Basics of the modelling of the ground deformations produced by an earthquake

EO Summer School 2014

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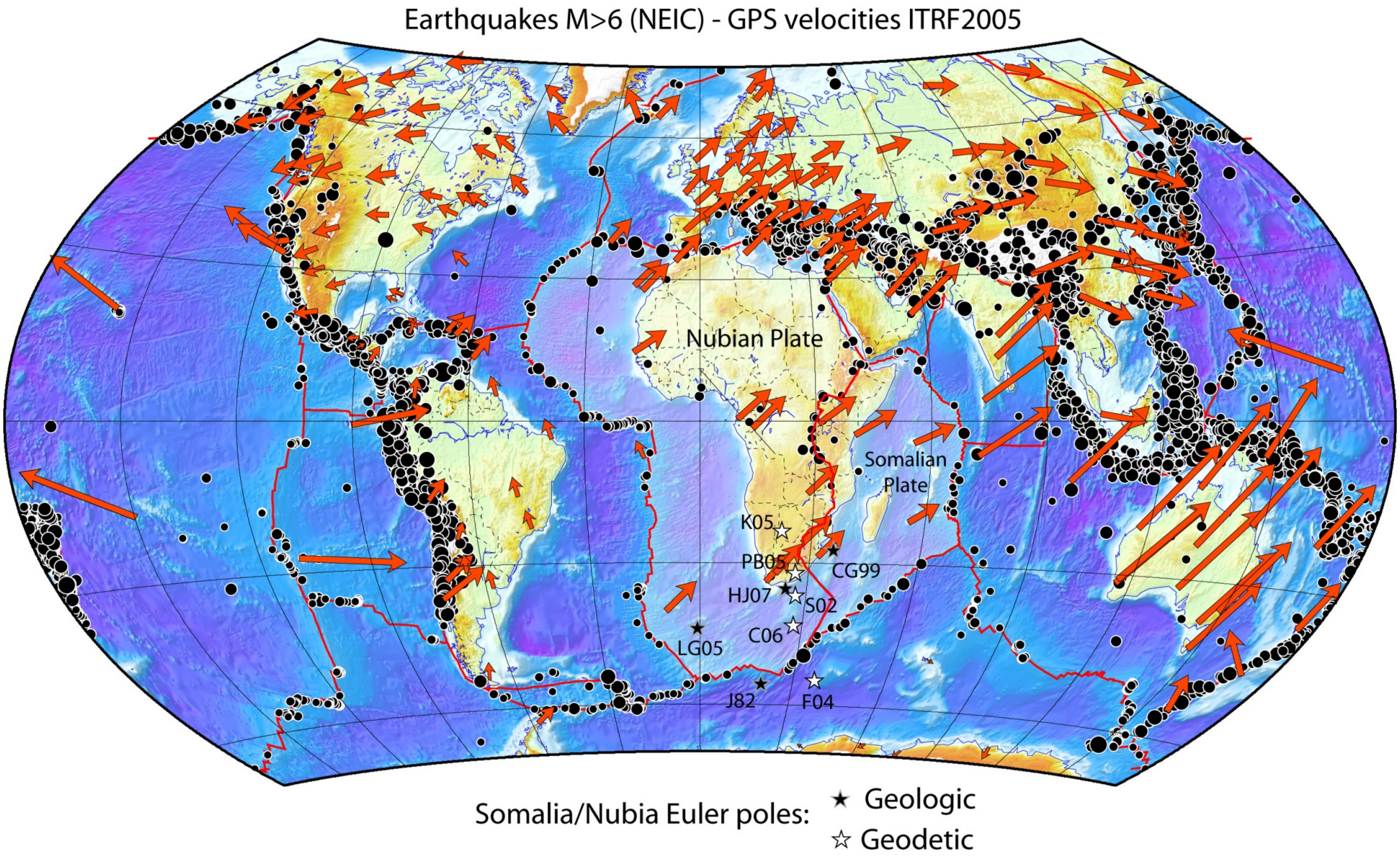
Content

- Earthquakes and faults
- Examples of SAR interferograms of earthquakes
- The earthquake cycle
- Elastic model
- Data needed to constrain the model and the complementarity of seismological, geodetic and geological data
- Example of models

Most earthquakes are located at plates boundaries



Earthquakes occur on faults (and faults grow with repeated earthquakes)

The Atalanti fault, Greece

Earthquakes produce ground deformations

Surface rupture produced by the 2010 Edgecumbe earthquake (New Zealand)

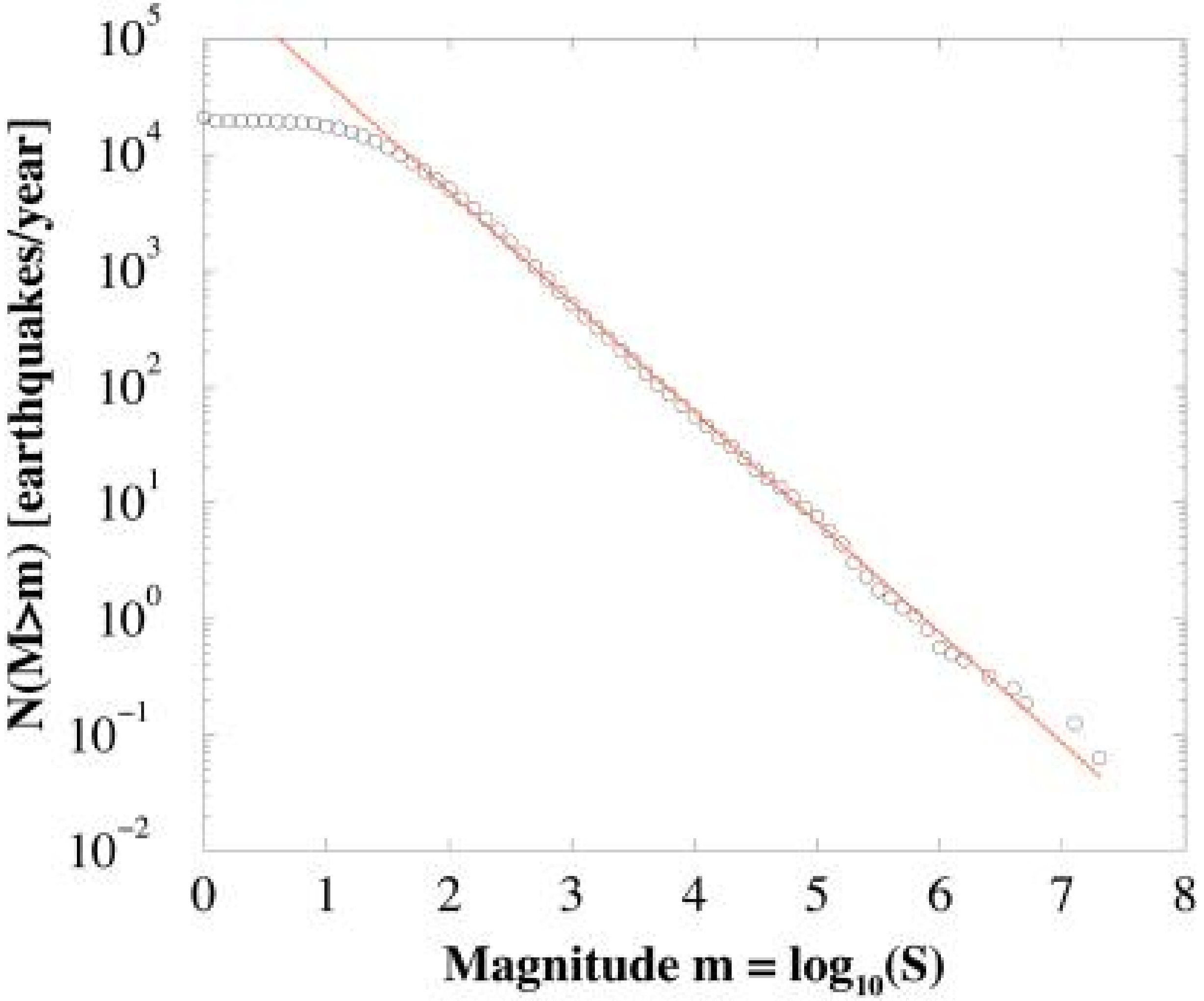
Cumulated earthquakes produce topography

The San Andreas fault: cumulated deformation along the fault

Uplifted marines terraces near Wellington (NZ)

Gutenberg – Richter law

Earthquakes per year in a given area = f(Magnitude)

