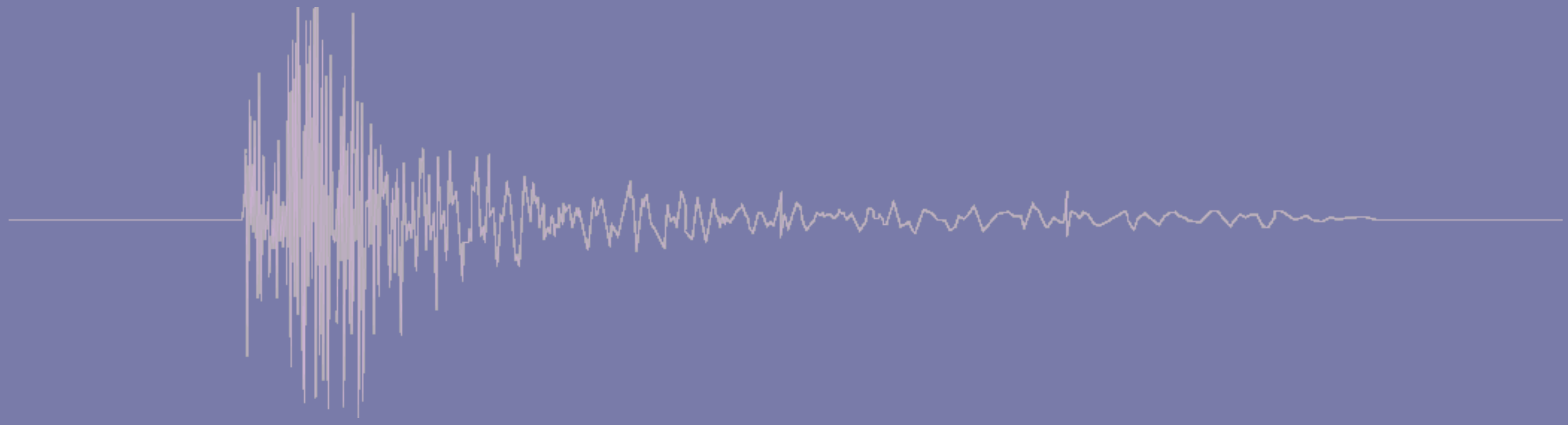
Overview of Volcano Seismology

Diana C. Roman (University of South Florida)
Greg P. Waite (Michigan Tech)



Talk Outline

- Introduction
- Networks and Instrumentation
- Event Classification
- Analysis and Interpretation
- Summary of Key Issues

Seismology is the study of vibrations within the Earth

Volcano Seismology is the study of vibrations resulting from volcanic processes (e.g., magma/gas/hydrothermal fluid movement)

- Uses similar instrumentation and analysis techniques
  - Smaller magnitudes
  - Noisy environments
  - Terrain issues
- Unique event types (requiring unique analytical approaches and interpretations)

Why monitor seismicity at potentially active volcanoes?

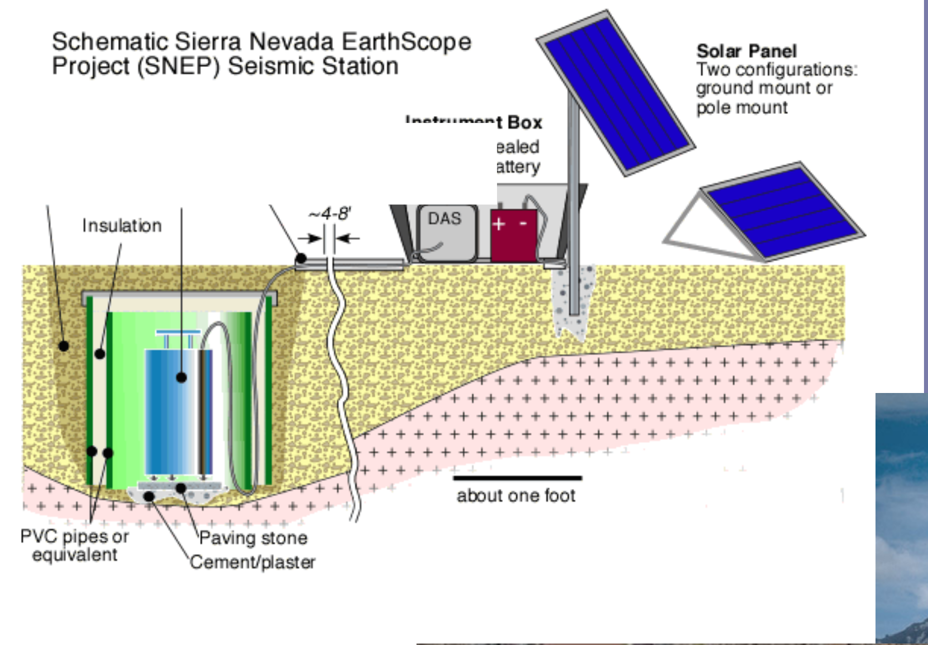
- An increase in seismicity is often one of the earliest detectable precursors
- Reasonably well-understood precursory patterns
- Remote sensing method

(Potential) information provided by volcanic seismicity:

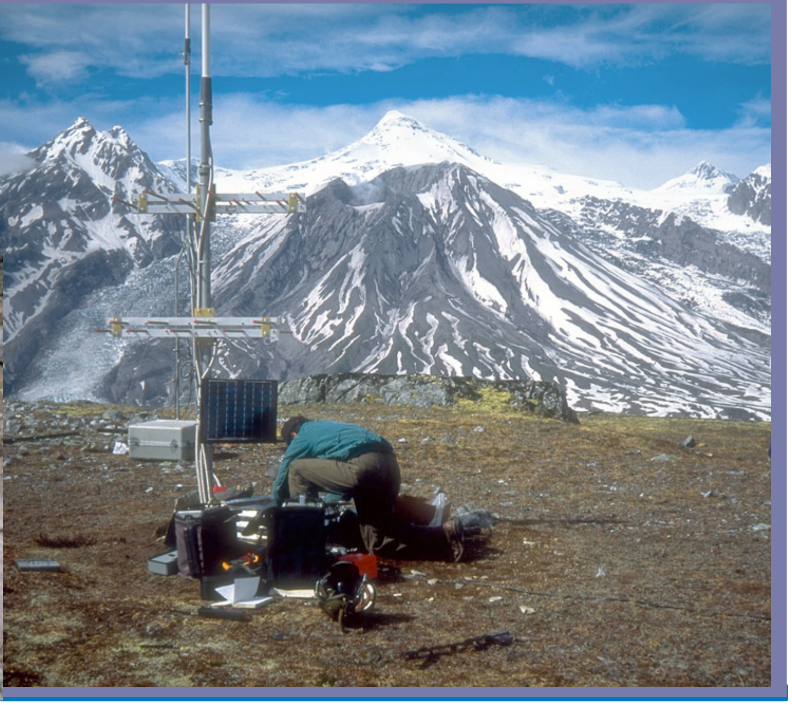
- Eruption likelihood, eruption timing, eruption location
- Based largely on a pattern-recognition approach supported by theoretical/experimental work
  - Highly data-limited field!

- Volcanic seismicity does not generally appear to indicate eruption size, eruption duration, or eruption style

Seismic station – seismometer, recorder and/or telemetry, power system



Portable vs. Permanent Configurations

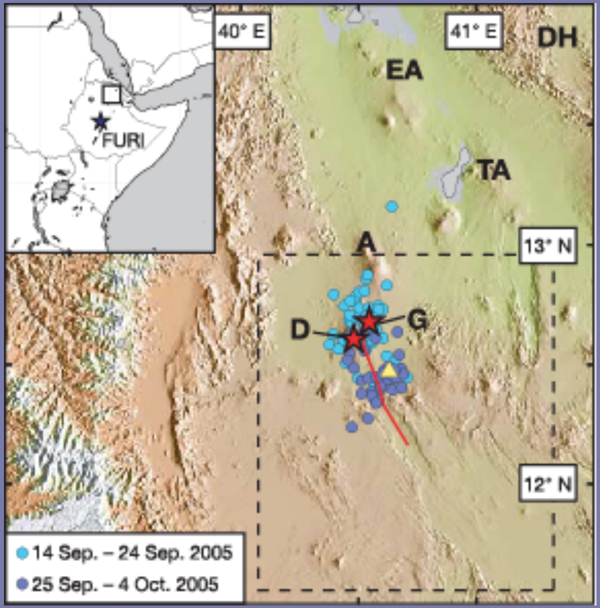


Seismic networks:

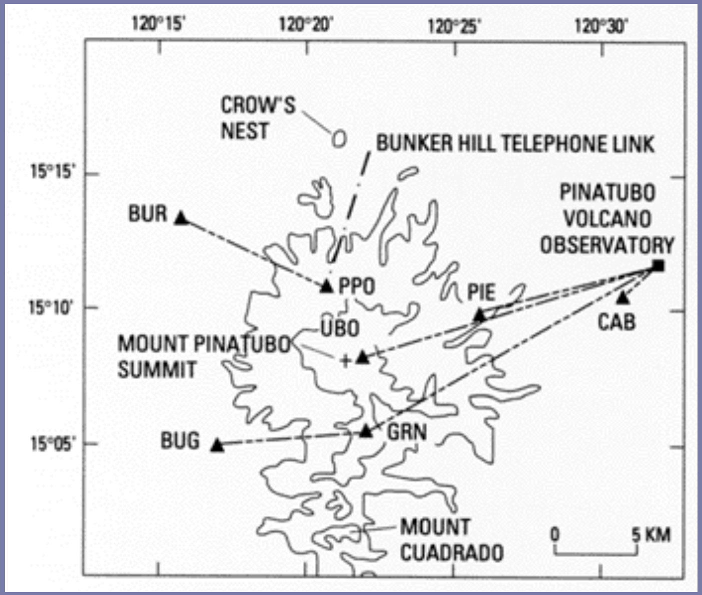
One station:
Event counts
Relative movement of events (P-S)
Changes in event type (SSAM)
Cannot distinguish volcanic/
nonvolcanic signals!

4-6+ stations:
High-accuracy locations
Fault-plane solutions/moment tensors
Tomography, etc.

- Often a two-stage network is utilized (problematic!)



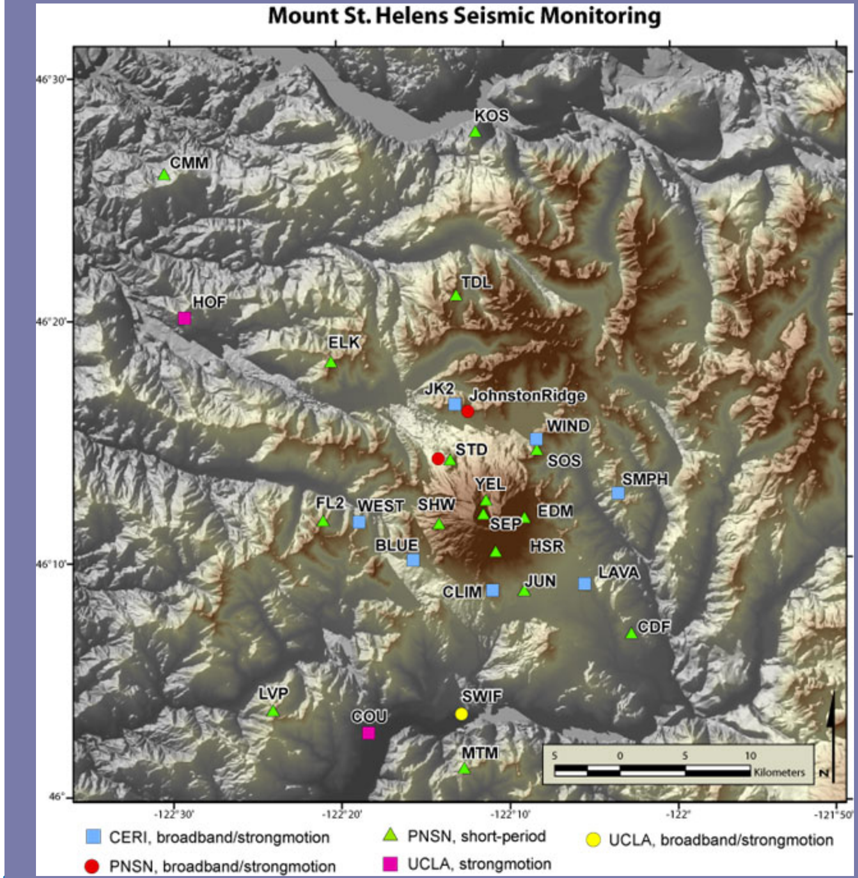
Single station network, northern Ethiopia

