The Abdus Salam
International Centre
for Theoretical Physics

United Nations
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2464-29

# Earthquake Tectonics and Hazards on the Continents

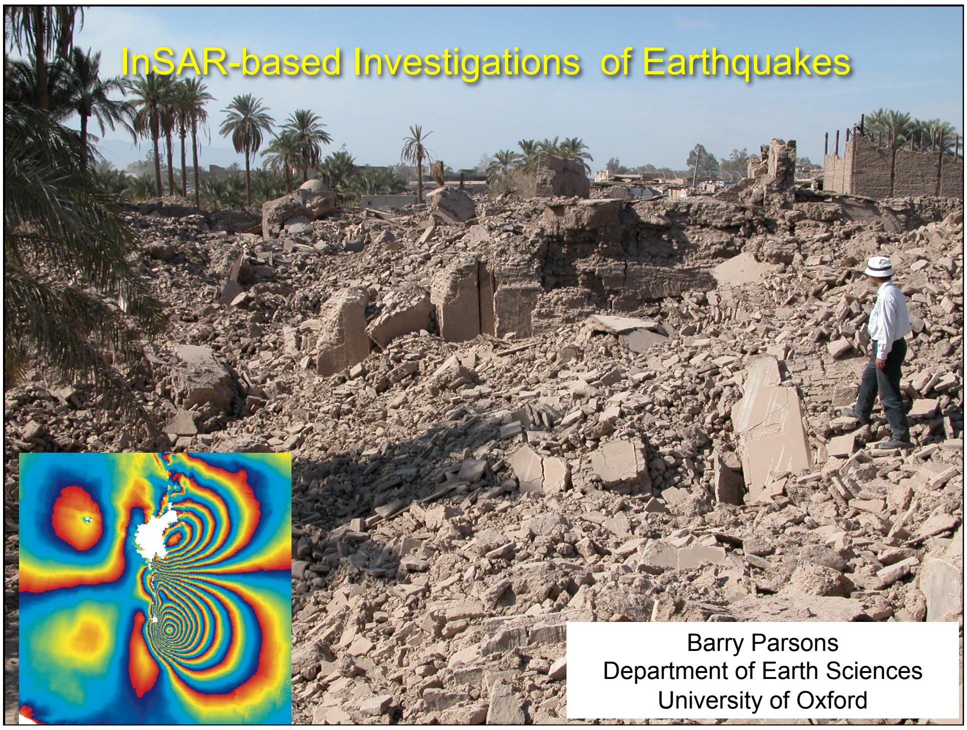
*17 - 28 June 2013*

## GPS and applications to the earthquake cycle, and use in particular earthquakes

B. Parsons

*University of Oxford*
*UK*

# InSAR-based Investigations of Earthquakes

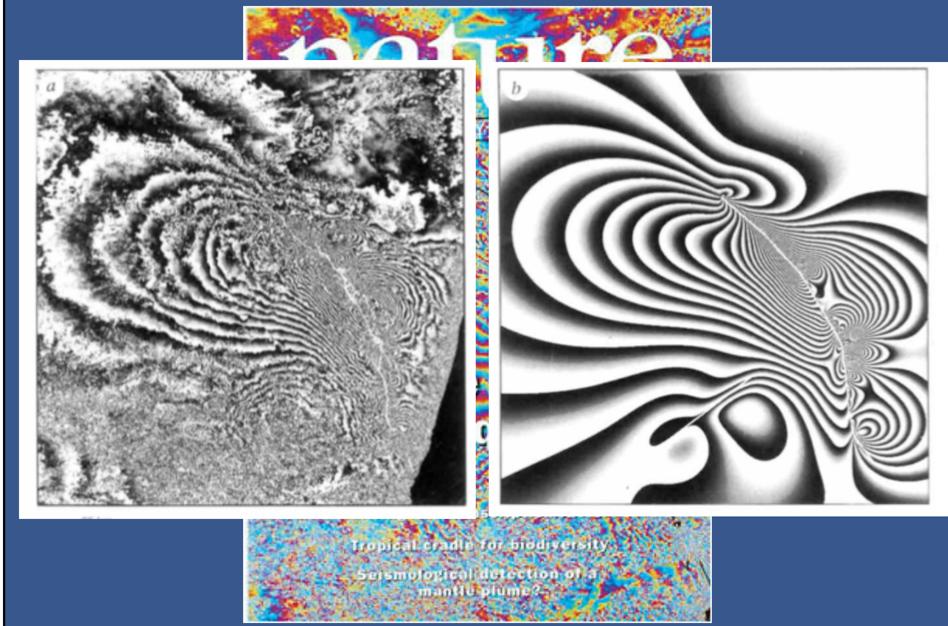


Barry Parsons
Department of Earth Sciences
University of Oxford

## InSAR Studies of Earthquakes, 1993-2012

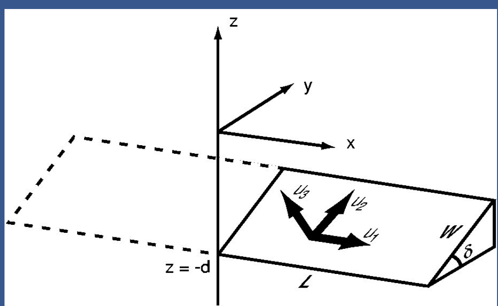

91 Earthquakes studied with InSAR, 1993-2012

## The 1992 Landers Earthquake, California




Massonnet et al, *Nature* (1993)

## Elastic Dislocation Modelling

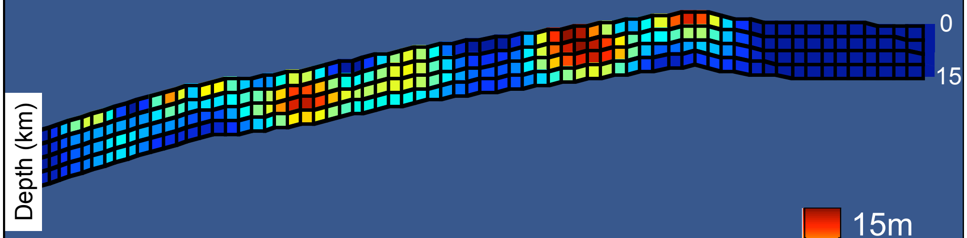


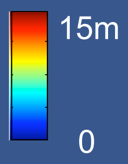

Y. Okada, 1985. Surface deformation due to **shear** and tensile faults in a half-space. *Bull. Seism. Soc. Am.*, 75, 1135-1154

To define a rectangular fault dislocation, need 10 parameters:

- Location of fault x,y,z (x=y=0, z = -d) in fault-centred reference frame with the x-axis pointing along strike [1]
- Length, Width and dip of the fault (L, W, $\delta$) [3]
- Slip components ($u_1$ = strike-slip; $u_2$ = dip-slip; $u_3$ = tensile) [3]
- Shift and rotate 3D Displacements calculated in the fault-centred reference frame to fit location and strike of model fault. [3]

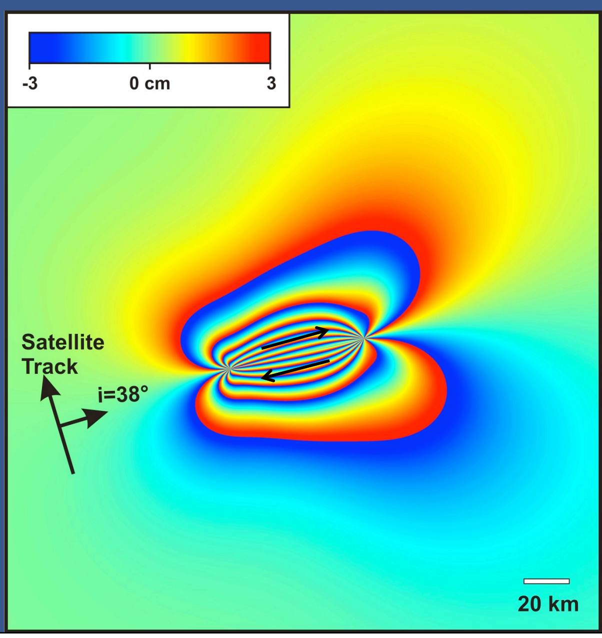
## Modelling Distributed Slip on Large Faults

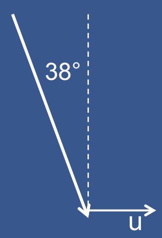



Subdivide fault into many small patches – treat each patch as an Okada dislocation. Given slip on each patch can calculate displacements everywhere else.