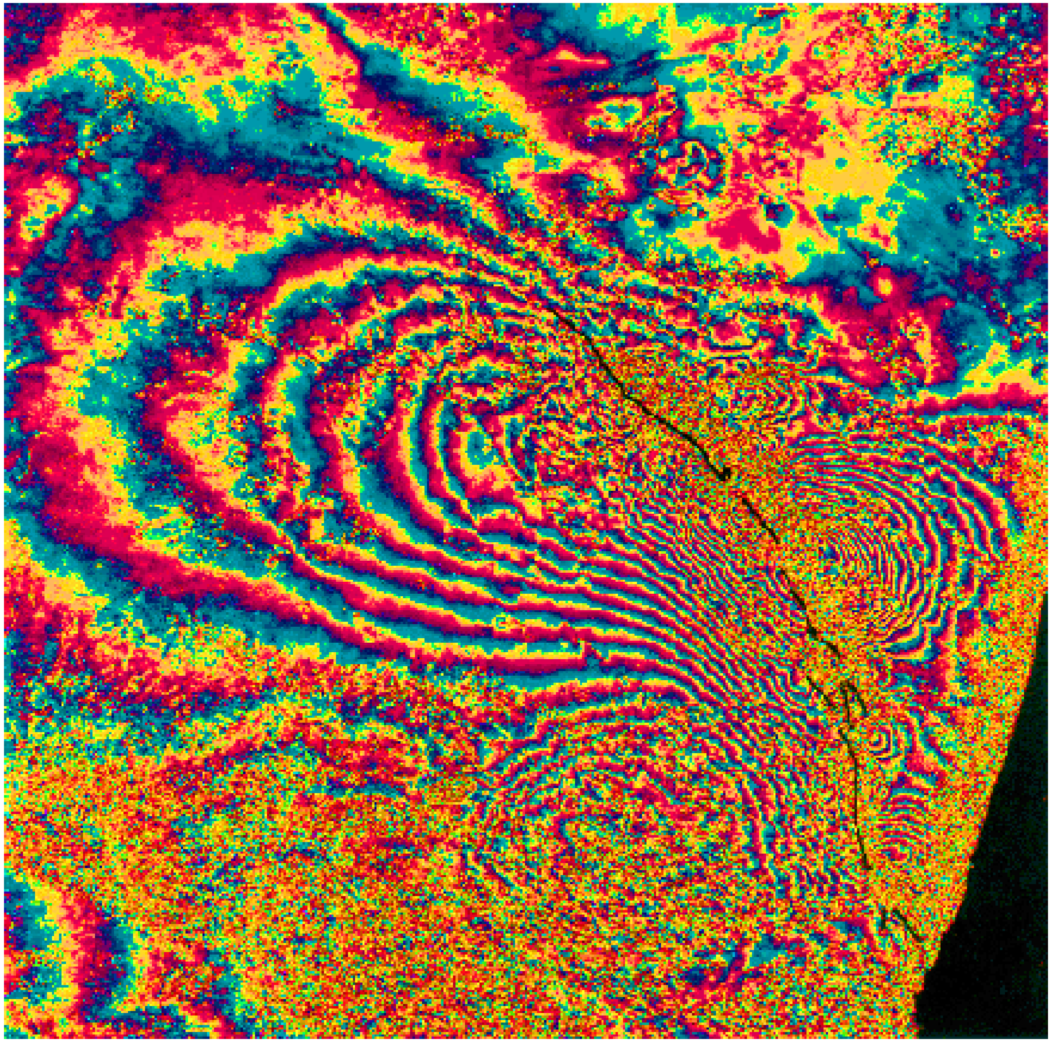


10 000

100

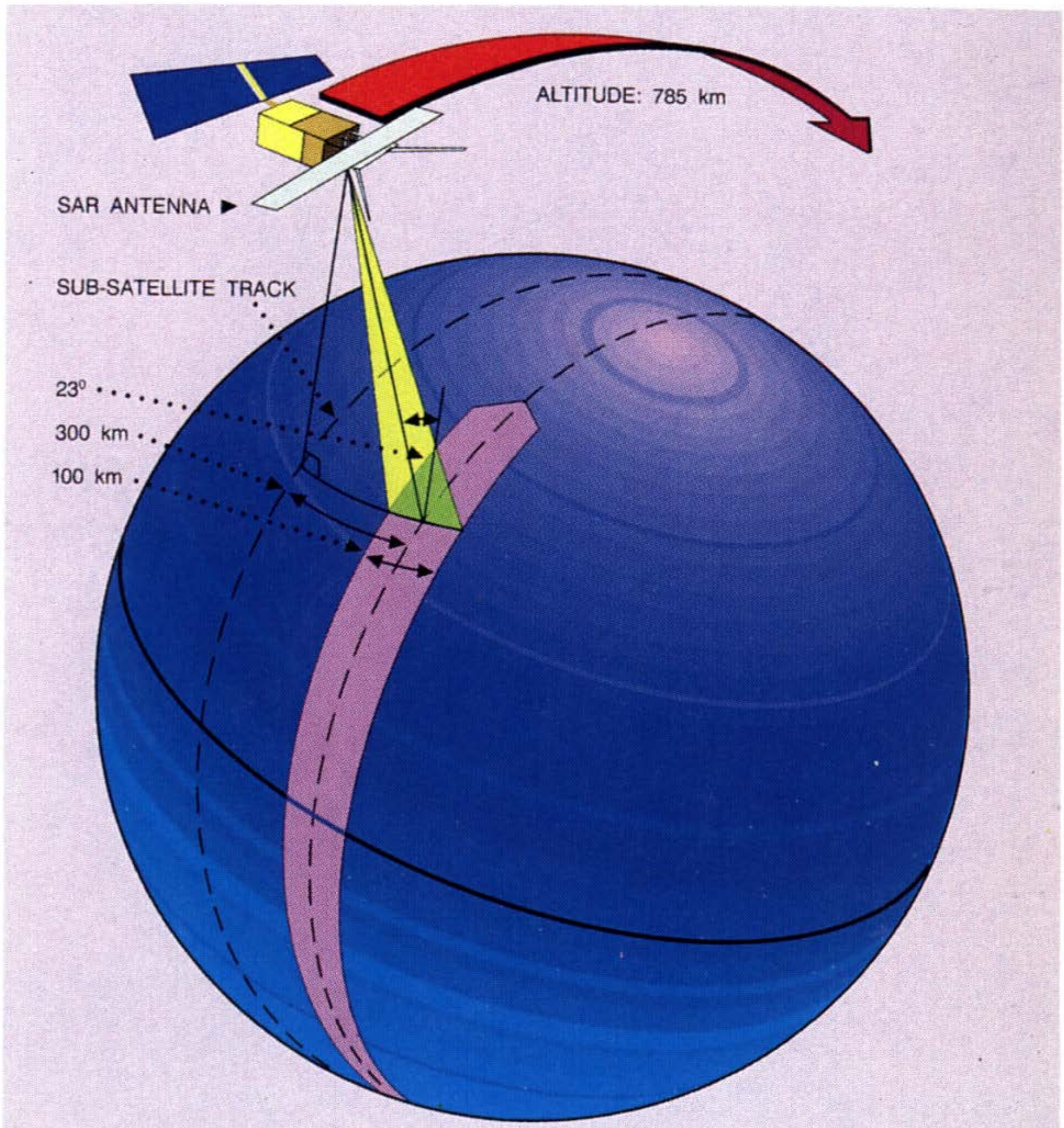
1

The first interferogram produced by ERS1

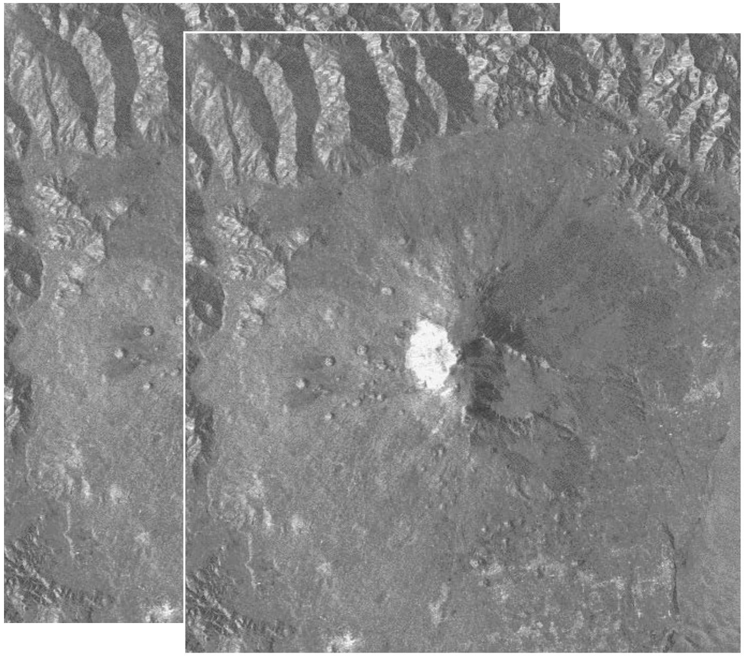


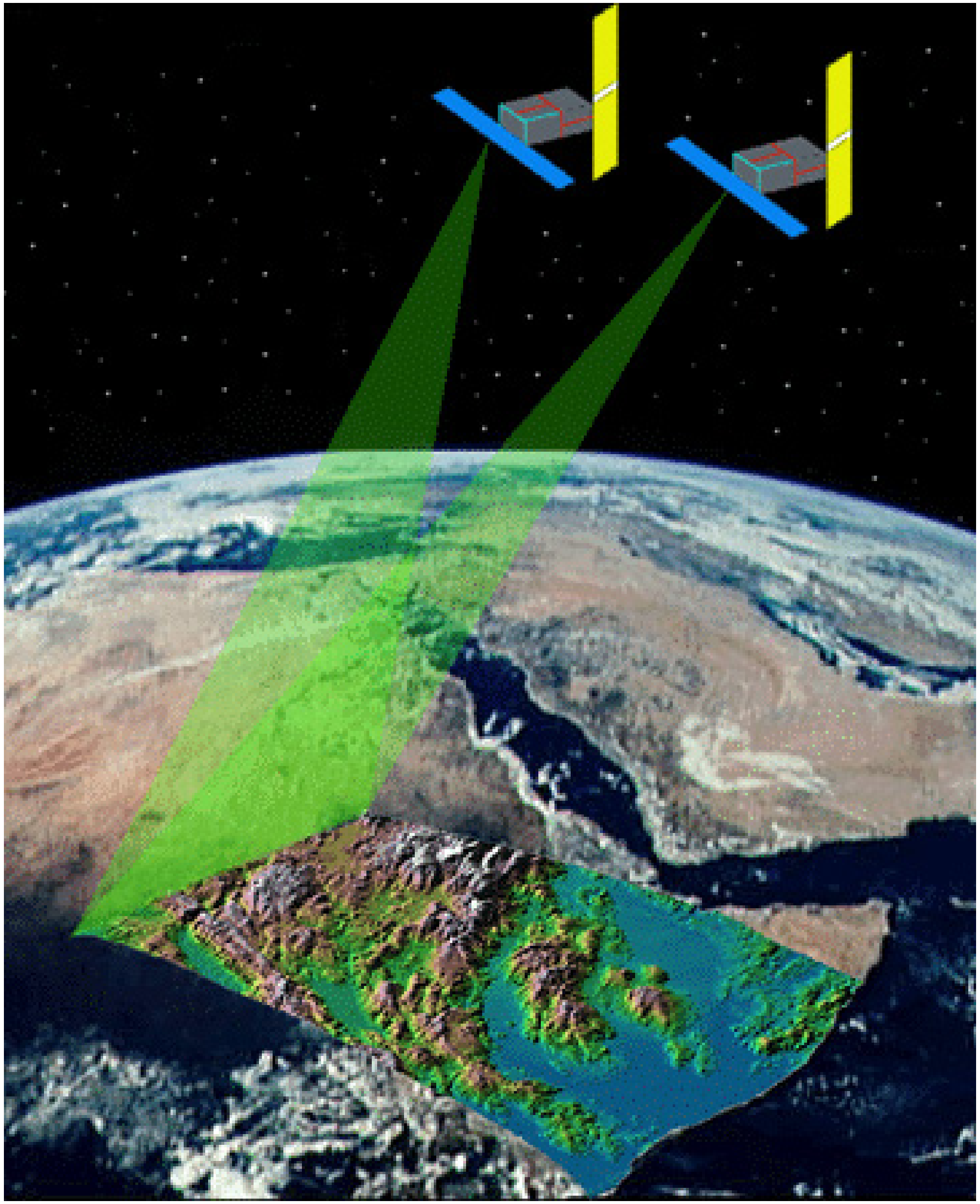
Landers earthquake (1992)
1 colour cycle = 28 mm in the satellite line of sight

