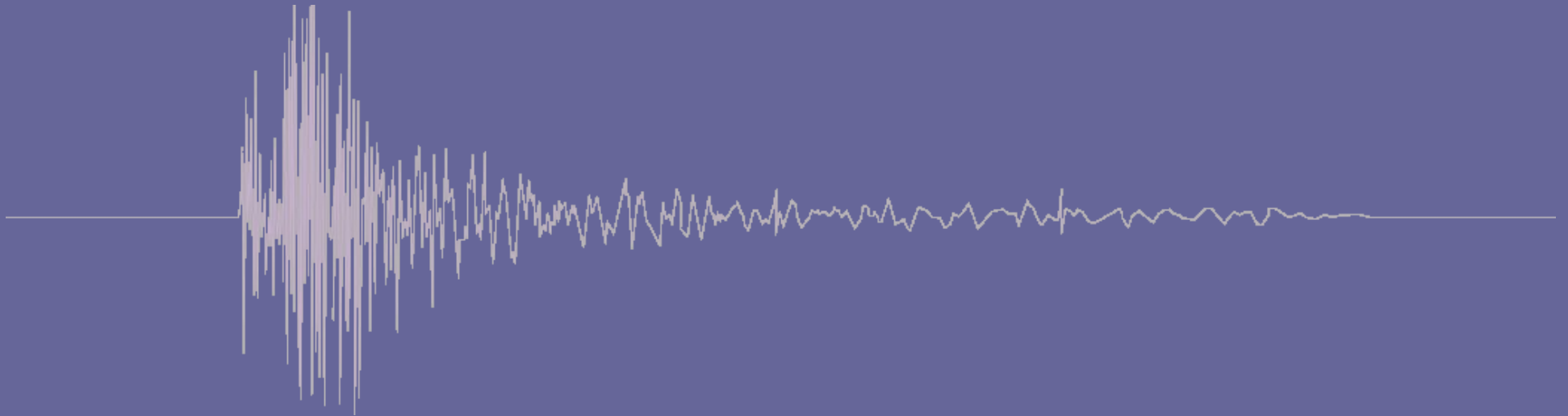


# Overview of Volcano Seismology

Diana C. Roman (Carnegie Institution of Washington)  
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)

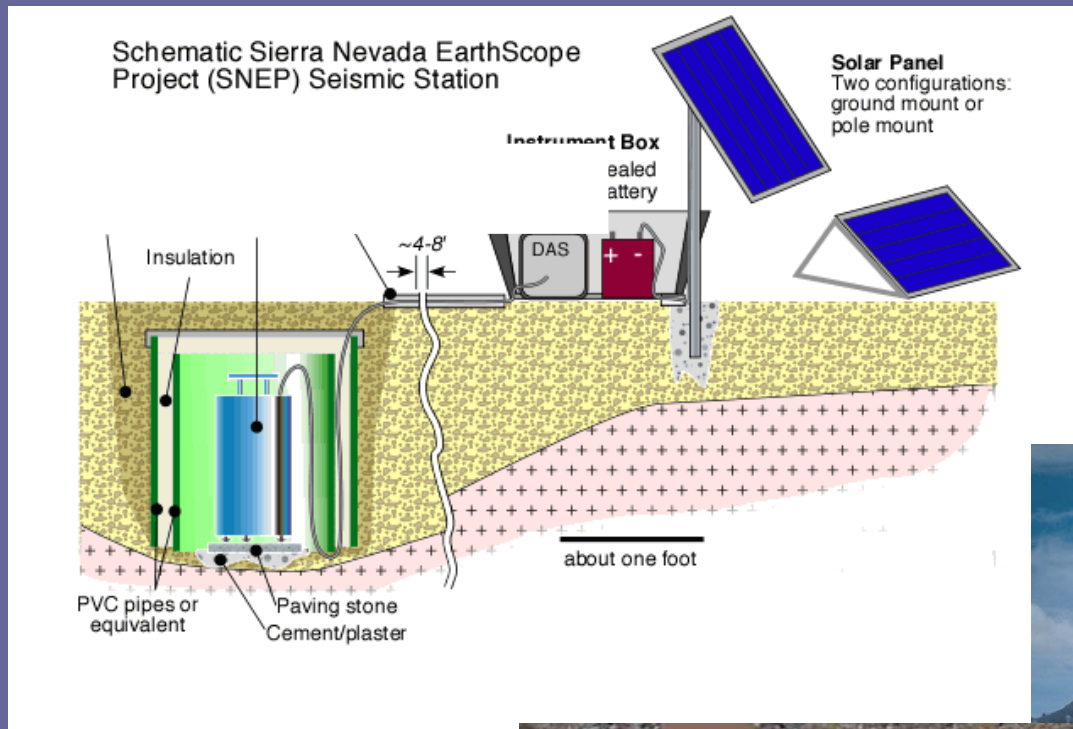
## Why monitor seismicity at potentially active volcanoes?

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

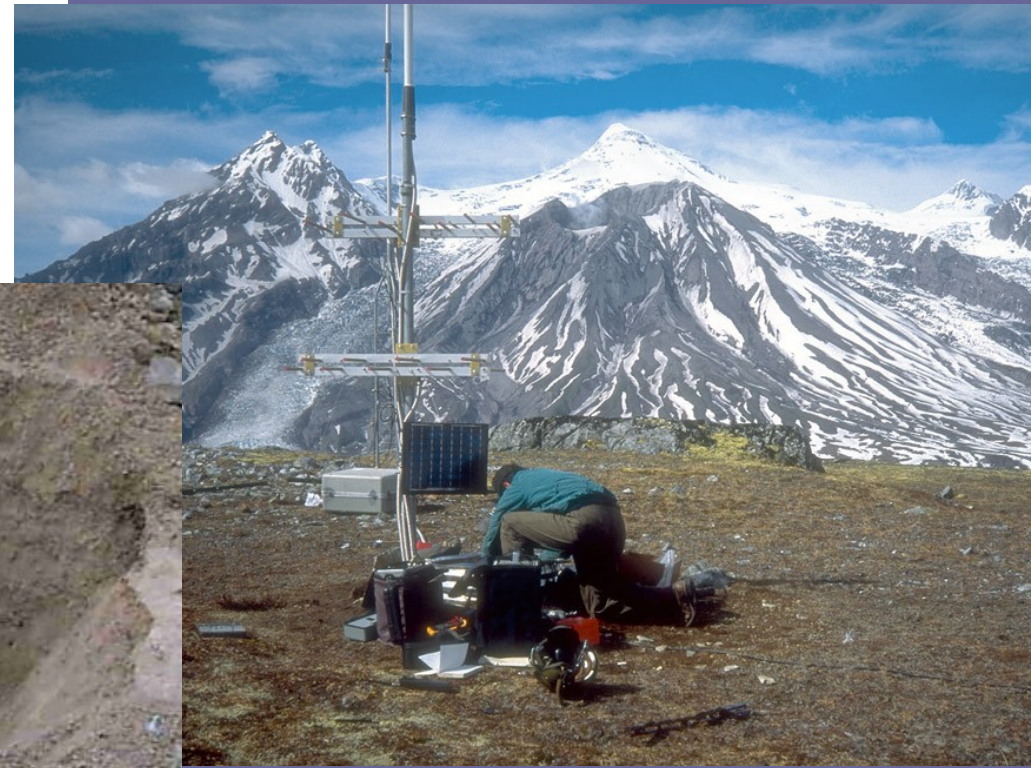
(Potential) information provided by volcanic seismicity:

- 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!

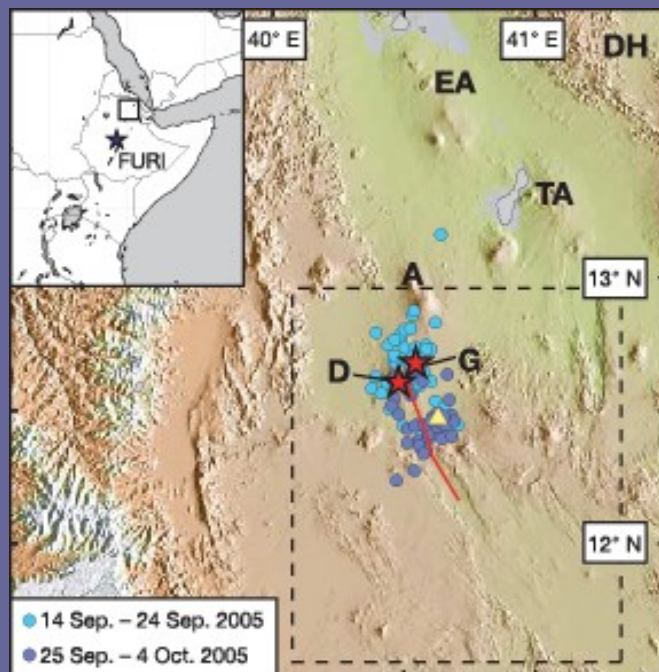
### 4-6+ stations:

High-accuracy locations

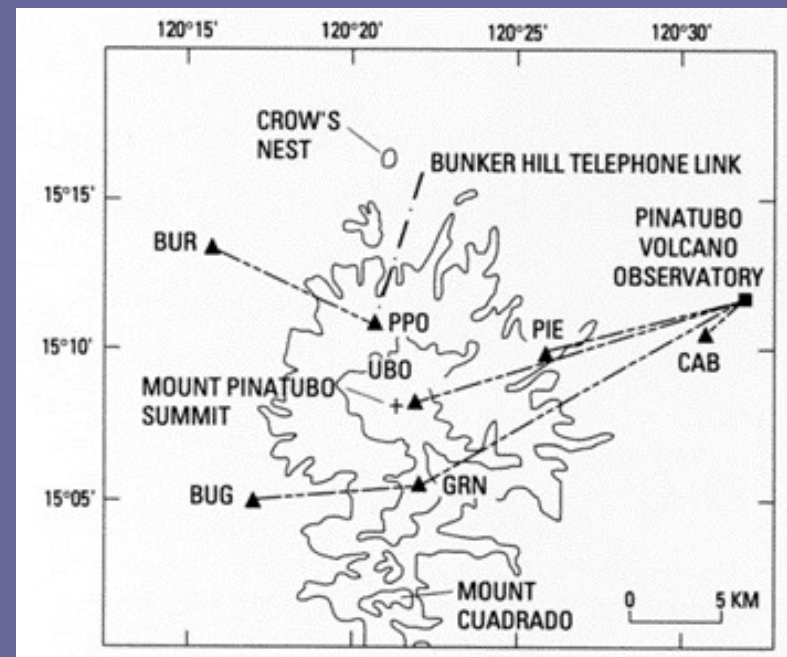
Fault-plane solutions/moment tensors

Tomography, etc.

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



*Single station network, northern Ethiopia*

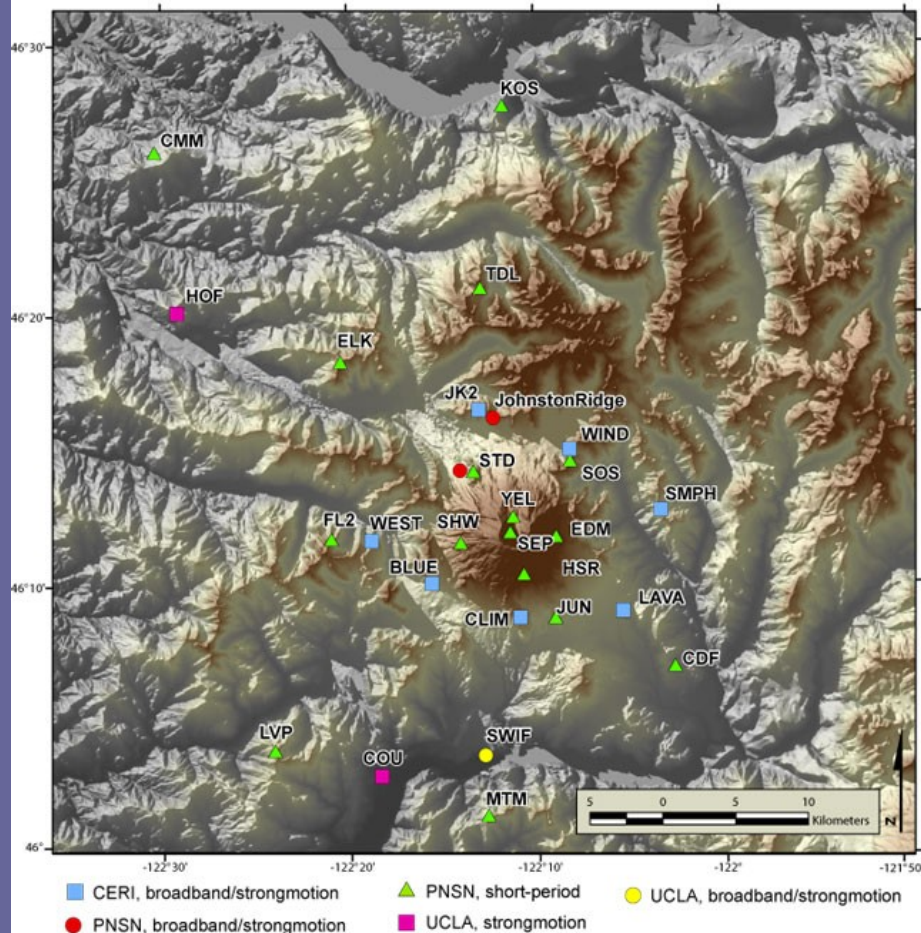


*Mt. Pinatubo seismic network*

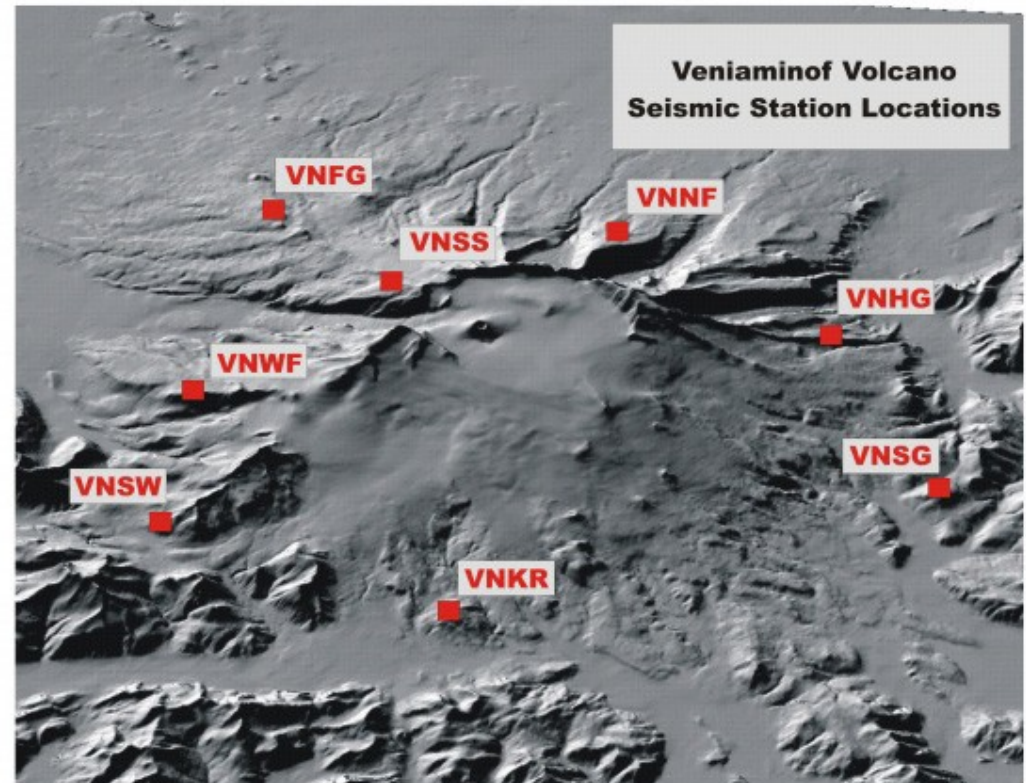
## Seismic network configuration:

