The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA
International Atomic Energy Agency

**2053-44**

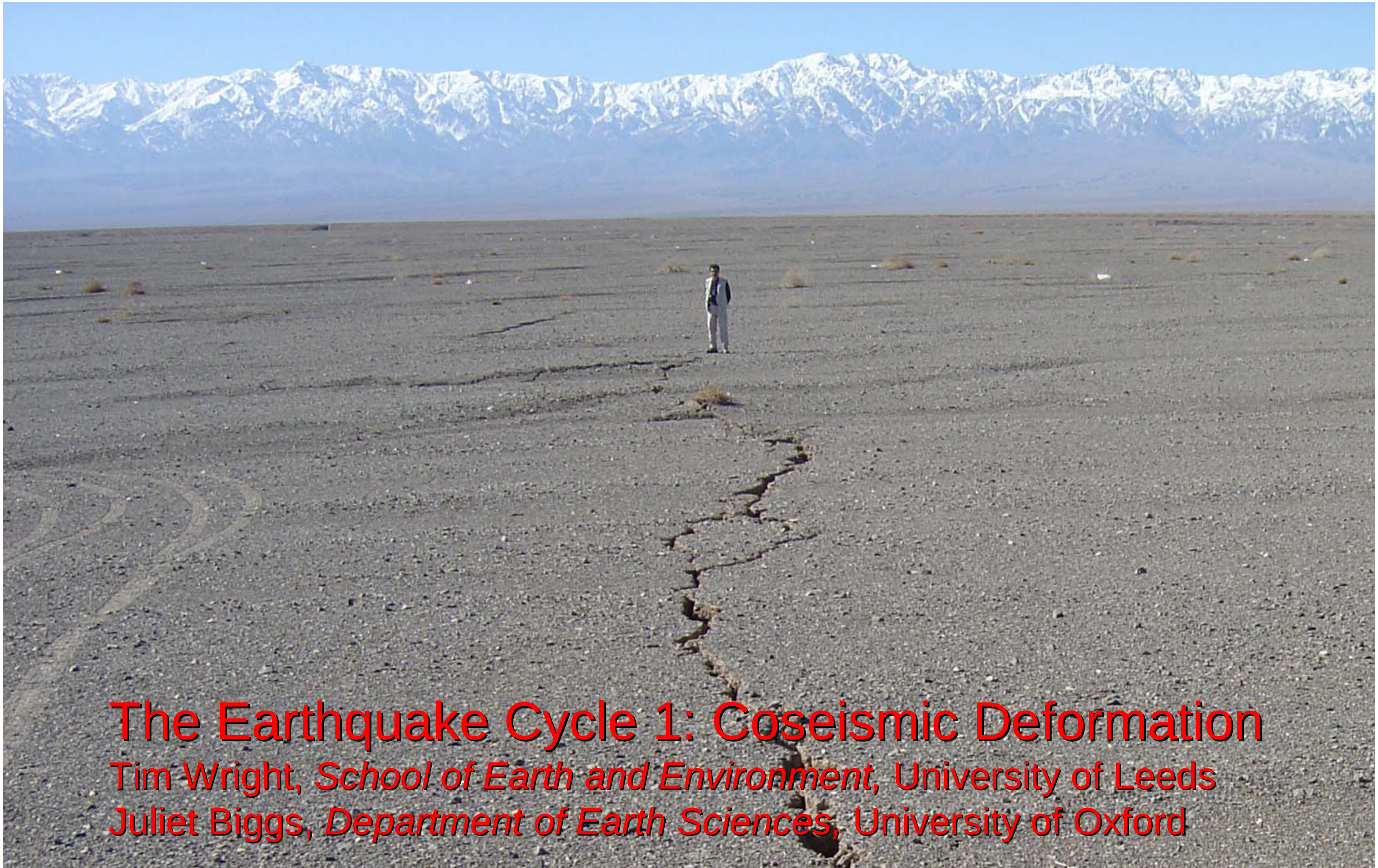
**Advanced Workshop on Evaluating, Monitoring and Communicating Volcanic and Seismic Hazards in East Africa**

***17 - 28 August 2009***

# The seismic cycle 1. Co-seismic deformation

Tim Wright
*University of Leeds*
*U.K.*

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

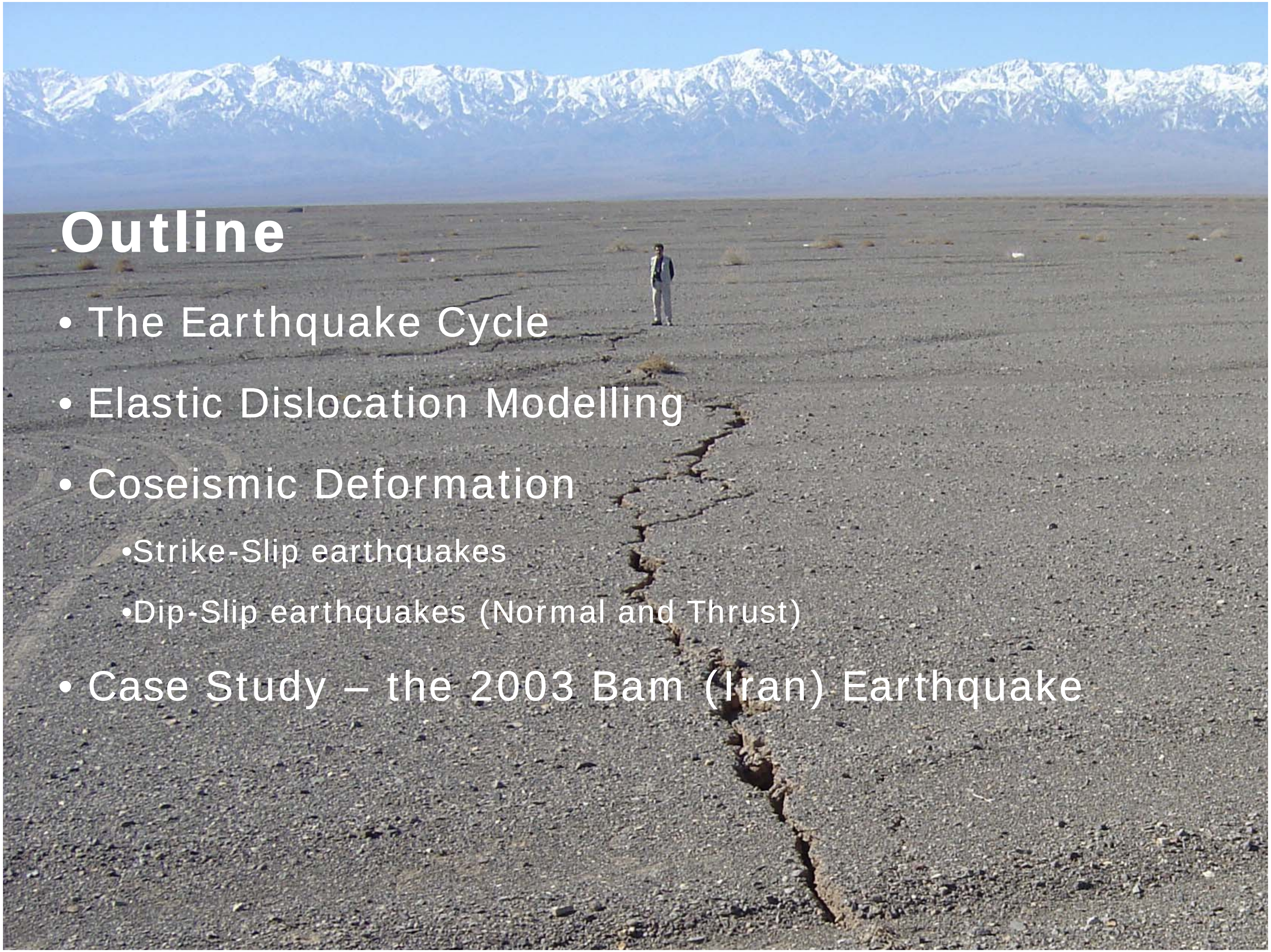


# The Earthquake Cycle 1: Coseismic Deformation

Tim Wright, *School of Earth and Environment*, University of Leeds
Juliet Biggs, *Department of Earth Sciences*, University of Oxford