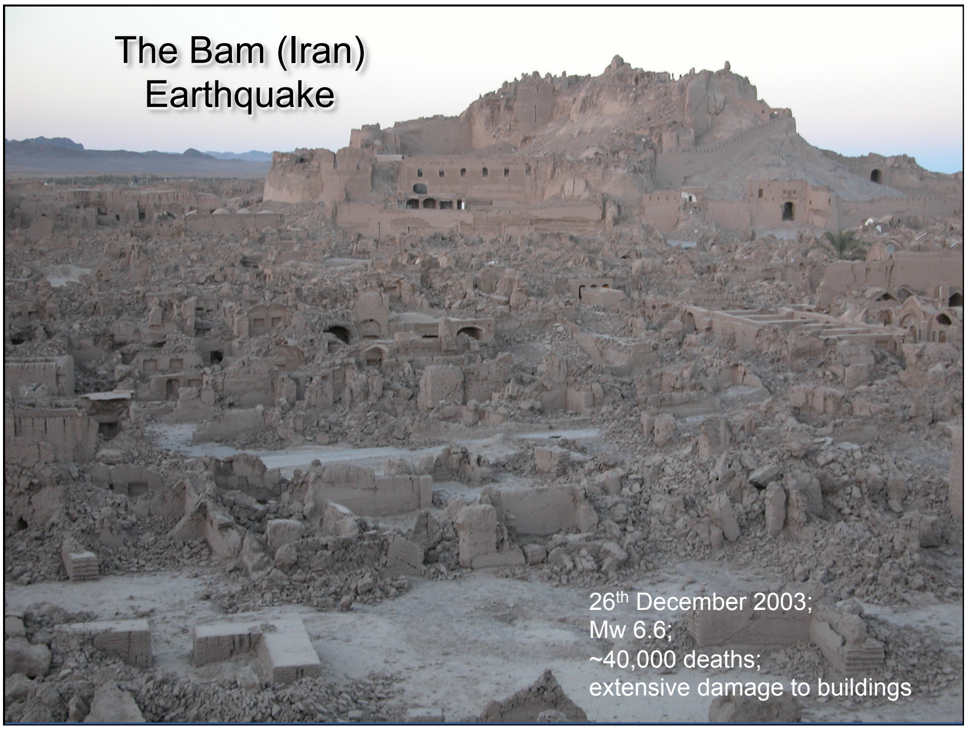
## An Interferogram for a Made-up Earthquake



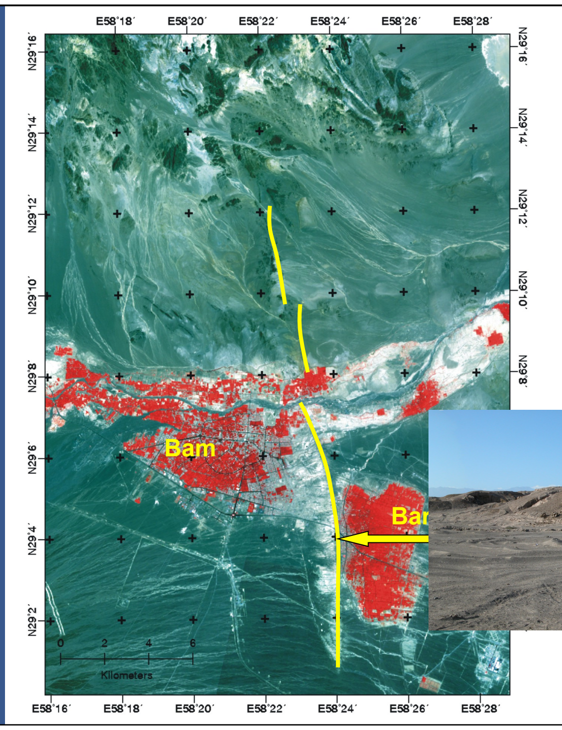




At the fault, displacements are horizontal and parallel to the fault:

$\Delta r = u \sin 38$




## The Bam Fault?

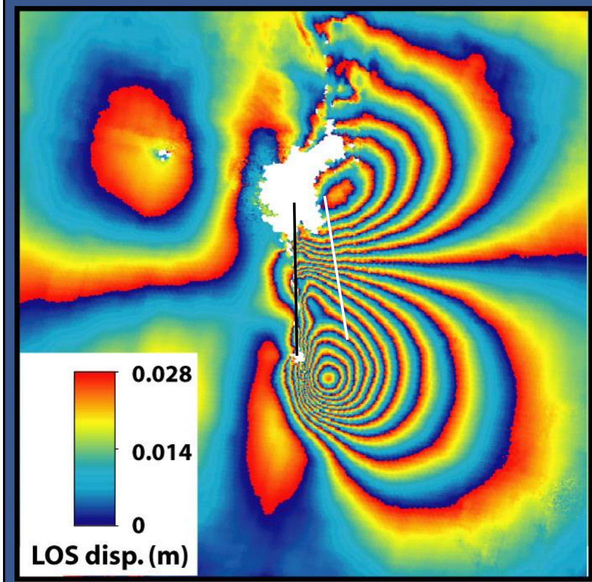



A fault trace running adjacent to Bam and Baravat, and marked by a 20-m high ridge, is

earthquake.

Aster 321

## Interferogram for the Bam Earthquake

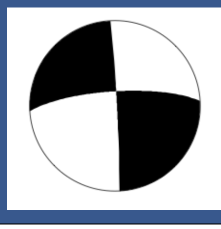



Interferogram, descending pass

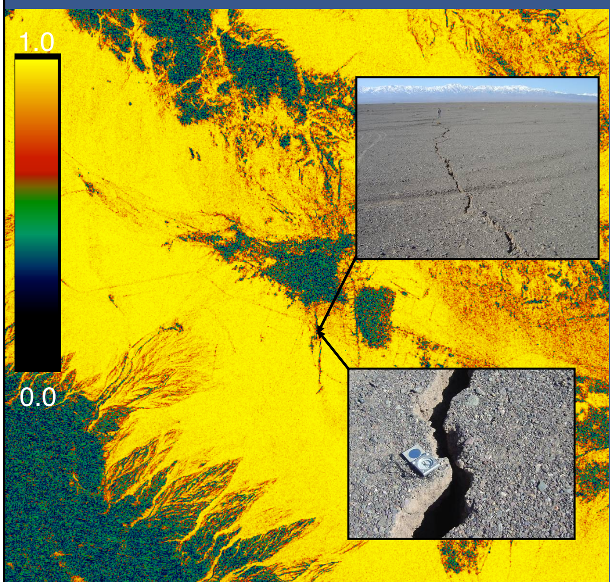
Funning et al, *JGR* (2005)

The first major earthquake for which a radar interferogram was constructed using Envisat ASAR data.

Elastic dislocation modelling of the interferogram showed that earthquake occurred on an unknown fault with no obvious surface features and not on any of the mapped faults.



## Interferometric Coherence for the Bam Earthquake



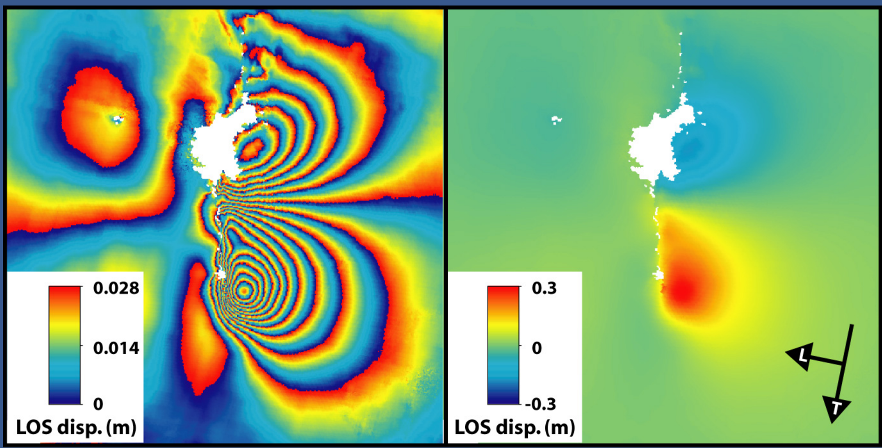

The first major earthquake for which an interferogram was constructed using Envisat ASAR data.

Elastic dislocation modelling of the interferogram showed that earthquake occurred on an unknown fault with no obvious surface features and not on any of the mapped faults.

The line of incoherence – disturbed ground – south of Bam was used to lead field workers to the right area.

Fielding et al, *JGR* (2005)

