Measuring sub-cm deformation from space

Cornell Andes Project

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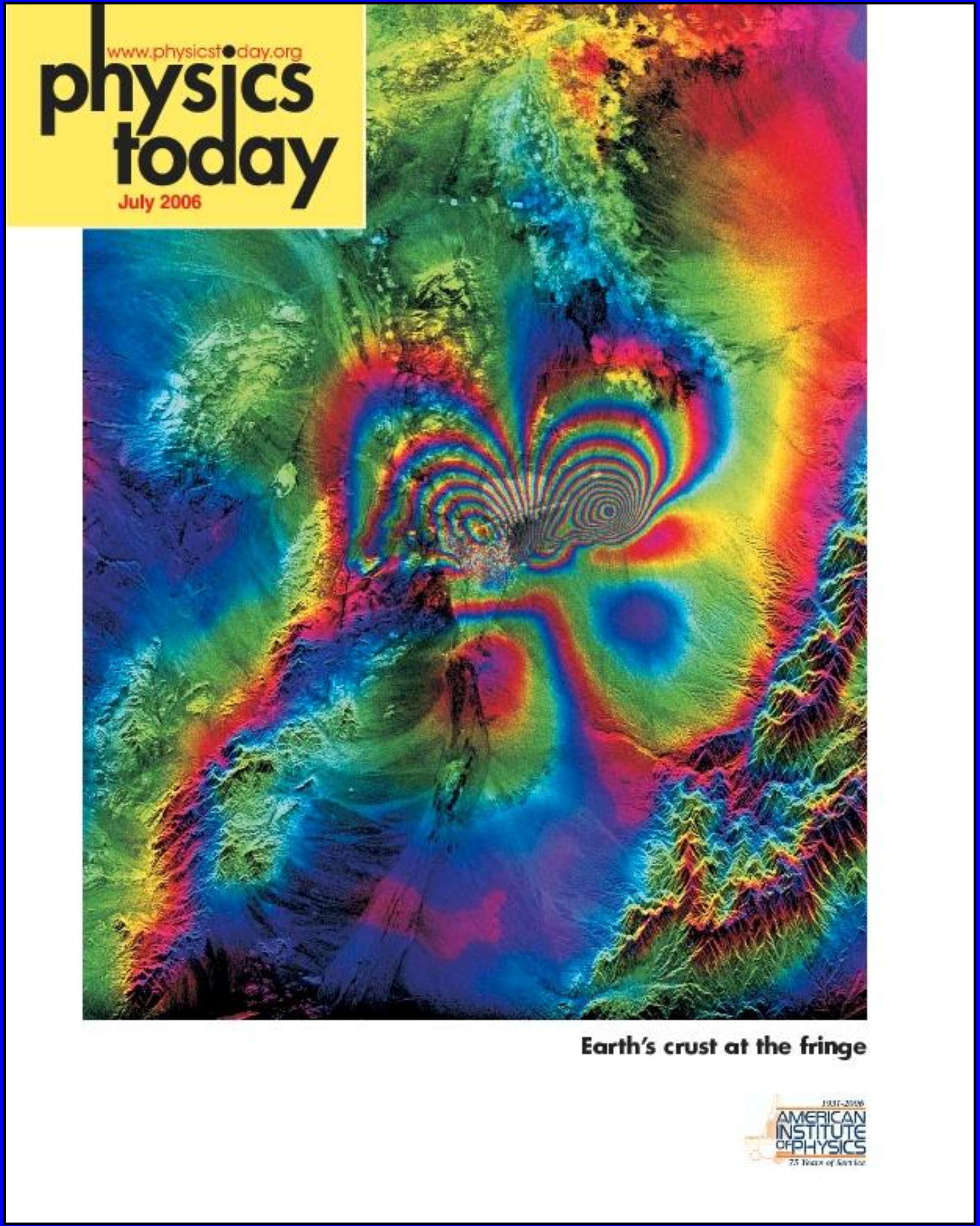
Bristol: Steve Sparks
Alaska: Steve McNutt
Bolivia: Mayel Sungua

Magnitude 6.6 Bam, Iran earthquake in 2003
Interferogram courtesy of Yuri Fialko

Measuring sub-cm deformation from space:



Outline:

Act 1: What am I looking at?

Introduction to InSAR: what it is, where it works, and where it doesn't work

Act 2: Who cares?

Magma migration at supposedly dormant volcanoes

Act 3: No, really: who cares?

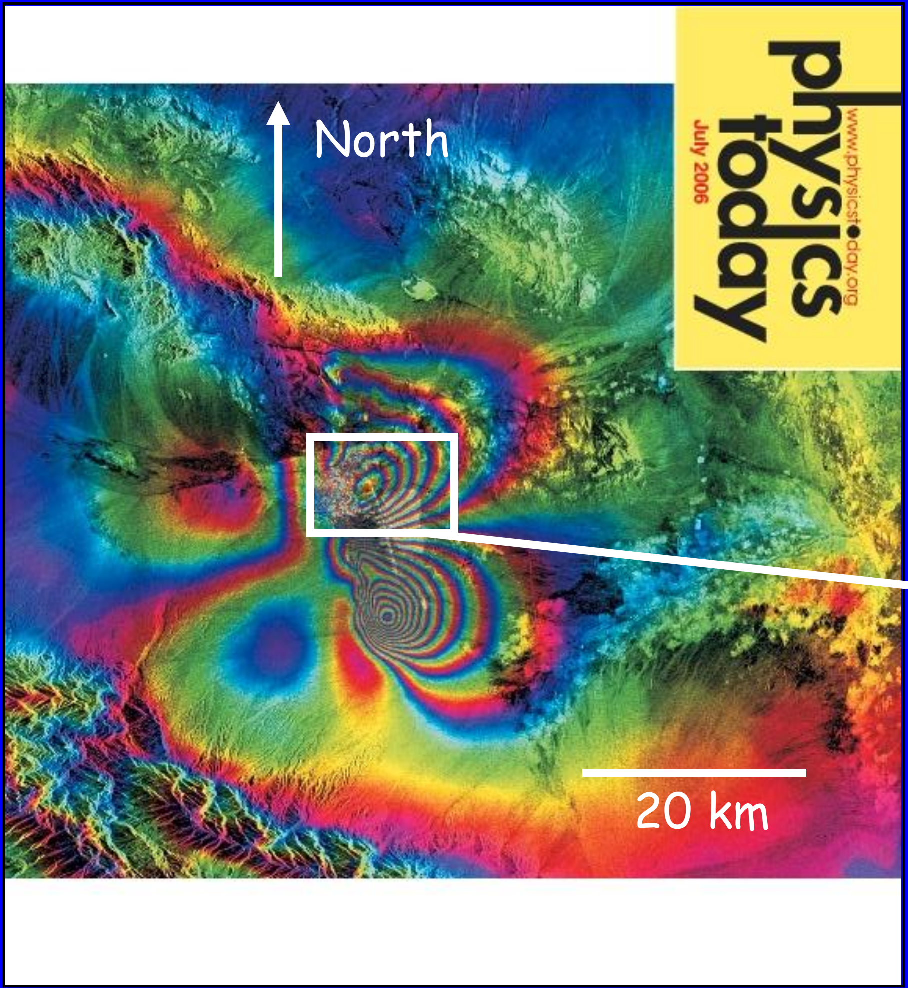
"Silent" earthquakes triggering real earthquakes

Interferogram courtesy of Yuri Fialko

Where in the world am I?

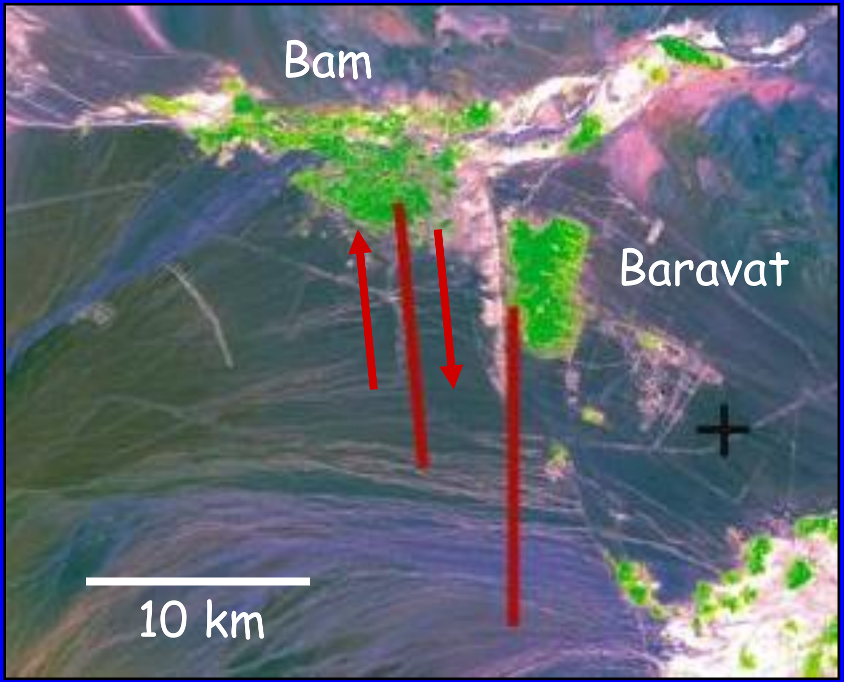
From: Farsinet.com

- Magnitude 6.6 earthquake: 26 December 2003 in Bam, Iran
- Arid and mountainous region with frequent earthquakes (collision between Arabian and Eurasian plates)



Interferogram courtesy of Yuri Fialko

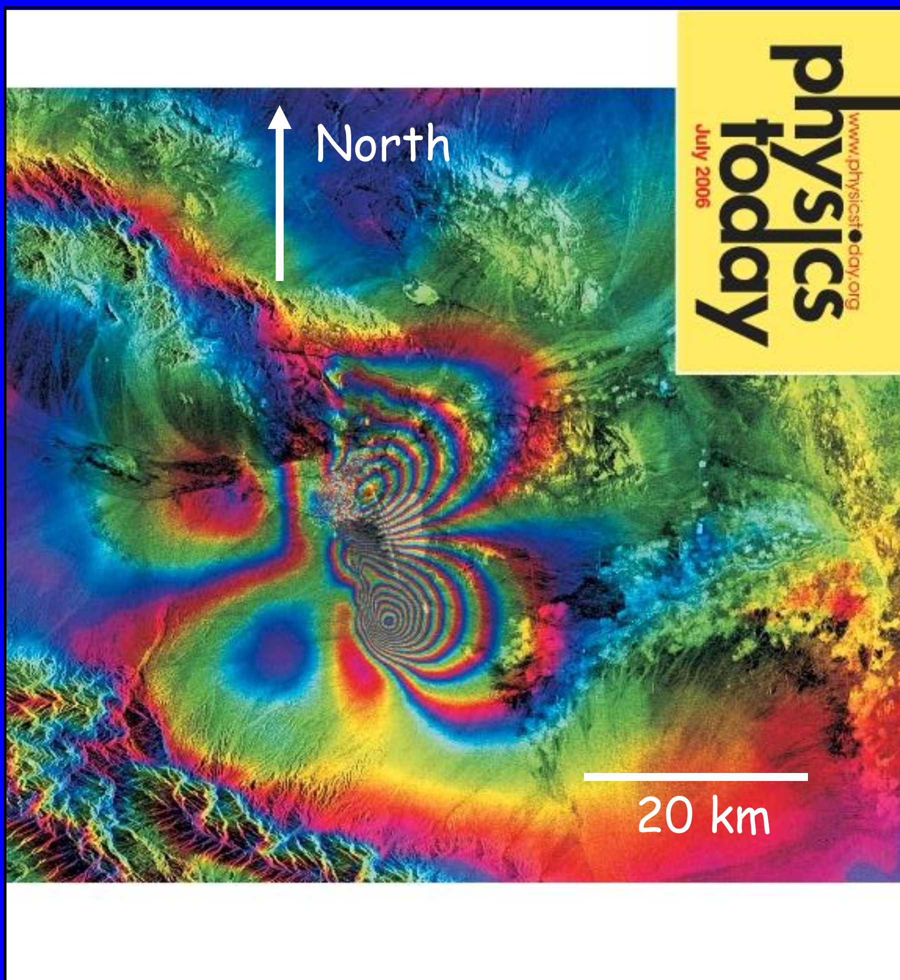
- Previously unmapped fault (right-lateral strike-slip)



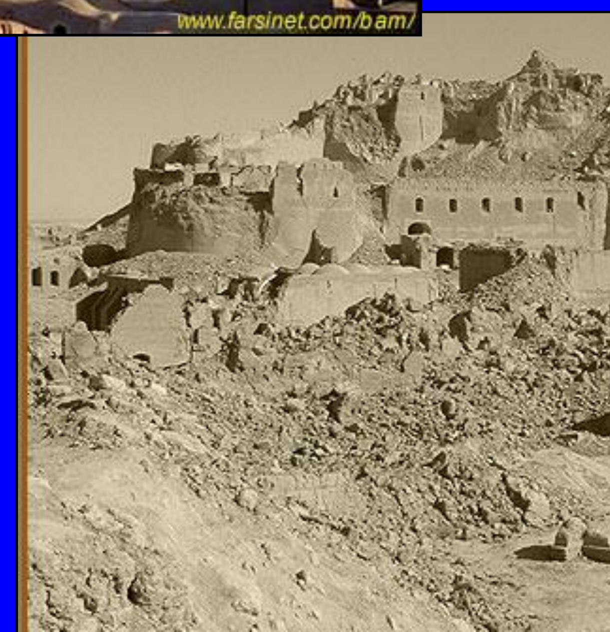
Landsat satellite image from 1999, from Funning et al., 2005

Where in the world am I?

•City of ~80,000 people -- about 80% of the city destroyed
~30,000 casualties, mostly from collapse of mud roofs



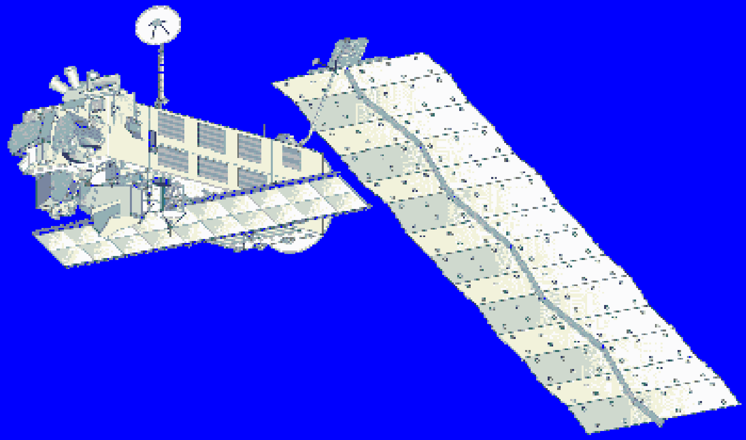
2,000(?) year old citadel destroyed by earthquake

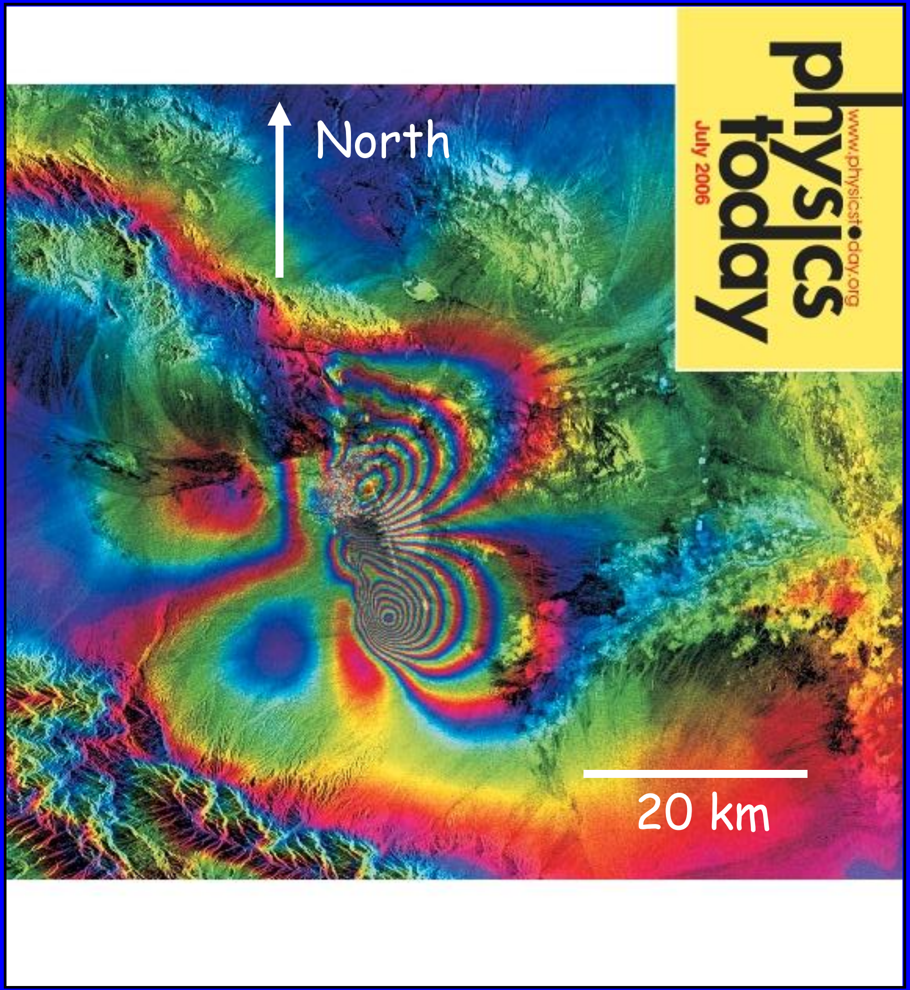


From: FEMA

What am I looking at?

- Each fringe: contour of ground deformation in direction of satellite radar beam





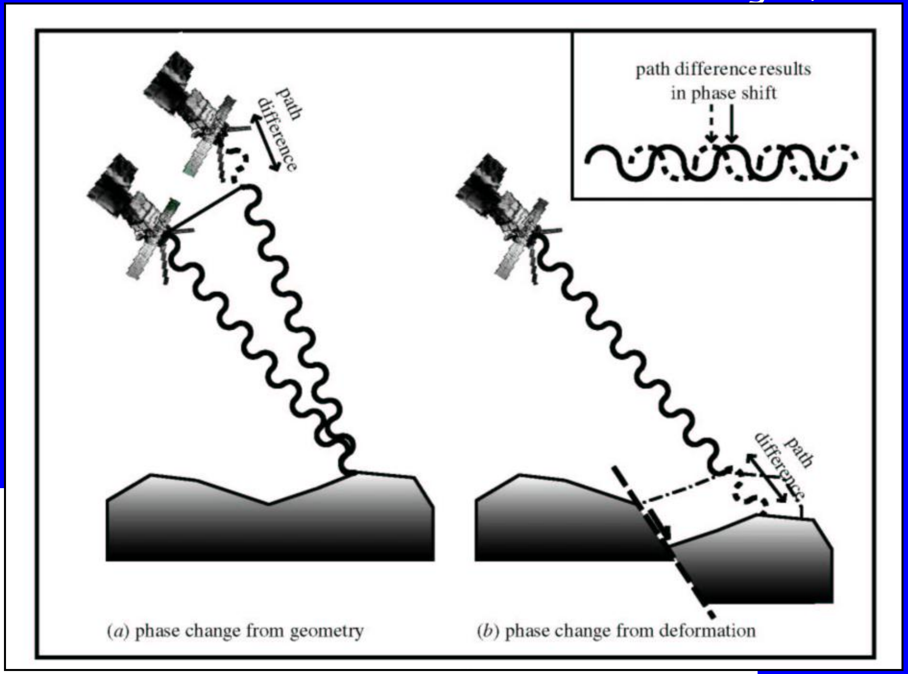
- Each scene:
  - 20 meters per pixel
  - 100's of km per image
  - Resolve deformation ~mm/year

- This example:
  - From European space Agency Envisat satellite (5.6 cm radar wavelength)

  - Each fringe is 2.8 cm of deformation

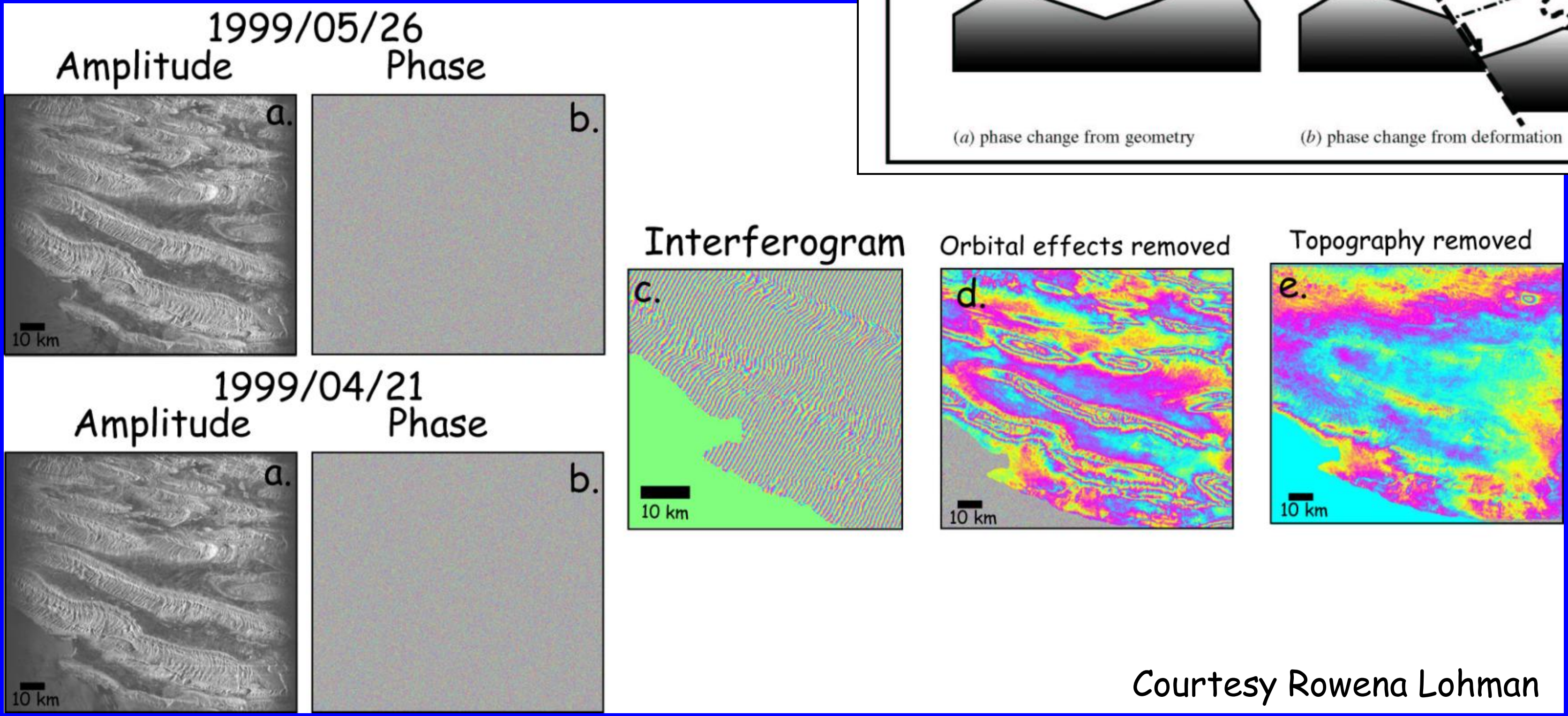
Intro to InSAR: How does it work?

