HAROKOPIO UNIVERSITY

→ 4th ADVANCED TRAINING COURSE IN LAND REMOTE SENSING

Terrain Motion 1: The Earthquake Deformation Cycle

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Outline

PART 1

- The Earthquake Cycle
- Earthquakes – some definitions
  - Strike/Dip/Rake
  - Moment
- Coseismic Deformation
  - Dip-Slip earthquakes (Normal and Thrust)
  - Strike-Slip earthquakes

PART 2

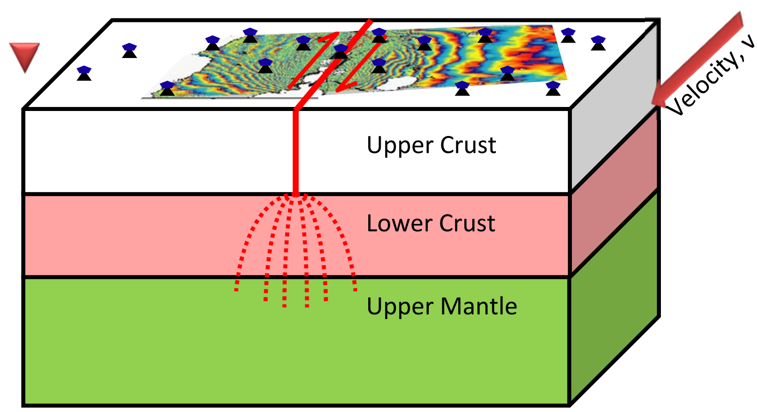
- Interseismic and Postseismic Deformation
- Models of Earthquake Cycle deformation

The Earthquake Cycle

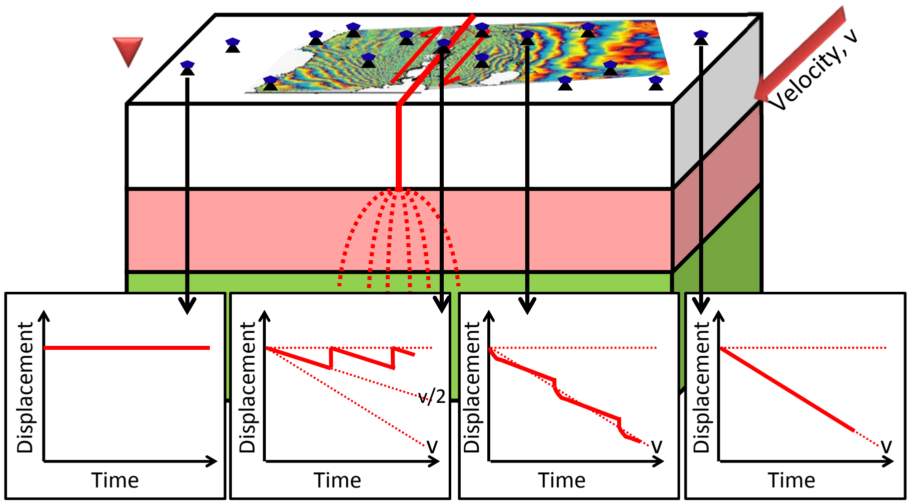
Animation courtesy Ross Stein, USGS

http://quake.usgs.gov/research/deformation/modeling/animations/

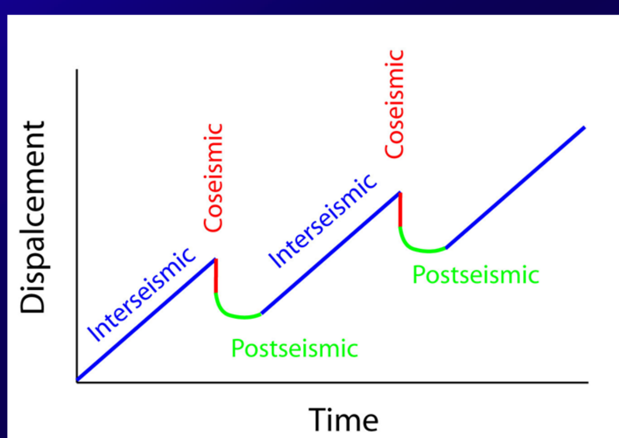
Intro: The Earthquake Deformation Cycle



Intro: The Earthquake Deformation Cycle

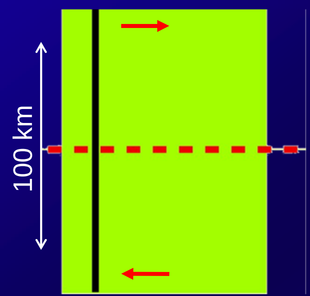


The deformation cycle

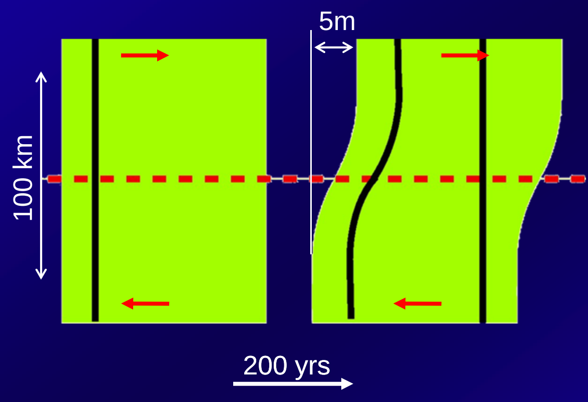


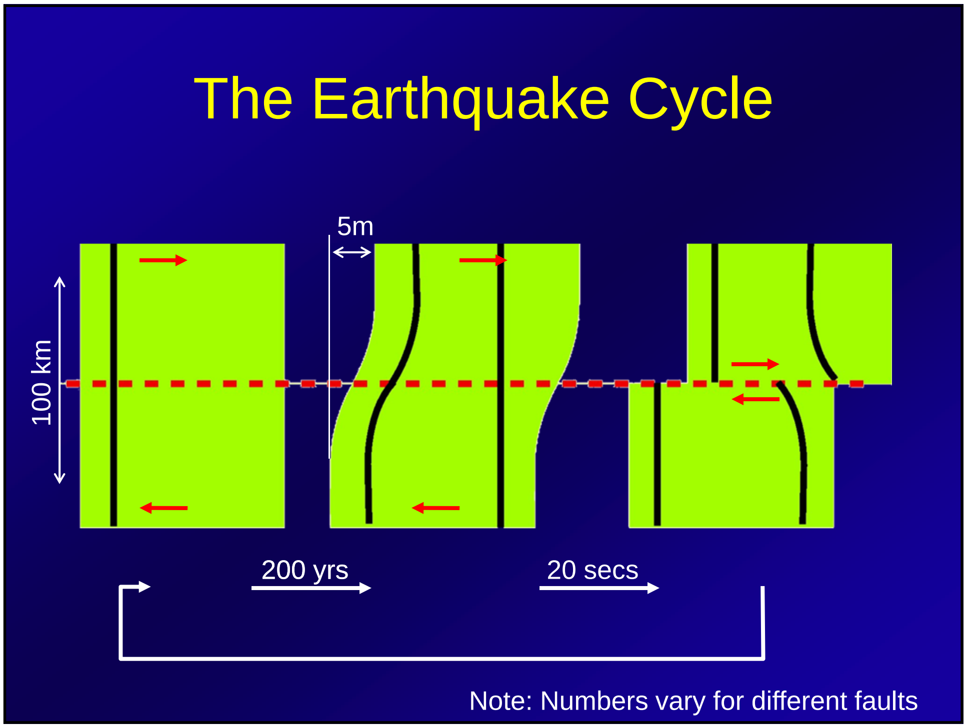
Theoretical geodetic time series

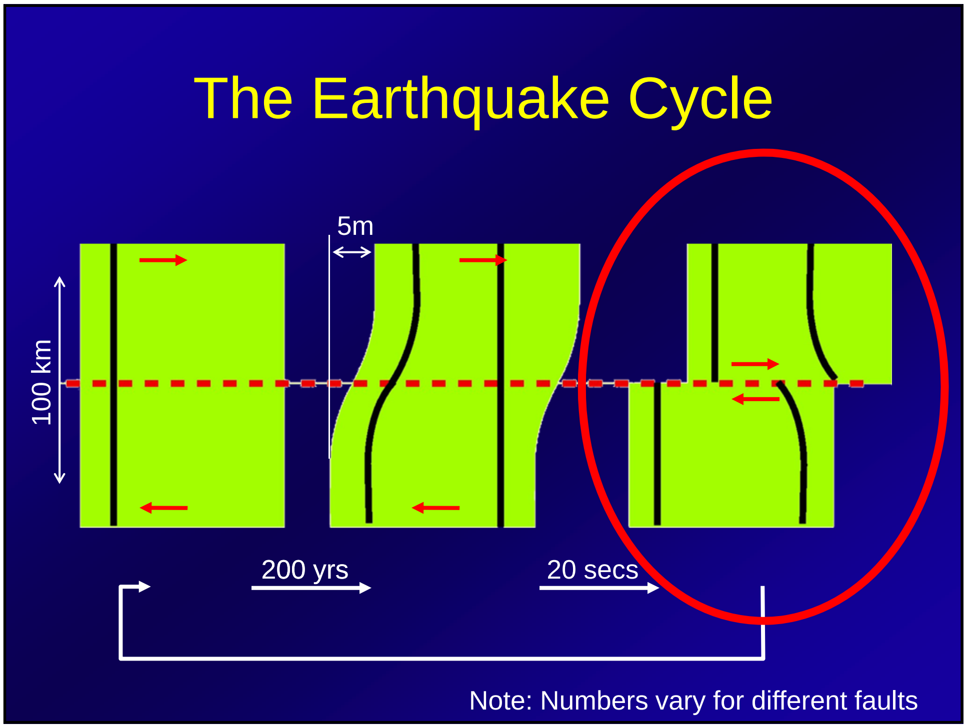
The Earthquake Cycle



The Earthquake Cycle




The Earthquake Cycle
5m
100 km
200 yrs
20 secs
Note: Numbers vary for different faults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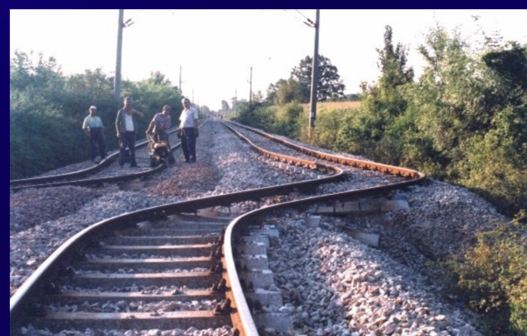
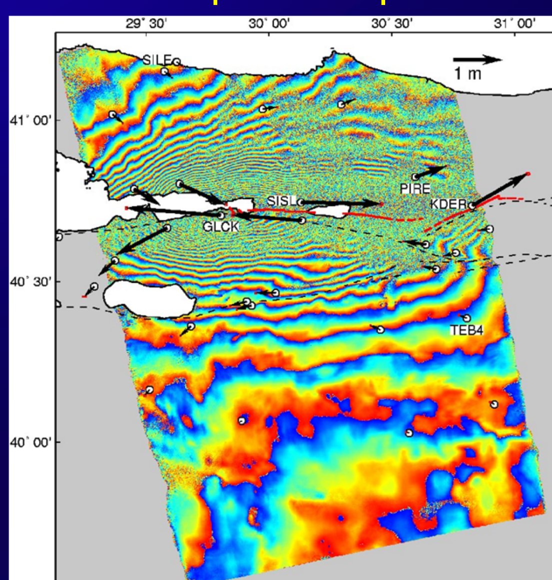
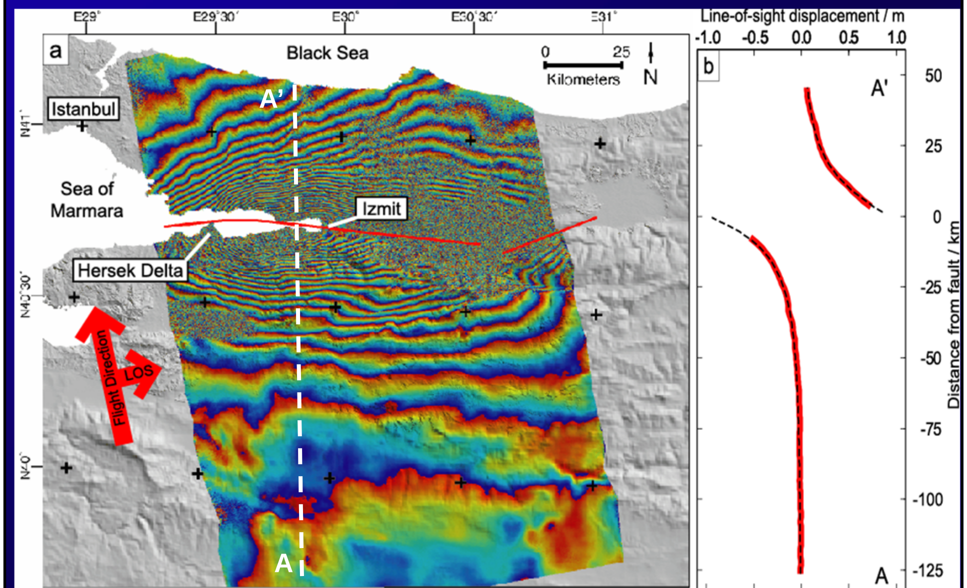
17 August 1999, Izmit Earthquake



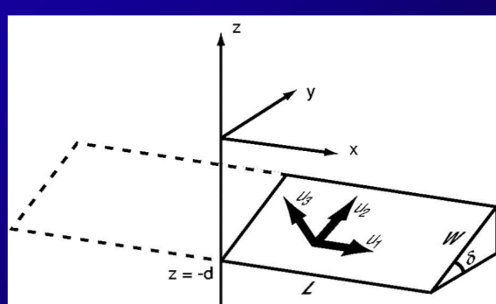
The Izmit earthquake displacement field





17 August 1999, Izmit earthquake (Turkey)

Elastic Dislocation Modelling



Y. Okada, 1985. Surface deformation due to **shear** and tensile faults in a half-space. *Bull. Seism. Soc. Am.*, 75, 1135-1154

To define a rectangular fault dislocation, need 10 parameters:

- Location of fault x,y,z (x=y=0, z = -d) [1]
- Length, Width and dip of the fault (L, W, δ) [3]
- Slip components (u_1 = strike-slip; u_2 = dip-slip; u_3 = tensile) [3]
- 3D Displacements can be calculated for a point (x_{obs}, y_{obs}) in the fault-centred reference frame, where the x-axis points along strike. [3]

Elastic Dislocation Modelling

Code in today's practical takes 7 'friendly' fault parameters:

- x, y-position of centre of fault's surface projection, set at 0,0 [0]
- Strike, Dip and Rake of fault (Aki, and Richards convention) [3]
- Magnitude of earthquake slip vector (u_3 = 0, i.e. no opening) [1]
- Top and Bottom Depths (measured vertically), Fault Length [3]

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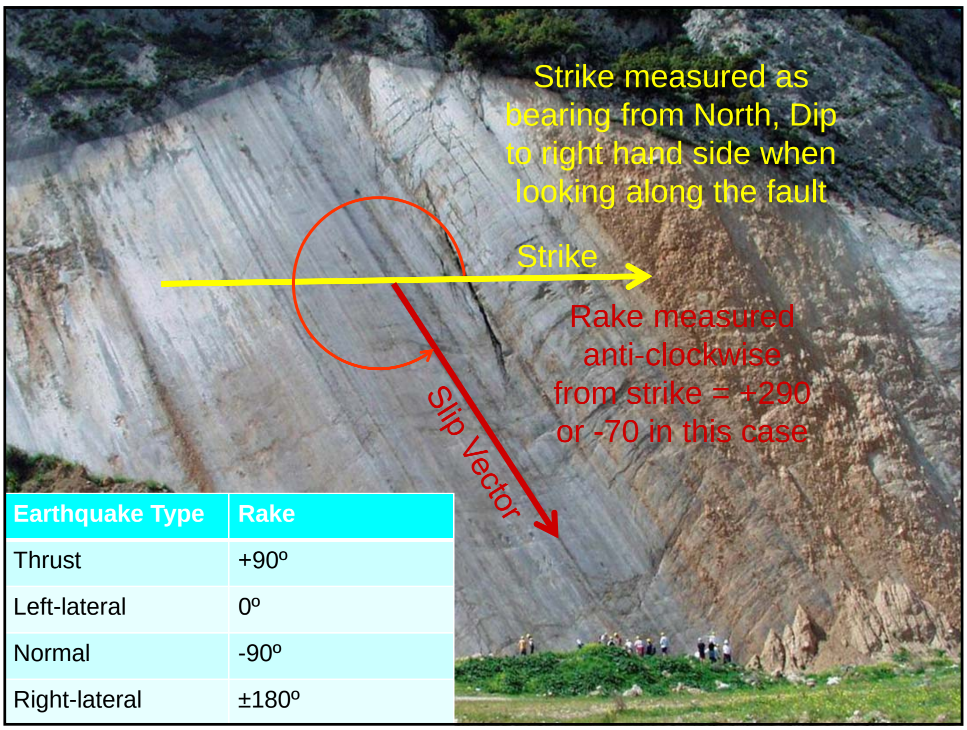
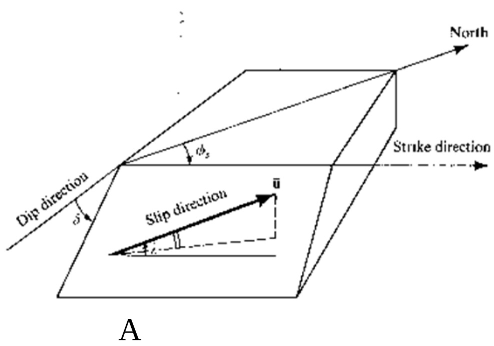


Earthquake Type	Rake
Thrust	+90º
Left-lateral	0º
Normal	-90º
Right-lateral	±180º

Earthquake Moment



The Moment of an earthquake is the product of the area, A, of a fault that slipped, with the magnitude, s, of the slip, and the shear modulus, m.

M_0 = m A s

Earthquake Magnitudes and Moments

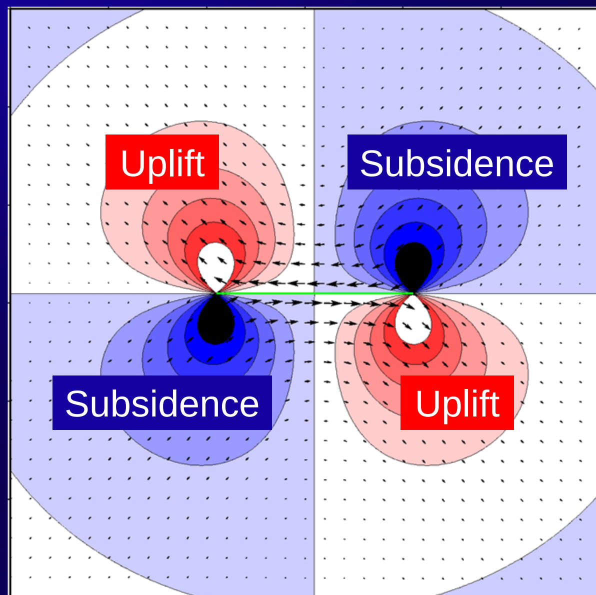
$$\mathbf{M_0} = \mu A s$$

SI units

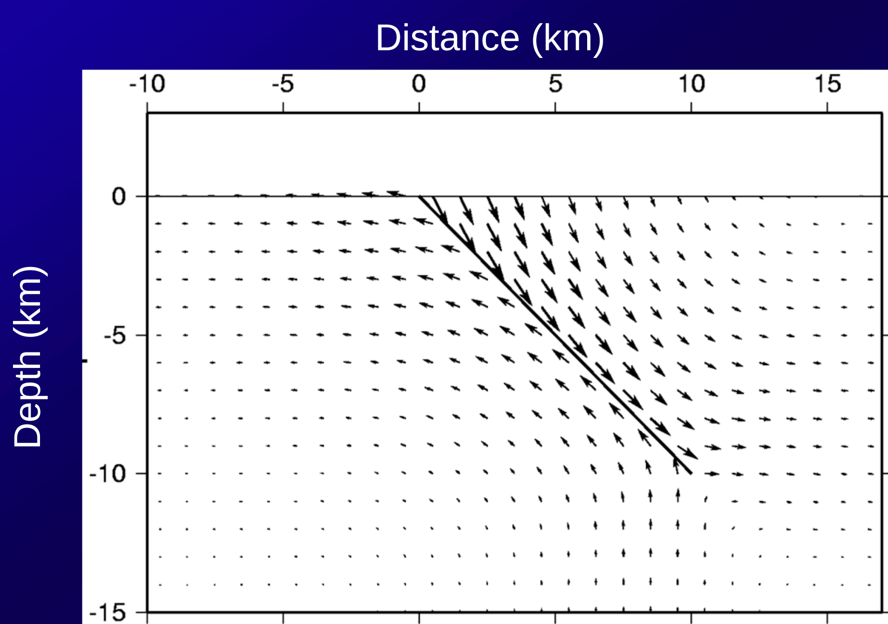
$$\mathbf{M_w} = \frac{2}{3}\log_{10}\mathbf{M_0} - 6.0$$

