Tectonic and Volcanic Geodesy

"investigations of the shape of the Earth"

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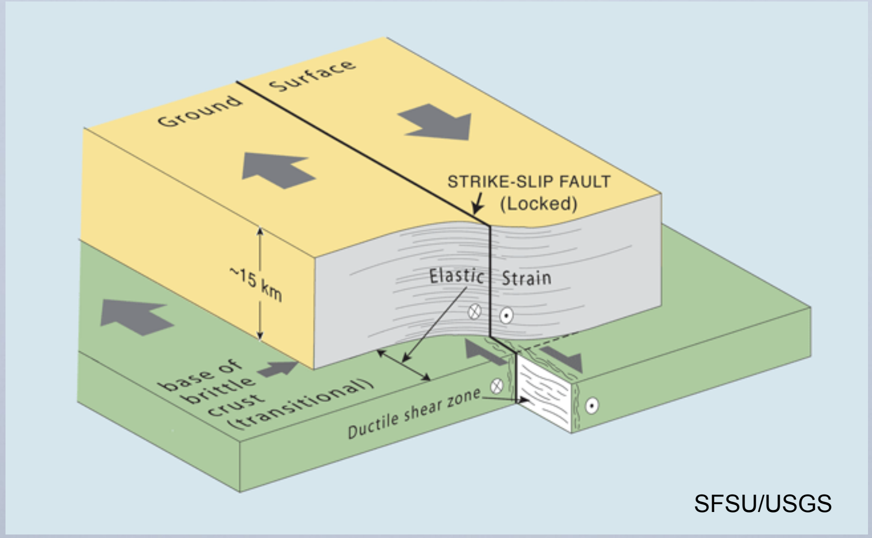
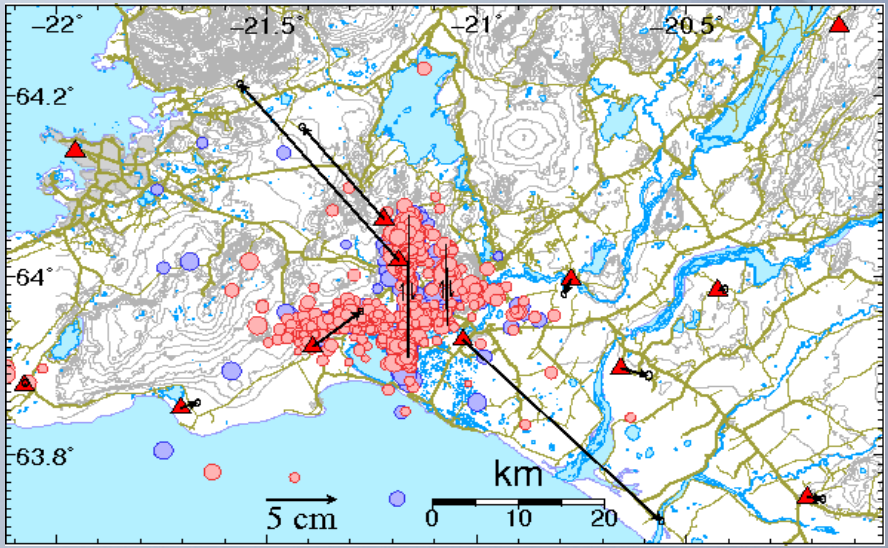
Overview

- Tectonic deformation
- Volcano deformation
- Tools for measuring deformation (InSAR, GPS, strain, tilt)
- Deformation models
- Complications
  - Other deformation processes (e.g., magma-tectonic deformation)
  - 3D-rheology and topography
- Case studies - Iceland and Central America

Tectonic Deformation

- Plate and fault motion
- The "earthquake cycle"
- Inter-seismic strain accumulation
- Co-seismic deformation
- Post-seismic deformation





Volcano Deformation

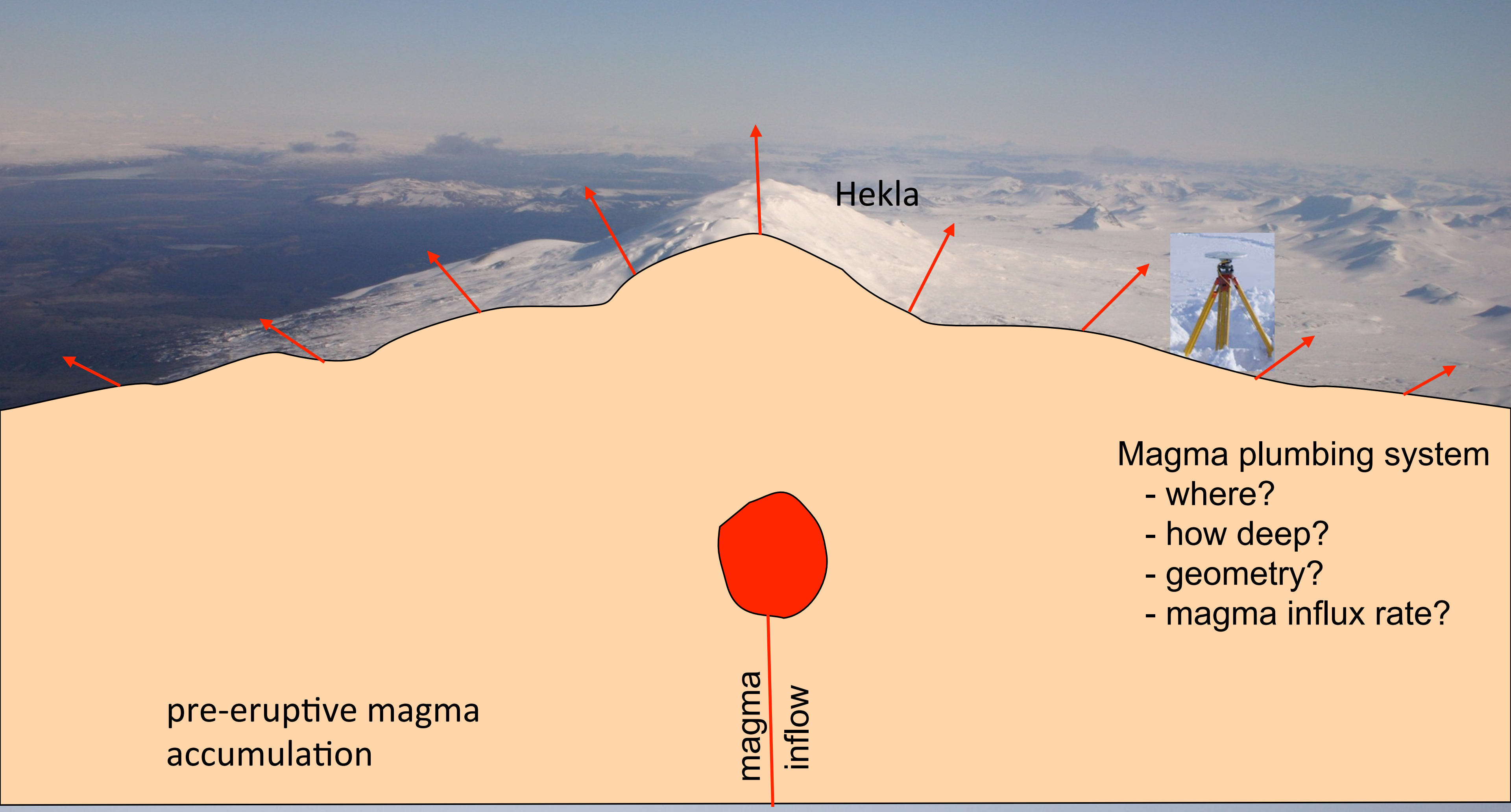
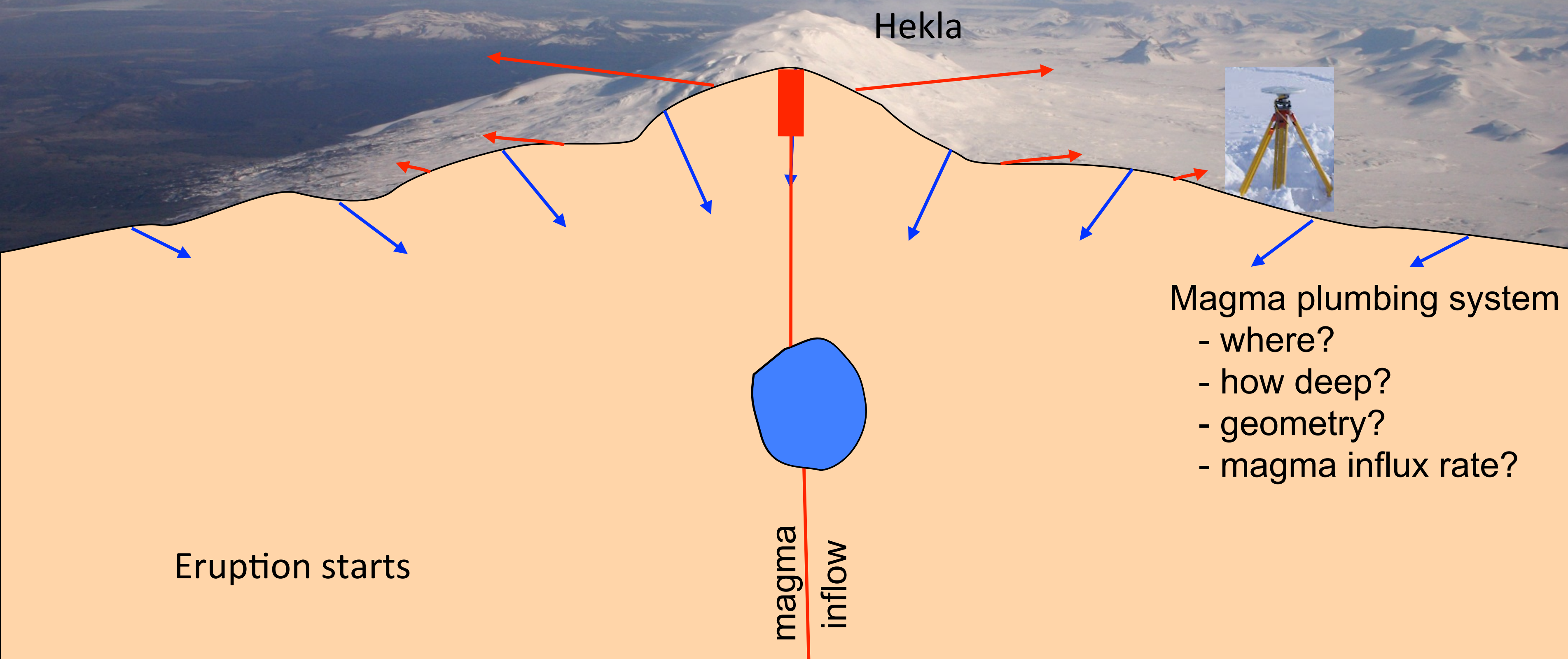


Photo: Matthew Roberts

Volcano Deformation



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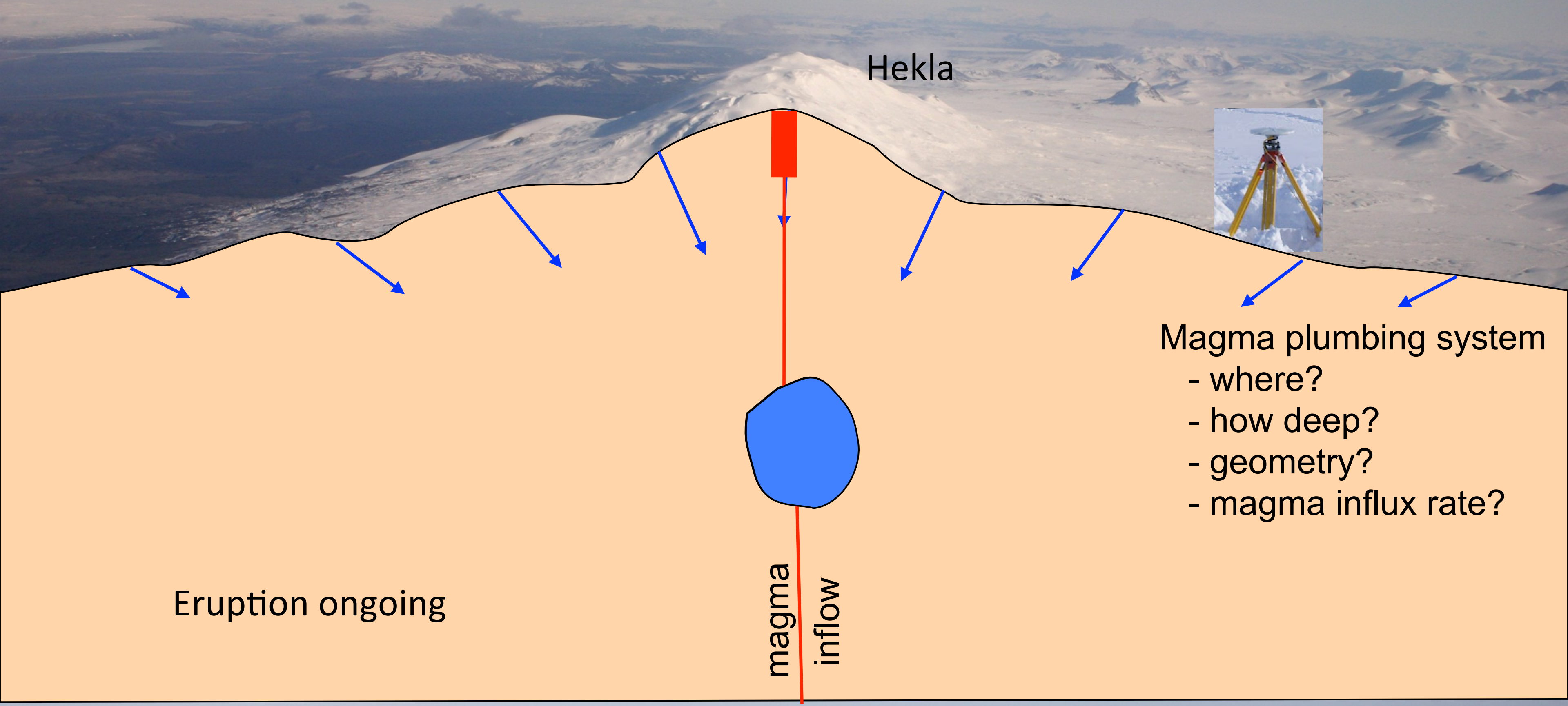
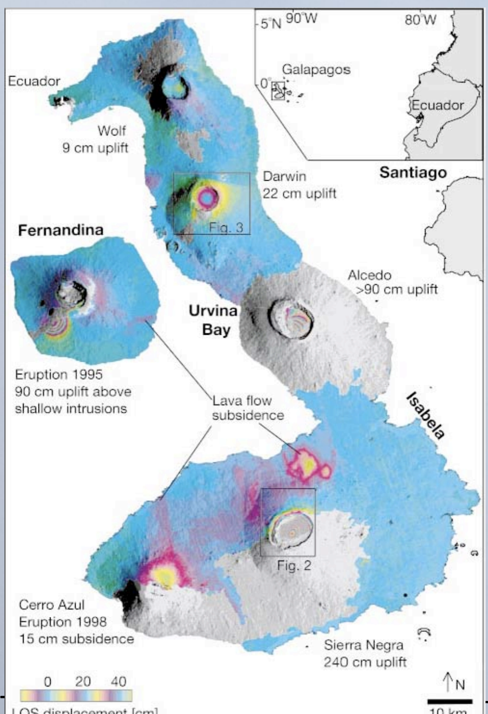


Photo: Matthew Roberts

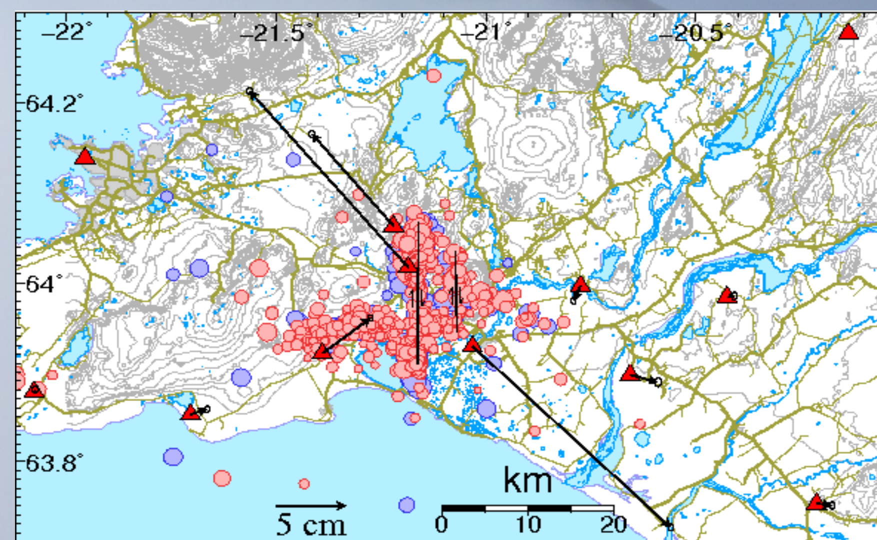
Tools

How do we measure crustal 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).



