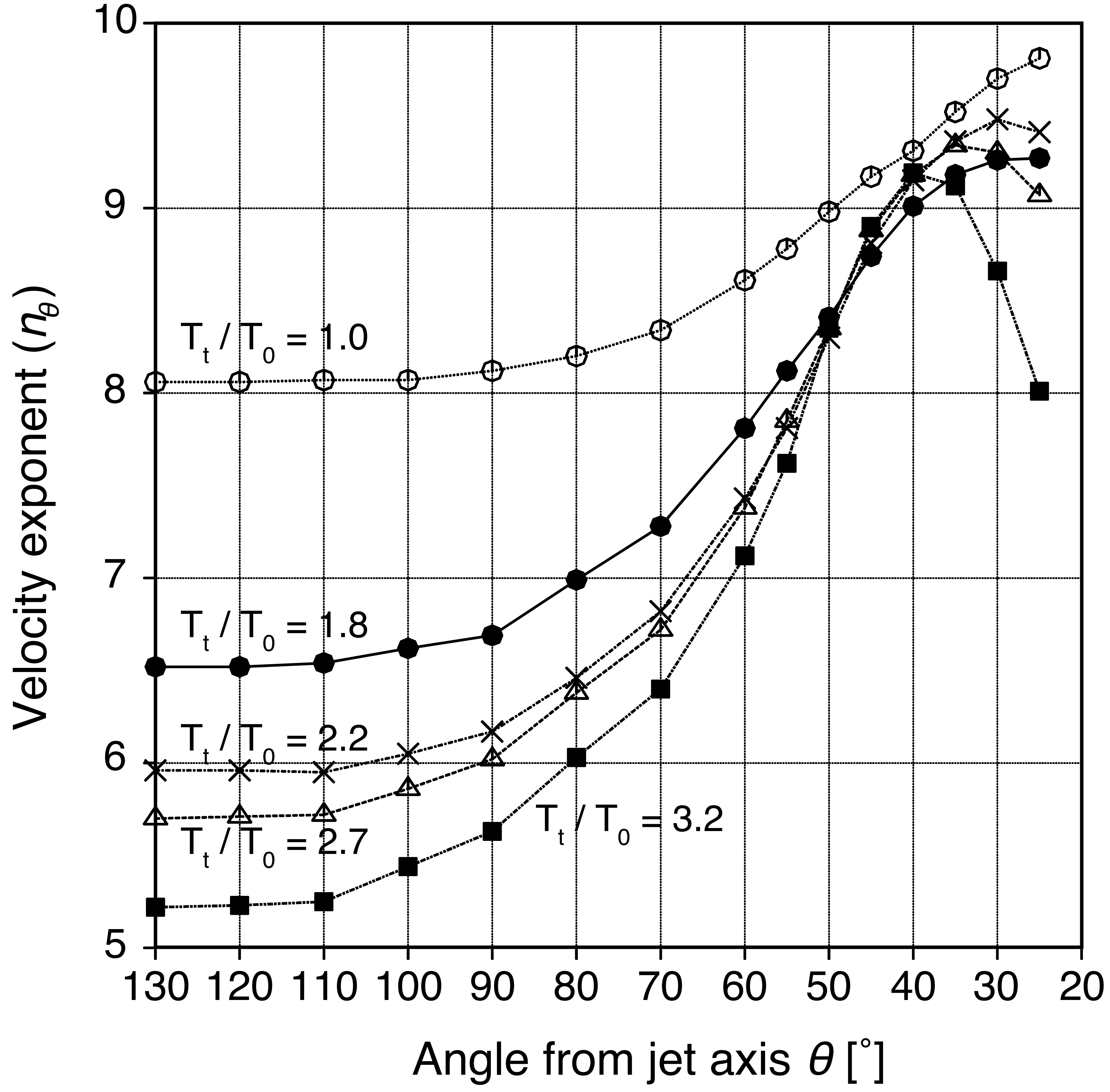
Contrast Woulff and McGetchin: 4, 6, or 8

Matoza et al. [2013]

