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The MFAST Shear-wave splitting program and its use as a volcano monitoring tool

Outline

- Motivation for use of anisotropy to study time-varying stress and possible eruption prediction
- The main principles of the technique
- Results: Ruapehu, New Zealand
- Asama, Japan
- Soufrière Hills
- Piton de la Fournaise

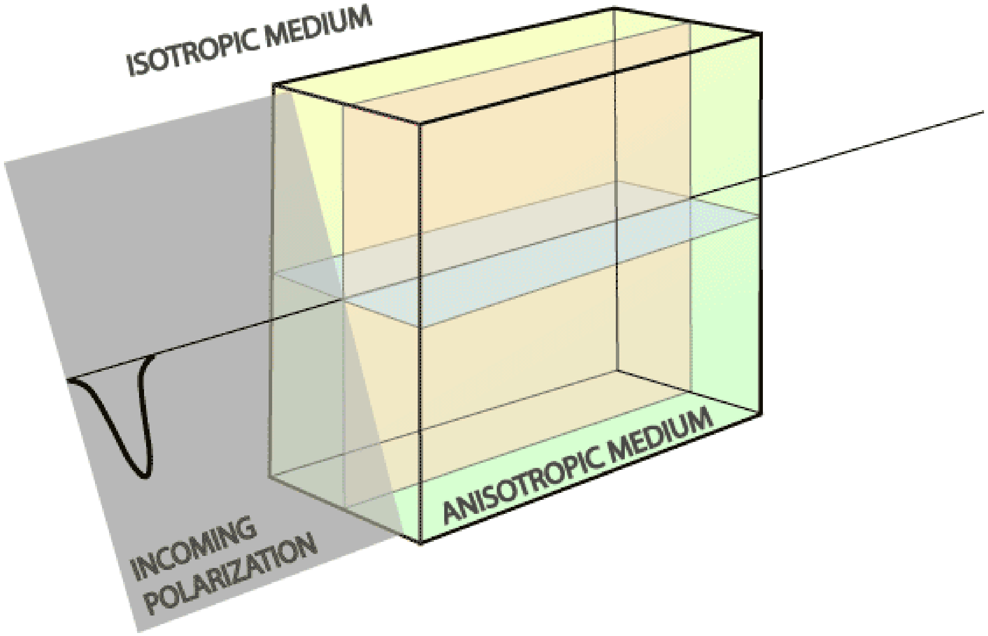
To get programs: http://mfast-package.geo.vuw.ac.nz/

Shear wave splitting to determine stress

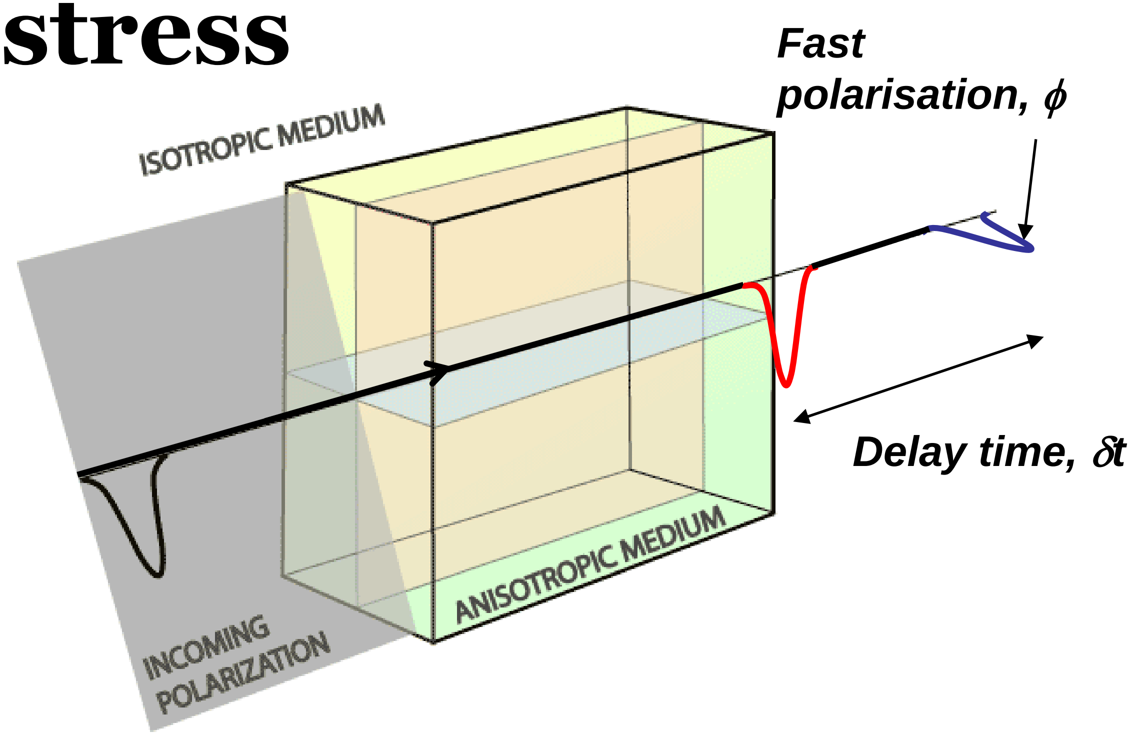
Anisotropy

Glacier crevasses

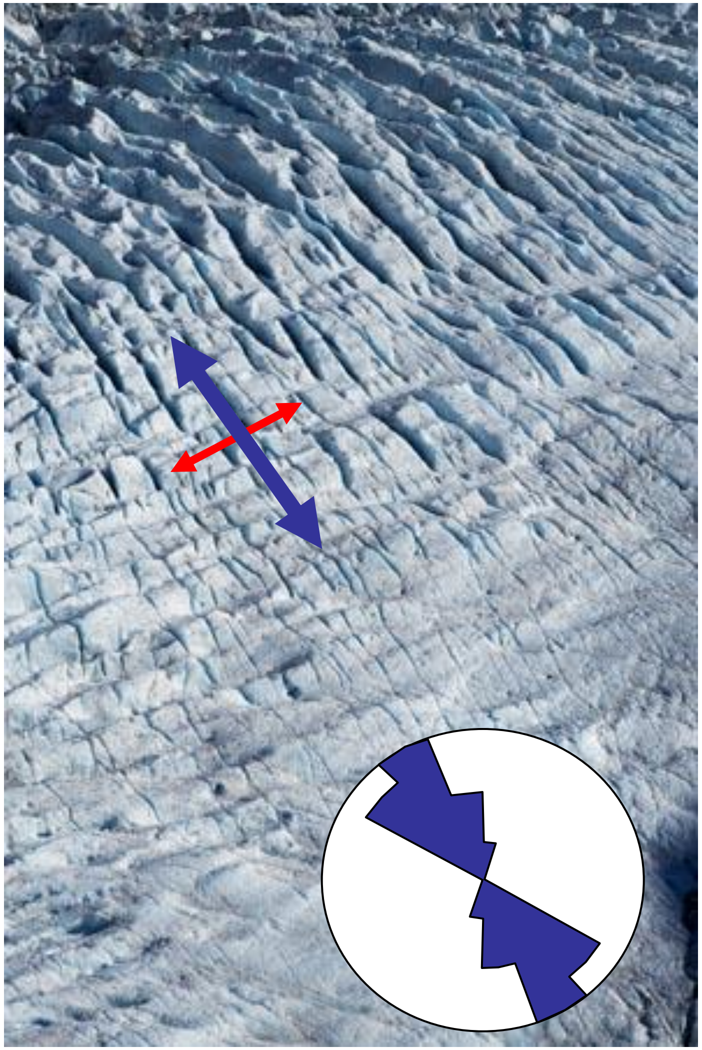
Shear wave splitting to determine stress

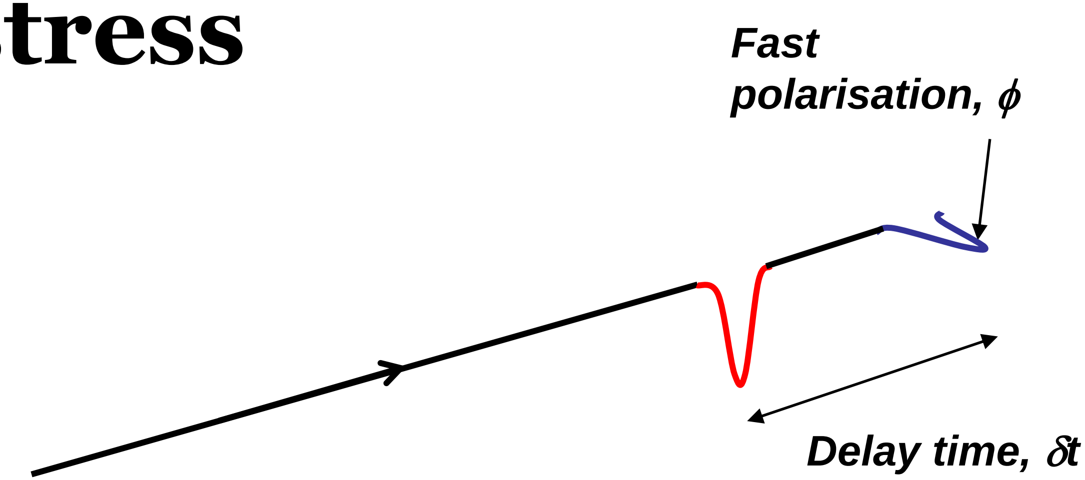


Shear wave splitting to determine stress

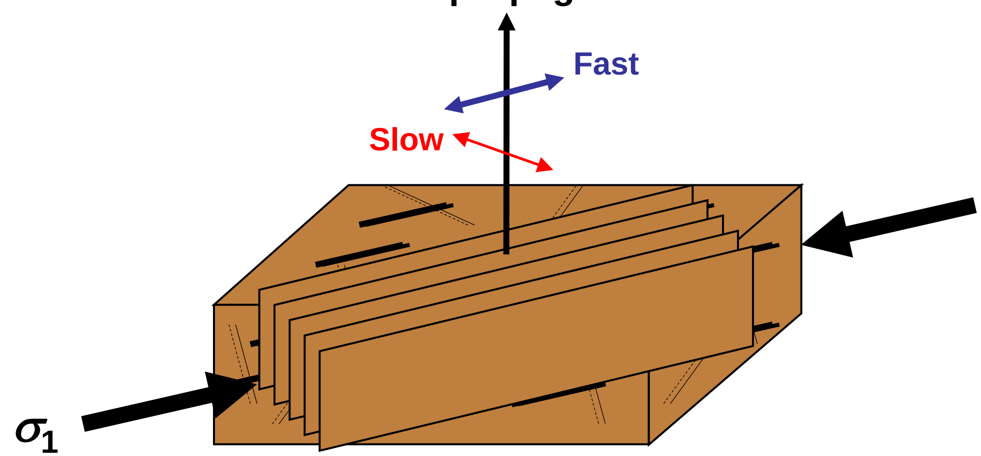


Shear wave splitting to determine stress





δt ***is*** proportional to % anisotropy (crack density)
And length of travel path



Measuring anisotropy is one of the few ways to monitor stress changes—possibly predicting consequences. However, …

- Is the anisotropy caused by structure/mineral alignment or cracks?
- Do cracks always align with stress?
- Are changes caused by fluid movement or stress change or by artefacts from path changes? (eq sources may move)

