The Origin of Volcanotectonic (VT) Earthquake Swarms

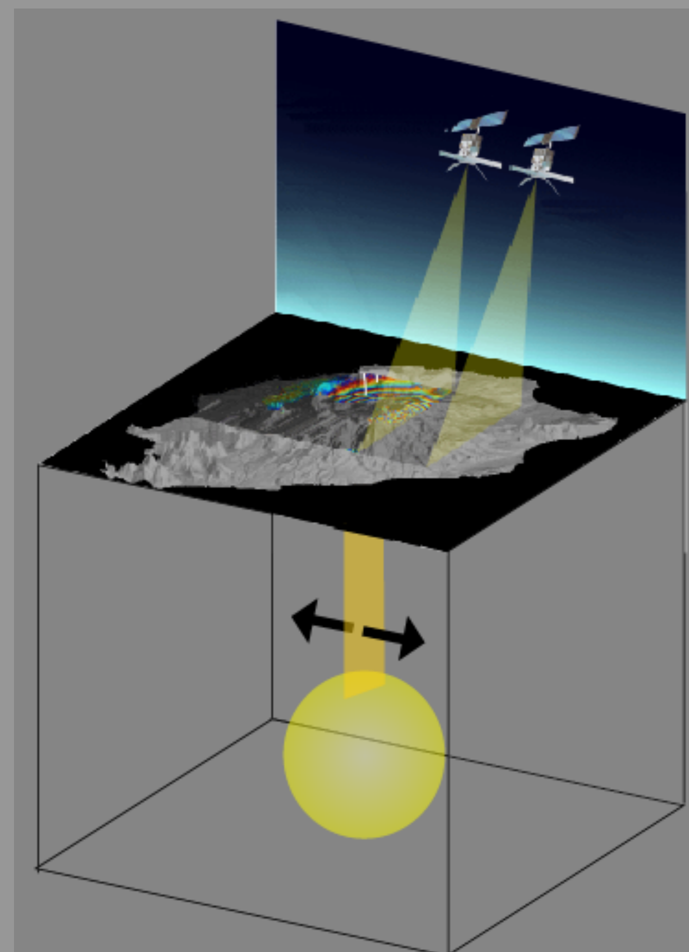
Diana Roman
Mel Rodgers
Matt Gardine
Heather Lehto
John O'Brien

Department of Geology
University of South Florida

Introduction and Motivation

Engraving of the Temple of Serapis, Campi Flegrei, Italy
Frontispiece, *Principles of Geology*, Lyell (1830)

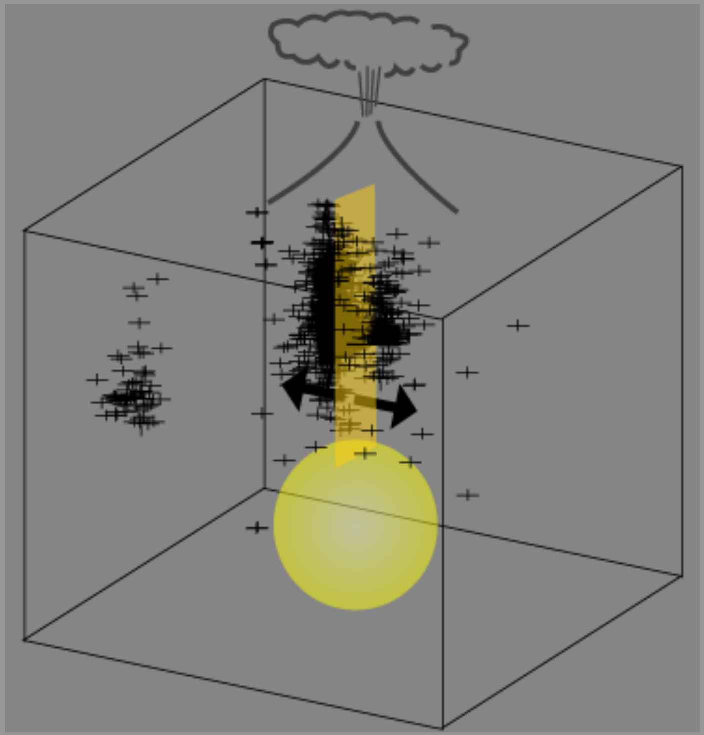
Modern satellite-based methods of volcano geodesy, e.g. GPS and SAR interferometry



Introduction and Motivation

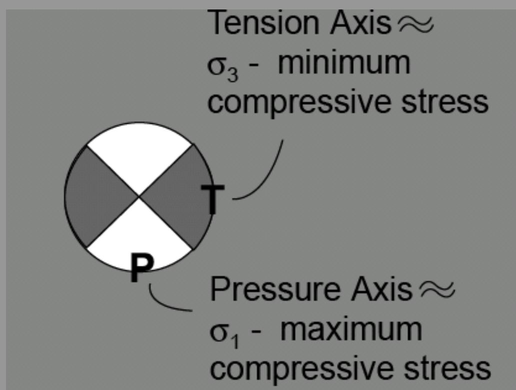
Volcanotectonic ('VT') earthquakes:

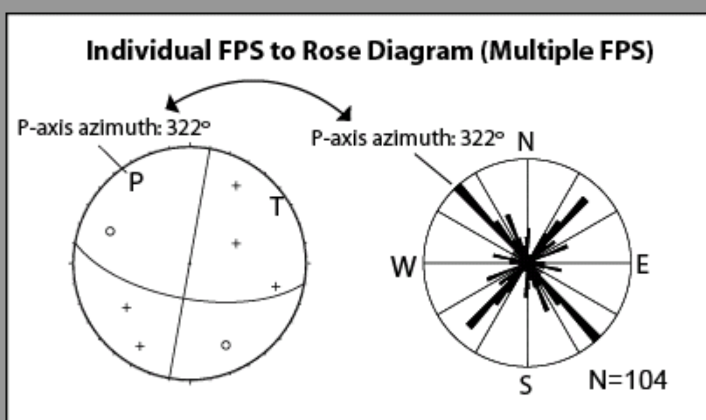
- Accompany and precede many eruptions
- Often precede onset of low-frequency seismicity
- Often include distal swarms
- Brittle response of host rock to processes in the magmatic system
- Waveforms contain information on orientation of local stresses

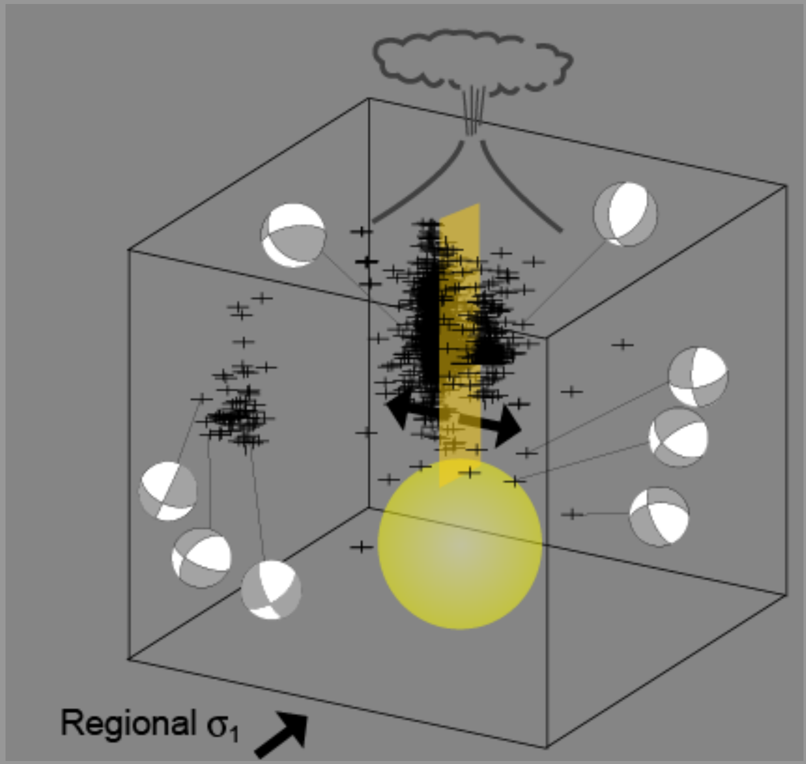


Understanding VT Earthquakes

1. Documentation of systematic changes in VT fault-plane solution orientations during episodes of volcanic activity





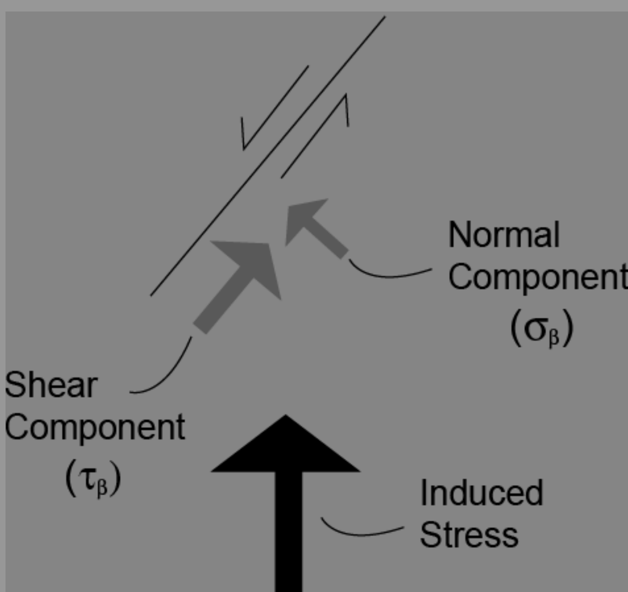


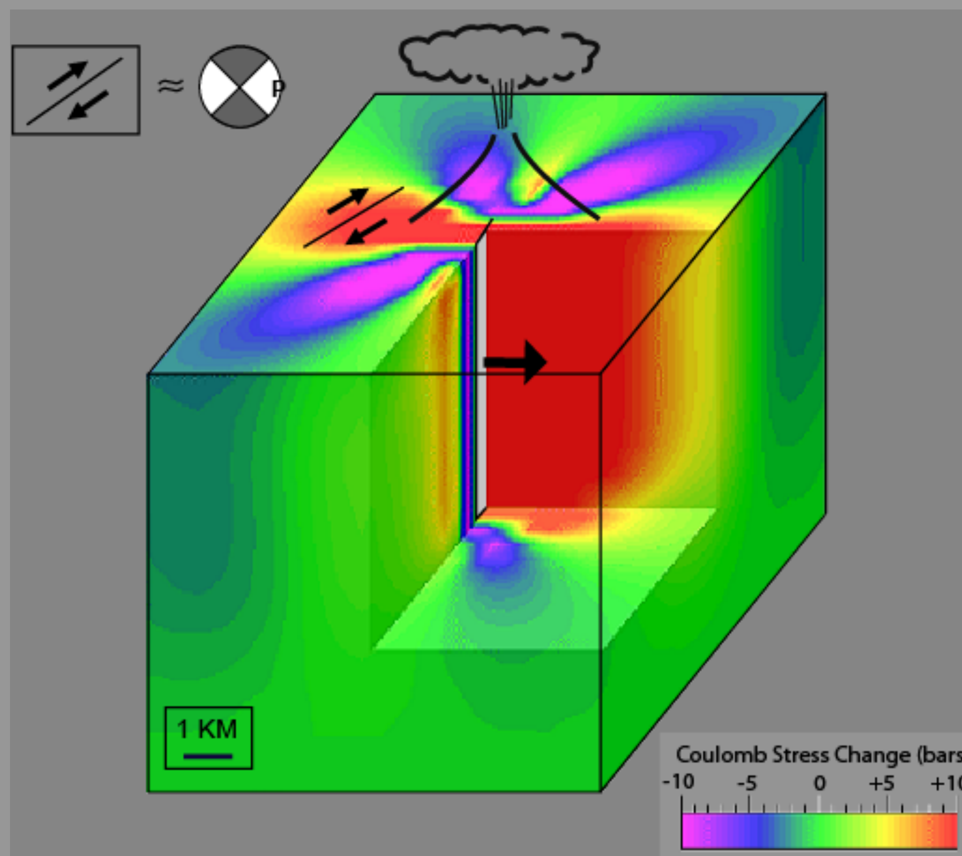
Understanding VT Earthquakes

2. Numerical modeling of hypothesized mechanisms for observed changes in fault-plane solution orientation

Coulomb stress change:

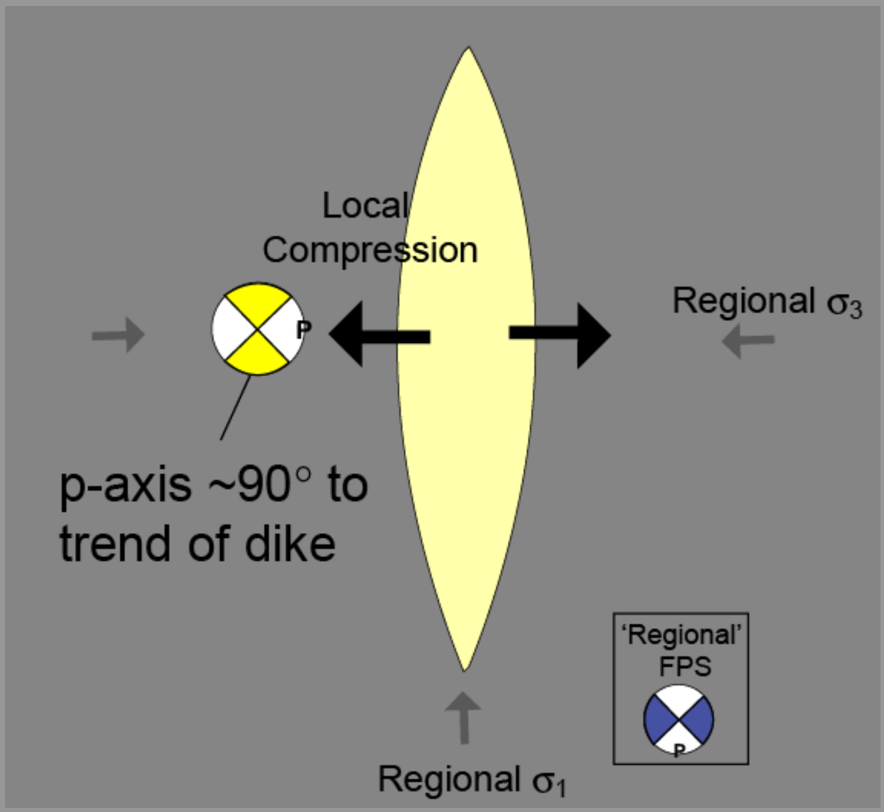
$$\Delta\sigma_f = \tau_\beta - \mu(\Delta\sigma_\beta - \Delta p)$$



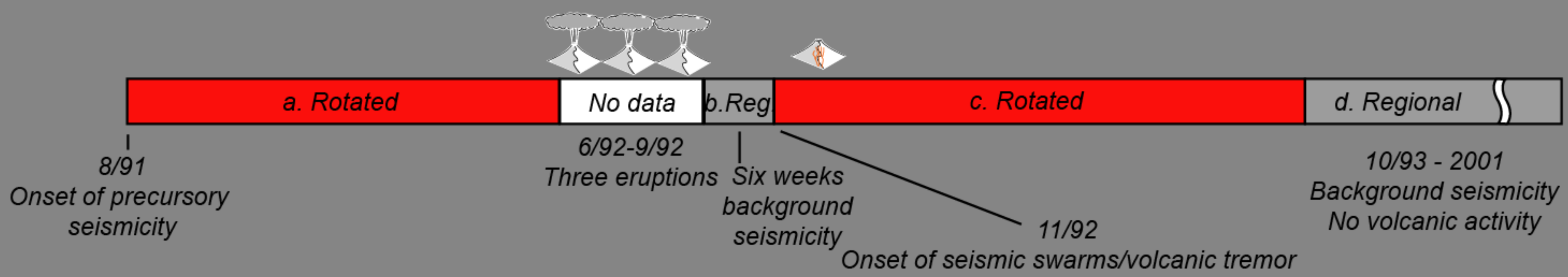


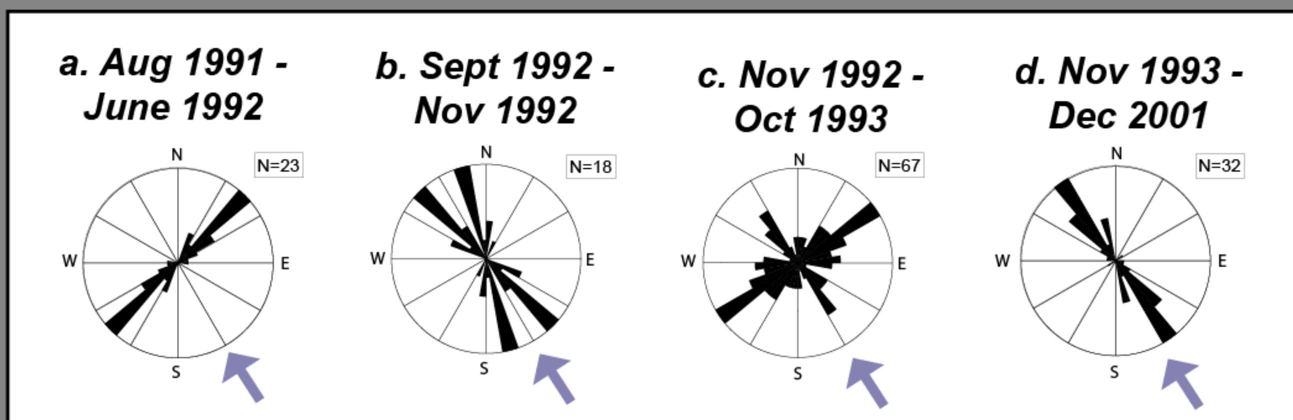
Geometric Relationships

- Geometric relationship between dike orientation and background/induced stress (Nakamura 1977)
- Results in a local ~90° reorientation of principal stresses:



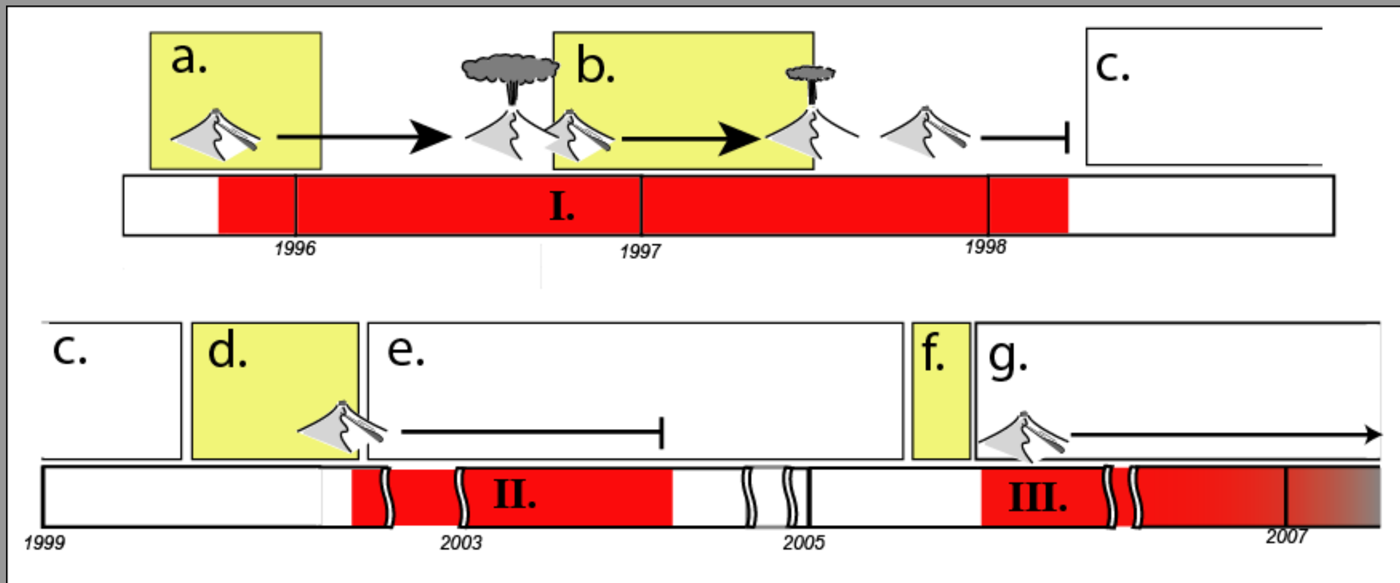
Seismological Analyses – Crater Peak (Mt. Spurr), Alaska

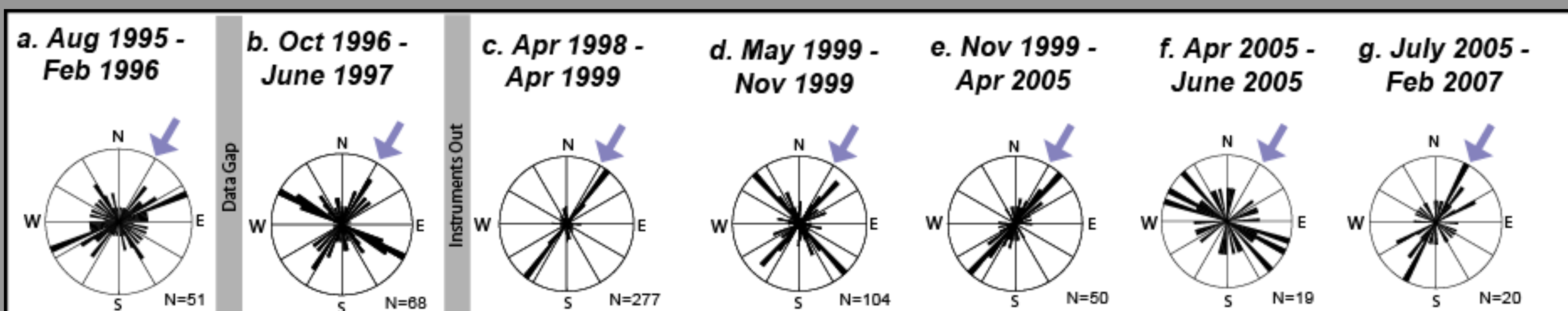




(Roman et al., 2004)

