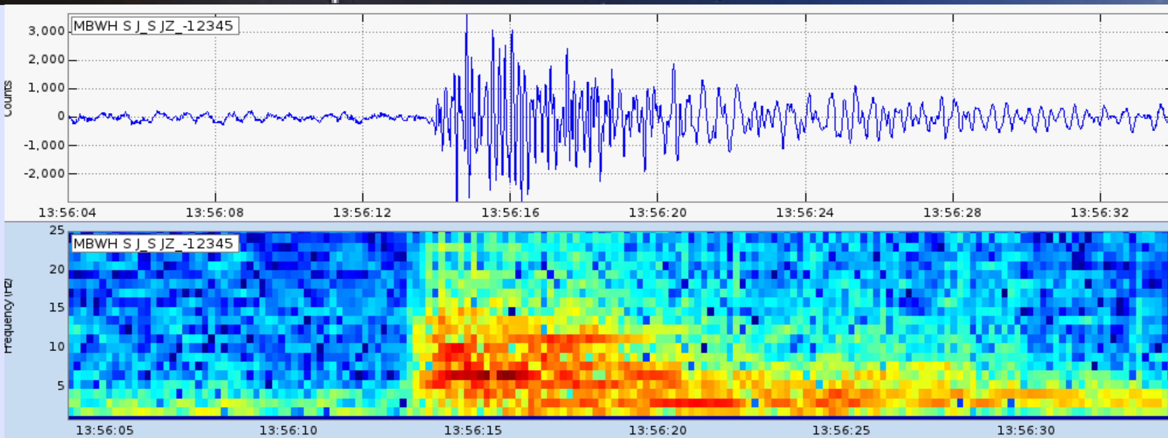
VT Earthquakes

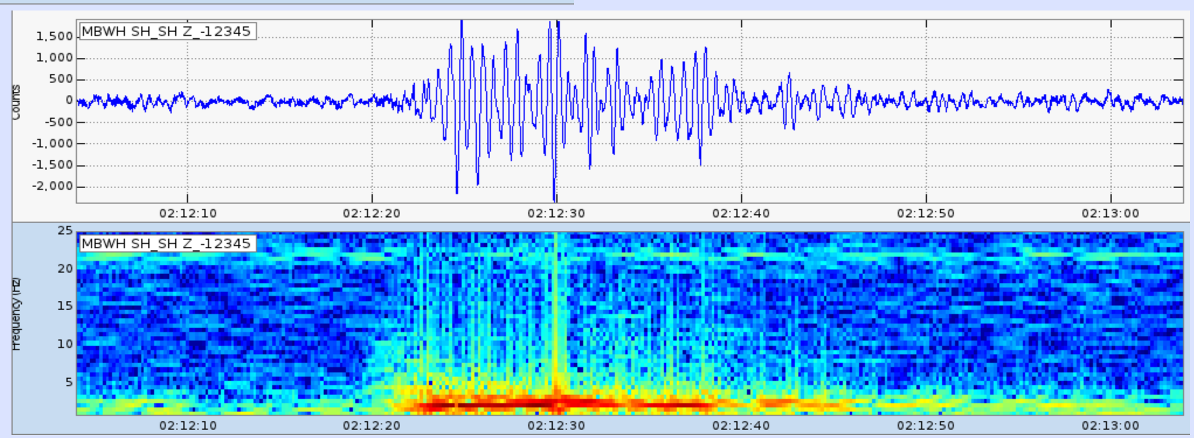
PASI on Magma-Tectonic Interactions
May 10, 2013

Diana C. Roman (DTM-CIW)

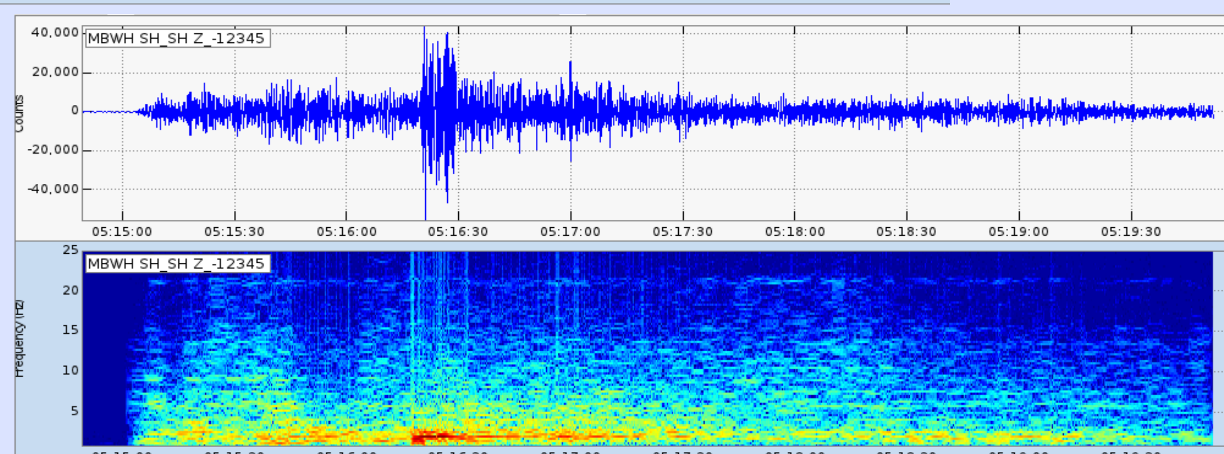
Introduction to VTs
- Volcano-Seismic Event Classification



Volcano-tectonic (VT) earthquake
(aka "High-frequency" earthquake)



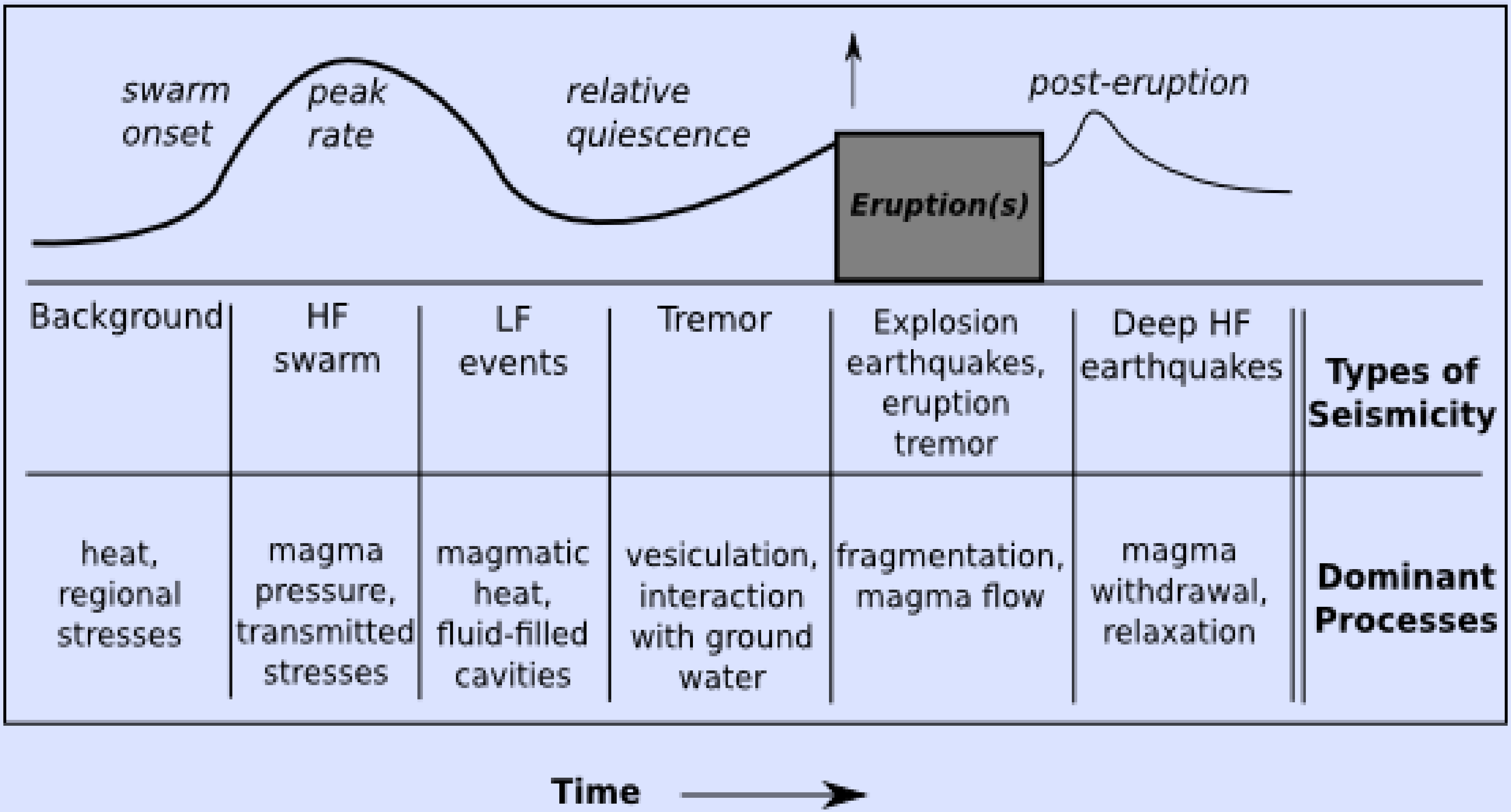
Long-period (LP) event
(aka "Low-frequency" event)



Seismic signature of a
Volcanic explosion

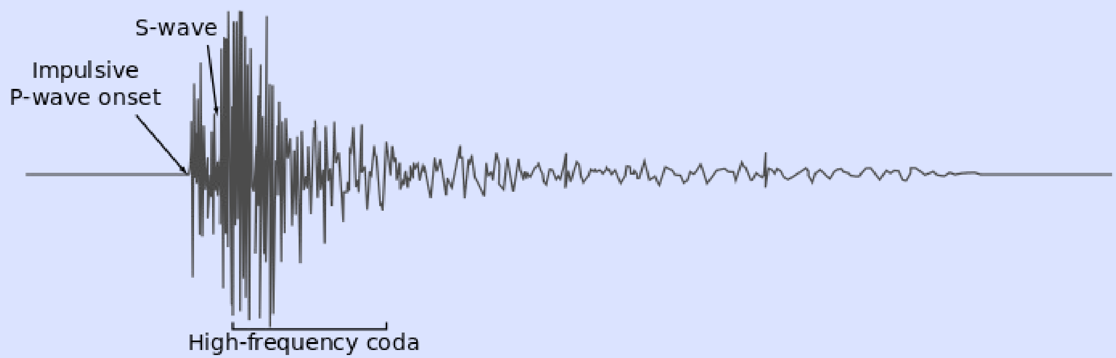
Introduction to VTs
- Timing of Occurrence

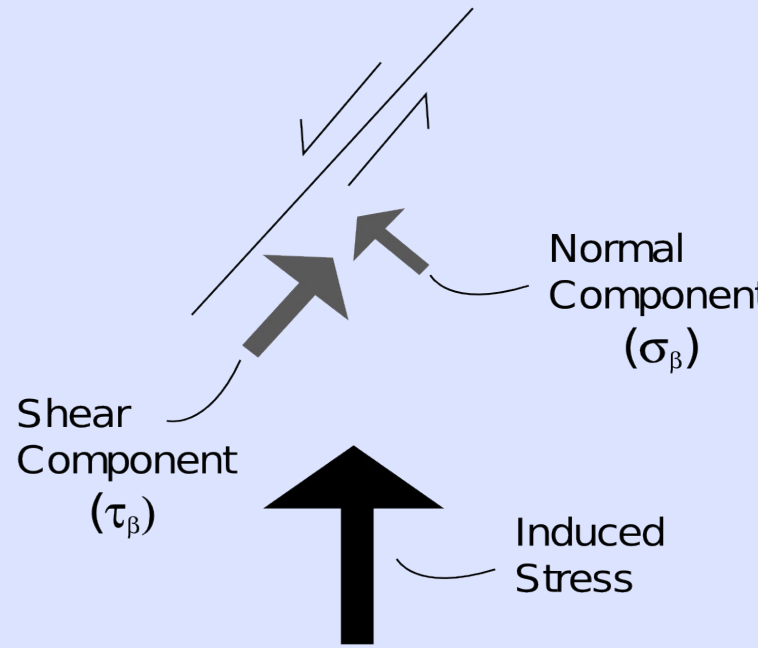
Generic Volcanic Earthquake Swarm Model



After McNutt and Benoit (1995)

Introduction to VTs
- Source process





Coulomb stress change:

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

How to generate a VT:
1. Increase shear stress
2. Decrease normal stress (directly)
3. Decrease normal stress (by increasing pore pressure)

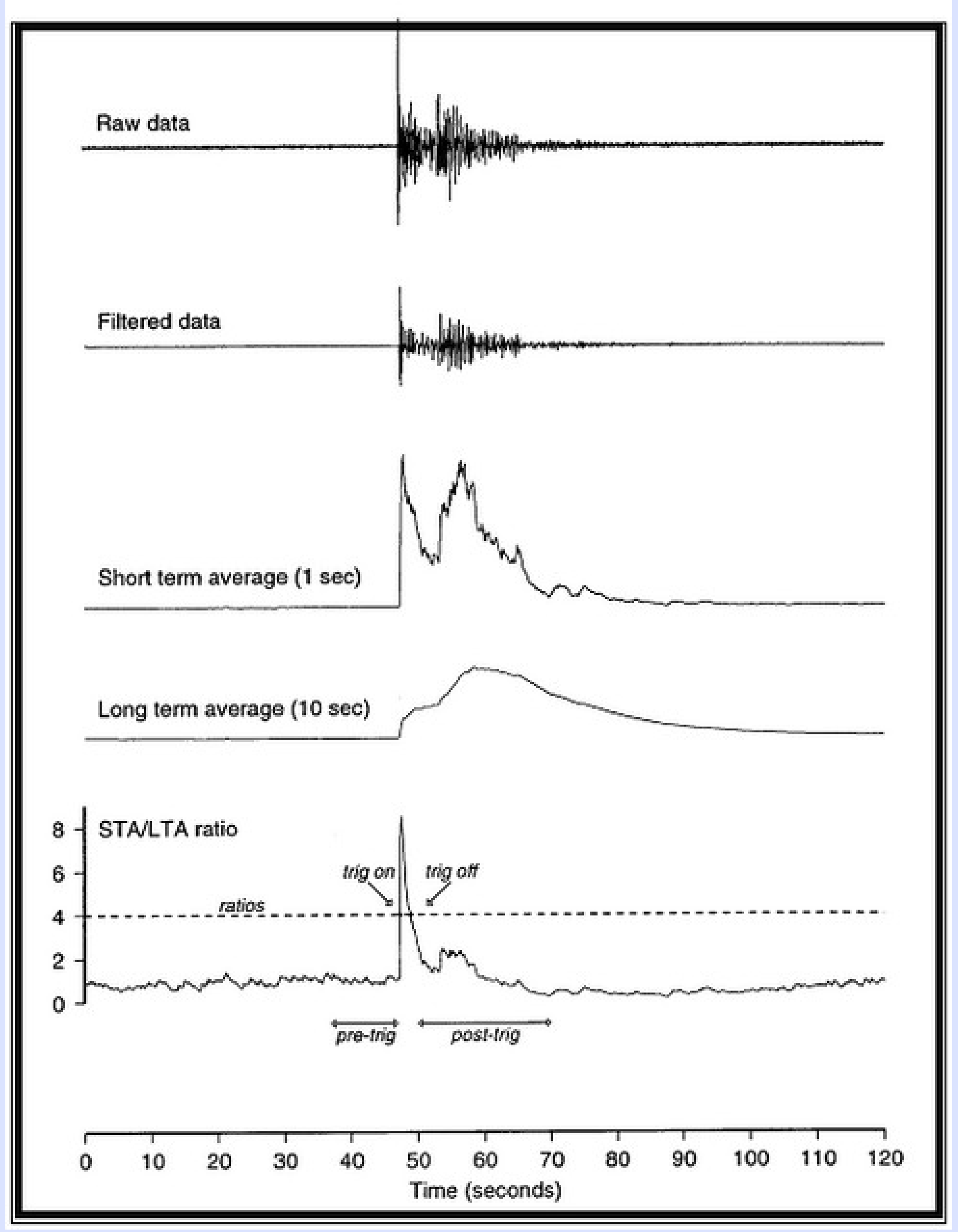
VT Analysis
- Summary of Analyses

- Identify changes in space and/or time in:
  - Rates
  - Multiplets
  - Locations
  - Magnitudes
  - Focal Mechanisms
  - Shear-wave splitting

- Model or invert (based on Coulomb stress transfer)
  VT locations +- focal mechanisms +- split s-waves

VT Analysis
- What can you do with a VT?