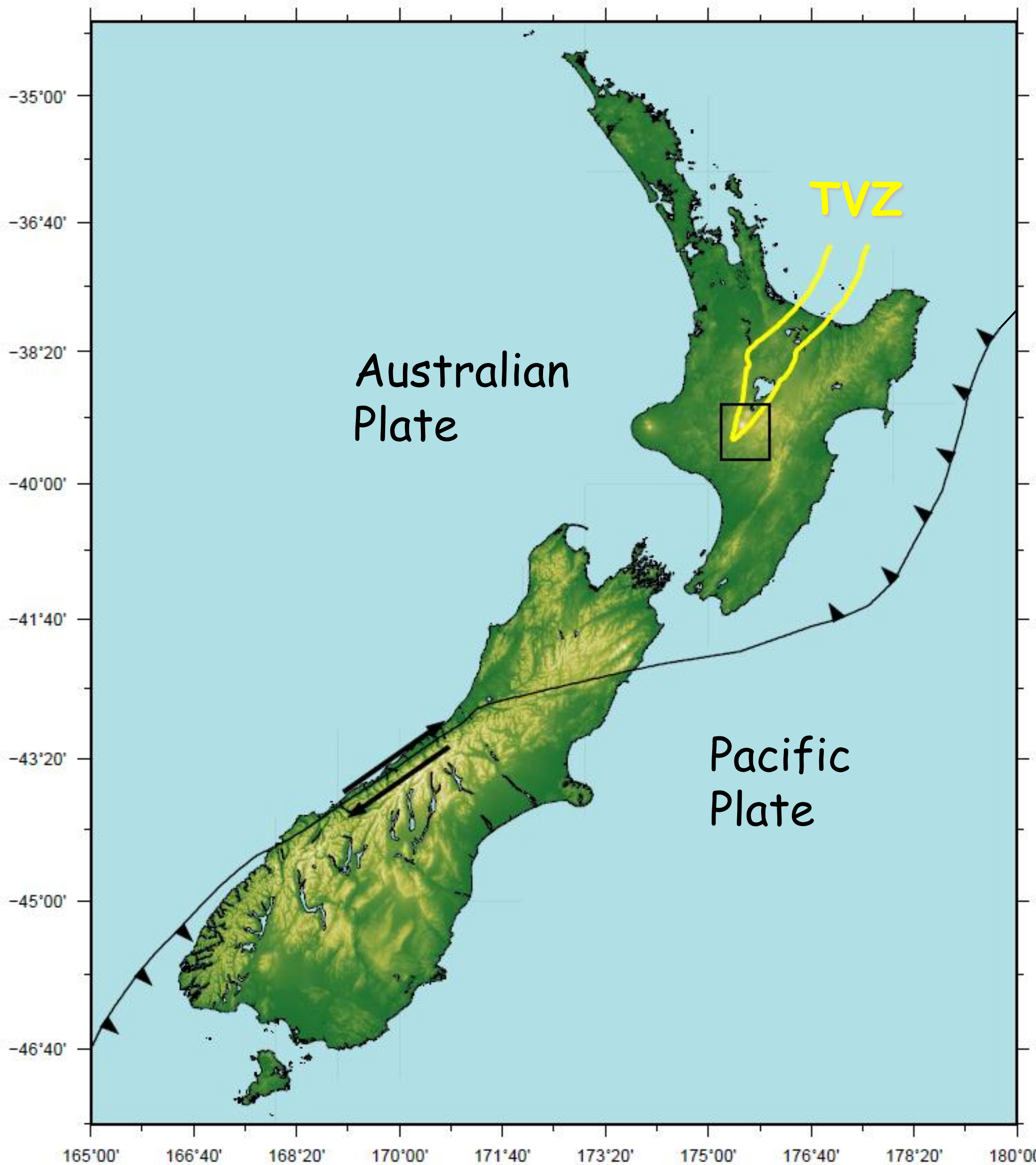
Oil Companies use anisotropy to:

- Make better images of subsurface
- Determine fracture patterns in reservoirs
- Helps to decide where to drill to get best production
- Permanent source & receivers in boreholes to monitor oil reservoir production

Testing the method

- Time variations would rule out structural anisotropy as the sole cause
- Use objective measurement technique
- Use sources that don't vary much or tomography to try to separate path effects
- Compare to other methods that are related to stress (GPS, Focal mechanisms)

Mount Ruapehu Volcano



- Large magmatic eruptions 1945, 1995/1996
- Phreatic eruptions 2006, 2007
- Little or no precursory seismicity

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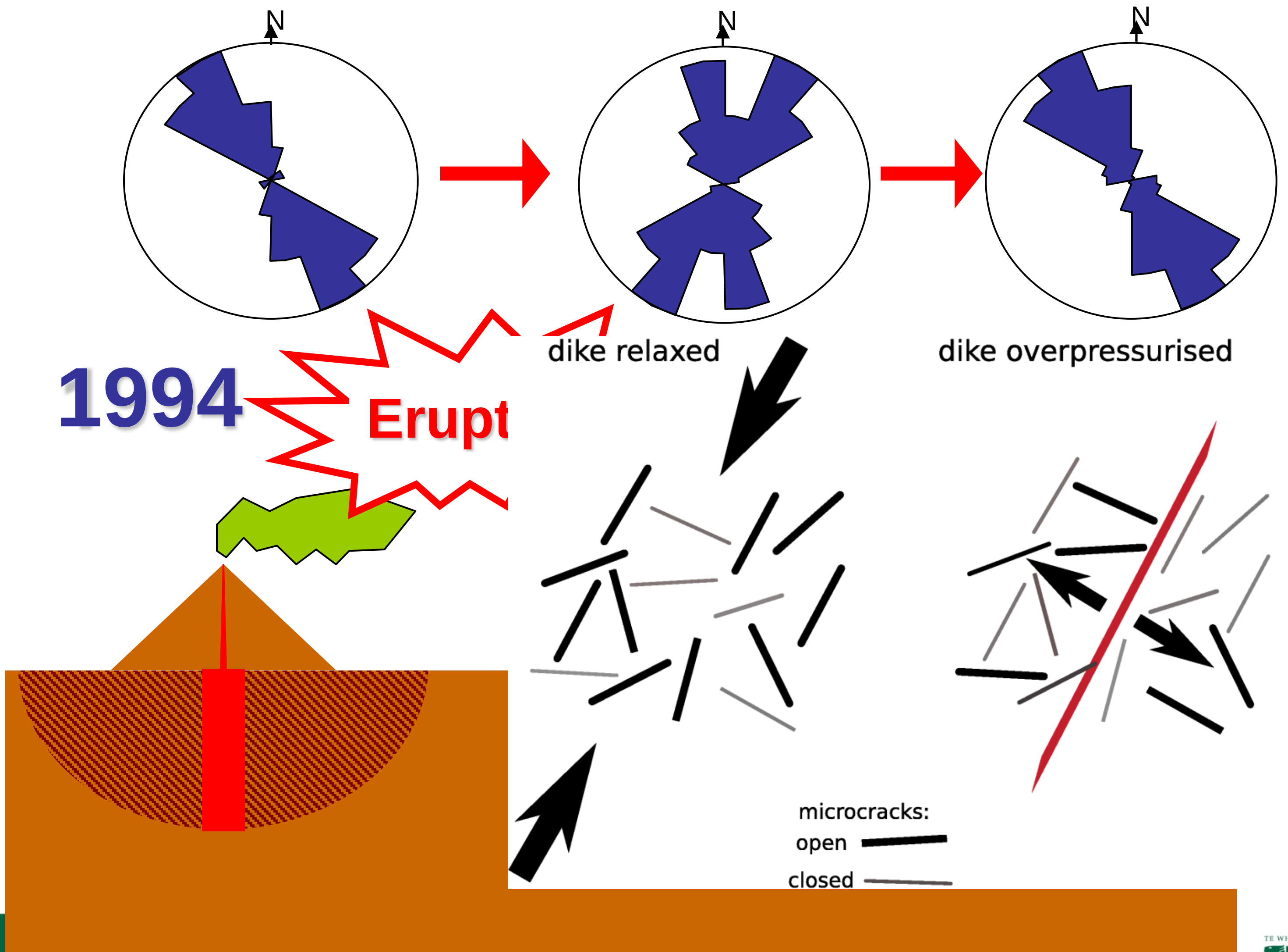
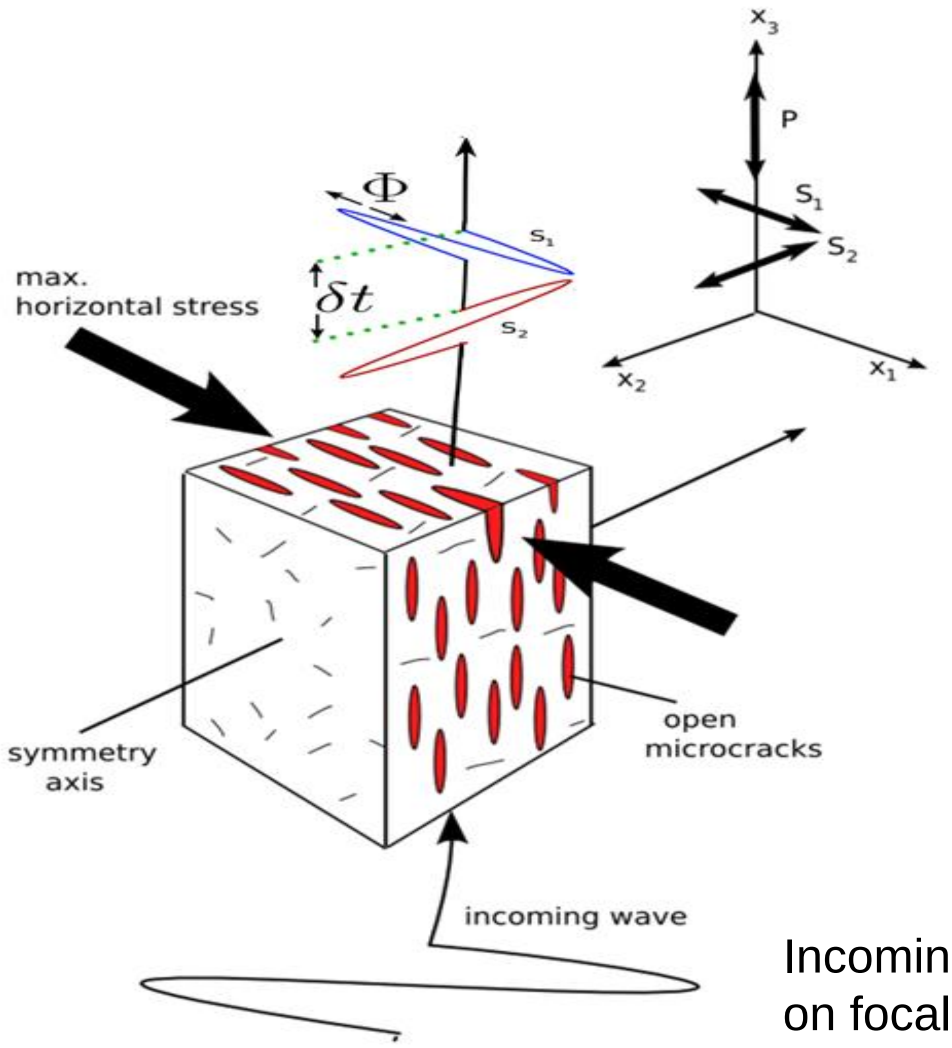
Shear wave anisotropy at Mt. Ruapehu-manual meas.



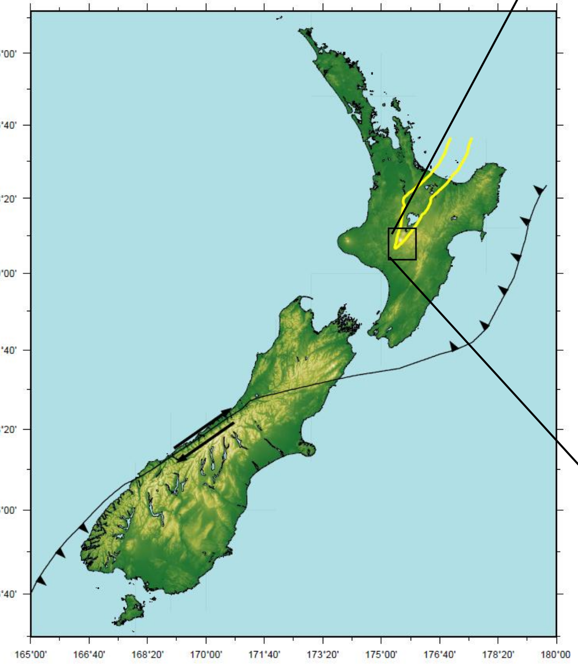
- Miller and Savage, Science, 2001; Gerst & Savage, Science, 2004