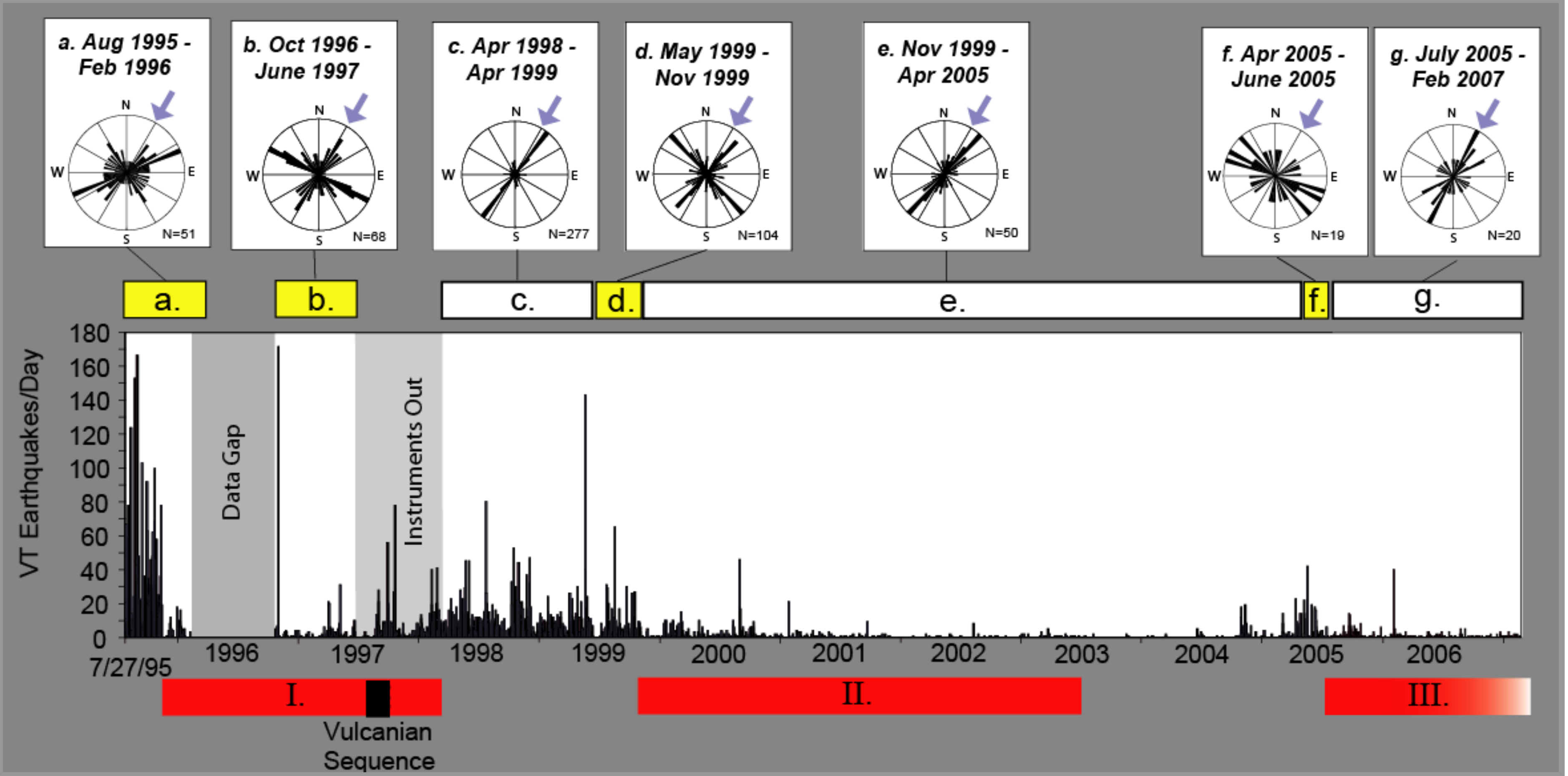
Seismological Analyses – Soufriere Hills, Montserrat





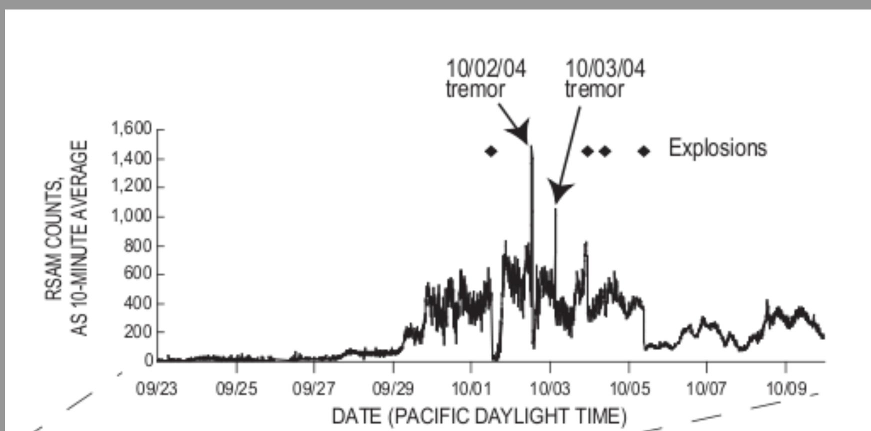
(Roman et al. 2006, 2008)

Seismological Analyses – Soufriere Hills, Montserrat

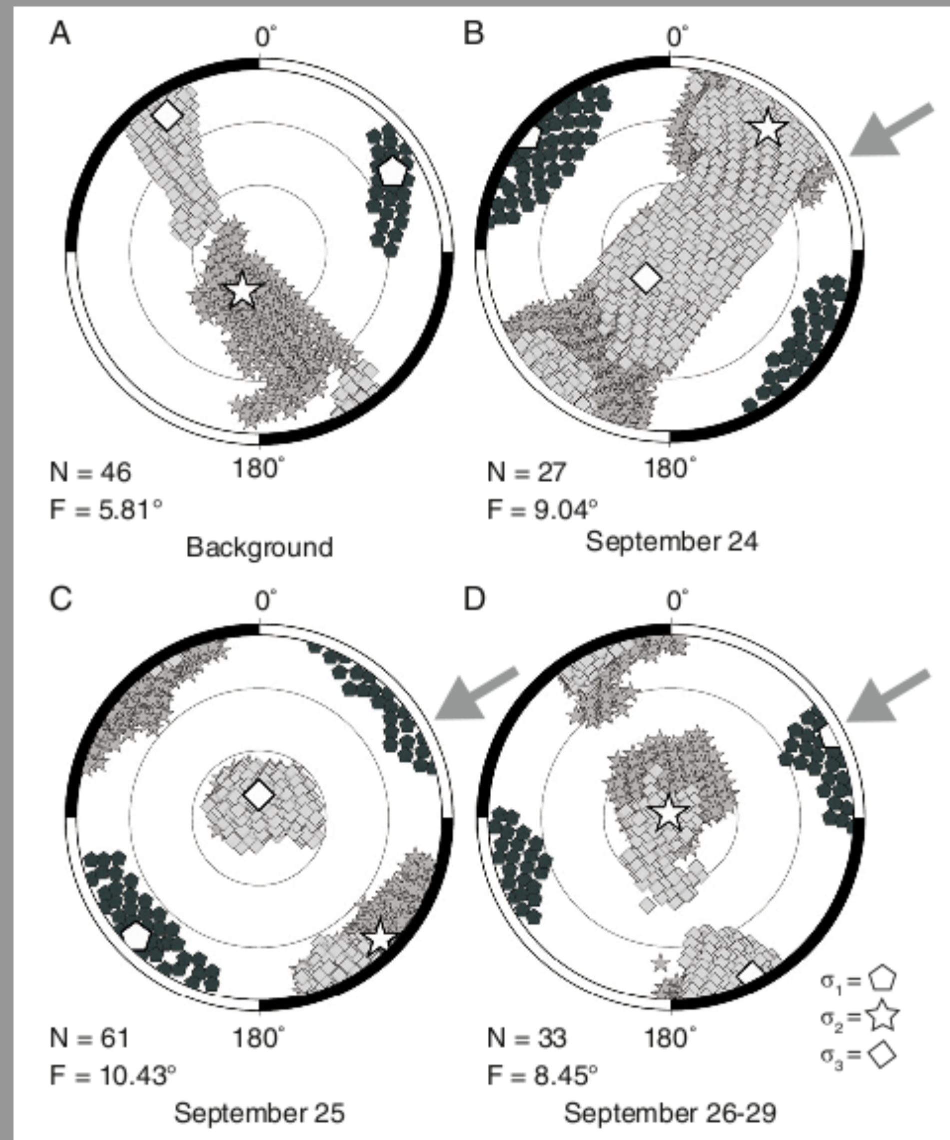


(Roman et al. 2006, 2008)

Seismological Analyses – Mt. St. Helens, Washington



(Moran et al., 2008)



(Lehto et al., 2010)

Seismological Analyses – Redoubt Volcano, Alaska

Group 1: March 21 05:46 UTC – March 22 10:04 UTC
Group 2: March 22 15:34 UTC – March 23 03:17 UTC
Group 3: April 7 12:52 UTC – April 22 17:14 UTC

Group 1 (early swarm)

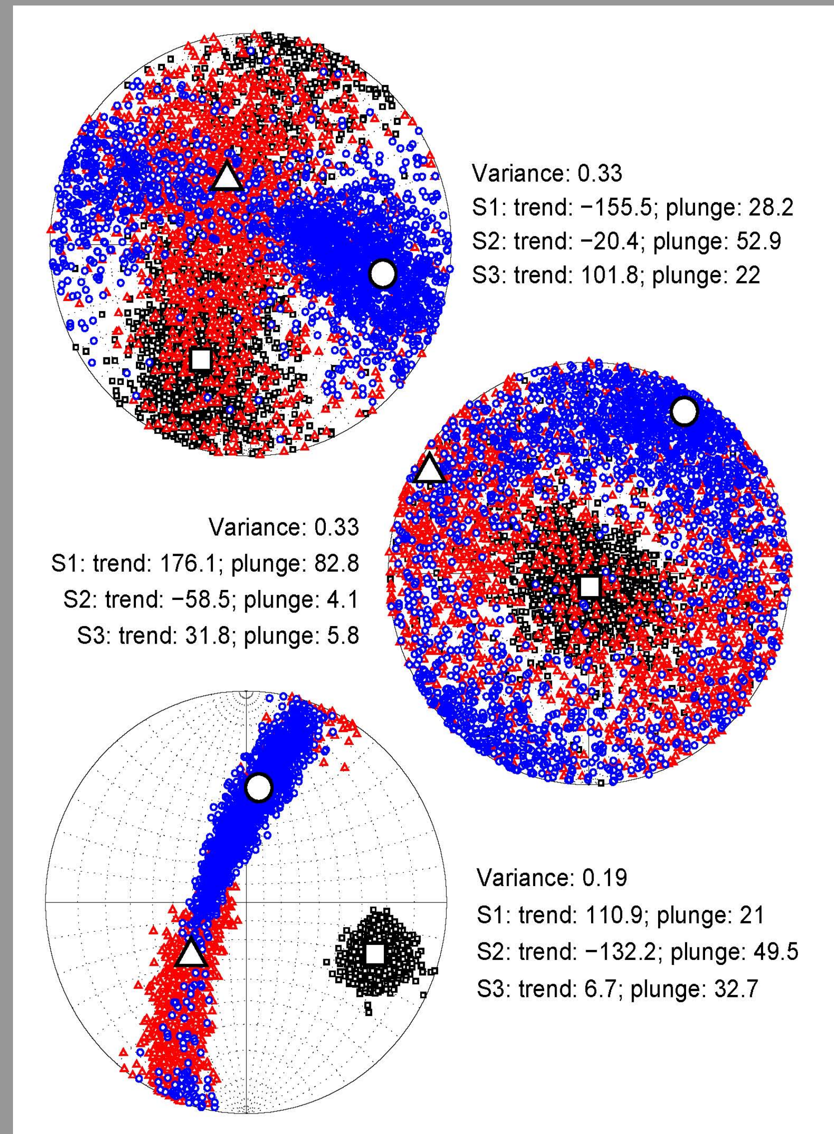
- P-axis (S1) rotation of 90° from regional
- Faulting type strike-slip

Group 2 (late swarm)

- P-axis (S1) near-vertical (normal faulting)
- S2, S3 unconstrained (S2 ≈ S3)