Radar satellite imagery



Radar images correlation

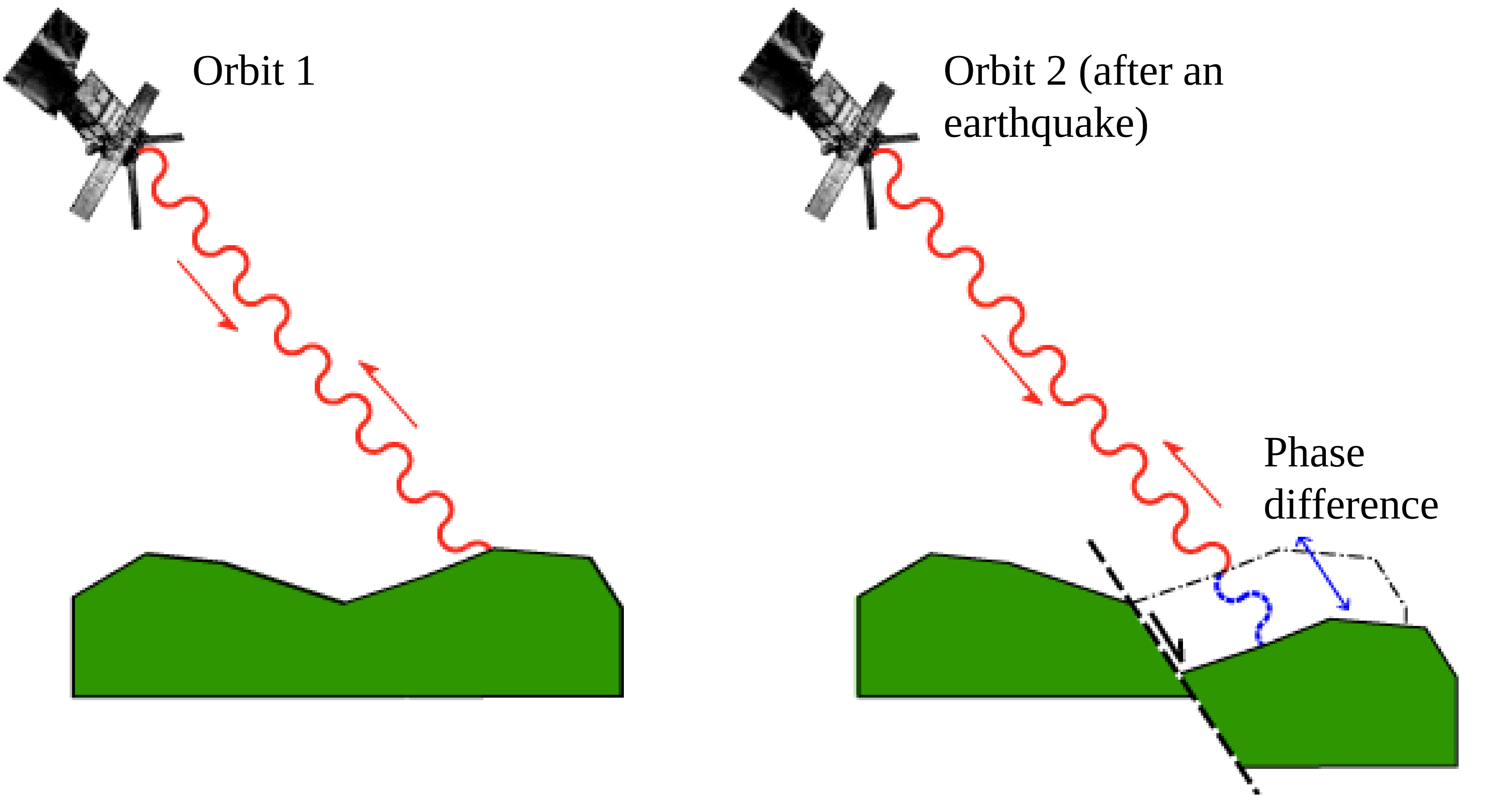




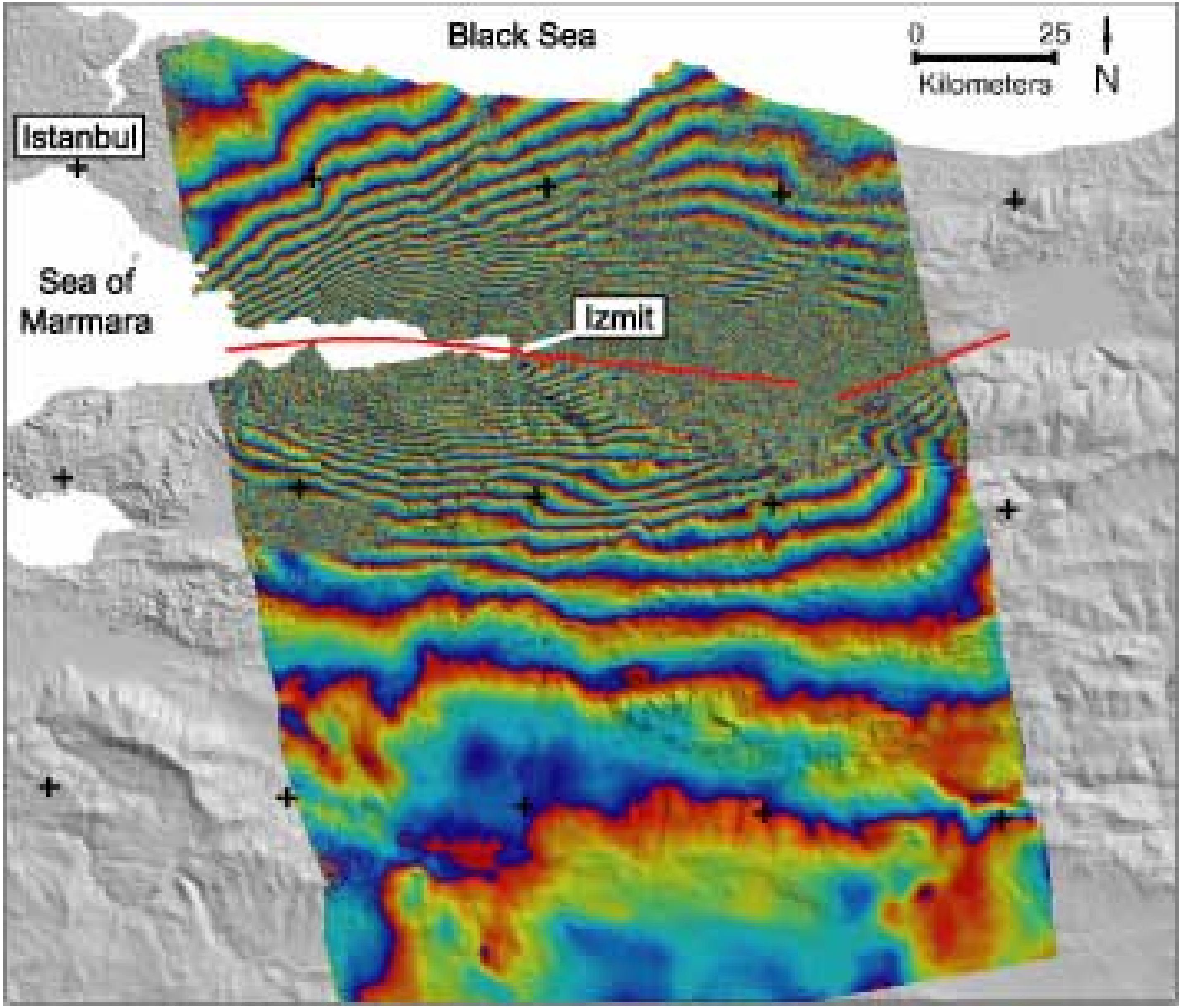
Principle: accurately co-register the amplitude images & compare phase images

Two acquisitions from almost identical orbits at two different epochs

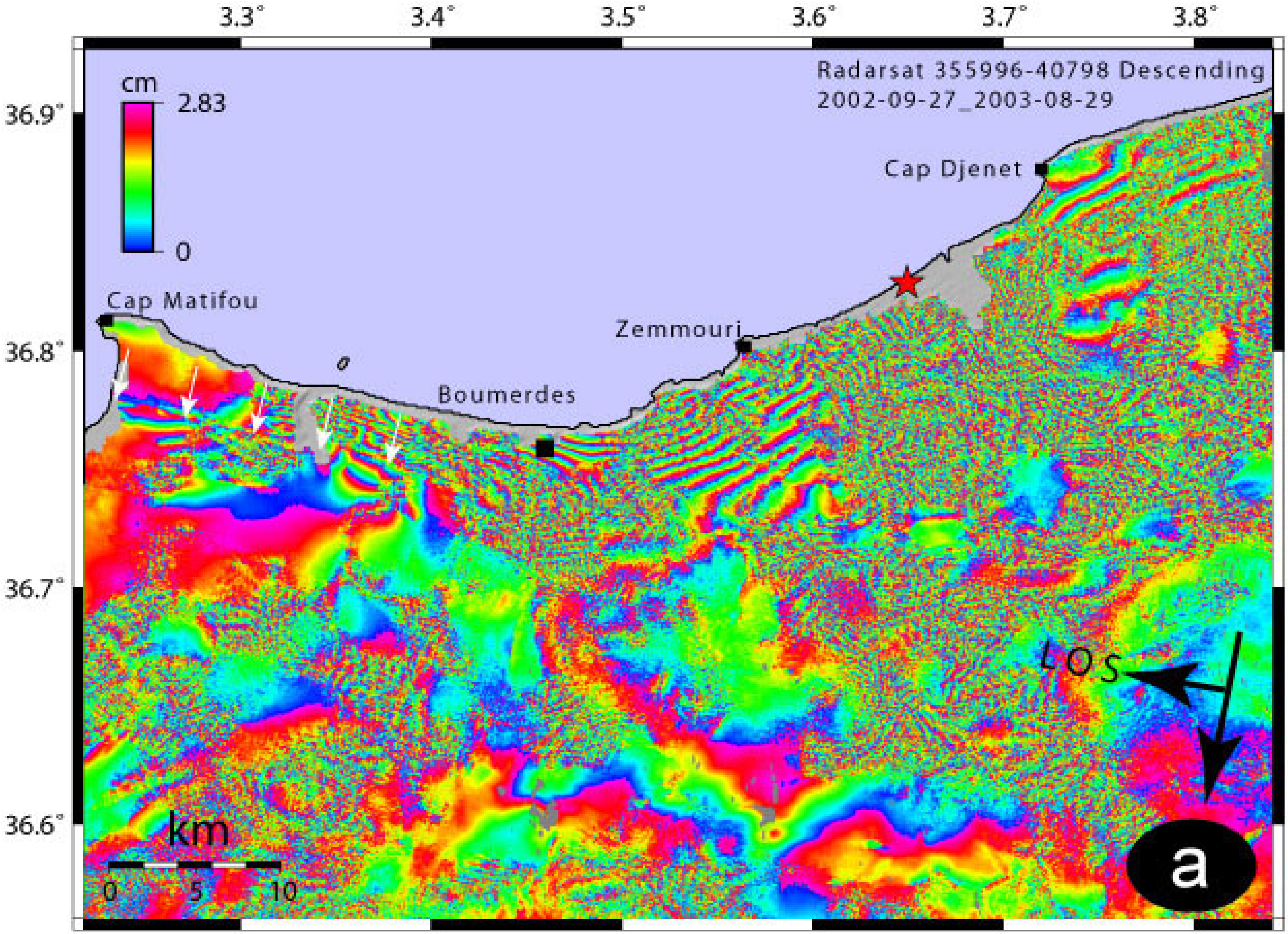
The slip on the fault induces a difference in the phase registered by the satellite