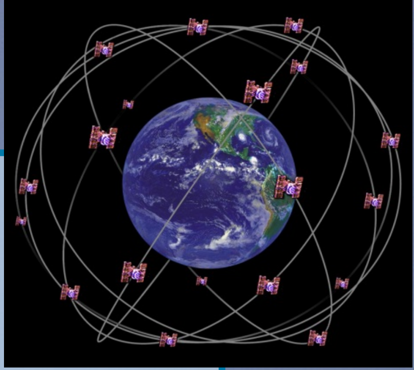
Co-seismic displacements of continuous GPS stations in south Iceland due to two M 6.1 earthquakes in 2008 (black vectors). Faults indicated in black; aftershocks in pink

or Geirsson)

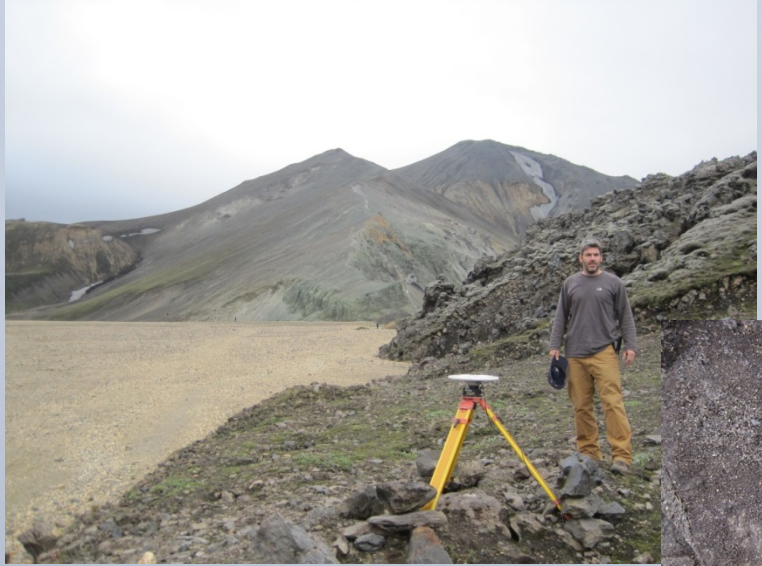
Tools for measuring surface deformation

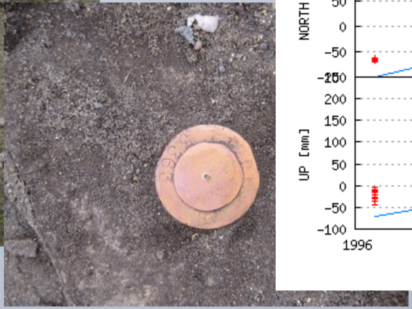
- GPS (GNSS)
  - Episodic, semi-continuous, continuous
  - Kinematic
- InSAR
- Borehole strain meters
- Tilt meters
- Leveling
- Electronic Distance Meters (EDM)
- Triangulation
- Photogrammetry (pixel-tracking)
- Paleo deformation

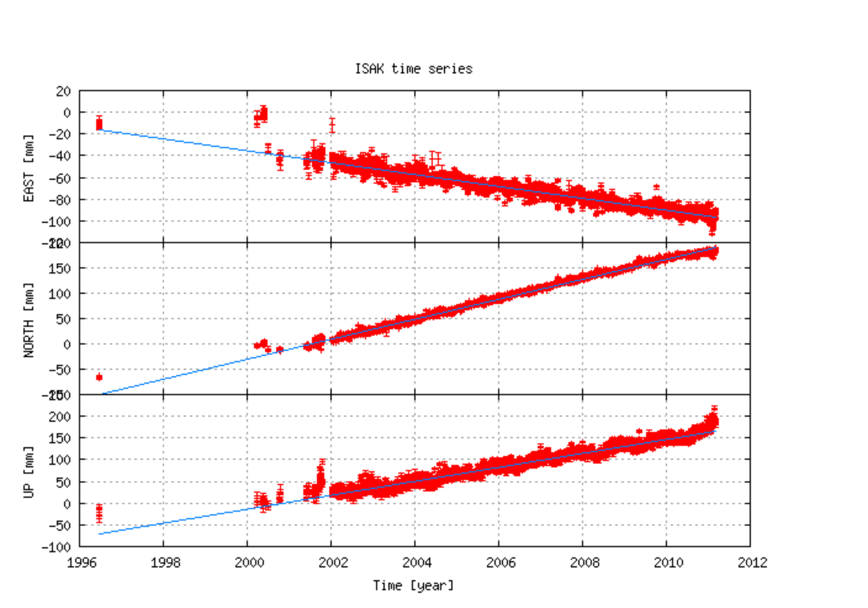
GPS (GNSS)



- “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)







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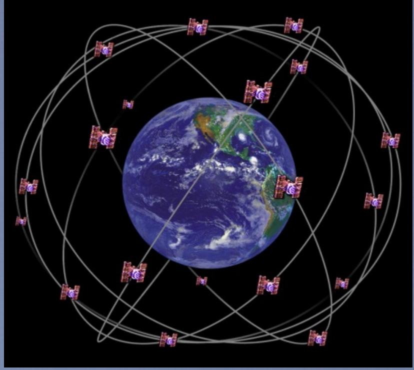
GNSS (Global Navigation Satellite Systems)

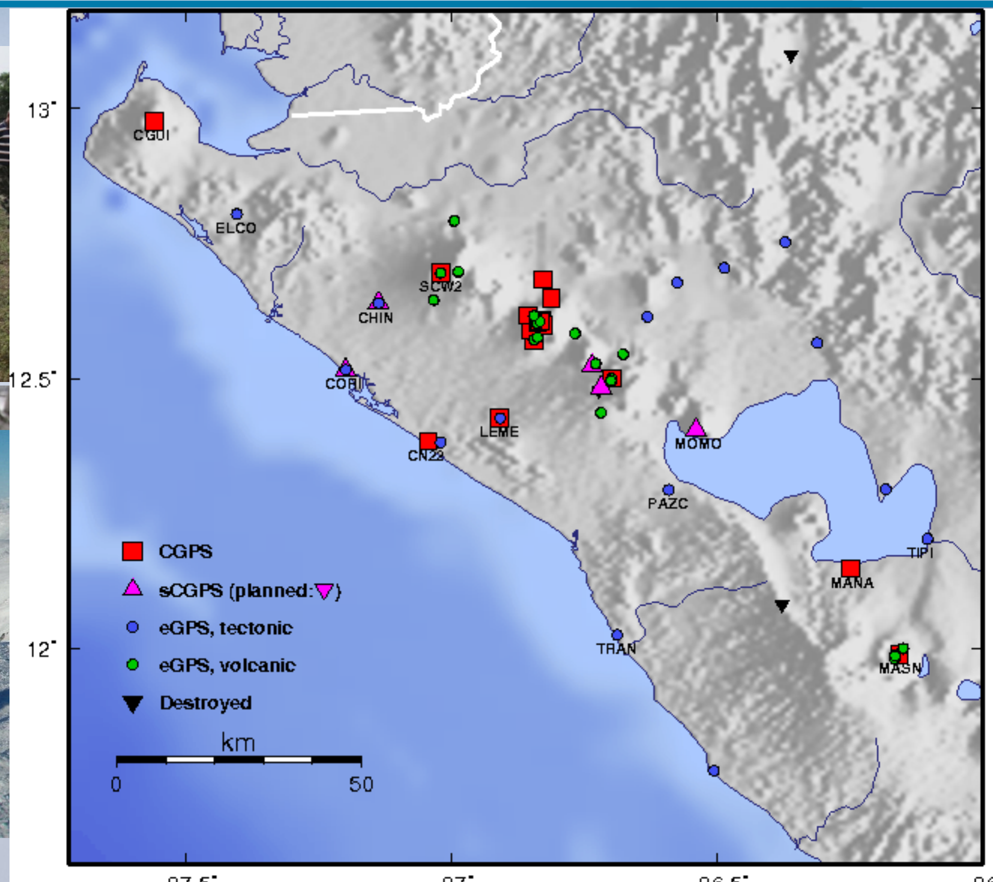


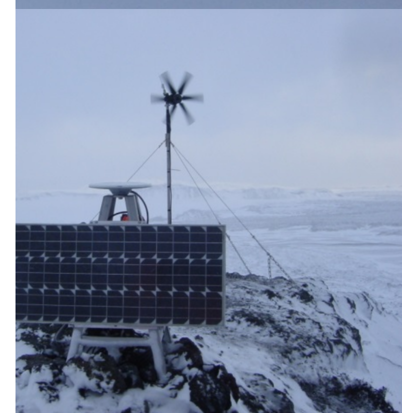
- Different satellite systems
- NAVSTAR (USA), known as “GPS”
- GLONASS (Russia), operational
- COMPASS (China), operational regionally, global operation by 2020
- GALILEO (European Union), should be fully functional by 2020

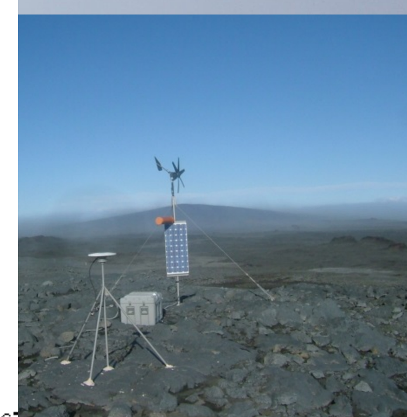
- Likely the improvement on 24-hour solutions will not be dramatic
- Benefits high-rate real-time applications

Episodic and Continuous GPS

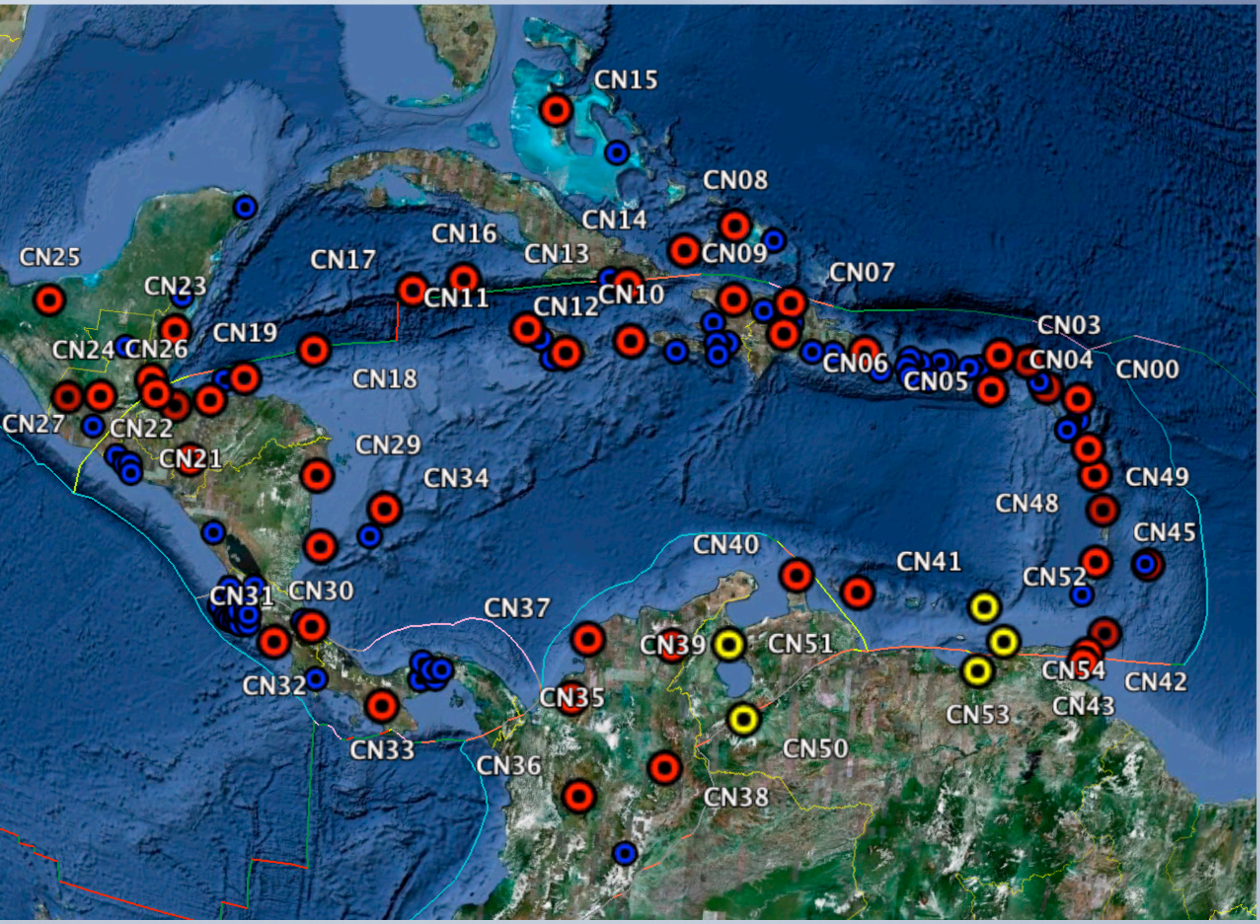
- Continuous networks are important to avoid **temporal aliasing** but expensive
- Episodic observations complement cGPS by improving **spatial density**
  - The networks are surveyed every few months to every few years
  - Each point is observed for 1-4 full days or longer





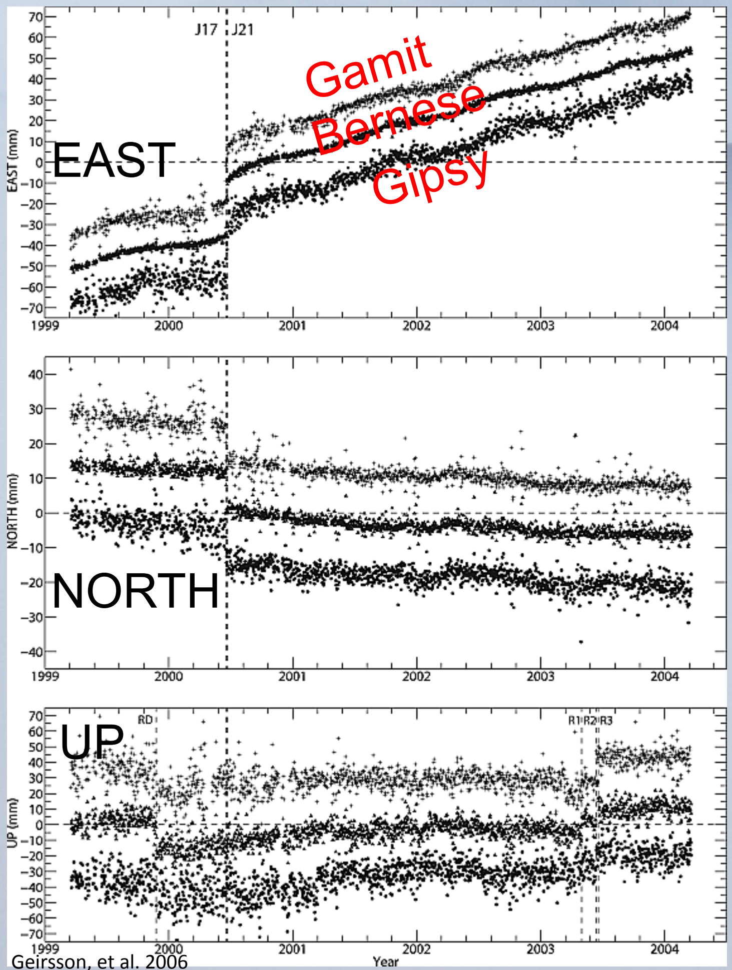


cGPS networks



- COCONet - a backbone network. Free data: “UNAVCO dai server”
- Network of networks
- Earthquake cycle
- Inter-, co-, & post-seismic
- Episodic slow slip
- Plate & block motions
- Volcano deformation
- Magma-Tectonic interactions
- Other uses: base stations for surveys, meteorology

