Volcano monitoring techniques: Deformation

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Overview

- Volcano deformation
- Measuring deformation (InSAR, GPS, strain, tilt)
- Volcano deformation models
- Complications
  - Other deformation processes
  - 3D-rheology and topography
  - The volcano “misbehaves” (does not do what you expected)
- Case studies - Iceland and Central America
- How much “gear” do we need to monitor deformation of a volcano properly?

Volcano Deformation

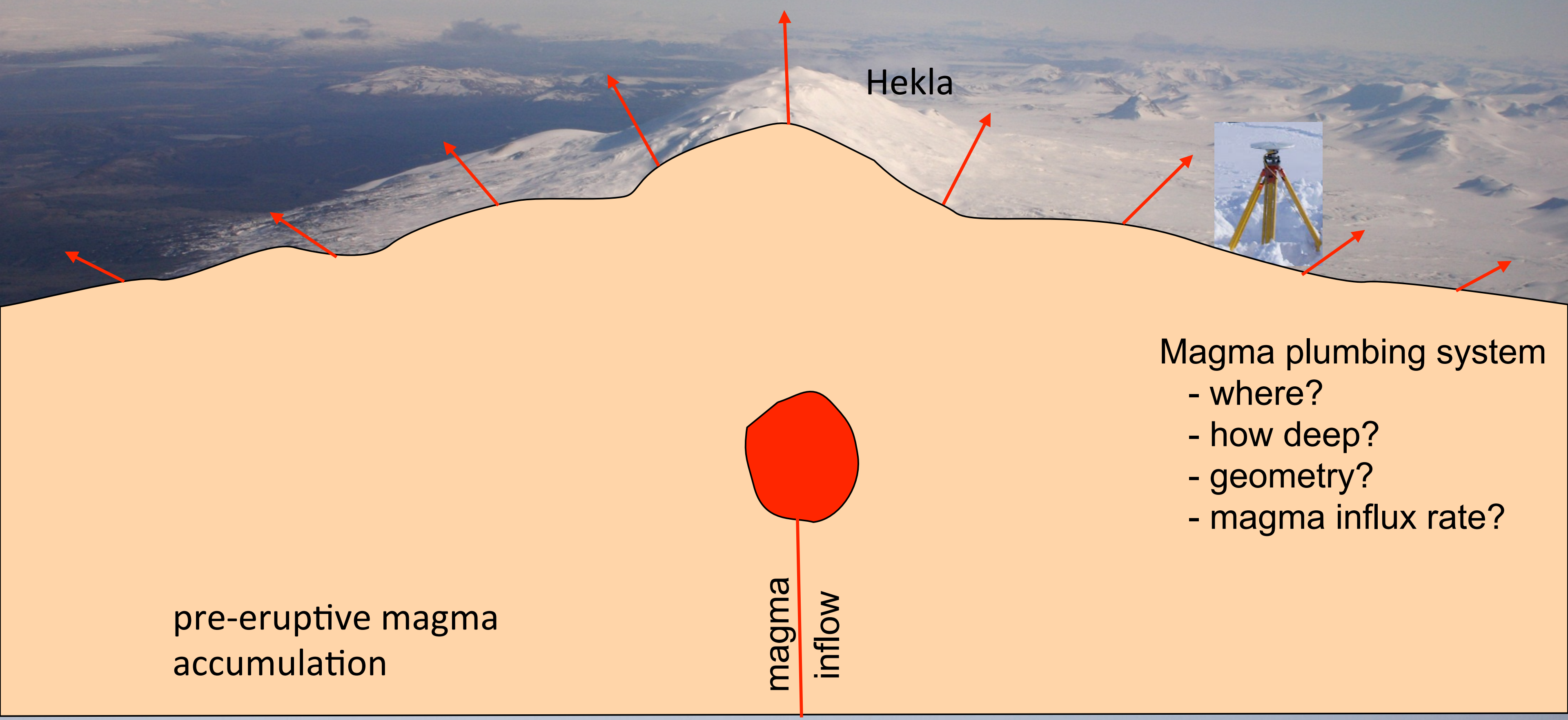


Photo: Matthew Roberts

Volcano Deformation

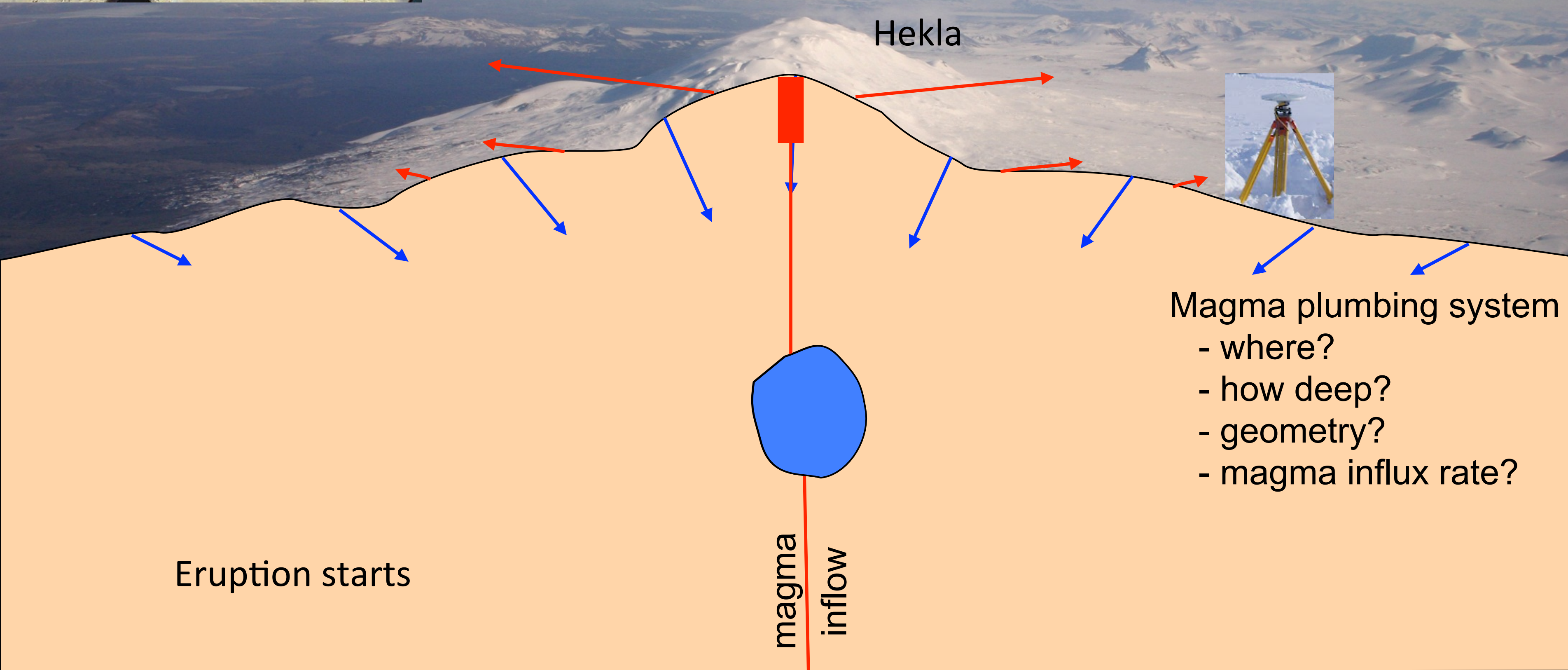


Photo: Matthew Roberts

Volcano Deformation

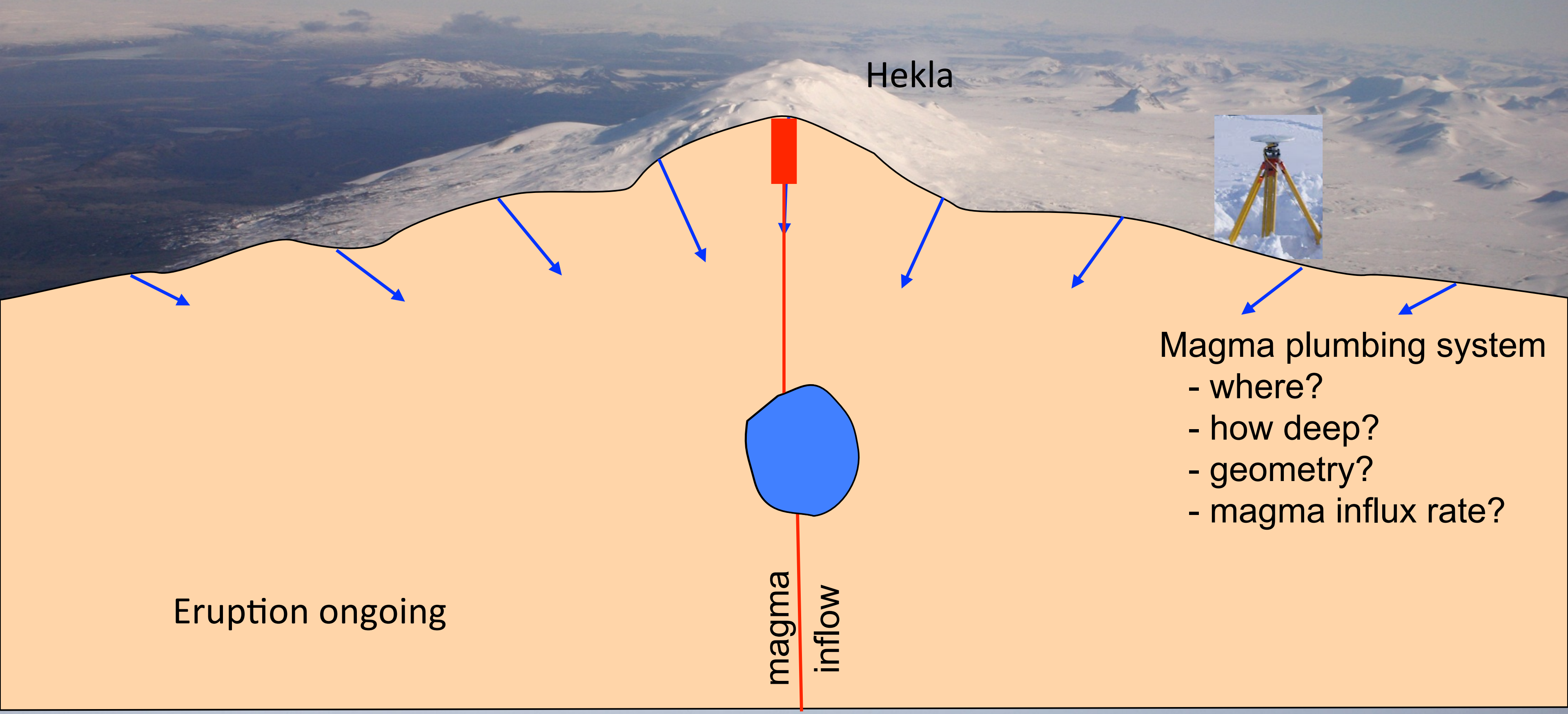
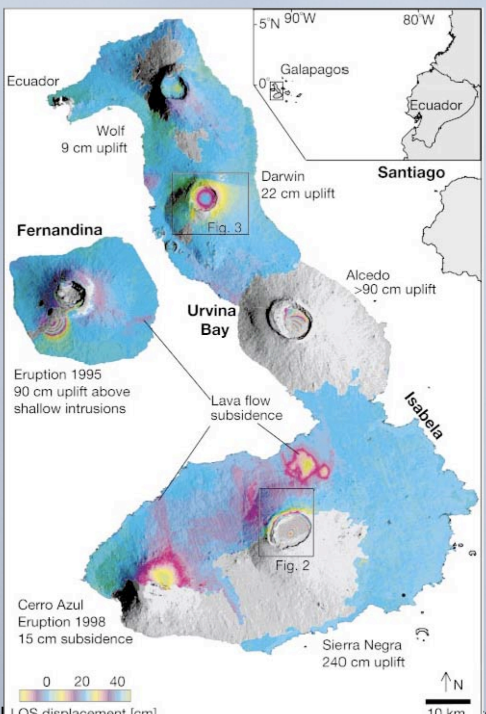


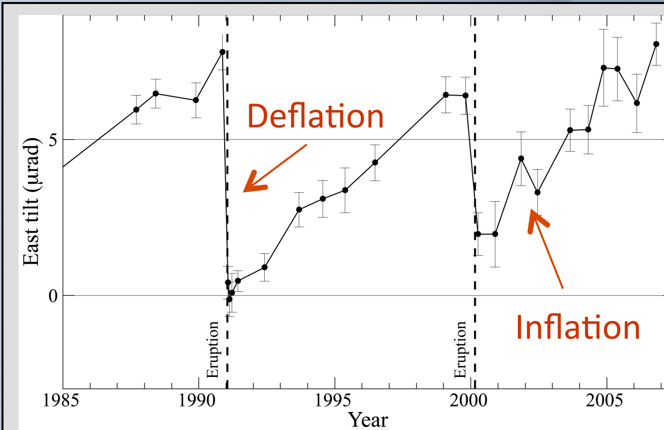
Photo: Matthew Roberts

How do we measure volcano deformation?

- Investigation of the shape of the Earth is called *geodesy*
- Terrestrial or ground based methods include leveling, tilt and/or electronic distance measurements (EDM)
- Satellite geodetic methods include the Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR).
- Usually the deformation is small → precise measurements



InSAR analysis of Fernandina Island, Galapagos Islands, Ecuador (from Amelung et al. 2000).



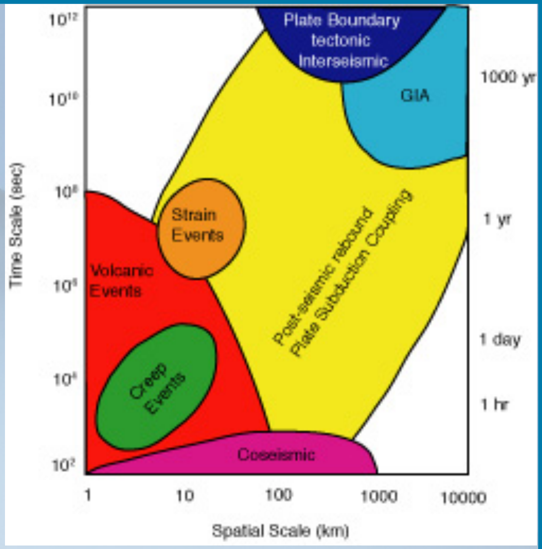
Tilt measured west of Hekla volcano, Iceland indicating pre-eruptive inflation, followed by co-eruptive subsidence for the last two eruptions (E. Sturkell).

Tools for measuring surface deformation: what do you want to measure?

