Training in Geodetic Techniques for Volcano and Tectonic Monitoring

Organized by the Kivu Rift US-NSF Project Team
Andy Newman, Derrick Murekezi @ Georgia Tech

Hosted by Catherine Mériaux, East African Institute for Fundamental Research

8-9 August 2024

NSF Grant: 2150965

Agenda

Day 1: Geodetic Measurements

Here → **9am** : **Introductions**
9:30 : Overview of Geodesy
10:30 : **Break**
10:45 : Detailed understanding/theory on GPS/GNSS
12:15 : **Lunch**
1:15 : *Group Photo and outdoor discussion of* GNSS field setups
2:00 : Kivu Rift Geophysics Project overview
3:30 : Adjourn with end-of-day **snack/coffee**

Day 2: Understanding Earth from Geodetic Modeling

9am : Detailed understanding/theory on InSAR
10:30: **Break**
10:45: Geophysical Modeling overview
12:15: **Lunch**
1:15 : QuadTree data reduction for Modeling
1:30 : Modeling deformation using GTDef (or other analytic tools)
3:30 : Discussion
4:00 : Adjourn with end-of-day **snack/coffee**

Logistics

- Internet in room:
  - SSID: **`EAIFR`**
  - Passkey: **`20!8@rwanda`**

- Please wear your name badge through meeting
- We will distribute an electronic sign-up form shortly

- We will stick to the organization of the schedule, but times will shift

Introductions

- Catherine Mériaux, EAIFR
- Go around the room, introduce yourself

Motivation for training sessions

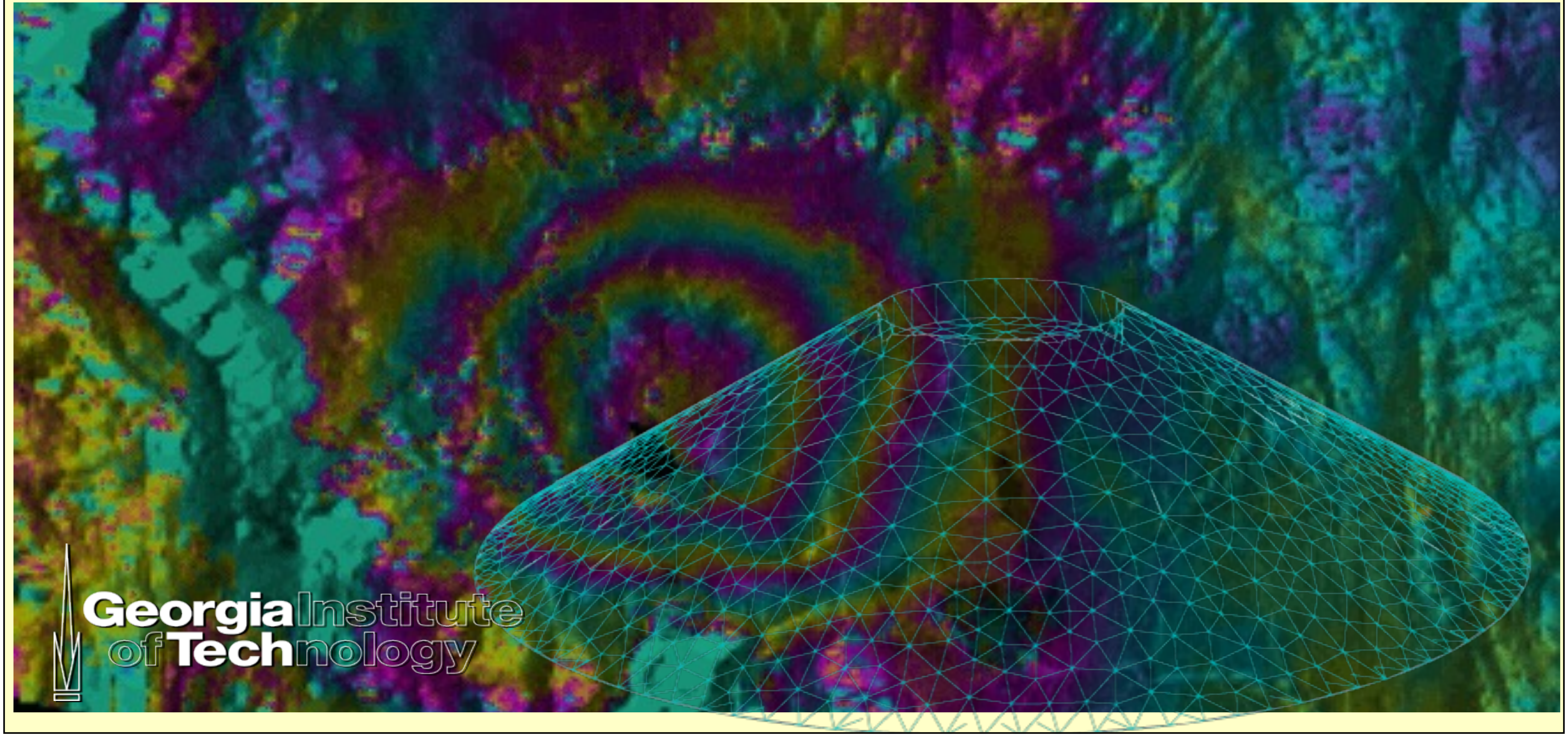
- Enhance capacity within the Kivu region for evaluating geologic processes that cause local geologic hazards
- Two-day session serves to give a detailed overview of the tools and methods for
  - Observing geodetic deformation
  - Evaluating data quality
  - Performing geophysical models to constrain processes

Does not replace longer-term training like done through a graduate degree program, or even extended training session on one aspect of this field

Questions?

Session 1

Geodetic Overview: Tools for observing and understanding ground deformation



Outline

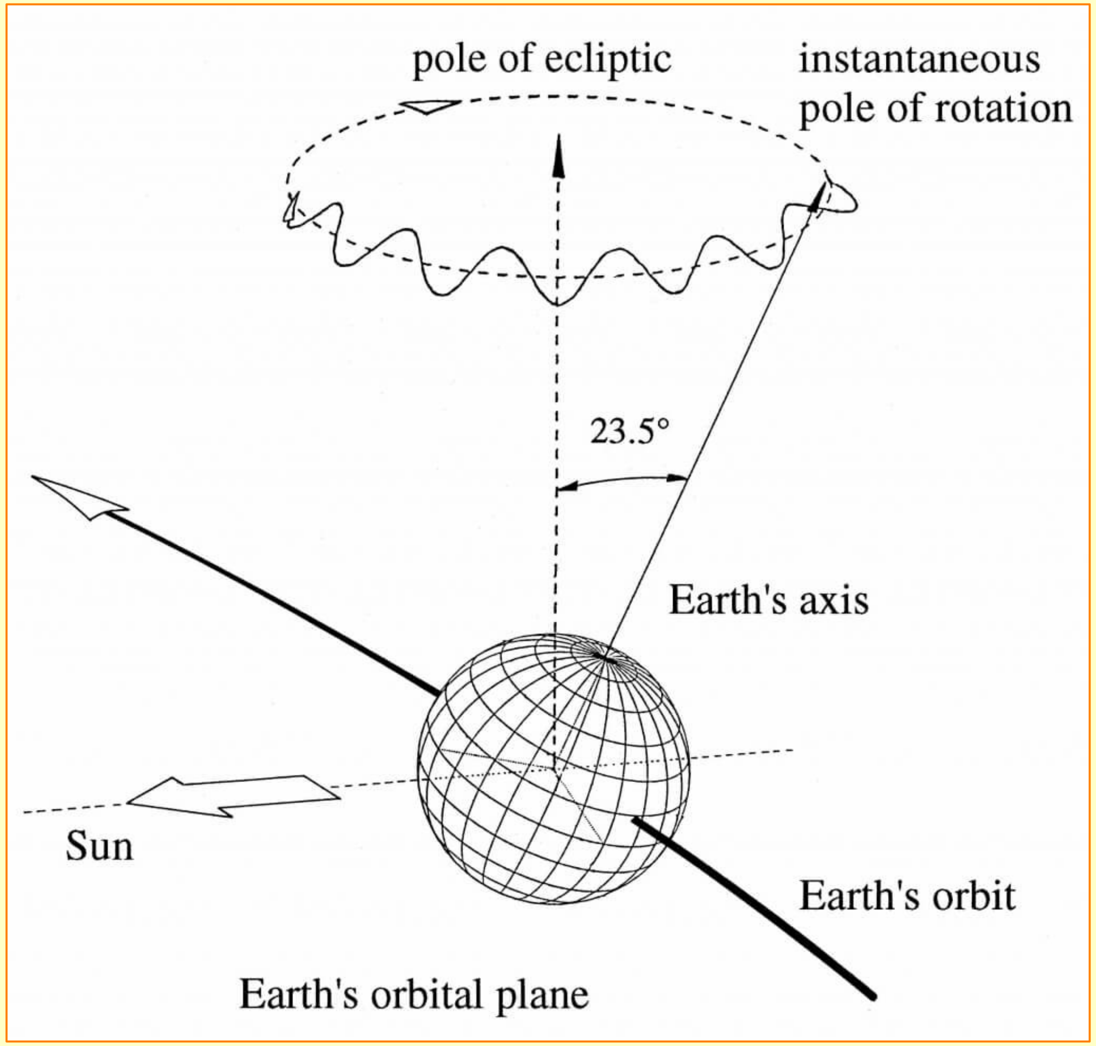
- What is geodesy?
- Types and utility of differing geodetic methods
- Application to earthquakes and volcanoes
- Some novel applications

Geodesy is ...

... one of the oldest branches of Geosciences, originally aimed to determine the shape and size of the earth.

Geodesy now:

- Earth orientation parameters
  - Procession and wobble
  - Length-of-Day
- Gravity/geoid field
- **Earth Deformation (shape change)**



What is Geodesy?

- Incorporating geodetic data into realistic models will allow for better understanding of dynamic forces responsible allowing for more informed decision-making for future geologic hazards/risks (earthquake/ volcanoes/ landslides)

- Most volcanoes experience significant surface deformation prior to eruption. Useful for determining source properties (with caveats):
  - location
  - shape
  - Volume
  - pressure
  - rheology
- Most earthquakes occur on faults that are tectonically loaded by far-field geologic strain. If we can observe this, we may be able to forecast risk.

Why study deformation?

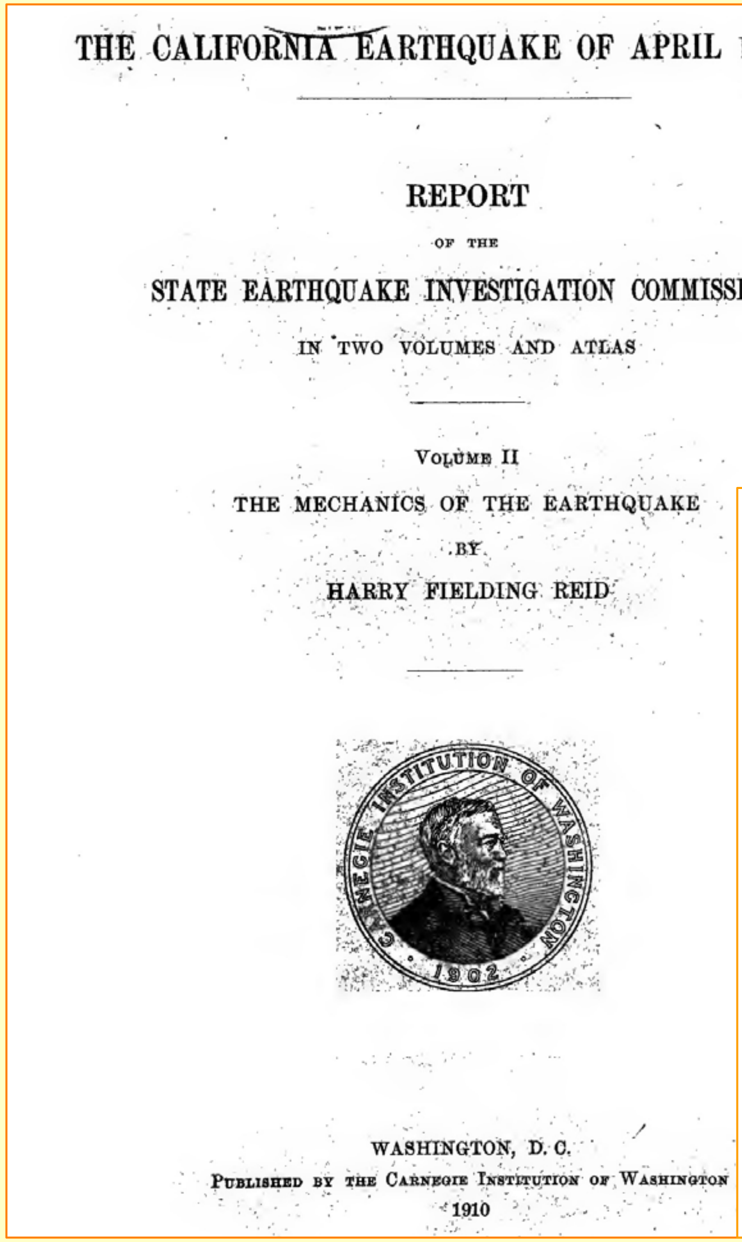
- **Natural Causes:**
  - Plate tectonics
  - Earthquakes
  - Volcanoes/magmatism
  - Glaciation
  - Flood/drought
- **Human Causes:**
  - Ground water withdrawal
  - Petroleum pumping
  - Well injection, including CO_2 sequestration

Lost Hills, CA oil field (+1mm/day)

Why study deformation?

- Incorporating geodetic **data** into realistic **models** allows **for better understanding of dynamic forces responsible**

Elastic Rebound Theory describes fault loading



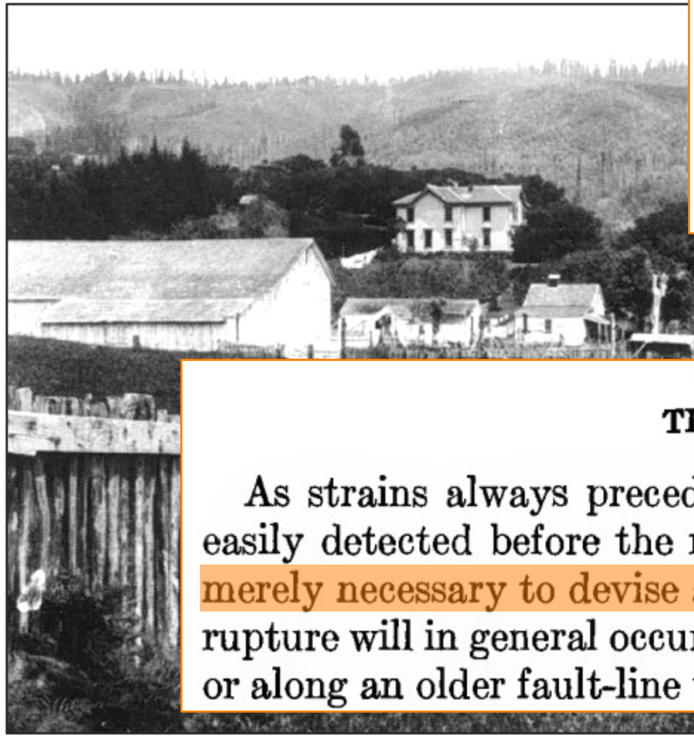
THE CALIFORNIA EARTHQUAKE OF APRIL 18, 1906

REPORT
OF THE
STATE EARTHQUAKE INVESTIGATION COMMISSION
IN TWO VOLUMES AND ATLAS

VOLUME II
THE MECHANICS OF THE EARTHQUAKE
BY
HARRY FIELDING REID

1902

WASHINGTON, D. C.
PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON
1910



PERMANENT DISPLACEMENTS OF THE GROUNDS.

THE RESULTS OF THE SURVEYS.

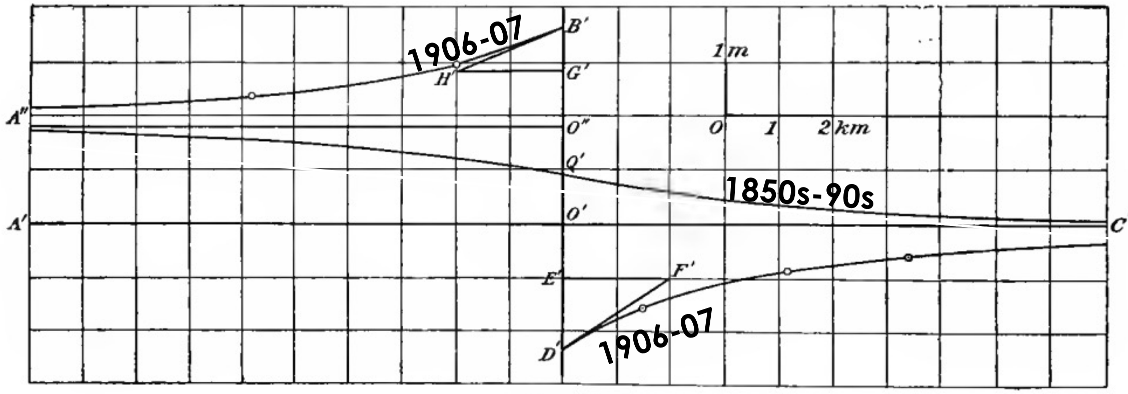


FIG. 5.

THE PREDICTION OF EARTHQUAKES.

As strains always precede the rupture and as the strains are sufficiently great to be easily detected before the rupture occurs, in order to foresee tectonic earthquakes it is merely necessary to devise a method of determining the existence of the strains; and the rupture will in general occur in the neighborhood of the line where the strains are greatest, or along an older fault-line where the rock is weakest. To measure the growth of strains,

Methods:

- **Leveling**: *relative elevation change*
- **Tilt**: *local rotational change*
- **Electronic Distance Measurements (EDM)**:
  - *relative line-length change*

Modern Tools:

- **Global Navigational Satellite Systems (GNSS**) measurements:

  absolute point measurements of X, Y, Z, t

- **Interferometric Synthetic Aperture Radar (InSAR)**:

  spatially dense line-of-sight relative displacement

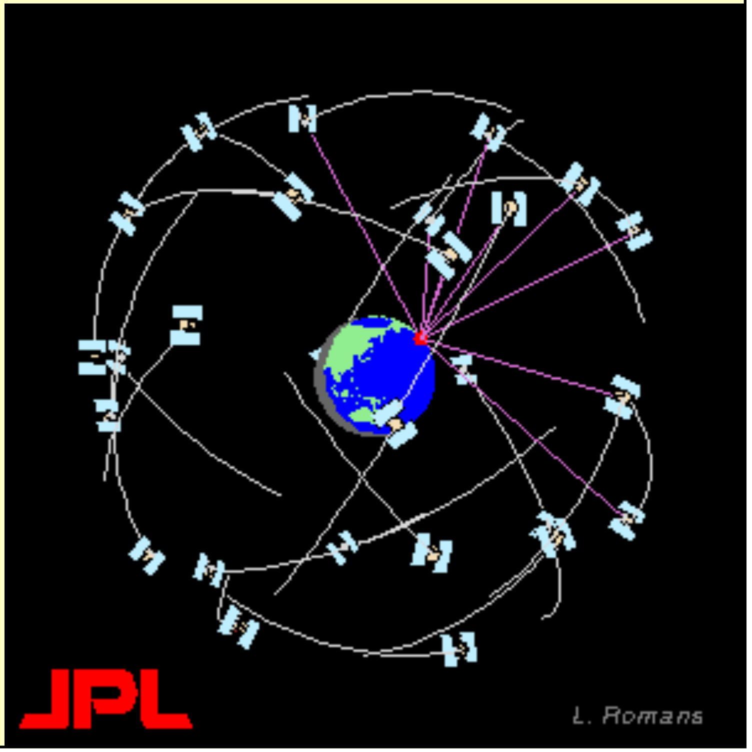
- **LiDAR, Photogrammetry (SfM)** – *not detailed here*

Tools for Geodetic Monitoring

Method	Component Displacement	Precision, mm	Sample Frequency	Survey scale
Borehole extensometry	vertical	0.01-0.1	continuous	point
Leveling	vertical	1-10	continuous-yearly	line
EDM	horizontal	1-10	daily-yearly	line
GPS/GNSS	horizontal Vertical	1-3 3-5	continuous-yearly	network of points
InSAR	near-vertical	1-3	~monthly/weekly	10m-1km map pixels

Global Positioning System (GPS)

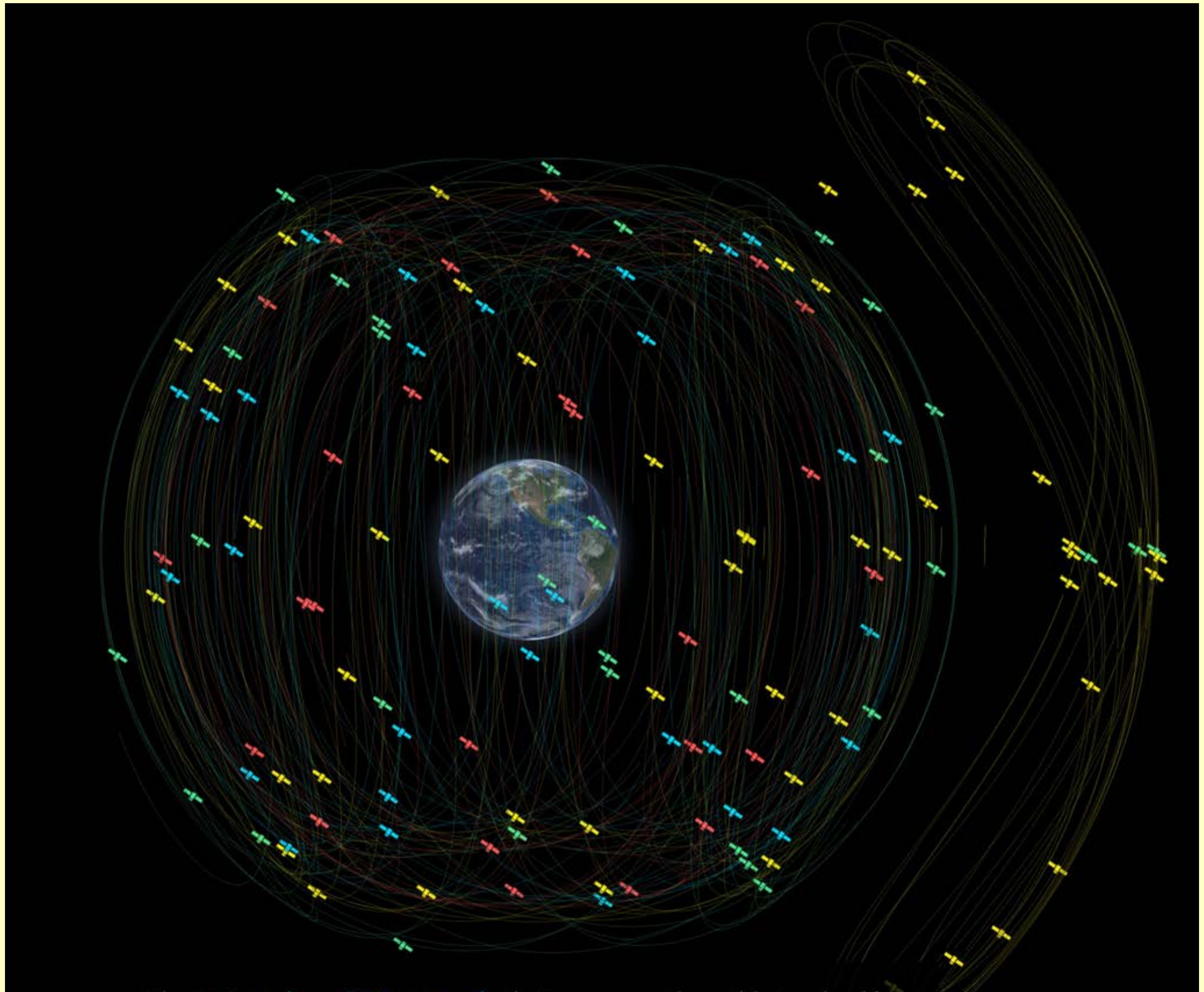
- Developed originally by the U.S. DOD for ICBM and Submarine tracking (1970s)
- Consists of 24 satellites (complete constellation) +backups/new
- At 20,000 km (Medium-Earth) orbit
- 12 hr period (always see > 5-6 in open sky)
- Annual cost ~$400M/yr
- L1/L2 band (19/24.4 cm ; 1.575/1.23 GHz)



Global Navigational Satellite Systems (GNSS): GPS +

- GLONASS (Russian)
  - Started in 1976
  - Medium Earth Orbit (same as GPS)
  - Fully restored (2011) due to reinvestment in the
  - L1/L2 1.6/1.2 GHz (modulated)
- BeiDou (Chinese)
  - Started in 2000s with full operation in 2020
  - Mix of Medium Earth Orbit and (inclined-) Geosynchronous
  - Similar frequencies (modulated)
- Galileo (ESA)
  - Started in 2000s
  - 20 operational as of Feb 2023, planned 30
  - Very similar to GPS, but with ~3x better broadcast orbits

Antennas and receivers that are specifically designed for these networks are necessary to include all signals

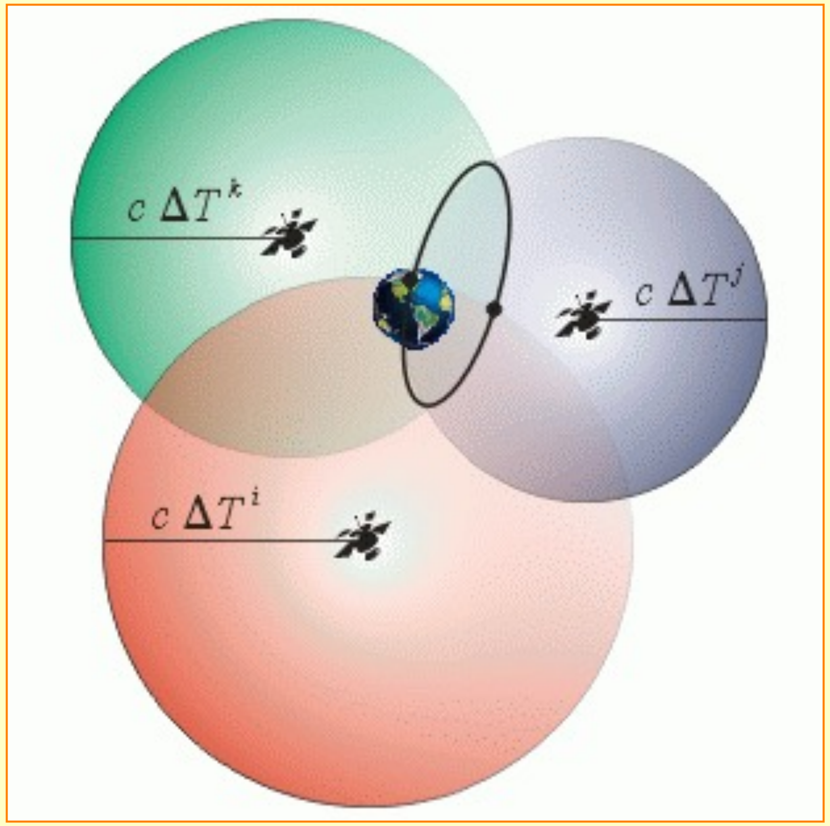


The American GPS network that was once the gold standard is at risk of becoming a relic as Chinese, Russian and European systems modernize.

NYT, 7/2/2024

GNSS Basic Operation

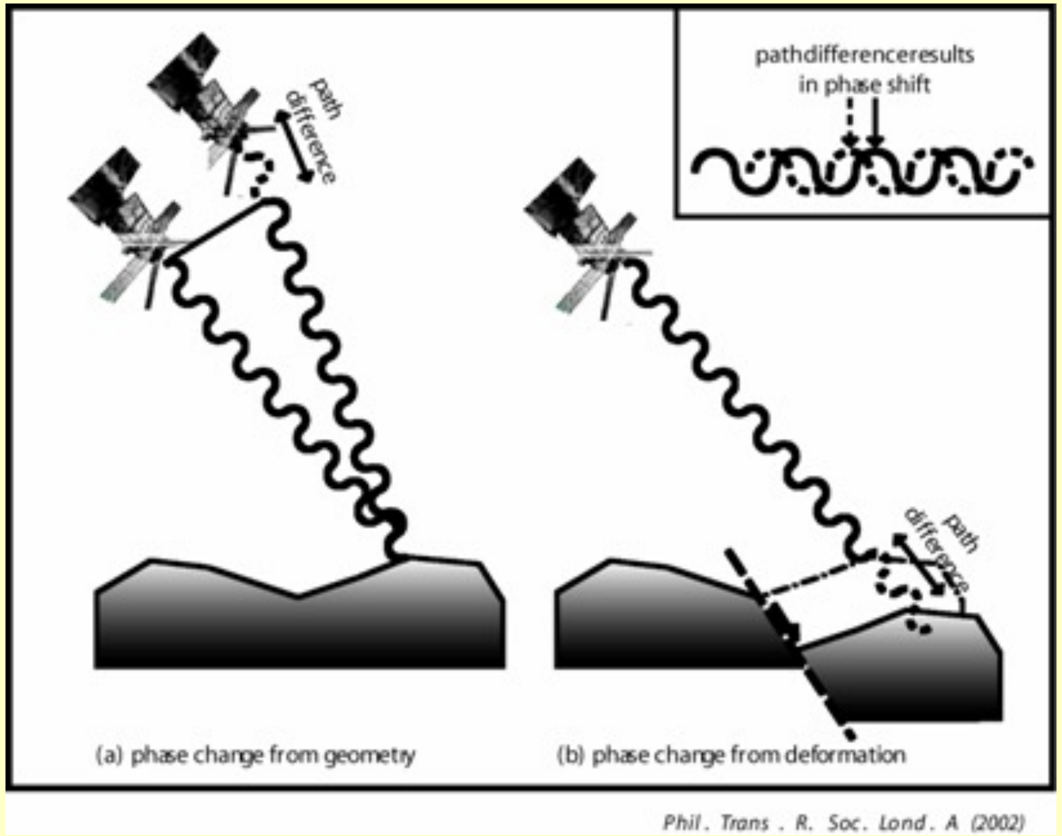
- Location based on **triangulation**
  - satellites report **precise timing**
- If receiver knows where satellites should be (ephemeris), it can triangulate the unique location that fits the travel-time delay
- Must account for **general** (gravity effect) and **special** (differential velocity) **relativities** accounting for 38 μs/day
- ***This is the perfect world situation.***



InSAR as a geodetic monitoring tool

- InSAR- **In**terferometric **S**ynthetic **A**perture **R**adar.
  (Satellites-- JERS-1/2, ERS-1/2, RADAR-SAT-1/2; EnviSAT, Terra-SARX, Cosmo-Skynet, NASA UAVSAR , NASA/India Space Agency satellite –soon NISAR)
- With repeat flybys (~ *weekly → monthly*), satellites record phase changes due to ground motion

Ultimately give an image of deformation in line-of sight (*LOS*) direction as phase shifts in repeat passes

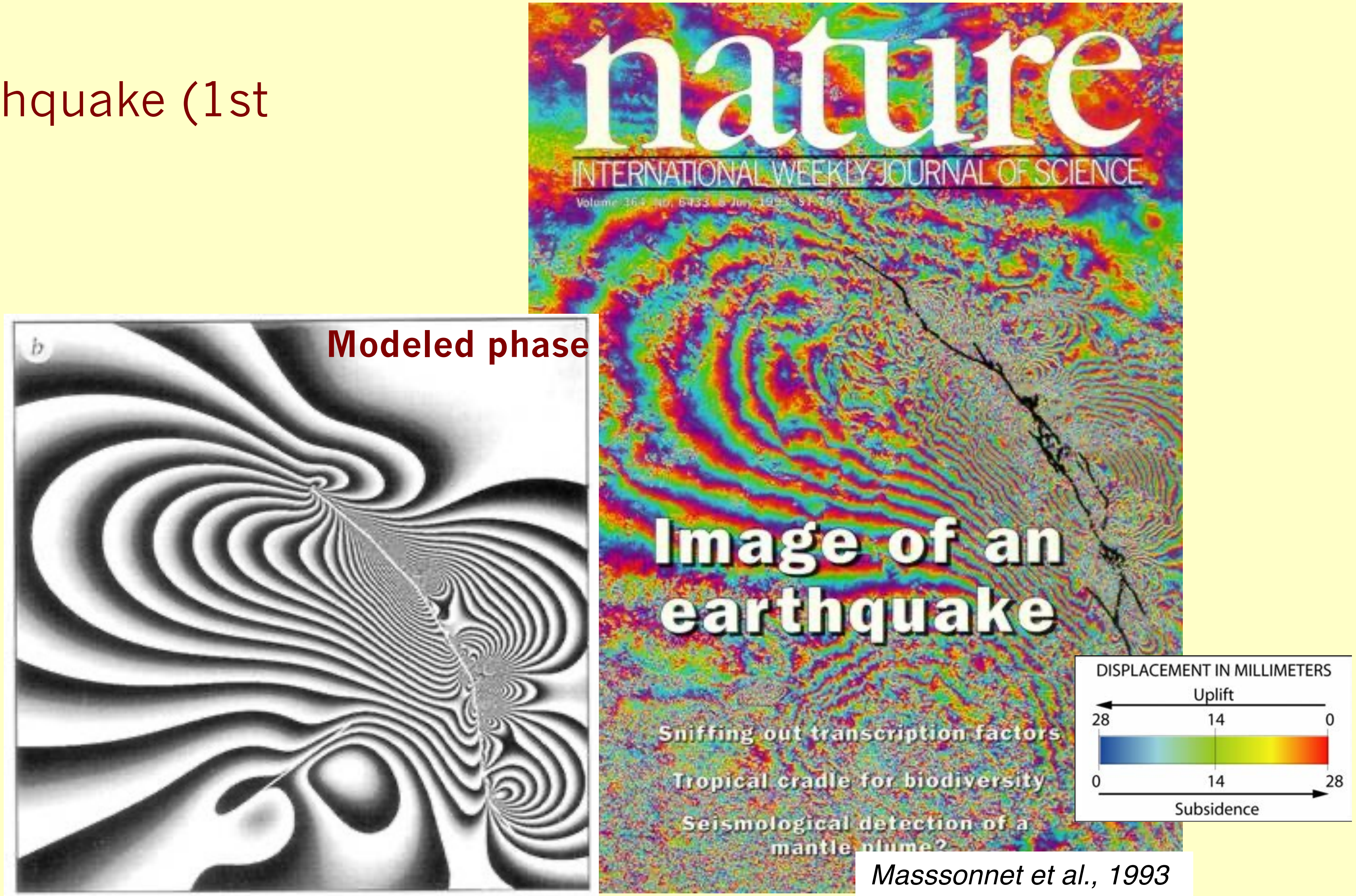


Phil. Trans. R. Soc. Lond. A (2002)

InSAR as a geodetic monitoring tool (cont)

Earthquakes

- Landers 1992 Earthquake (1st EQ interferogram)



nature

INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

Image of an earthquake

Sniffing out transcription factors

Tropical cradle for biodiversity

Seismological detection of a mantle plume?

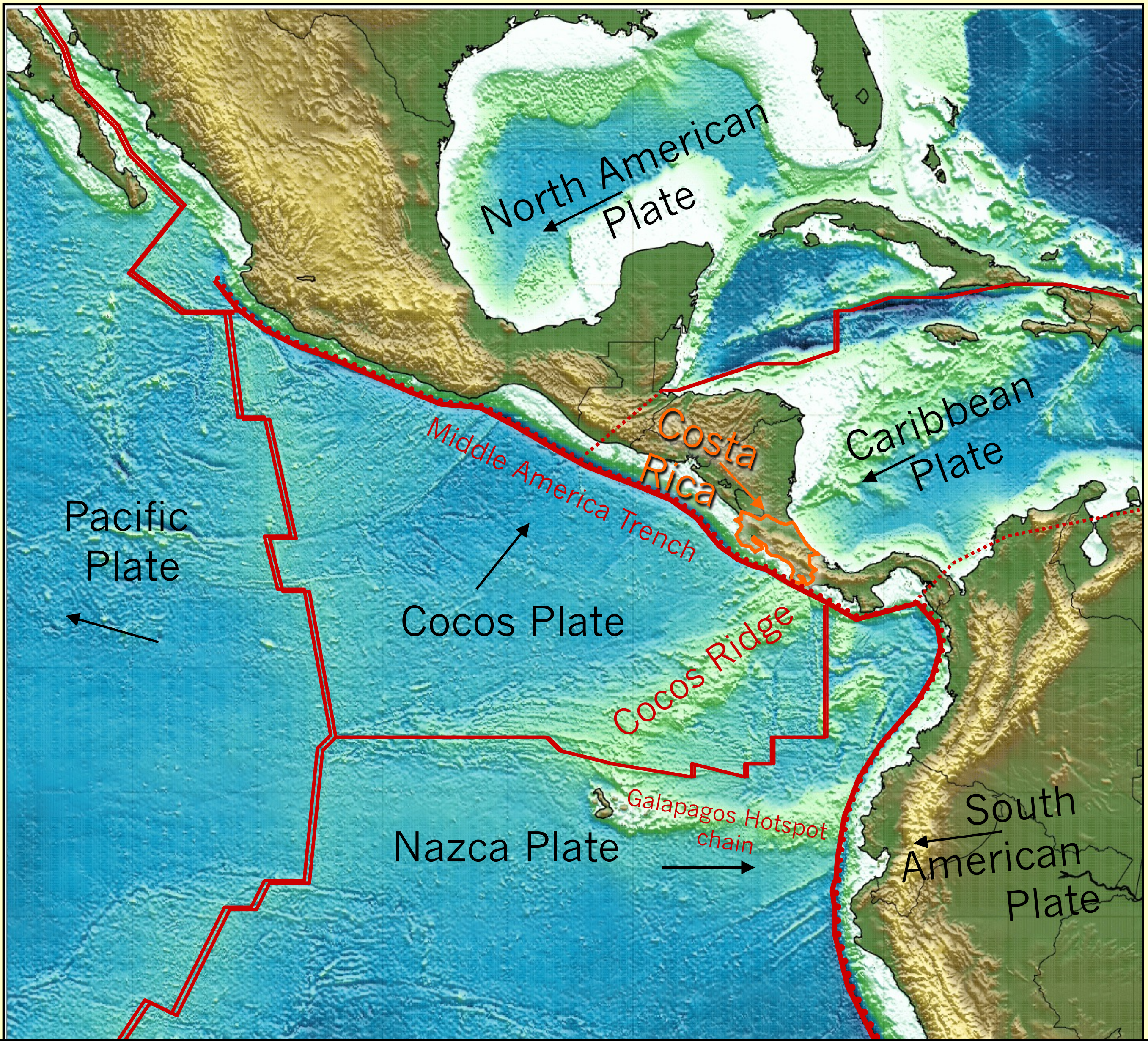
Masssonnet et al., 1993

Application to Earthquakes

Central American physiography
and tectonic boundaries

In Costa Rica, the Cocos plate subducts beneath the Caribbean at a rate of ~8.5 cm/yr.