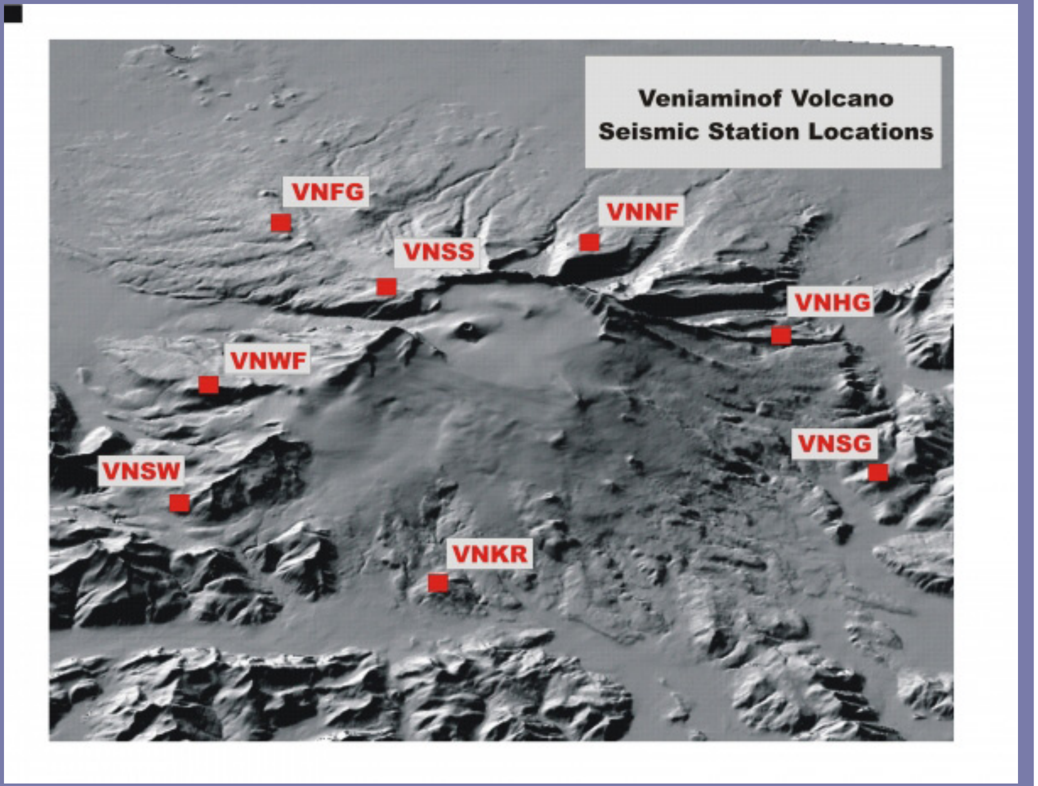


Mt. Pinatubo seismic network

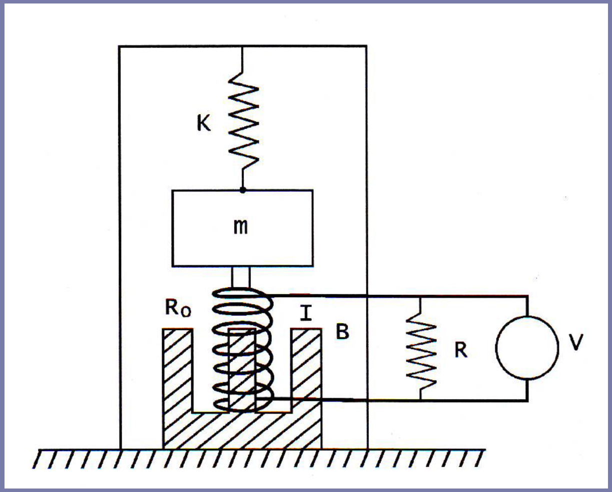
Seismic network configuration:

- Limited by terrain/telemetry considerations (power/noise/safety/accessibility)
- Local/regional, depth control, no azimuthal gaps





Seismometers:



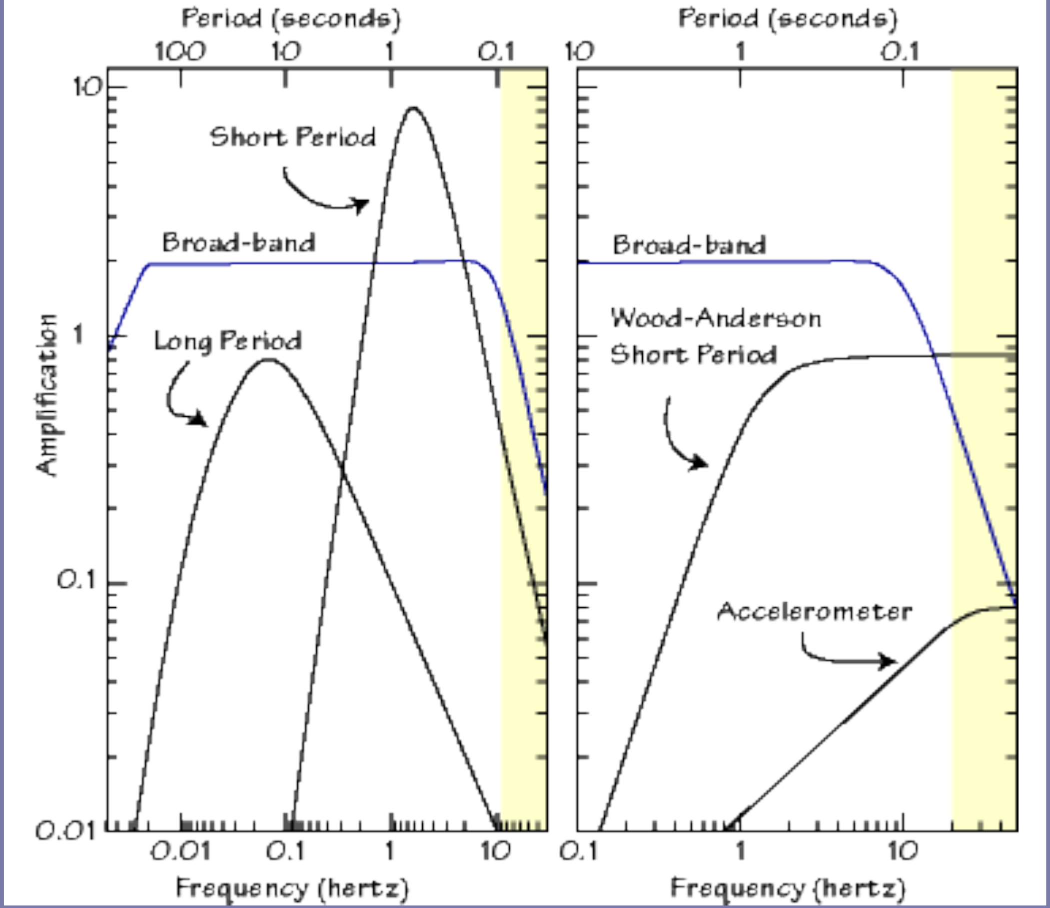
Frame fixed to Earth, free (damped) pendulum, electric coil moving in magnetic field, generates current proportional to relative velocity of mass and frame (must integrate for ground displacement)

Broadband instruments – force feedback

Signal is amplified and converted from analog to digital at an appropriate frequency (0.1-200 Hz)

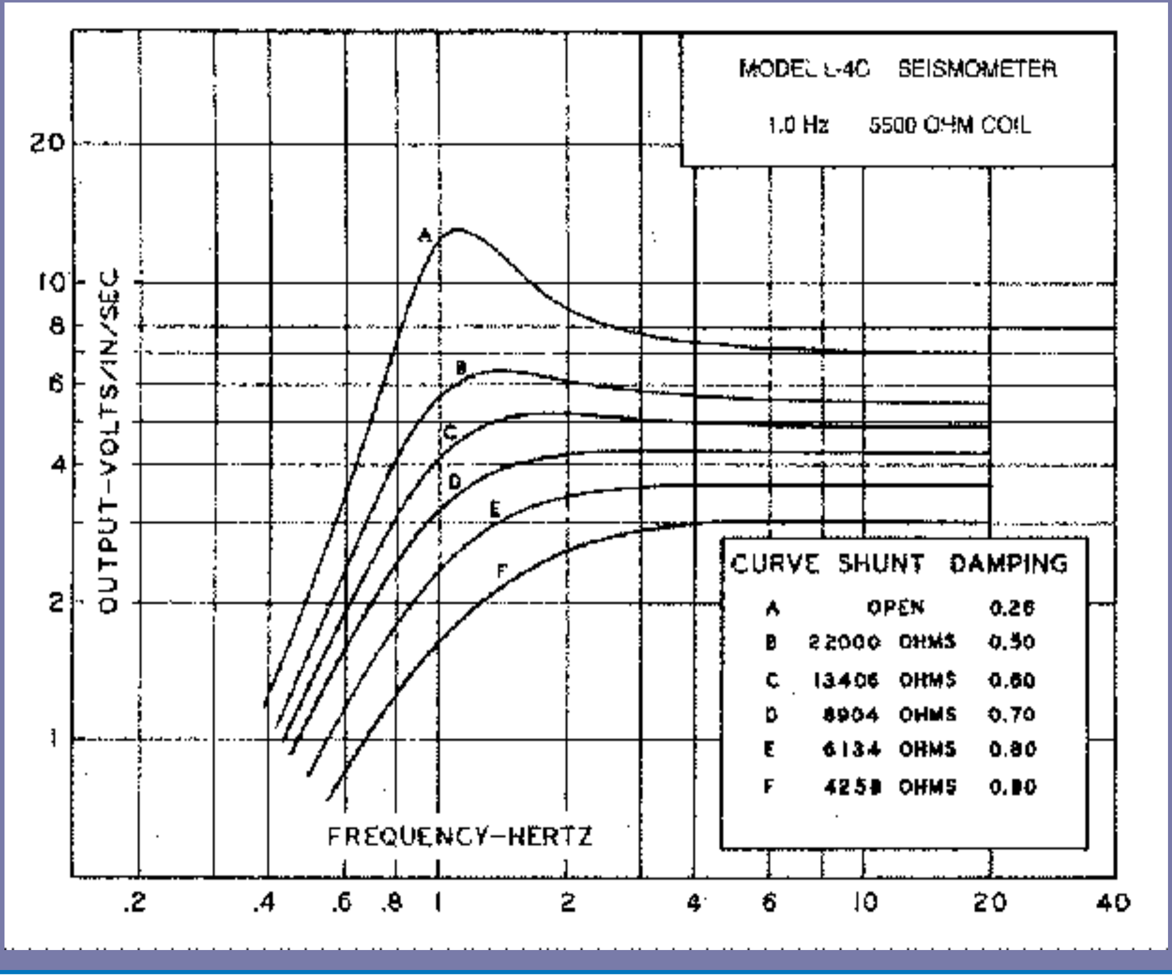
Seismometer classes:

- 1-c (vertical) vs. 3-c (vertical and horizontal)
- Borehole (attenuation is greatest in upper 100m)
- Strong-motion (accelerometer – not common on volcanoes)
- Short-period/broadband



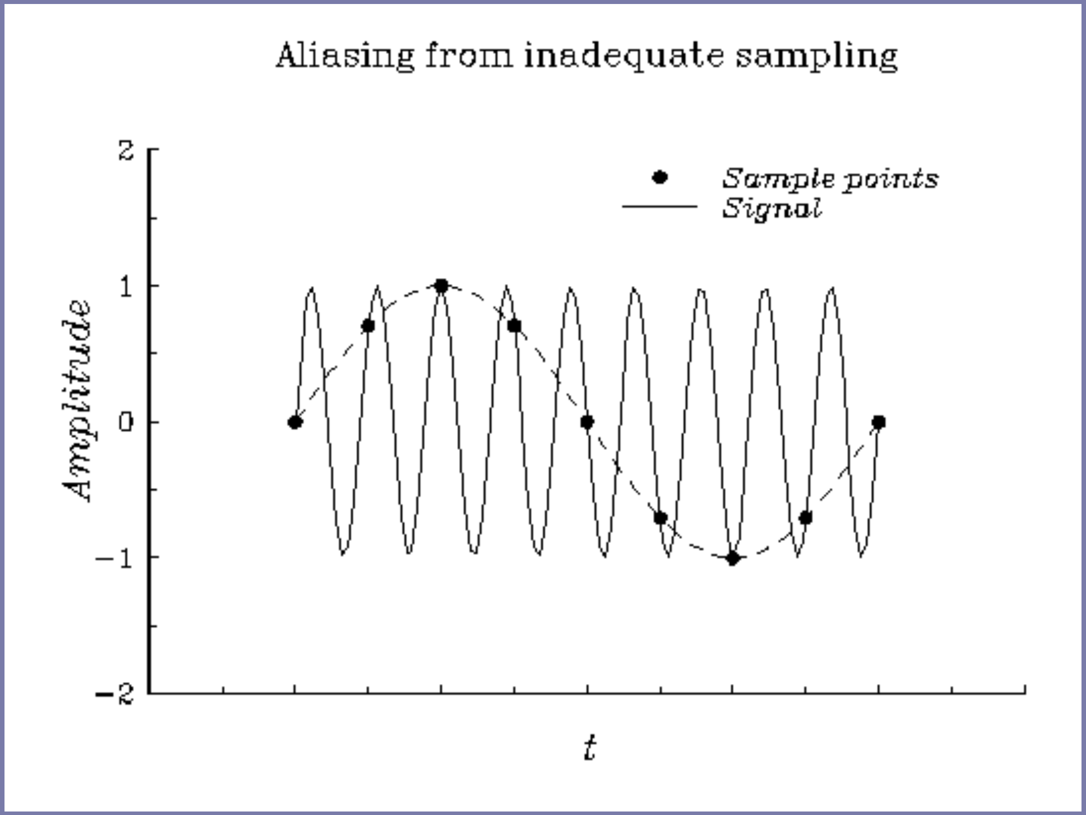
Seismometers as filters:

Natural frequency of the instrument
(amplifies response at this frequency)



Seismometers as filters:

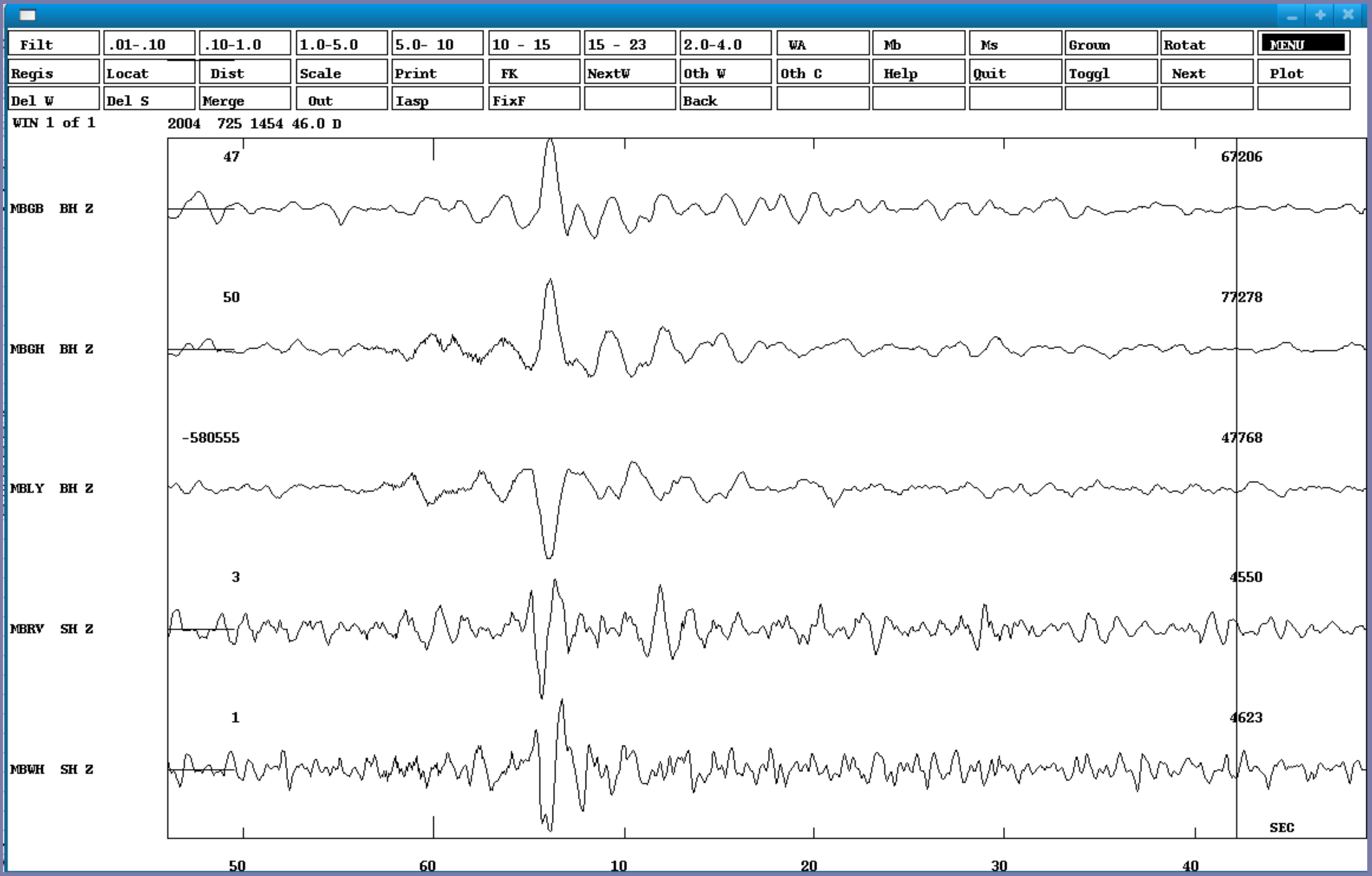
Aliasing (sampling frequency too low)



Anti-aliasing filters, Nyquist frequency

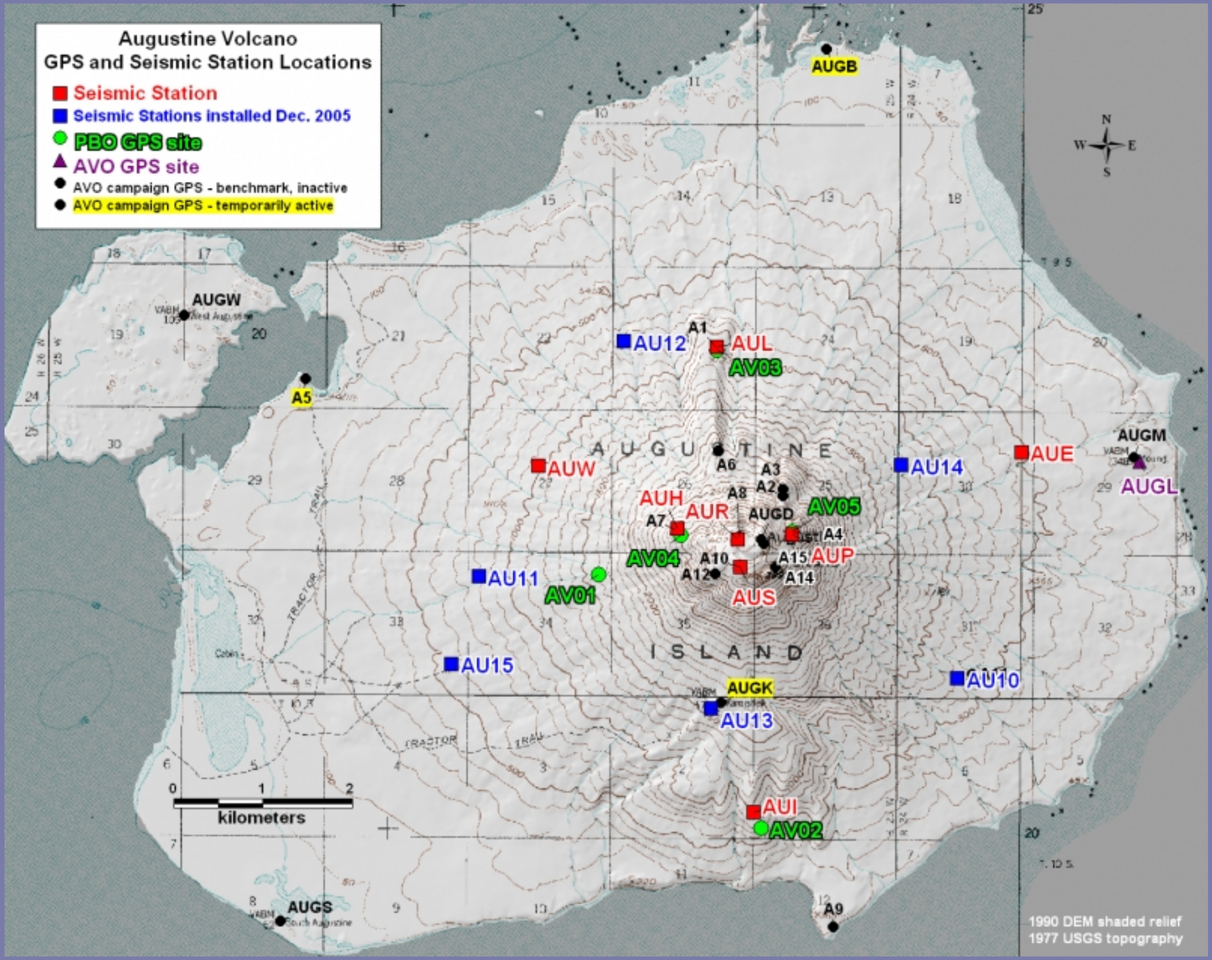
Instrumentation Problems:

- Polarity reversal (teleseisms)



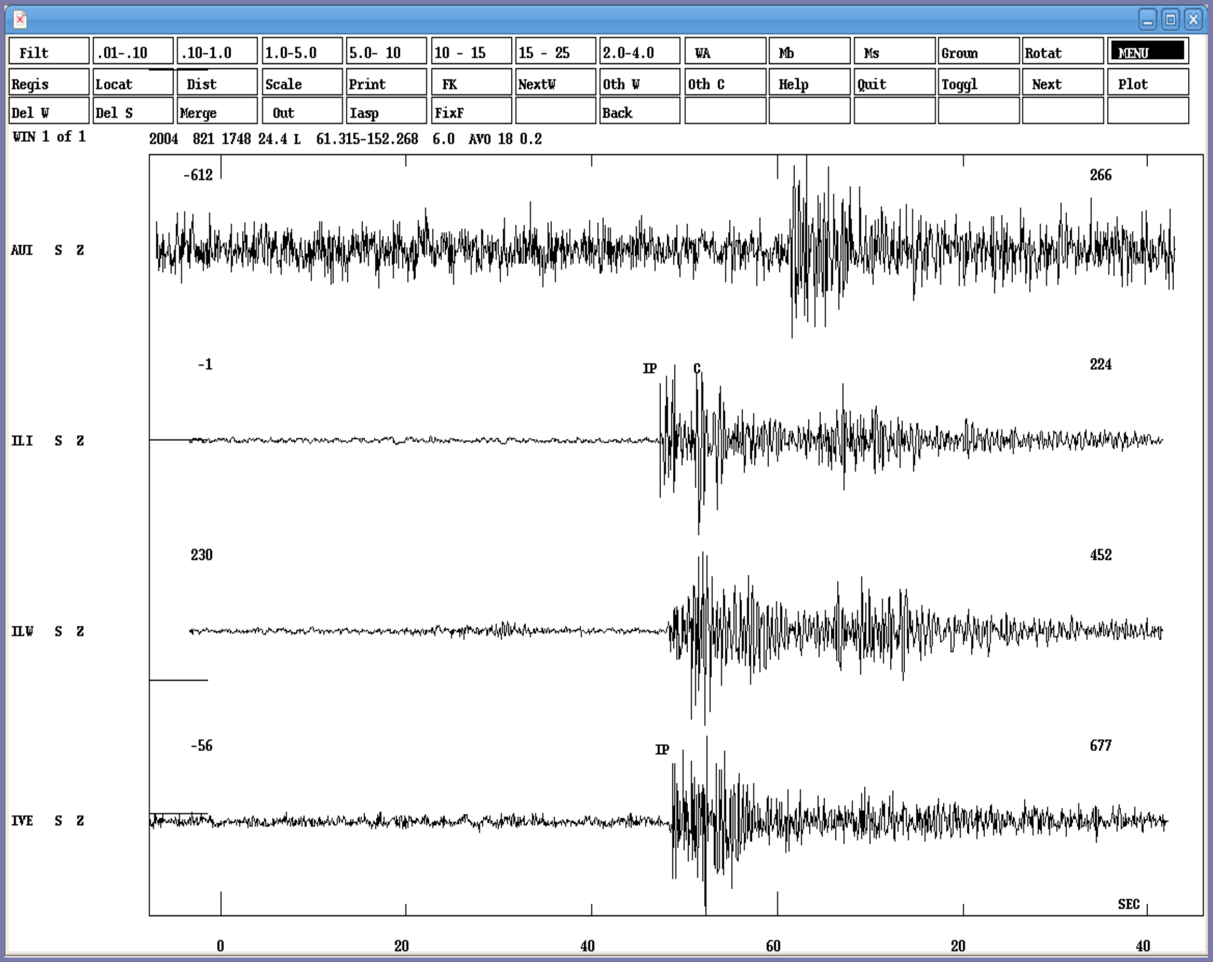
Instrumentation Problems:

- Site effects (noise amplification)



Instrumentation Problems:

- Site effects (noise amplification)



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2004  821 1748 24.4 L  61.315-152.268  6.0  AVO 18 0.2
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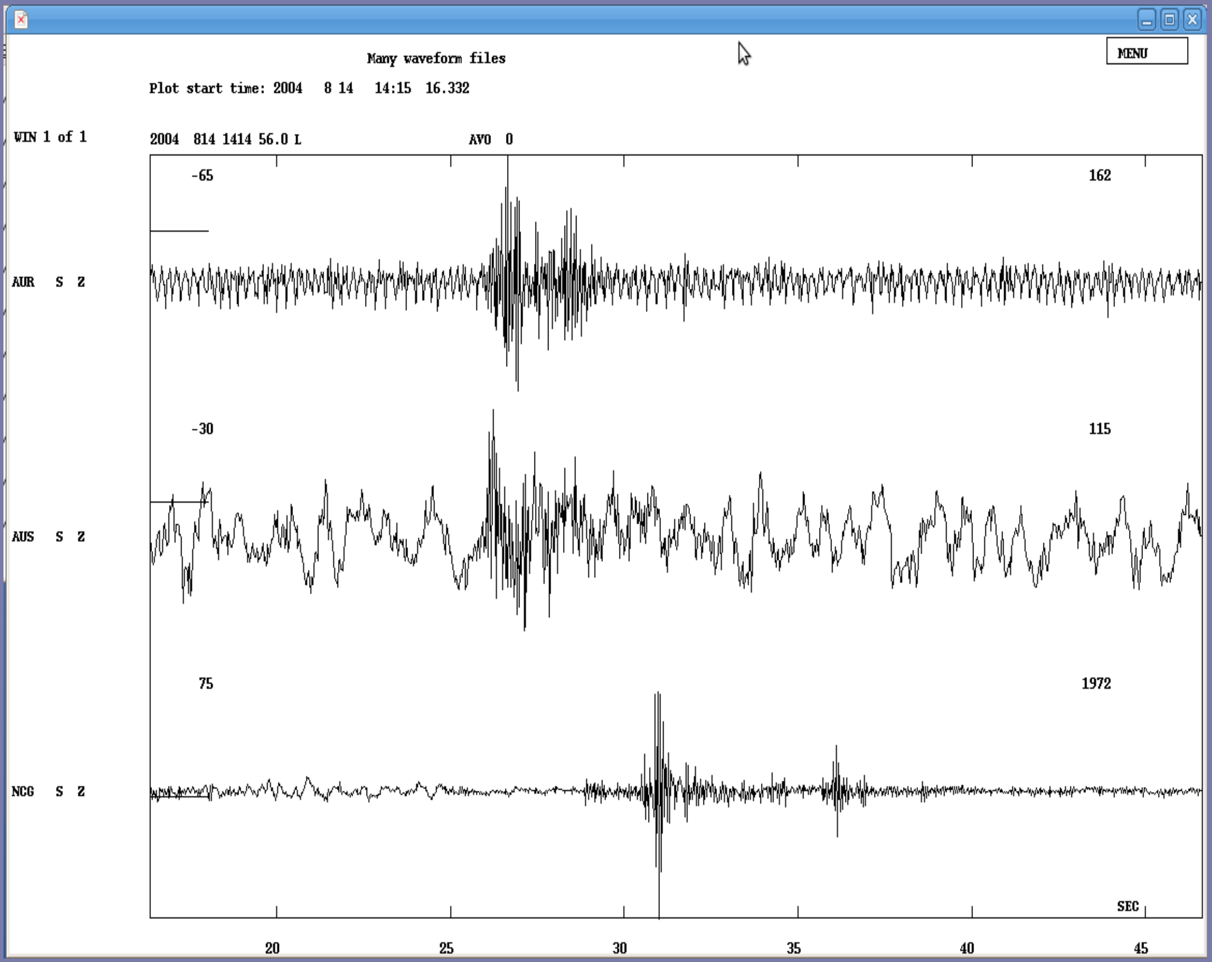
Instrumentation Problems:

- Site effects (noise amplification)



```
Many waveform files
Plot start time: 2004   8 14   14:15  16.332
WIN 1 of 1
2004  814 1414 56.0 L                    AVO  0
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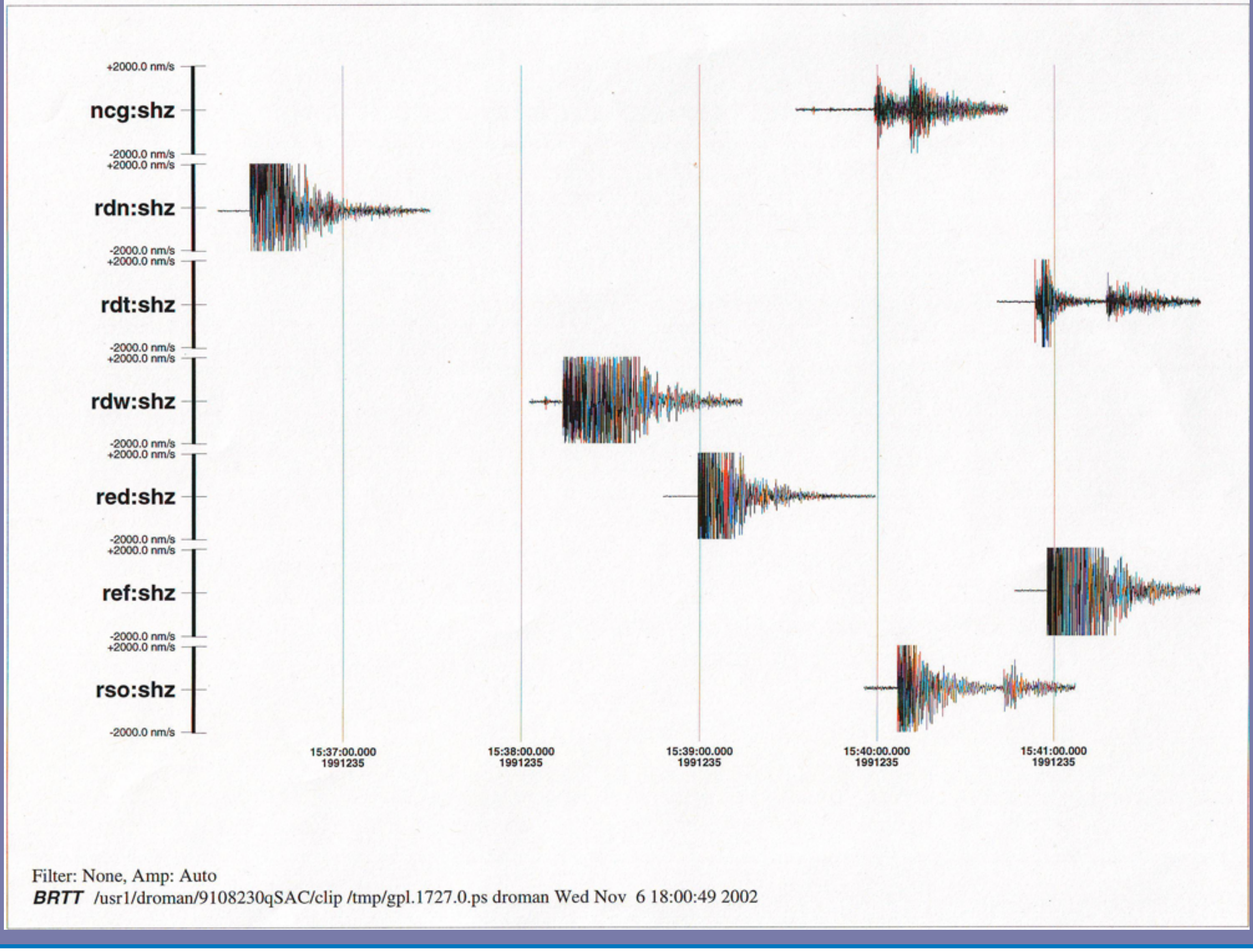
Instrumentation Problems:

- Clipping (dynamic gain-ranging, high/low-gain sensors, broadband instruments, strong-motion instruments)



Filter: None, Amp: Auto
BRTT /usr1/droman/9108230qSAC/clip /tmp/gpl.1727.0.ps droman Wed Nov 6 18:00:49 2002

Recording of seismic data:

- Continuous
- Event-detected (e.g., increase in STA/LTA at 3+ stations – write one minute of data)
- Data storage – magnetic tape, optical disks, CDs (can degrade or become obsolete)

Data formats:

- e.g., SAC, SEED, mini-SEED, AH (ascii/binary)
- Possible to convert between formats given adequate documentation
- Many are obsolete and/or obscure

Why is seismic event classification so important?

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

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 Types:

High frequency (~‘A-type’)
- VTs

Low frequency (~‘B-type’)
- LPs, (harmonic) tremor, VLPs, DLPs, tornillos

Surface signals
- Explosions
- Rockfalls/Pyroclastic Flows
- Icequakes
- Helicopter/wind/car/etc. noise

Regional/teleseismic events

Classification Schemes:

Based on dominant frequency and shape of onset/waveform (impulsive vs. emergent, envelope, length)

Minakami (1974) - “Seismology of volcanoes in Japan”

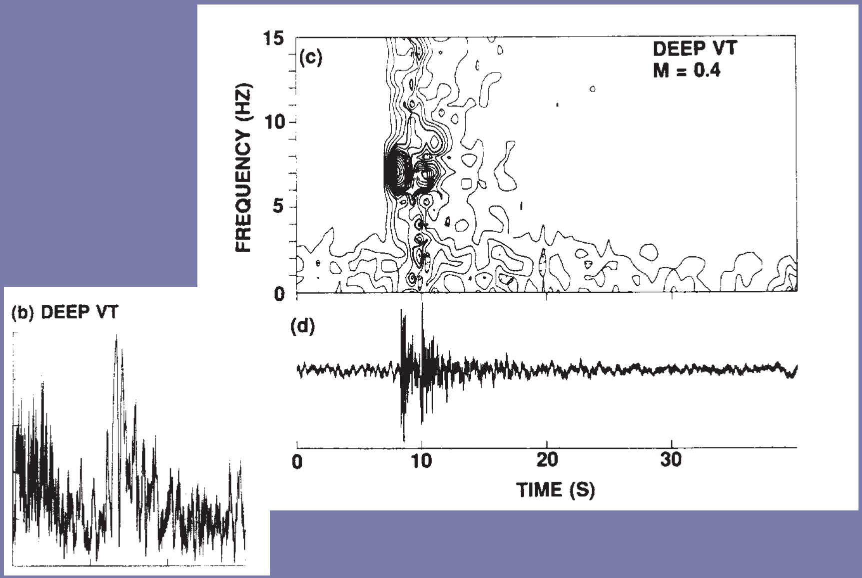
Lahr et al. (1994) – Redoubt Volcano
“Earthquake classification, location, and error analysis in a volcanic environment”

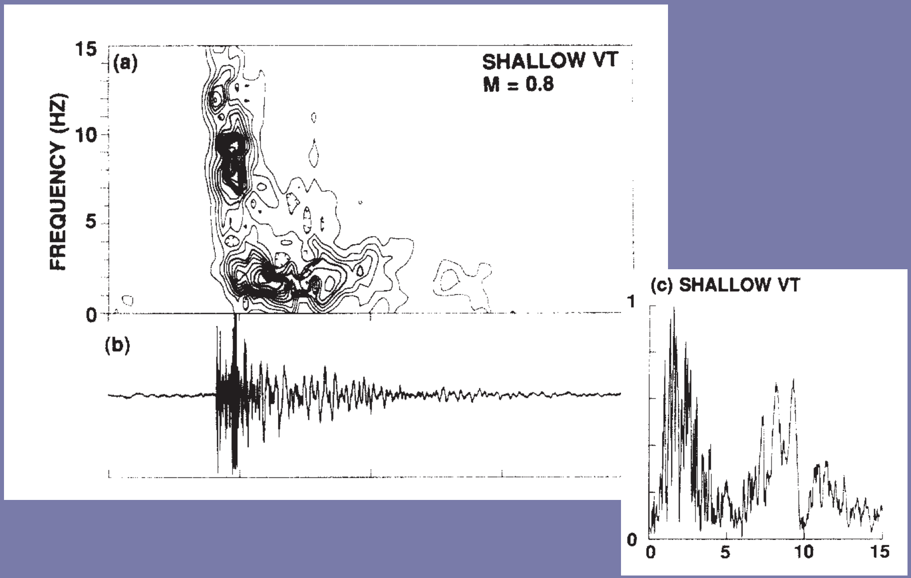
Miller et al. (1998) – Soufriere Hills Volcano