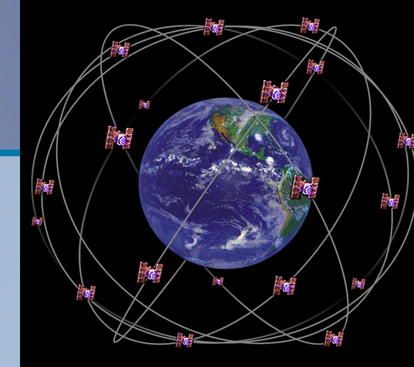
- GPS (GNSS)
  - Episodic, semi-continuous, continuous
  - Kinematic
- InSAR
- Borehole strain meters
- Tilt meters
- Leveling
- Electronic Distance Meters (EDM)
- Photogrammetry (pixel-tracking)
- Paleo-deformation

- Real-time vs near-real-time vs post-processing

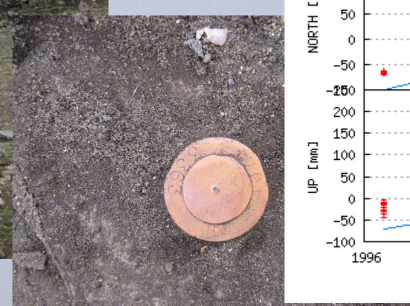
- All these data need to be archived, processed, visualized, interpreted, and integrated with other data

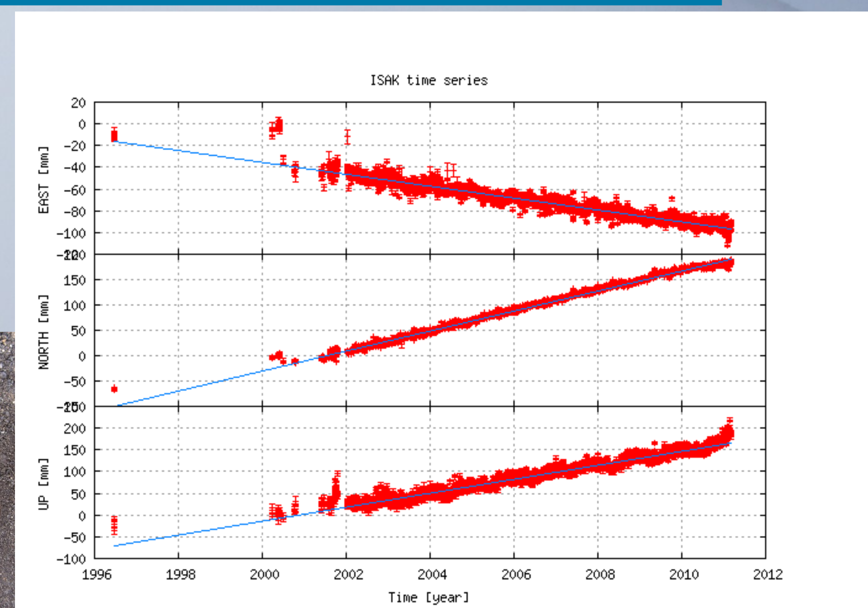


GPS (GNSS)

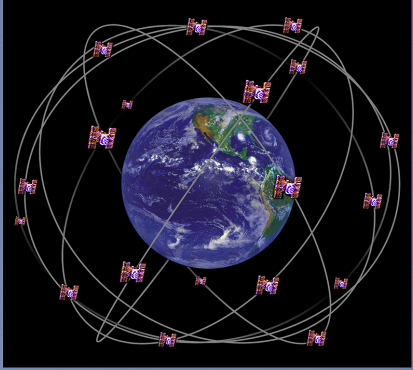


- "Geodetic quality" measurements of satellite signals give 3-D daily position accuracy of a few mm (up component is noisier)
- All-weather, all-season application (almost)
- Episodic, continuous, semi-continuous occupations
- Pros: 3-D displacements and velocities; offers continuous observations; wide range of sampling rates; good long-term stability for good benchmarks
- Cons: point measurements (spatial aliasing)





GNSS (Global Navigation Satellite Systems)

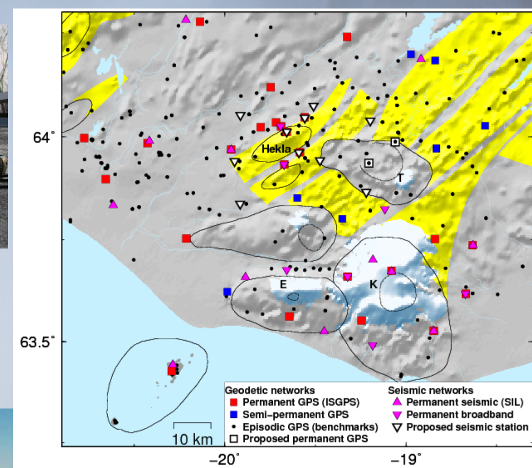


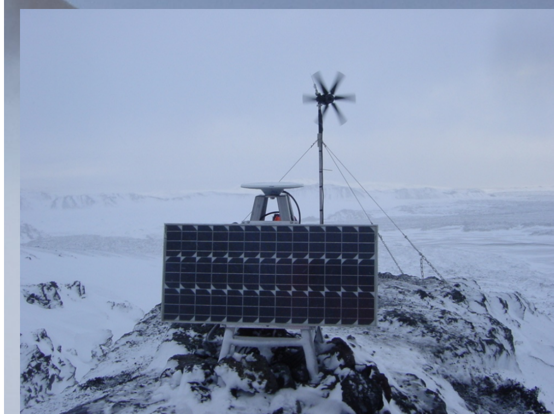
- Different satellite systems
- NAVSTAR (USA), known as “GPS”
- GLONASS (Russia), operational
- COMPASS (China), operational regionally, global operation by 2020
- GALILEO (European Union), should be fully functional by 2020

- Likely the improvement on 24-hour solutions will not be dramatic
- Benefits high-rate real-time applications

Episodic and Continuous GPS

- Continuous networks are important to avoid **temporal aliasing** but expensive
- Episodic observations complement cGPS by improving **spatial density**
  - The networks are surveyed every few months to every few years
  - Each point is observed for 1-4 full days or longer





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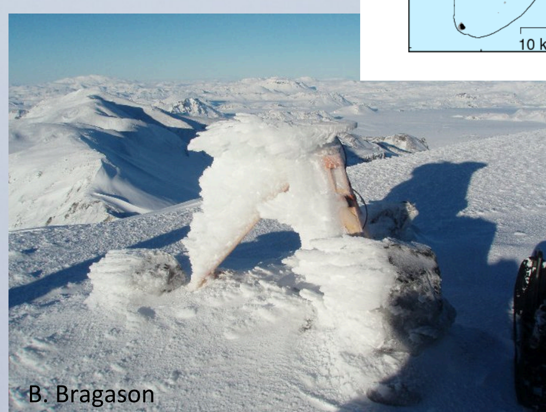
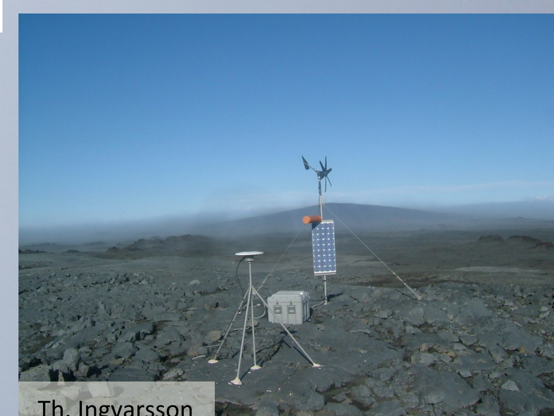
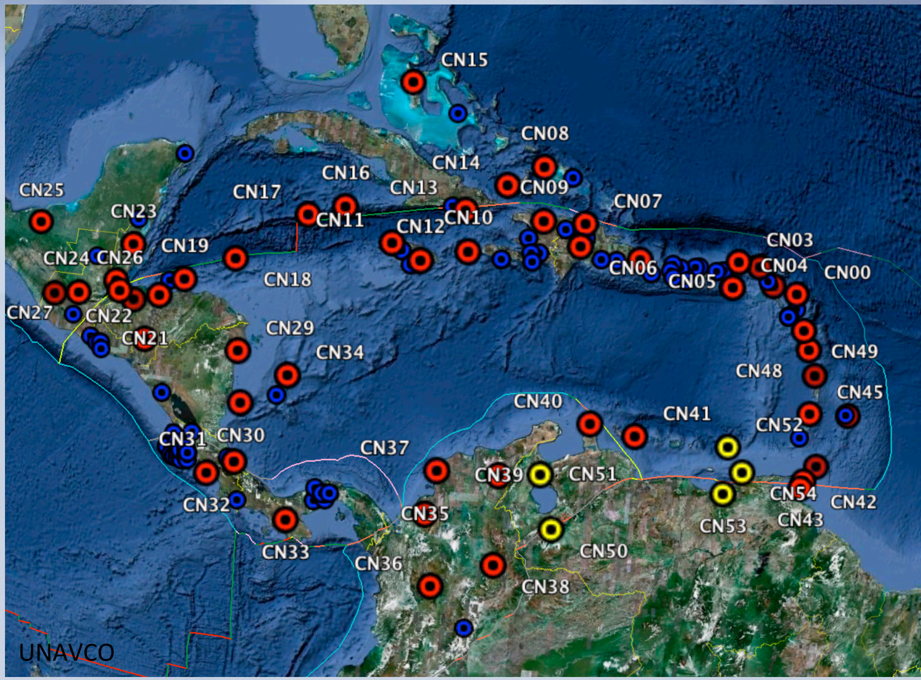


B. Bragason



Th. Ingvarsson

cGPS networks



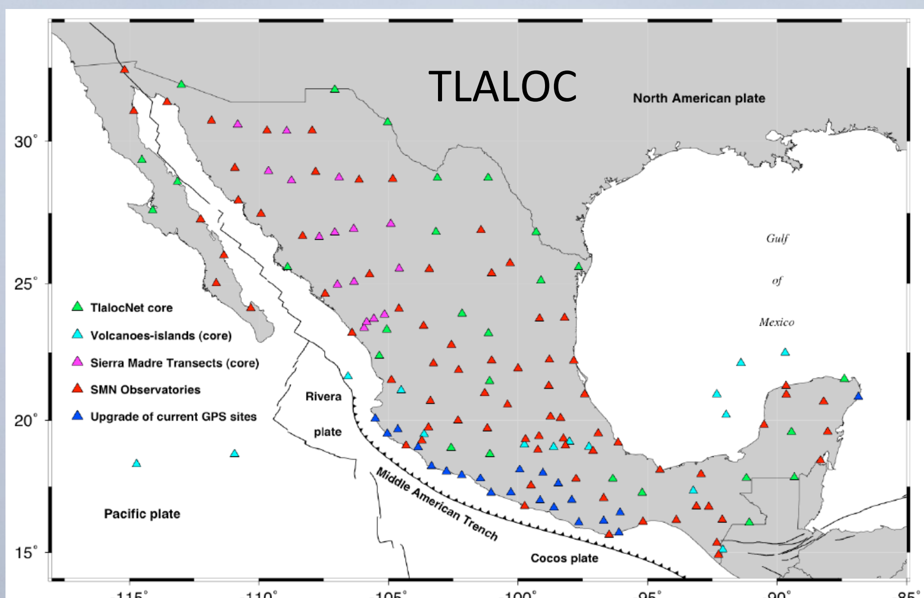
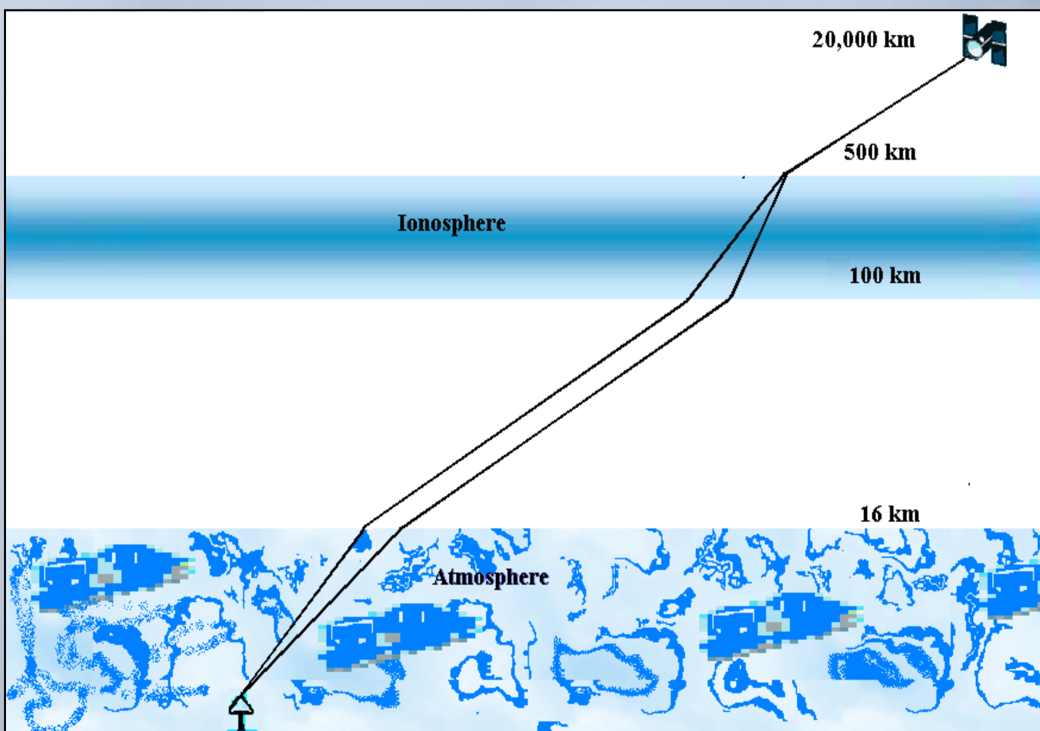


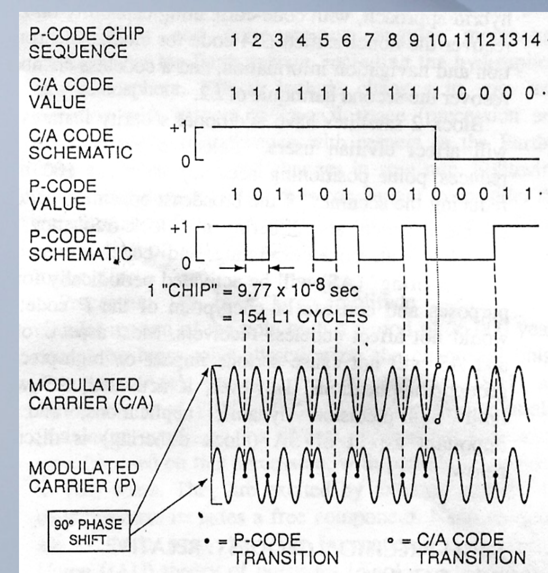
Figure from TLALOC white paper

- COCONet - a backbone network
- Free data
- "Network of networks"
- Study targets:
  - Earthquake cycle
  - Inter-, co-, & post-seismic
  - Episodic slow slip
  - Plate & block motions
  - Volcano deformation
  - Magma-Tectonic interactions
- Other uses: base stations for surveys, meteorology
- TLALOC: Proposed cGPS network in Mexico