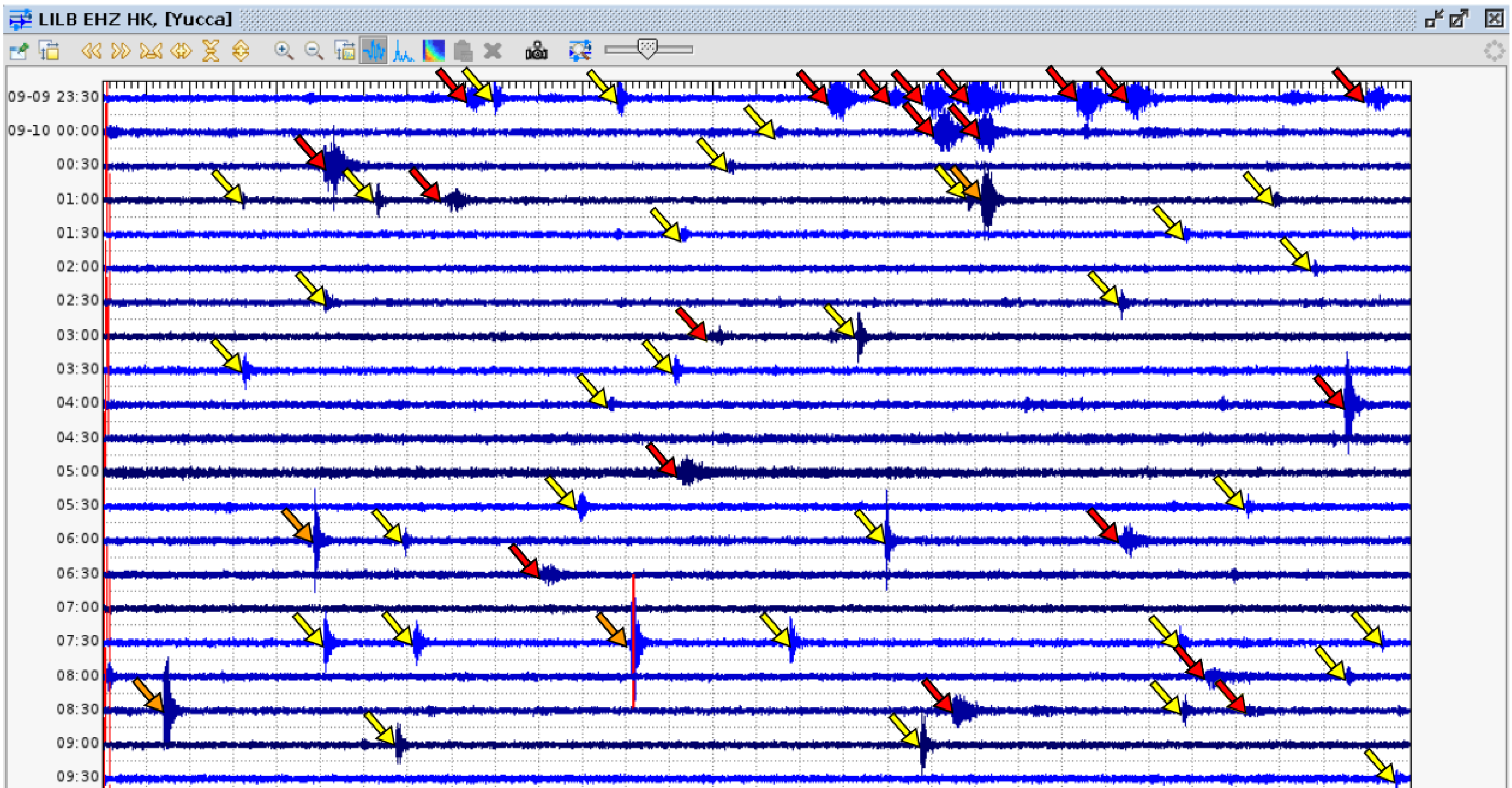
- Detect them (single-station)
- Count them (single-station)
  - Automatically



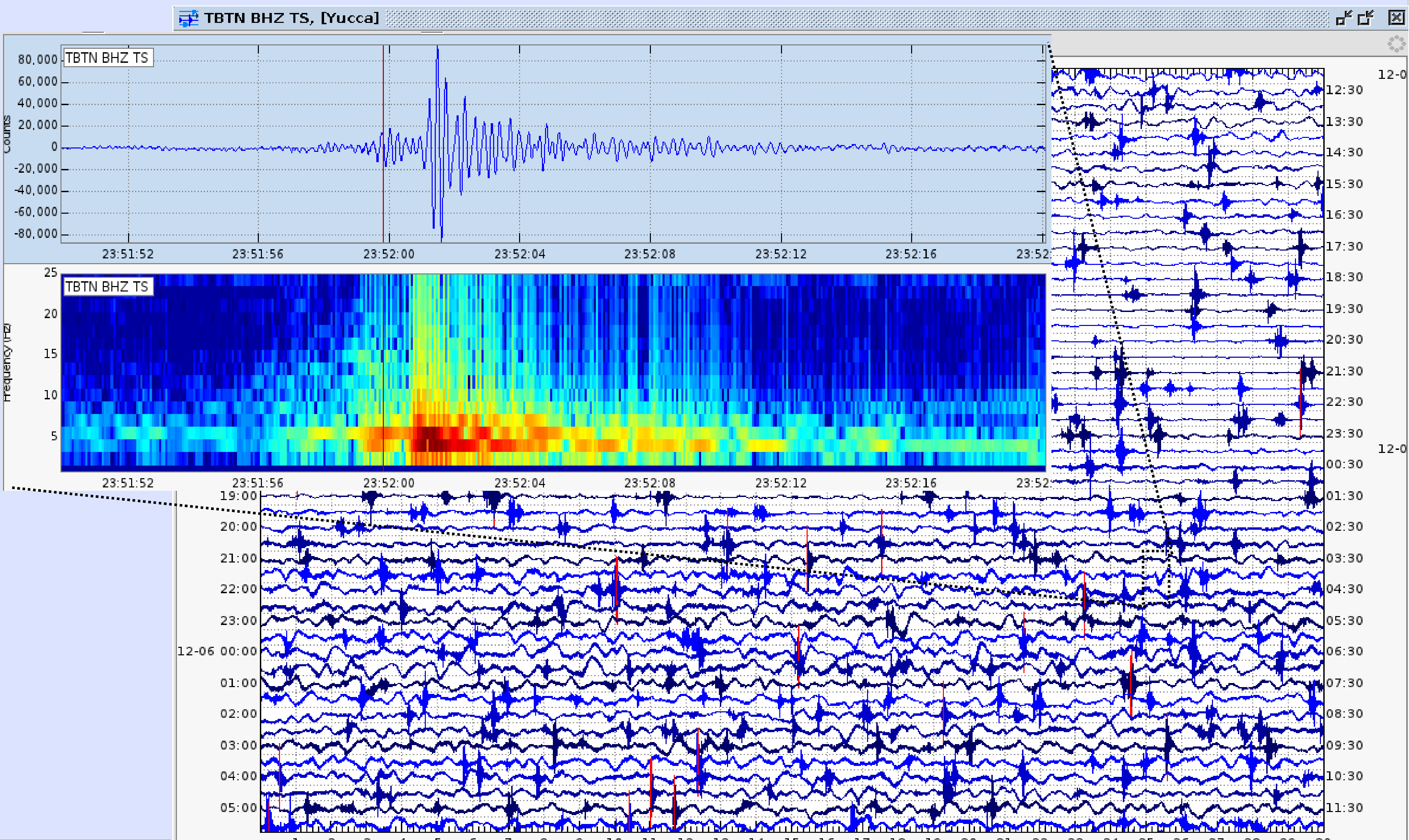
From Guralp Systems

VT Analysis
- What can you do with a VT?

- Detect them (single-station)
- Count them (single-station) - Manually

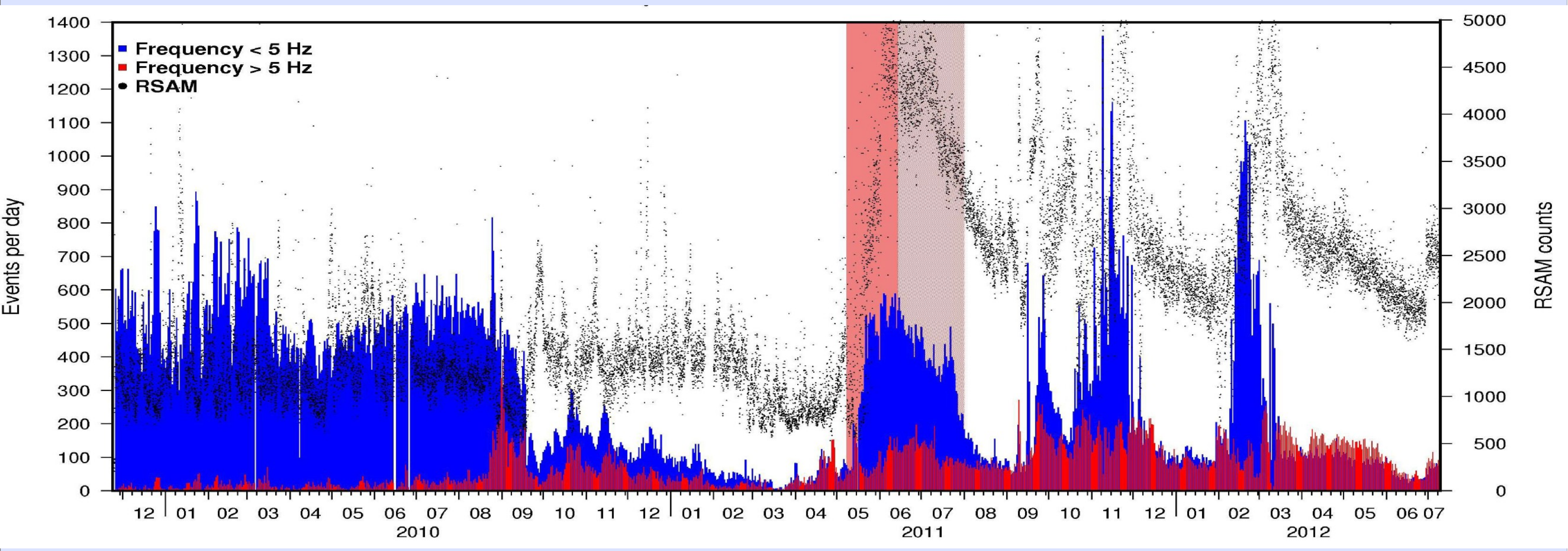


Case Study
- Telica Volcano, Nicaragua



Case Study
- Telica Volcano, Nicaragua

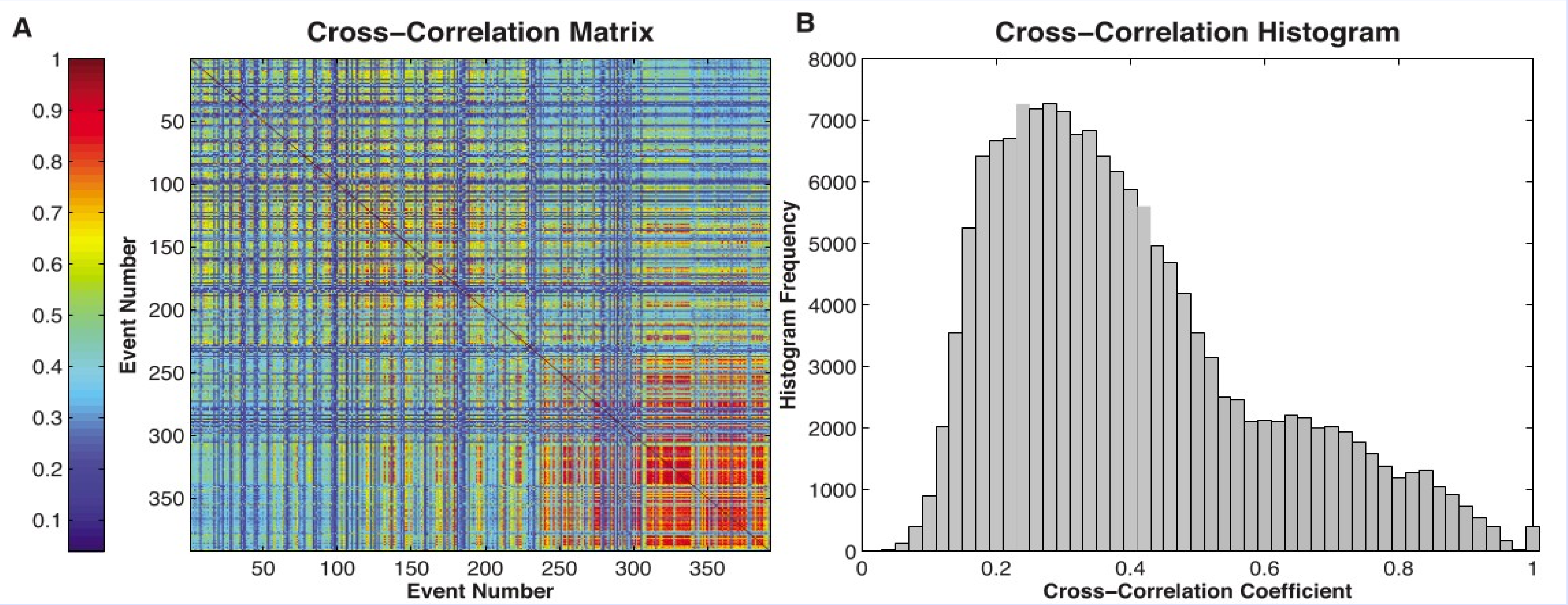
← 2011 Eruption →



From Geirsson et al., in prep;
Rodgers et al., in prep

VT Analysis
- What can you do with a VT?

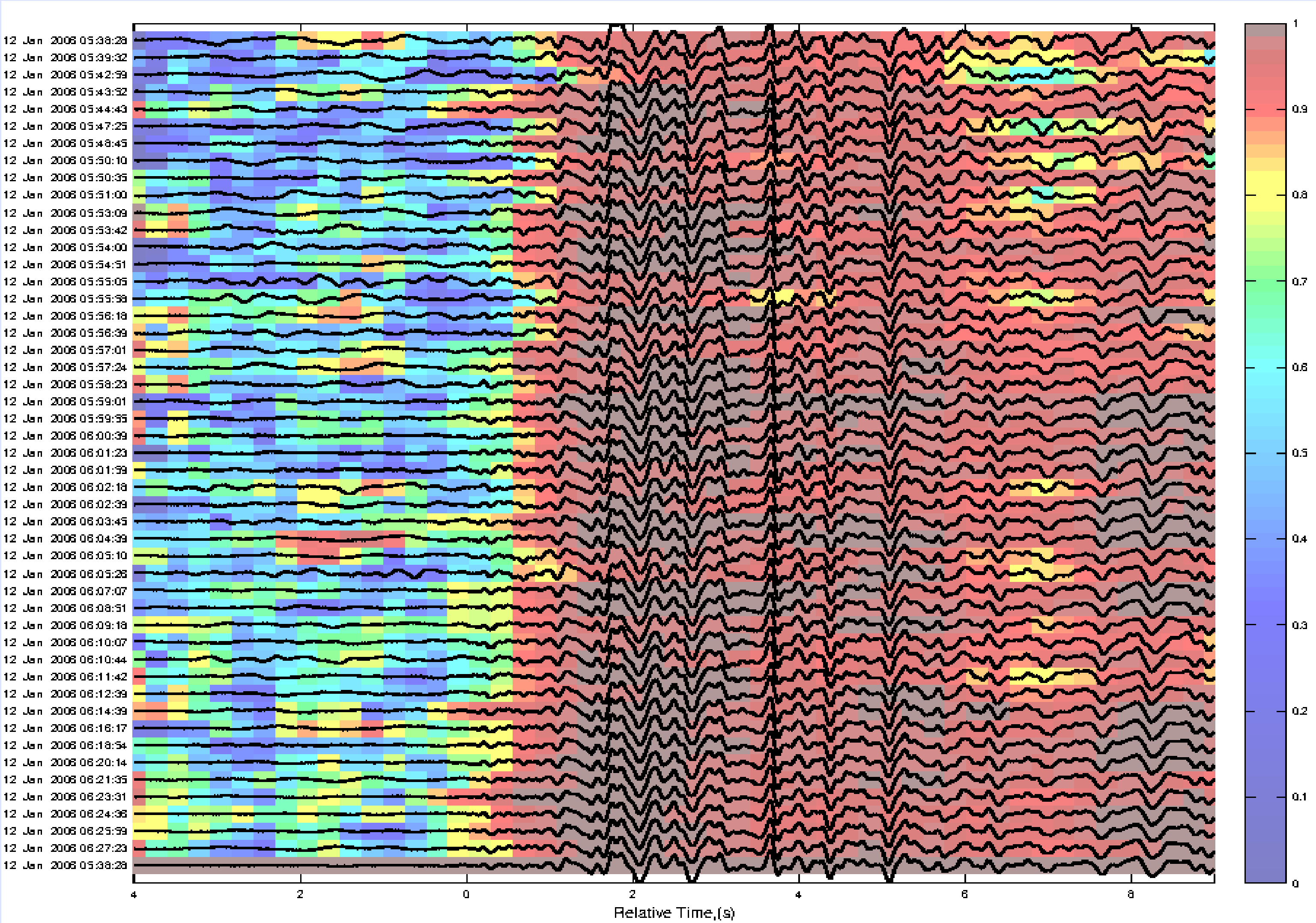
- Look for waveform similarity (single station) - multiplets
  - Identified through waveform cross-correlation
  - Similar waveforms implies similar location/source process
  - Reverse multiplets also sometimes observed