Izmit, 1999

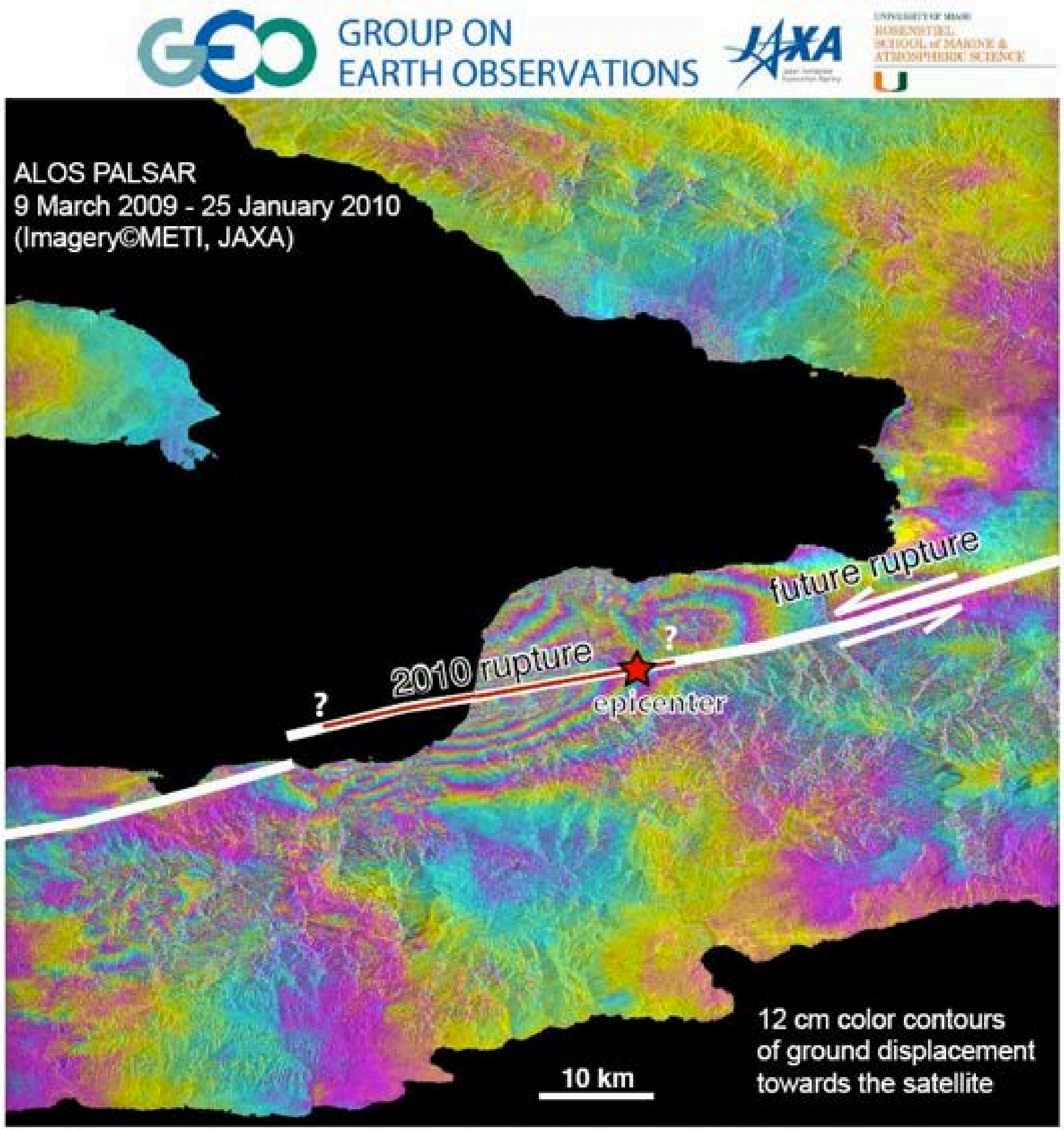


Boumerdes, M_w=6.8, 21/05/2003



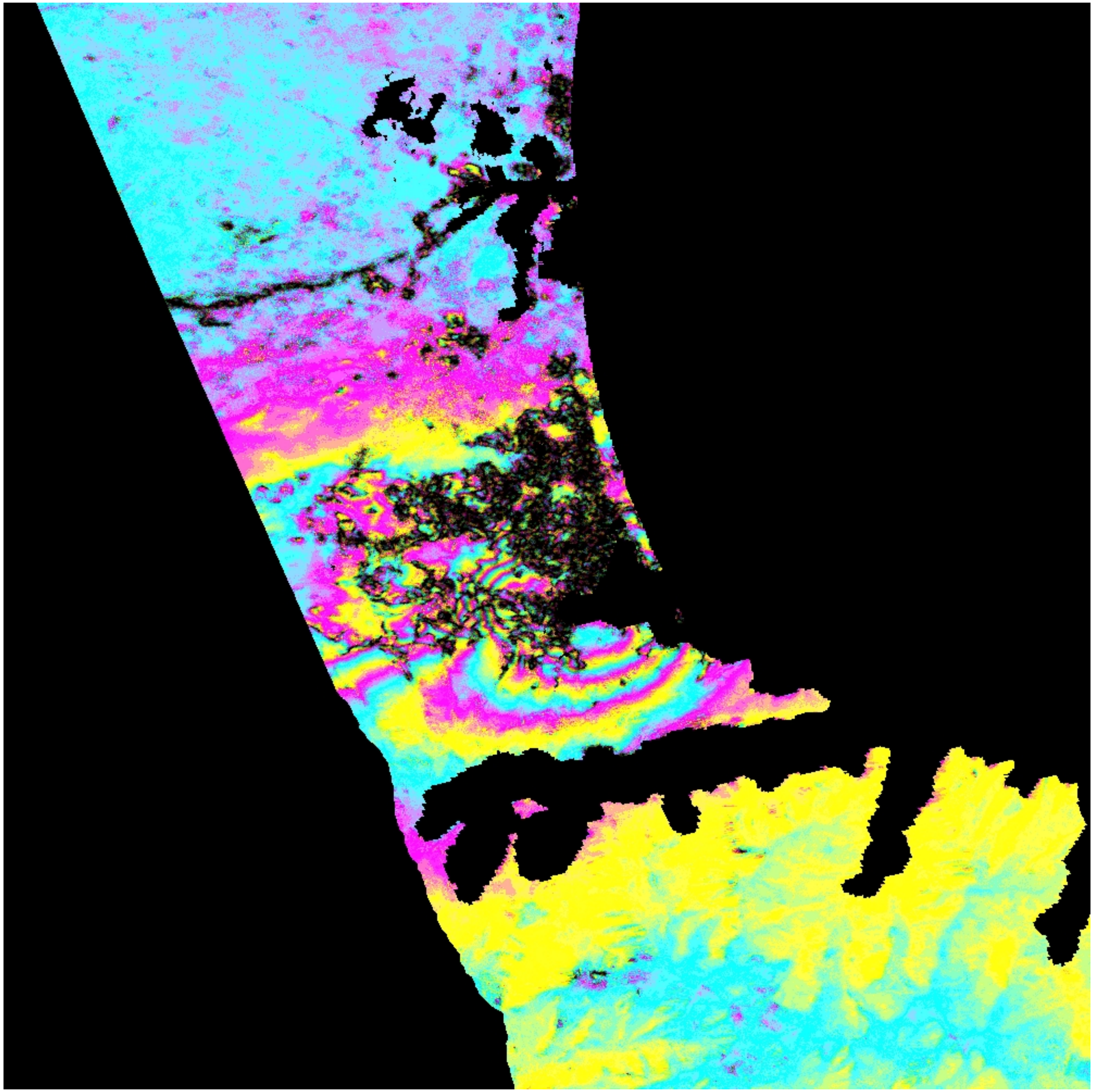
Meghraoui et al., 2007

Haiti earthquake 2010

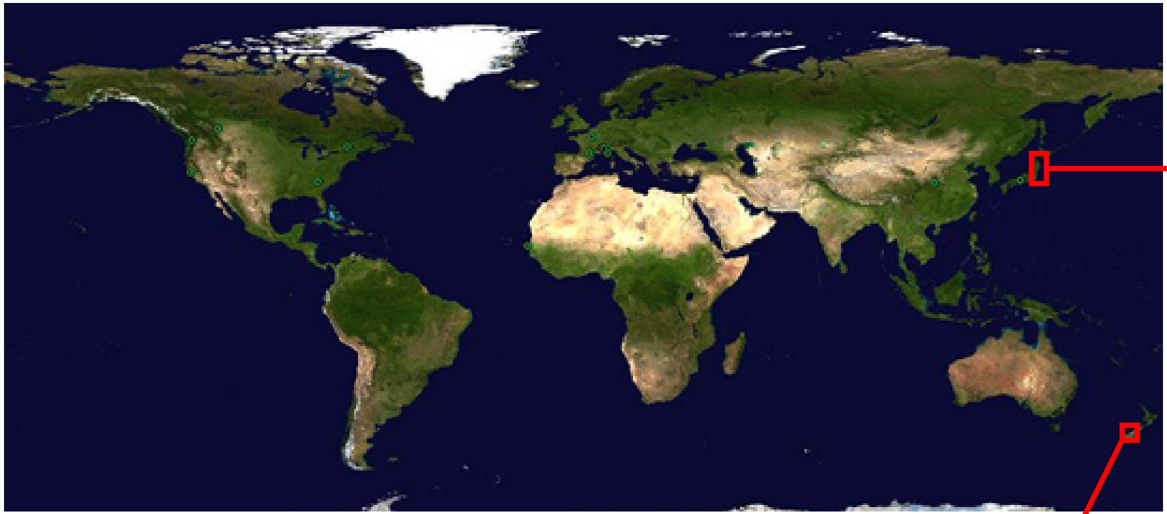


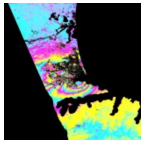
Sang-Hoon Hong, Falk Amelung, Tim Dixon, Shimon Wdowinski, Guoqing Lin, Fernando Greene
Rosenstiel School of Marine & Atmospheric Science, University of Miami

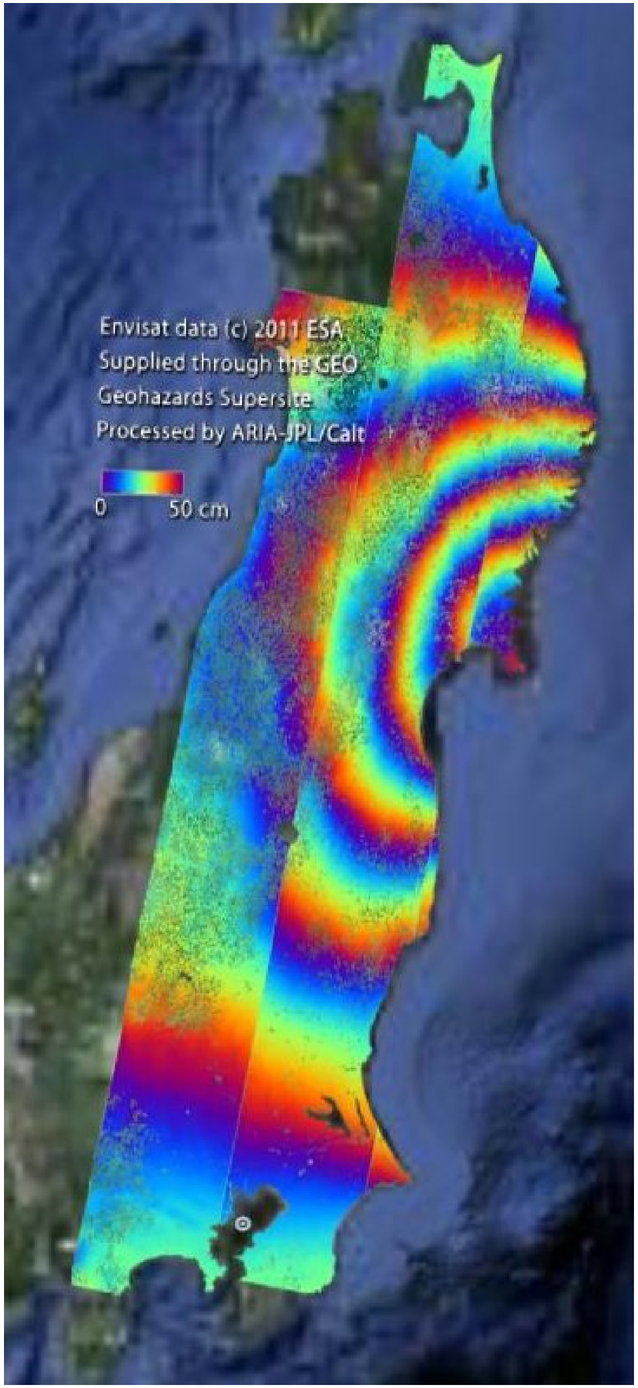
Christchurch, 22/2/2011



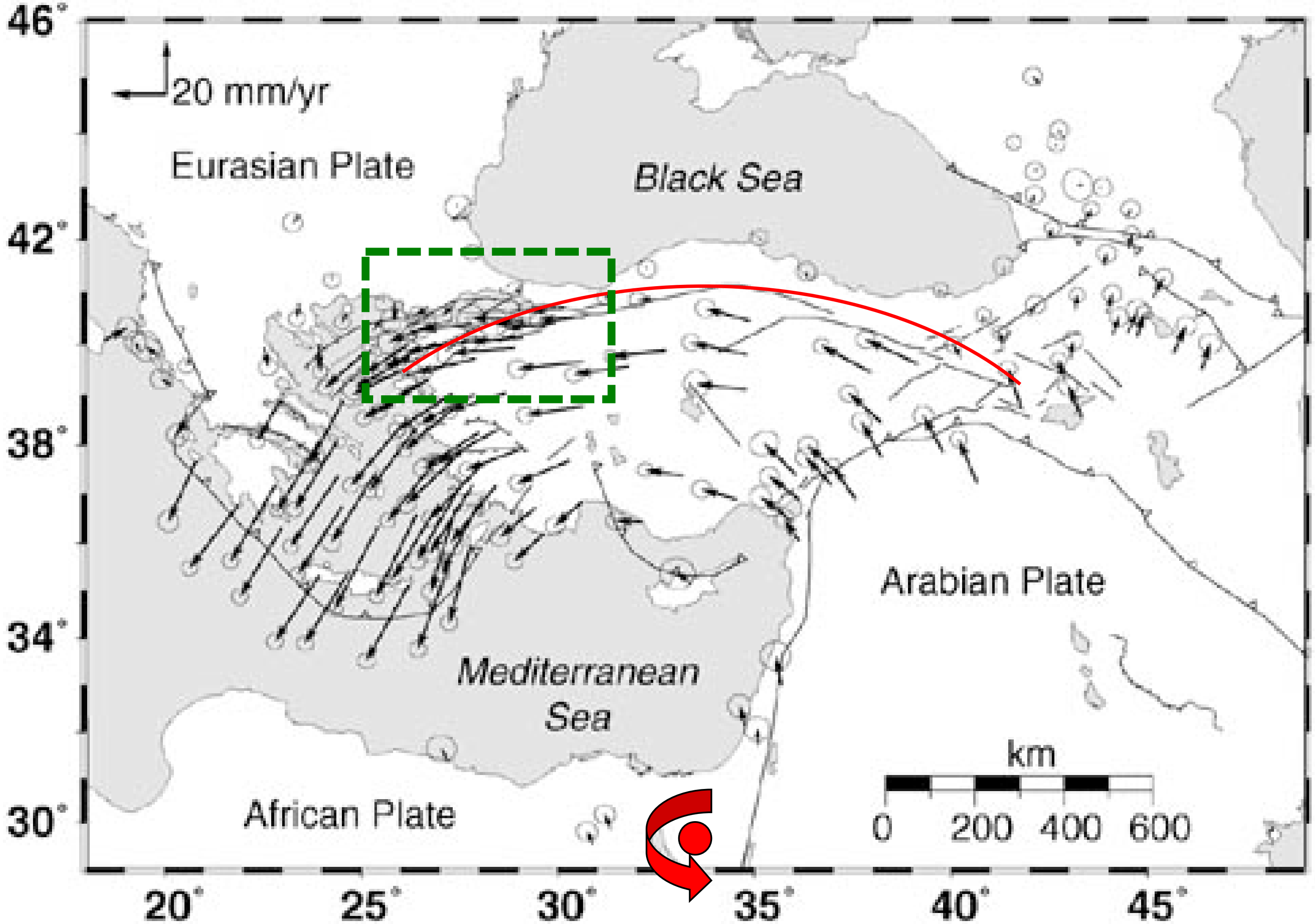
Envisat interferograms of the Christchurch (22/2/2011) and Tohoku (11/3/2011) earthquakes