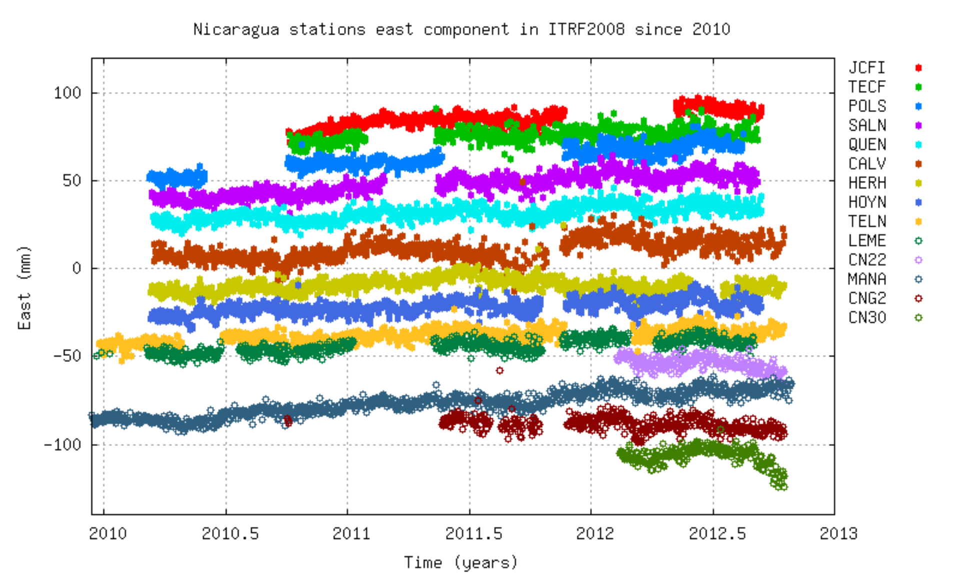
GPS/GNSS processing software

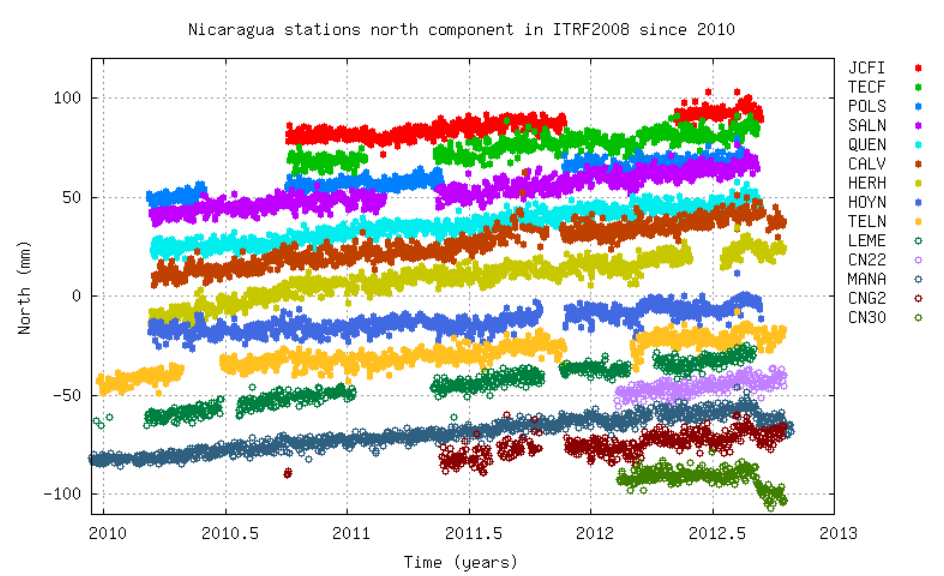


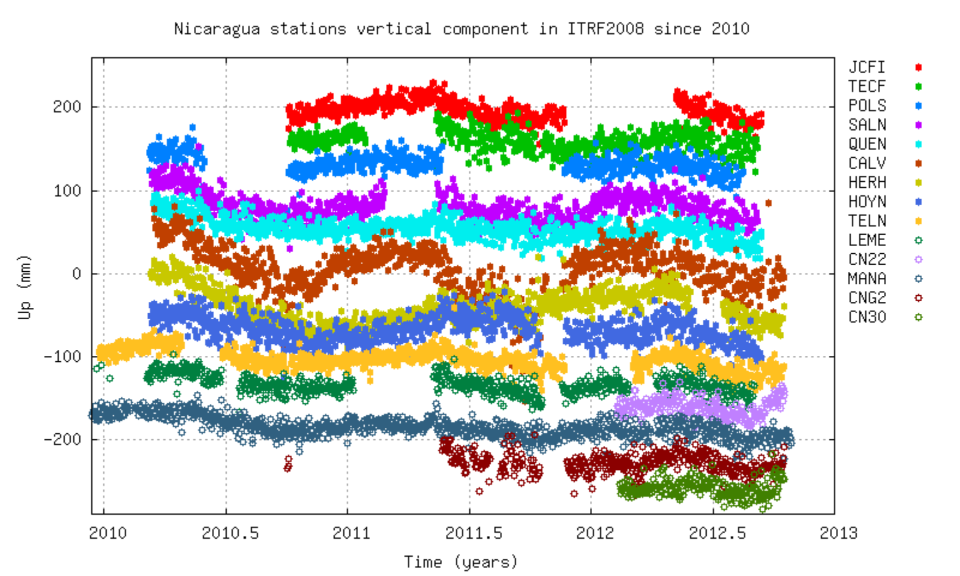
Time series from three different softwares for a 35 km baseline

- 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
  - Accuracy decreases with shorter timespan

GPS/GNSS time series



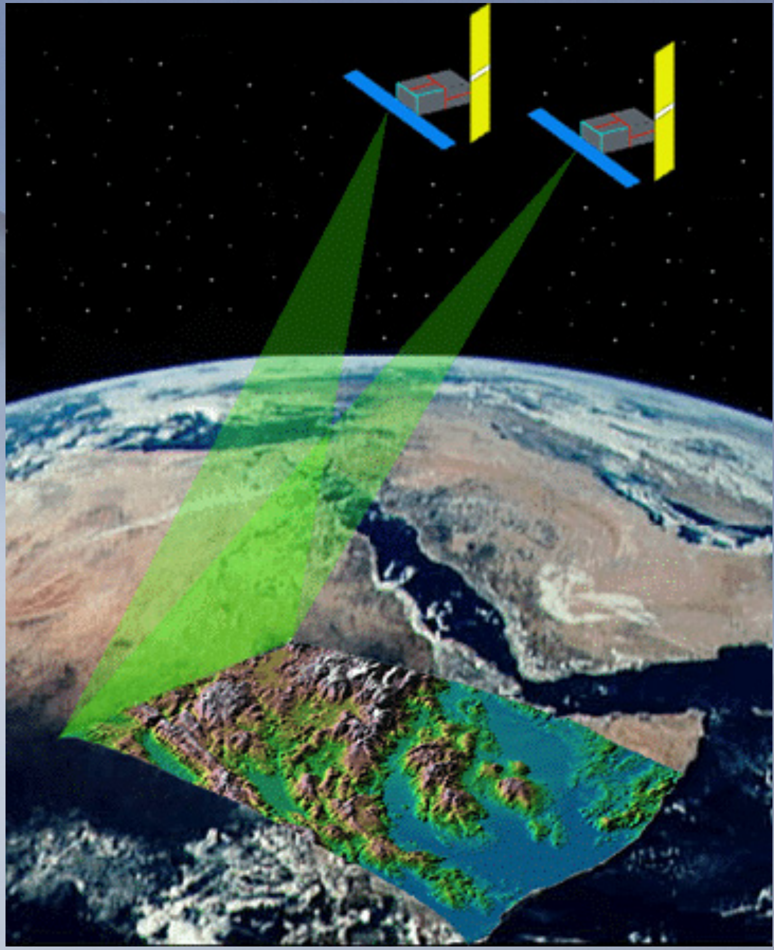


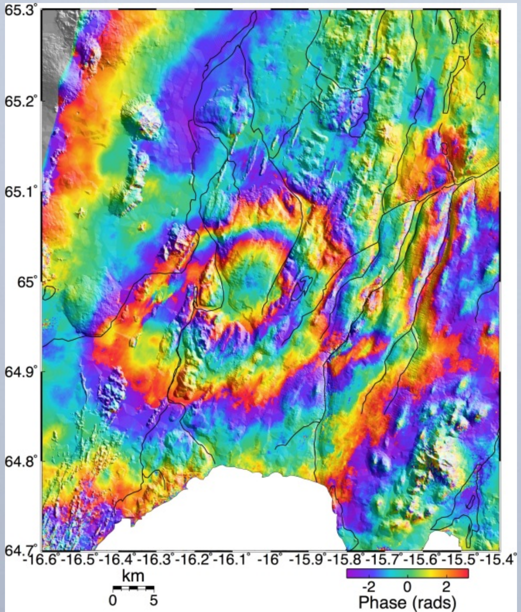


- These time series are from cGPS sites in Nicaragua
- Seasonal signals
- Common-mode network filters
- Benefits of interpreting data from a wide network

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
- <u>Pros:</u> Superb spatial coverage
- <u>Cons:</u> Long repeat-time; poor absolute vertical reference; limited footprint; vegetation & snow cover issues

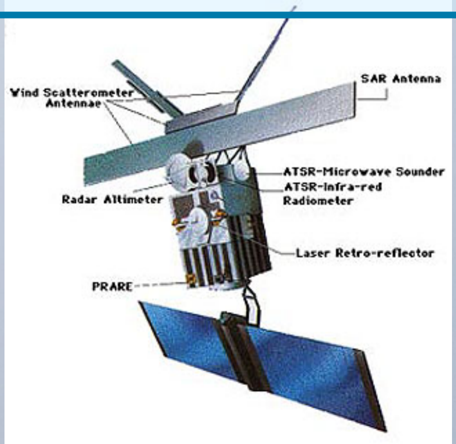




Interferogram from a 45° dipping ~planar intrusion at 14 km depth. Upptyppingar, Iceland.
Courtesy of A. Hooper

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

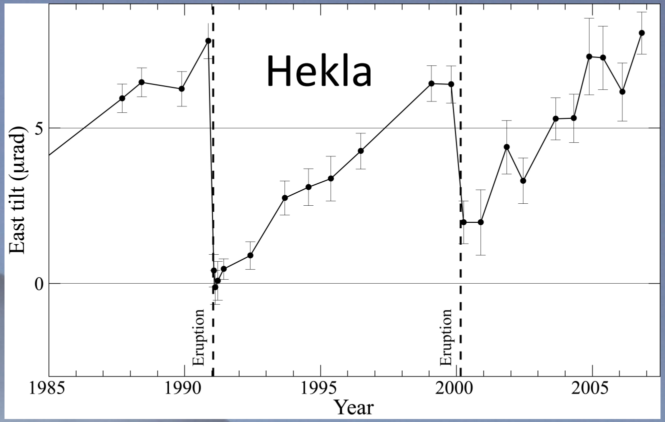


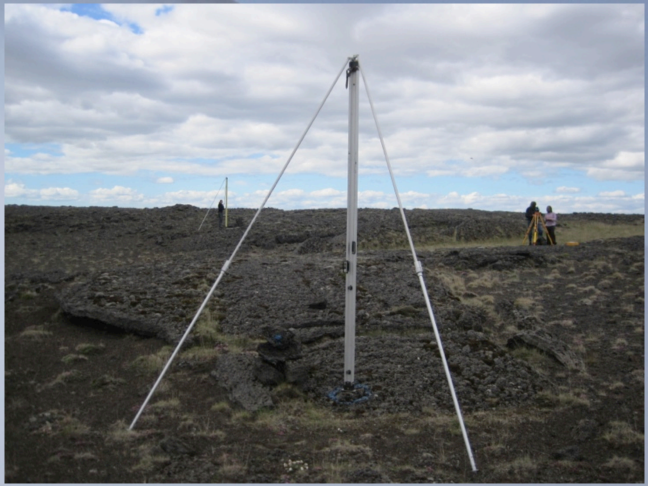
InSAR processing

- 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

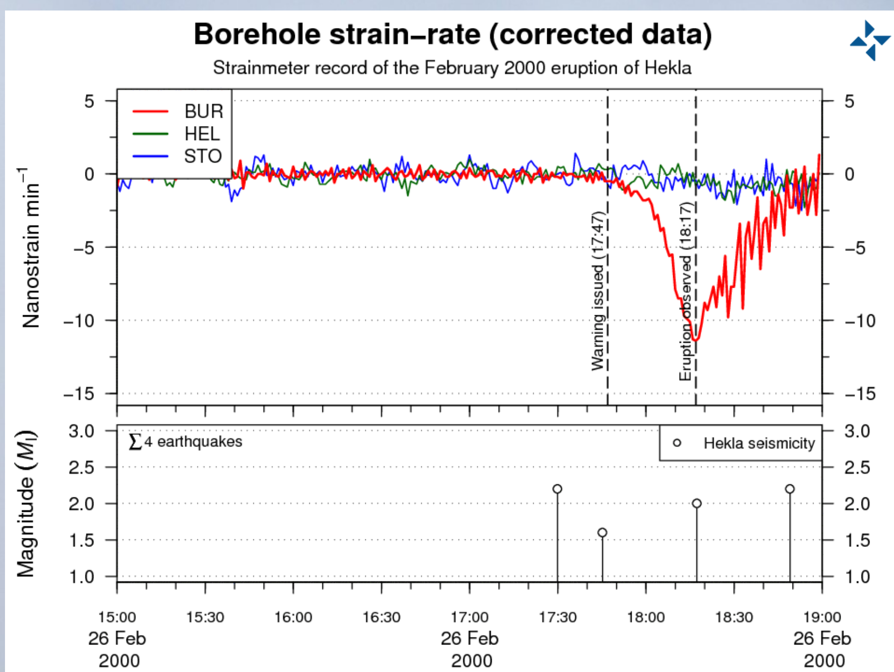
- Measure the temporal variations in surface slope
- Different ways to measure tilt include
  - Electrolyte bubble levels
  - Long-base fluid tiltmeters
  - Short leveling lines (T, L, O, X – shaped)
  - Lake leveling
- Pros: Rapid and independent results; high sampling rates possible; can be very sensitive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

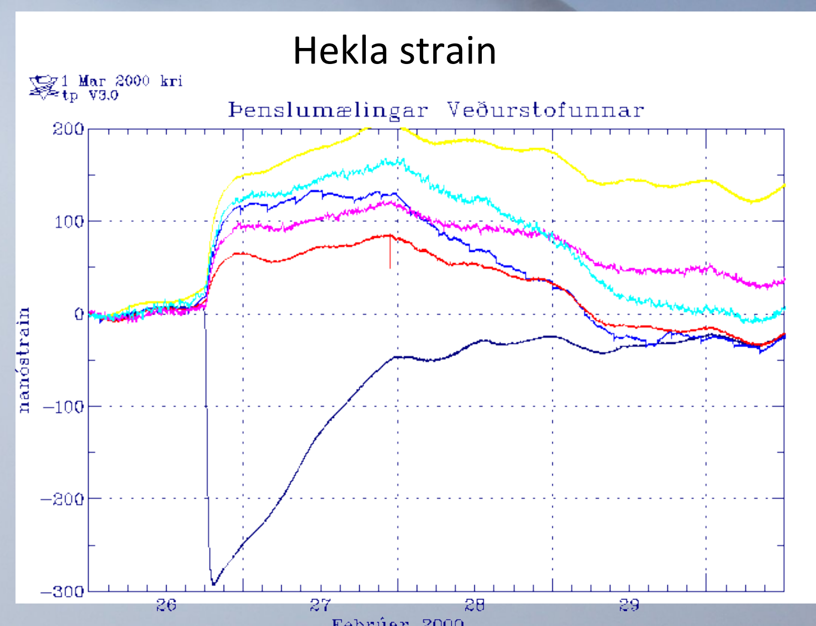




Borehole strain meters

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





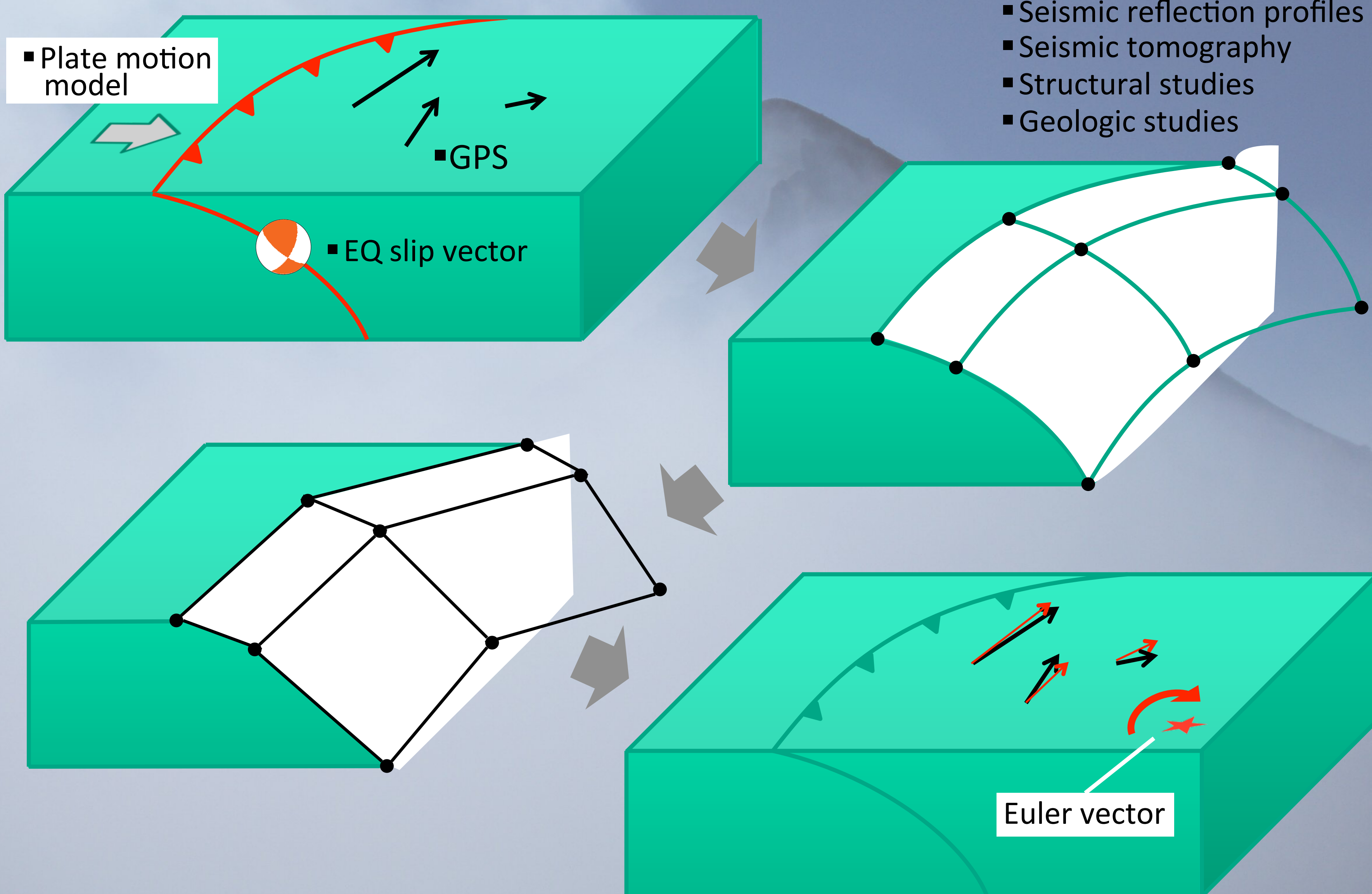
Plots of strain rate and strain for the Hekla 2000 eruption