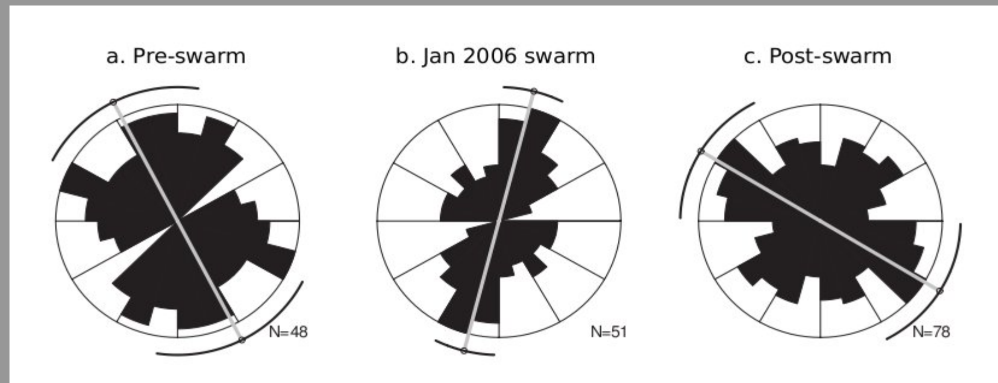
Group 3 (post-eruption)

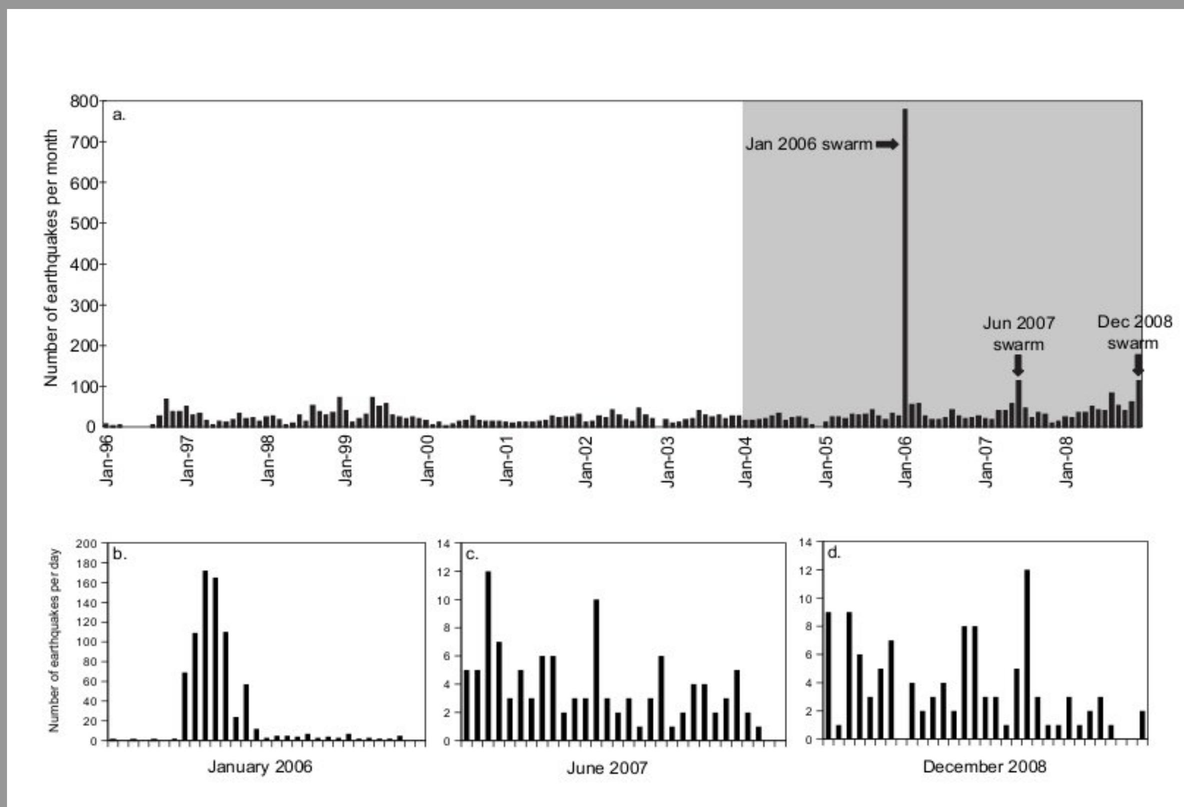
- P-axis (S1) returns to regional
- Faulting type strike-slip



(Gardine et al., in prep)

Seismological Analyses – Mt. Martin (Katmai), Alaska

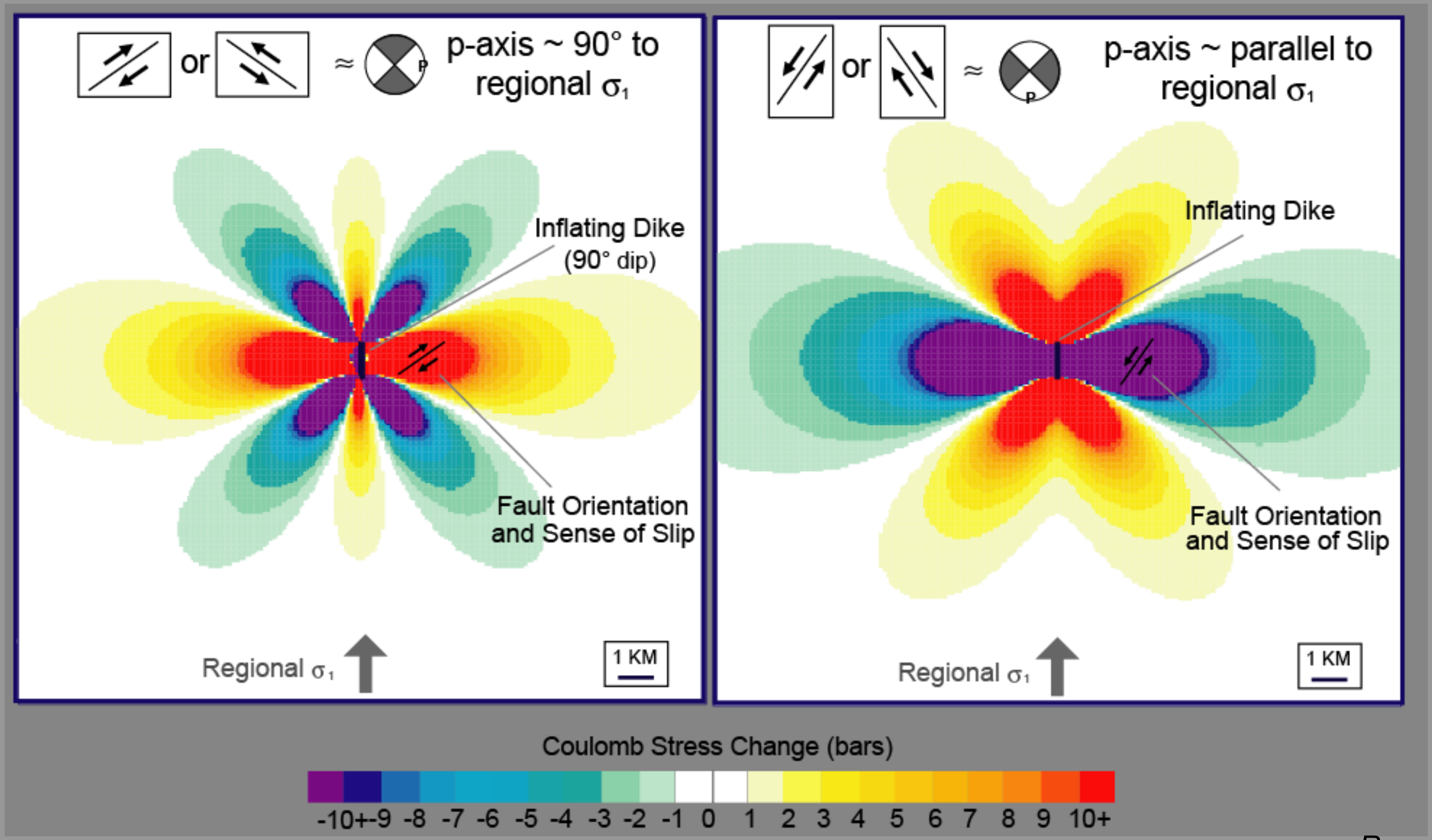




(O'Brien et al., in prep)

Numerical Modeling – 'Generic' dikes

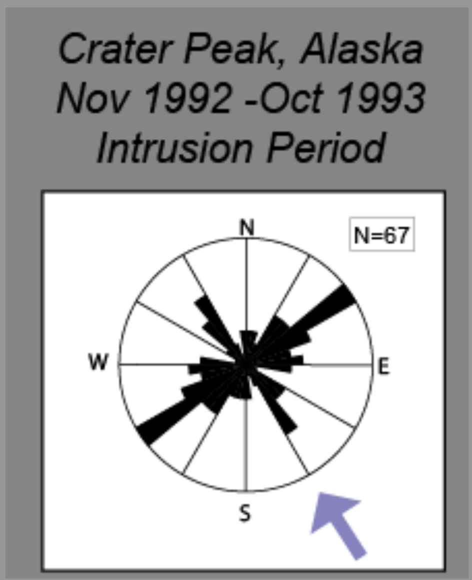
- Models predict ~90° reorientation of local FPS
- Also predict co-occurrence of 'rotated' and 'regional' FPS

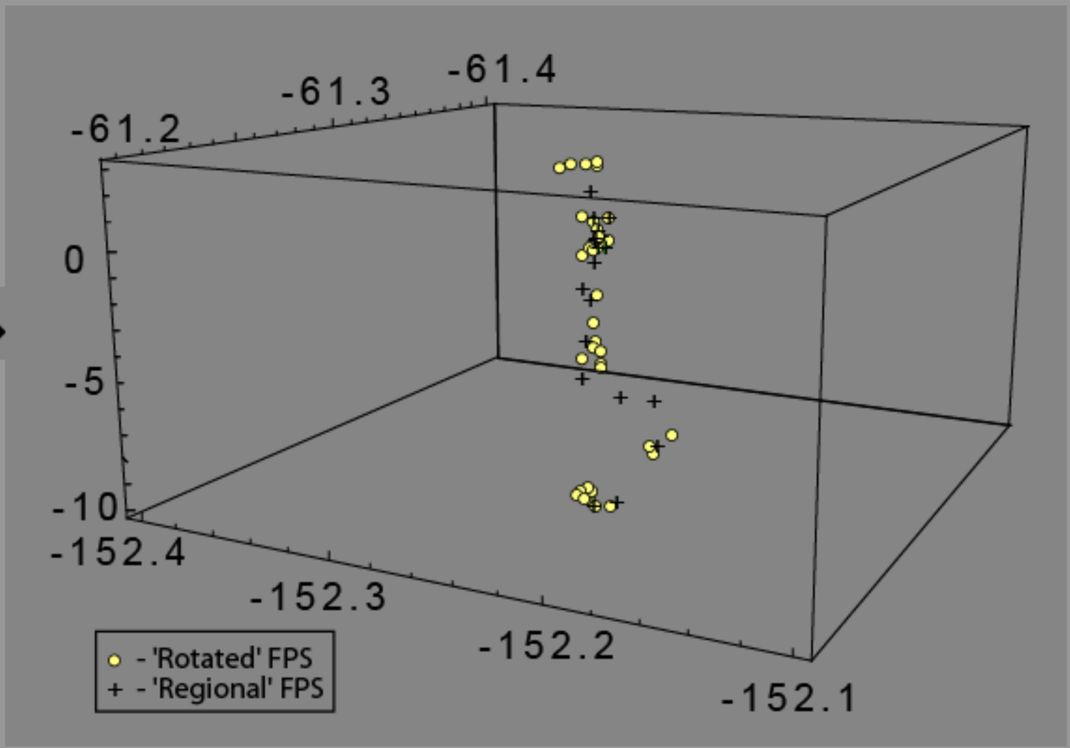


Roman (2005)