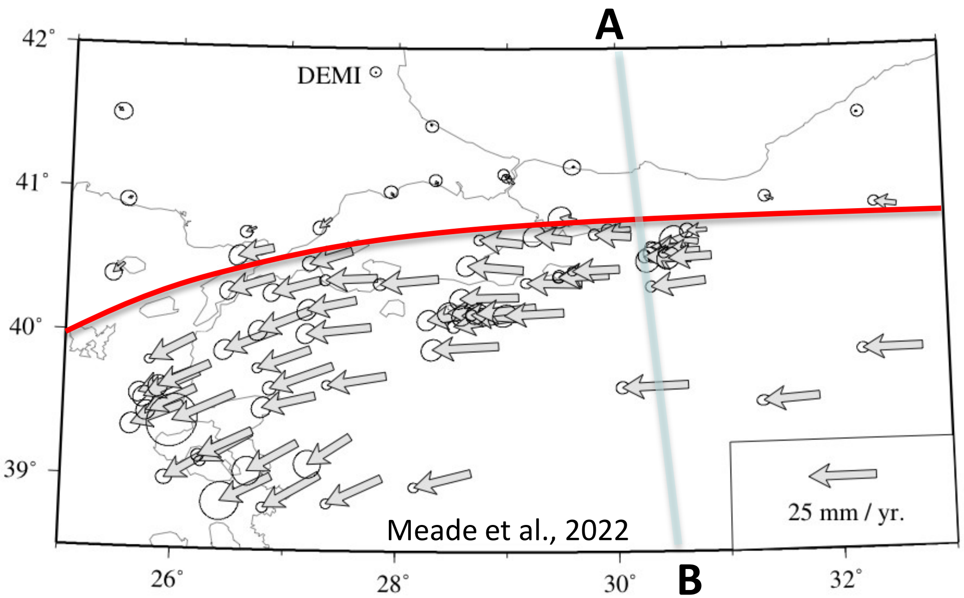


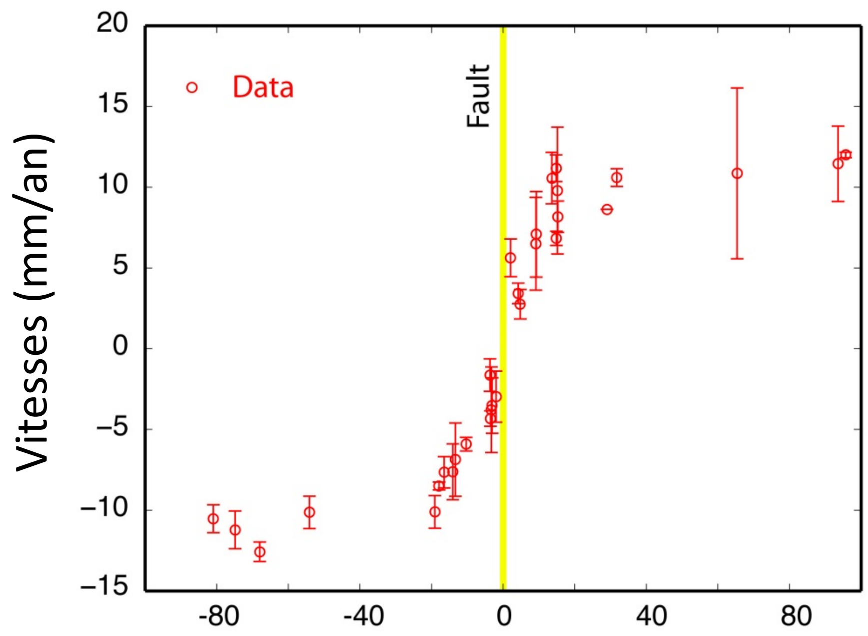


The deformation cycle across a fault



Inter-seismic deformation near an active fault



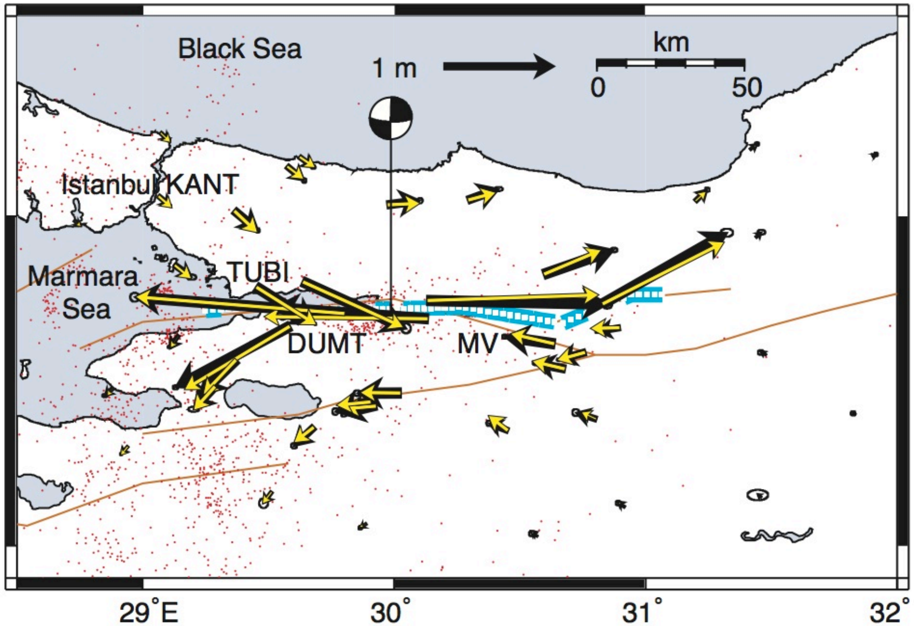


Distance to the fault (km)

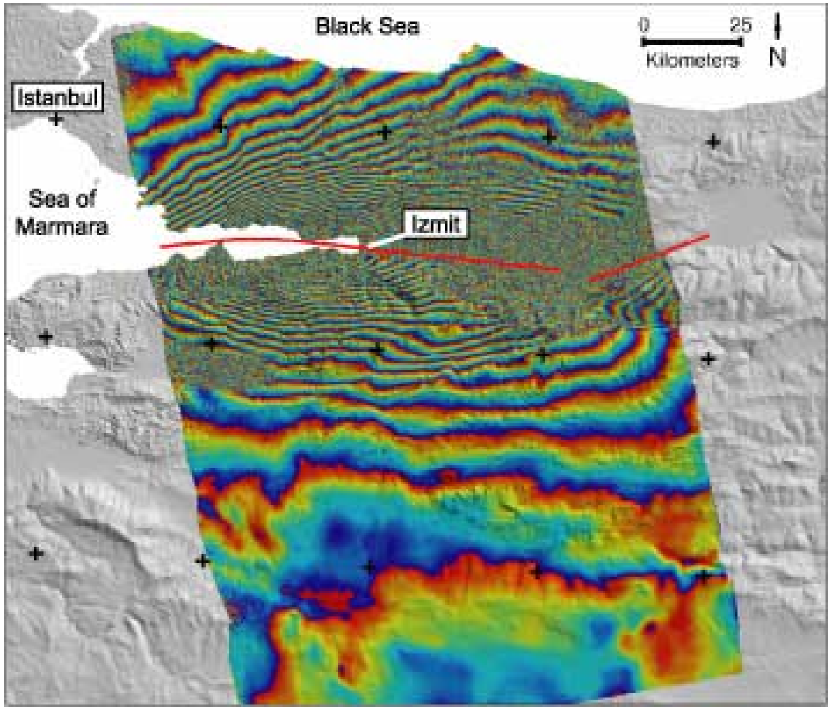
Between major earthquakes:

- the active faults are « locked »
- the surrounding region deforms in a continuous manner, measurable until a distance of ~50km
- velocity gradient looks like a sigmoid

Coseismic deformation around an active fault

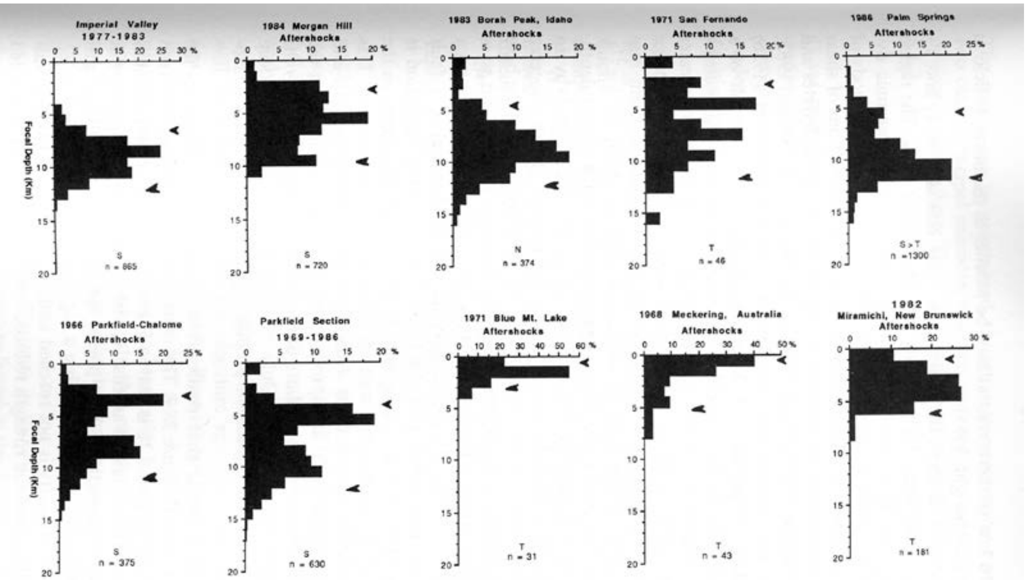


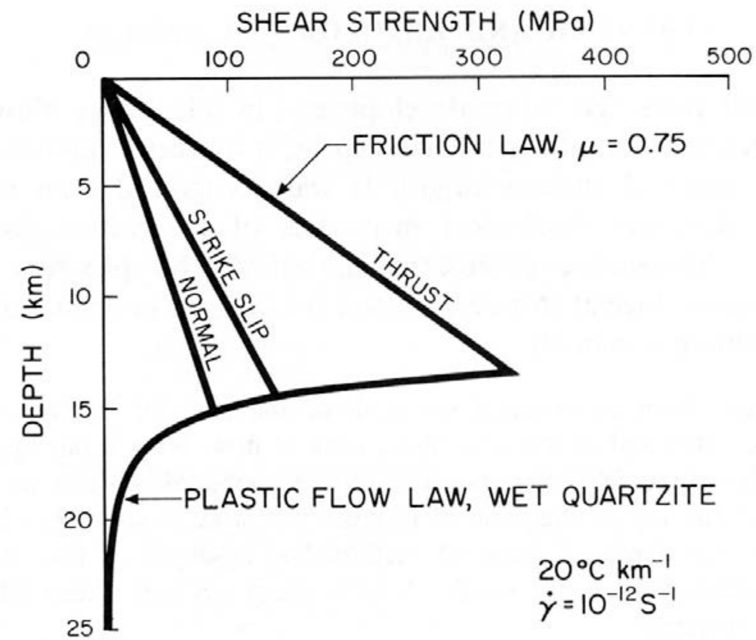
Reilinger et al., 2001



- The co-seismic deformation can be observed:
  - by GPS
  - by SAR interferometry
- Observed displacements:
  - up to 5.7 m near the fault
  - decreasing to the N and S away from the fault

Some basic of mechanics



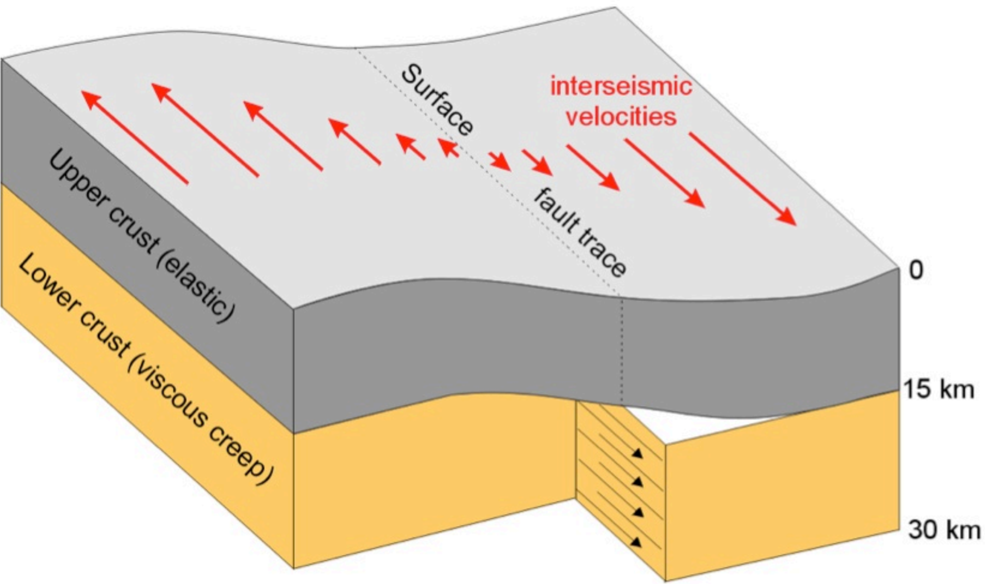


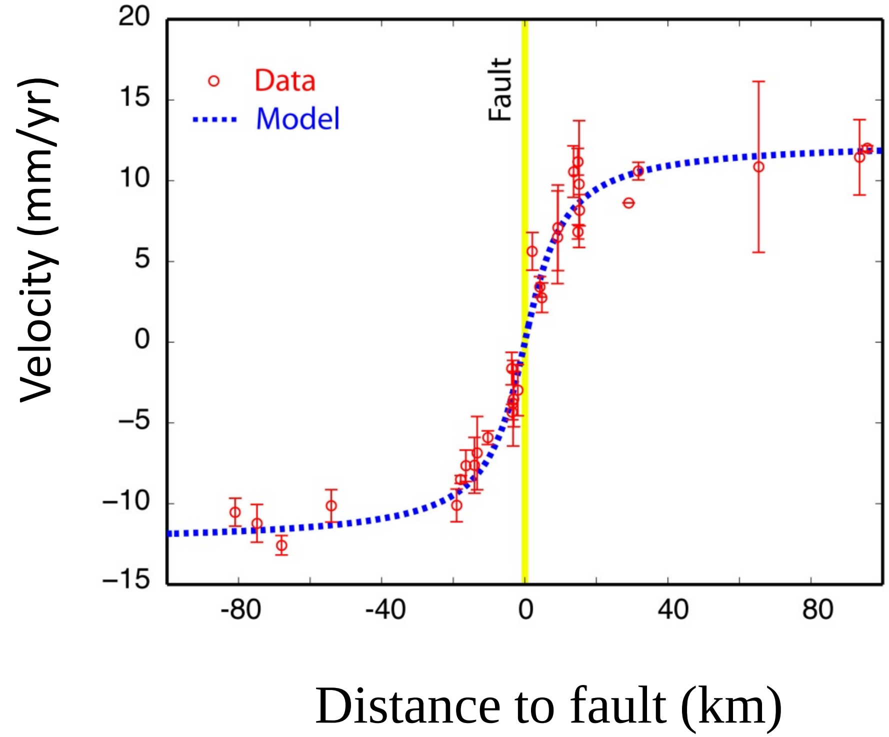
Strike-slip earthquakes in continental crust occur in the ~15 shallowest kilometres of the crust (the brittle/elastic part of the crust)

Laboratory rock mechanics indicate that the rocks behave:

- elastically above ~15 km, with friction law governing the triggering of slip above a threshold
- in a ductile and mostly aseismic manner below 15 km