From Thelen et al. 2011

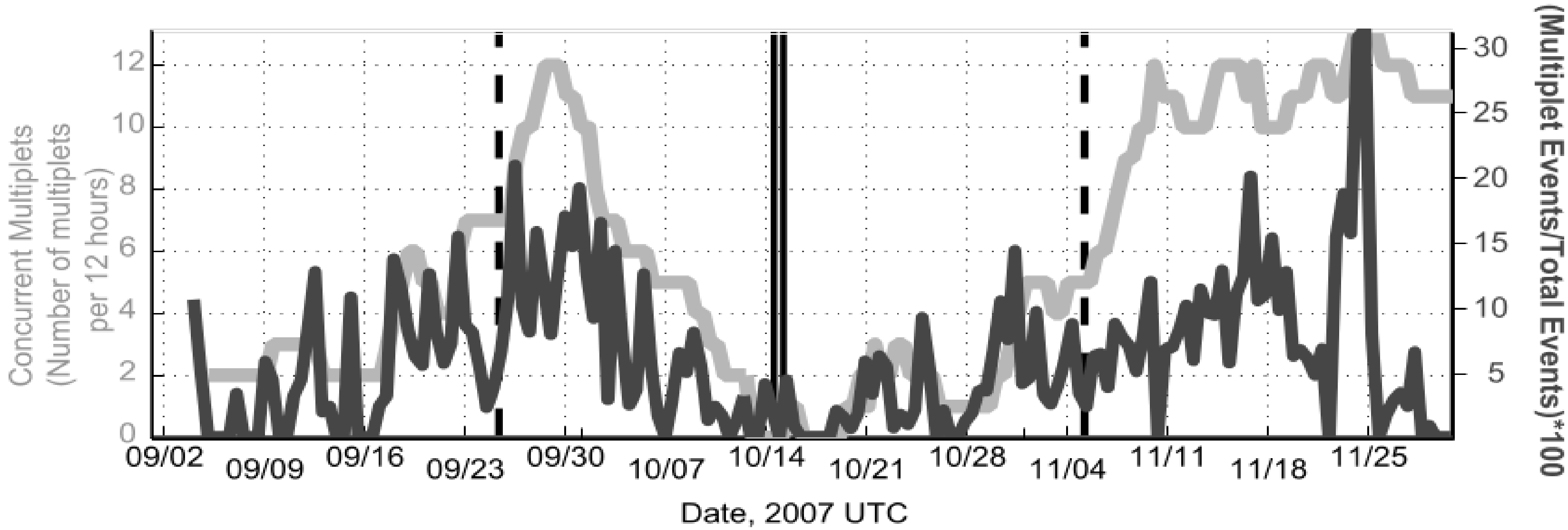
VT Analysis
- What can you do with a VT?

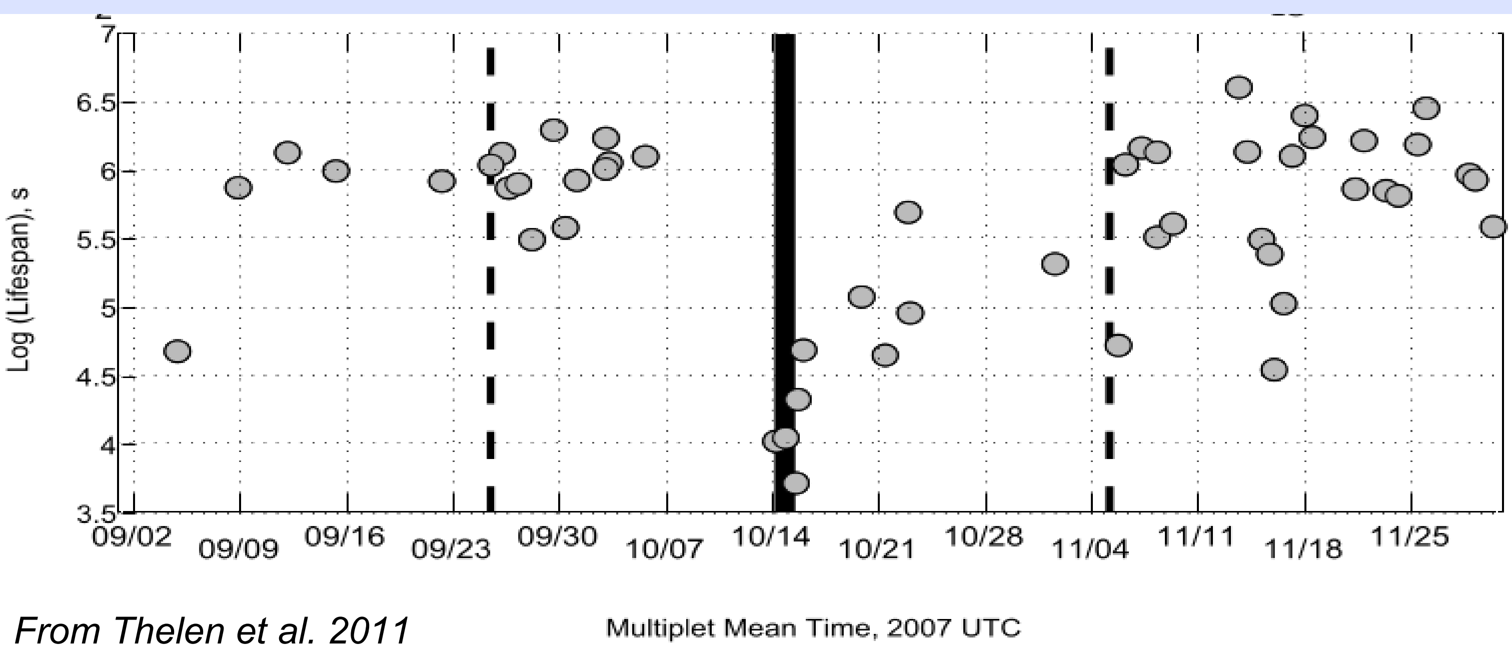
- Look for waveform similarity (single station) - multiplets



From Mike West

Case Study
- Bezymianny Volcano, Russia



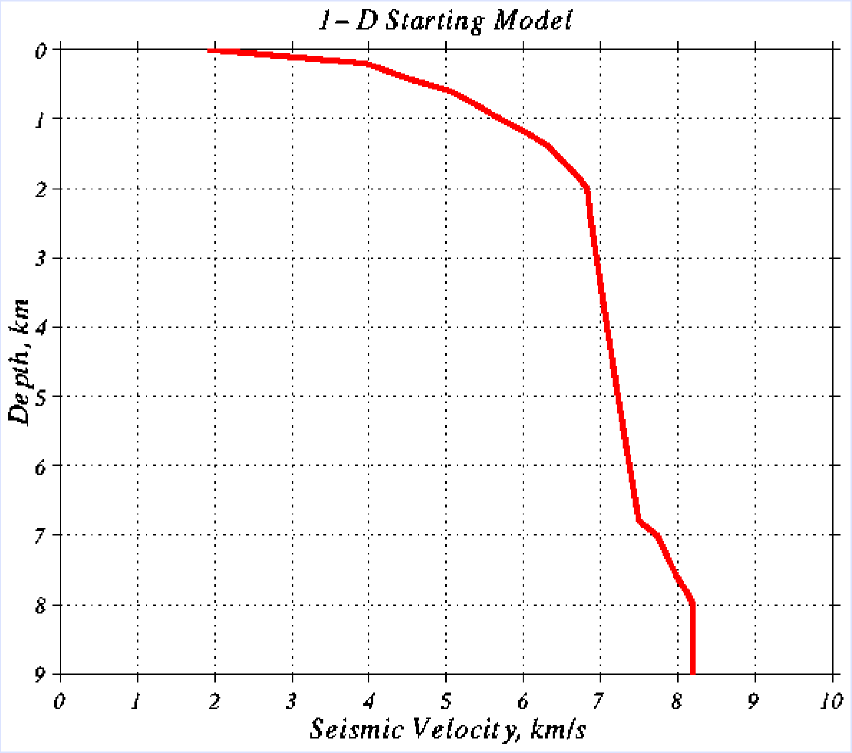


From Thelen et al. 2011

VT Analysis
- What can you do with a VT?

- Locate them (4+ stations, velocity model)

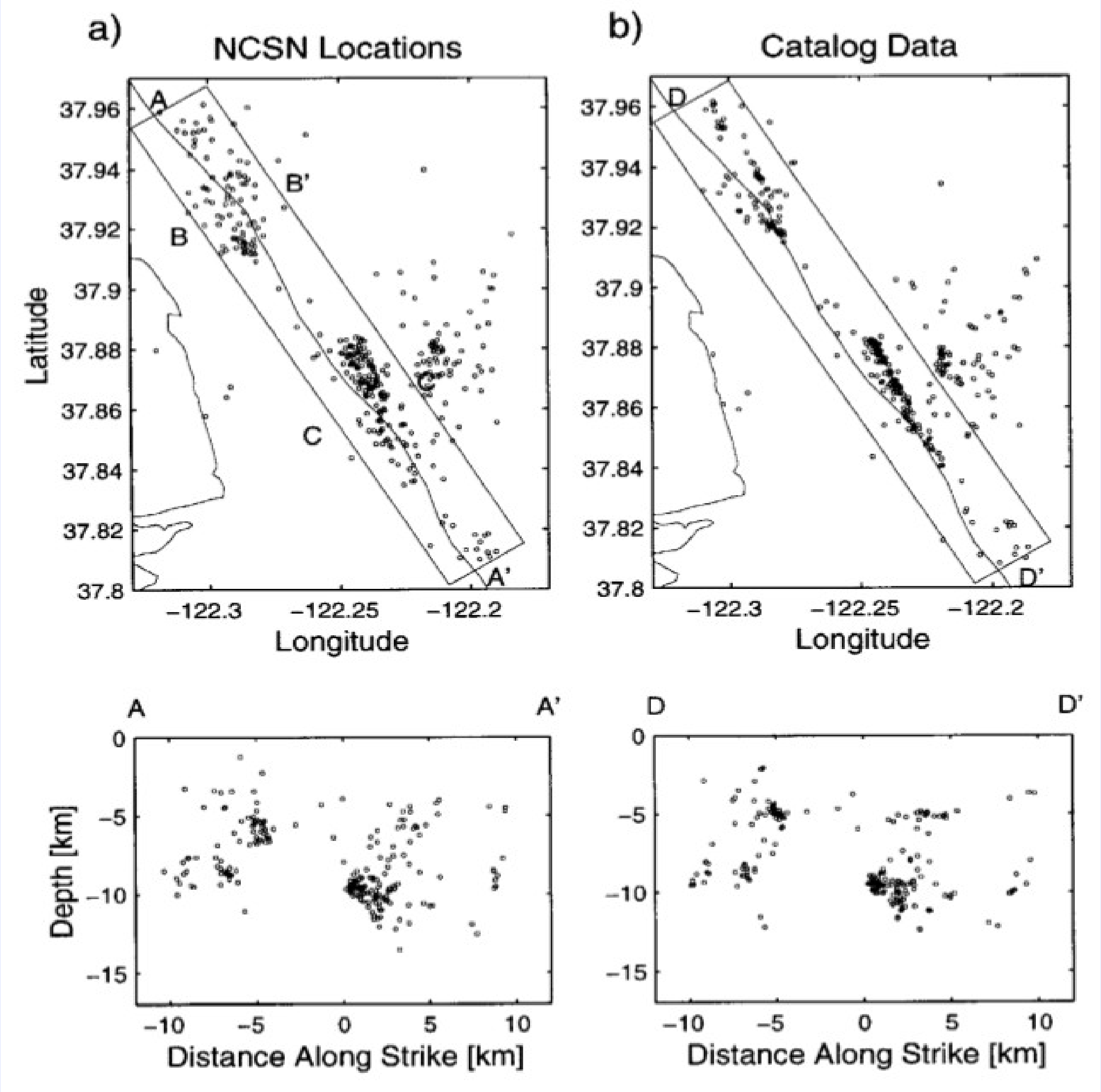
1. Absolute location (Geiger 1910, 1912):
 - Iterative least-squares approach
 - Answer depends on spatial distribution of observations
 - Requires a model of seismic velocities (P and S)

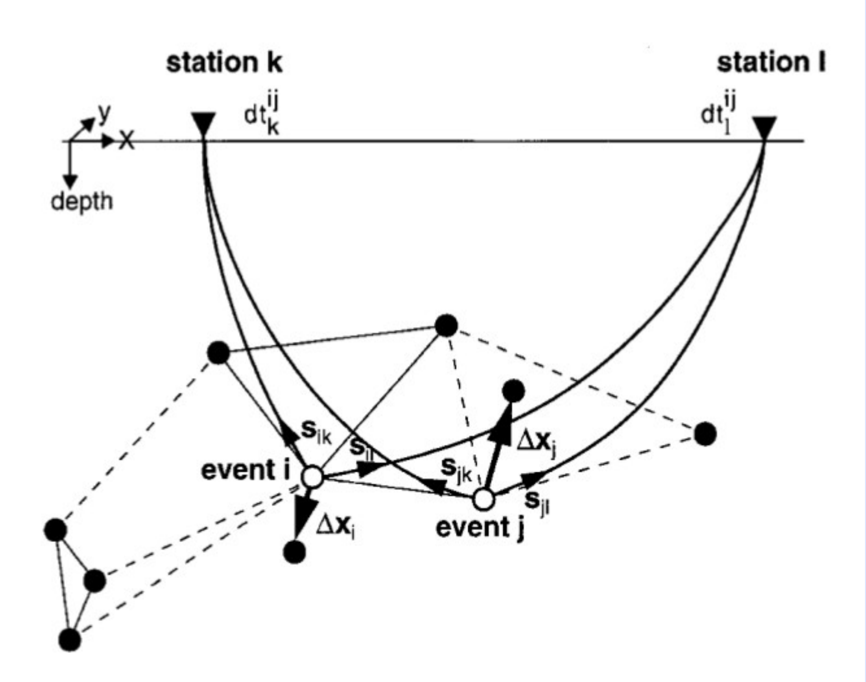


VT Analysis
- What can you do with a VT?