“Seismicity associated with dome growth and collapse at the SHV, Montserrat”

Lahr et al. (1994) definitions and type events:

Volcanotectonic (VT) earthquake:

- Short-period earthquakes resulting from brittle failure in response to stress changes associated with magmatic activity
- Clear high-frequency P and S waves, peak frequencies above 5 Hz, short coda

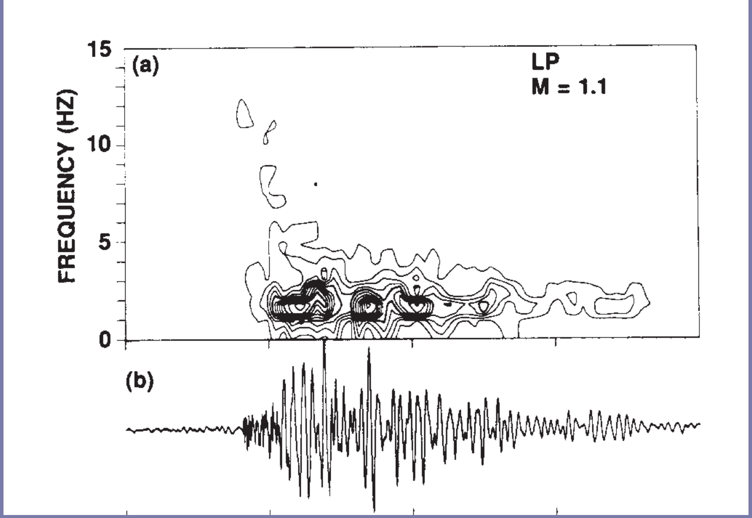


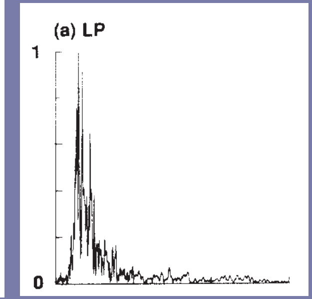


Lahr et al. (1994) definitions and type events:

Long period (LP) (aka 'low frequency') event:

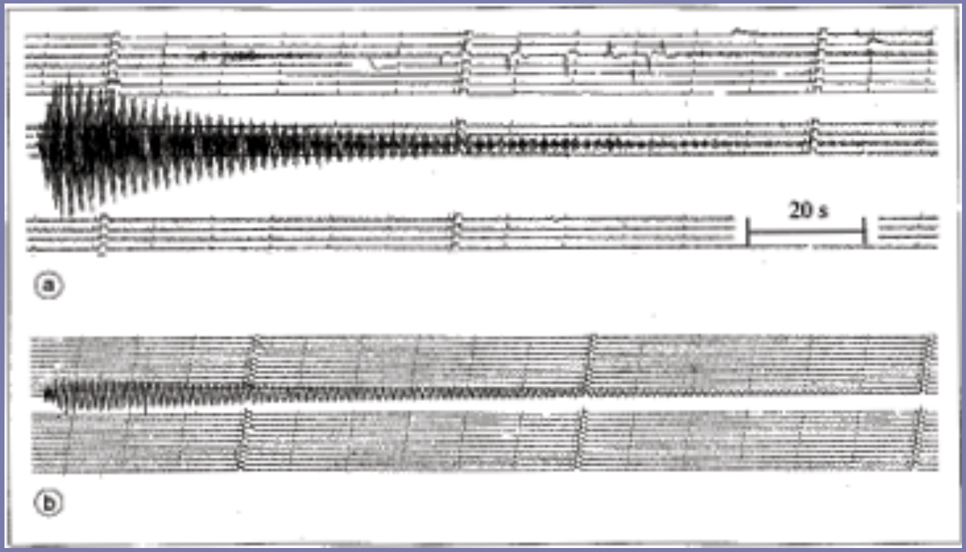
- Long-period 'earthquake' resulting from the resonance of fluid-filled cracks or conduits induced by pressure transients in the fluid
- Weak high-frequency onset followed by quasi-monochromatic oscillations with peak energy near 1.5 Hz, lasting 20s or more



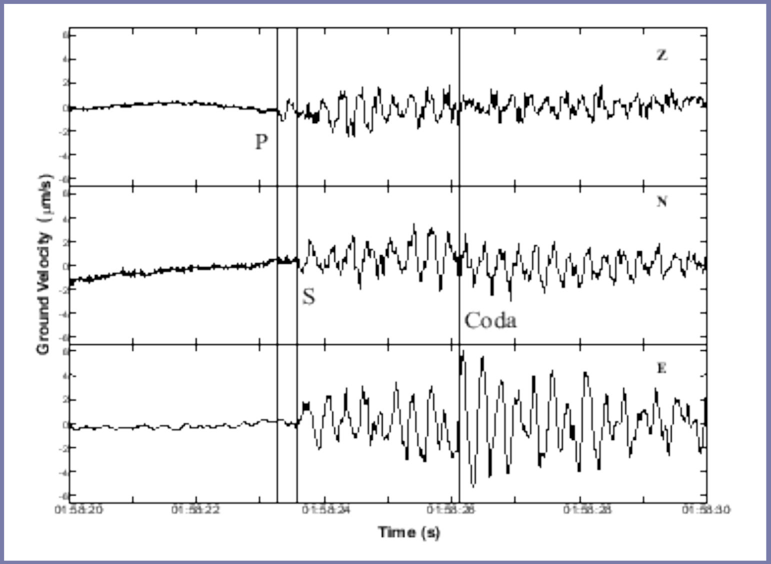


Tornillo:

Long-period event with a ‘screw-shaped’ coda, in some cases appear to have S-waves



Example from Galeras, Gomez et al. 1999

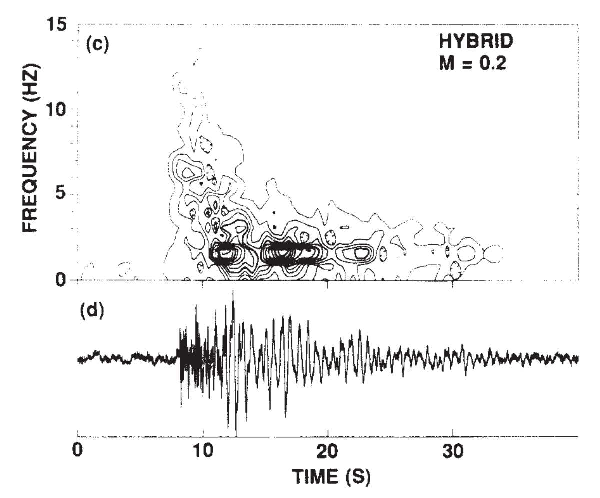


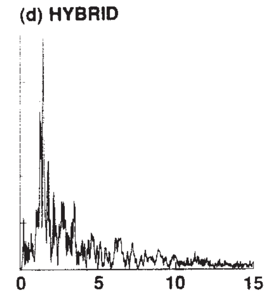
Example from Galeras, M. Hellweg, unpublished

Lahr et al. (1994) definitions and type events:

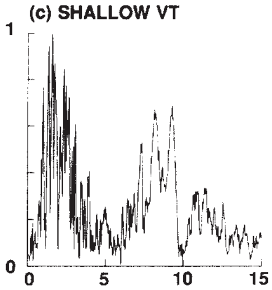
Hybrid event:

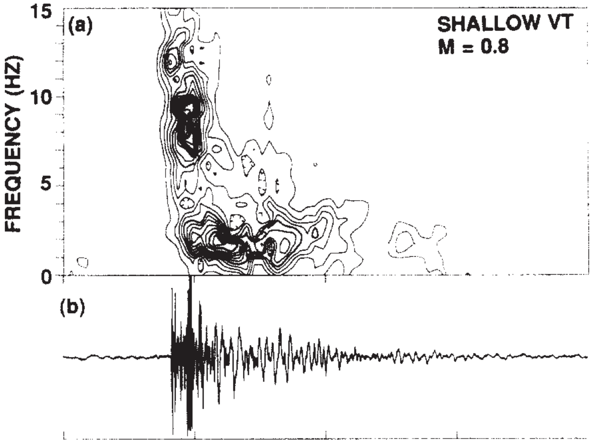
- Events resulting from brittle faulting in zones of weakness intersecting or nearby a fluid-filled crack (?)
- Mixed event consisting of a high-frequency onset and low frequency coda, mixed first-motions, non-dispersive harmonic wavetrain in coda

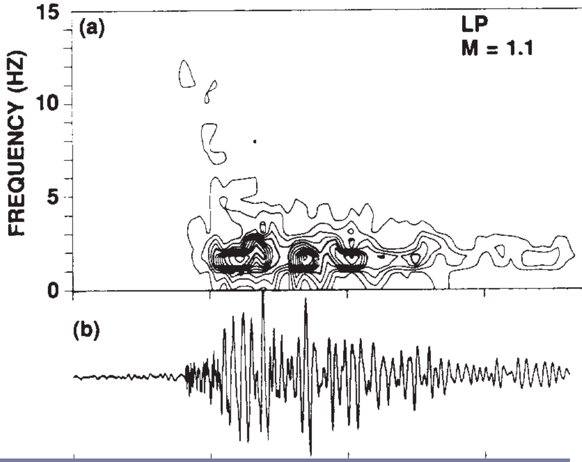


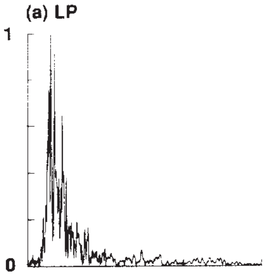


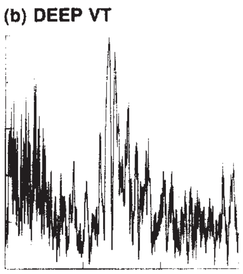
Overview Lecture/Event Classification

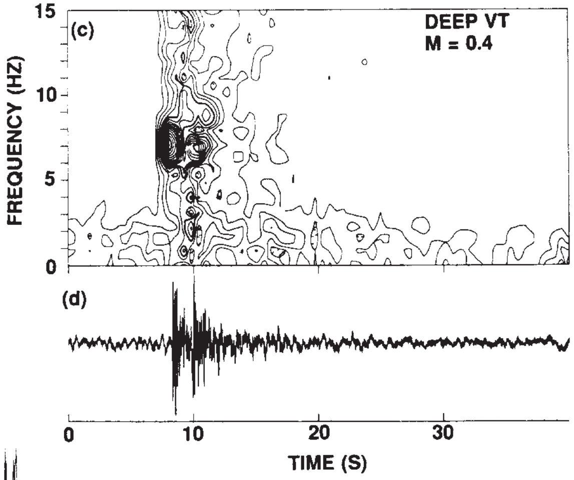