UNIVERSITY OF OXFORD

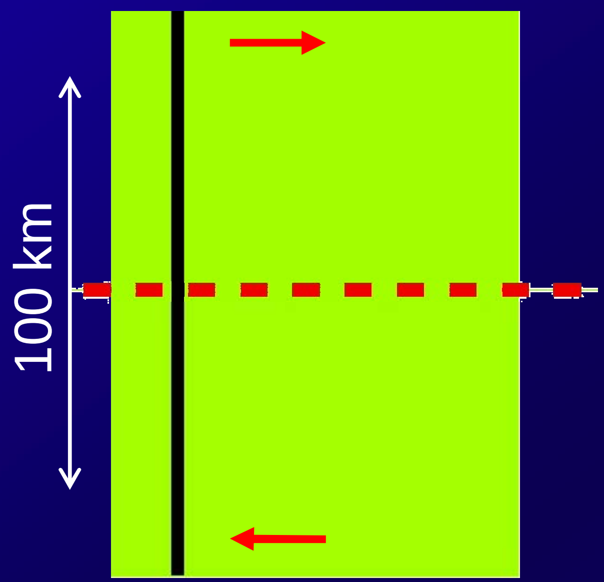
UNIVERSITY OF LEEDS



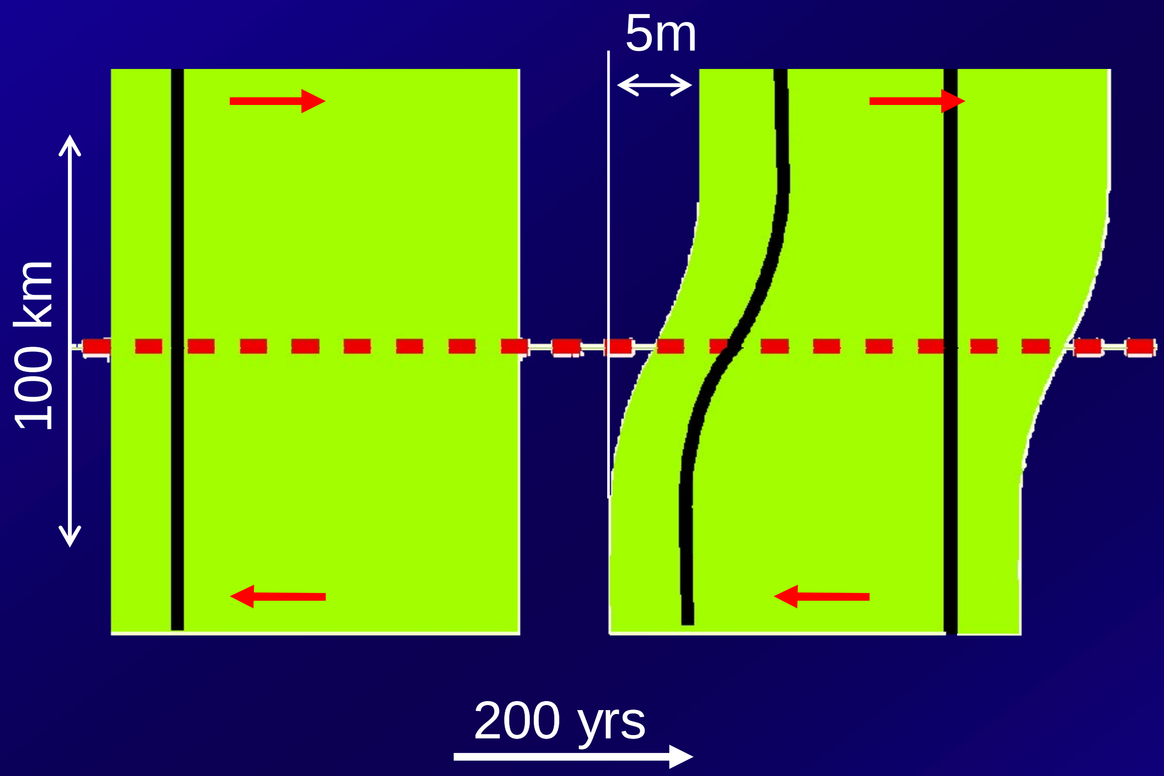
# Outline

- The Earthquake Cycle
- Elastic Dislocation Modelling
- Coseismic Deformation
  - •Strike-Slip earthquakes
  - •Dip-Slip earthquakes (Normal and Thrust)
- Case Study – the 2003 Bam (Iran) Earthquake