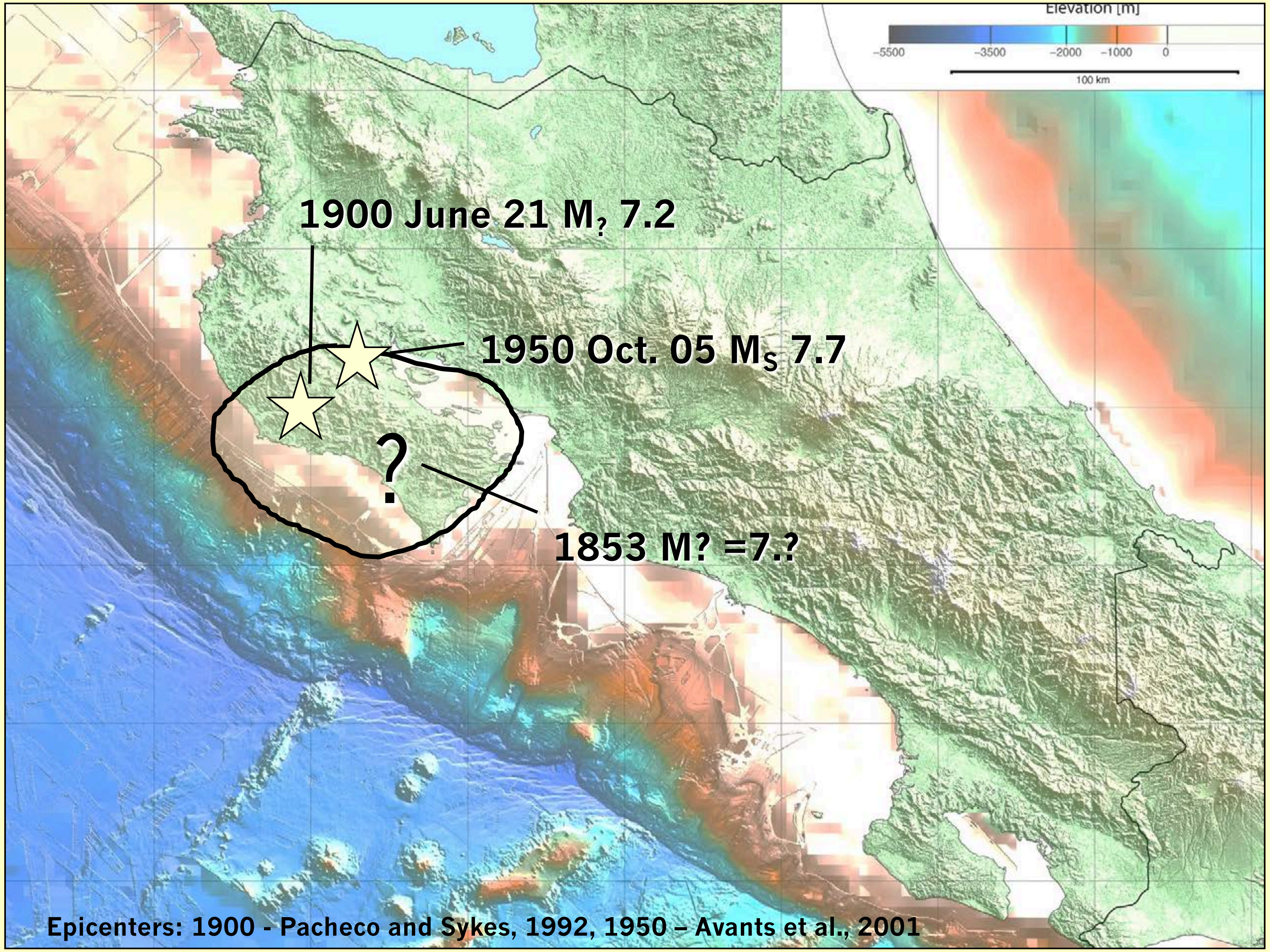
The Nicoya and Osa peninsulas form landmasses close very close to the trench



1950 **M**7.7 Nicoya Earthquake

Preceded by similar earthquakes in 1853 and 1900

Roughly 50 year repeat



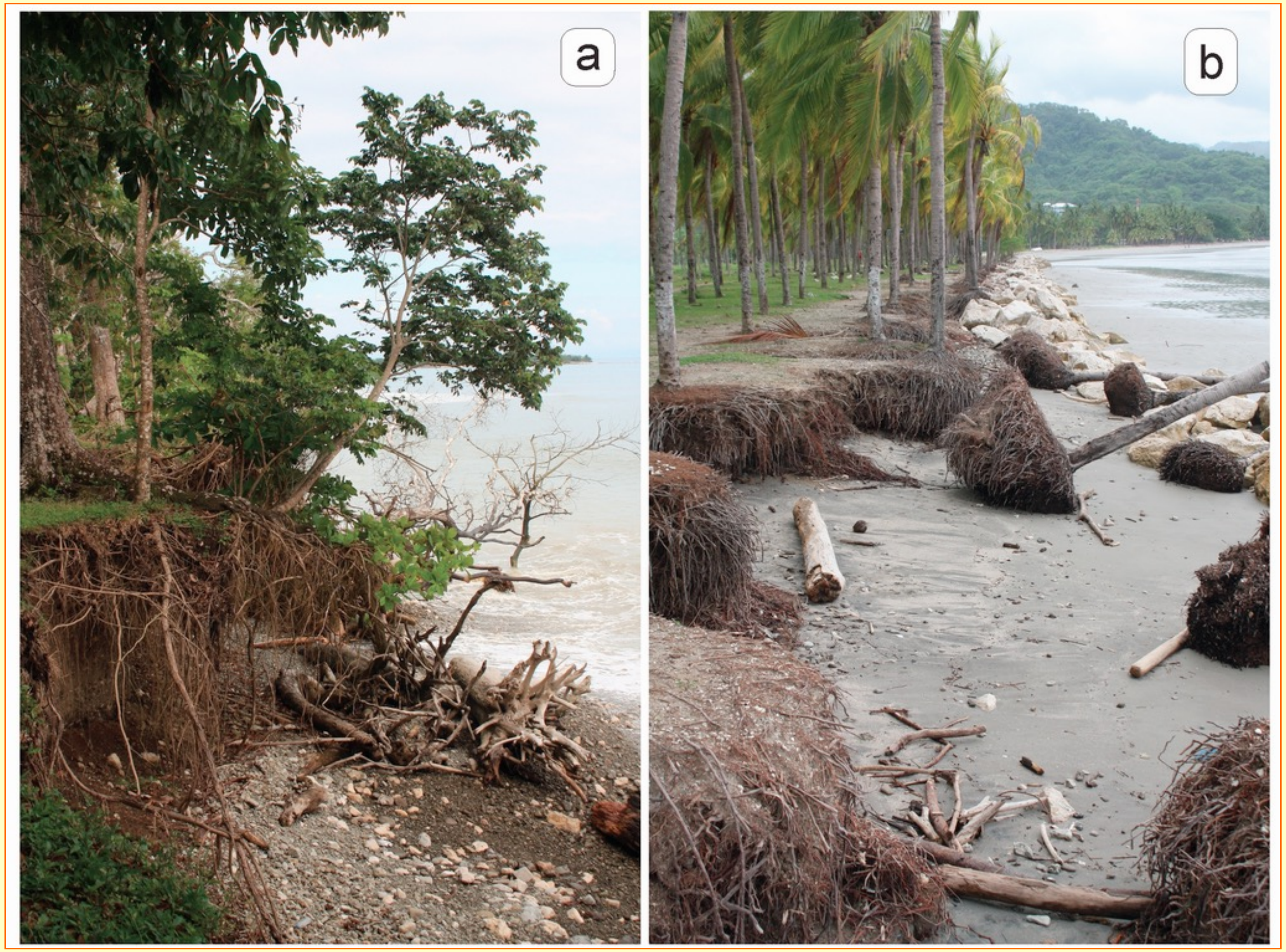
Epicenters: 1900 - Pacheco and Sykes, 1992, 1950 – Avants et al., 2001

Geodetic Inversions:

Late-interseismic locking in Costa Rica

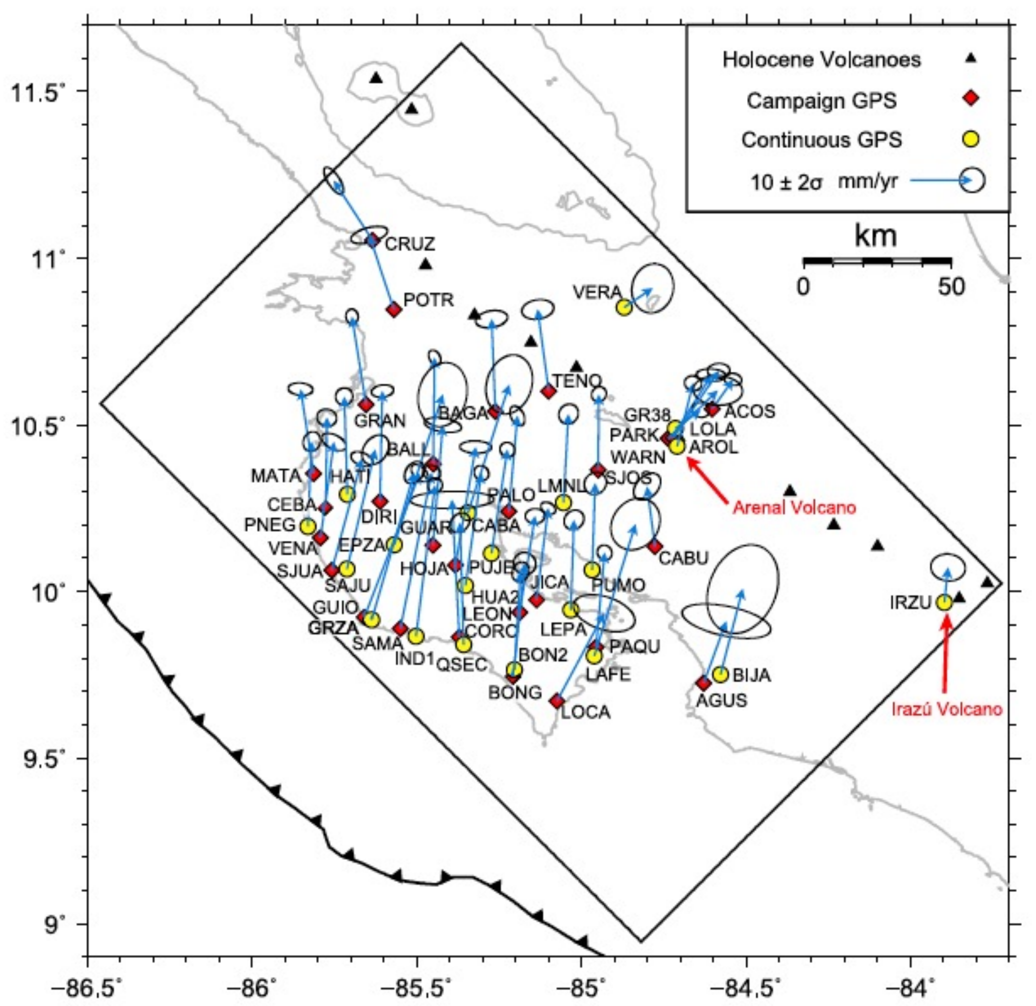
2010 Field Campaign

Coastal Erosion in Nicoya



Late-interseismic locking

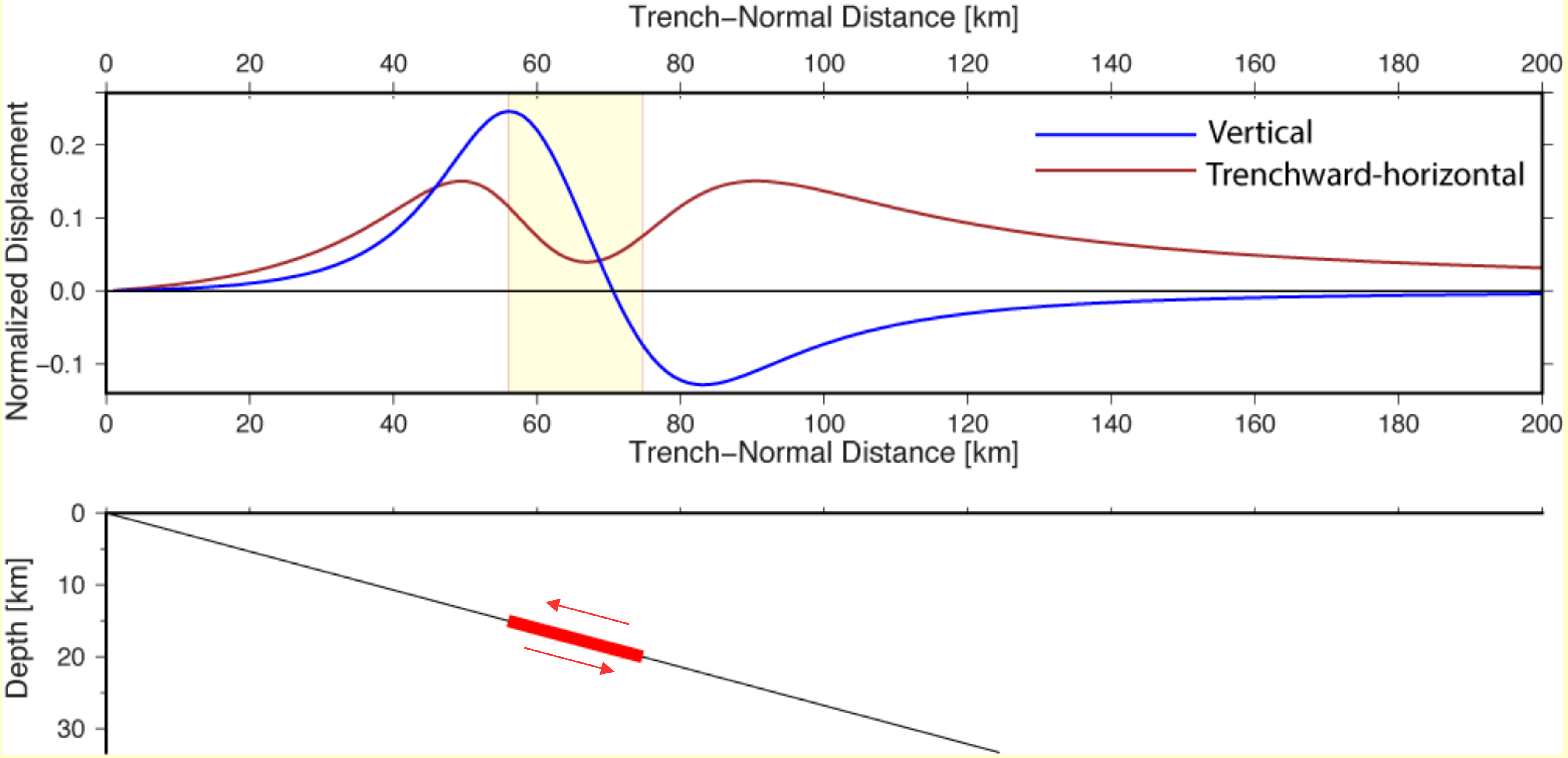
(1996-2010)



Feng et al. JGR 2012

Model Deformation:

- For a prescribed fault motion, we can predict surface deformation [*Okada*, 1985]



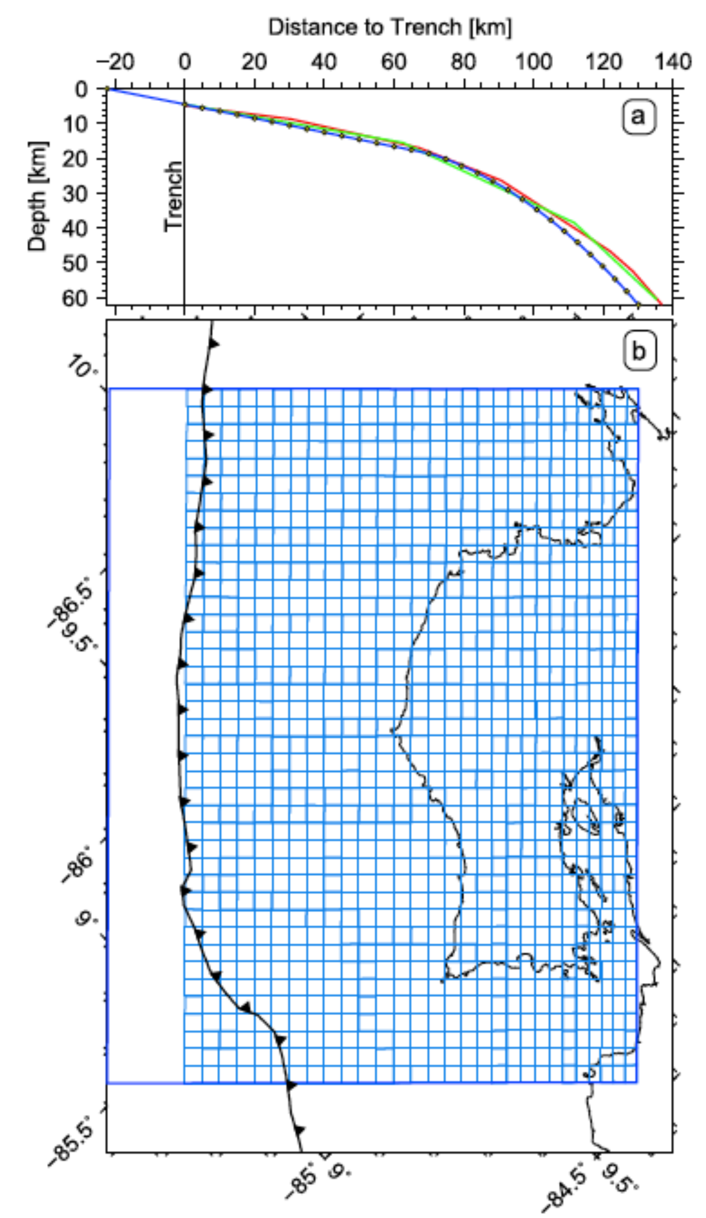
- Adapt method for a plane of discrete dislocation sub-fields (to model distributed rather than uniform slip)

Inversion of Okada Dislocations

- **GTDef**: Chen et al. (2009, *GRL*) implementation of Okada elastic equations (*BSSA*, 1985)

$$\begin{bmatrix} Wd \\ 0 \end{bmatrix} = \begin{bmatrix} WG \\ \kappa^2 D \end{bmatrix} m$$

- Linear least squares inversion of weighted, *w*, data, *d*, to solve for slip on fault, *m*. Greens functions reprenting Okada equation, *G*, with 2D smoothing parameter, κ, on "roughness" of the displacement field, $D = \nabla^2 u$.

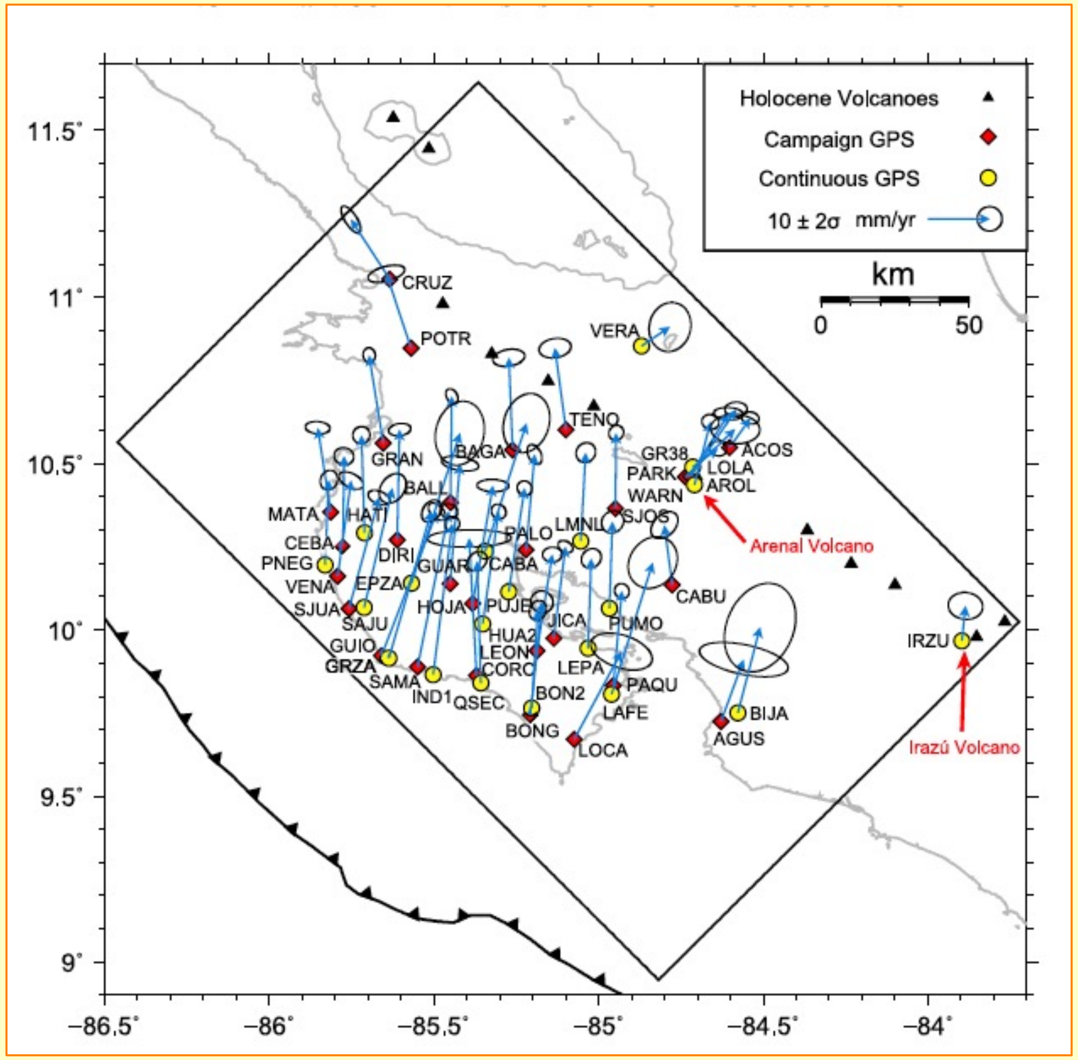


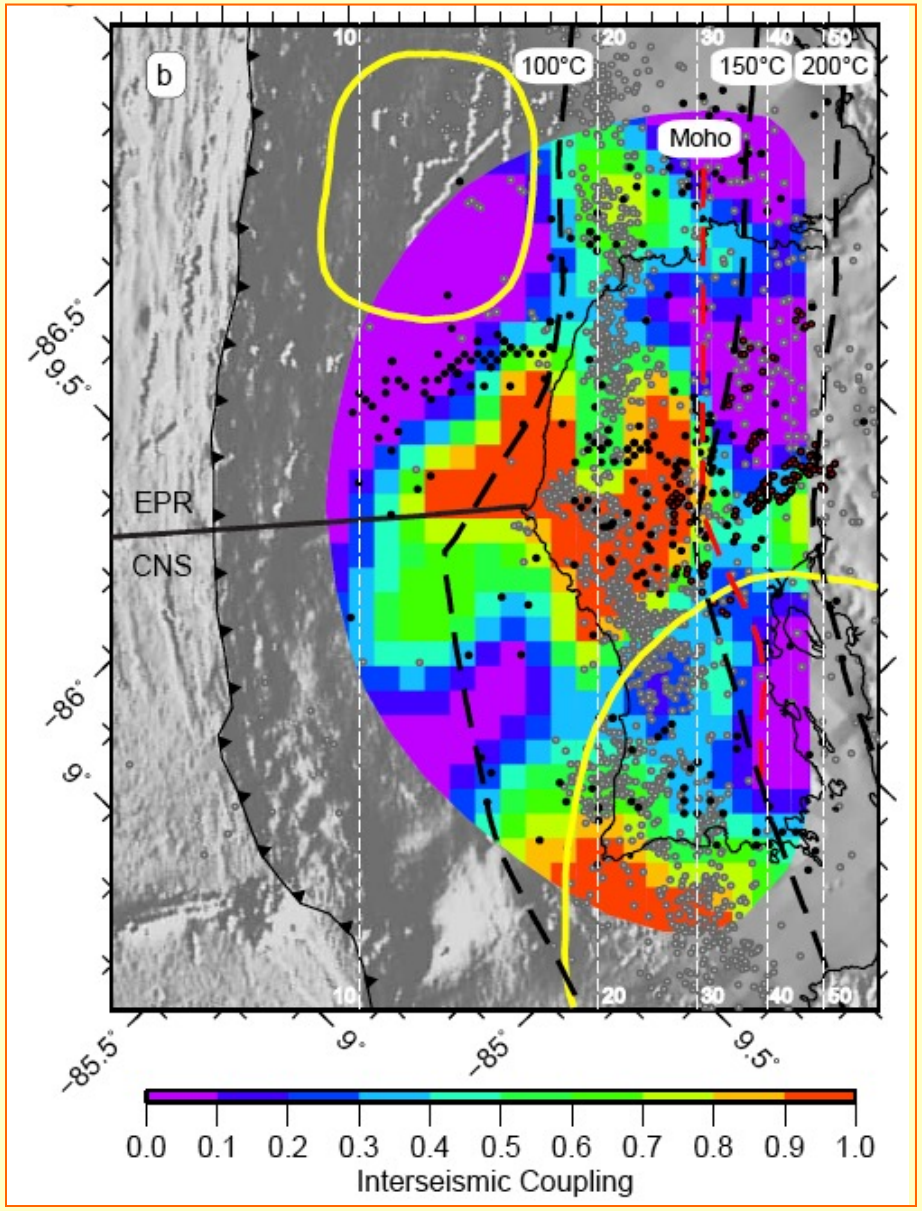
Feng et al. (2012) *JGR*

Method following *Jónsson et al., BSSA, 2002.*

Late-interseismic locking

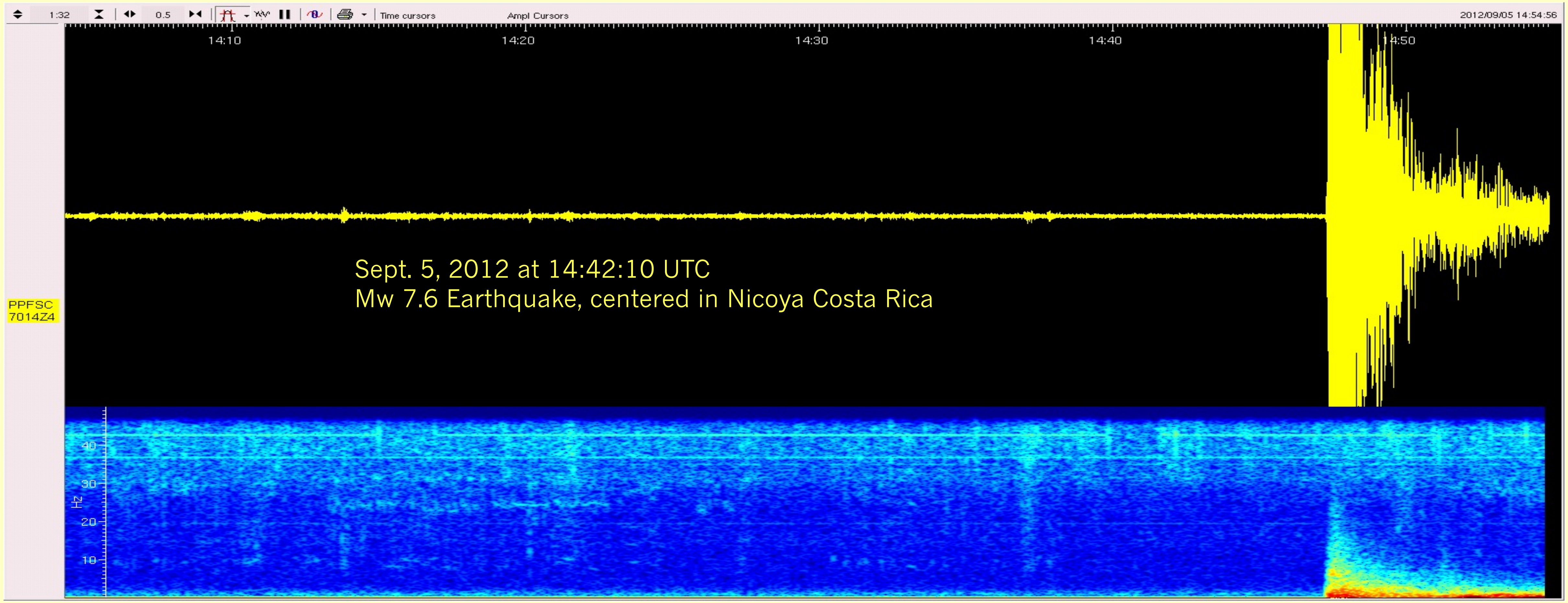
(1996-2010)





Feng et al. JGR 2012

Coseismic slip:

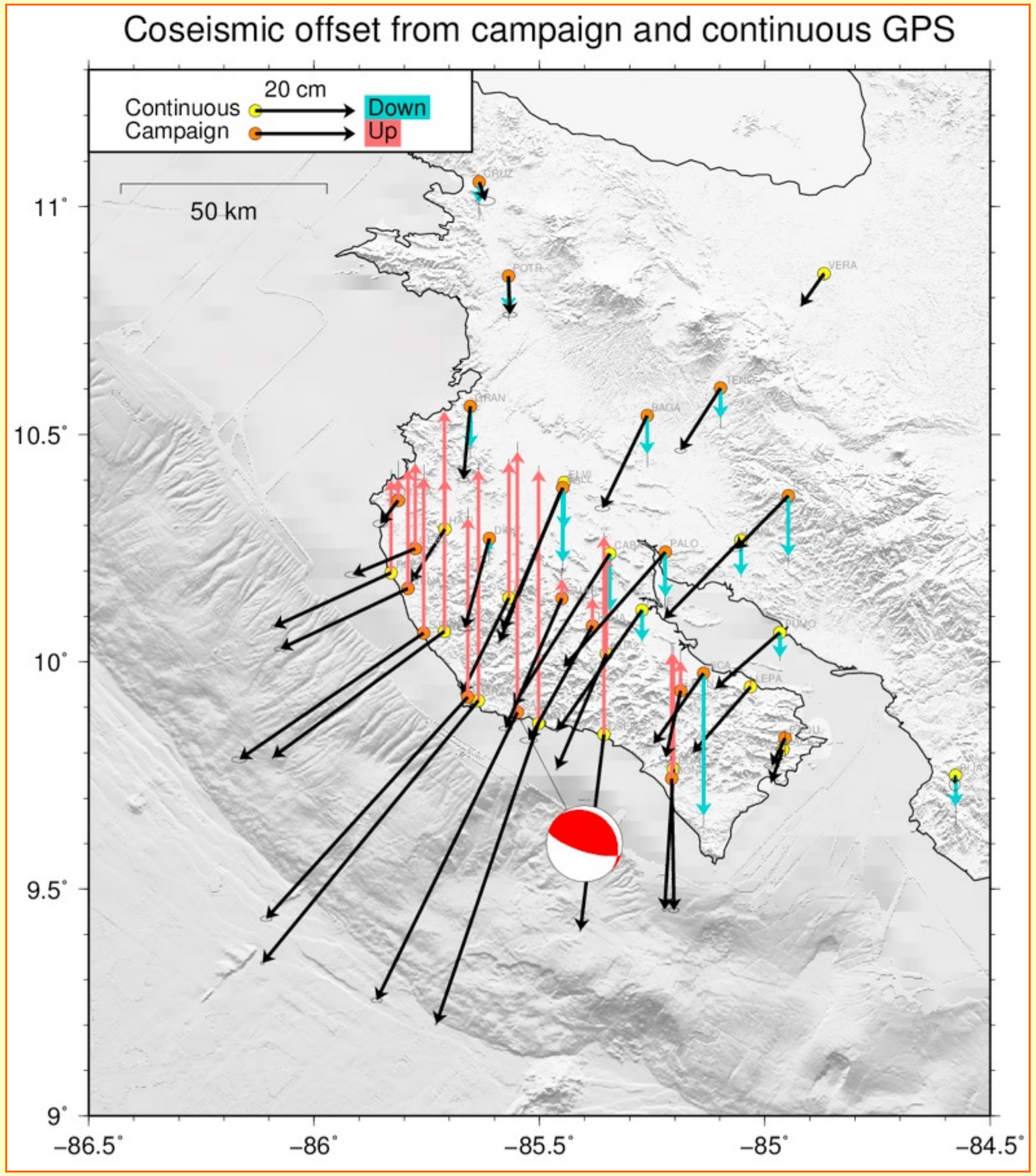


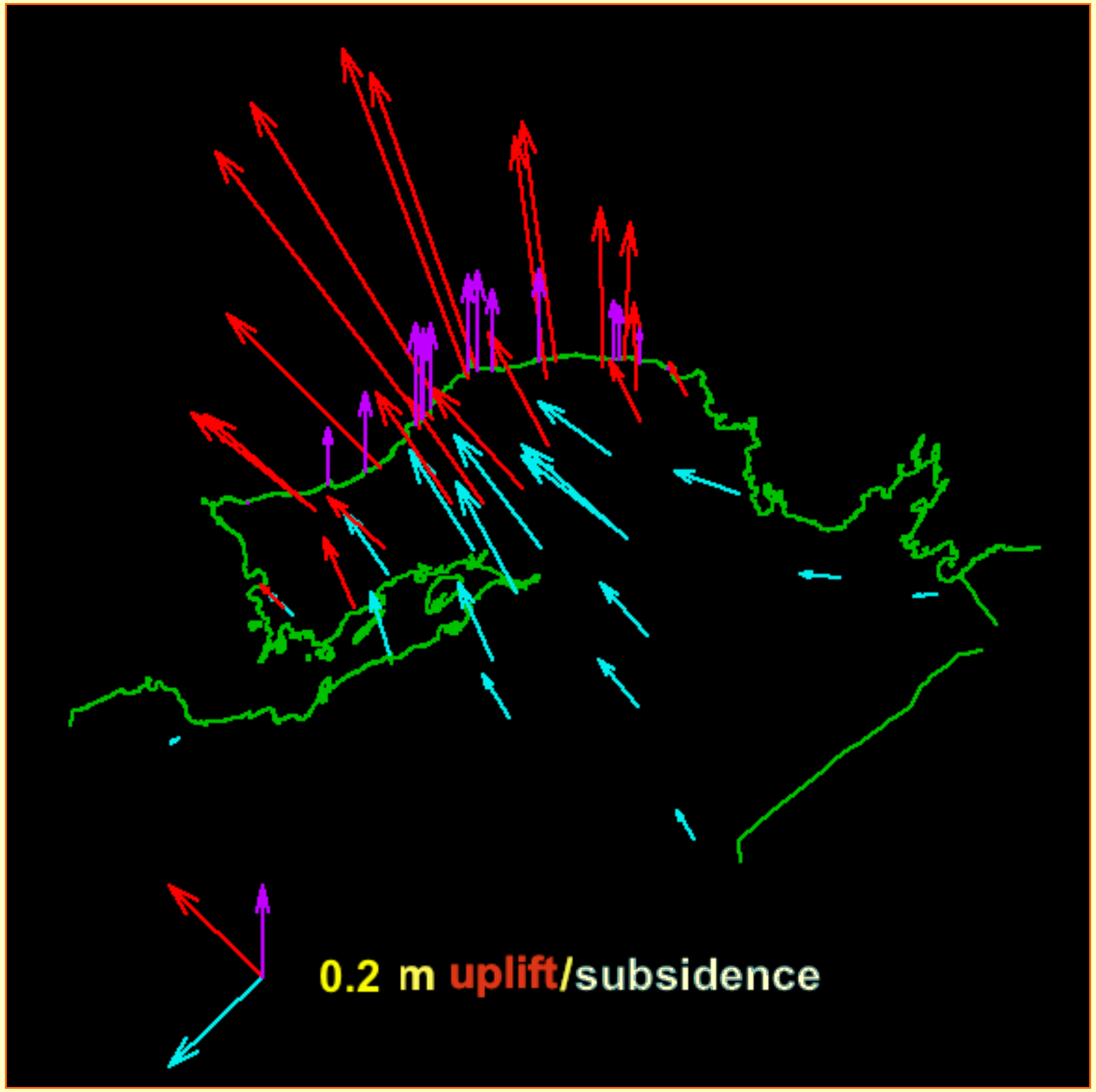
Sept. 5, 2012 at 14:42:10 UTC
Mw 7.6 Earthquake, centered in Nicoya Costa Rica

Two days later in Costa Rica:

Observations of Coastal Change

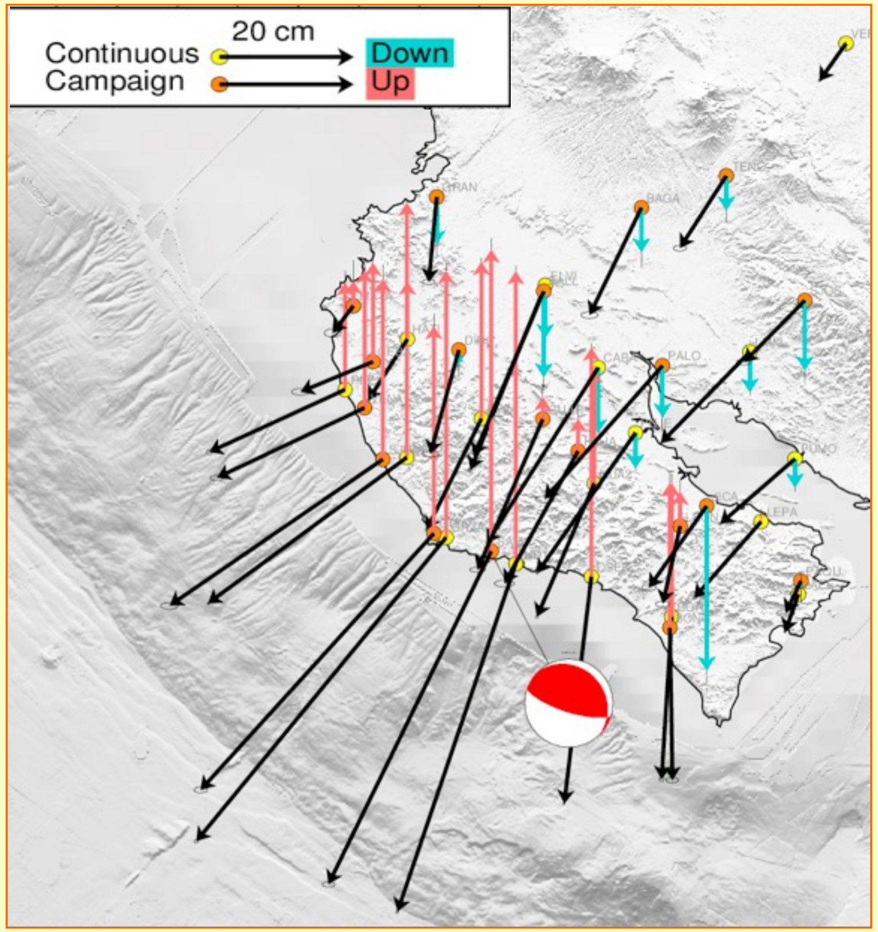
Campaign/Continuous GPS Displacement field



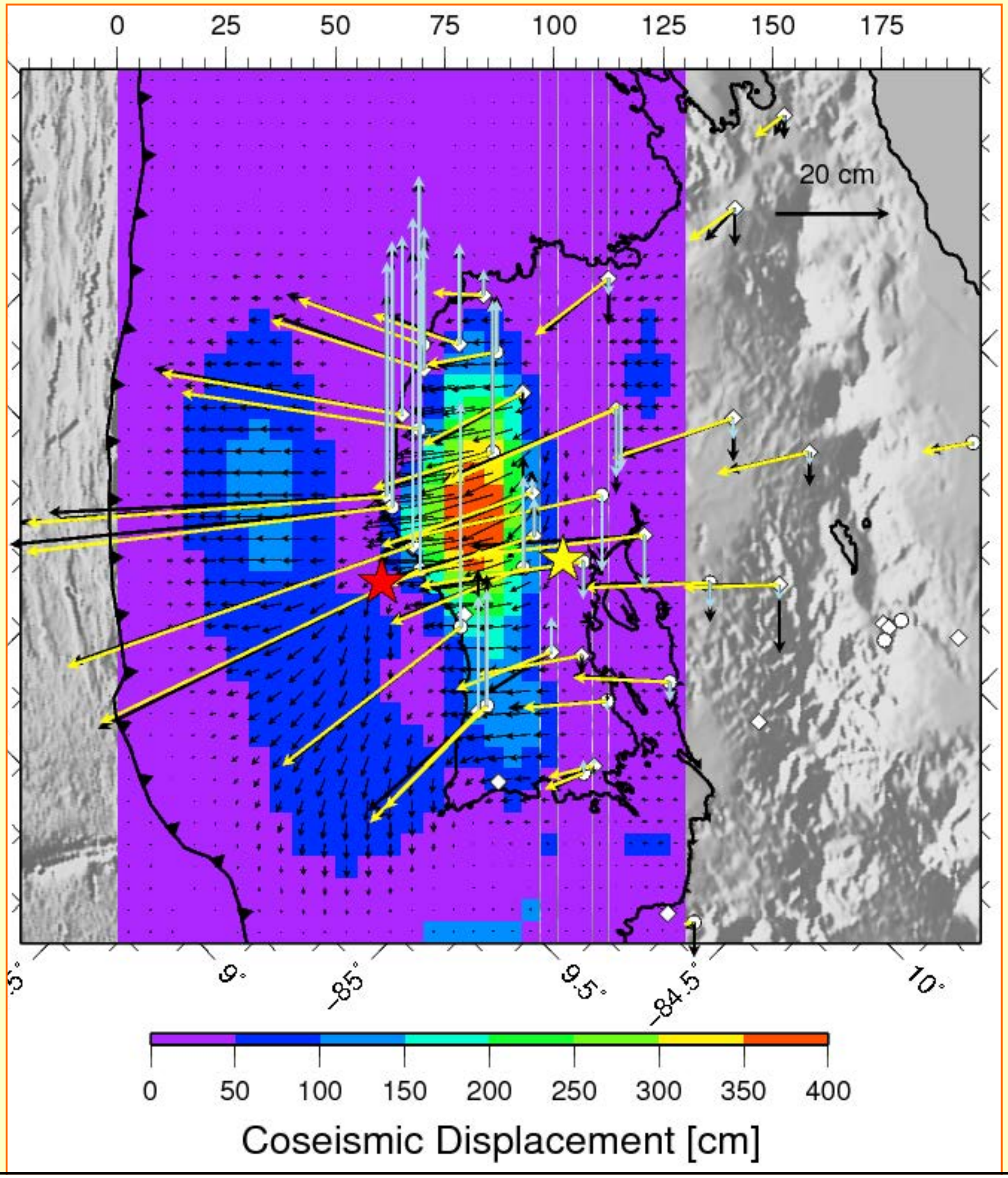


Coseismic slip

- Sept. 5, 2012, M_W 7.6
- Result are combination of continuous and campaign GPS over 24hr – 1 week



Protti et al., Nat. Geosc. 2014



Can we predict earthquakes?