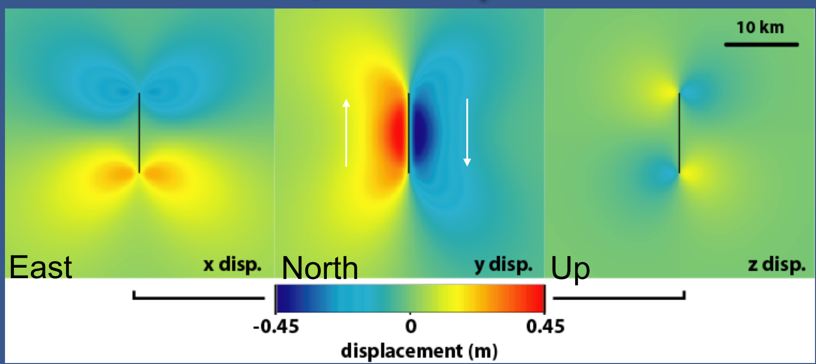
## Descending Track Interferogram

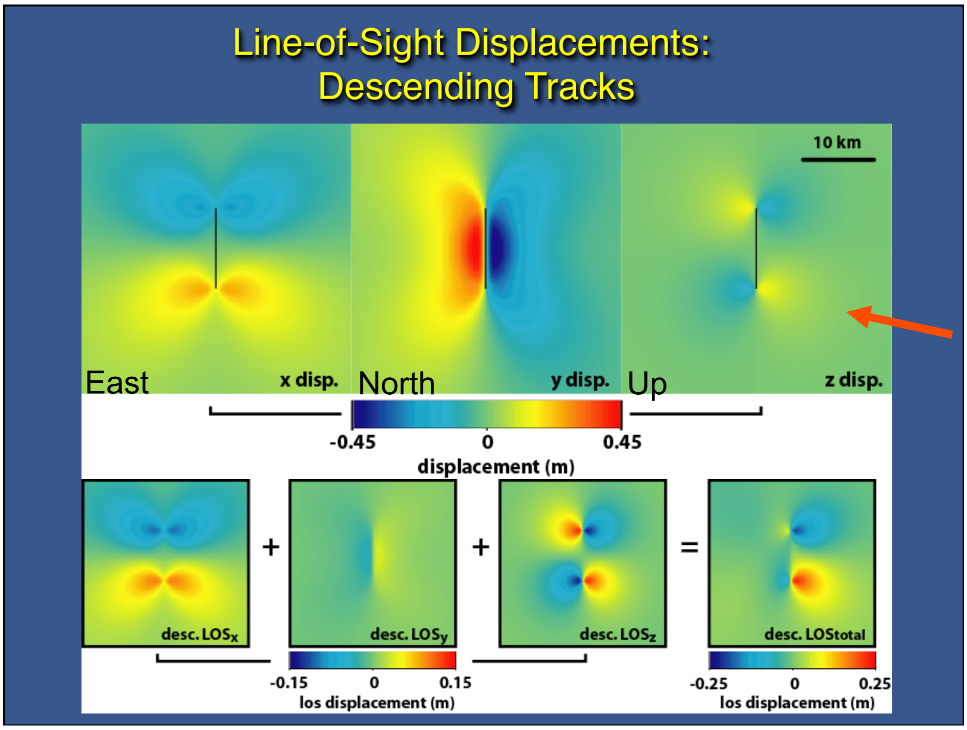


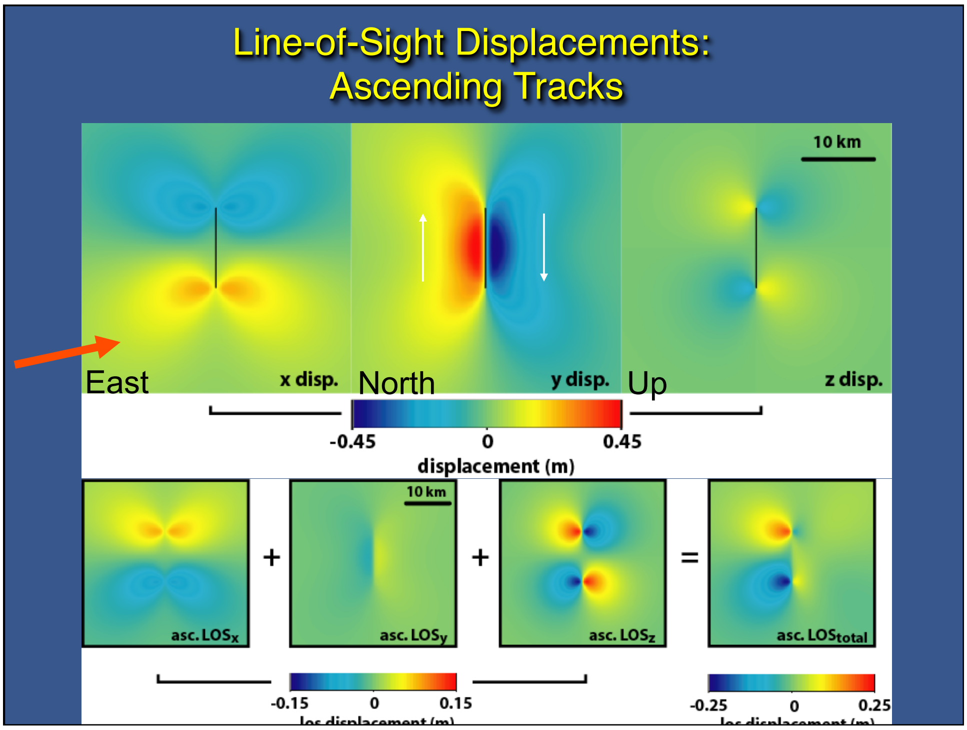

Wrapped Unwrapped

Track 120, beam mode I2, 03/12/2003 – 07/02/2004, Bperp = 4 m.

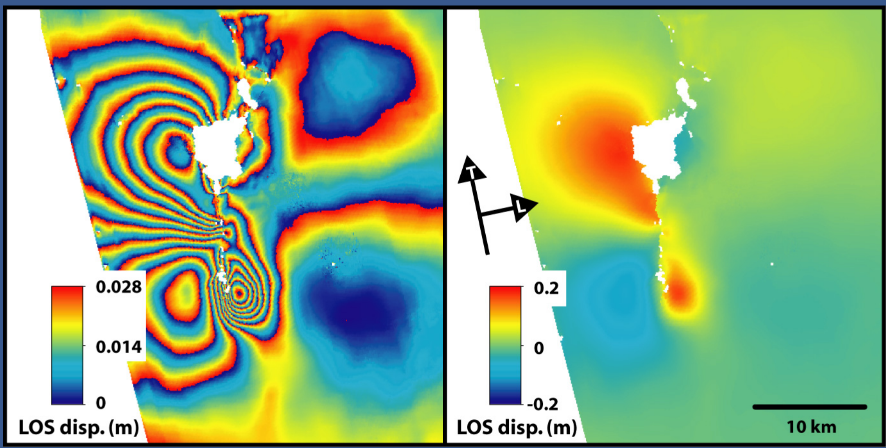
## Displacements for Vertical, North-South, Strike-Slip Fault




Line-of-Sight Displacements:
Descending Tracks
10 km
East
x disp.
North
y disp.
Up
z disp.
-0.45
0
0.45
displacement (m)
+
+
=
desc. LOSx
desc. LOSy
desc. LOSz
desc. LOStotal
-0.15
0
0.15
los displacement (m)
-0.25
0
0.25
los displacement (m)


Line-of-Sight Displacements:
Ascending Tracks
10 km
East
x disp.
North
y disp.
Up
z disp.
-0.45
0
0.45
displacement (m)
10 km
+
+
=
asc. LOSx
asc. LOSy
asc. LOSz
asc. LOStotal
-0.15
0
0.15
-0.25
0
0.25

## Ascending Track Interferogram

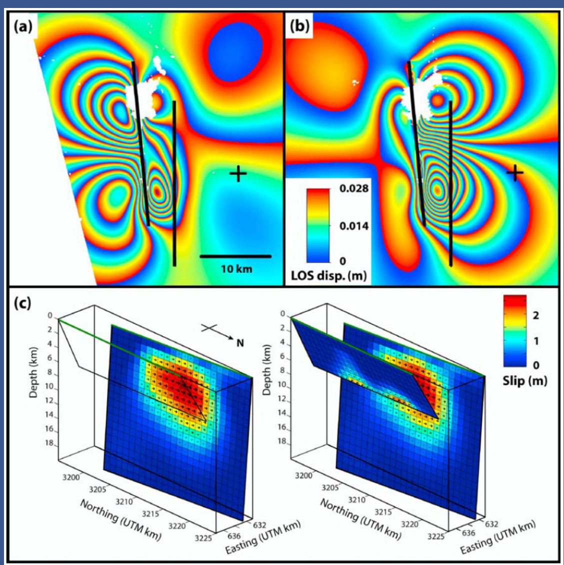



Wrapped

Unwrapped

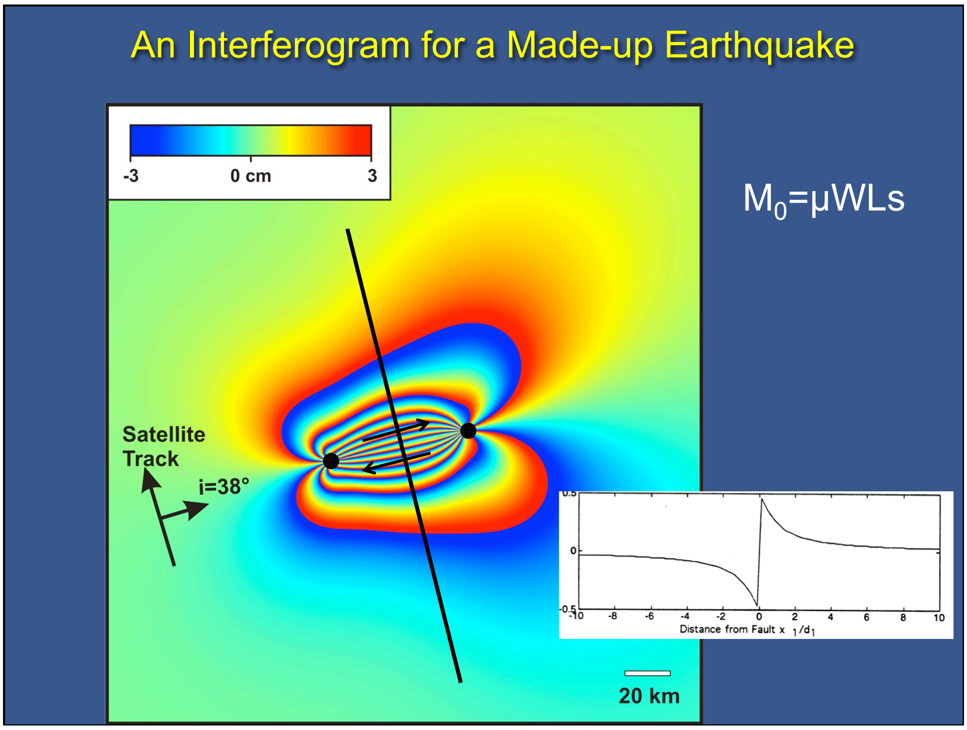
Track 385, beam mode I2, 16/11/2003 – 25/01/2004, $B_{perp}$ = 50 m.