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

Mount St. Helens Seismic Monitoring

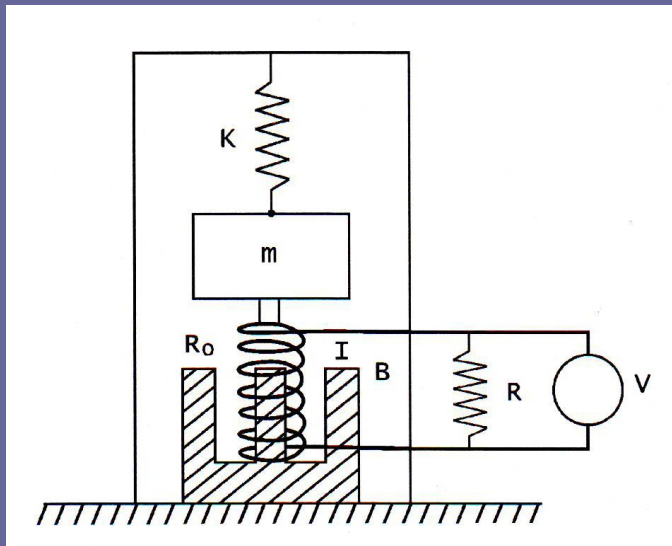


Veniaminof Volcano Seismic Station Locations





## 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)

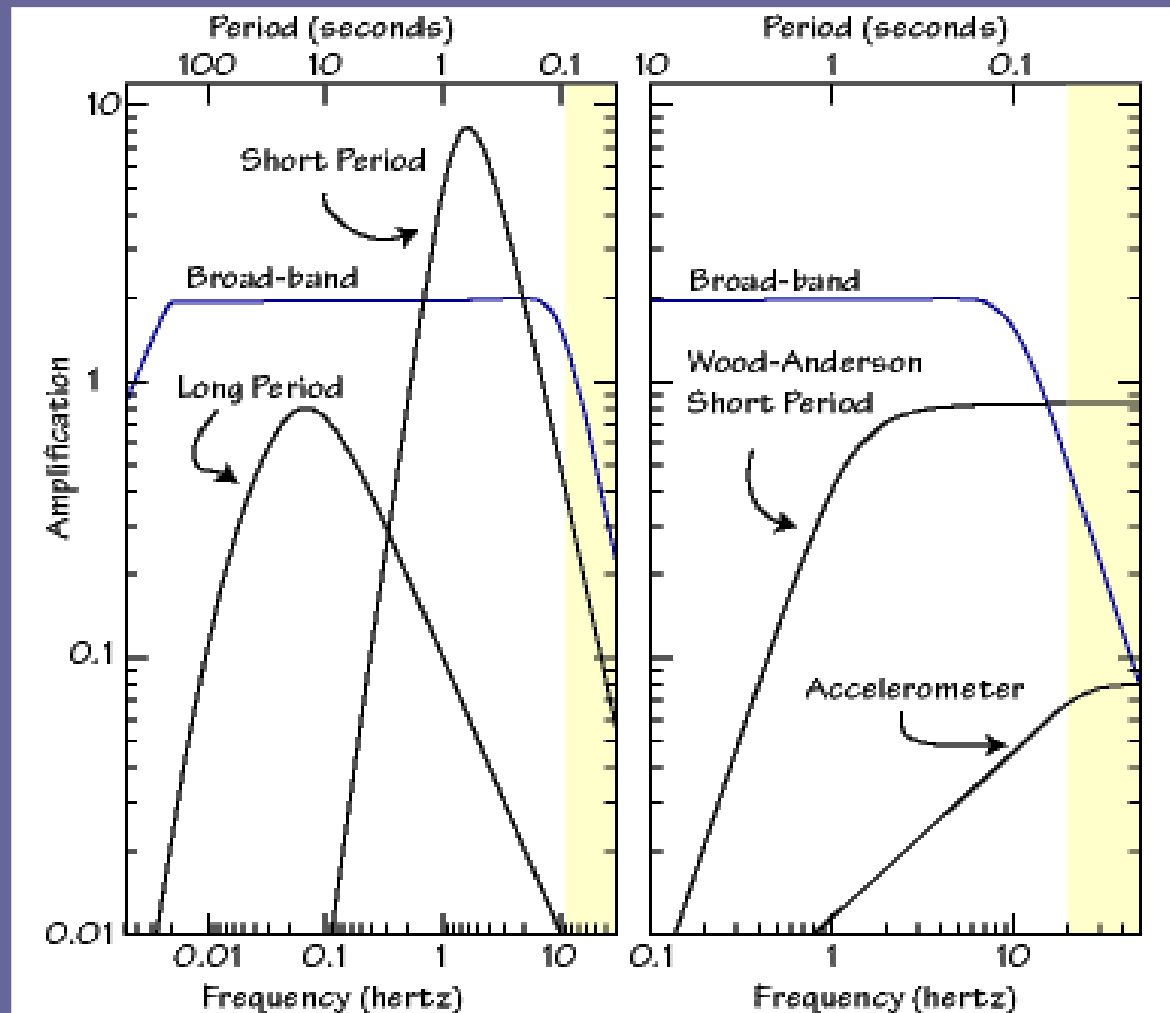
Broadband instruments – force feedback

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



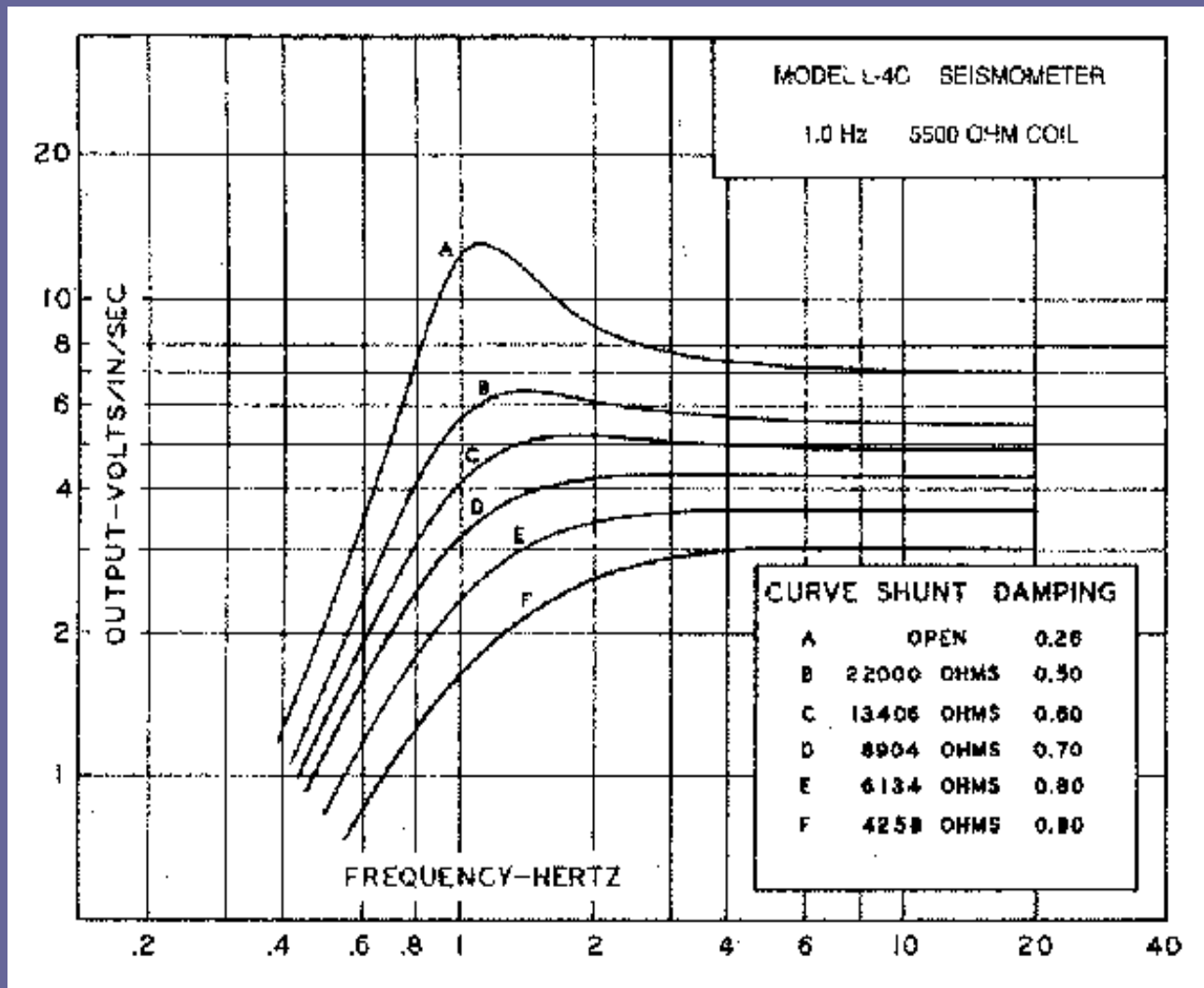
## Seismometer classes:

- 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



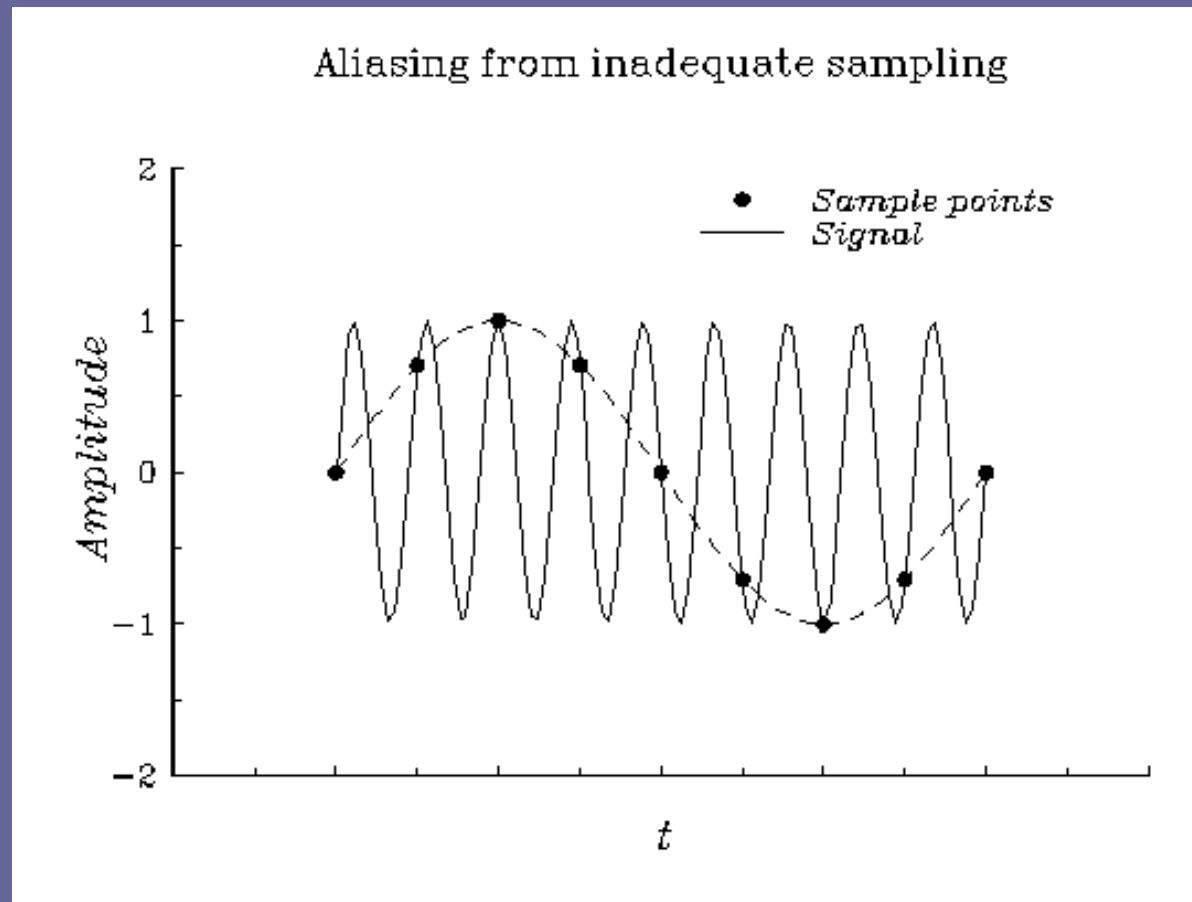
## Seismometers as filters:

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



## Seismometers as filters:

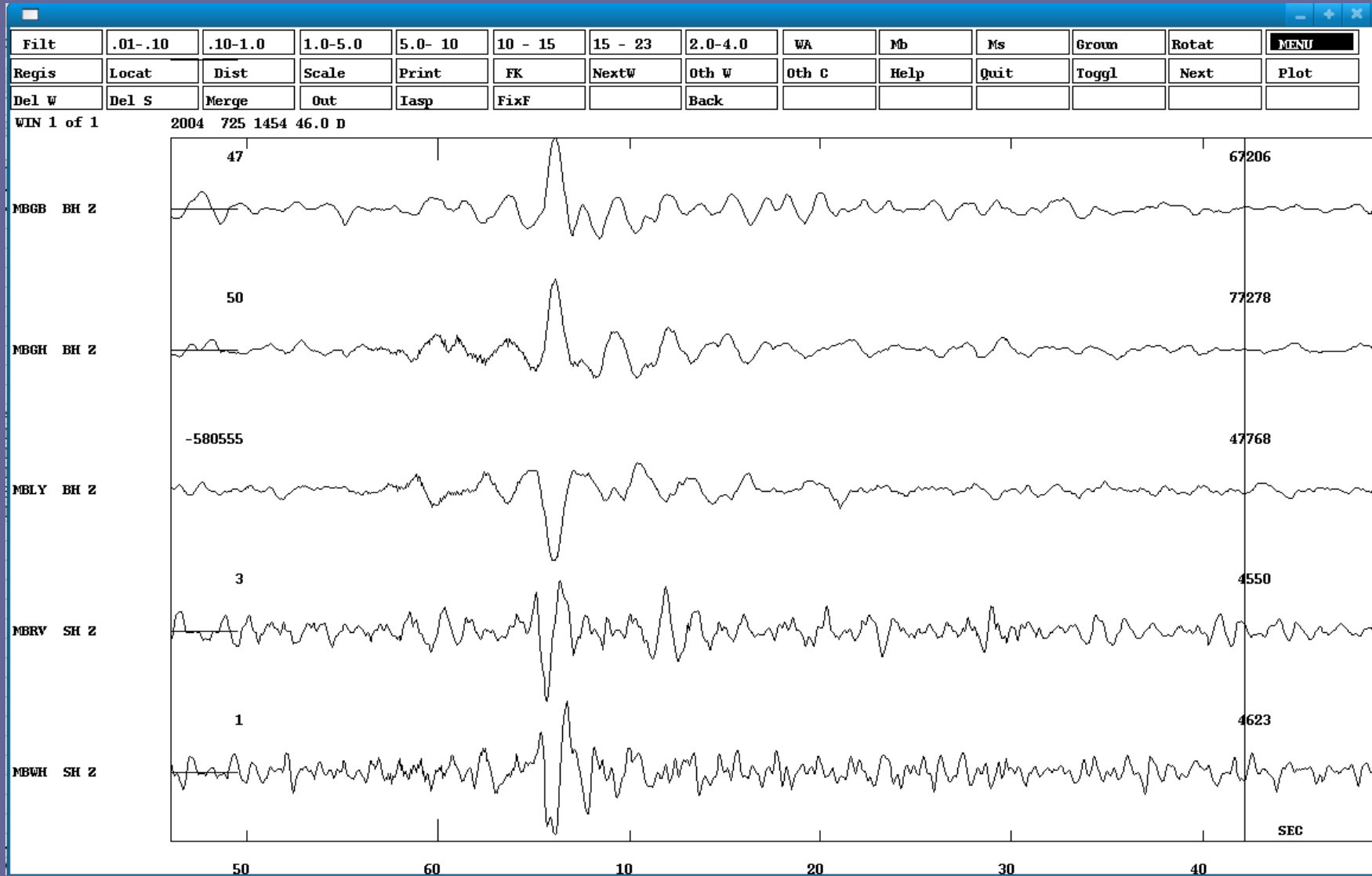
## Aliasing (sampling frequency too low)



Anti-aliasing filters, Nyquist frequency

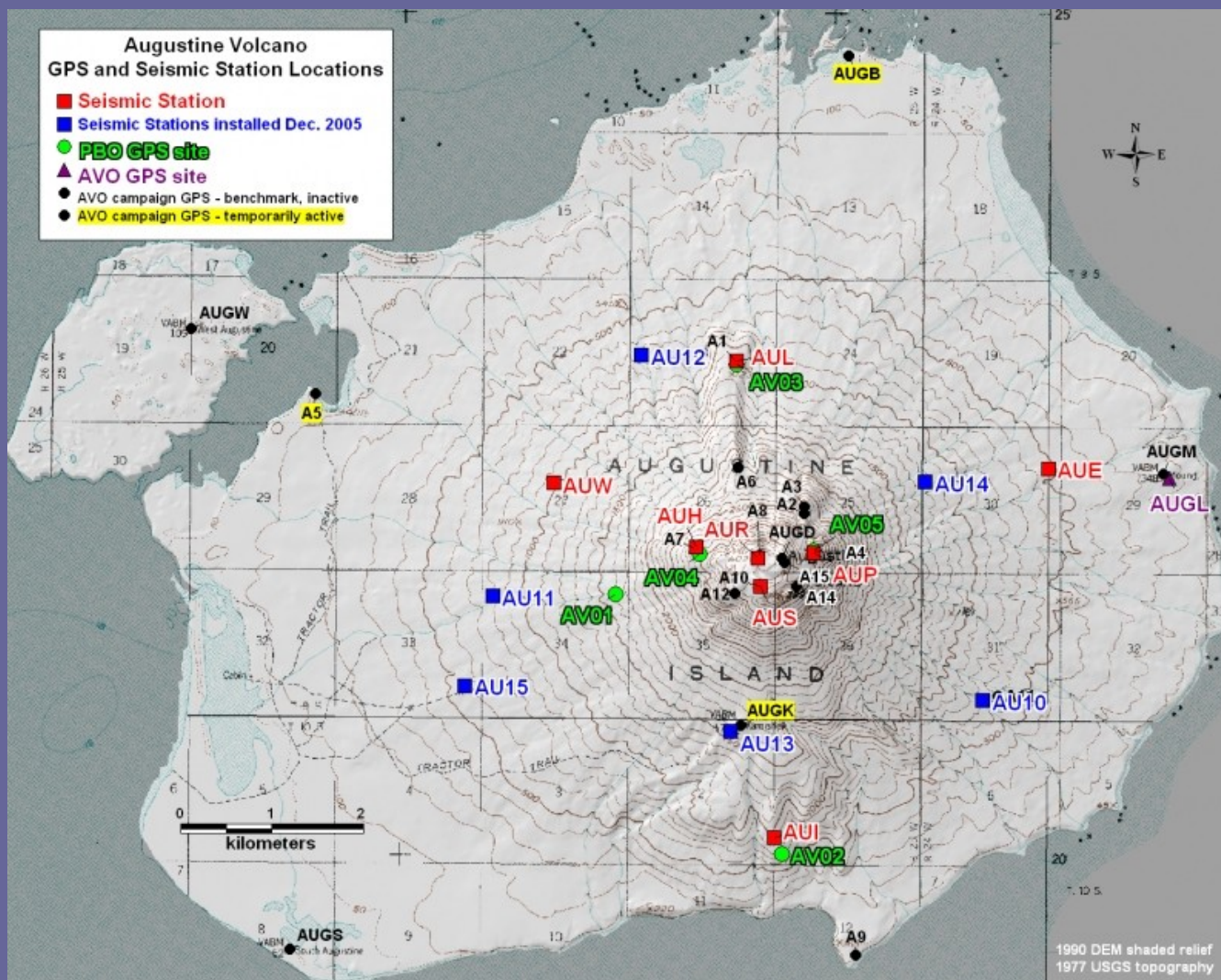
## Instrumentation Problems:

- Polarity reversal (teleseisms)



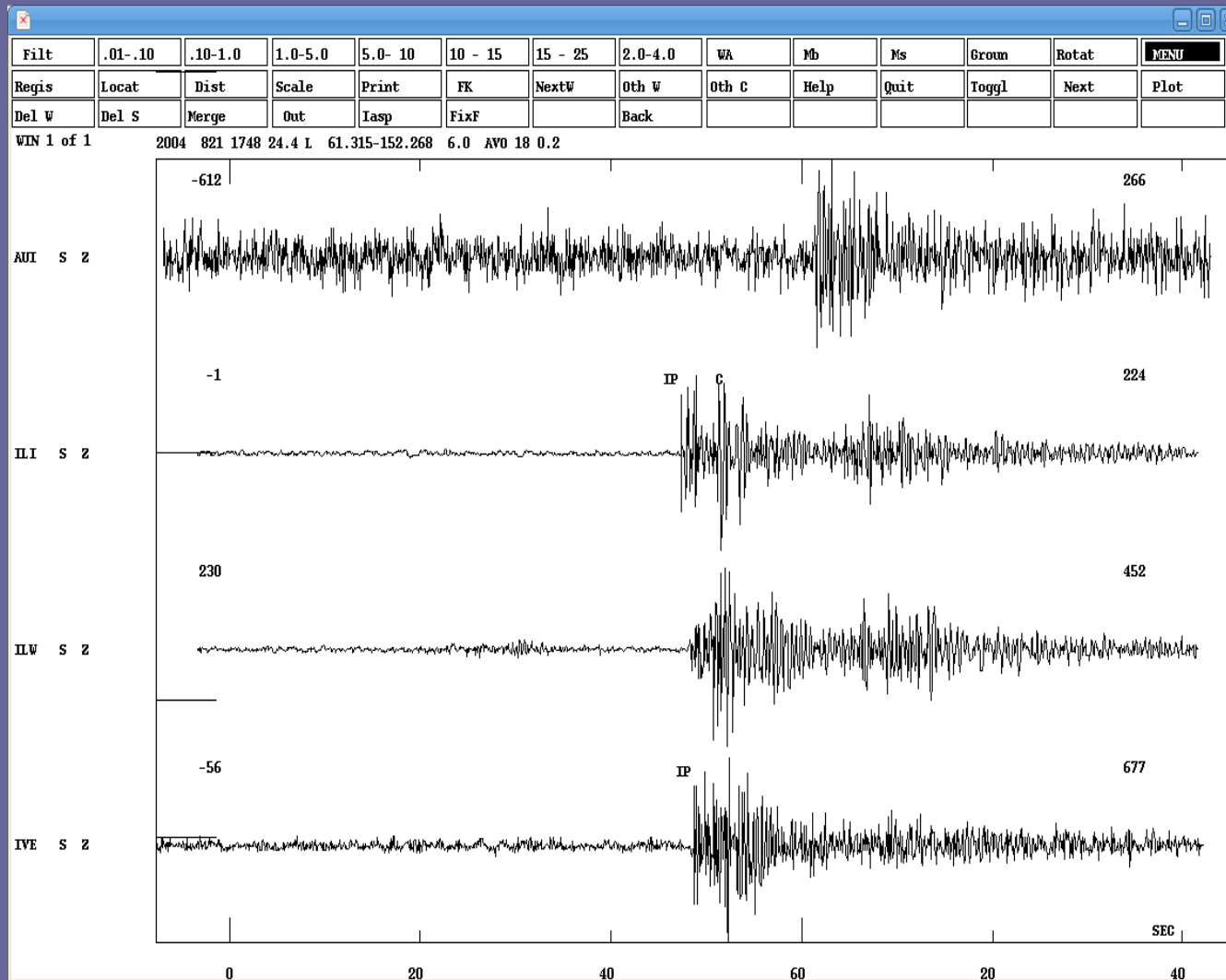
# Instrumentation Problems:

- Site effects (noise amplification)



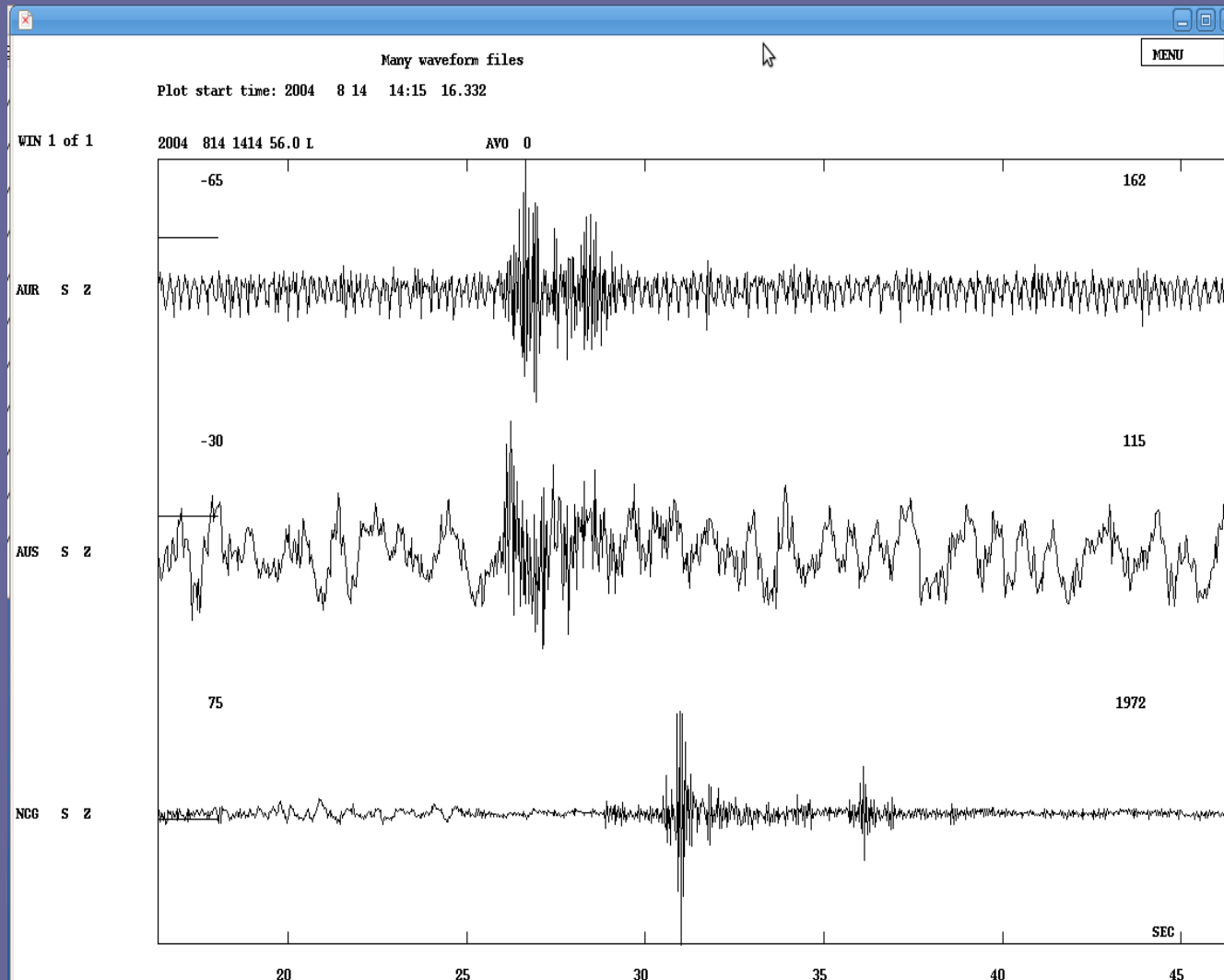
# Instrumentation Problems:

- Site effects (noise amplification)