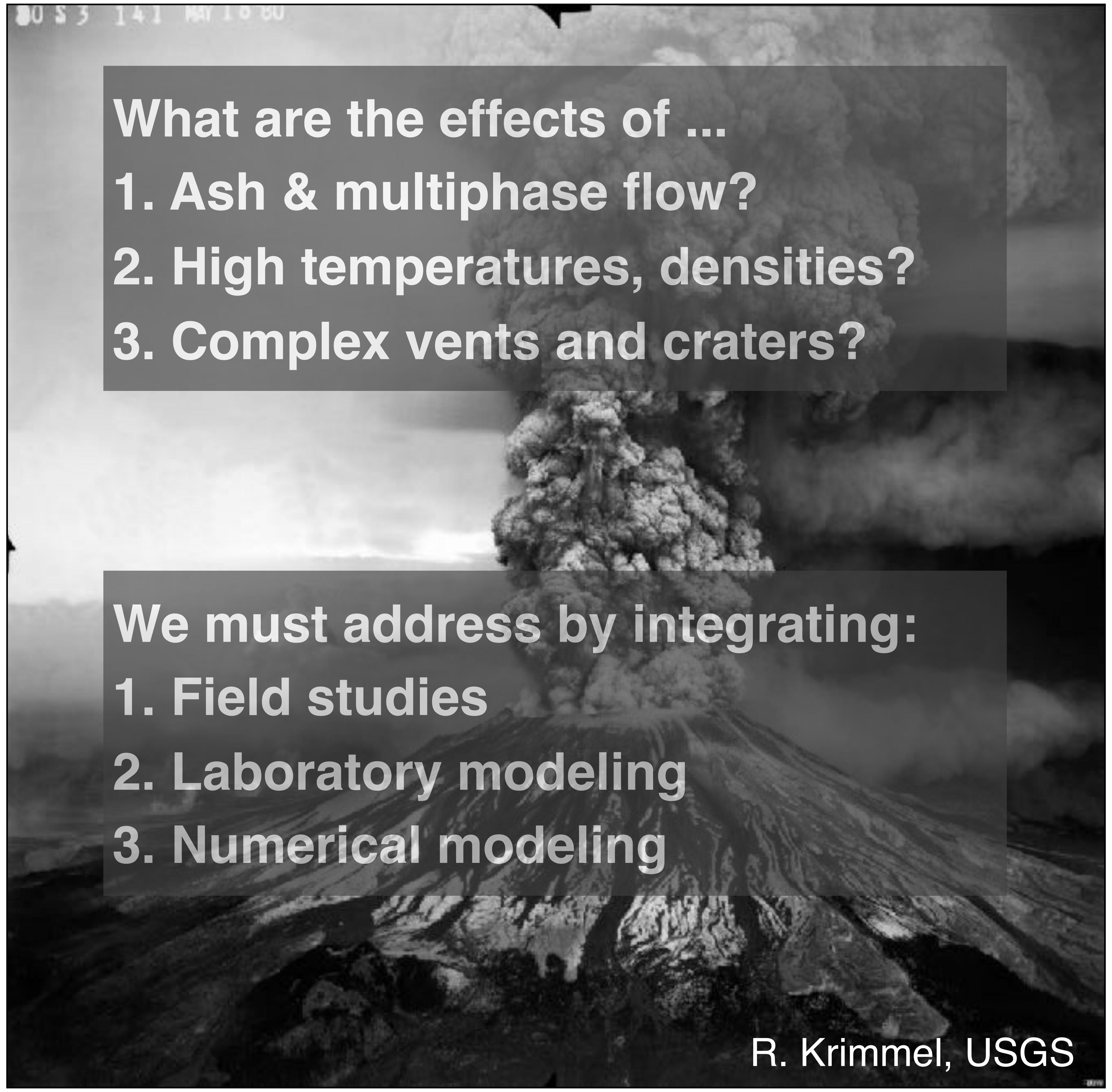
Implications for volcano acoustics

What are the exponents for acoustic intensity for a volcanic jet?

Results from pure-air jet noise studies:



Viswanathan [2006]



What are the effects of ...