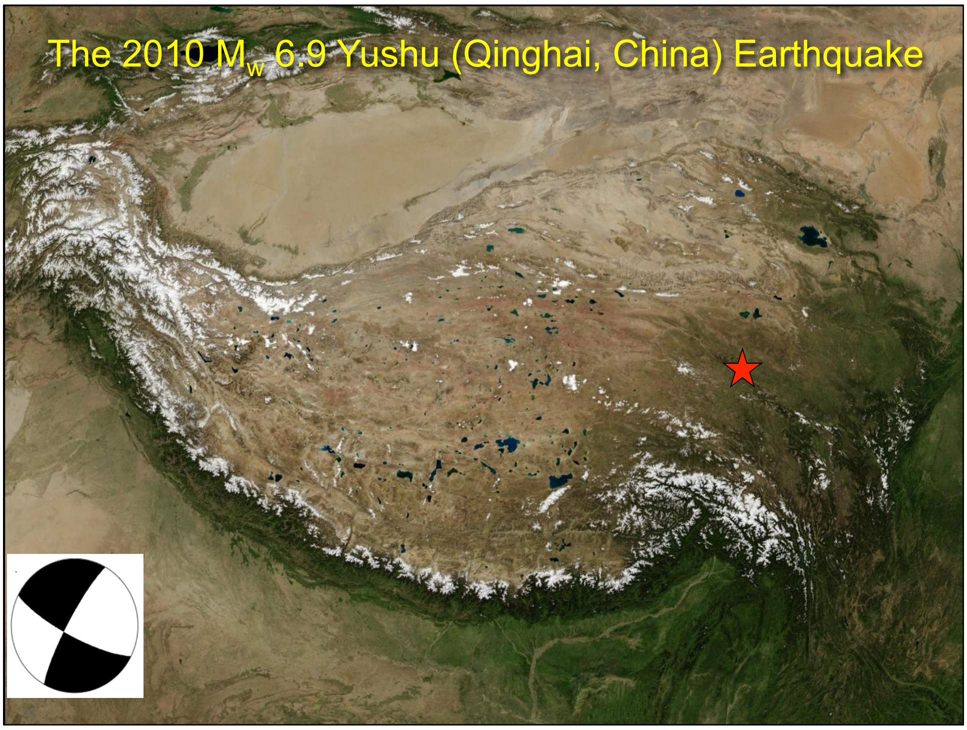
## Fault Models for Bam




Elastic dislocation modelling of the interferogram showed that earthquake occurred on an unknown fault with no obvious surface features and not on the mapped fault.

This fault dips in towards the fault on which the main rupture occurred and may interact with it. A small amount of slip may have occurred on the mapped fault near it intersection with the main fault.


An Interferogram for a Made-up Earthquake
-3
0 cm
3
Satellite Track
i=38°
20 km
Distance from Fault
M0=μWLs


The 2010 Mw 6.9 Yushu (Qinghai, China) Earthquake

## The 2010 $M_w$ 6.9 Yushu (Qinghai, China) Earthquake

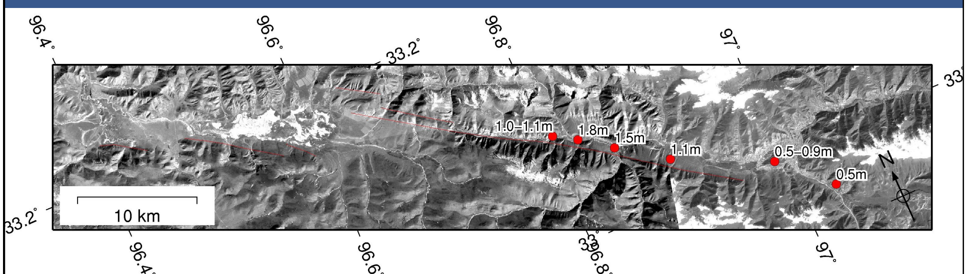
The earthquake occurred at 23:49 on 13 April, 2010 (UTC; 07:49, 14 April 2010, local)

Approximately 70% of houses collapsed.

~2,700 people were killed and over 12,000 injured

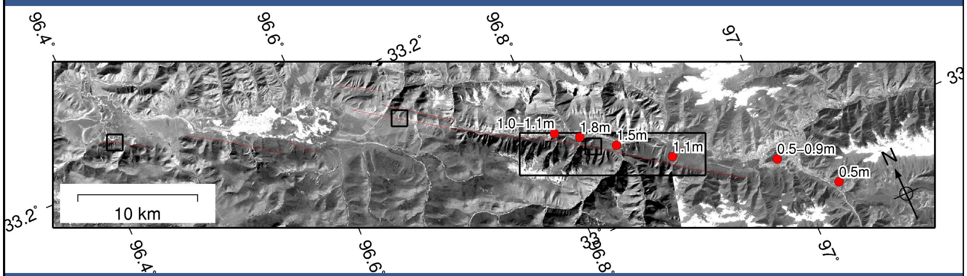
Gyegu Monastery

## SPOT 5 Imagery for the Yushu Earthquake

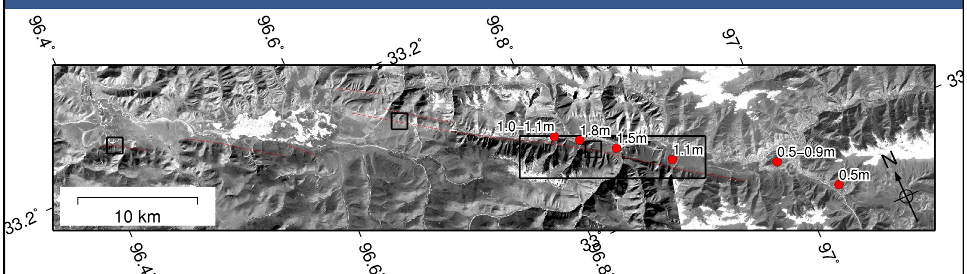


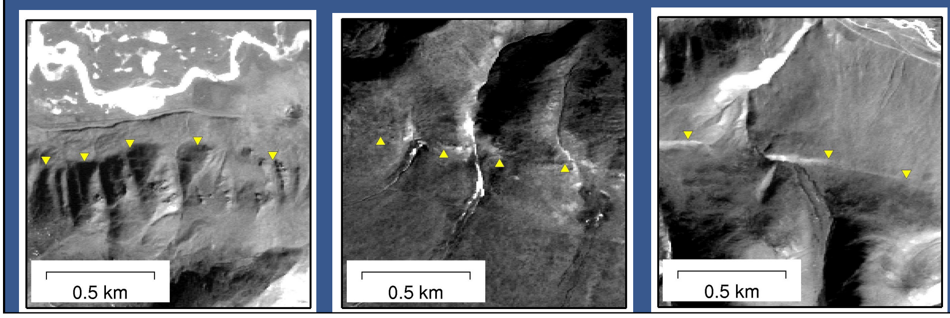

Panchromatic, 2.5 m resolution

# SPOT 5 Imagery for the Yushu Earthquake




# SPOT 5 Imagery for the Yushu Earthquake



## Surface Ruptures of the Yushu Earthquake

Earthquake occurred on the Yushu-Garzê-Xianshuihe Fault System

Surface rupture traced for about 35 km with a peak slip of 1.8m

## Estimating the Length of the Fault from the Seismic Moment

$$M_0 = \mu L W \bar{u}$$

Assume:

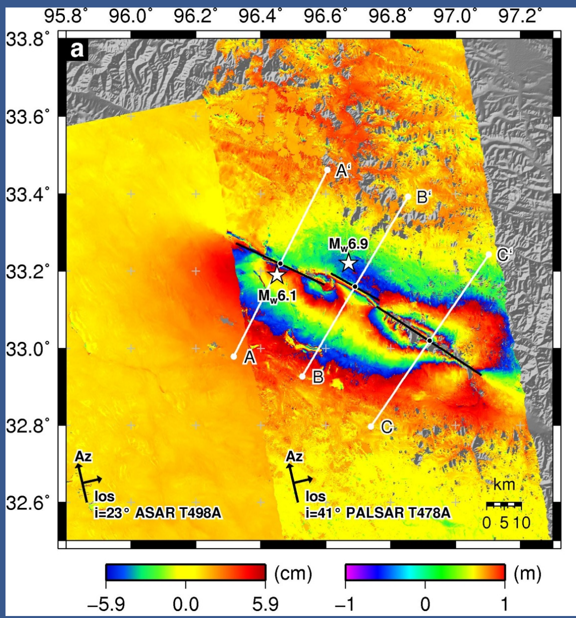
$\mu = 3.2\times10^{10}$ Pa, W = 15 km,

u = 1.5 m, $M_0 = 2.5\times10^{19}$ N m (GCMT),

then

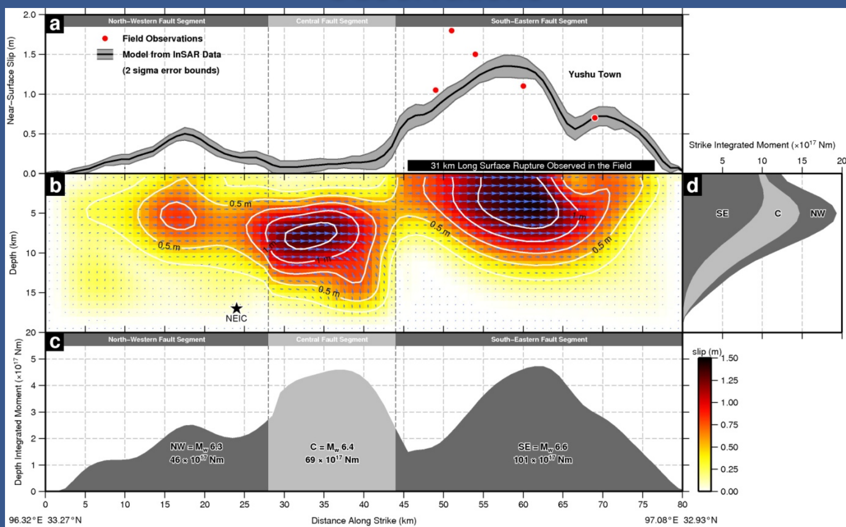
L = 35 km

## Interferograms for the Yushu Earthquake




Li et al, *JGR* (in review)