$$\mathbf{M_0} = 10^{[1.5\mathbf{M_w} + 9]}$$

Surface displacements of strike-slip faults

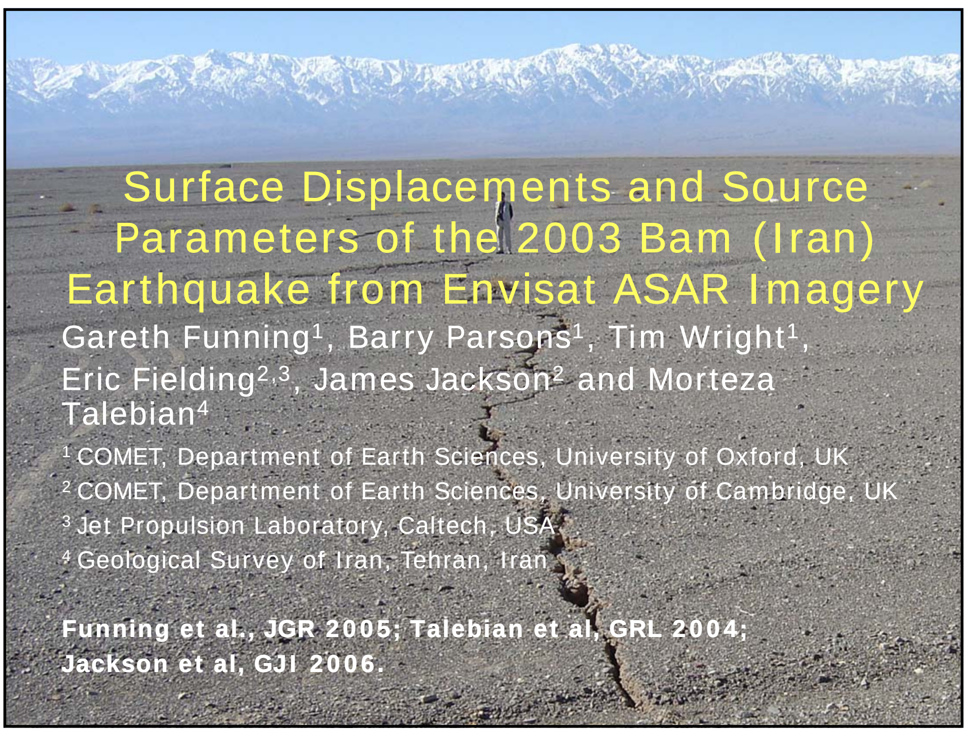


Displacements of normal faults



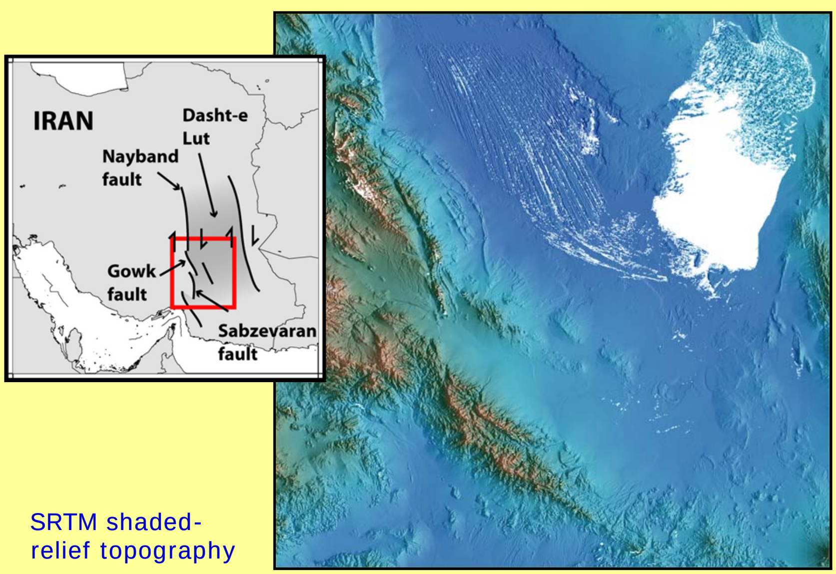
Determining best-fit elastic models

- Calculating the predicted displacements from a specified fault geometry (forward modelling) is relatively easy.
- The inverse problem (finding the model that fits a given set of displacements) is harder:
  - Finding the fault geometry is a non-linear inversion problem.
  - Determining slip distributions for a fixed fault geometry is a linear problem.



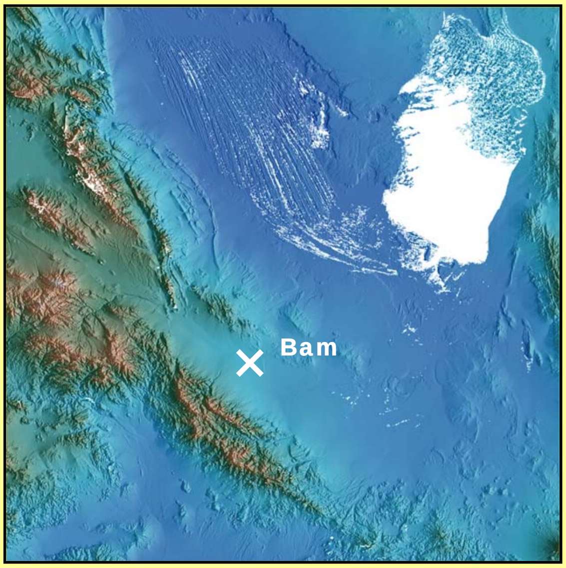
26th December 2003, M_w 6.6

Tectonic setting



SRTM shaded-
relief topography

Tectonic setting



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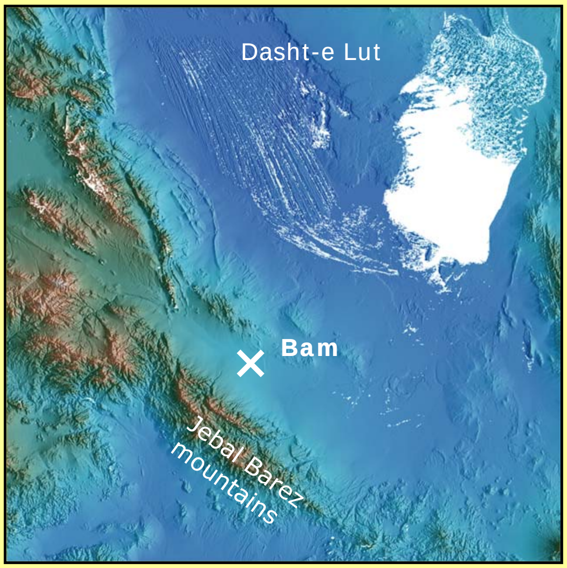
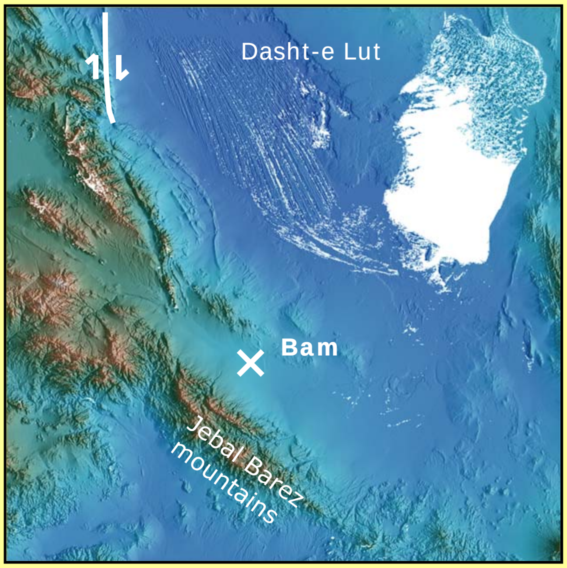


SRTM shaded-relief topography

Tectonic setting

Nayband fault

SRTM shaded-
relief topography

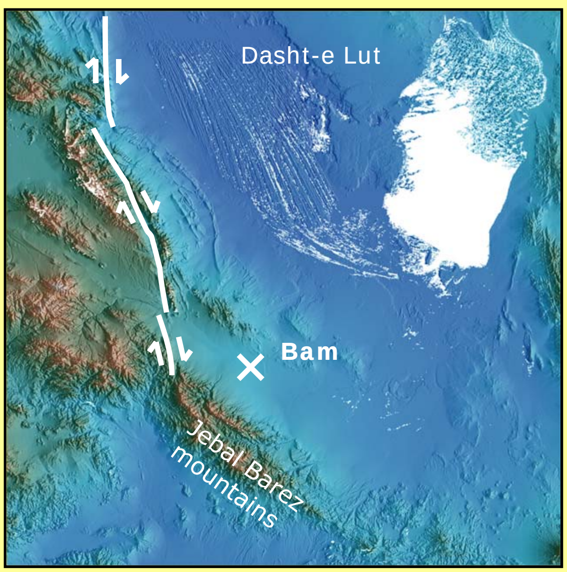


Tectonic setting

Nayband fault

Gowk fault

SRTM shaded-
relief topography



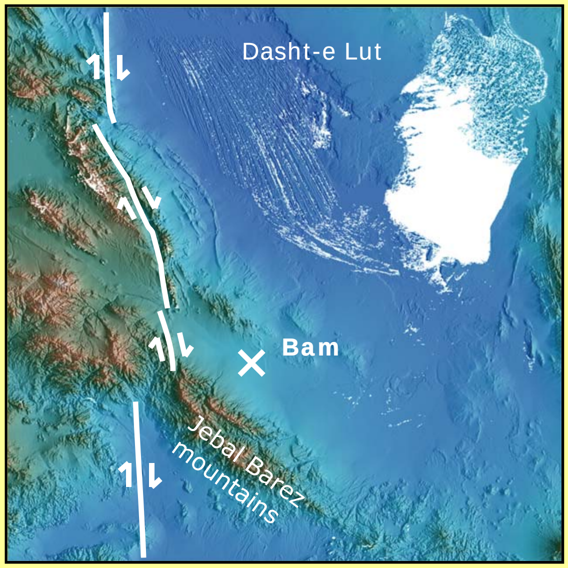
Tectonic setting

Nayband fault

Gowk fault

Sabzevaran fault

SRTM shaded-relief topography



Tectonic setting

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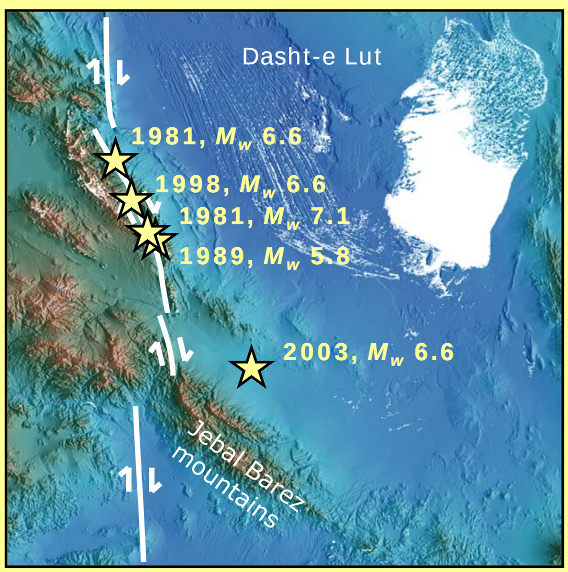

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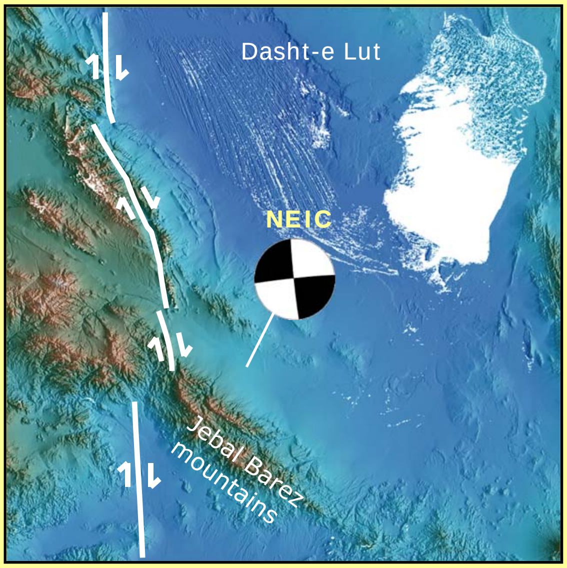

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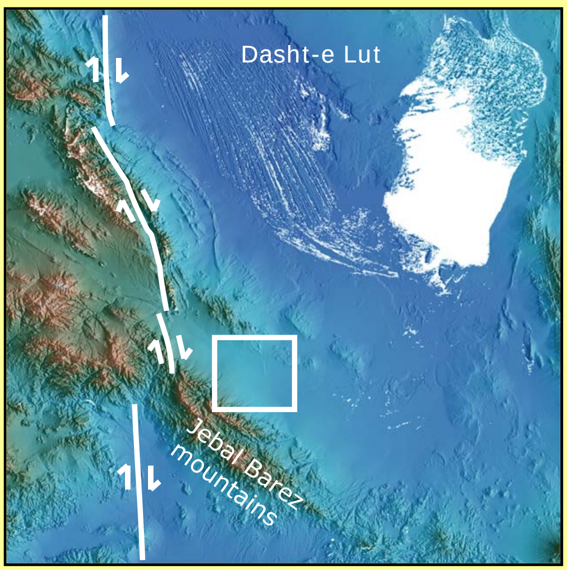
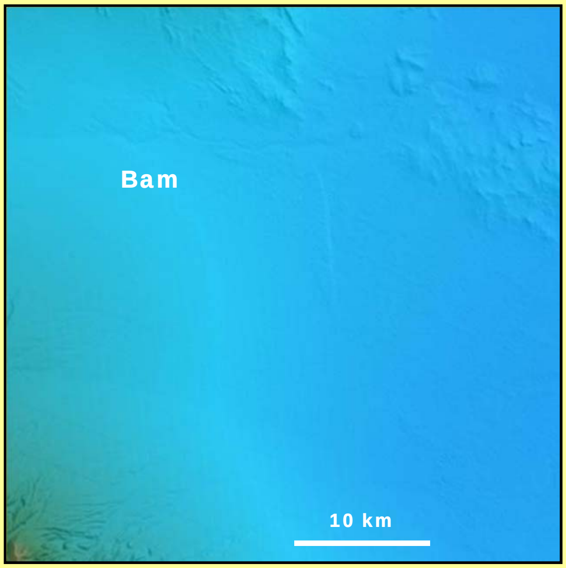


The Bam area

Main geomorphic features of the Bam area:



SRTM shaded relief topography

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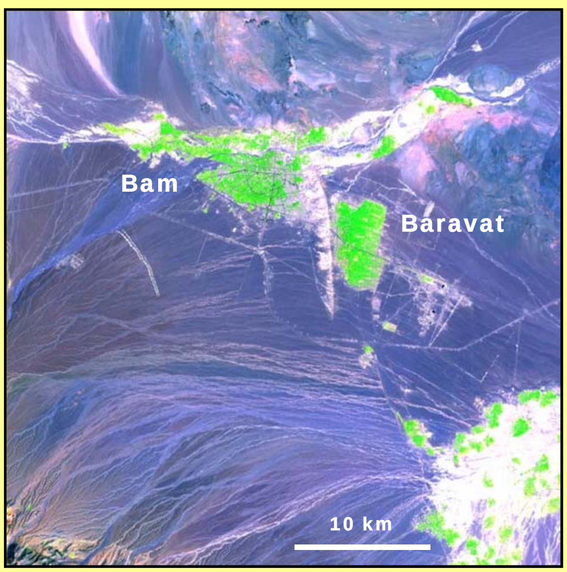
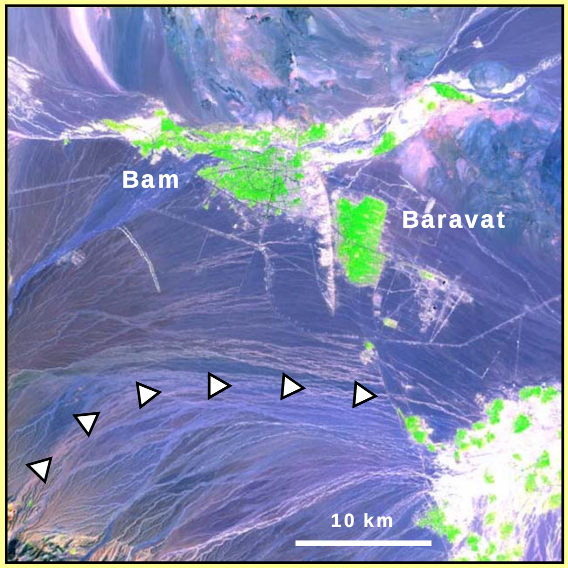


LANDSAT-7 ETM 541 false colour green=vegetation

The Bam area

Main geomorphic features of the Bam area:

1: Alluvial fans from the Jebal Barez mountains to the SW

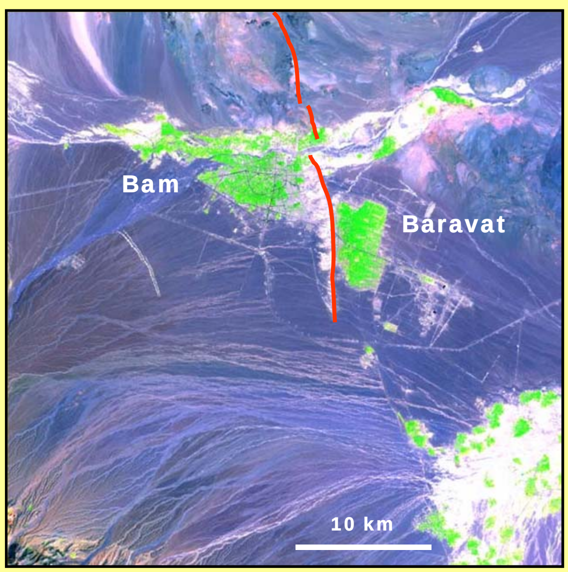


LANDSAT-7 ETM 541 false colour green=vegetation

The Bam area

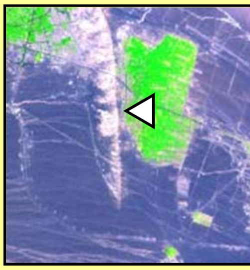
Main geomorphic features of the Bam area:

2: The Bam fault – a prominent ridge running between Bam and Baravat



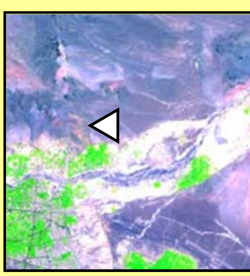
LANDSAT-7 ETM 541 false colour green=vegetation

The Bam fault



Post-earthquake field surveys found only minor cracking at the foot of the ridge...

The Bam fault



...and fault ruptures observed in the north were also minor (< 5 cm offset)

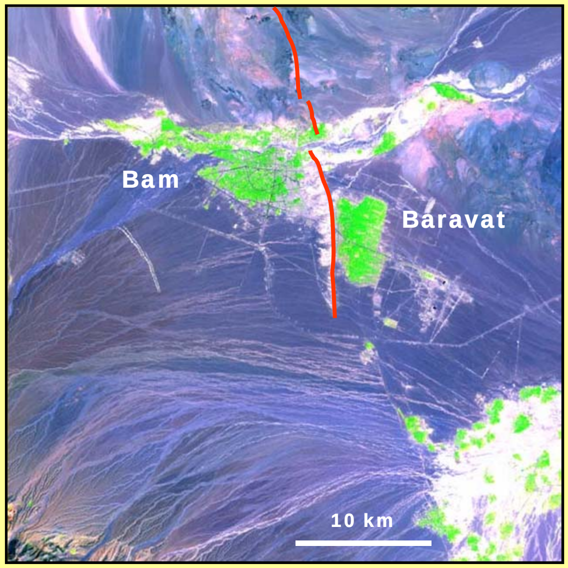
The Bam fault ?