- Locate them (4+ stations, velocity model)

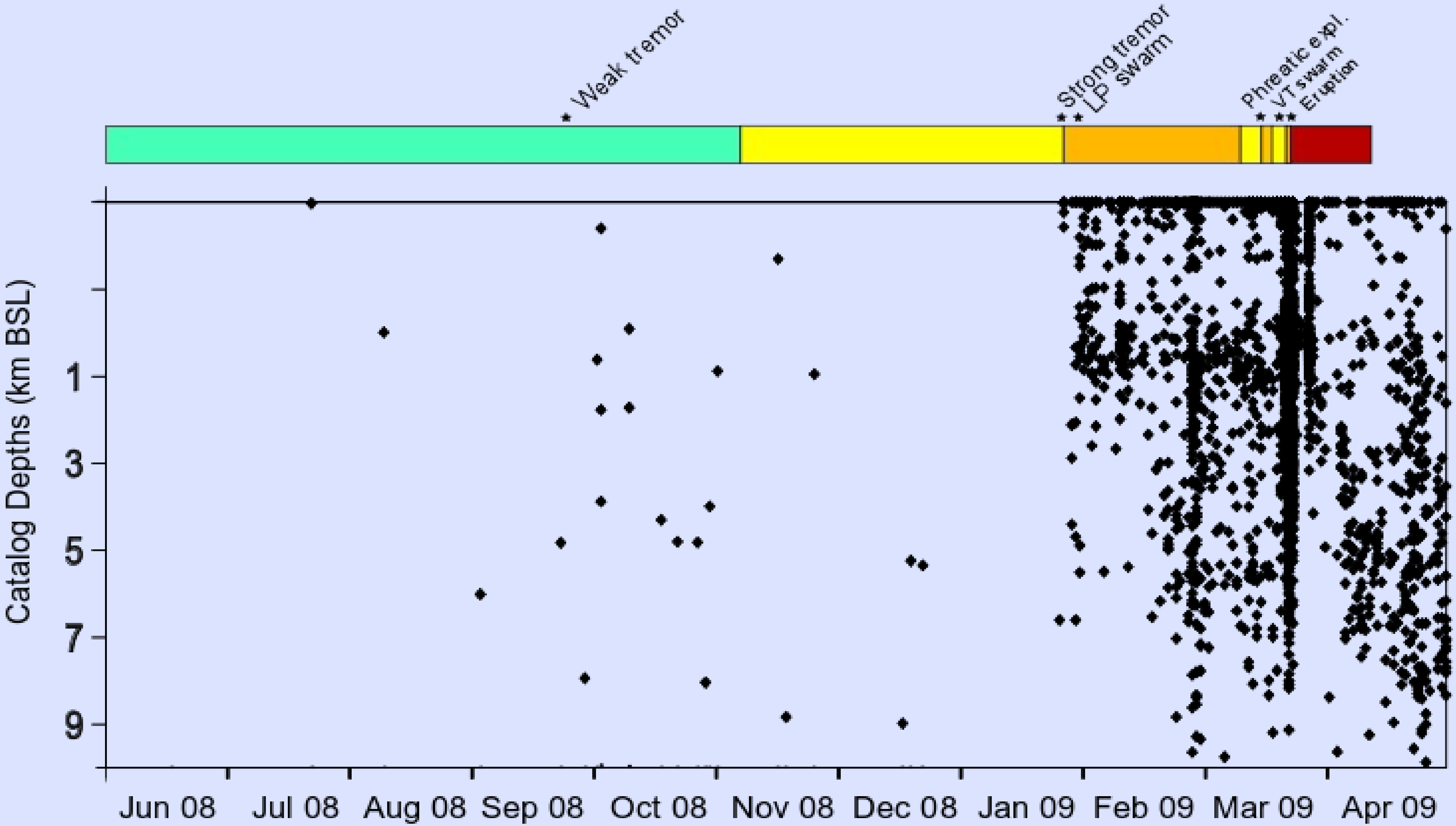
2. Relative location (Double-Difference Method):





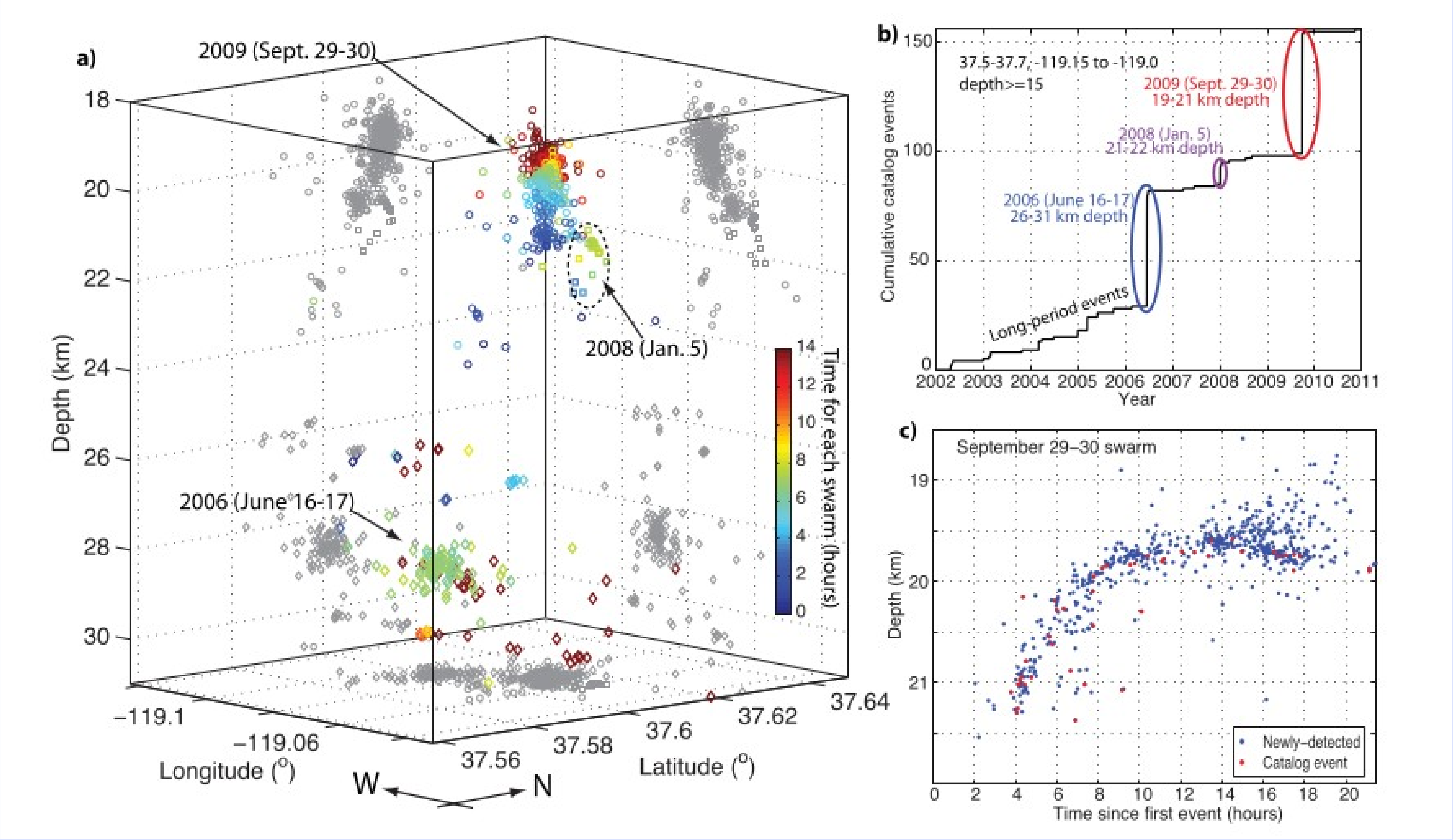
From Waldhauser and Ellsworth 2001

Case Study
- Redoubt Volcano, Alaska



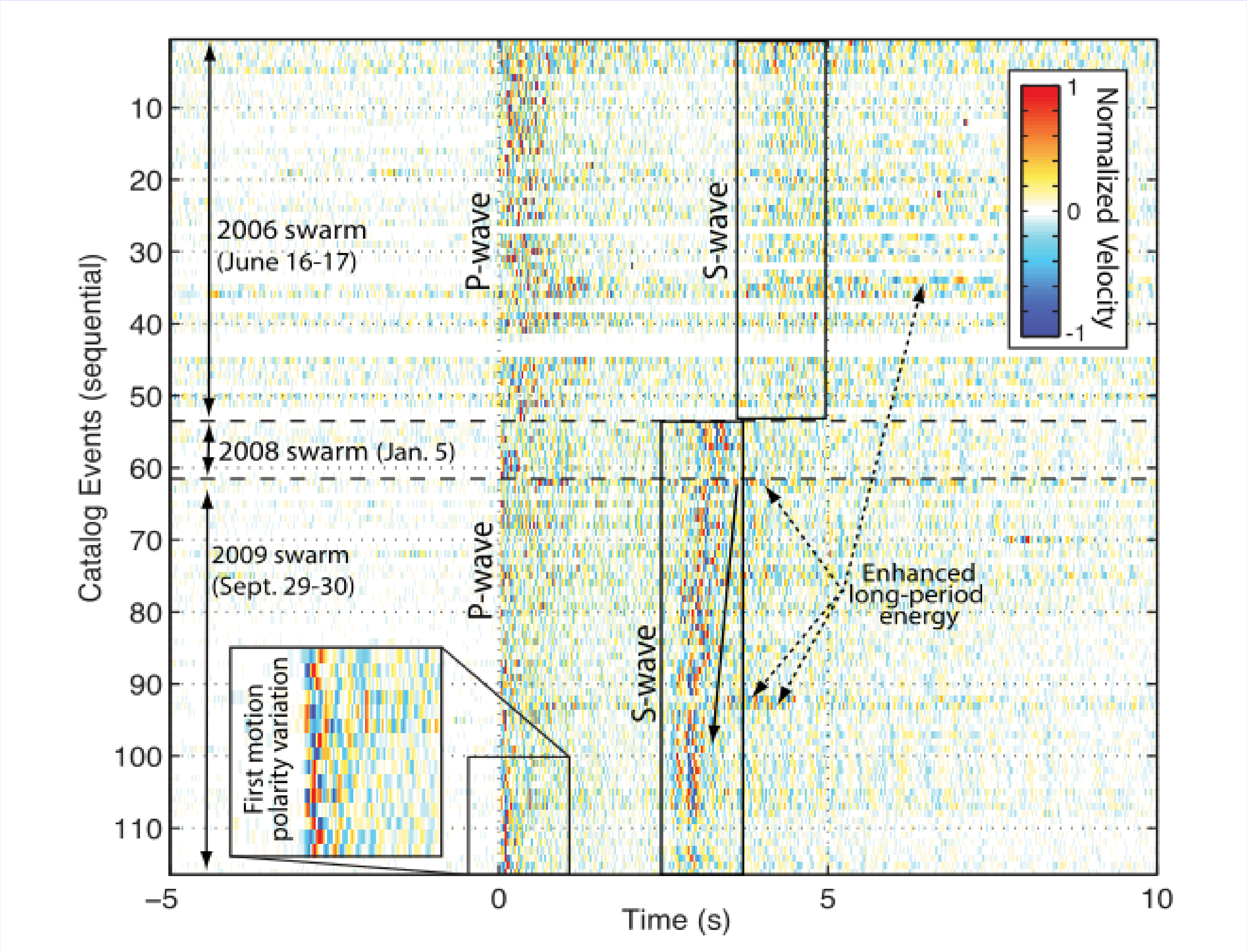
From Roman and Gardine 2013

Case Study
- Long Valley, California



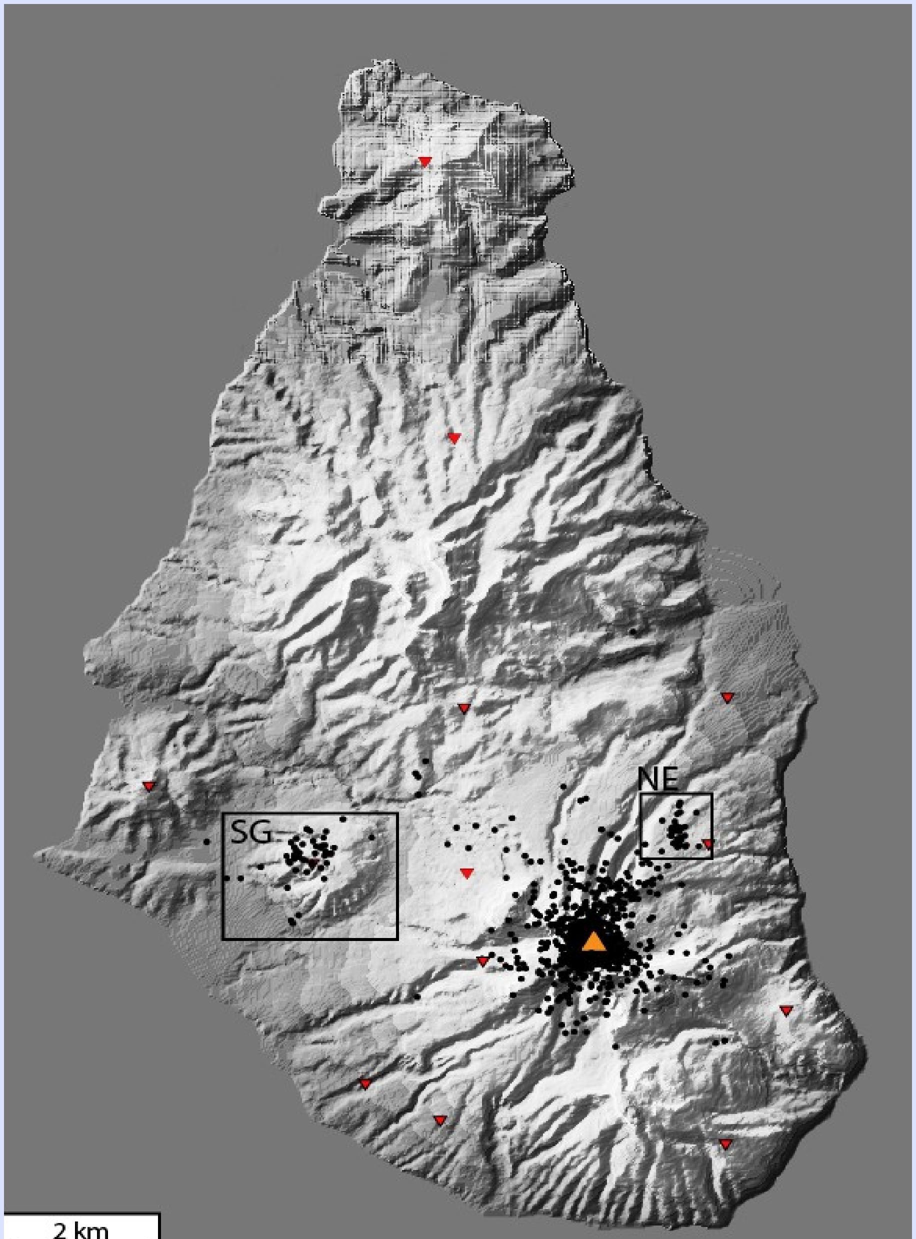
From Shelly and Hill 2011

Case Study
- Long Valley, California



From Shelly and Hill 2011

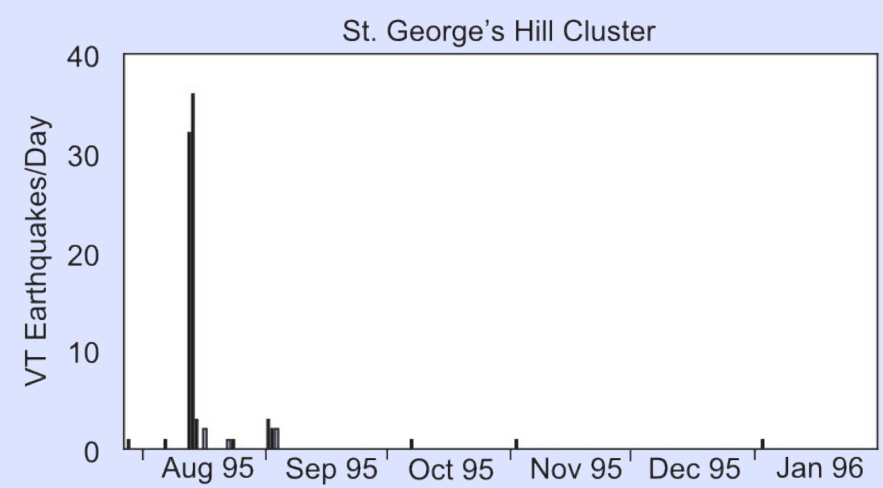
Case Study
- Soufriere Hills, Montserrat



- Most VTs locate within 1 km of vent
- Two distal VT clusters:

1. St. George's Cluster
   Jul 1995 – Mar 1996

2. NE Cluster
   August 5-6, 1995



From Roman et al. 2008

VT Analysis
- What can you do with a VT?