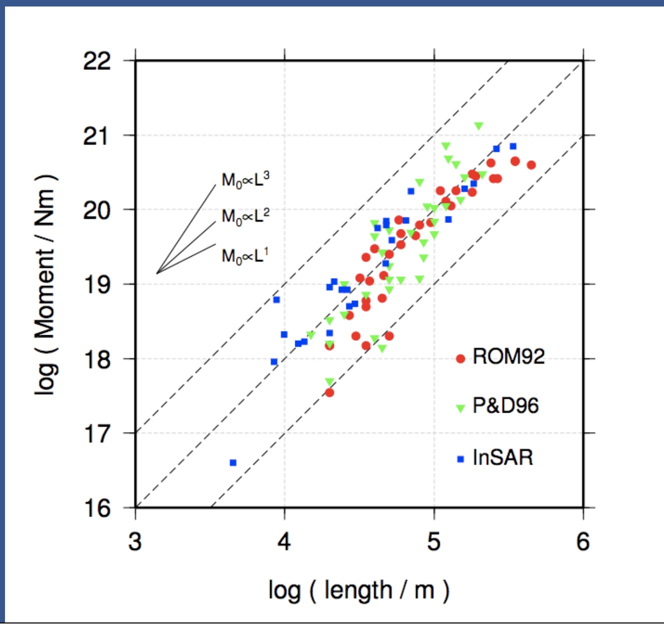
## Moment Release Distribution and Surface Observations




Li et al, *JGR* (in review)

Majority of moment release above 10 km. Three slip patches. NW patch is due to the $M_w$ 6.1 aftershock.

## Moment versus Length, Strike Slip Earthquakes



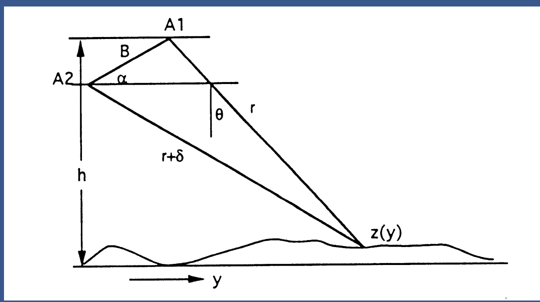

## What are the Advantages of InSAR over Seismology in Studying Earthquakes?

- Satellite radar interferometry can be used to study all stages of the earthquake process – interseismic strain accumulation, the earthquake itself, and transient postseismic adjustments.

- Modelling allows the factors of the amount of slip and the length and width of fault, that determine the magnitude of the earthquake, to be determined separately.

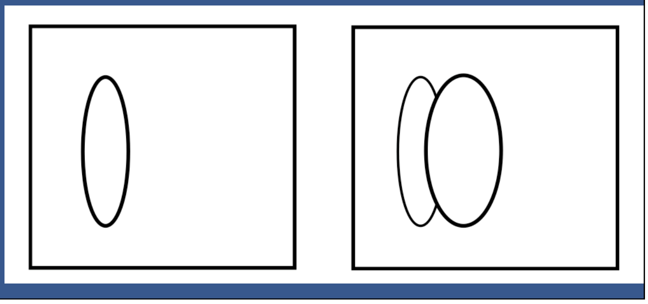
- Perhaps the most important, often unmentioned, advantage is that InSAR provides an accurate reference frame within which the surface deformation due to earthquakes is located, and hence accurate earthquake fault locations.

## Geometrical Effects on SAR Images

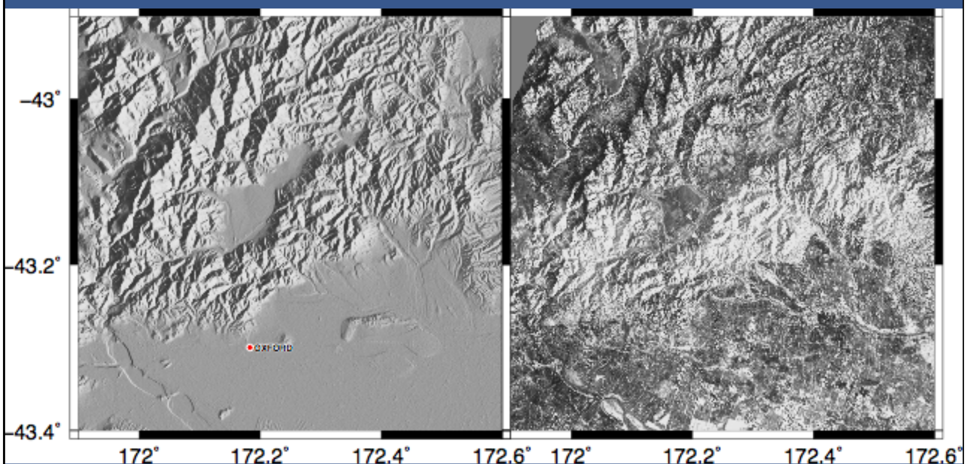



If there is pre-existing digital topography, can use it to fully remove geometric effects from measured path differences. Need to match images to topography to do this.

Different SAR viewpoints produce shift and stretch in the amplitude images. Match corresponding parts of the image. This matching also contains information about surface displacements



## Canterbury Region: Shaded Relief and SAR Amplitude Image




Shaded relief:

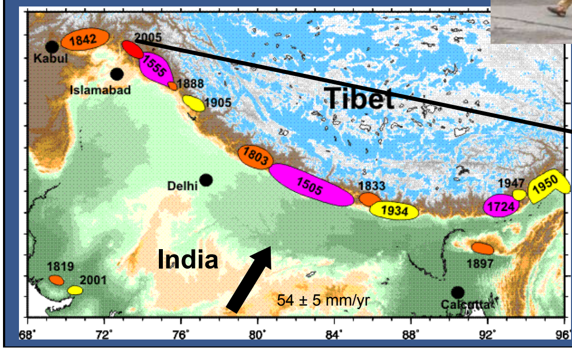
sun azimuth 103°, elevation 45°

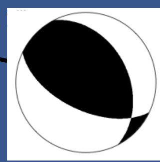
ALOS PALSAR amplitude image:

Look direction 283°, incidence angle 38°

## The 2005 Mw 7.6 Muzaffarabad Earthquake

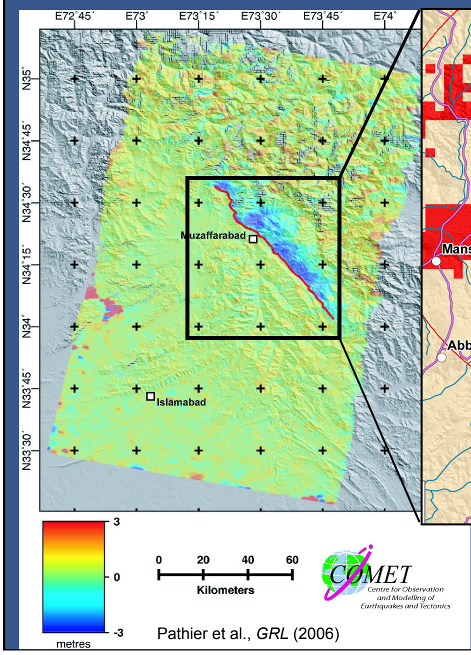
- 75,000+ killed, 106,000+ injured.
- India-Eurasia convergent plate-boundary
- Active tectonics in the Kashmir area is poorly understood, but earthquakes of this type and magnitude to be expected.