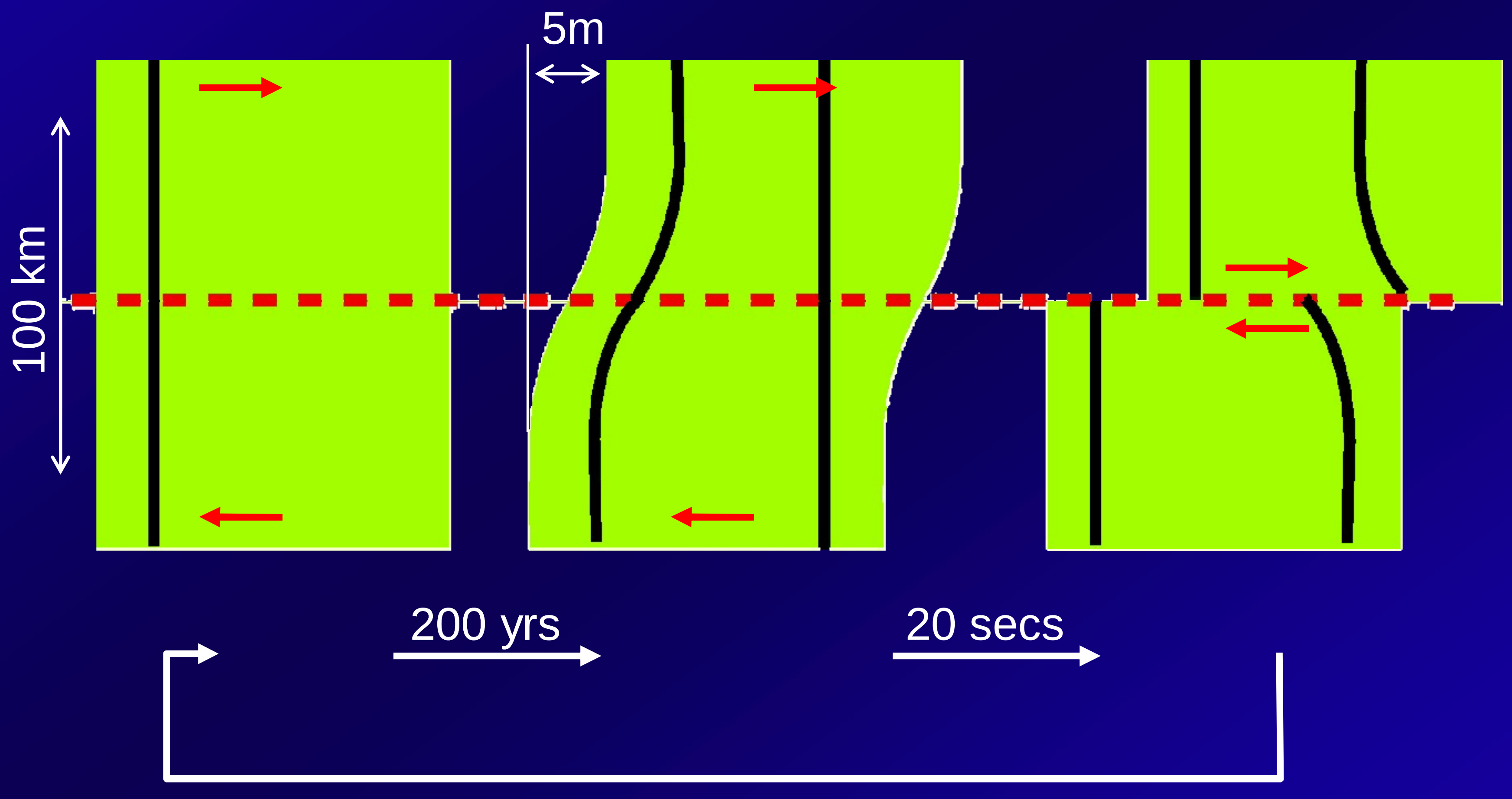
# The Earthquake Cycle



# The Earthquake Cycle

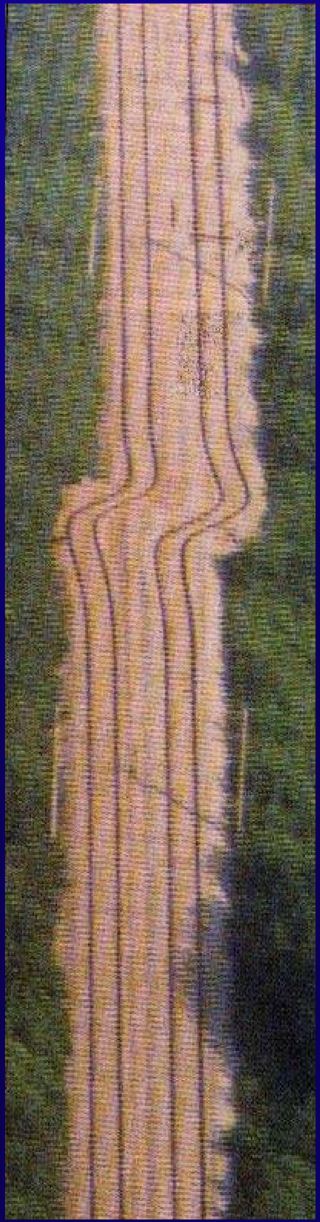


# The Earthquake Cycle

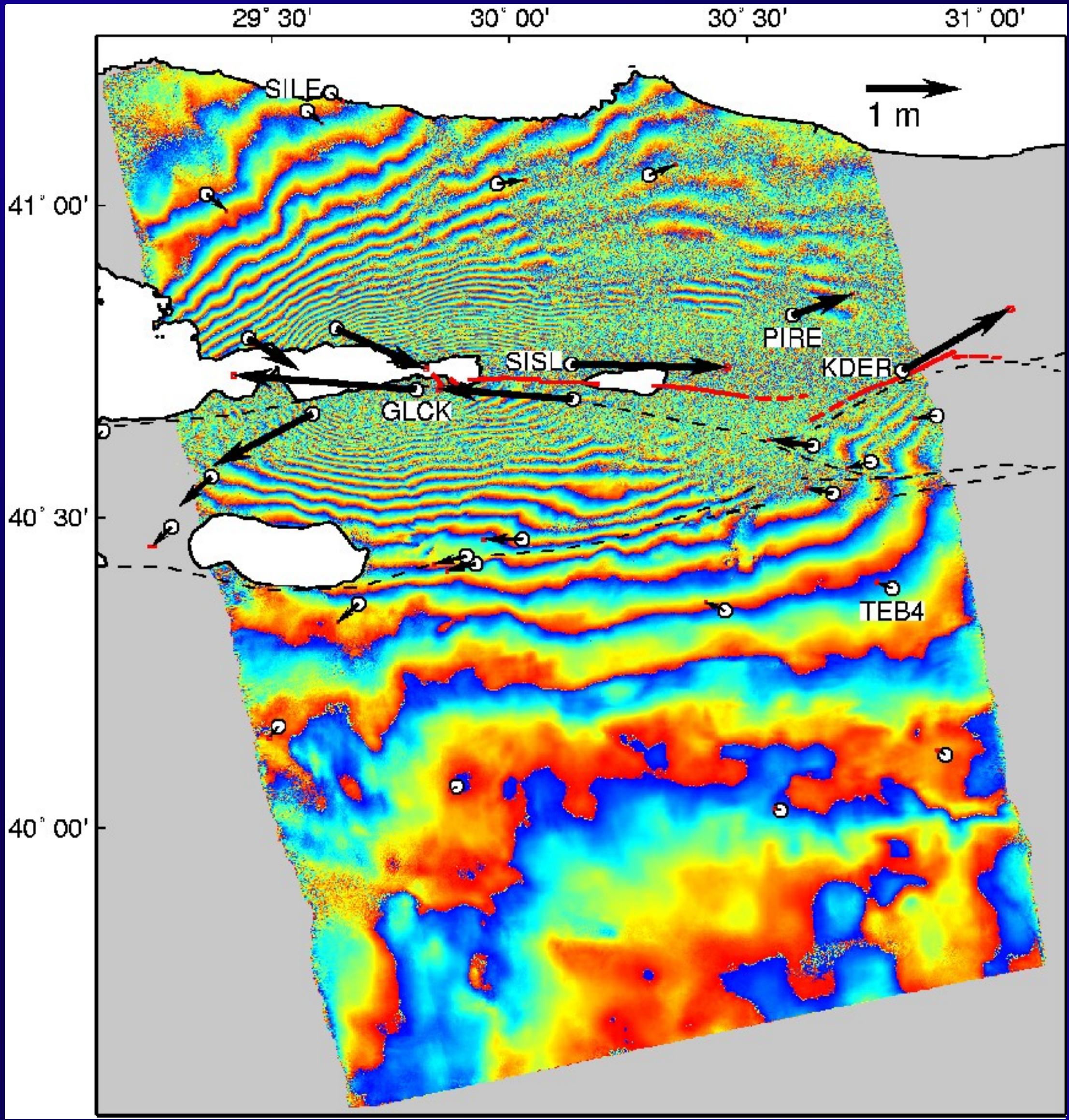


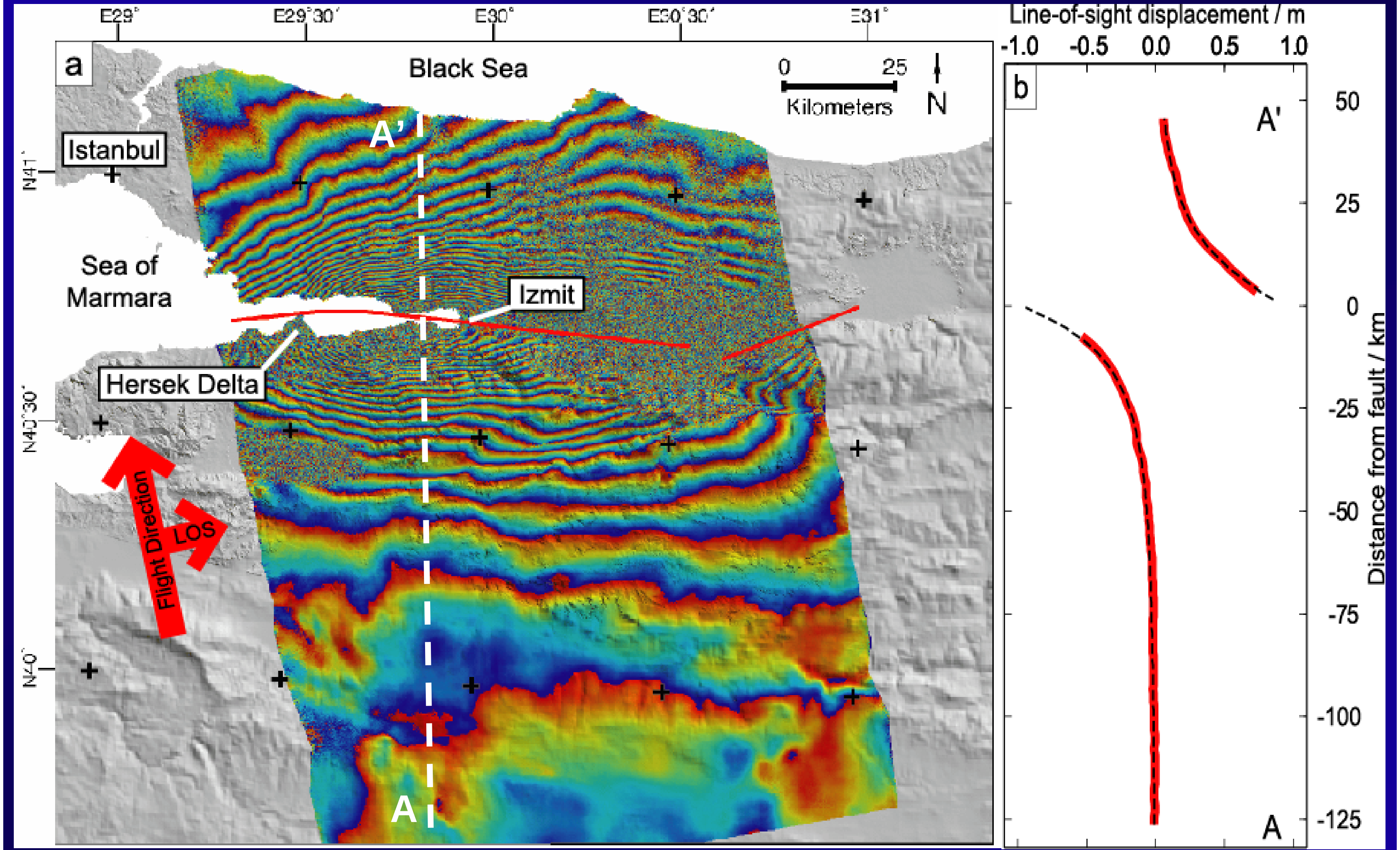

Note: Numbers vary for different faults

# 17 August 1999, Izmit Earthquake



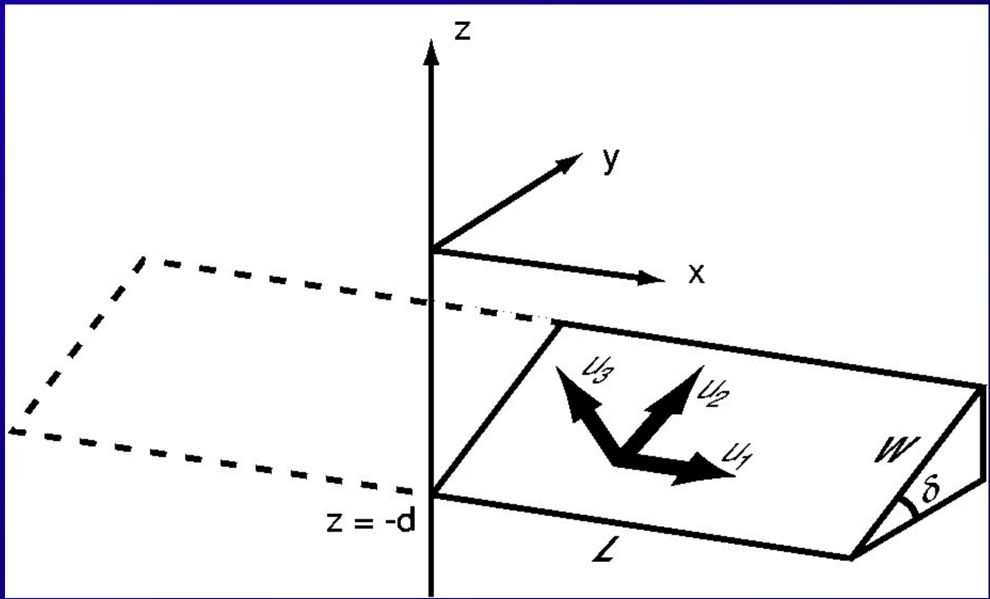
# The Izmit earthquake displacement field






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, $\delta$) [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

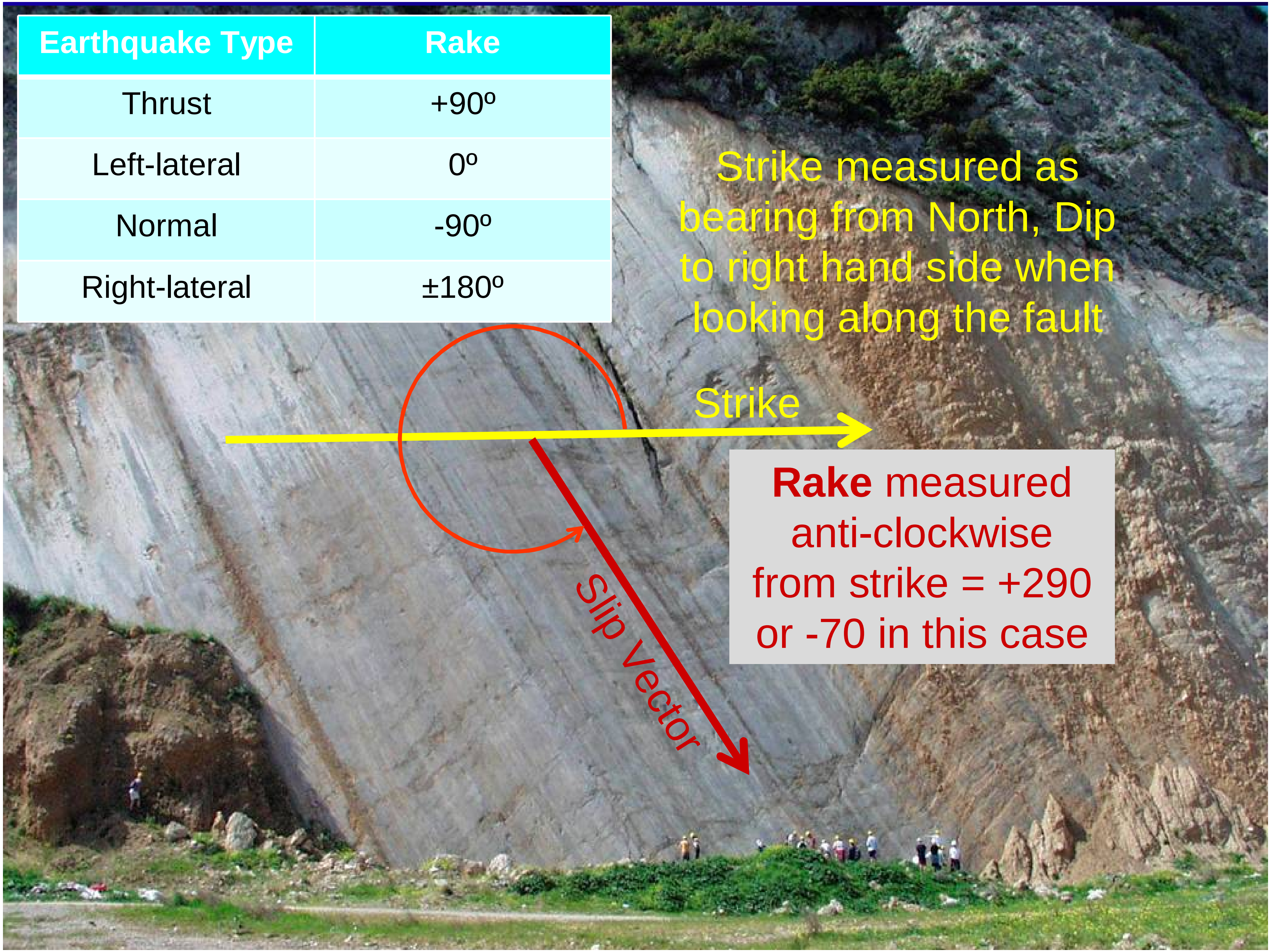
Code in today's practical takes 9 'friendly' fault parameters:

- x, y-position of centre of fault's surface projection in a map projection [2]
- 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]