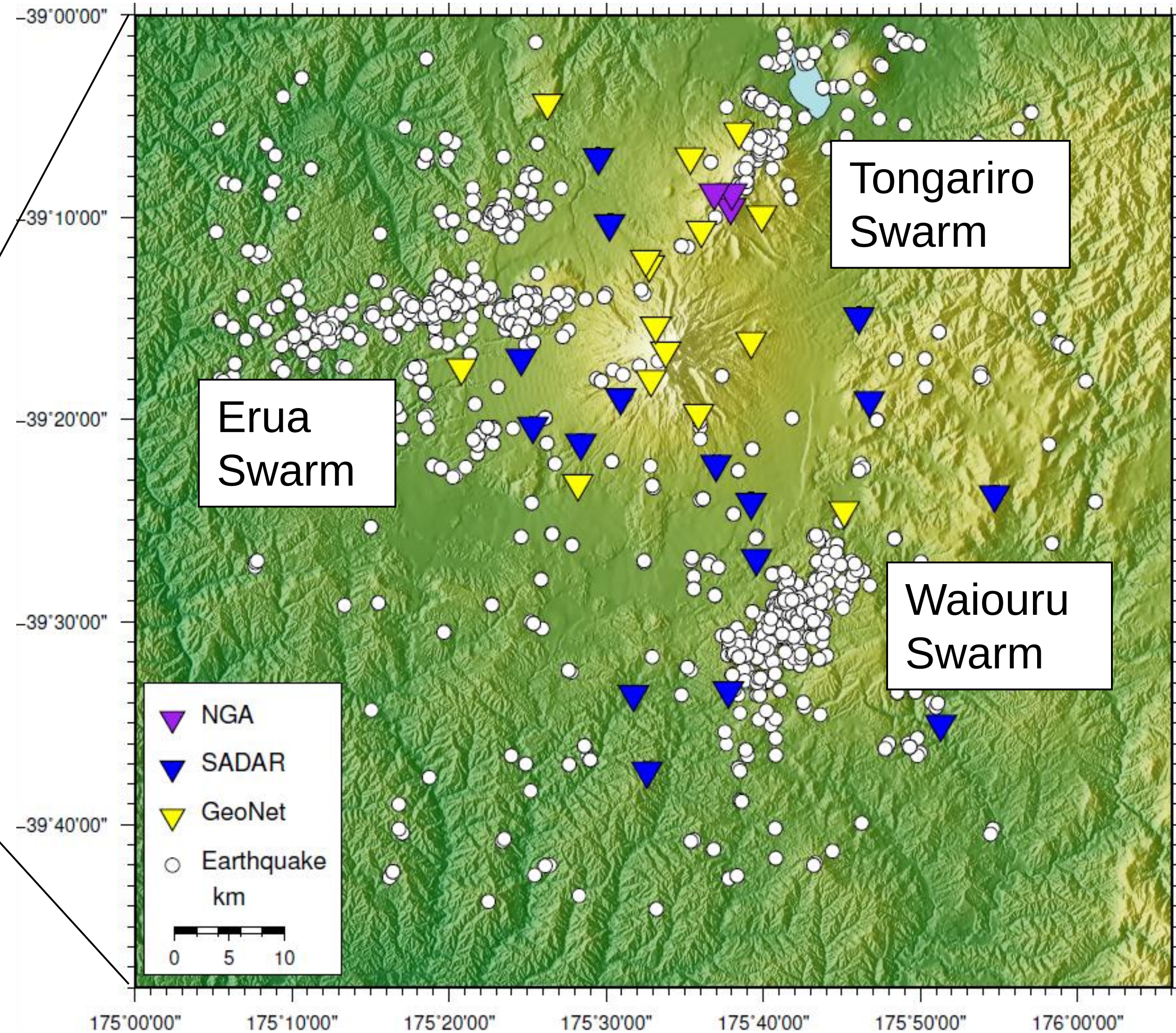


Incoming polarization depends on focal mechanism and path before

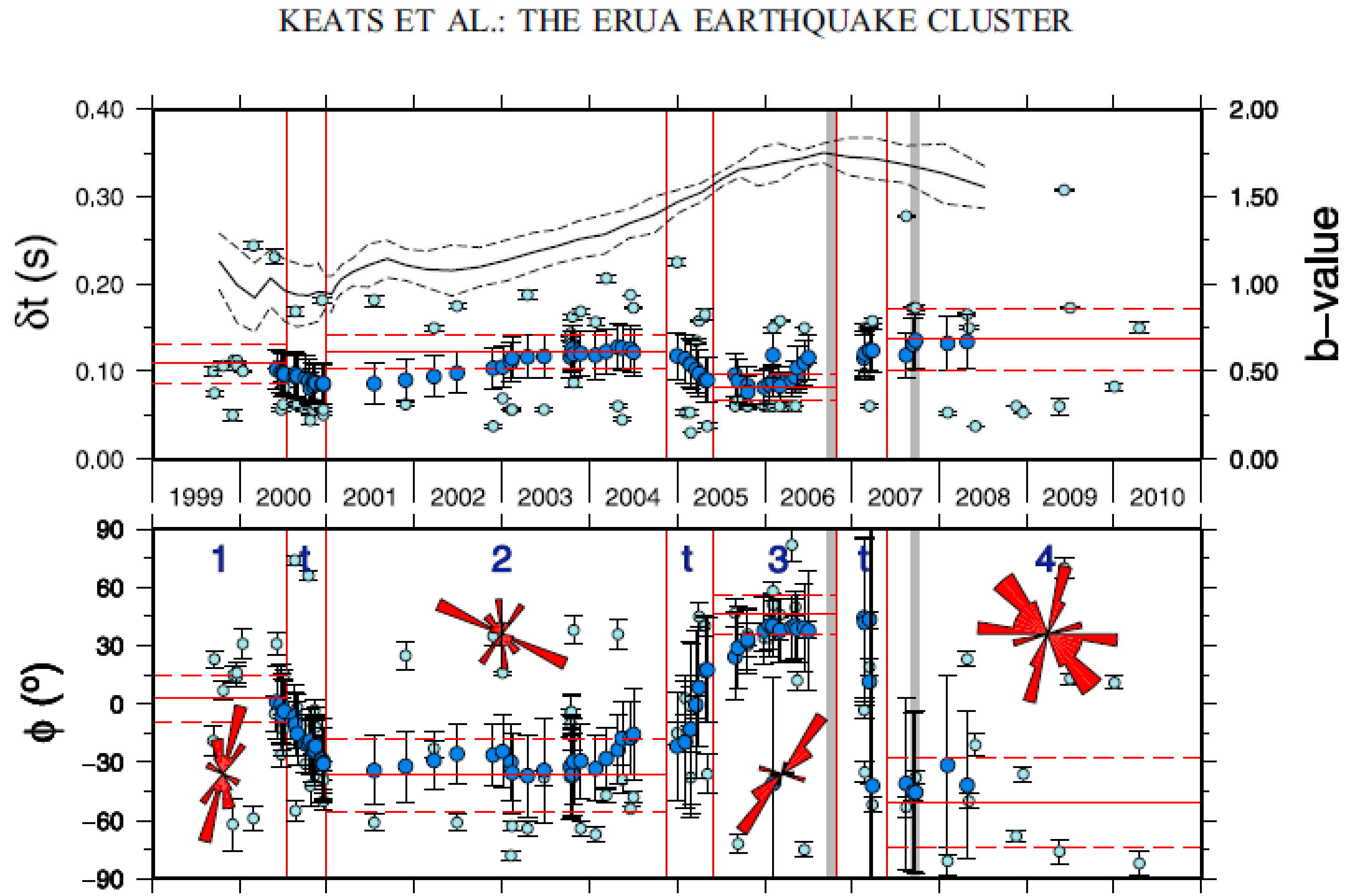
Seismic network and data

- 2008
- 15 Permanent (GeoNet) seismic stations
- 15 Temporary (SADAR) seismic stations
- 929 Earthquakes
- (>M1.0)





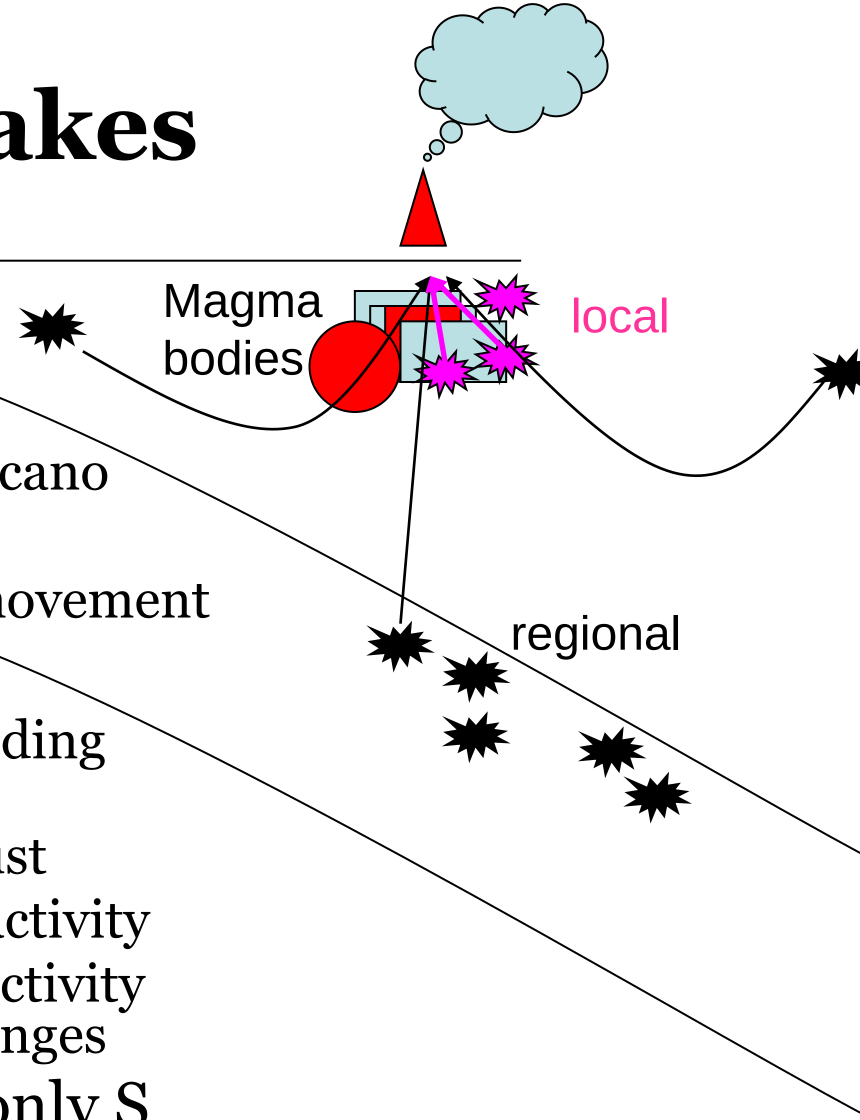
Time Varying Anisotropy?



Conclusion: Enhanced fluid flux during 2005-2006 drove increased b-values, decrease in dt, change in ϕ and eruptions

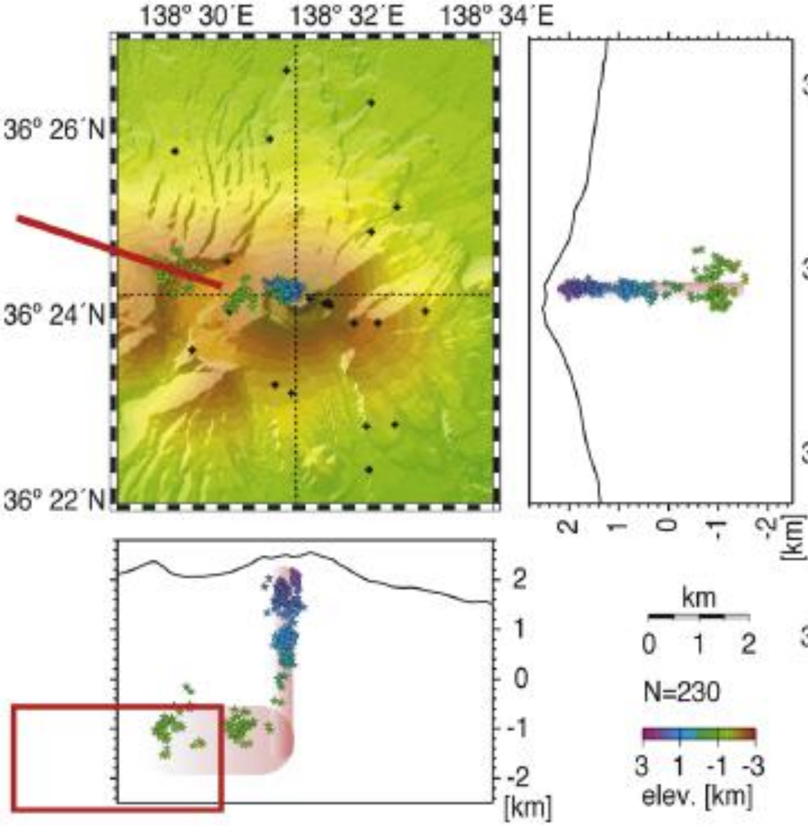
Keats et al. GRL 2011

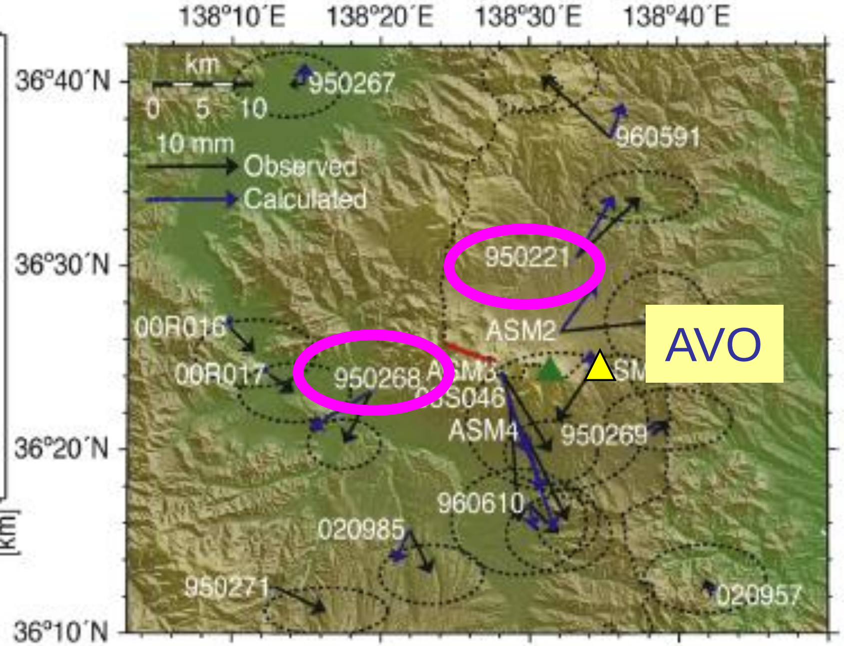
Sources of Earthquakes



- Local
  - May be numerous, and close to volcano
  - Path uncomplicated
  - But—locations vary with magma movement
- Regional
  - From subducting slab and surrounding crust
  - Path includes mantle as well as crust
  - But sources unrelated to volcanic activity
  - Changes correlated with volcanic activity must come from stress or fluid changes
- Method: Automatic, objective (only S pick is manual; Savage et al., JGR 2010)