Wright, 2002



- Two Radar images from space:
  Data is complex: has amplitude and phase

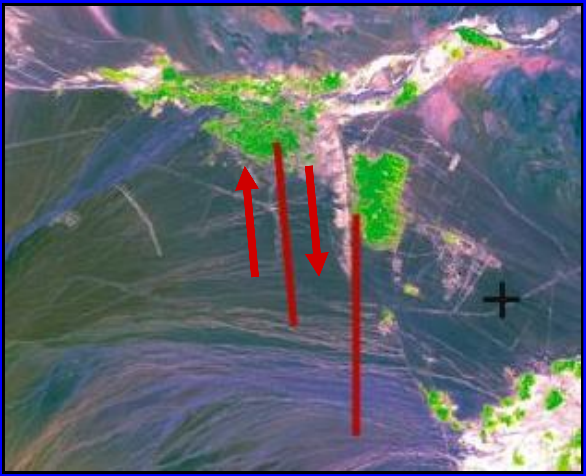
- Phase change between images depends on several factors that must be removed before measuring deformation

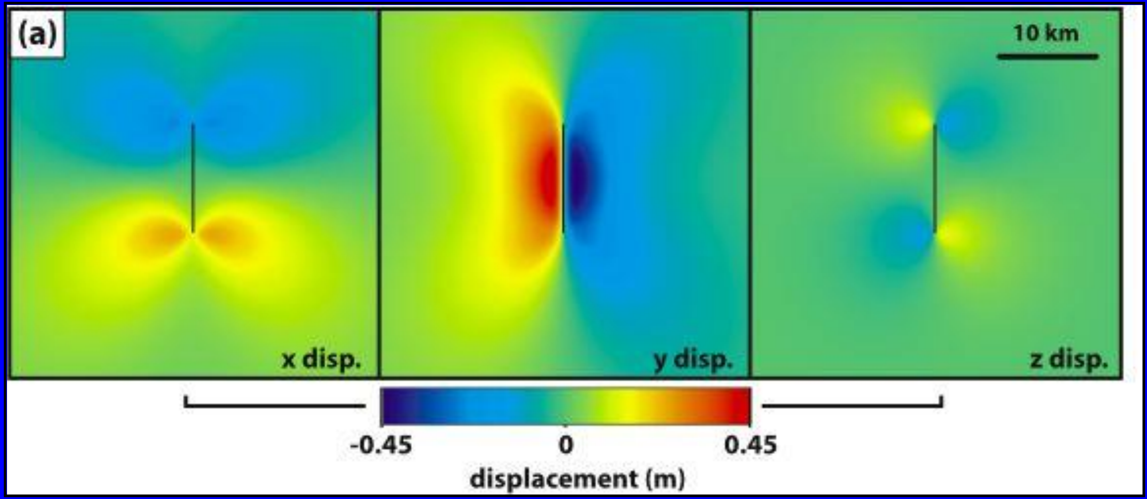


Courtesy Rowena Lohman

Visualizing 3D deformation in a 1D interferogram

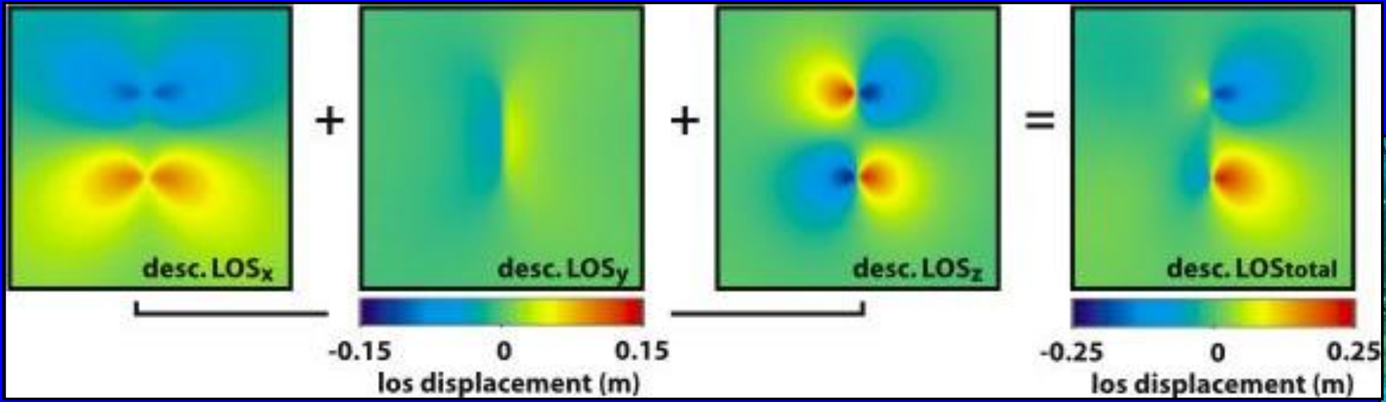
- Step 1: Fault motion produces 3D deformation field

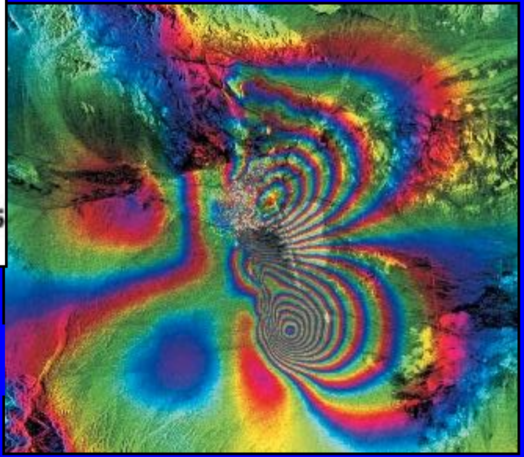




- Step 2: Project 3D deformation onto satellite radar line-of-sight

Both images:
Funning et al., 2005



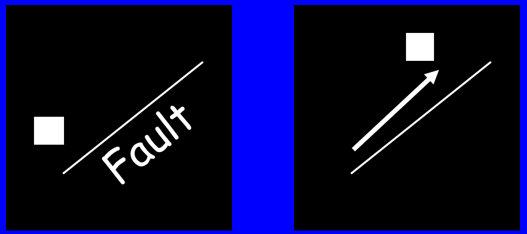


- Step 3: Create a fringe every /4 centimeters ("wrapped image")

Reconstructiong the full 3D deformation field

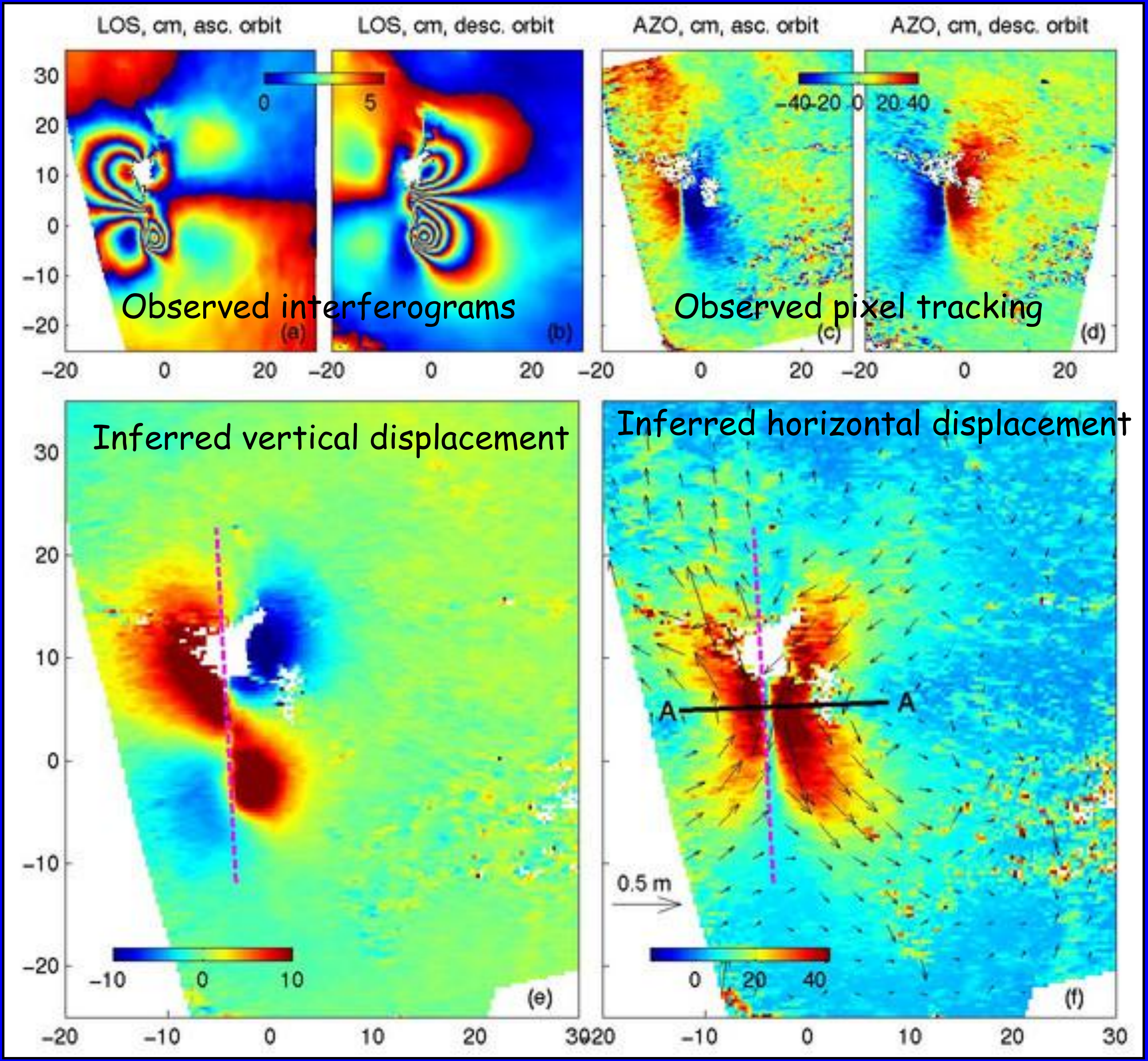
- Use interferograms from different satellite look directions

- PLUS: use the amplitude images to track pixels that moved



Before

After



Fialko et al., 2005

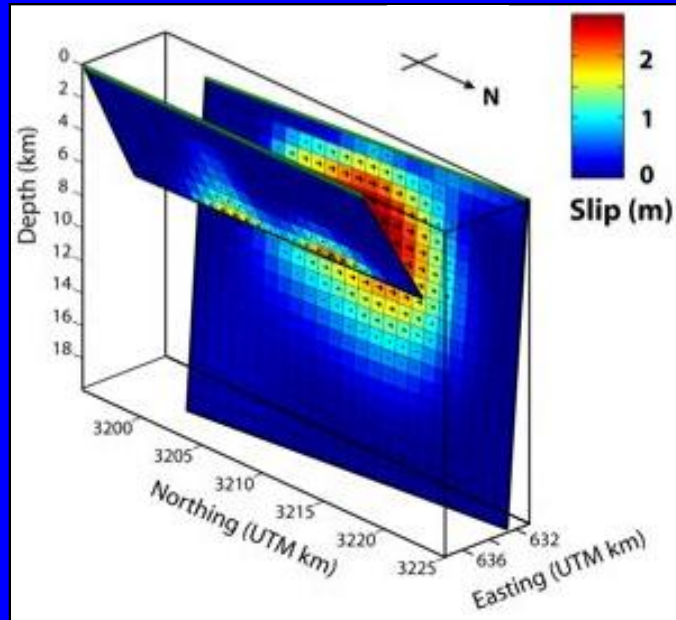
Who cares? What have we learned about earthquakes?

1) Shallow slip deficit

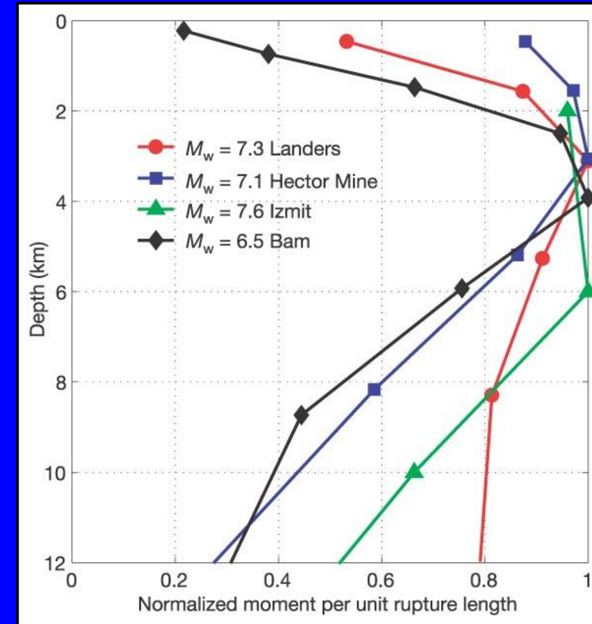
•To be released in future earthquakes?

•To be released aseismically?

•Result of bulk Inelastic failure? (e.g., numerous small faults instead of 1 big one?)



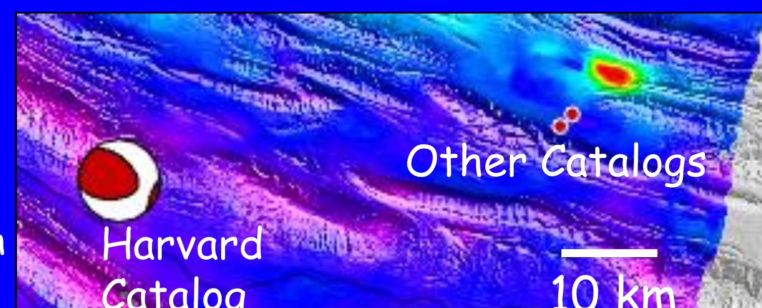
Funning et al., 2005



Fialko et al., 2005

2) Earthquakes mislocated up to 30-50 km by global seismic networks

Mw 5.3 earthquake in southern Iran
From: Lohman and Simons, 2005

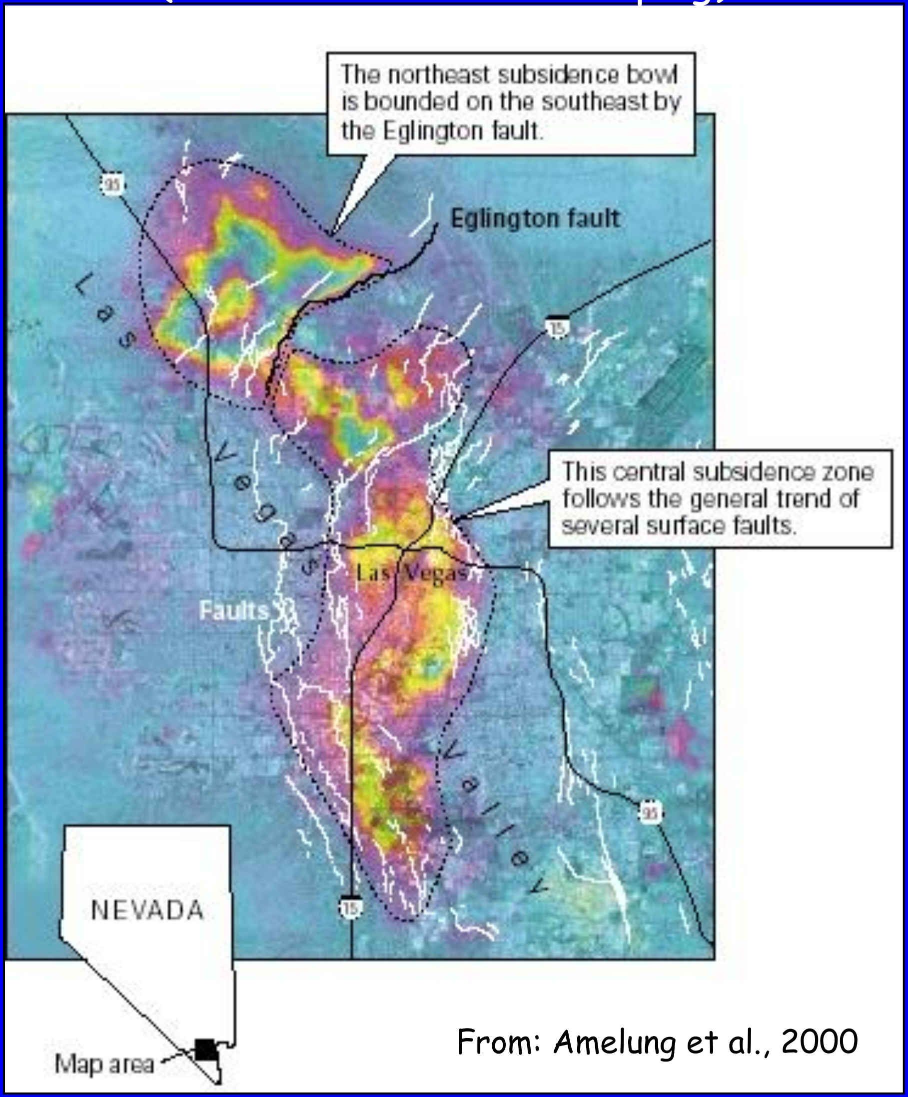


3) Power-law viscoelastic and poroelastic response to sudden slip

4) Slow (aseismic slip) triggering earthquakes (e.g., Act 3 of this talk)

Don't care about earthquakes?
Some of InSAR's other greatest hits

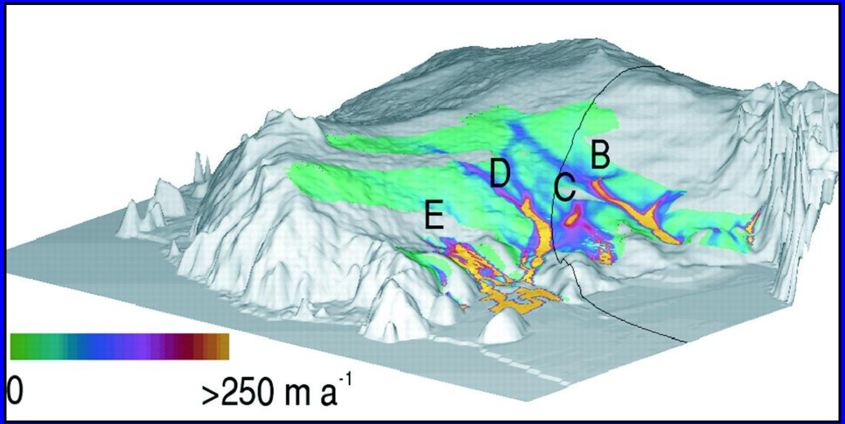
The Ups and downs of Las Vegas
(From Groundwater Pumping)



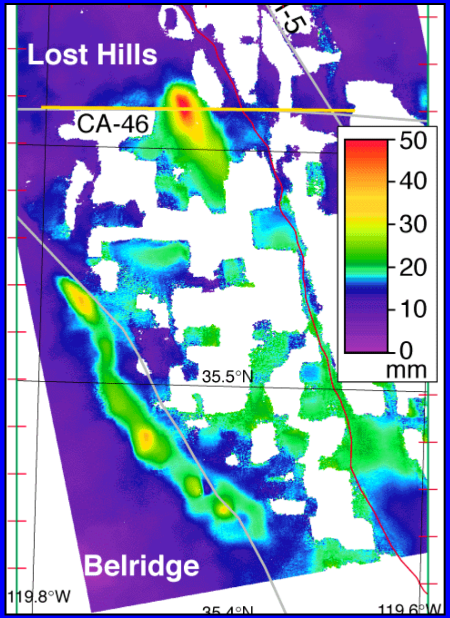
From: Amelung et al., 2000

Antartica ice stream velocities from InSAR/feature tracking

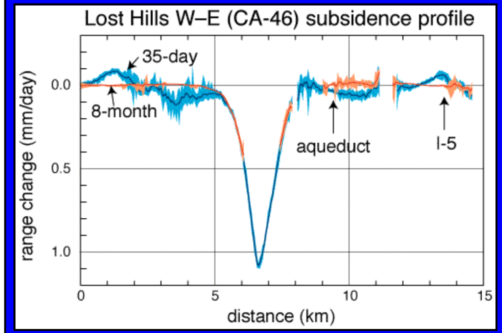
Also: glacier speed-up in Greenland: Implications for sea-level rise



From: Bamber et al., 2000



Lost Hills, CA Oil Field subsidence
Fielding et al., 1998



InSAR: practical considerations

1) Data availability: None of these opimized for InSAR!