Late-interseismic locking and earthquake rupture

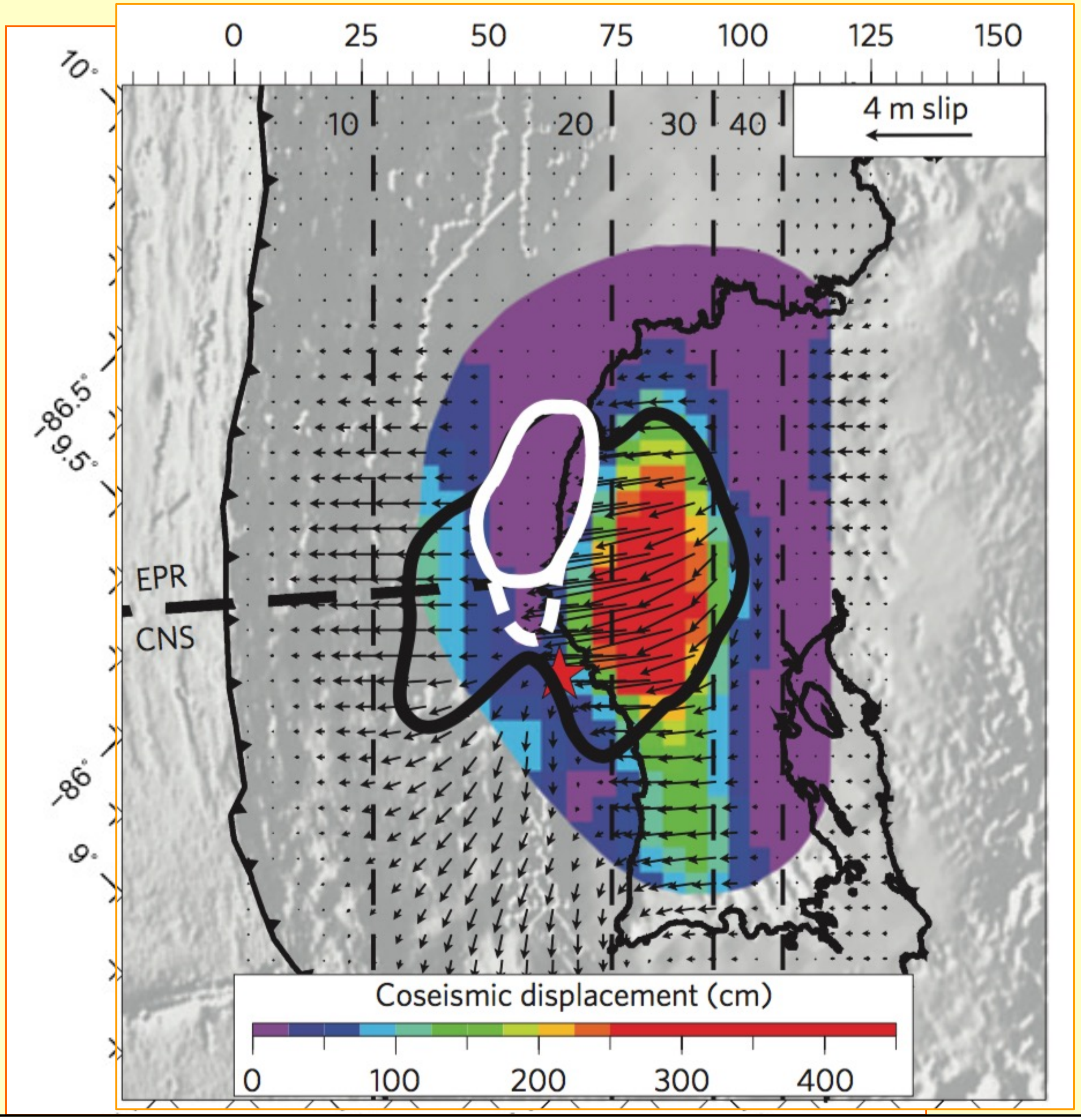
Late interseismic locking can be used to estimate earthquake potential, given sufficient imaging.

Seismic moment accumulation rate,
$\dot{M}_0$ = 9.0 x10^{18} N m yr^{-1}

Earthquake potential = $\dot{M}_0$ x interval:
= 9.0 x 10^{18} N m/yr * 62 years
= 5.6 x 10^{20} N m
= M_W 7.8

Feng et al. JGR June-2012

2012 Nicoya earthquake
=3.4 x 10^{20} N m (gCMT)
= Mw 7.62



Protti et al., Nat. Geosc. 2014

Late-interseismic locking and earthquake rupture

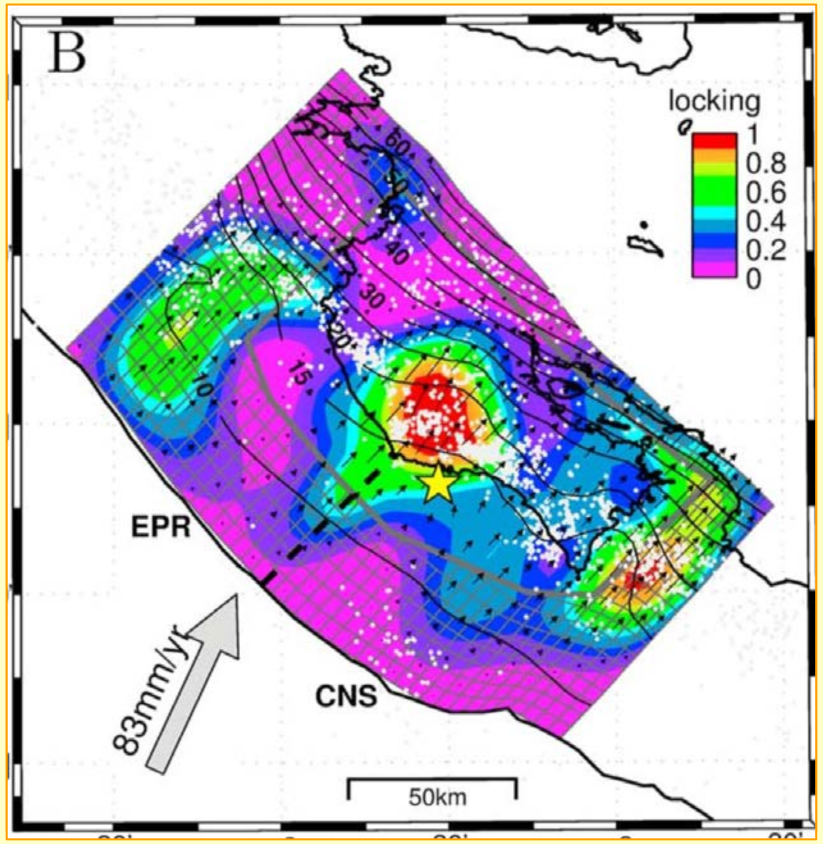
3D Late interseismic locking using new MAT geometry

Earthquake potential = $\dot{M}_0$ x interval:

= 3.5 x 10^{20} N m

= M_W 7.63

Kyriakopoulos and Newman, JGR, 2016



2012 Nicoya earthquake
=3.4 x 10^{20} N m (gCMT)
= Mw 7.62

Can we predict earthquakes?

Given enough observations of the pre-earthquake strain field, we CAN forecast the Where? and How Big? Of at least some events… timing still difficult.

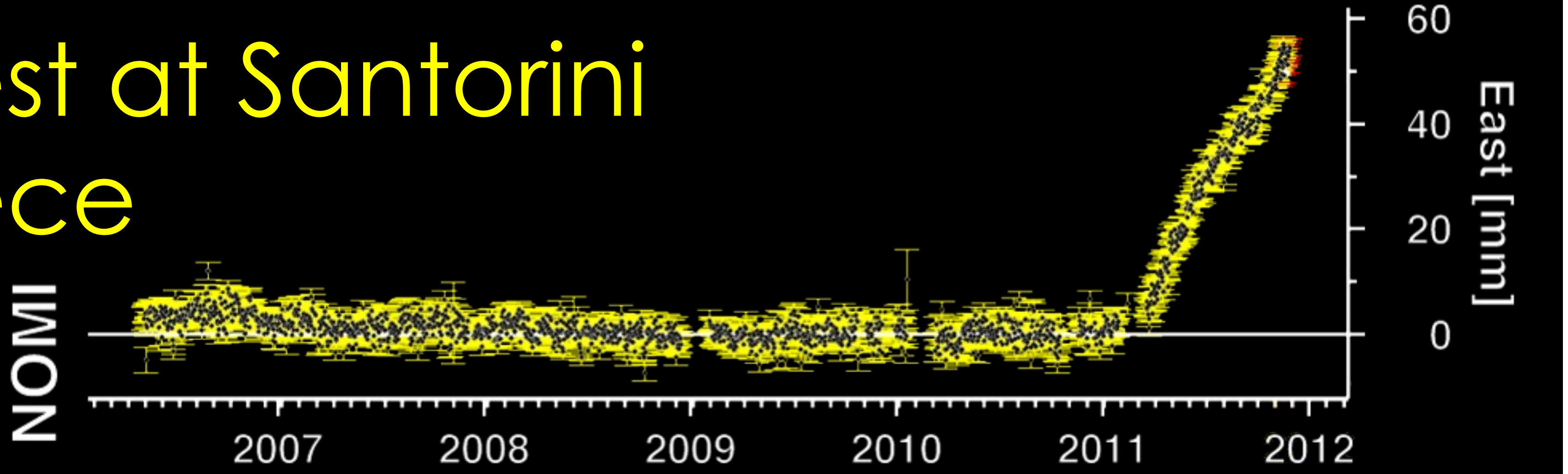
Application to volcanism

Santorini Caldera, Greece

GT research on volcano

Massive Minoan Eruption ~3500ya

Renewed Unrest at Santorini Volcano, Greece



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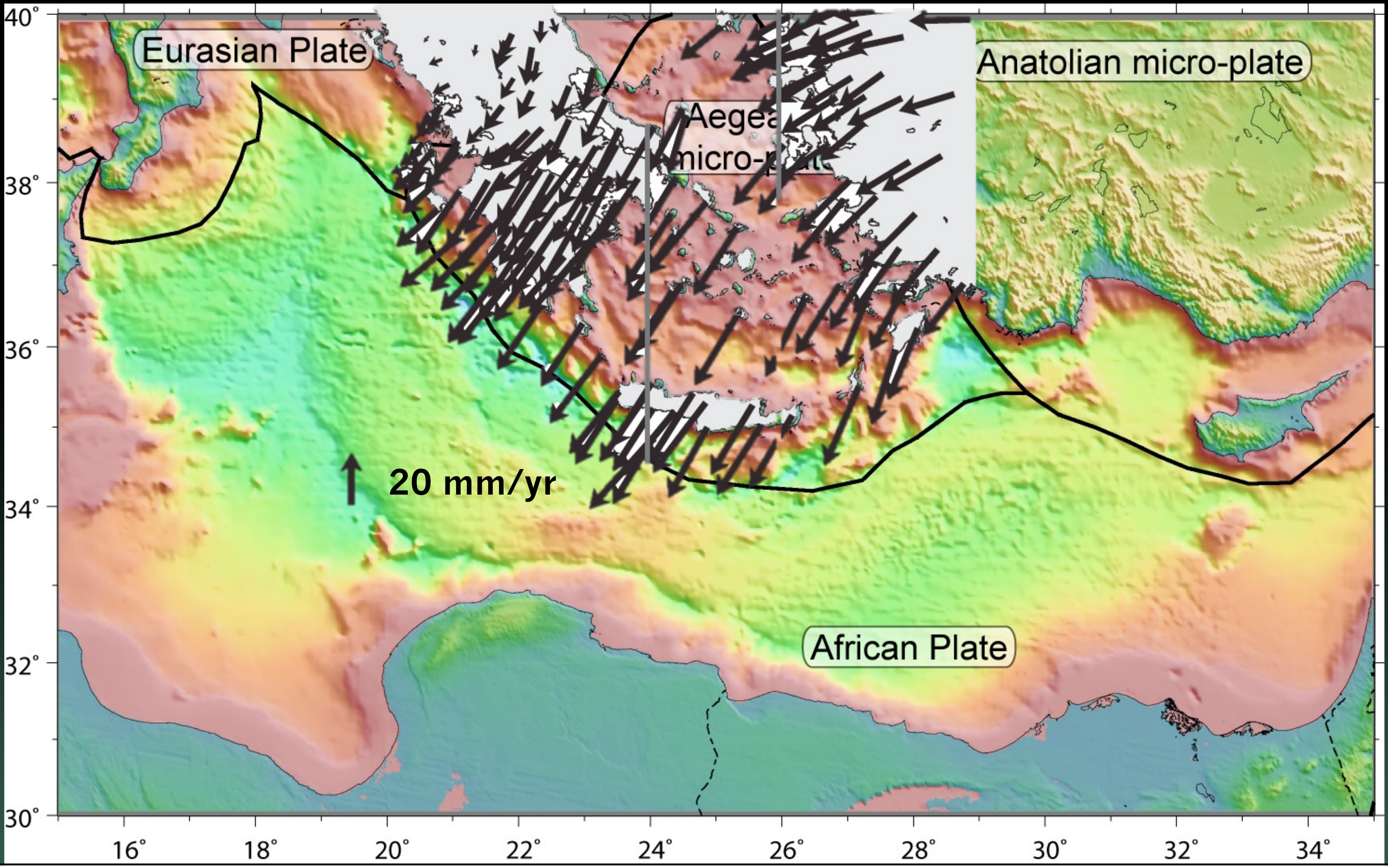
Georgia Institute of Technology

UNAVCO

NSF

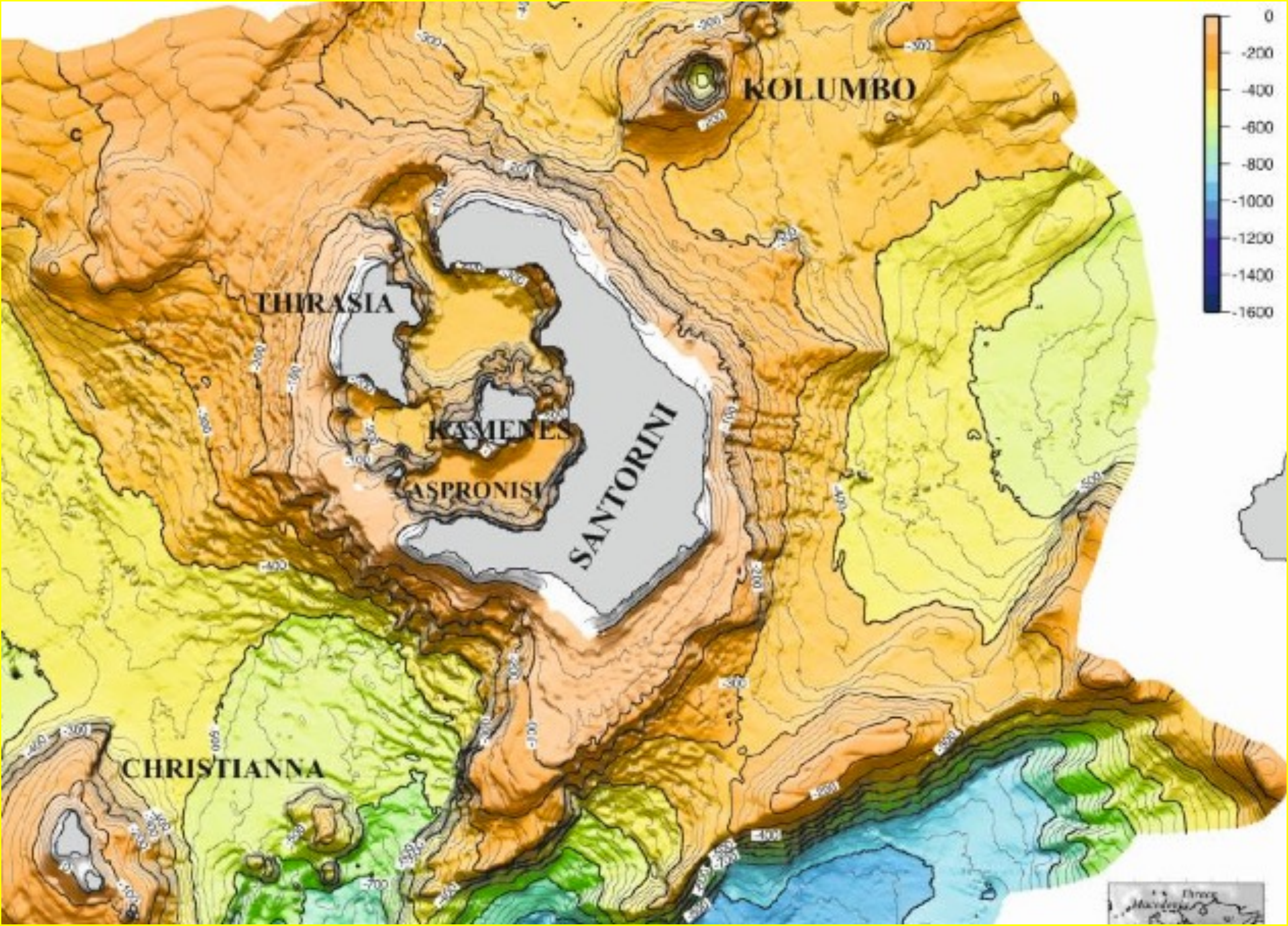
Regional Tectonic Environment

Endrun et al. 2010 (after Floyd et al. 2010)



Multi-beam Bathymetry

40 – 60 km^3 DRE from Minoan Eruption



(Nomikou et al., Glob. Plan. Change, 2012; after Sigurdsson et al., EOS, 2006)

Eruptions:

3 to 4 caldera eruptions in past 600 ka

Last caldera (Minoan) eruption
- ~1650 BC
- Likely from northern zone

Recent activity
- Over past 1000 yrs
- Small pyroclastic and phreatic eruptions dominated
- Forming Palea and Nea Kameni.

[Heiken and McCoy, 1984; Druitt *et al.*, 1989]

Unique risks

Summer population > 100,000

Many stay on en echelon housing built along steep caldera walls

Strong EQ (M7.7) in 1956 devastated area

- Land slides
- Collapsed domiciles
- Tsunami

- *Fortunately, volcano-induced seismicity is generally much smaller*

Photos: Grant Farmer

Unique risks

Many cruise ships anchor inside caldera (and directly over 2011 seismic activity)

Phreatic blasts are a particular concern for tsunami inside the caldera

Source: http://blog.travelpod.com/travel-photo/aslightdetour/

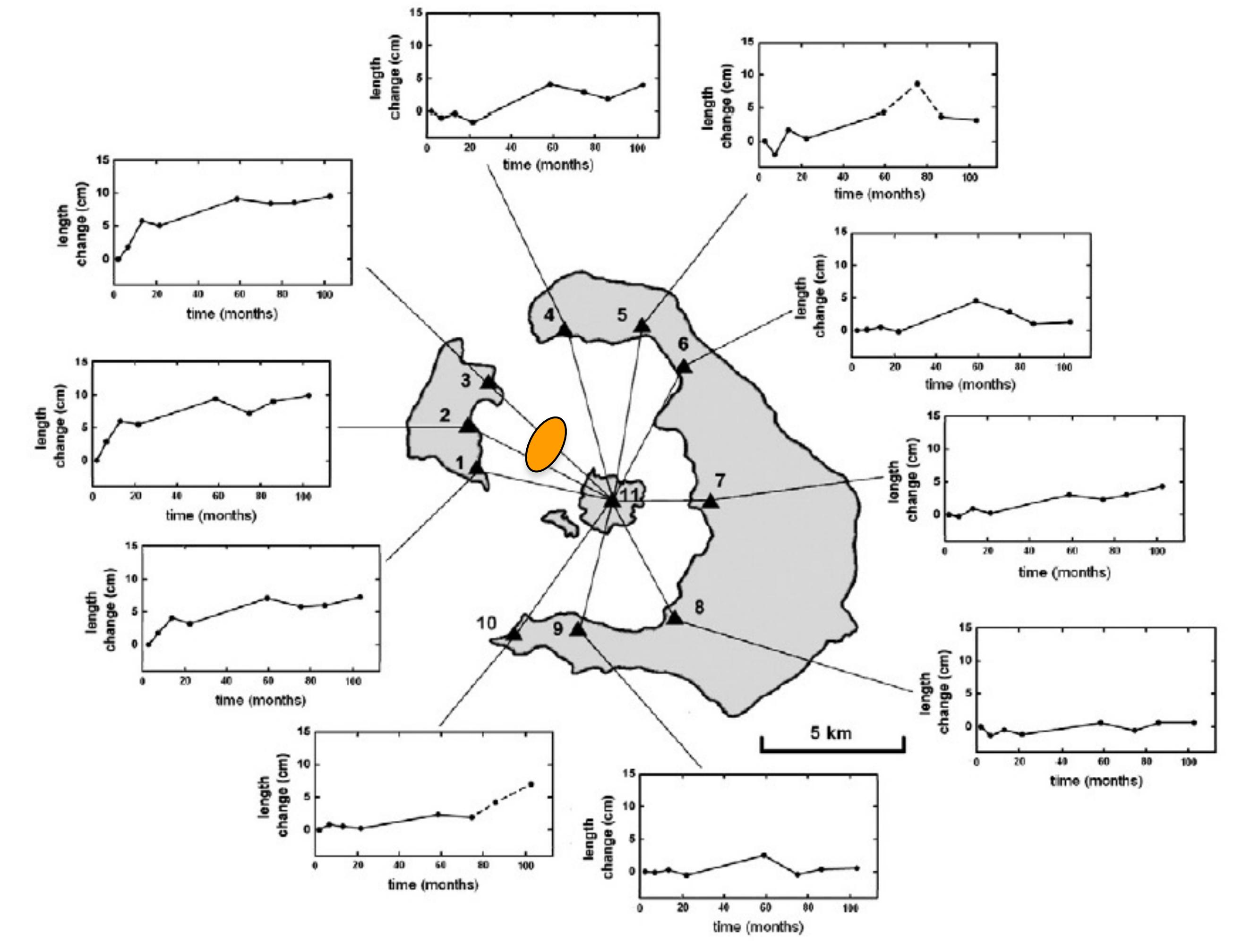
Minoan Ignimbrite Deposits

30 – 50 m thick in places

Ancient City of Akrotiri buried (no apparent fatalities!)

EDM observations in 1990s

Possible 2-5 cm extension episode between 1994 and 2000

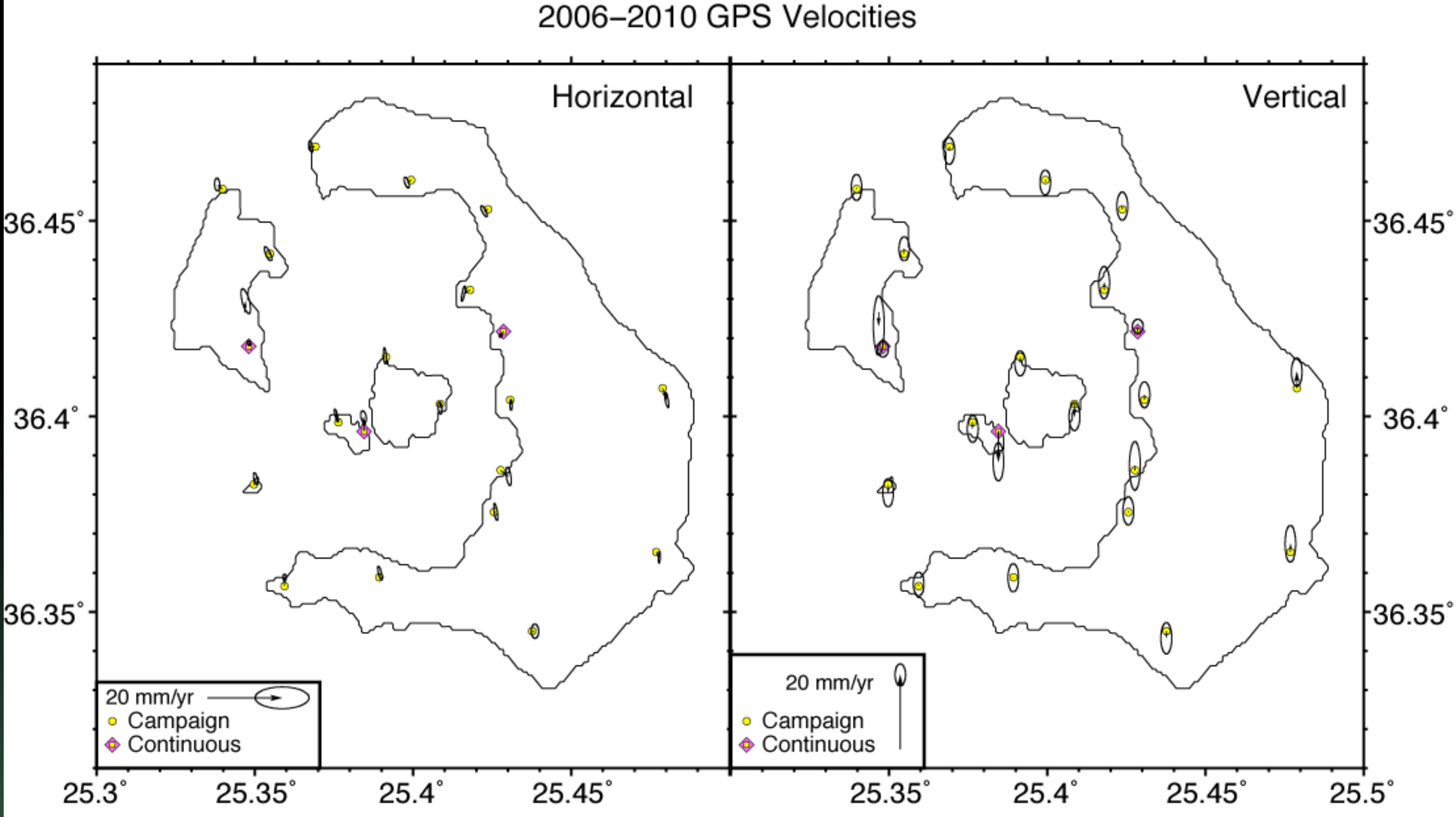


Stiros et al., Tectonophysics, 2010

2006 Initial Deployment

with repeat surveys in 2008 and 2010

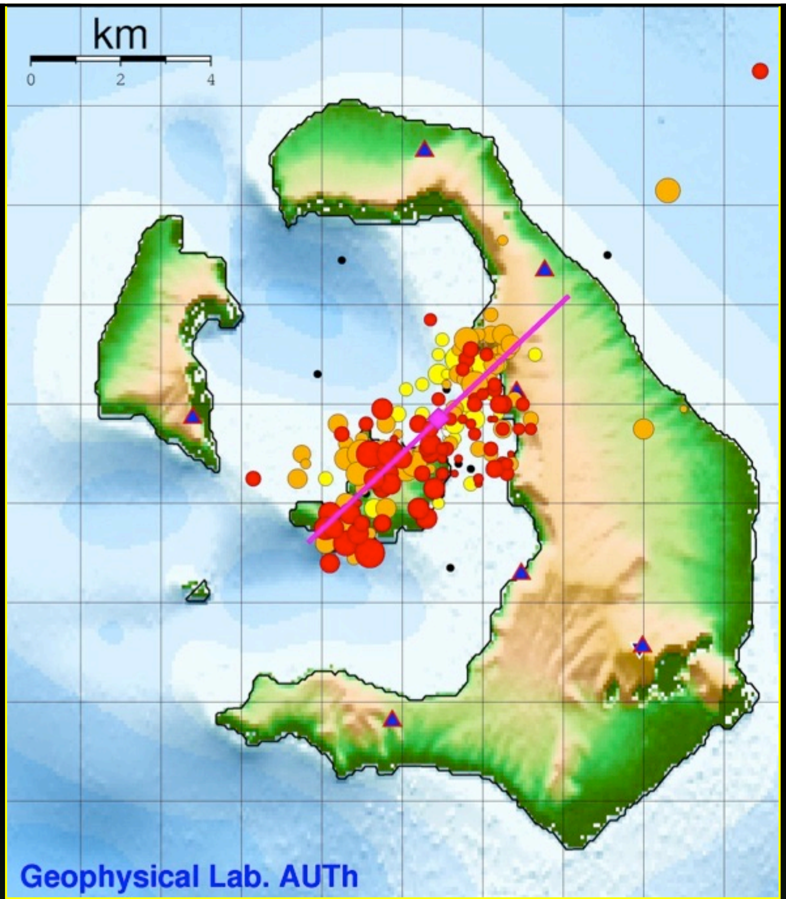
Campaign and Continuous GPS

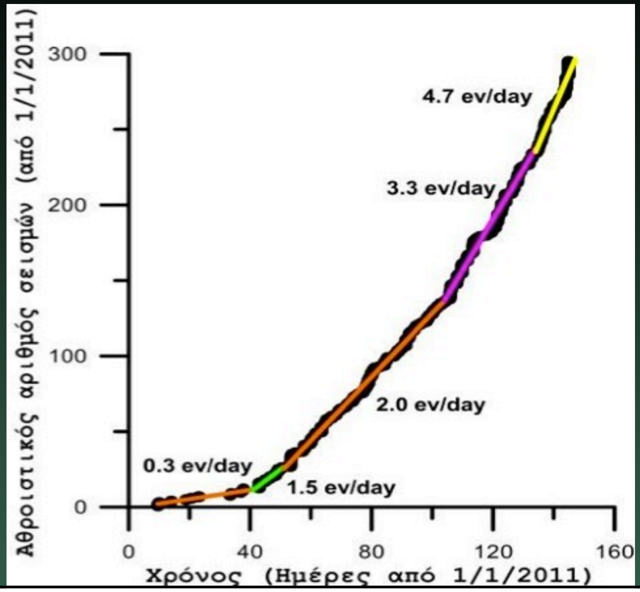


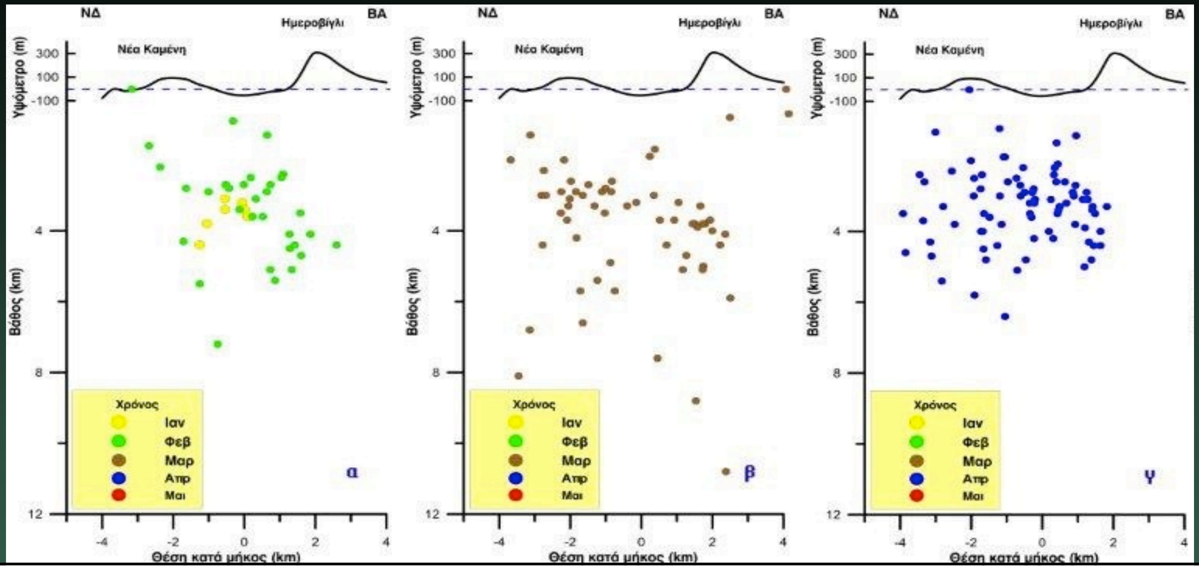
Processed w/ GIPSY 6.1 in ITRF2008 (mean island signal removed E 7.06, N -15.78 mm/yr)

Onset of Microseismicity

- Recorded by a growing network at the Aristotle University of Thessaloniki
- First significant earthquake activity known within caldera since the last eruption in 1950
- Most recorded activity $1 \leq M_L \leq 3.2$
- Follows along eruptive Kameni Line



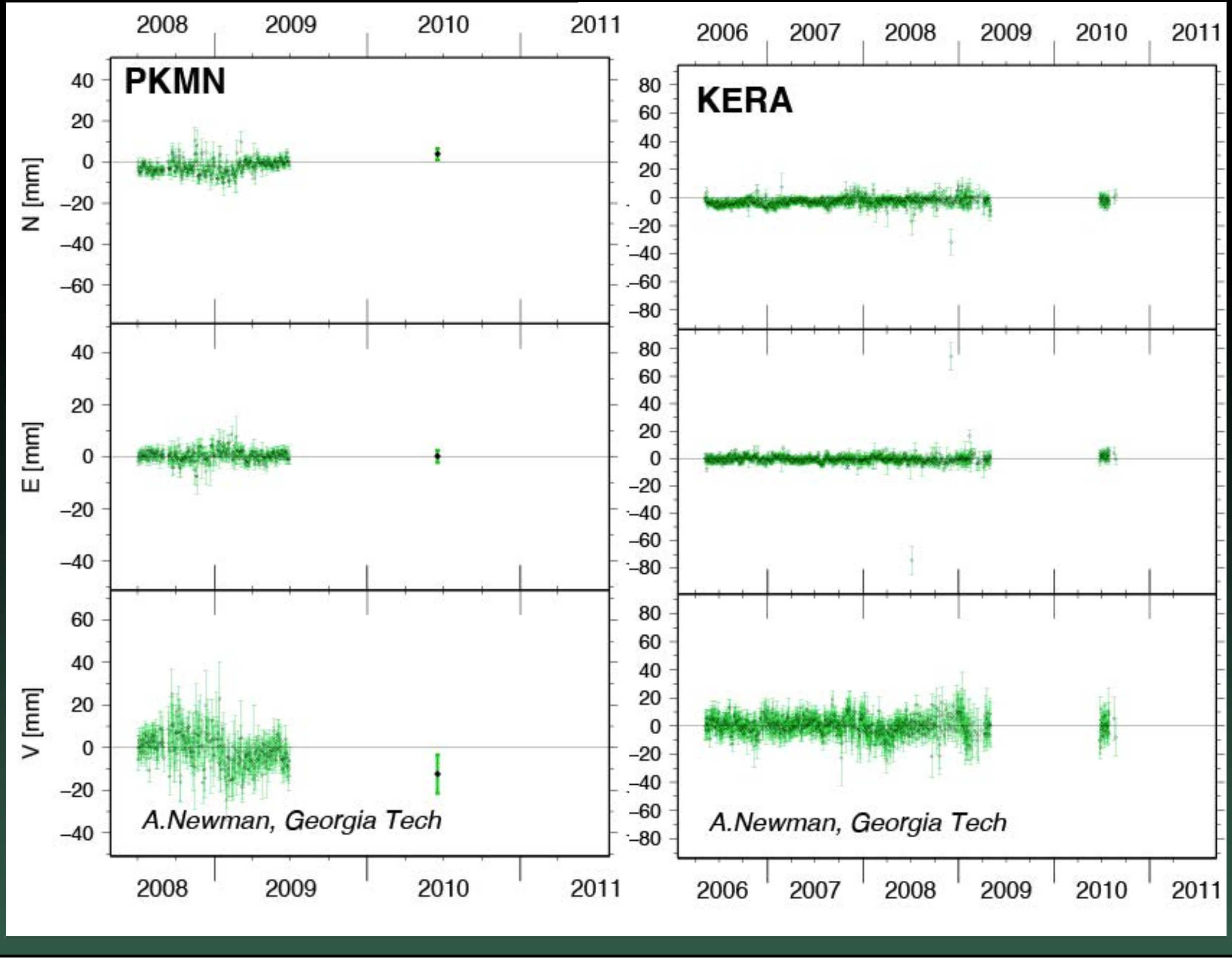


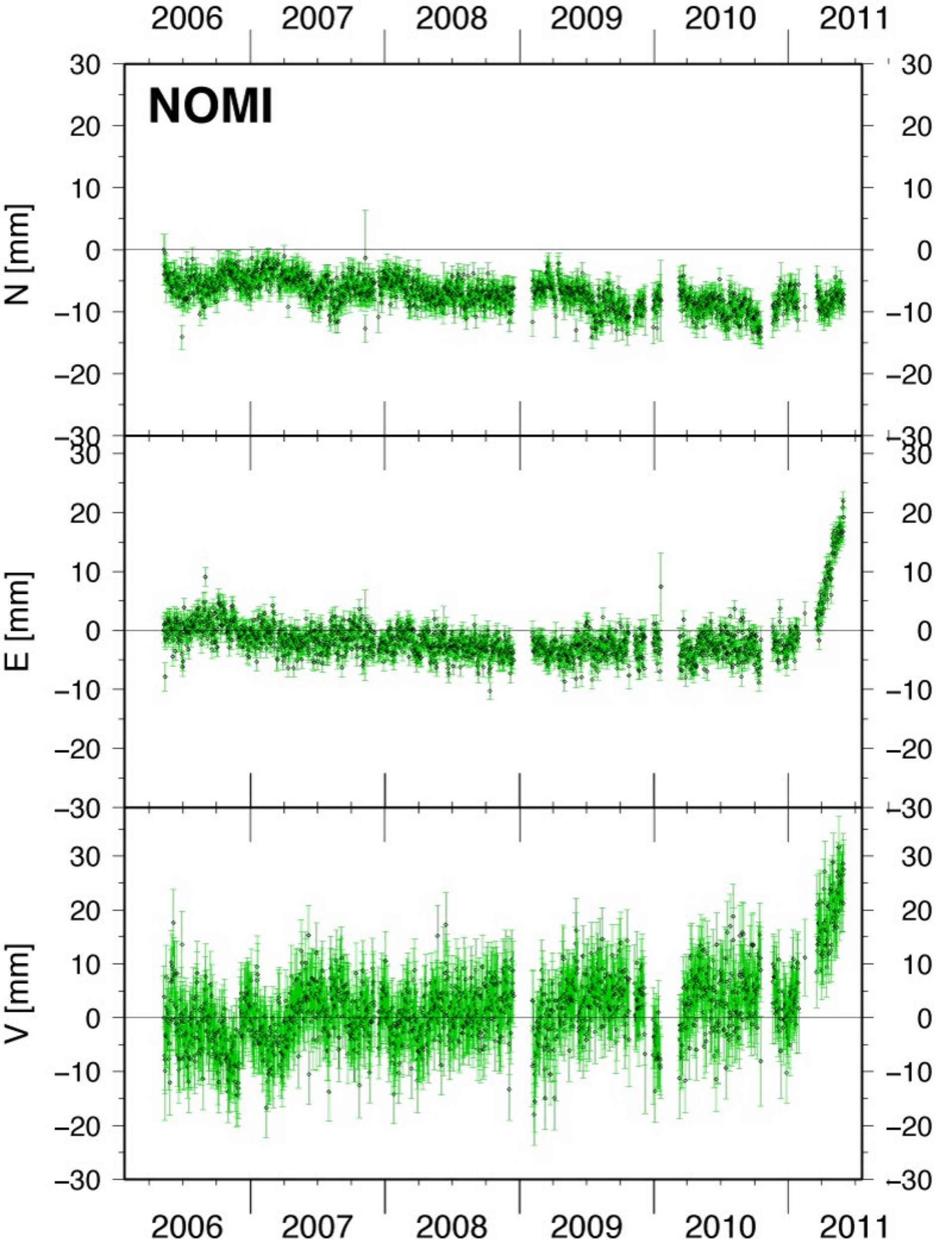


GPS (through early 2011)