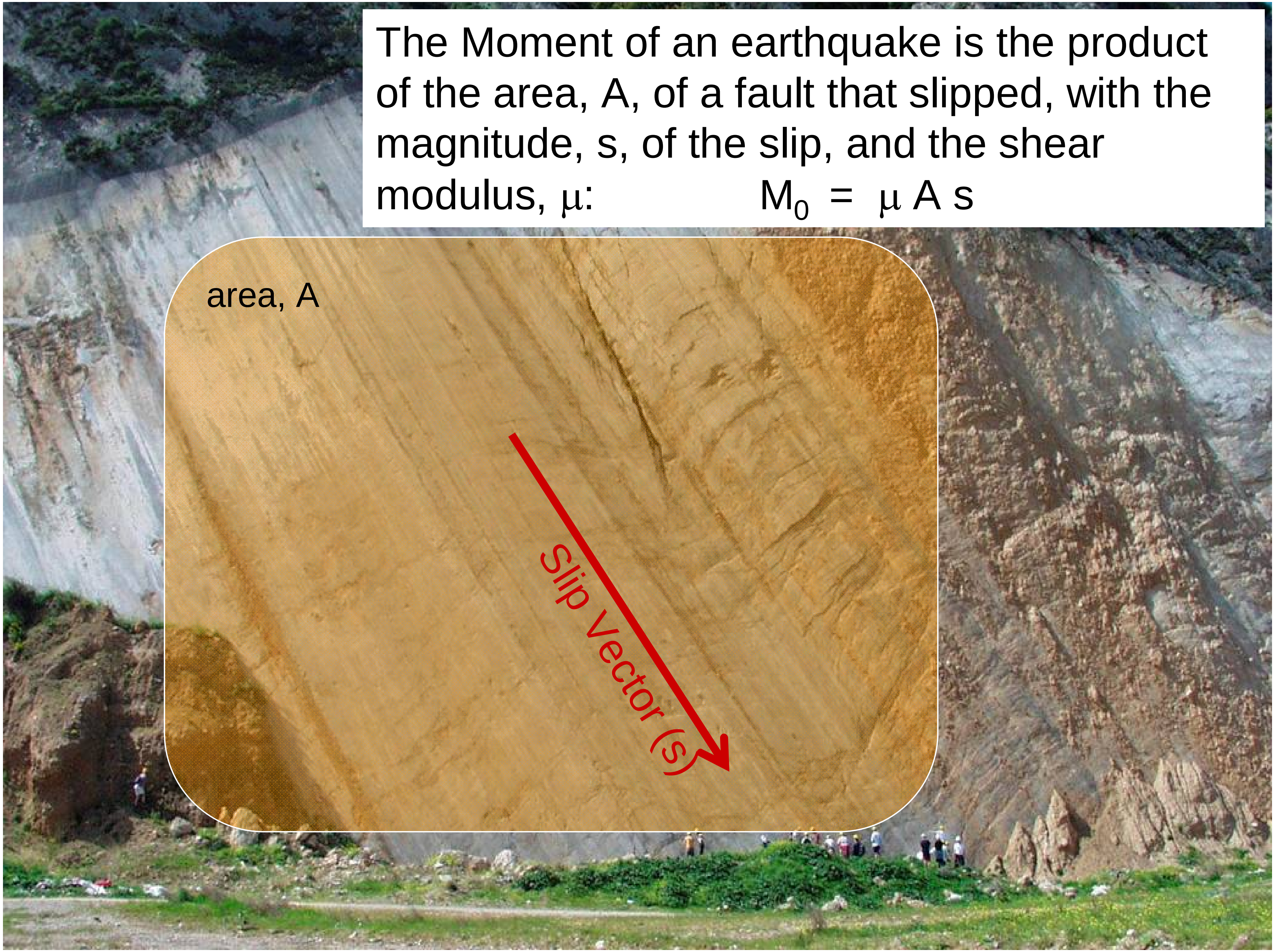
To define a rectangular fault dislocation, need 10 parameters:

- Location of fault x,y,z (x=y=0, z = -d) [1]
- Length, Width and dip of the fault (L, W, $\delta$) [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]

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



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, $\mu$:  $M_0 = \mu A s$



# Earthquake Magnitudes and Moments

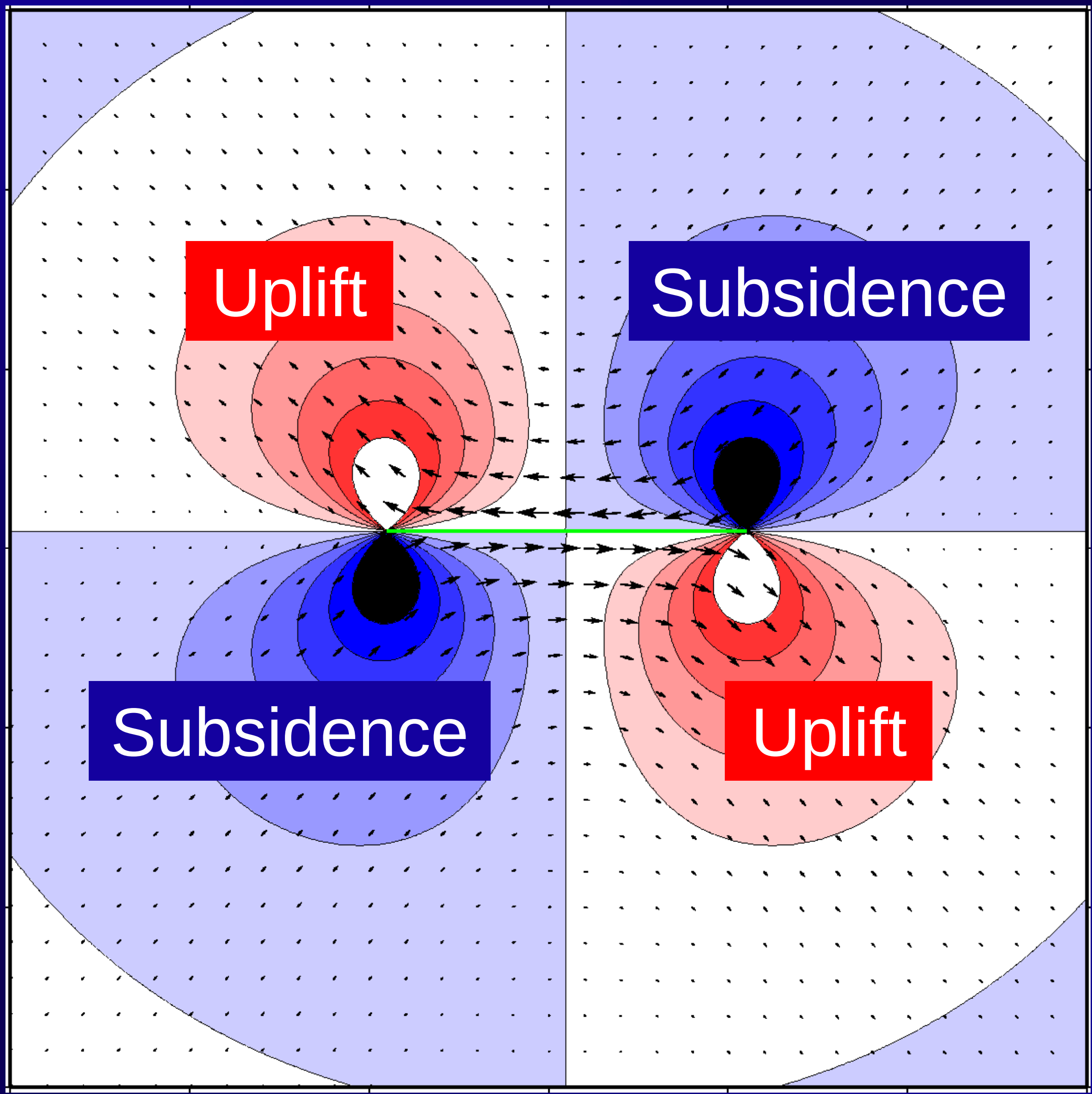
$$M_0 = \mu A s$$

SI units

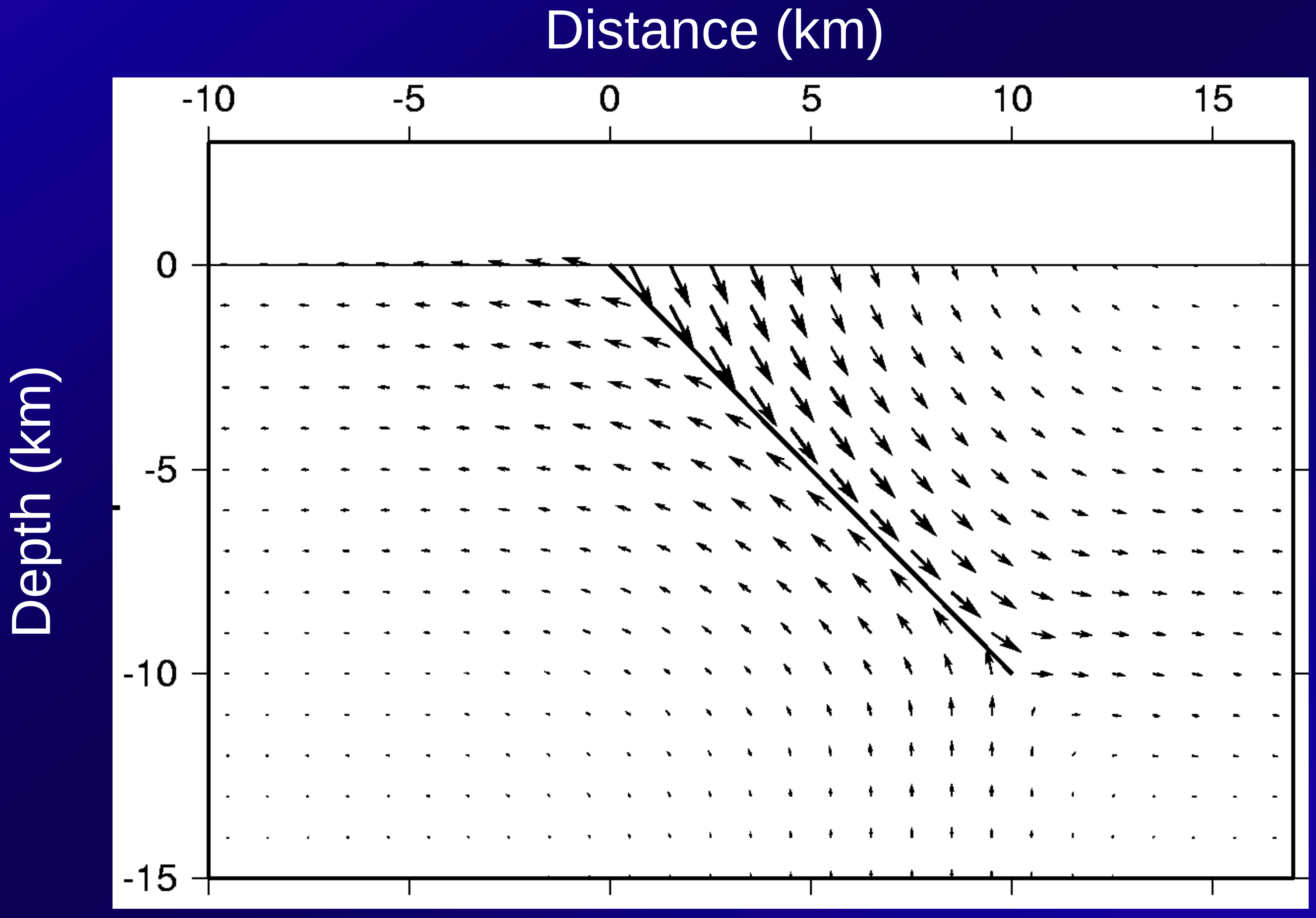
$$M_w = \frac{2}{3}\log_{10} M_0 - 6.0$$