Past: European (ERS-1/2; 5.6 cm); Japanese (JERS; 24 cm)
Present: European (Envisat; 5.6 cm); Canadian (RADARSAT-1; 5.6 cm); Japanese (ALOS; 24 cm)
Future: Canadian (RADARSAT-2; 5.6 cm);

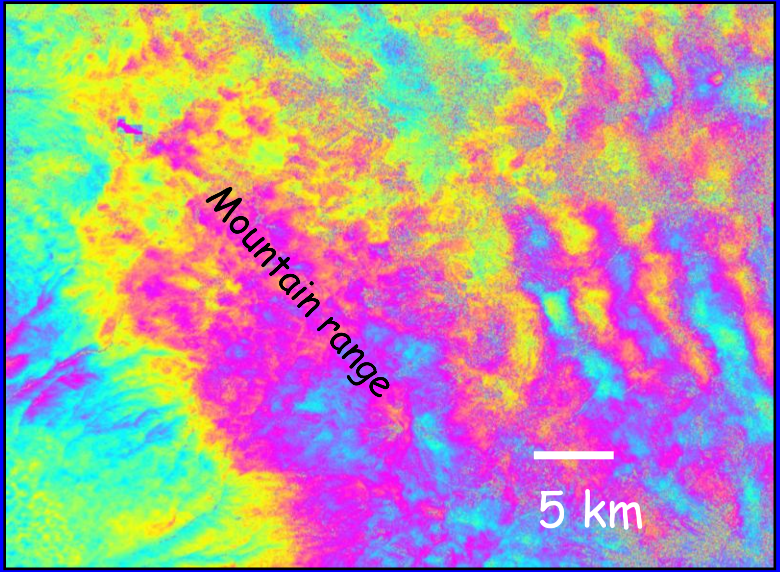
Repeating passes every 20-30 days; more frequent for special orbits

Data not acquired during every overflight; can be expensive $100-1000's per scene

2) Orbit control: Need repeat passes within few 100's m

3) Atmospheric effects: Not always water vapor measurements to remove this effect -- can use multiple acquisitions to reduce this effect

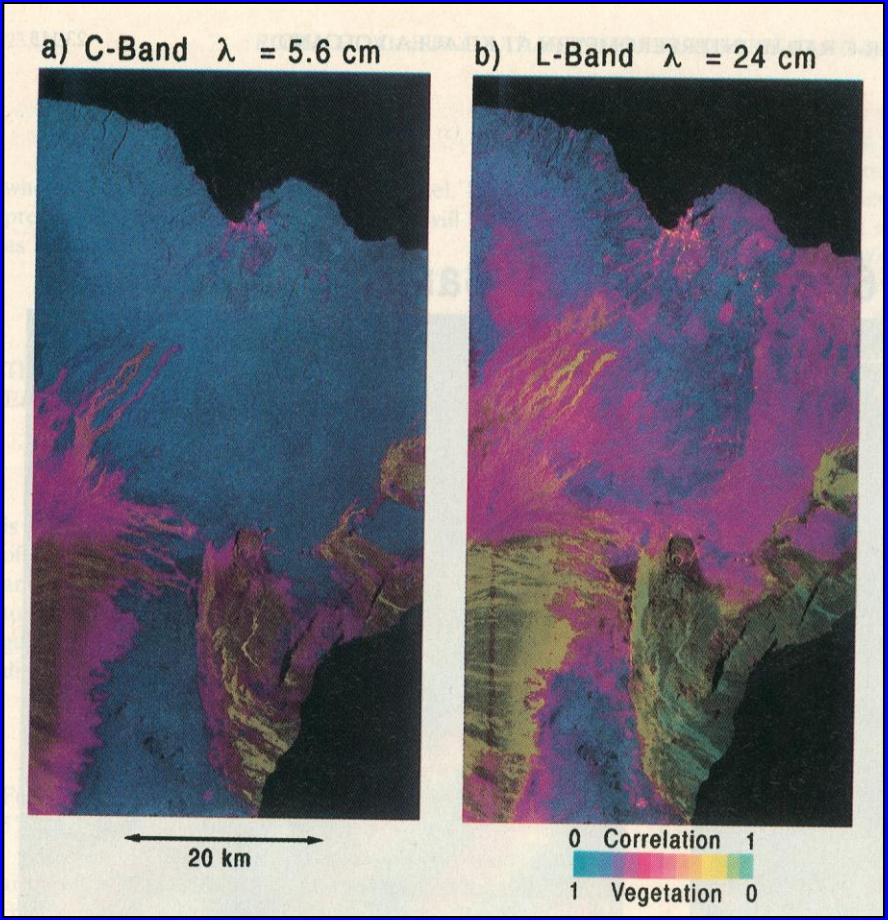
4) Wavelength: Prefer longer wavelength to penetrate vegetation



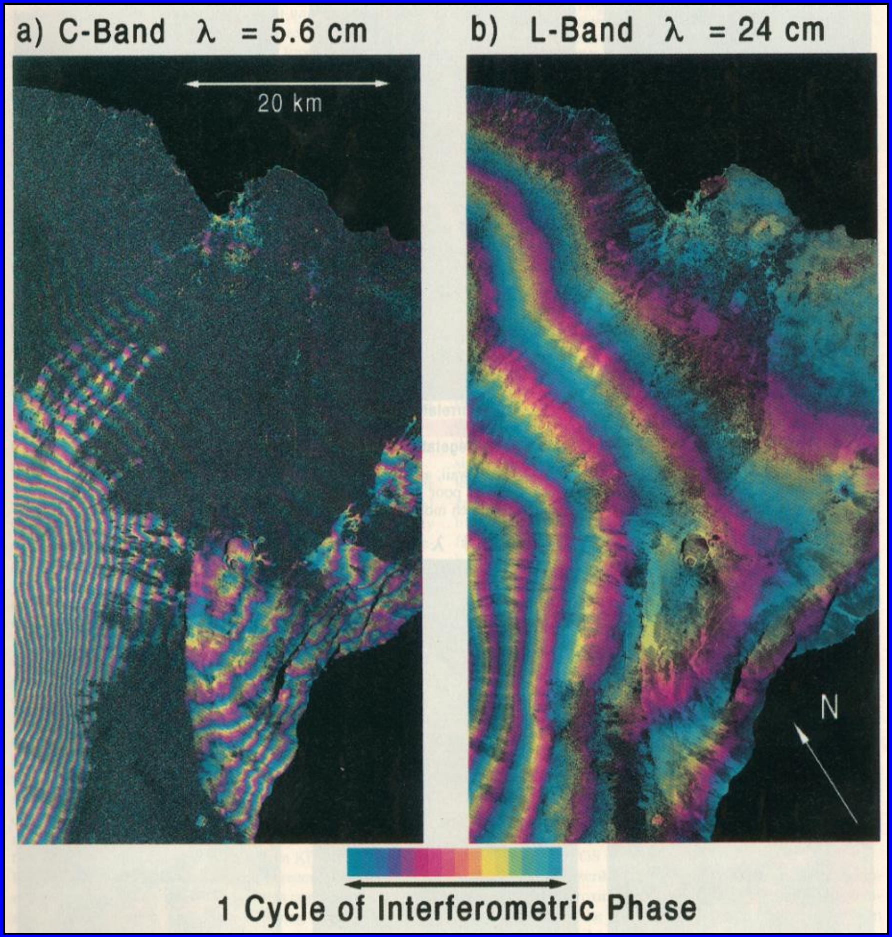
Lee waves east of the Andean Western Cordillera

Comparing radar wavelengths at Hawaii

Correlation maps



Interferograms

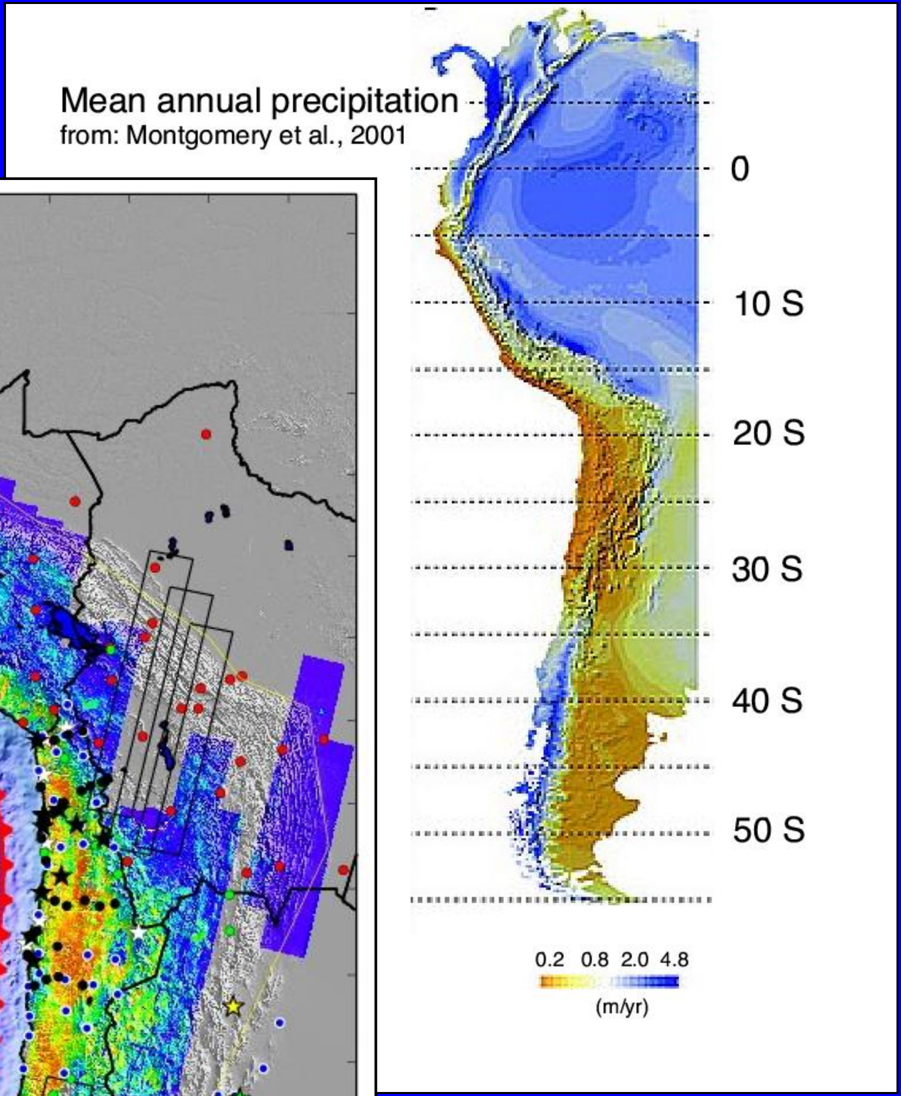


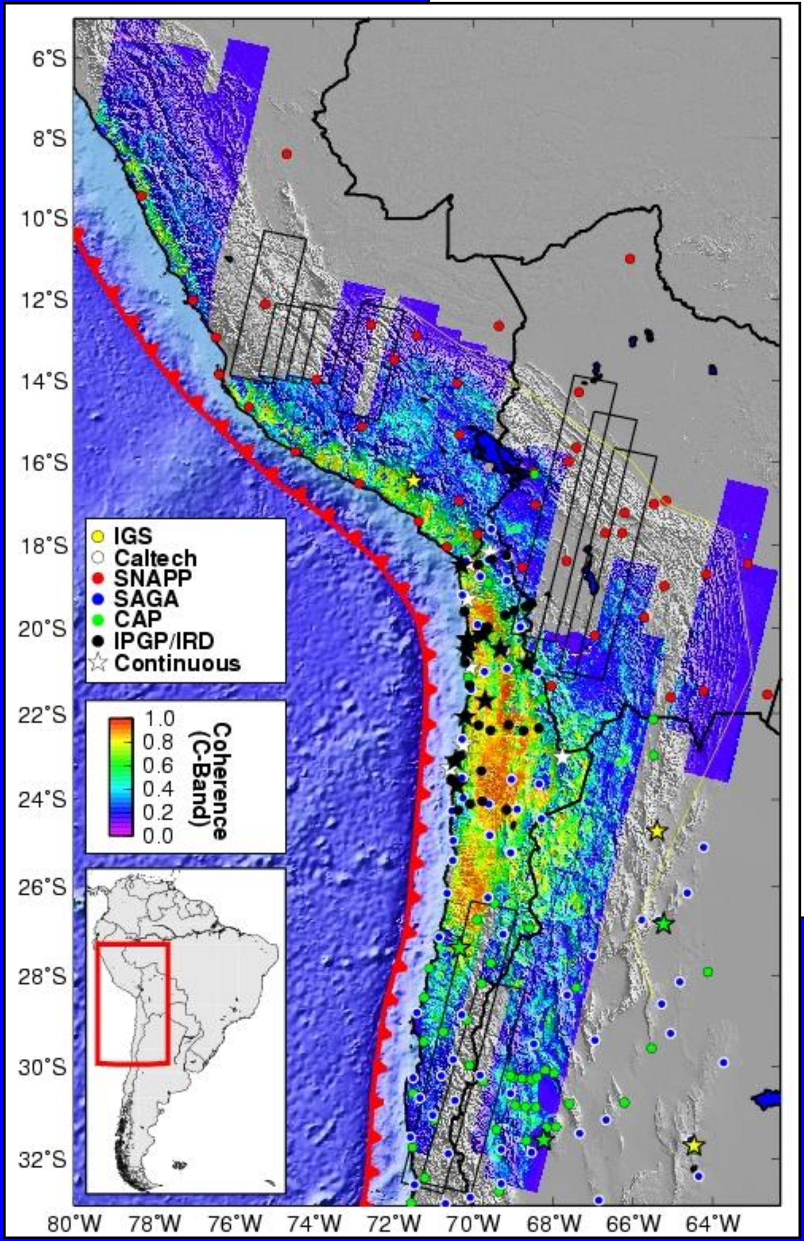
All images from Space Shuttle (SIR-C) span Apr-Oct

From: Rosen et al., 1996

C-band coherence

- High coherence in dry areas (near coast)
- North-south variations also related to regional climate

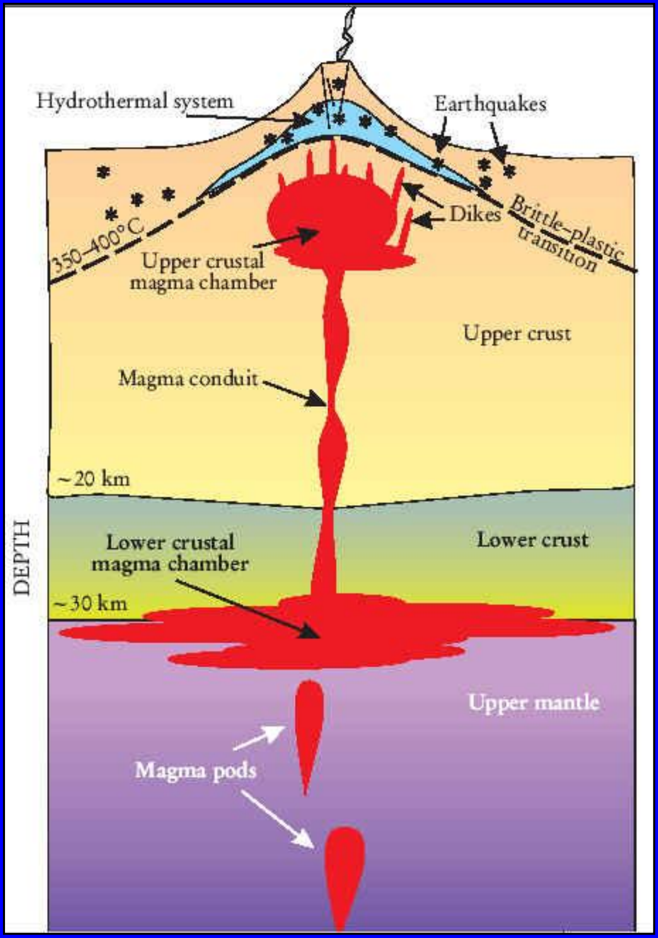




Uncovering the hidden lives of volcanic arcs

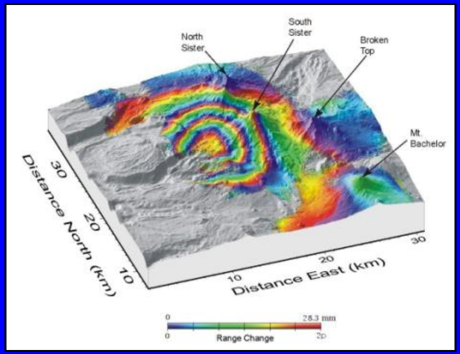
- A few volcanoes are obviously active

1999 Eruption of
Kliuchevskoi volcano,
Kamchatka
Photo by: A. Logan



From: Hill et al., 2002

- … But some appear dormant and aren't



South Sister, Oregon
From: Wicks et al., 2001

- Surface deformation exposes subsurface magma movements

Why expose volcanoes' hidden lives?

1) Hazard:
Understanding eruptive threat

Can surface deformation be used to predict eruptions?

- Only rarely – need to establish case history at each volcano

Airplane routes,
From: USGS

Gain a more complete picture of volcano life cycle
What really happens during long repose times?

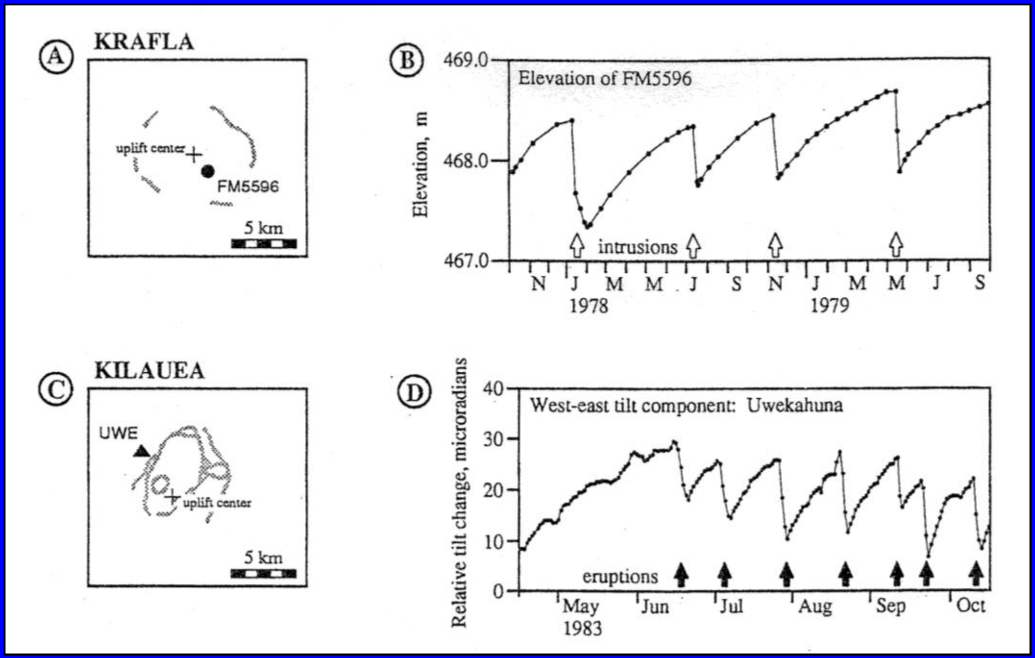
2) What are the rates of magmatism in different areas?

Separate rate of intrusion and extrusion:
Example: Hawaii and Iceland. Same output, but maybe different inputs

Why do rates of magmatism vary within arcs and between arcs?

Volcano personalities

- Different volcanoes have different behaviors
  - Deformation and no eruption: e.g. Long Valley caldera
  - Eruption and no deformation: e.g. Lascar, Chile (this study)
  - Deformation and eruption:
    - Pattern: pre-eruptive inflation, co-eruptive deflation, post-eruptive inflation



Dvorak and Dzurisin, 1997

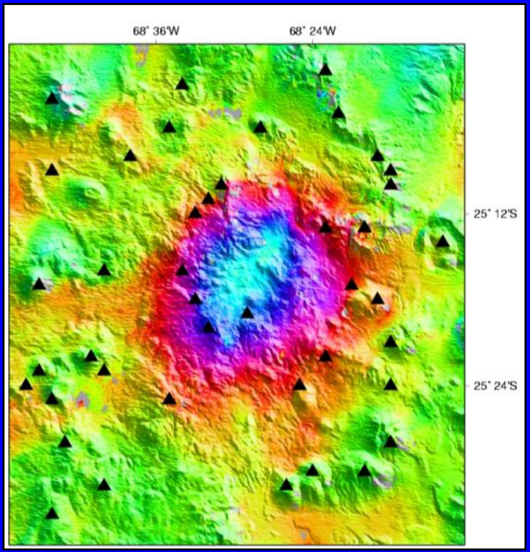
From: J. D. Griggs

Lazufre: An intrusion without a volcano?