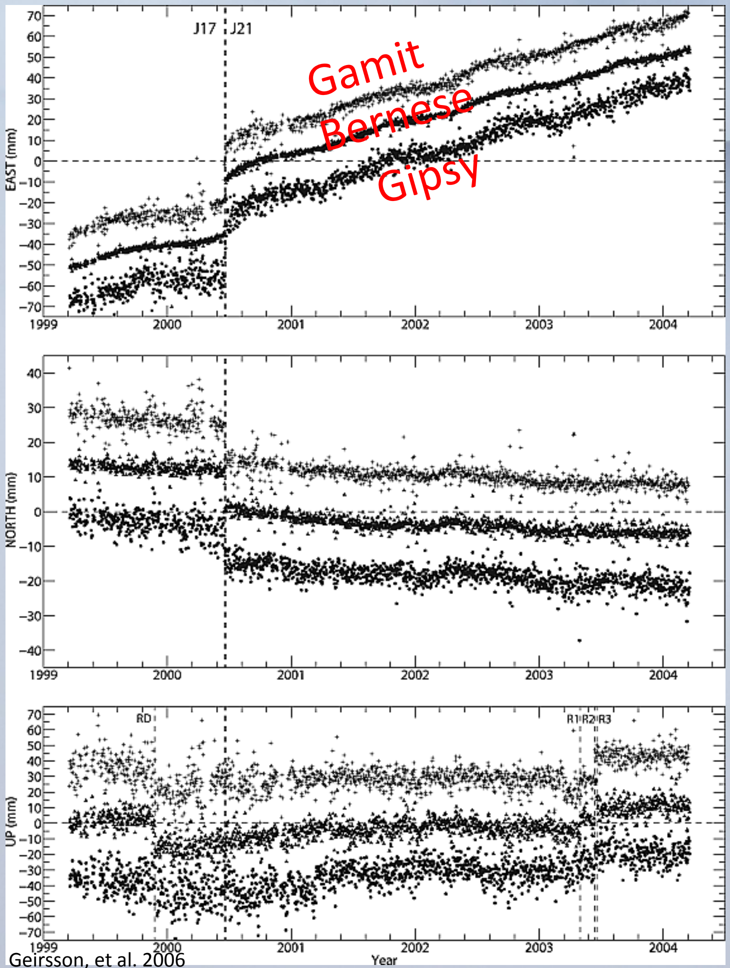
GPS/GNSS for geodetic positioning

- Use the phase measurements from the satellite
- Two carrier wave frequencies (L1 and L2)
- Position is affected by signal delays by passing through the ionosphere and troposphere, signal reflections (multipath), clocks, monument stability and setup repeatability, orbits and reference systems





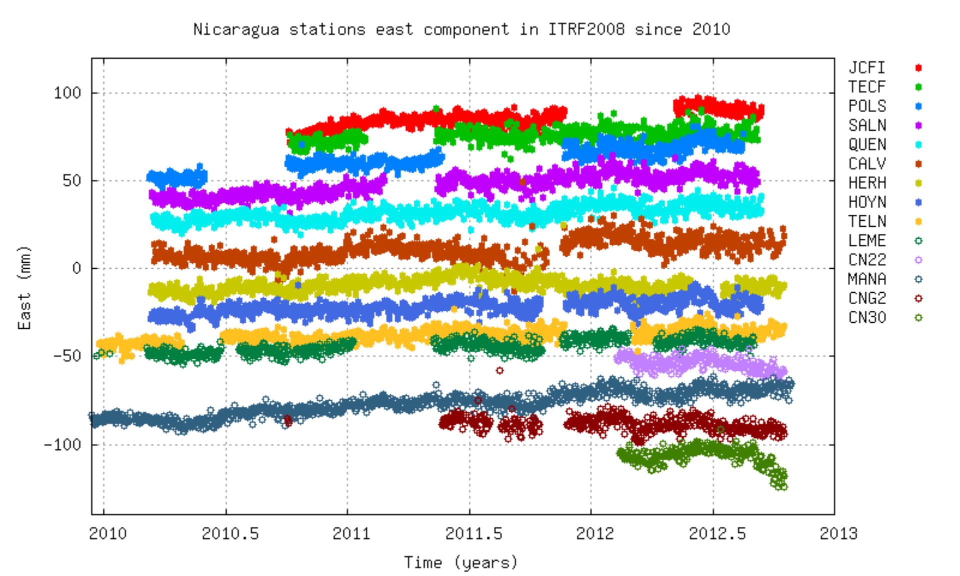
GPS/GNSS processing software

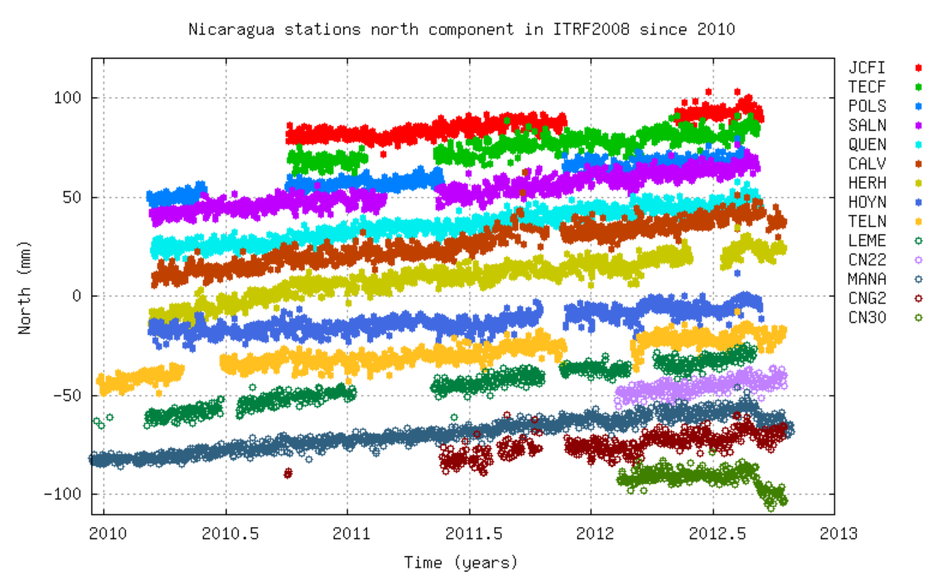


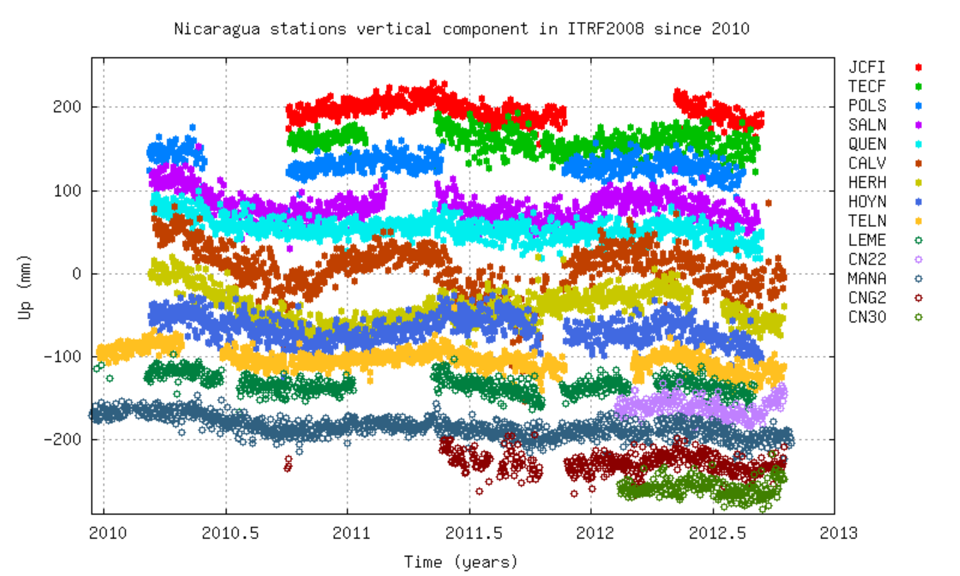
Time series from three different softwares for a 35 km baseline

- It is important to process the data collected (!)
- Allocate time and resources
- Most use Gamit-Globk, Gipsy-Oasis or Bernese
  - Double differencing vs precise point positioning (PPP)
  - Reference frames vs reference stations
- Daily solutions vs sub-daily solutions
  - A new point every second?
  - Accuracy decreases with shorter timespan

GPS/GNSS time series



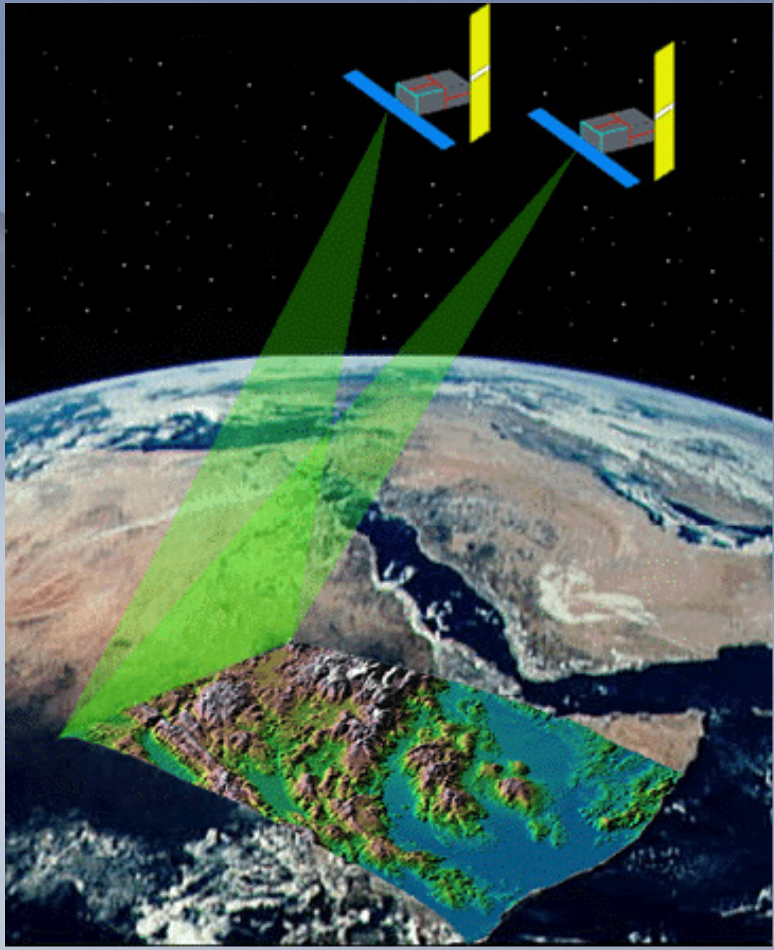


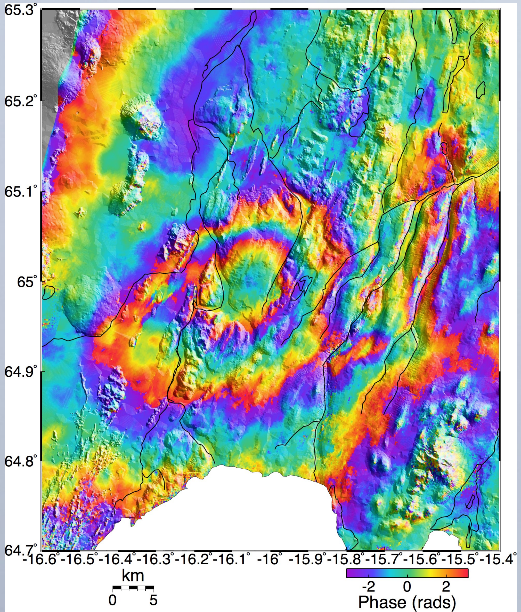


- These time series are from cGPS sites in Nicaragua
- Seasonal signals
- Common-mode network filters
- For monitoring: what is the meaning of the latest data point?
- Benefits of interpreting data from a wide network

InSAR: Interferometric Synthetic Aperture Radar

- Two or more data acquisition of the same area from nearby location (<1000 m)
- Enables detection of surface deformation with cm or sub-cm level accuracy
- Pros: Superb spatial coverage
- Cons: Long repeat-time; poor absolute vertical reference; limited footprint; vegetation & snow cover issues

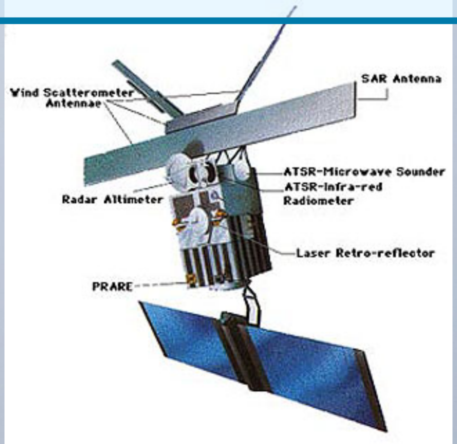




Interferogram from a 45° dipping ~planar intrusion at 14 km depth. Upptyppingar, Iceland.
Courtesy of A. Hooper

SAR satellites

- A few different radar-satellite systems exist from which interferograms can be formed
- Each satellite has a limited lifetime and can generally not be used with other satellite types to generate interferograms
- ERS1&2, ENVISAT, JERS1, ALOS, TERRASAR-X, COSMO-SKYMED, RADARSAT, TANDEM-X, …
- Some data are freely available, some not
- The systems have different radar frequencies
  - L,C,X-band. L-band works great in vegetated areas
  - High-resolution over small areas <-> lower-resolution over large areas

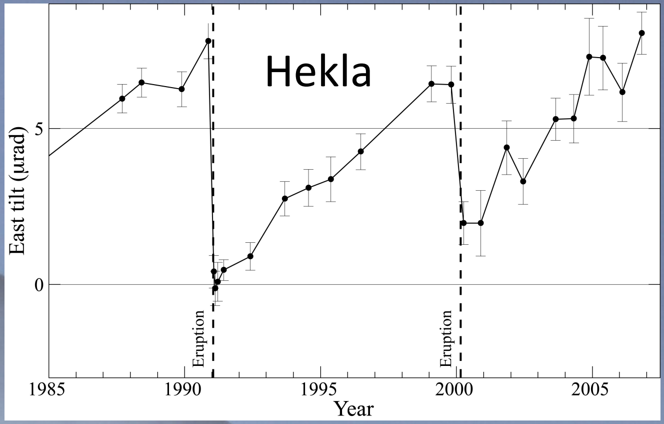


InSAR processing

- Establish access to data (may be non-trivial) and find out what data exists
- Different processing softwares: GMTSAR, ROI-PAC, DORIS, DIAPASON, Gamma, SARscape, NEST, …..
- One-to-one interferograms, time series, stacking, persistent scatterers imaging
- Ascending and descending image pairs allow a 3D velocity field to be created
- Issues: incoherence (scatterer properties change), troposphere, ionosphere, orbital errors, needs accurate DEM (Digital elevation model), "unwrapping"
- Pixel-tracking (using radar images)
- Ground-based SAR can be used (flank monitoring)

Tilt

- Measure the temporal variations in surface slope
- Different ways to measure tilt include
  - Electrolyte bubble levels
  - Long-base fluid tiltmeters
  - Short leveling lines (T, L, O, X – shaped)
  - Lake leveling
  - Seismometers (VLPs; mass positions)
- <u>Pros:</u> Rapid and independent results; high sampling rates possible; can be very sensitive if well placed
- <u>Cons:</u> Sensitive to surface effects and temperature changes → shallow borehole installations