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

# Surface displacements of strike-slip faults

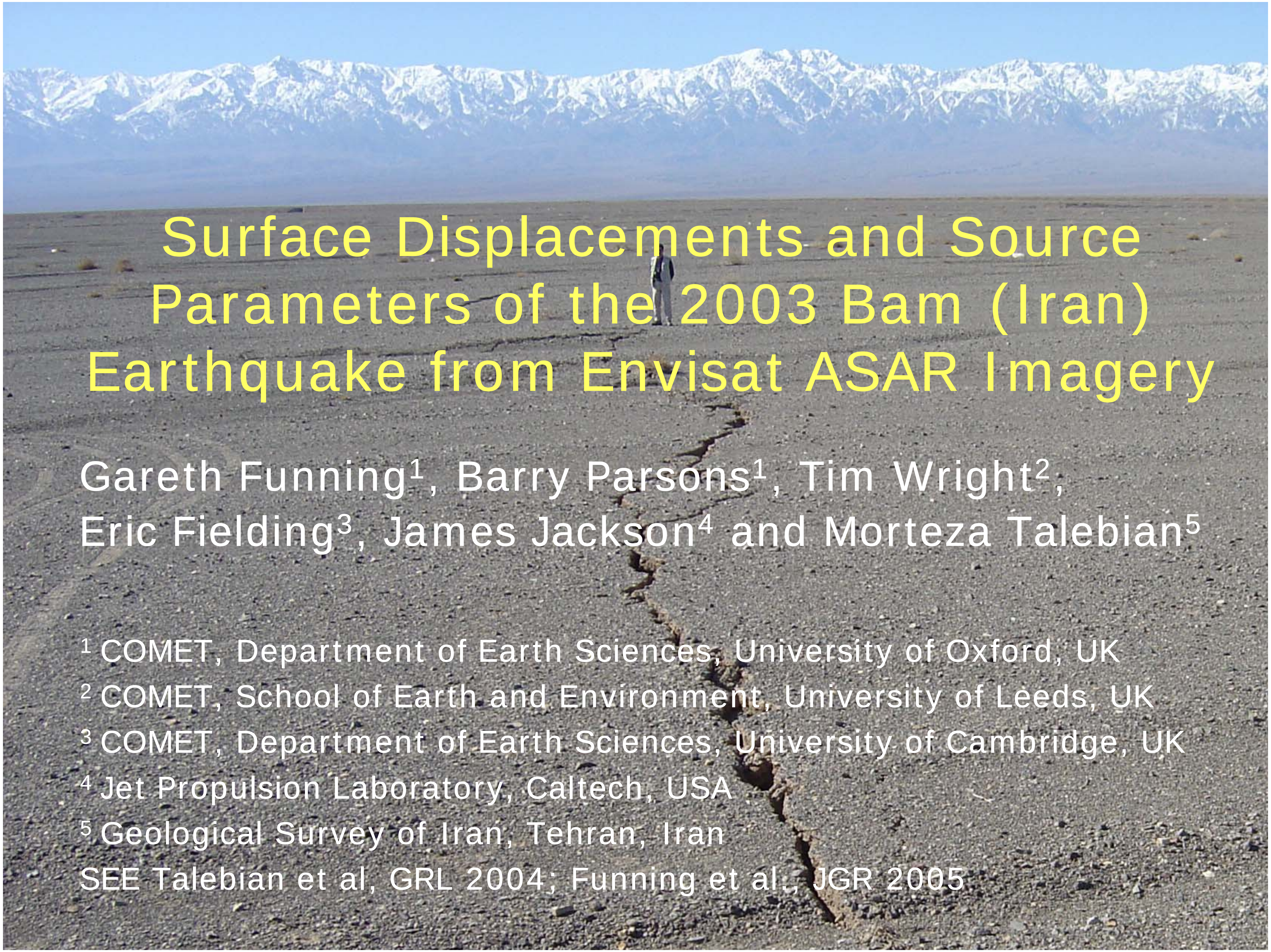


# Displacements of normal faults



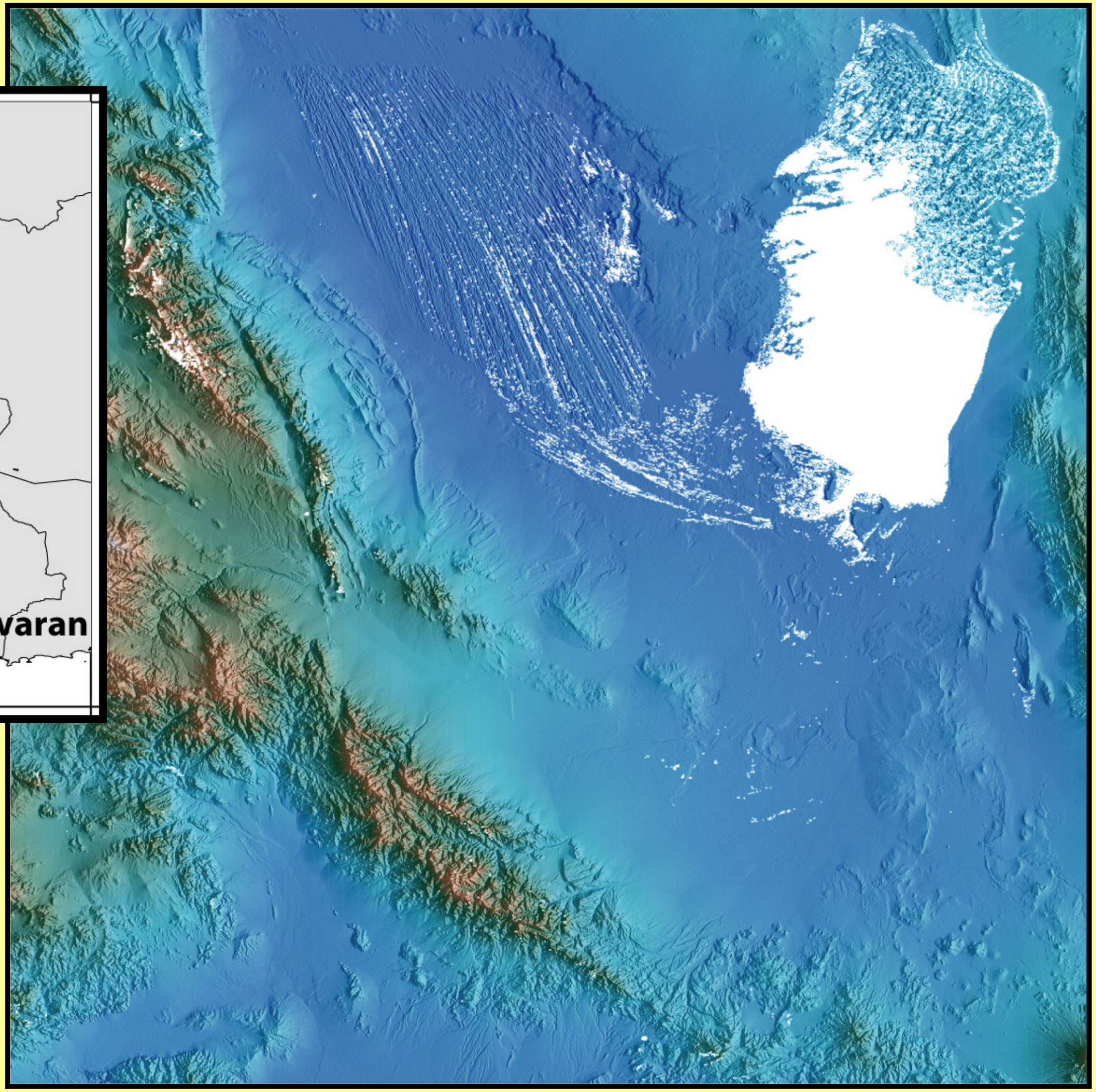
# Determining best-fit elastic models

- 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.


Surface Displacements and Source Parameters of the 2003 Bam (Iran) Earthquake from Envisat ASAR Imagery
Gareth Funning[1], Barry Parsons[1], Tim Wright[2],
Eric Fielding[3], James Jackson[4] and Morteza Talebian[5]
[1] COMET, Department of Earth Sciences, University of Oxford, UK
[2] COMET, School of Earth and Environment, University of Leeds, UK
[3] COMET, Department of Earth Sciences, University of Cambridge, UK
[4] Jet Propulsion Laboratory, Caltech, USA
[5] Geological Survey of Iran, Tehran, Iran
SEE Talebian et al, GRL 2004; Funning et al., JGR 2005