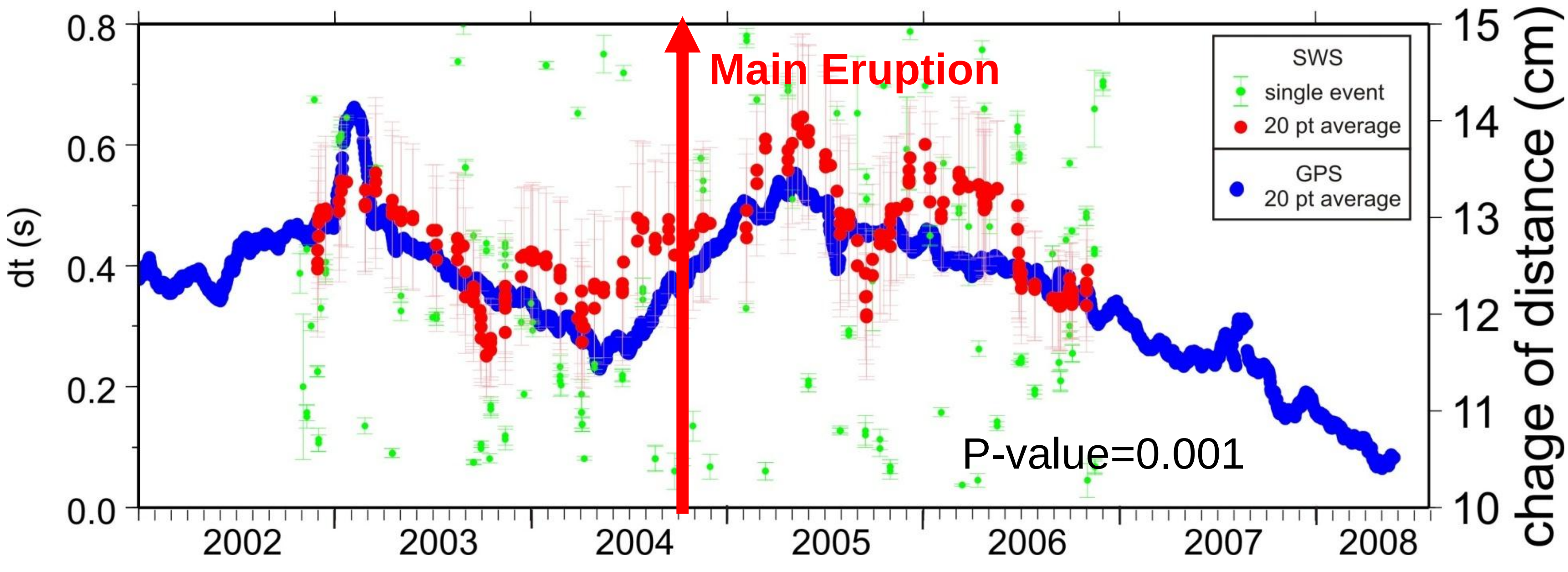
Mt. Asama 2004: GPS-inferred dike model





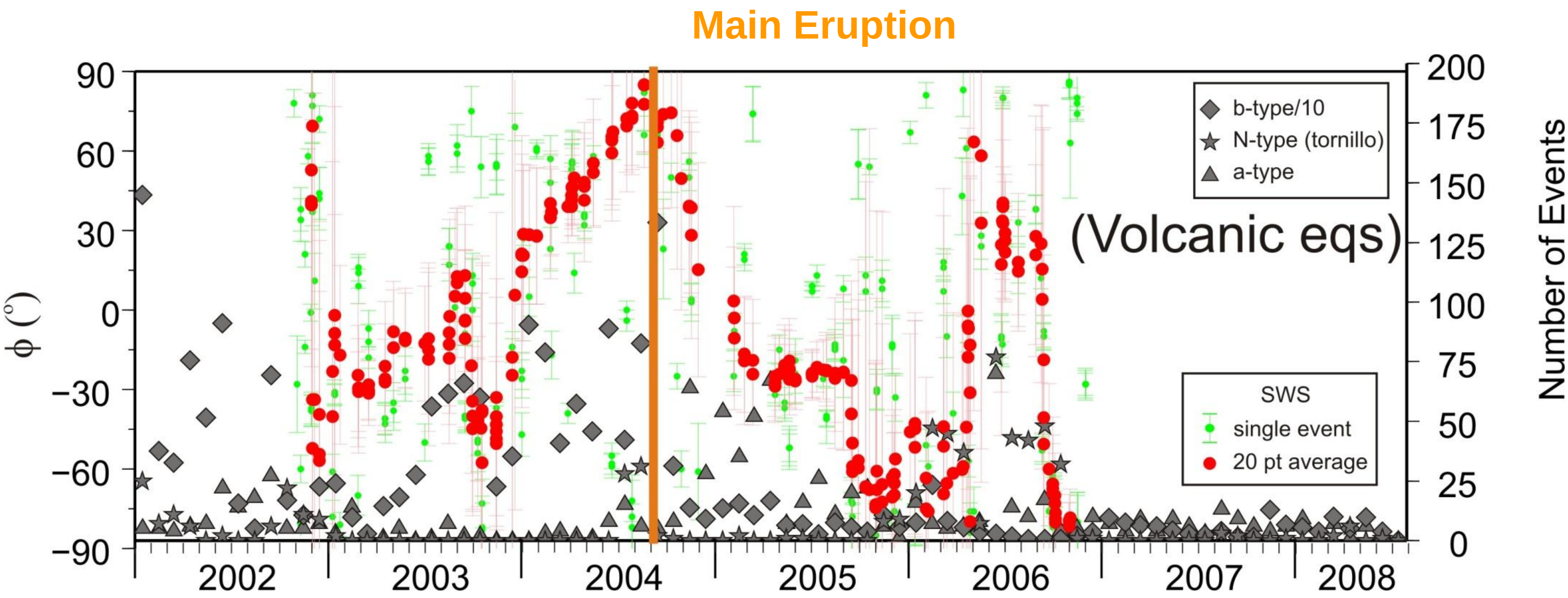
Length: 4.1 km, Width: 2.1 km
Depth from the ground surface: 3.0 km
Strike: N64°W, Dip: 101°,
Opening: 0.8 m (volume 6.8×10^6 m^3)

GPS baseline change compared to splitting dt at station AVO for deep (>40 km) regional events



Can combine techniques—get crack aspect ratio ~10^{-5} if GPS and dt caused by crack opening & closing over same path.

Fast direction and numbers of volcanic earthquakes change at eruption

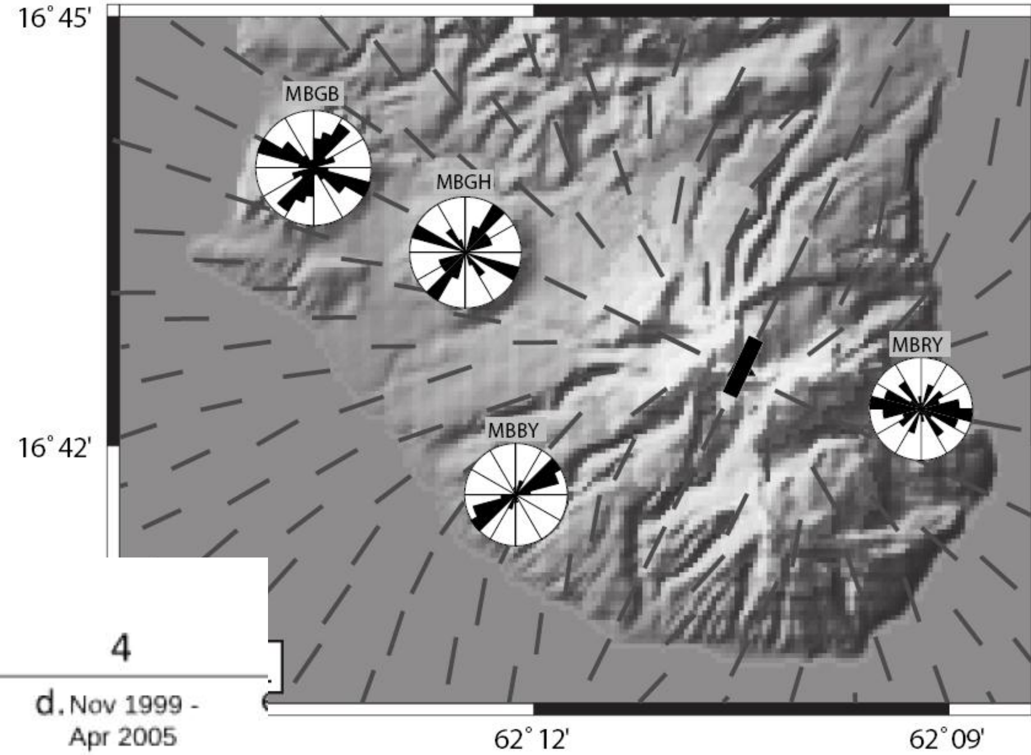


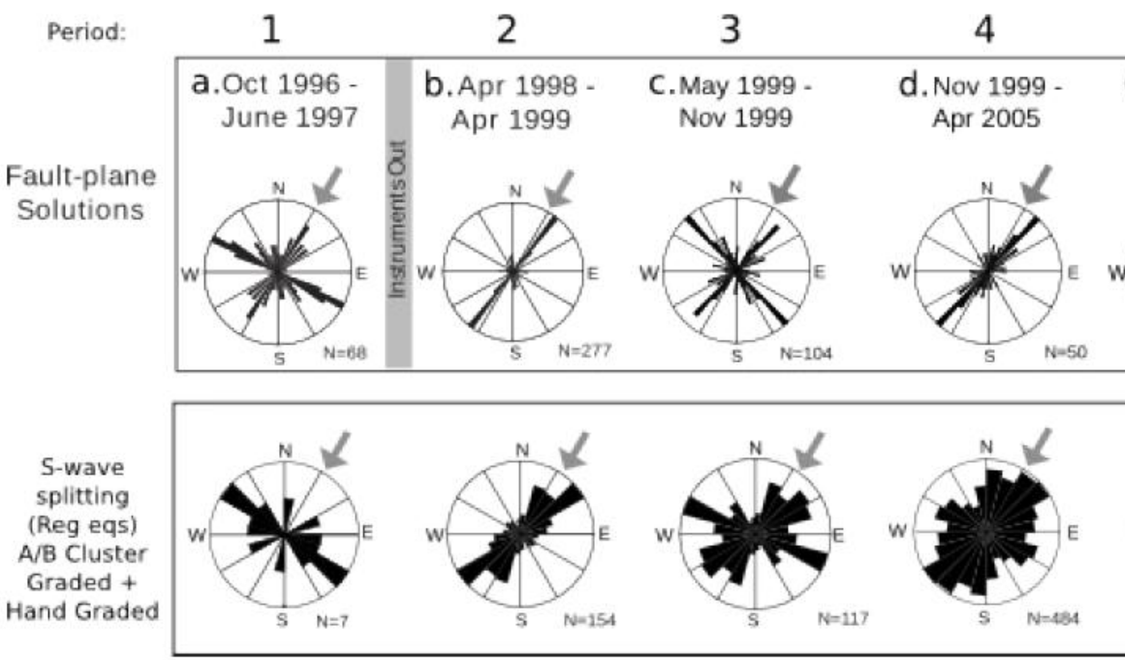
Can combine techniques to follow magma movements hopefully leading to eruption predictions.