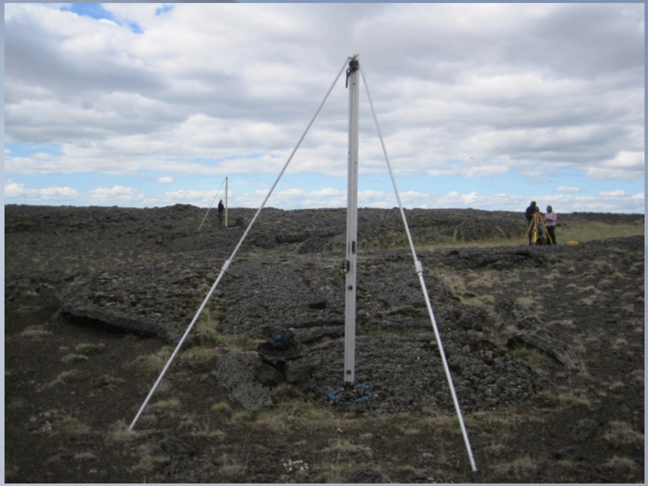
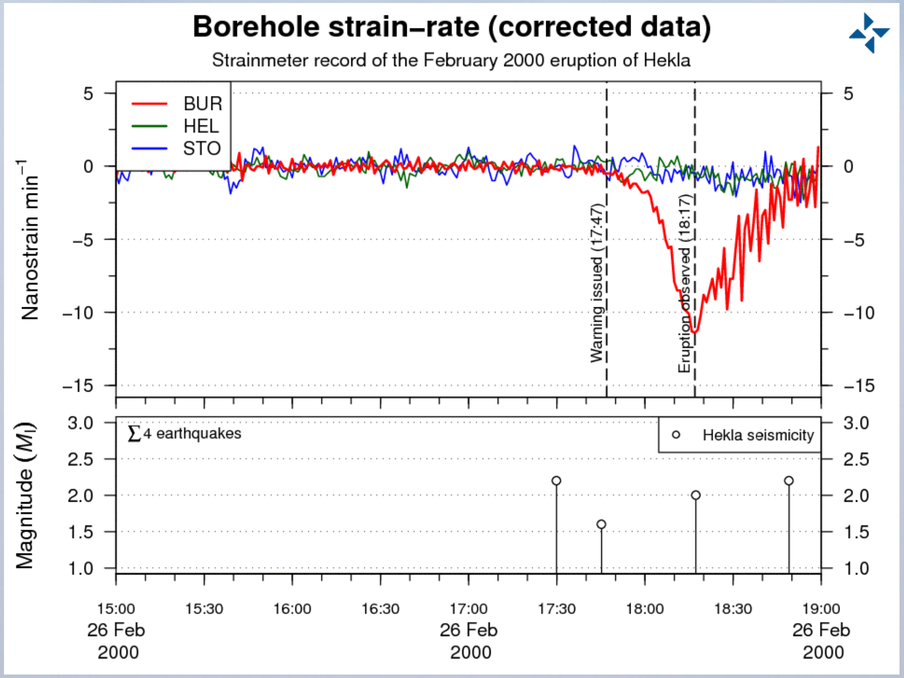
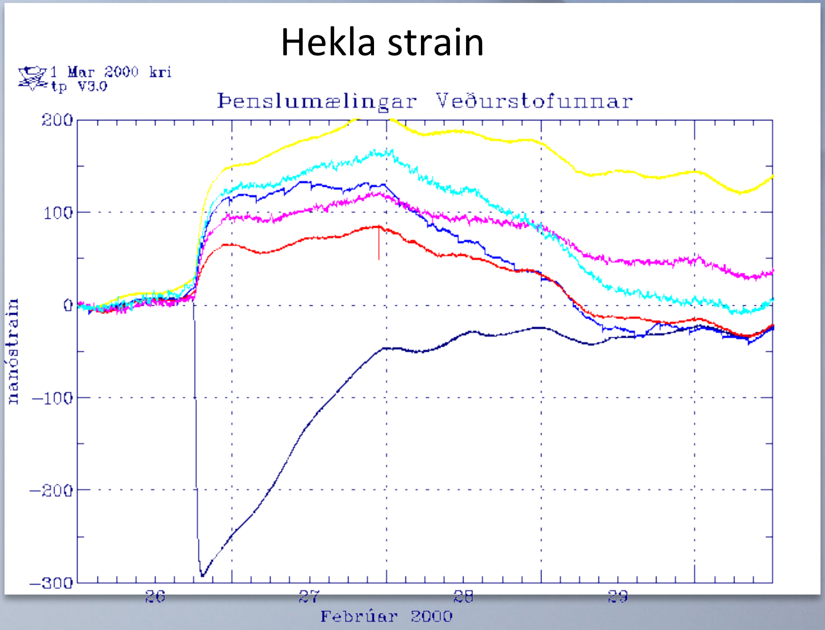


Photo: JH

Borehole strain meters

- Measure strain in shallow (100s of m) boreholes
- Volumetric strain vs 3-component strain meters
- <u>Pros:</u> Rapid and independent results; high sampling rates; sensitive
- <u>Cons:</u> No long-term stability; expensive installation





Plots of strain rate and strain for the Hekla 2000 eruption


Deformation models

Modeling of volcano deformation

- Interpret data in terms of source location, source geometry, source strength
- Analytical models in an elastic halfspace
- Different sources (spheres, dikes, sills, slope creep, …)
- Data inversions & forward models
- Finite Element Modeling
- Deformation models do not distinguish between what causes pressurization
- Complications
    - Topography
    - Rheology
    - Other deformation processes
        - Plate boundary deformation
        - Earthquakes, post-seismic movements
        - Loading/unloading
    - Spatial and temporal aliasing

The Mogi model (K. Mogi, 1958)

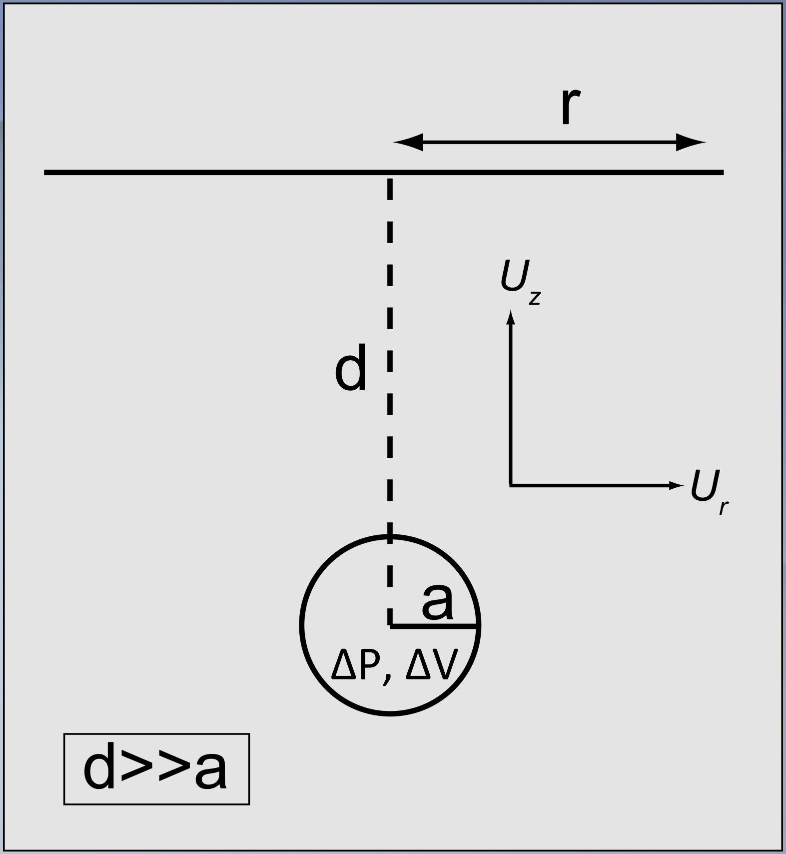
The relationship between surface displacements and pressure change for a spherical source in an elastic half-space (Poisson ratio = 0.25):

Vertical Displacement (uplift or subsidence):

$$U_z = \frac{3a^3 \Delta P d}{4G(d^2 + r^2)^{1.5}}$$

Horizontal Displacement:

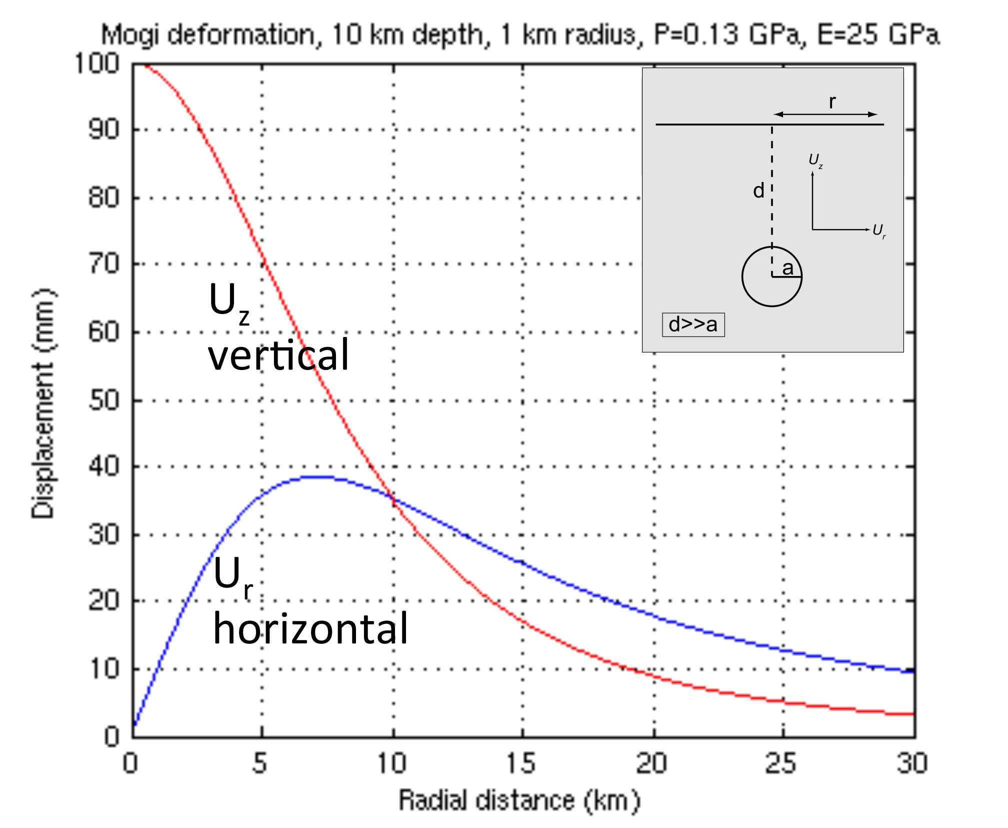
$$U_r = \frac{3a^3 \Delta P r}{4G(d^2 + r^2)^{1.5}}$$



In terms of volume change:

$$U_z = \frac{3\Delta V d}{4\pi(d^2 + r^2)^{1.5}} \qquad U_r = \frac{3\Delta V r}{4\pi(d^2 + r^2)^{1.5}}$$

The Mogi model (K. Mogi, 1958)



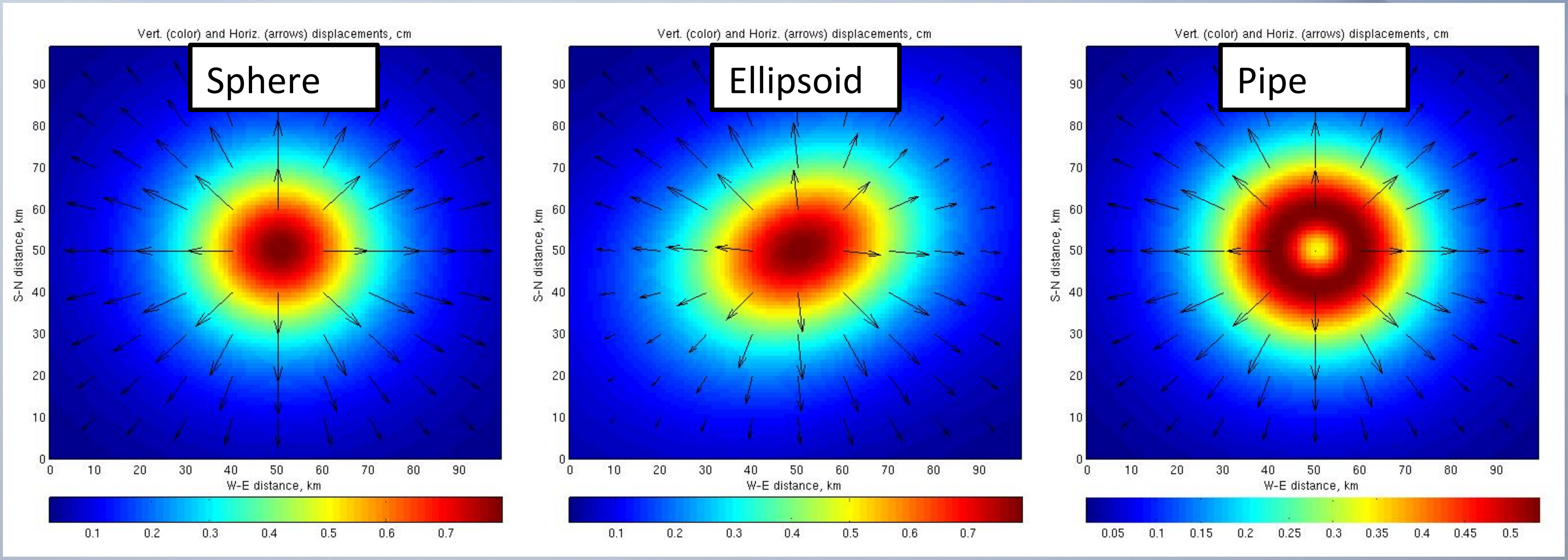
- Vertical deformation decays
- Horizontal deformation has a <u>maximum</u> at r=d/sqrt(2)
- For shallower depths the deformation is greater and drops off more quickly
- The amplitude scales directly with the volume (or pressure) change
- Important for network design
- This model often works great to a first degree

Equations

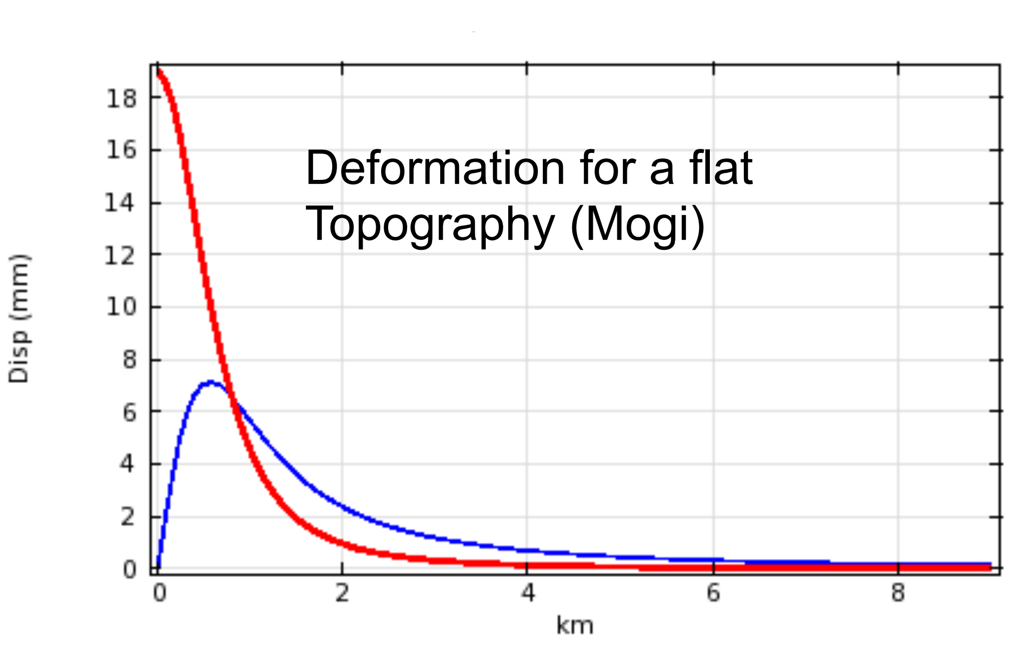
$$U_z = \frac{3\Delta V d}{4\pi(d^2 + r^2)^{1.5}} \qquad U_r = \frac{3\Delta V r}{4\pi(d^2 + r^2)^{1.5}} \qquad U_z = \frac{3a^3\Delta P d}{4G(d^2 + r^2)^{1.5}} \qquad U_r = \frac{3a^3\Delta P r}{4G(d^2 + r^2)^{1.5}}$$