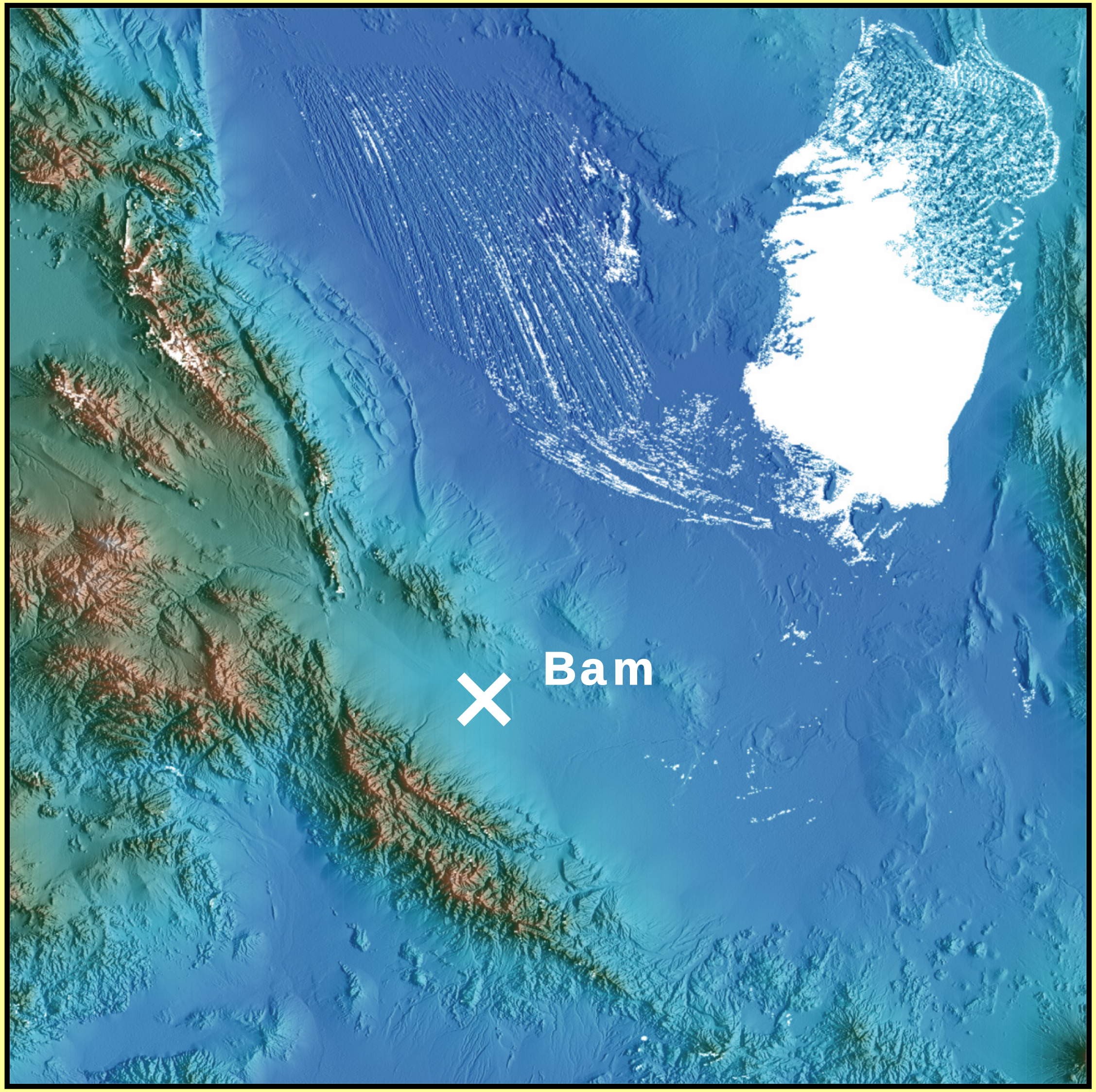
# 26th December 2003, $M_w$ 6.6

# Tectonic setting

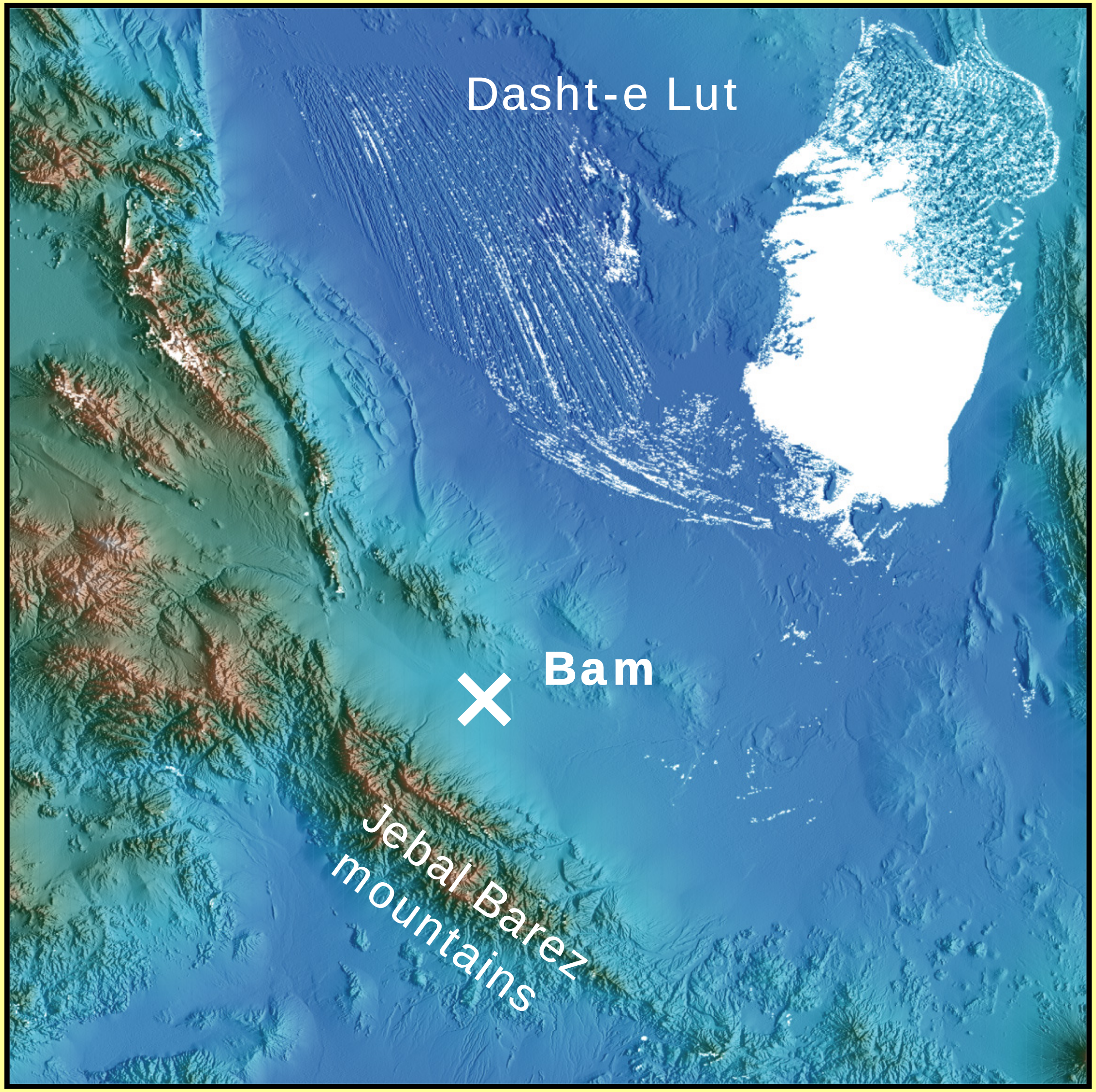
SRTM shaded-relief topography

# Tectonic setting




SRTM shaded-relief topography

# Tectonic setting

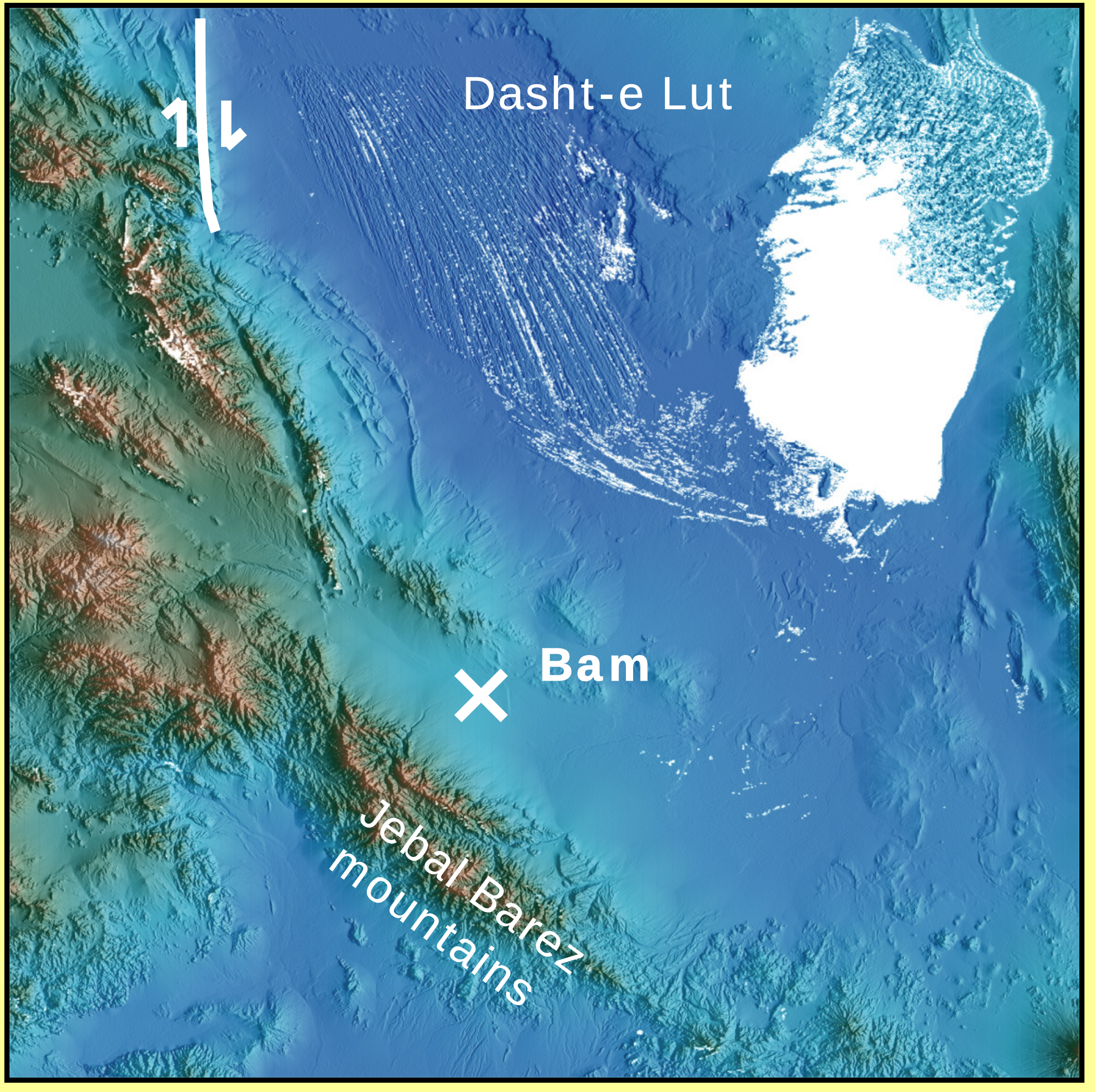



SRTM shaded-relief topography

# Tectonic setting

Nayband fault

SRTM shaded-
relief topography