- Determine the magnitude

- Based on amplitudes,
  e.g., Richter magnitude

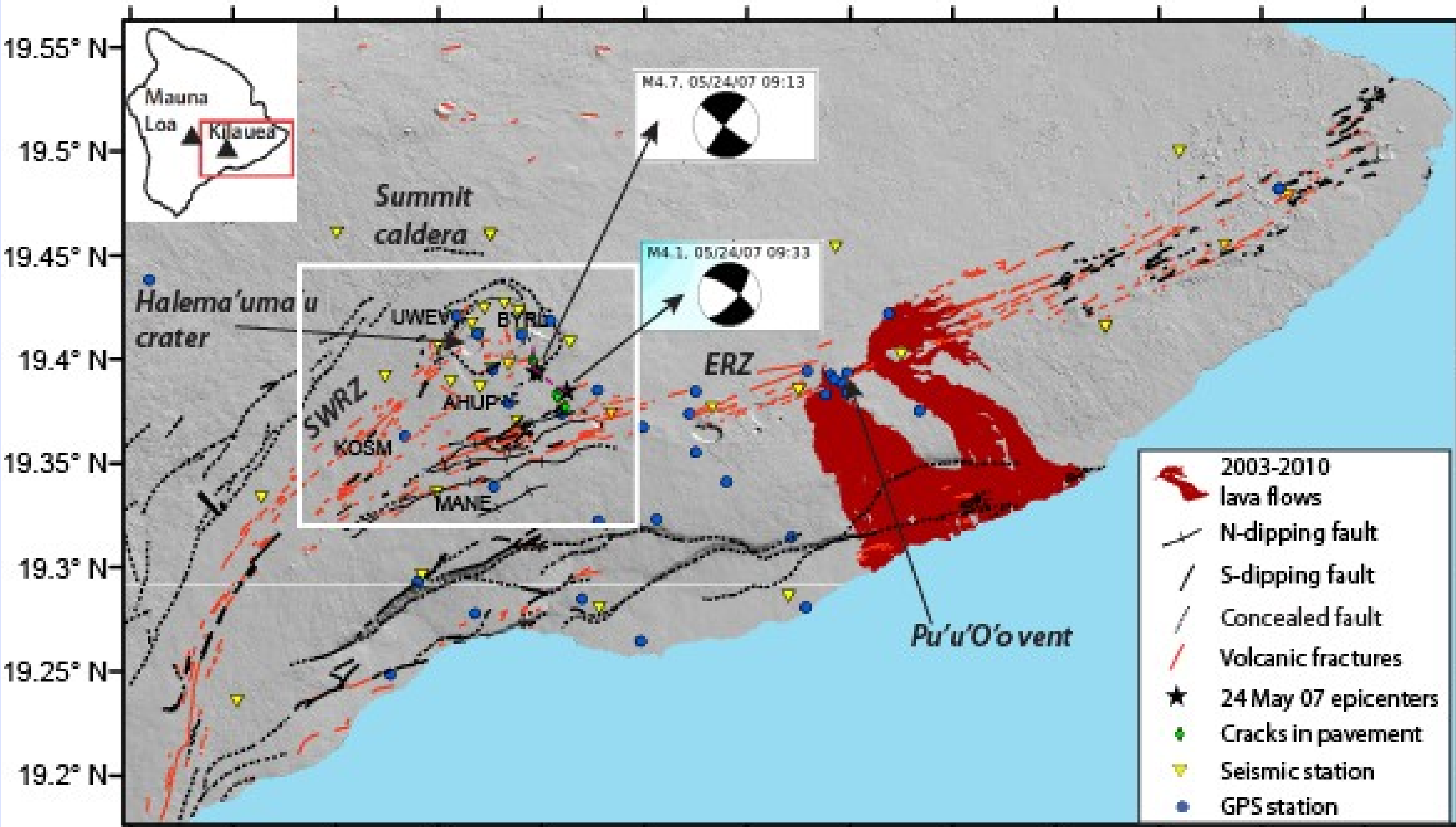
$$XMAG = \log\left(\frac{A}{2}\right) + \left[-B_1 + B_2 \log X^2\right] + G$$

$$X = \sqrt{D^2 + Z^2}$$

- Based on event duration,
  e.g., Coda magnitude (Lee and others, 1972; Lahr and others, 1975; Bakun and Lindh, 1977)

$$FMAG = C_1 + C_2 \log_{10}(F *_C) + C_3 D + C_4 Z + C_5 \left(\log_{10}(F *_C)\right)^2$$

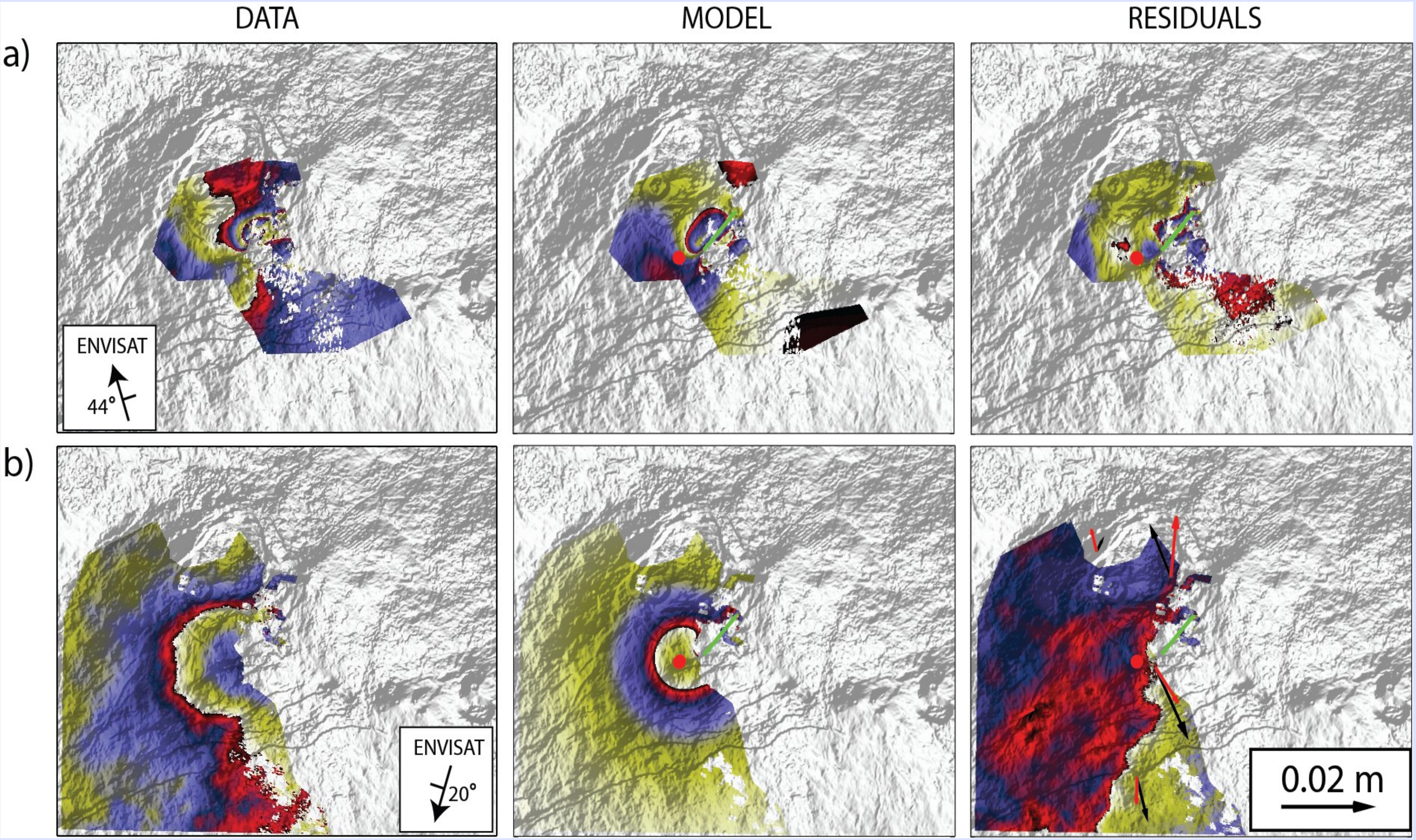
Case Study: VT Magnitudes - Kilauea Volcano, Hawai'i



From Wauthier et al., in prep

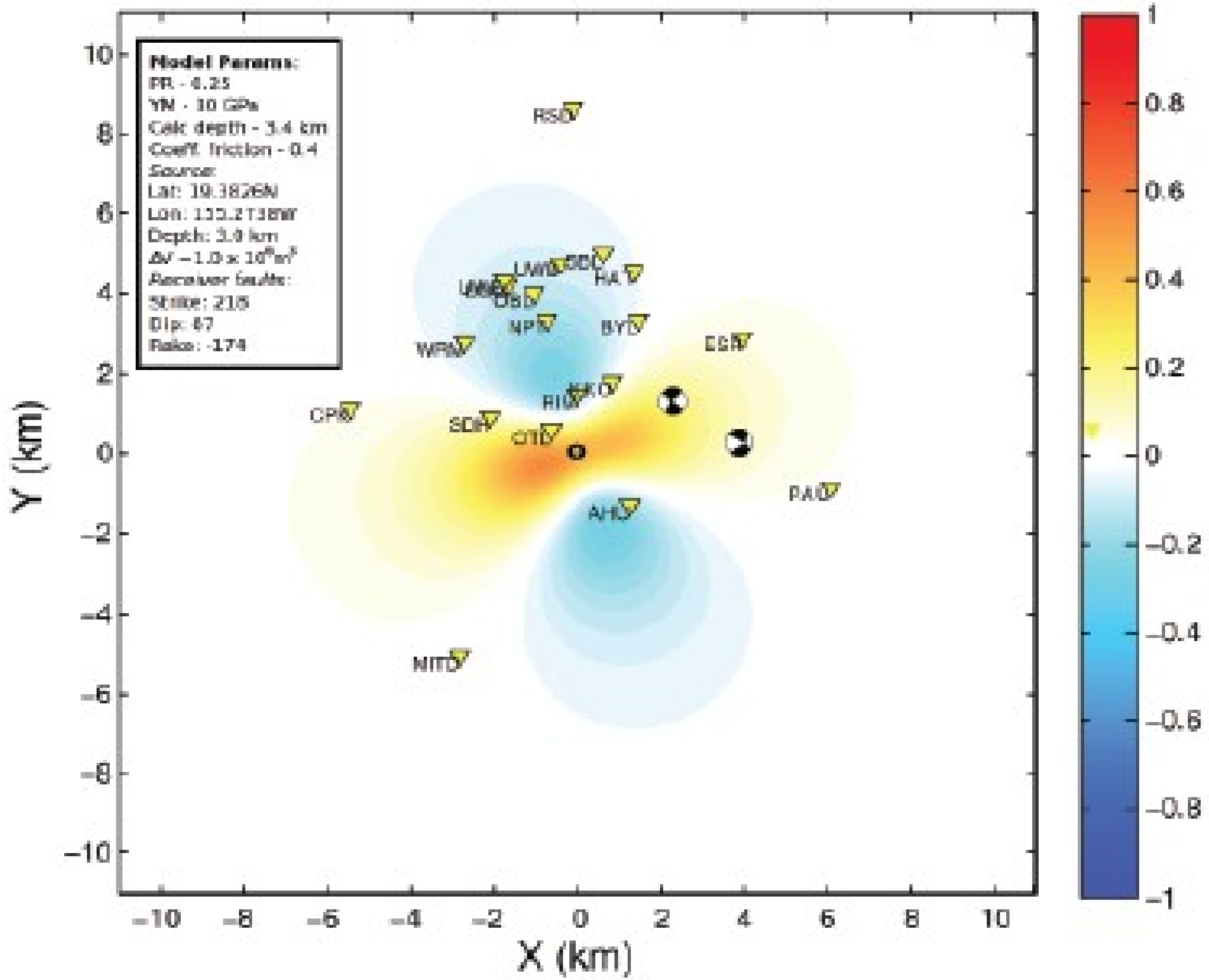
Figure 1

Case Study: VT Magnitudes - Kilauea Volcano, Hawai'i



From Wauthier et al., in prep

Case Study: VT Magnitudes
- Kilauea Volcano, Hawai'i

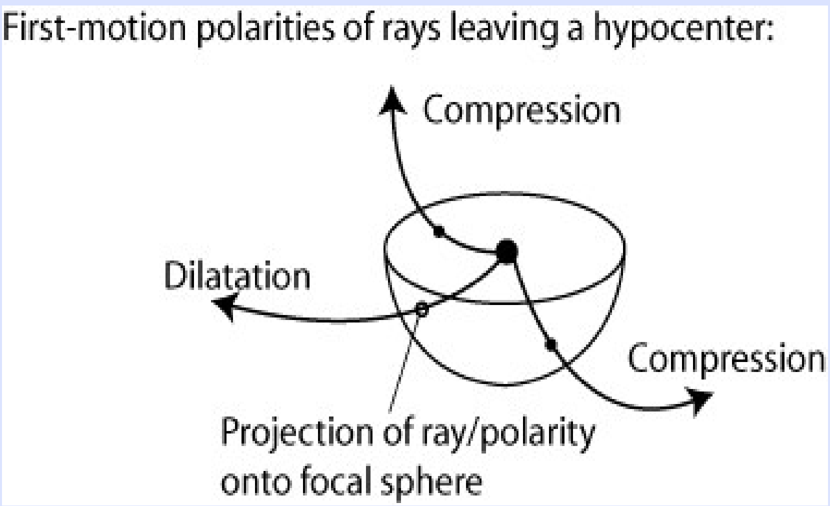


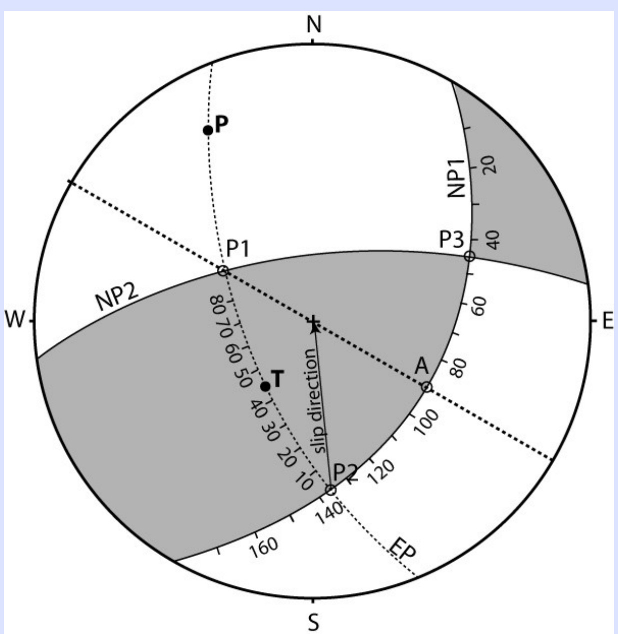
From Wauthier et al., in prep

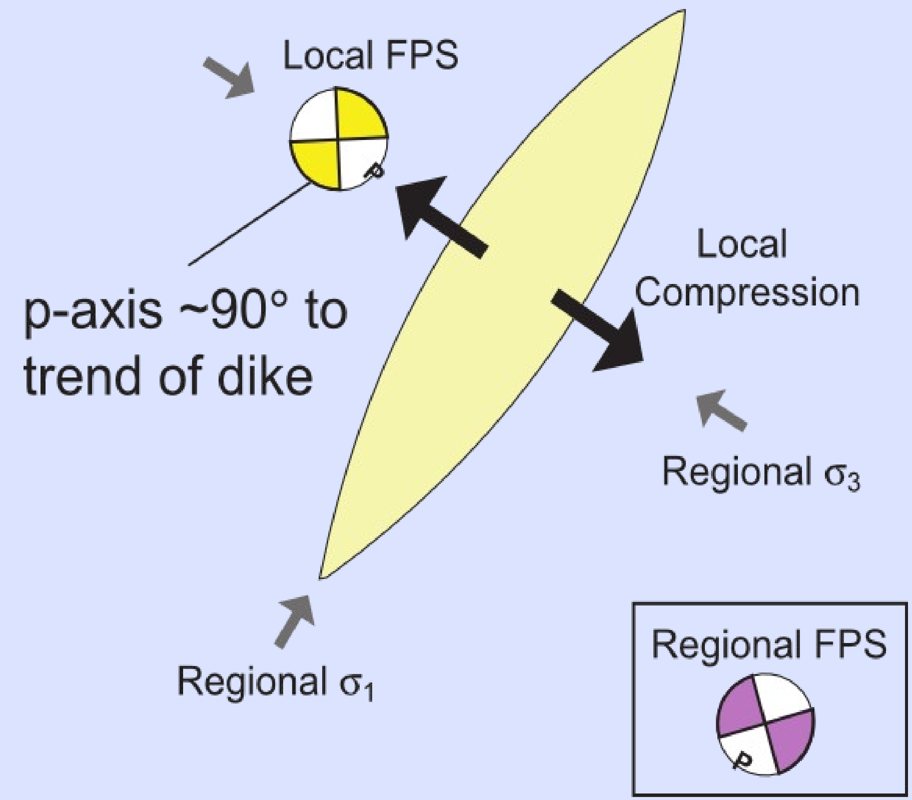
Figure 4

VT Analysis
- What can you do with a VT?