Inter-seismic deformation





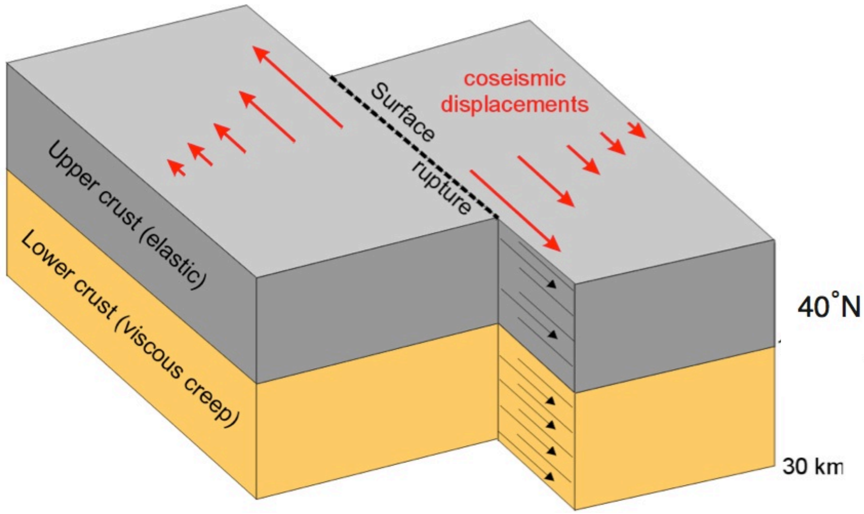
$$V_{GPS} = \frac{v}{\pi} \times \text{atan}\left(\frac{d}{p}\right)$$

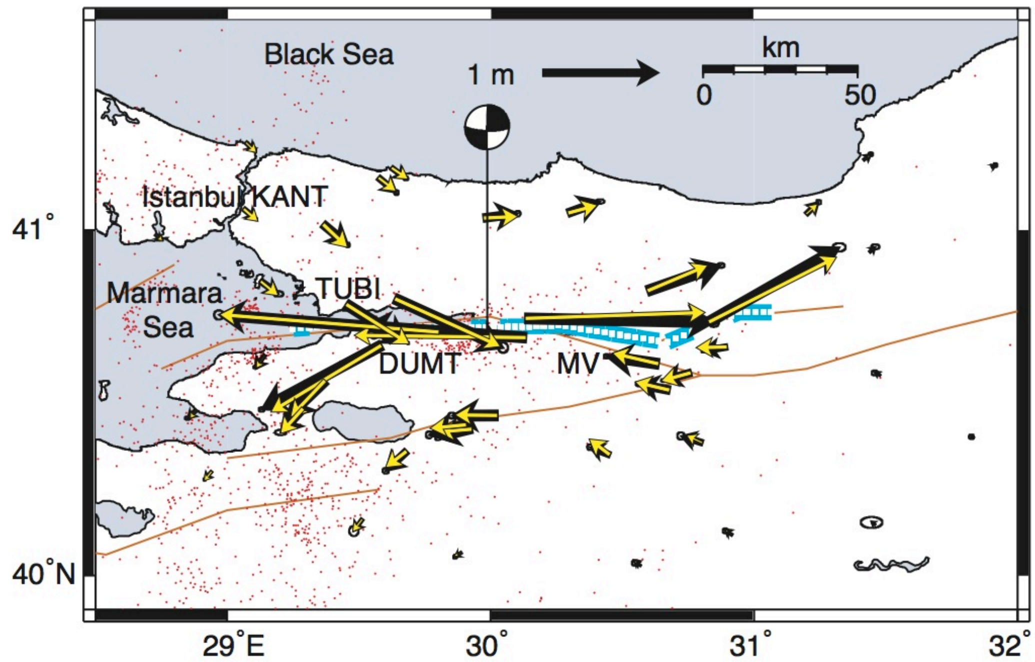
- Locked fault at shallow depth
- Aseismic creep in the lower crust
- For a infinite fault length:

v = relative plates velocity (in the far field)
d = perpendicular distance to the fault
p = ‘locking’ depth of the fault

At the surface the deformation cumulates in a broad area, and the deficit near the fault plane will be recovered during the earthquake.

Coseismic deformation

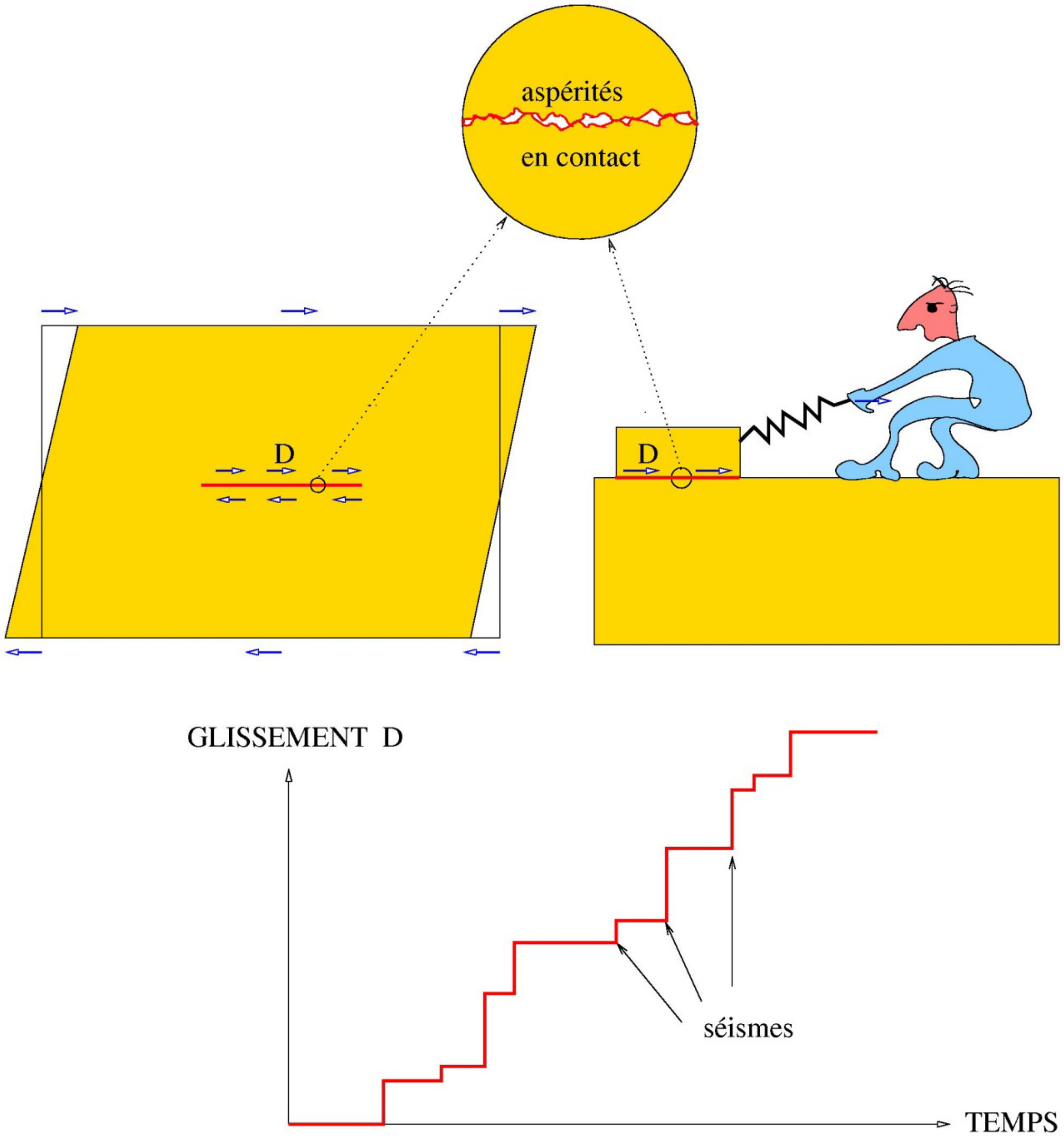




Reilinger et al., 2001

- M_w=7.5 August 17, 1999, Izmit earthquake: strike-slip on the north Anatolian fault
- Conceptual model:
  - The accumulated elastic strain is released during the rupture
  - The rupture concerns a fraction only of the entire fault (short => low magnitude, long => high magnitude)

Variability of the earthquakes



Dislocation model: rectangular fault within an elastic half-space

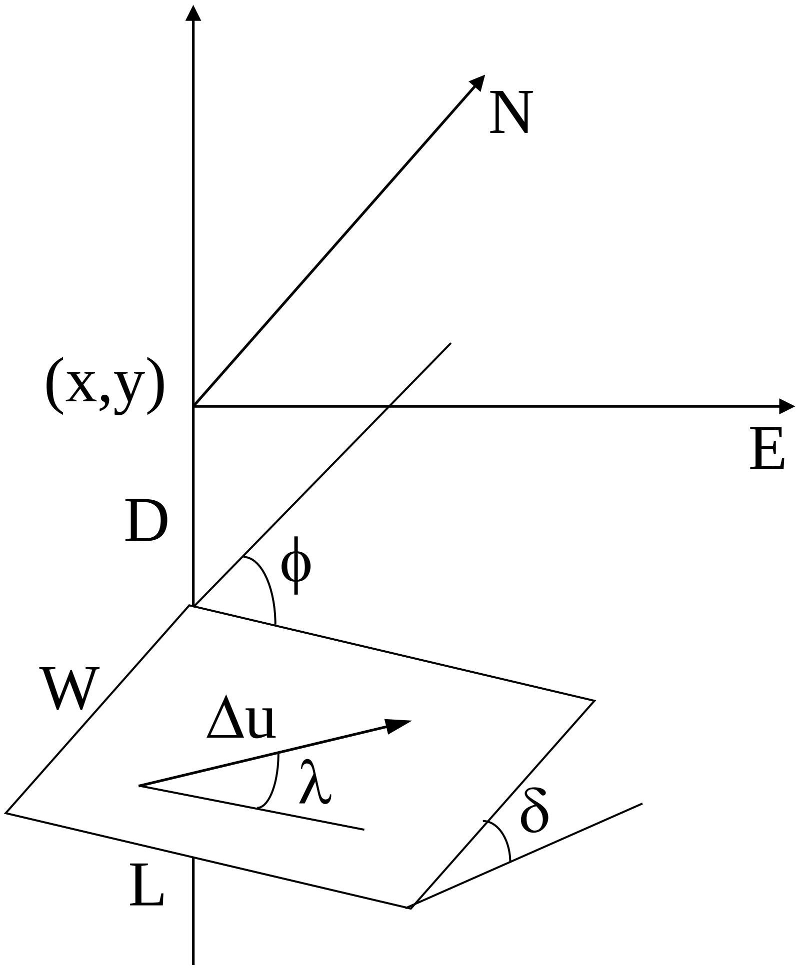
Nine parameters:

- 3 coordinates of the centre of the upper edge of the fault

- 2 angles (azimuth, dip)

- length and width

- dip-slip and strike-slip (or slip and rake)



- Okada(1985) BSSA, 75, 1135
- Okada(1992) BSSA, 82, 1018

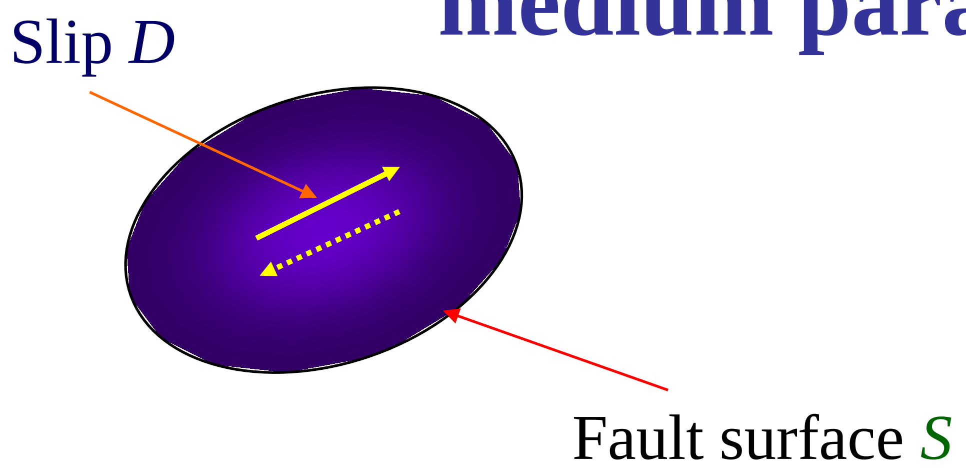
Data constraining the nine parameters

- Seismological data
  - Seismic moment } (Scale laws)
  - Source duration
  - Focal mechanism
- Geodetic data
  - Co-seismic deformations
- Geological data
  - Morphology (cumulated)
  - Direct observation of the fault (and the rupture)

1. Contraints from seismology

- Seismology constrains relatively well the azimuth and dip angles of the fault (most of the time better than geodesy and geology)
- Seismology constrains well the energy released and therefore the product of the fault surface and slip