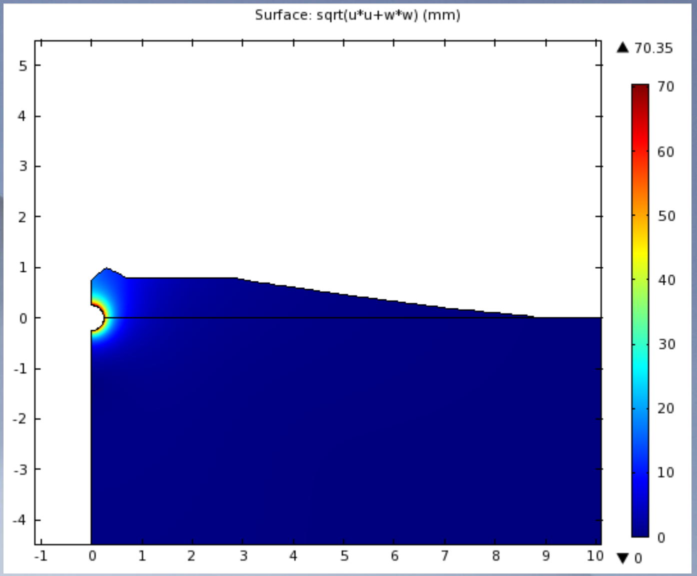
Other shapes of deformation sources

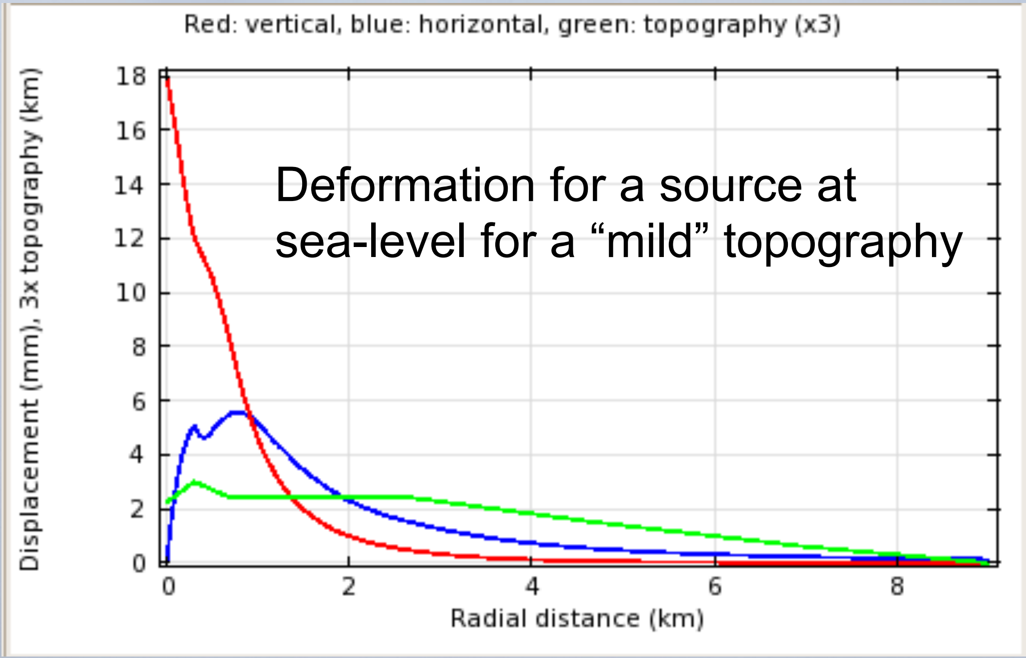
- Ellipsoidal, pipe (open and closed), dike (rectangular, circular), sill (rectangular, circular), penny shaped crack, …
- Dikes and sills of spatially (and/or temporarily) variable opening
- Mickey Mouse (arbitrary shapes – FEM modeling)
- Often the data does not allow us to distinguish between different shapes



Effects of topography

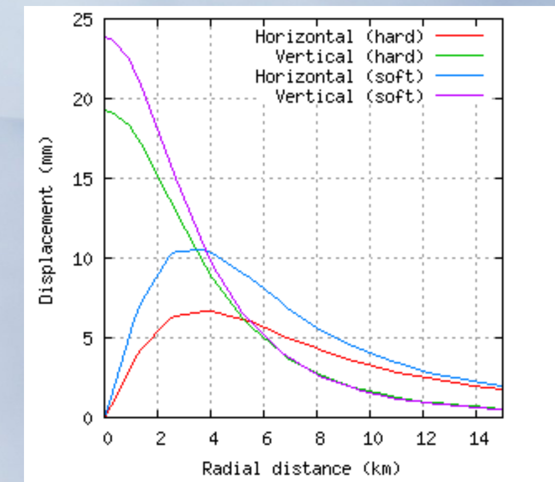


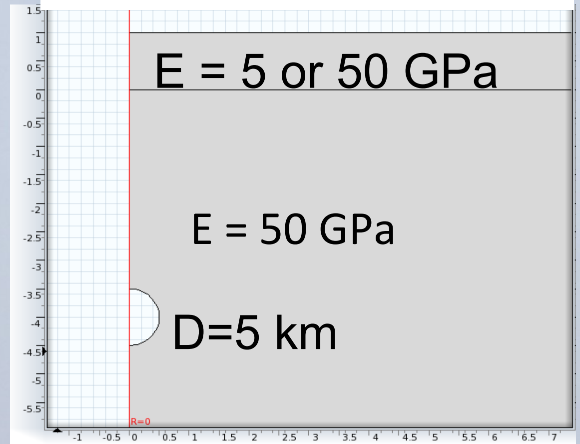




Topography is not very important even for rather shallow sources. The source essentially has to be within the edifice, or the topography quite steep for topography to matter.

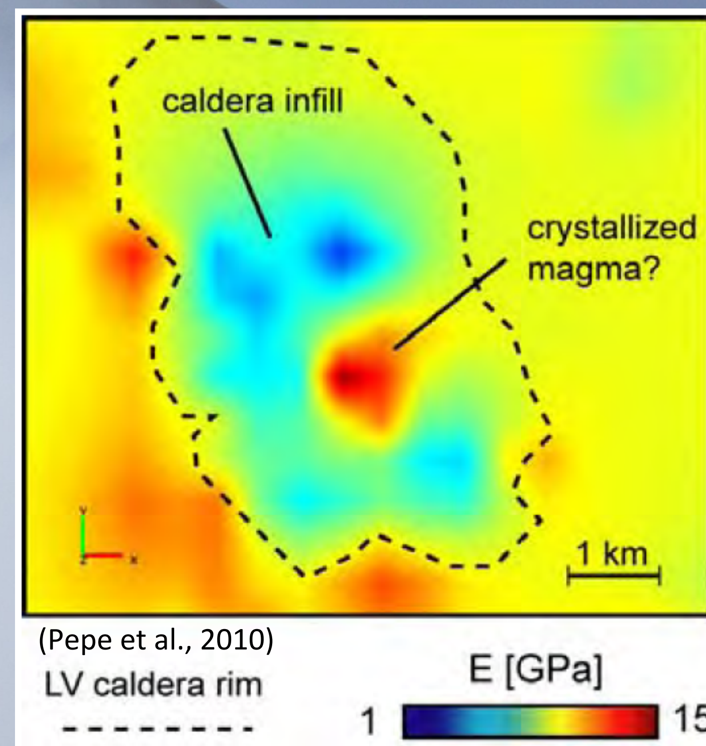
Rheology matters





A weak top-layer, and 3-D elastic structure in general, can have a significant effect on the observed deformation field

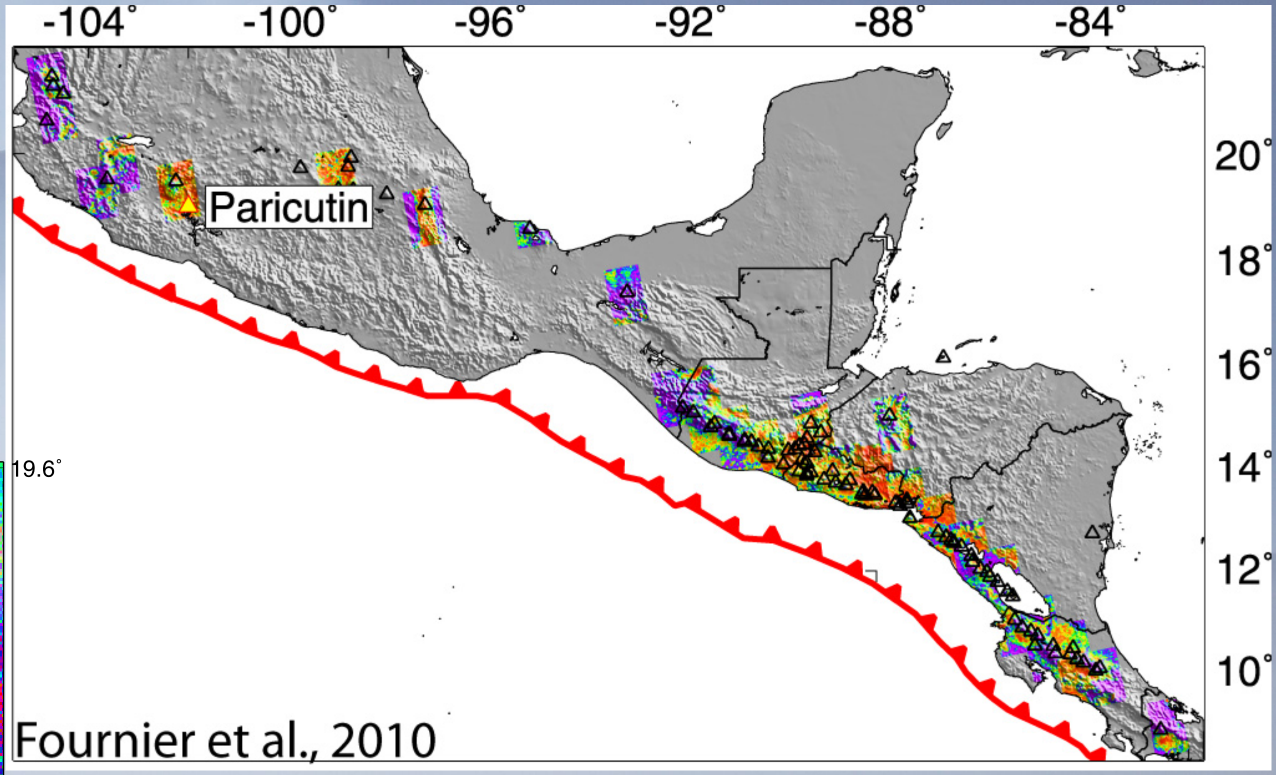
3-D elastic parameters from seismic studies (tomography) can be used as input into deformation models

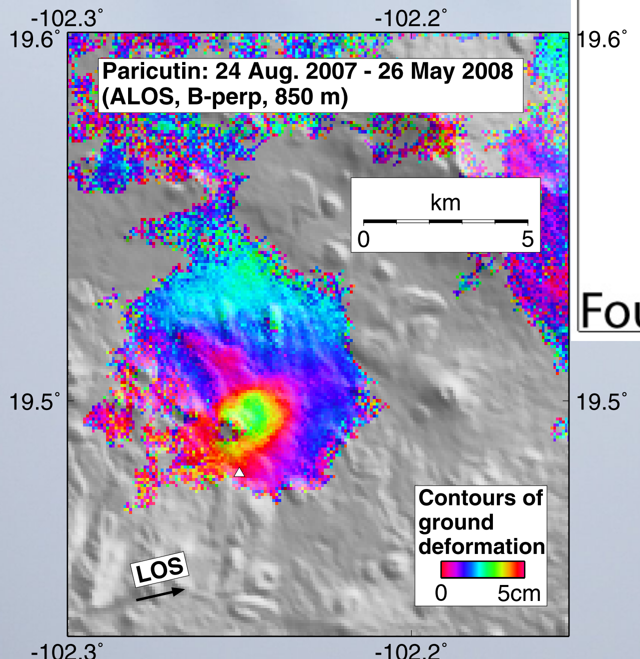


Variable Young's modulus at 1 km depth in Long Valley Caldera from seismic tomography