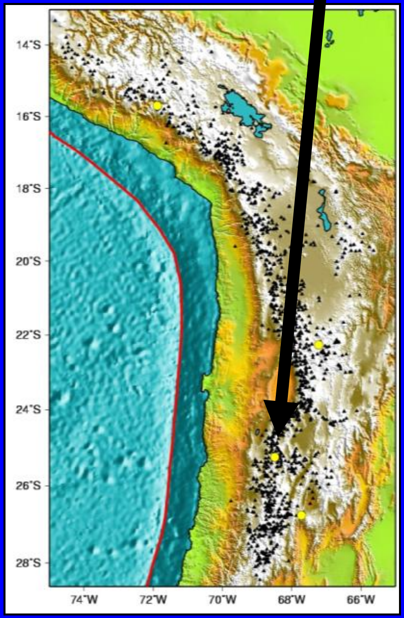
- Clear lava flows at Lastarria …

- … But nothing in between “Lazufre”

- Clear lava flows at Cordon del Azufre



Source location



Lastarria fumaroles in …

Photo by M. Simons

2002

Photo by J. Naranjo

Late 1980's

No fumaroles at Lazufre

Photo by M. Simons

Lastarria: fumaroles and sulfur lava flows

Pahoehoe-like flow features in sulfur lava flows from mobilization of fumarolic deposits (Naranjo, 1987)

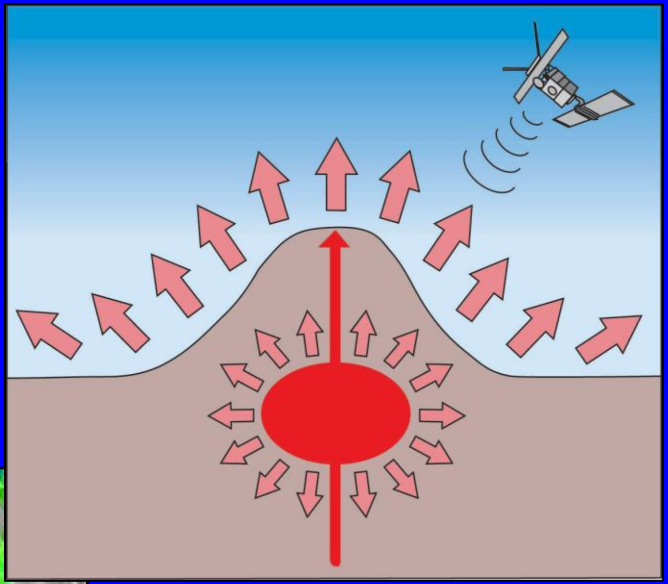
Photos by M. Simons

Visualizing volcano deformation

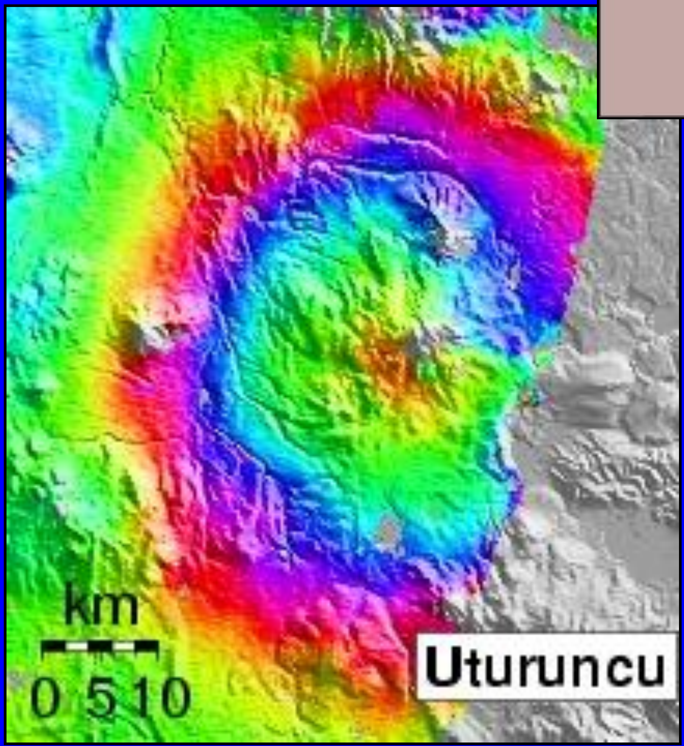
What we would like to know:

-How deep is the magma chamber?

-How much magma might be moving?
(Assuming that in is magma movement and not just a pressure/phase change)



Cross-section

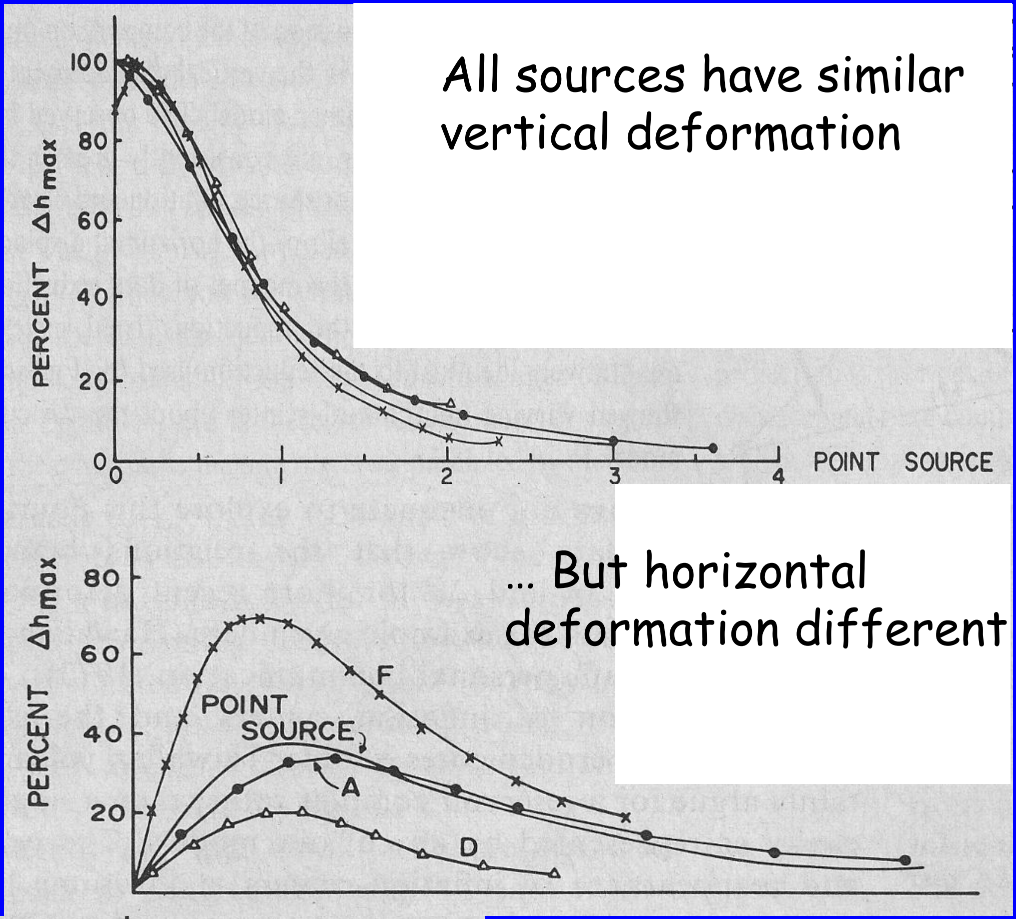


Map view

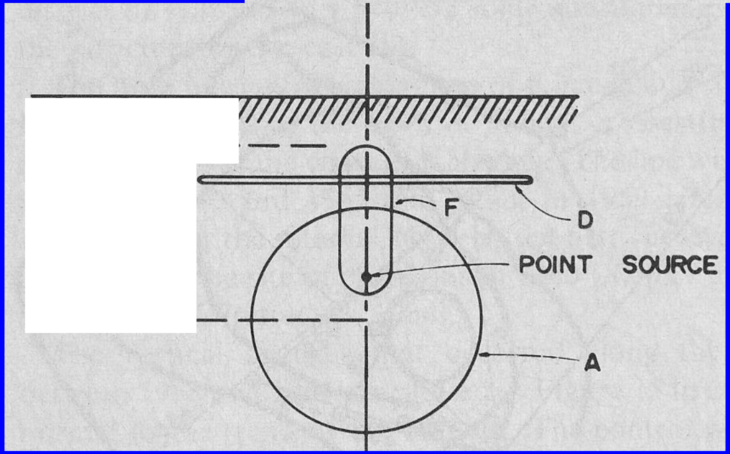
Vary shape of “magma chamber”

•Data are subject to multiple interpretations!

•Bottom line:
With only one component of deformation: all shapes can fit data, but have different inferred depths and volume change

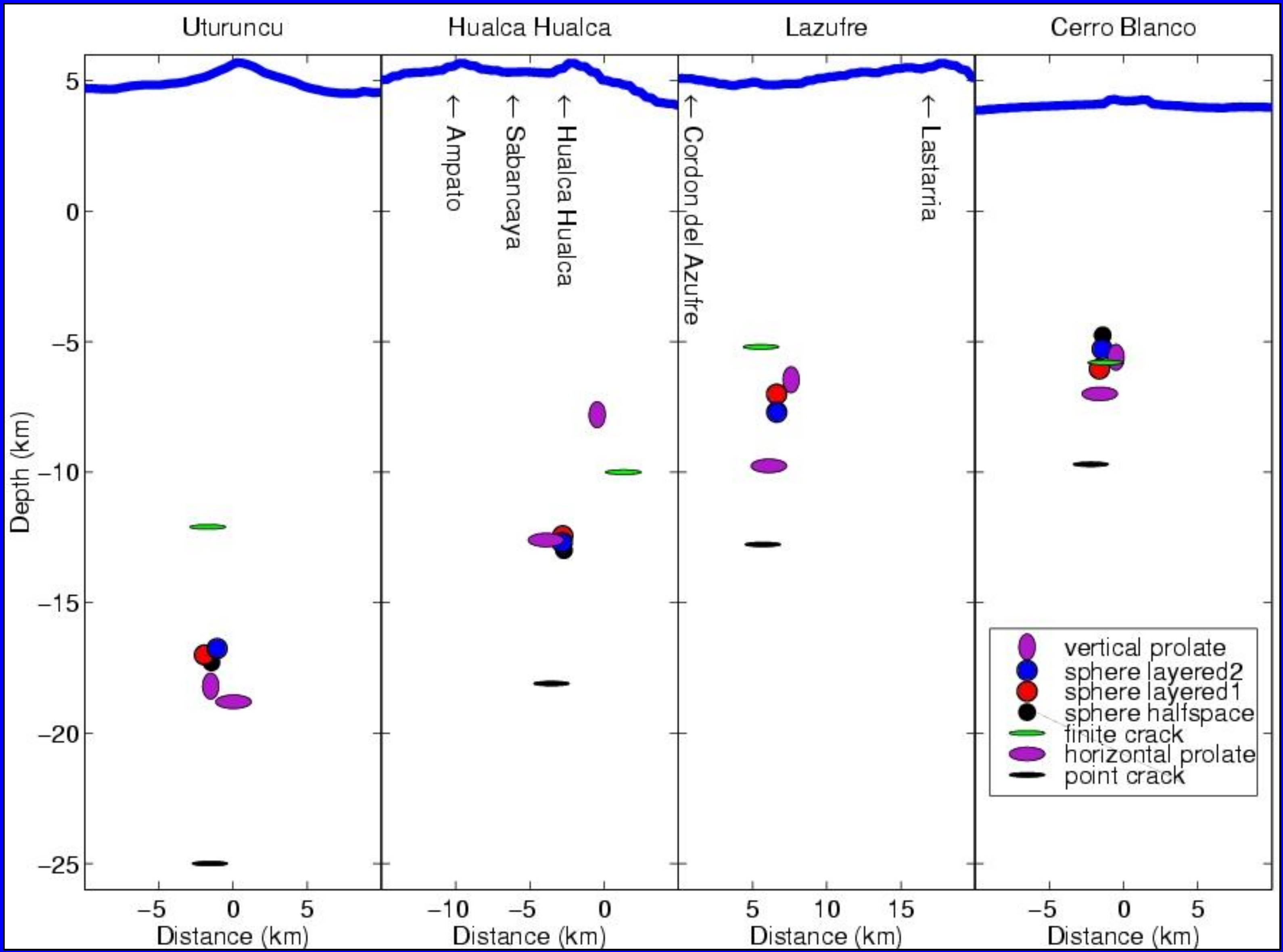


Consider:
•Spherical point source
•Prolate ellipsoid (football)
•Oblate ellipsoid (frisbee)
•Finite sphere



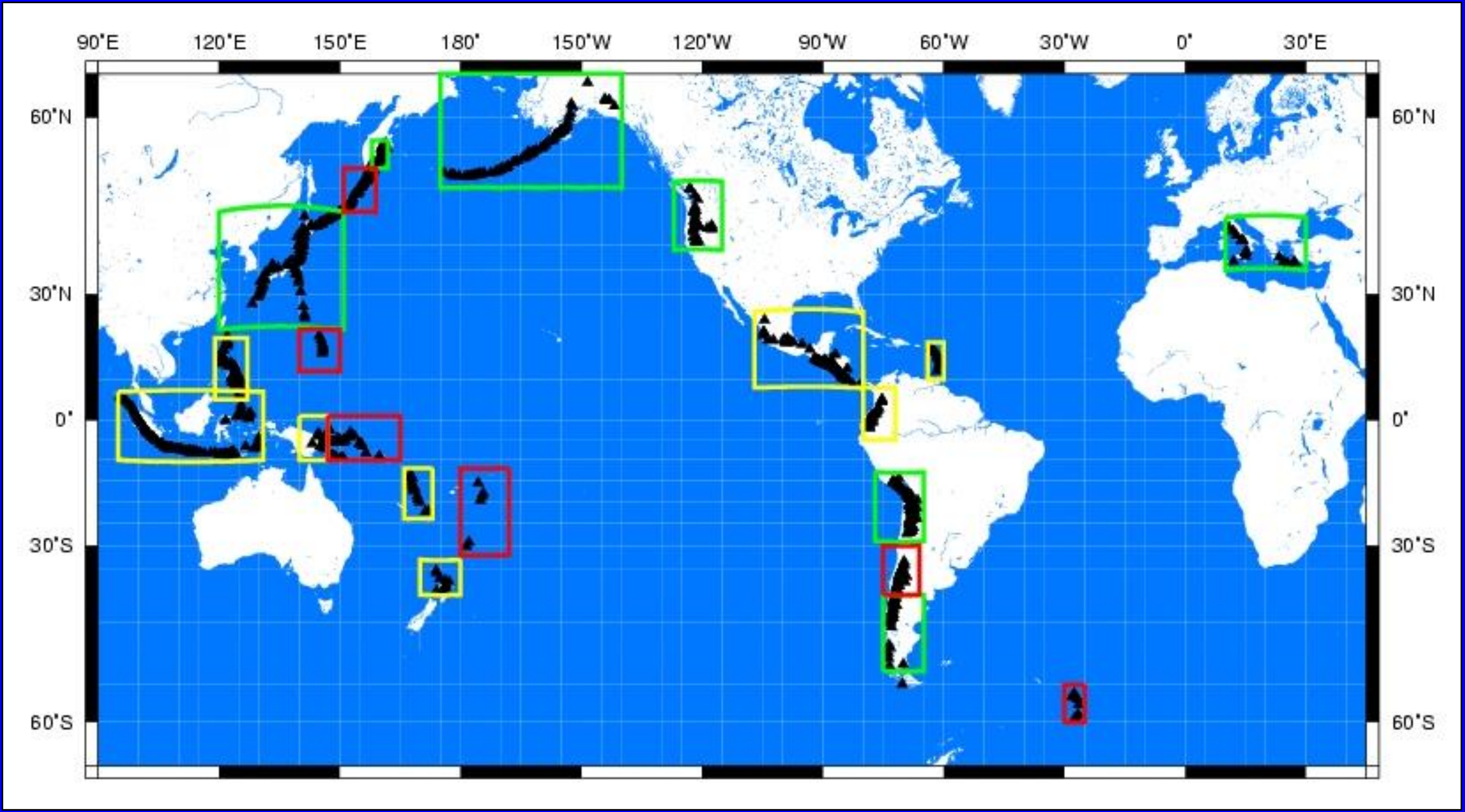
Dieterich & Decker, 1975

Effects of source geometry on inferred depth



Pritchard and Simons, *G*-cubed, 2004

Monitoring all the volcanic arcs in the world



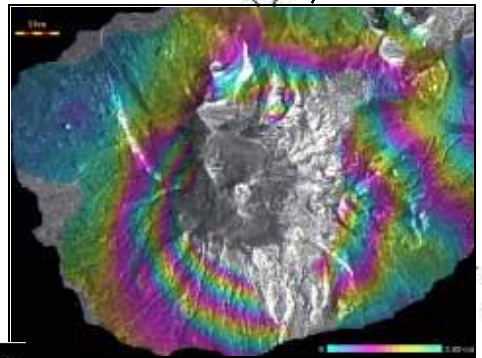
Can we survey this arc?

- Green: Yes, deformation measured
- Yellow: Maybe, data is available
- Red: Not yet, need more data

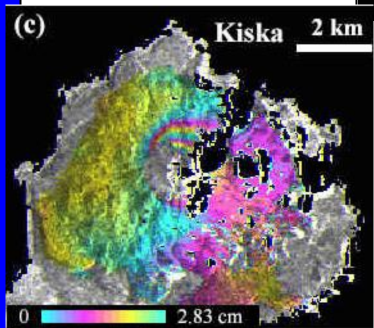
Pritchard and Simons, *GSA Today*, 2004

Alaska/Aleutians

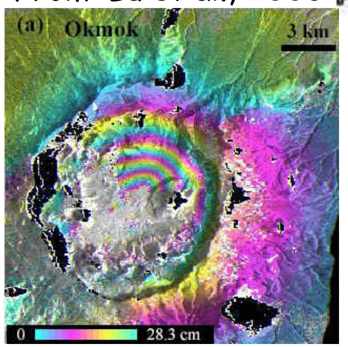
From: Lu et al., 2000

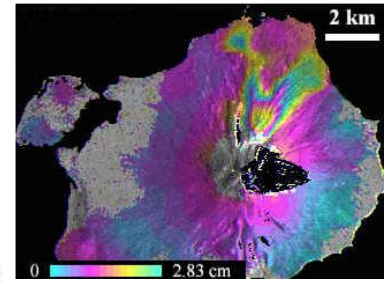


From: Lu et al., 2003



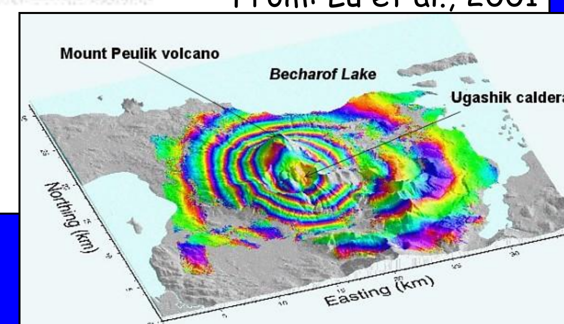
From: Lu et al., 2003

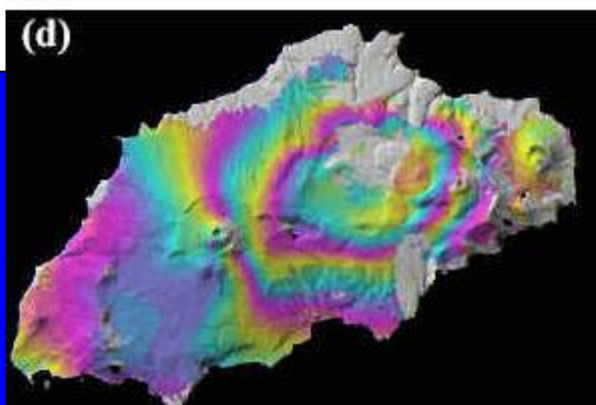




From: Lu et al., 2003

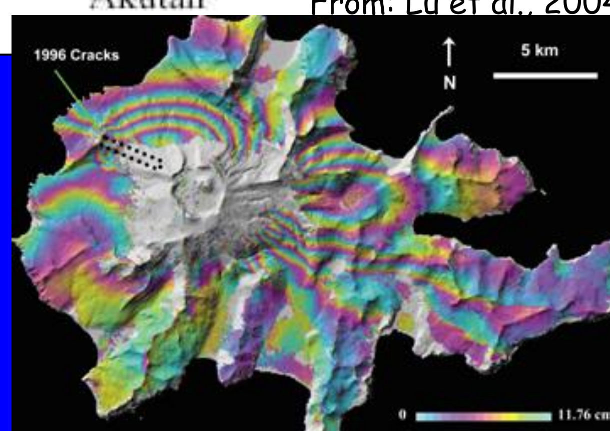
From: Lu et al., 2001





From: Lu et al., 2003

From: Lu et al., 2004



- 9 deforming volcanoes
- Subsiding pyroclastic flow
- Eruptions with no deformation
- Studies are ongoing

Global Synthesis: What have we learned from InSAR?