BUT…

More damage in Bam than Baravat

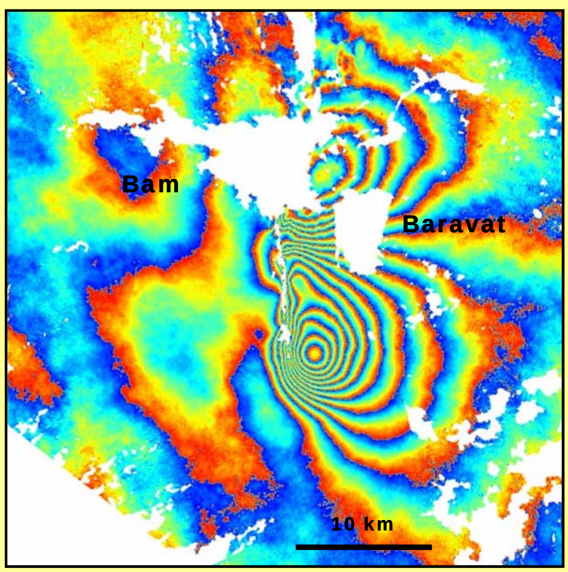
Peak vertical acceleration of ~1g in central Bam

Very small surface rupture on Bam fault



LANDSAT-7 ETM 541 false colour green=vegetation

Preliminary InSAR data



First Bam interferogram (each colour cycle=2.8cm of deformation)

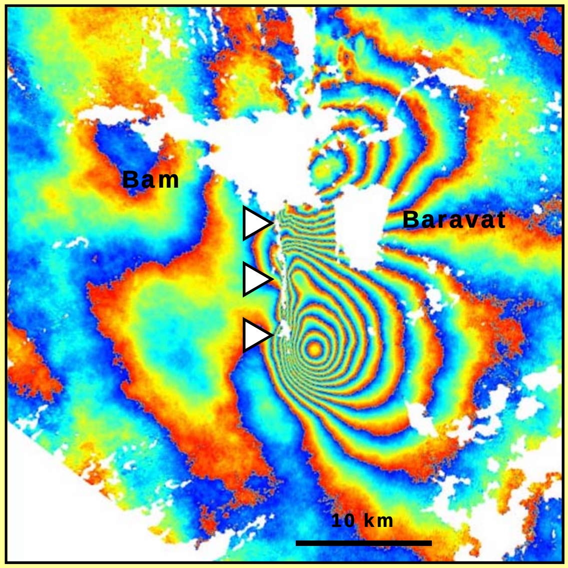
Constructed from Envisat ASAR data released for free by ESA

Preliminary InSAR data

There is a prominent band of incoherence running S of Bam

First Bam interferogram (each colour cycle=2.8cm of deformation)

Constructed from Envisat ASAR data released for free by ESA

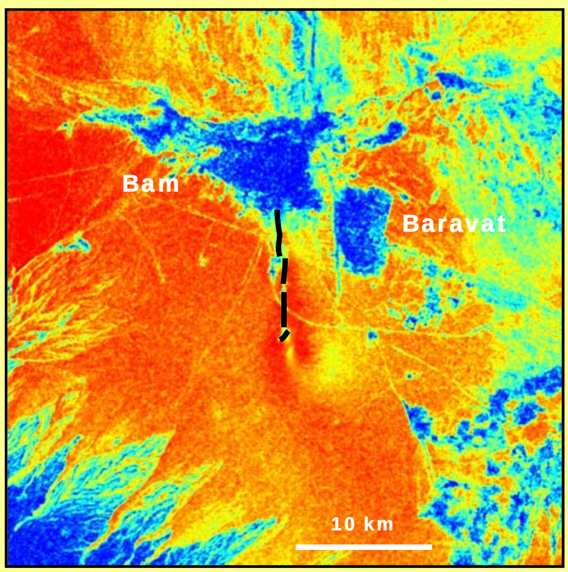


The Bam earthquake main fault

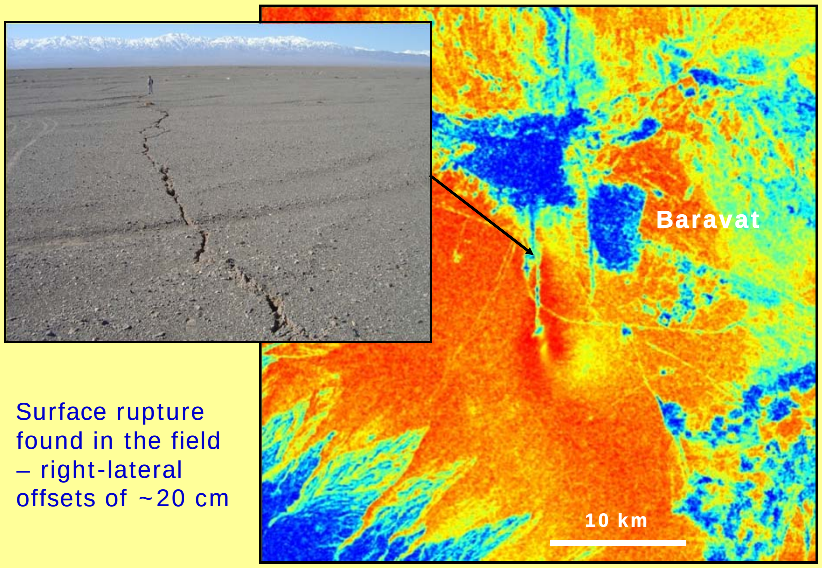
Low coherence indicates vegetation and surface damage

Interferometric coherence
Red = high
Blue = low

Constructed from Envisat ASAR data released for free by ESA

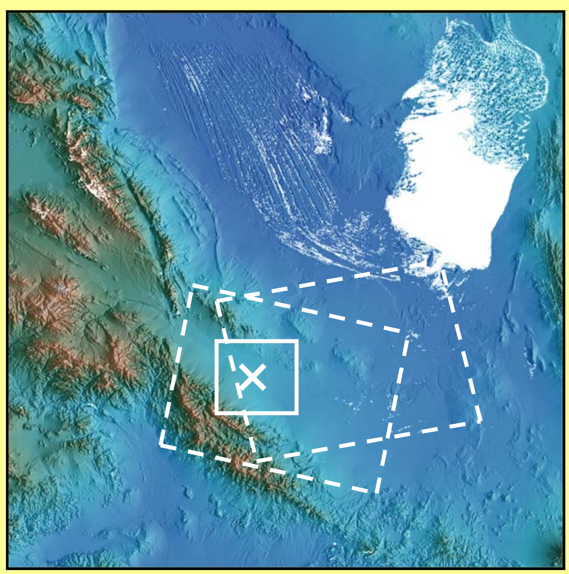


The Bam earthquake main fault



Surface rupture found in the field – right-lateral offsets of ~20 cm

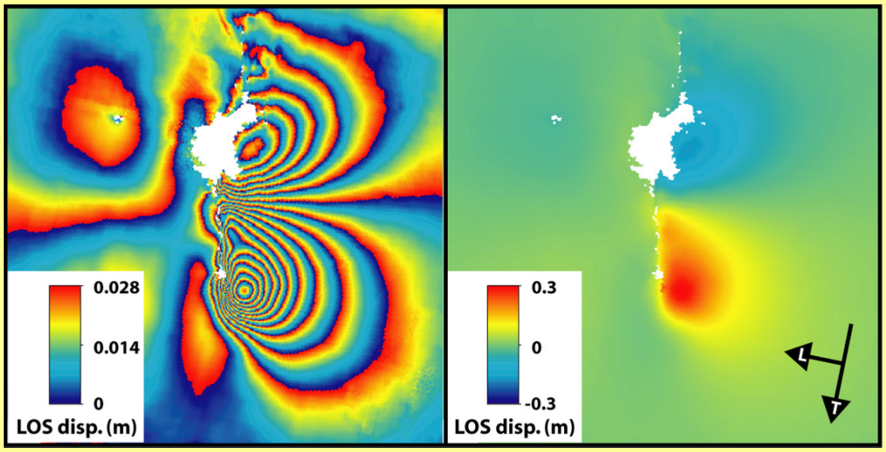
ASAR data for the Bam earthquake



SRTM shaded-relief topography

Descending track interferogram

Track 120, beam mode I2, 03/12/2003 – 07/02/2004

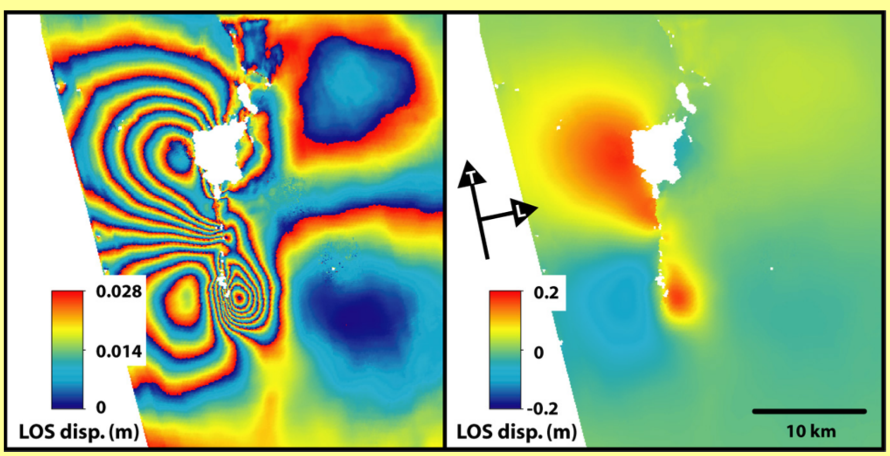


Wrapped

Unwrapped

Ascending track interferogram

Track 385, beam mode I2, 16/11/2003 – 25/01/2004

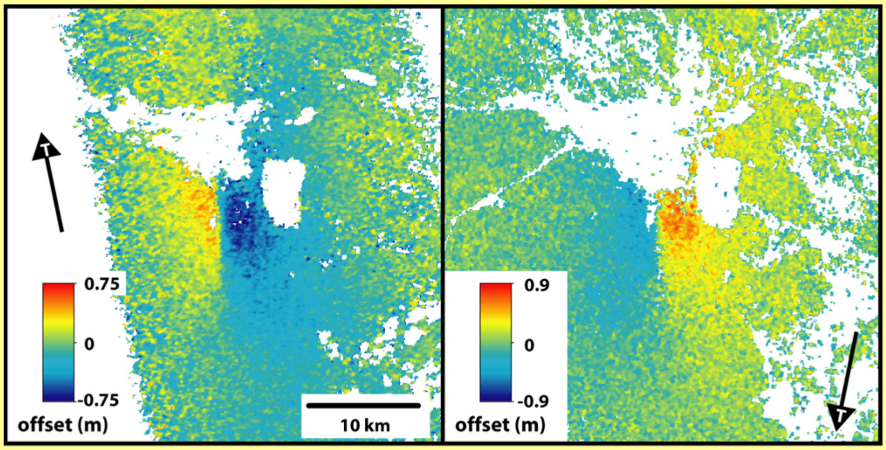


Wrapped

Unwrapped

Azimuth offsets

Ascending Descending



Determining 3D displacements

If the 3D displacement at a pixel is given by **u** = $[u_x, u_y, u_z]$, then…

Ascending interferogram, $d_1 = \mathbf{los_A} \cdot \mathbf{u}$

Descending interferogram, $d_2 = \mathbf{los_D} \cdot \mathbf{u}$

Ascending az. offsets, $d_3 = \mathbf{los_{AO}} \cdot \mathbf{u}$

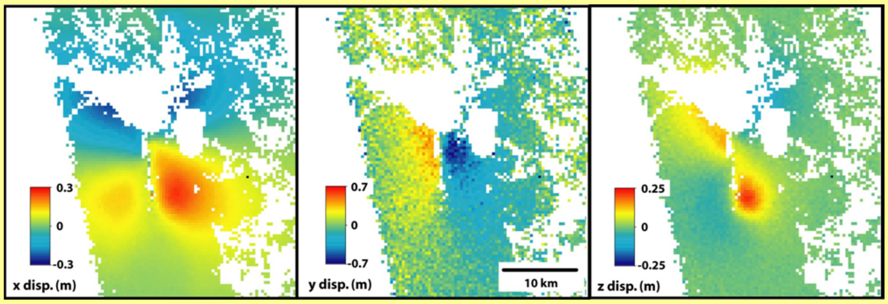
Descending az. offsets, $d_4 = \mathbf{los_{DO}} \cdot \mathbf{u}$

Which can be rewritten as a matrix equation, **d** = **Lu,** and solved for **u**.

See e.g. Wright, T.J, B. Parsons, Z. Lu., Geophys Res. Lett. 30(18), p.1974, 2003

Bam earthquake 3D displacements

East North Up



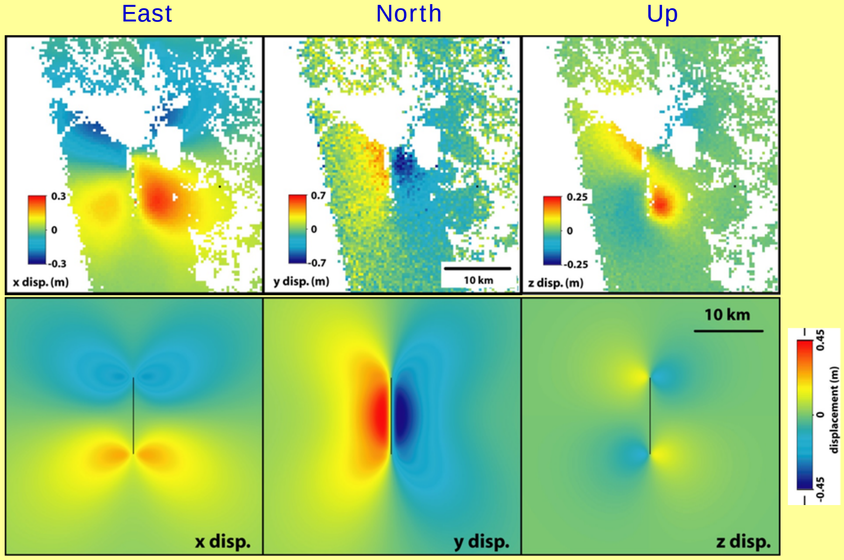
σ = 0.01 m σ = 0.09 m σ = 0.01 m

Bam earthquake 3D displacements

East North Up

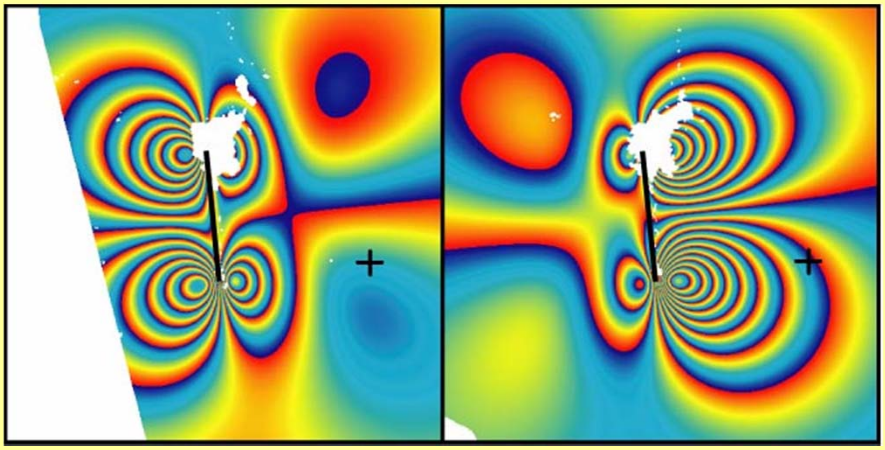
Data

Vert. pure s-s



Single fault, uniform-slip model

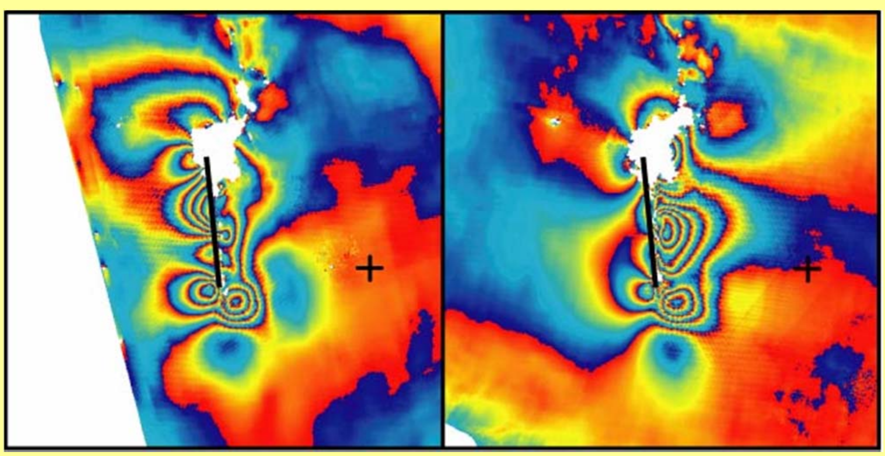
About 2m slip on 12 km long fault in top 10 km of crust



Ascending model | Descending model

Single fault model

Large residuals, especially in SE quadrant (rms = 25 mm)



Ascending residual | Descending residual

Bam earthquake 3D displacements

East North Up

Data

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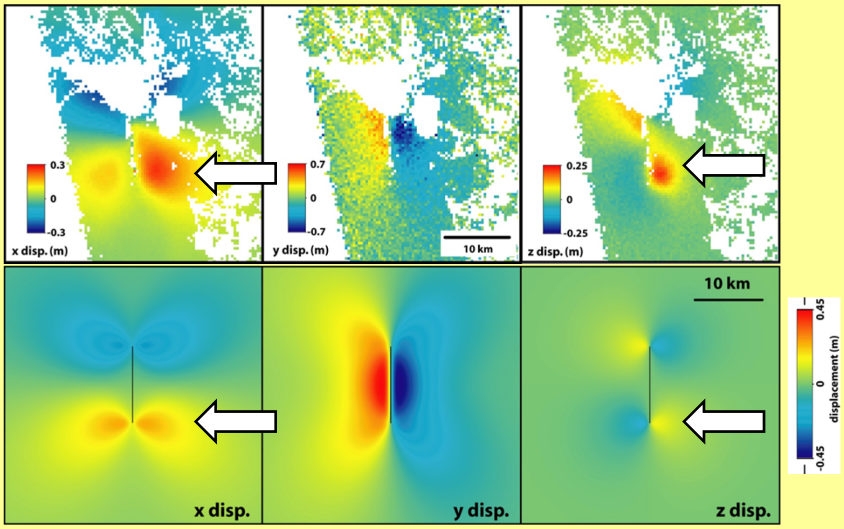
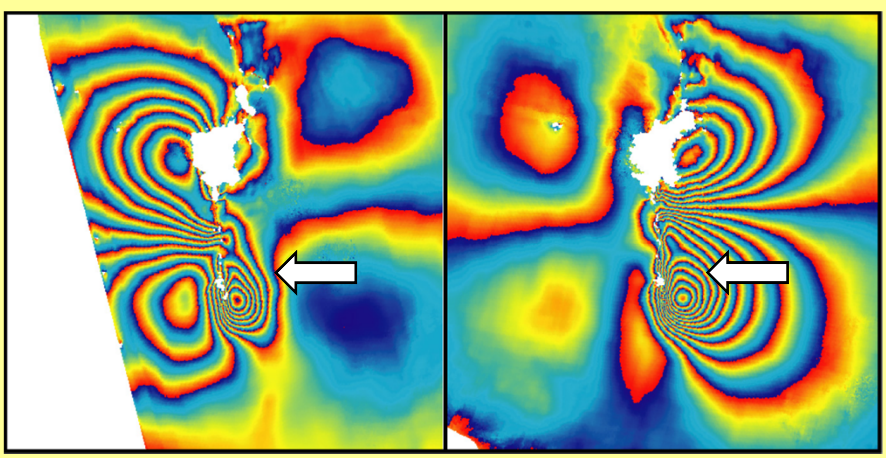
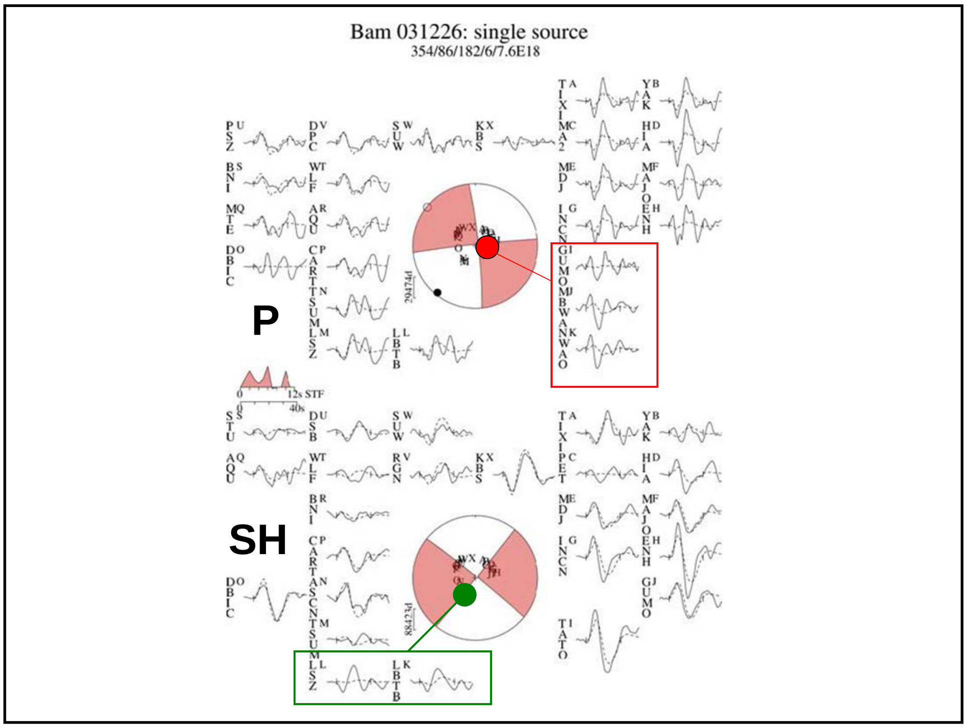


Is it a single fault…?