Soufrière Hills

Changes in Focal mechanisms match changes in splitting

SHmax from Dike source matches fast direction

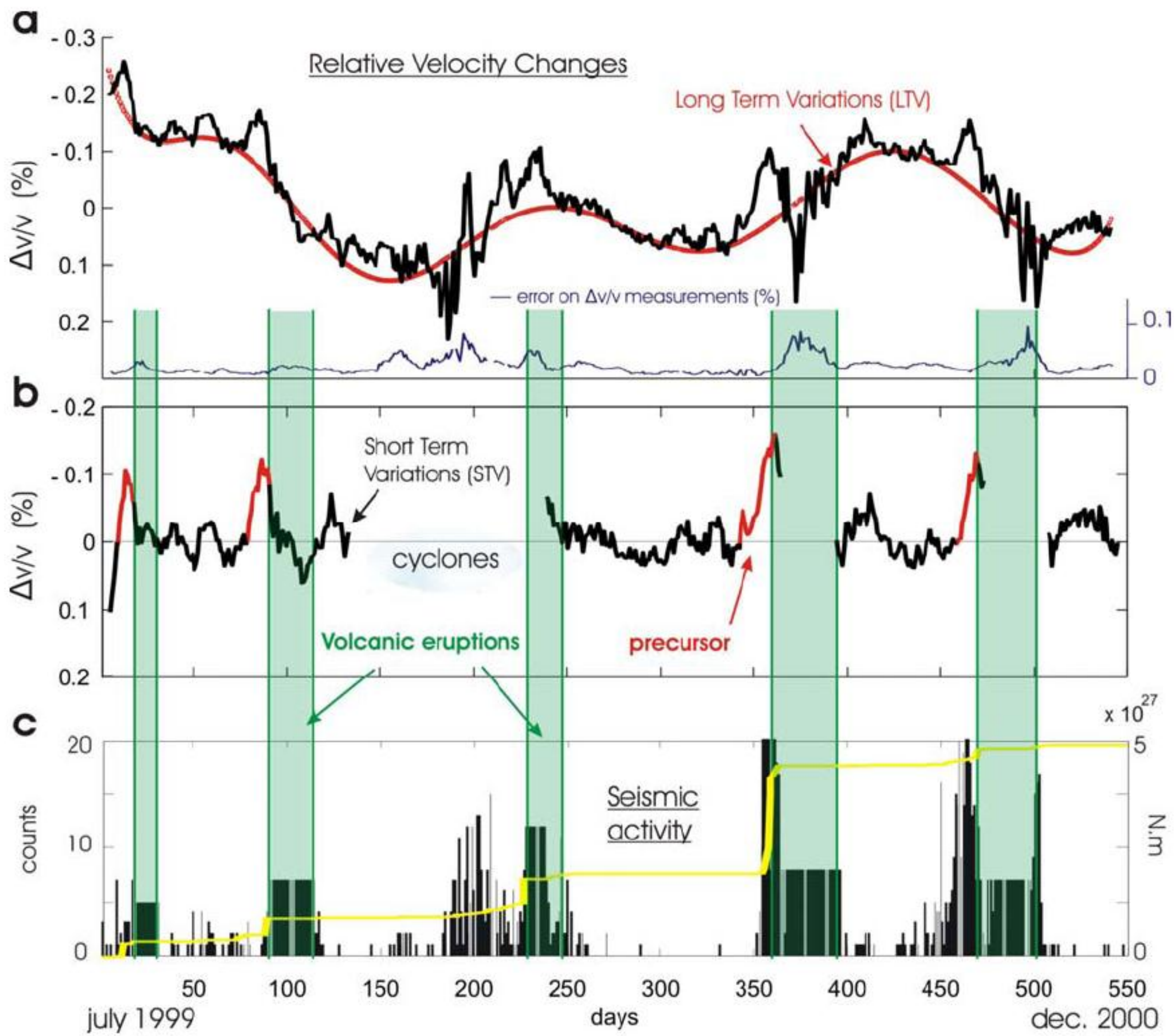




Map for time Period 3

Roman et al. JGR 2011

Piton de la Fournaise Volcano, La Reunion



Brenguier et al. Nature 2008

From Peltier (2006)

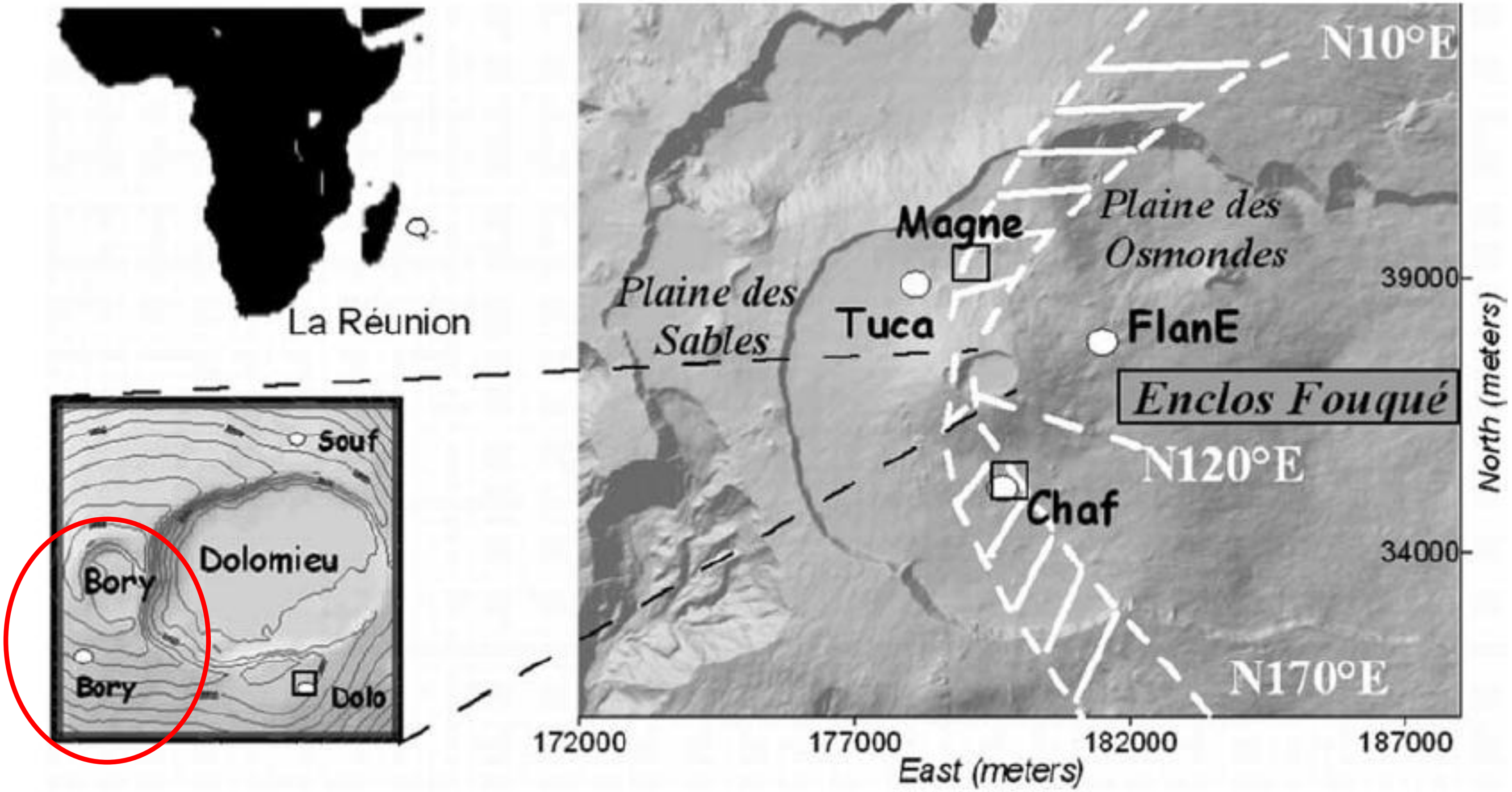


Figure 1. Structural map of Piton de la Fournaise volcano (Gauss Laborde Reunion coordinates). The rift zones are indicated by white dashed lines. The black squares and white dots indicate the locations of extensometers and tiltmeters, respectively.

From Peltier et al. 2010

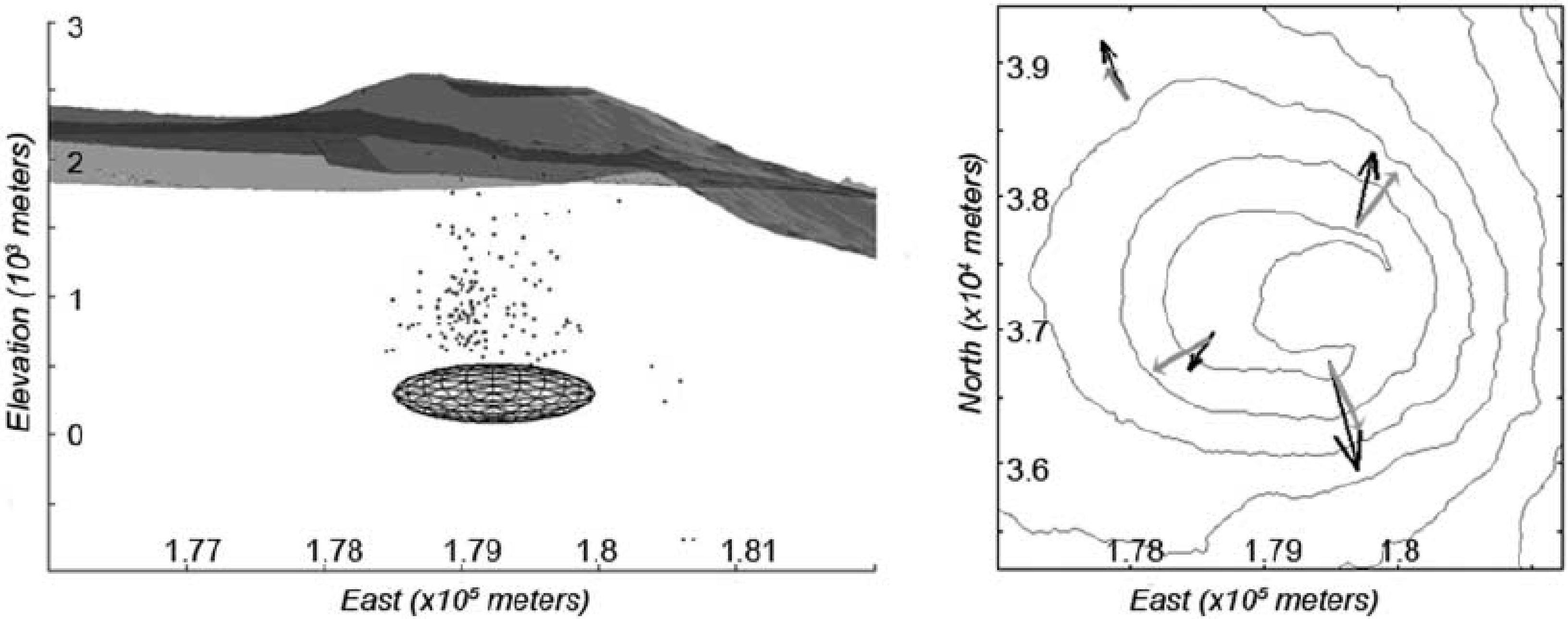
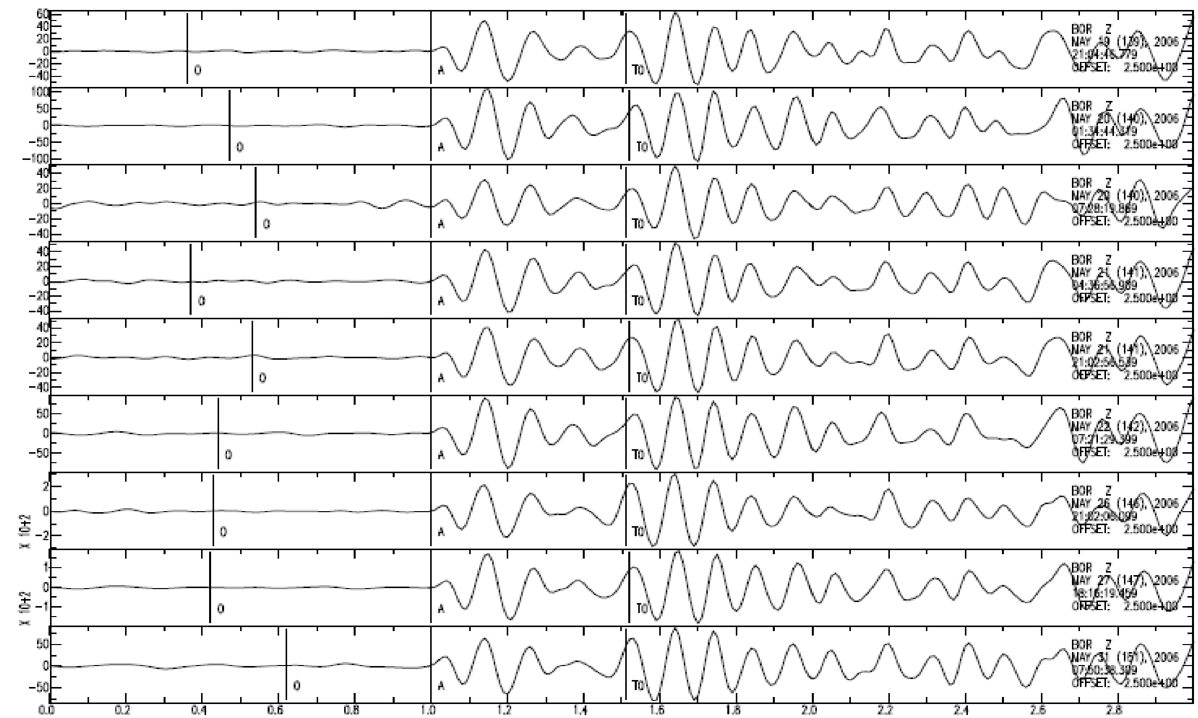