Model predictions vs. seismological observations

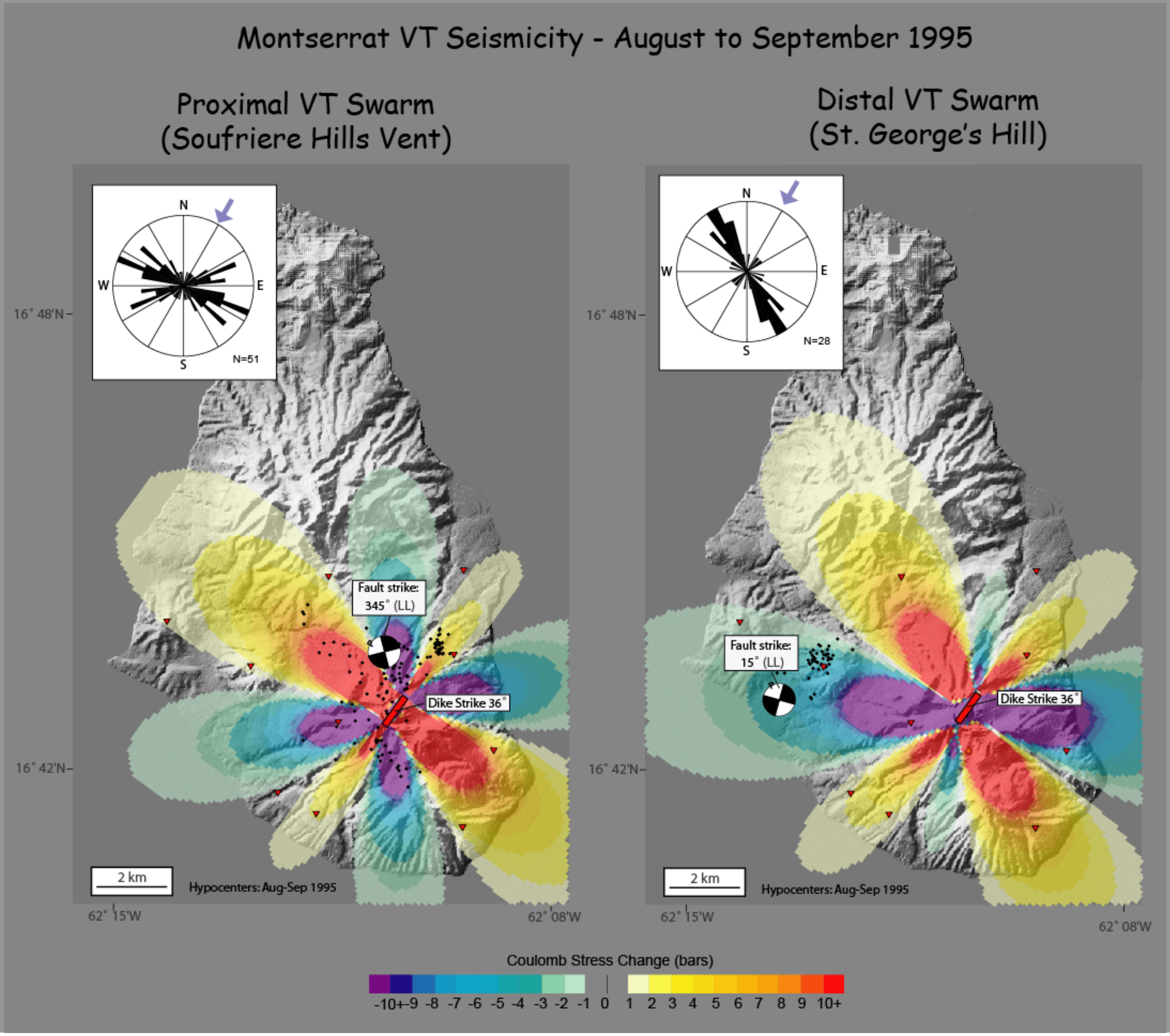
- Mixing of ‘rotated’ and ‘regional’ FPS commonly observed in VT data – no spatial separation (may be resolvable with high-precision relative relocations)





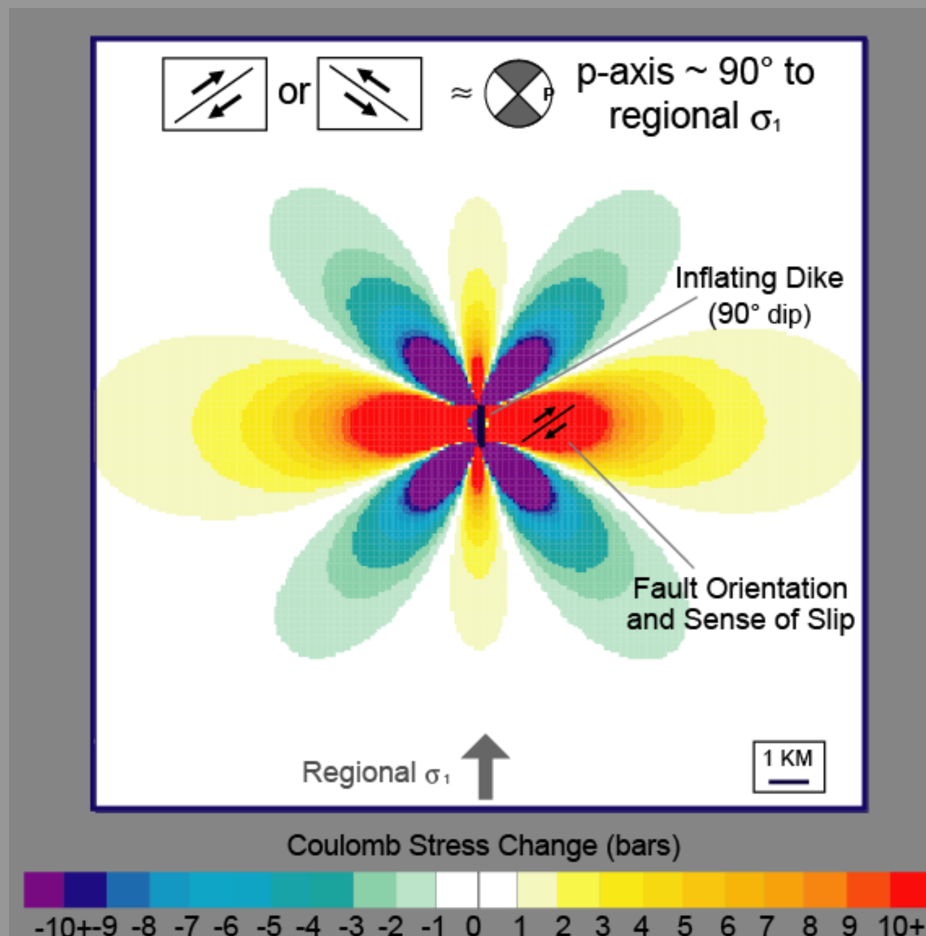
Roman et al. (2004)

Model predictions vs. seismological observations: Distal VT Swarms



Model predictions vs. seismological observations

- Is 90° FPS reorientation a universal phenomenon?



Seismological Analyses – Other Eruptions

Volcano	Eruption	Study	~90° Rotation
Unzen, Japan	1990-1995	Umakoshi et al. (2001)	✔
Usu, Japan	2000	Fukuyama et al. (2001)	✔
Mt. St. Helens, USA	1980-1986	Barker and Malone (1991)	✔
Guagua Pichincha, Ecuador	1998	Legrand et al. (2002)	✔
Mt. Ruapehu, New Zealand	1995-1996	Miller and Savage (2001)	✔
Mt. Etna, Italy	Multiple eruptions	e.g., Patane et al. (2003)	✔

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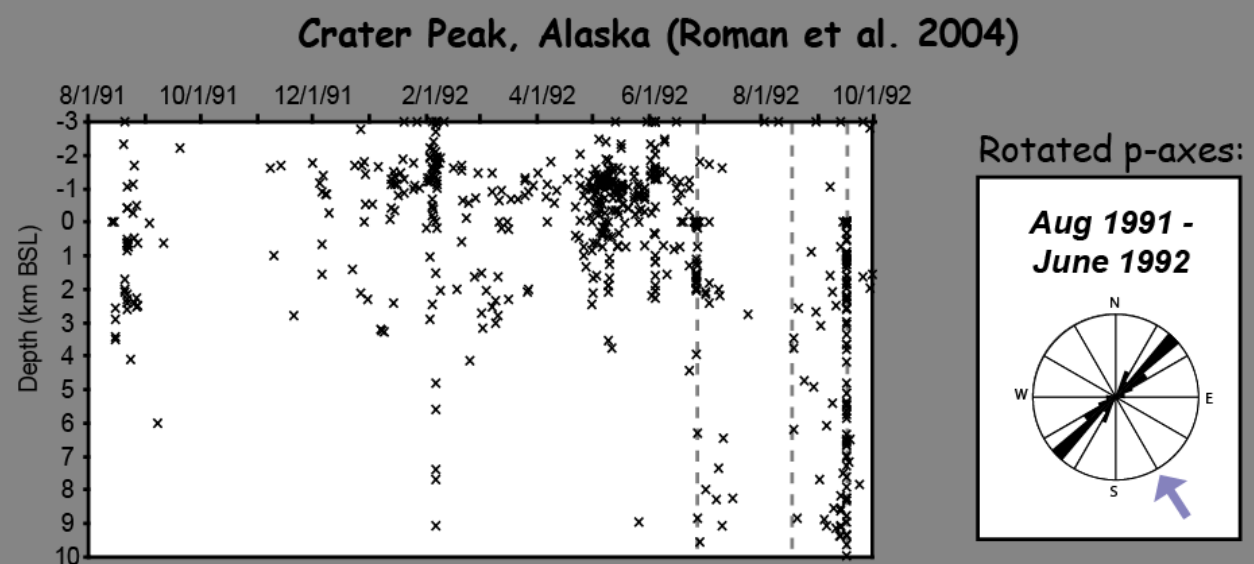
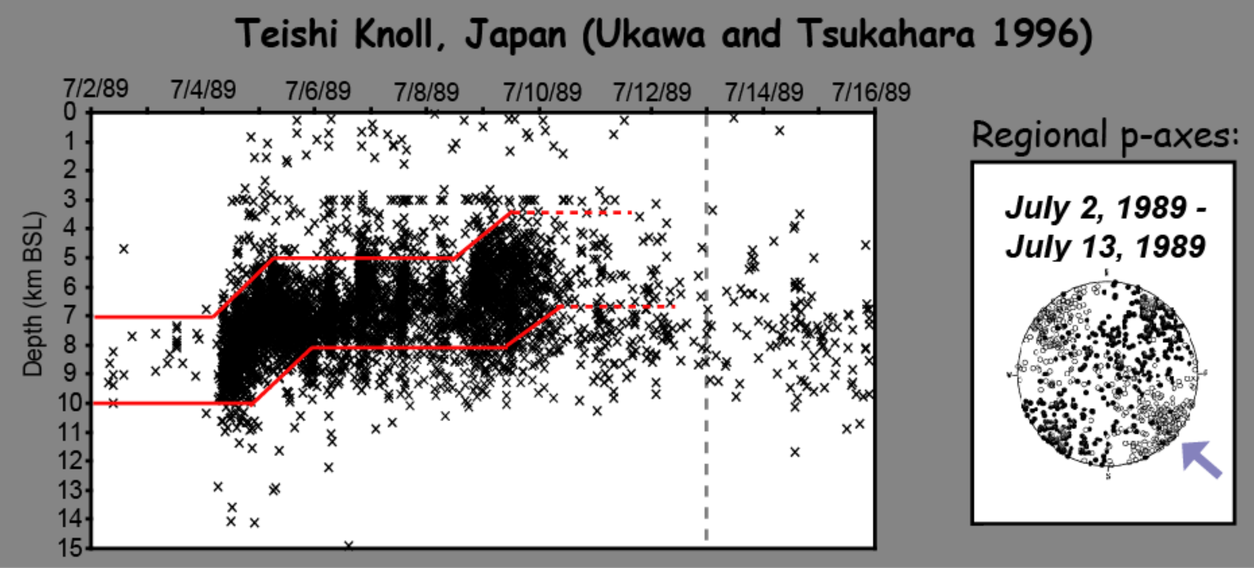
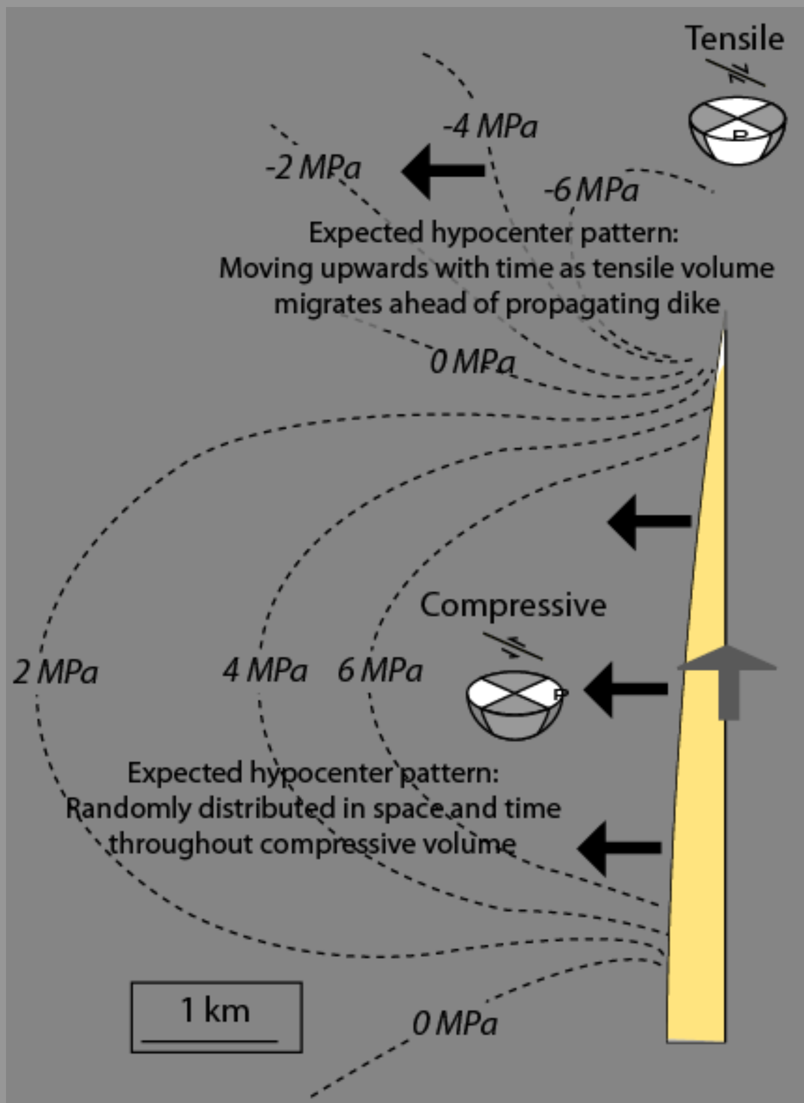
Guagua Pichincha, Ecuador	1998	Legrand et al. (2002)	✓
Mt. Ruapehu, New Zealand	1995-1996	Miller and Savage (2001)	✓
Mt. Etna, Italy	Multiple eruptions	e.g., Patane et al. (2003)	✓
Teishi Knoll, Japan	1989	Ukawa and Tsukahara (2001)	✗
Miyake-jima, Japan	2000	Fukuyama et al. (2001)	✗
Izu-Oshima, Japan	1987	Aramaki (1988)	✗