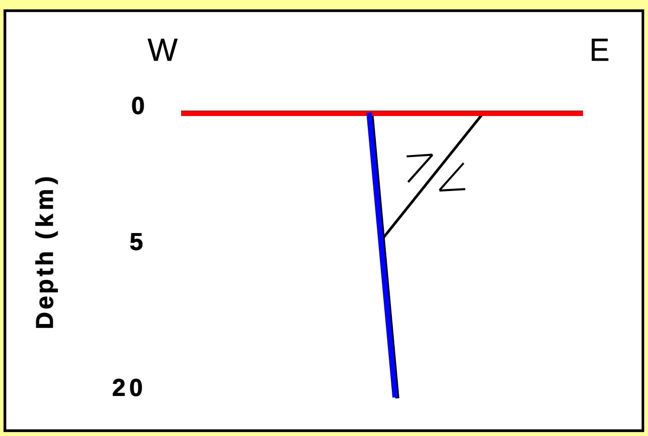
There is an ‘extra’ amount of displacement in the SE quadrant



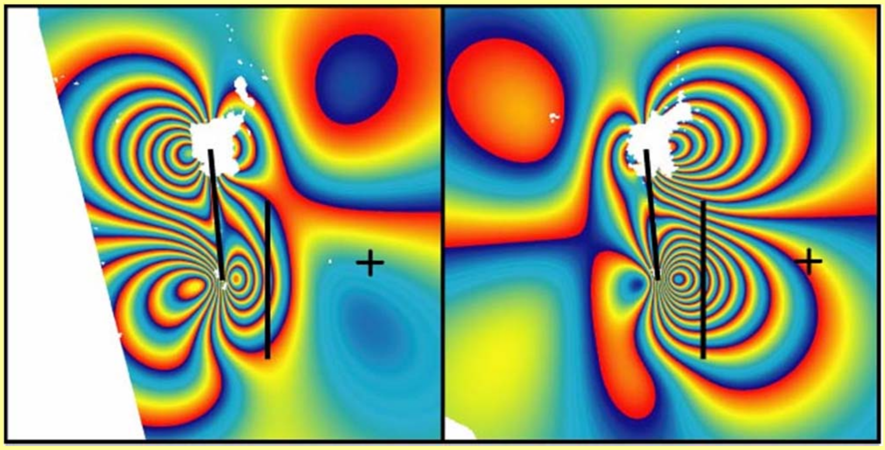
Ascending interferogram Descending interferogram



Two fault model



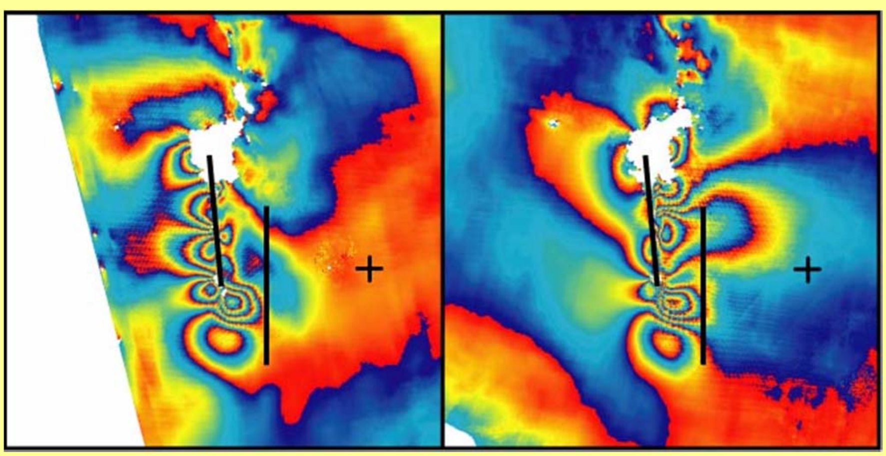
Two fault model (uniform slip)



Ascending model Descending model

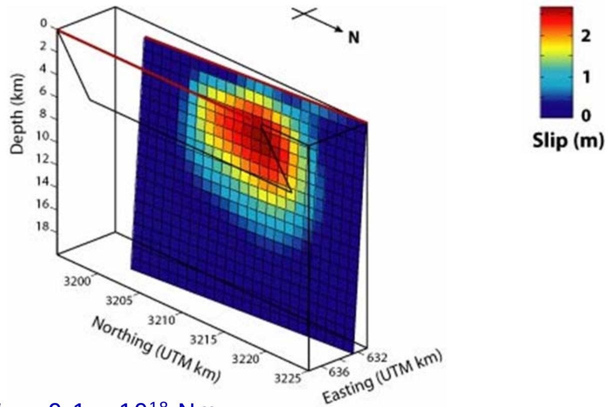
Two fault model (uniform slip)

Improved fit in SE quadrant (rms = 17 mm)



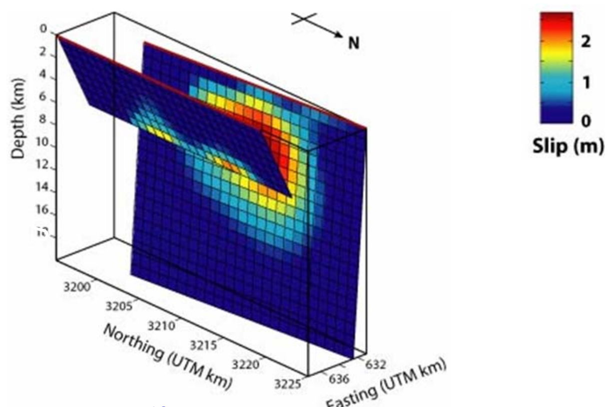
Ascending residual Descending residual

Variable slip model



Main fault, M_0 = 9.1 x 10^{18} Nm

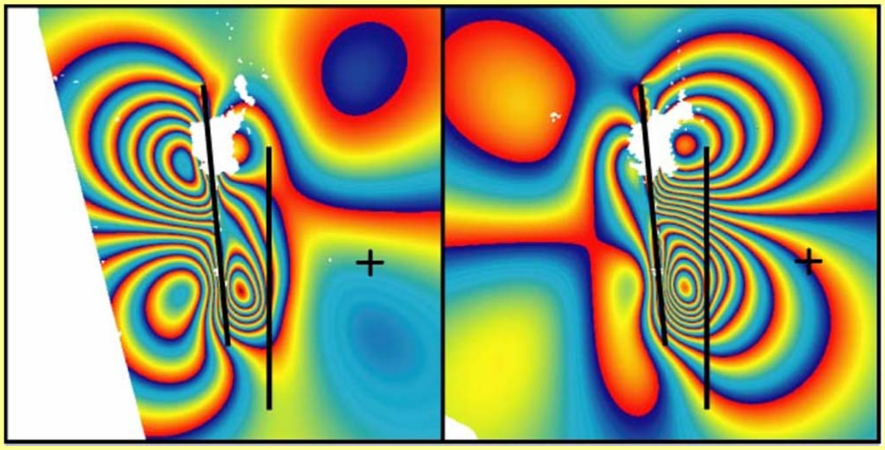
Variable slip model



Main fault, M_0 = 9.1 x 10^{18} Nm

Secondary fault, M_0 = 1.6 x 10^{18} Nm

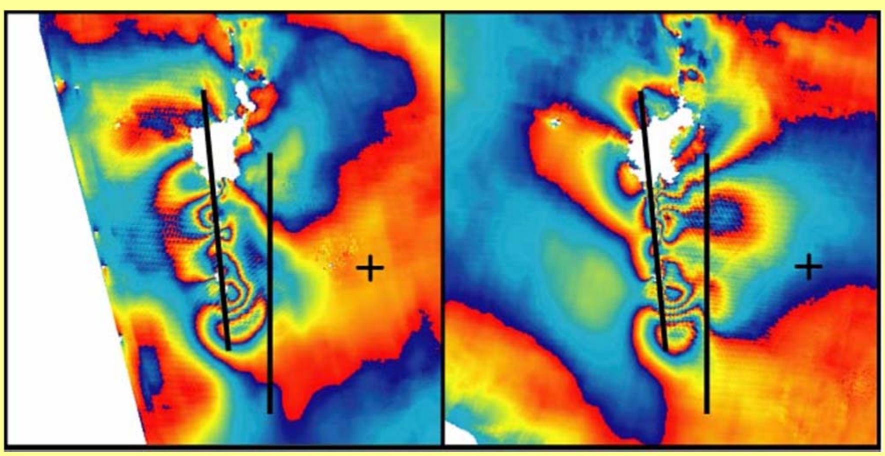
Variable slip model



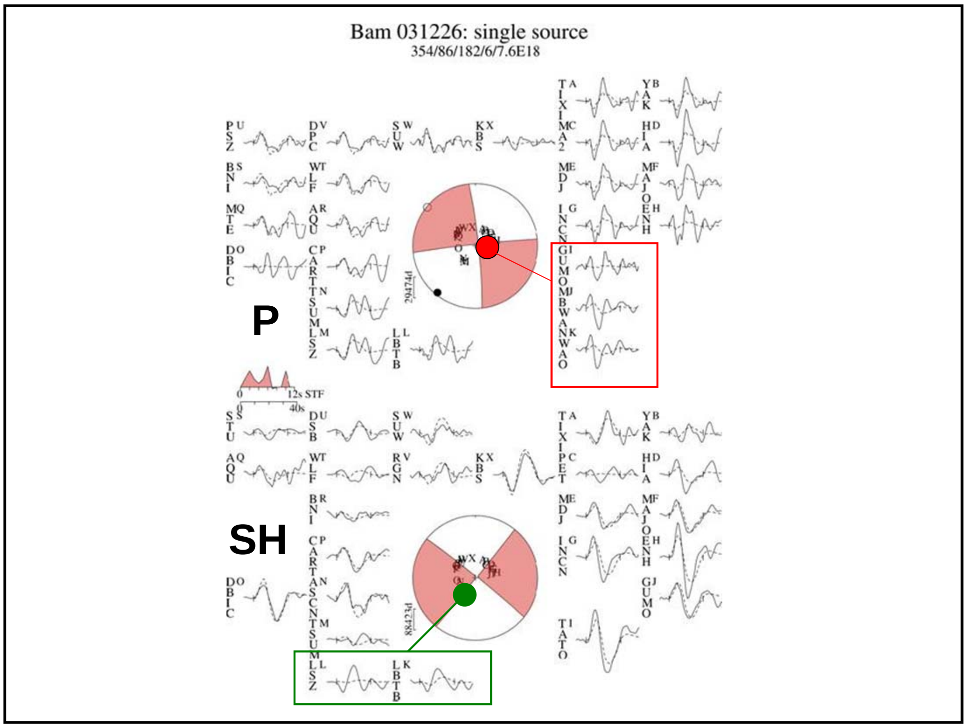
Ascending model | Descending model

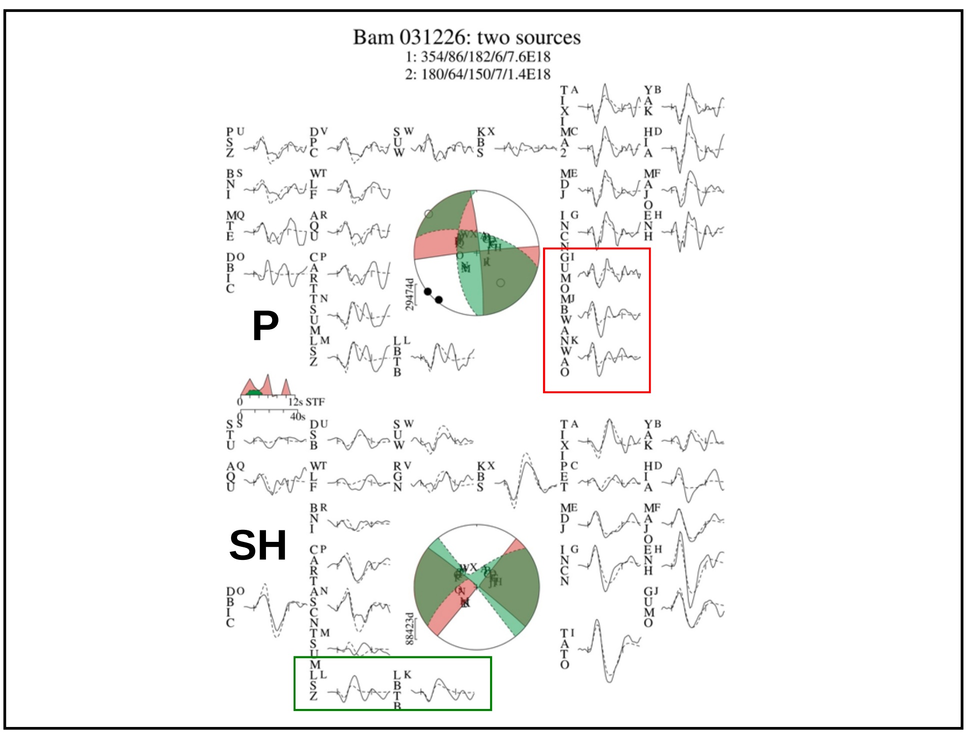
Variable slip model

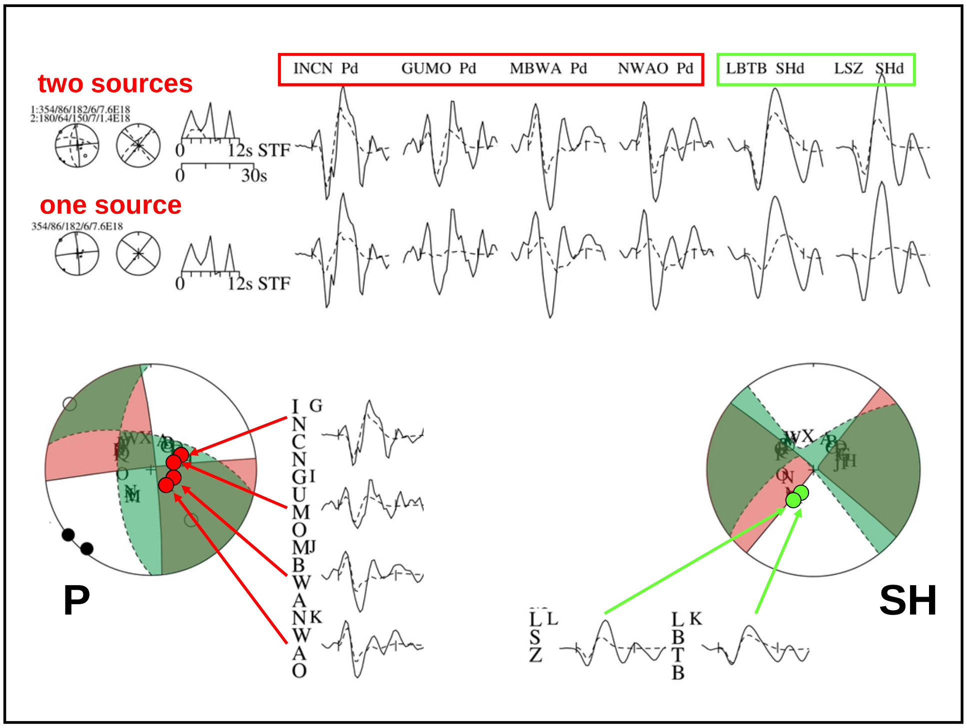
Significantly improved fit (rms = 13 mm)



Ascending residual | Descending residual


Bam 031226: single source
354/86/182/6/7.6E18
P
SH
12s STF
40s

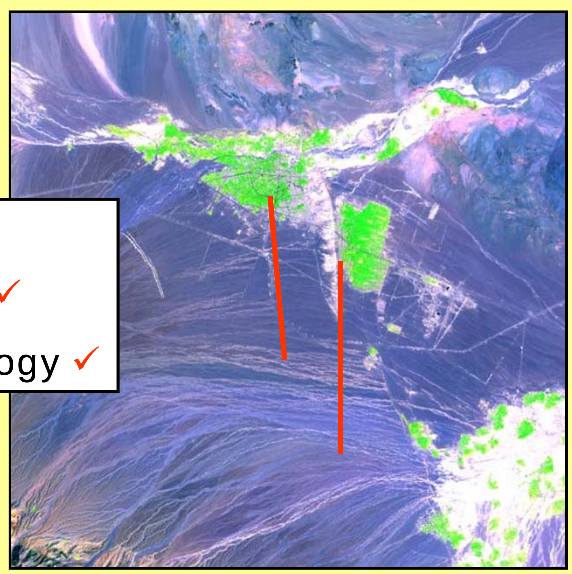

Bam 031226: two sources
1: 354/86/182/6/7.6E18
2: 180/64/150/7/1.4E18
P
SH
12s STF
40s



Two fault model

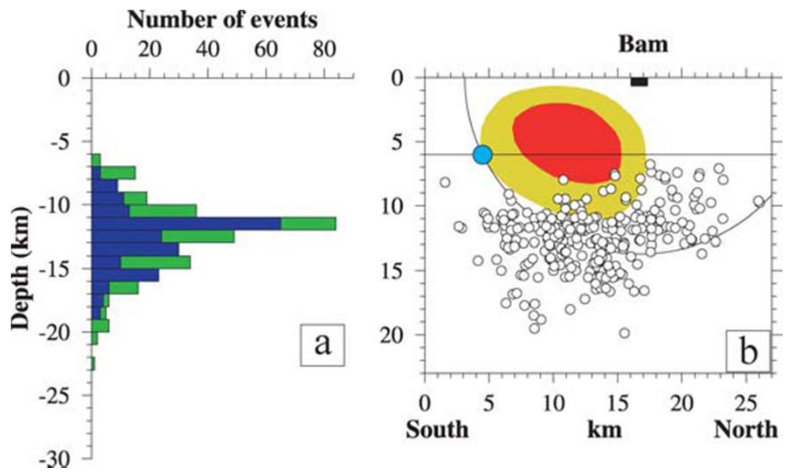
Secondary fault appears to be a southward continuation of the Bam fault

Geodesy ✓
Seismology ✓
Geomorphology ✓

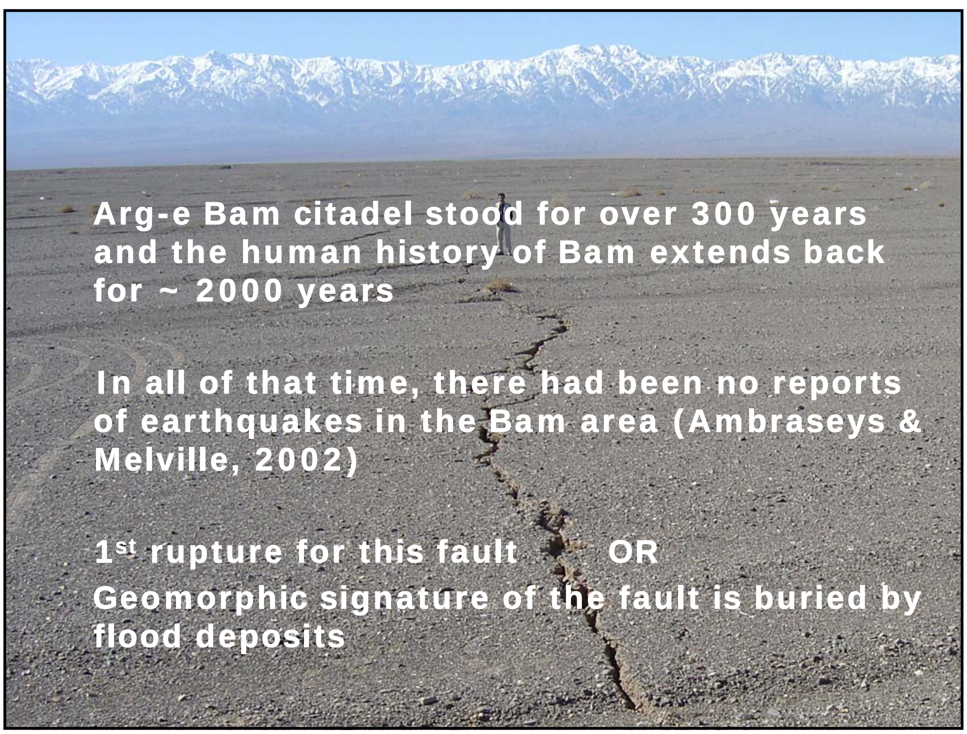


LANDSAT-7 ETM 541 false colour green=vegetation

What is the seismic hazard now in Bam?

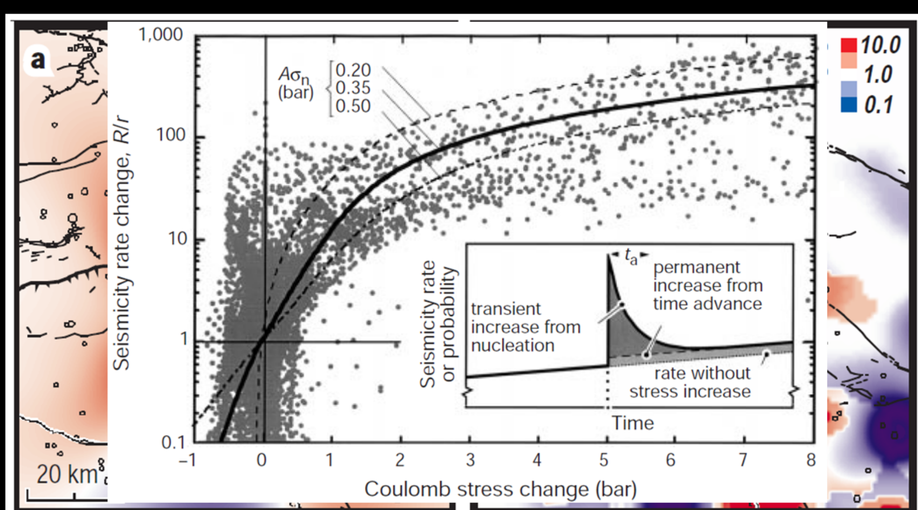



Arg-e Bam citadel stood for over 300 years and the human history of Bam extends back for ~ 2000 years
In all of that time, there had been no reports of earthquakes in the Bam area (Ambraseys & Melville, 2002)


Arg-e Bam citadel stood for over 300 years and the human history of Bam extends back for ~ 2000 years
In all of that time, there had been no reports of earthquakes in the Bam area (Ambraseys & Melville, 2002)
1st rupture for this fault OR
Geomorphic signature of the fault is buried by flood deposits