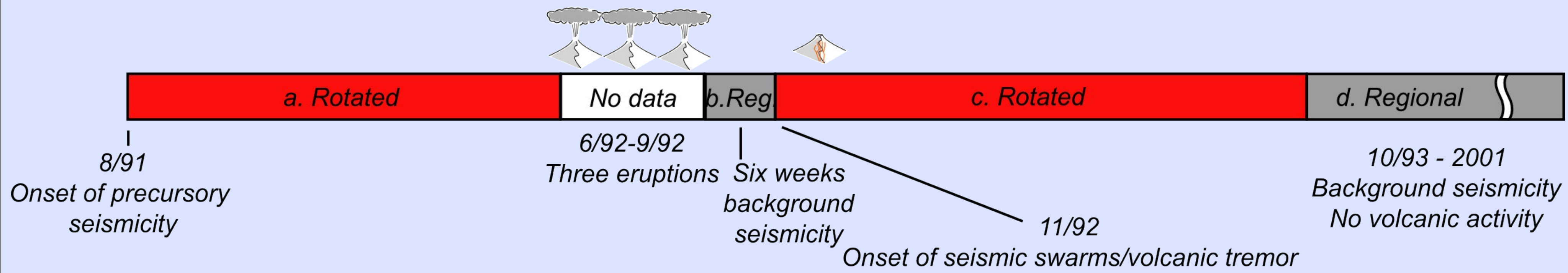
- Determine/model the focal mechanism

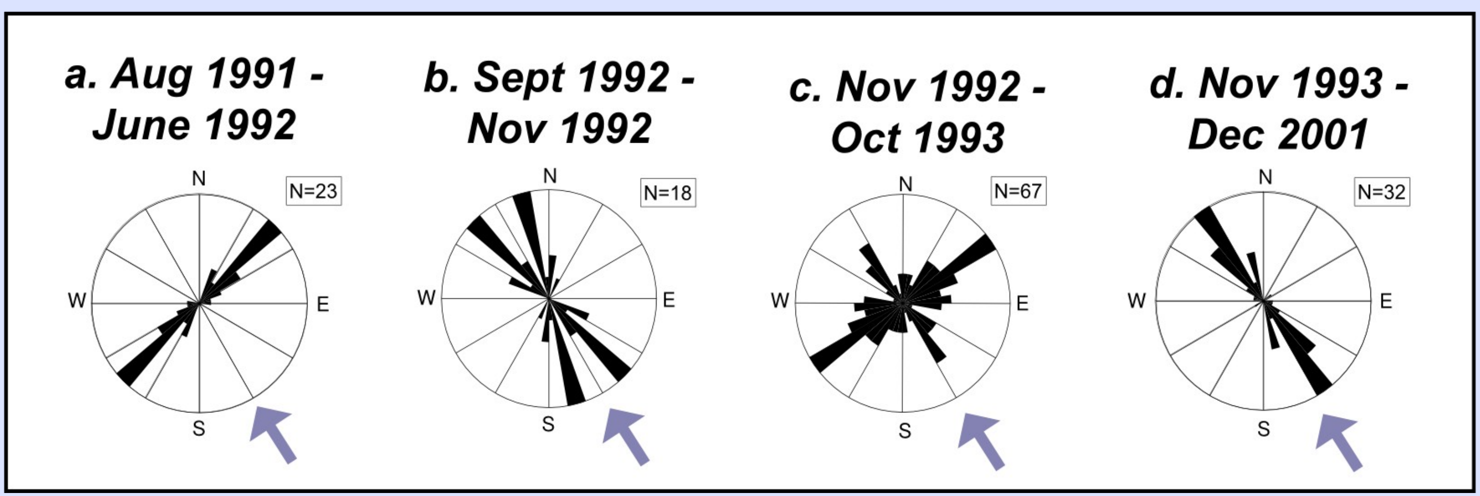






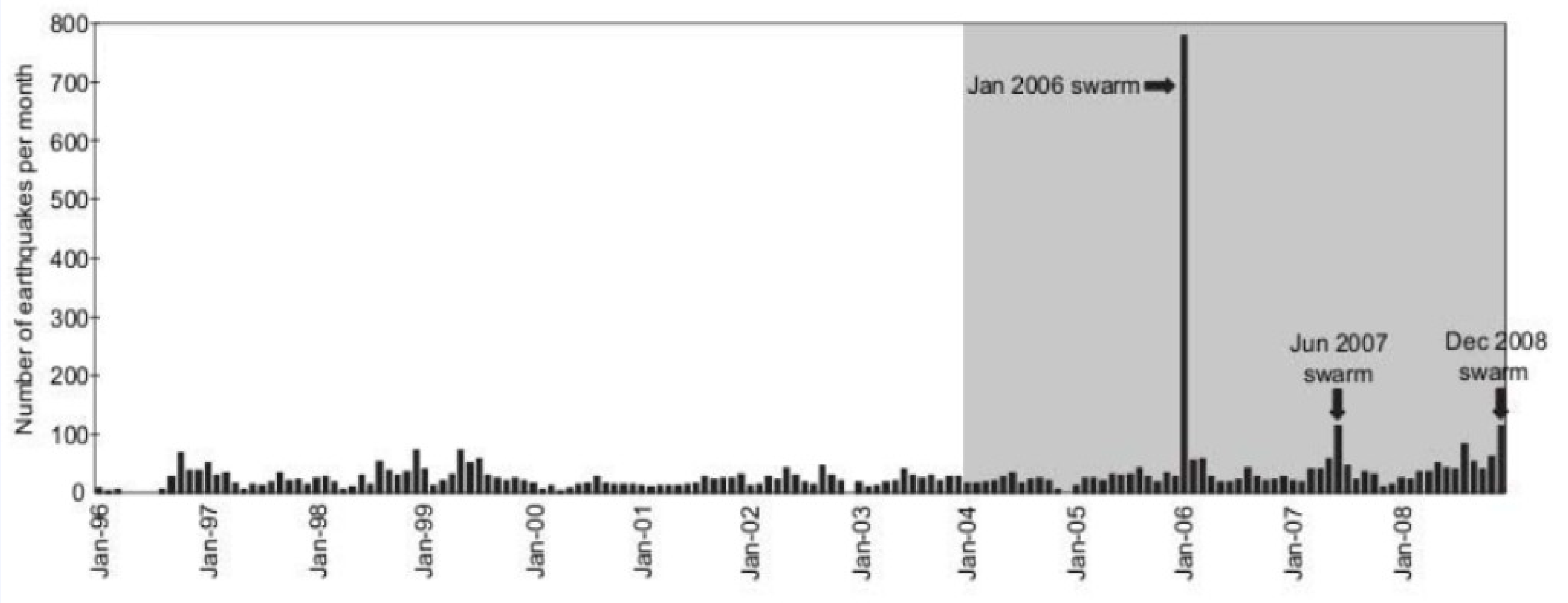
Case Study: Focal Mechanisms - Mt. Spurr, Alaska

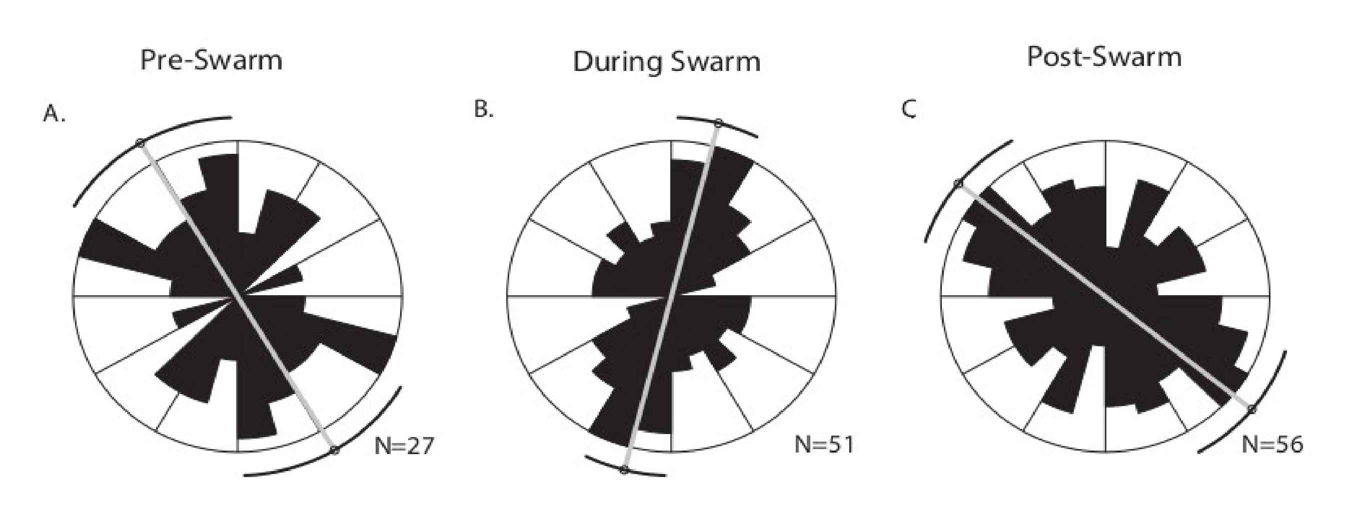




From Roman et al. (2004)

Case Study: Focal Mechanisms - Mt Martin (Katmai), Alaska

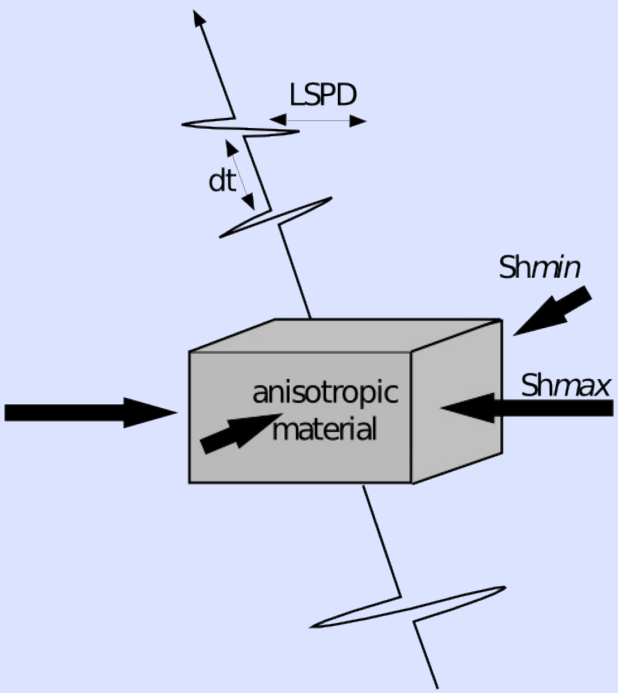


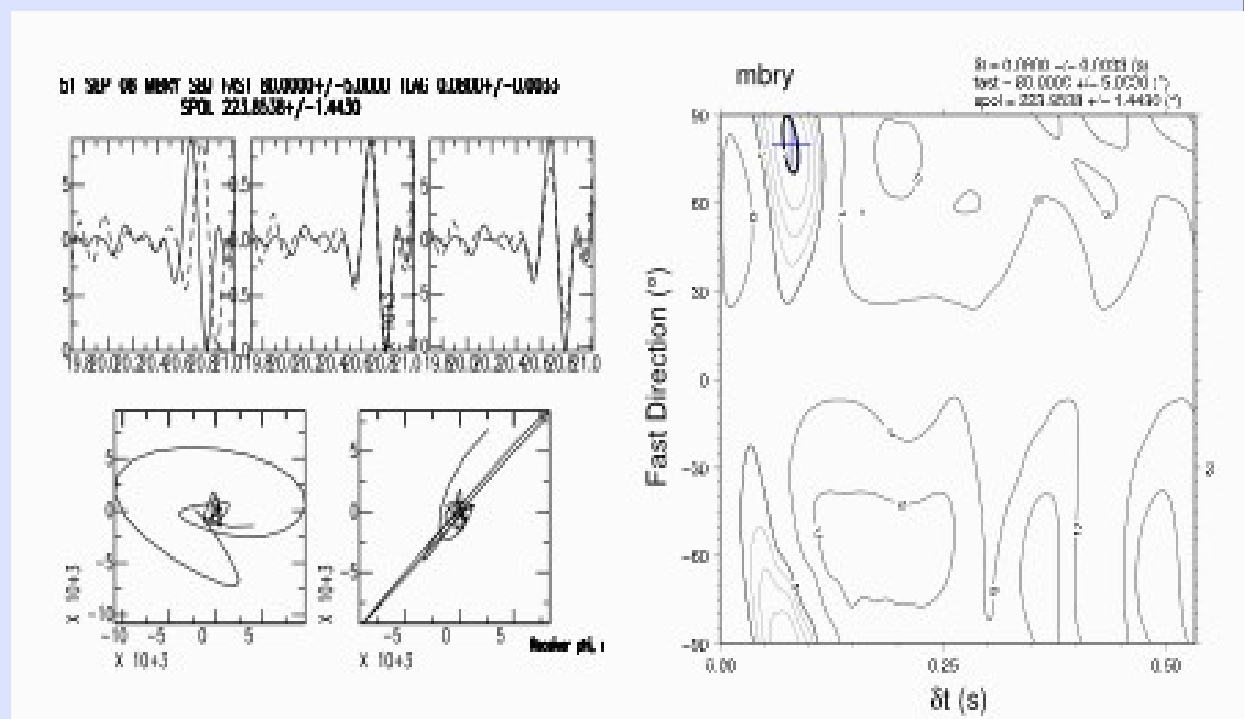


From O'Brien et al. (2012)

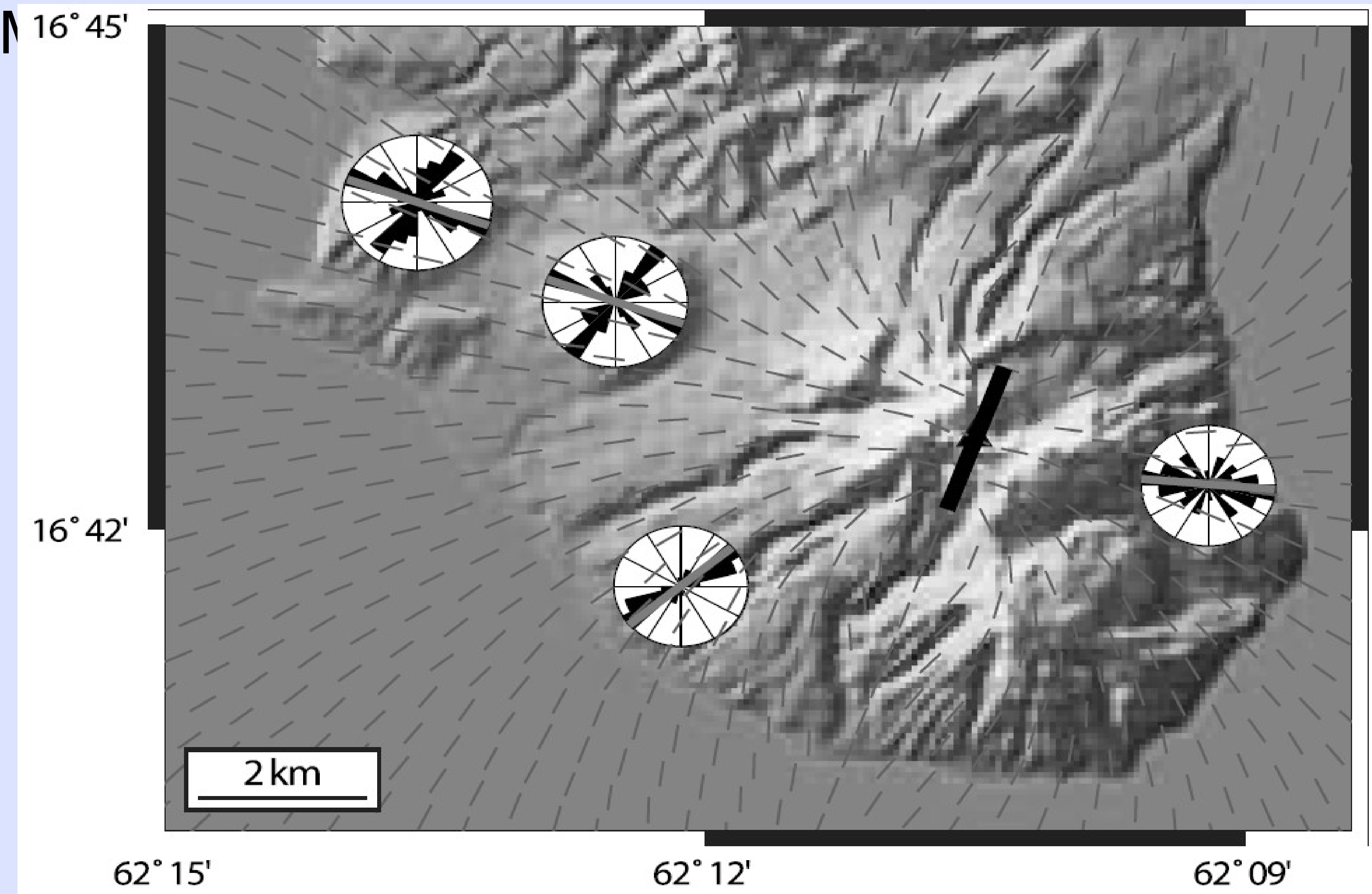
VT Analysis
- What can you do with a VT?