Deformation models

Modeling of volcanic and tectonic deformation

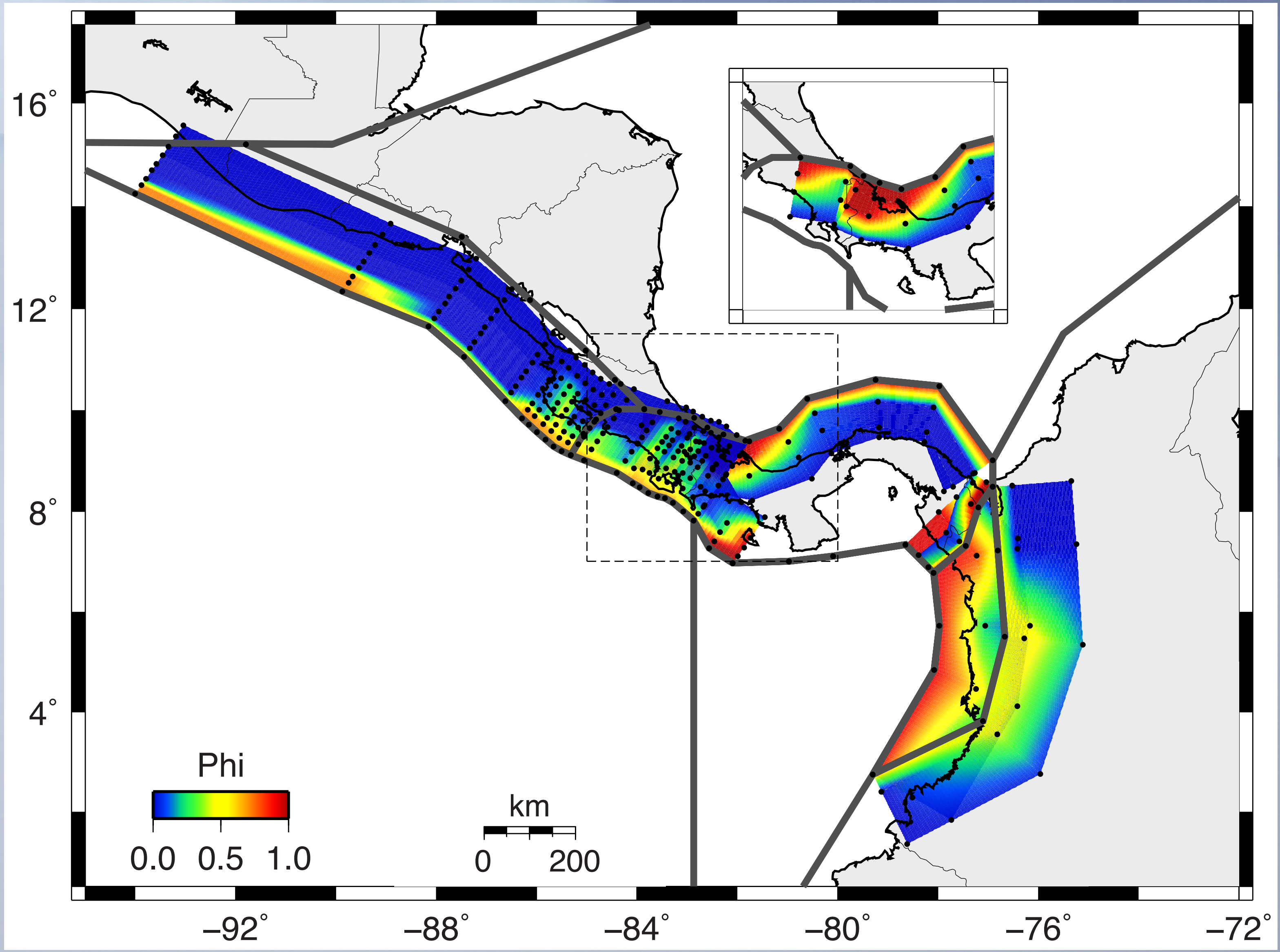
- Interpret data in terms of source location (plate boundary location, magma chamber, magma intrusion, ...), source geometry (fault strike and shape, interseismic coupling; volcanic: sphere, dike, sill, ...), source strength (amount of slip or slip rate, magma volume or volume rate, viscoelastic response)
- Analytical models in an elastic half-space
- Finite Element Modeling
- Data inversions & forward models
- Complications
  - Topography
  - Rheology
  - Other deformation processes
    - Loading/unloading
  - Spatial and temporal aliasing

Modeling of tectonic deformation – block models



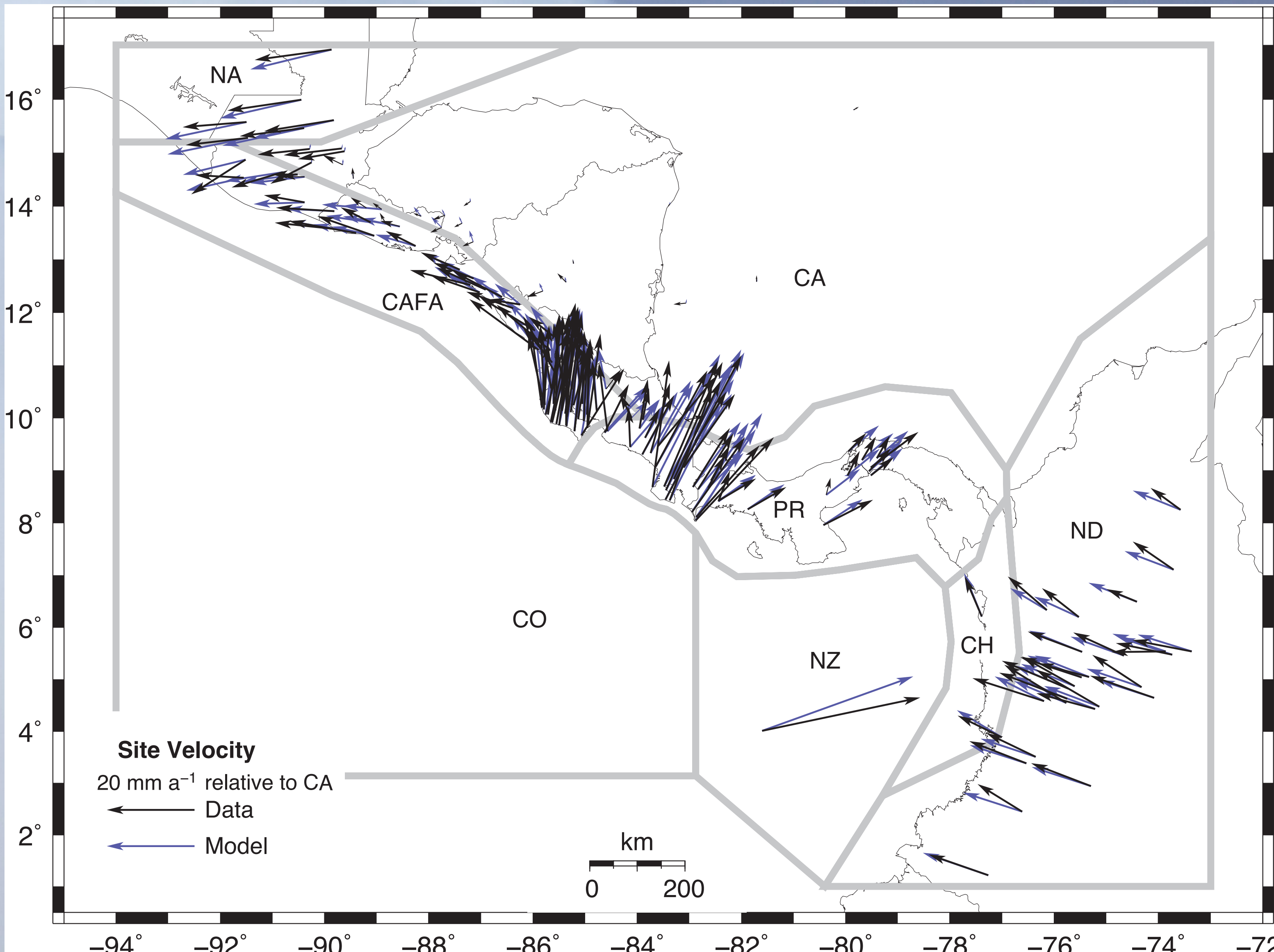
Graphics courtesy of Daisuke Kobayashi

Modeling of tectonic deformation – block models



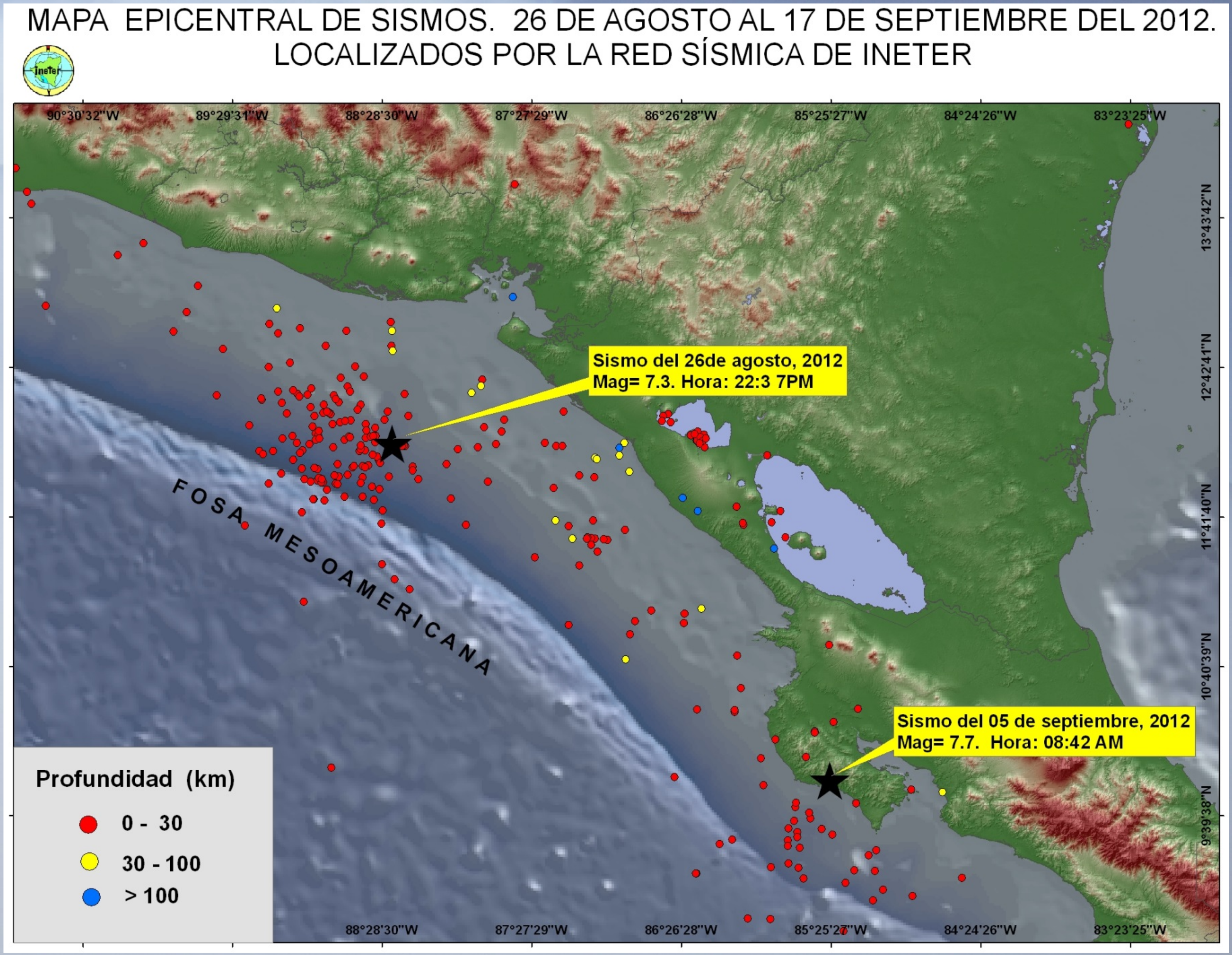
Kobayashi et al., in preparation

Modeling of tectonic deformation – block models



Kobayashi et al., in preparation

The 2012 El Salvador and Costa Rica earthquakes



Tectonic and volcanic geodesy (Halldor Geirsson)

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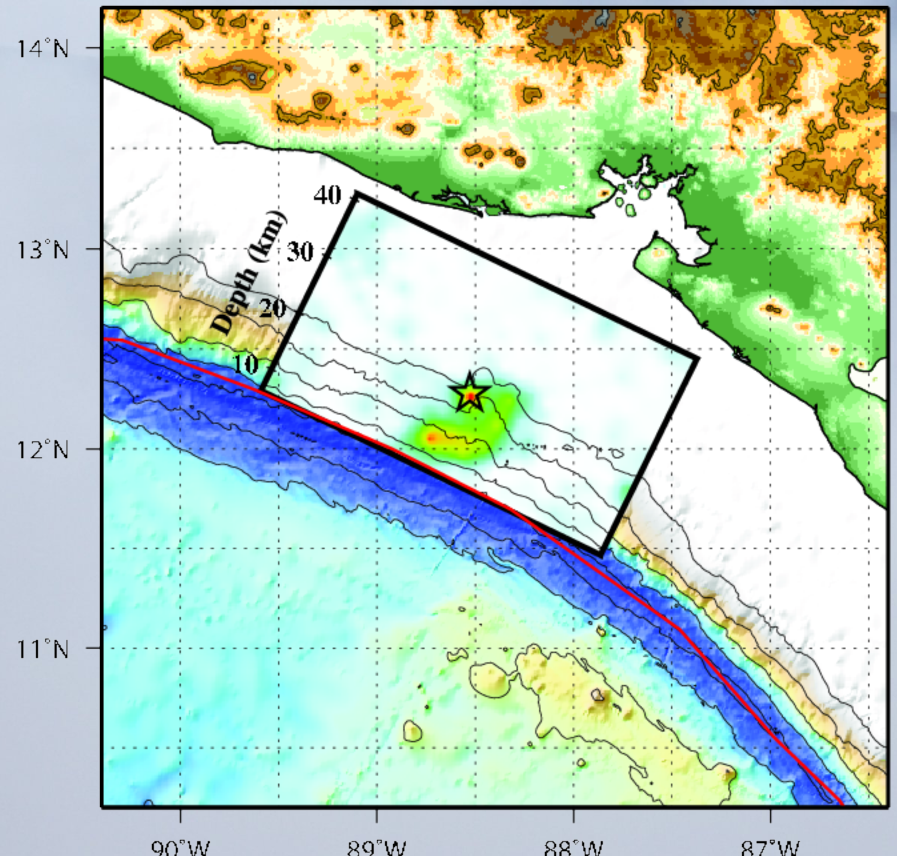
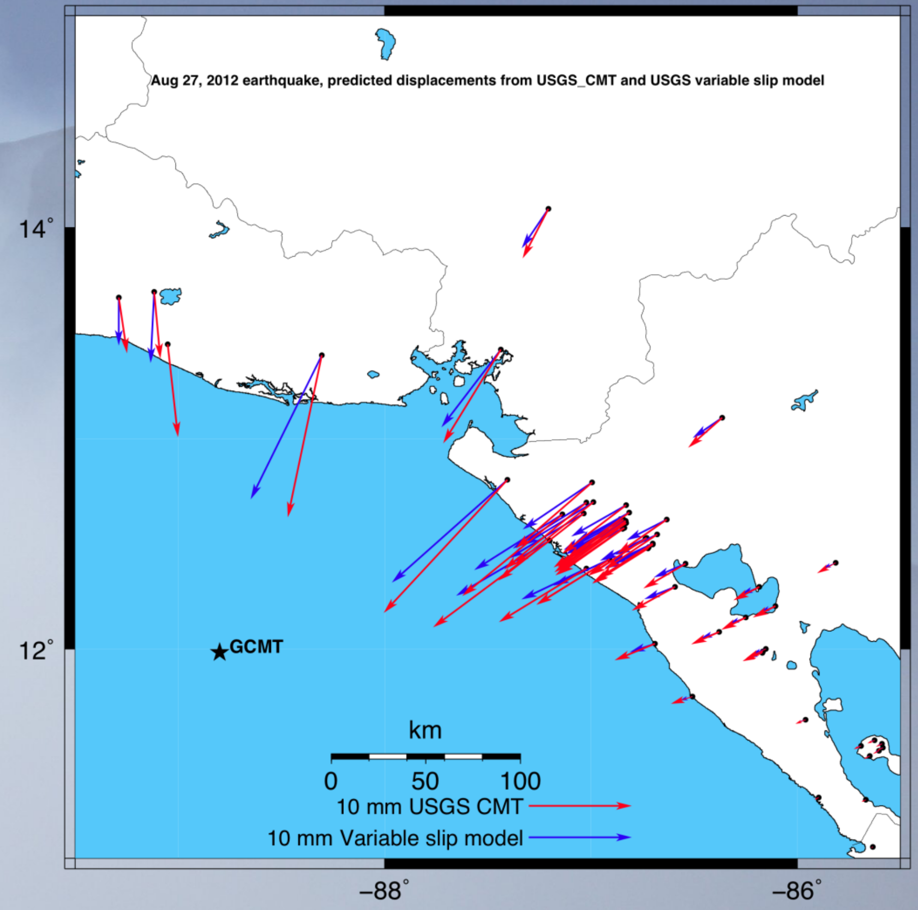