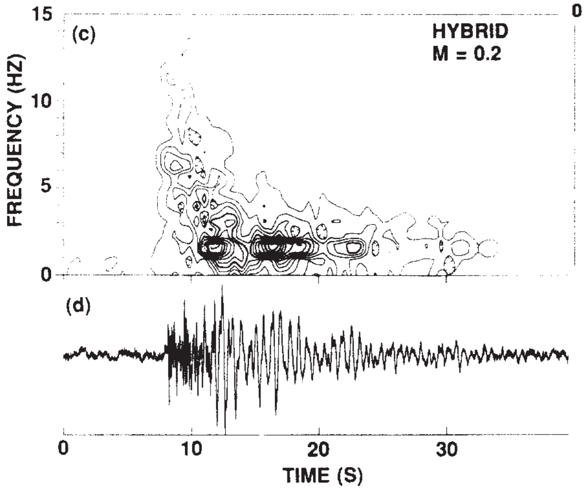


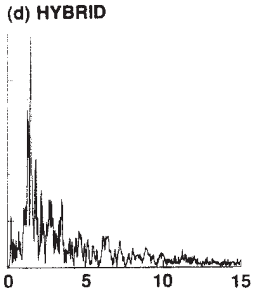












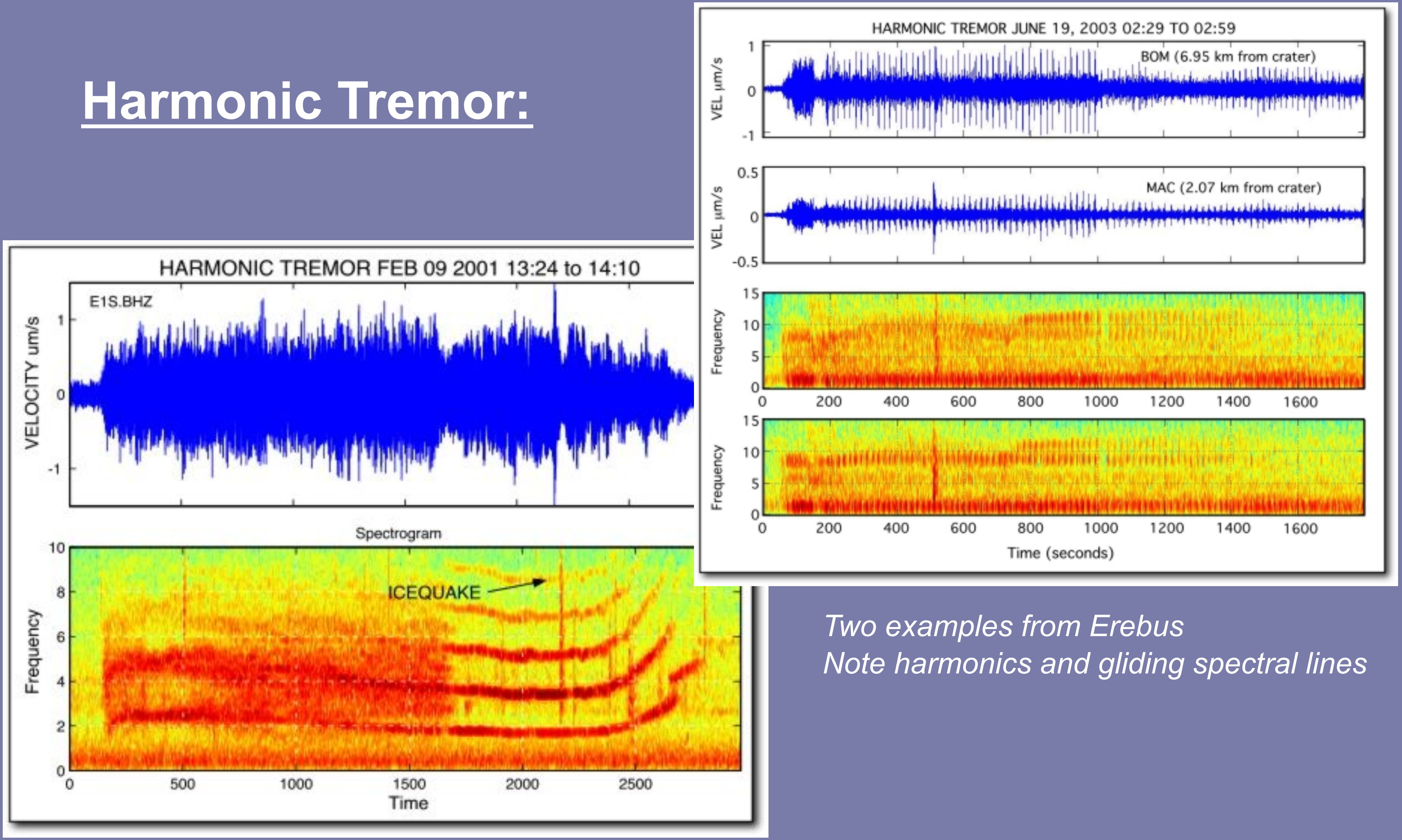
Figures from Lahr et al (1994)

Tremor (Miller et al. 1998):

A continuous seismic disturbance lasting for several minutes.

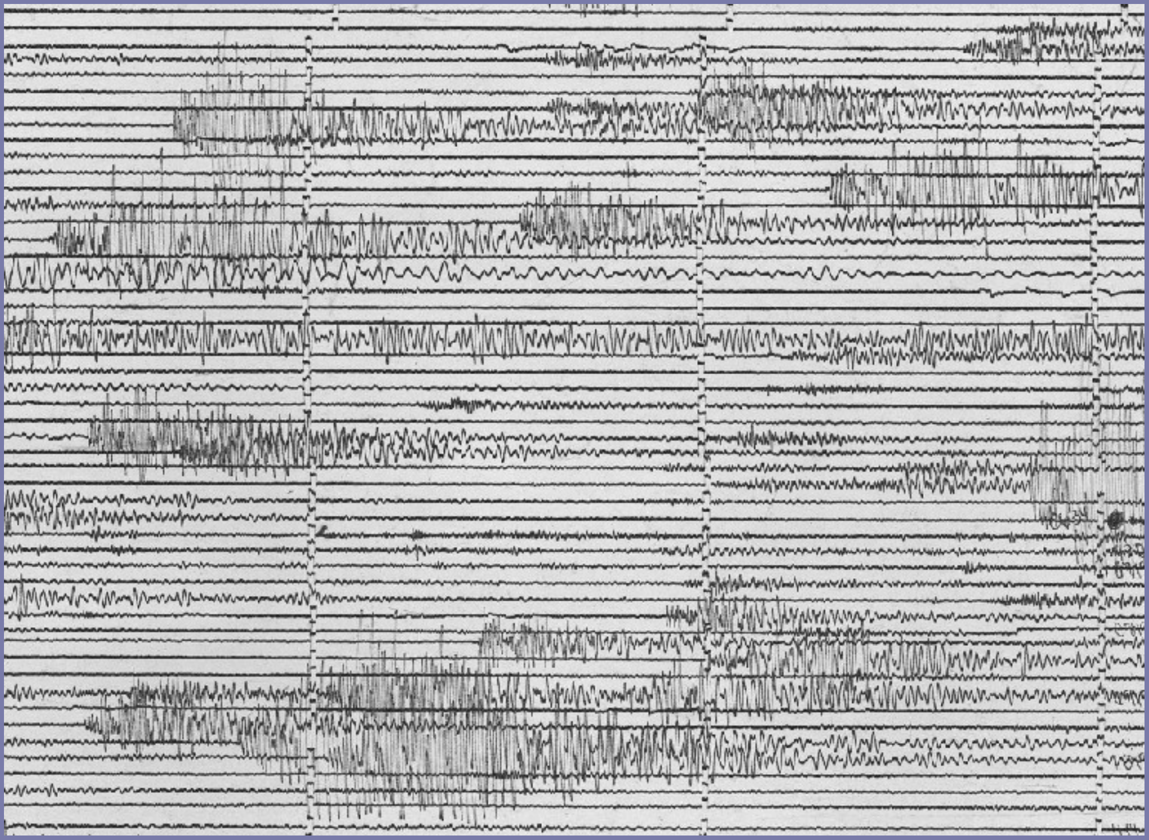
- *Harmonic tremor*: a low (fundamental) frequency sine wave with smoothly varying amplitude.
- *Spasmodic tremor*: a higher or more broadband frequency, pulsating, irregular signal.

Harmonic Tremor:



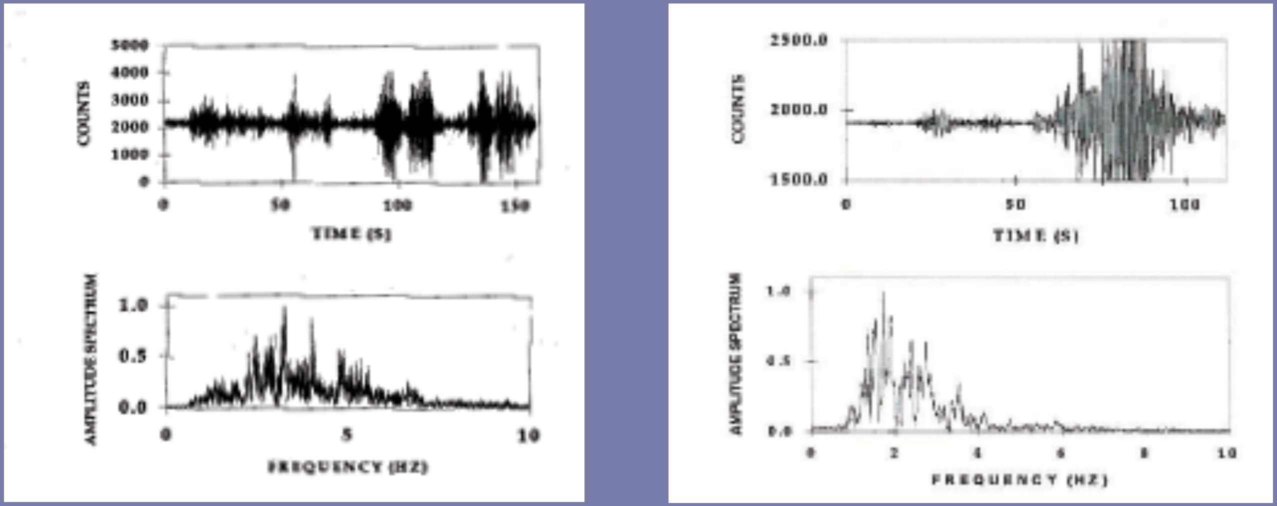
Two examples from Erebus
Note harmonics and gliding spectral lines

Harmonic Tremor:



Harmonic tremor, MSH, April 2, 1980

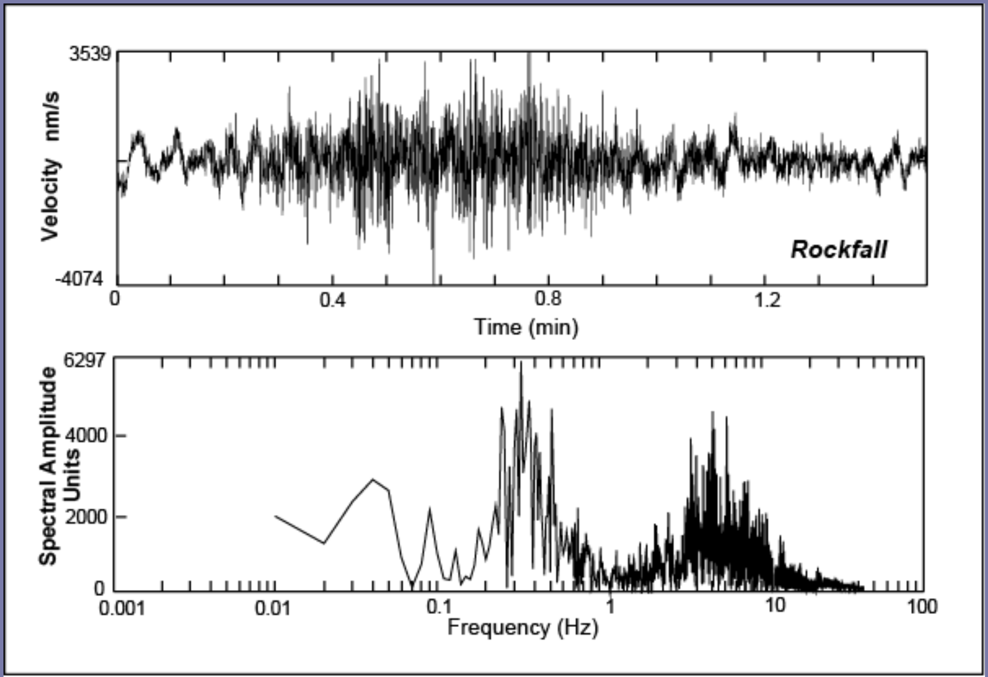
Spasmodic Tremor:



Examples from Galeras Volcano
Gil Cruz (1999)

Rockfall events (Miller et al. 1998):

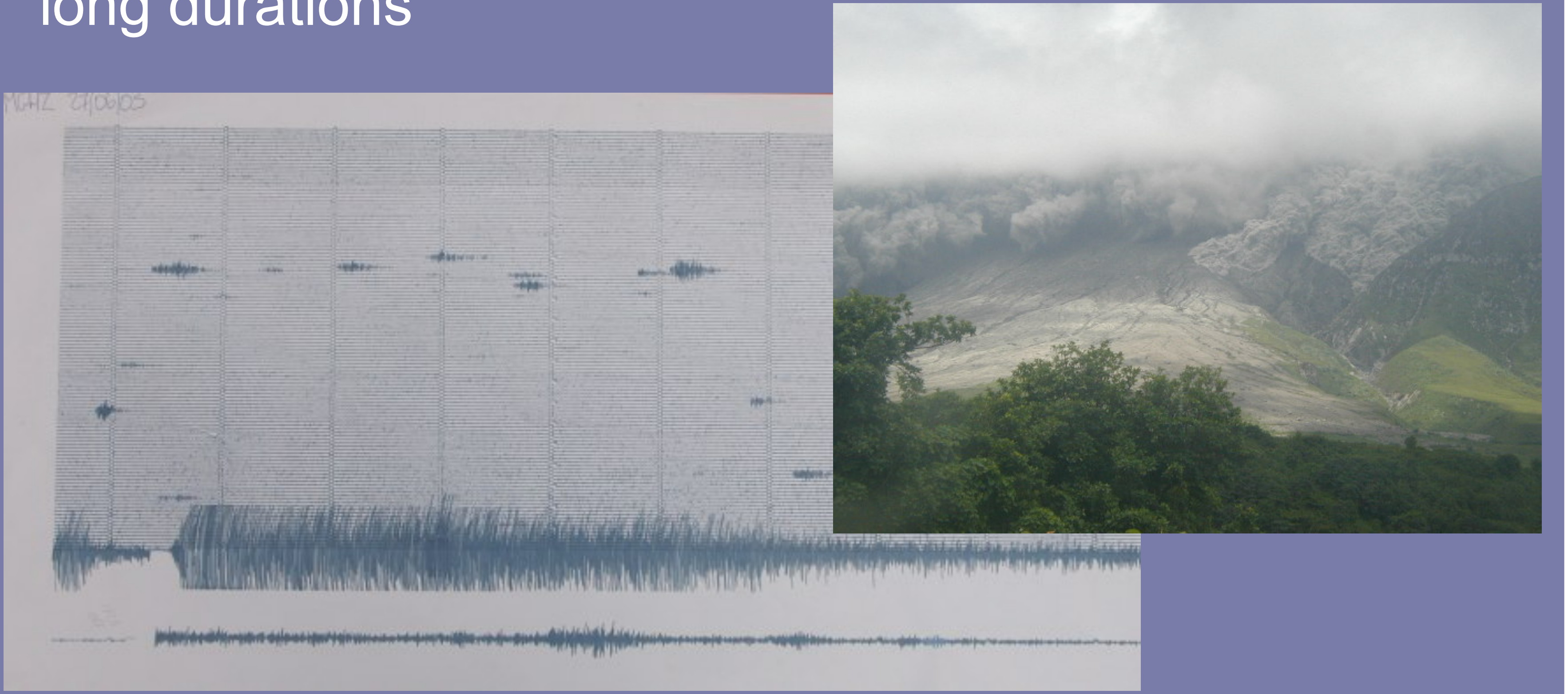
Emergent, phaseless, high-frequency signals correlated with observed rockfalls or pyroclastic flows [often having a cigar-shaped envelope]



Soufriere Hills rockfall event (LF component is weather-related)

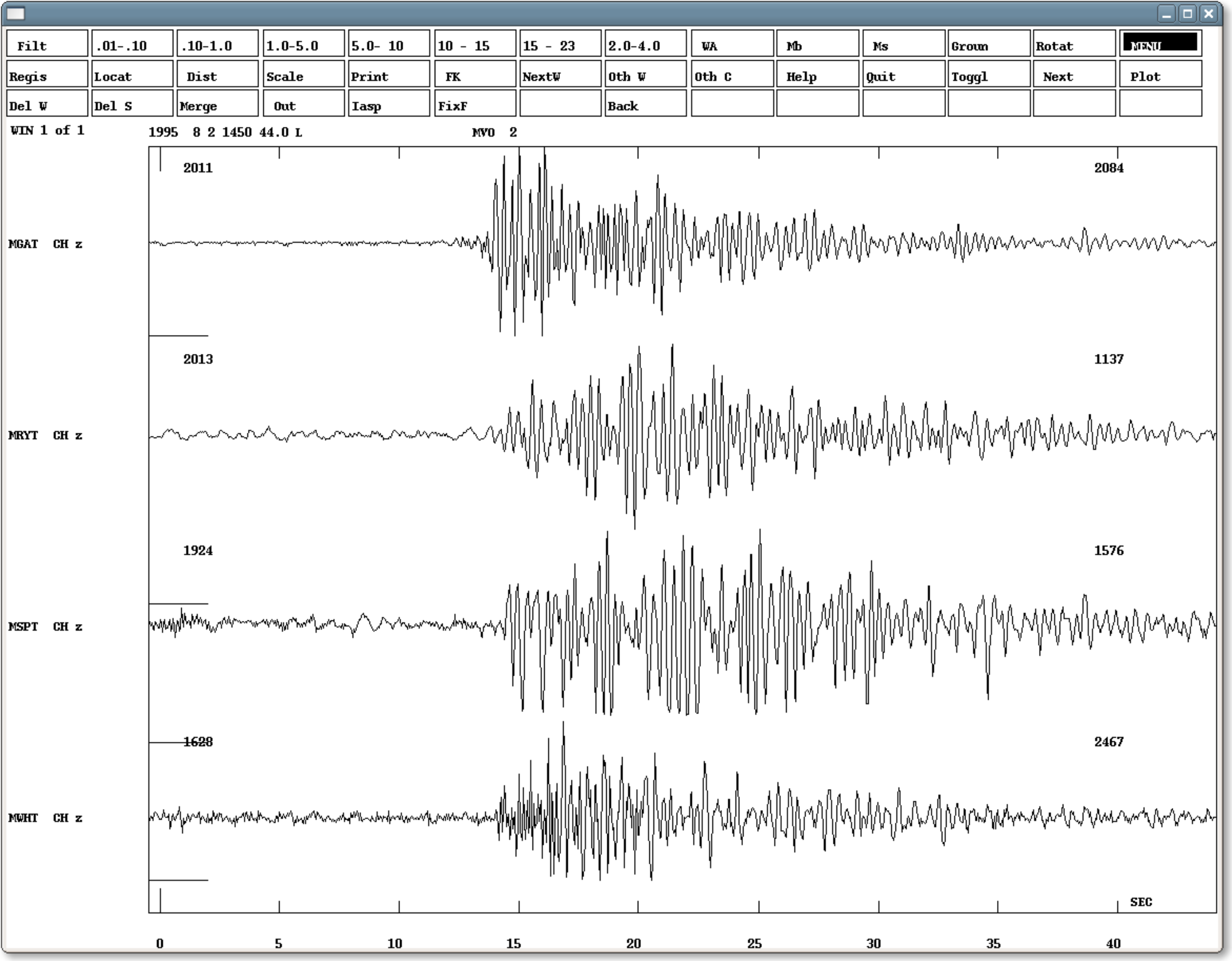
Explosion events:

Can be emergent or impulsive, high or low frequency, may involve an air shock phase, characterized mostly by long durations



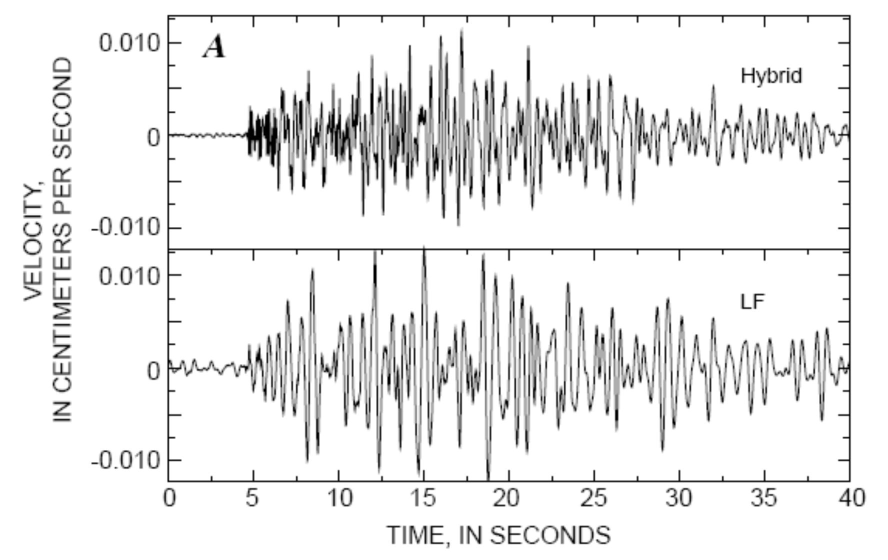
June 28, 2005 Montserrat

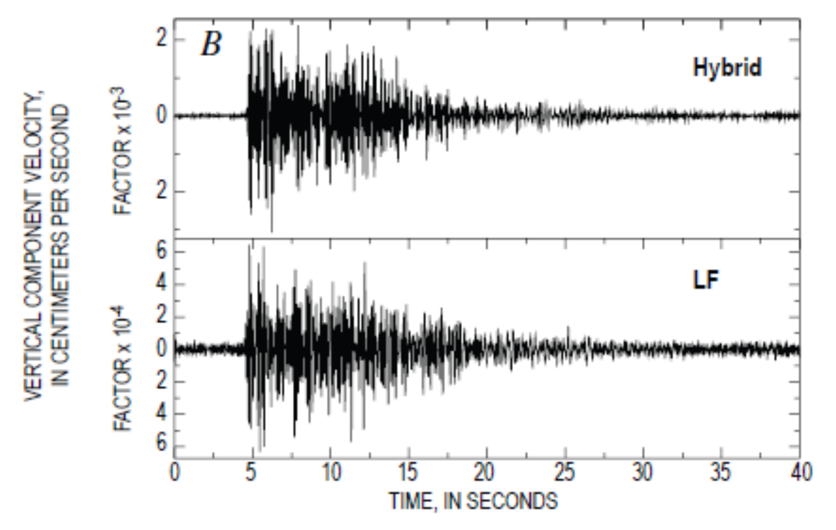
Station-to-station variations



Soufriere Hills Volcano, August 1995

Gradation between Hybrids/LPs





Mt. St. Helens, Washington, October 2004 – Unfiltered hybrid and LP From Horton et al. (2008)

Mt. St. Helens, Washington, October 2004 – Same two events – highpass-filtered @ 7 Hz

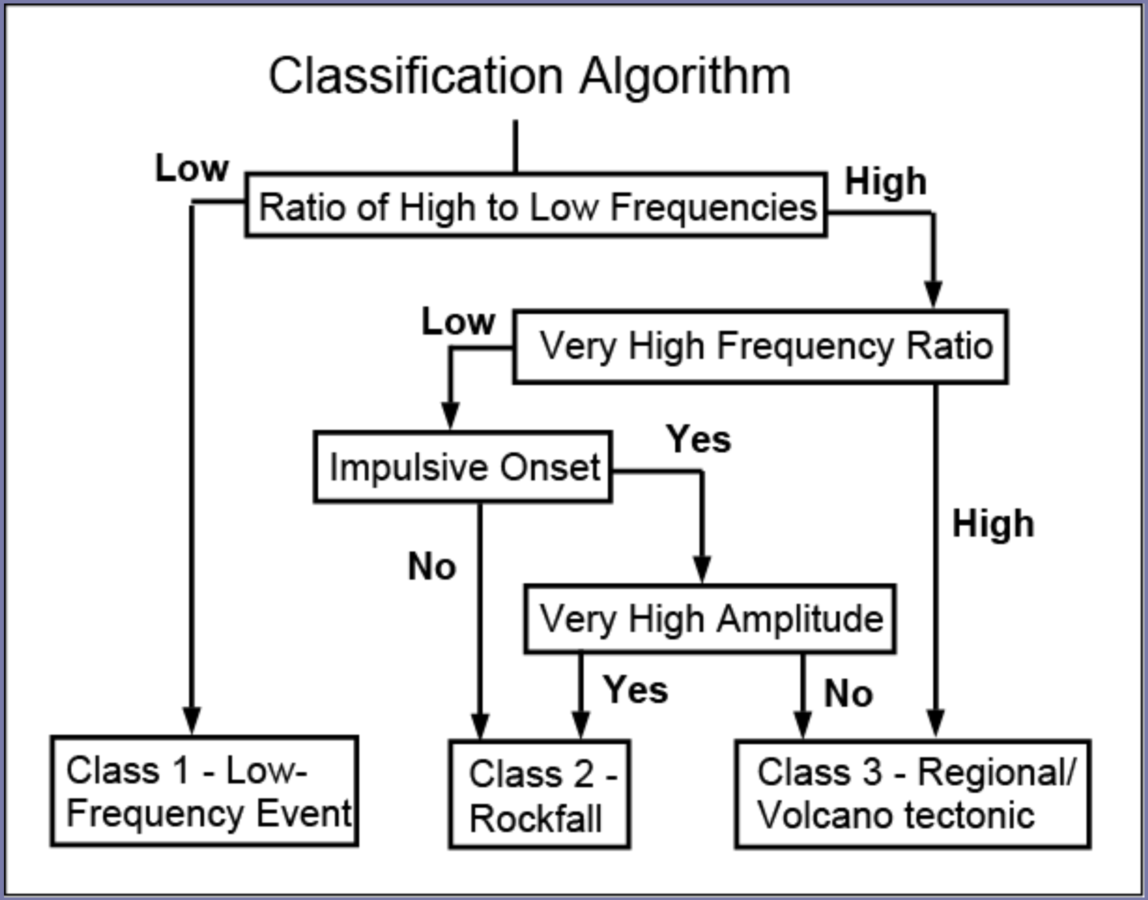
Classification Methods:

Analyst classifications –