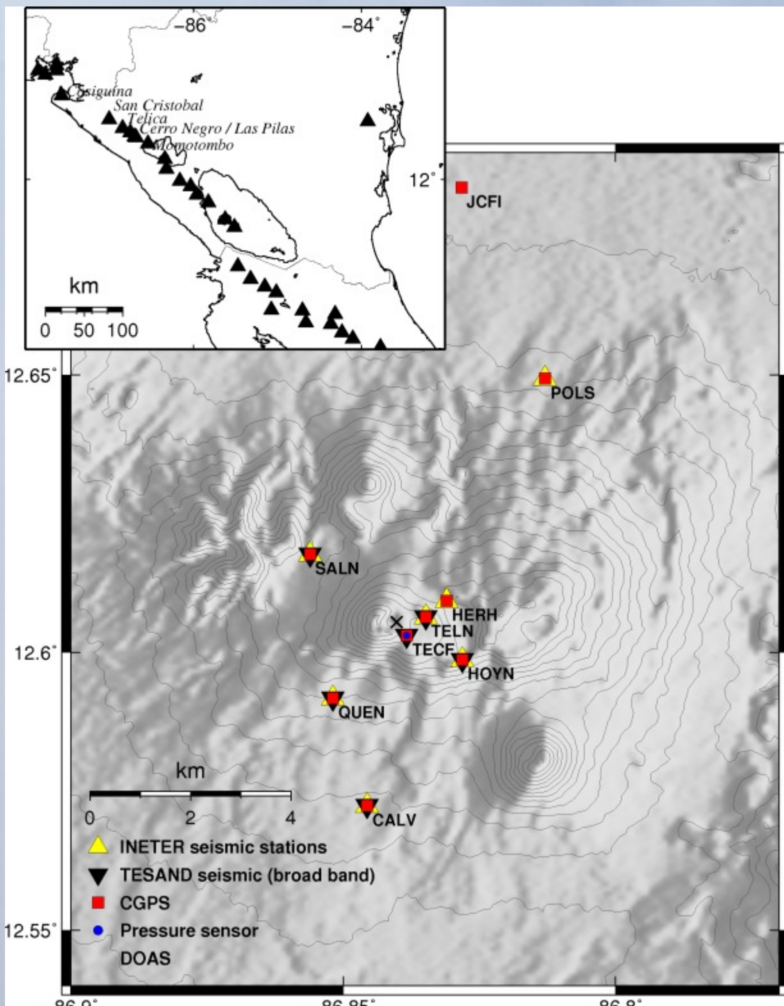
Case studies

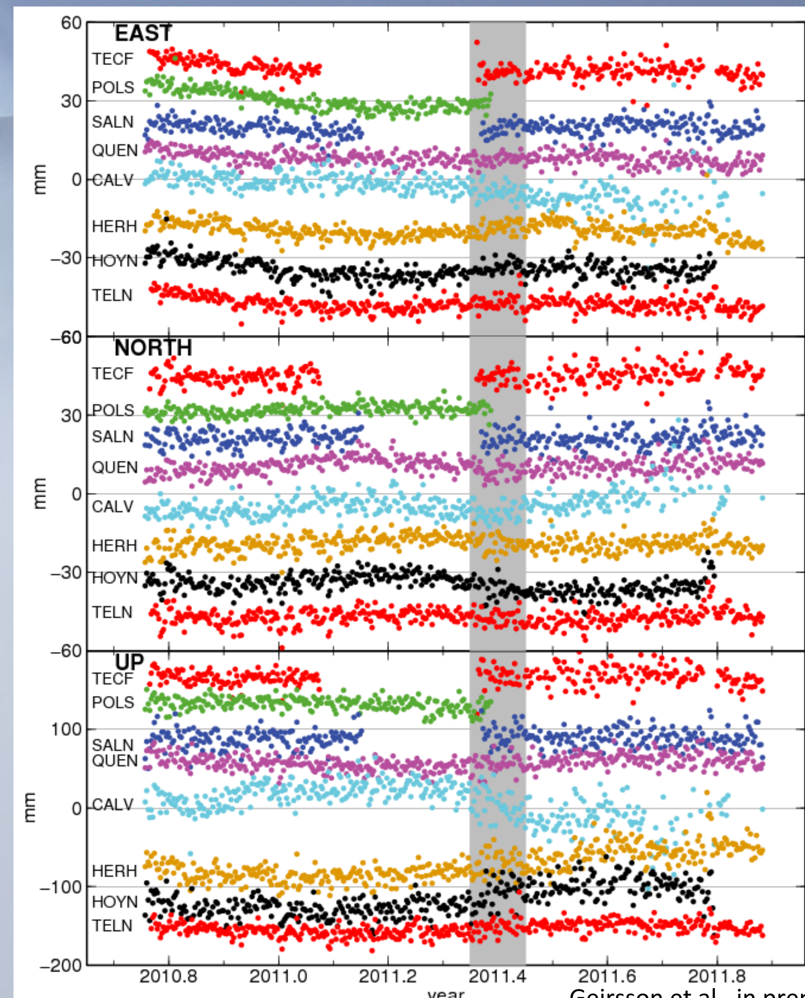
InSAR surveys of Central American volcanoes show little deformation (over ~ 1 year)





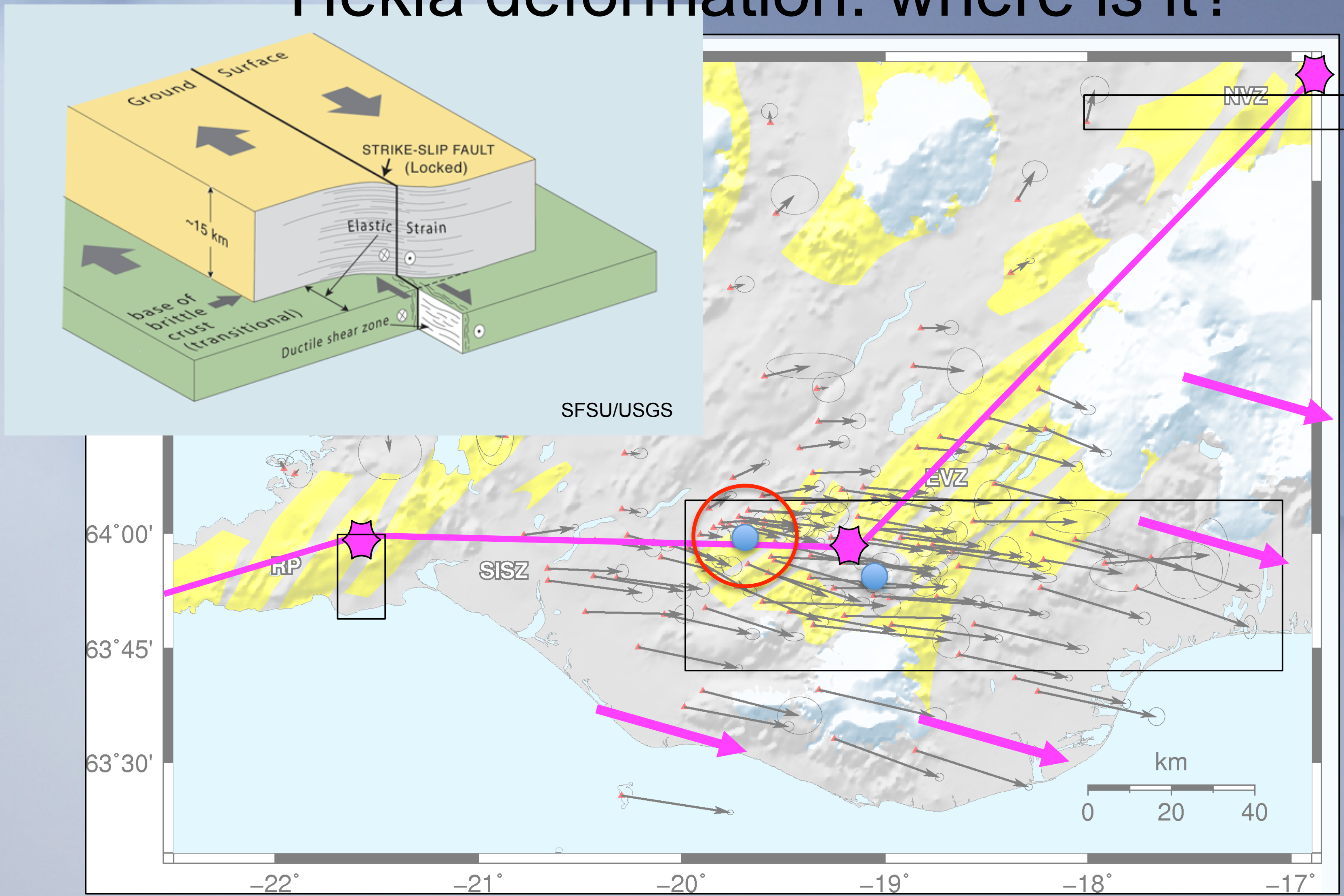
No detectable deformation was observed for the 2011 Telica (Nicaragua) eruption





Geirsson et al., in prep

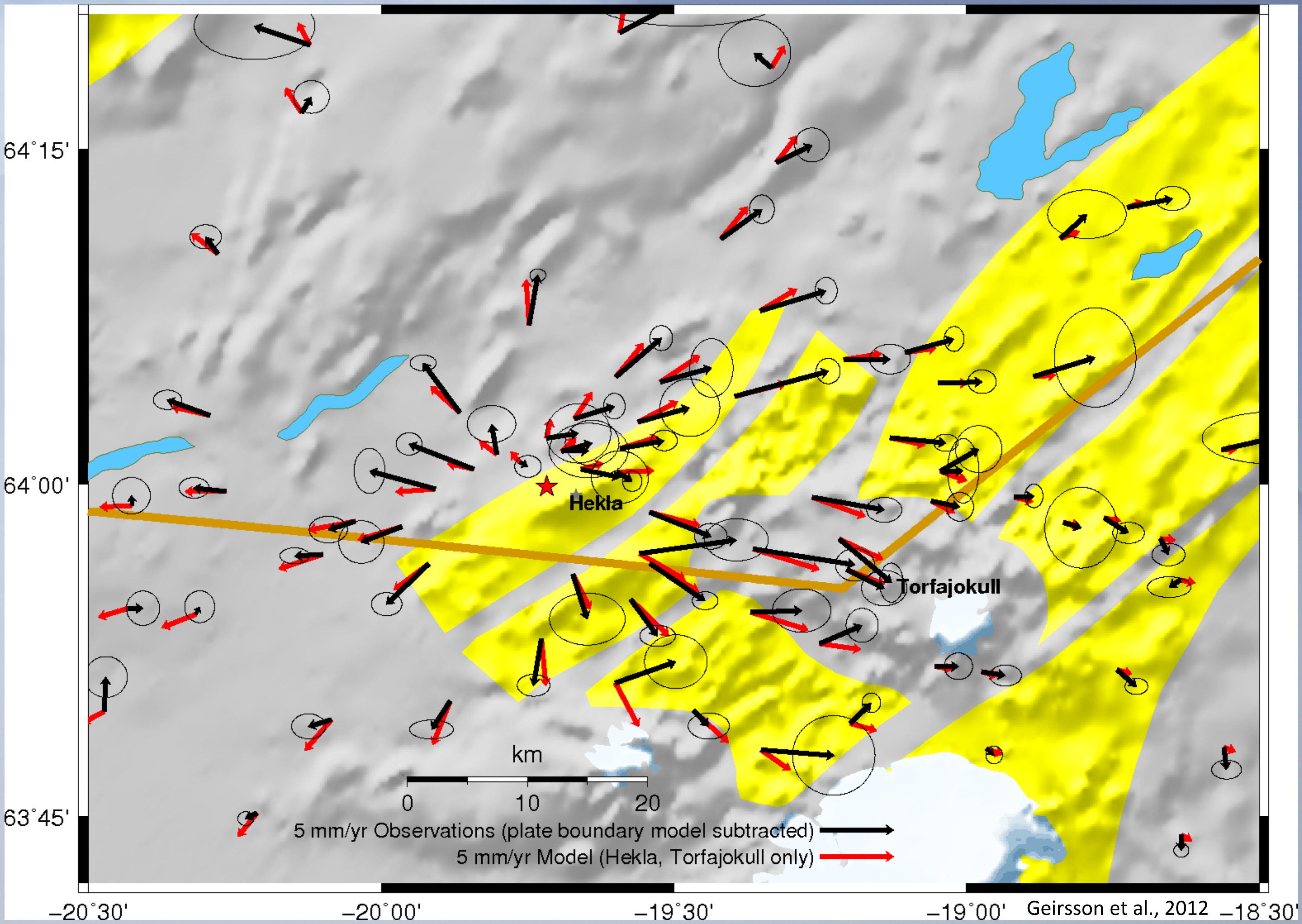
Hekla deformation: where is it?



GPS velocities, relative to N. America, 2000-2010
Time series corrected for 2008 co-seismic offsets
Velocities corrected for the effects of glacier unloading

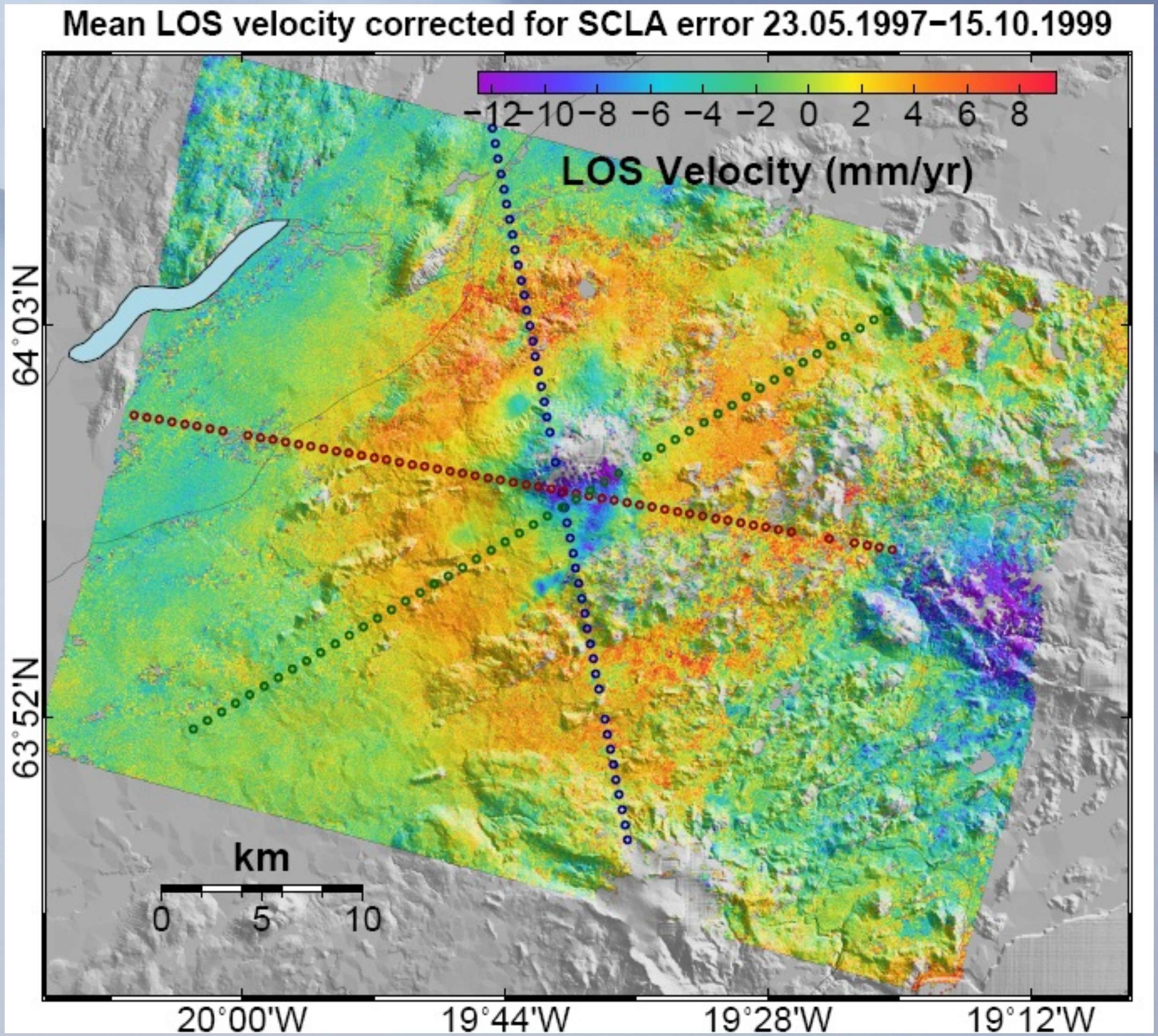
Solve for plate boundary location
Block motion (MORVEL)
Plate boundary strain accumulation