G. Hayes (USGS NEIC, 2012)



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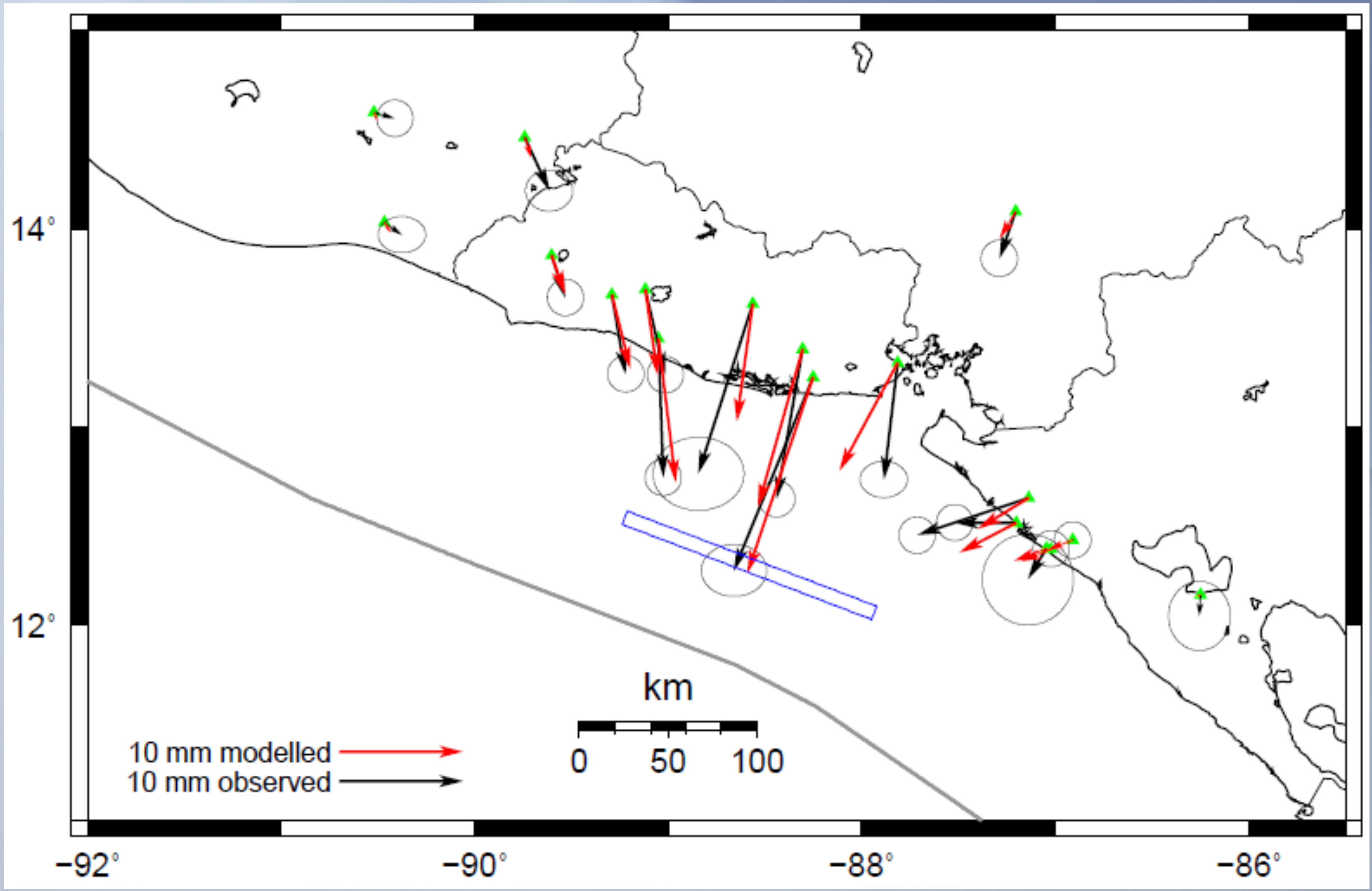

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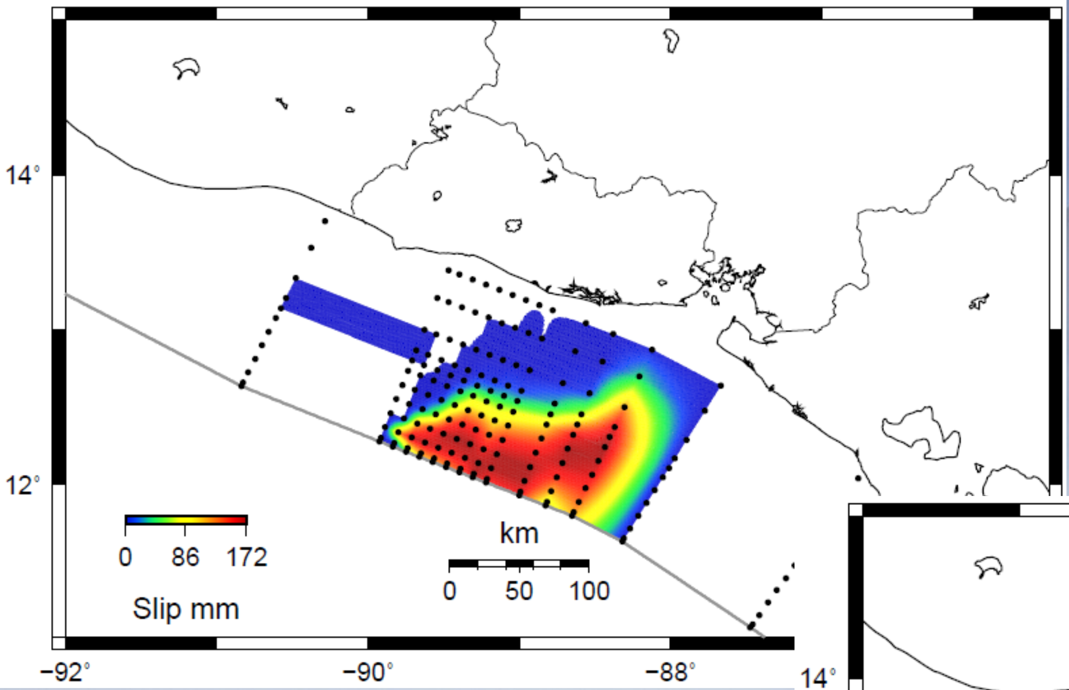
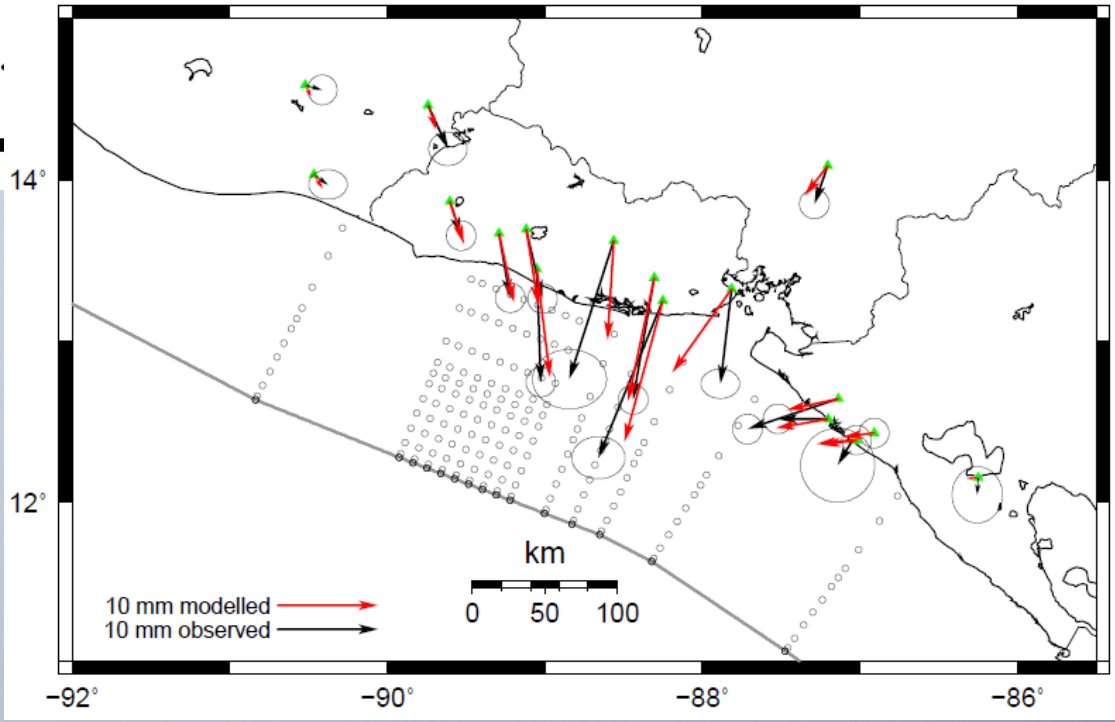
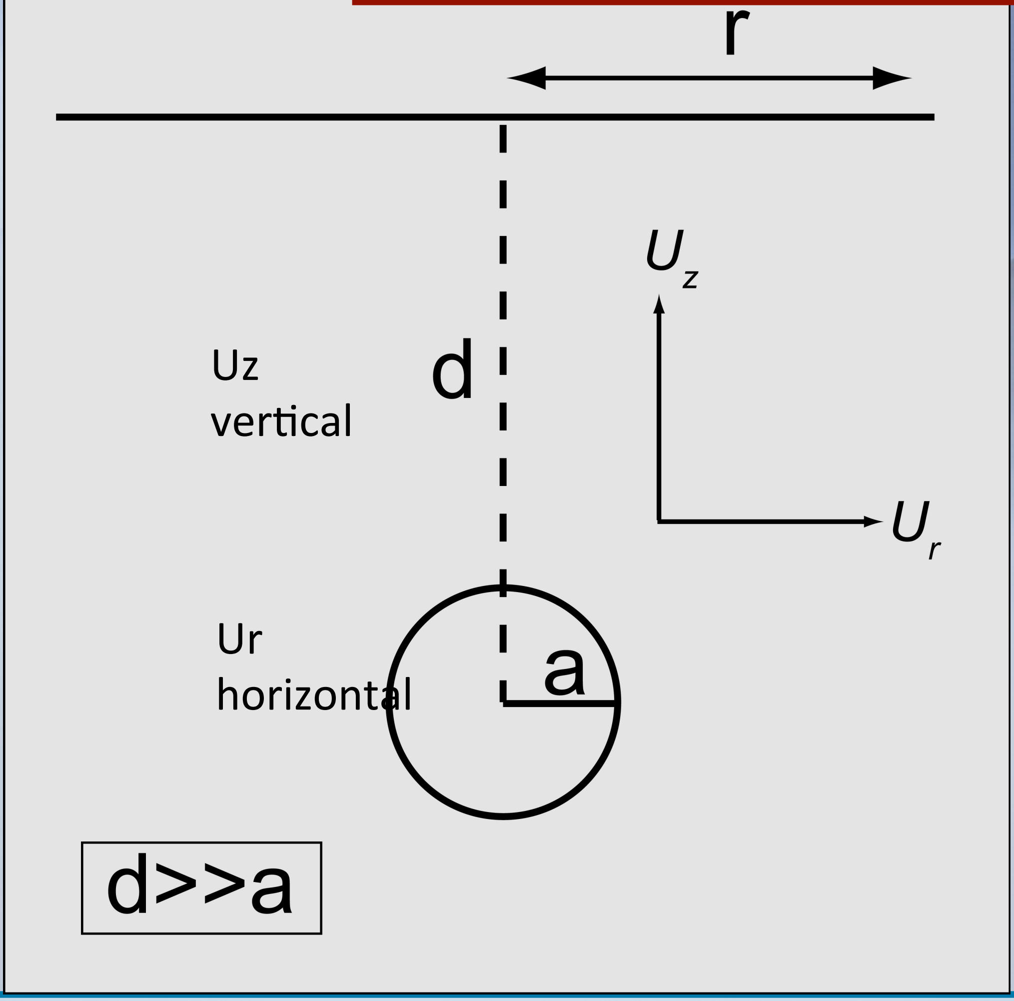




Tectonic and volcanic geodesy (Halldor Geirsson)

Volcanic deformation: The "Mogi model"



- 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

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

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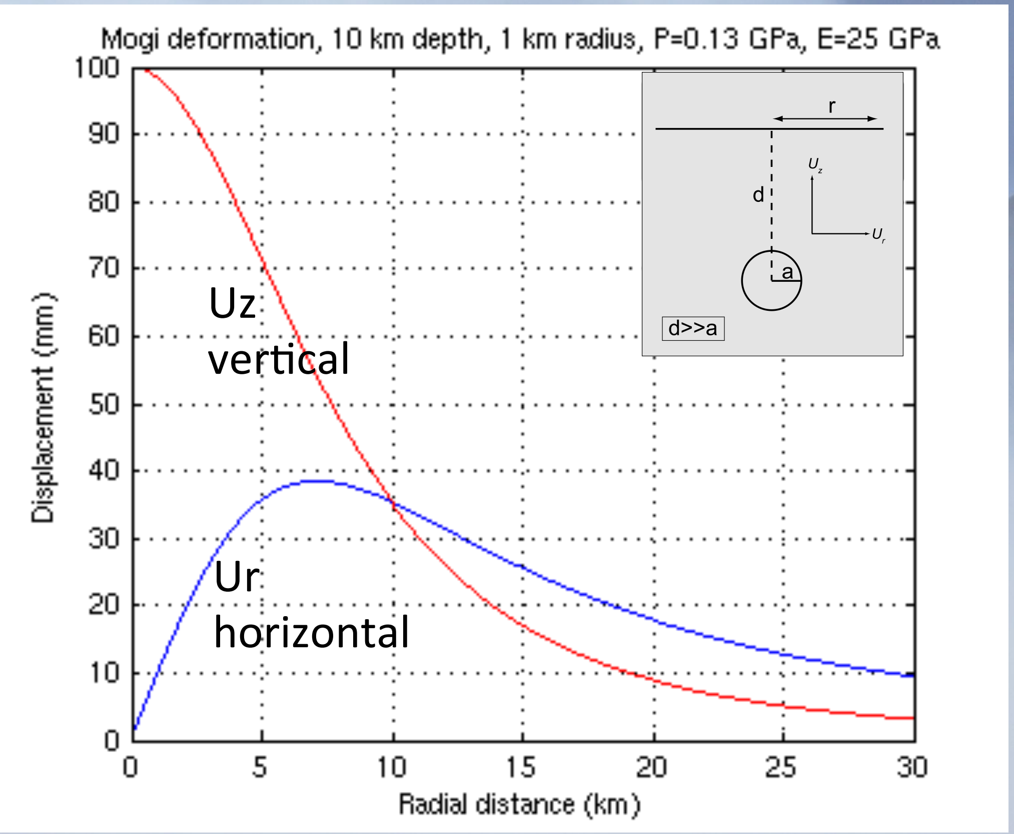