Seismological Analyses – Hypocenter Migration





Numerical Models – Dike-induced stress regimes



<u>Two induced stress regimes</u>

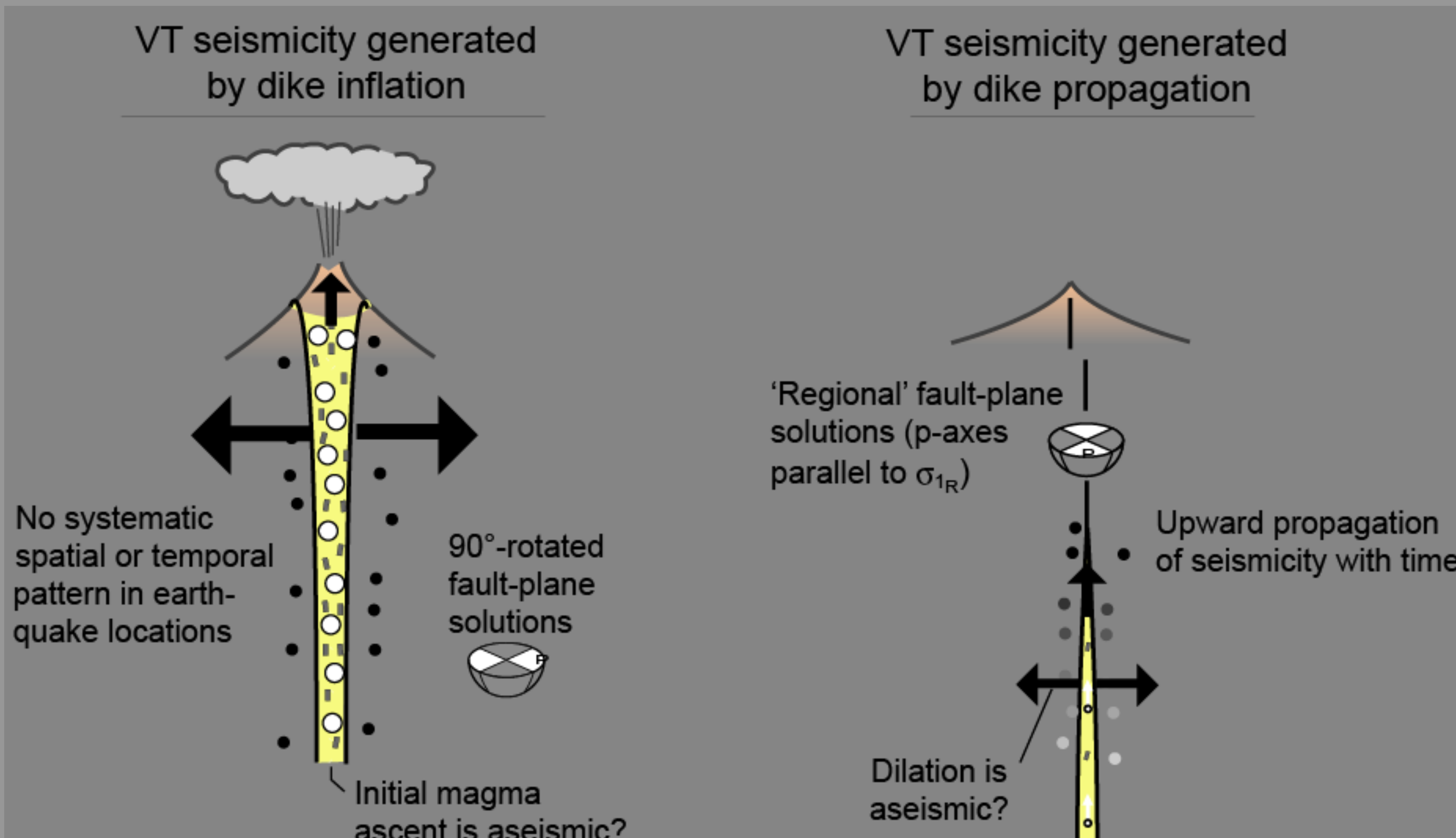
- Compressive in walls of dike (hypocenters random in space)
- Tension above propagating dike (hypocenters migrating ahead of dike tip)

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

Seismological Analyses – Eruption Summary

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)	✗	✓

Seismological Analyses – Origin of VT Swarms



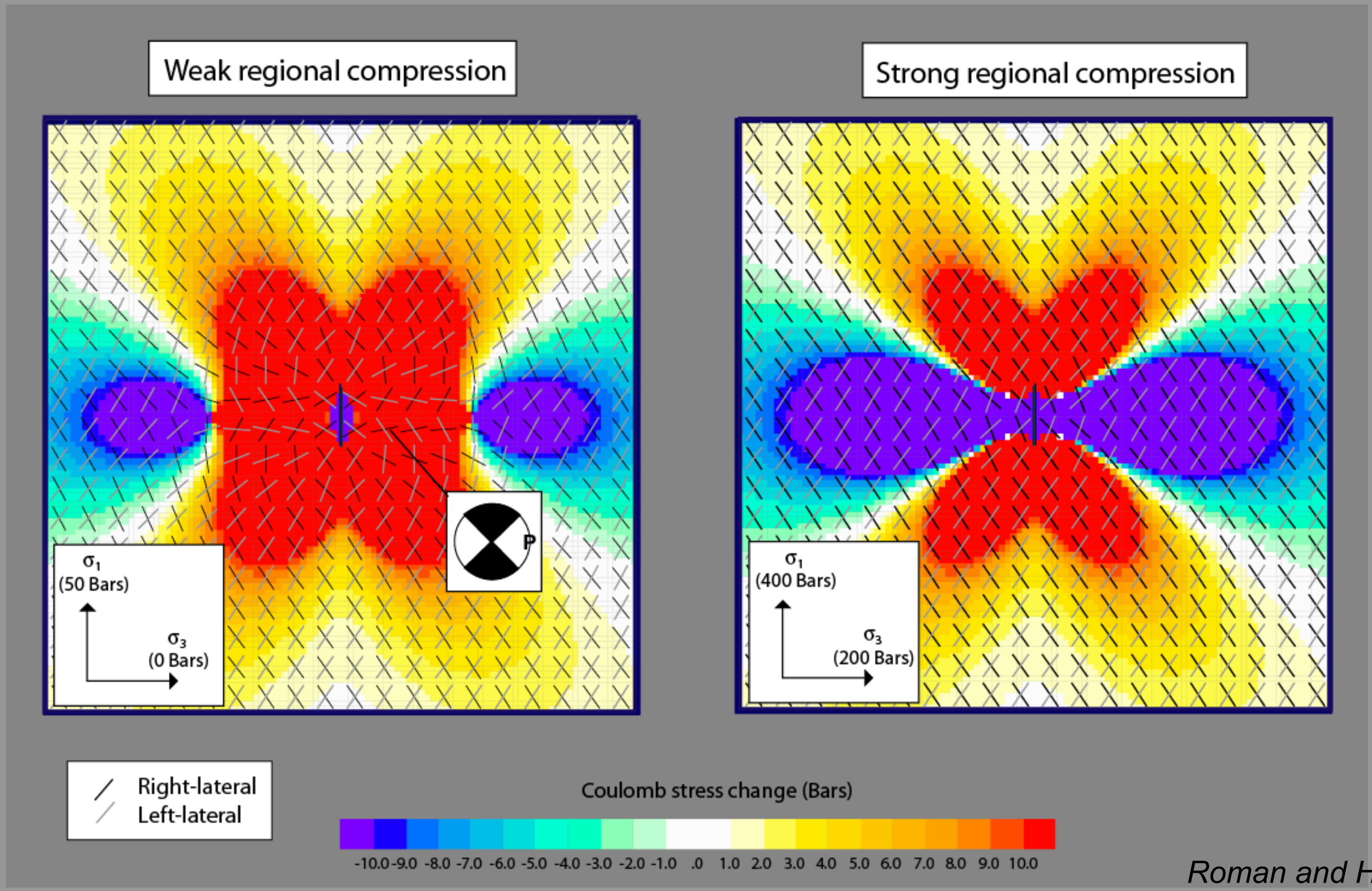
(Roman and Cashman, 2006)