- Volcano life cycle:
  - Magmatic intrusions w/o eruption might be frequent and short-lived
  - These intrusions are mostly aseismic
  - Implications for hazard

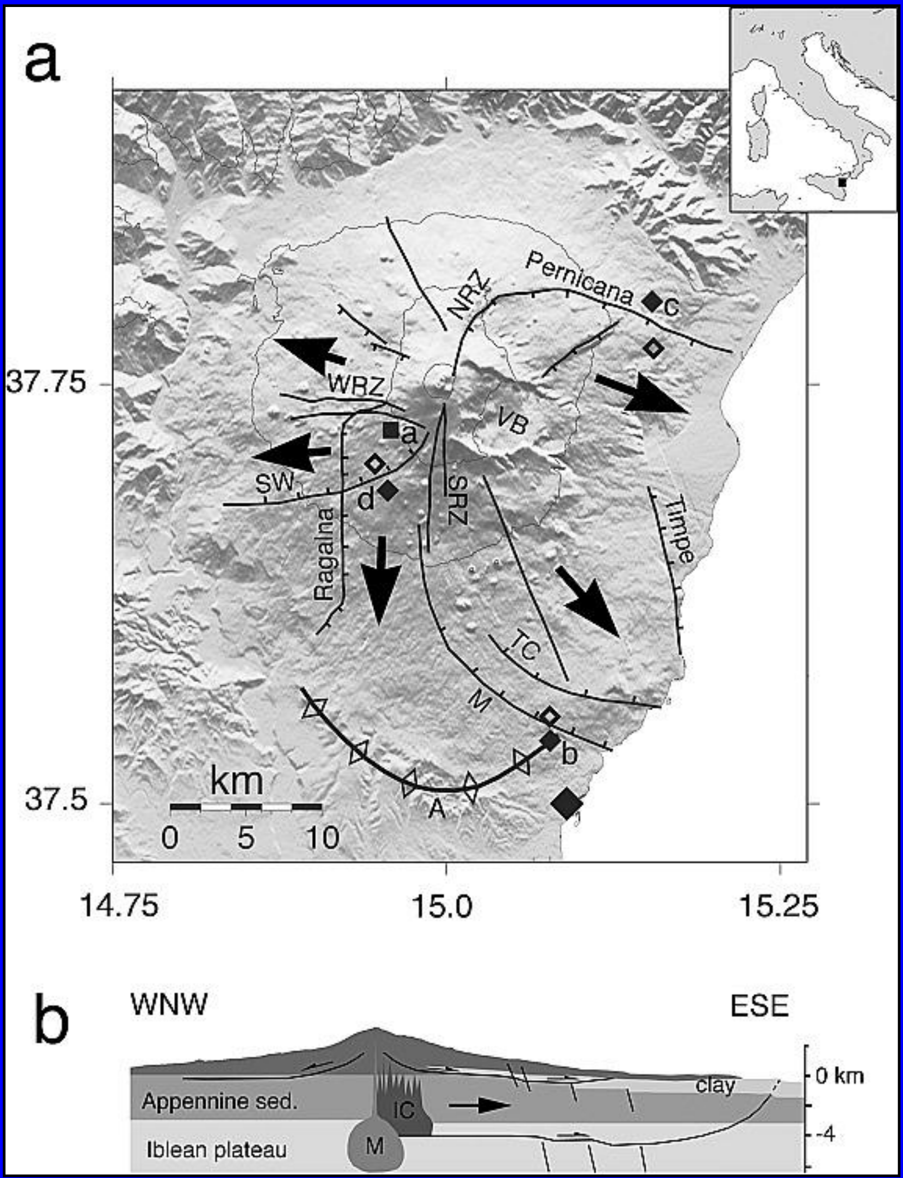
- Magma plumbing
  - Image spatial complexity of deformation (or lack of complexity)

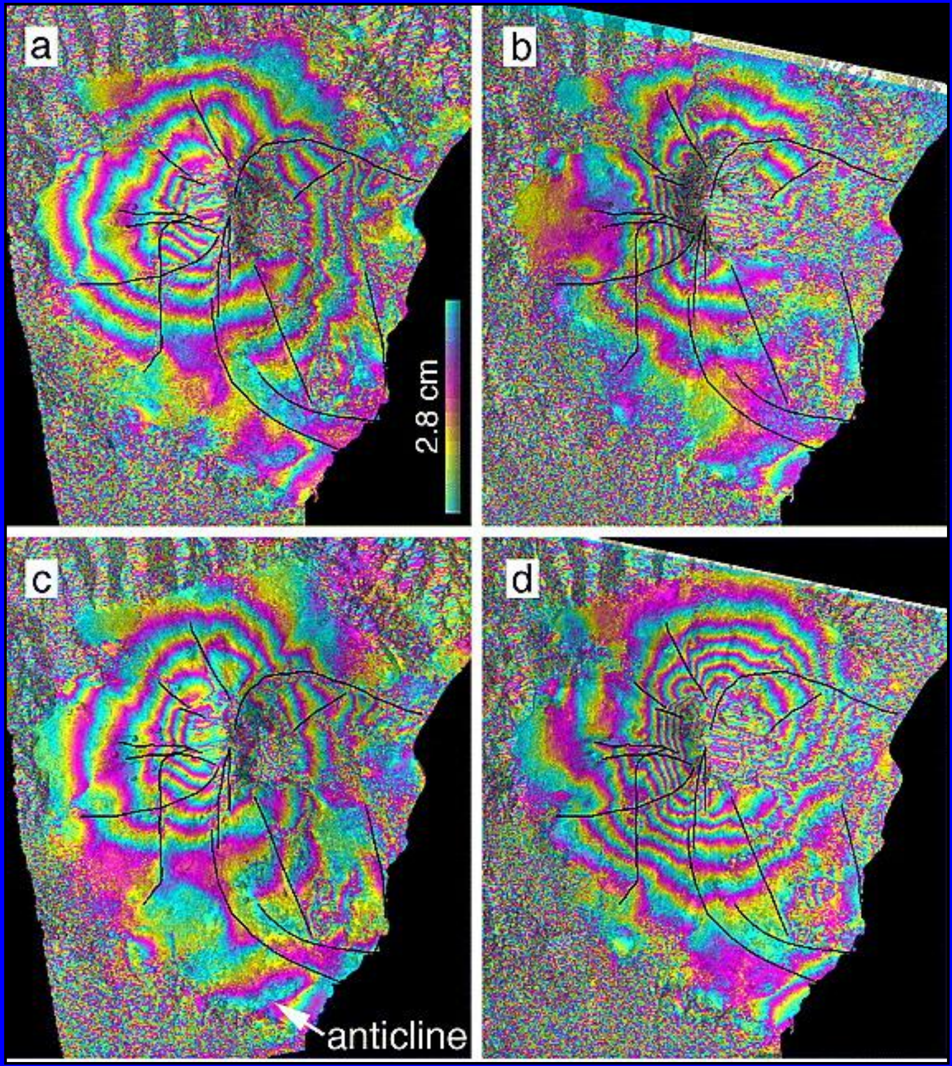
- Non-magmatic deformation
  - Lava flow and pyroclastic flow subsidence
  - Geothermal areas

- Eruptions with no deformation observed
  - Maybe chambers are deep
  - Maybe chambers quickly refill

- Different rates of activity in different arcs

Magma inflation & sector collapse: Mt. Etna





Above: Interferograms spanning 1993-1999 with faults from left; From: Lundgren et al., 2004

Inter-arc comparison

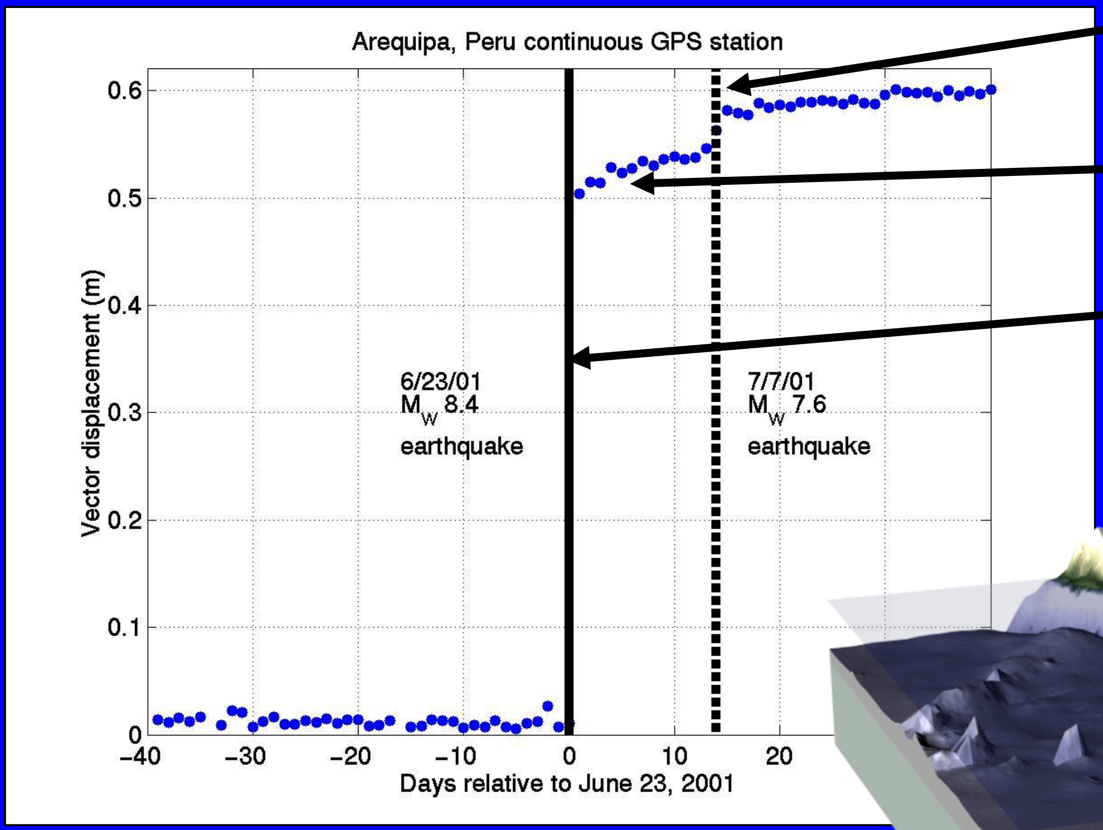
Arc	# volcanoes	# with historic eruptions	# with eruptions this decade	# of volcanoes actively deforming
C. Andes	65	17	4	3-4
Alaska/ Aleutians	80	46	17	8[1]

- Although Alaska/Aleutian arc seems more active, geologic averaged magma flux about the same (Reymer and Schubert, 1984)
- Central Andes different because of 70 km thick crust or magma composition?
- Or amount of sediment subducted?
- Or type of lava (basalt vs. andesite/dacite)?
- No single global explanation for the inter-arc variation in magma flux (Simkin and Siebert, 1984)

[1]Based on published work of Lu et al. 1997-2002

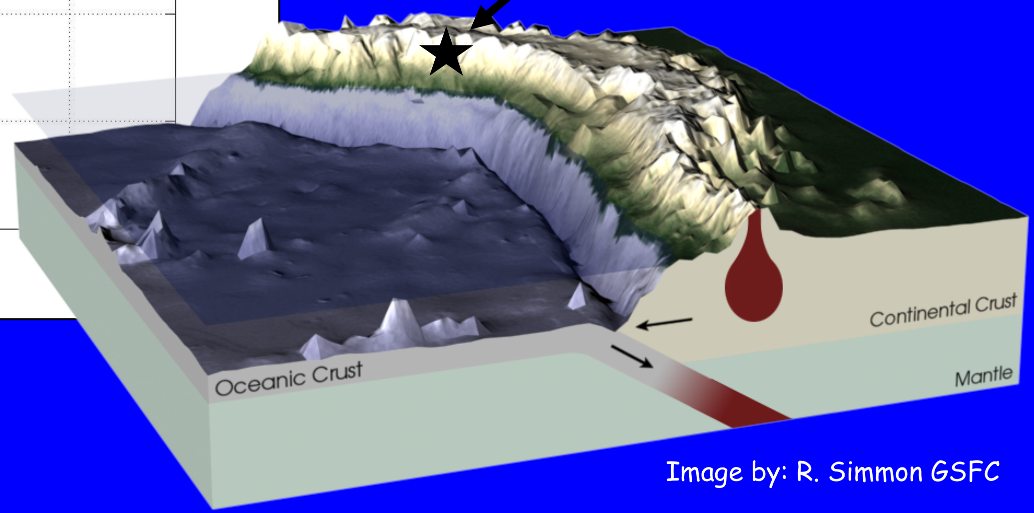
Deformation in Arequipa, Peru

- Continuous GPS station measures three types of deformation



- Large aftershock
- Aseismic slip
- Large earthquake

Arequipa: 100 km to coast



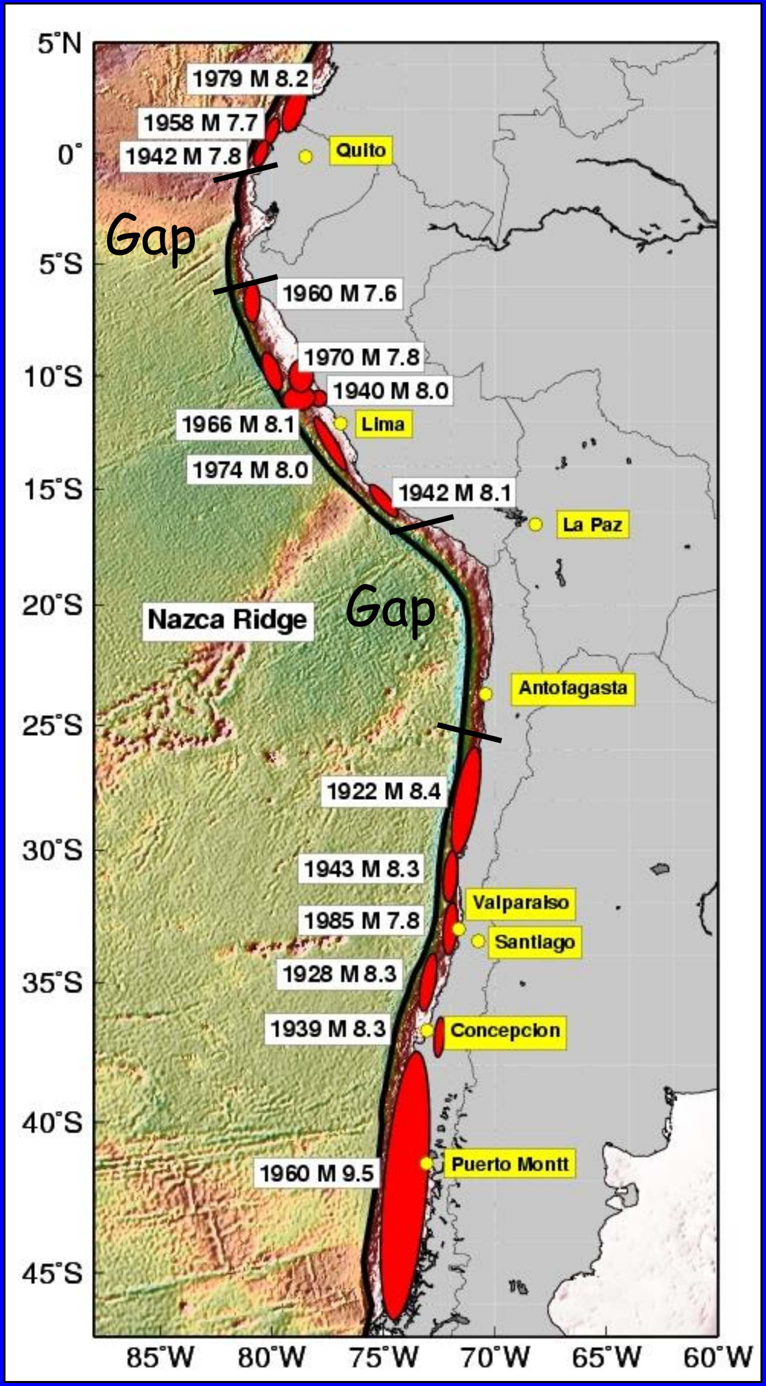
Data processed by: SOPAC

Image by: R. Simmon GSFC

- Where do these slip events occur relative to one another?

Why care about location of fault slip?

- Sausages show "rupture areas" of past earthquakes
- Big picture hazard:
  - Based on past slip, where are slip gaps?
  - Gaps = places that might slip in future



Earthquakes 1900-1990

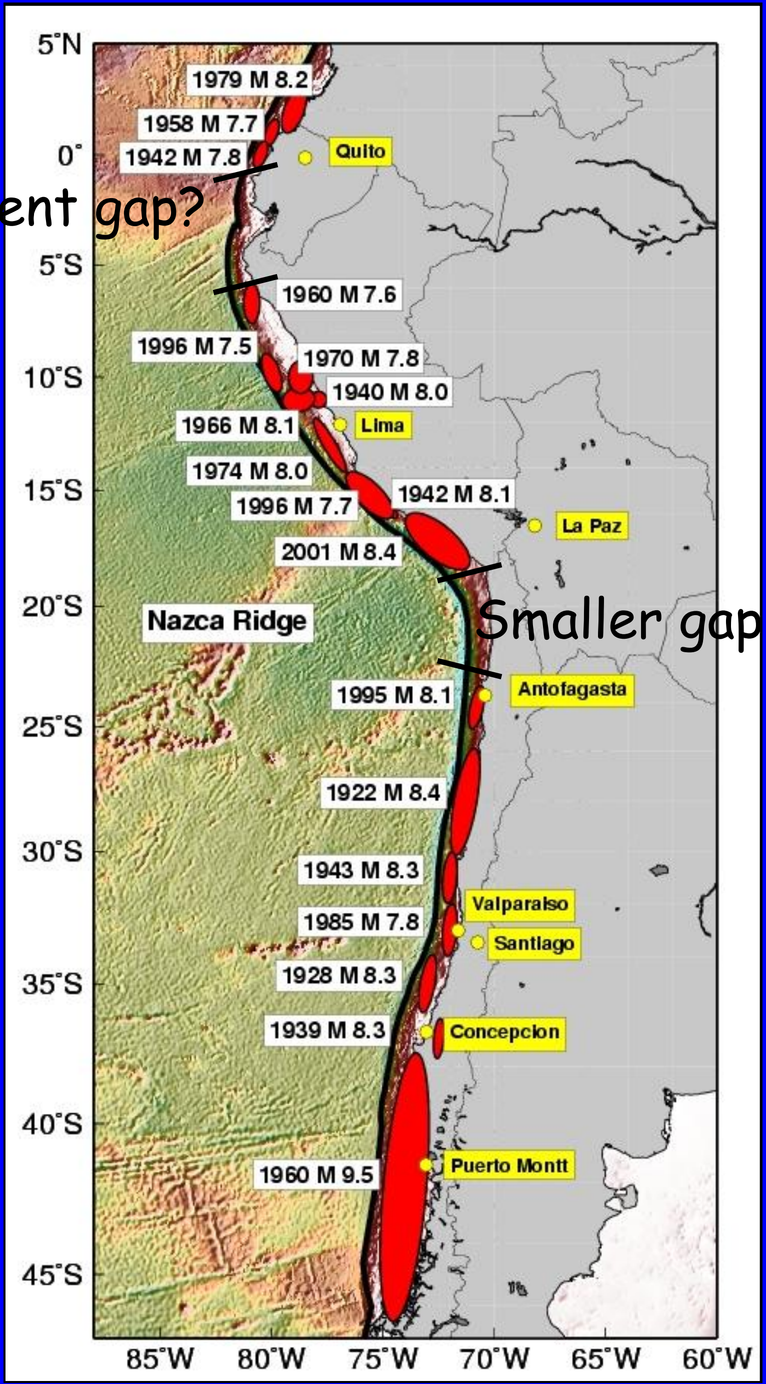
Why care about location of fault slip?

- How accurate are slip gap predictions?