# Instrumentation Problems:

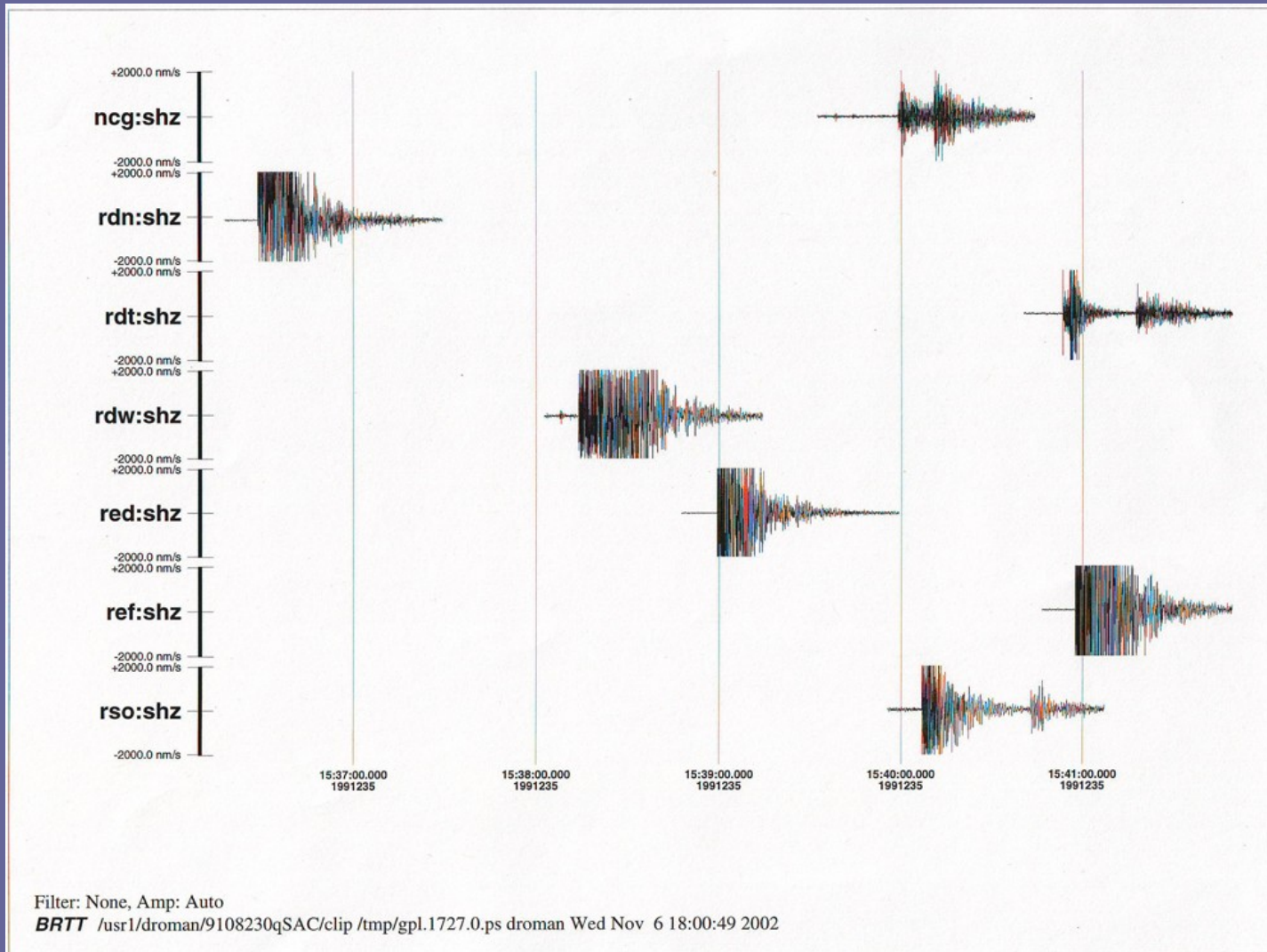
- Site effects (noise amplification)





# Instrumentation Problems:

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



## 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/teleaseismic 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”

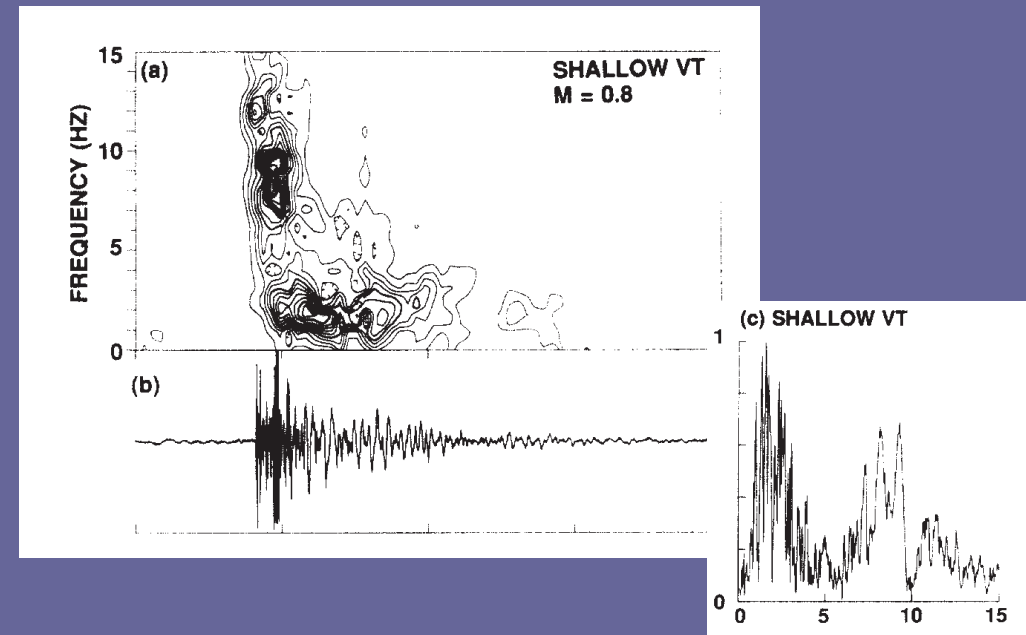
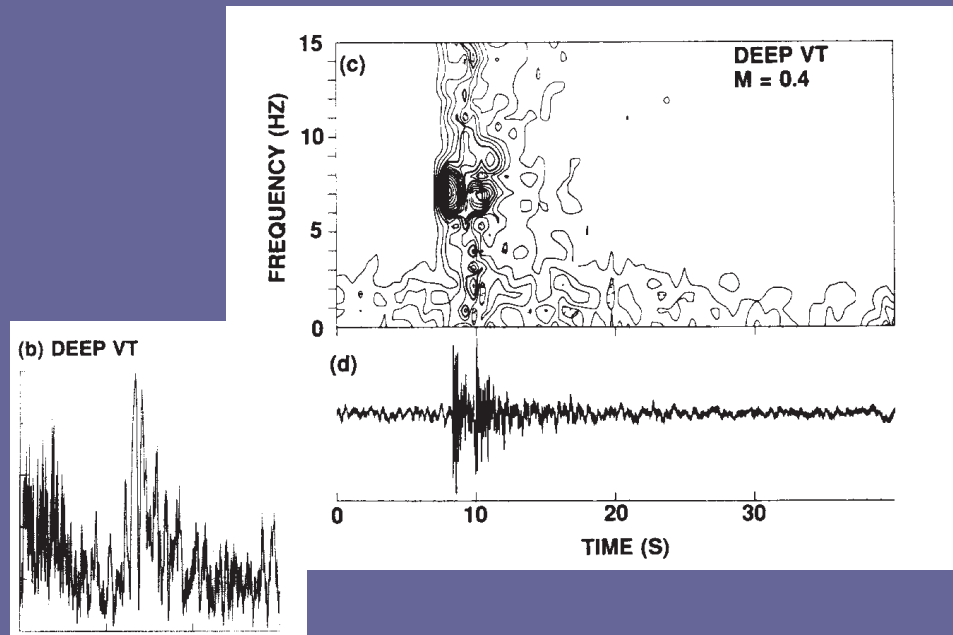
Miller et al. (1998) – Soufriere Hills Volcano

“Seismicity associated with dome growth and collapse at the SHV, Montserrat”

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

## Volcanotectonic (VT) earthquake:

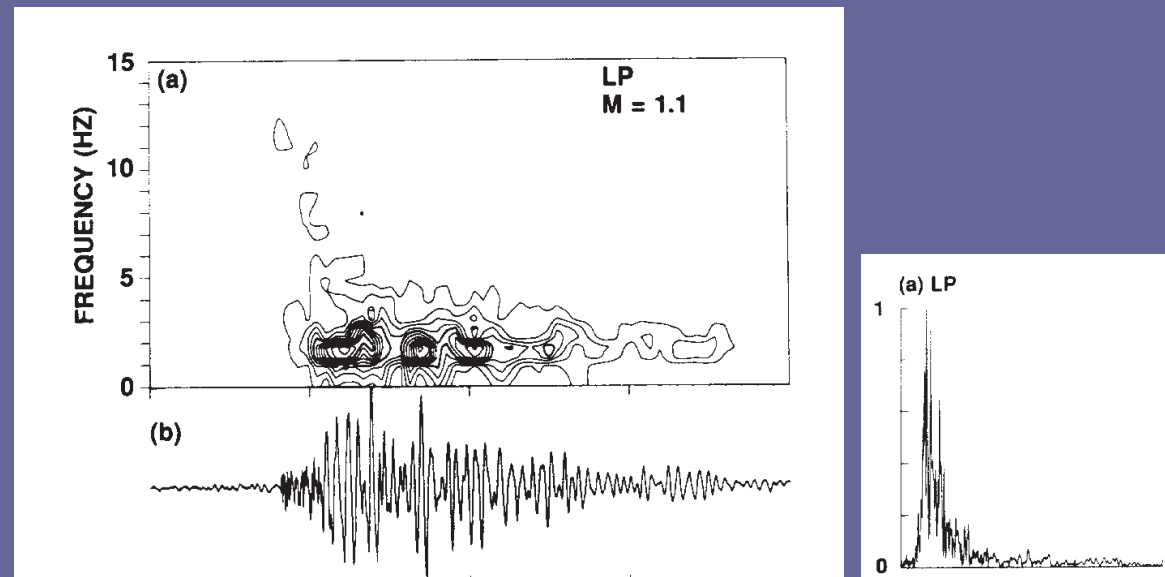
- Short-period earthquakes resulting from brittle failure in response to stress changes associated with magmatic activity
- Clear high-frequency P and S waves, peak frequencies above 5 Hz, short coda



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

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

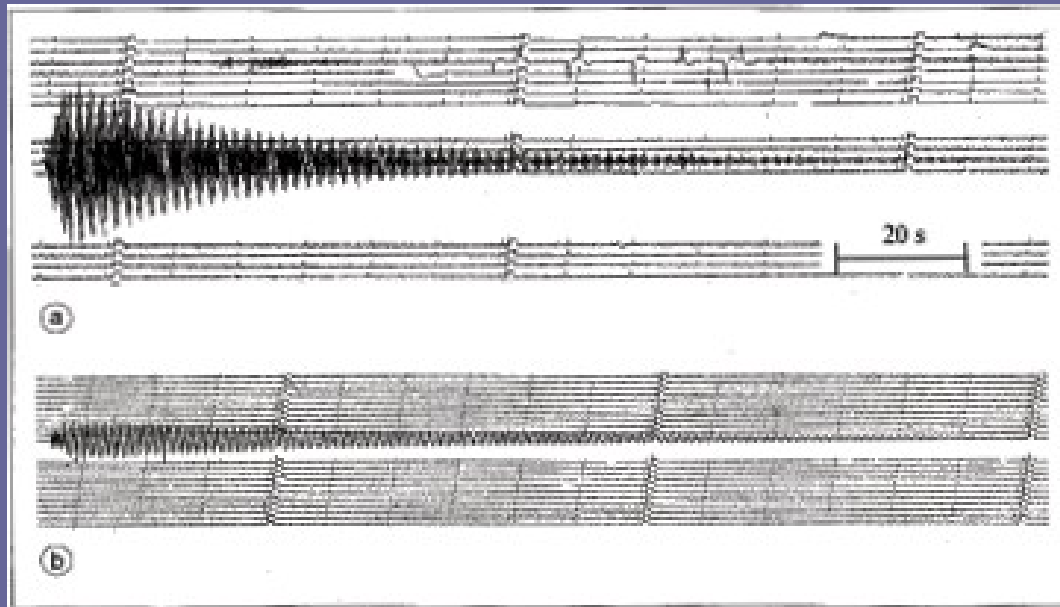
- Long-period 'earthquake' resulting from the resonance of fluid-filled cracks or conduits induced by pressure transients in the fluid
- Weak high-frequency onset followed by quasi-monochromatic oscillations with peak energy near 1.5 Hz, lasting 20s or more



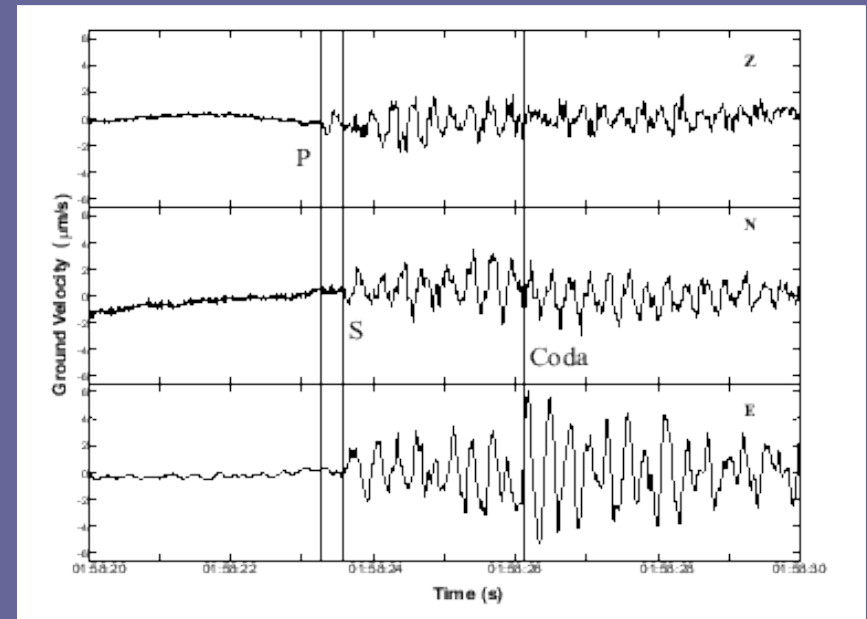


## Tornillo:

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



Example from Galeras, Gomez et al. 1999

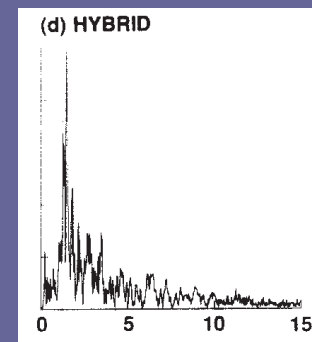
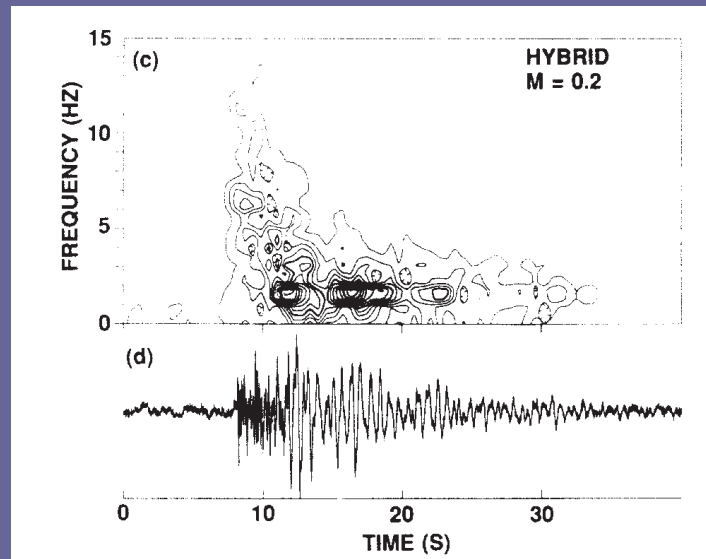