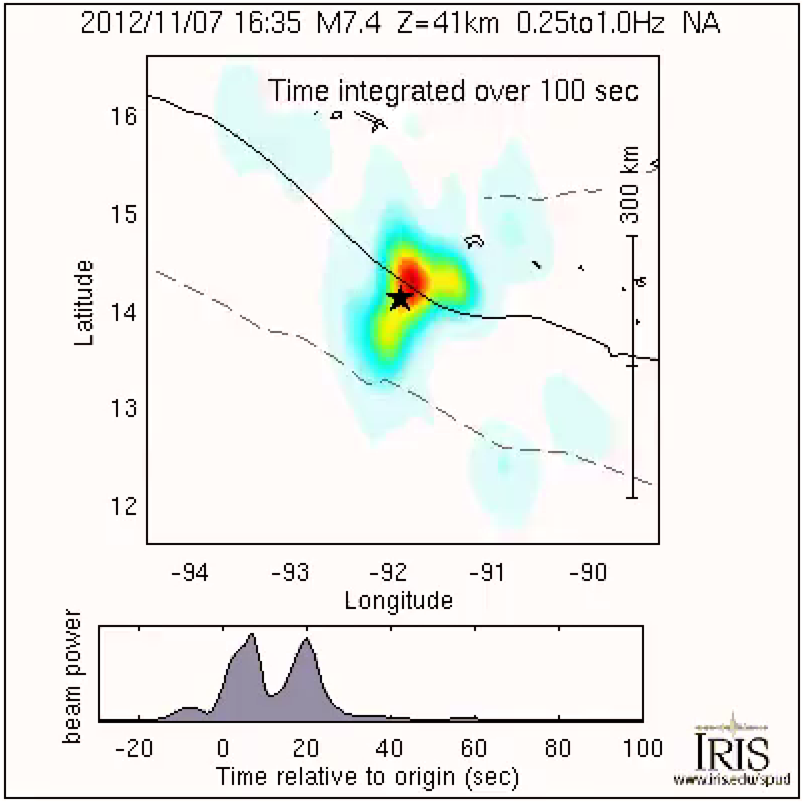
<u>Seismic moment</u> and the relation between the energy released and the fault and medium parameters



$$M_o = \mu \; D \, S$$

μ Medium rigidity

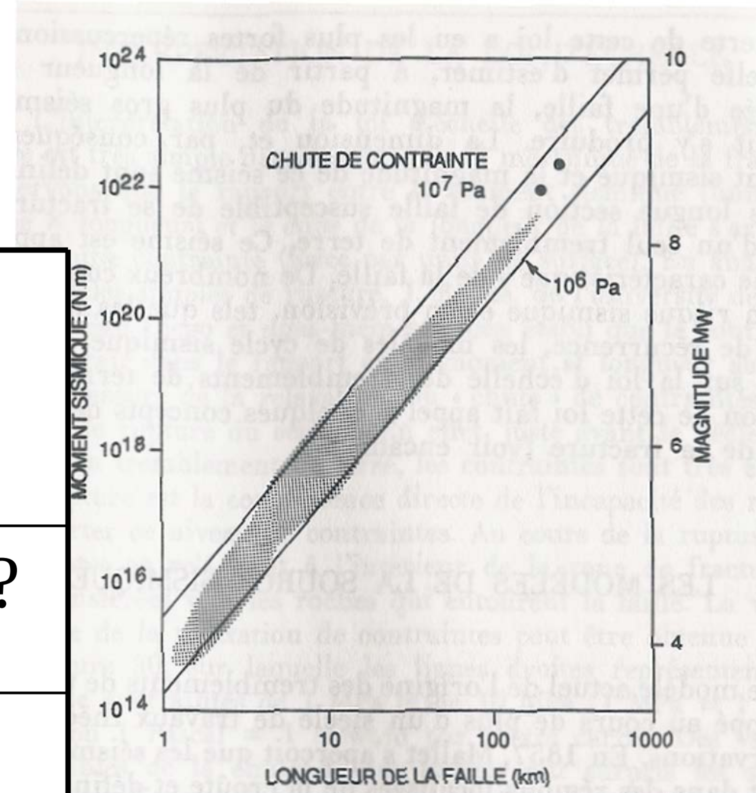
Source duration



Example of the M=7.4 Guatemala earthquake of November 7, 2012

Scale laws

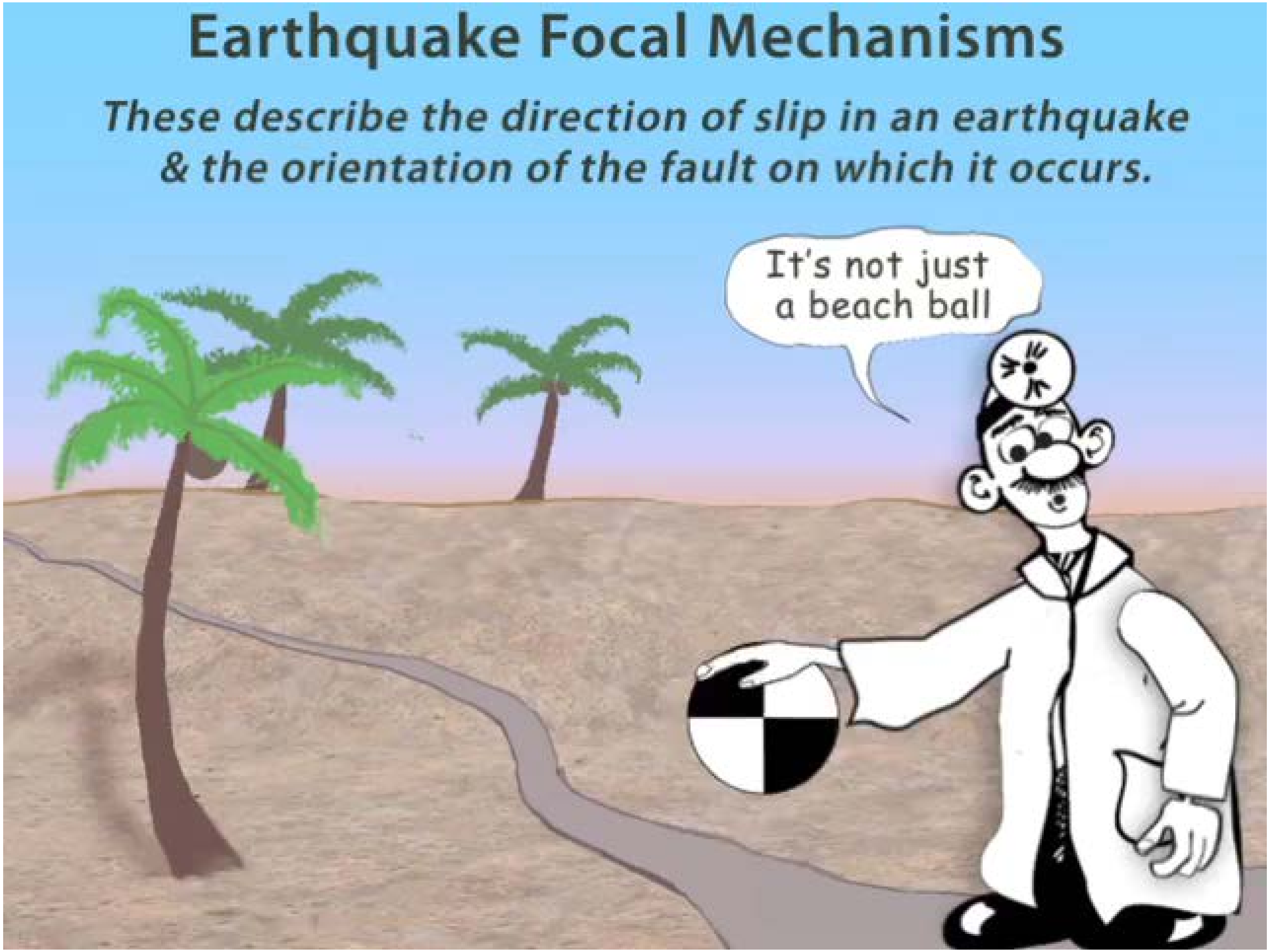
Magnitude (M_w)	Moment (Nm)	Length (km)	Duration (s)	Slip (m)
10	10^{24}	1000?	300?	100?
9	3.10^{22}	300	100	30
8	10^{21}	100	30	10
7	3.10^{19}	30	10	3
6	10^{18}	10	3	1



Magnitude / Moment relation

$$\log_{10} M_0(Nm) = 1.5 M_w + 9.3$$

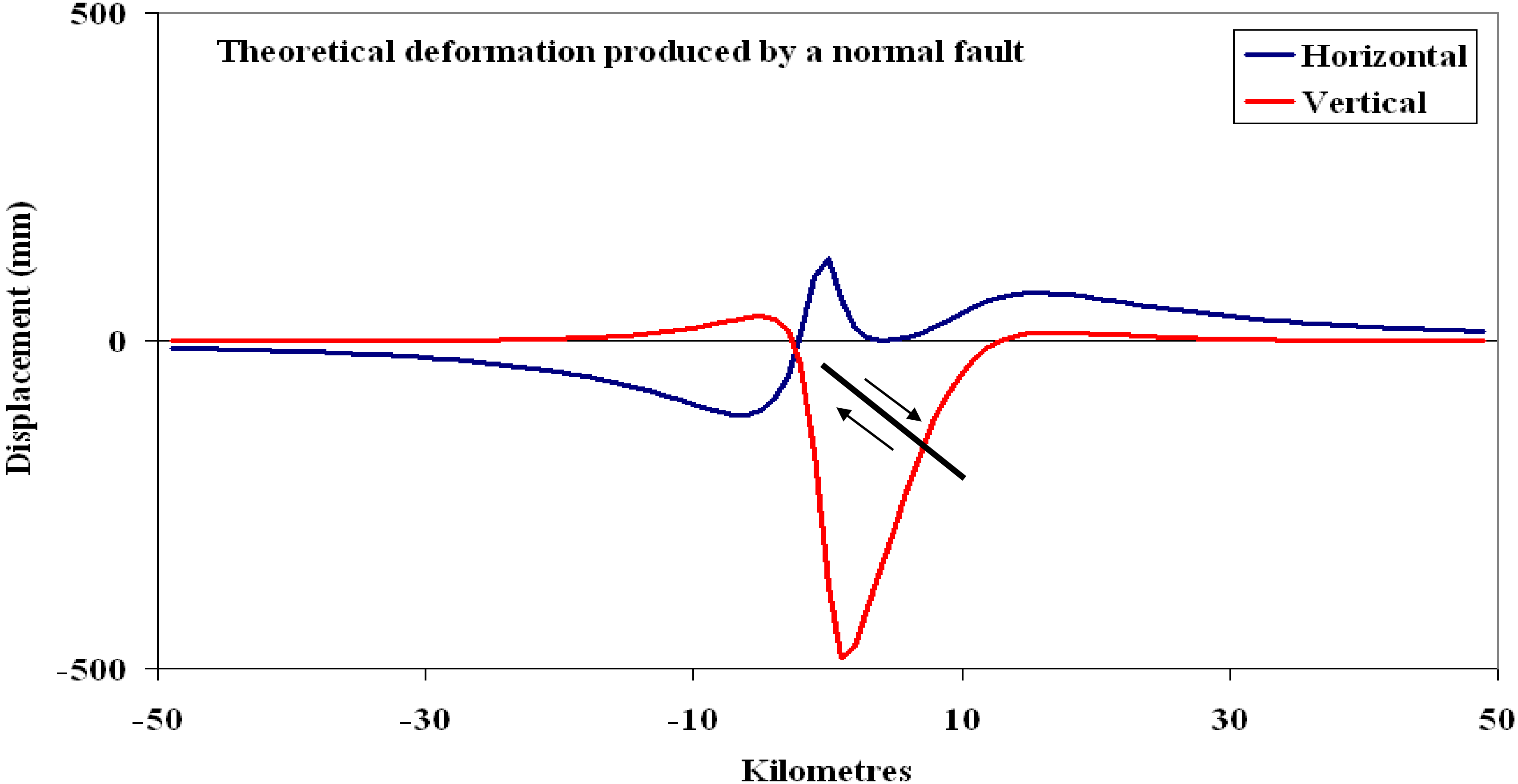
Focal mechanism *(video from IRIS)*



2. Contraints from geodesy

- Geodesy gives good constraints of the fault location
- It gives also good constraints on the fault length and width
- It gives good constraints on the slip on fault
- It constrains poorly the fault dip angle