- Complication:

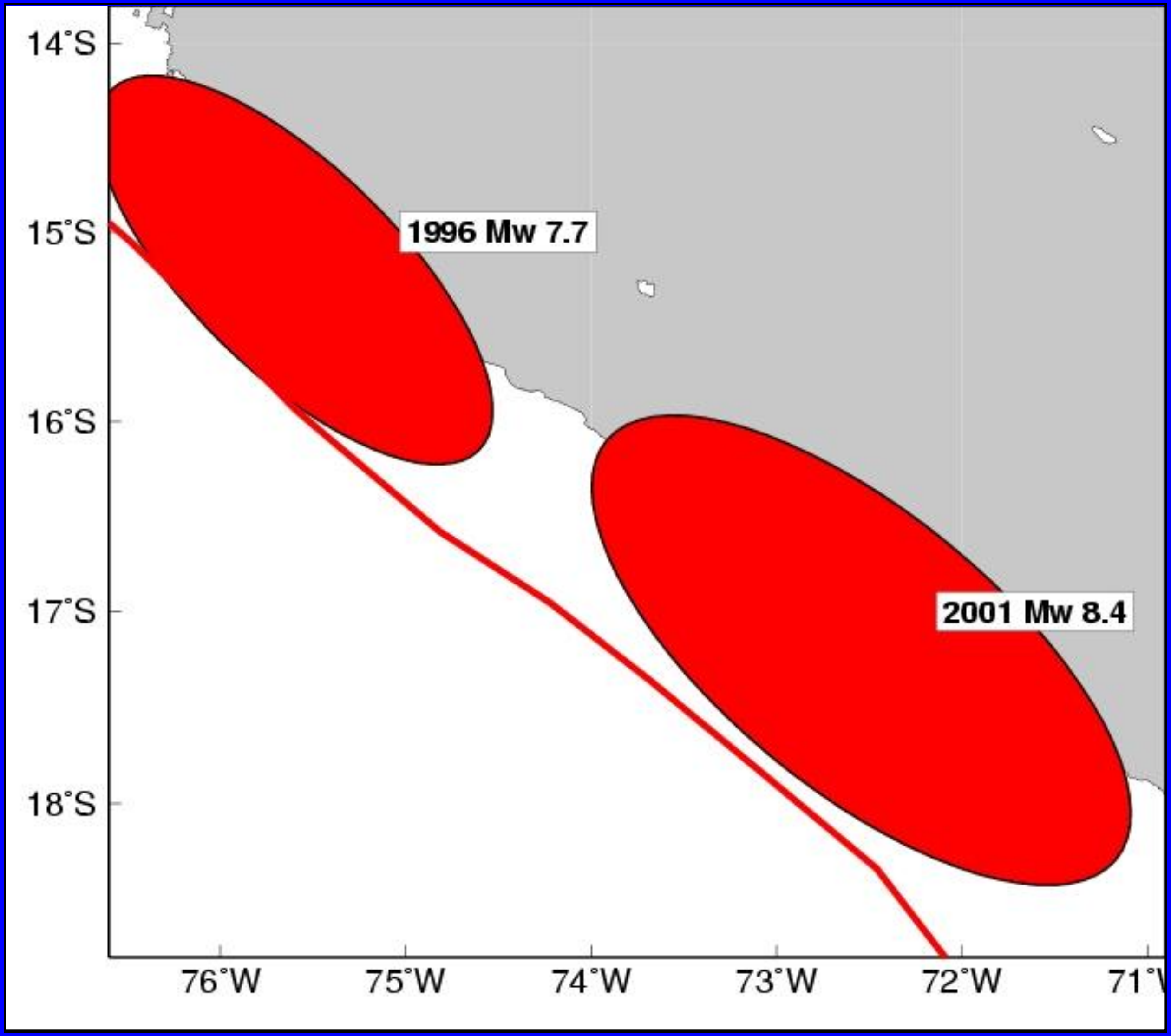
    - Some areas may not have large earthquakes

    - Different fault friction may lead to aseismic slip



Earthquakes 1900-2004

Further complications within sausages

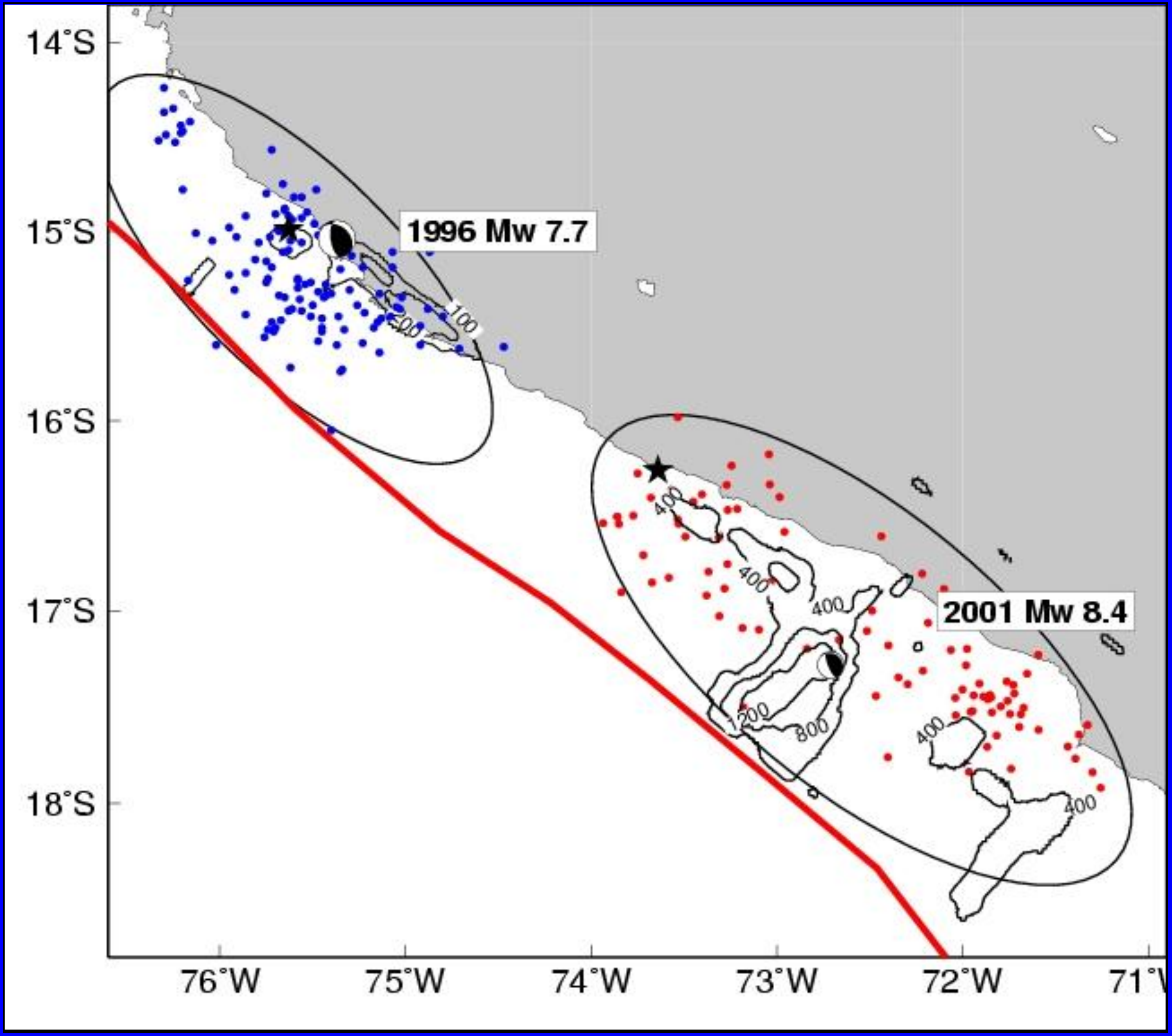


For historical earthquakes:

Define “rupture area” by aftershocks

But, slip is not uniform within “rupture area”

Details of slip distributions



For modern earthquakes:

More accurate maps of slip location

Shown as contours in meters

Aftershocks shown as dots

How is slip released outside of contours?

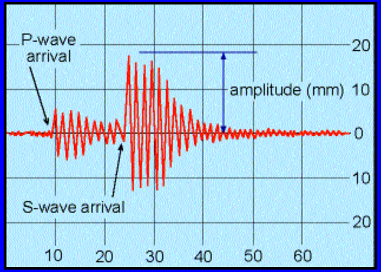
In future earthquakes?

In aseismic slip events?

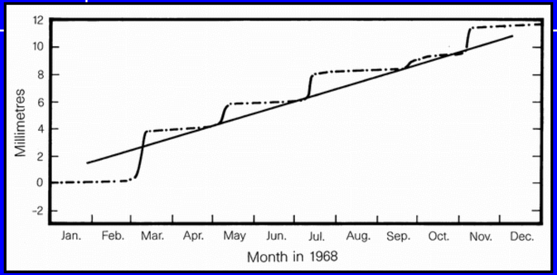
Slip maps from: Pritchard et al., JGR, 2007

Variety of "Earthquakes"

Type of Fault slip	Rupture speed	How to measure?	Example
Earthquake	2-4 km/s	Seismic waves/deformation	From: Steve Sheriff
"Tsunamigenic Earthquake"	~1 km/s Kikuchi and Kanamori, 1995	Abnormally large tsunami, Deformation/seismic waves	1992 Nicaragua Kikuchi and Kanamori, 1993
Slow earthquake	0.1-1 km/s McGuire et al., 1996	Special analysis of seismic data	1989 Macquarie Ridge Ihmle et al., 1993
Silent earthquake	~cm/sec e.g., McGuire and Segall, 2003	Deformation/ seismic tremor?	Episodic creep measured at surface of San Andreas From: Scholz, 1998



From: Steve Sheriff



Episodic creep measured at surface of San Andreas From: Scholz, 1998

Abstract:
Mapping fault slip

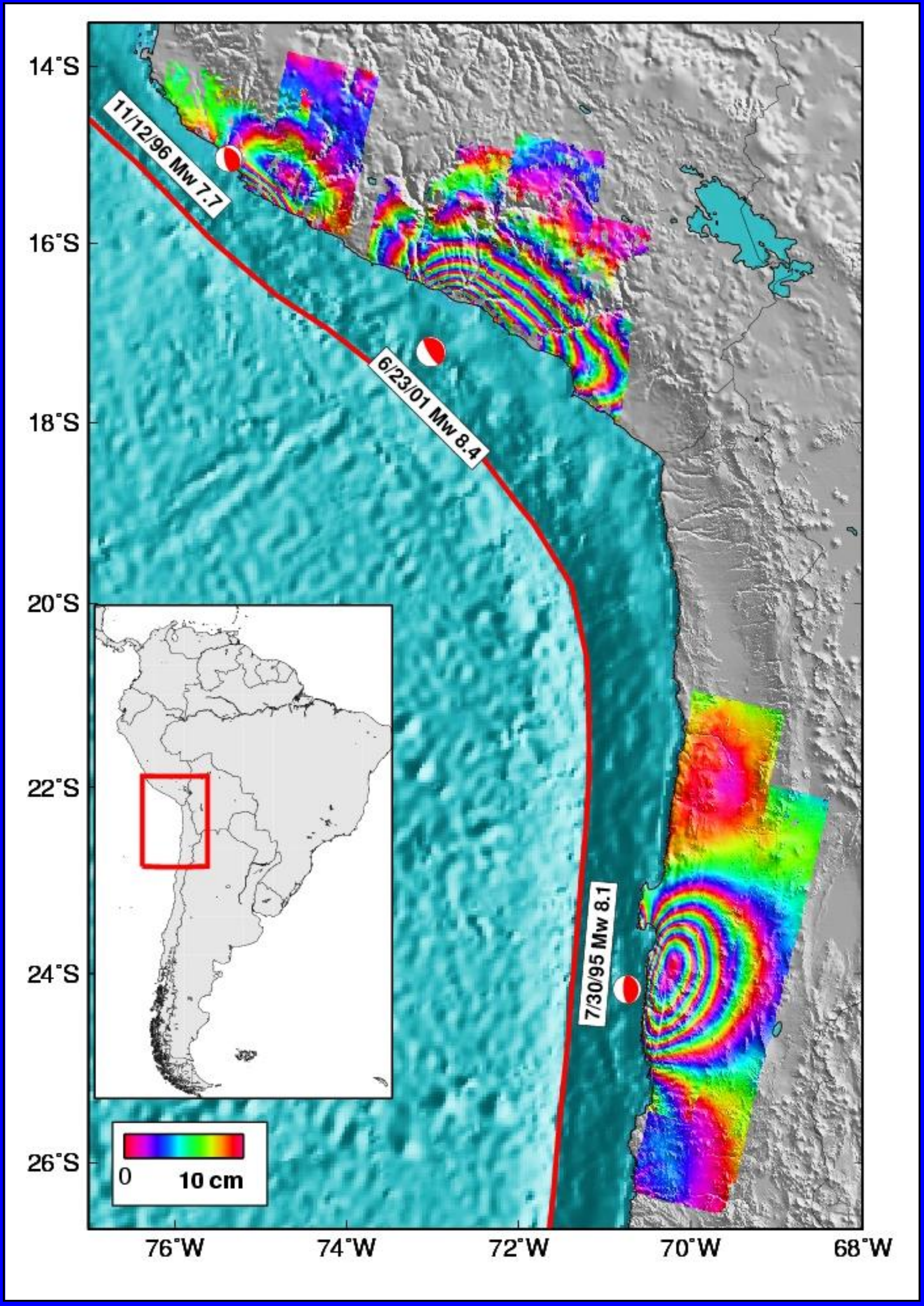
1) Goal: Locate seismic and aseismic slip on fault

2) Problem: No perfect dataset

3) Approach: Multiple types of data
   * Teleseismic
   * InSAR and GPS
   * Strong motion seismographs

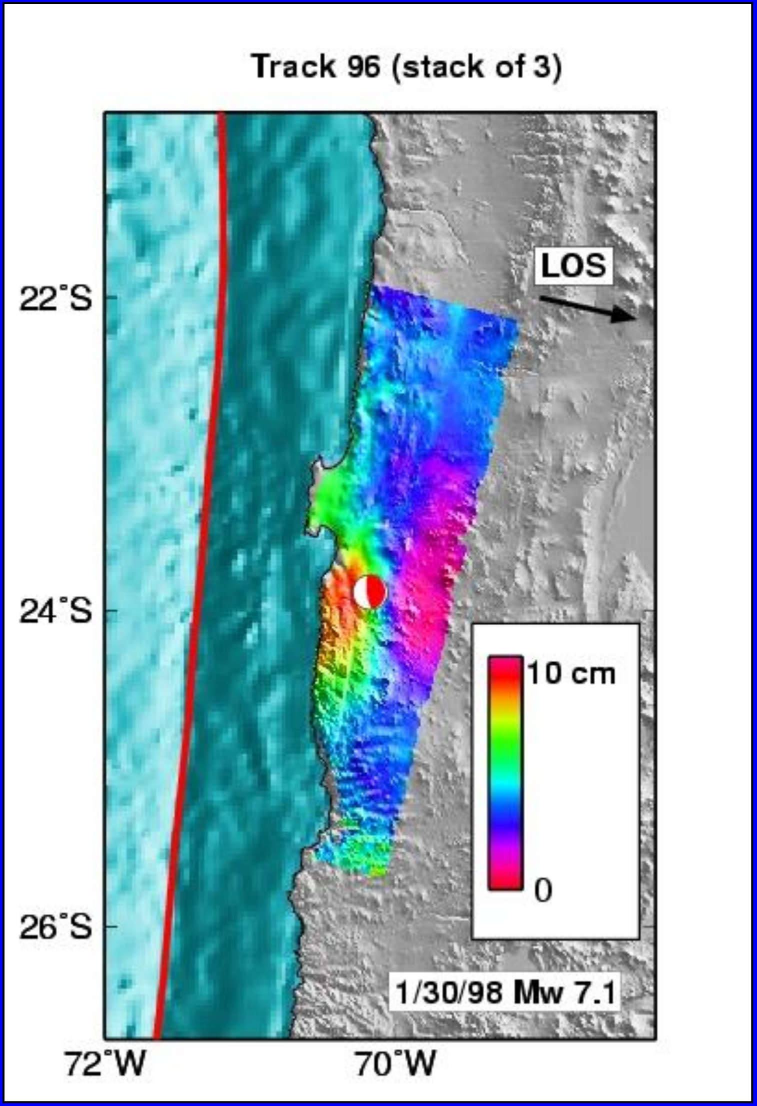
4) Compare 6 earthquakes

5) Evidence for a "silent earthquake"

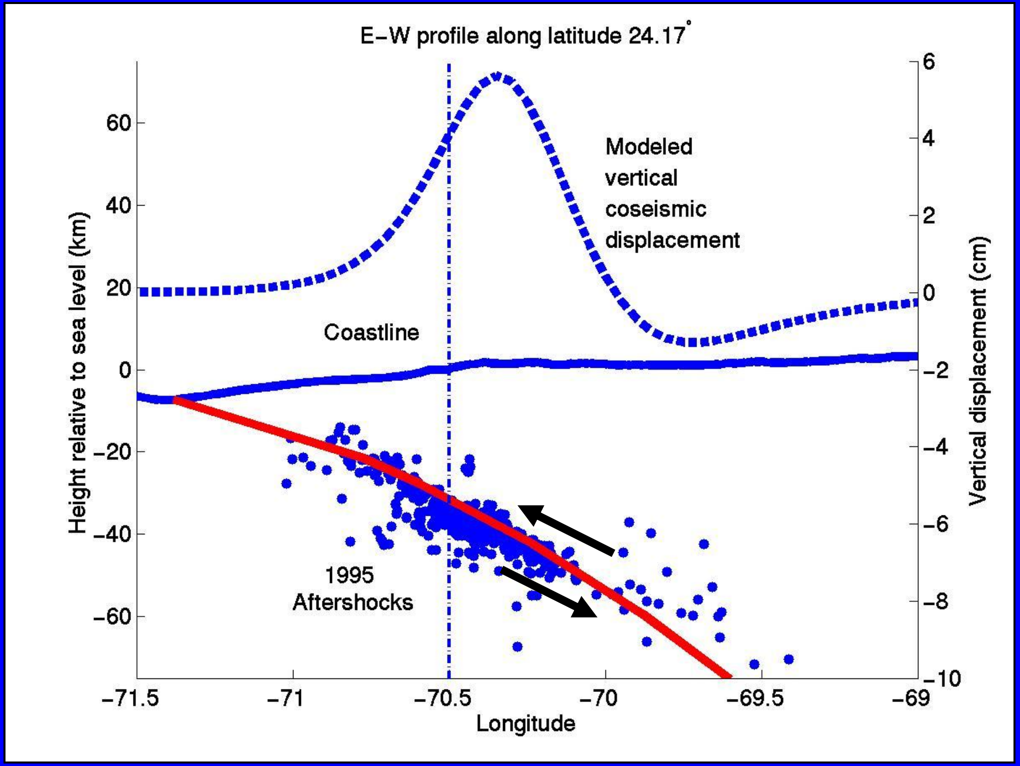


Example: 1998 Mw 7.1 earthquake

Map view

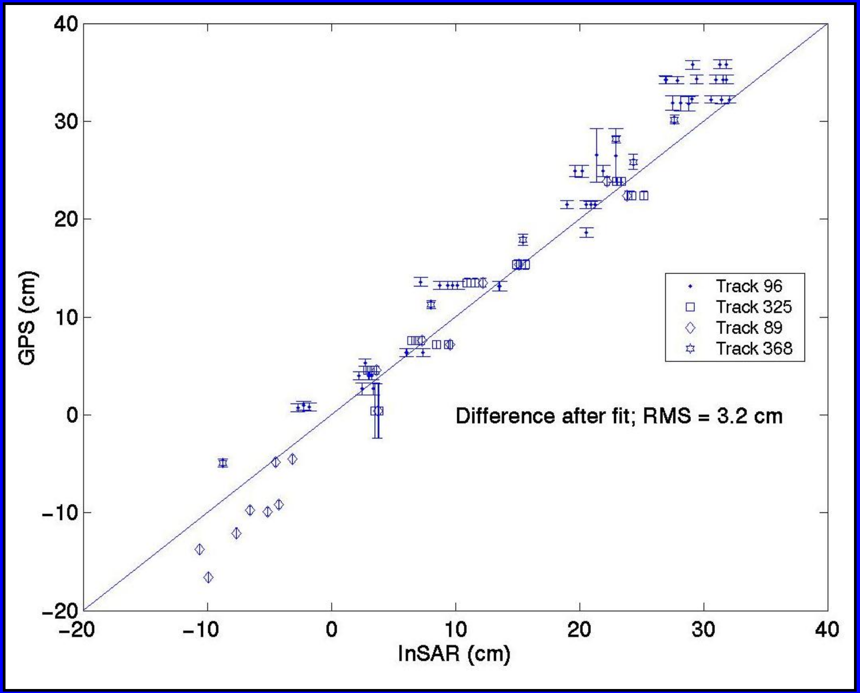


Cross-section

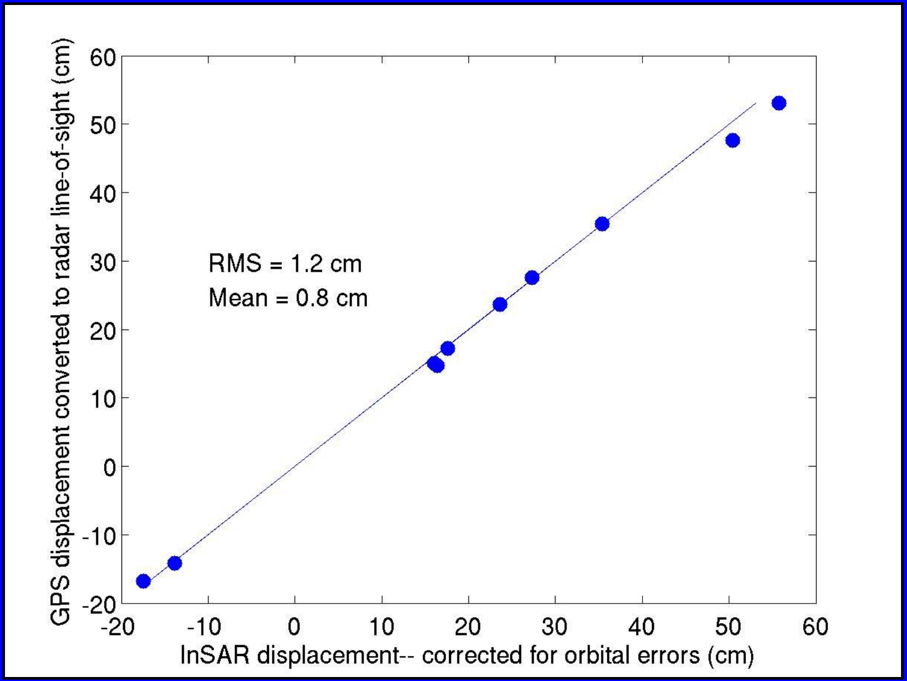


Comparing InSAR with ground truth

- Compare with GPS measurements in South America: RMS different few cm



90 InSAR and GPS points for Mw 8.1 Antofagasta, Chile earthquake. GPS stations first occupied in 1992, so GPS was immature (Pritchard et al., 2002)