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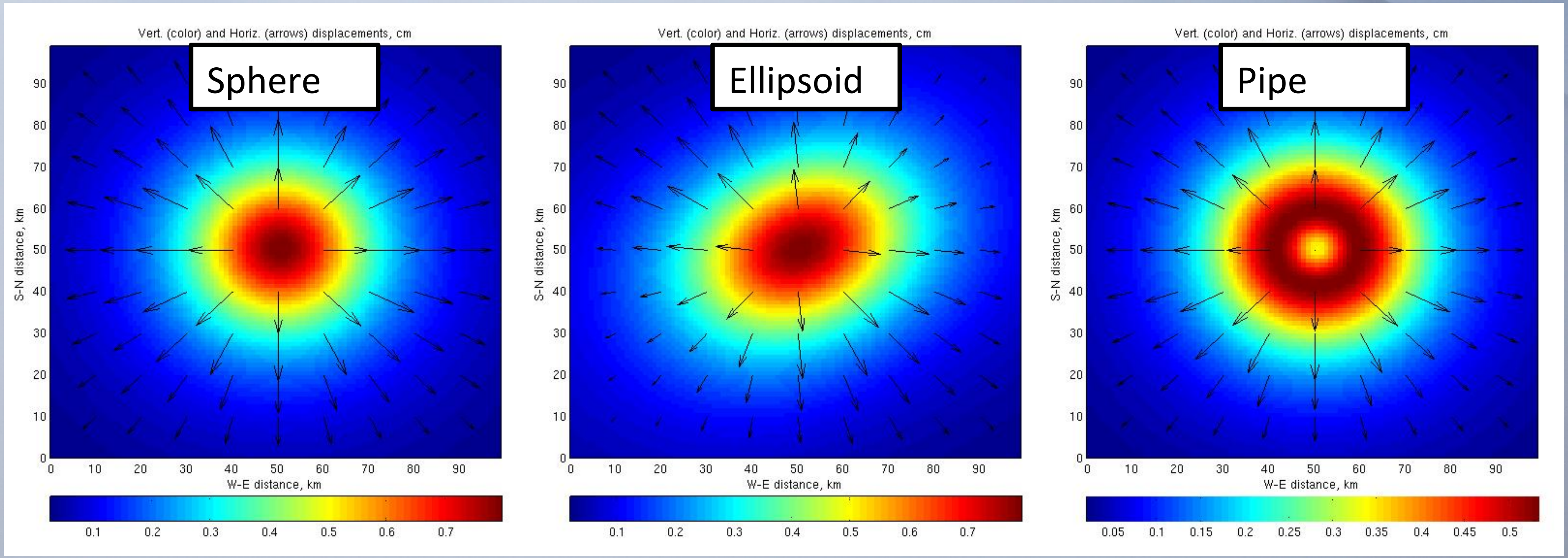
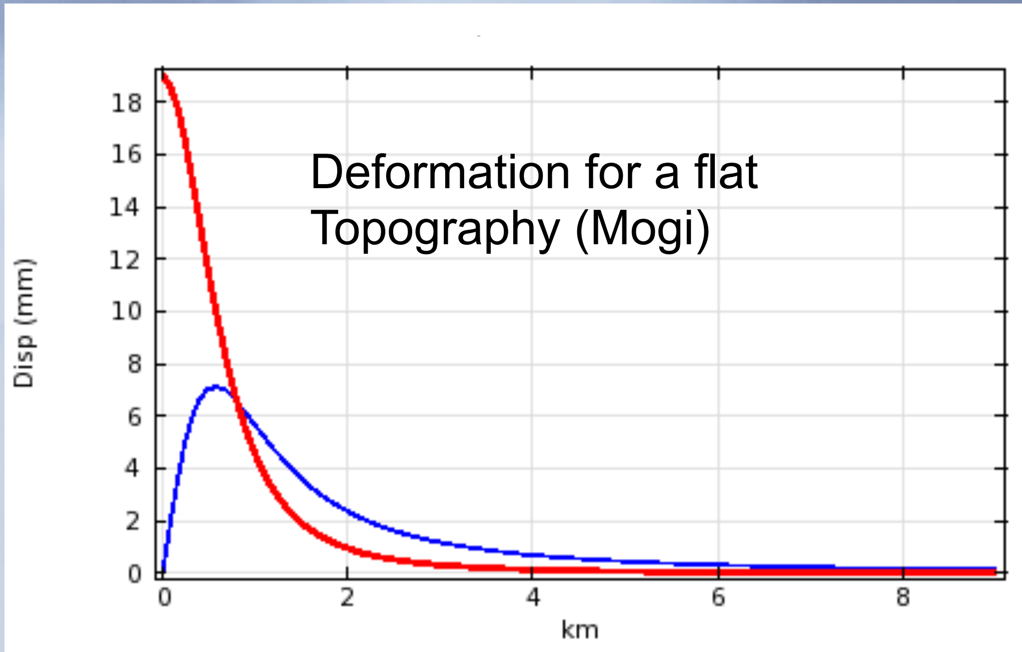
Other shapes of deformation sources

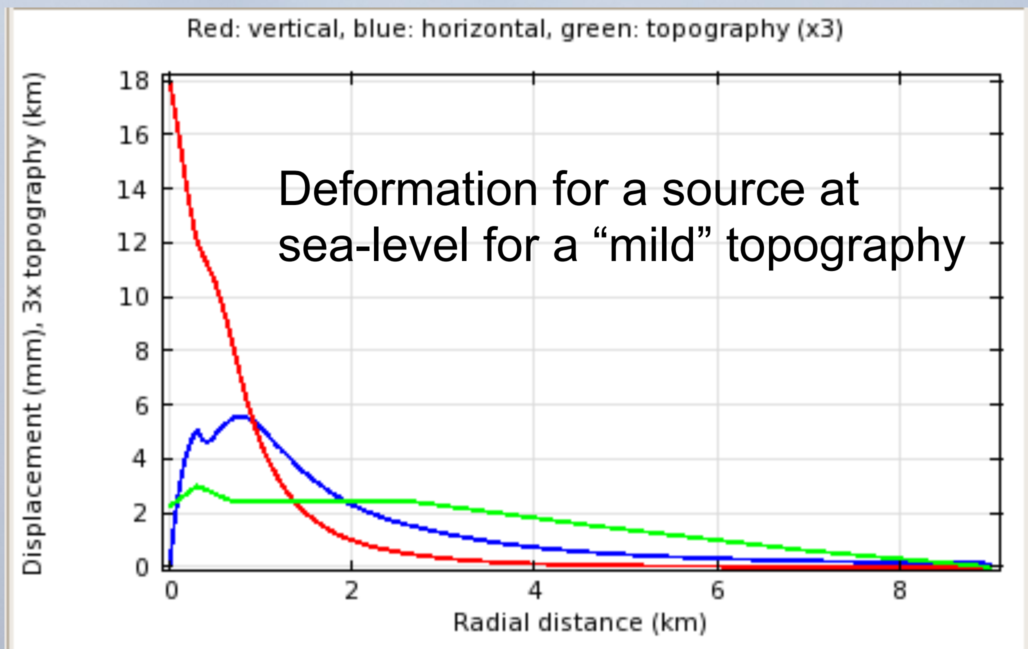
- Ellipsoidal, pipe (open and closed), dike (rectangular, circular), sill (rectangular, circular), penny shaped crack, …
- Dikes and sills of spatially (and/or temporarily) variable opening
- Mickey Mouse (arbitrary shapes – FEM modeling)
- Often the data does not allow us to distinguish between different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

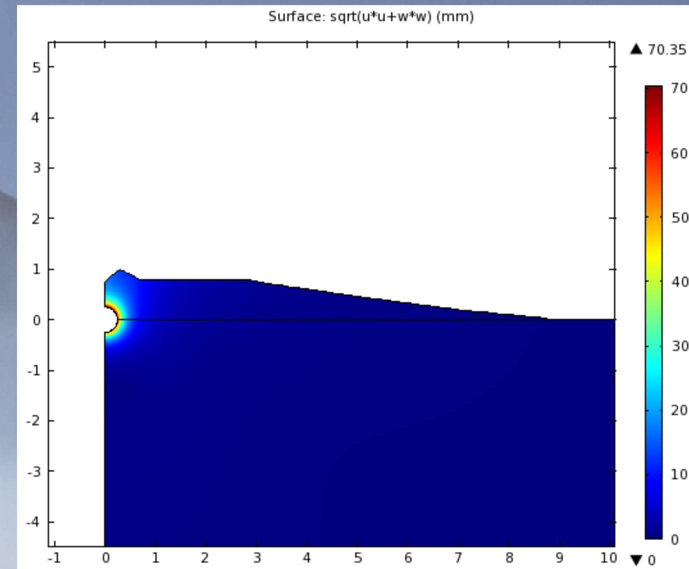


Tectonic and volcanic geodesy (Halldor Geirsson)

Effects of topography

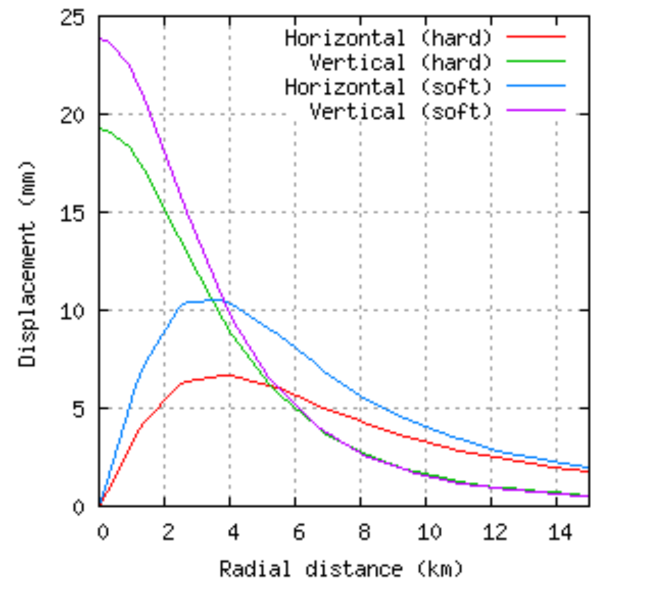


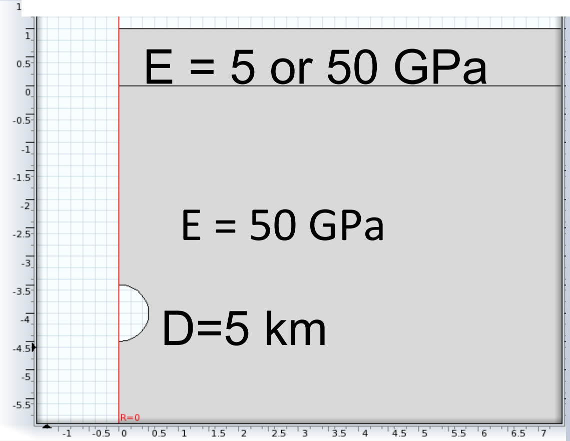




Topography is not very important even for rather shallow sources. The source essentially has to be within the edifice, or the topography quite steep for topography to matter.

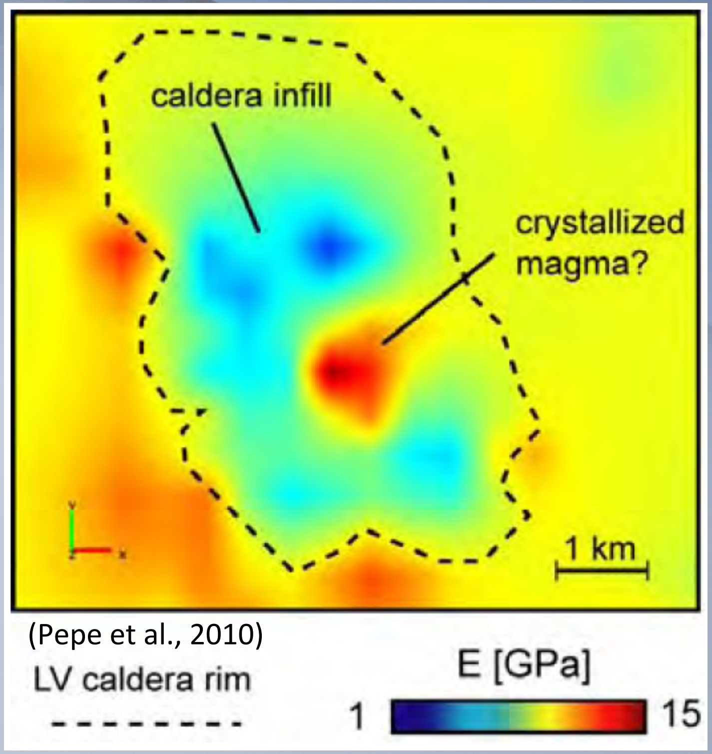
Rheology matters





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

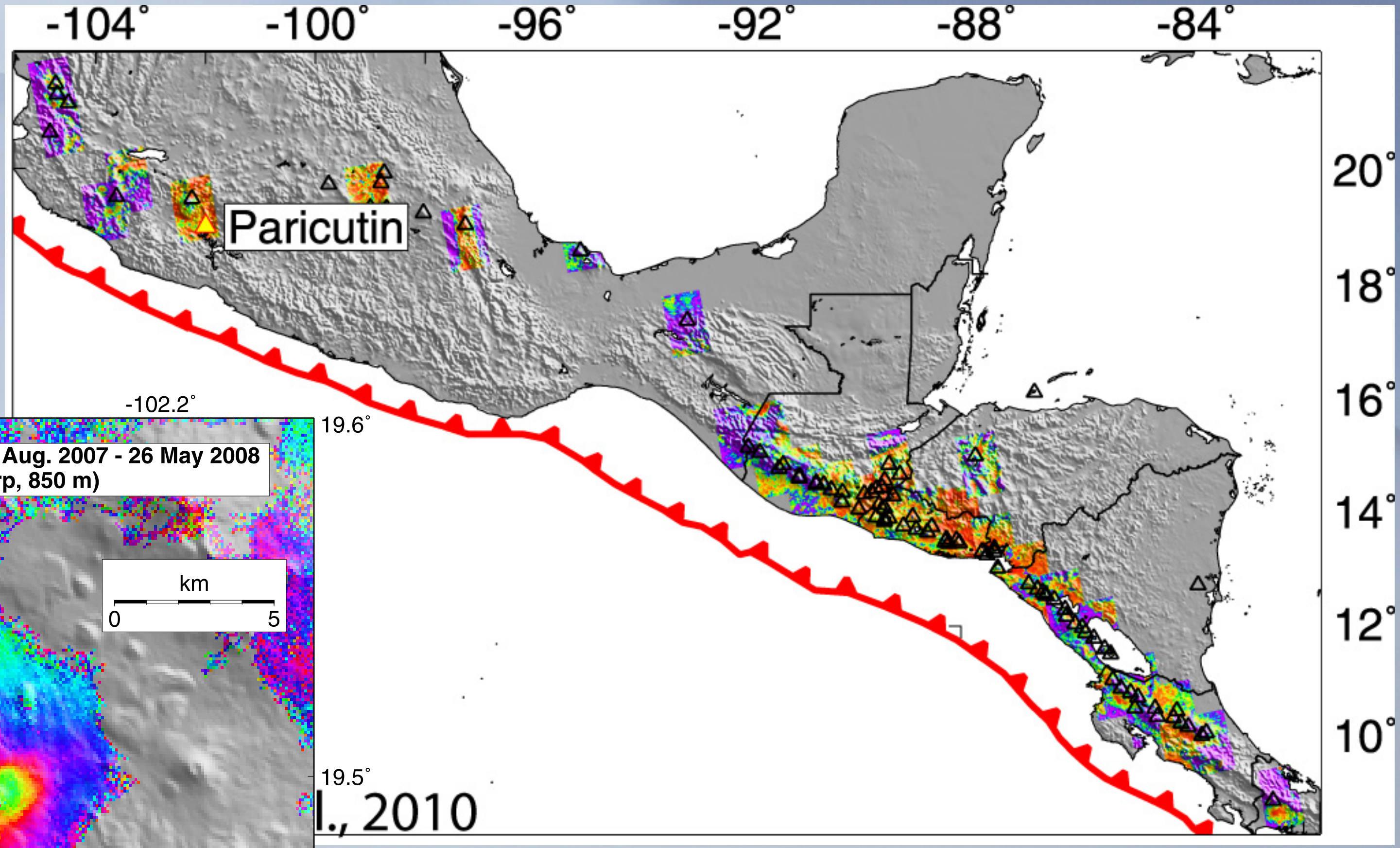
3-D elastic parameters from seismic studies (tomography) can be used as input into deformation models

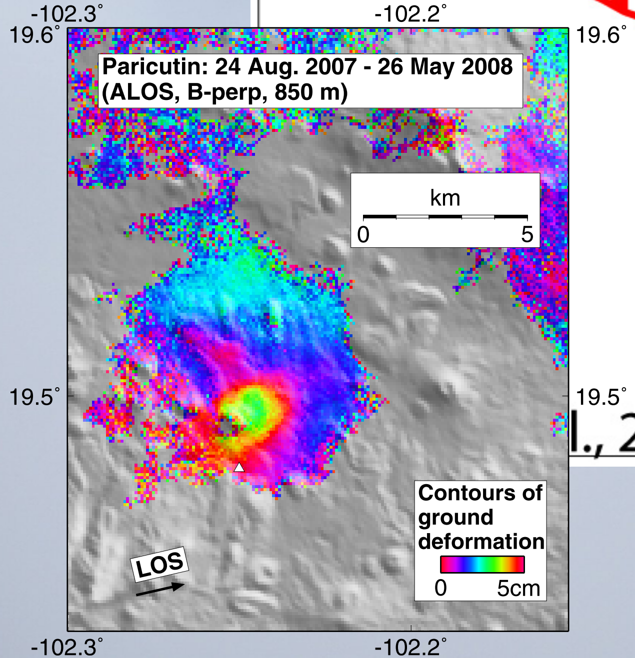


Variable Young's modulus at 1 km depth in Long Valley Caldera from seismic tomography