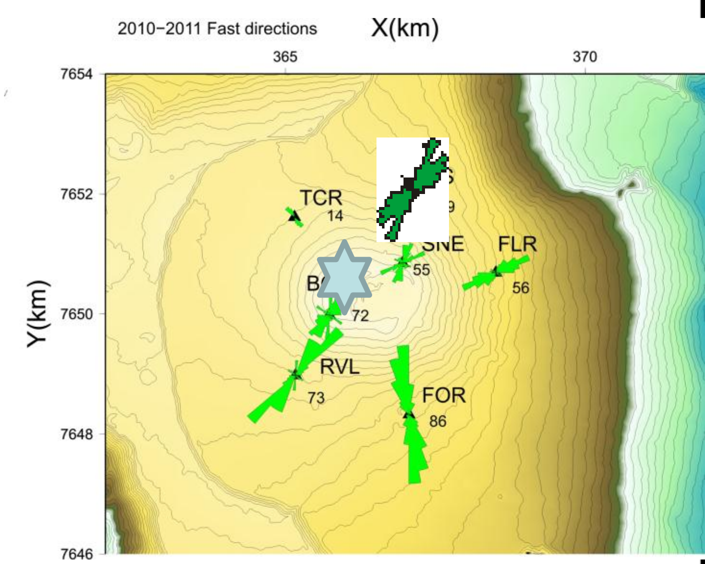
Figure 10. (left) Model of the pressure source inducing deformation before September 2003 eruption (Gauss Laborde Réunion map coordinates). (right) Comparison between observed (black) and calculated (gray) tilt variations associated with this pressure source. Earthquakes hypocenters related to the eruptions of 2003 are located by black points.

Event Families-Elodie Rivemale

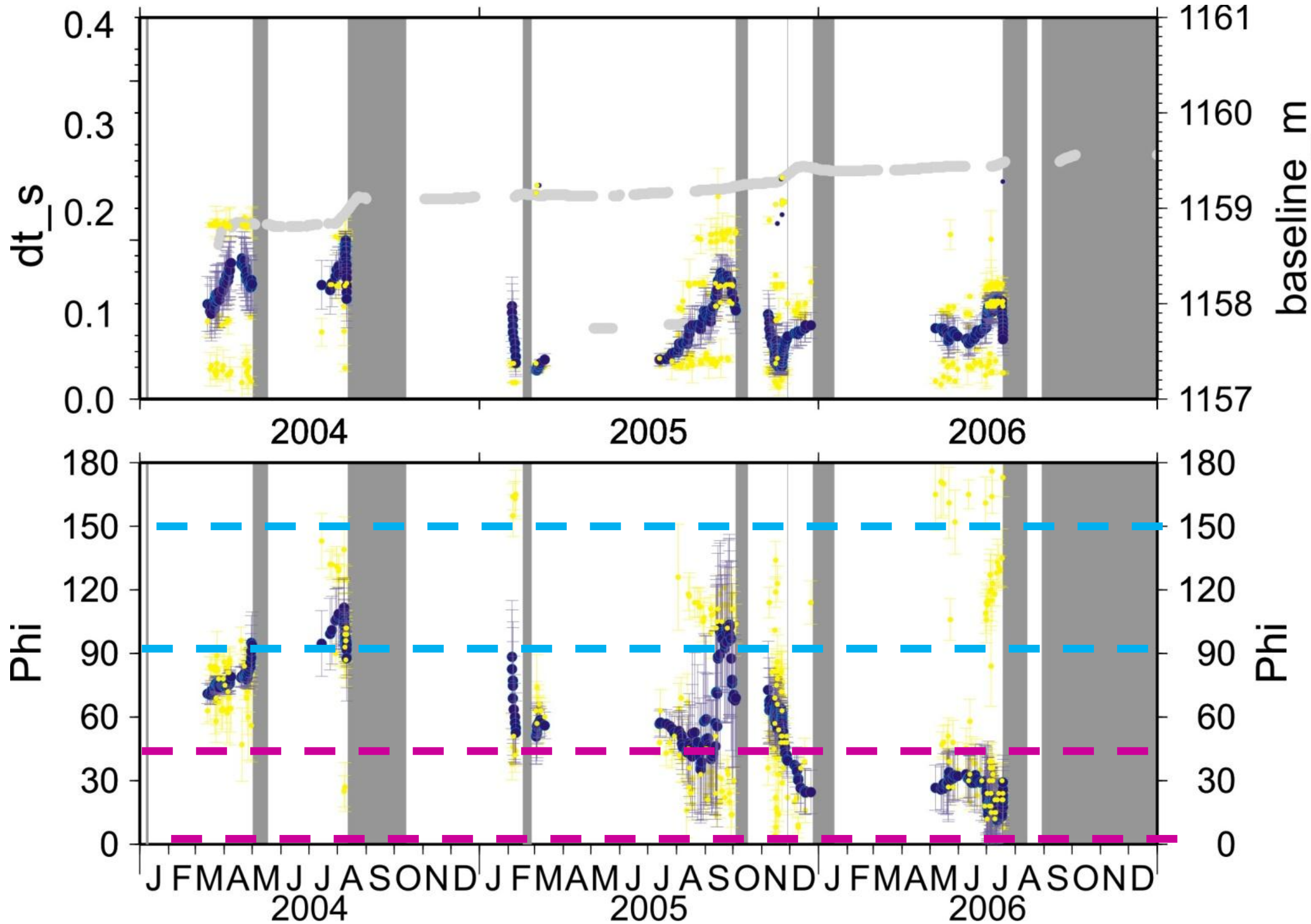
- Cross-correlation on vertical component
- Cparse algorithm
- minimum waveform coherency of 90%.
- average depth 0.6 km with no systematic variation over time.

Family 001
Station BOR
328 events





Moving Averages for BOR Family 1



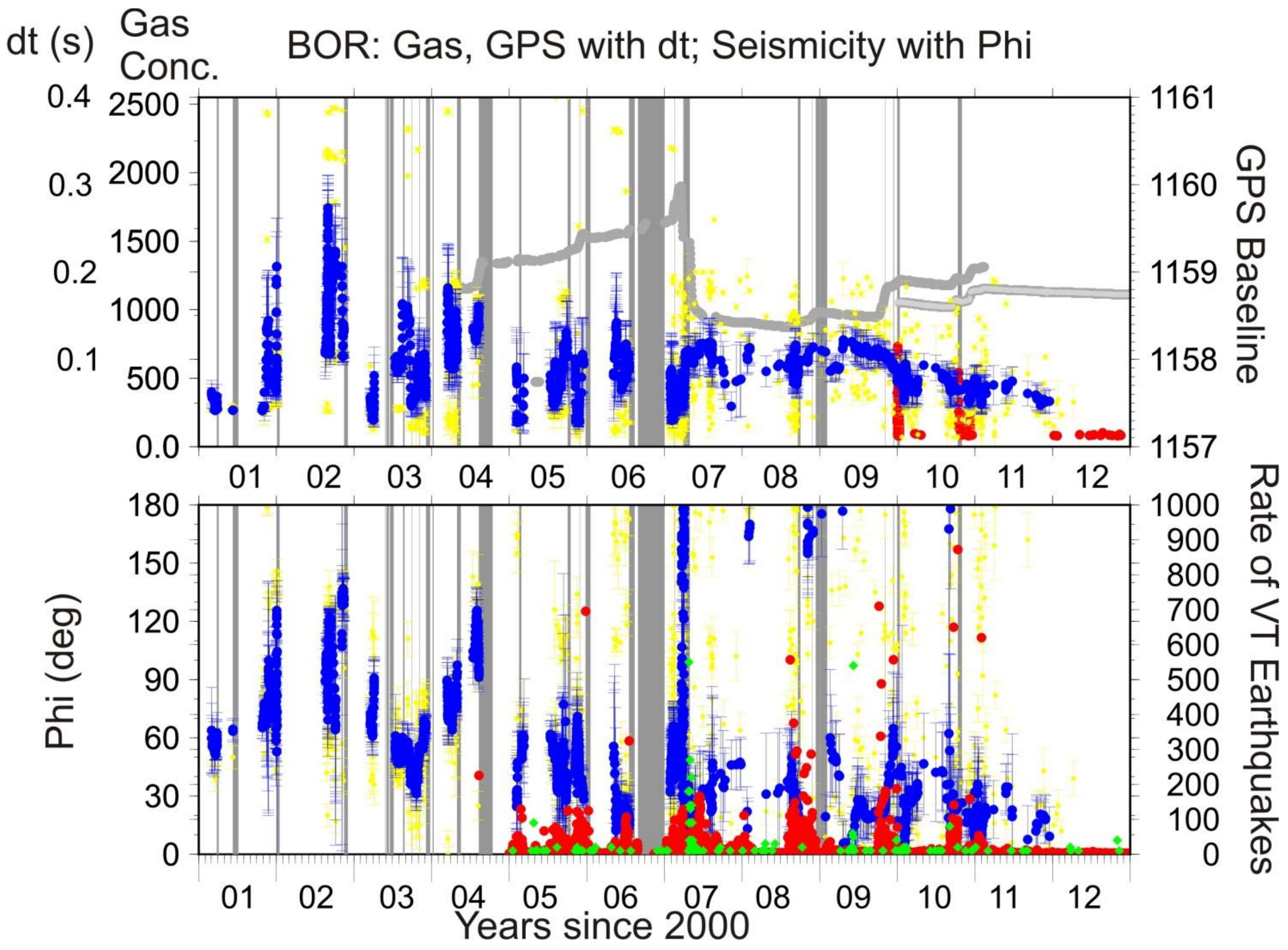
Splitting: Yellow= individual measurements