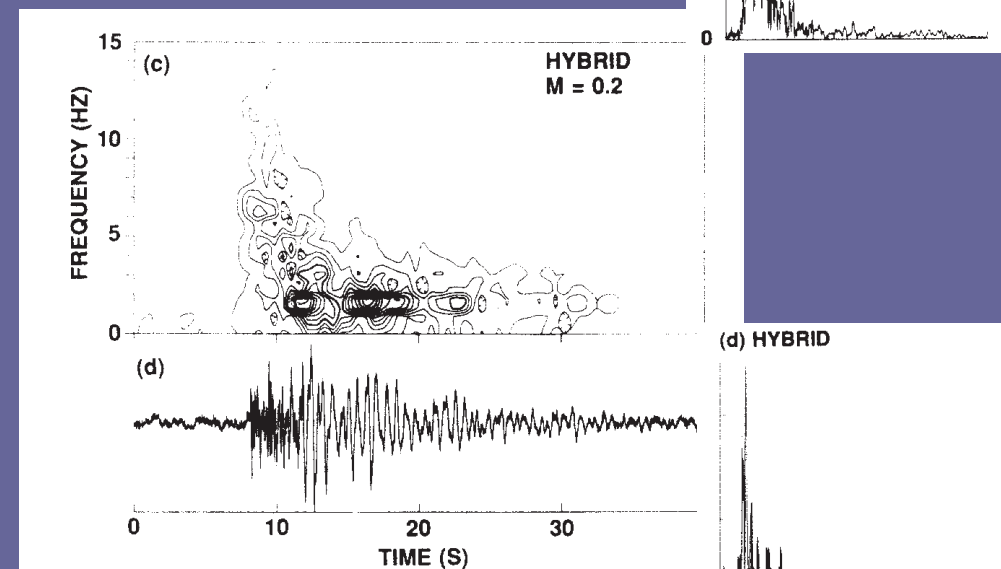
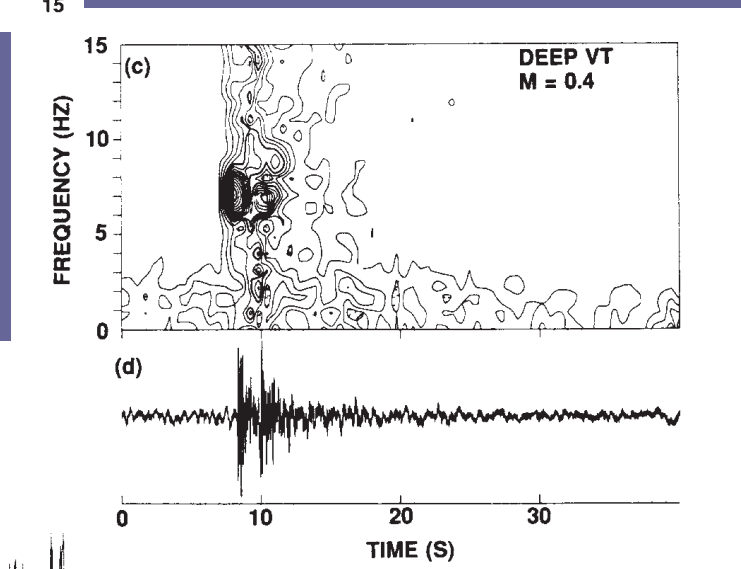
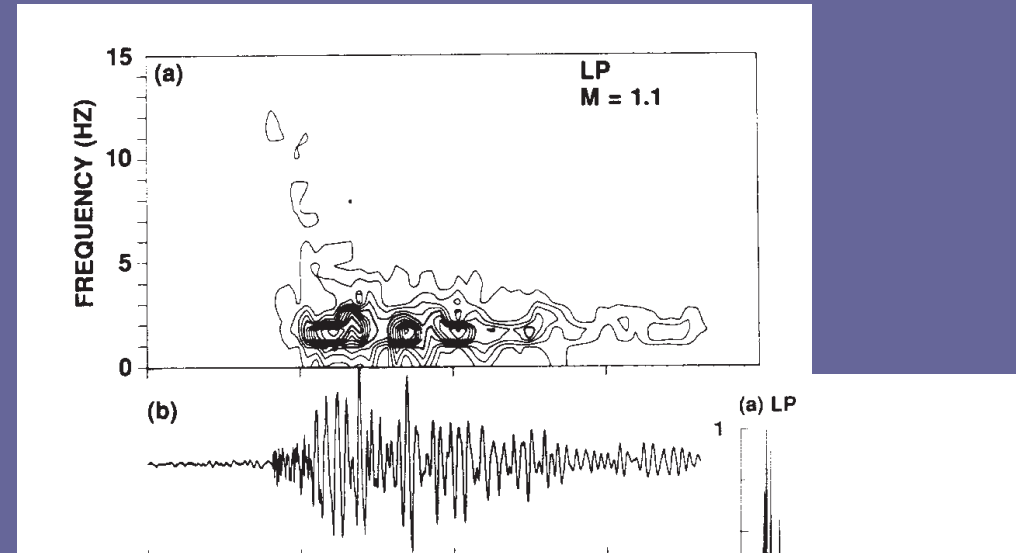
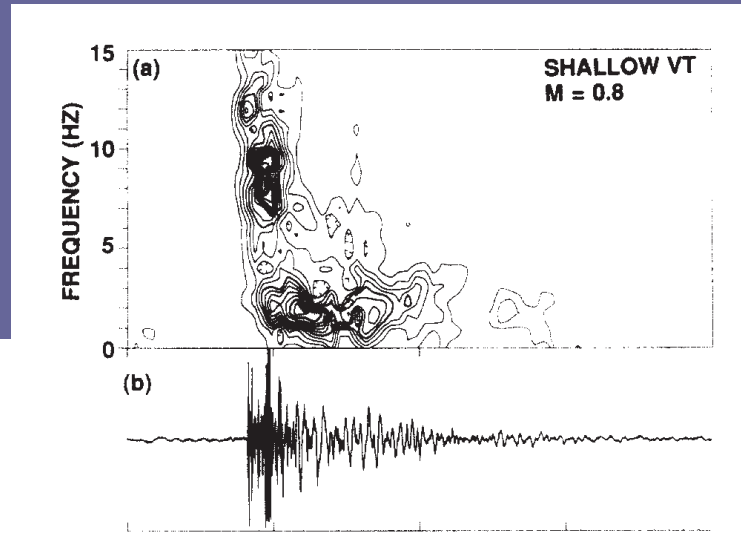
Example from Galeras, M. Hellweg, unpublished

## 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





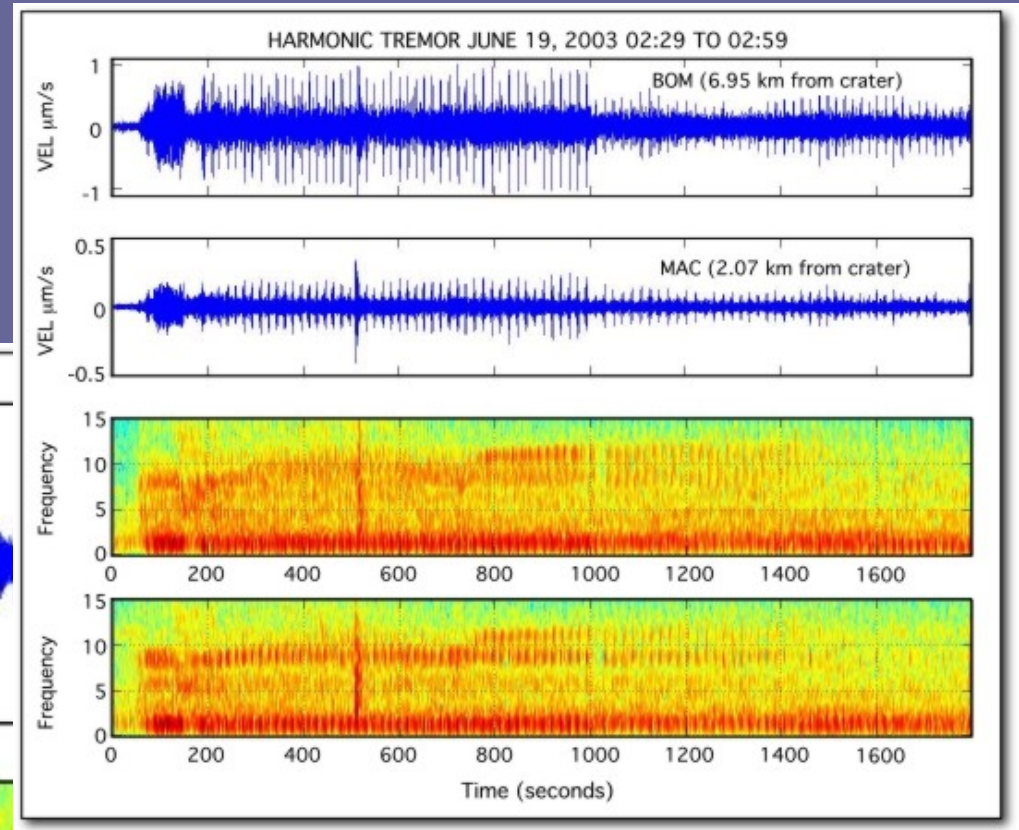
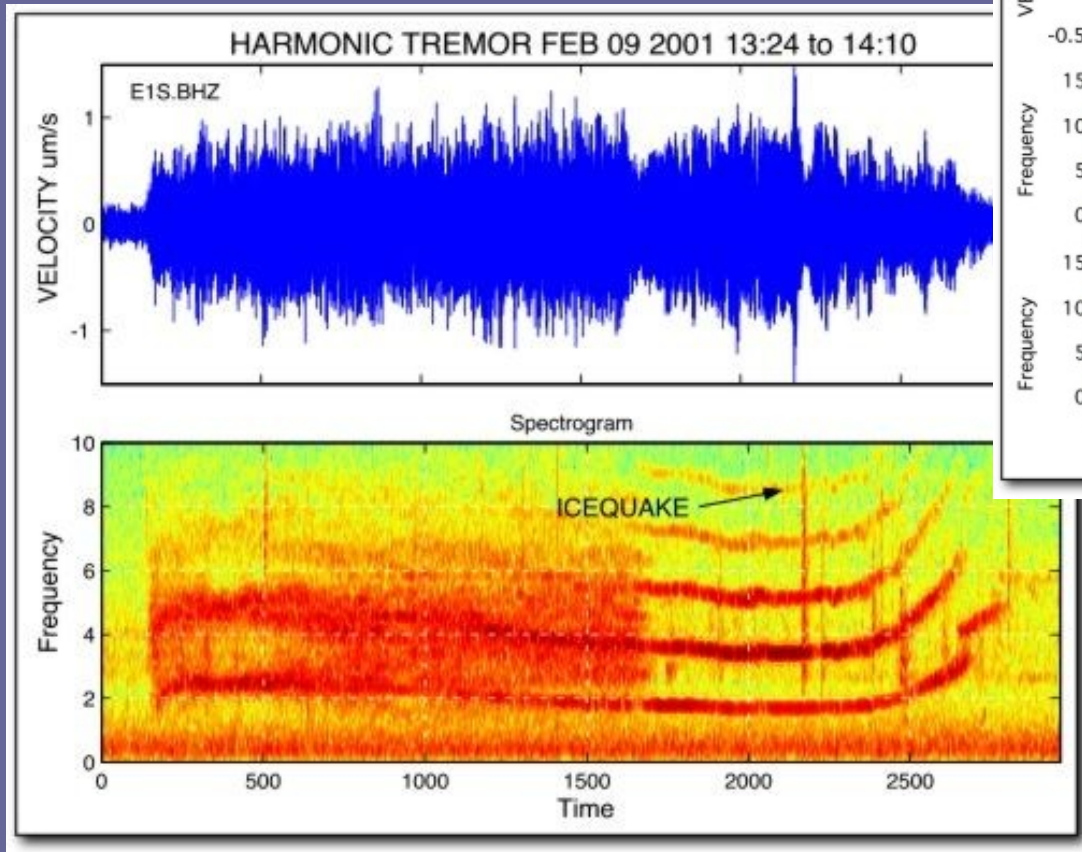
Figures from Lahr et al (1994)

## Tremor (Miller et al. 1998):

A continuous seismic disturbance lasting for several minutes.