Can detect subtle differences in event type, note events that do not fit within classification scheme

Often do not do thorough analyses of events (classification by eye), can produce different results than another analyst

Classification Methods: Automatic classifications –



Powell (2004)

Classification Methods:

Automatic classifications –

Consistent and systematic classification according to predefined rules

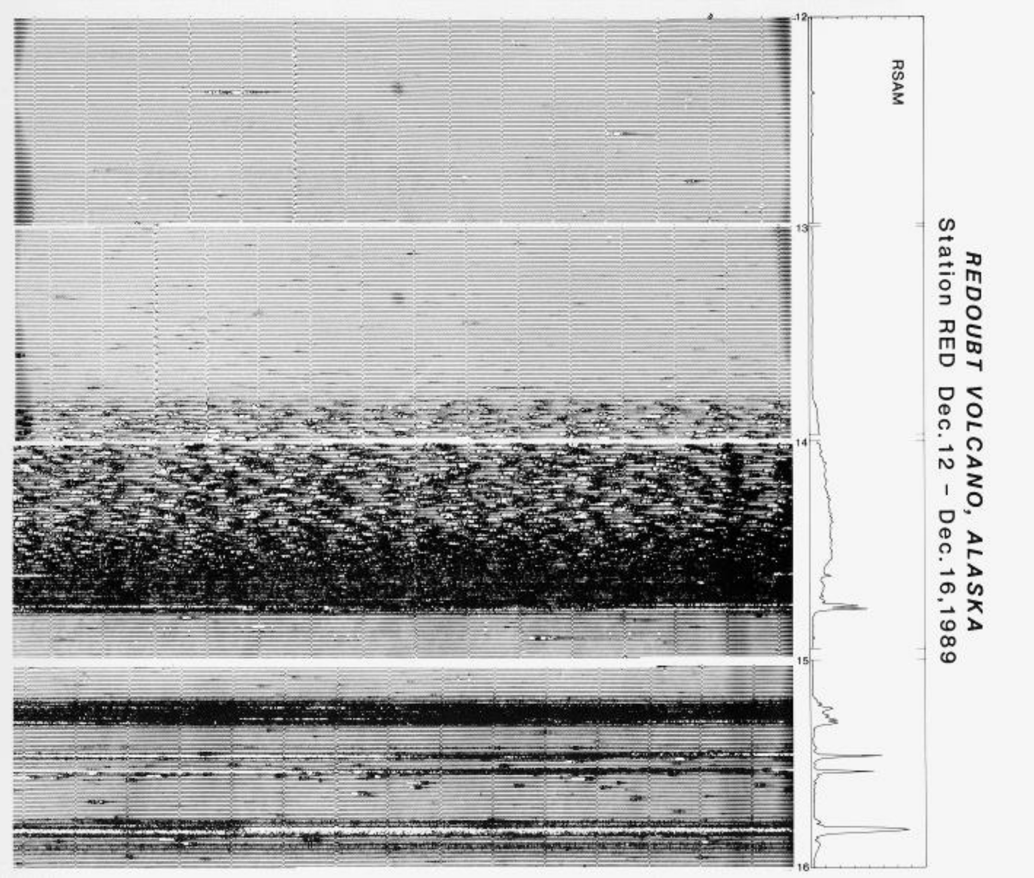
Analysis of critical parameters (e.g., frequency) for each event

May classify noise, fit unique events into a predefined (incorrect) category

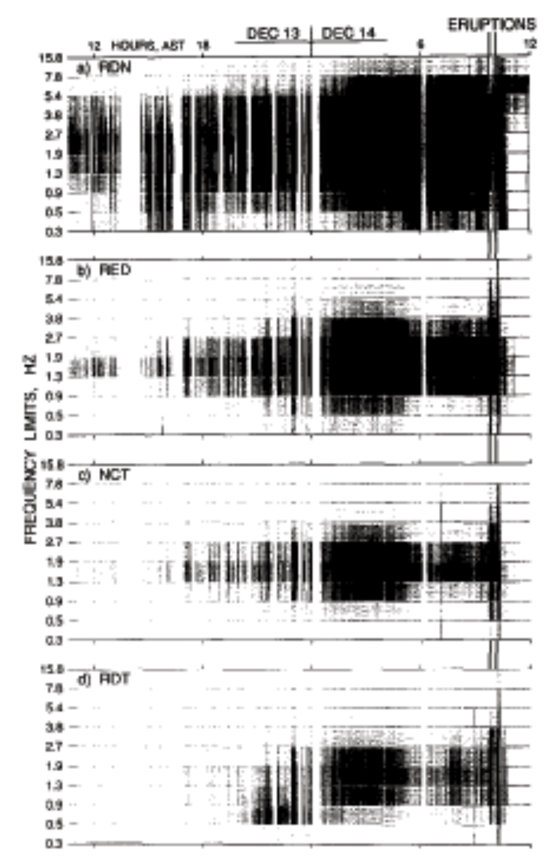
Classification (or lack thereof) Methods:

Real-time Seismic Amplitude Measurement (RSAM)

Spectral Seismic Amplitude Measurement (SSAM)



Power et al (1994)



Stephens et al (1994)

Majority of info comes from very basic analyses:

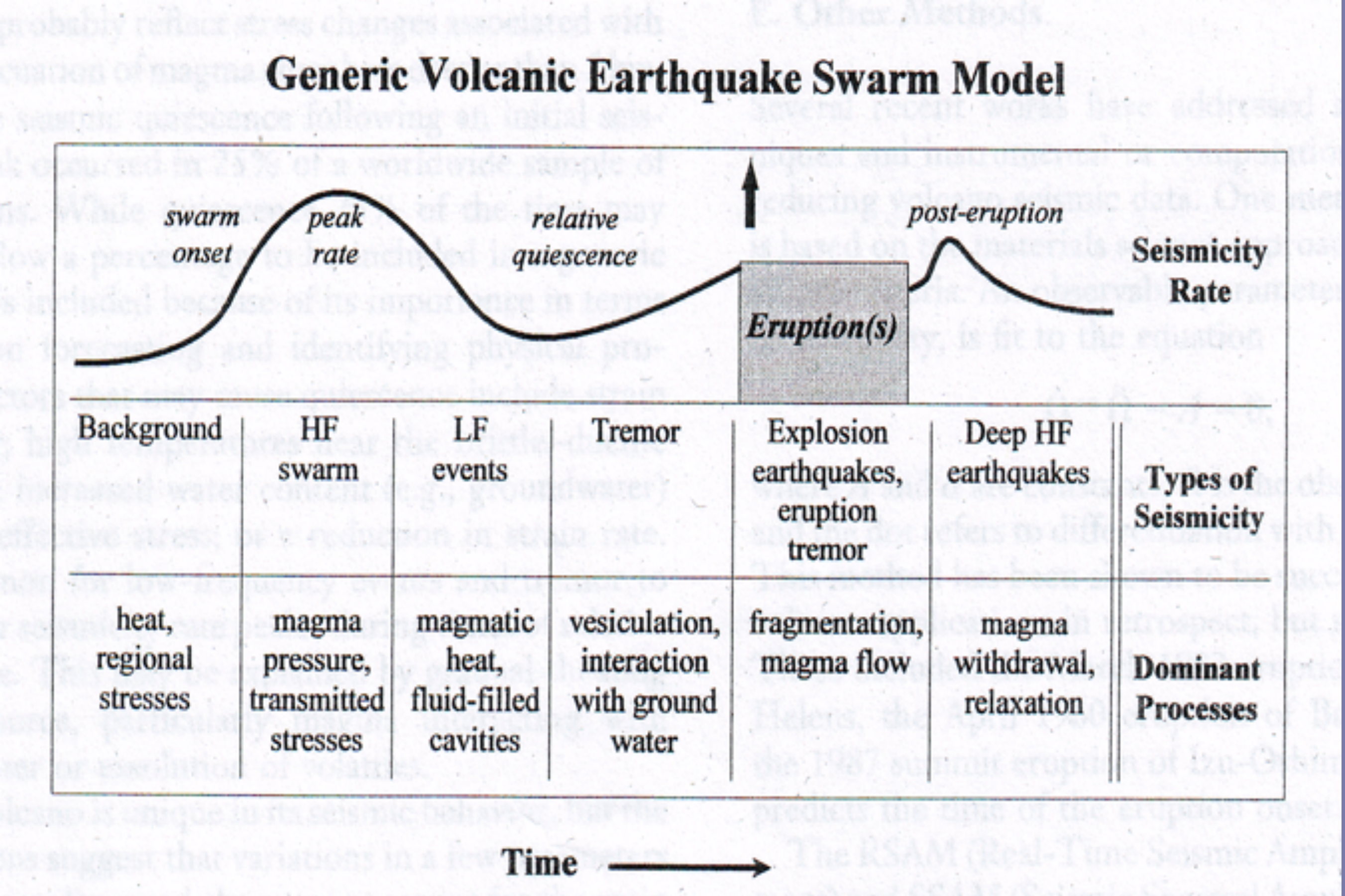
- Event Classifications
- Event Rates (by class)
- Locations
- Magnitudes
- Source Mechanisms (Double-Couple FPS)

Advanced analyses (often requires broadband/3-C):

- Travel time inversions (tomography, relative relocations)
- Waveform analysis/modeling (multiplet analysis, moment tensor inversions, shear-wave splitting analysis, ambient noise analysis, array processing)

Patterns in volcanic seismicity

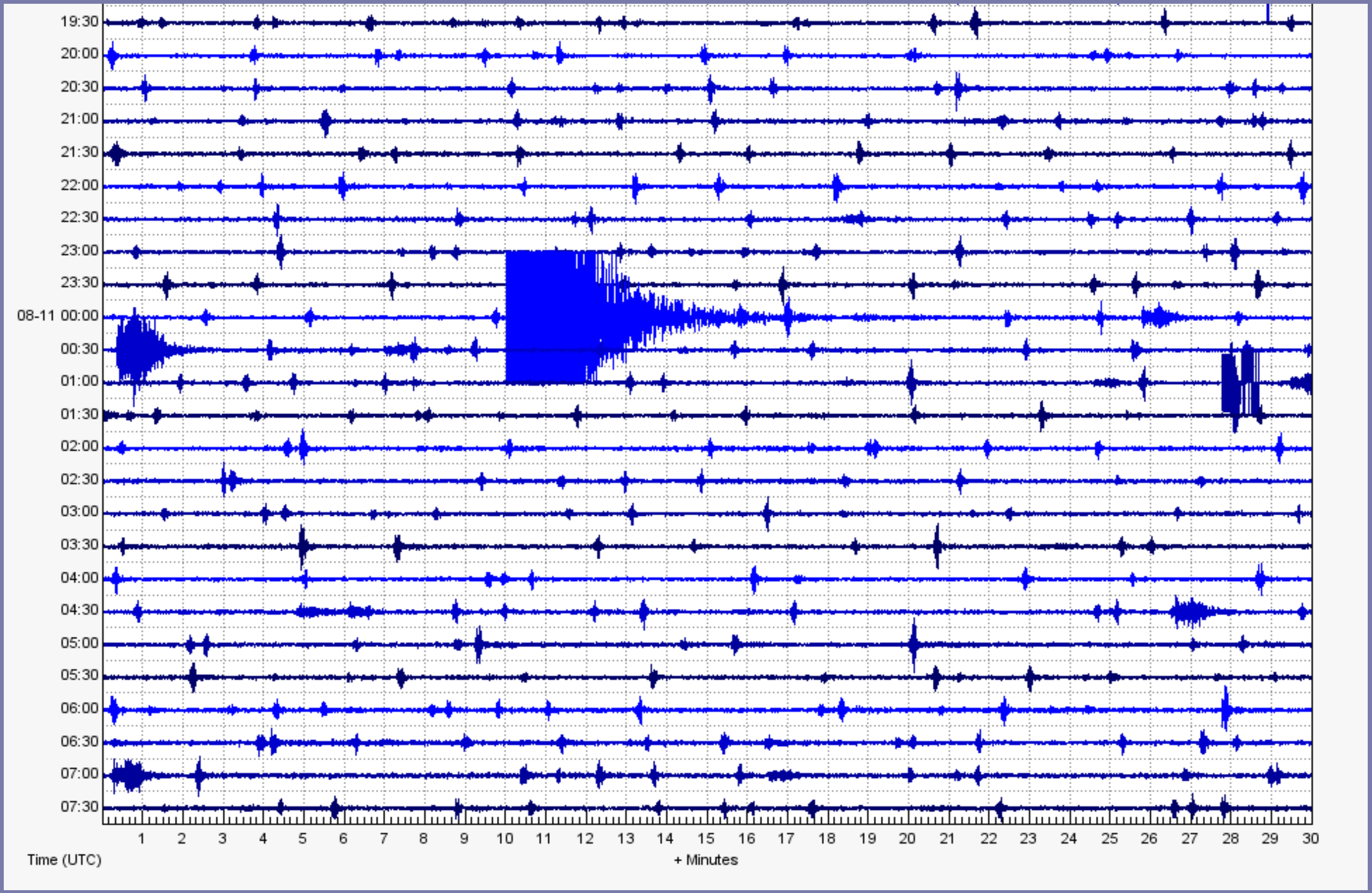
(May begin months to hours before eruption)



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)

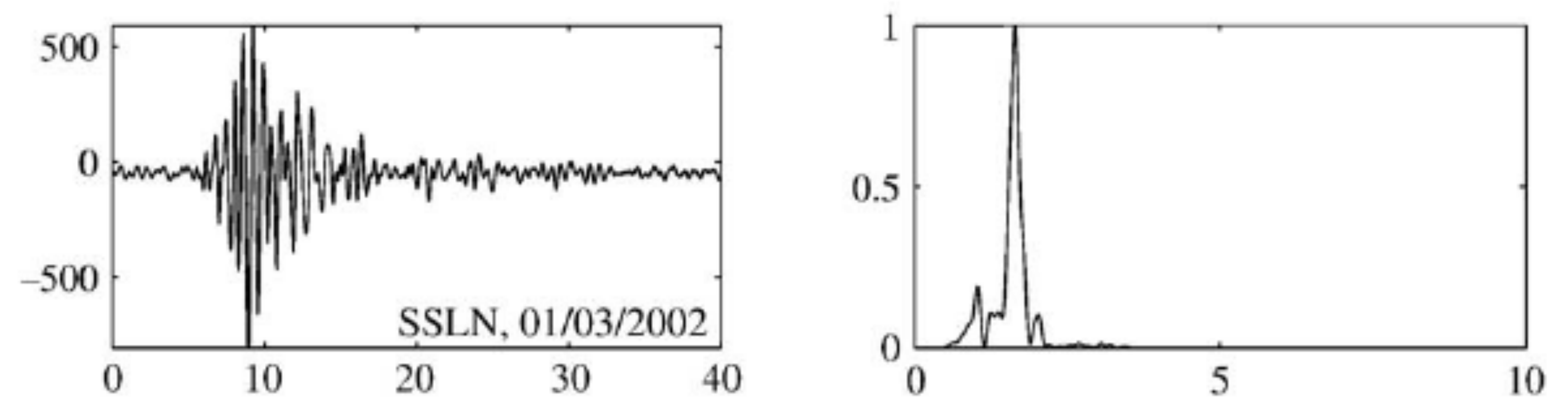
High-Background (LP)-Seismicity volcanoes:



12-hour helicorder plot from Shishaldin Volcano, Alaska showing high background rate of LP seismicity

High-Background (LP)-Seismicity volcanoes:

Shishaldin Volcano, Alaska
Poas Volcano, Costa Rica