Only 1 Continuous site operational at the time
(flash drives died on 2 receivers)

Short-duration measurements were made in 2010
using replacement receivers





GPS (campaign June 2011)

Funding from U. Patras for seminar

Truncated campaign

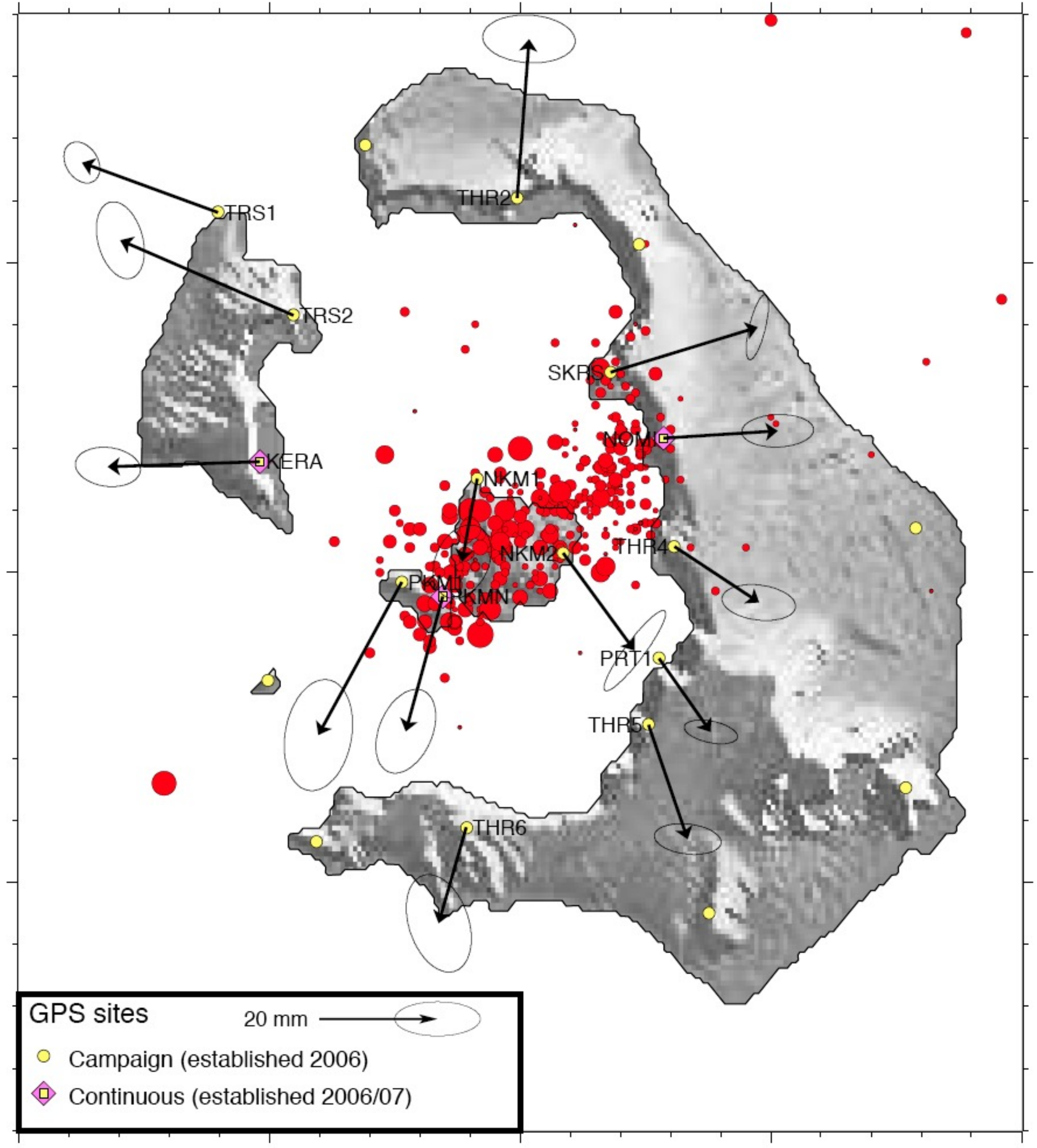
- 11 sites
- ~36 hr each

Different instrumentation/masts

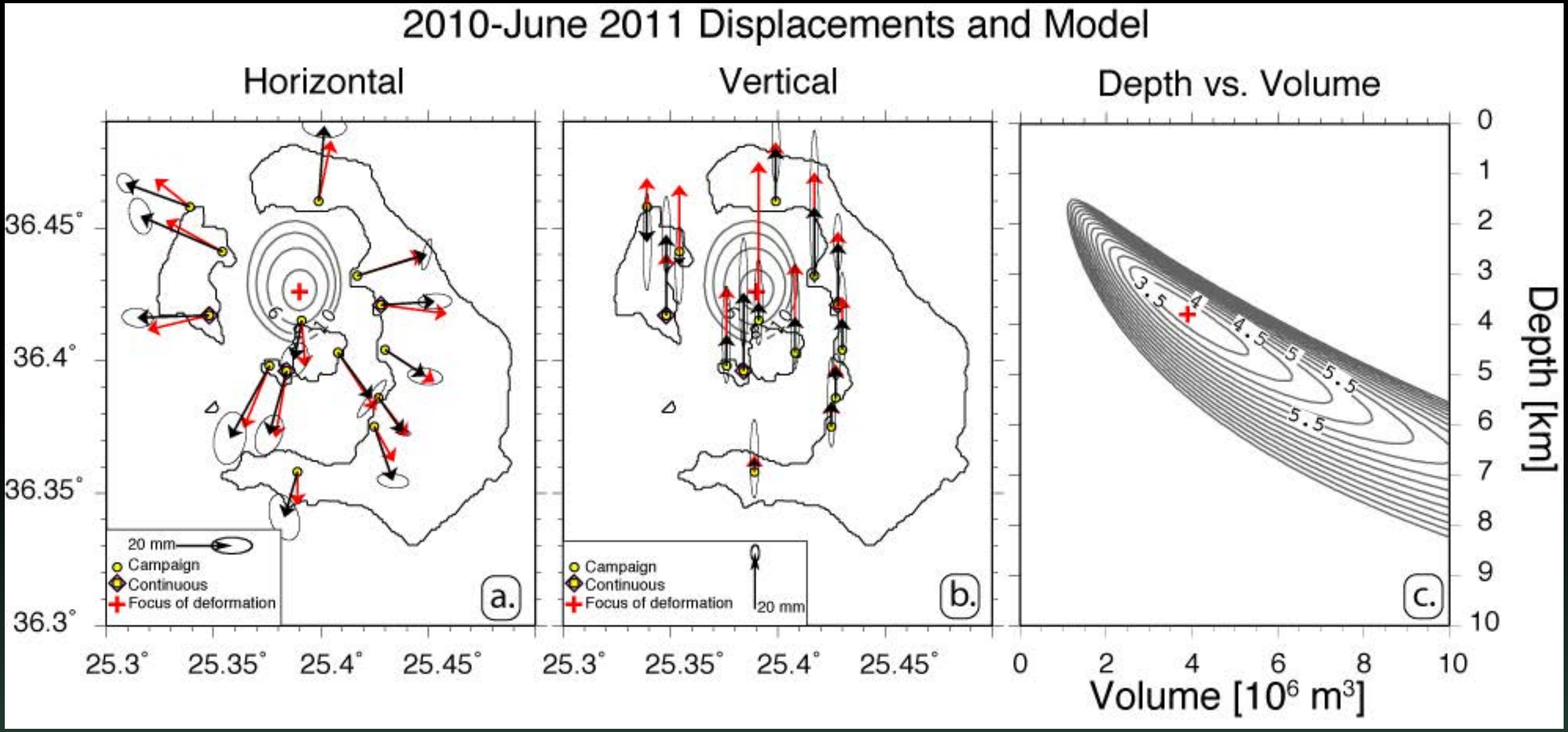
GPS (June 2010 -June 2011)

Near-radial expansion source

Dike opening along seismic line is excluded



GPS (June 2010 – June 2011)



Mogi approximation well describes deformation
(depth = 3.9 km , $\Delta V = 4.1 \times 10^6$ m^3 ; RMS = 1.1 cm)

GPS (Sept. 2011)

NSF-RAPID funding for:

- Upgrade GPS infrastructure
- 2 New installations
- Complete campaign

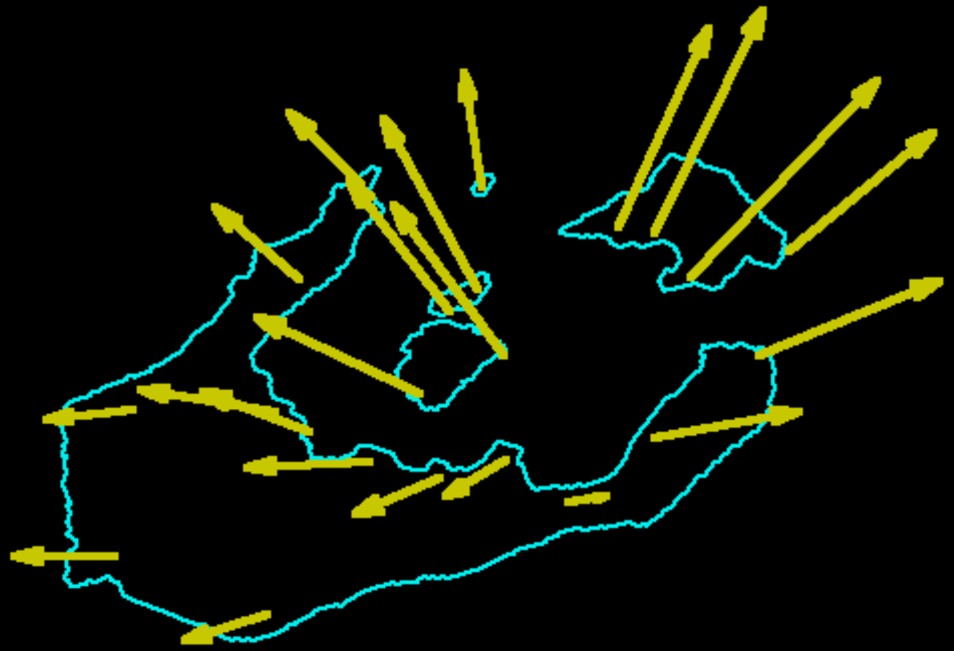
UNAVCO

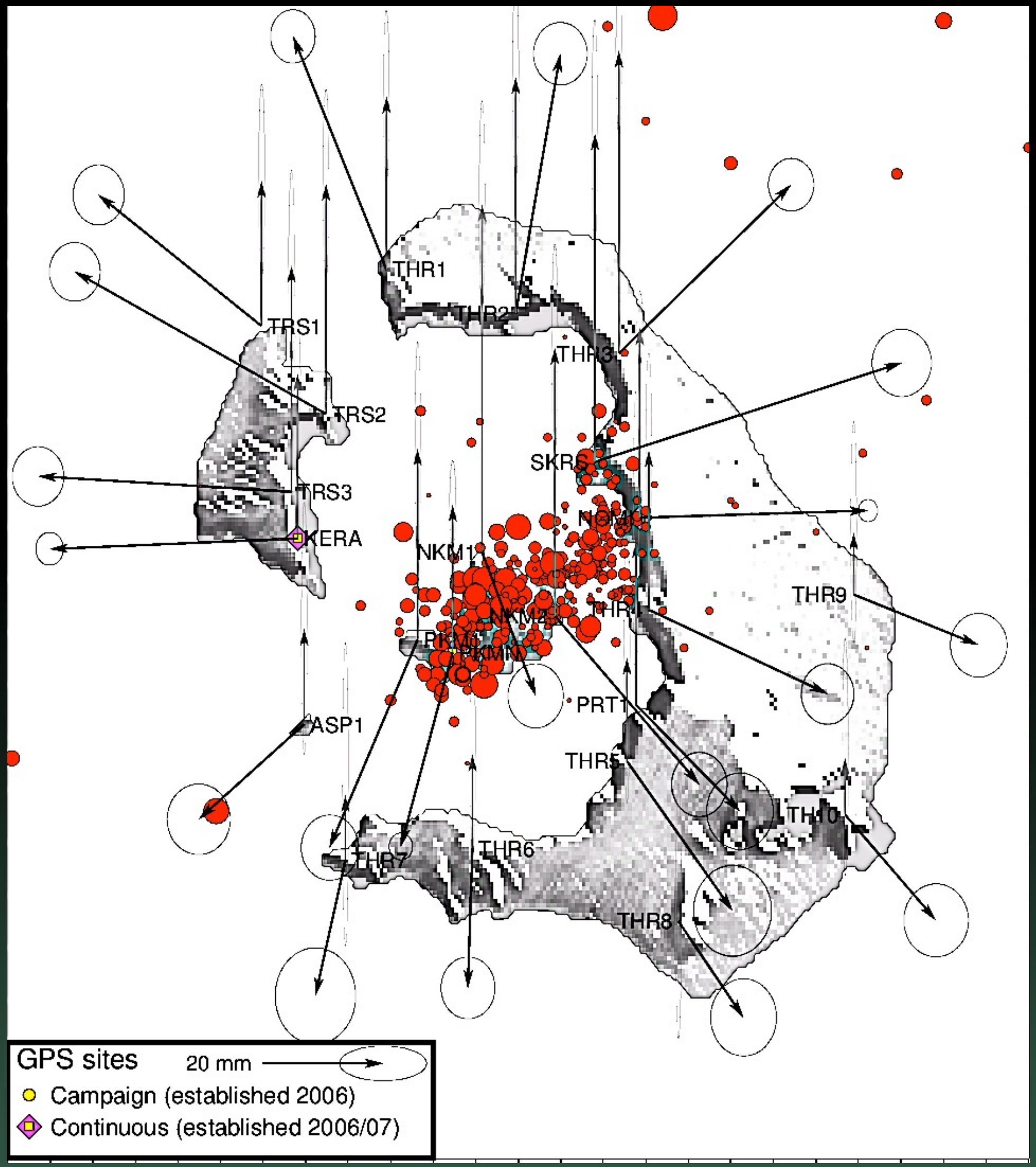
GPS (2010 – Sept. 2011)

NSF-RAPID funding for:

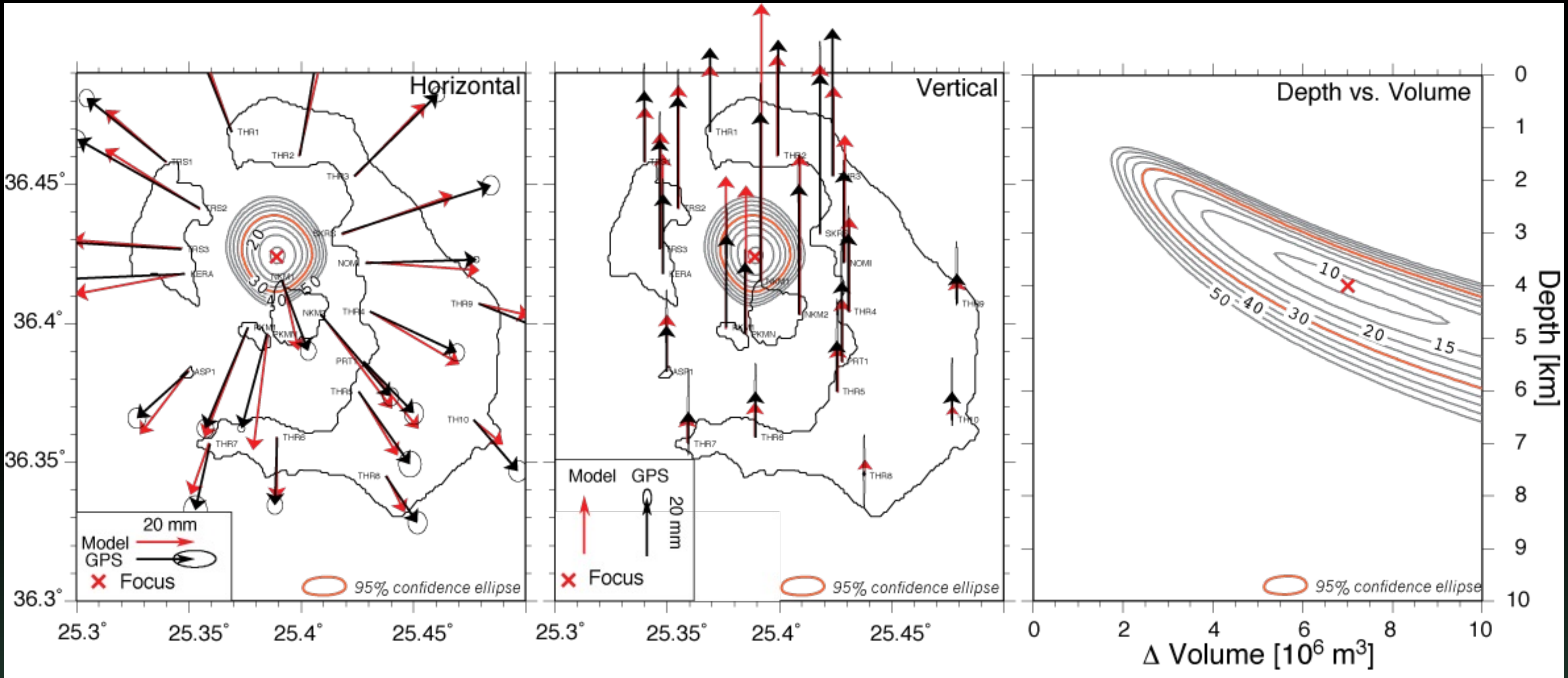
- Upgrade GPS infrastructure
- 2 New installations
- Complete campaign

New displacement field with 19 campaign and 3 continuous results





GPS (June 2010 – Sept. 2011)



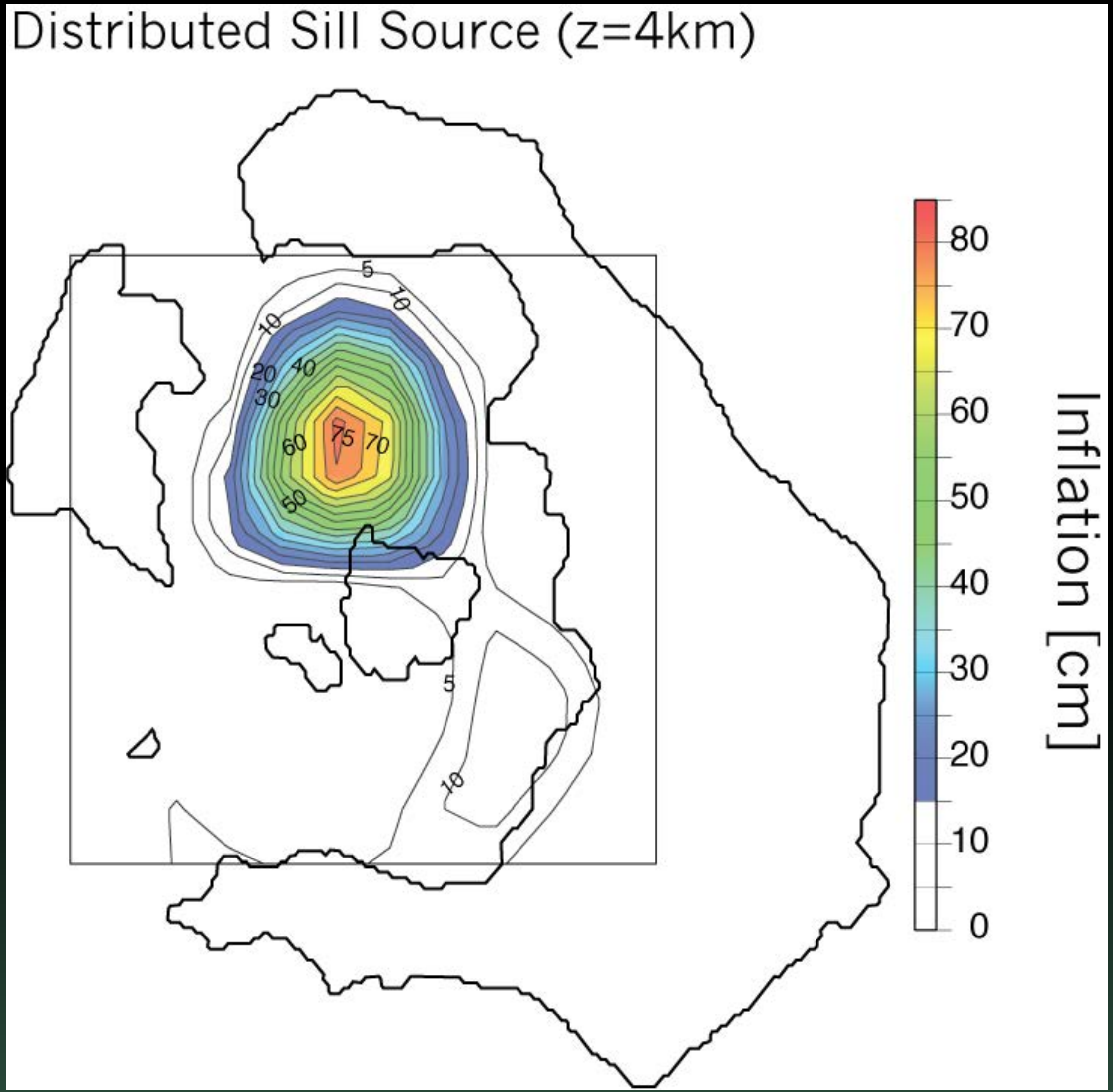
Mogi approximation well describes deformation
(depth = 4.0 km , ΔV = 7.0 x 10^6 m^3 ; RMS = 0.8 cm)

Distributed sill model

3D fit to GPS displacements between June 2010 and August 2011

Highly non-unique and has larger error

Identifies some spatial contribution



Distributed Sill (*fixed* depth= 4 km), max U_z = 80cm, ΔV = 9.2 x 10^6 m^3 ; RMS =1.5 cm)

Summary for Santorini:

- Santorini entered an state of unrest with seismicity and deformation. Largest since eruption in 1950
- Cumulative growth ~14 x10^6 m^3
  - about 1/3000th the product of the Minoan Eruption
  - Inflation ceased mid-2012 without any volcanic activity
- It was not clear that an eruption is imminent.
- Low-latency results are reported to an international team of volcanologists, Greek scientists, and civil defense
  - Latency 2-days (daily positions); 2-hour or less for kinematic
  - Greek government were cautious about unregulated flow of information.

Agenda

Day 1: Geodetic Measurements

9am : **Introductions**
9:30 : Overview of Geodesy
10:30 : **Break**
Here → **10:45** : Detailed understanding/theory on GPS/GNSS
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1:30 : Modeling deformation using GTDef (or other analytic tools)
3:30 : Discussion
4:00 : Adjourn with end-of-day **snack/coffee**

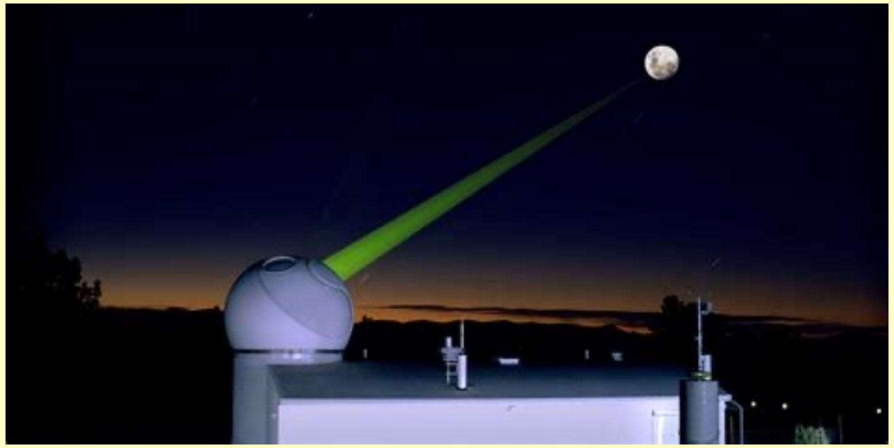
Details of GNSS

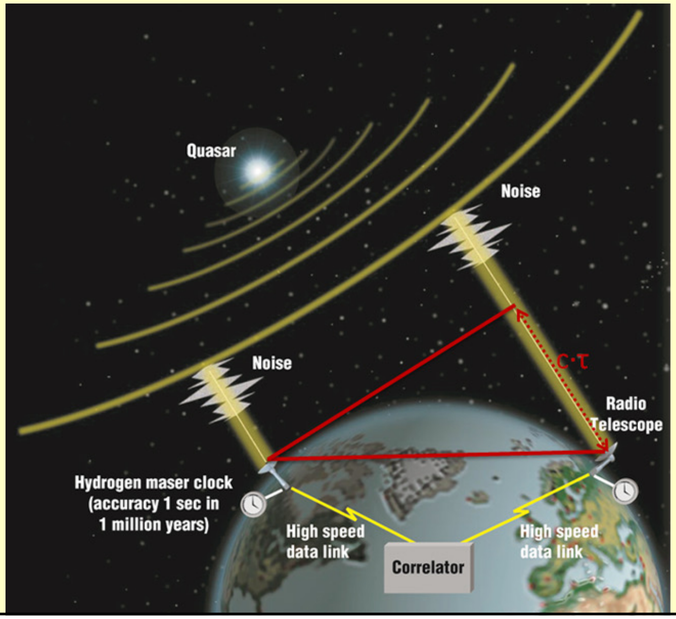
GNSS: Getting precision solutions

- Satellites have errors in orbits
  - **Atmospheric drag** (small)
  - **Non-symmetric gravity** (small)
  - **Sun/moon forcing** (predictable)
  - **Solar radiation pressure** (large, and unpredictable)
    - Complex sat/solar panel geometry
    - Changes in solar activity
    - Earth eclipses
    - Causes m-level shifts in a single pass.

GNSS: Getting precision solutions

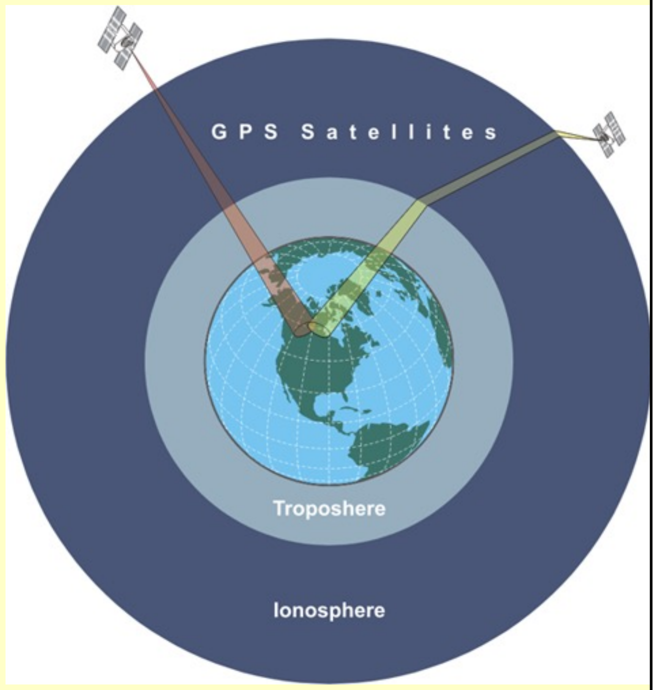
- Satellite orbits need to be corrected relative to ground-based reference stations across globe, putting satellites in precision earth reference frame.
- NASA-JPL and other groups produce precise (cm-level) orbits with about 2 wks latency (more rapid, less precise solutions are also available)
- Earth reference frame is maintained by combination of GNSS, Satellite laser ranging, and Very-Long Baseline Interferometry.





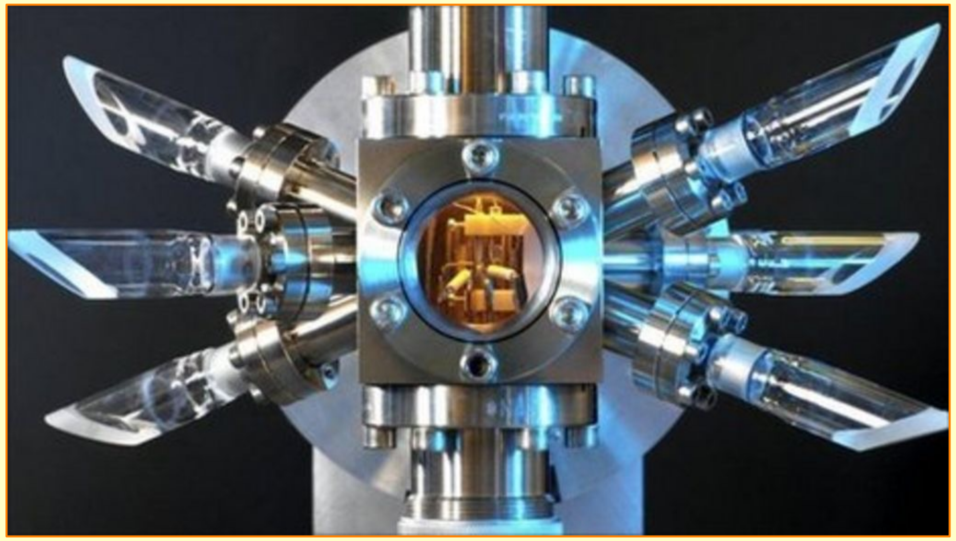
GNSS: Getting precision solutions

- GNSS signals are perturbed by:
  - **Ionosphere** (dispersive-delays each frequency differently)
    - L1-L2 can can correct
    - L1-only (e.g. your phone) cannot correct for this
      - Depend on broadcast estimated delay based on time of day and incidence angle
    - Changes due to solar activity, and atmospheric waves (Rossby, pressure waves, tsunami)
  - **Troposphere**
    - Dry-delay (pressure) from both stratified and weather-related pressure is mostly predictable
    - Wet-delay (moisture) is much more difficult, and requires detailed models (1° 12-hour global moisture models used)



Most signal errors can be corrected using 3D atmospheric models based on weather and large-scale GNSS data

GNSS: Getting precision solutions



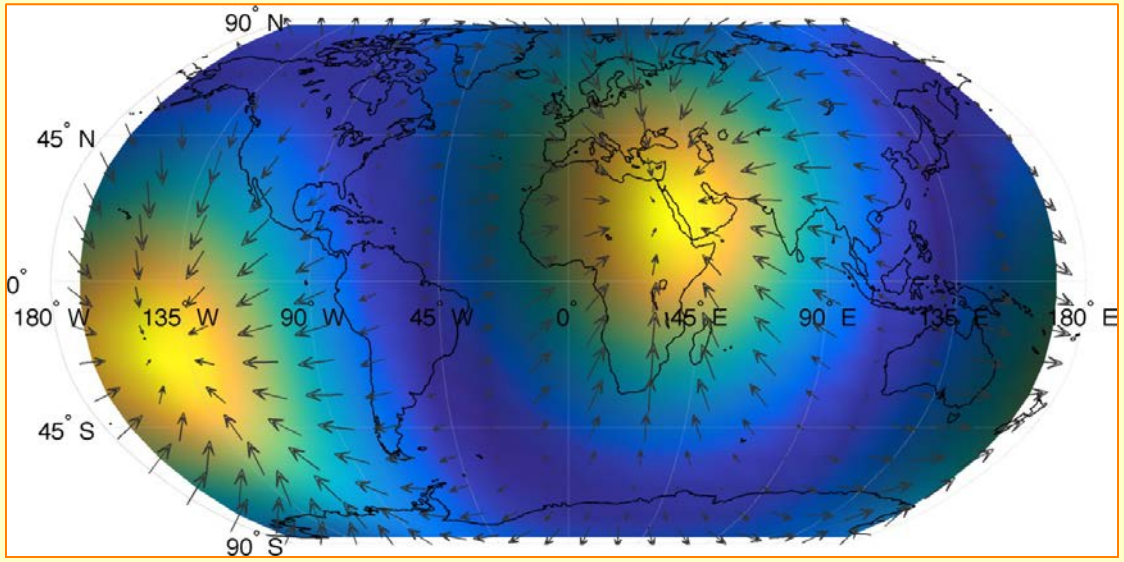
- **GNSS receivers**:
  - Timing (μs precision needed)
    - 1 ms = 3m satellite motion+3cm earth rotation.
  - Precision phase-center location
  - Ground reflections (backscatter)

- Timing of receiver corrected by satellites (which have Rb/Cs clocks)

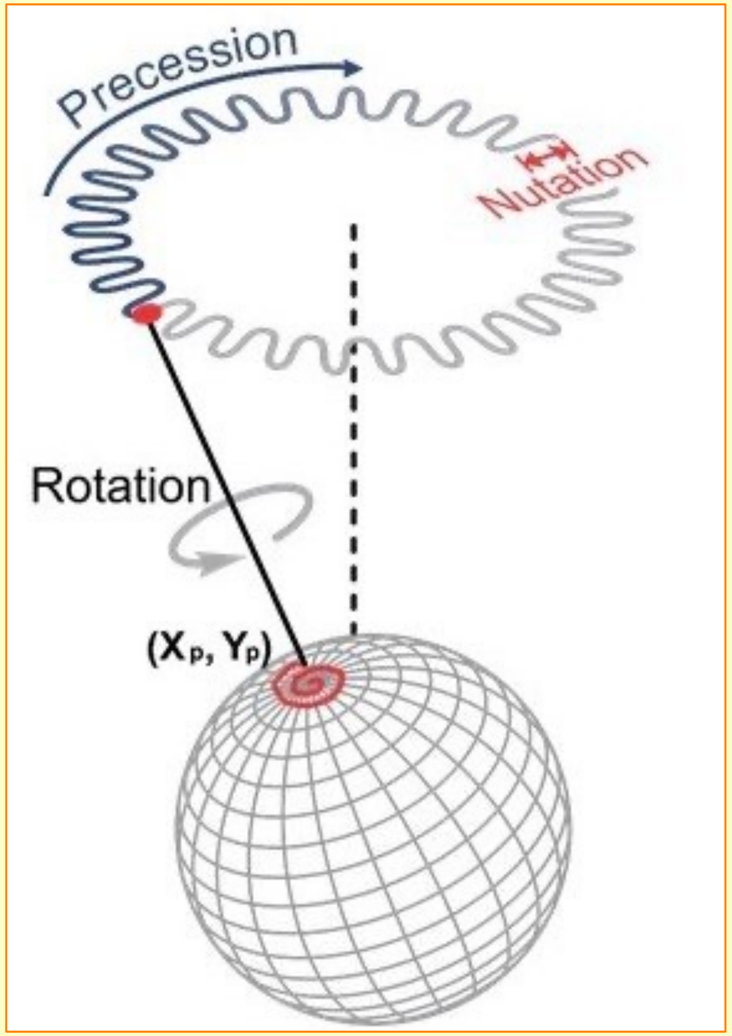
- Using repeat instrumentation reduces phase-center and ground reflection error.

GNSS: Getting precision solutions

- Earth motion needs to be corrected:
  - Earth tides (~50 cm)
  - Ocean loading (~5 cm)
  - LOD: Time-varying rotation (~1cm)
  - Nutation/Precession changes (~1cm)
  - Atmospheric loading (~1mm)



Modeled Earth Tides



Earth Orientation Parameters

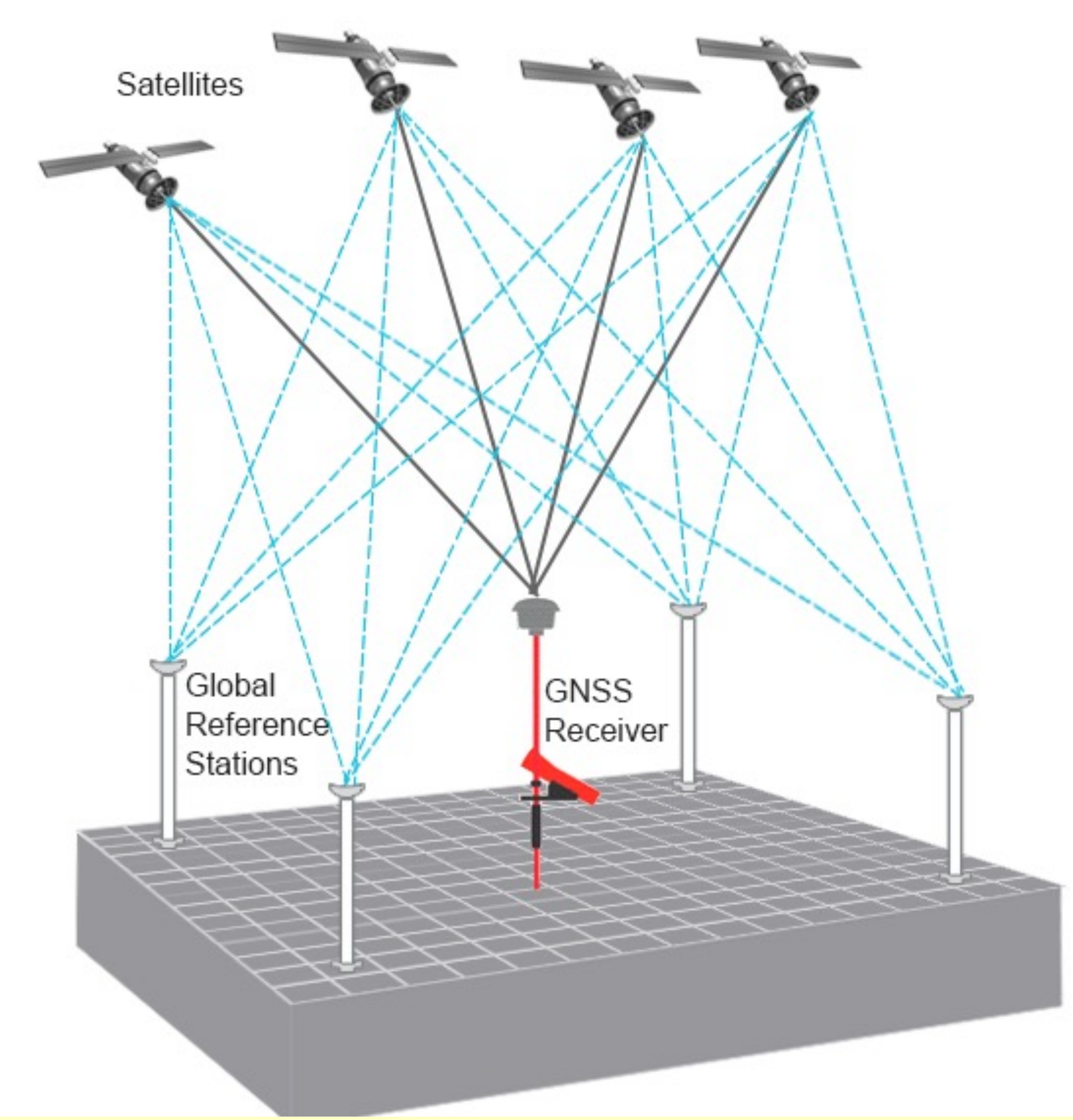
GNSS: Getting precision solutions

Finally: accurate position relative to Earth’s center of mass.

- Solutions are 3D
- Time-component dependent on sampling/precision needed.
- 1-day average solution error
  - 2,4,7 mm (N,E,V)
- 1-yr solution error down ~4 mm/yr motion, depending on regional seasonal effects.