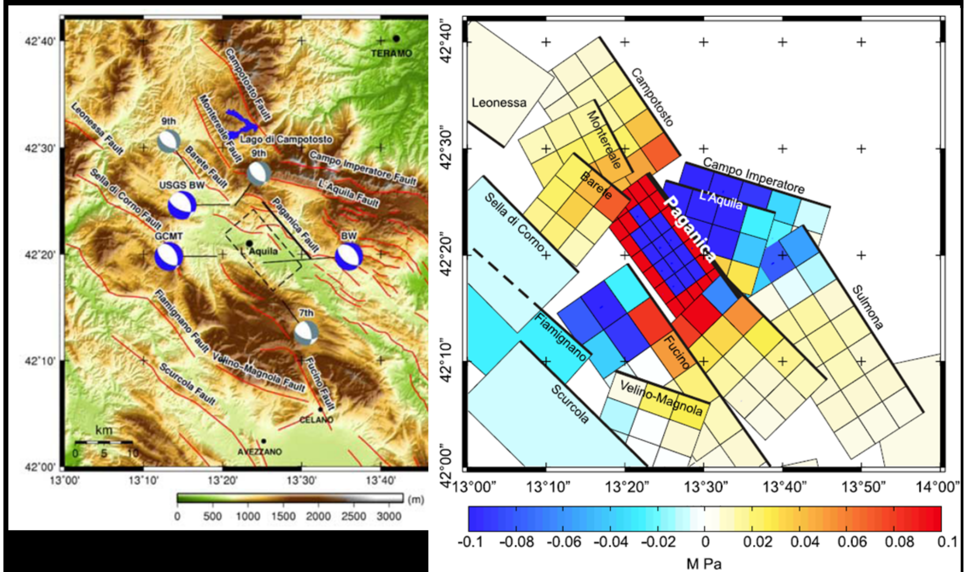
Stress Transfer

Stress changes from the 1994 Northridge Earthquake



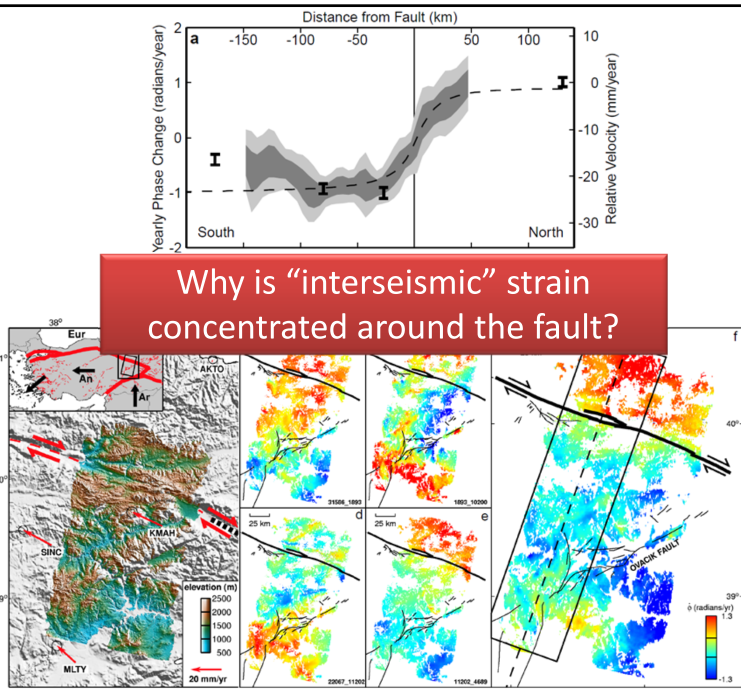
Stein, Nature 1999

The 2009 L'Aquila (Italy) earthquake



Walters et al, GRL 2009

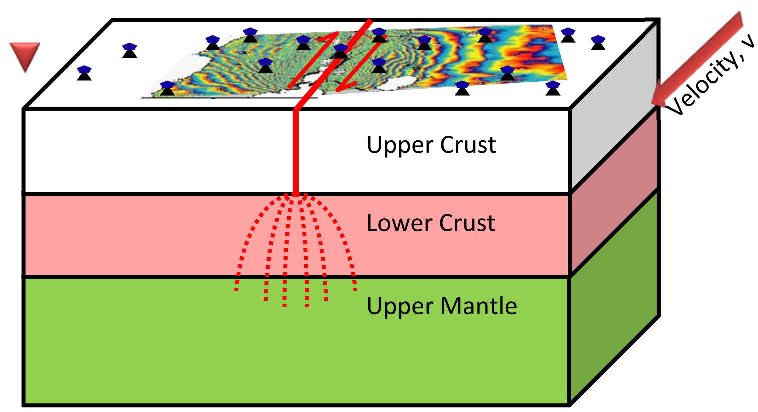
Part 2: Interseismic and Postseismic Deformation



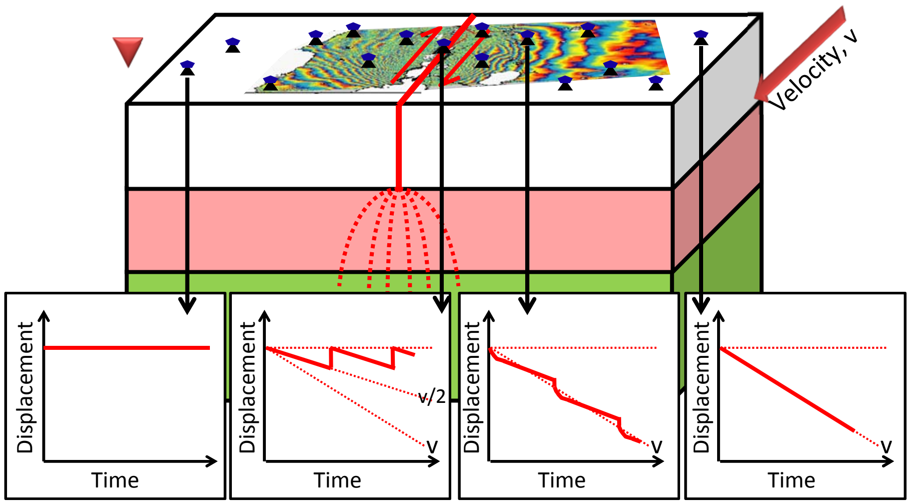
Why is “interseismic” strain concentrated around the fault?

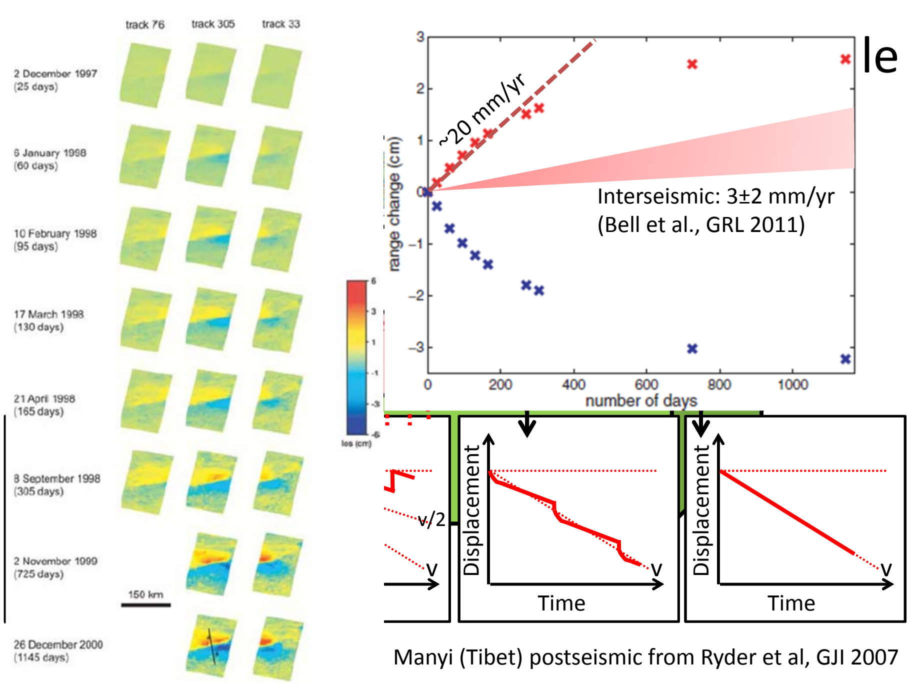
Wright et al., GRL 2001

Intro: The Earthquake Deformation Cycle



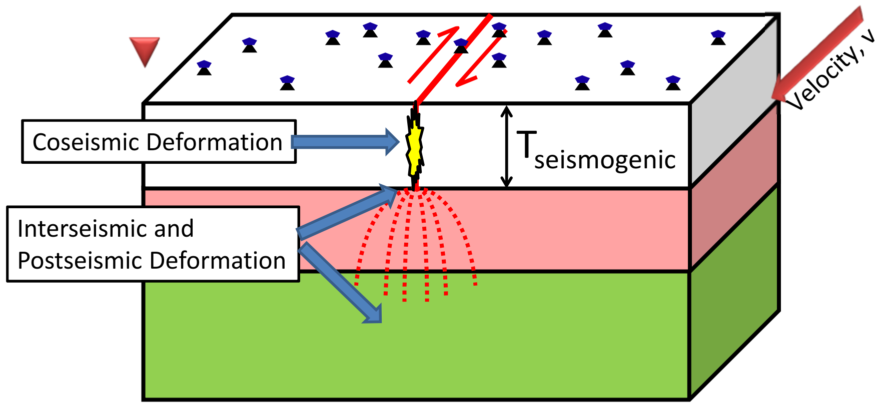
Intro: The Earthquake Deformation Cycle





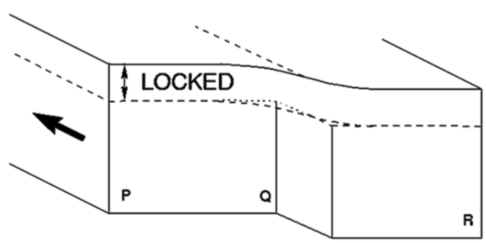
Manyi (Tibet) postseismic from Ryder et al, GJI 2007

Intro: The Earthquake Deformation Cycle



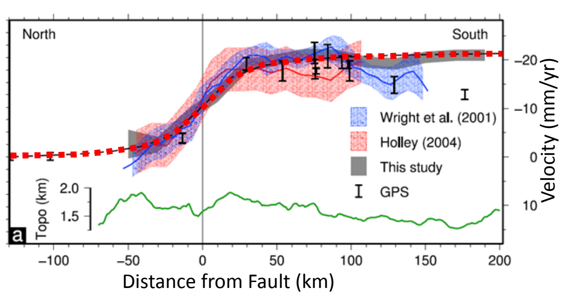
- Spatial pattern ⇨ $T_{seismogenic}$
- Time dependence ⇨ rheology

Interseismic Deformation



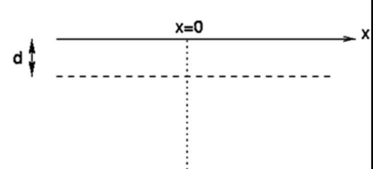
$$y = \frac{s}{\pi} \tan^{-1} \frac{x}{d}$$

Screw dislocation model, after Weertman and Weertman (1964), Savage and Burford (1973)

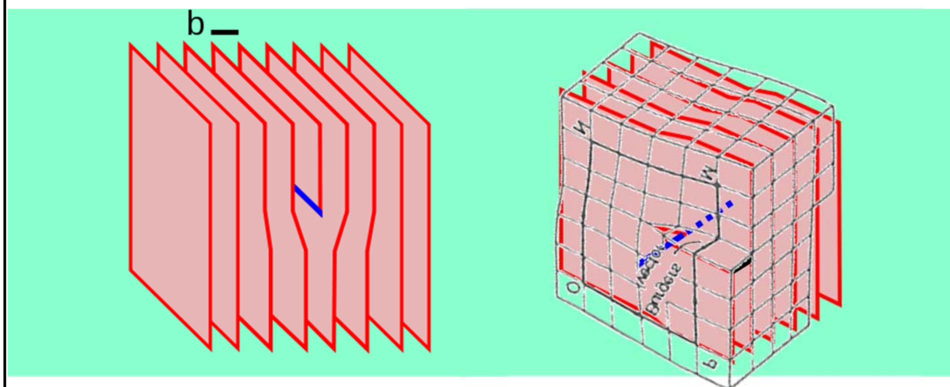


Interseismic deformation across the North Anatolian Fault, from Walters et al (GRL 2011)

Cross section perpendicular to Fault

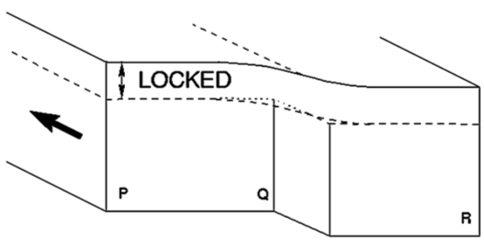


Dislocations in Crystals



Edge dislocation	Screw dislocation
• Extra plane of crystals inserted into lattice	• Extra plane of crystals inserted into lattice
• Dislocation line (blue) perpendicular to Burger's vector (black)	• Dislocation line (blue) parallel to Burger's vector (black)
• Large scale analogy – dyke intrusions	• Large scale analogy – faults

Interseismic Deformation



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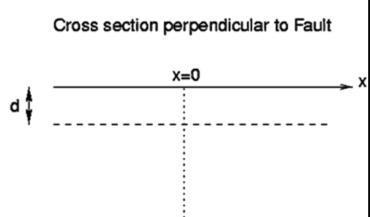
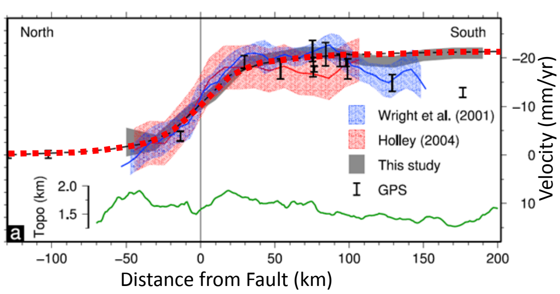
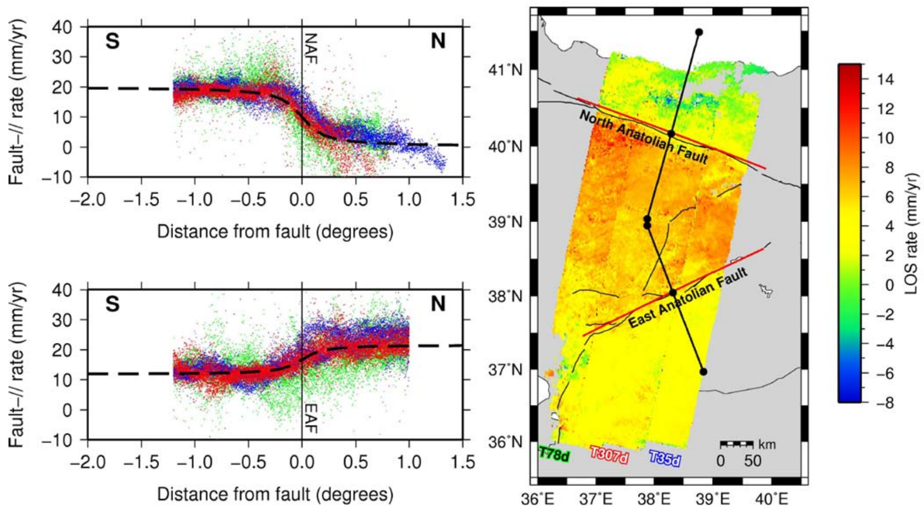
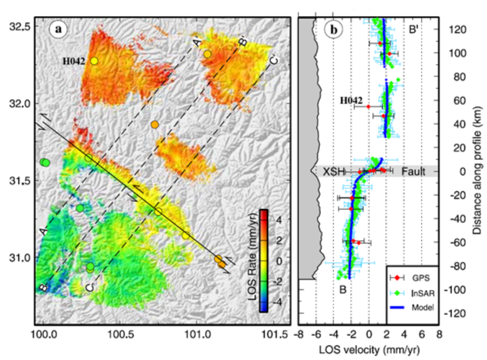




Interseismic deformation across the North Anatolian Fault, from Walters et al (GRL 2011)

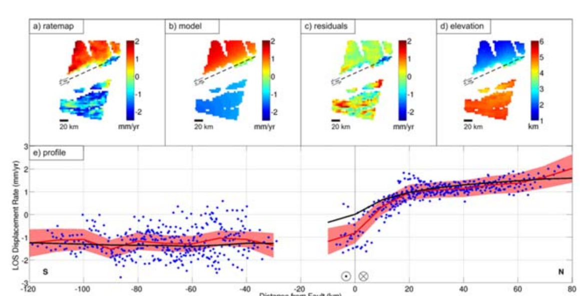
North and East Anatolian Fault (Richard Walters, PhD 2013)



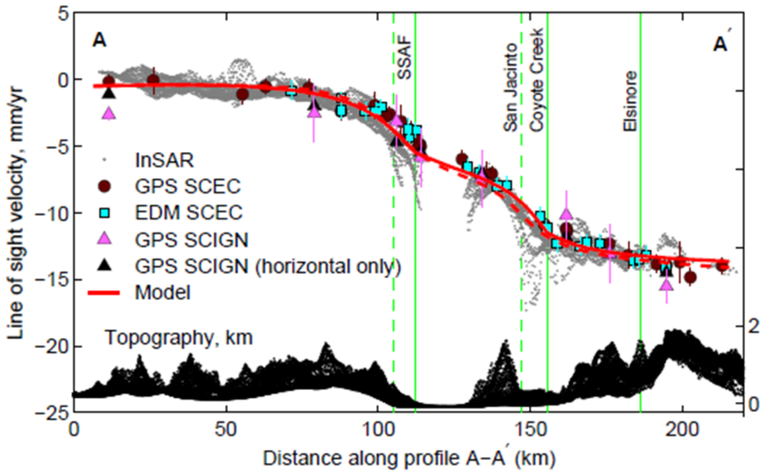


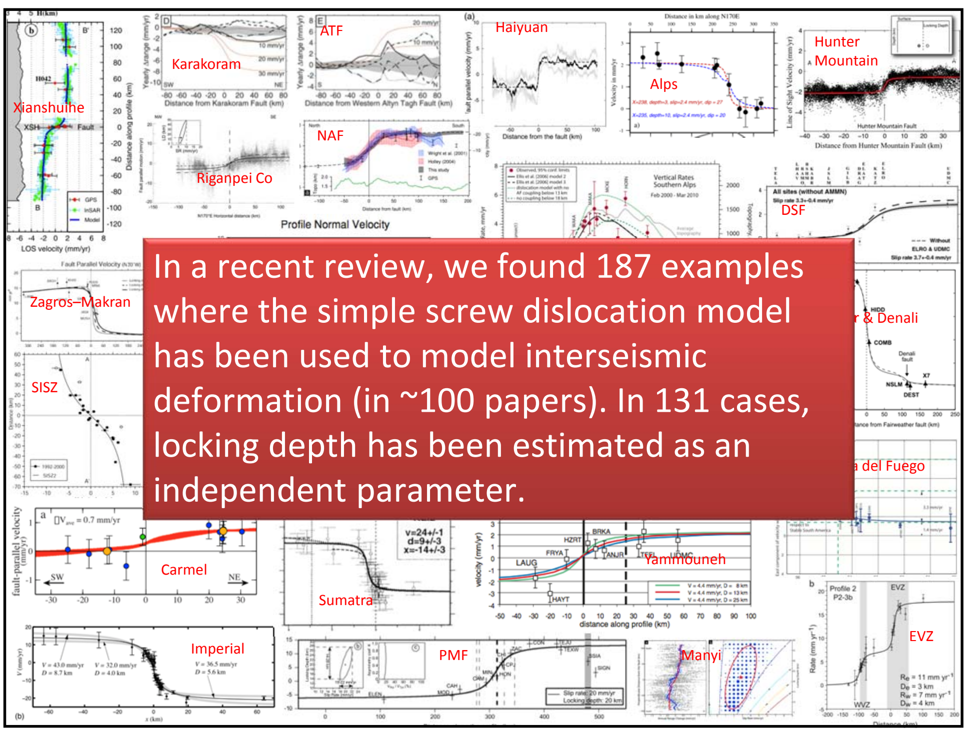
Xianshuihe Fault, East Tibet
Wang et al. (GRL, 2008)

Altyn Tagh Fault, Tibet
Elliott et al. (GRL, 2008)



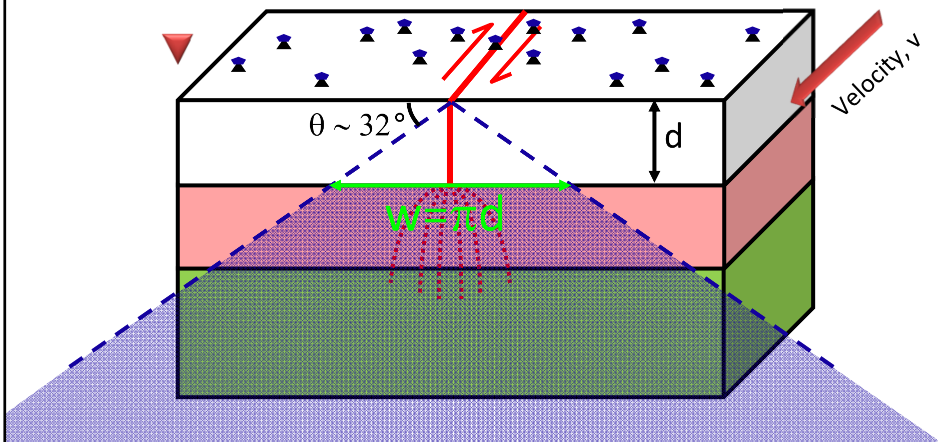
San Andreas Fault Zone (Fialko, Nature 2006)





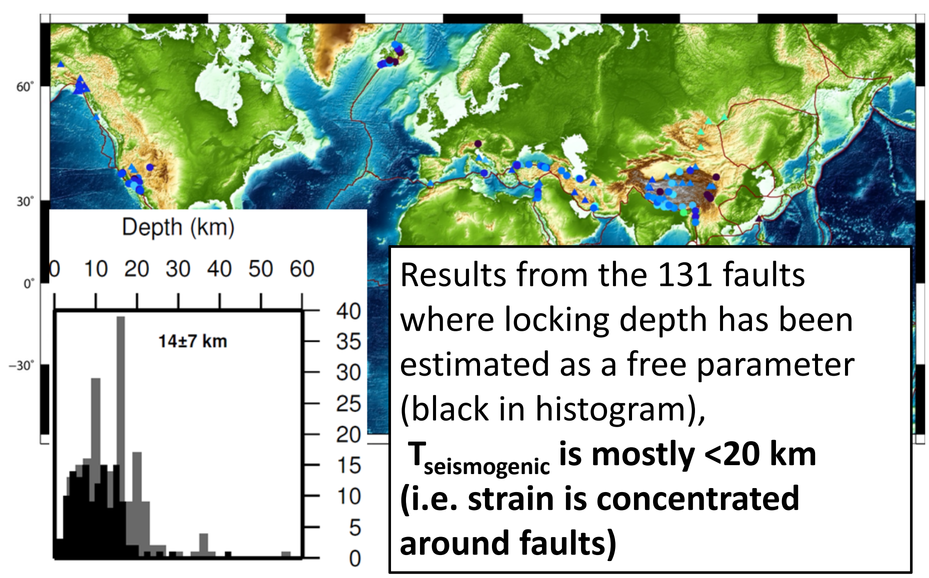
In a recent review, we found 187 examples where the simple screw dislocation model has been used to model interseismic deformation (in ~100 papers). In 131 cases, locking depth has been estimated as an independent parameter.