- Compare waveform on different seismometer components e.g., shear wave splitting, particle motions



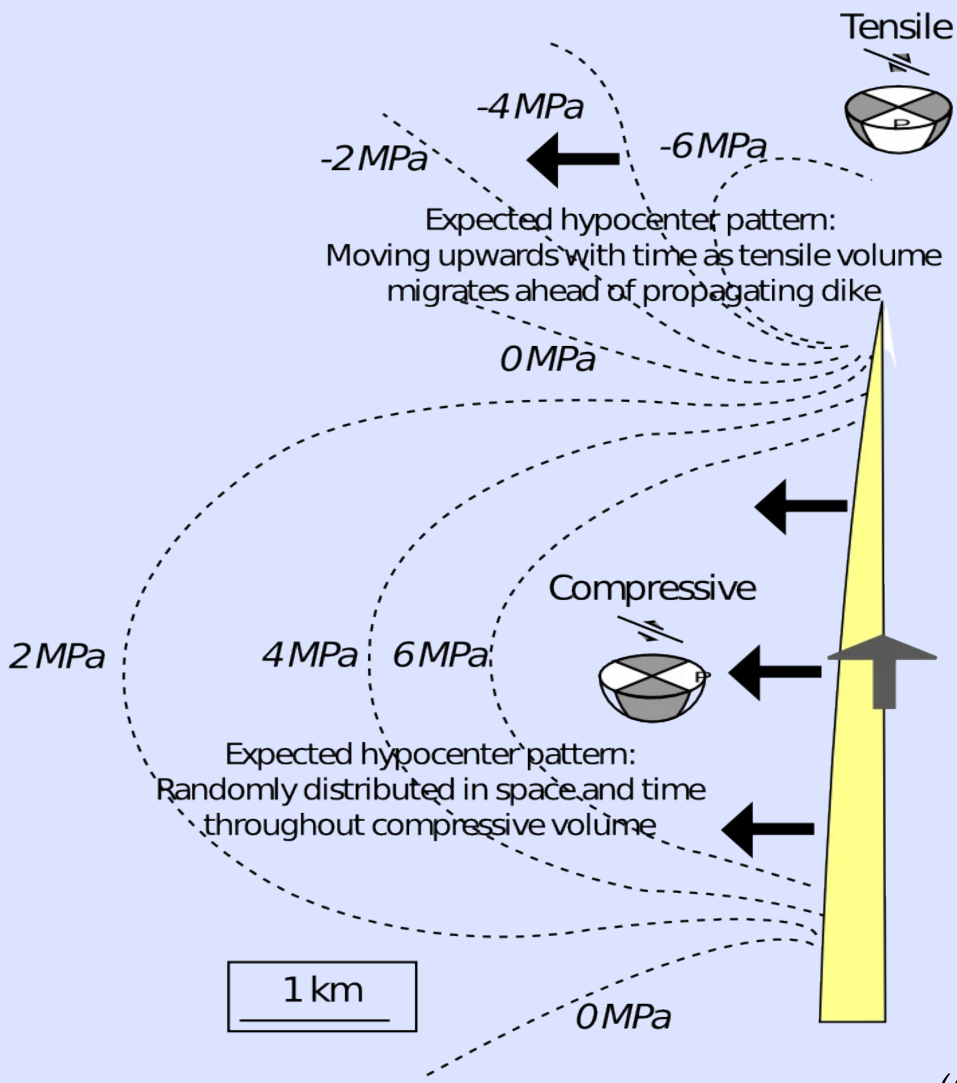


Case Study
- Soufriere Hills, Montserrat



From Roman et al. 2011

Models for the Origin of VTs
- Numerical Models

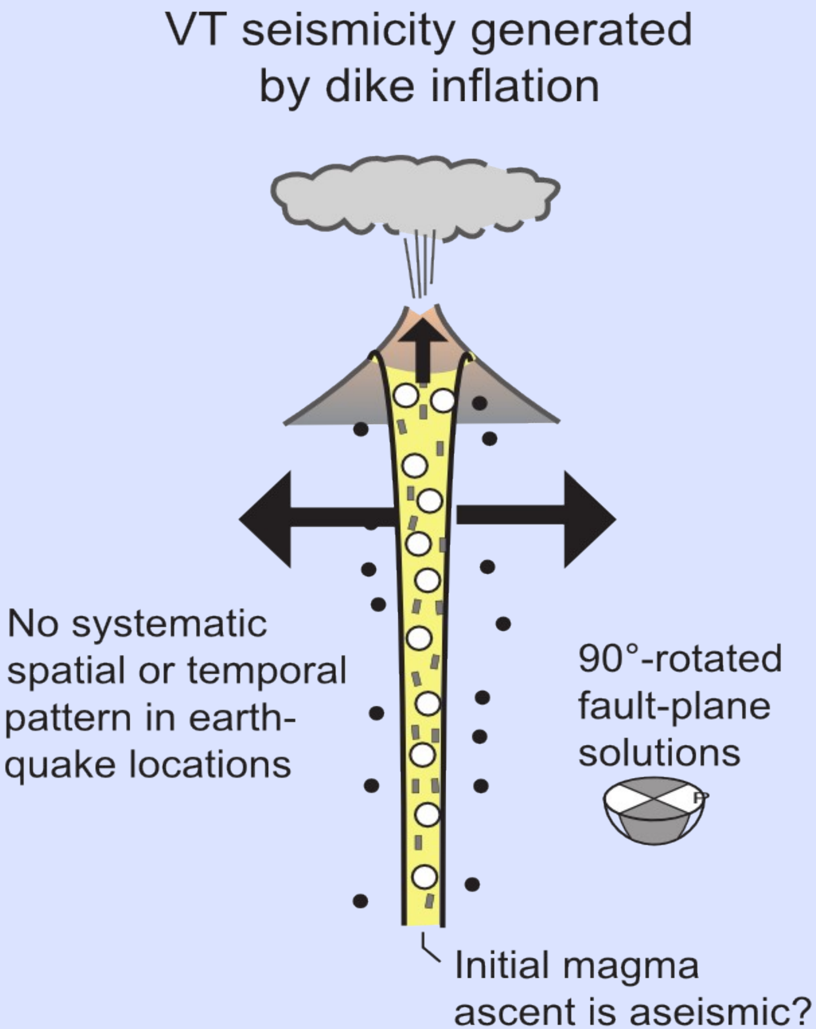


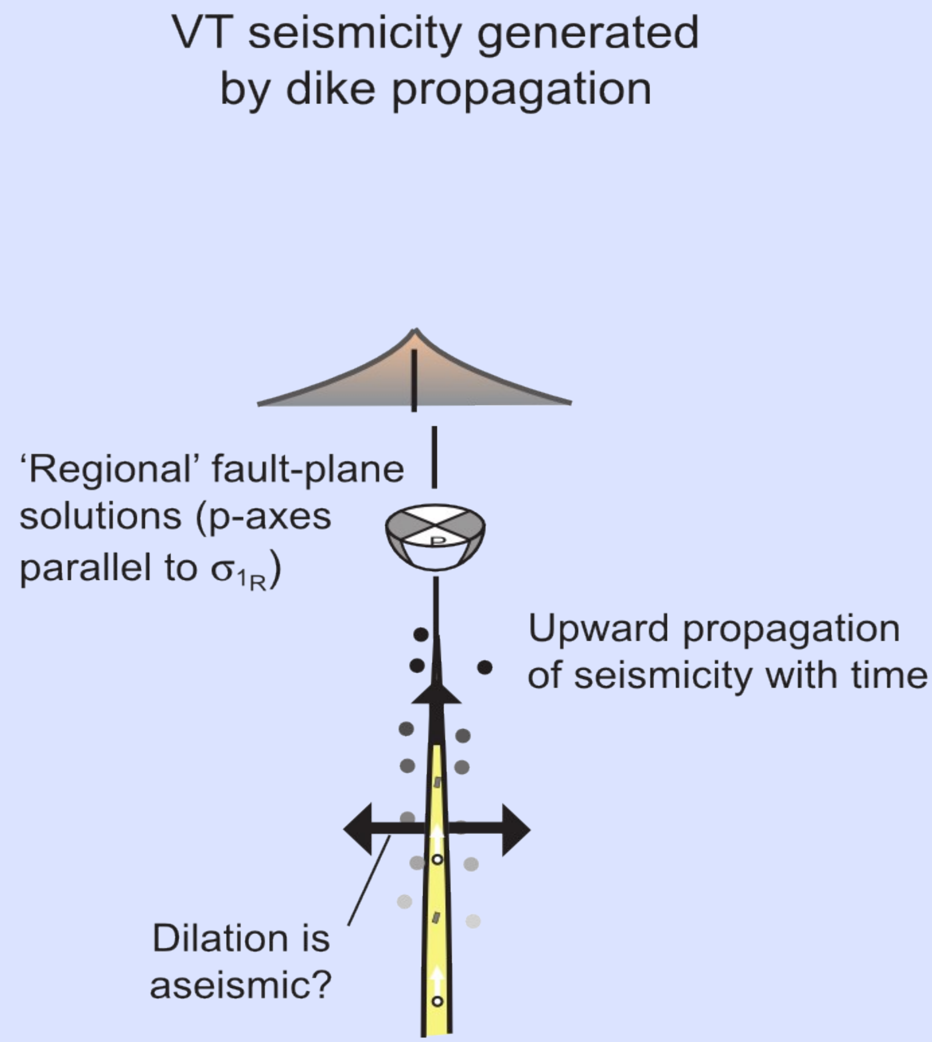
<u>Two induced stress regimes</u>

- Compressive in walls of dike
  (hypocenters random in space)
- Tension above propagating dike
  (hypocenters migrating ahead
  of dike tip)

(After Rubin and Pollard 1988, Ukawa and Tsukahara 1996)

Models for the Origin of VTs - Observational Models





(Roman and Cashman, 2006)

Models for the Origin of VTs - Observational Models

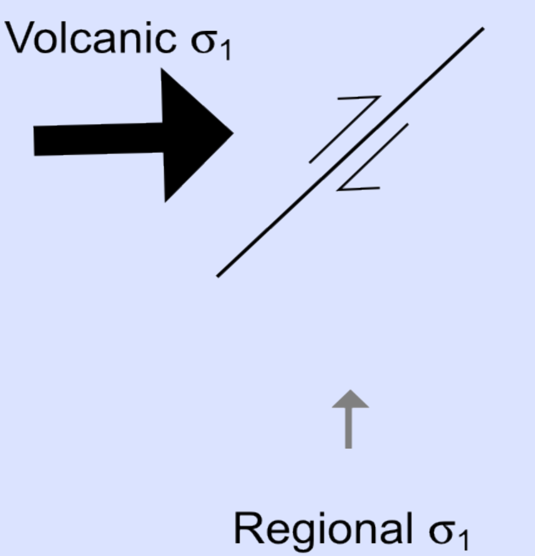
Volcano	Eruption	Study	~90° Rotation	Hypocenter Migration
Unzen, Japan	1990-1995	Umakoshi et al. (2001)	✓	✗
Usu, Japan	2000	Fukuyama et al. (2001)	✓	✗
Mt St. Helens, USA	1980-1986 2004	Barker and Malone (1991) Lehto et al. (2010)	✓	✗
Guagua Pichincha, Ecuador	1998	Legrand et al. (2002)	✓	✗
Crater Peak, Alaska	1992	Roman et al. (2004)	✓	✗
Soufriere Hills, Montserrat	1995-2007	Roman et al. (2006, 2008)	✓	✗
Redoubt Volcano, Alaska	2009	Gardine et al. (in prep)	✓	✗
Mt Etna, Italy	Multiple	e.g., Patane et al. (2003)	✓	✗
Teishi Knoll, Japan	1989	Ukawa and Tsukahara (2001)	✗	✓
Miyake-jima, Japan	2000	Fukuyama et al. (2001)	✗	✓
Izu-Oshima, Japan	1987	Aramaki (1988)	✗	✓

Influence of Tectonic Stress - Patterns of VT seismicity

- In compressional environments, strongly deviatoric regional stresses can override volcanic stresses
- Results in shadow zones where faults are locked

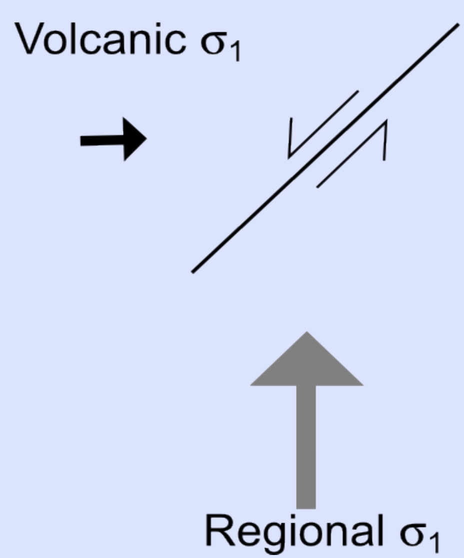
1. $\sigma_{1_V} >> \sigma_{1_R}$

'Reversed' slip



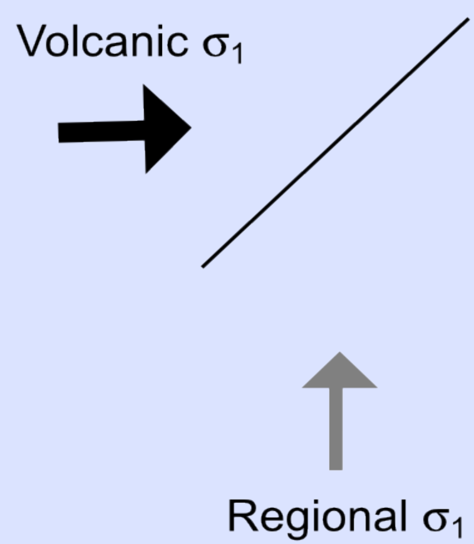
2. $\sigma_{1_V} << \sigma_{1_R}$

'Regional' slip



3. $\sigma_{1_V} \approx \sigma_{1_R}$

No slip



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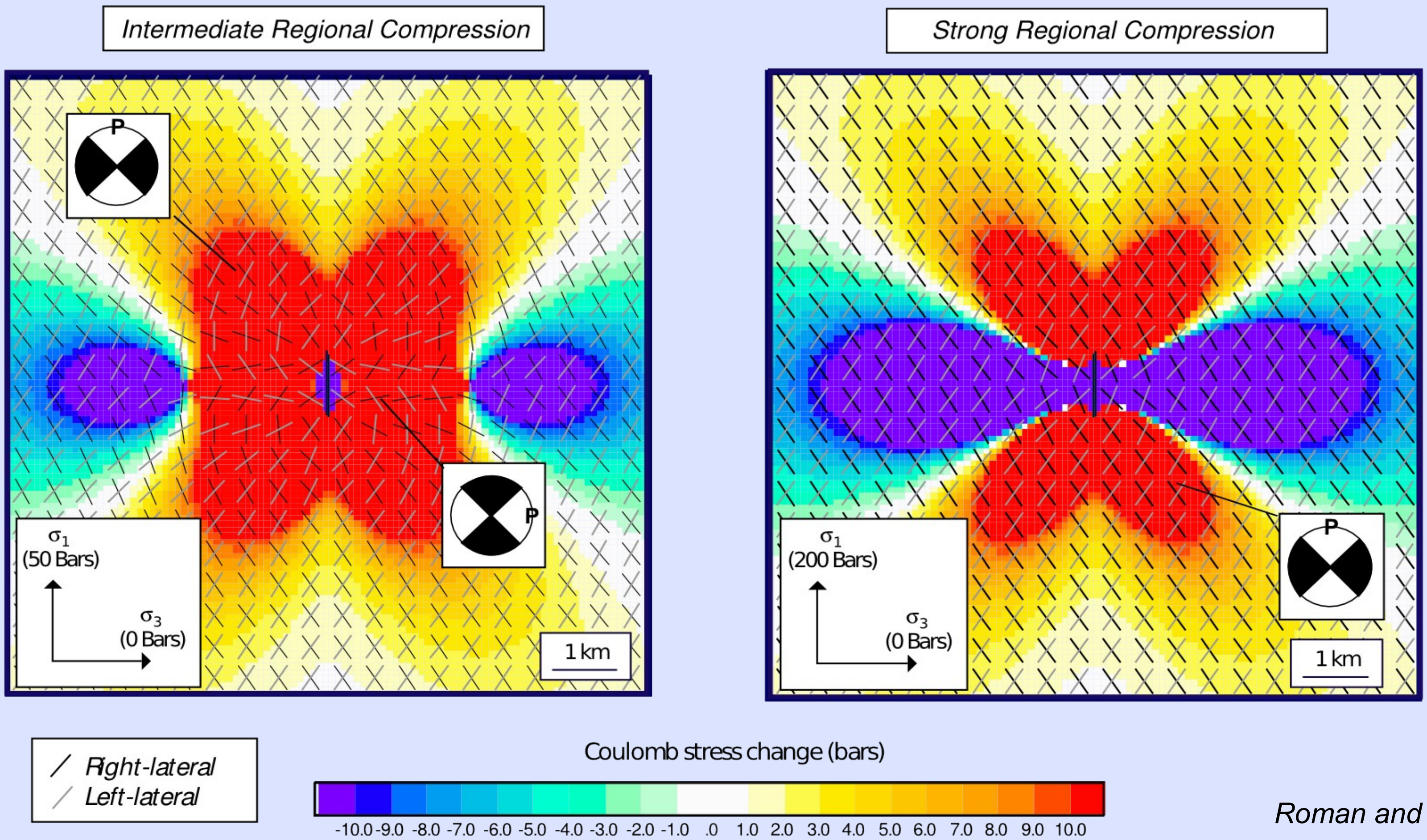

Roman and Heron (2007)