Static vs kinematic measurements

- **Static Processing**
  - Ideal for slow-moving long-lived signals
  - Solutions average several hours to 1-day data for mm-level precision that can be in a global reference frame
  - Modern methods use Precise-Point-Positioning (PPP)
    - put results in global reference frame.
    - grows linearly with data used
  - Older, network-based solutions grew quadratically with stations (not good for large networks)



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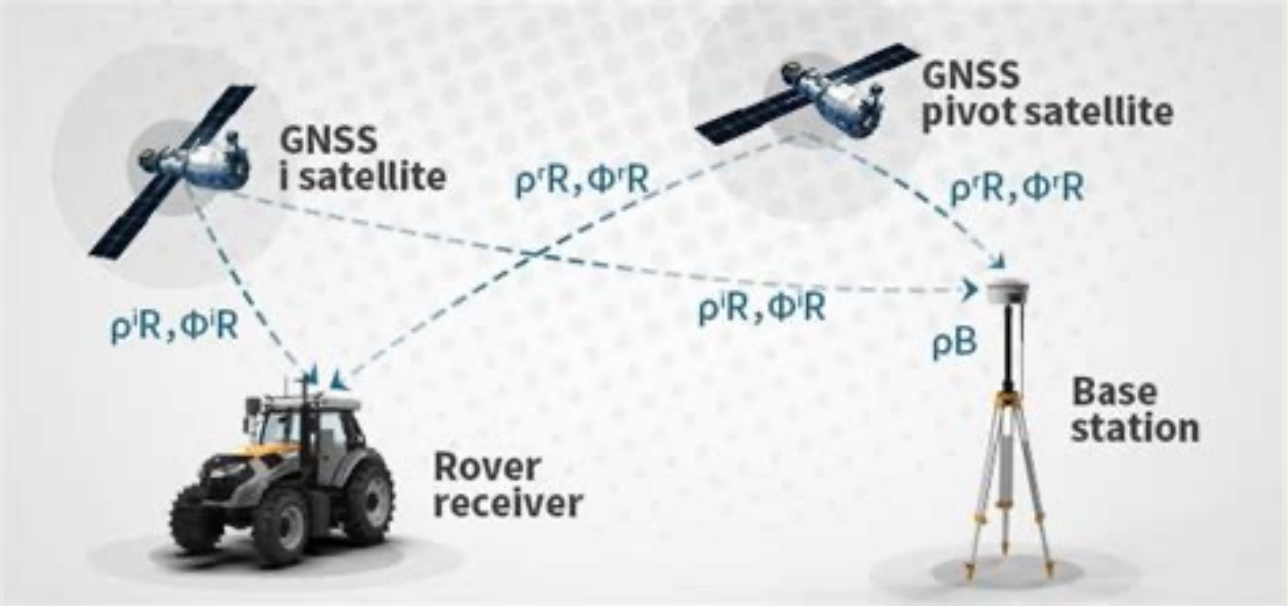
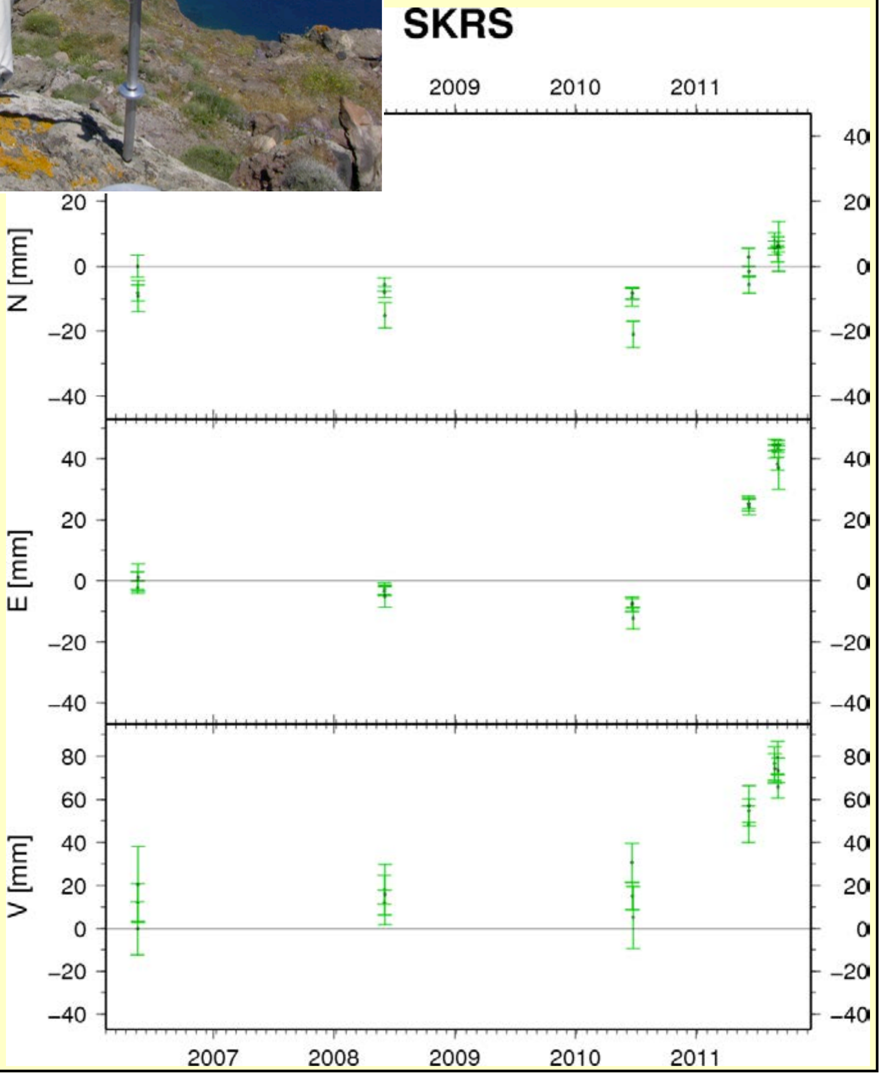
    - put results in global reference frame.
    - grows linearly with data used
  - Older, network-based solutions grew quadratically with stations (not good for large networks)

- **Kinematic Processing**
  - Ideal for fast-moving signals
  - Errors are cm-dm level relative to base station (may be statically resolved)



GNSS Monumentation

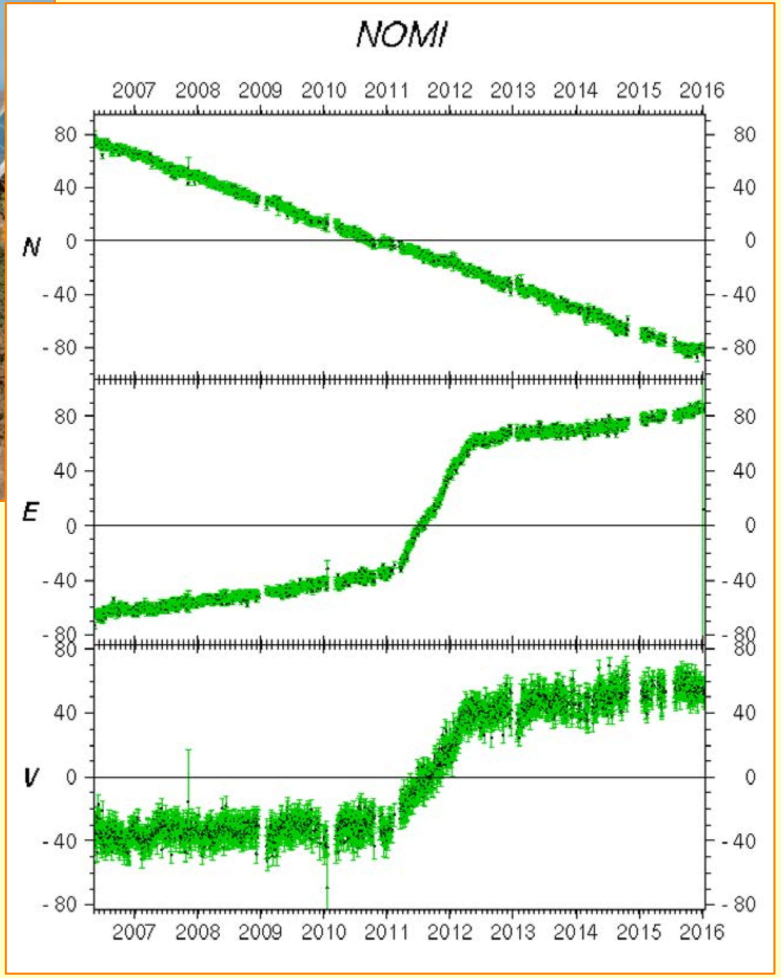
- **Campaign-style GNSS**
  - Small survey pins/benchmarks
  - Setup for short (1-5 day surveys)
  - rarely telemetered
  - Capable of capturing secular/ long-term changes
  - Setup is done on a tripod or spike-mount (shown)



GNSS Monumentation

- **Continuous GNSS**
  - Long-term observation capabilities
  - Capable of observing changes over seconds to years
  - Requires:
    - Stable monumentation
    - Power
    - Access
    - Security
    - Usually telemetered

Direct-to-bedrock monument



Short drill-brace monument

GNSS Monumentation

- **Continuous GNSS**
  - Stable robust monumentation
  - Long-term observation capabilities
  - Usually telemetered
  - Capable of observing changes over seconds to years

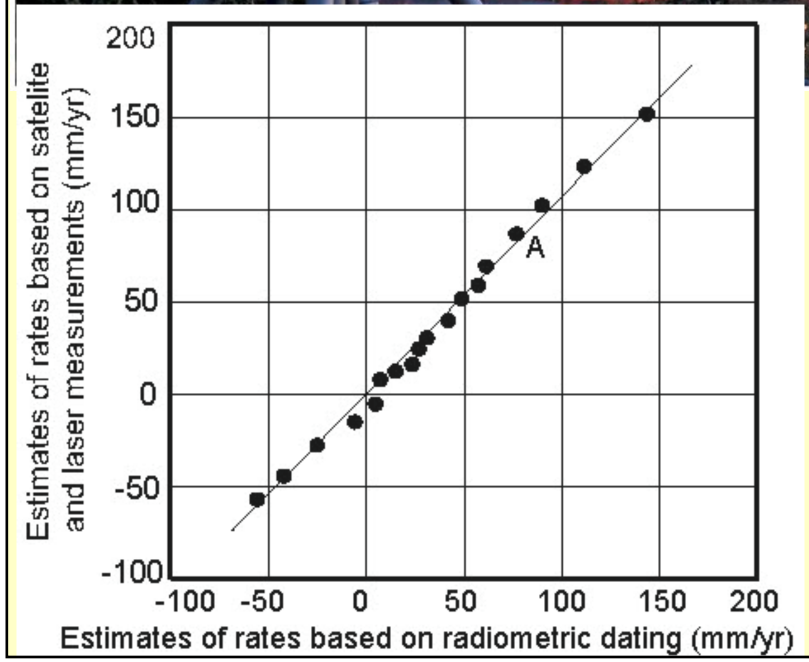
- Some Major International Networks
  - **IGS** (International GNSS Service)
  - **CORS** (Continuously Operating Reference Stations)
    - Primarily serve for kinematic base stations
  - **NOTA** (Network of the Americas)
  - **ANET** (Antarctica Network)
  - **GeoNET** (New Zealand Geologic Hazards Network)
  - **GEONET** (Japan GNSS Network)

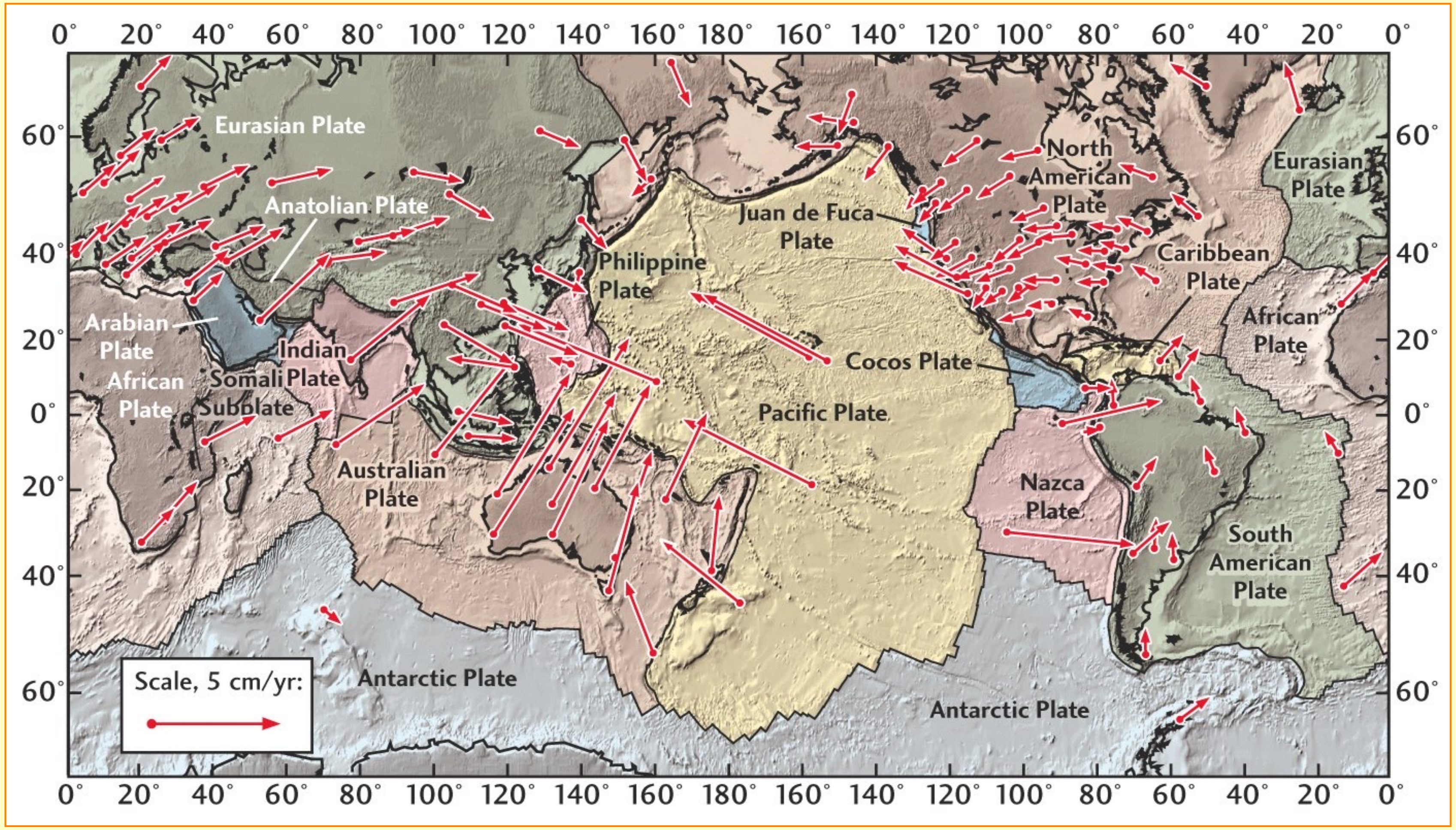
Ideal conditions for GNSS

- Area of geologic **interest** (hazards, tectonics, etc)
- **Direct attachment** to stable structure

  Hard bedrock > soft bedrock > low building > tall building > large boulder > soft sediment/soil
- **Clear view** of the sky (ideally nothing above 15° from horizon)
  - Avoid changing environment
    - small bushes growing to large trees
    - Bananas, other tall grasses
- **Accessible** to install/service (safety and time)
- **Secure** (hidden or inaccessible to others)
- Access for data **telemetry**

Global Plate Motions

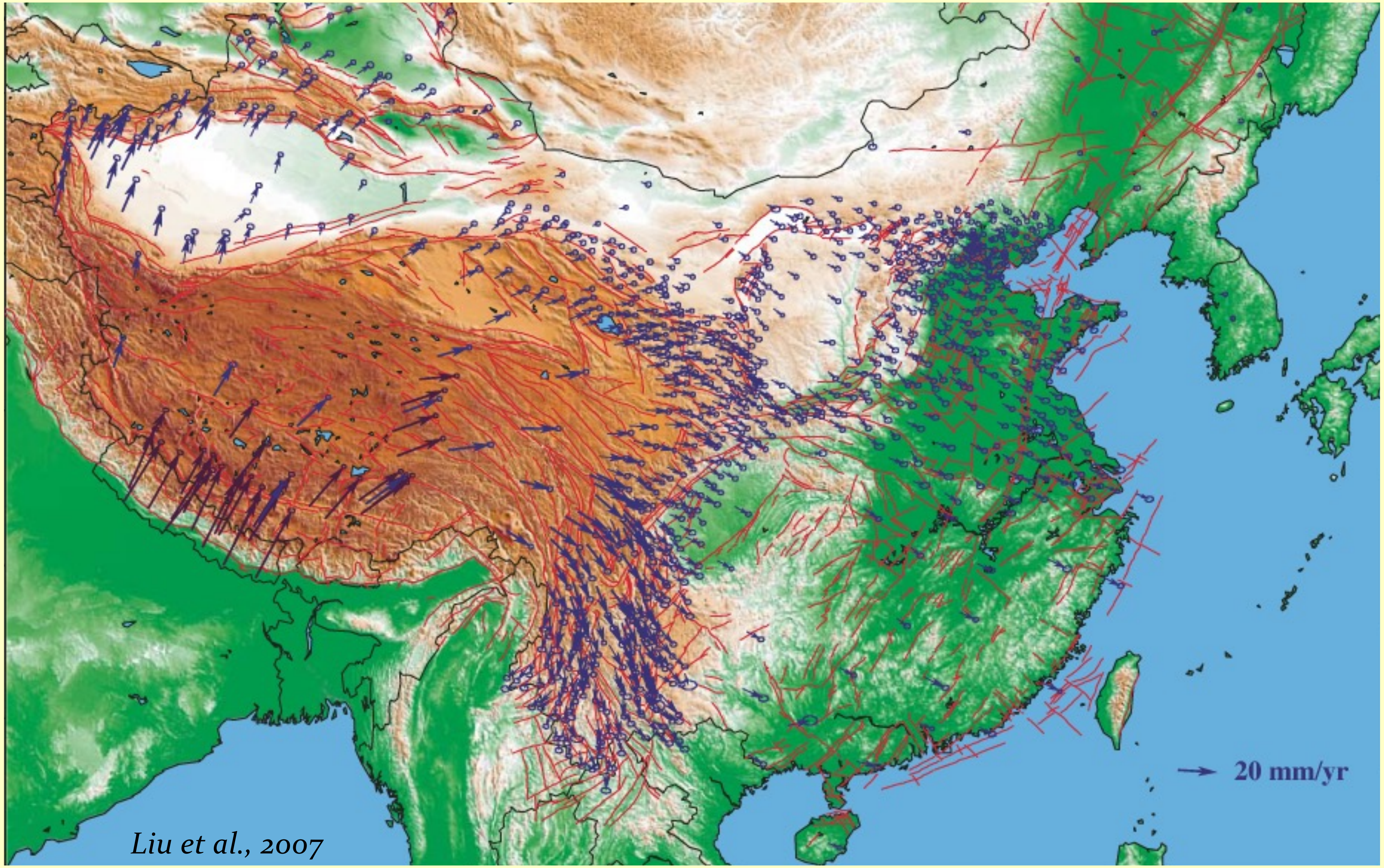




GNSS Plate rates match between Geologic (10 Ma average) and modern (10 yr average)

Robbins et al., 1993

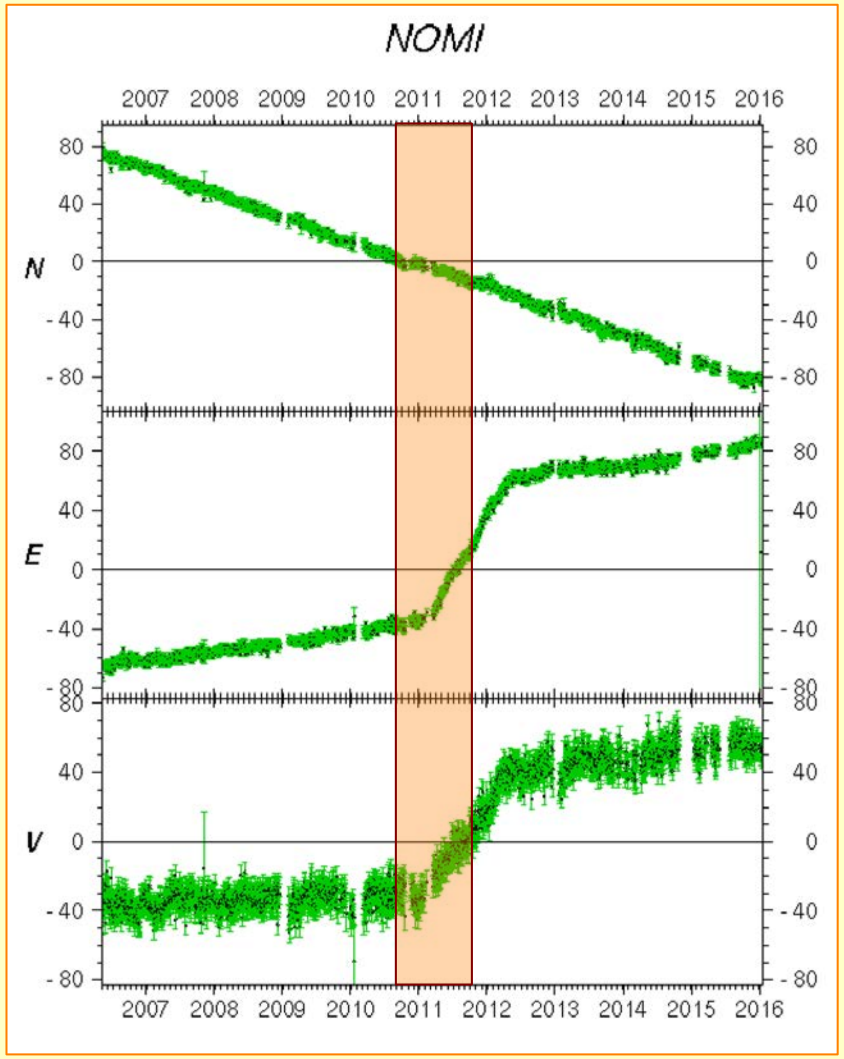
Plate Interiors

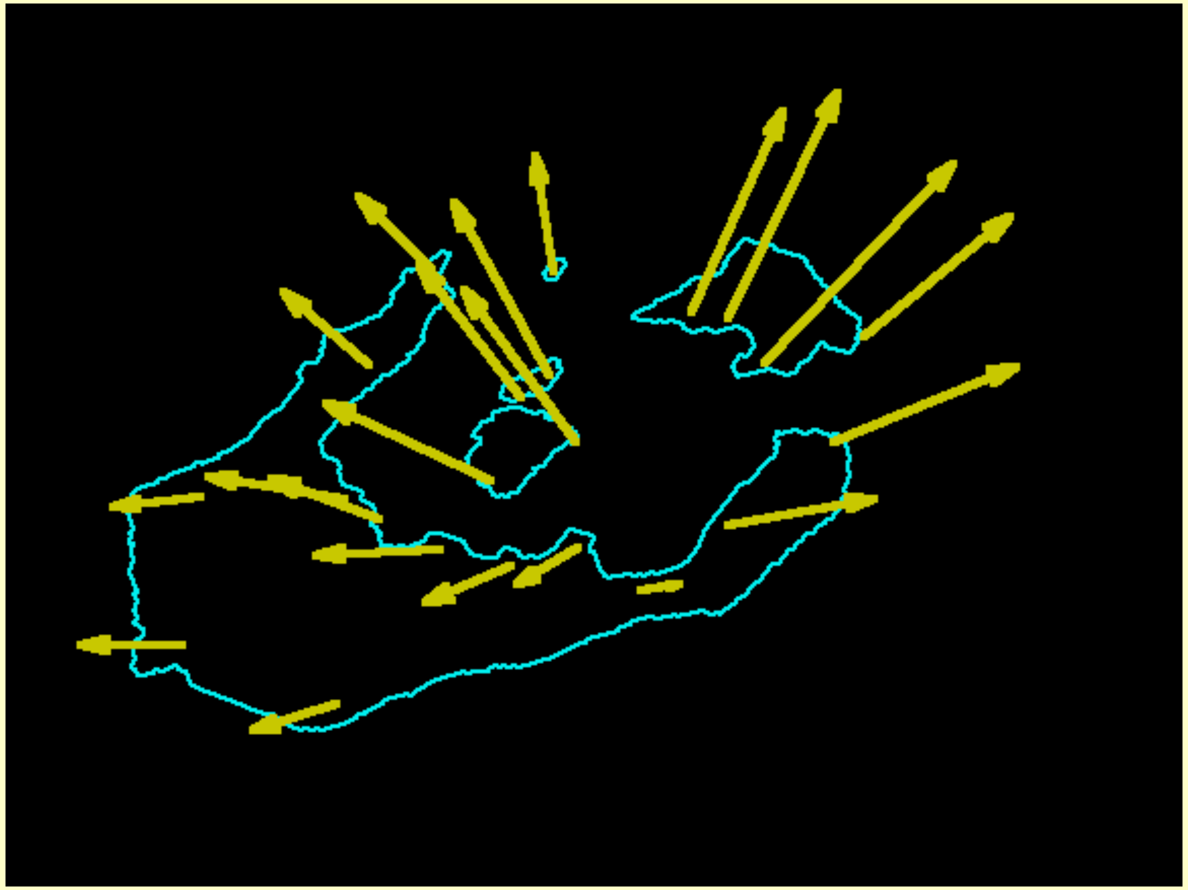


Liu et al., 2007

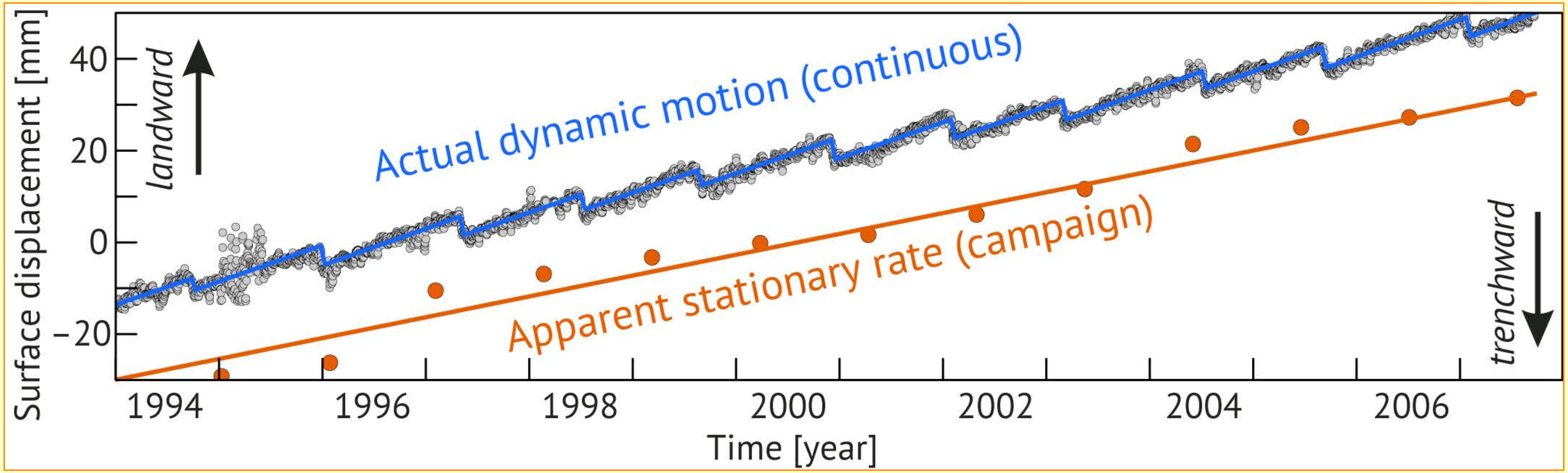
Example from my research

- Santorini Caldera



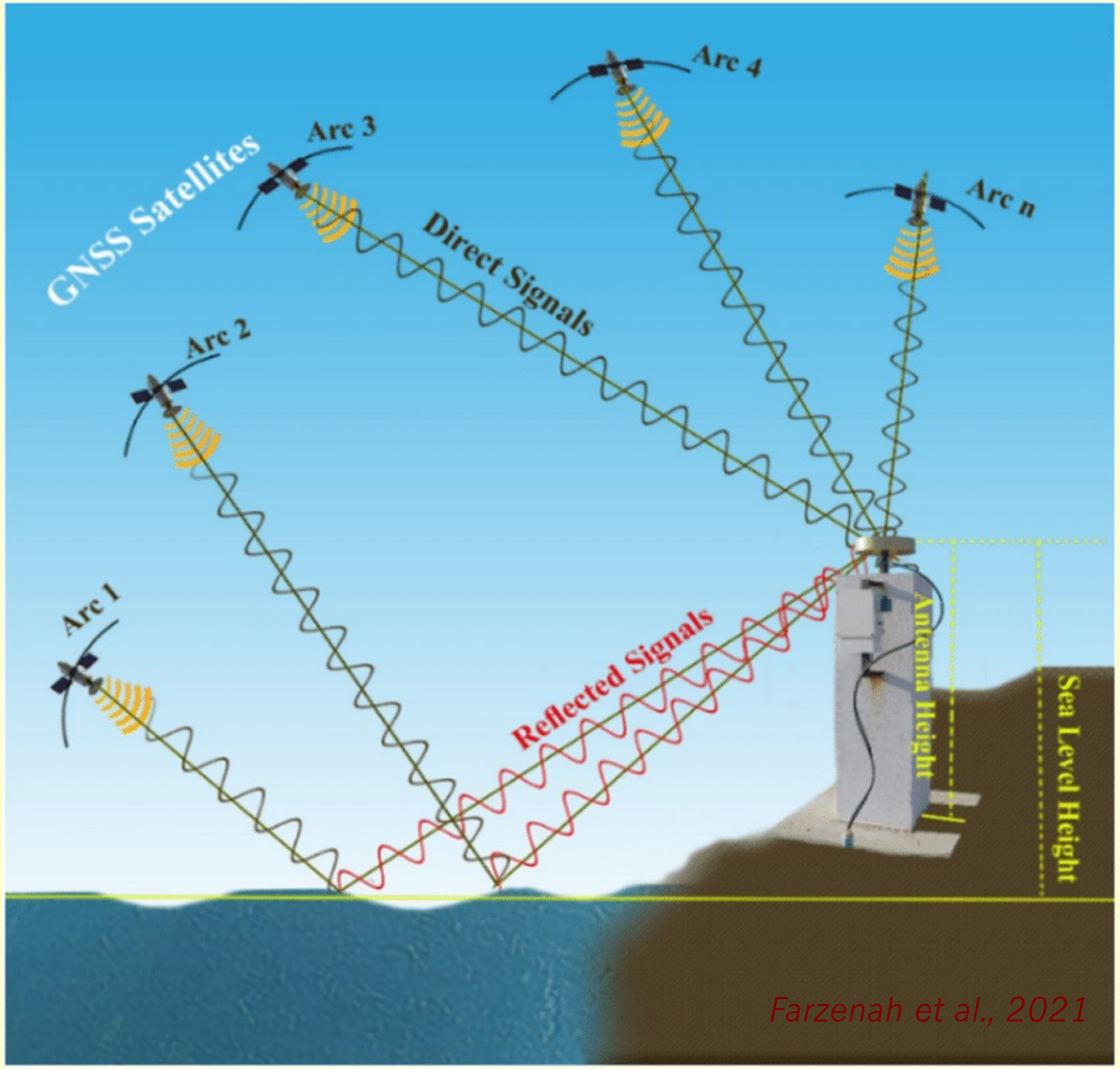


Continuous vs. Campaign GNSS



GNSS-IR (Interferometric Reflectometry)

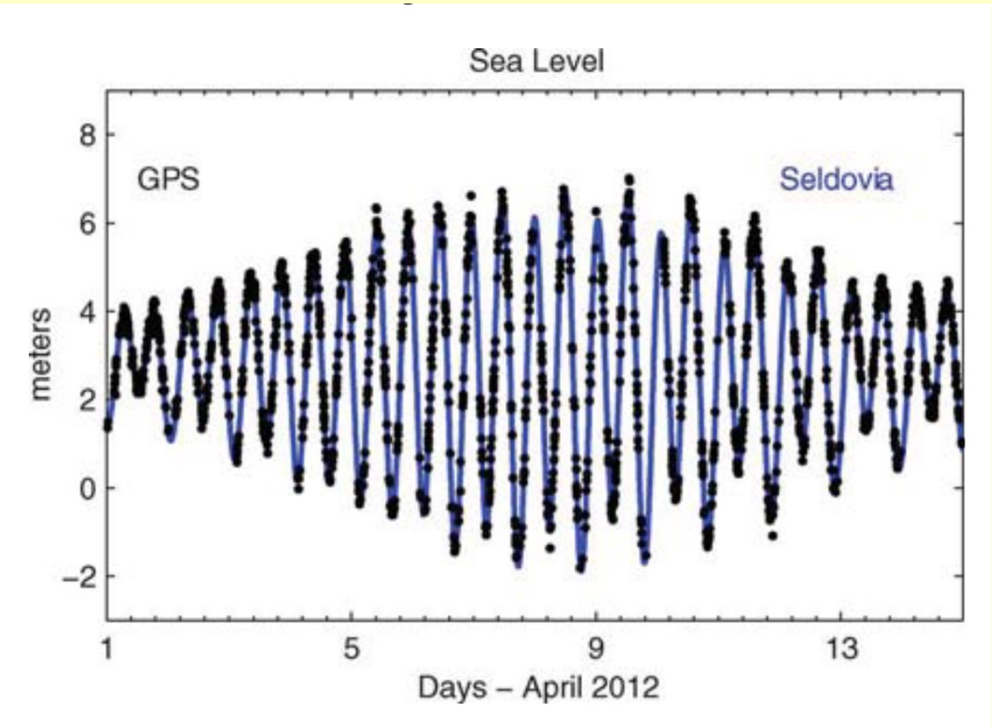
- Interference between direct-path and reflected paths
- Frequency of interference pattern controlled by difference in height between antenna and reflector



Farzenah et al., 2021

GNSS-IR (Interferometric Reflectometry)

- **Water level changes**

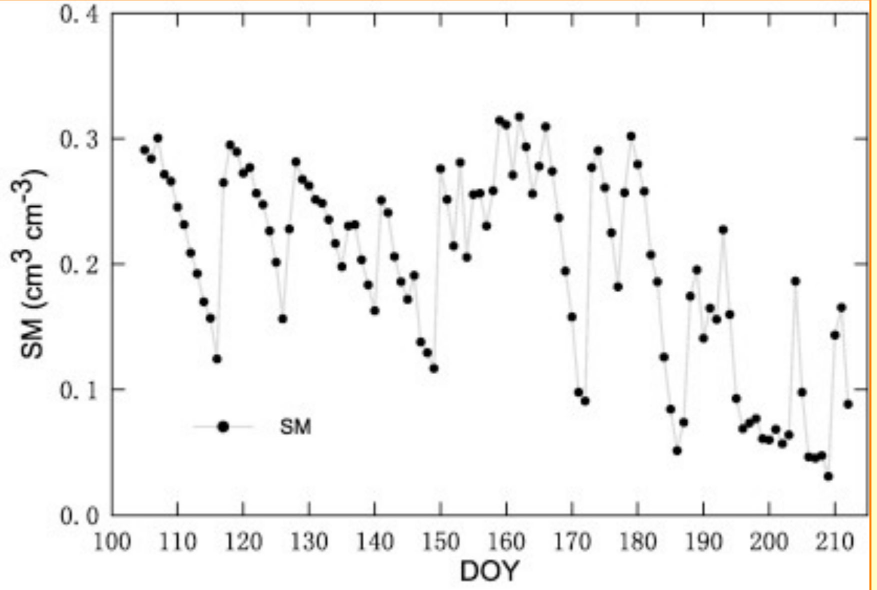


Larson et al., 2013

GNSS-IR (Interferometric Reflectometry)

- **Soil Moisture**

(a) (b)

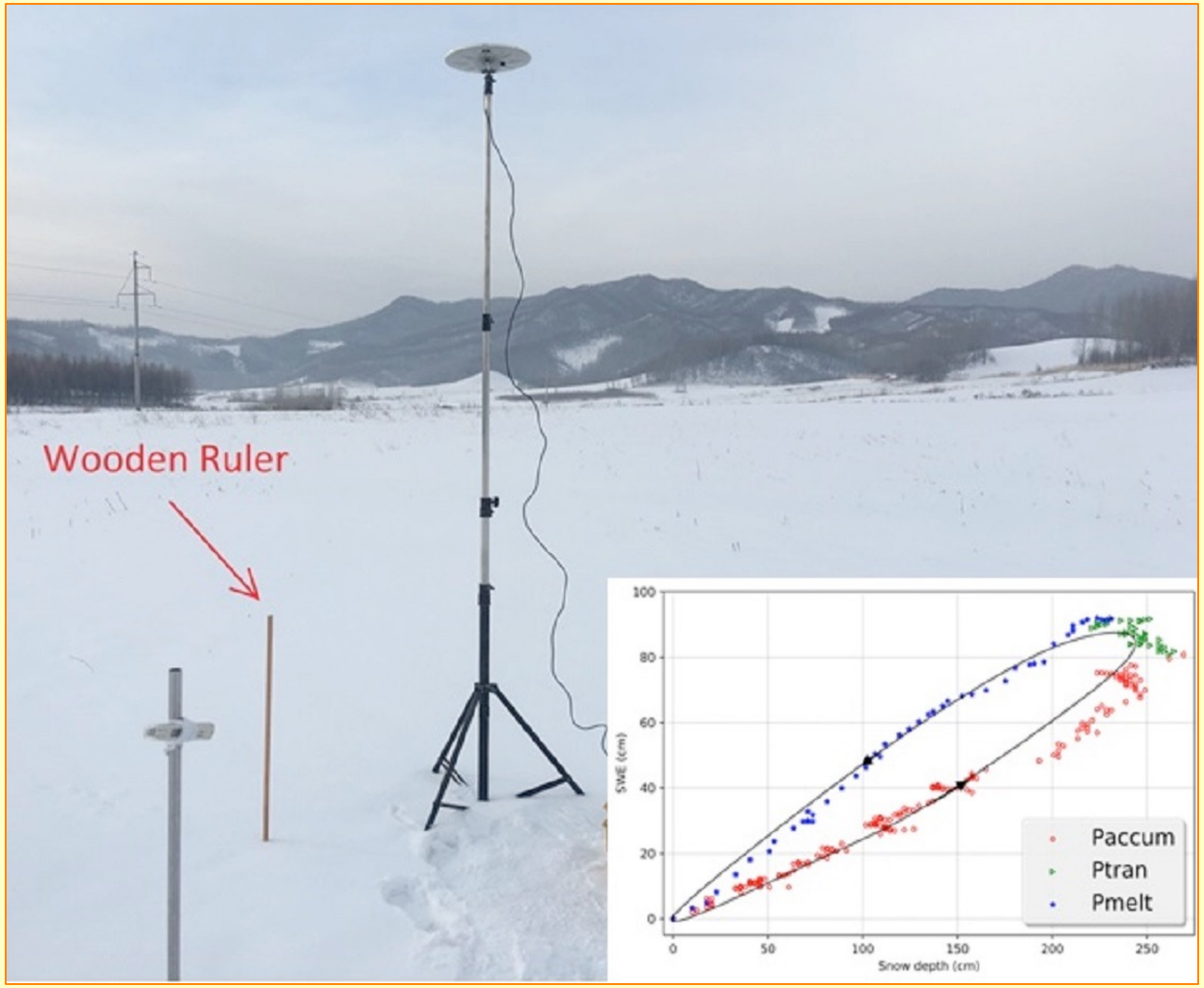


(b)

Liang et al., 2022

GNSS-IR (Interferometric Reflectometry)