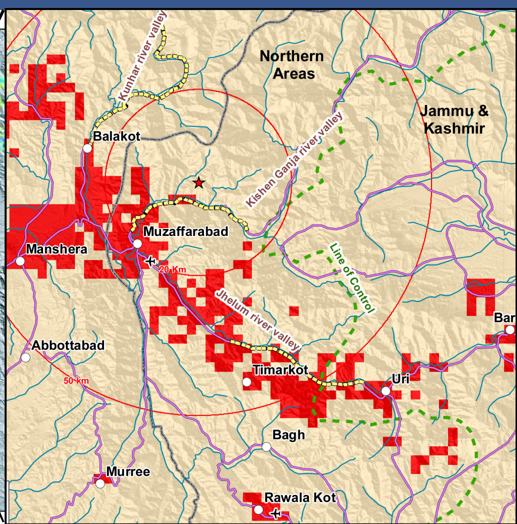



Roger Bilham

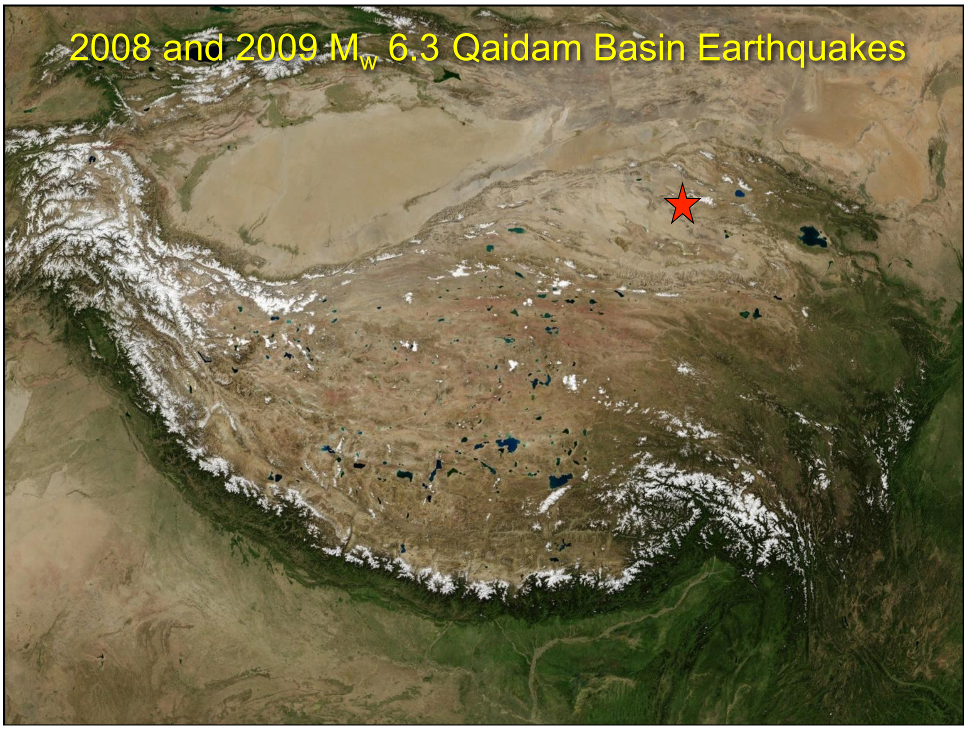
## Rapid Remote-sensing Determination of Fault Locations

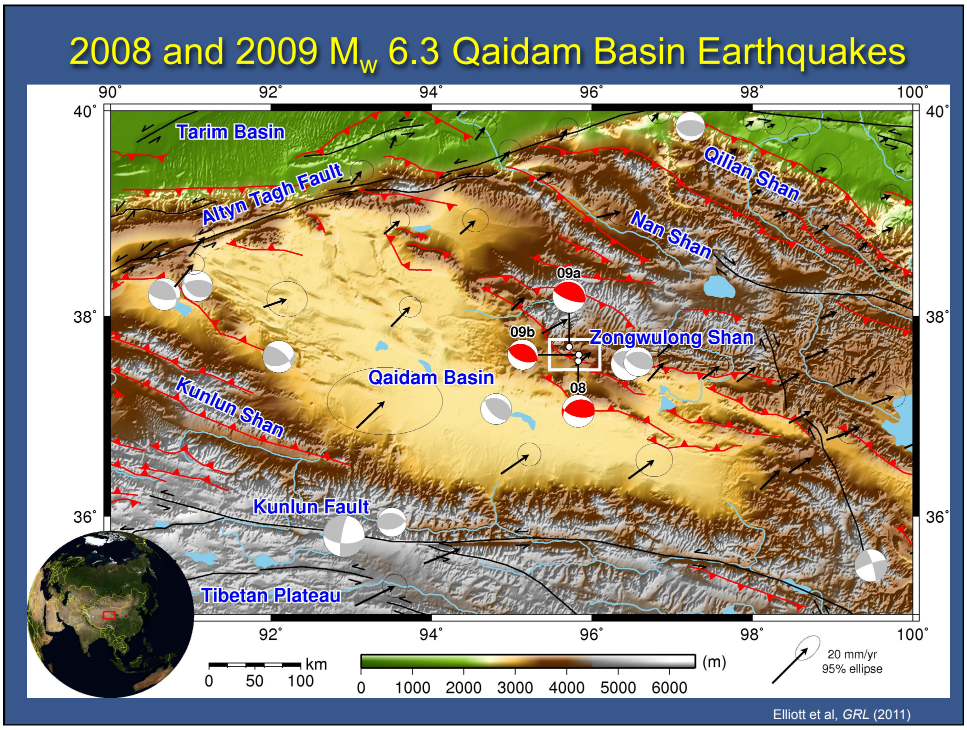



Pathier et al., *GRL* (2006)

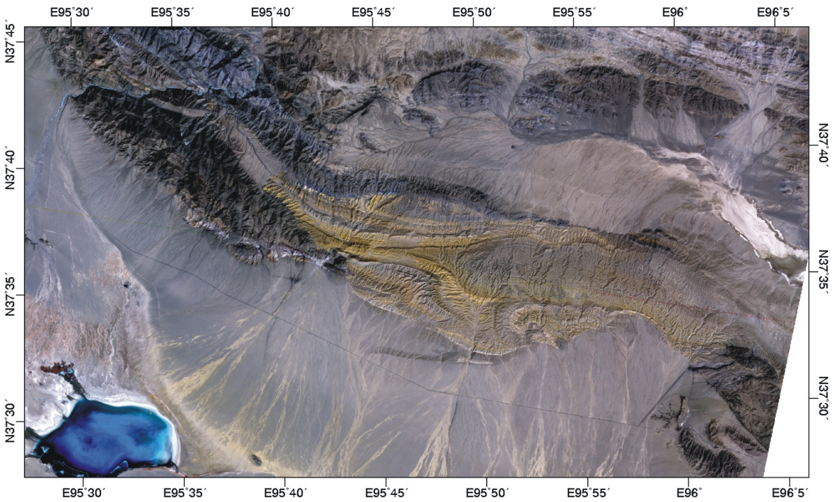



Map of the affected area (from EC-JRC)
Most of damaged areas in mountainous regions with access impeded by landslides that blocked the roads.


2008 and 2009 $M_w$ 6.3 Qaidam Basin Earthquakes

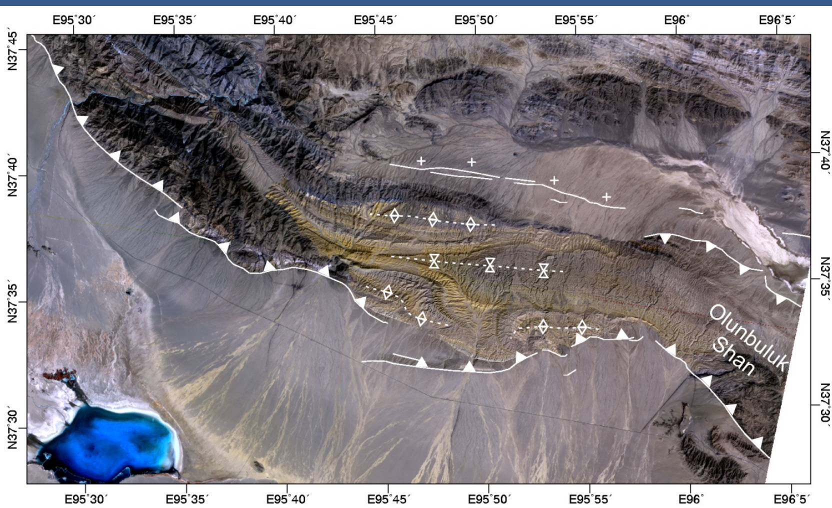

2008 and 2009 $M_w$ 6.3 Qaidam Basin Earthquakes
90˚
92˚
94˚
96˚
98˚
100˚
40˚
38˚
36˚
Tarim Basin
Altyn Tagh Fault
Qilian Shan
Nan Shan
09a
09b
08
Zongwulong Shan
Qaidam Basin
Kunlun Shan
Kunlun Fault
Tibetan Plateau
km
0 50 100
0 1000 2000 3000 4000 5000 6000 (m)
20 mm/yr
95% ellipse
Elliott et al, GRL (2011)

## Faulting from ASTER Satellite Imagery



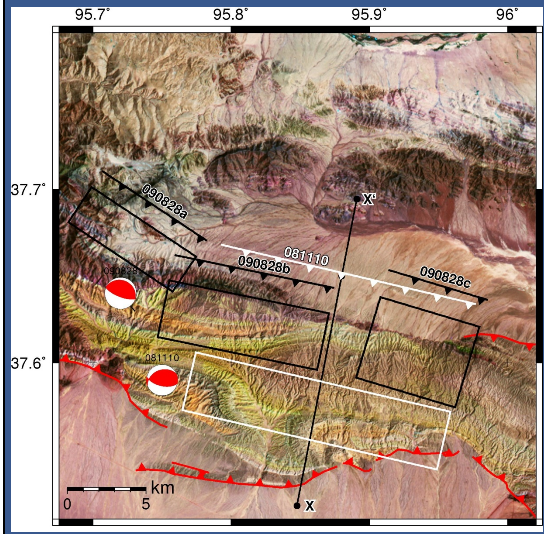

ASTER mosaic (R,G,B bands 3,2,1)

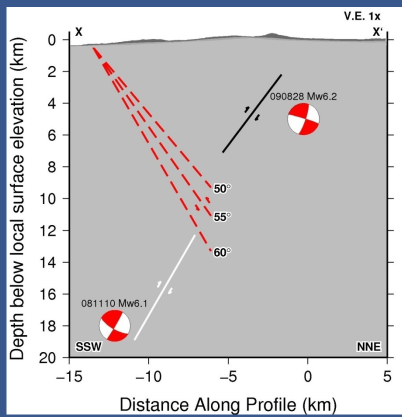
## Faulting from ASTER Satellite Imagery




ASTER mosaic (R,G,B bands 3,2,1)