Interseismic Deformation



All anti-symmetric deformation in the blue zone gives surface motions that indistinguishale from slip on a single deep fault.

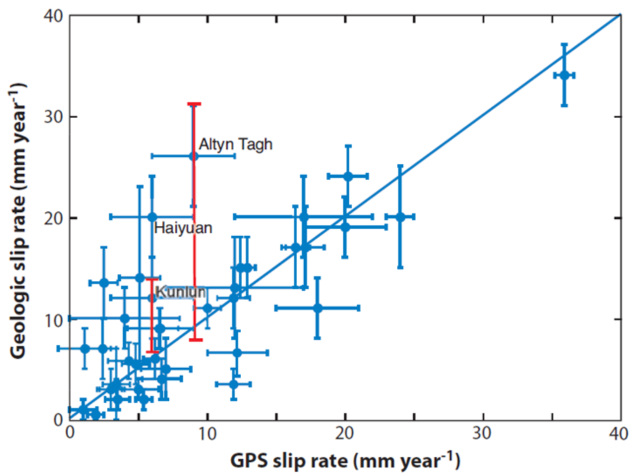
Interseismic Deformation



Results from the 131 faults where locking depth has been estimated as a free parameter (black in histogram),

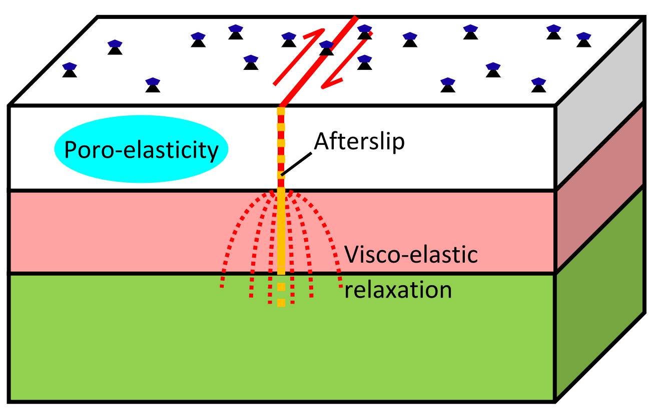
$T_{seismogenic}$ is mostly <20 km (i.e. strain is concentrated around faults)

Geologic vs Geodetic rates for major faults

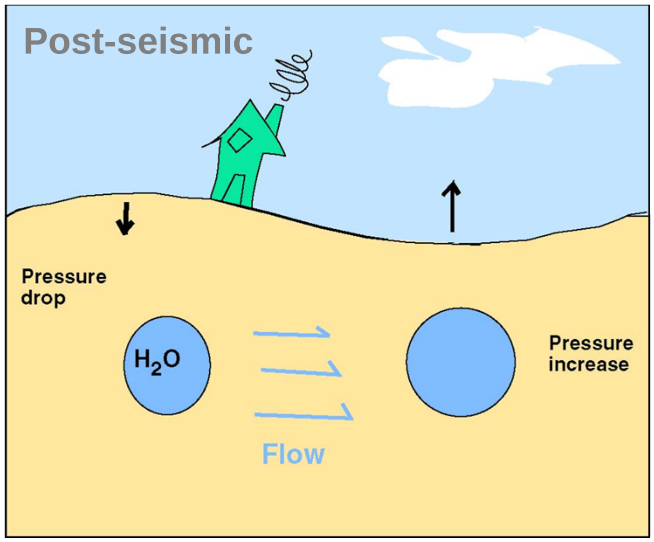


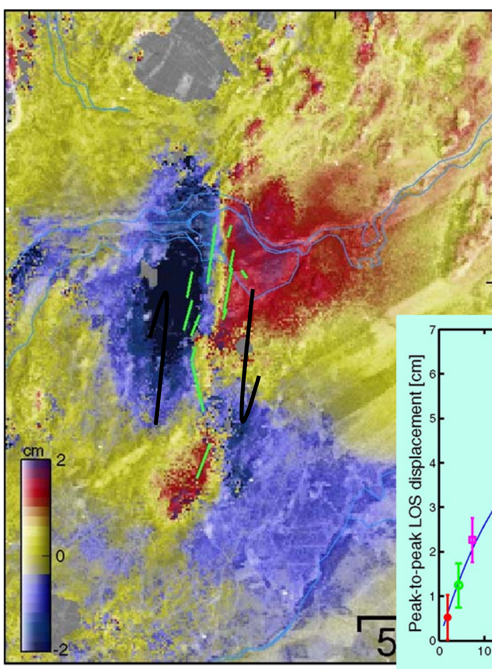
Thatcher, Annual Reviews 2009

Postseismic Deformation



Poro-elastic rebound

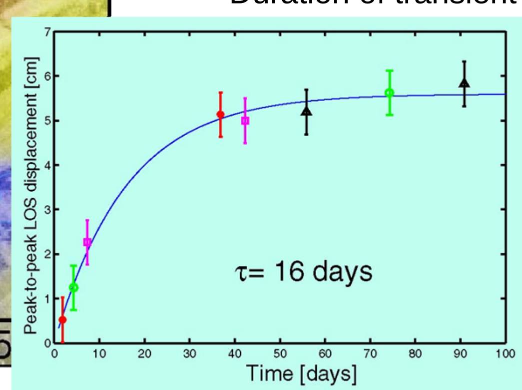




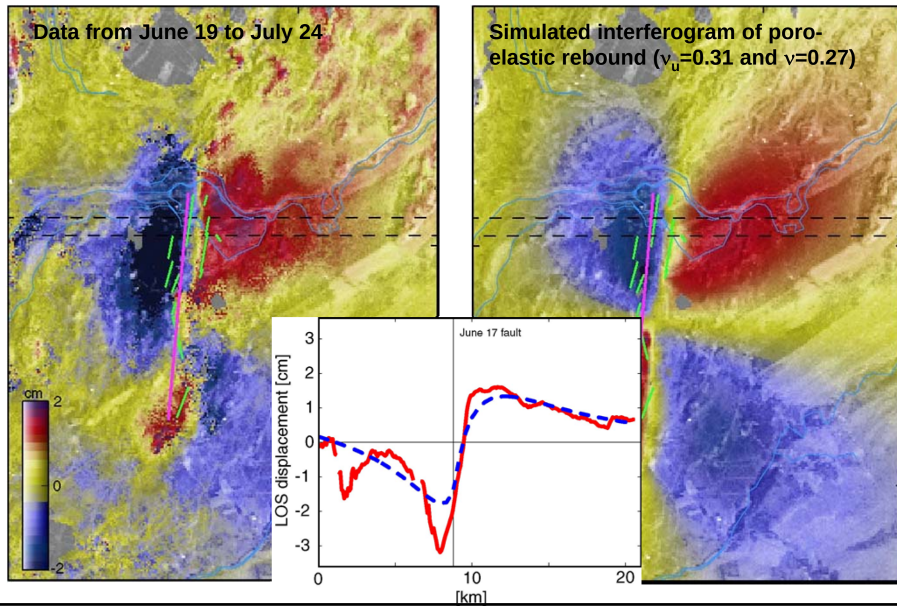
Post-seismic deformation during June 19 – July 24

2-37 days after earthquake

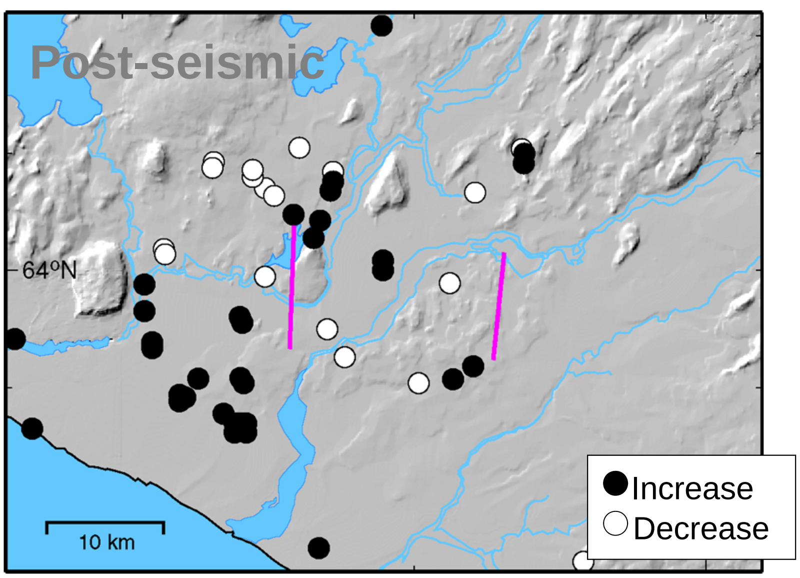
Duration of transient



Poro-elastic rebound near the June 17 fault

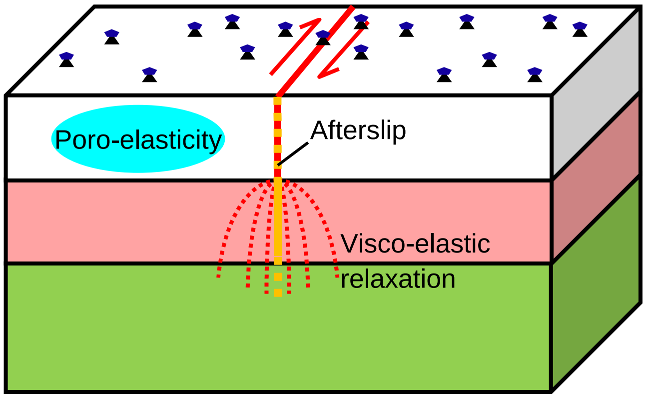


Water Level Changes in Geothermal Wells



Jónsson et al., Nature, 2003

Postseismic Deformation



Denali Earthquake

USGS Press Release

3 November 2002. M_w 7.9.

340 km rupture on Denali, Susitna Glacier and Totshunda Faults.

Max. offset = 9m.

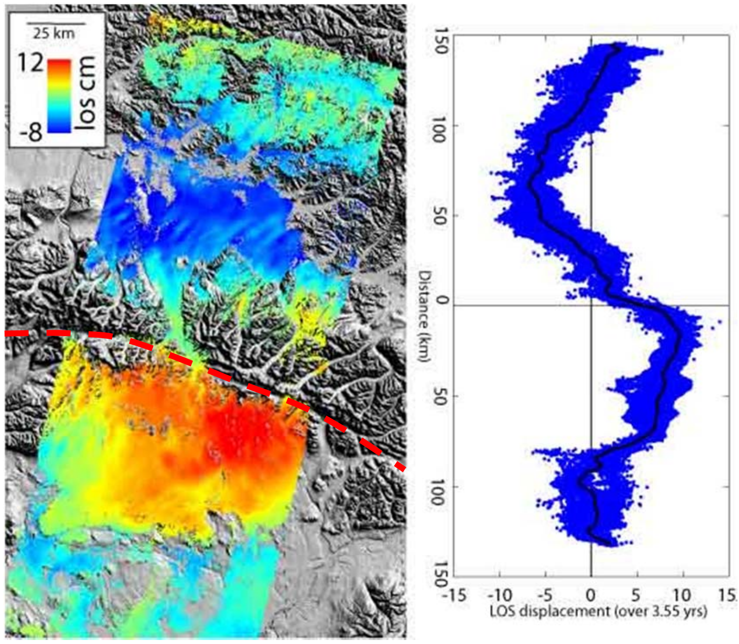
Denali Earthquake

Trans Alaska Pipeline and Richardson Highway

Denali Earthquake

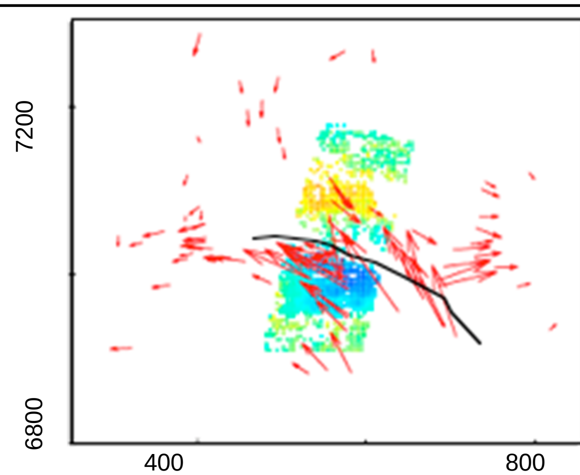
Trans Alaska Pipeline

Richardson Highway



Summer 2003 (8 months) - Summer 2004 (20 months)

Biggs et al, 2009



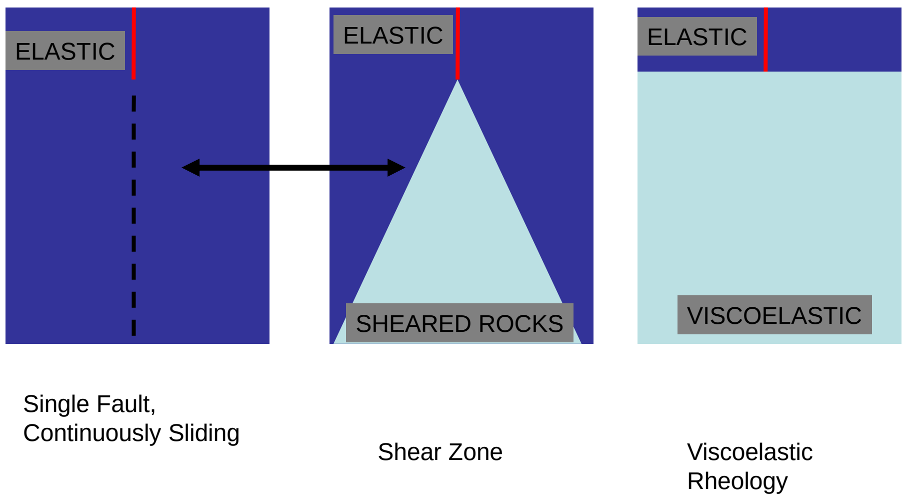
INSAR:

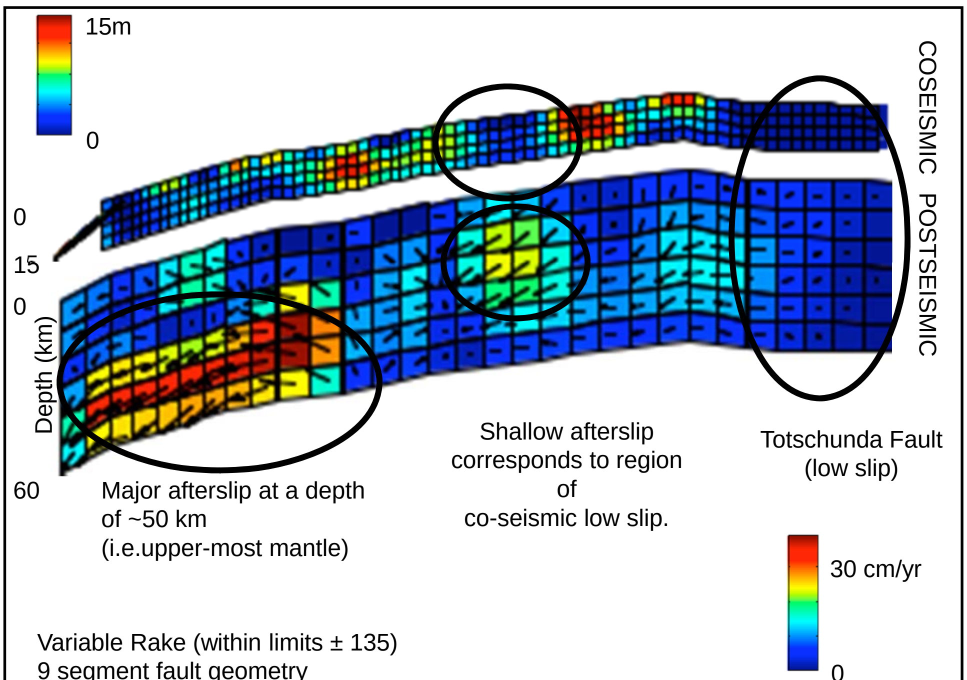
- Sub-sampled (1185 pts)
- Satellite line of sight (~23^{o} to vertical)

GPS:

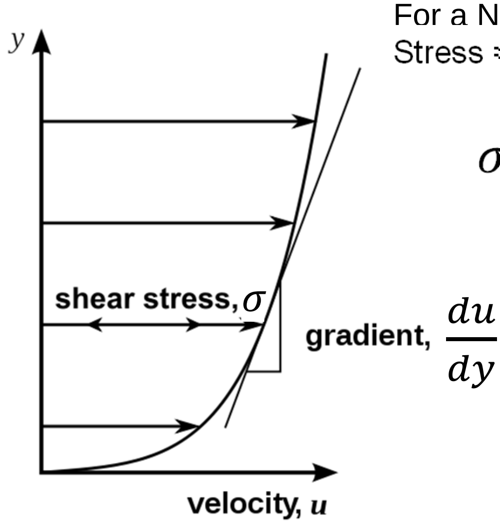
- 86 sites (errors < 1cm/yr)
- East and North components
- Corrected for interseismic vel. (Elliott et al)

What happens under the seismogenic layer?





Viscosity



For a Newtonian (linear) viscous fluid,
Stress = viscosity x strain rate

$$\sigma = \eta\dot{\varepsilon} = \eta\frac{du}{dy}$$

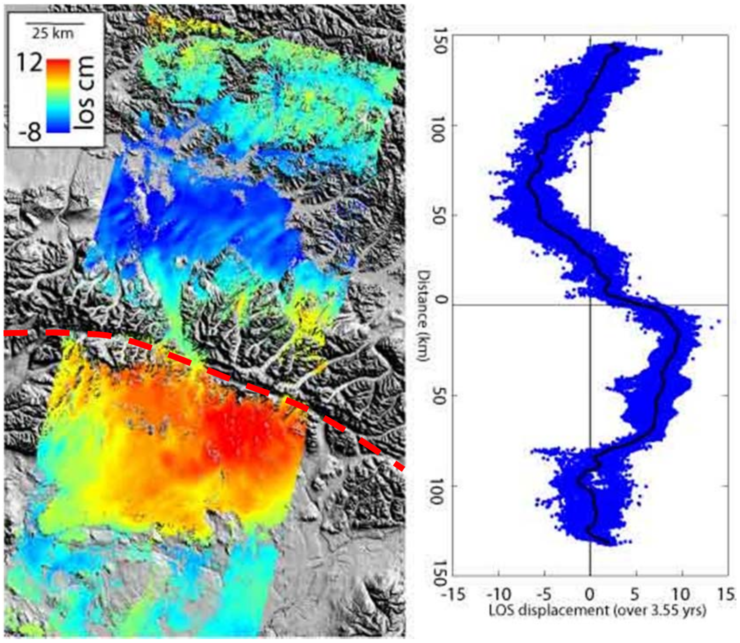
Stress Diffusion

- For an elastic lid over a viscous channel, we can show that the deformation at the surface obeys the diffusion equation.
- Hence solution is identical to heat flow in the oceans.