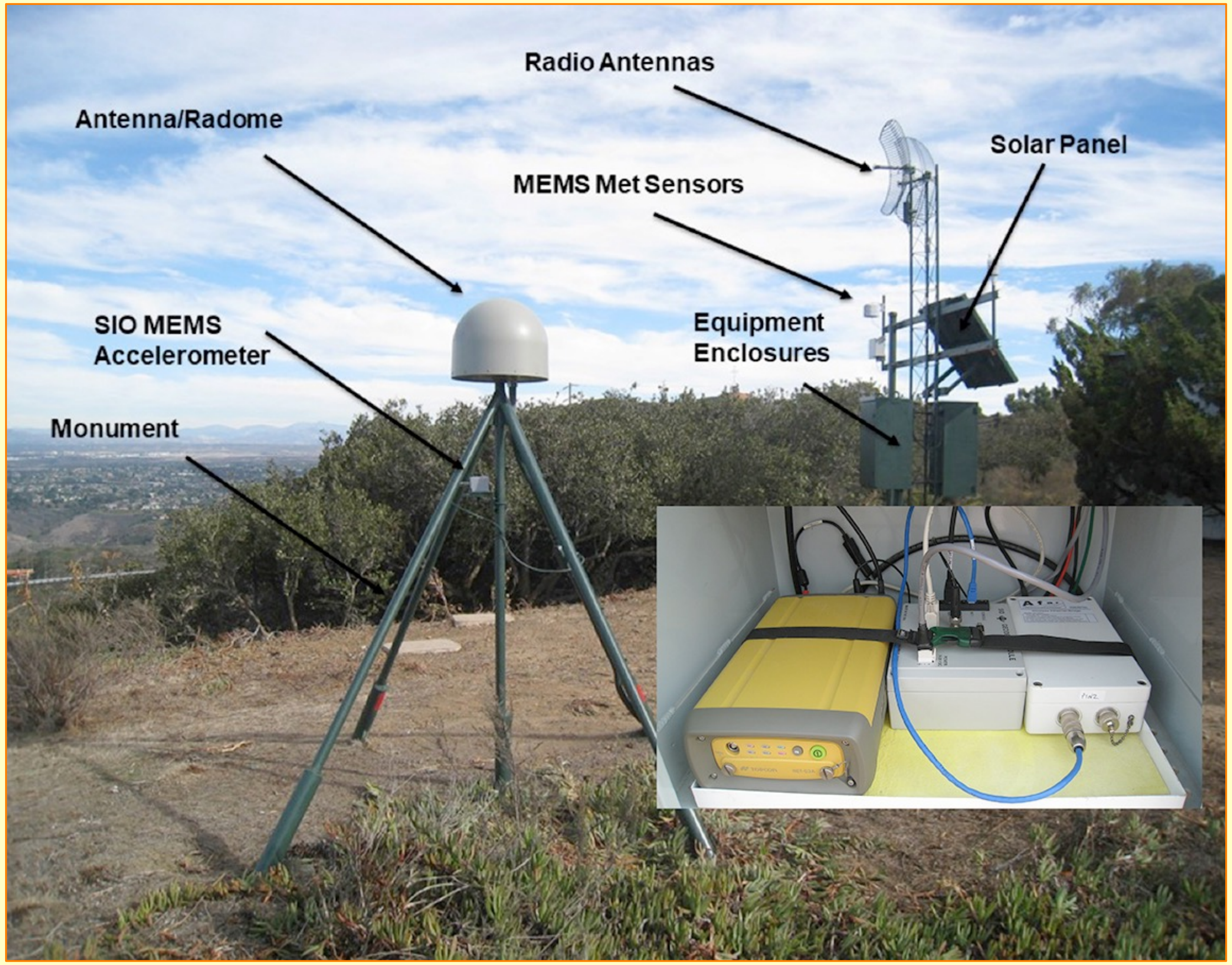
- **Snow pack**



Yu et al., 2020

Seismo-Geodesy

- Combining GNSS with high-rate accelerometers allows for large amplitude signals to be rapidly recorded near source
- GNSS - **Large amplitude** <u>displacements</u> that do not "clip"
- Accelerometer – **high-rate** <u>accelerations</u> that give rapid change



Geng et al., 2019

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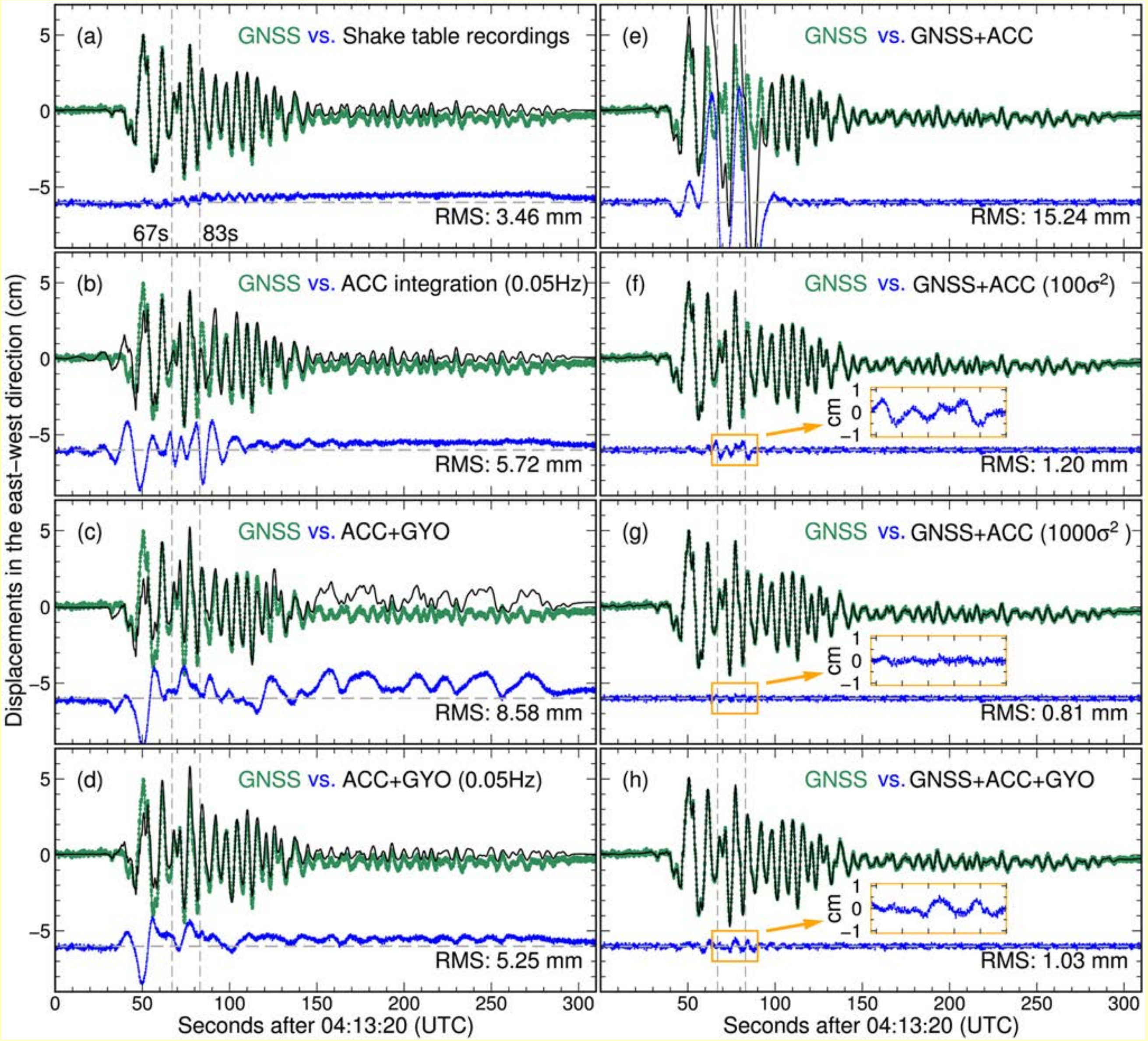


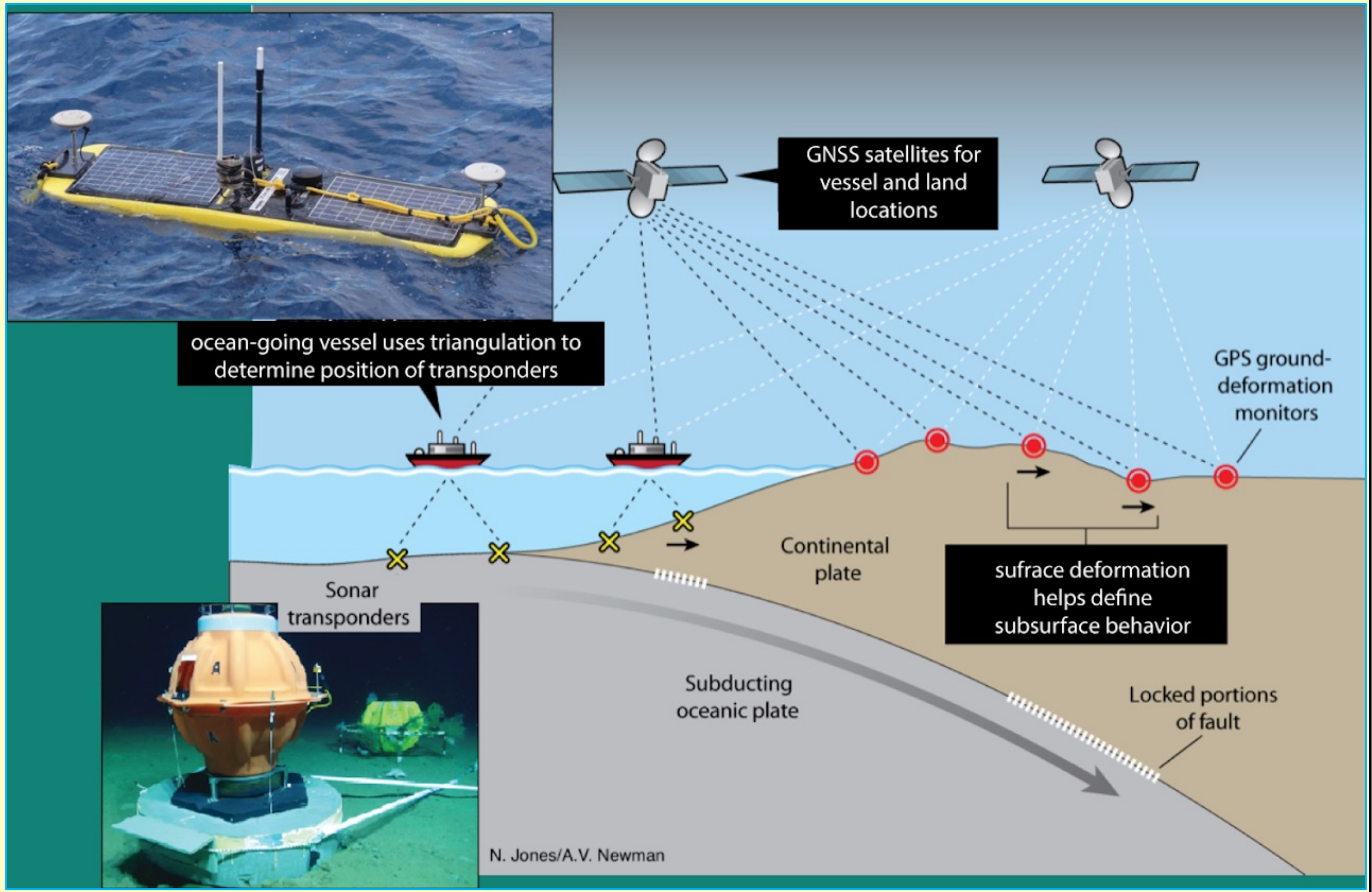
Geng et al., 2019

…90% of plate boundaries are offshore

(… and their deformation)

NSF-Funded Seafloor Geodetic Instrument Pool

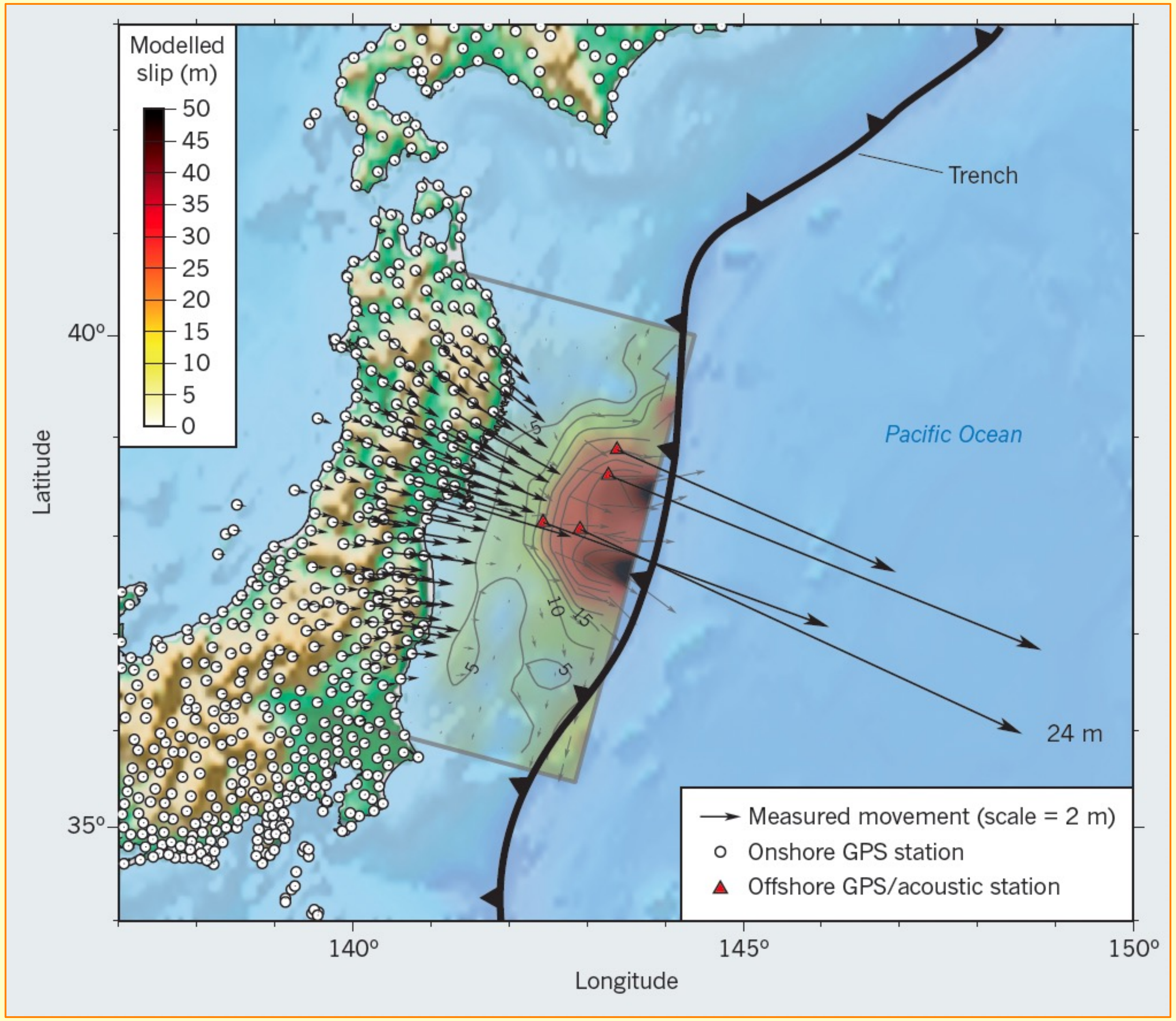
- 16 GNSS-Acoustic/seafloor pressure sites capable of
  - <cm/yr horizontal (long-term)
  - <cm/mo vertical (short-term)
  - 3 Wave Gliders for data collection
- Currently developing community workshop and proposal for offshore deployment in Cascadia and/or Alaska



N. Jones/A.V. Newman

Lopsided measurements

- More than **1,000 land-GPS**
- **4 - ocean-bottom** GPS-Acoustic sites
  - **Not running long enough before** to get good locking model
  - Observed **24 m movement** in earthquake
- M9.0 Earthquake
  - **~50 m of maximum slip**
  - **30 m-high tsunami** near Fukushima
  - **>20,000 casualties**



Newman, Nature, 2011

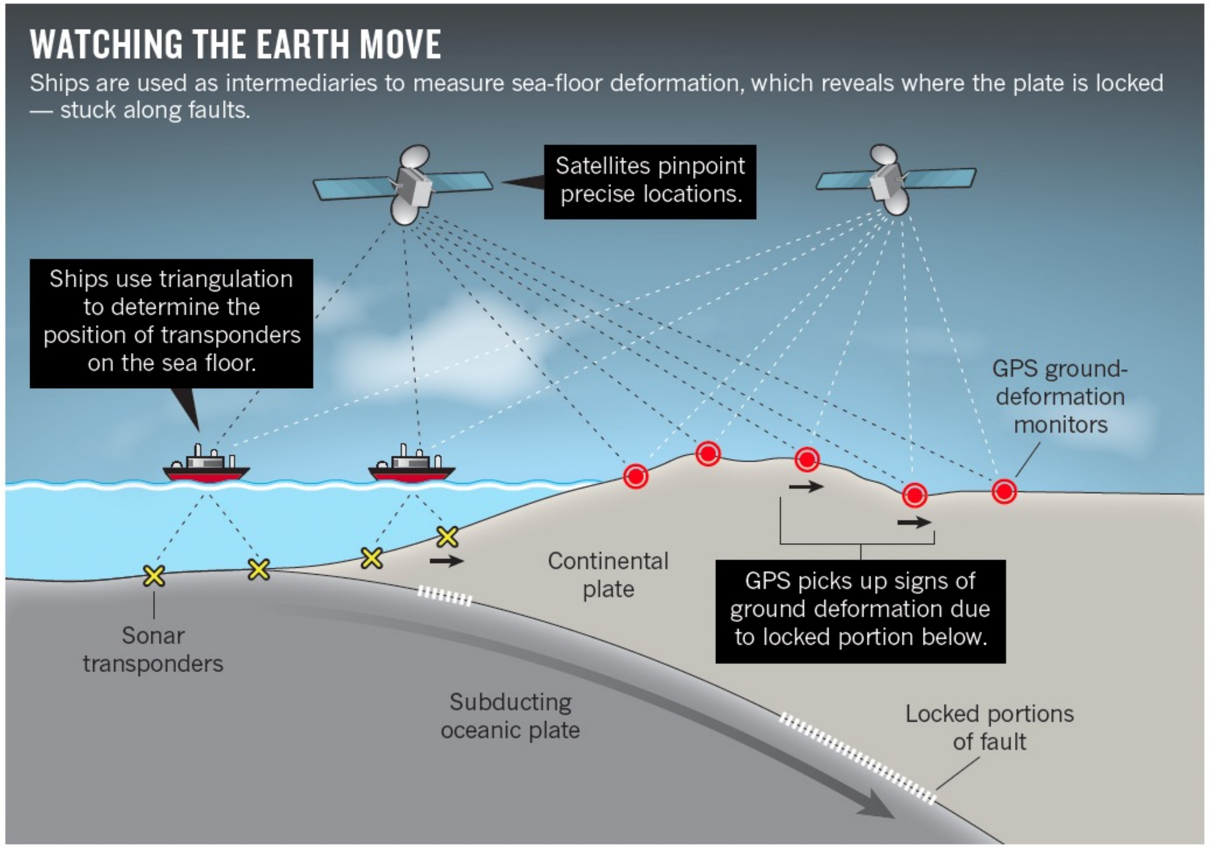
Call to action

H. NEW/REUTERS

The wave that hit Miyako City on Japan's east coast during the 11 March tsunami caught researchers by surprise.

Hidden depths

A staggering lack of undersea data hampers our understanding of earthquakes and tsunamis. Geophysicists must put more instruments offshore, says **Andrew V. Newman**.



WATCHING THE EARTH MOVE

Ships are used as intermediaries to measure sea-floor deformation, which reveals where the plate is locked — stuck along faults.

Satellites pinpoint precise locations.

Ships use triangulation to determine the position of transponders on the sea floor.

GPS picks up signs of ground deformation due to locked portion below.

N. JONES/A. V. NEWMAN

Newman, Nature, 2011

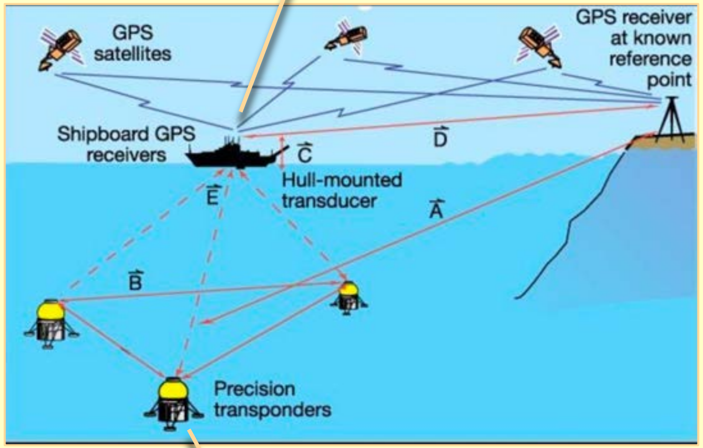
- Seafloor instrumentation is >**$400k** per site
- **Observation** with large research vessel can exceed **$200k per site per survey** (many over years needed)

- ***Costs need to be reduced for substantial adoption***

Seafloor Geodetic Instrument Pool (SGIP)

Develop Team: Chadwell, Schmidt, Newman, Jackson, Webb, Zumberge

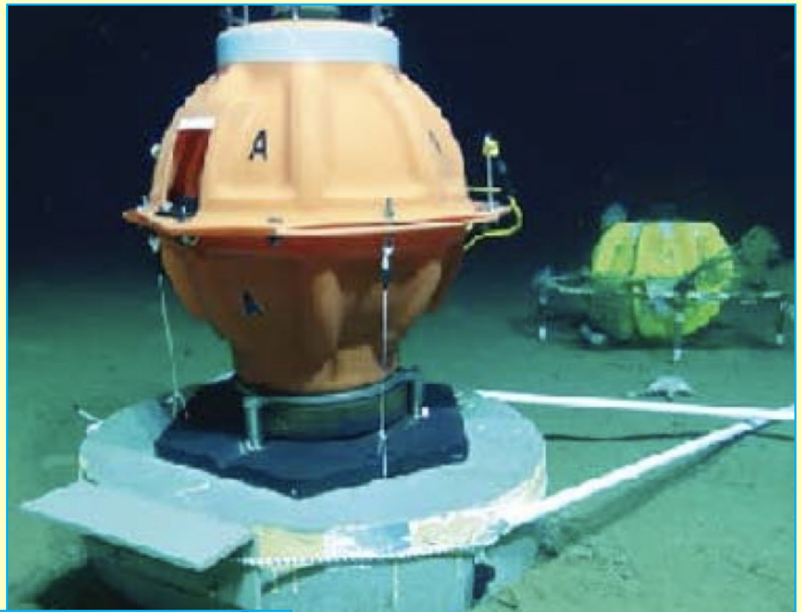
- **51** (17 sites) Acoustic **transponders**, 10 yr batteries
  - ~cm/yr+ horizontal motions (long-term)
  - Rated for 3000 m water depth
- **17** Absolute Pressure Gauges (**APG**) within transp. housing
  - ~cm/mo vertical motions (short-term)
- **48** reusable kinematic **benchmarks**
- **3 Wave Glider** autonomous green-powered surface vehicles

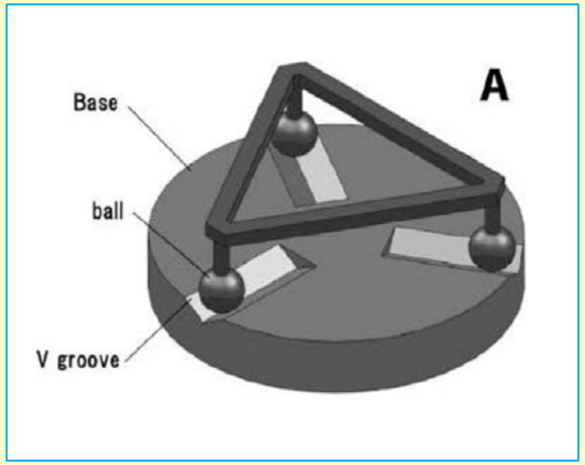


Funding in 2019 from NSF GEO Directorate,
Front office, Polar Programs, and OCE

17 GNSS-Acoustic/APG sites

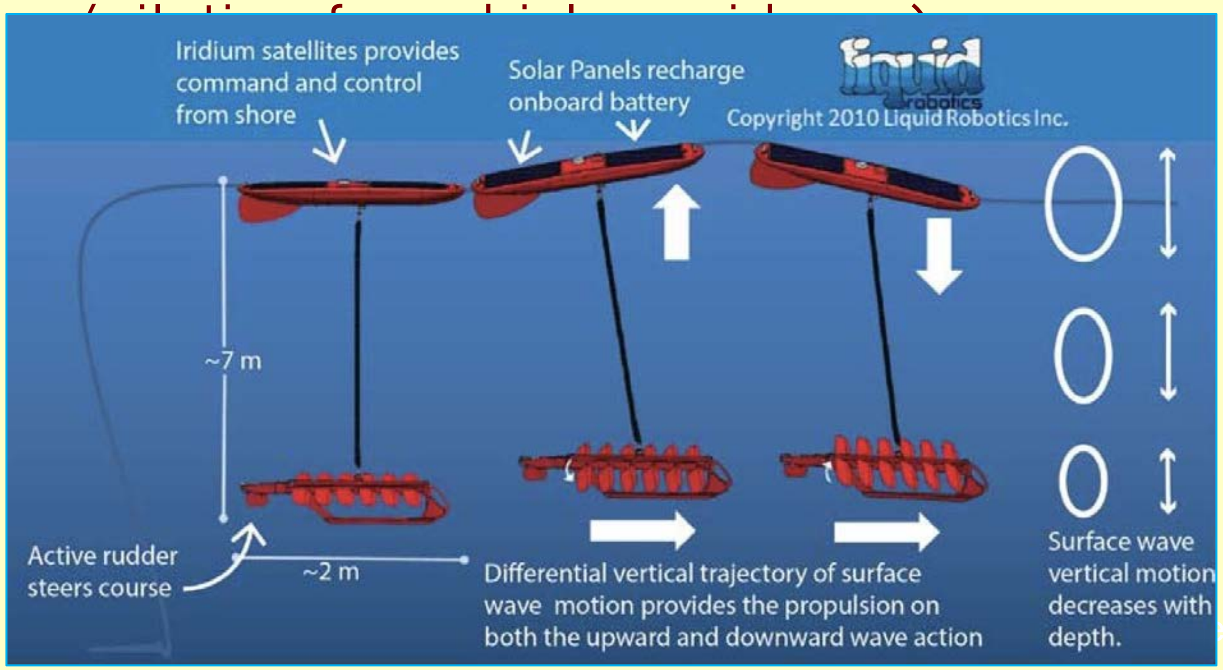
- 51 Transponders (1 in 3 with pressure sensor integrated within housing)
- 48 reusable kinematic benchmarks
  - Transponder is attached at time of deployment but can be remotely released
  - Titanium V-grooves essential for mm-level sensor replacement



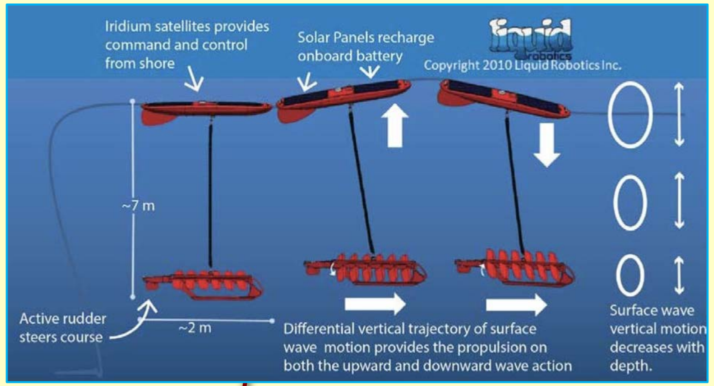


Wave Gliders

- 3 Wave Gliders (sv3)
  - Locomotion by differential vertical wave heights
  - Comms and acoustics from solar
  - Require slow current (~<2 kt)
  - Semi-autonomous (programmed nav.

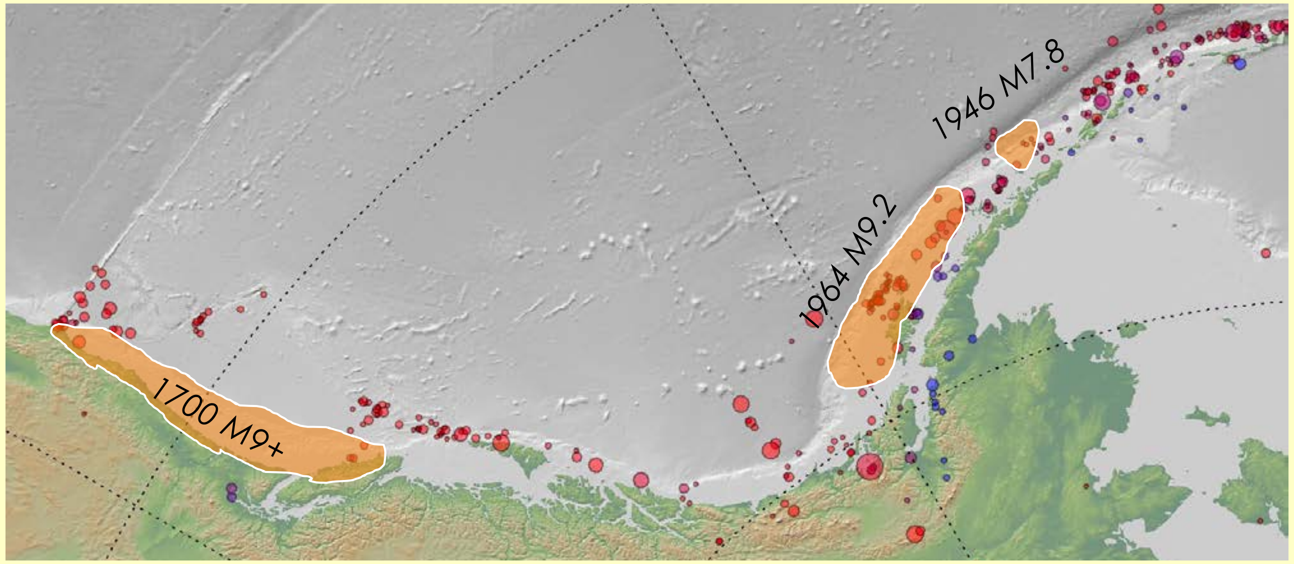


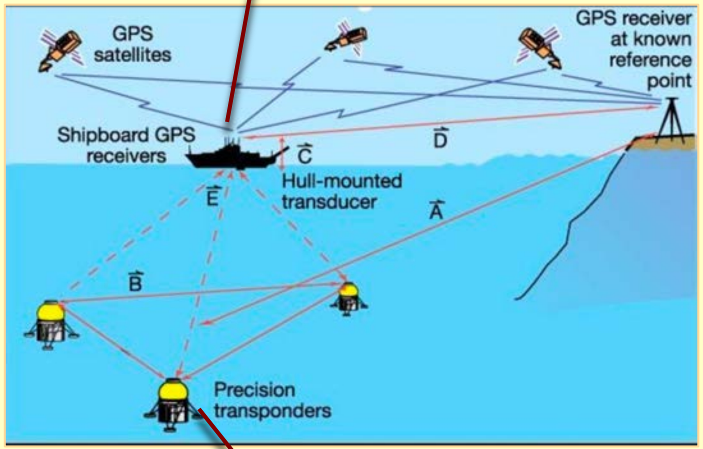
Unlock the trench with seafloor data



Now starting major experiments in the areas that the US has had the largest tsunamis

- 1964 Kodiak, Alaska **(M9.2) 30 M** high tsunami (1 M Japan)
- 1946 Unimak, Alaska **(M7.8) 40 M** high tsunami (2 M Japan?)
- 1700 Cascadia Earthquake **(M9?)** 3 M tsunami in Japan



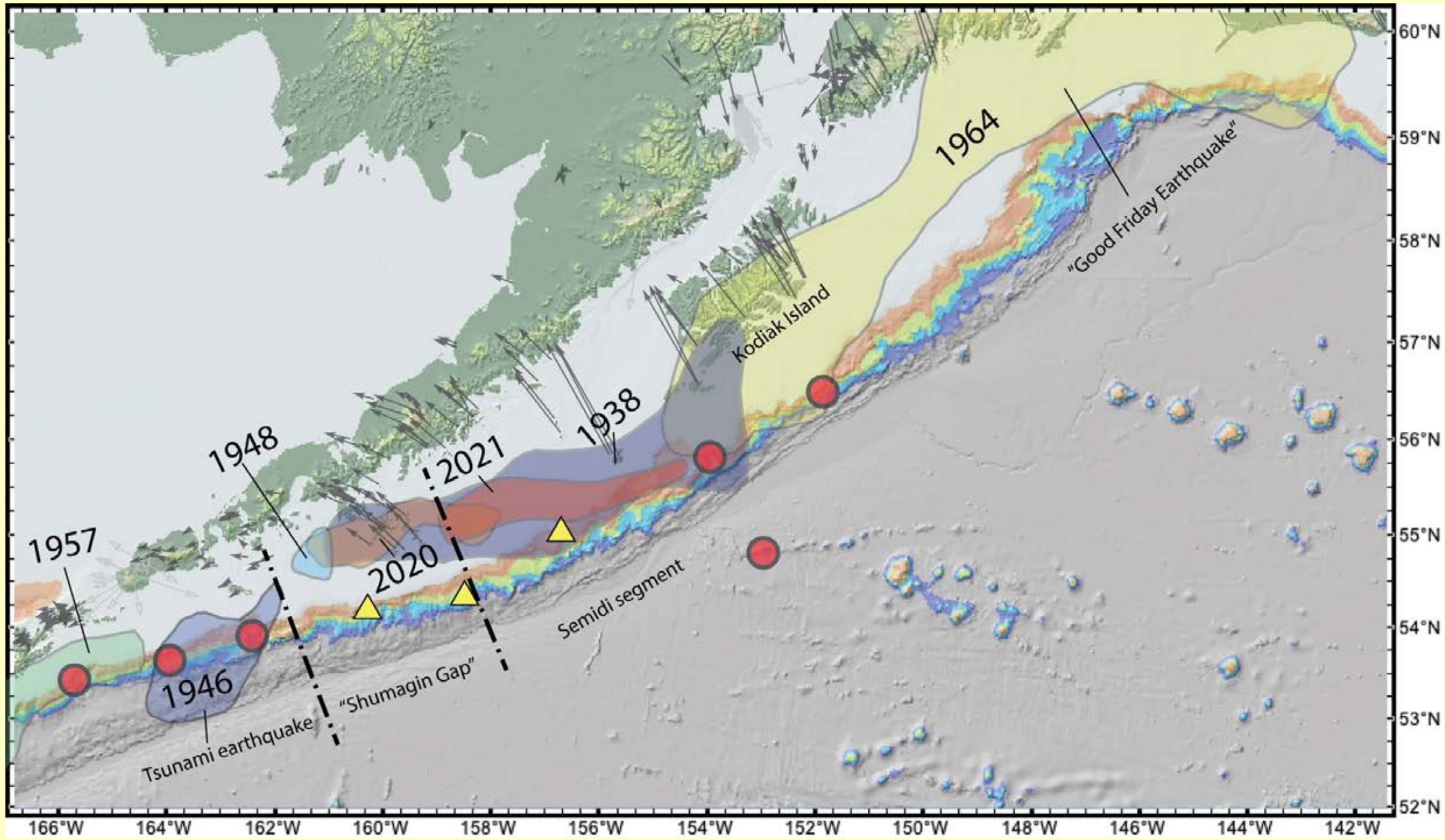


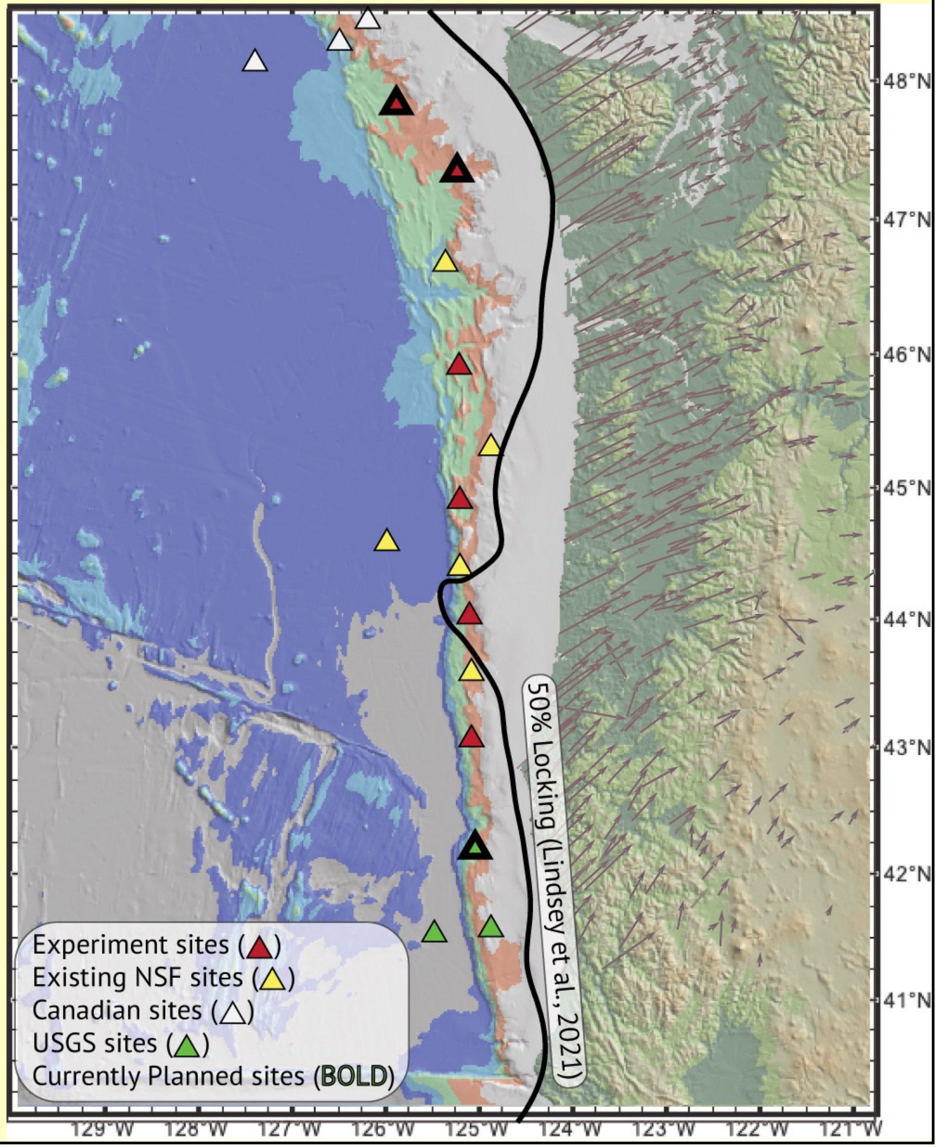
Funding ($13M) over past 5 years for instrumentation, testing, deployments and training

www.seafloorgeodesy.org

Near-Trench Community Geodetic Experiment

- 12 GNSS-Acoustic sites offshore Alaska and Cascadia





www.seafloorgeodesy.org

Near-Trench Community Geodetic Experiment

- 12 GNSS-Acoustic sites offshore Alaska and Cascadia

Alaska 2024

Cascadia 2023

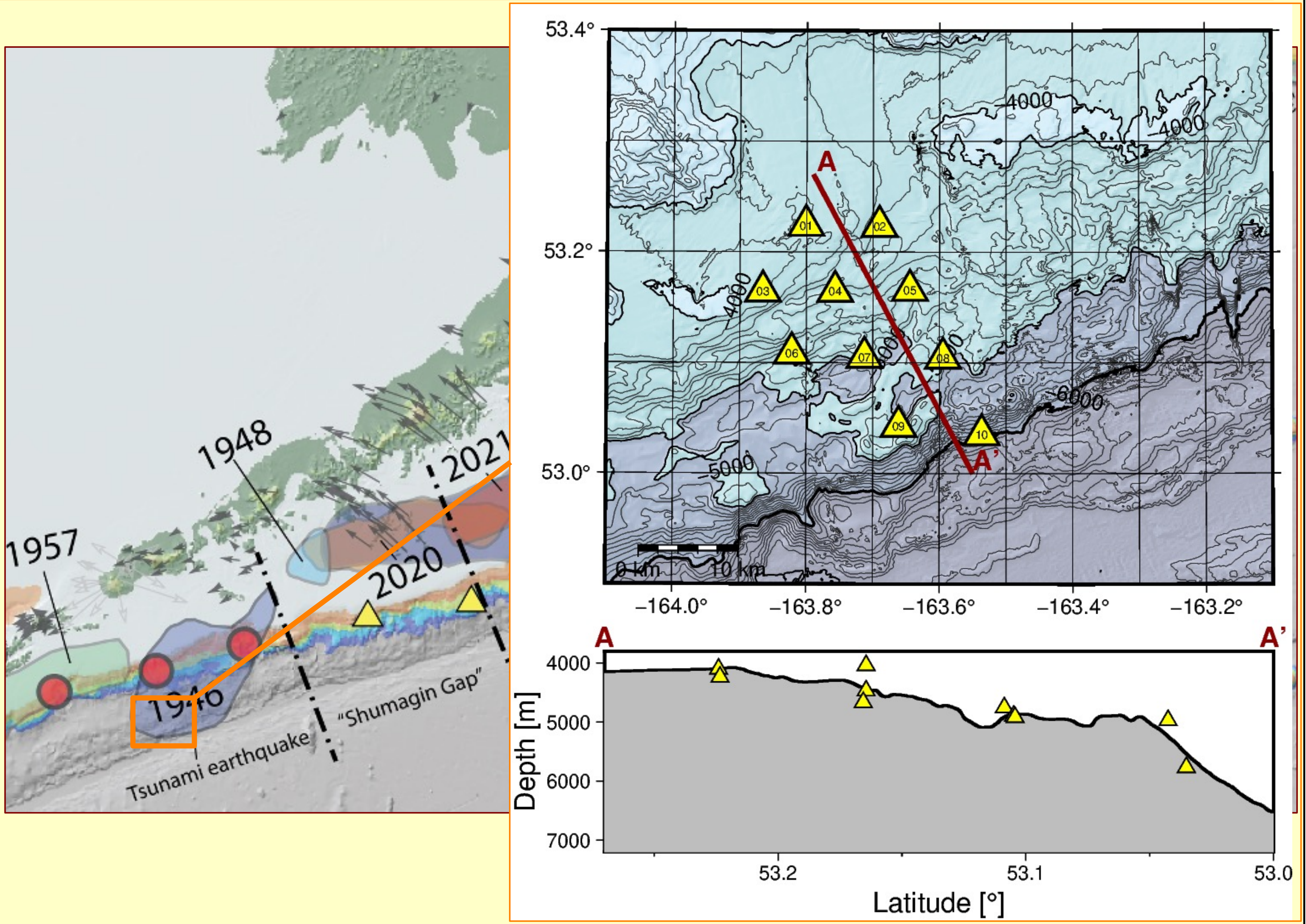
We're training the next generation of scientists

www.seafloorgeodesy.org

Deployment planned near-trench of 1946 EQ

- **Mw 7.8 created 40+m local** tsunami and **10+ m tsunami** as far south as Hilo, Hawaii