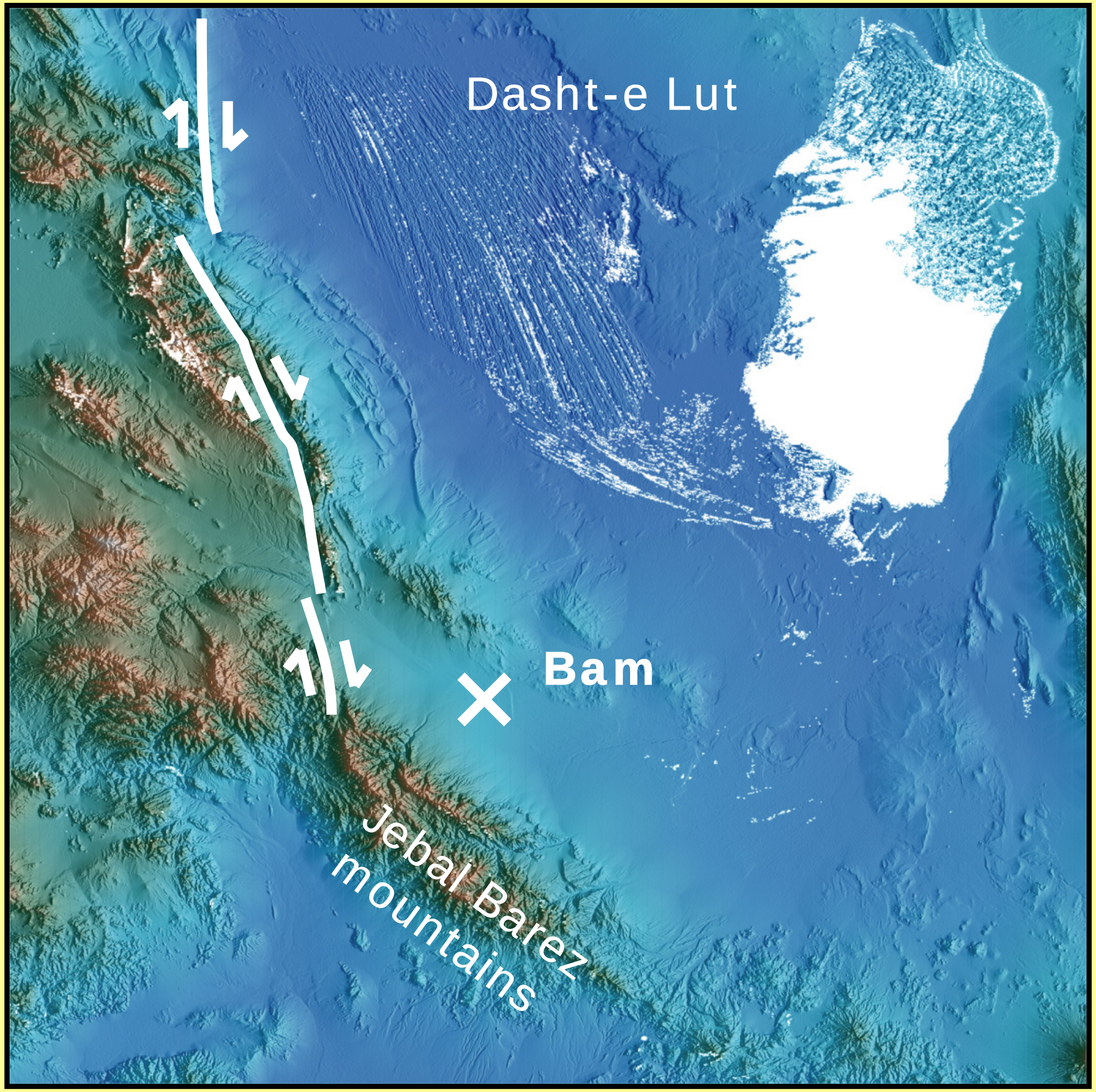


# Tectonic setting

Nayband fault

Gowk fault

SRTM shaded-relief topography



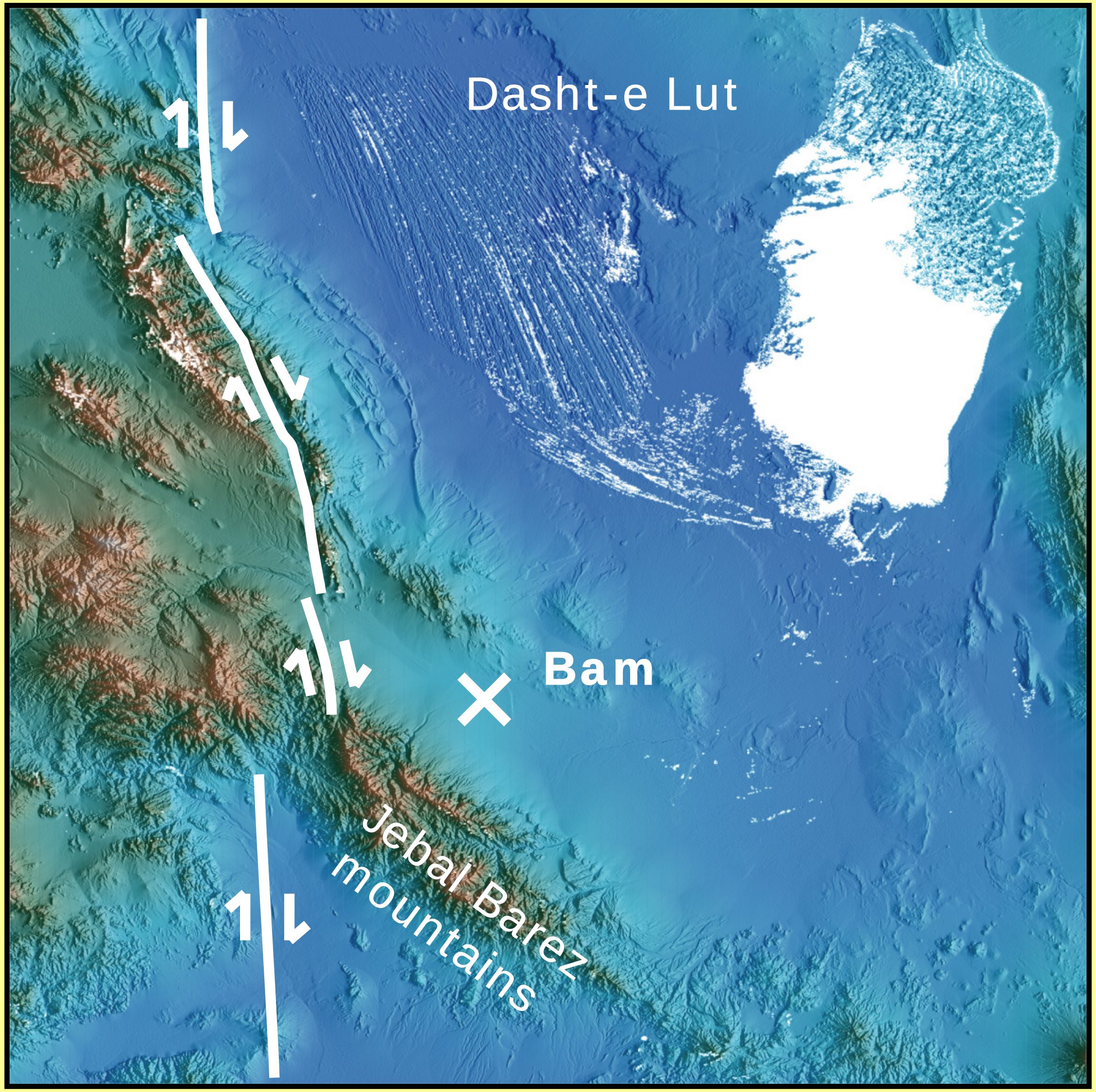
# Tectonic setting

Nayband fault

Gowk fault

Sabzevaran fault

SRTM shaded-
relief topography



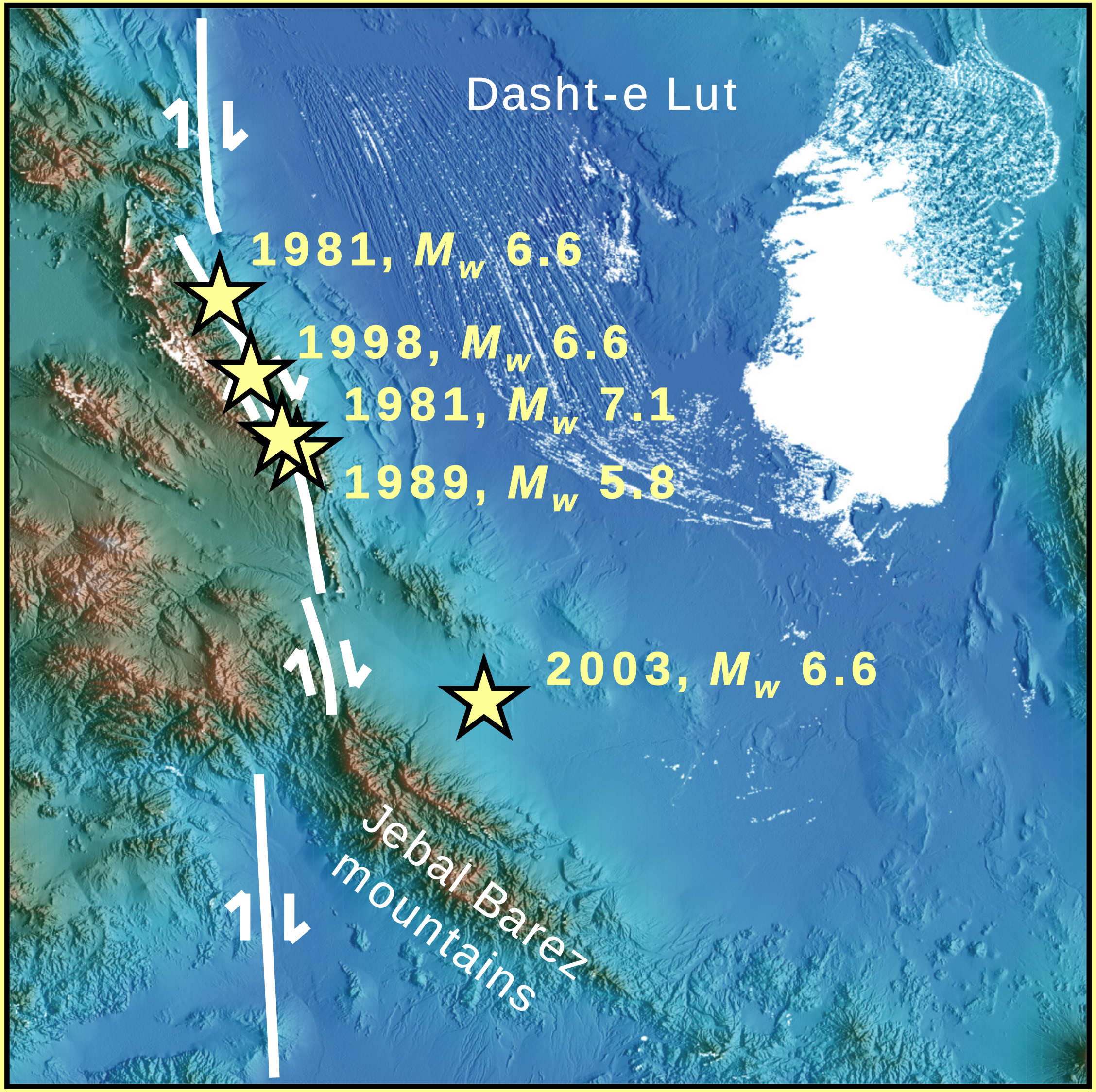
# Tectonic setting

Nayband fault

Gowk fault

Sabzevaran fault

SRTM shaded-
relief topography