Blue=20 pt moving average

light grey circles=GPS baseline across caldera

Grey boxes=eruptions

12 Years of measurements



Splitting: Yellow= individual measurements

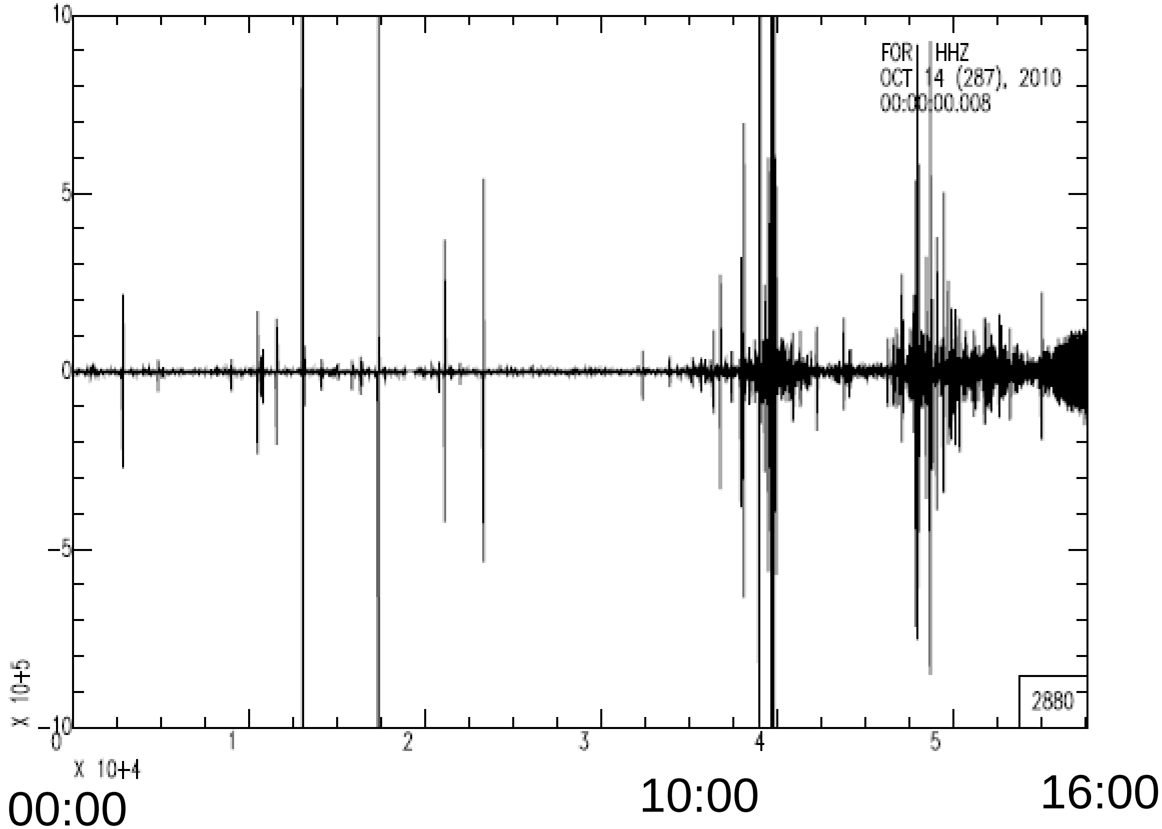
Blue=20 pt moving average

light grey circles=GPS baseline across caldera

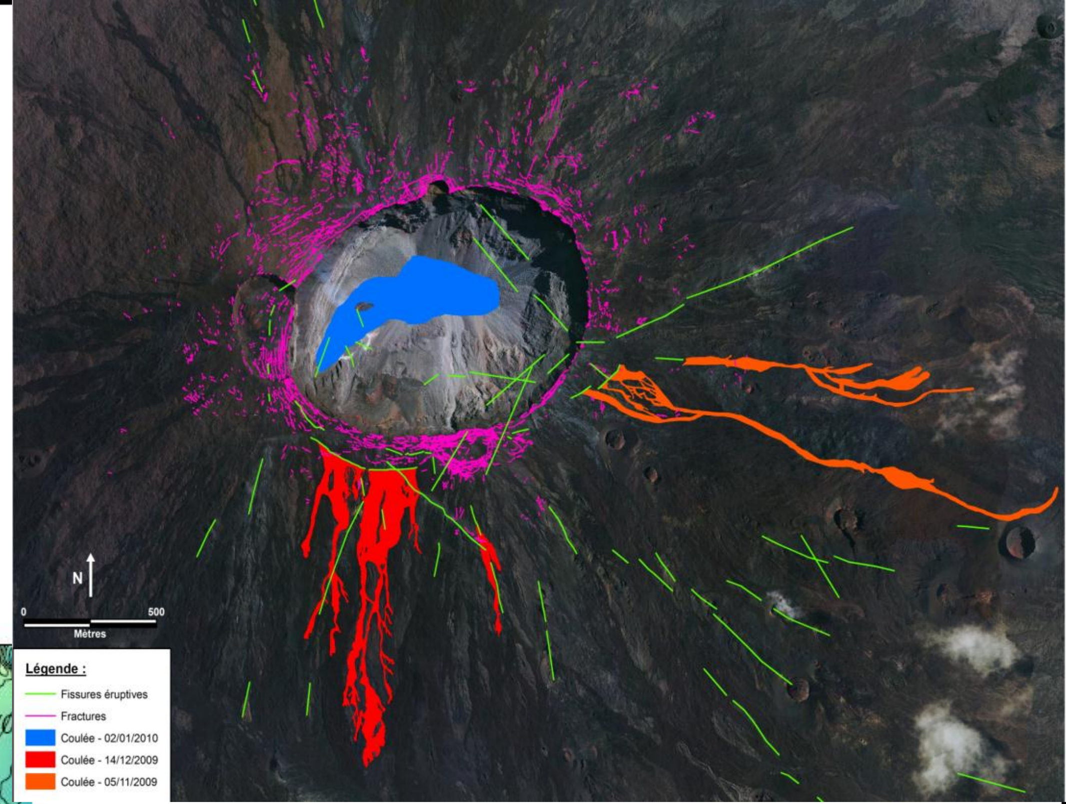
Grey boxes=eruptions Red=VT eqs (bottom) or doass s02 (top)

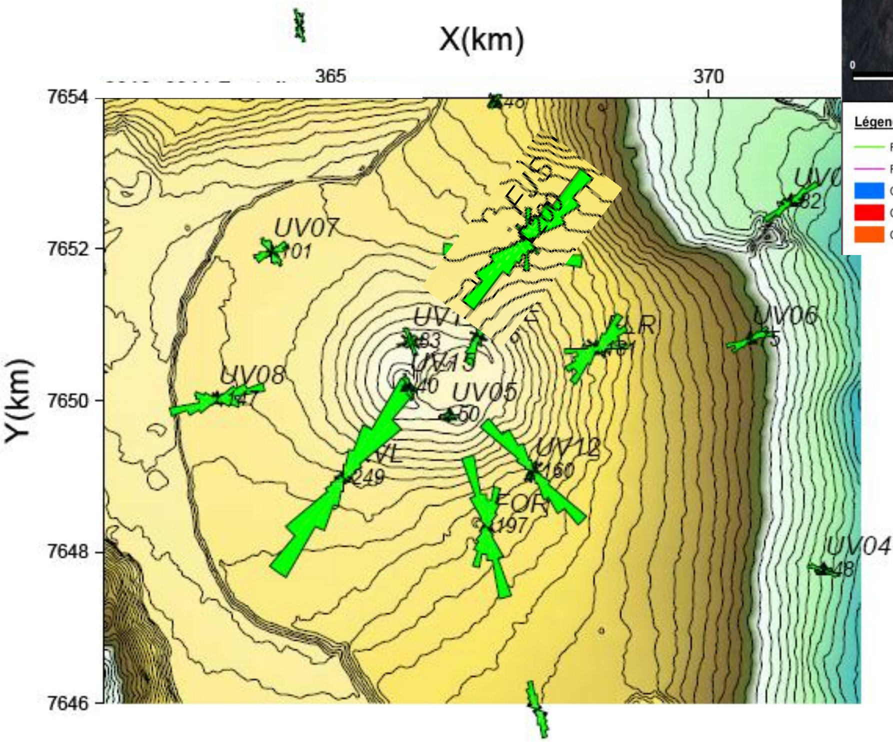
Seismic Crisis Oct. 14 2010

- FOR-near vent

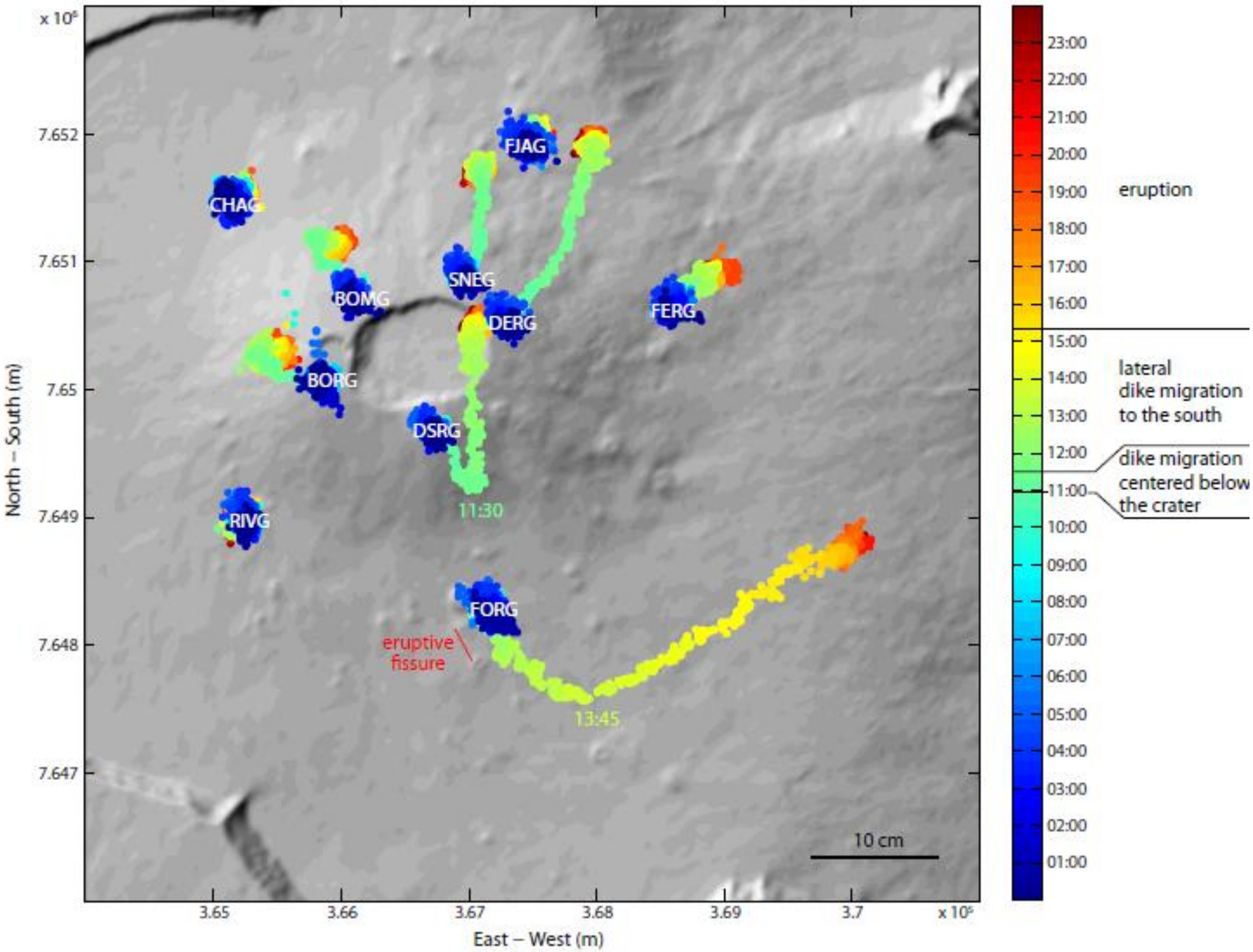


Seismic Crisis 14 Oct. 2010



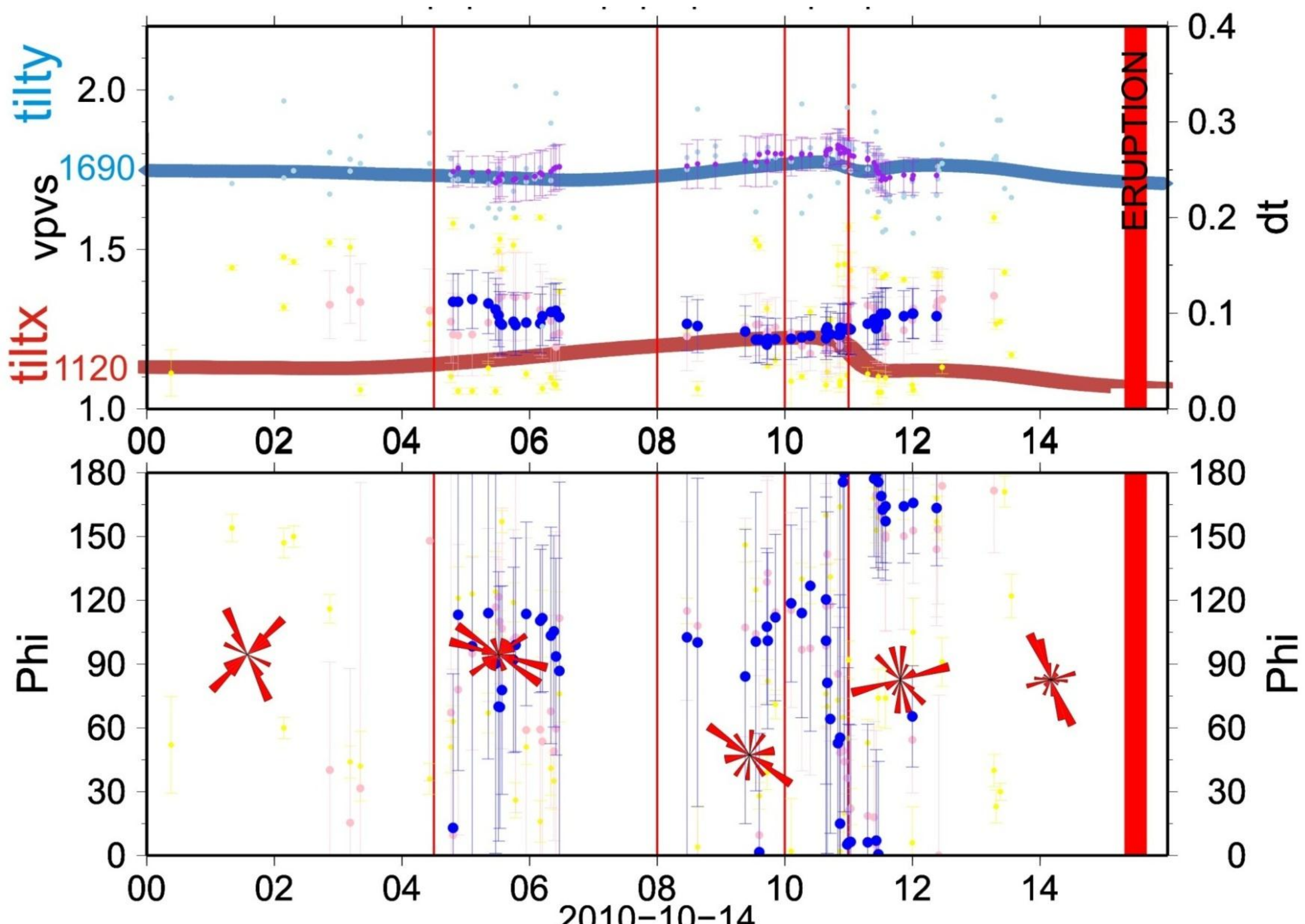


From Aline Peltier (2013)