- Testing new **Mesh design** for lower-cost high-definition deformation



Day 2:

Agenda

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Day 2: Understanding Earth from Geodetic Modeling

9:15am *: Kivu MagnetoTellurics*
9:30 : Detailed understanding/theory on InSAR
10:30: **Break**
11:00: Nyiragongo Supersite presentation: Charles Balagizi (OVG)
11:15: Geophysical Modeling overview
12:15: **Lunch**
1:15 : QuadTree data reduction for Modeling
Here → **1:30** : Modeling deformation using GTDef (or other analytic tools)
3:30 : Discussion and adjourn with end-of-day **snack/coffee**

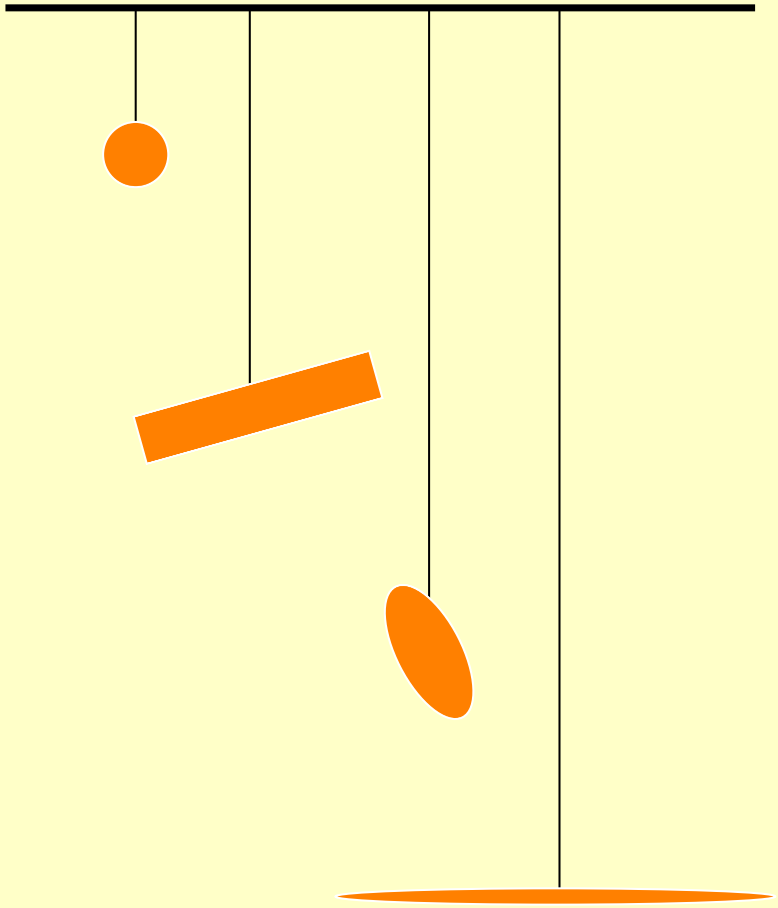
Modeling Overview

Understanding deformation

- Geodetic modeling falls along two main camps: **analytical** or **numerical**

Analytical models:

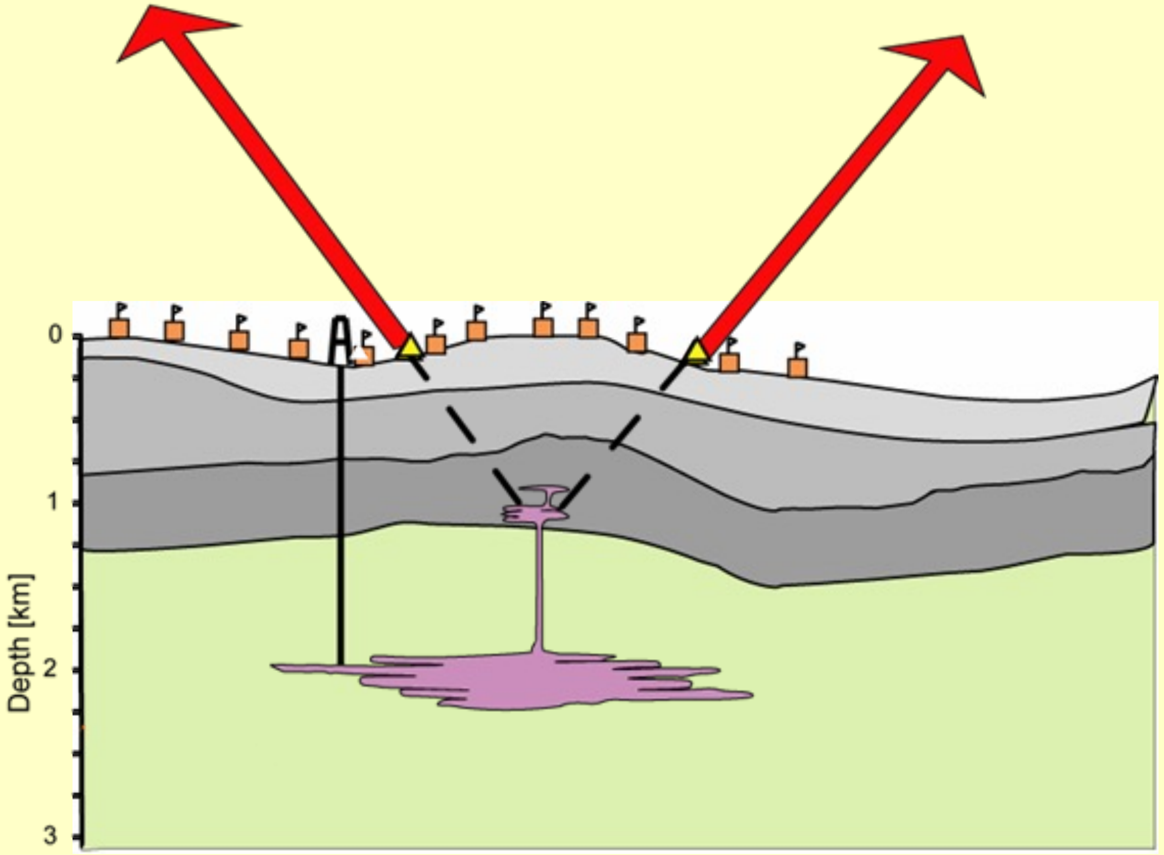
- **Commonly available methods:**
  - Mogi (1958):
    - Point (small **spherical**) source
    - *Simplest analytic source*
  - Okada (1985):
    - **planar** dislocation (slip + dilatation) source
    - *Faulting*
    - *Dike/sill intrusion/cooling*
  - Yang et al (1988):
    - prolate **spheroid** (ellipsoidal) source
    - *Spherical-to-conduit sources*
  - Fialko et al (2001):
    - **penny-shaped** crack (circular crack)
    - *Circular sill intrusion/cooling*



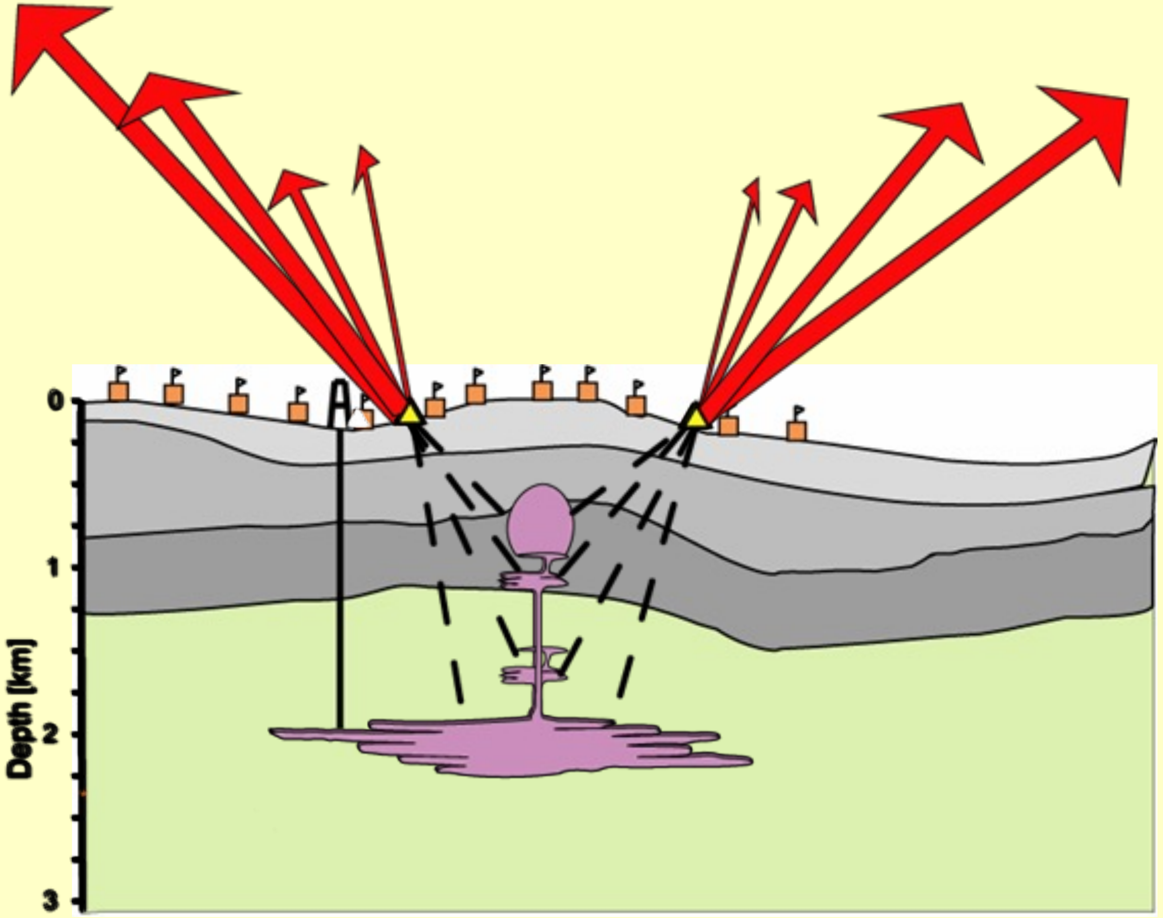
- These models all assume homogeneous elastic surroundings

Simple Volcanic Inflation (spherical Mogi)

If crust behaves like a homogeneous elastic solid, we can extrapolate observed deformation paths (vectors) back to the source inflation source

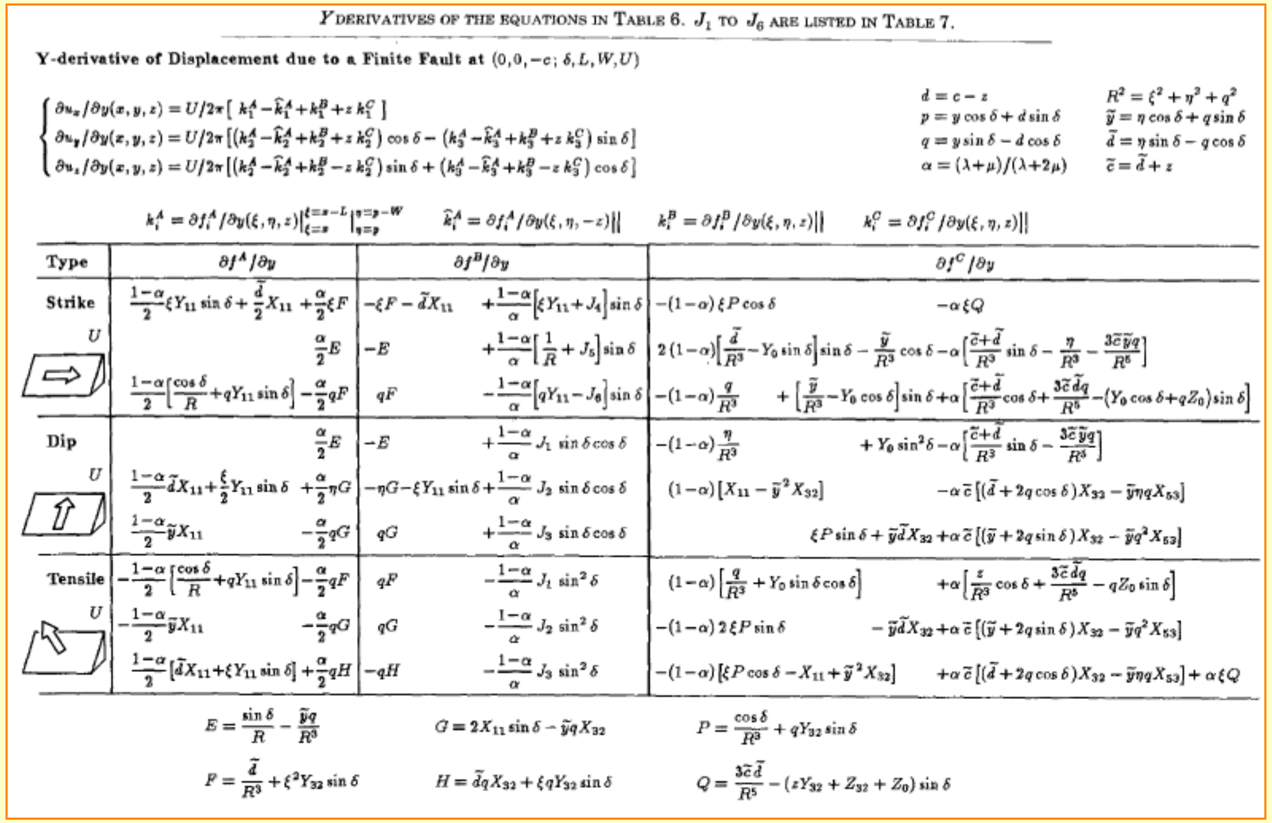


Simple Volcanic Inflation (spherical Mogi)



Fault Dislocation (planar Okada)

- Okada(1985) describes strike-slip, dip-slip, and opening across a planar dislocation



Y DERIVATIVES OF THE EQUATIONS IN TABLE 6. J_1 TO J_6 ARE LISTED IN TABLE 7.

Y-derivative of Displacement due to a Finite Fault at $(0,0,-c;\ \delta, L, W, U)$

$$\begin{cases} \partial u_x/\partial y(x,y,z) = U/2\pi\left[\ k_1^A-\hat{k}_1^A+k_1^B+z\,k_1^C\ \right] \\ \partial u_y/\partial y(x,y,z) = U/2\pi\left[\left(k_2^A-\hat{k}_2^A+k_2^B+z\,k_2^C\right)\cos\delta-\left(k_3^A-\hat{k}_3^A+k_3^B+z\,k_3^C\right)\sin\delta\right] \\ \partial u_z/\partial y(x,y,z) = U/2\pi\left[\left(k_2^A-\hat{k}_2^A+k_2^B-z\,k_2^C\right)\sin\delta+\left(k_3^A-\hat{k}_3^A+k_3^B-z\,k_3^C\right)\cos\delta\right] \end{cases}$$

$d = c - z$
$p = y\cos\delta + d\sin\delta$
$q = y\sin\delta - d\cos\delta$
$\alpha = (\lambda+\mu)/(\lambda+2\mu)$

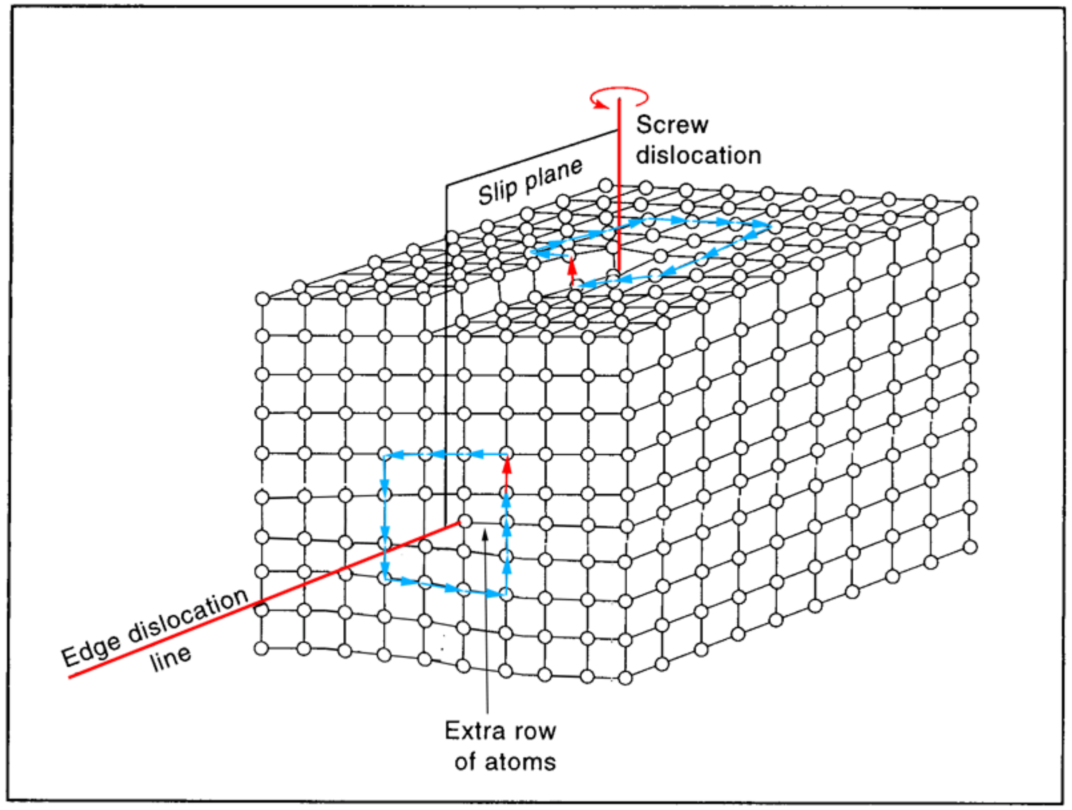
$R^2 = \xi^2+\eta^2+q^2$
$\tilde{y} = \eta\cos\delta + q\sin\delta$
$\tilde{d} = \eta\sin\delta - q\cos\delta$
$\tilde{c} = \tilde{d} + z$

$$k_i^A = \partial f_i^A/\partial y(\xi,\eta,z)\Big|_{\xi=x}^{\xi=x-L}\Big|_{\eta=p}^{\eta=p-W} \qquad \hat{k}_i^A = \partial f_i^A/\partial y(\xi,\eta,-z)\Big\|\qquad k_i^B = \partial f_i^B/\partial y(\xi,\eta,z)\Big\| \qquad k_i^C = \partial f_i^C/\partial y(\xi,\eta,z)\Big\|$$

Type	$\partial f^A/\partial y$	$\partial f^B/\partial y$	$\partial f^C/\partial y$
Strike	$\frac{1-\alpha}{2}\xi Y_{11}\sin\delta+\frac{\tilde{d}}{2}X_{11}+\frac{\alpha}{2}\xi F$	$-\xi F-\tilde{d}X_{11}+\frac{1-\alpha}{\alpha}\left[\xi Y_{11}+J_4\right]\sin\delta$	$-(1-\alpha)\,\xi P\cos\delta \qquad -\alpha\xi Q$
U	$\frac{\alpha}{2}E$	$-E+\frac{1-\alpha}{\alpha}\left[\frac{1}{R}+J_5\right]\sin\delta$	$2(1-\alpha)\left[\frac{\tilde{d}}{R^3}-Y_0\sin\delta\right]\sin\delta-\frac{\tilde{y}}{R^3}\cos\delta-\alpha\left[\frac{\tilde{c}+\tilde{d}}{R^3}\sin\delta-\frac{\eta}{R^3}-\frac{3\tilde{c}\tilde{y}q}{R^5}\right]$
	$\frac{1-\alpha}{2}\left[\frac{\cos\delta}{R}+qY_{11}\sin\delta\right]-\frac{\alpha}{2}qF$	$qF-\frac{1-\alpha}{\alpha}\left[qY_{11}-J_6\right]\sin\delta$	$-(1-\alpha)\frac{q}{R^3}+\left[\frac{\tilde{y}}{R^3}-Y_0\cos\delta\right]\sin\delta+\alpha\left[\frac{\tilde{c}+\tilde{d}}{R^3}\cos\delta+\frac{3\tilde{c}\tilde{d}q}{R^5}-(Y_0\cos\delta+qZ_0)\sin\delta\right]$
Dip	$\frac{\alpha}{2}E$	$-E+\frac{1-\alpha}{\alpha}J_1\sin\delta\cos\delta$	$-(1-\alpha)\frac{\eta}{R^3}+Y_0\sin^2\delta-\alpha\left[\frac{\tilde{c}+\tilde{d}}{R^3}\sin\delta-\frac{3\tilde{c}\tilde{y}q}{R^5}\right]$
U	$\frac{1-\alpha}{2}\tilde{d}X_{11}+\frac{\xi}{2}Y_{11}\sin\delta+\frac{\alpha}{2}\eta G$	$-\eta G-\xi Y_{11}\sin\delta+\frac{1-\alpha}{\alpha}J_2\sin\delta\cos\delta$	$(1-\alpha)\left[X_{11}-\tilde{y}^2X_{32}\right] \qquad -\alpha\tilde{c}\left[(\tilde{d}+2q\cos\delta)X_{32}-\tilde{y}\eta qX_{53}\right]$
	$\frac{1-\alpha}{2}\tilde{y}X_{11}-\frac{\alpha}{2}qG$	$qG+\frac{1-\alpha}{\alpha}J_3\sin\delta\cos\delta$	$\xi P\sin\delta+\tilde{y}\tilde{d}X_{32}+\alpha\tilde{c}\left[(\tilde{y}+2q\sin\delta)X_{32}-\tilde{y}q^2X_{53}\right]$
Tensile	$-\frac{1-\alpha}{2}\left[\frac{\cos\delta}{R}+qY_{11}\sin\delta\right]-\frac{\alpha}{2}qF$	$qF-\frac{1-\alpha}{\alpha}J_1\sin^2\delta$	$(1-\alpha)\left[\frac{q}{R^3}+Y_0\sin\delta\cos\delta\right] \qquad +\alpha\left[\frac{z}{R^3}\cos\delta+\frac{3\tilde{c}\tilde{d}q}{R^5}-qZ_0\sin\delta\right]$
U	$-\frac{1-\alpha}{2}\tilde{y}X_{11}-\frac{\alpha}{2}qG$	$qG-\frac{1-\alpha}{\alpha}J_2\sin^2\delta$	$-(1-\alpha)\,2\xi P\sin\delta \qquad -\tilde{y}\tilde{d}X_{32}+\alpha\tilde{c}\left[(\tilde{y}+2q\sin\delta)X_{32}-\tilde{y}q^2X_{53}\right]$
	$\frac{1-\alpha}{2}\left[\tilde{d}X_{11}+\xi Y_{11}\sin\delta\right]+\frac{\alpha}{2}qH$	$-qH-\frac{1-\alpha}{\alpha}J_3\sin^2\delta$	$-(1-\alpha)\left[\xi P\cos\delta-X_{11}+\tilde{y}^2X_{32}\right] \qquad +\alpha\tilde{c}\left[(\tilde{d}+2q\cos\delta)X_{32}-\tilde{y}\eta qX_{53}\right]+\alpha\xi Q$

$$E=\frac{\sin\delta}{R}-\frac{\tilde{y}q}{R^3} \qquad G=2X_{11}\sin\delta-\tilde{y}qX_{32} \qquad P=\frac{\cos\delta}{R^3}+qY_{32}\sin\delta$$

$$F=\frac{\tilde{d}}{R^3}+\xi^2Y_{32}\sin\delta \qquad H=\tilde{d}qX_{32}+\xi qY_{32}\sin\delta \qquad Q=\frac{3\tilde{c}\tilde{d}}{R^5}-(zY_{32}+Z_{32}+Z_0)\sin\delta$$

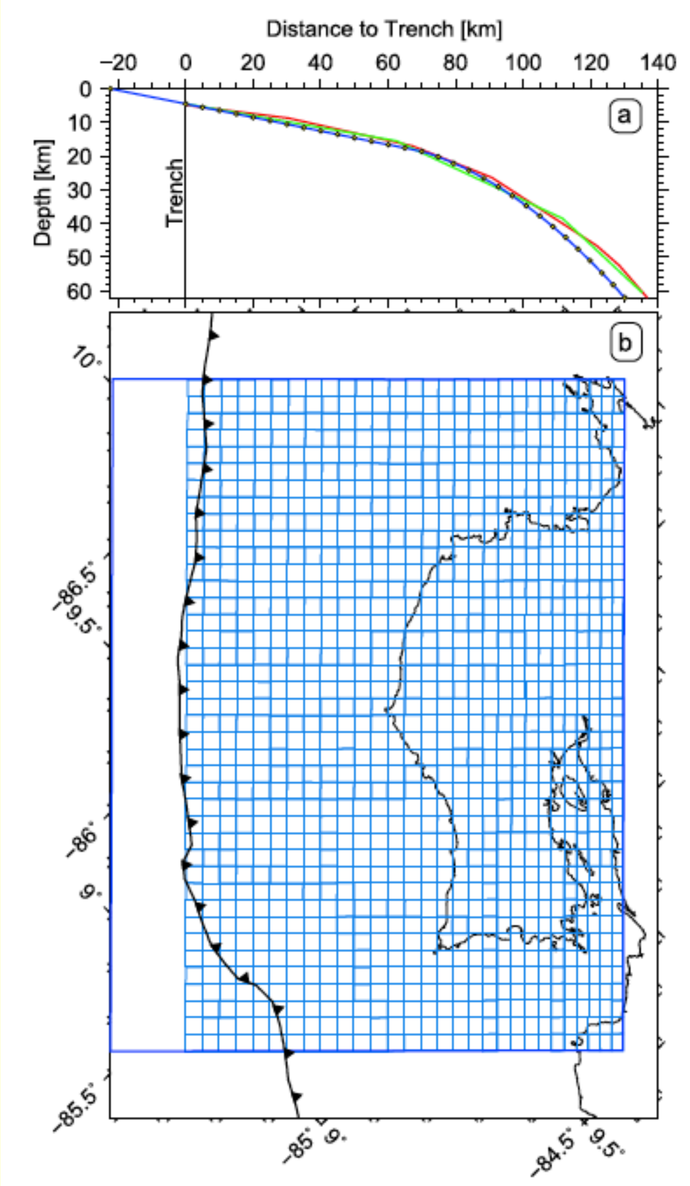


Inversion of distributed deformation

- **GTDef**: Chen et al. (2009, *GRL*) implementation of Okada elastic equations (*BSSA*, 1985)

$$\begin{bmatrix} Wd \\ 0 \end{bmatrix} = \begin{bmatrix} WG \\ \kappa^2 D \end{bmatrix} m$$

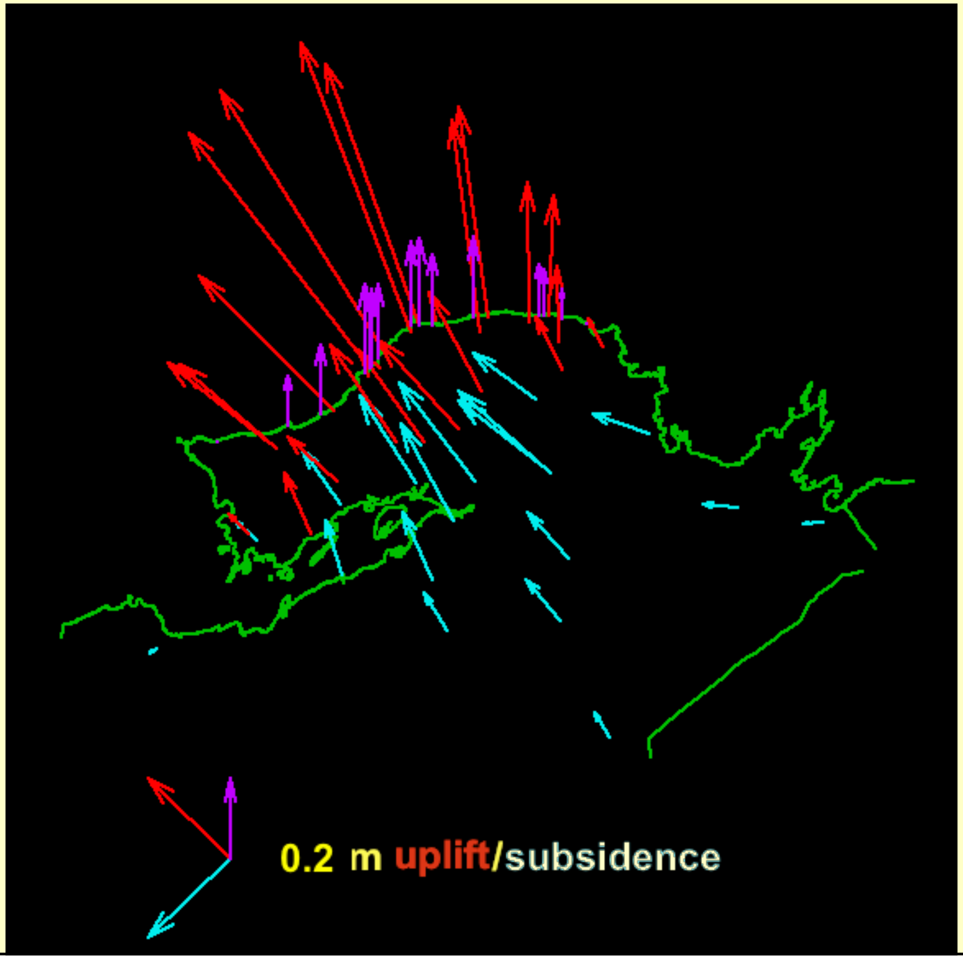
- Linear least squares inversion of weighted, *w*, data, *d*, to solve for slip on fault, *m*. Greens functions reprenting Okada equation, *G*, with 2D smoothing parameter, κ, on "roughness" of the displacement field, $D = \nabla^2 u$.
- Total 1200 patches, approximately 5 km square. Strike 315°

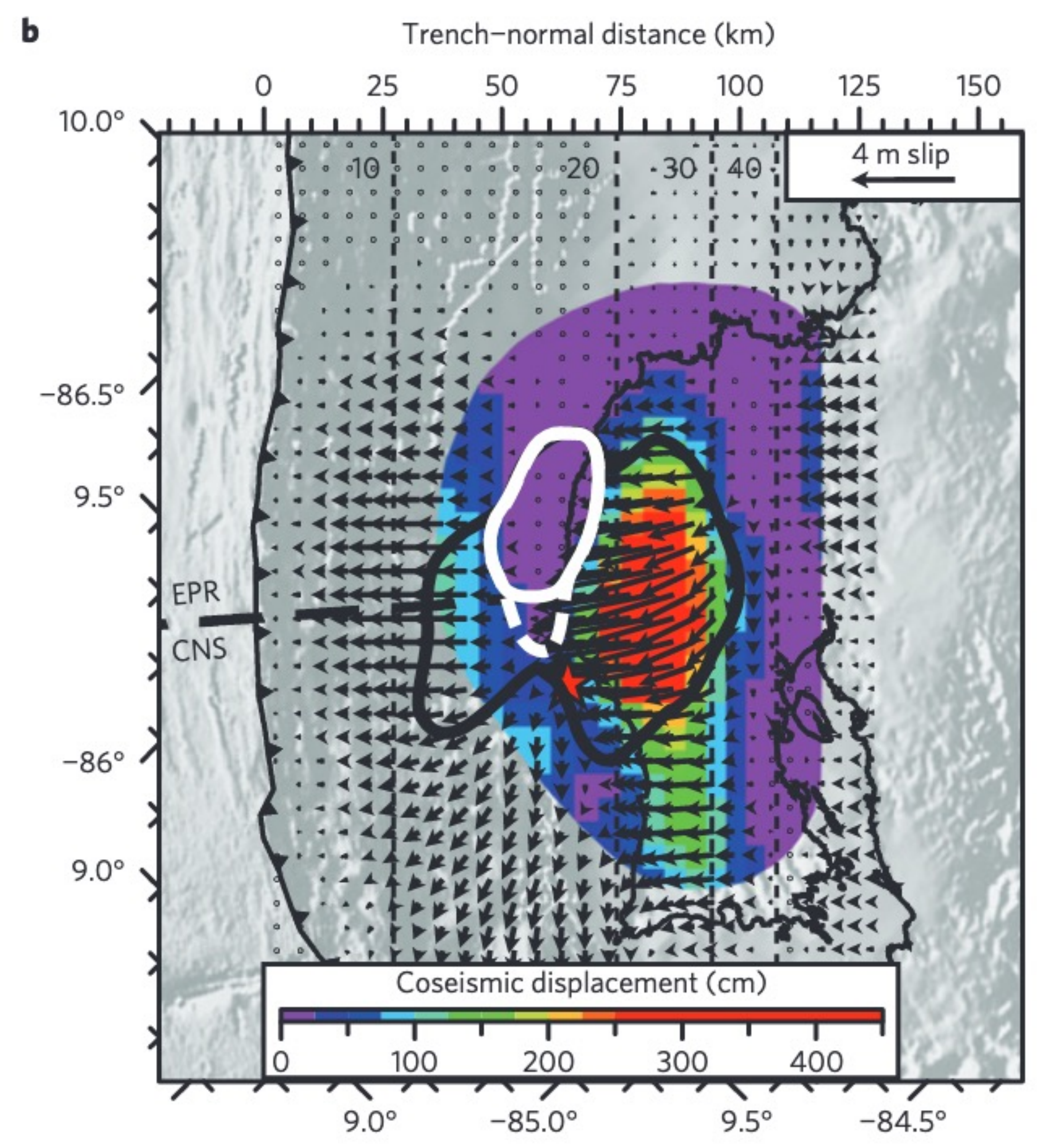


Following methods of Jonsson et al., 2002

Fault Interface Slip

- Solving the distributed slip equation for a large earthquake





Analytical models:

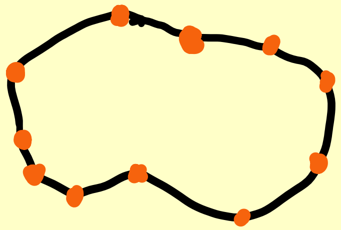
Some Analytic modeling codes:

- **GTDef** (Georgia Tech Deformation) Murekezi et al., 2020
  - Uses discrete and distributed Okada model
  - Incorporates external model geometries and Greens functions
  - Can include layered earth rheology
  - Incorporates many data types
    - GNSS, InSAR, baselines, vertical-only change
  - Open-source, but requires commercial software (Matlab) to run

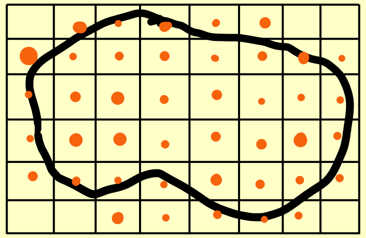
- **VMOD** (Versatile Modeling of Deformation) Angarita et al., G^3, 2024
  - Similar to GTDef, has some advanced simulation methods
  - Uses completely open-source software (python)

Numerical Methods:

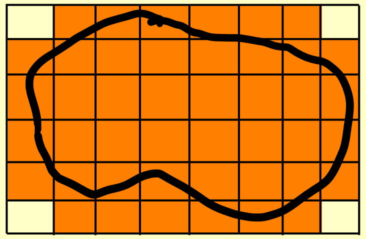
- A range of numerical methods are used to define geophysical problems, and fall in 4 classes:
  - **Boundary Element Methods (BEMs):** Integrate Partial Differential Equations (PDEs) across the entire region of study (does not allow internal structure/rheology changes—linear homogenous media)



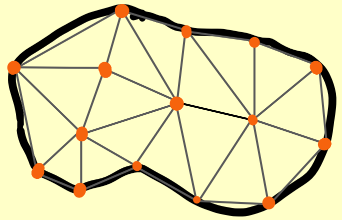
  - **Finite Difference Methods (FDMs):** Directly solves the PDEs across individual elements (works well with structured grids, and allows regular changes)



  - **Finite Volume Methods (FVMs):** Directly solve PDEs for average values across elements, represented as fluxes across volumes (particularly useful for fluid dynamics)



  - **Finite Element Methods (FEMs):** Approximates solution by summing PDEs across nodes (can easily accommodate unstructured grids, requires constant values within elements)



Finite Element Method (FEM):

- **For complex problems**: Numerical method that solves partial differential equations for problems with complex boundary conditions
- **Discrete solutions**: Complex problem divided into small regions (elements) in which the equations are approximately solved and combined for the solution of the whole.
- **The Mesh**: elements are connected by nodes by which equations are continuous across, forming a mesh by which to solve the model.
  - Speed/accuracy of solution heavily controlled by this.