Gareloi Volcano, Alaska
Telica Volcano, Nicaragua
Ngaururhoe, New Zealand
Others?...



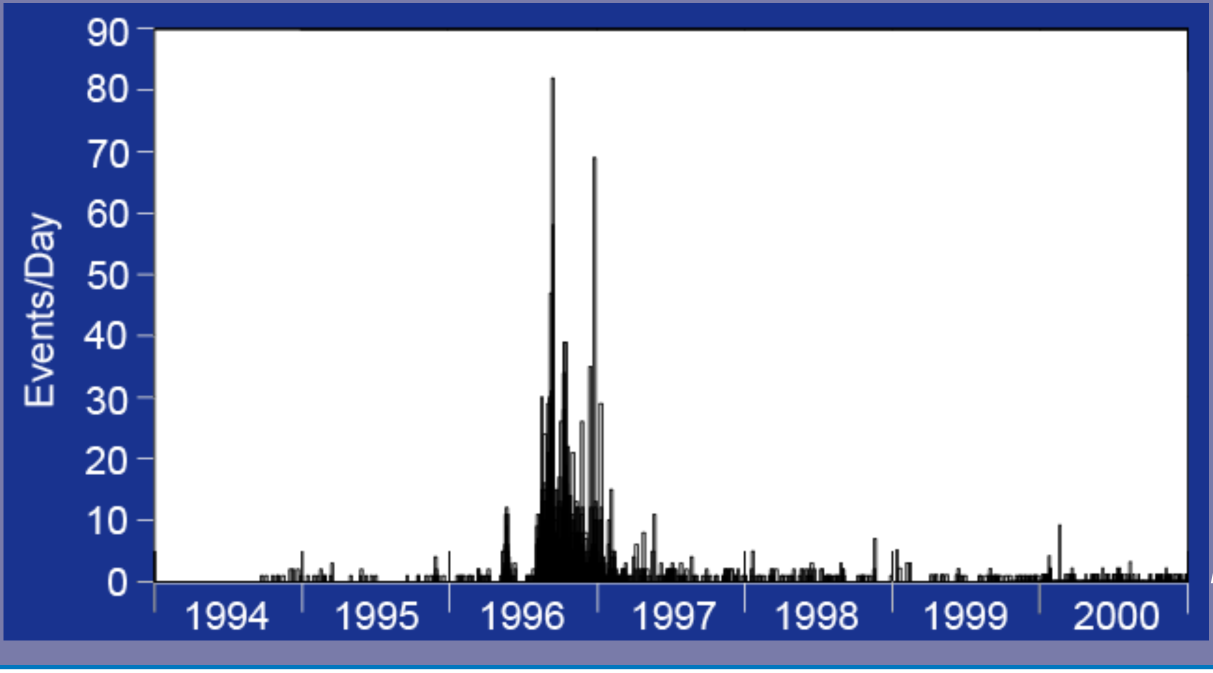
Petersen et al. (2006)

Non-eruptive earthquake swarms:

- Episodes of seismic unrest (often accompanied by increased degassing, deformation, etc.)
- Superficially similar to pre-eruptive unrest
- Previously thought to represent stalled intrusions
- Recent evidence that some may not directly involve shallow magma emplacement
  - Deep intrusion
  - Hydrothermal unrest
  - Other causes?

Iliamna Volcano, Alaska

- Non-eruptive crisis: May 1996 – mid 1997
- Two shallow VT earthquake swarms accompanied by elevated CO_2 and SO_2 emissions
- Triggered by deep or shallow intrusion?



Roman et al. (2004)

“Stealth” magma ascent:

No precursory seismicity or extremely short-duration (hours to days) precursory seismicity

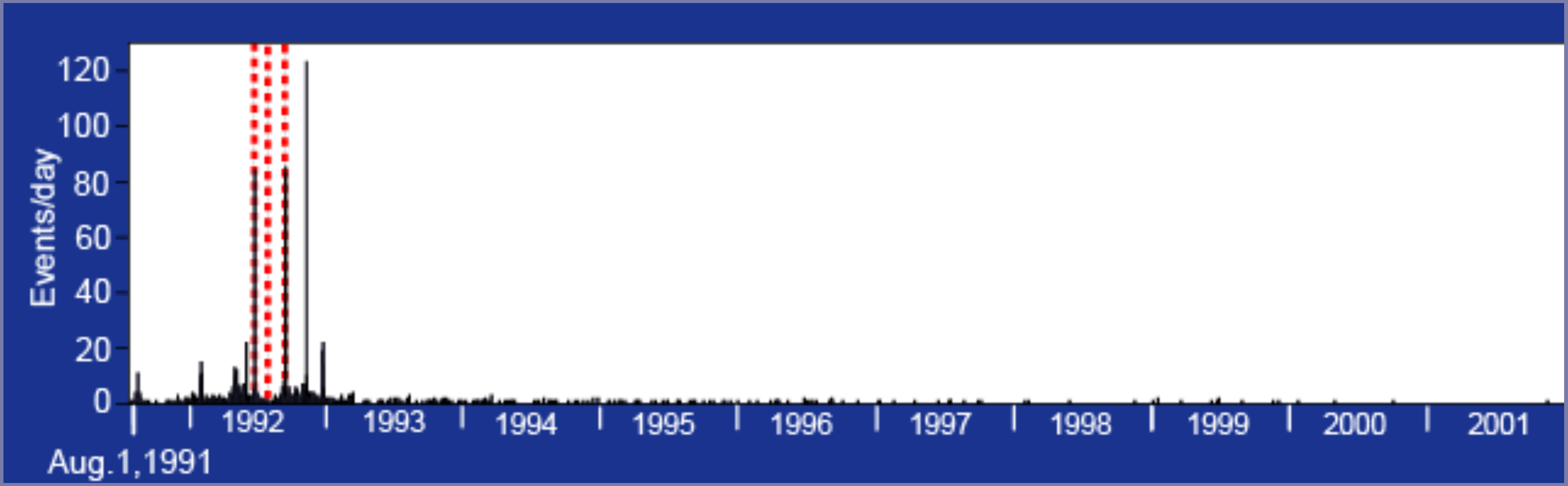
Redoubt Volcano, Alaska; Hekla Volcano, Iceland, Okmok, Alaska, Others...

Mechanisms of “Stealth” magma ascent:

- Open/weakened conduit systems?
- Slow strain rates?

Mechanisms of “Stealth” magma ascent:

Aseismic 2nd eruption - 1992 Crater Peak, Alaska
No significant difference from (seismic) 3rd eruption



Roman et al. (2004)

Current key issues in volcano seismology:

1. The availability of good data sets

- Pattern recognition approach is driven by good data!
- Data/current understanding biased to certain eruption Types (long-term, effusive...)
- Monitoring networks vs. research networks
- Difficult for researchers to collect long-term data sets

2. Event resolution – small events in a noisy environment

- Installation/terrain limitations
- Destruction of instrumentation by eruptions

3. Lack of dedicated instrumentation(?)