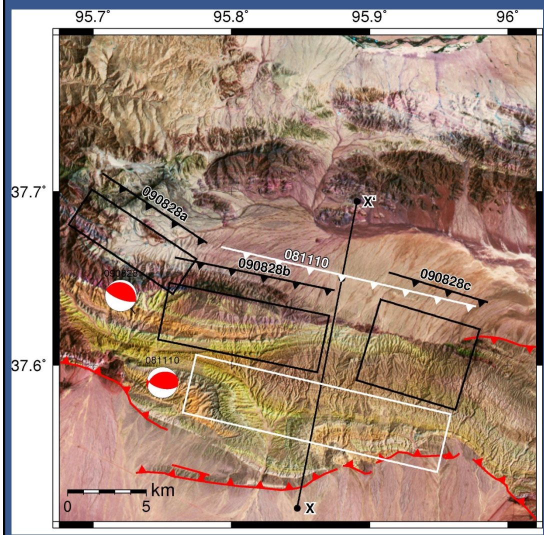
## Evidence for Segmentation of a Fault with Depth

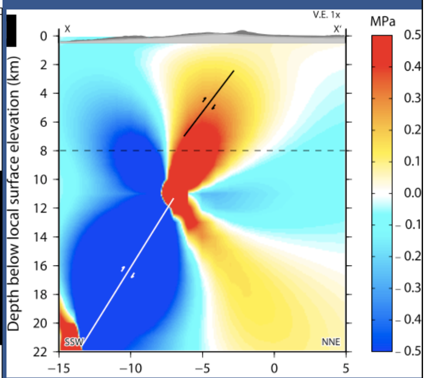



Elliott et al, *GRL* (2011)

## Coulomb Stress Changes due to the 2008 Earthquake



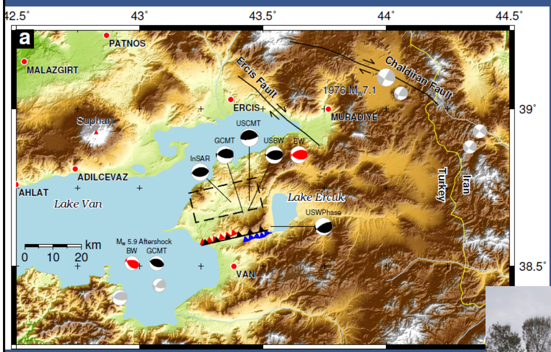

Elliott et al, *GRL* (2011)

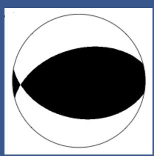
Coulomb stress

$$\Delta\tau = \Delta\bar{\tau}_f - \mu\,(\Delta\sigma_n - \Delta p)$$

$$\Delta\tau = \Delta\bar{\tau}_f - \mu'\ \Delta\sigma_n$$

## 2011 Van Earthquake, Eastern Turkey

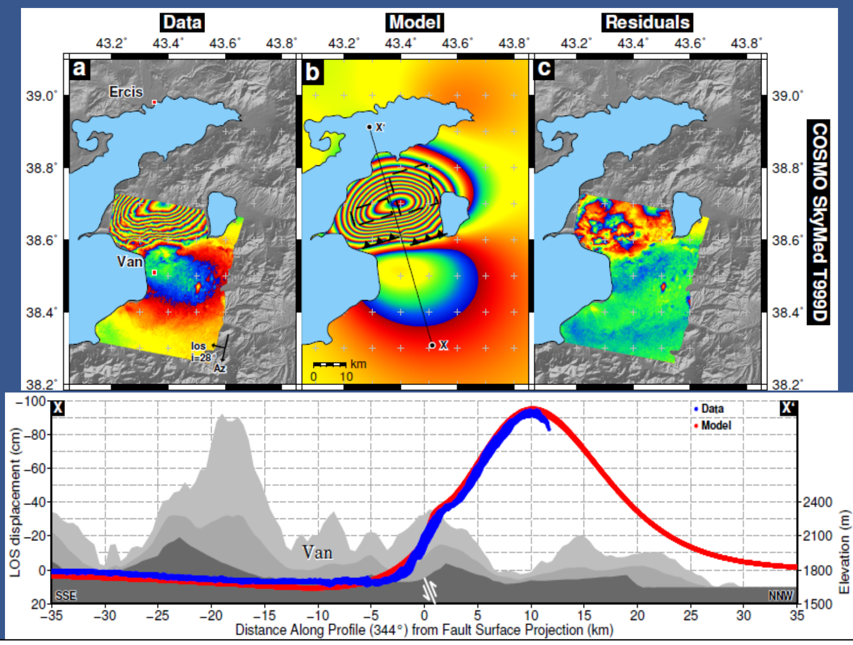


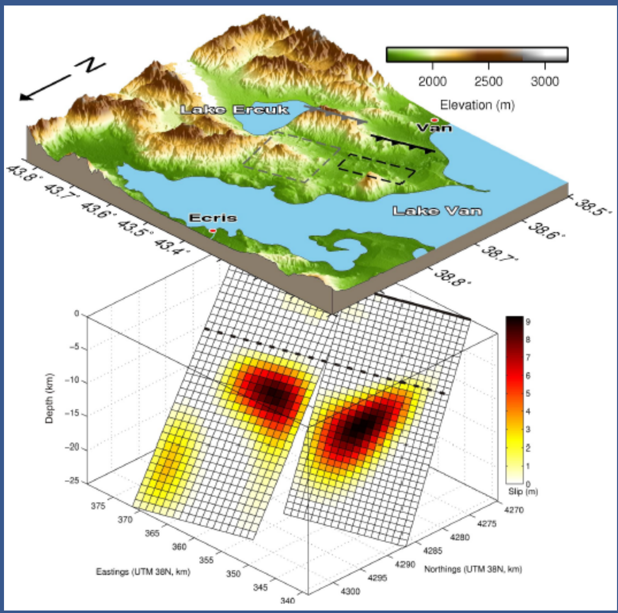
604 killed, 4,152 injured,
~60,000 homeless