Seismological Analyses – Apparent Relationships

	Volcano	Migration?	~90° Rotation	Composition	Crystallinity
Hydrous/crystalline magmas	Crater Peak	✗	✓	Andesite	High
	Soufriere Hills,	✗	✓	Dacite	High
	Unzen	✗	✓	Dacite	High
	Usu	✗	✓	Dacite	Probably High
	Mt. St. Helens	✗	✓	Dacite	High
	Guagua Pichincha	✗	✓	Dacite	High
	Mt. Ruapehu,	✗	✓	Andesite	High
	Mt. Etna	✗	✓	Basalt	High
	Redoubt	✗	✓	Dacite	High
Strong regional differential stress	Miyake-jima	✓	✗	Basalt	Low
	Izu-Oshima	✓	✗	Basalt	Low
	Teishi Knoll	✓	✗	Basalt	Low

Numerical Modeling – Regional Stresses

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



Roman and Heron (2007)

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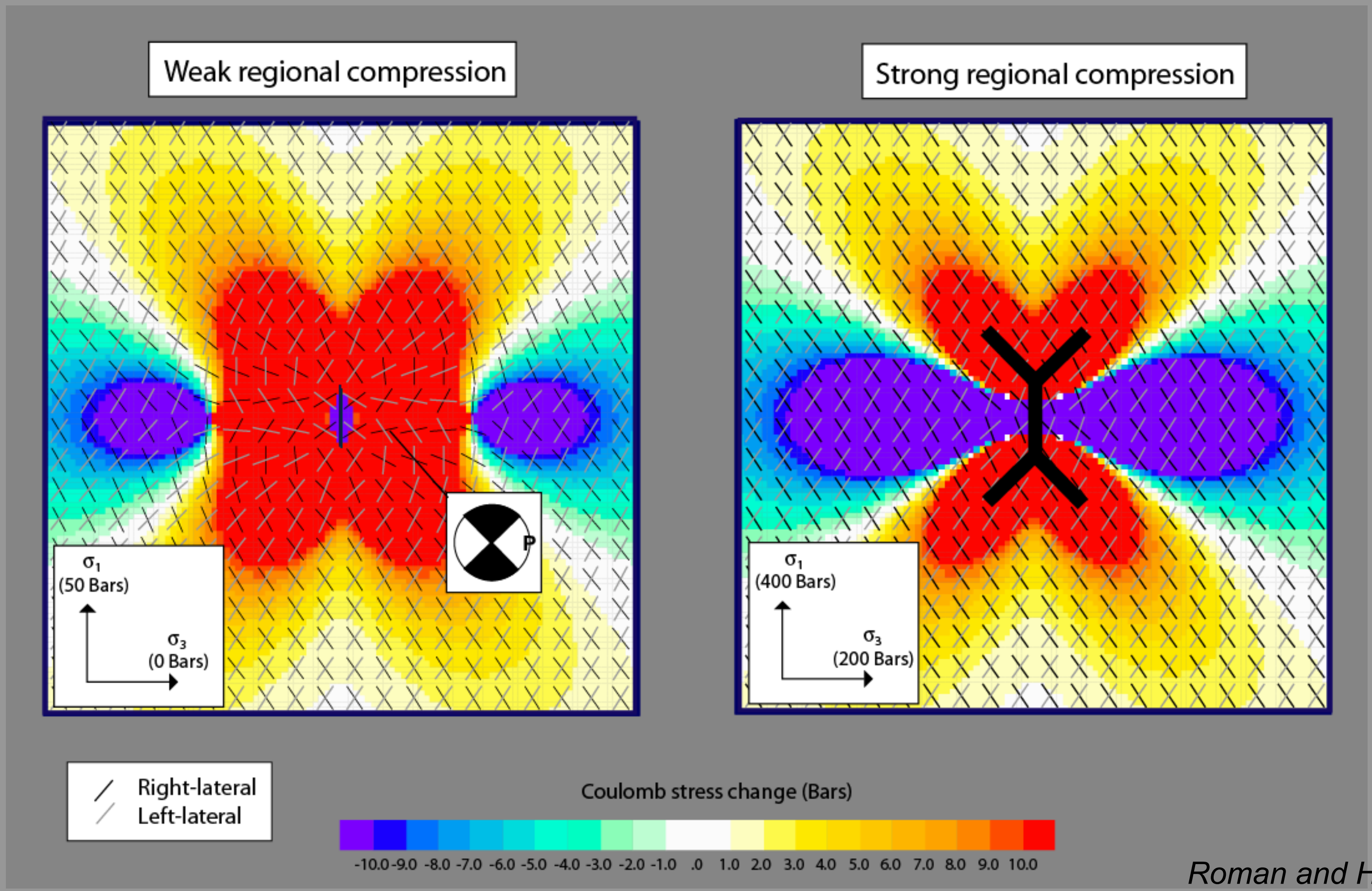

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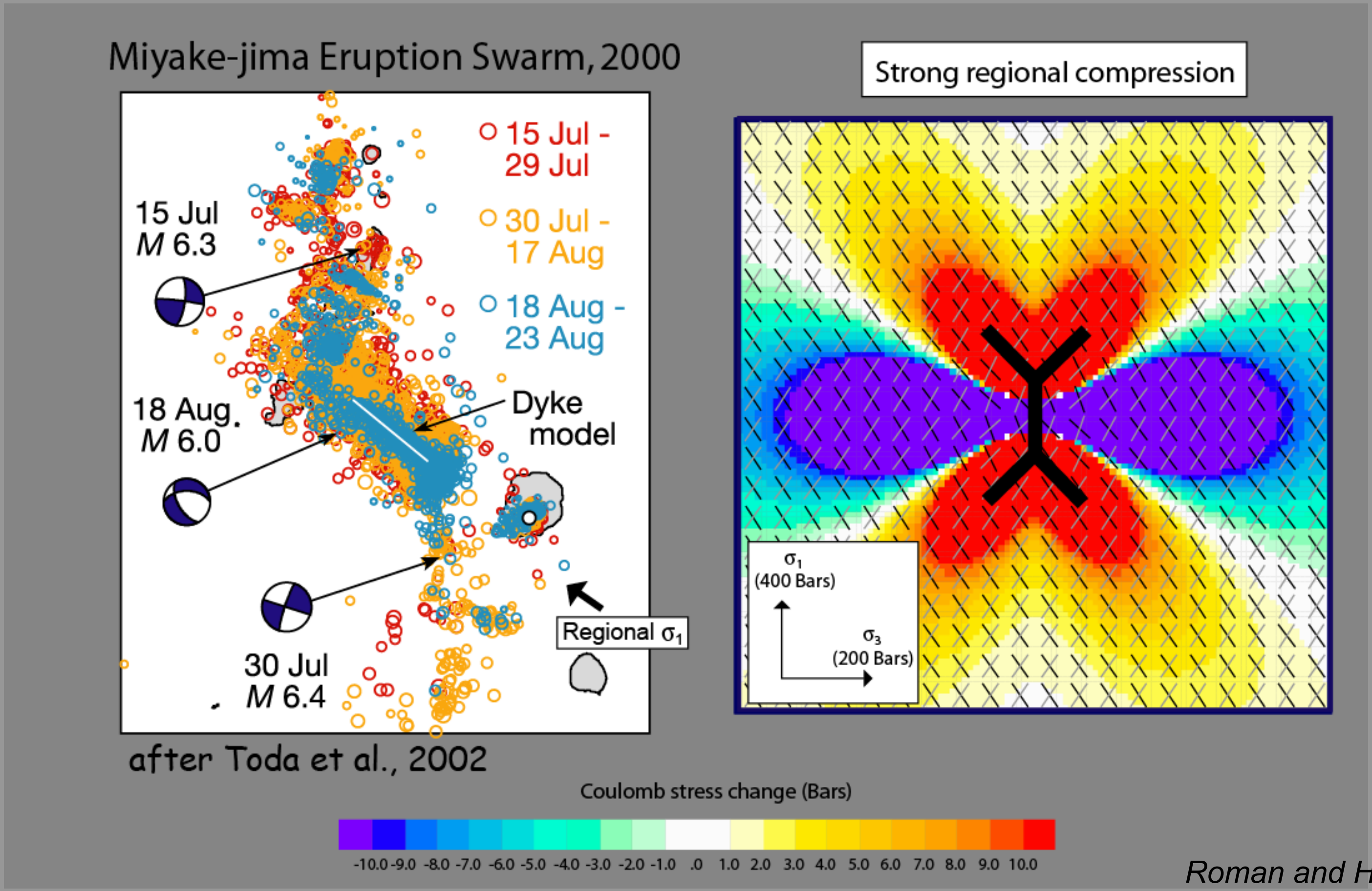
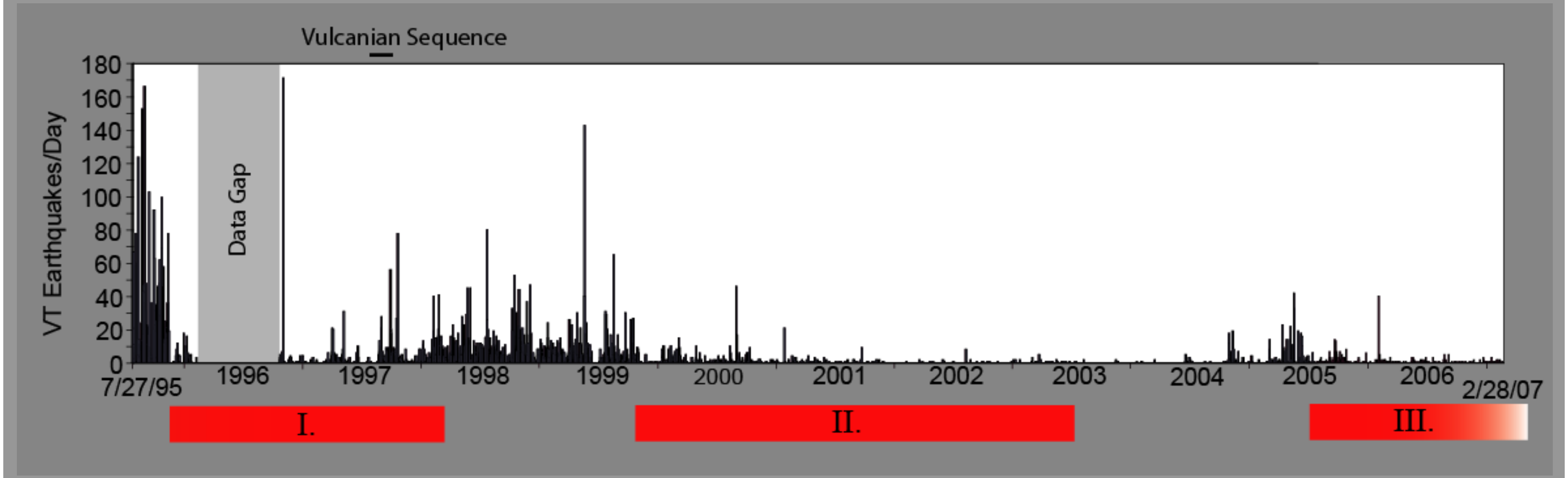


Roman and Heron (2007)