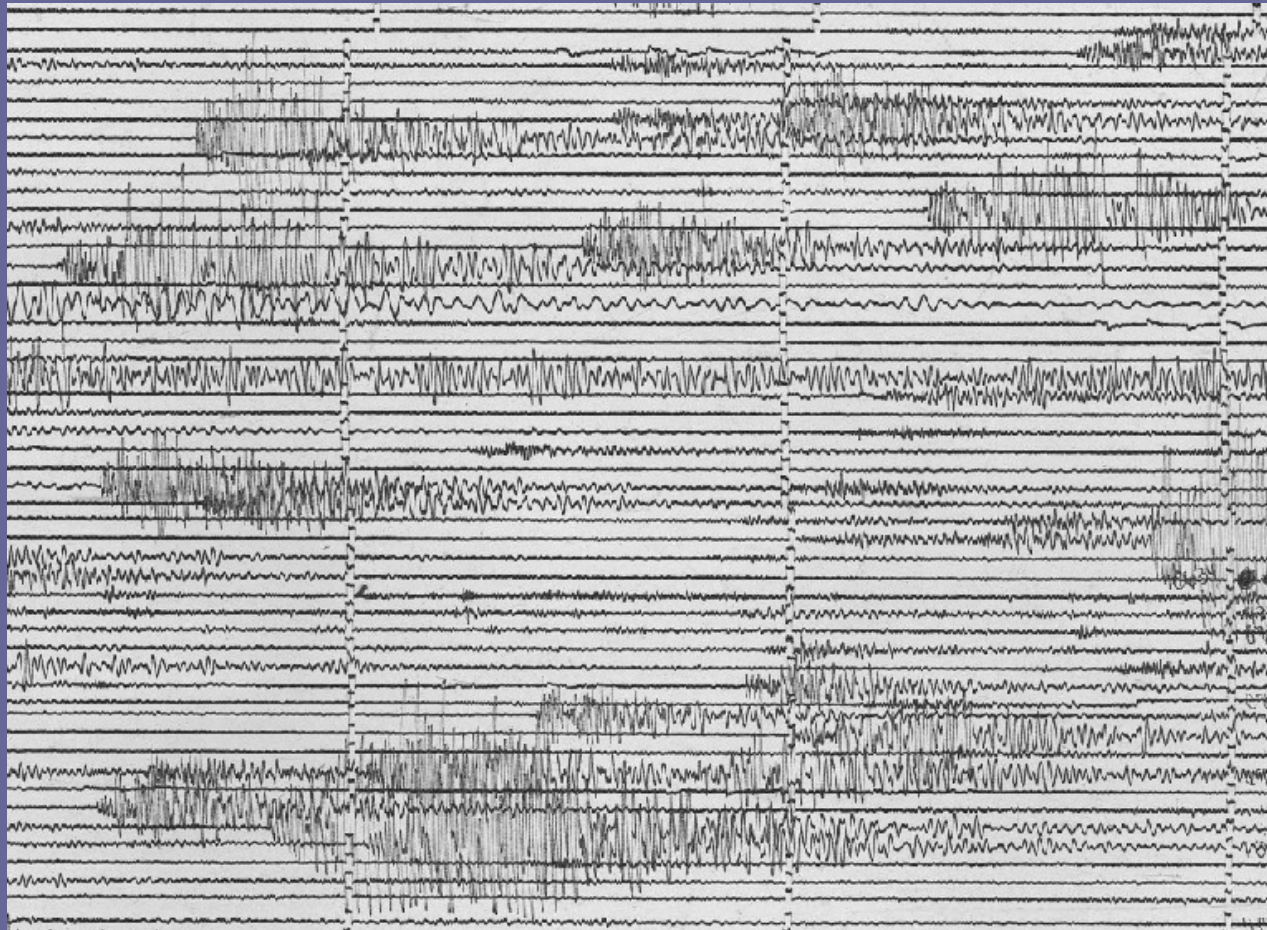
- *Harmonic tremor*: a low (fundamental) frequency sine wave with smoothly varying amplitude.
- *Spasmodic tremor*: a higher or more broadband frequency, pulsating, irregular signal.

# Harmonic Tremor:



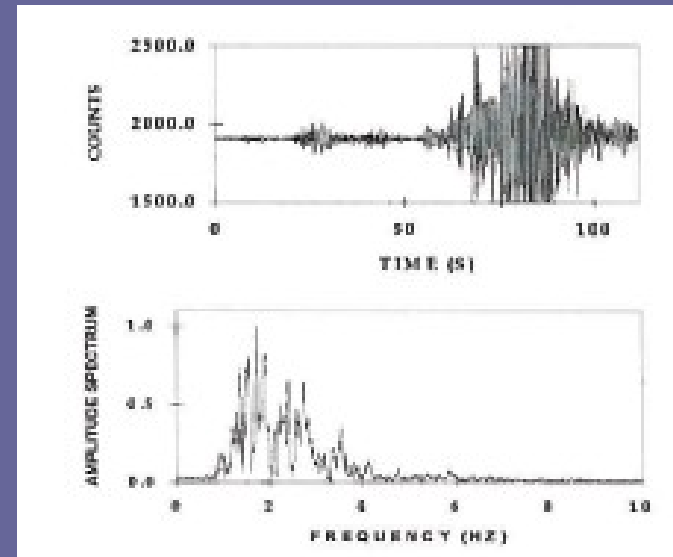
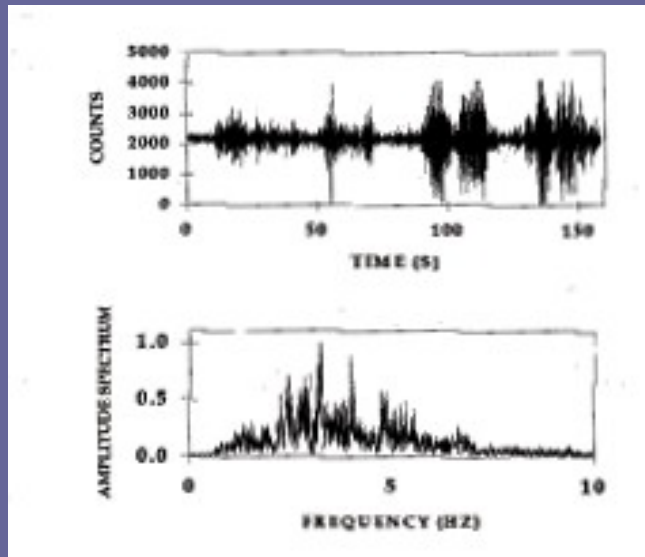
*Two examples from Erebus  
Note harmonics and gliding spectral lines*

## Harmonic Tremor:



*Harmonic tremor, MSH, April 2, 1980*

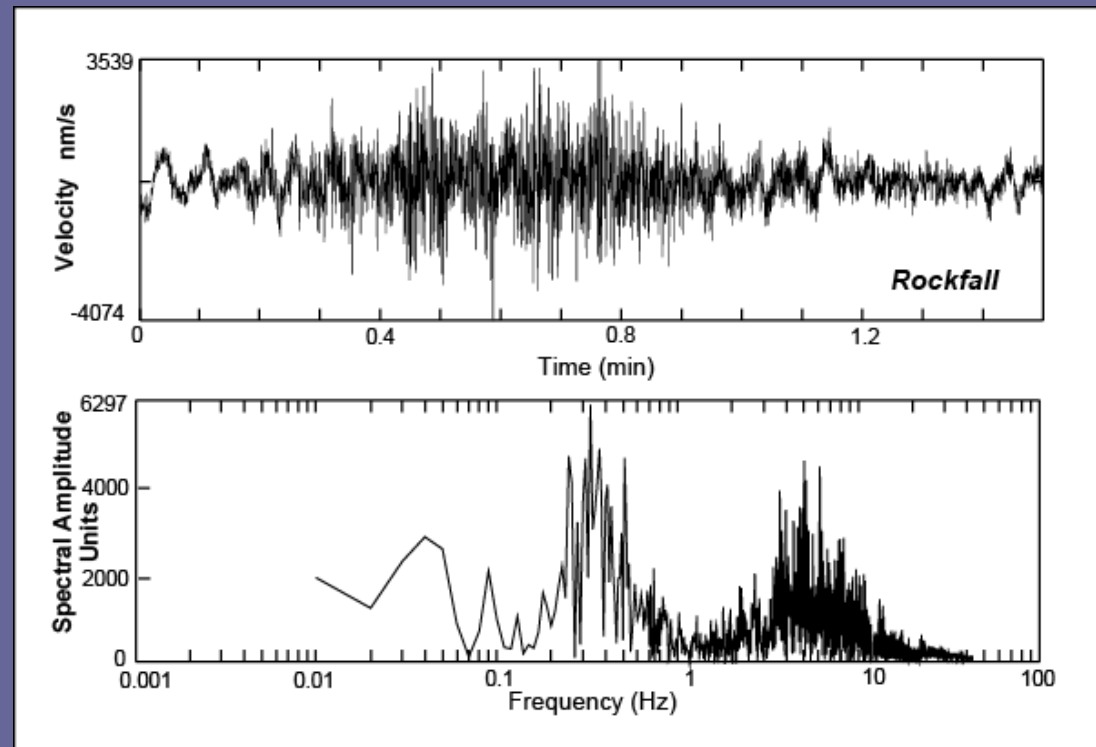
## Spasmodic Tremor:



*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]

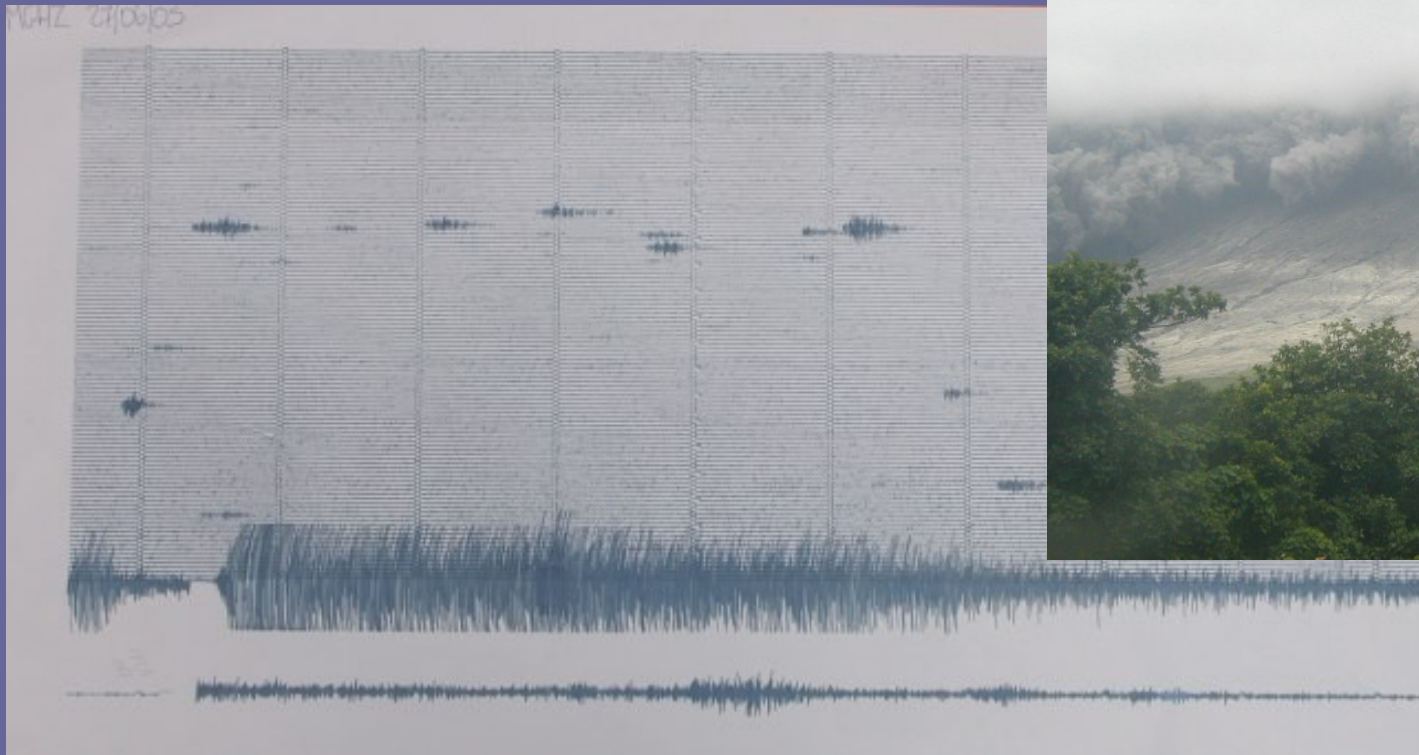


*Soufriere Hills rockfall event  
(LF component is weather-  
related)*



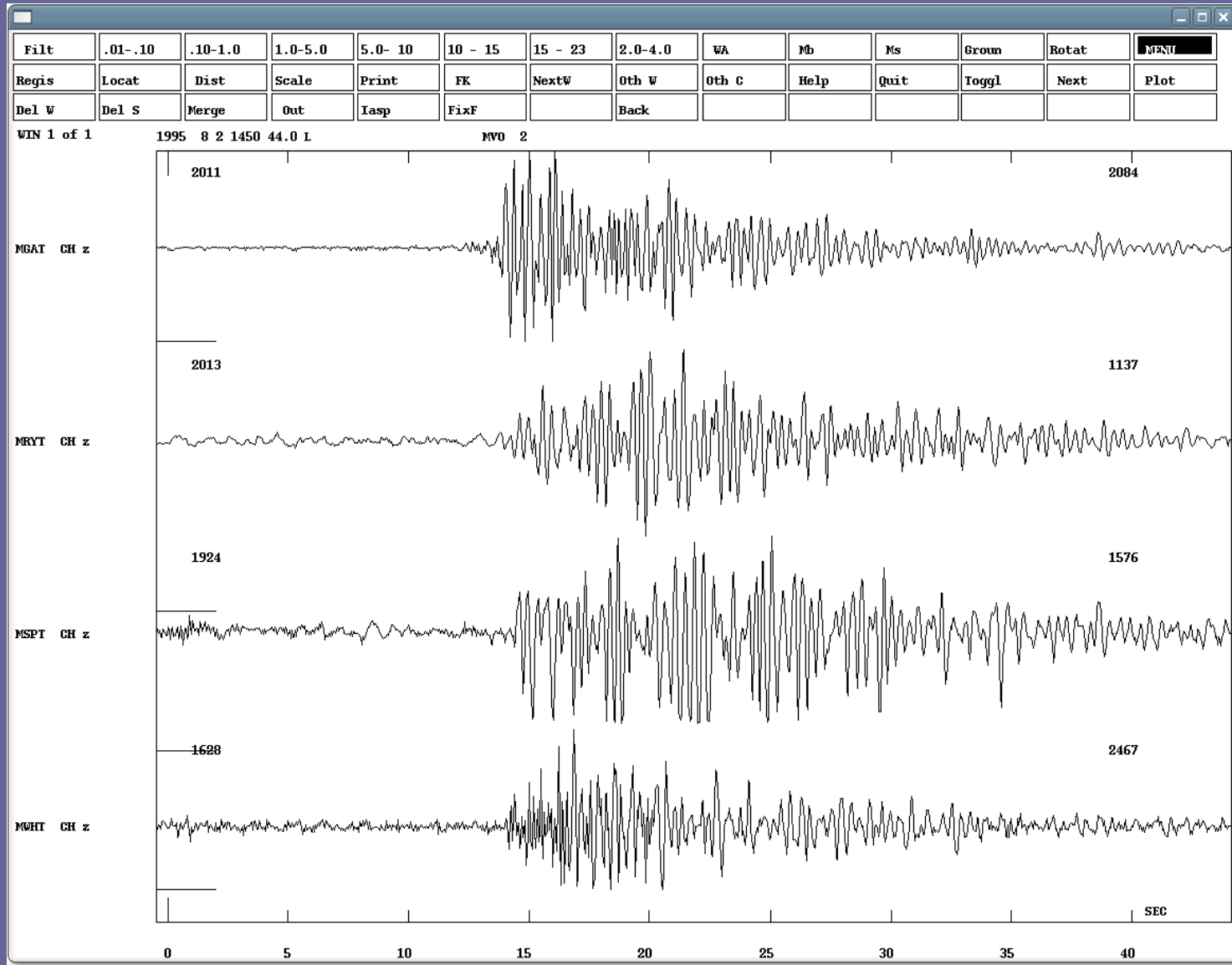
## Explosion events:

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



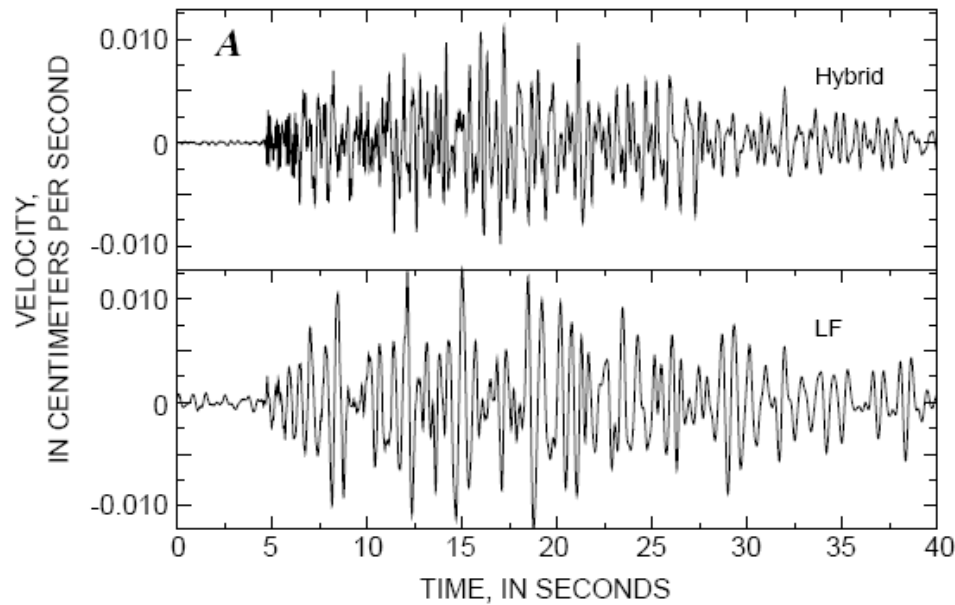
*June 28, 2005 Montserrat*

# Station-to-station variations

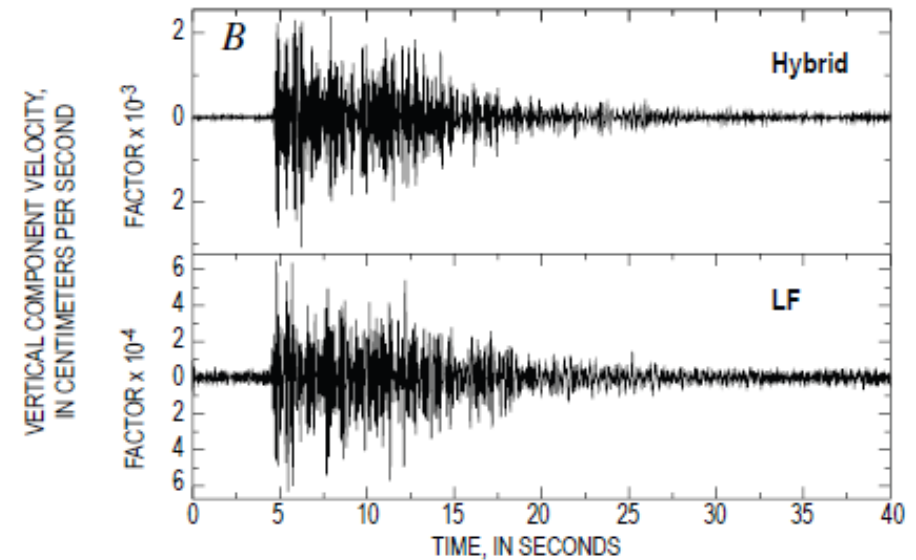


*Soufriere Hills Volcano, August 1995*

# 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*

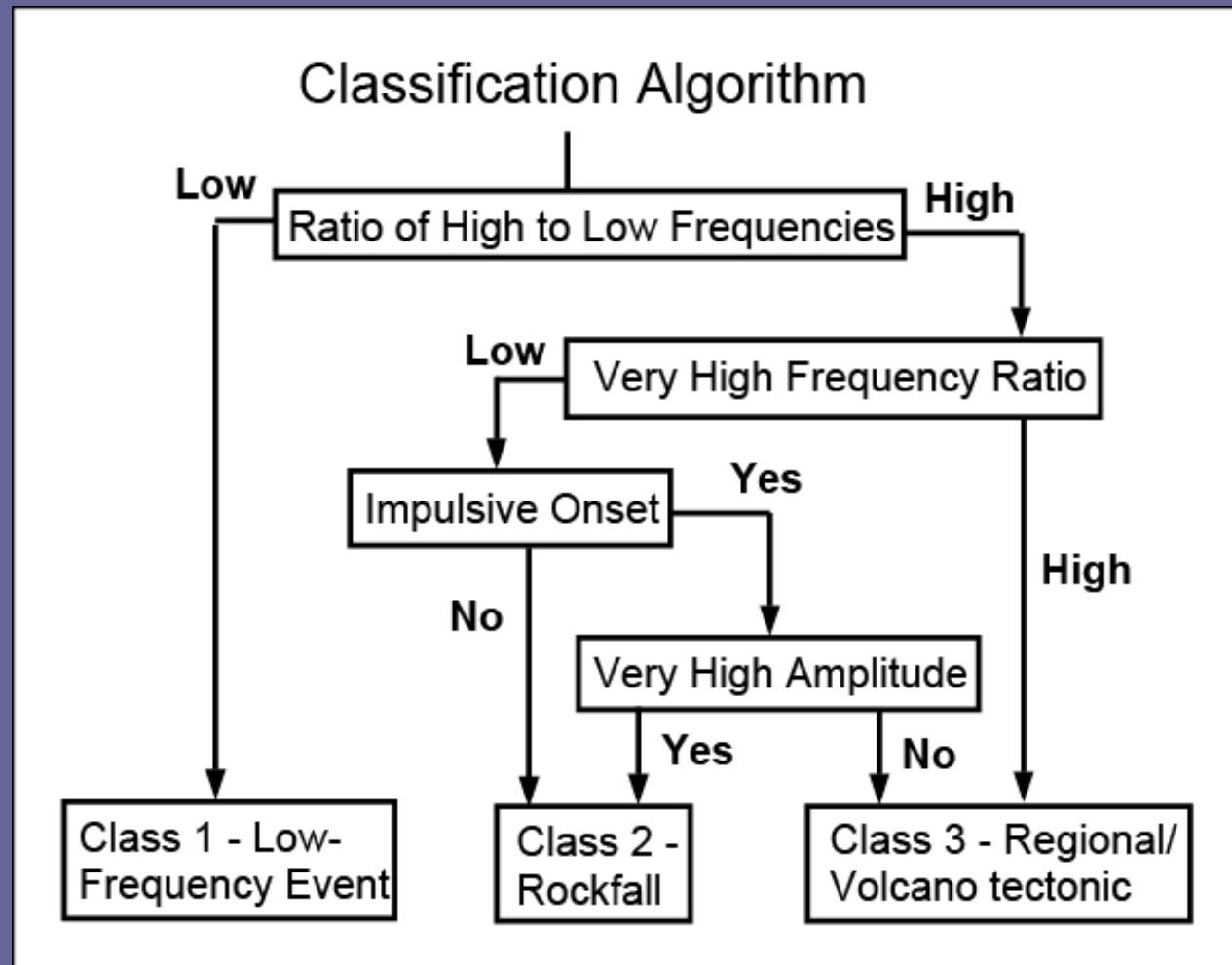
## Classification Methods:

### 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 –

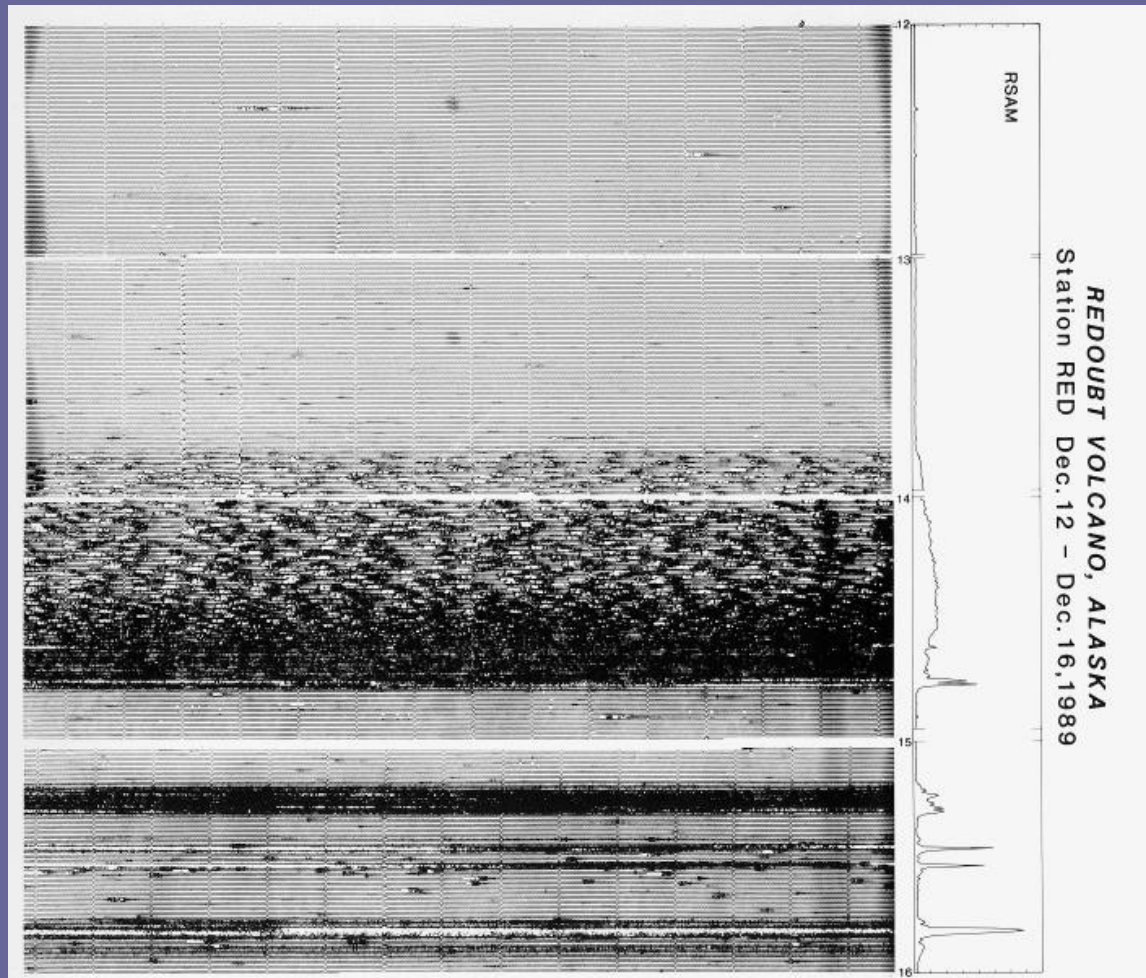
Consistent and systematic classification according to predefined rules

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

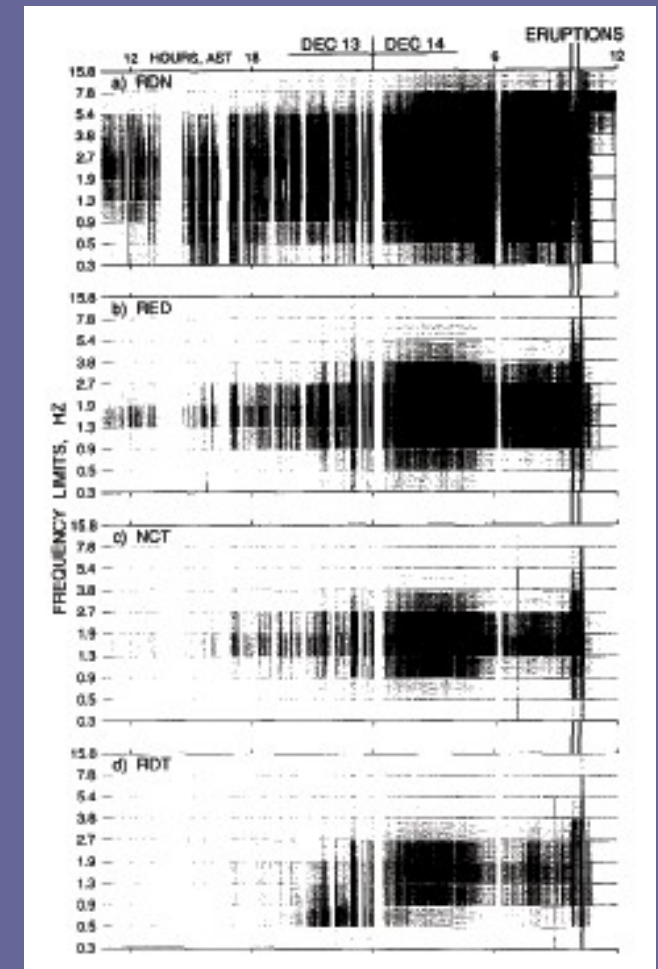
May classify noise, fit unique events into a predefined (incorrect) category