Influence of Tectonic Stress
- Locations and FPS of VT earthquakes

- In compressional environments, strongly deviatoric regional stresses can override volcanic stresses
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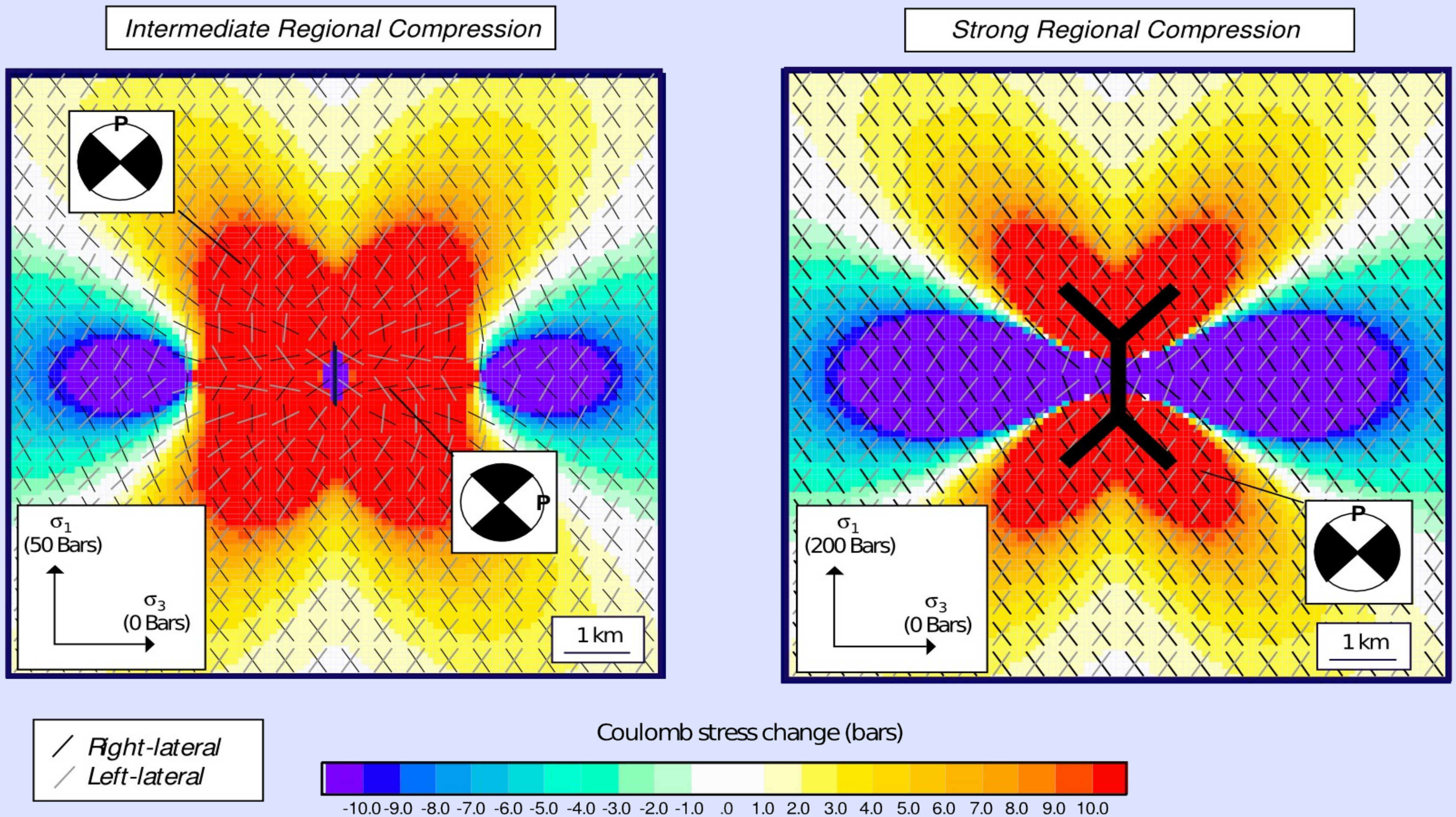

Roman and Heron (2007)

Influence of Tectonic Stress
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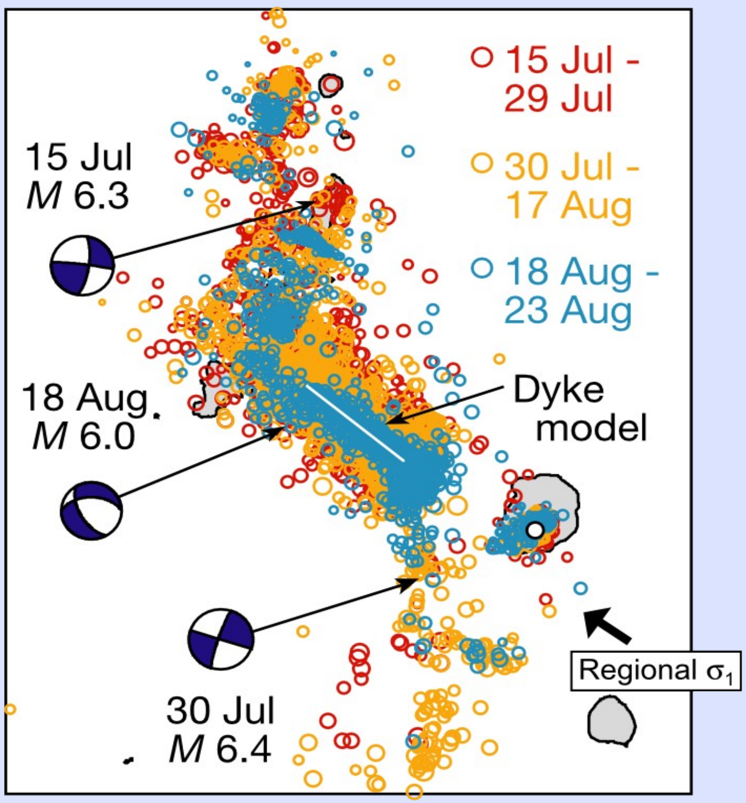
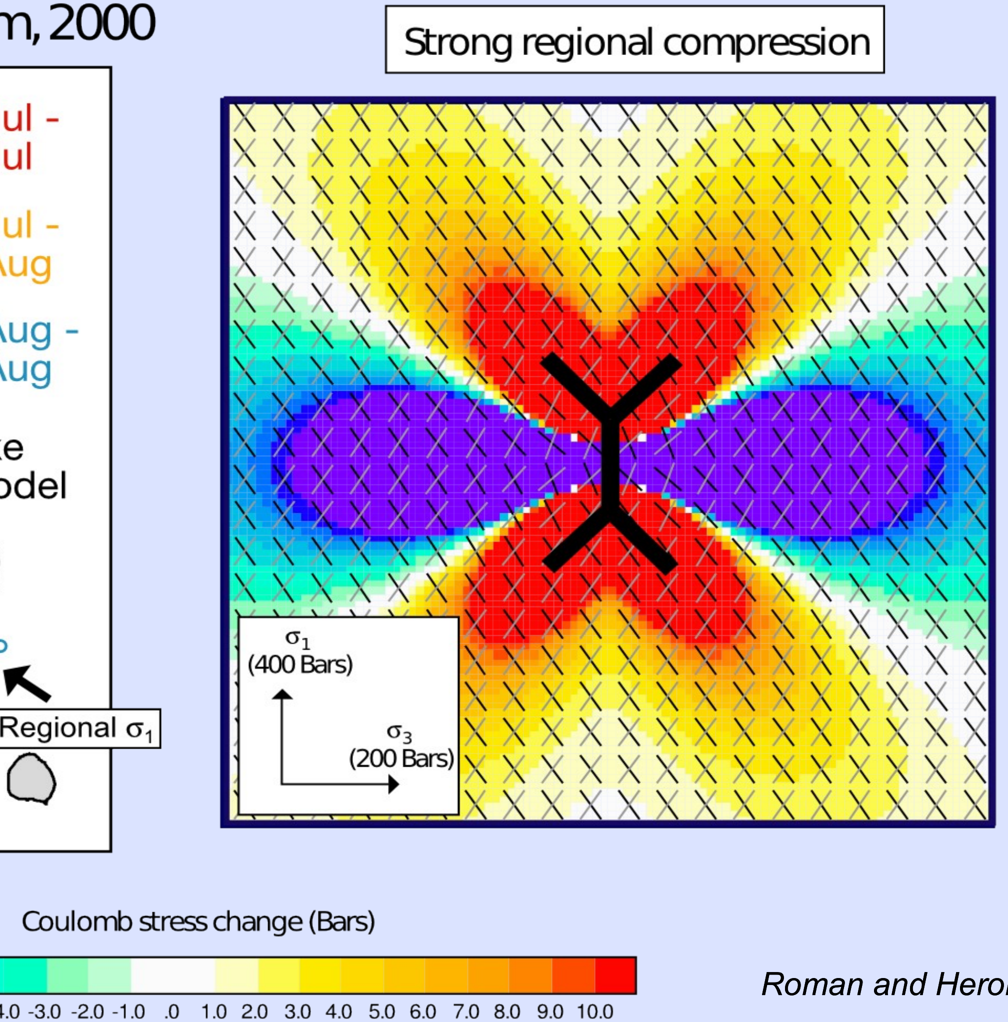
Miyake-jima Eruption Swarm, 2000



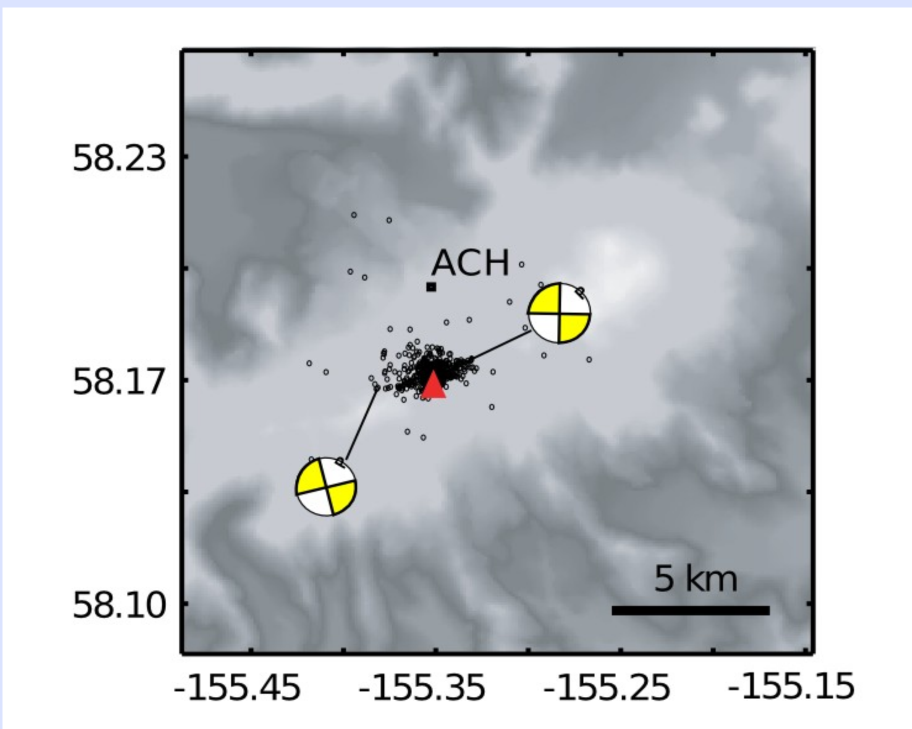
after Toda et al., 2002

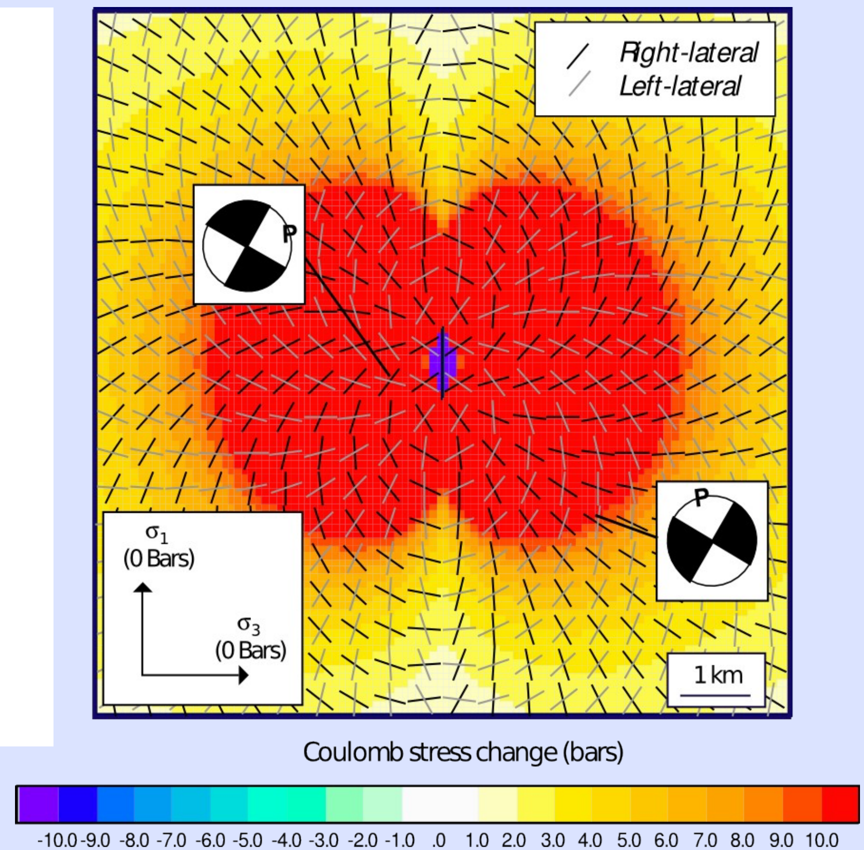


Roman and Heron (2007)

Influence of Tectonic Stress
- Locations and FPS of VT earthquakes

- In isotropic environments, weak volcanic stresses dominate sense of fault slip





After Dixon et al. (2007)

Influence of Tectonic Stress - Patterns of VT seismicity

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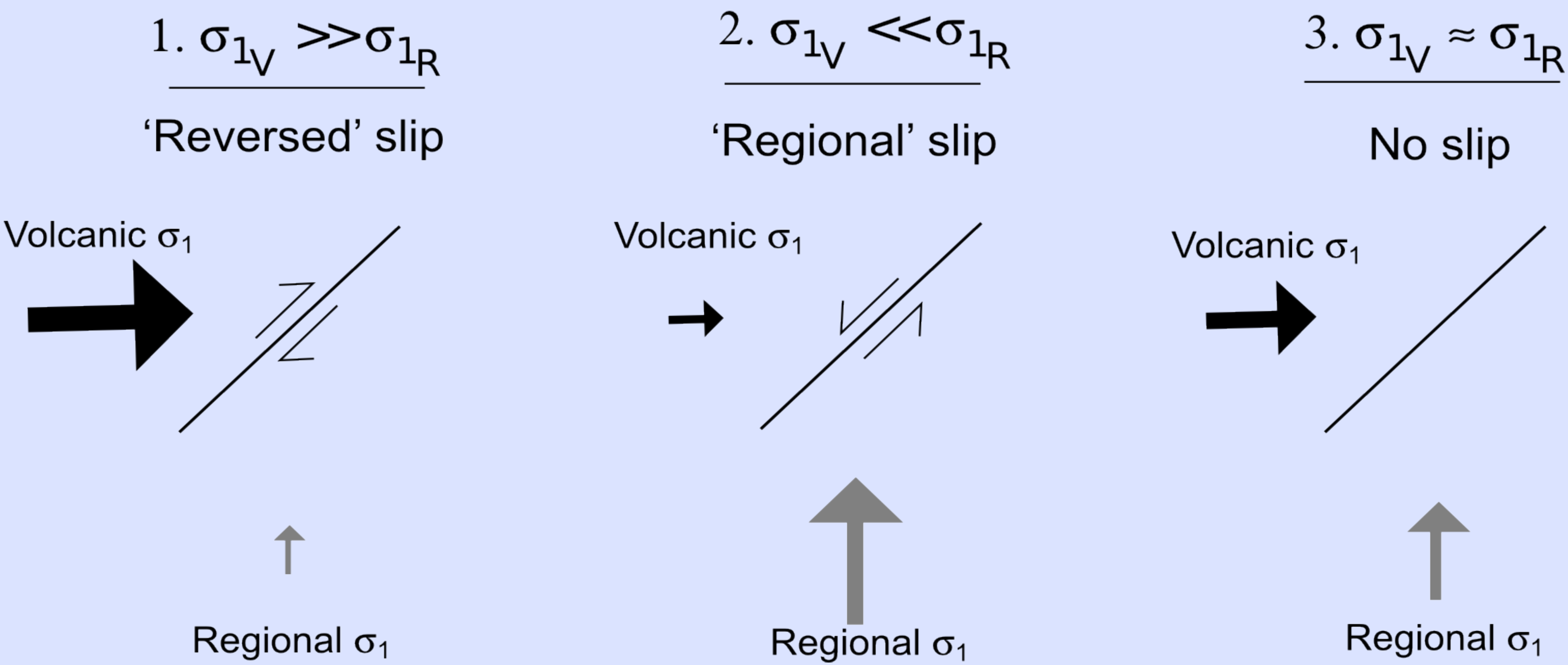

Concluding Comments

- VTs are ubiquitous at active volcanoes and reflect the modification of stress in the crust by magma, fluid, and gas.

- Changes in properties of VTs through time can be indicative of changes in the magmatic system, and may form the basis for eruption forecasts.

- Patterns of VT seismicity are highly susceptible to the background state of stress in the crust, which can strongly influence the rates, locations, and focal mechanisms of VTs.