Timing of VT seismicity at open-vent volcanoes

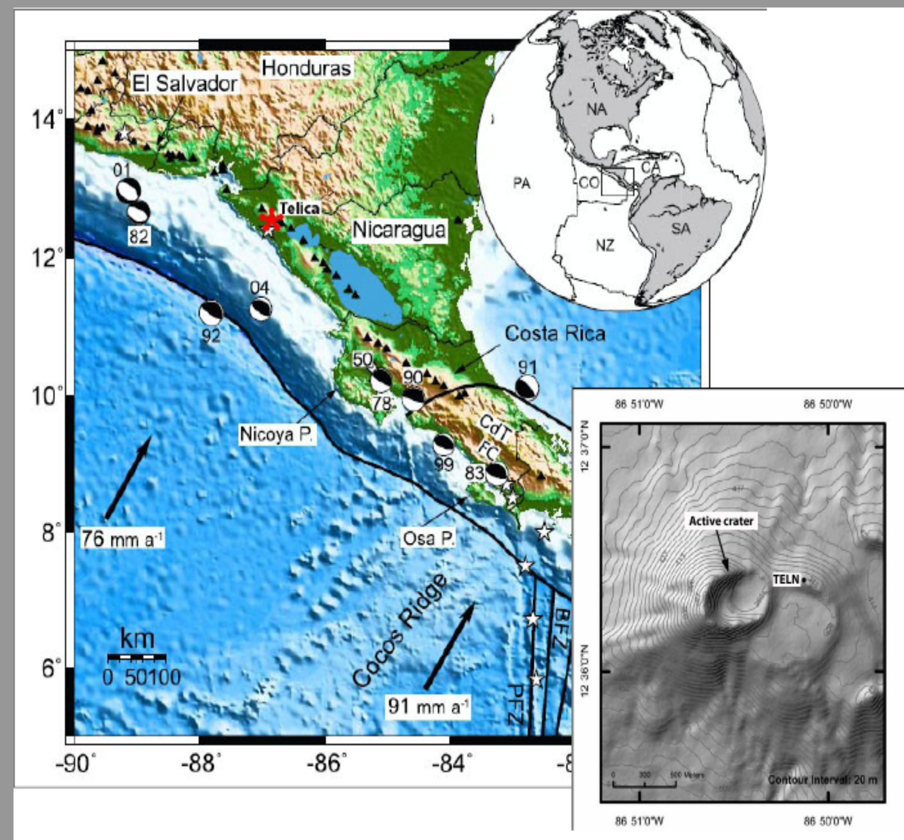
- Four eruption phases to date (I, II, III; IV not shown)
- High rates of VT seismicity:
  1. Prior to each eruption phase
  2. Prior to 1997 Vulcanian sequence
  3. During first pause in eruption
- Long-term decrease in VT seismicity rate – transition to open vent?



Timing of VT seismicity at open-vent volcanoes

Telica Volcano, Nicaragua

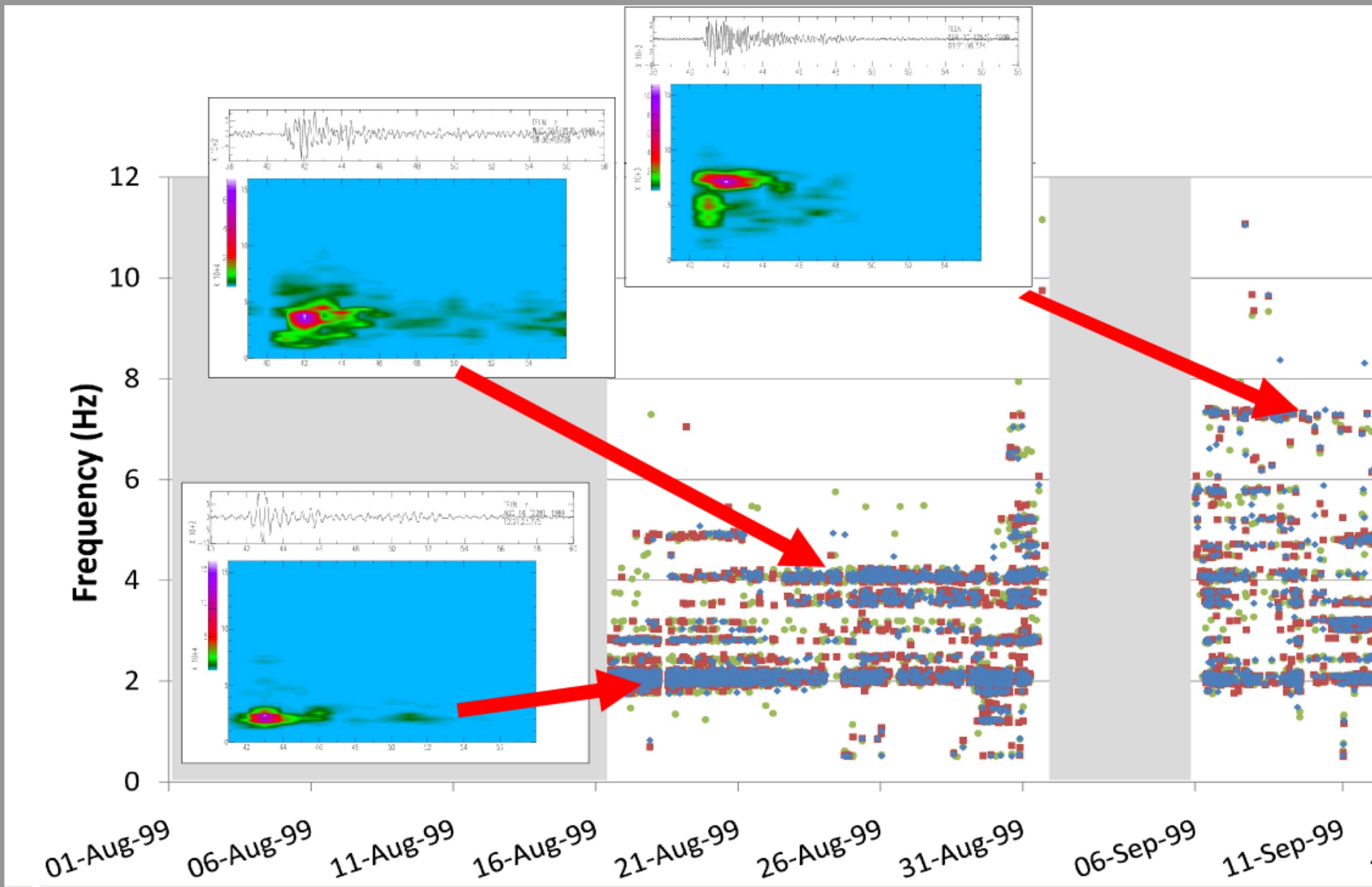
- High-rate 'background' LP seismicity
- Series of explosions/eruption in mid to late 1999



Rodgers et al., unpublished

Timing of VT seismicity at open-vent volcanoes

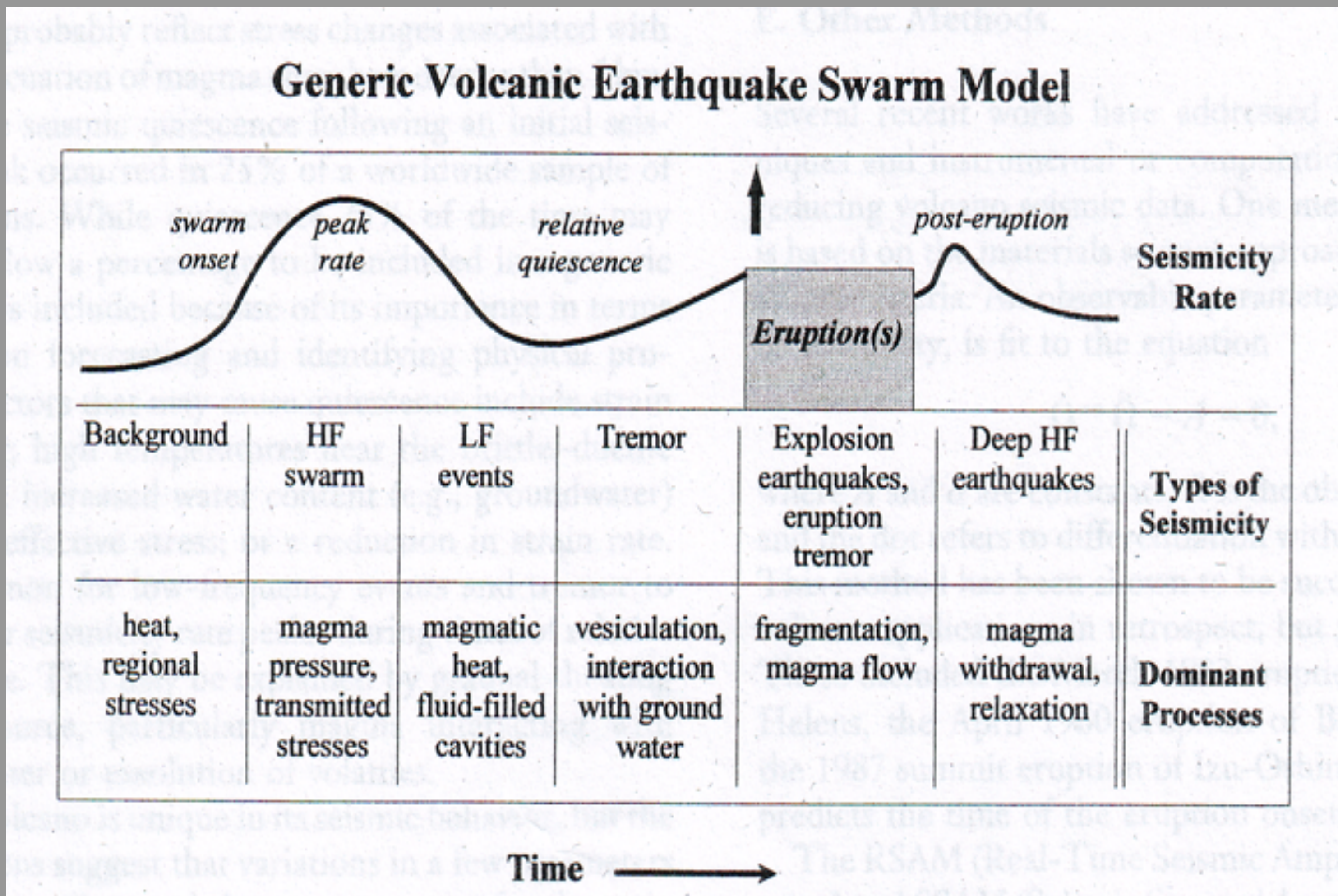
- Transition from LP to VT seismicity preceding explosions



Rodgers et al., unpublished

Timing of VT seismicity at open-vent volcanoes

- Need for an alternate model for open-vent volcanoes?



McNutt and Benoit (1995)

Summary 1: What (we think) we've figured out

- 90° changes in VT FPS orientation reflect conduit inflation and often precede eruptions by days to months (generally concurrent with an increase in the rate of VTs)

- 90° changes in VT FPS orientation can also accompany episodes of volcanic unrest (magma intrusions) that do not proceed to Eruption

- VT seismicity can reflect dike inflation, dike deflation, or dike propagation – initial magma ascent appears to be aseismic in some (high-crystallinity or high-viscosity?) systems

- The observed pattern of VT seismicity is likely influenced by a combination of factors, including the tectonic setting/ambient stress field, magma composition/rheology, and magma volume.

- Volcanic stress field analysis has demonstrated potential as a technique for monitoring and forecasting at restless volcanoes

Summary 2: What we don’t understand (yet!)

Our understanding of the mechanisms and patterns of VT seismicity is currently based on a small number of detailed studies of VTs – there are still many questions to address through additional case study and modeling, e.g.:

- What are the controls on observed stress field response? Is a 90° reorientation of FPS indicative of magma rheology or perhaps eruption style/explosivity?
- What drives distal VT swarms? What controls their occurrence?
- Can FPS based on precisely-located earthquakes map out numerically-modeled spatial patterns of stress?
- Can analysis of VT earthquakes provide any indication of volcanic ‘false alarms’?
- What is the nature of VT seismicity at open-vent volcanoes?

Acknowledgements

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Seth Moran, John Power, Kathy Cashman, Jurgen Neuberg, Richard Luckett, Willy Aspinall, Philip Heron, Silvio De Angelis, Lars Ottemoller, Brian Baptie, Joan Latchman, Richard Arnold, and the staffs of the Montserrat, Cascades, and Alaska Volcano Observatories

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NSF

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