Kate Scharer, USGS, Nov 2011

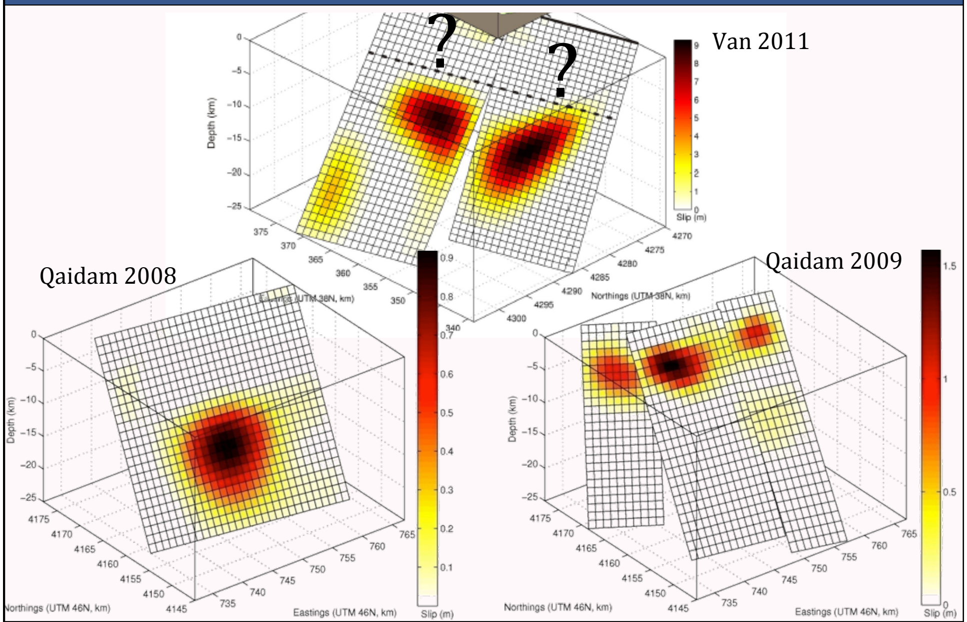
## Cosmo-Skymed Interferometry



## Van Earthquake: Buried Slip



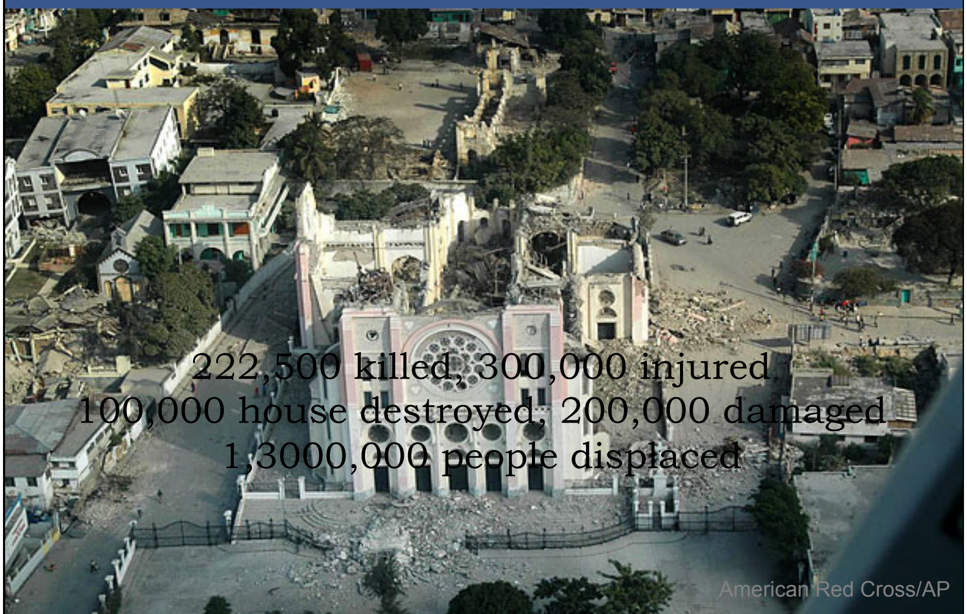

## Future Hazard?



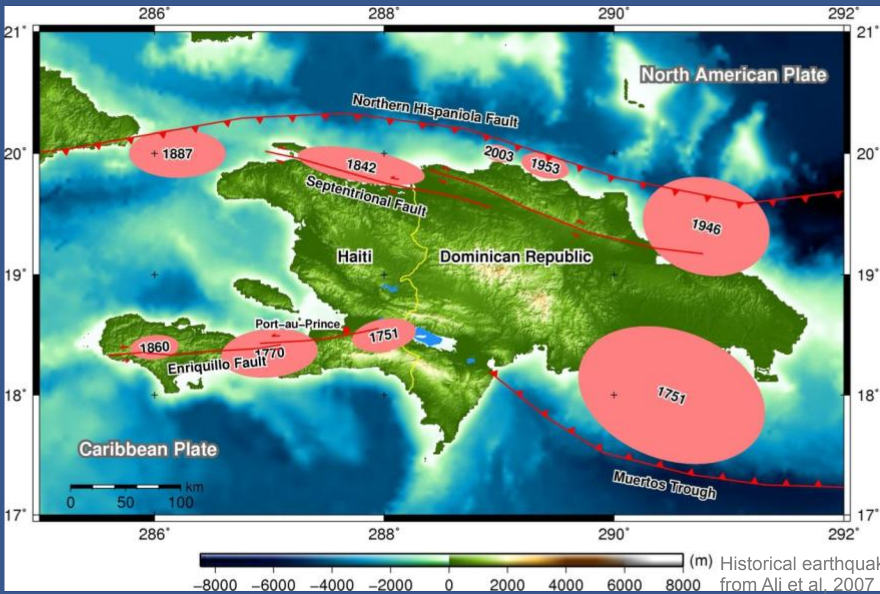
## Surface Expression of Faulting

Kate Scharer, USGS, Nov 2011

## Haiti Earthquake, Mw 7.0 ,12th January 2010

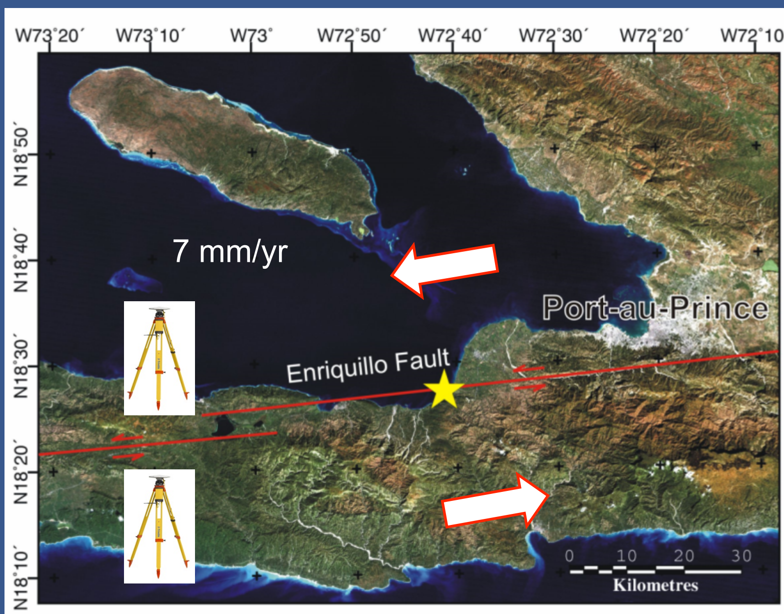


## Hispaniola: Major Historical Earthquakes



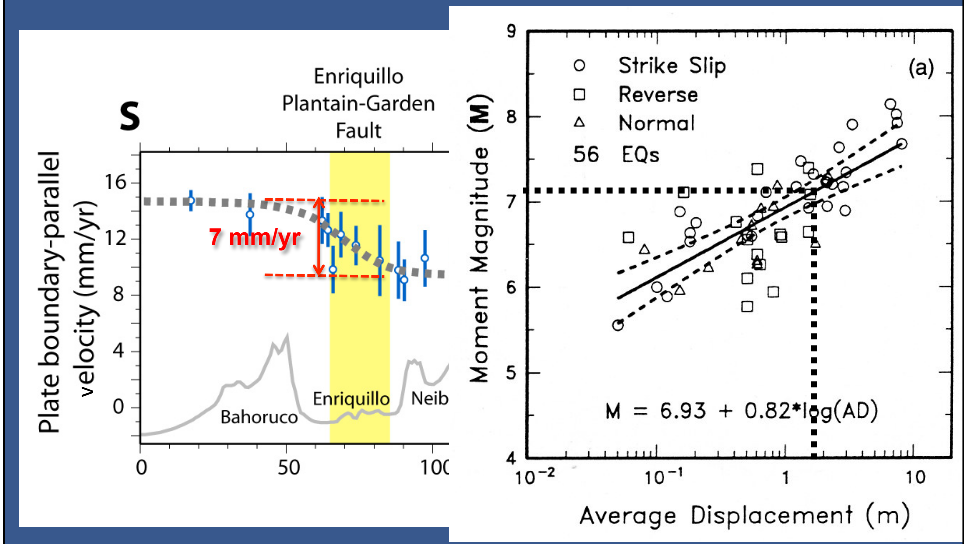

Historical earthquakes from Ali et al. 2007

## The Enriquillo Fault, Haiti



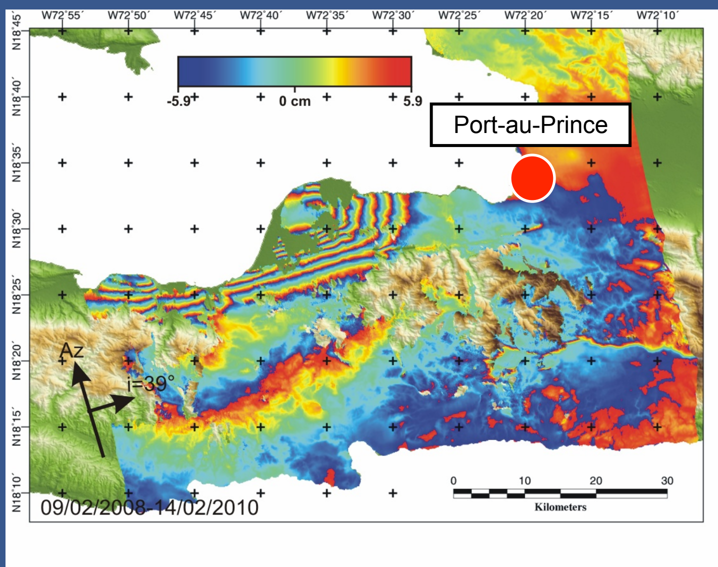

GPS from Manaker et al. 2008

## A Quantifiable Threat

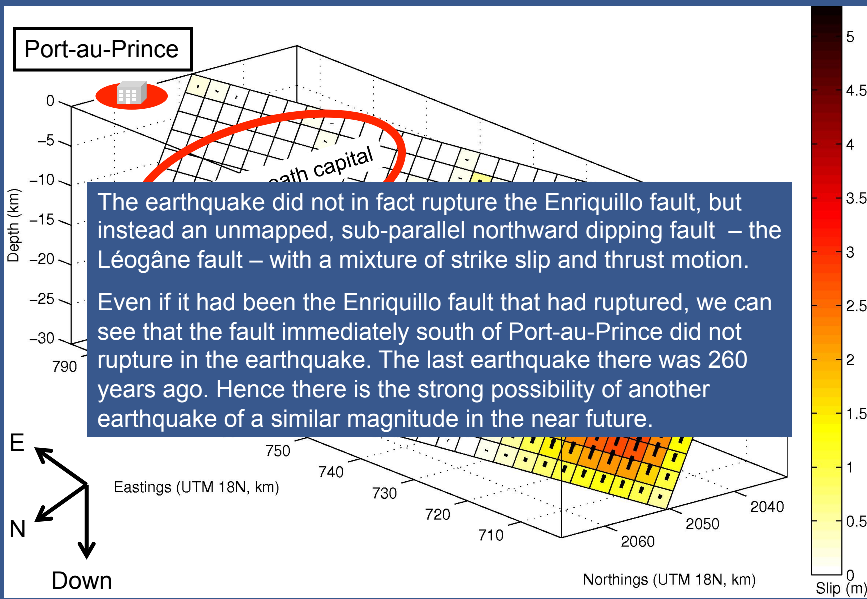



- Strain builds up since being released in the last earthquake 250 years ago.
- A deficit of slip equal to 250 yr x 7 mm/yr, ~1.8 m, has accumulated.
- If this were released as slip in one event, it would result in a magnitude ~7.2 earthquake.

## ALOS Interferometry for the Haiti earthquake



# Fault Models for the Haiti Earthquake




The earthquake did not in fact rupture the Enriquillo fault, but instead an unmapped, sub-parallel northward dipping fault – the Léogâne fault – with a mixture of strike slip and thrust motion.

Even if it had been the Enriquillo fault that had ruptured, we can see that the fault immediately south of Port-au-Prince did not rupture in the earthquake. The last earthquake there was 260 years ago. Hence there is the strong possibility of another earthquake of a similar magnitude in the near future.