Case studies

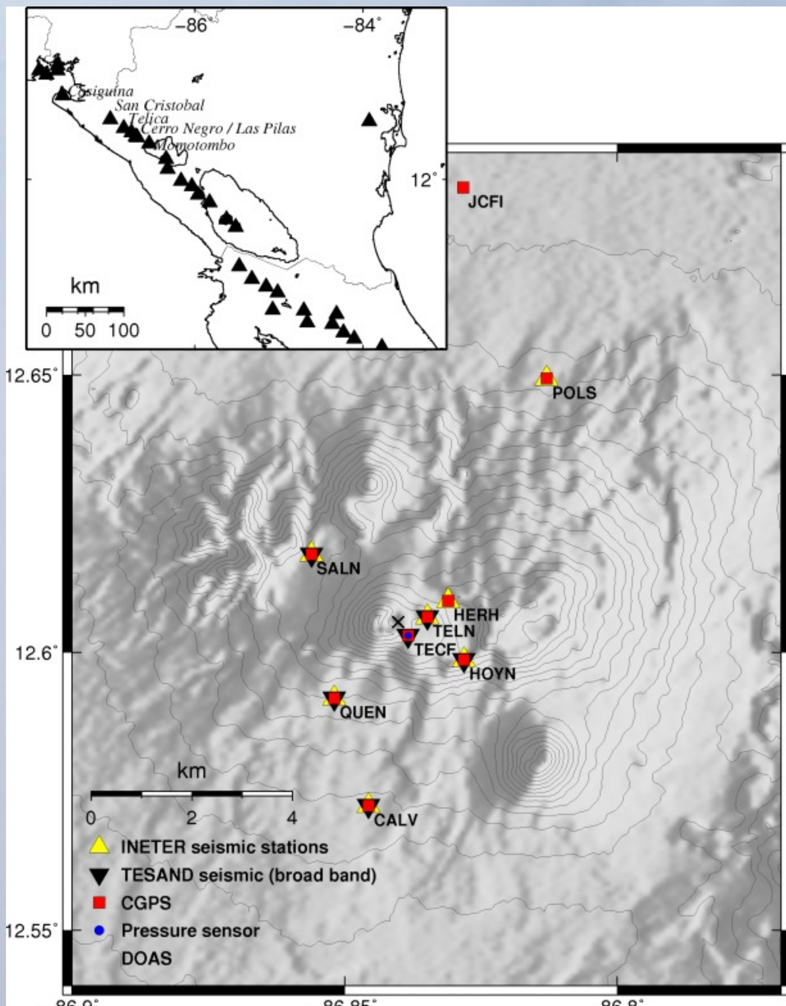
InSAR surveys of Central American volcanoes show little deformation (over ~ 1 year)

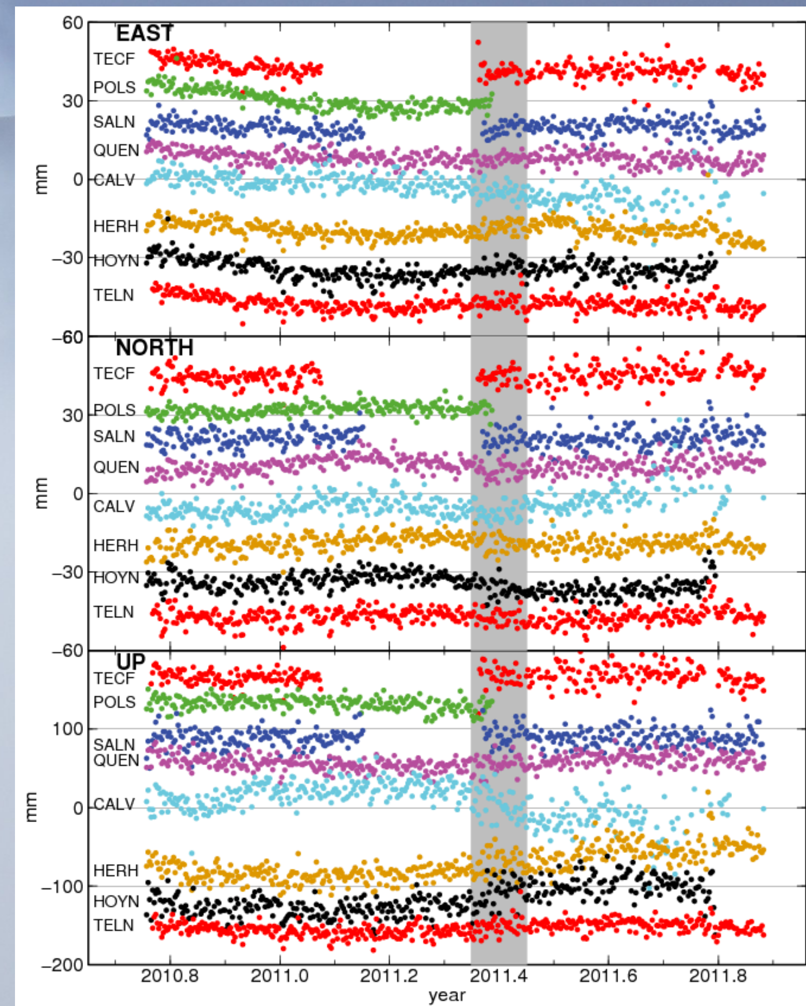




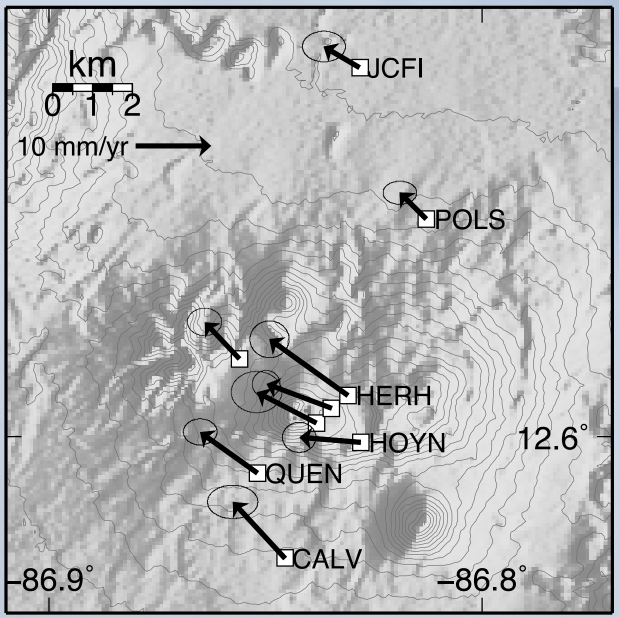
Tectonic and volcanic geodesy (Halldor Geirsson)

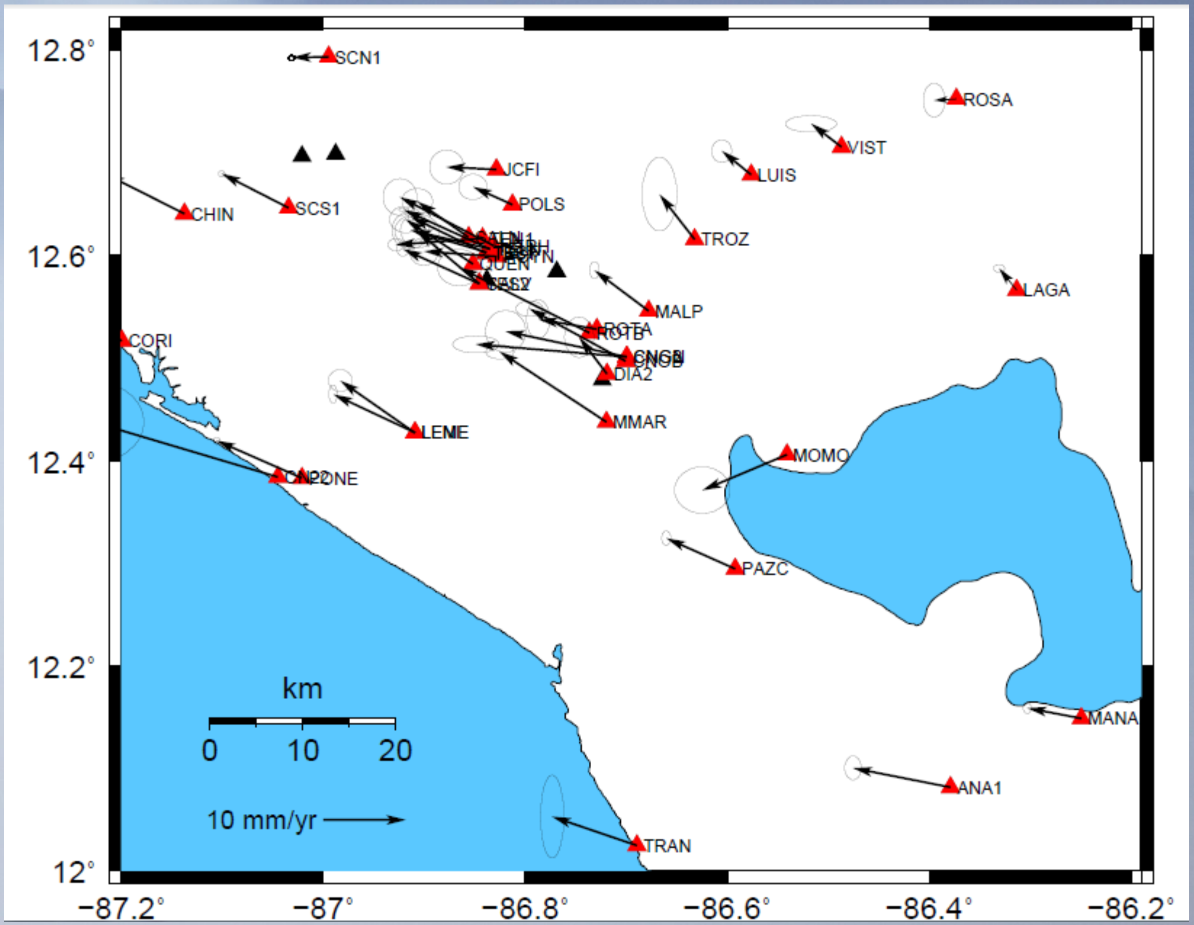
No detectable deformation was observed for the 2011 Telica (Nicaragua) eruption





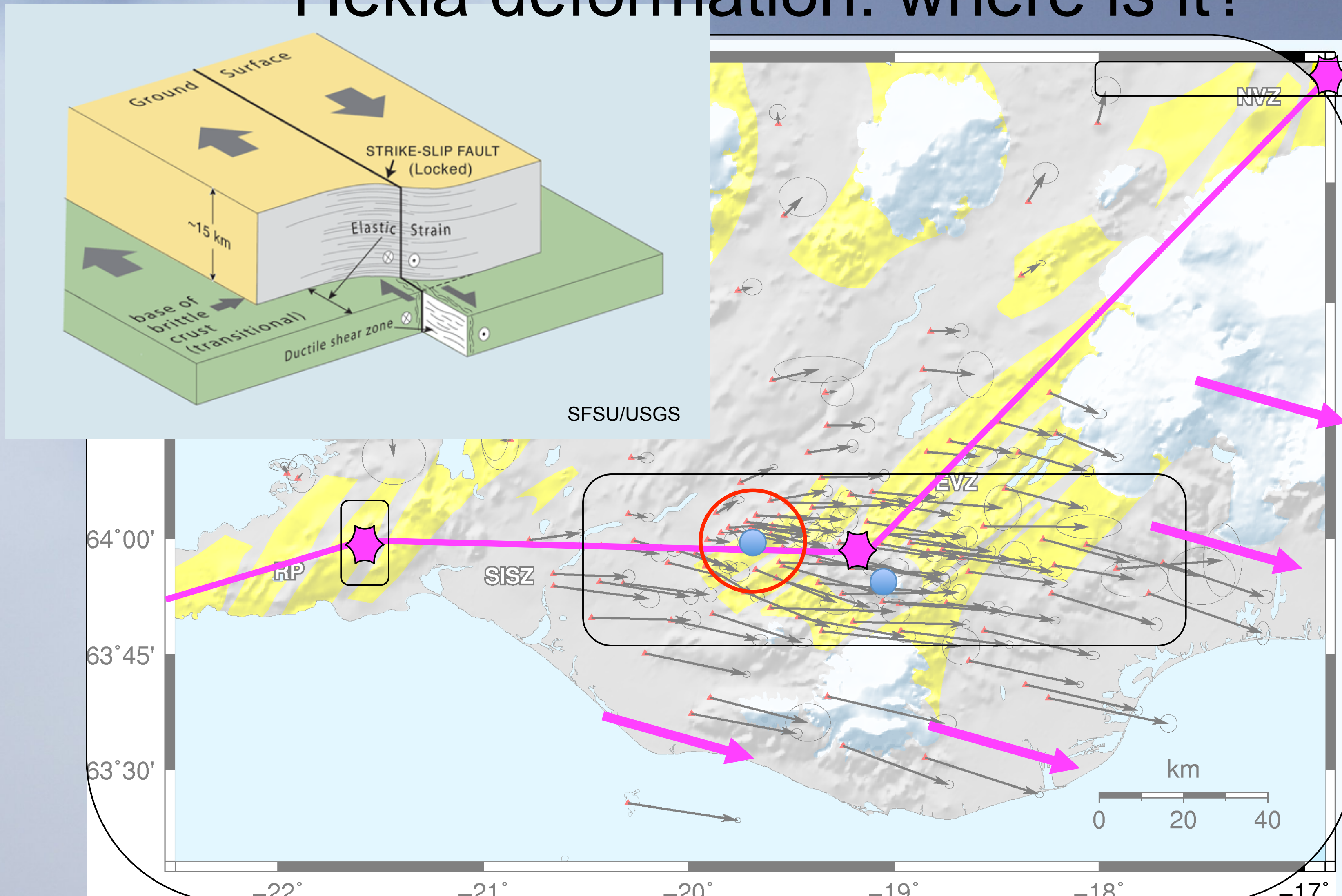
However, Telica is in the shear zone of the Forearc – Caribbean boundary





Parts of data courtesy of Glen Mattioli

Hekla deformation: where is it?



Geirsson et al., 2012

GPS velocities, relative to N. America, 2000-2010

Time series corrected for 2008 co-seismic offsets

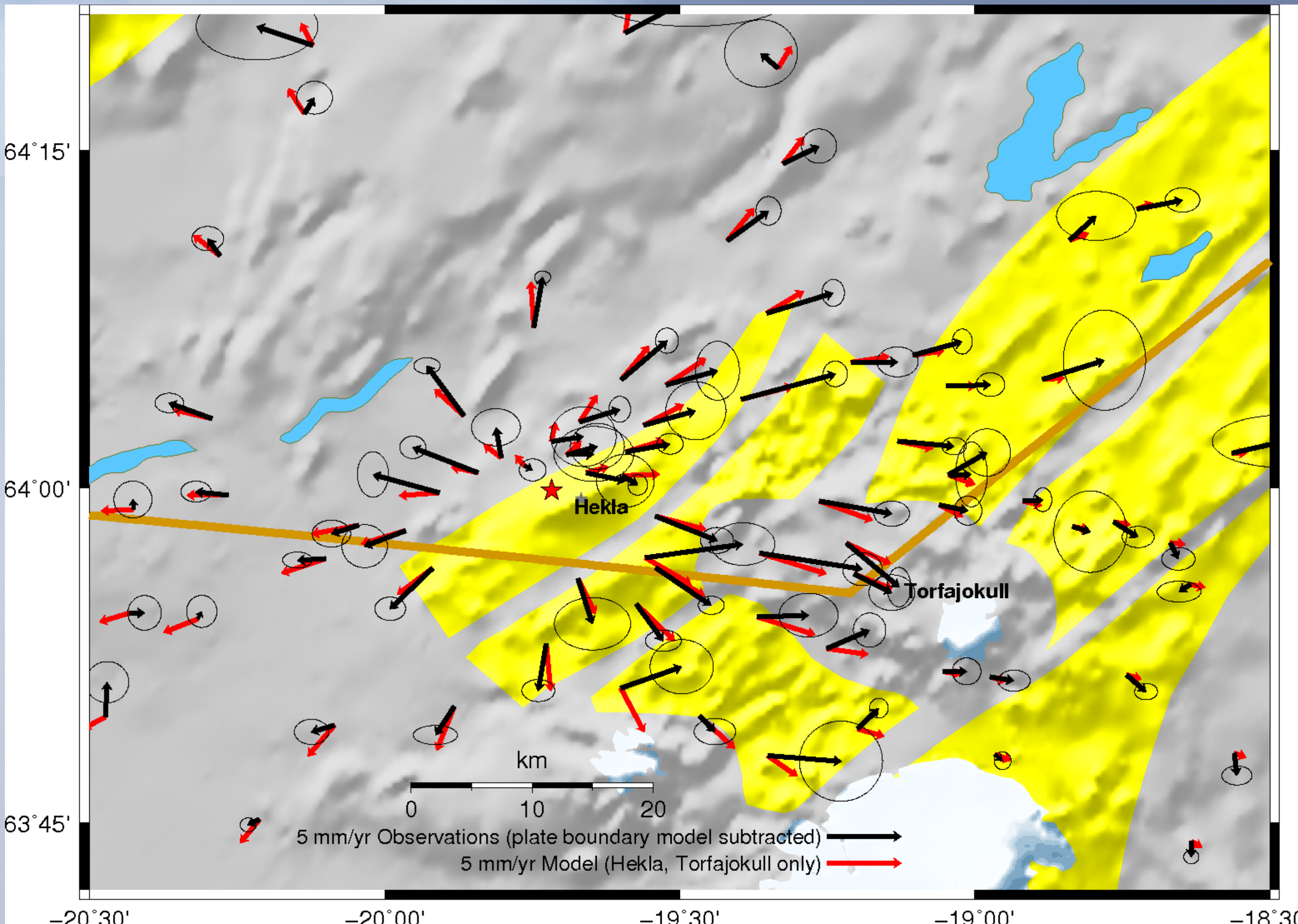
Velocities corrected for the effects of glacier unloading

Solve for plate boundary location

Block motion (MORVEL)