Movements of GPS stations during Oct. 14 crisis

Time Variation-Sta UV11



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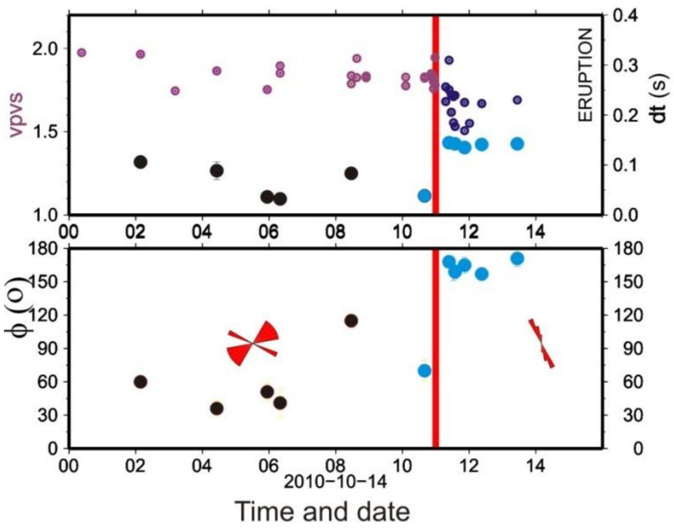
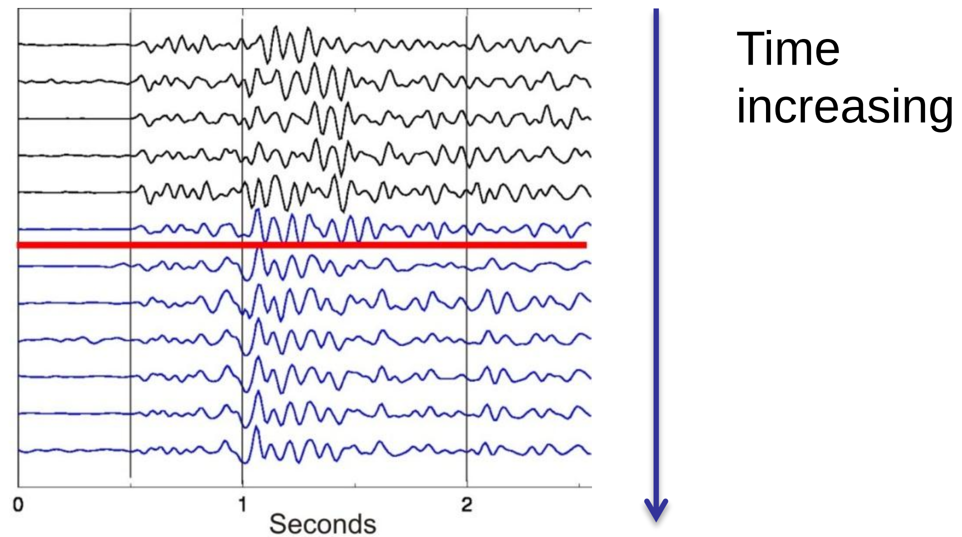
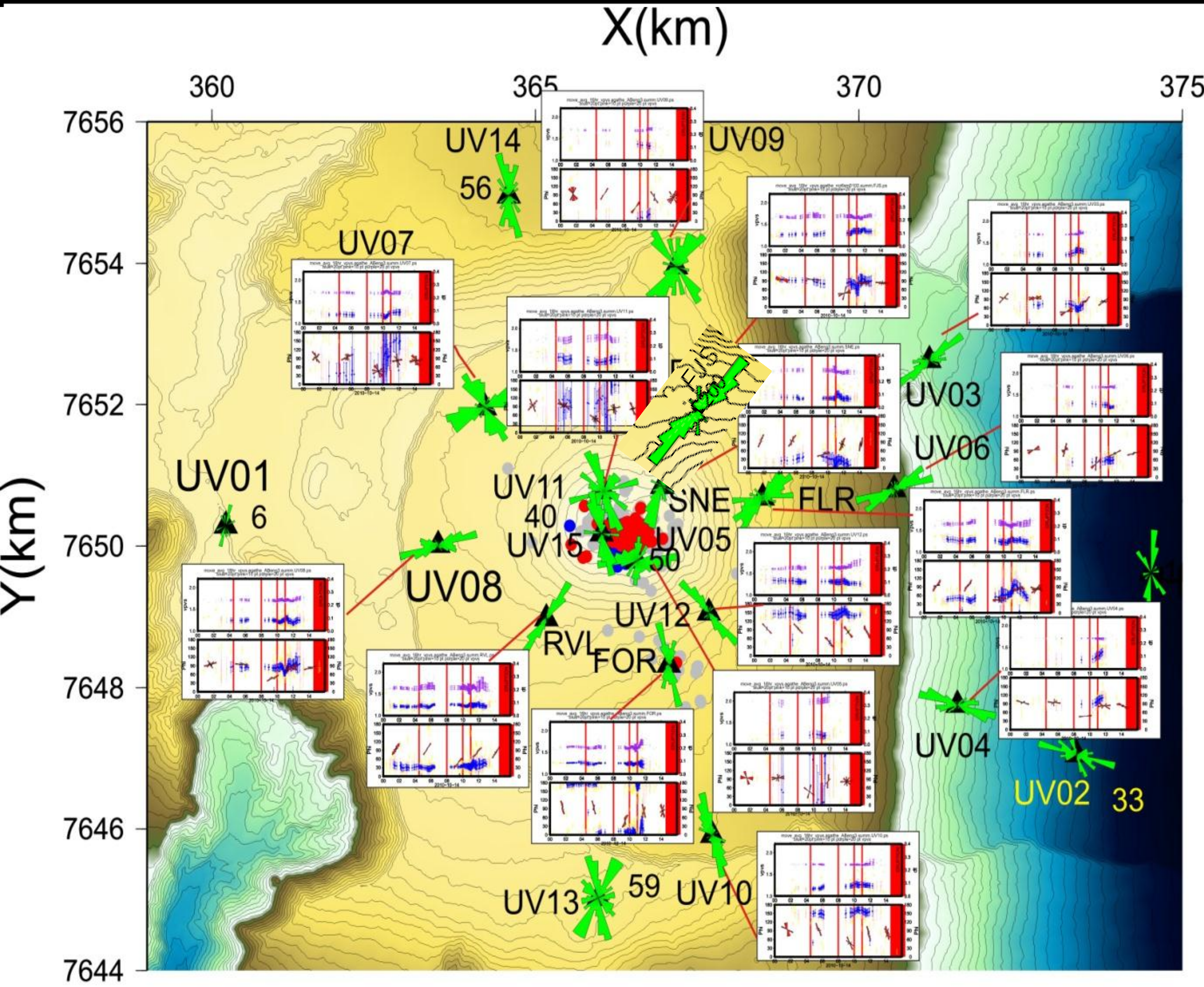
- Highest Quality Measurements at UV11
- Same event family







Map of Piton de La Fournaise with rose diagrams of fast directions and time variation of delay times and fast directions.

Conclusions

– Anisotropy changes with time and is correlated with changes in GPS, b-values and focal mechanisms near some volcanic systems
– Geothermal areas may have higher delay times due to more cracking and/or mineral alterations
– Relation between anisotropy and Vp/Vs ratios may tell about fluid type

Conclusions-Piton de la Fournaise

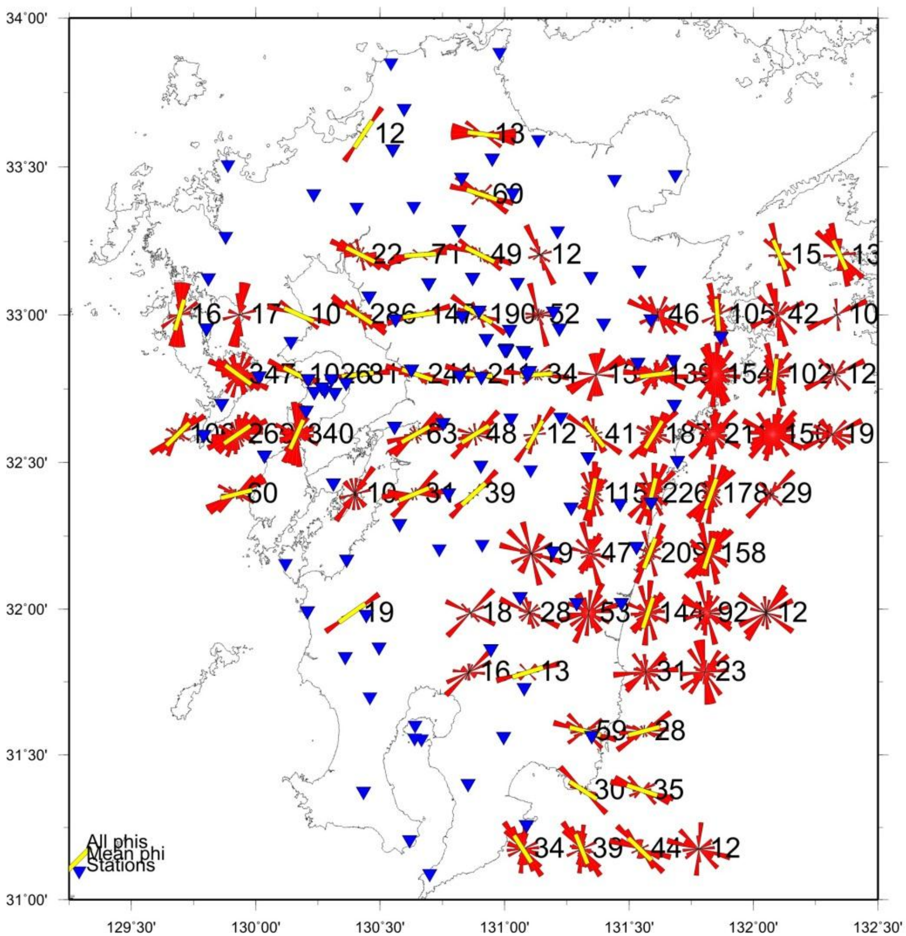
- Fast polarisations ➔ horizontal compressional stress perpendicular to cone ➔ cracks radial to the central cone.
- Low Vp/Vs on flanks ➔ gas release through cracks
- Variation with time➔ consistent with isotropic velocity variations (Brenguier et al., 2008) with increasing numbers of cracks before the eruptions.
- Oct. 14 2010 has very rapid changes with time in S-wave splitting and other parameters; could be focal mechanisms changing

Ongoing Anisotropy Research:

- PhD student Adrian Shelley & Charles Williams: Finite Element modeling of strain from magma sources to compare to splitting to determine physical relations
- Ernestynne Walsh & Richard Arnold: Enhancing error analysis to allow better data averaging
- More volcanoes-Kirishima
- http://mfast-package.geo.vuw.ac.nz/

TESSA Results-Kyushu

15 km grid depth < 40 km includes all stations in Kyushu



15 km grid best measurements