Simulation of a M=6.2 normal faulting earthquake



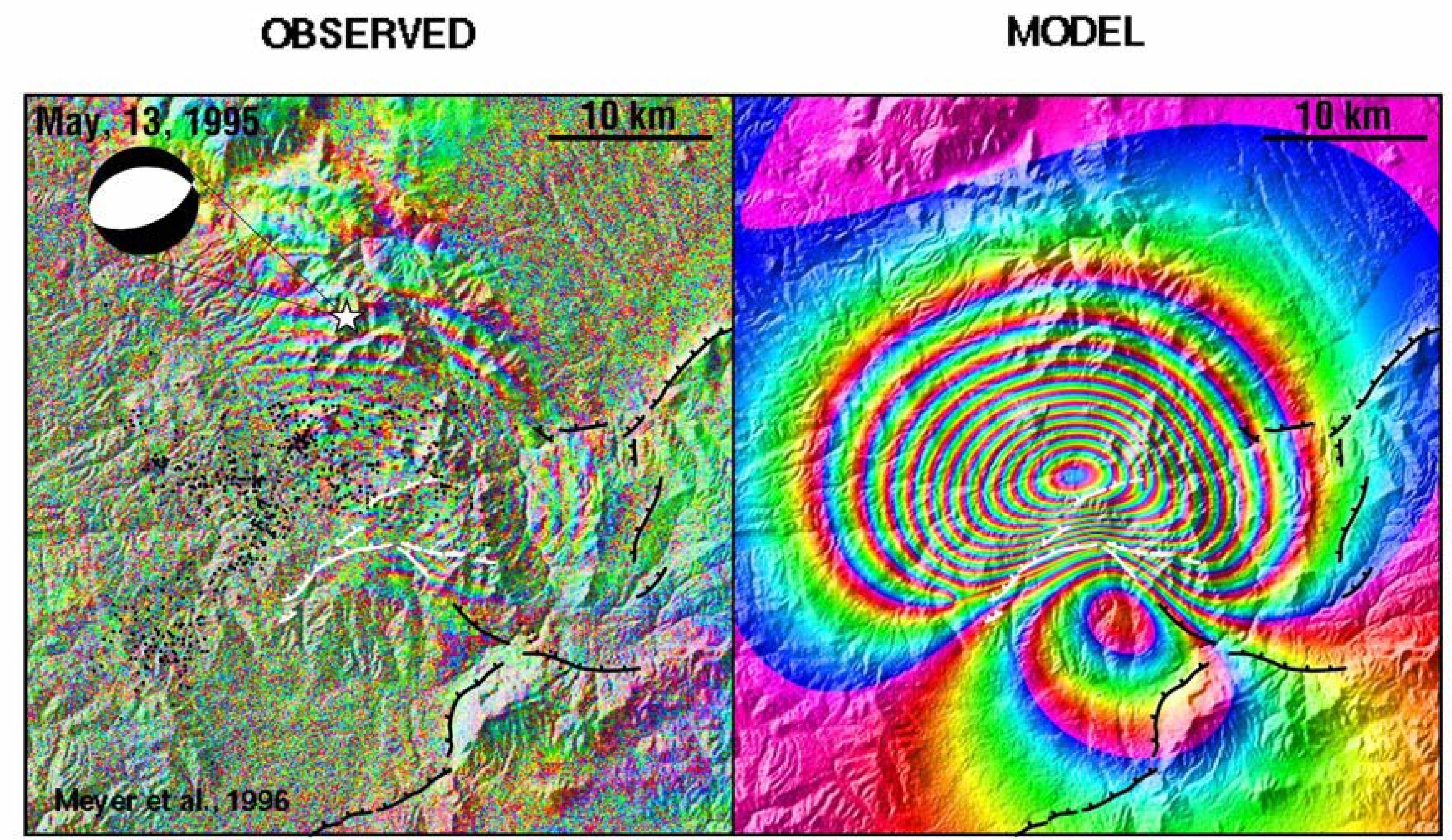
- Vertical displacements larger than horizontal in the near field, and maximum subsidence ~four times maximum horizontal motion

- Horizontal displacements dominate in the far field (still significant at distances larger than 50km

3. Contraints from geology

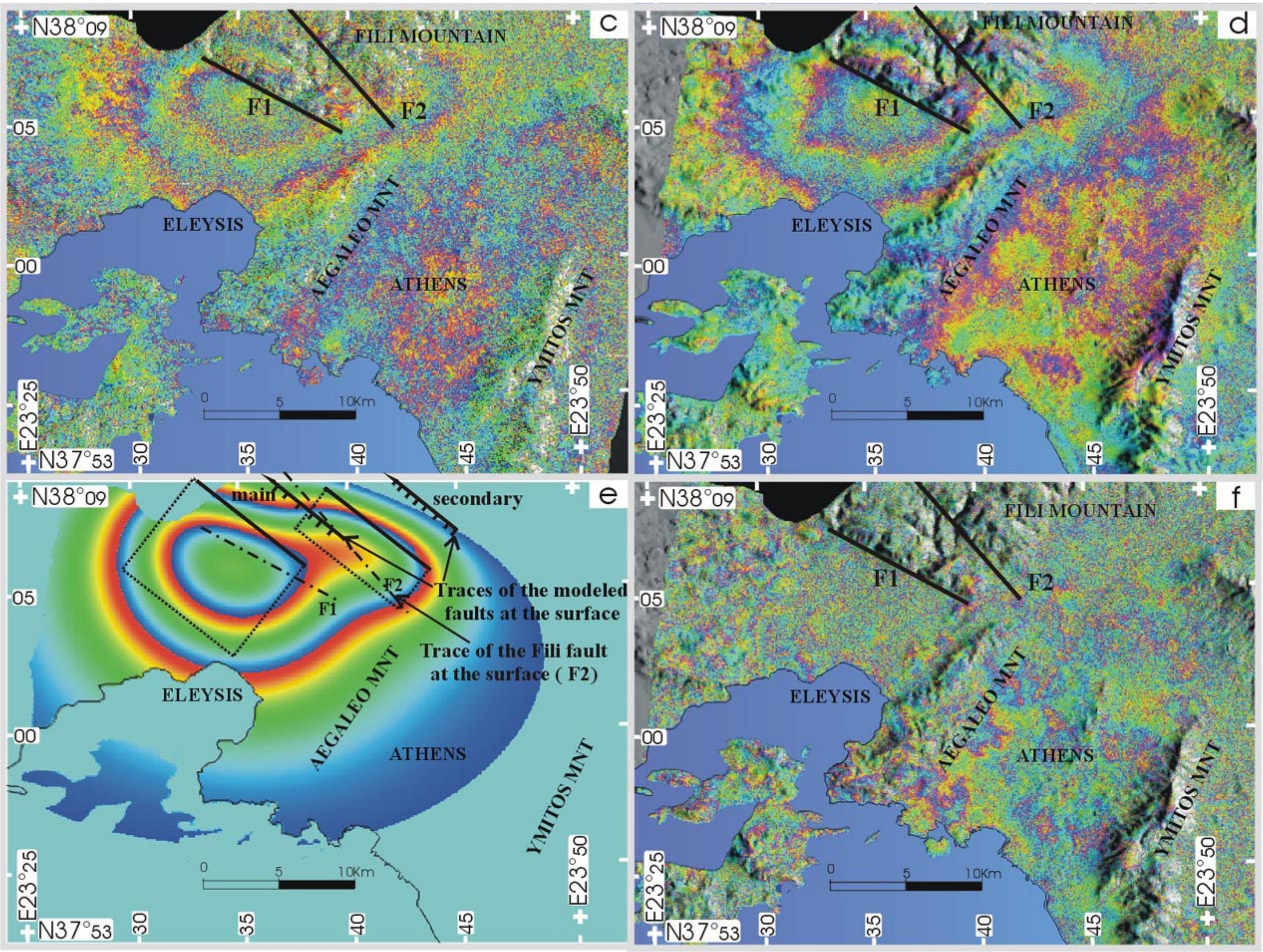
- Geology constrains relatively well the location of the fault
- Often it gives also good constraints on the fault azimuth (and sometimes its dip angle)

Grevena earthquake, M_s=6.6, May 13, 1995

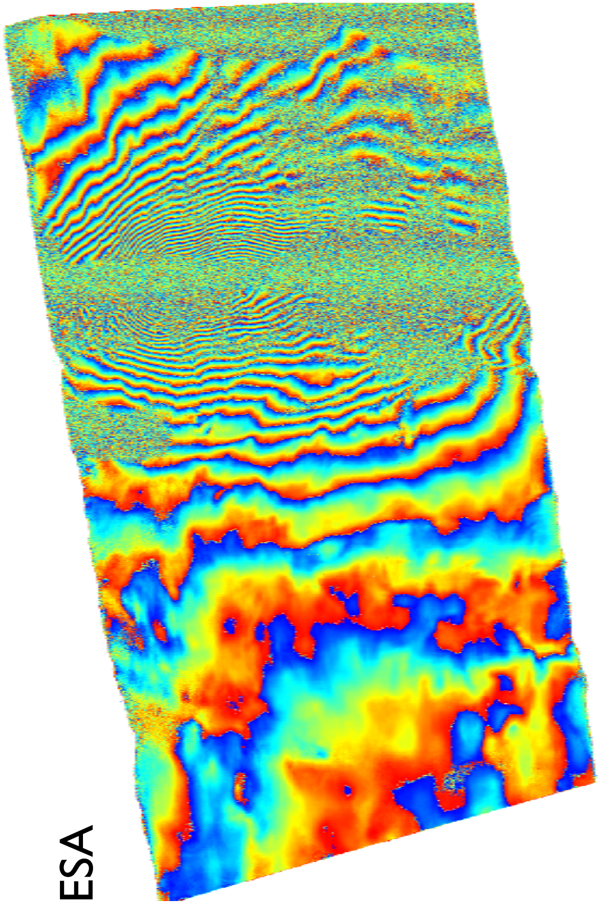


Interferogram and model of the Grevena earthquake (Meyer et al., 1996)

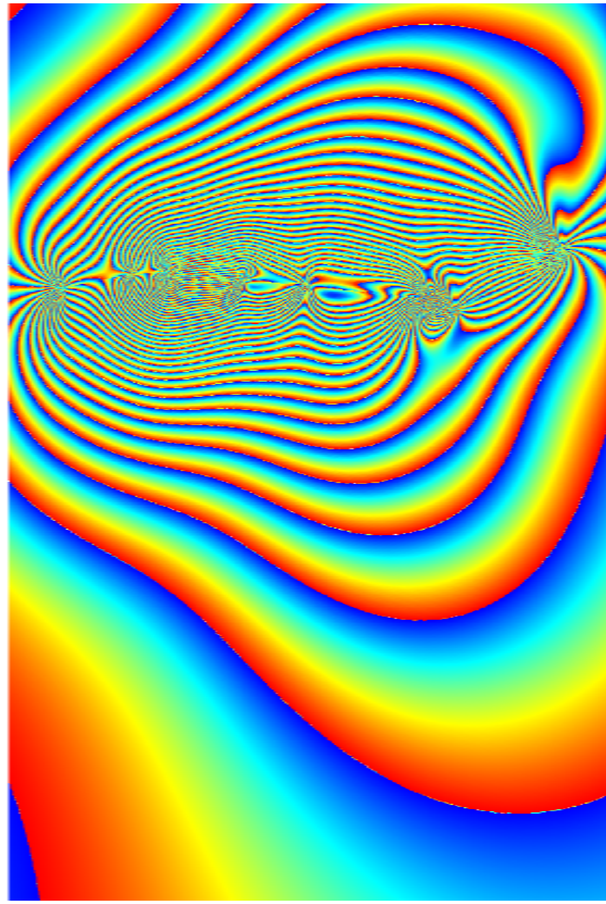
Model of the Athens, 1999 earthquake



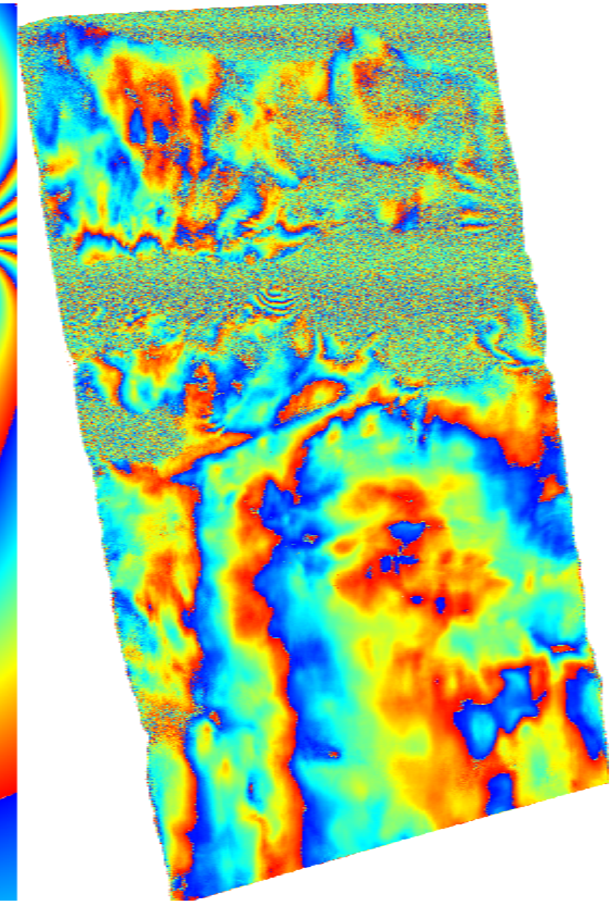
Model of the Izmit, 1999 earthquake



Interferogram



Synthetic interferogram (assuming a dislocation in an elastic half-space)



Residual interferogram

Model of the Bam, 2003, earthquake