Common Codes:

- **Commercial**
  - ABAQUS

    www.simulia.com
  - ANSYS

    www.ansys.com
  - FEMLAB

    www.femlab.com
  - Cubit (mesh algorithm)

    www.sandia.gov
- **Free and Open-Source**
  - (G-)TECTON

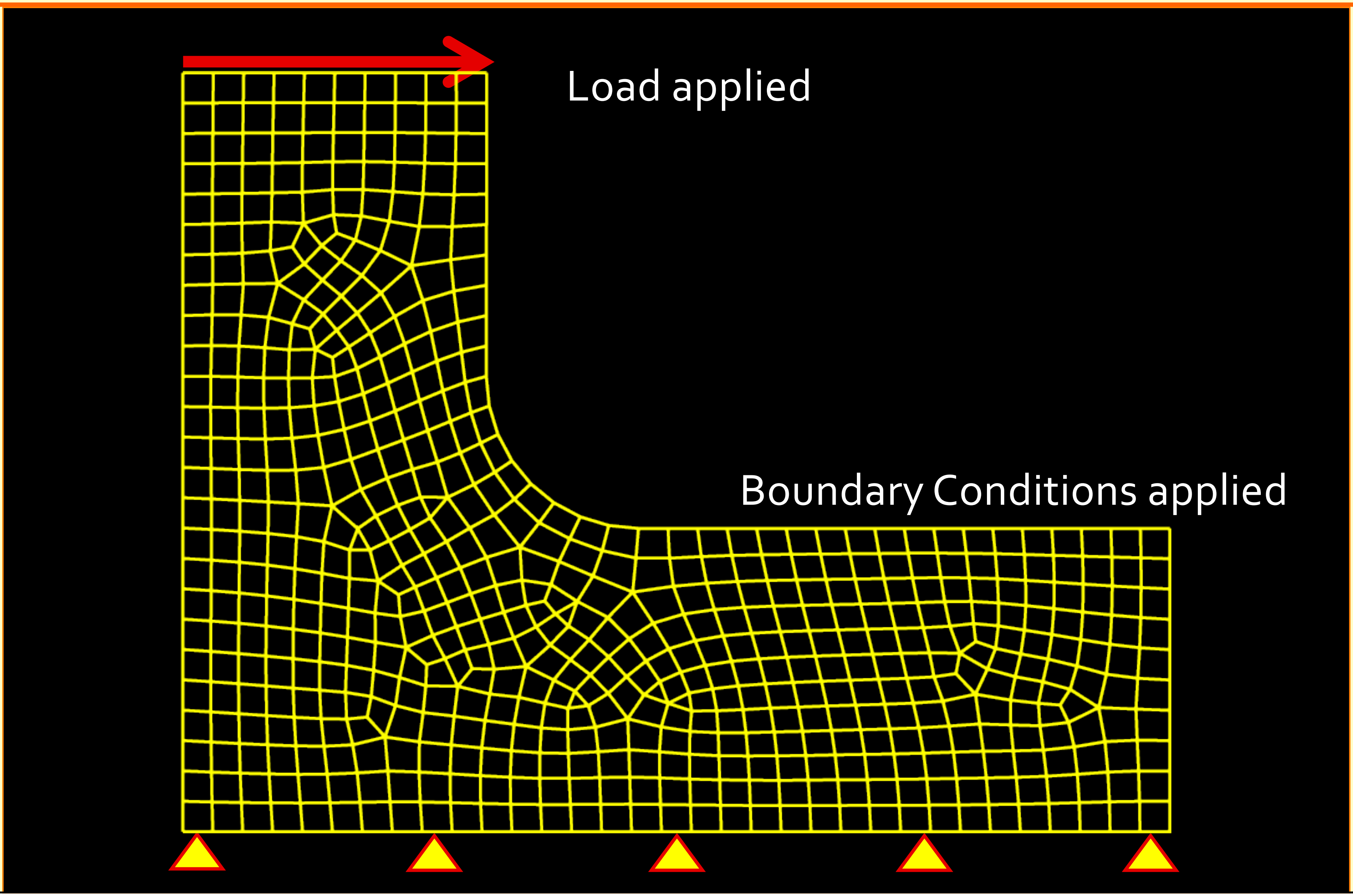
    Melosh & Raefsky, 1980
  - PyLith

    www.geodynamics.org
  - Adeli

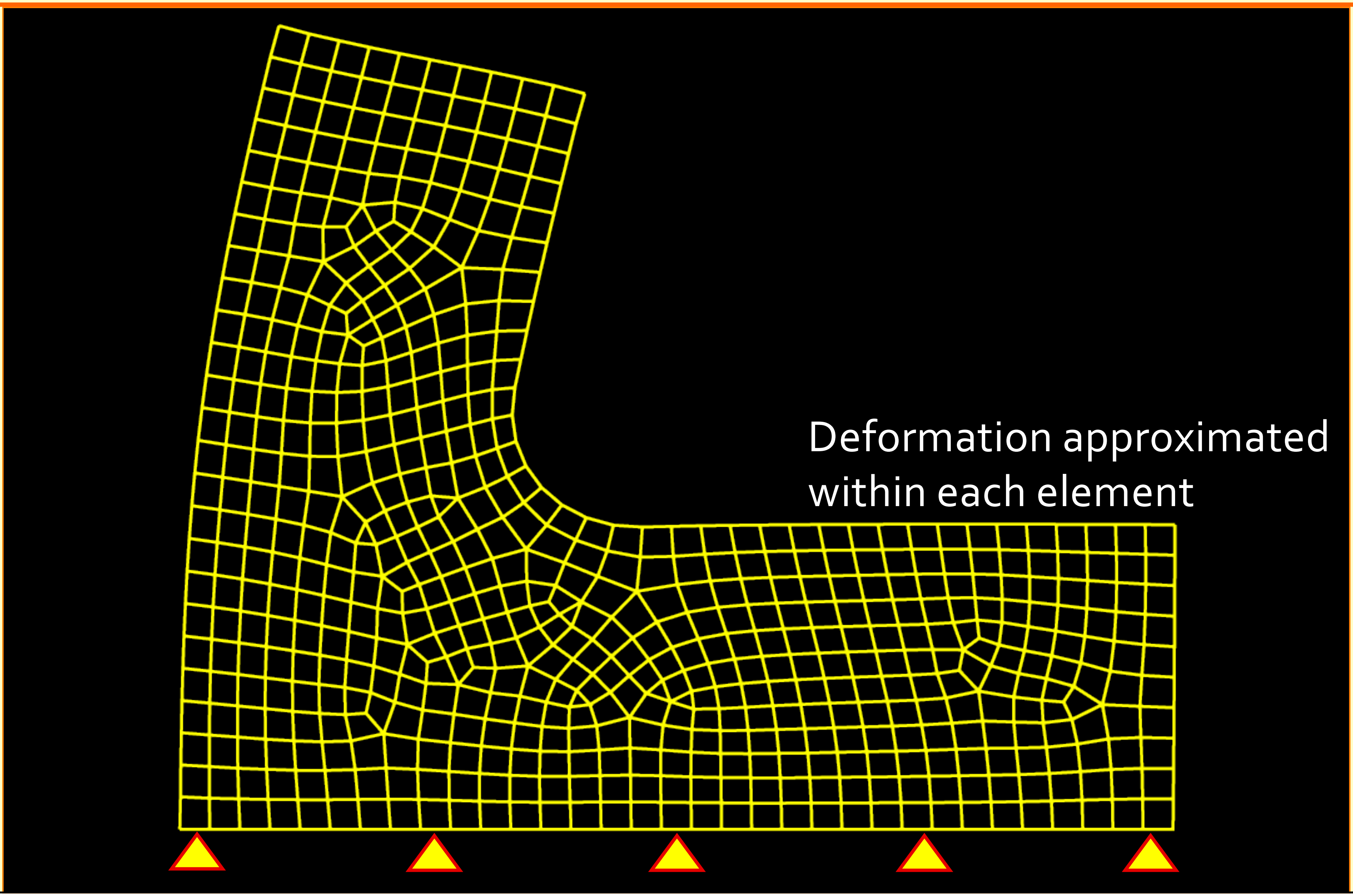
    www.dstu.univ-montp2.fr/PERSO/chery/Adeli_web
  - geoFEST (solver)

    www.physics.hmc.edu/GL/geofest/

Utility of Finite Element

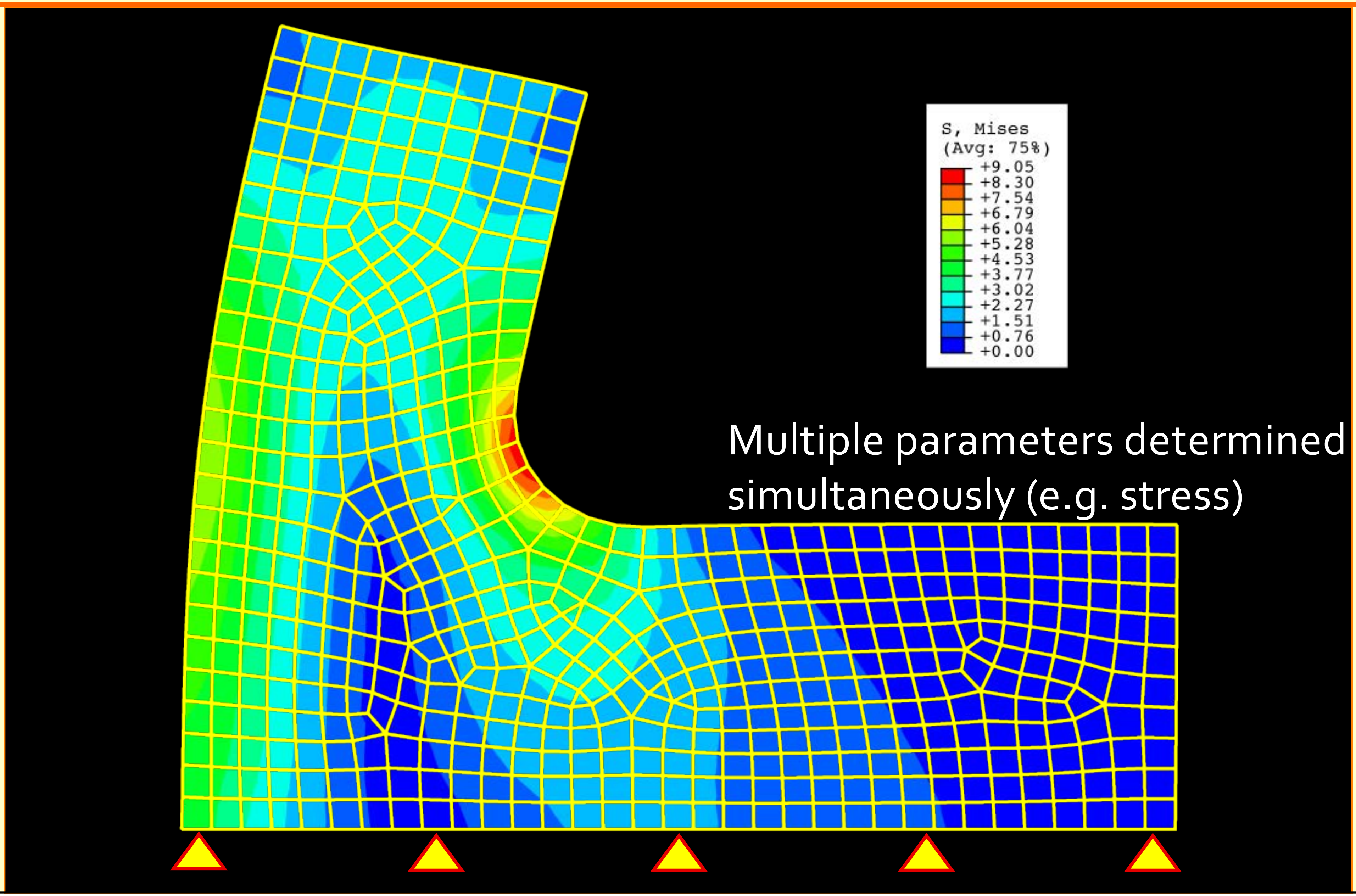


Utility of Finite Element



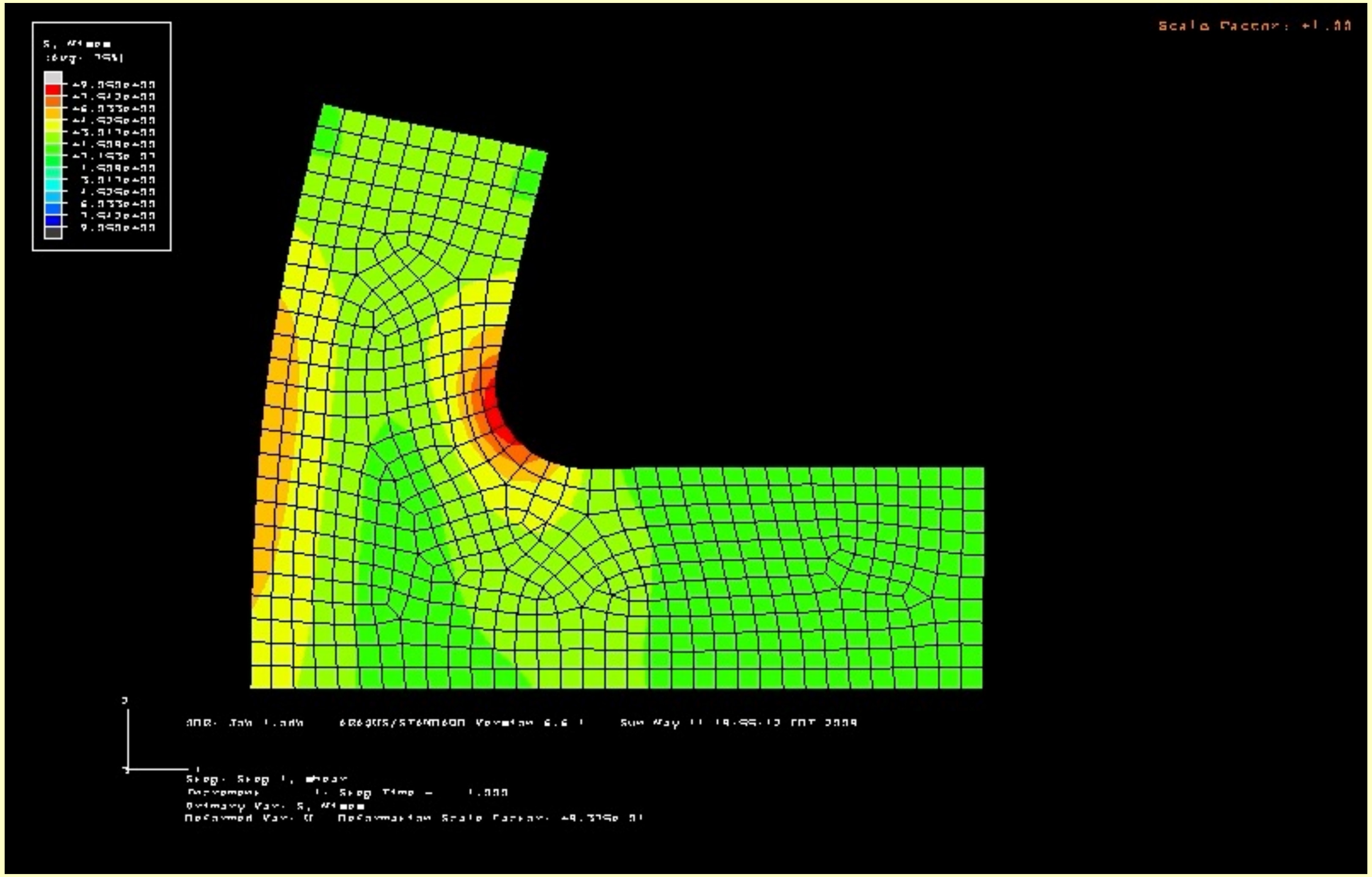
Deformation approximated within each element

Utility of Finite Element



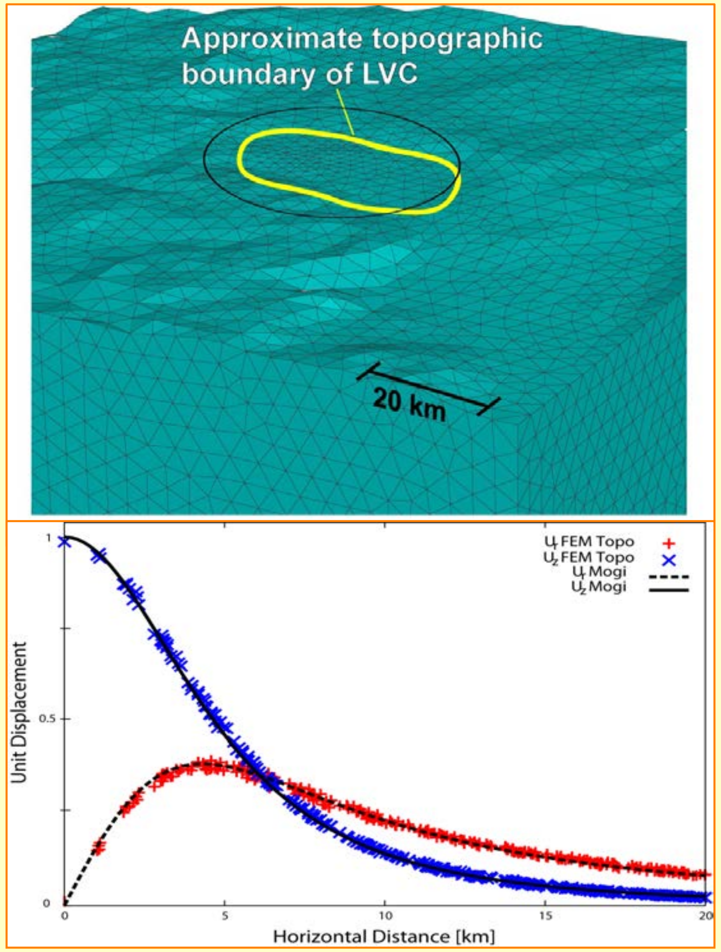
Multiple parameters determined simultaneously (e.g. stress)

Utility: Time-dependent deformation



Utility: Topography

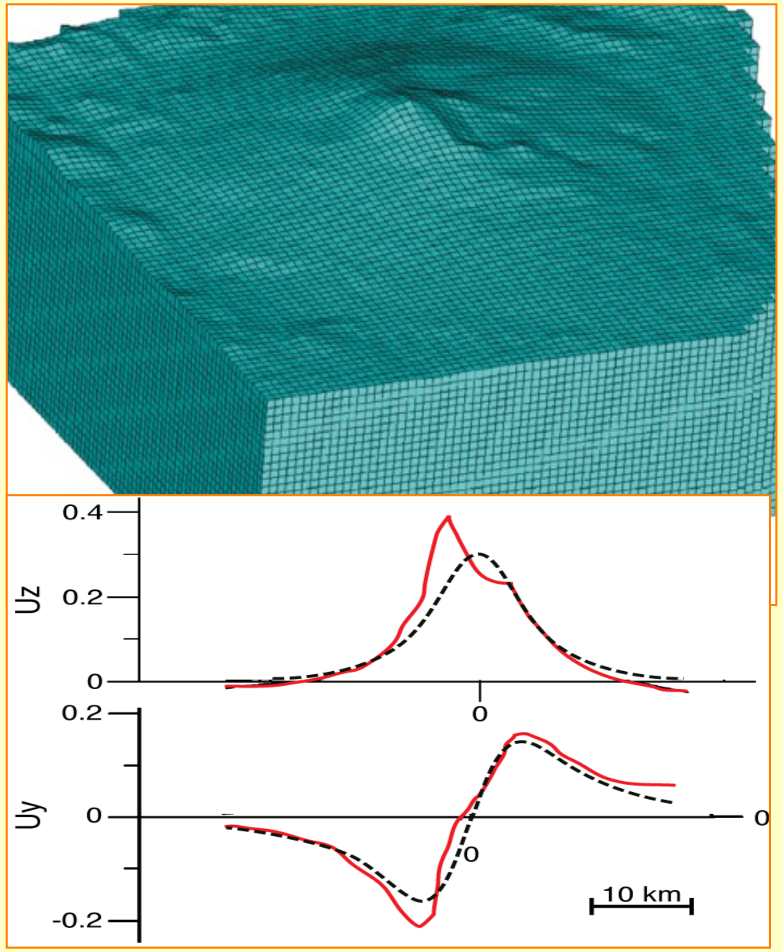
Long Valley Caldera



Feng and Newman, 2008

Doesn’t matter much

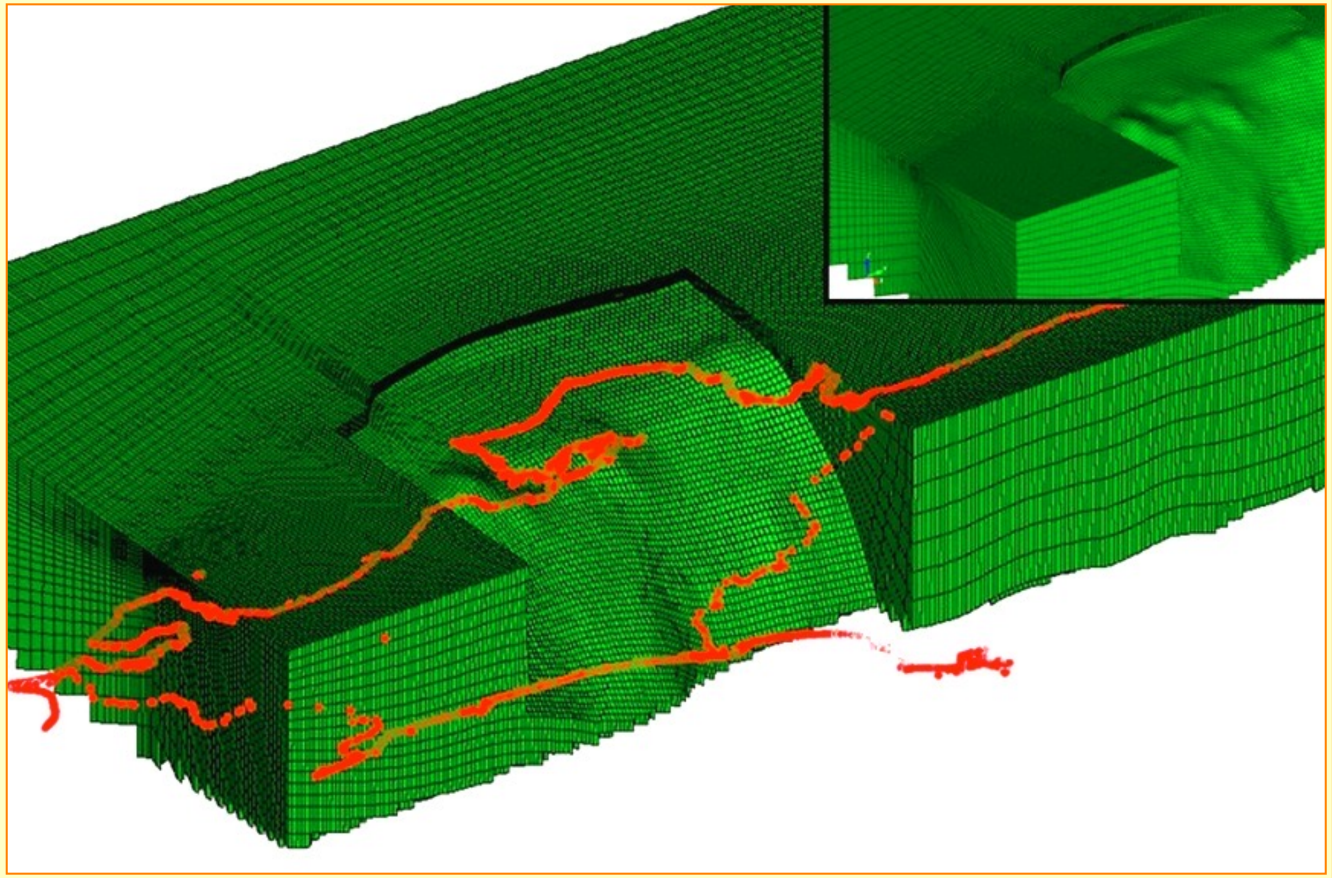
Mt. Etna

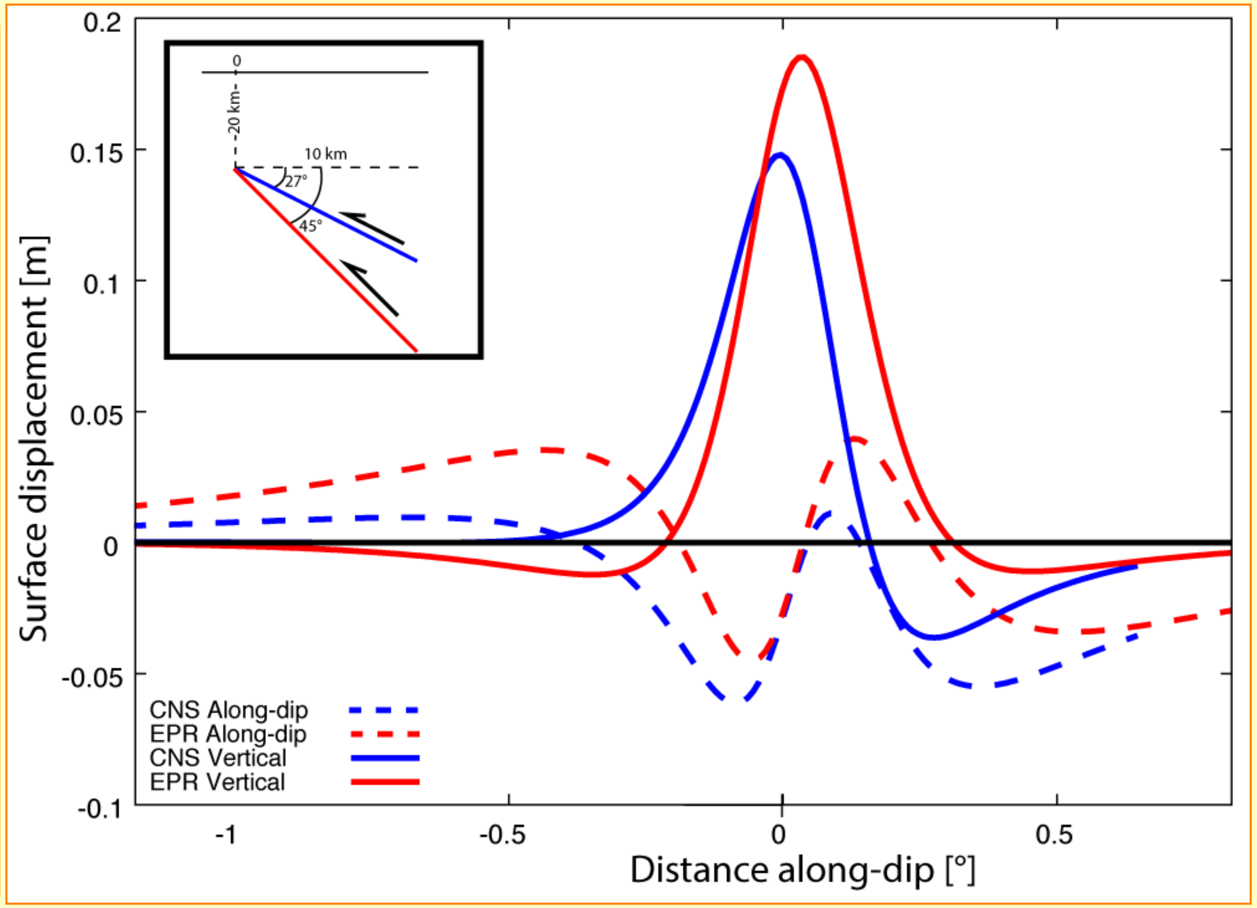


Lungarini et al, JVGR, 2005

More important

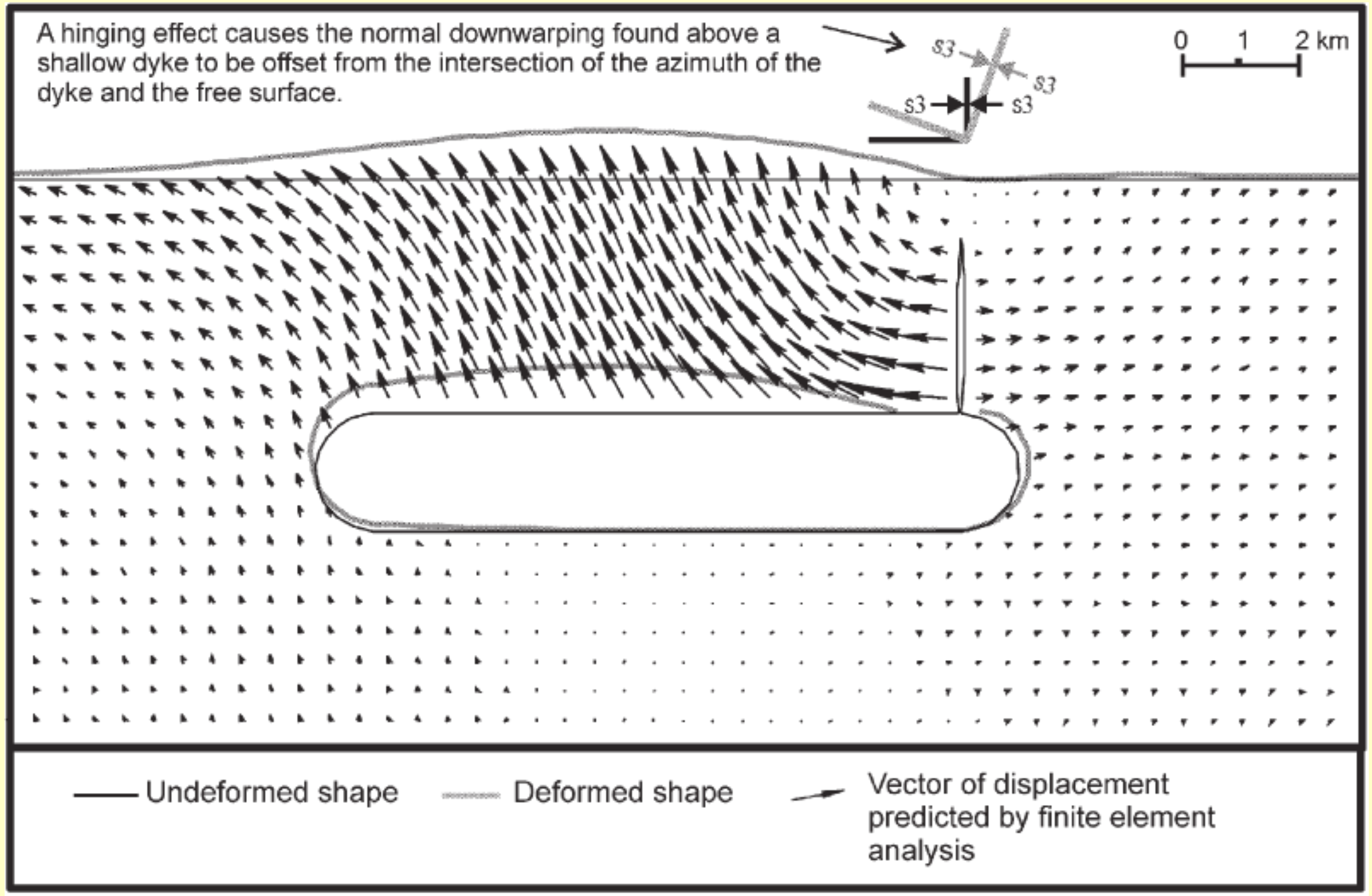
Utility: 3D Structure





Kyriakopoulos and Newman, JGR 2016

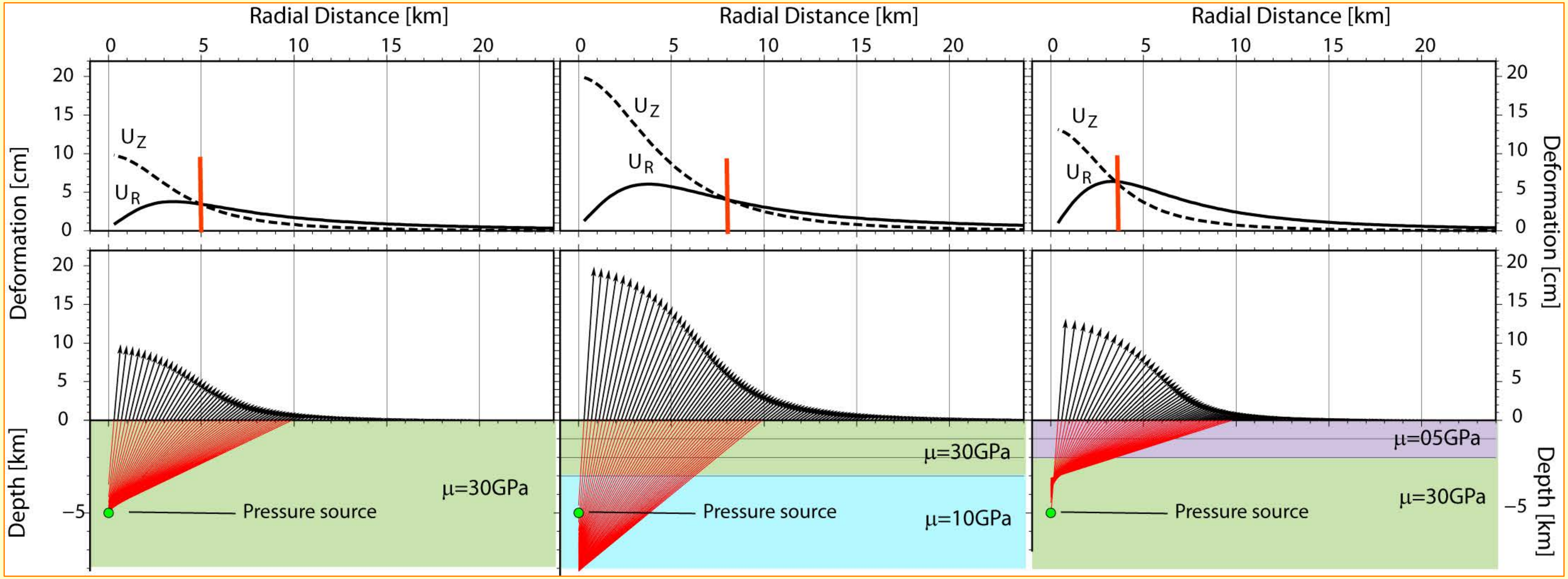
Utility: Fault interactions



A hinging effect causes the normal downwarping found above a shallow dyke to be offset from the intersection of the azimuth of the dyke and the free surface.

Saunders, B. Volc, 2005

Utility: Layered Rheology on deformation

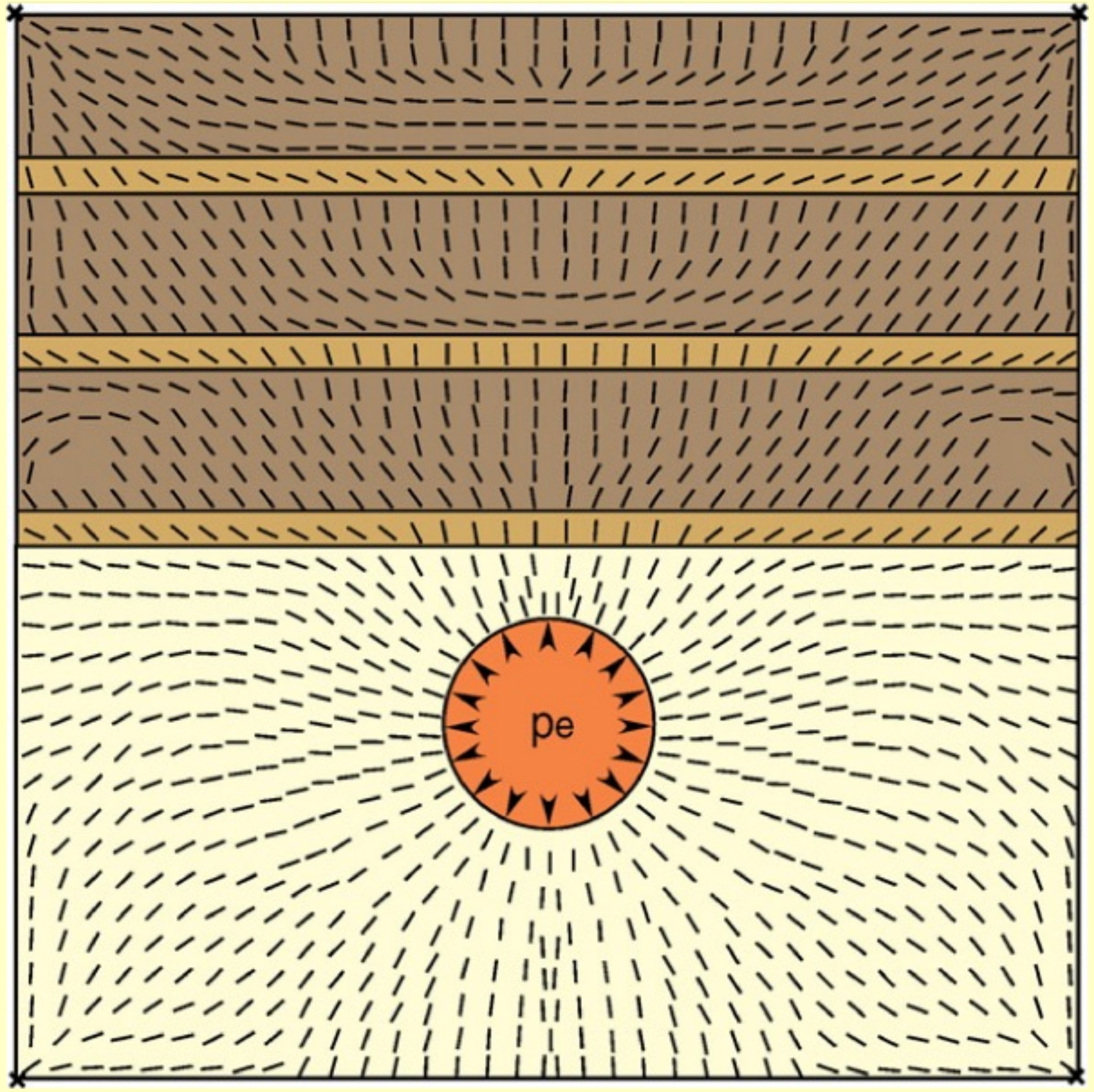


Mogi-like

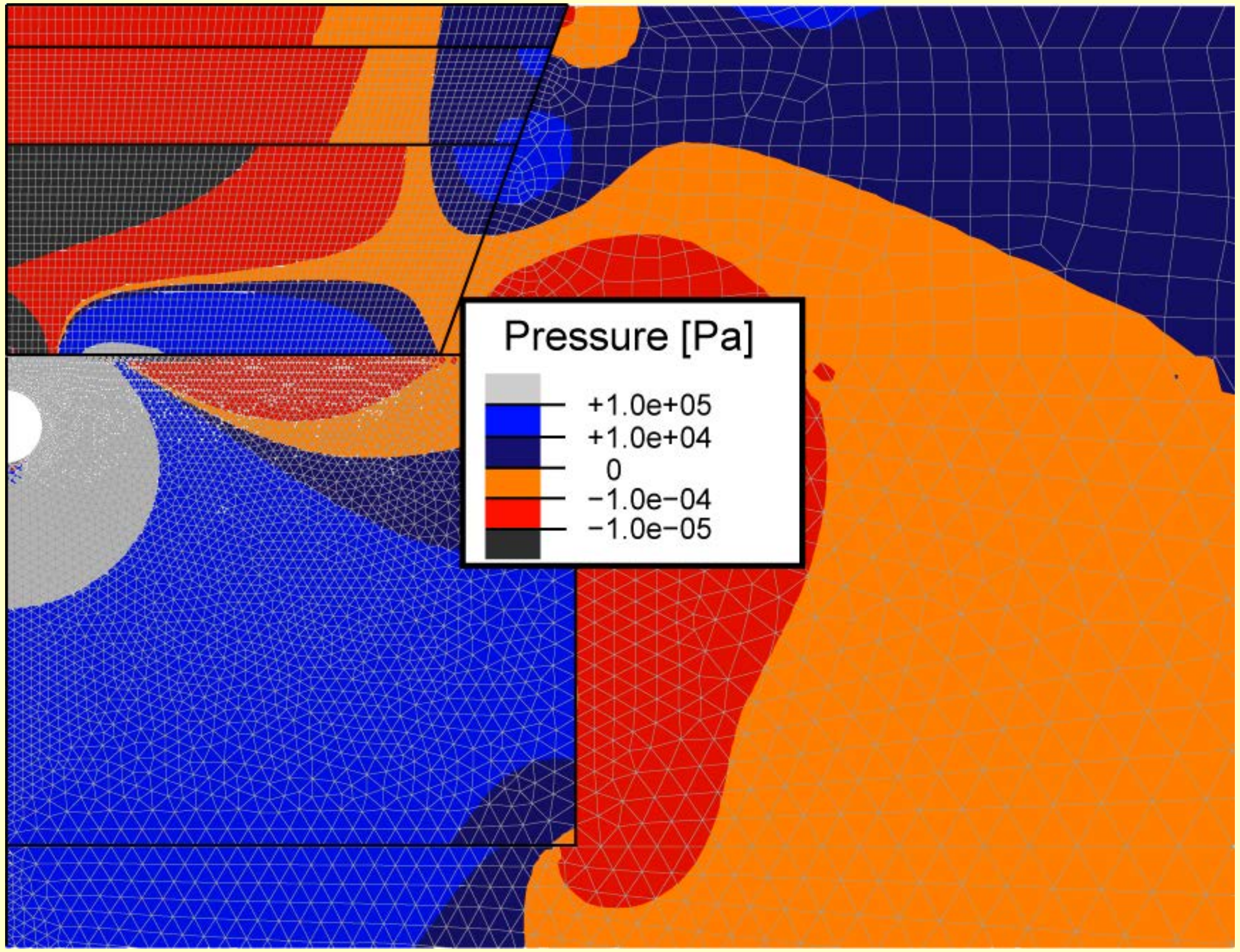
Weaker at depth increased uplift Appears deeper

Weaker near surface increased uplift appears shallow

Utility: Layered Rheology on internal stress



Gudmundsson, ESR, 2006



Newman, unpublished

Summary of Geodetic Methods:

Modern Space-based methods can give detailed and precise measurements of surface deformation:

- **InSAR** ideal for capturing spatial extent of deformation. Snow, Δ vegetation, loose terrain, steep slopes are problematic.
- **GNSS** can be globally referenced, gives 3D deformation, and can yield rapid relative rate changes. Spatially limited
- **Combining GNSS with InSAR** give 4-D image of surface deformation -- incredibly useful for understanding the geometry and movement of fluids at depth.
- **Analytic and Numerical Methods (incl. FEM)** can give great insight into likely subsurface processes driving deformation