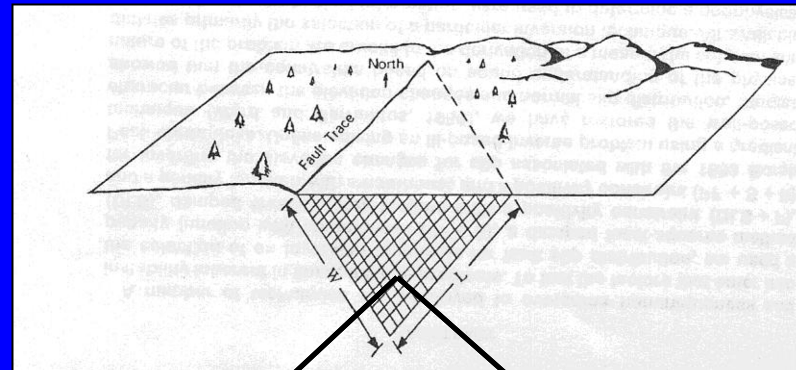


10 InSAR and GPS points for Mw 8.4 Arequipa, Peru earthquake. Only 4 different GPS stations included (Pritchard et al., 2007)

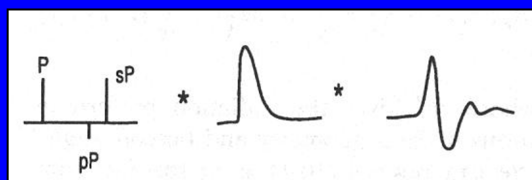
- For other earthquakes also agree to few cm: Landers, Northridge, Hector Mine (Massonnet et al., 1993, 1998; Zebker et al., 1994; Fialko et al., 2001; Jonsson et al., 2002)

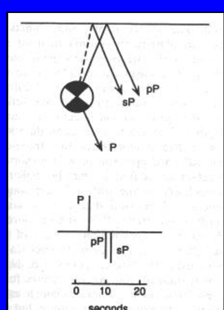
Reconstructing earthquake slip history

* Radiated seismic energy = information on evolution of rupture



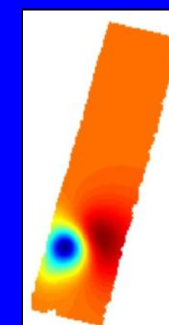
Step 1: Parameterize Fault



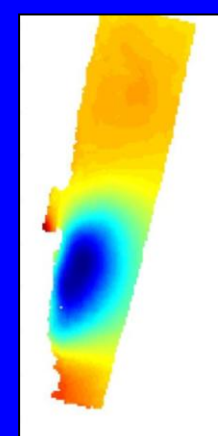


Step 2- Seismology: Calculate time series of radiated waves from each patch

Step 2- Geodesy: Calculate permanent displacement from each patch

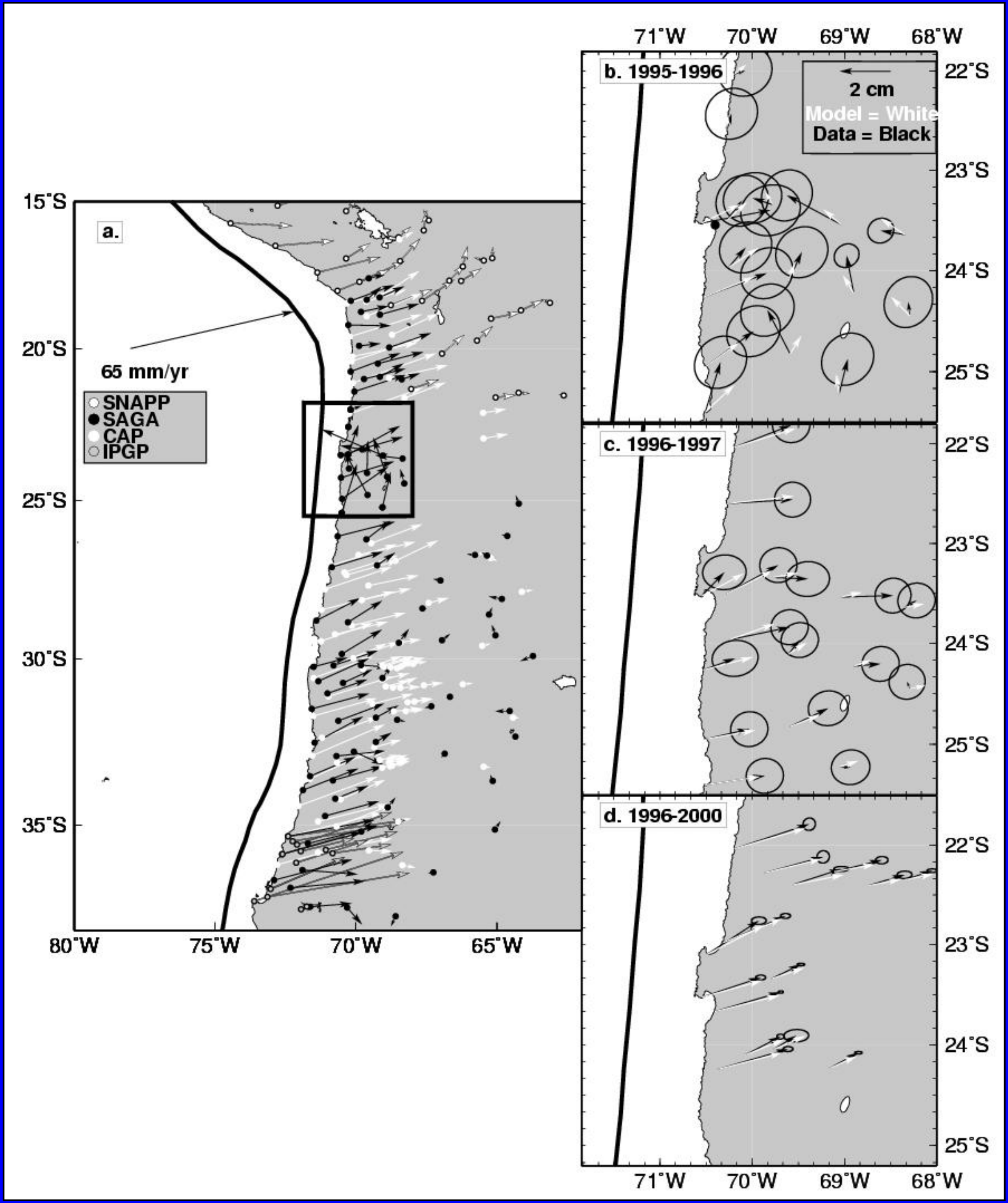


Step 3: Combine together to match data



Post-seismic deformation, 1995 Mw 8.1: GPS

- South America GPS stations:
- Most move NE: inter-seismic
- But near 1995 earthquake stations move west: post-seismic
- Temporal variations in post-seismic deformation:
- After-slip over by 1997

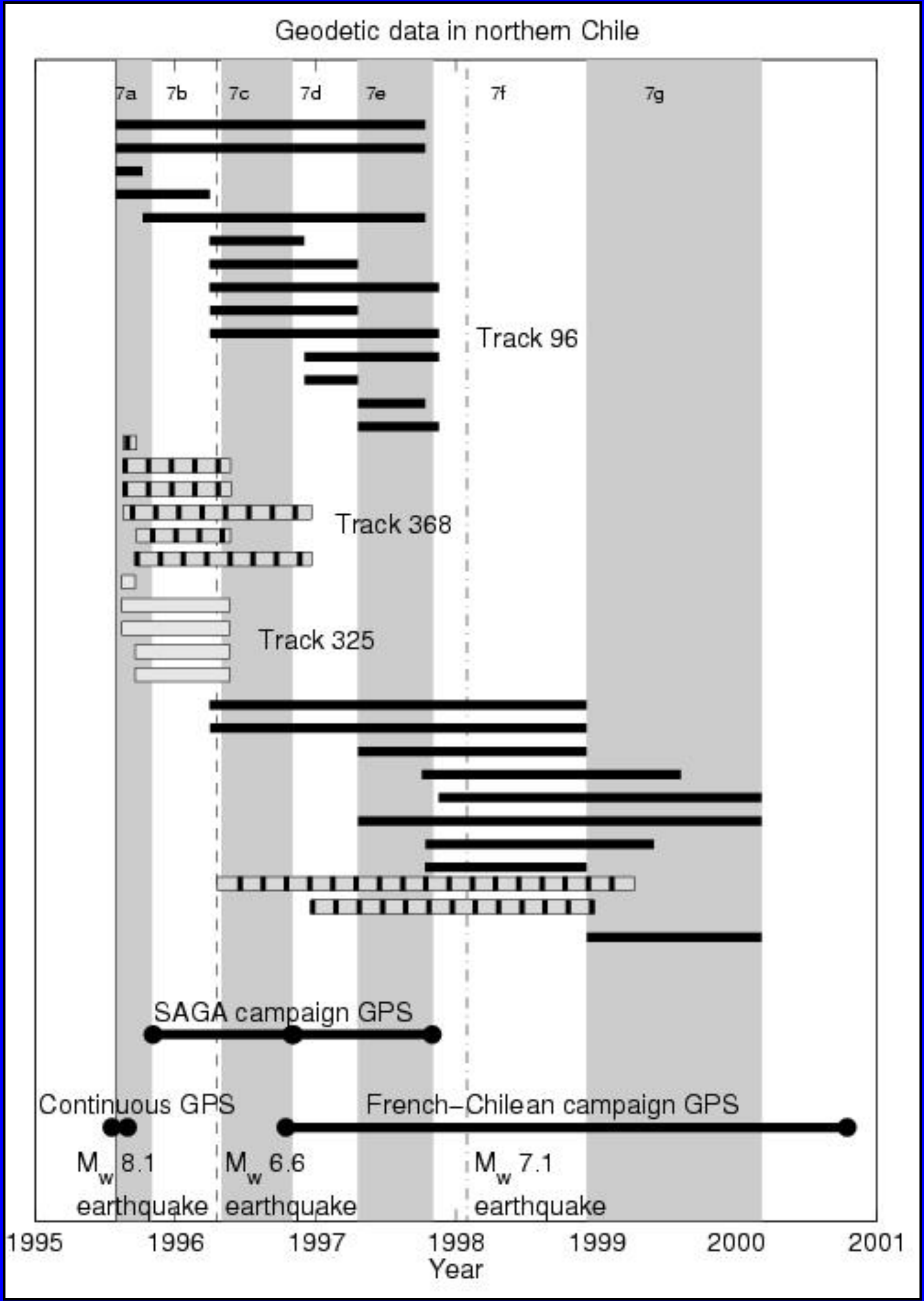


Data compiled by:
Pritchard and Simons, JGR, 2006

Sources:
Norabuena et al., 1998
Kendrick et al., 2001
Klotz et al., 2001
Ruegg et al., 2002
Khazaradaze and Klotz, 2003
Chlieh et al., 2004

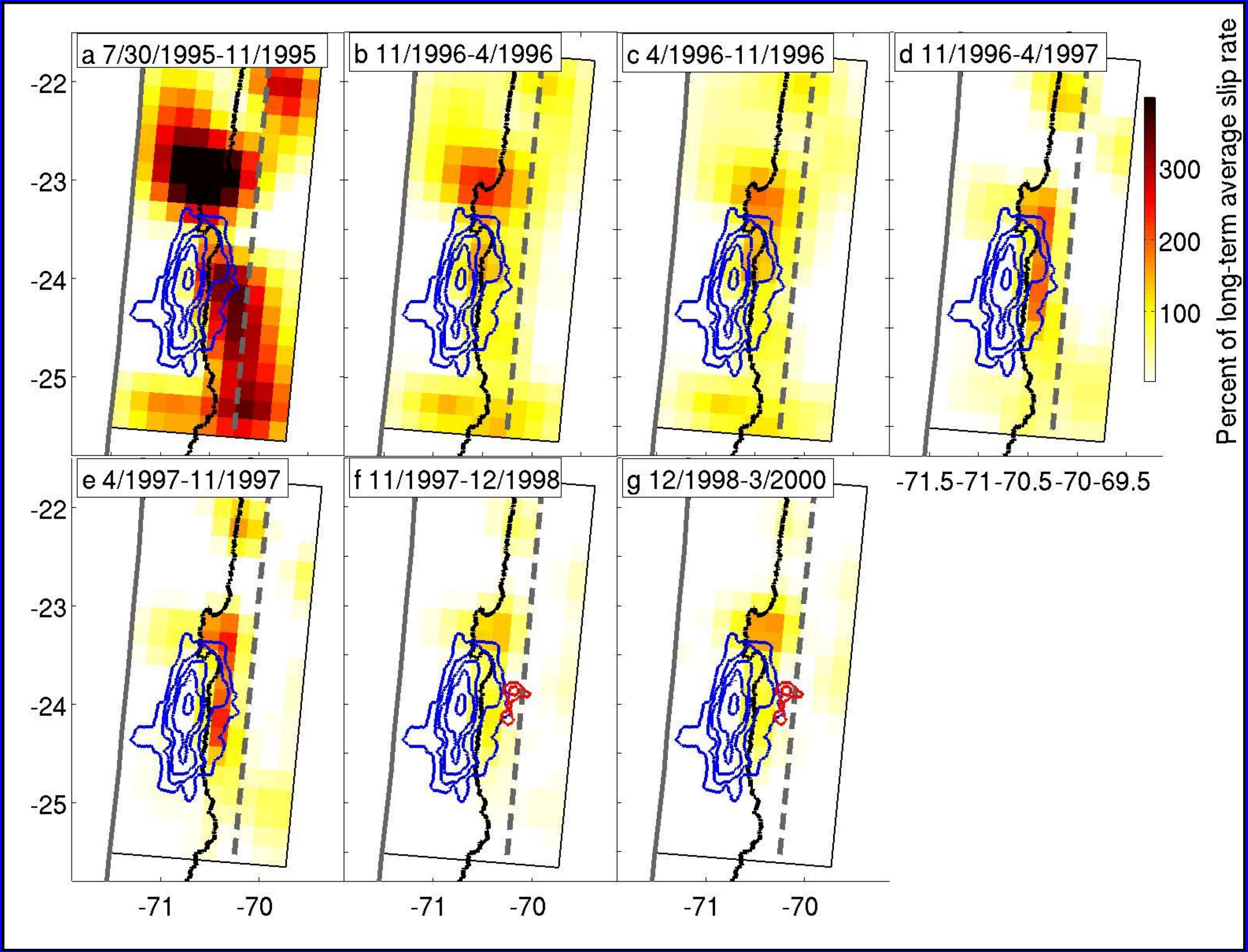
InSAR and GPS data available for northern Chile

- Build time-series of slip on subduction interface 1995-2000:
- Remove earthquake deformation using joint geodetic/seismic inversions
- Use all data types to do linear inversion for fault slip as a function of time (e.g., Lundgren et al., 2001; Schmidt and Burgmann, 2003)
- Spatial and temporal smoothing
- *GPS data: Klotz et al., 1999; Klotz et al., 2001; Melbourne et al., 2002; Khazaradze and Klotz, 2003.*



Pritchard and Simons, JGR, 2006

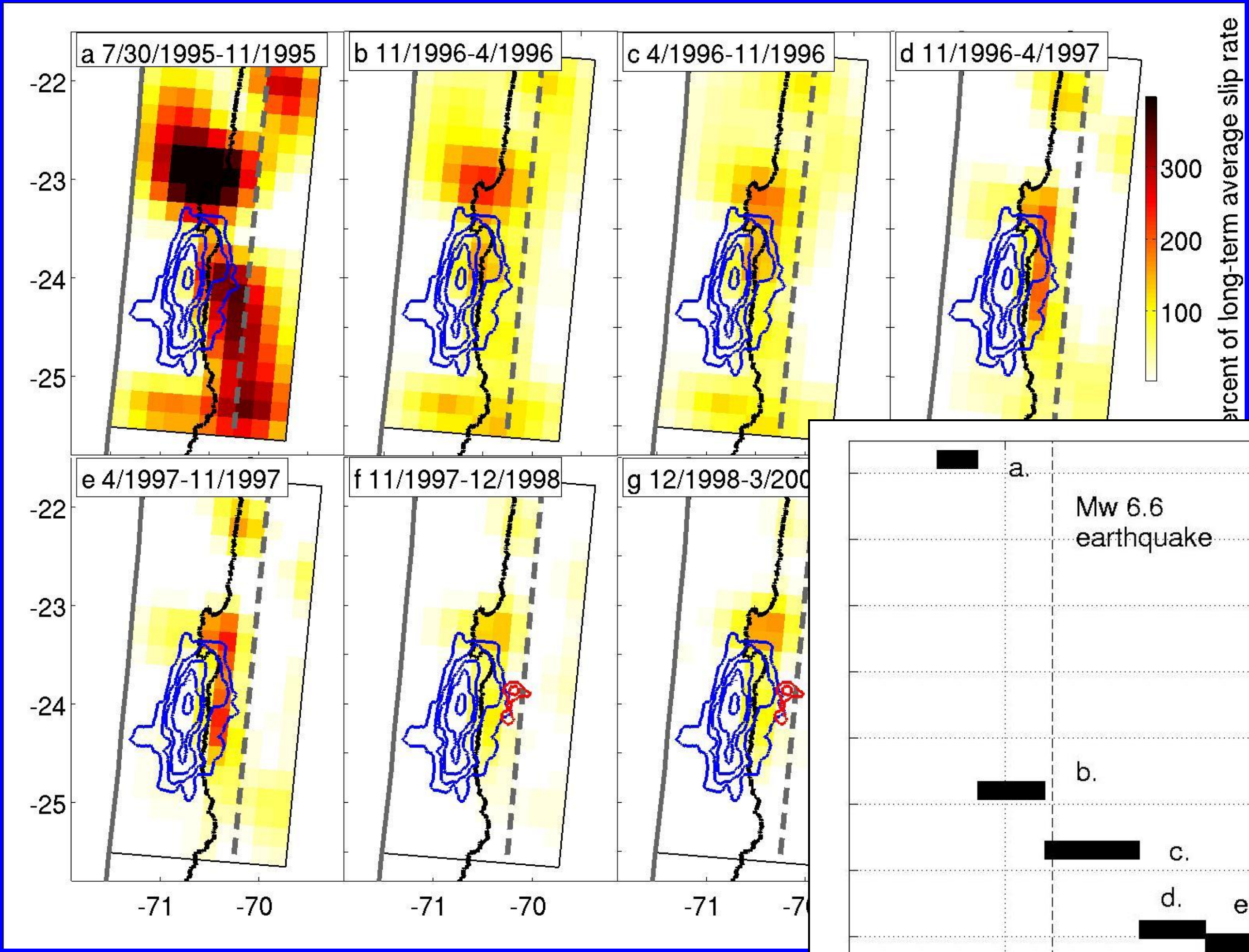
Space-time plot of after-slip



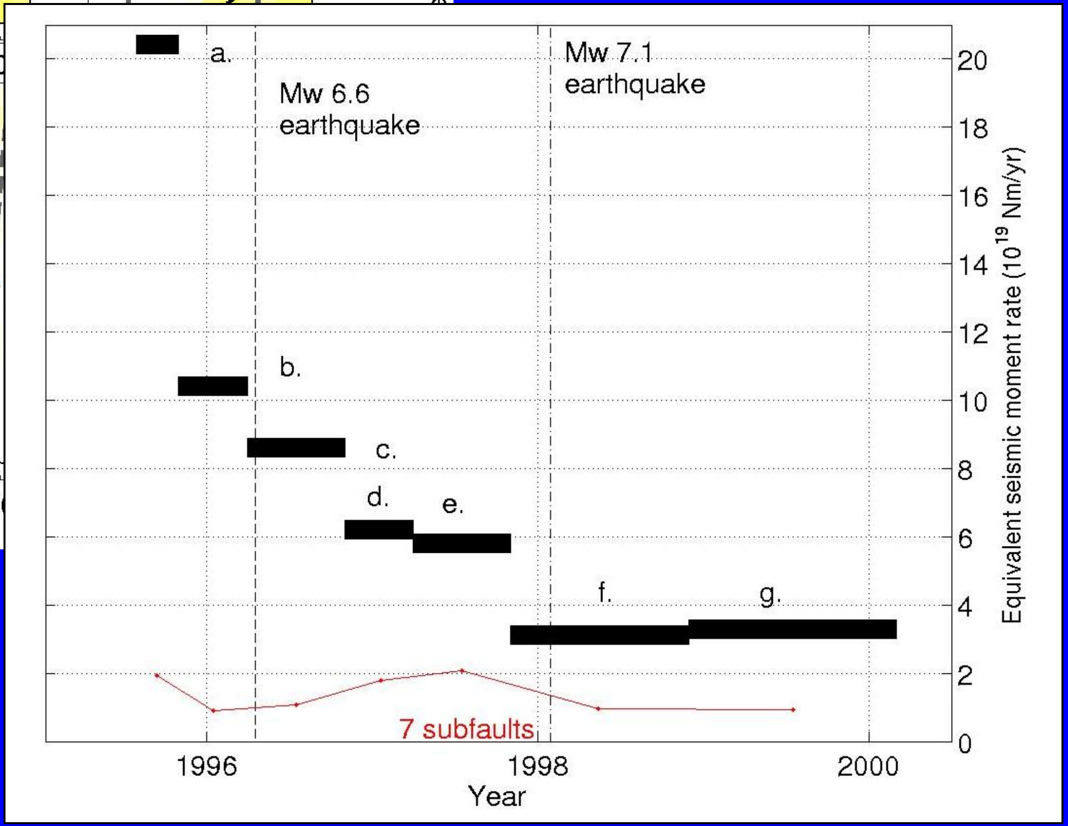
- Blue contours: 1m co-seismic slip in 1995
- Red contours: 1m co-seismic slip in 1998
- Slip decreases with time

Pritchard and Simons, JGR, 2006

Moment-rate and possible slip pulse



- Overall decline in slip with time
- But slip pulse before 1998 earthquake?