Denali Earthquake

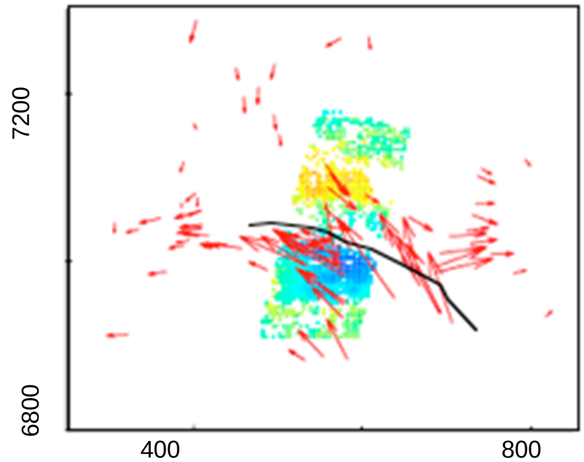
Trans Alaska Pipeline

Richardson Highway



Summer 2003 (8 months) - Summer 2004 (20 months)

Biggs et al, 2009



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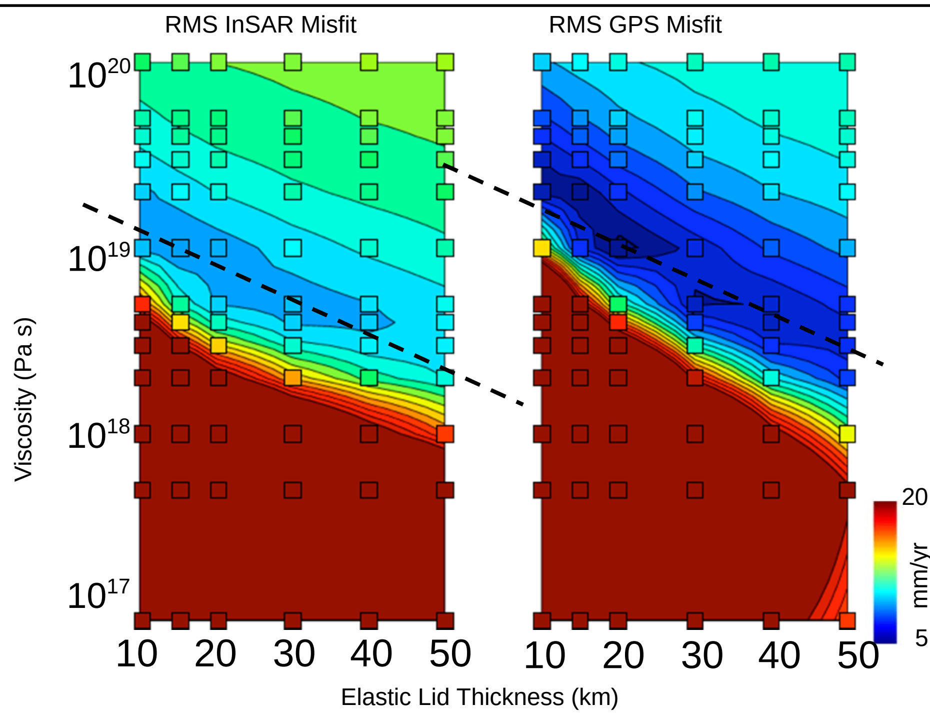
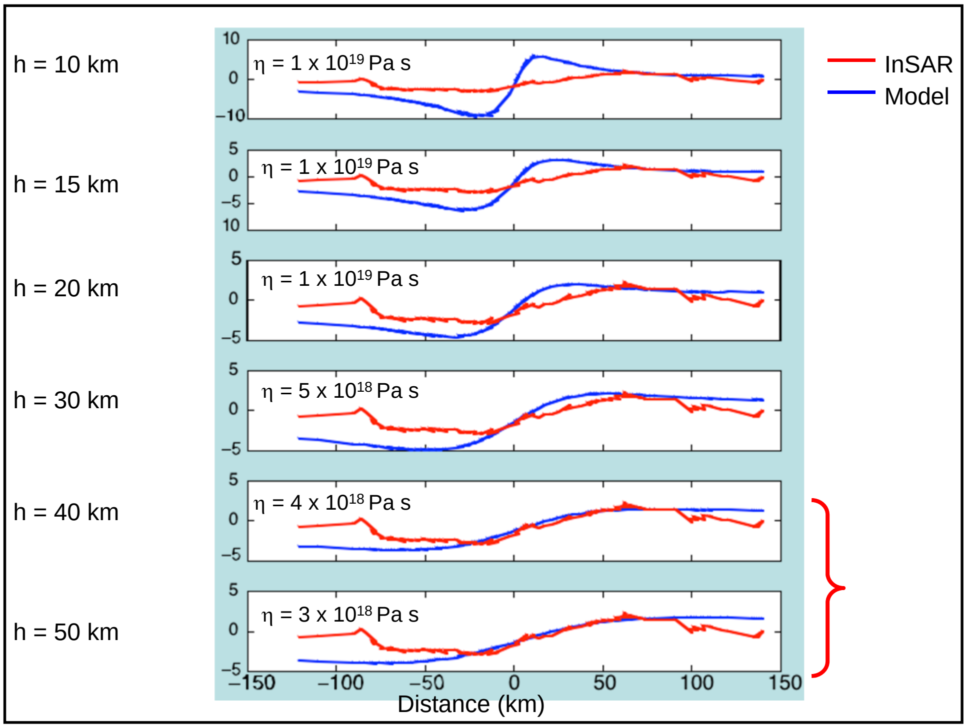
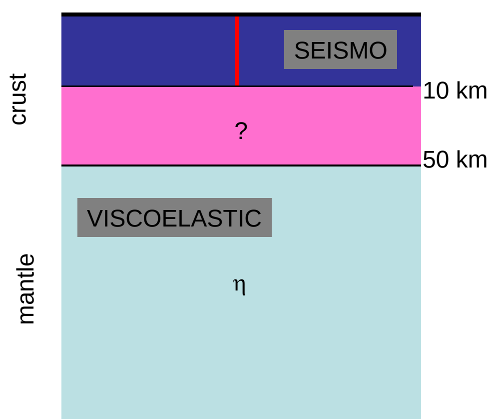




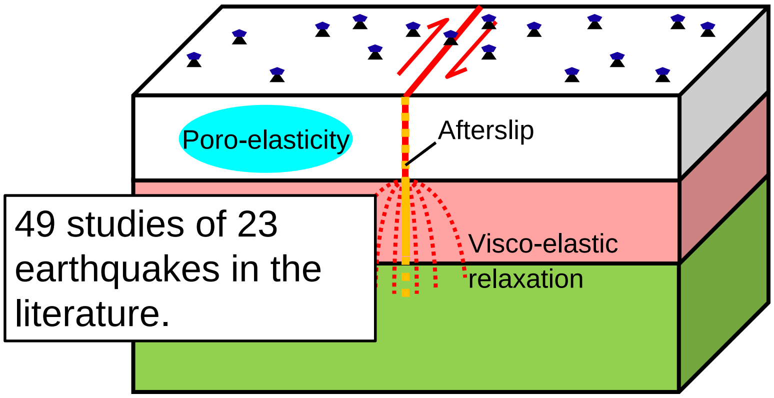
What is the elastic lid?



Elastic lid does not necessarily corresponds to seismogenic layer.

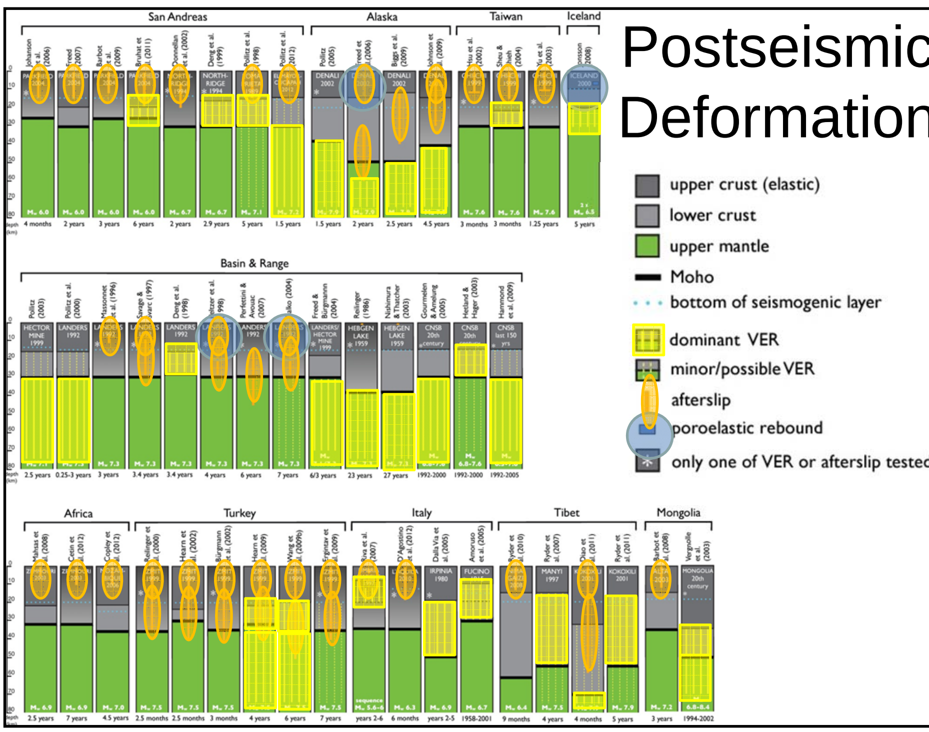
In this case, the lower crust is elastic, or at least has a higher viscosity than the upper mantle.

Postseismic Deformation

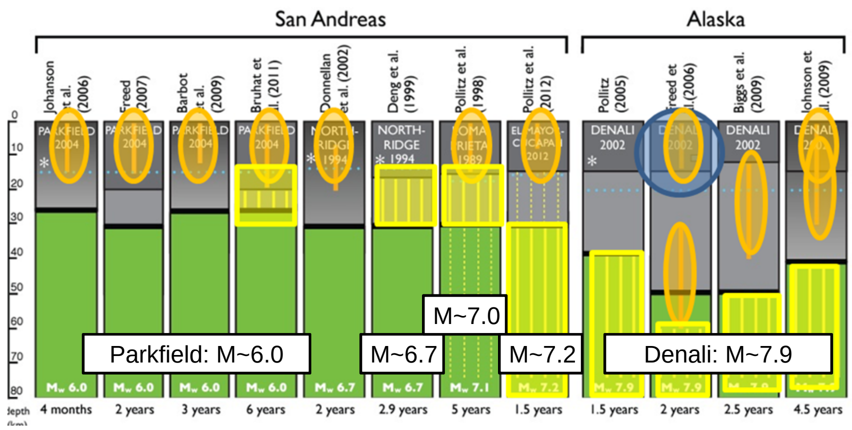


49 studies of 23 earthquakes in the literature.

Postseismic Deformation

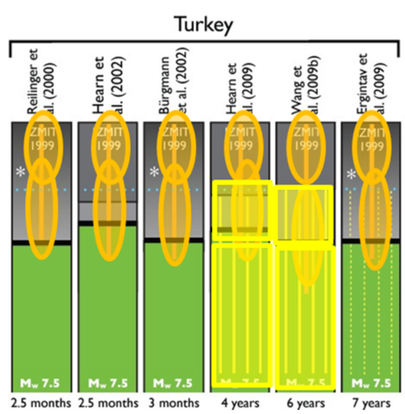


Postseismic Deformation



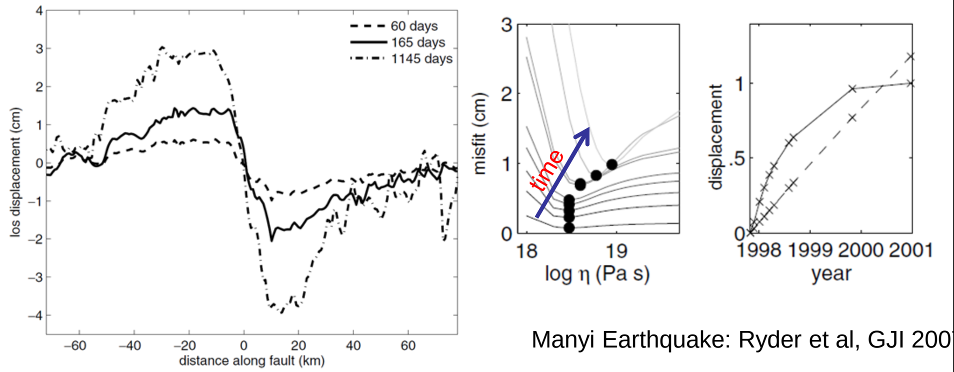
• Inferred mechanisms vary as a function of the size of the earthquake: small earthquakes do not cause deep flow

Postseismic Deformation



• Inferred mechanisms and timescales vary as a function of the time period of observation

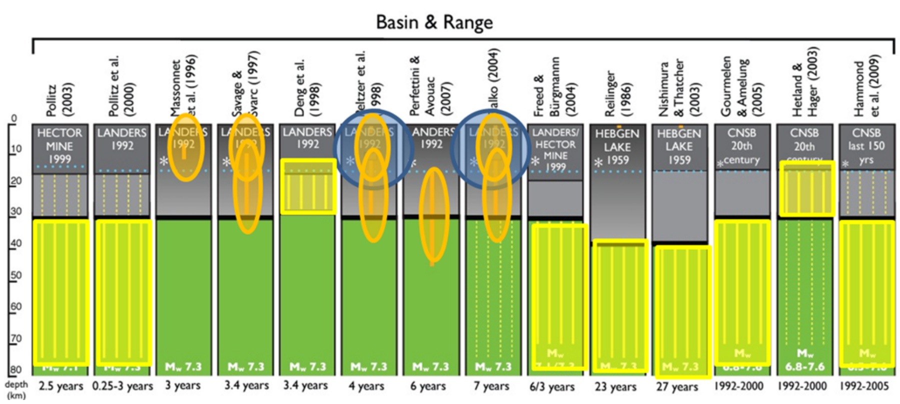
Postseismic Deformation



Manyi Earthquake: Ryder et al, GJI 200

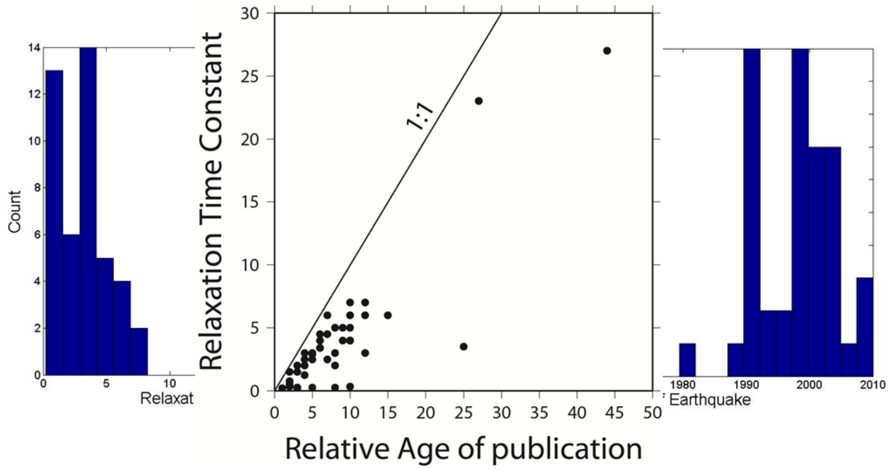
• Inferred mechanisms and timescales vary as a function of the time period of observation

Postseismic Deformation

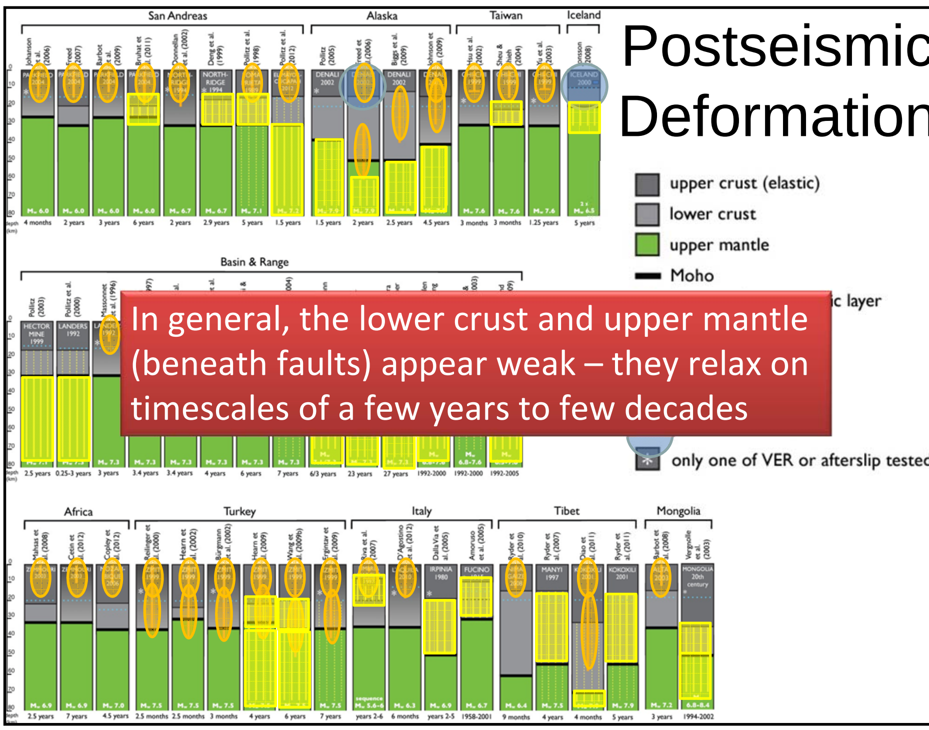


• Inferred mechanisms and timescales vary as a function of the time period of observation

Postseismic Deformation



Postseismic Deformation



In general, the lower crust and upper mantle (beneath faults) appear weak – they relax on timescales of a few years to few decades

Summary of Observations

Coseismic deformation:

Earth behaves elastically

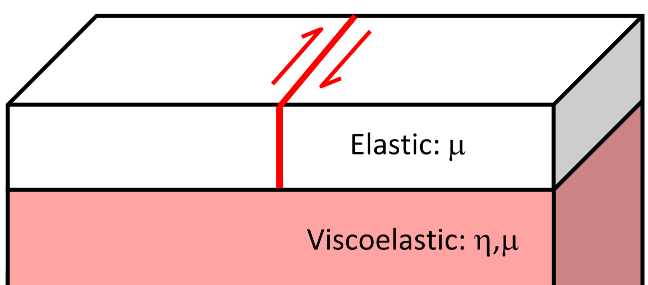
Interseismic deformation:

Strain is focussed around major faults

Postseismic deformation:

Rapid deformation transients occur

Simplest earthquake cycle model

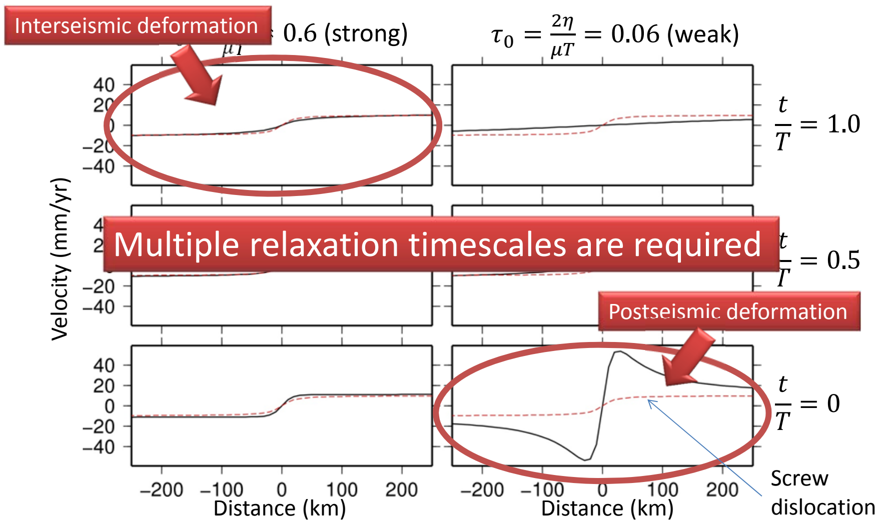


Key parameter is the ratio (τ_0) between Maxwell relaxation time, ($2\eta/\mu$), and earthquake repeat time (T):

$$\tau_0 = \frac{2\eta}{\mu T}$$

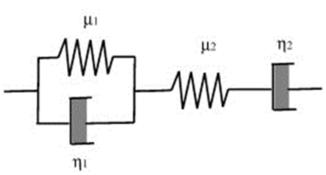
Viscoelastic coupling model, Savage & Prescott 1978; Savage 2000

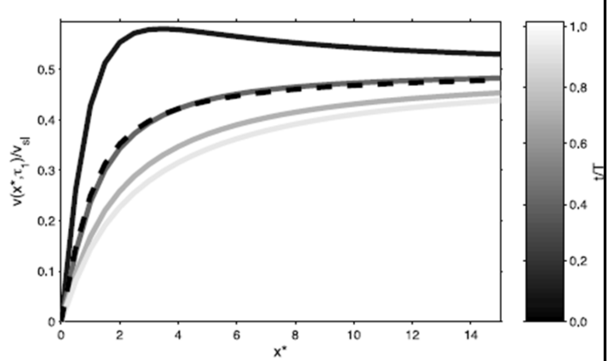
Simplest earthquake cycle model



Viscoelastic coupling model, Savage & Prescott 1978; Savage 2000

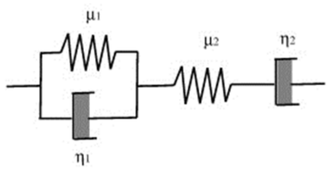
Alternatives: 1. Burger's body rheology

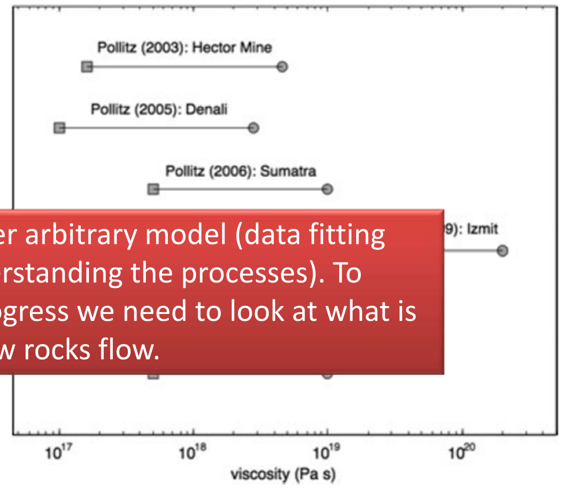




Hetland and Hager, JGR 2005

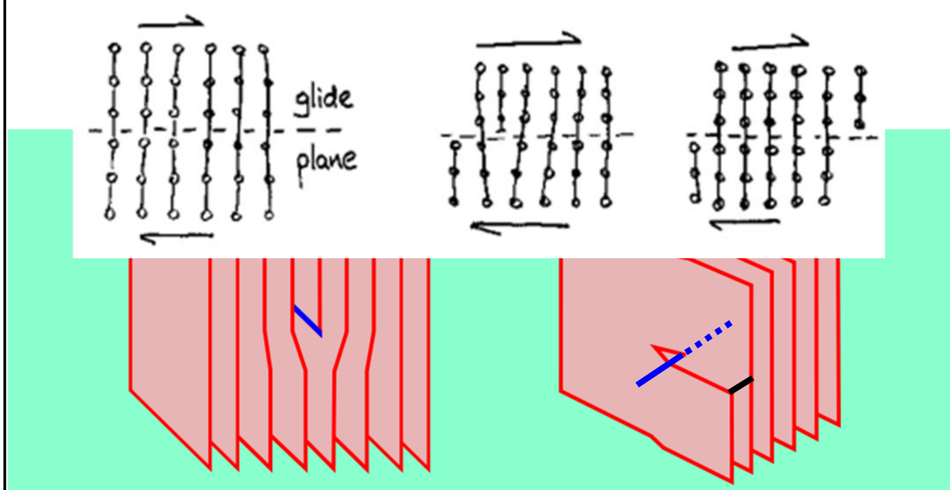
Alternatives: 1. Burger's body rheology





But this is a rather arbitrary model (data fitting rather than understanding the processes). To make further progress we need to look at what is known about how rocks flow.