Hekla: Plate boundary deformation removed



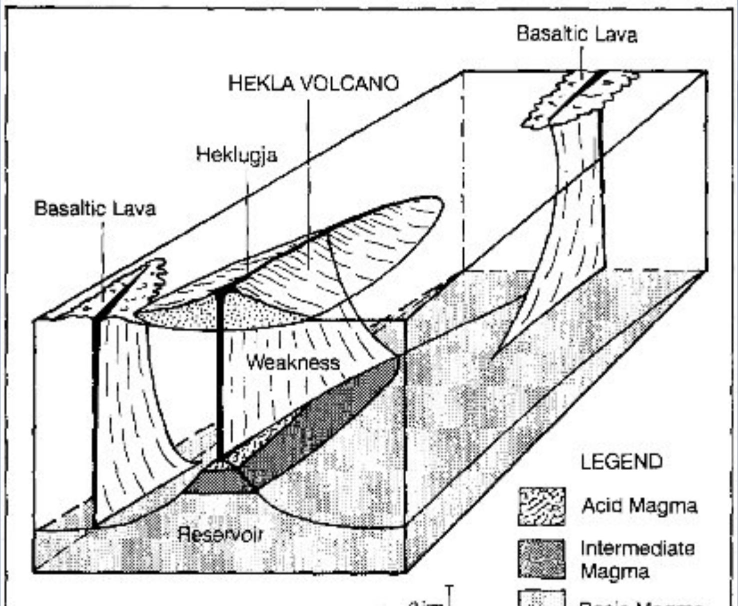
Radial deformation

Hekla: Stacked inter-eruptive interferogram

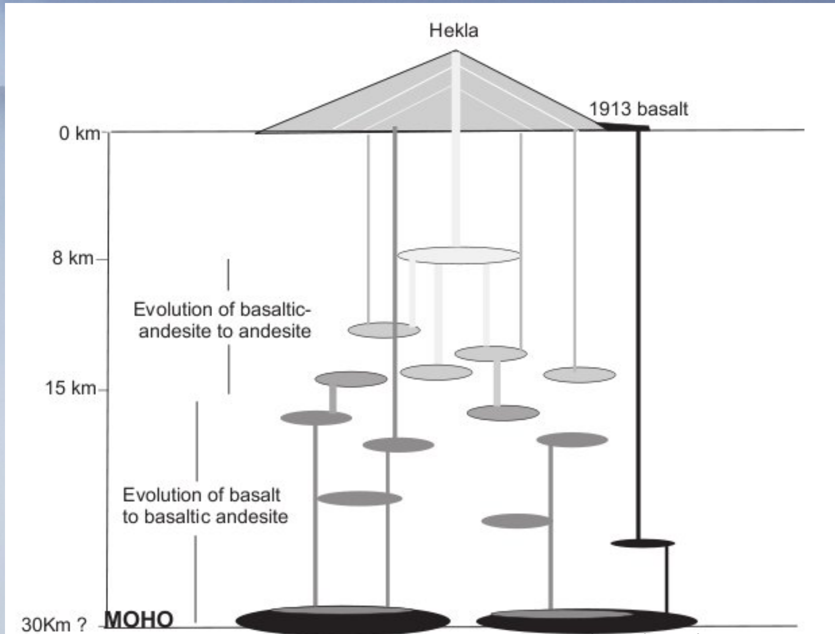


Ofeigsson et al., 2011

Magma plumbing system of Hekla

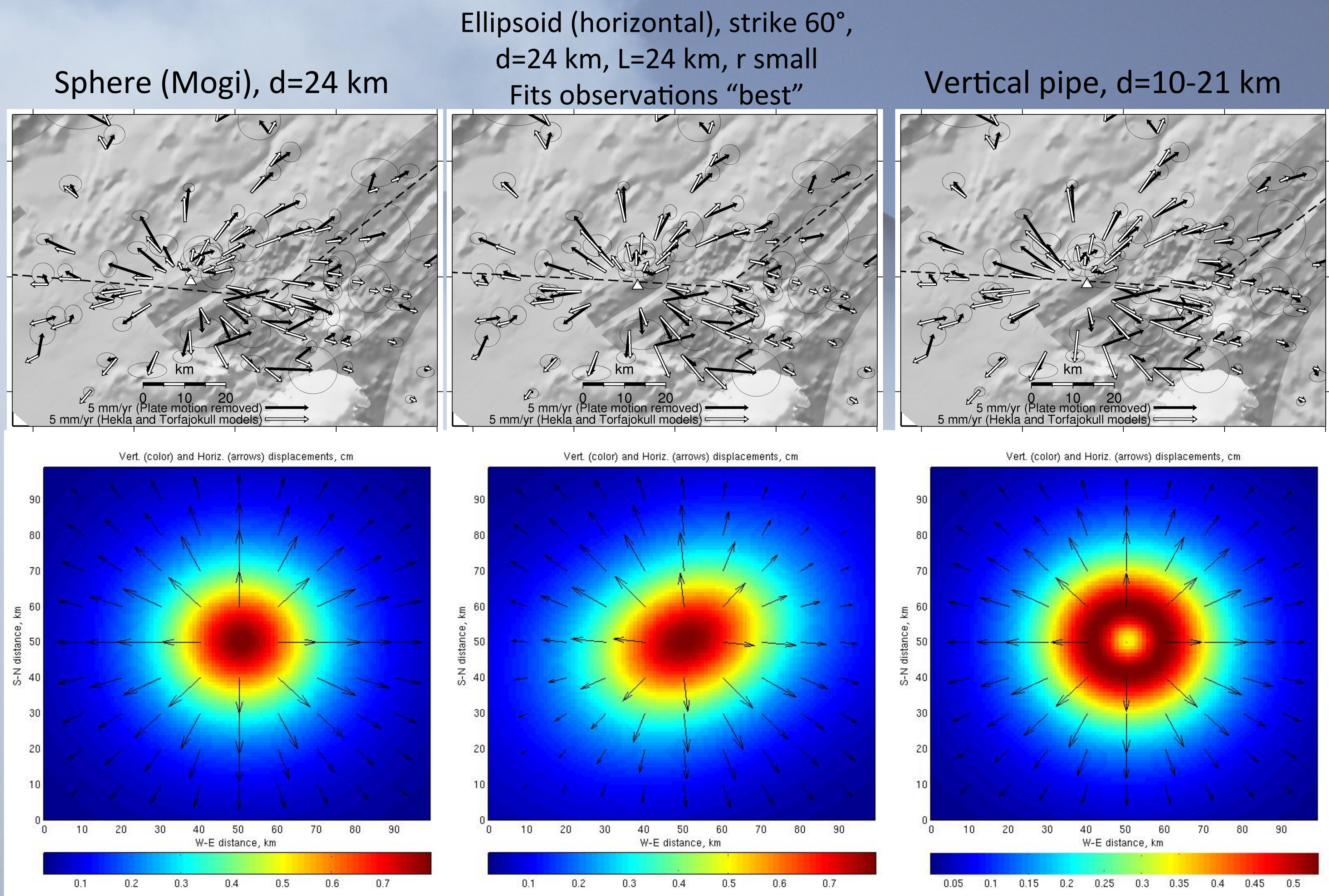


Gudmundsson et al., 1992



Checol et al., 2011

Hekla source geometry comparison

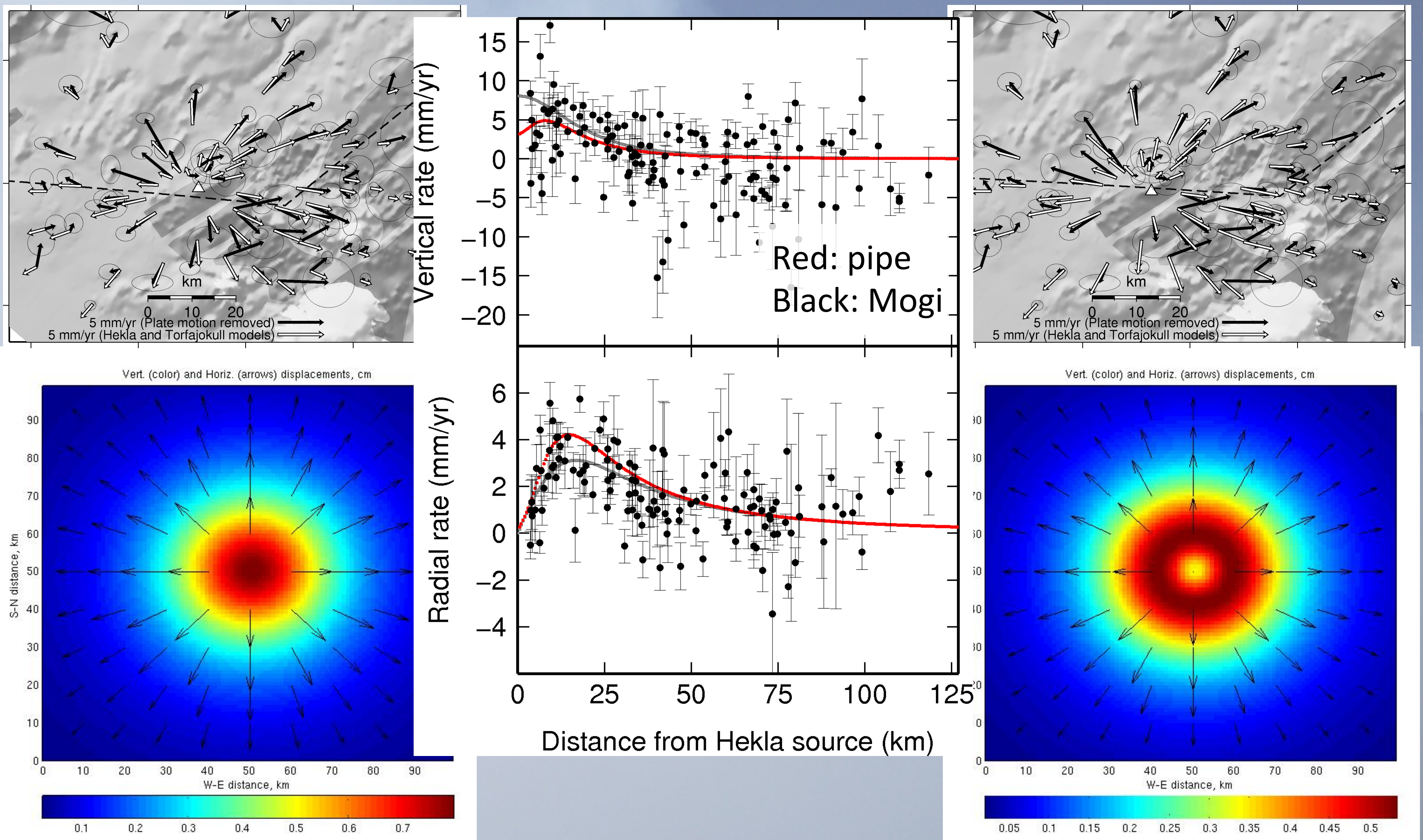


Geirsson et al., 2012

Hekla source geometry comparison

Sphere (Mogi), d=24 km

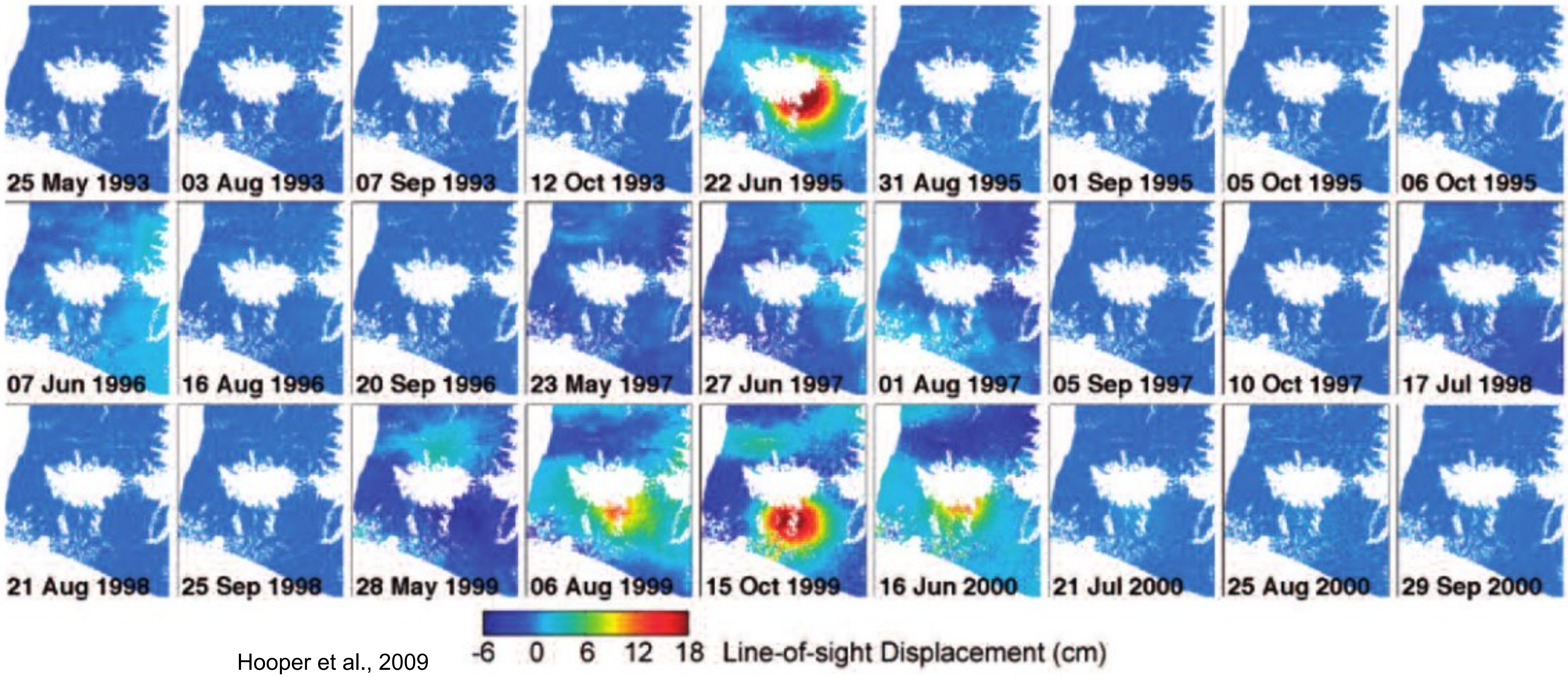
Vertical pipe, d=10-21 km



Geirsson et al., 2012

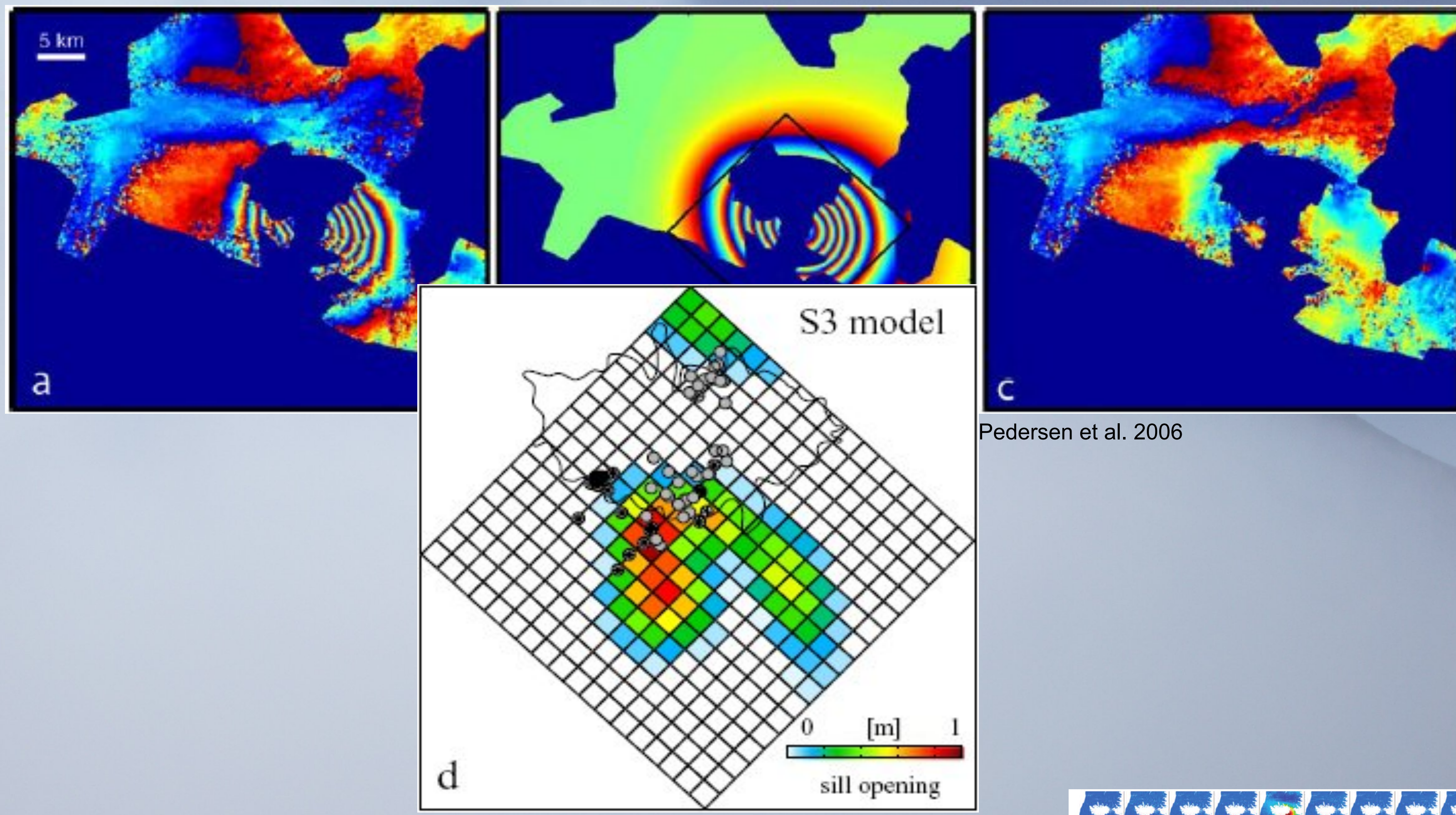
Eyjafjallajökull 2010 eruption

Intrusions under Eyjafjallajökull in 1994 and 1999 - InSAR time series analysis

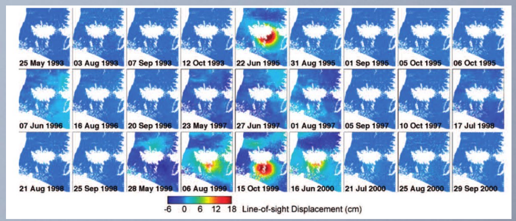


Hooper et al., 2009

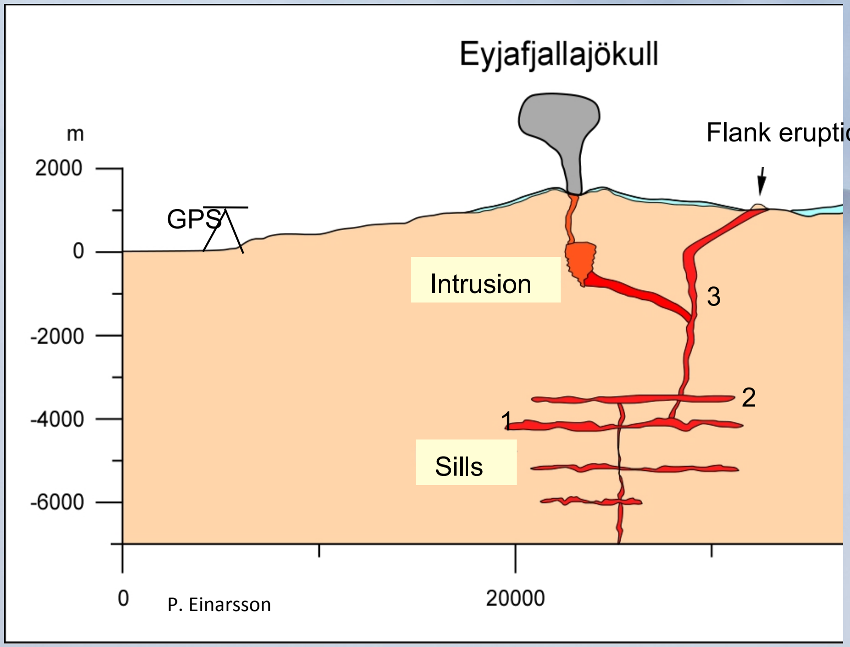
The 1999 Eyjafjallajökull intrusion

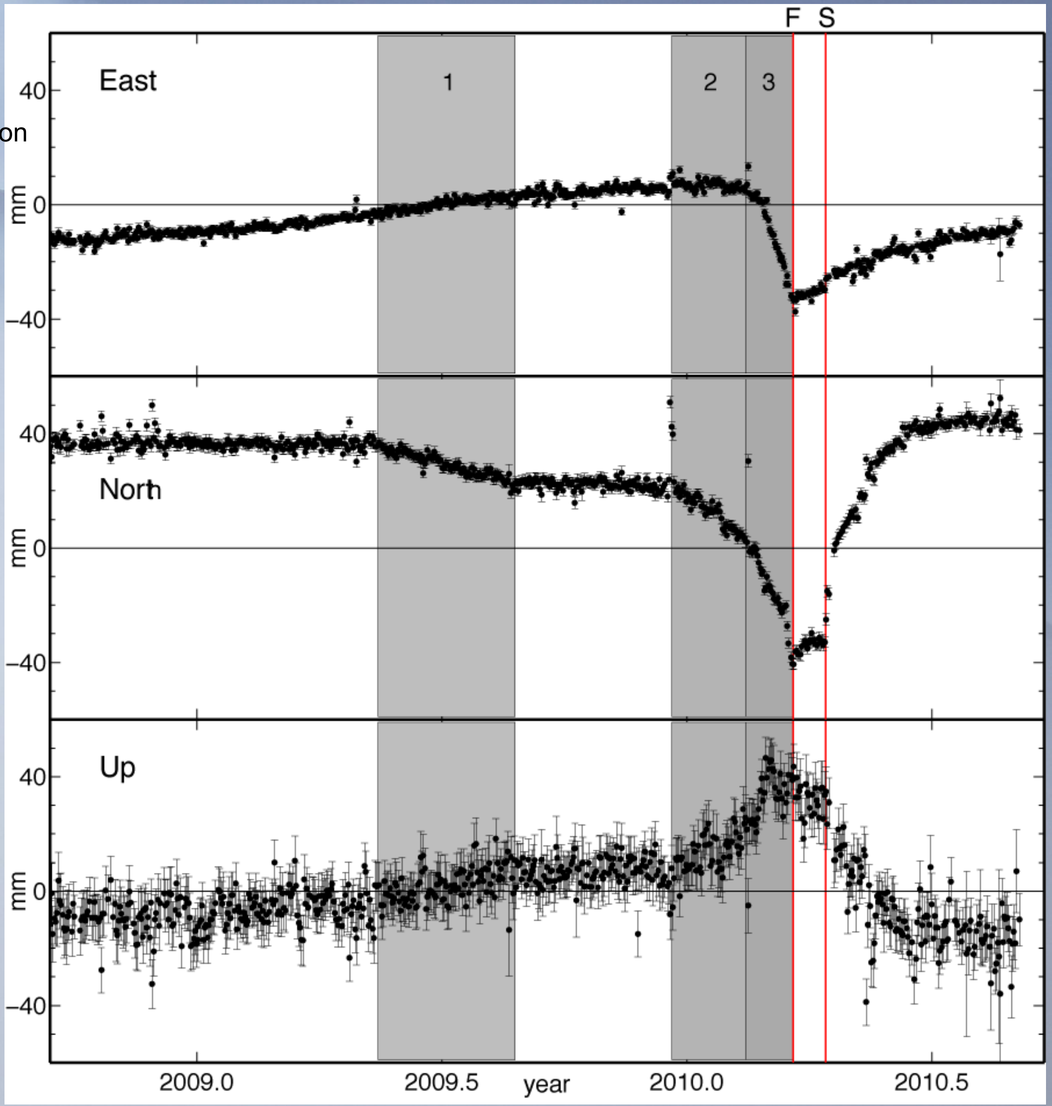


Pedersen et al. 2006



Eyjafjallajökull GPS time series



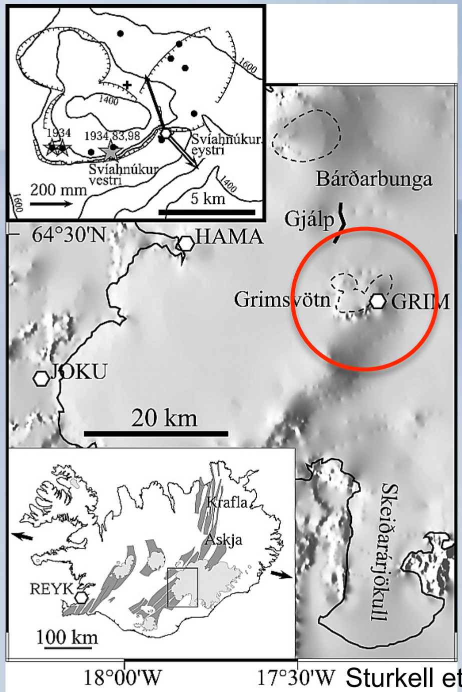


Geirsson et al., 2010

So, how much gear do we need?