Plate boundary strain accumulation

Hekla: Plate boundary deformation removed



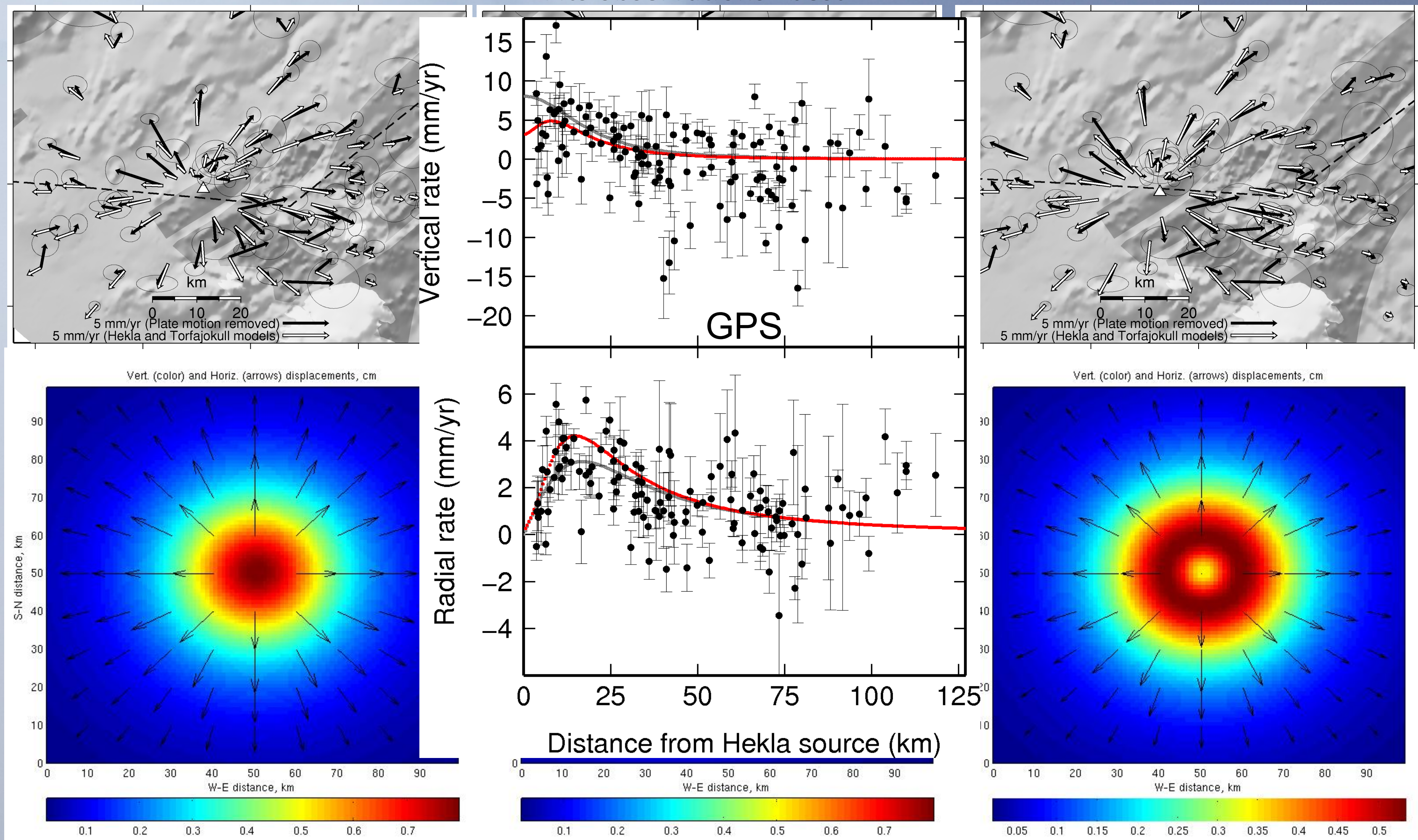
Radial deformation

Hekla source geometry comparison

Sphere (Mogi), d=24 km

Ellipsoid (horizontal), strike 60°,
d=24 km, L=24 km, r small
Fits observations “best”

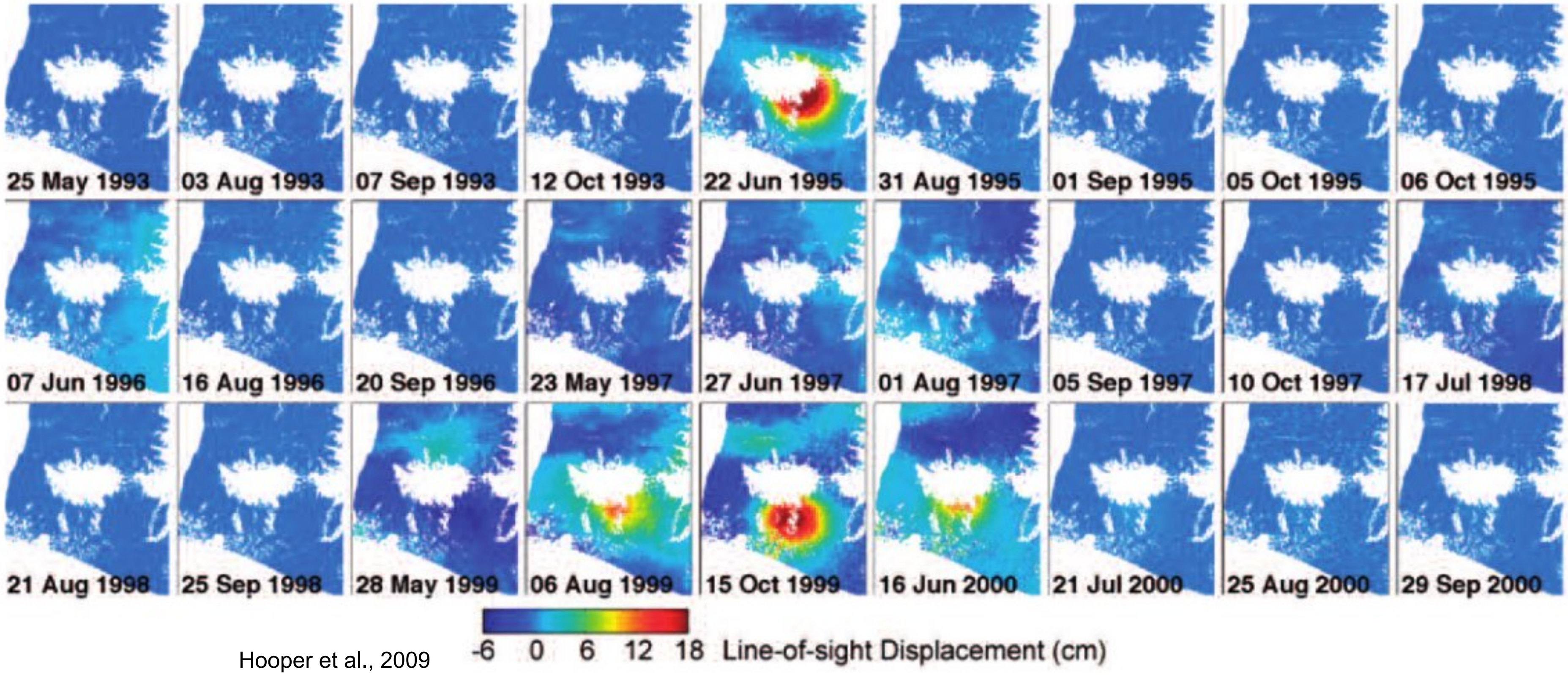
Vertical pipe, d=10-21 km



Tectonic and volcanic geodesy (Halldor Geirsson)

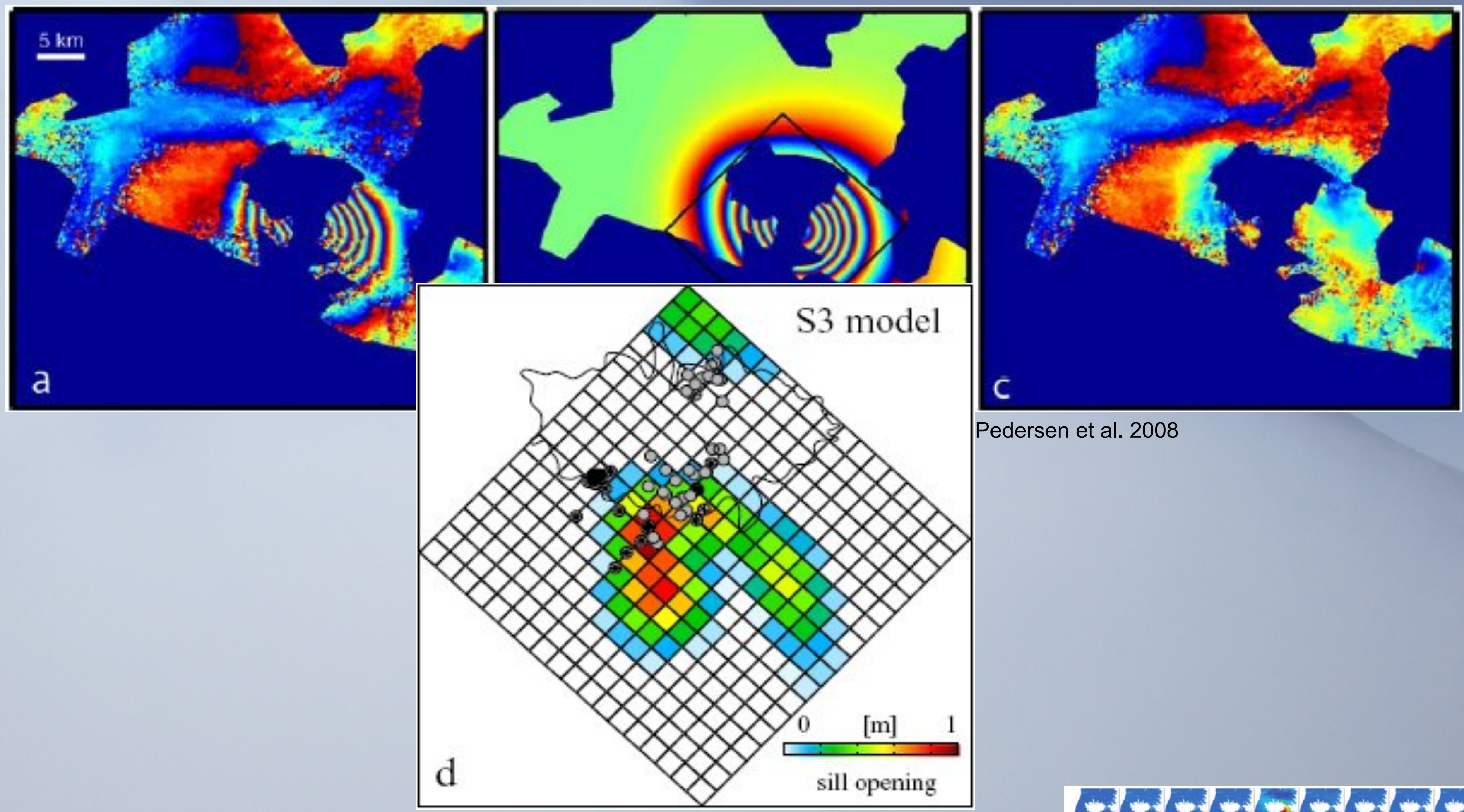
Eyjafjallajökull 2010 eruption

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

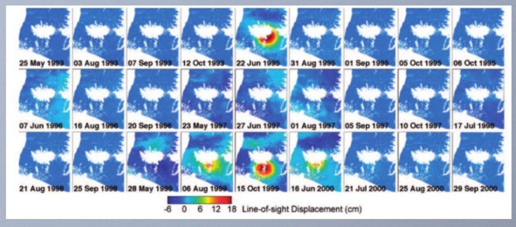


Hooper et al., 2009

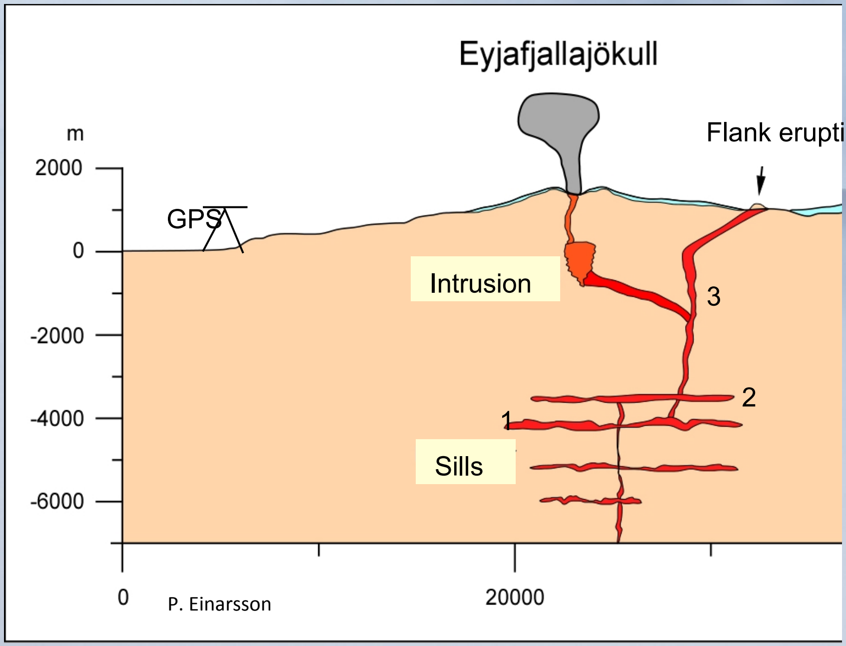
The 1999 Eyjafjallajökull intrusion

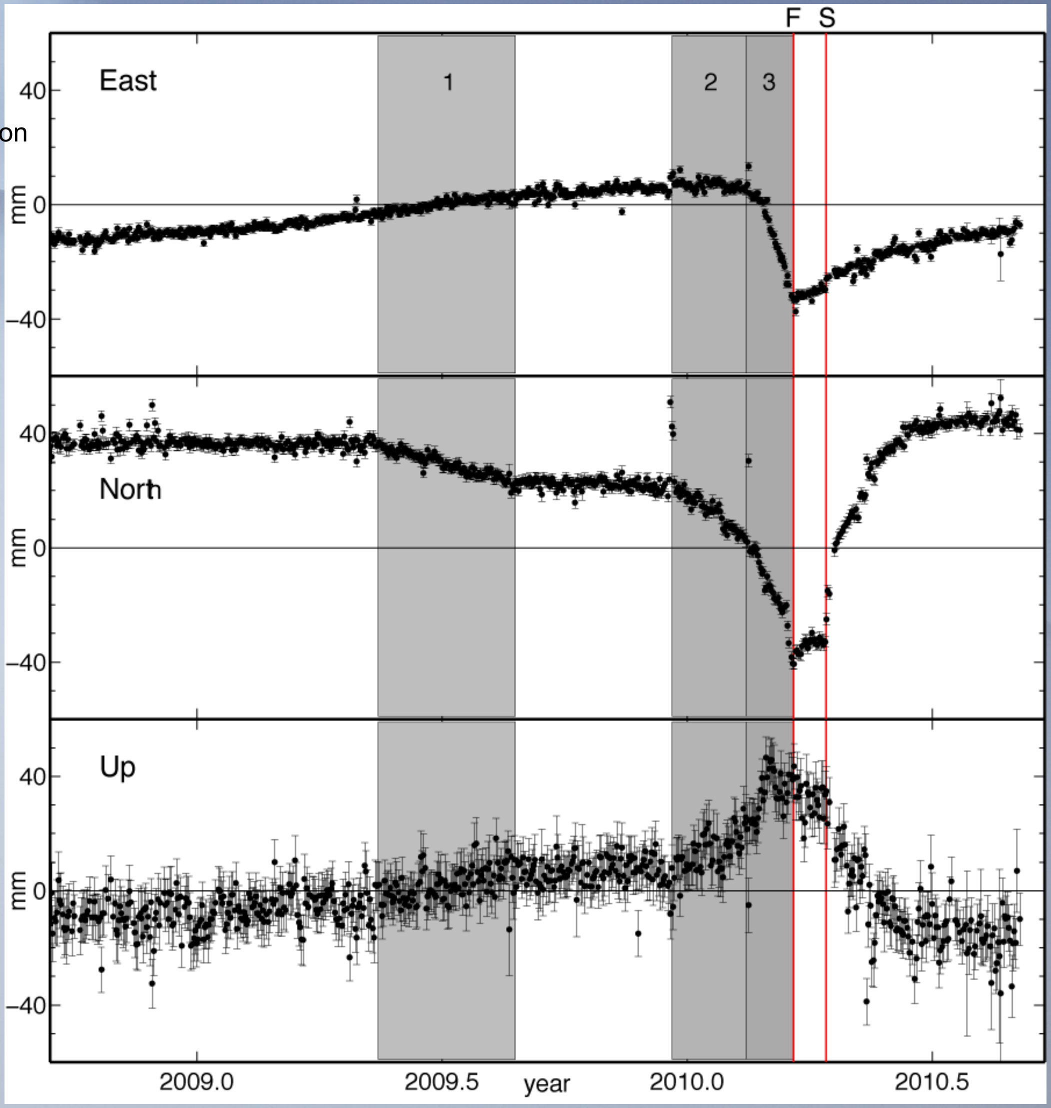


Pedersen et al. 2008



Eyjafjallajökull 2010 eruption





Geirsson et al., 2010

Tectonic and volcanic geodesy (Halldor Geirsson)

Summary

- Application of multiple techniques (GPS, InSAR, tilt, strain) is beneficial because each of the techniques has its limitations (spatial, temporal, cost, logistical)
- Modeling can be done in various ways, depending on the "amount" of the geodetic measurements, information of rheology, and the nature of the process being studied
- Studying deformation of magma-tectonic processes involves acknowledging that sometimes both magmatic and tectonic processes need to be considered and accounting for that in network design, modeling, and interpretation