## 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)

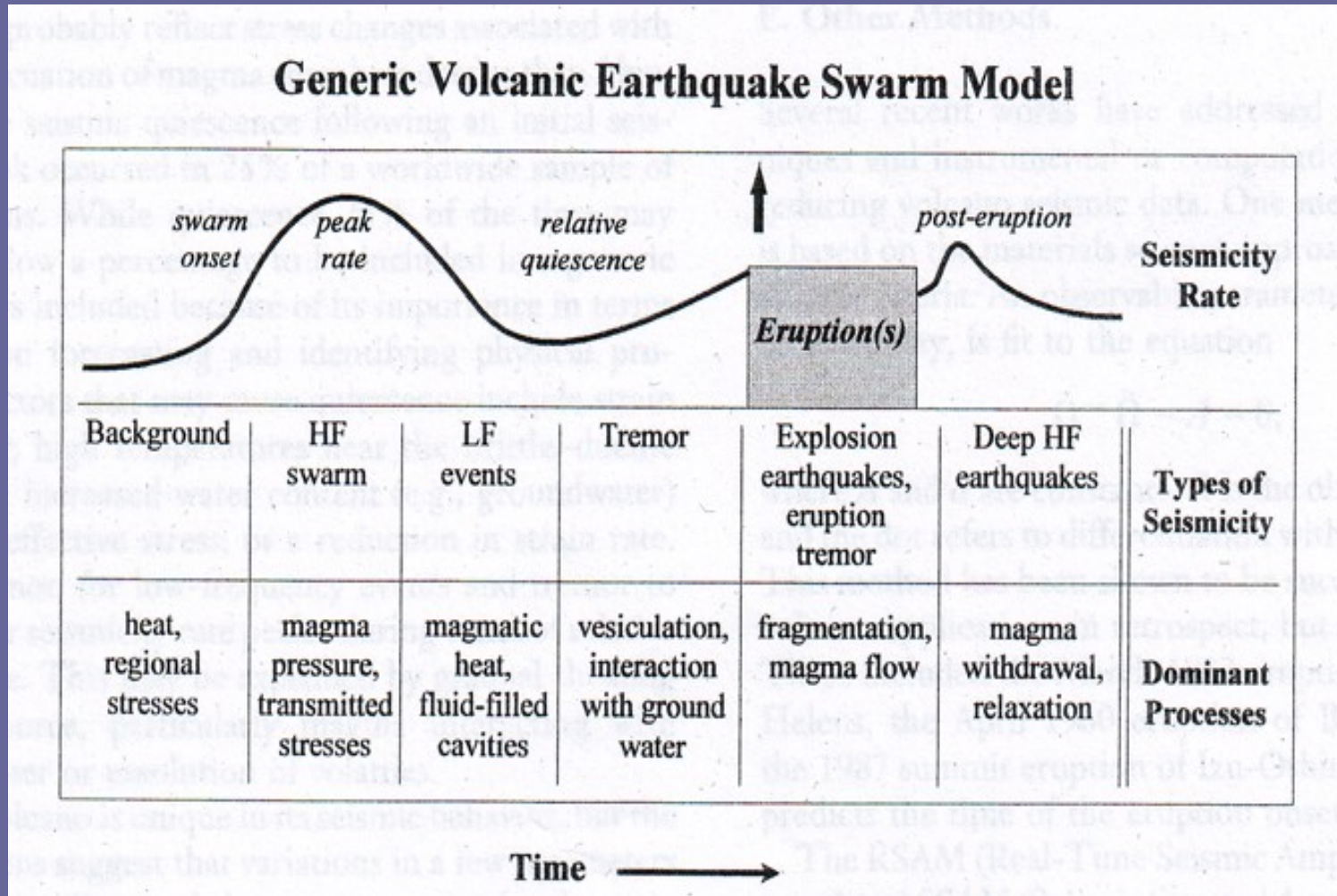
Advanced analyses (often requires broadband/3-C):

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

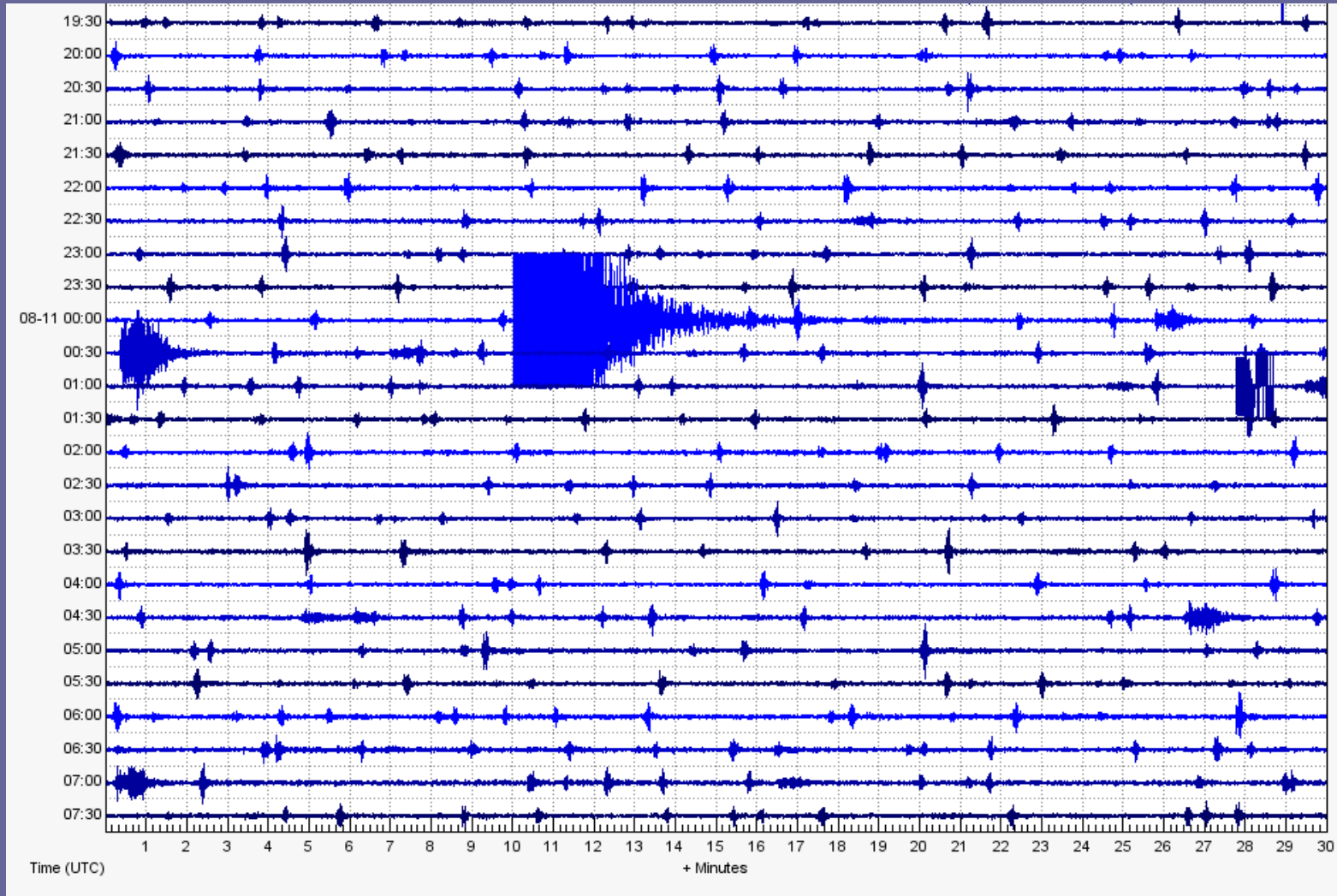


# Patterns in volcanic seismicity

(May begin months to hours before eruption)



# 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

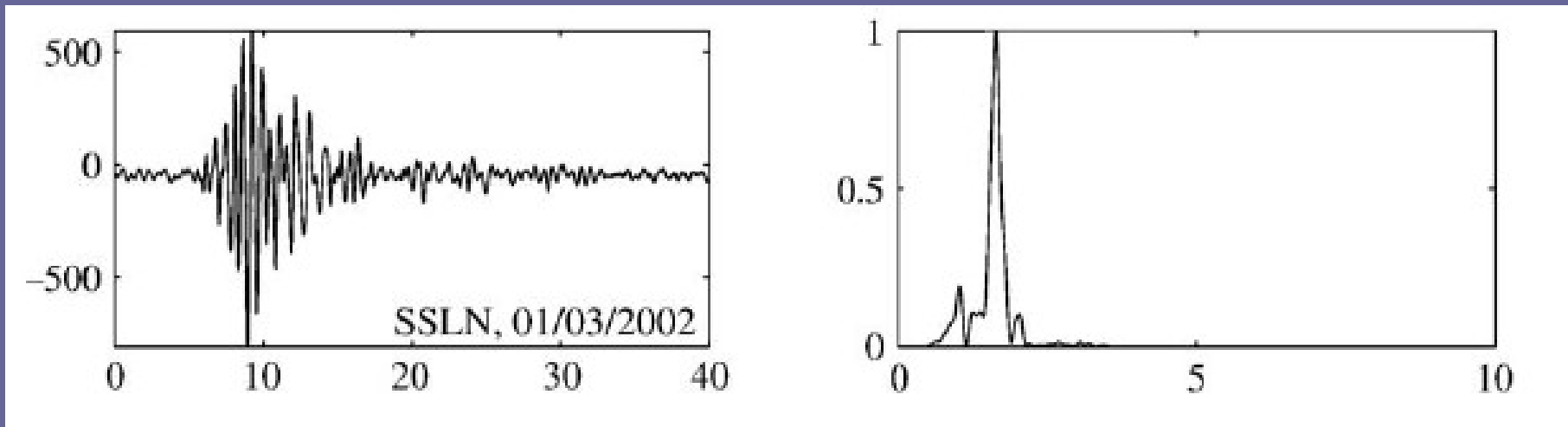
Poas Volcano, Costa Rica

Gareloi Volcano, Alaska

Telica Volcano, Nicaragua

Ngaururhoe, New Zealand

Others?...

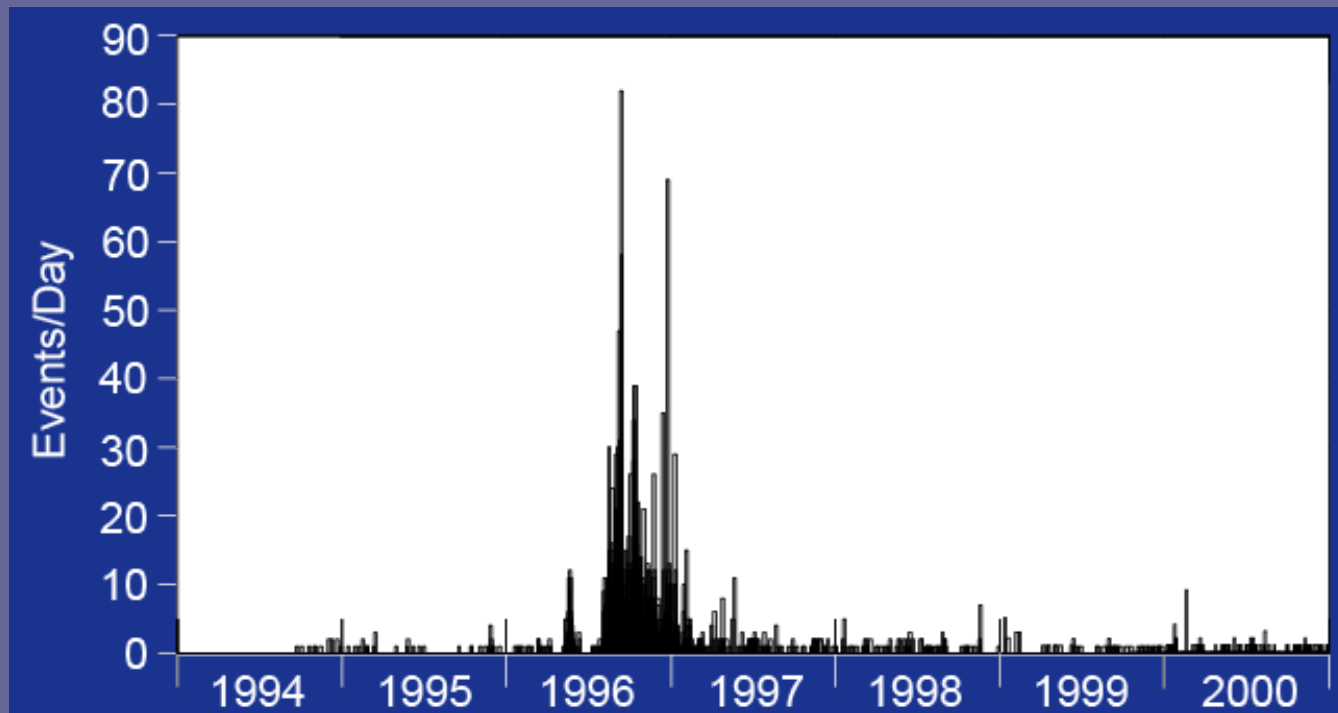


## Non-eruptive earthquake swarms:

- 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<sub>2</sub> and SO<sub>2</sub> 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...

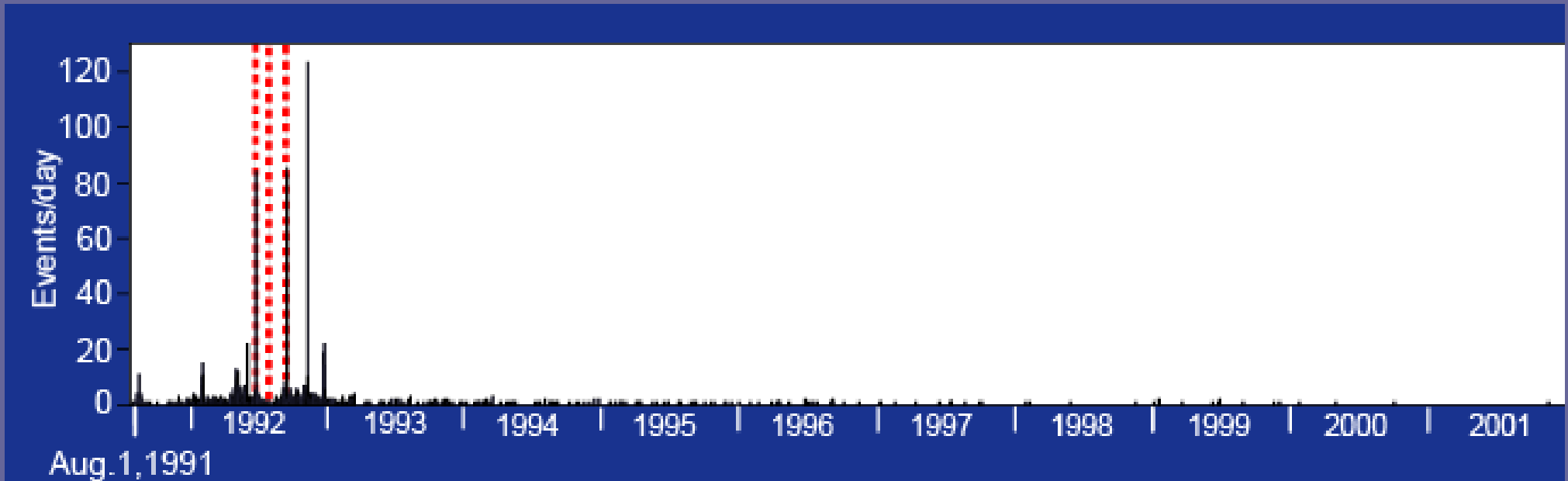
## **Mechanisms of “Stealth” magma ascent:**

- 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(?)