- How many eGPS? How often to repeat the measurements? How many cGPS? Where? Can InSAR be applied? Tilt? Strain? Leveling? Flank monitoring? Real-time?
- The right answer is: "It depends".
- Spatial and temporal aliasing
- Shallow, medium, and deep processes
- Interfering deformation fields
- Accessibility
- Previous activity of the volcano
- Funding
- Hazards & risk

Sometimes, one GPS point may go a long way!



Sturkell et al. 2003

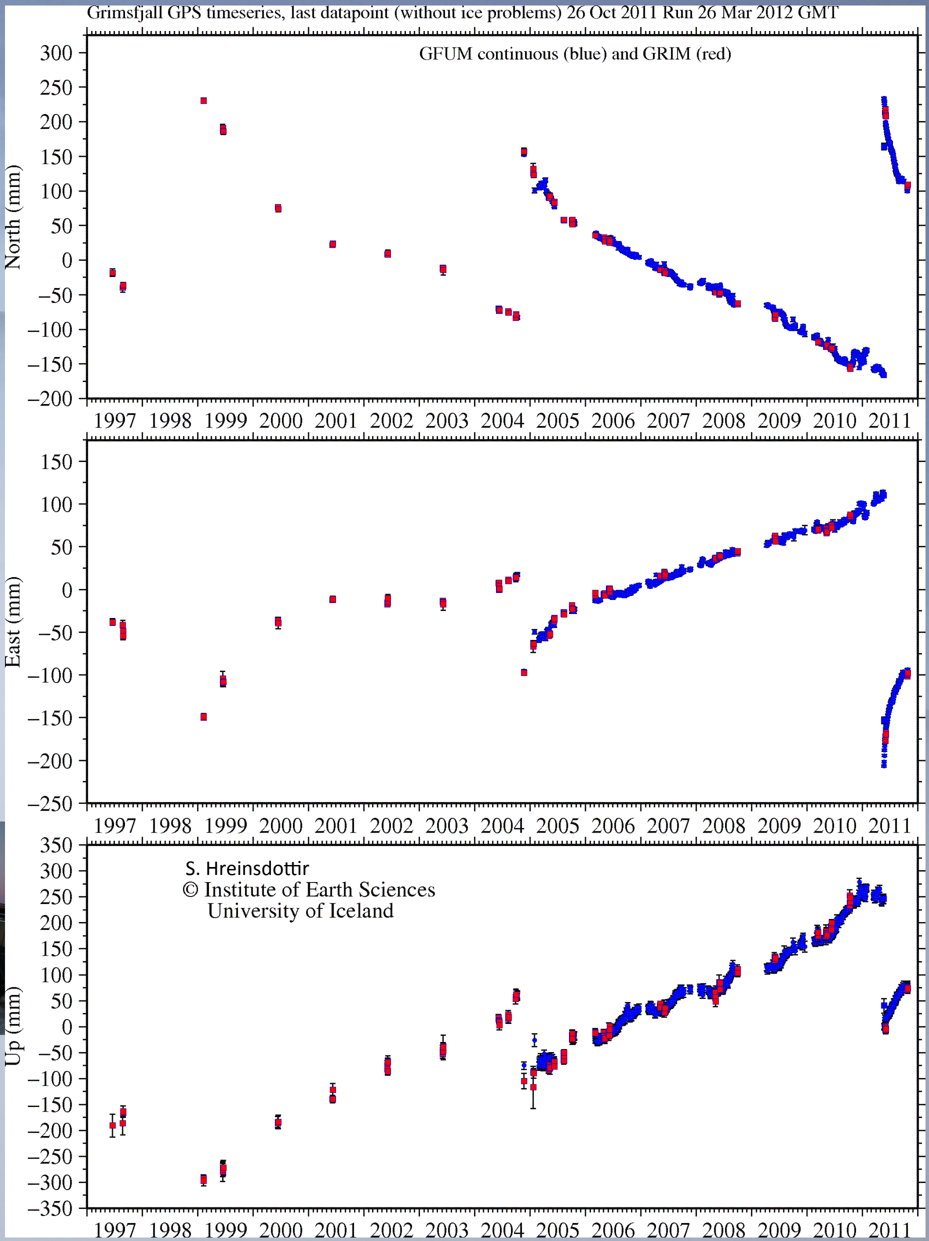
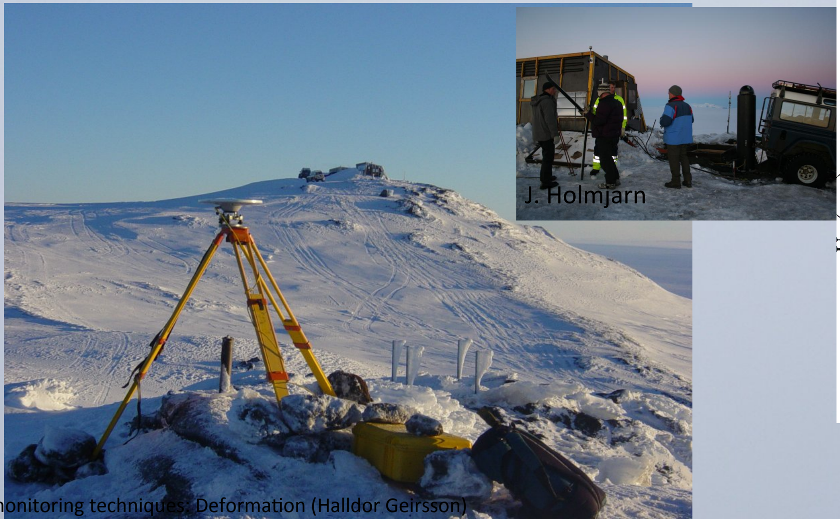


Figure: Sigrun Hreinsdottir



Summary

- Monitoring volcano deformation is useful (usually…)
- A multitude of techniques (GPS, InSAR, tilt, strain) is beneficial because each of the techniques has its limitations (spatial, temporal, cost, logistical)
- Monitoring volcanoes is a long-term task (indefinite) but benefits from cooperation with short-term projects as well
- Volcanoes behave differently and evolve with time
- Worst – case scenarios. Be pessimistic; expect the (reasonably) unexpected.

Further reading

- Volcano Deformation, D. Dzurisin
- Earthquake and Volcano Deformation, P. Segall