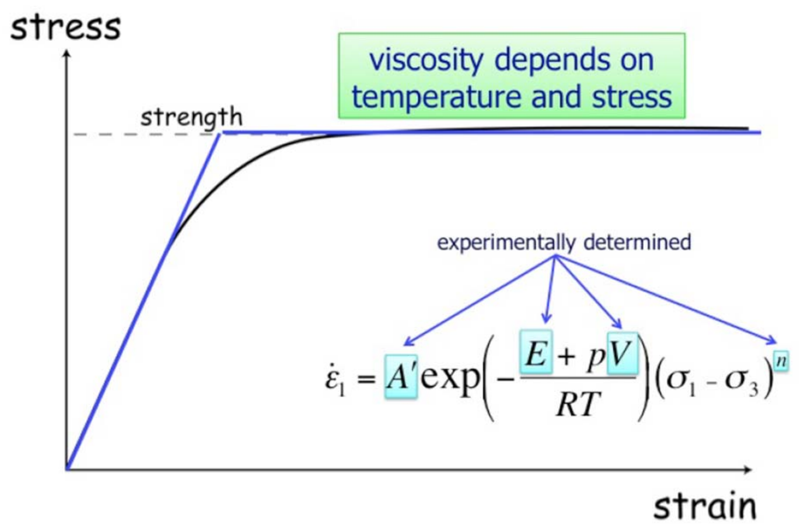
Ryder et al, GJI 2011



- Occurs when dislocation lines move through the crystal lattice
- Plane along which the movement takes place is called a glide plane
- Strain rate is dependent on $(\text{stress})^n$, hence sometimes called "power-law creep"

[Cartoon from http://ijolite.geology.uiuc.edu/07fallclass/geo411/Ductile/ductile.html]

Viscous flow by *power-law creep*

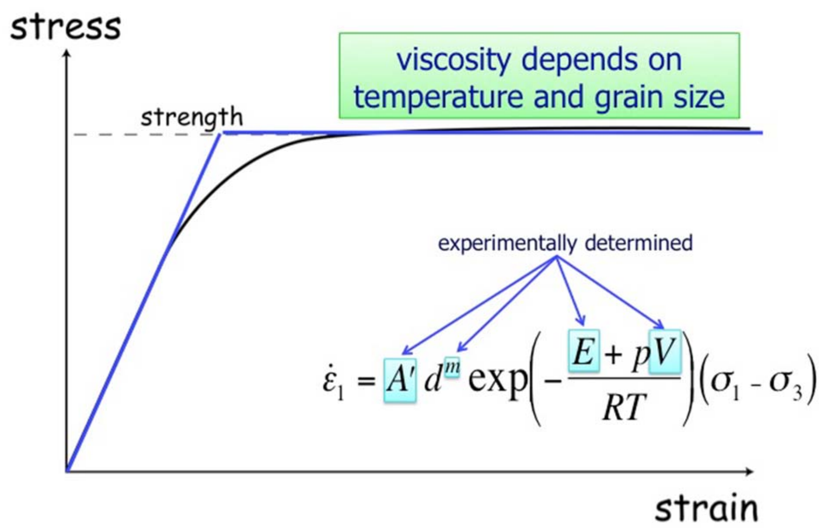


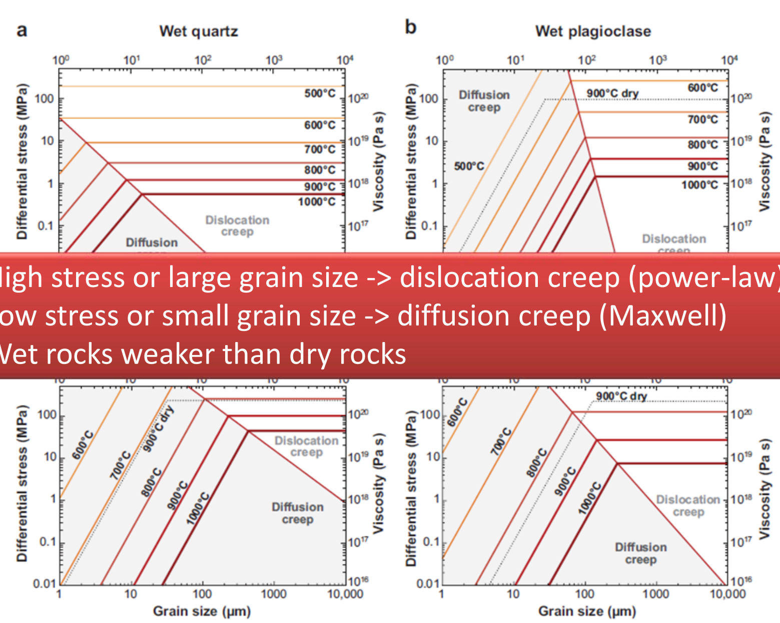
Diffusion Creep

- Point defects come in three basic forms:
  (i) Vacancies (where an atom is missing from the lattice, leaving a hole)
  (ii) Interstitial defects (where an extra atom is inserted into the lattice)
  (iii) Substitutional defects (where a different atom replaces what should be there, inducing strain in the crystal lattice)
- Defects move through crystal by diffusion – thermally activated process.
- Linearly dependent on stress, but grain size is important

[Cartoon from http://ijolite.geology.uiuc.edu/07fallclass/geo411/Ductile/ductile.html]

Viscous flow by *diffusion creep*





High stress or large grain size -> dislocation creep (power-law)
Low stress or small grain size -> diffusion creep (Maxwell)
Wet rocks weaker than dry rocks

Strain rates 10^{-12} s^{-1}; Burgmann and Dresen, Ann Rev 2008

Laboratory experiments

Deviatoric stress, Water fugacity, Pressure, Deviatoric strain rate, Grain size, Activation energy, Activation volume

$$\dot{\varepsilon} = A\sigma^n d^{-m} f_{H_2O}^r \exp\left(-\frac{Q+pV}{RT}\right)$$

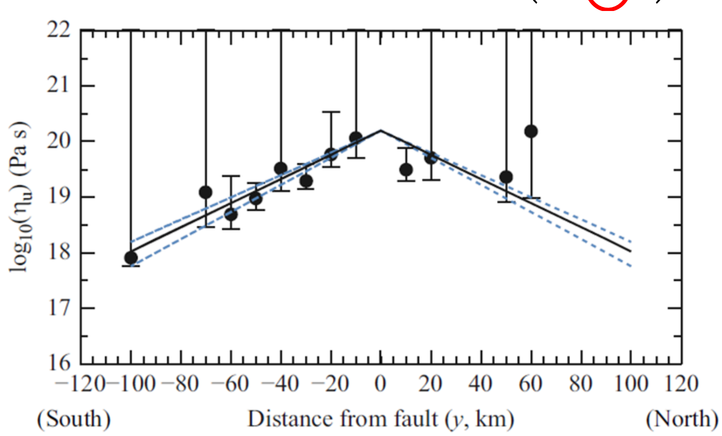
Temperature

$$\eta_{eff} = \frac{\sigma}{\dot{\varepsilon}} = A^{-1}\sigma^{1-n} d^m f_{H_2O}^{-r} \exp\left(\frac{Q+pV}{RT}\right)$$

"Effective viscosity"

Temperature (Depth) dependence

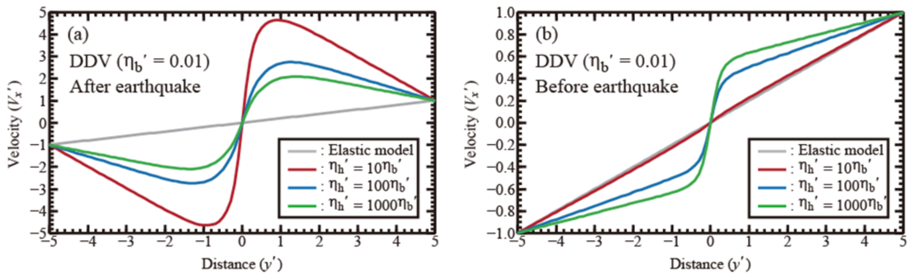
$$\eta_{eff} = A^{-1}\sigma^{1-n} d^m f_{H_2O}^{-r} \exp\left(\frac{Q+pV}{RT}\right)$$



Yamasaki and Houseman, EPSL 2012

Temperature (Depth) dependence

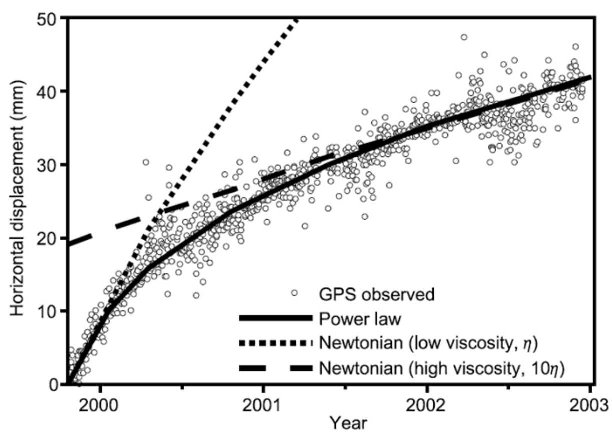
$$\eta_{eff} = \mathrm{A}^{-1}\sigma^{1-n} d^{m} f_{H_2O}^{-r} \exp\left(\frac{Q+pV}{RT}\right)$$



Yamasaki , Wright and Houseman, in prep 2013

Power-law

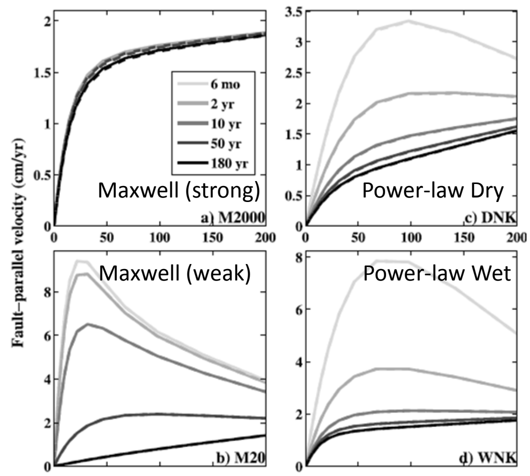
$$\eta_{eff} = \mathrm{A}^{-1}\sigma^{1-n} d^{m} f_{H_2O}^{-r} \exp\left(\frac{Q+pV}{RT}\right)$$



n~3-3.5: Freed and Burgmann, Nature 2004

Power-law

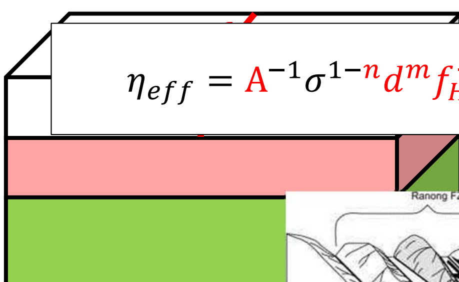
$$\eta_{eff} = A^{-1}\sigma^{1-n}d^{m}f_{H_2O}^{-r}\exp\left(\frac{Q+pV}{RT}\right)$$



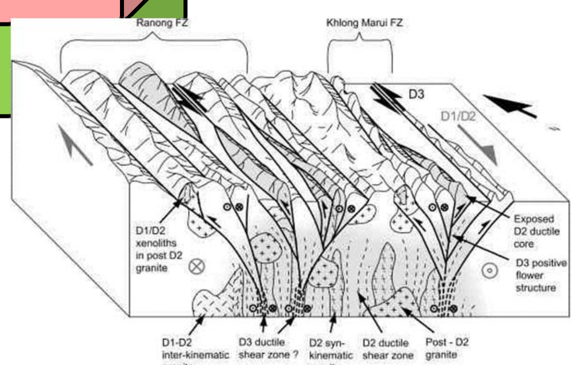
Takeuchi and Fialko (JGR, 2012) Earthquake cycle with power law + Temperature dependence

Spatial variations in properties

$$\eta_{eff} = A^{-1}\sigma^{1-n}d^{m}f_{H_2O}^{-r}\exp\left(\frac{Q+pV}{RT}\right)$$

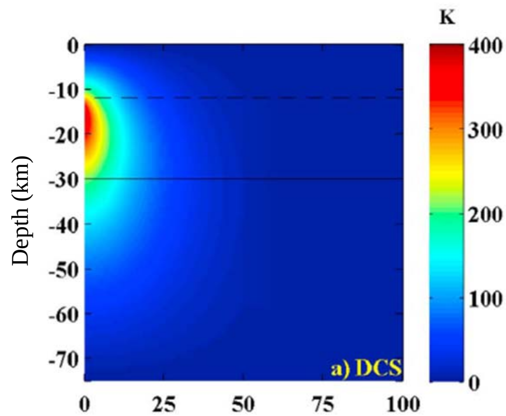


Geologist's view of a fault zone



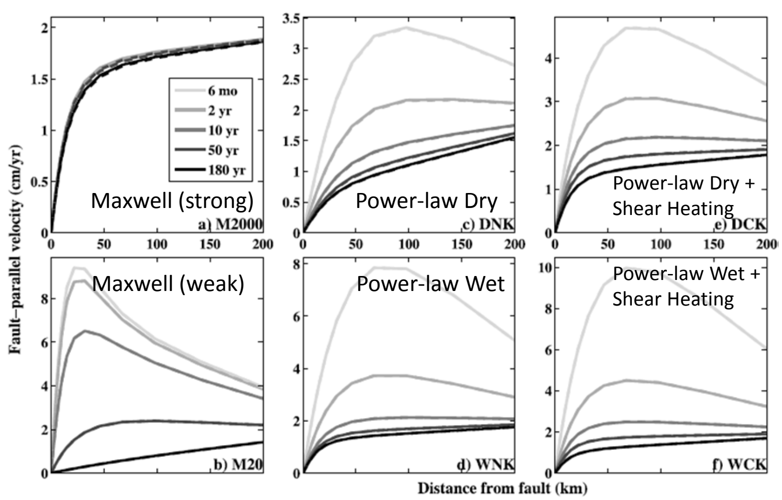
Watkinson et al., J. Struct. Geol. 2008

Spatial variations in properties: 1. Shear heating



Takeuchi and Fialko (JGR, 2012)

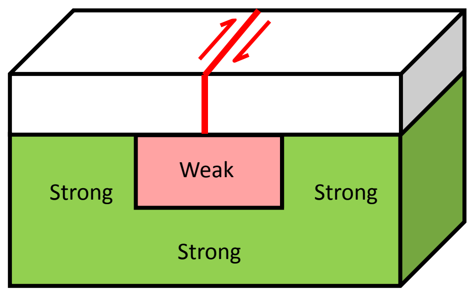
Spatial variations in properties: 1. Shear heating



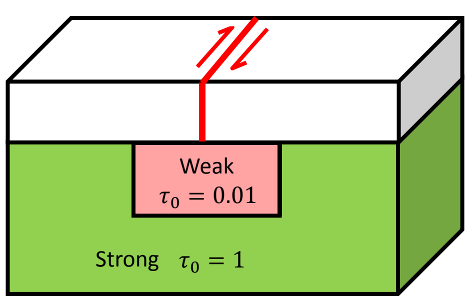
Takeuchi and Fialko (JGR, 2012)

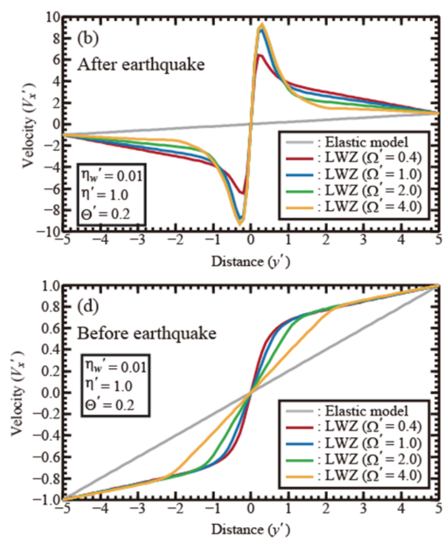
Spatial variations in properties: 2. Material properties (weak zone)

$$\eta_{eff} = A^{-1}\sigma^{1-n}d^m f_{H_2O}^{-r}\exp\left(\frac{Q+pV}{RT}\right)$$



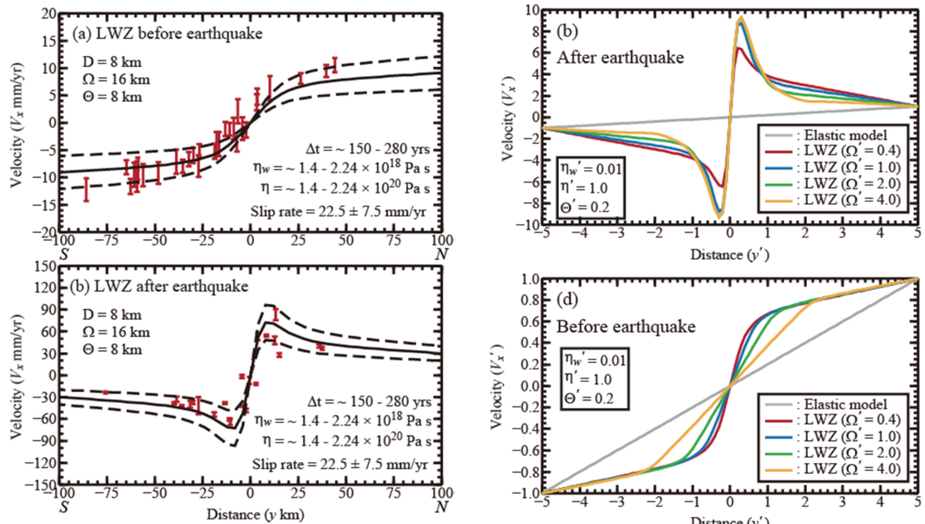
Spatial variations in properties: 2. Material properties (weak zone)





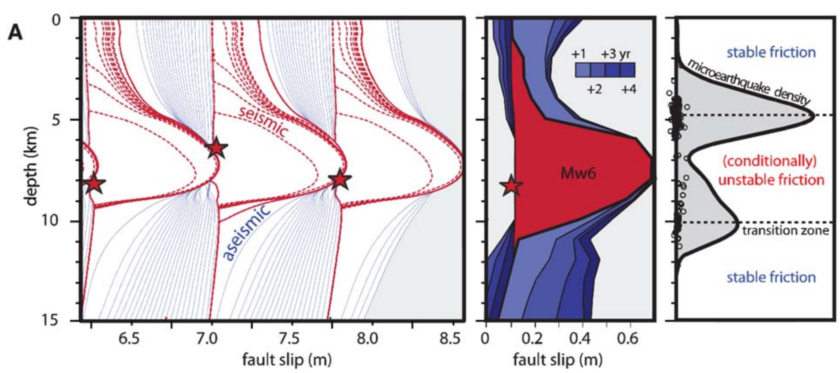
Yamasaki , Wright and Houseman, in prep 2013

Spatial variations in properties: 2. Material properties (weak zone)



Yamasaki , Wright and Houseman, in prep 2013

Alternative approach: Friction, deep fault extension

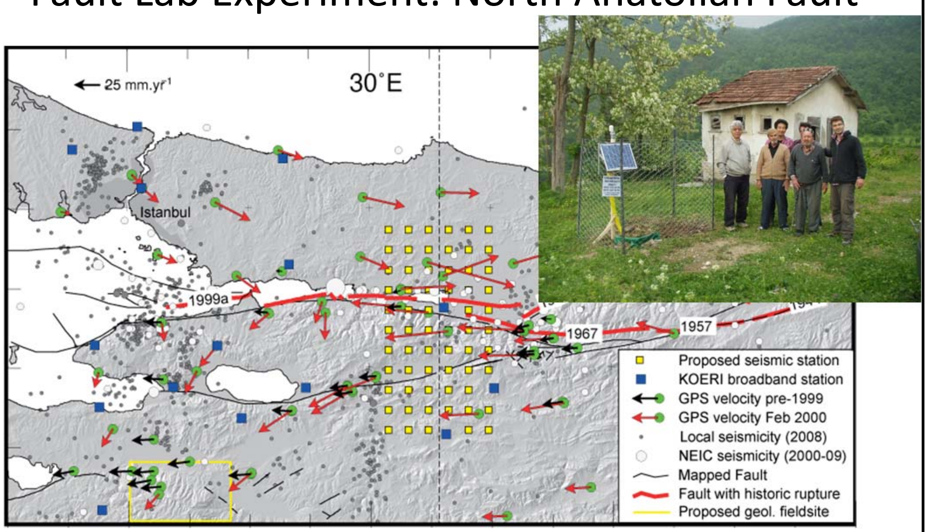


Barbot, Lapusta and Avouac, Science 2012

Summary of modelling

- Strong material required to match interseismic deformation
- Weak material required to match postseismic deformation
- Several strategies can fit both coseismic and postseismic simultaneously.
- Spatial variation in material properties is most likely explanation (power law may not be required).
- Geodetic data are non-unique – independent constraints required

Future perspectives
Fault Lab Experiment: North Anatolian Fault



Conclusions

- Quantity and quality of geodetic observations of earthquake cycle deformation has dramatically increased in last 20 years.
- Simple rheologies are incompatible with both postseismic and interseismic deformation.
- Spatial variations in material properties provide the most satisfactory solution.
- Further work required to integrate geological, geodetic, seismic, model, and lab views of fault zones.