Pritchard and Simons, JGR, 2006

Post-seismic slip in subduction zones

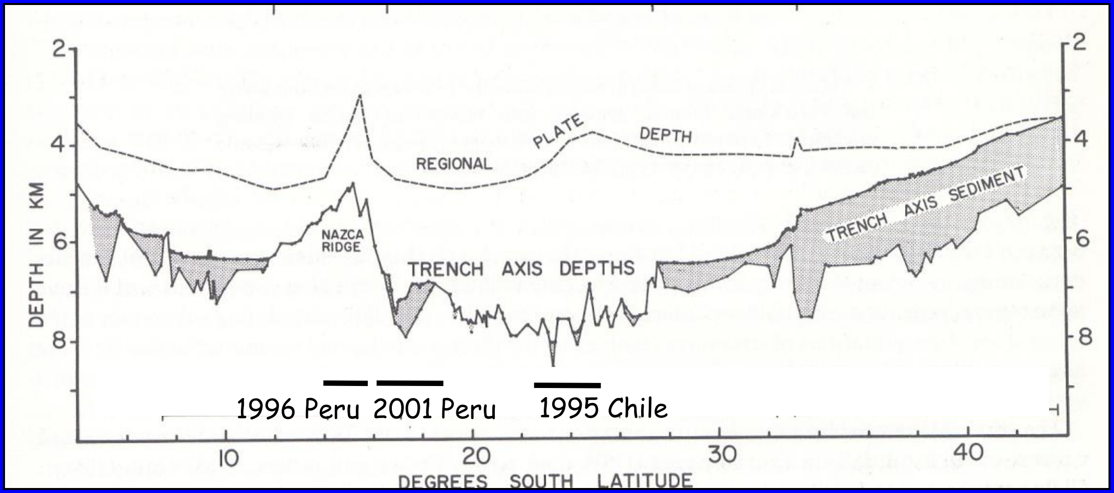
Earthquake	Co-seismic Moment	Post-seismic (fraction of co-seismic)	Method
2005 Nias-Simeulue[0]	8.7	>25% in 9 months	GPS
2004 Sumatra-Andaman[1]	9.1	50% in 5 months	GPS
2003 Tokachi-Oki, Japan[2]	8.0	20-40% in 30 days	GPS
2001 Arequipa, Peru[3]	8.4	20-40% in 1 yr	GPS/InSAR
1997 Kamchatka[4]	7.8	100% 20-60 days	GPS
1996 Nazca, Peru	7.7	< 10% (after 1st 60 days)	InSAR
1996 SW Japan[5]	6.7 (2 quakes)	100% ~ 1 yr	GPS
1995 Jalisco, Mexico[6]	8.1	40% in 15 days	GPS
1995 Antofagasta, Chile[7]	8.1	10-20% in 1 yr	InSAR/GPS
1994 NE Japan[8]	7.6	100% in 1 yr	GPS
1992 NE Japan[9, 10]	6.9	100% 5 days	strainmeter
1989 NE Japan[10]	7.4	100% 50 days	strainmeter

Data compiled in Pritchard and Simons, JGR 2006: [0]Hsu et al., 2006, Kreemer et al., 2006; [1]Vigny et al., 2005, Subarya et al., 2006, Hashimoto et al., 2006 ; [2]Miyazaki et al., 2004; [3]Melbourne et al., 2002; Ruegg et al., 2001, this study; [4]Burgmann et al., 2001; Gordeev et al., 2001; [5]Yagi et al., 2001; [6]Hutton et al., 2001; Melbourne et al., 2002; [7]Melbourne et al., 2001, Chlieh et al., 2004, this study; [8]Heki et al., 1997a and 1997b, Nishimura et al., 2000, Yagi et al., 2003; [9]Kawasaki et al., 1995; [10]Kawasaki et al., 2001

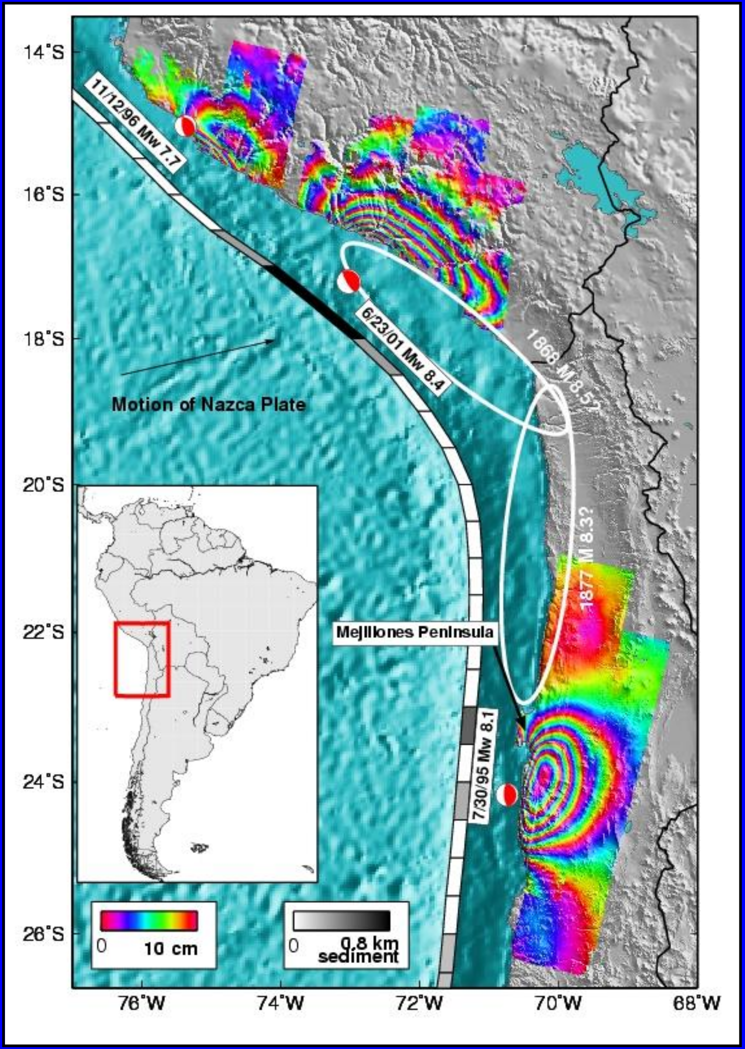
After-slip – Why and Where?

- After-slip:
  - More following the 2001 earthquake than the 1995 earthquake;
  - unmeasureable following the 1996 earthquake

- Variations in sediment subducted in these areas
  More sediment =
  more water transported to depth =
  materials more likely to undergo after-slip

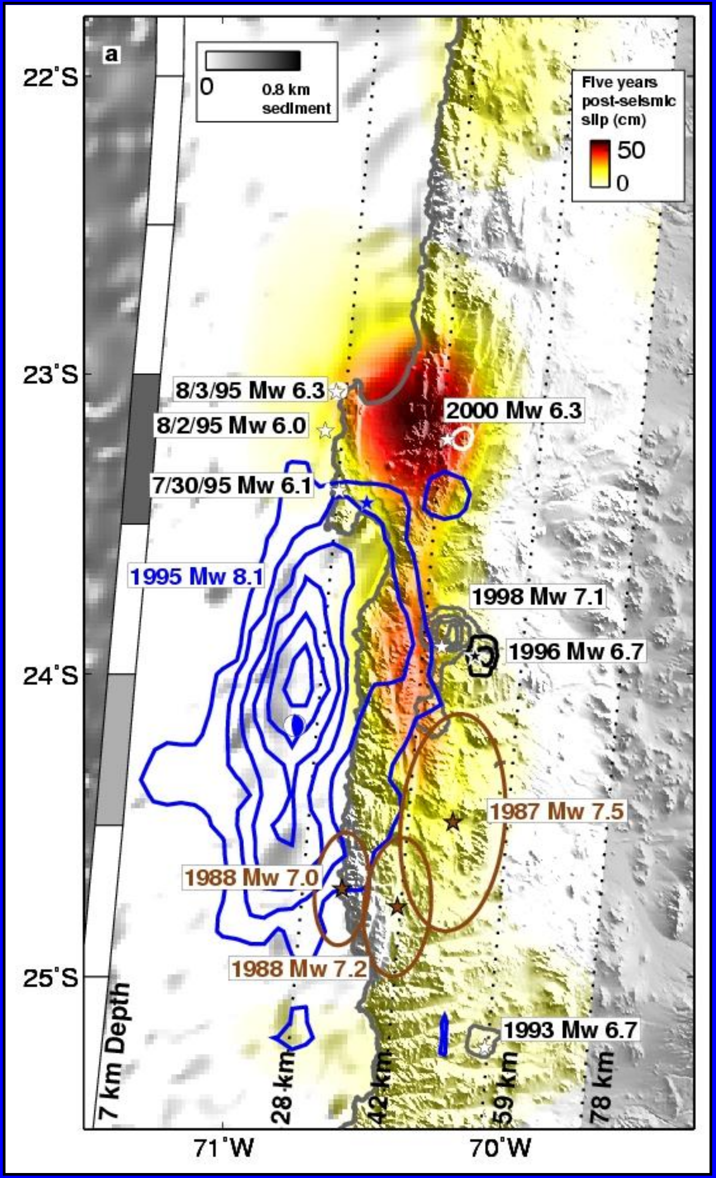


Schweller et al., 1981



Pritchard and Simons, JGR, 2006

Conclusions: Megathrust slip



1) Along-strike variations in coupling & after-slip not obviously related to plate age/tractions (e.g., Miyazaki et al., 2004; Chlieh et al., 2006)

- Anomalous Mejillones Peninsula
- Differences between N. Chile and S. Peru

2) Maybe sediments responsible for along-strike variations?

3) No single, uniform depth to "seismogenic zone"

Pritchard and Simons, JGR, 2006

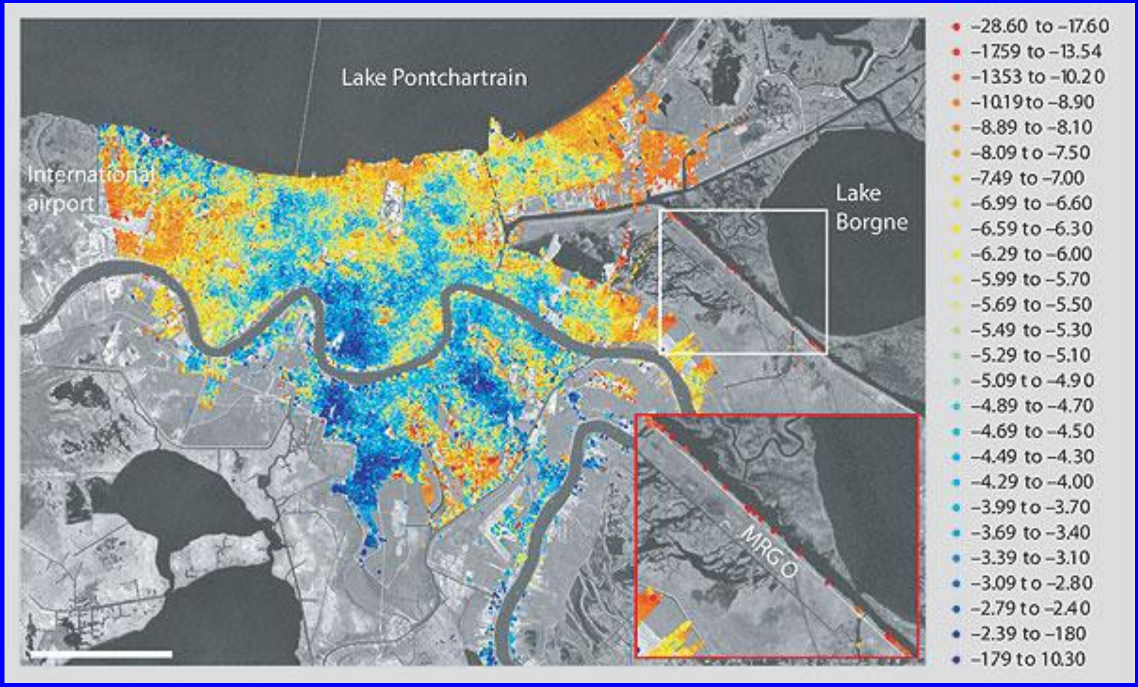
Summary and Future directions

InSAR and pixel tracking major advance over point measurements of deformation

New phenomena and sources of deformation discovered:
- Magma movements at supposedly dormant volcanoes
- “Silent” earthquakes
- Power-law viscoelastic response to large earthquakes
- Poro-elastic response to large earthquakes
- Dynamic acceleration of icesheets in response to surface melting
- Antropogenic deformation

Near term developments (next 5-10 years):

1) Larger datasets (detect smaller deformation rates)
2) Extracting information from discontinuous images
3) Dedicated U.S. InSAR satellite?
 Maybe around another planet first?



Subsidence in New Orleans before Katrina measured by “permanent scatterers” From: Dixon et al., 2006

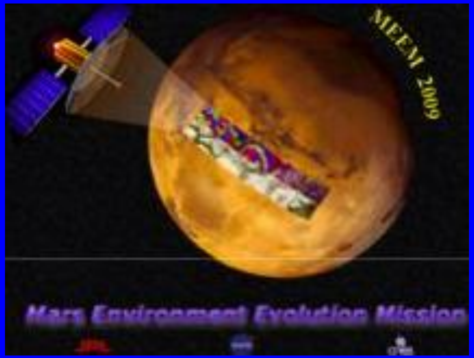
Longer term:
- Constellations of satellites
- Geostationary InSAR?: Near real-time capability

Planetary InSAR

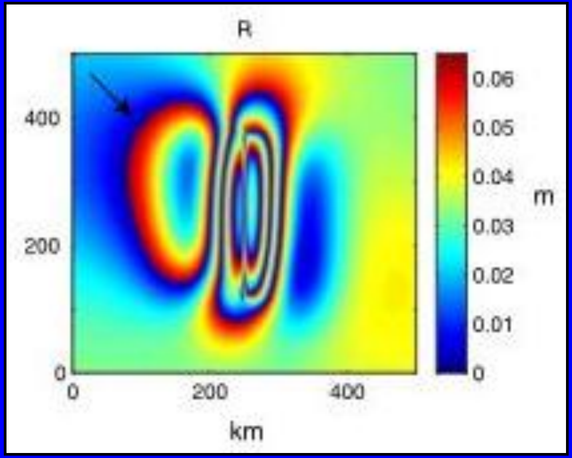
SAR images require Gigabytes -- hard to image entire planets, especially distant ones

Mars: Repeat pass InSAR is possible
(can control baseline to 100 m however orbit knowledge is limited to about 5-10 m requiring baseline determination from SAR data directly: Paul Rosen & Scott Hensley, JPL)

Moon: Difficult to control orbits, useful for topographic mapping



Mars InSAR mission concept: Paillou et al., 2001



Europa/Io: Difficult radiation environment & orbit control

Titan: Cassini Radar (0.4-1.7 km pixel resolution; Ku band, 2 cm), but no repeating orbits yet - burst mode operation makes interferometry unlikely.

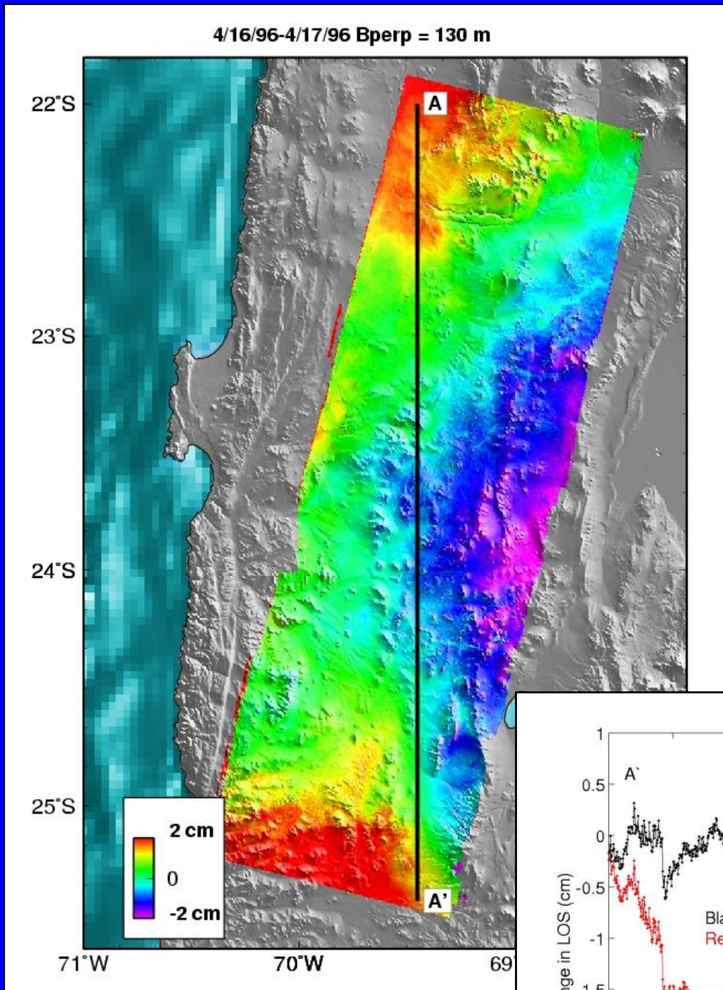
Synthetic interferogram of tidal strain at crack on Europa
S-band (13 cm) in 1000 km orbit. Thin Shell (3-30 km, with crack through most of it.
(Sandwell et al., 2004)

Another Challenge for InSAR: Orbital errors

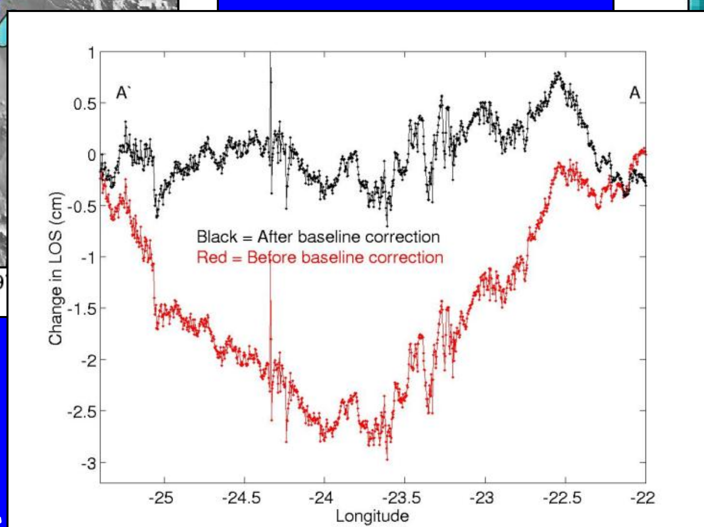
Interferograms span 1 day
Should not include any signal

Long-wavelength signal related to orbital errors

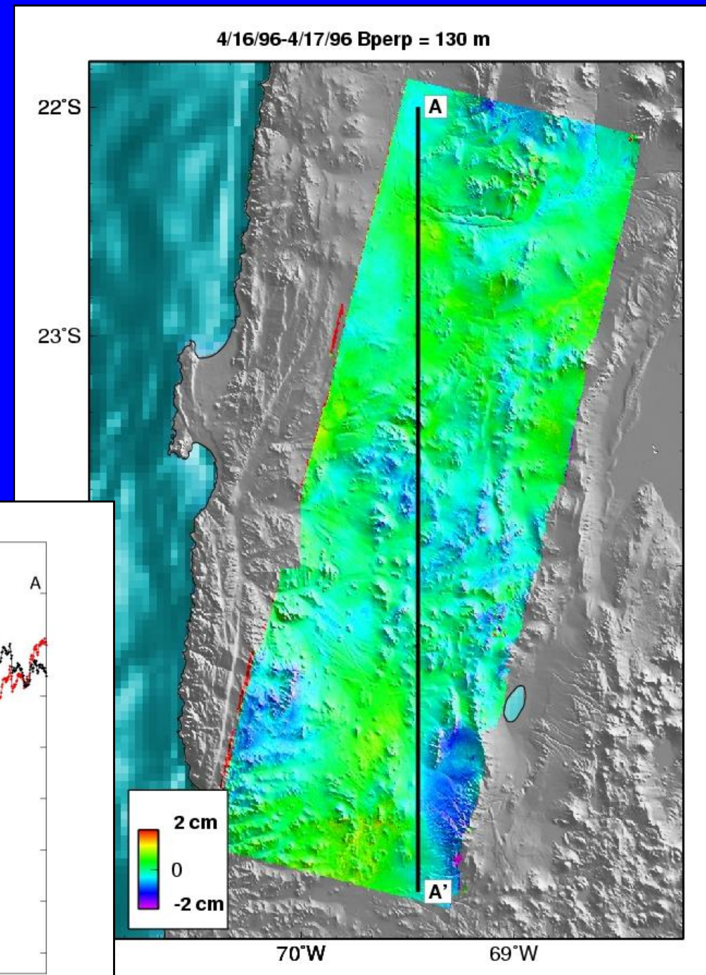
Implications for measuring post-glacial rebound: need ground control on long wavelength deformation pattern



Before baseline correction



Profiles



After baseline correction