1. **Ash & multiphase flow?**
2. **High temperatures, densities?**
3. **Complex vents and craters?**

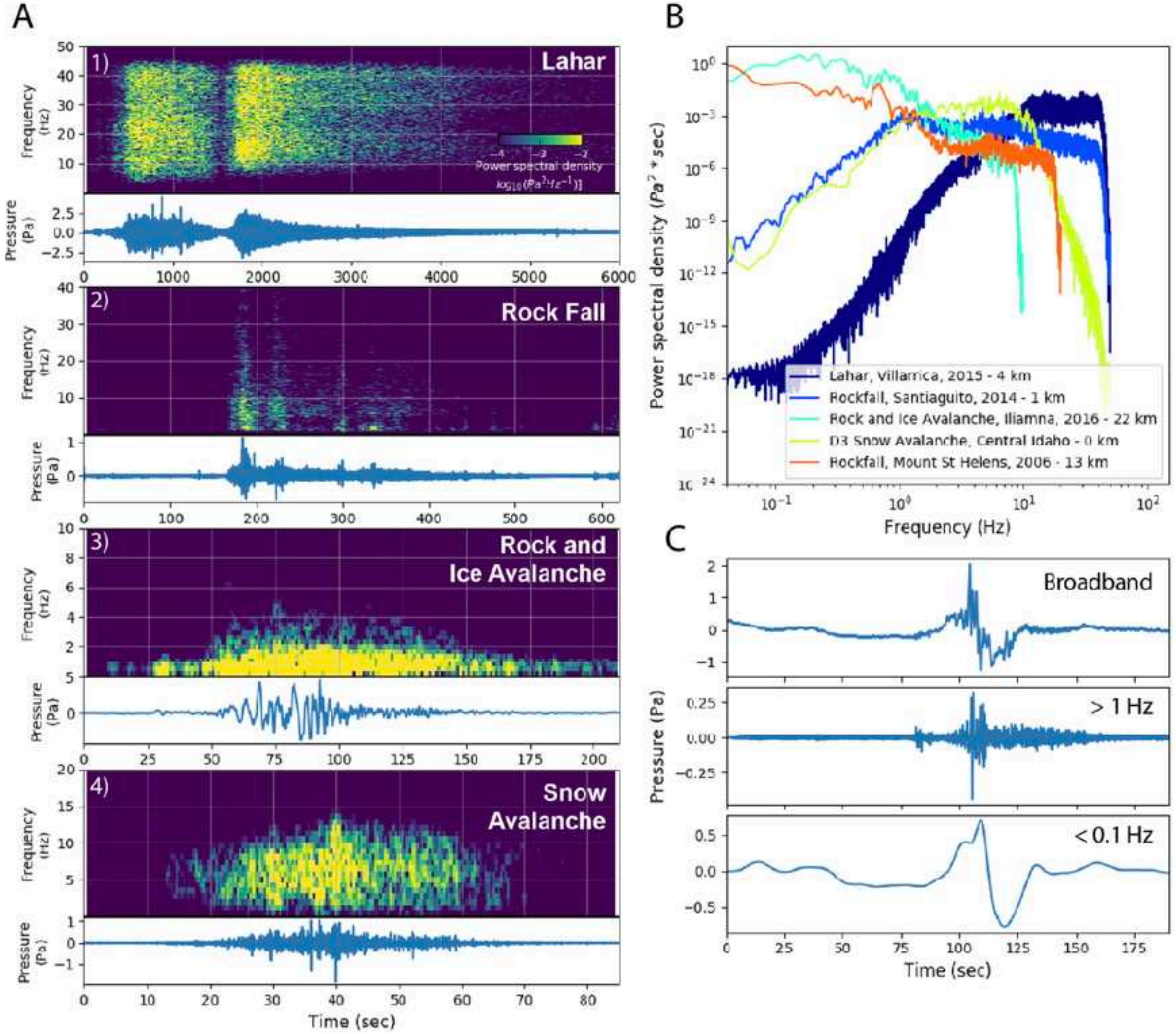
We must address by integrating:

1. **Field studies**
2. **Laboratory modeling**
3. **Numerical modeling**

R. Krimmel, USGS

Matoza et al. [2013]

Surficial mass movements at volcanoes



Allstadt, K.E., R.S. Matoza, A.B. Lockhart, S.C. Moran, J. Caplan-Auerbach, M.M. Haney, W.A. Thelen, and S.D. Malone (2018), Seismic and acoustic signatures of surficial mass movements at volcanoes, J. Volcanol. Geotherm. Res., 364, 76-106, doi:10.1016/j.jvolgeores.2018.09.007

Volcano Seismo-Acoustics: Future Directions

- Reanalysis of key data sets with new auto-classification tools – comparison to SO_2, tectonics, hydrothermal systems, etc.
- Integrated multi-parametric constraints on volcanic ground water systems
- Multi-parameter quantification of eruption columns