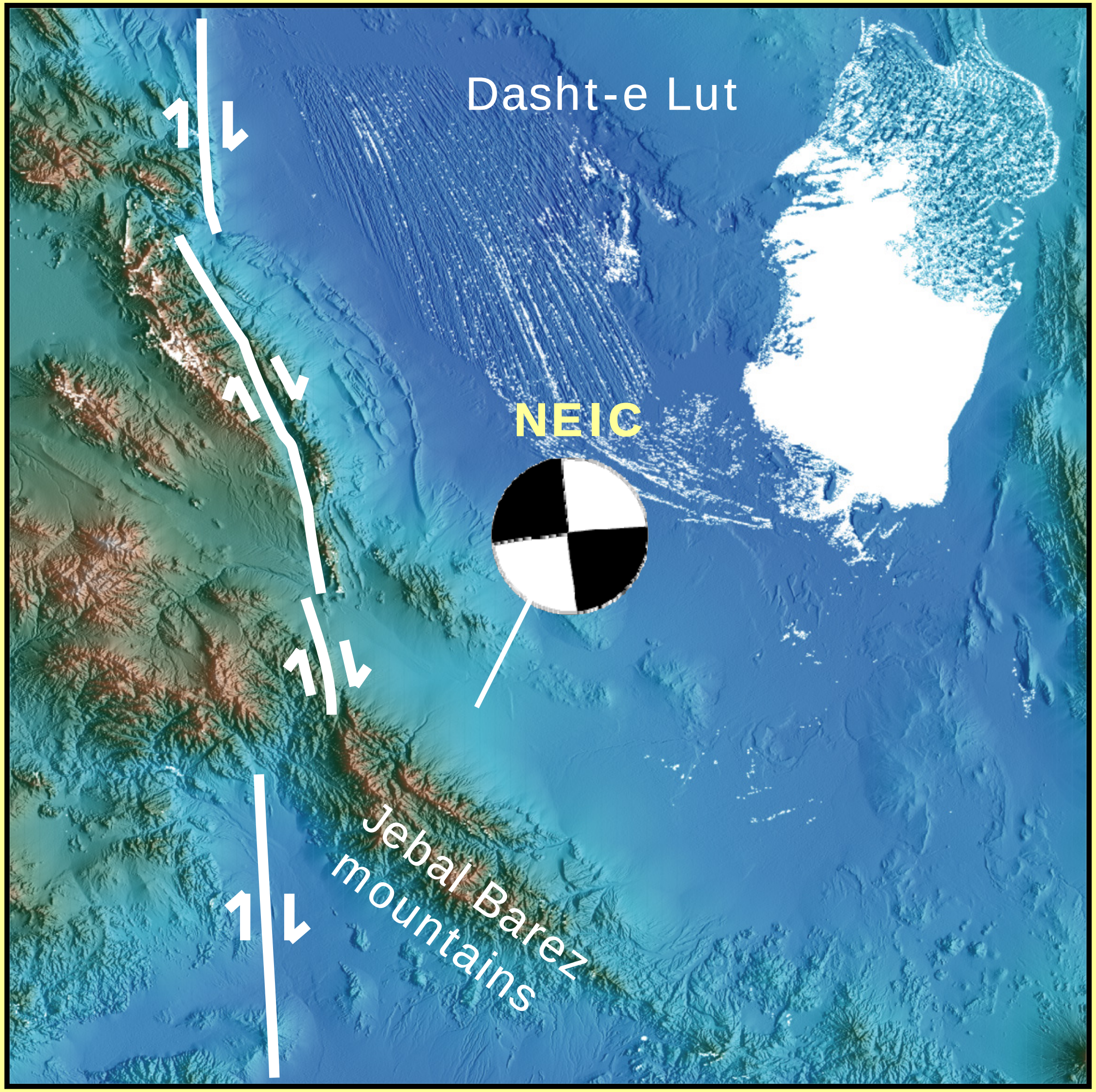
# Tectonic setting

Nayband fault

Gowk fault

Sabzevaran fault

SRTM shaded-relief topography



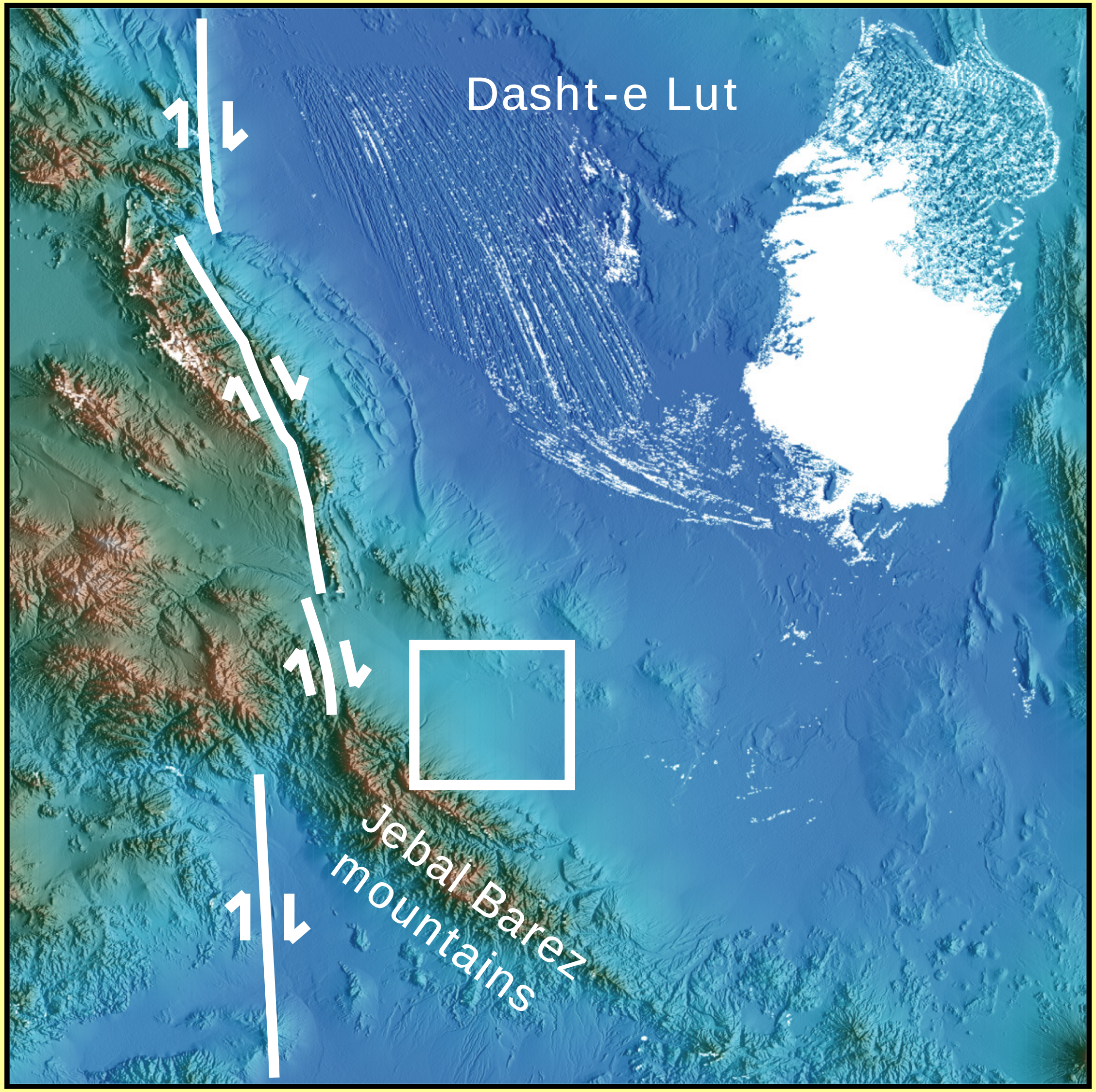
# Tectonic setting

Nayband fault

Gowk fault

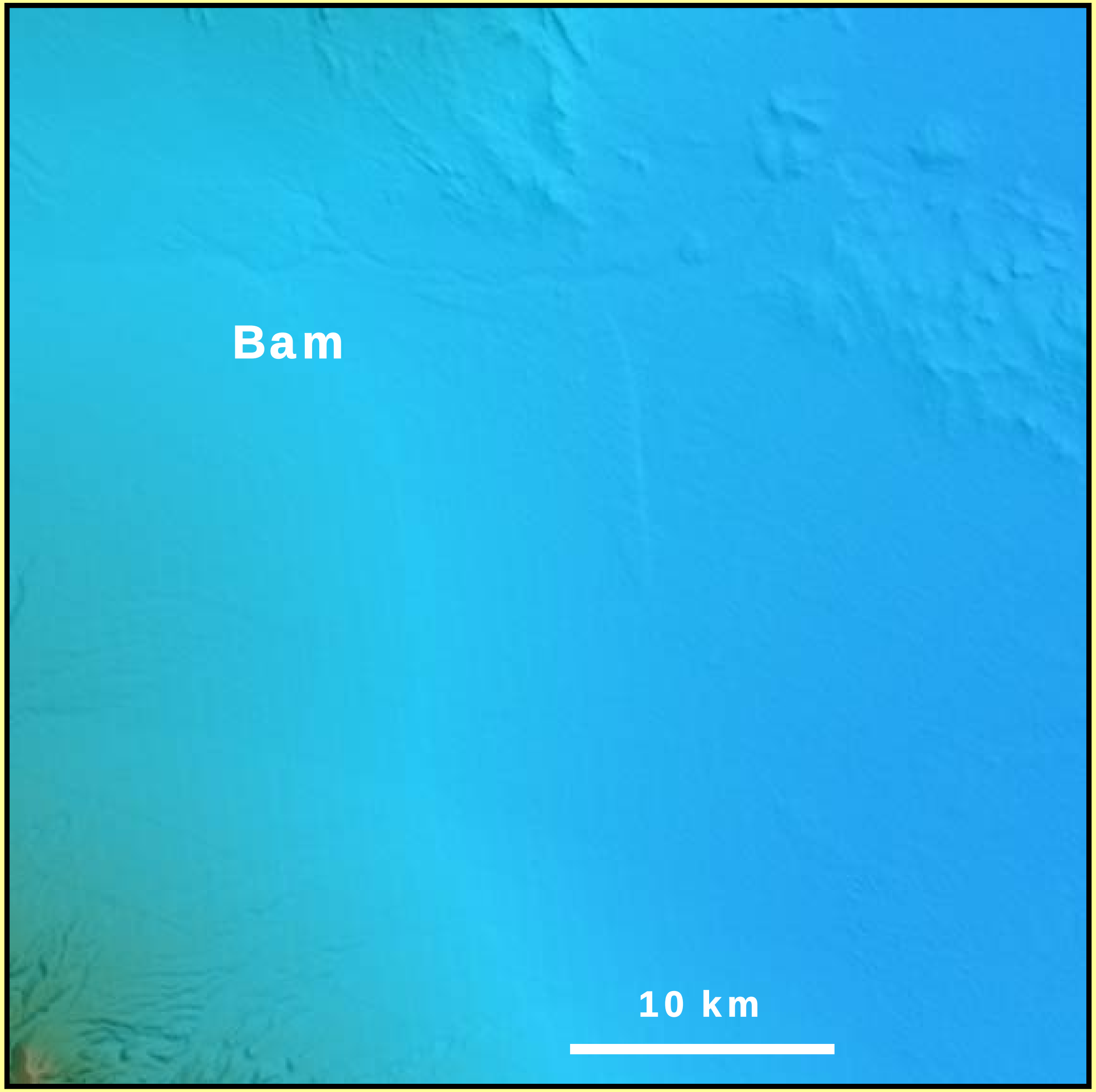
Sabzevaran fault

SRTM shaded-relief topography



# The Bam area

Main geomorphic features of the Bam area:



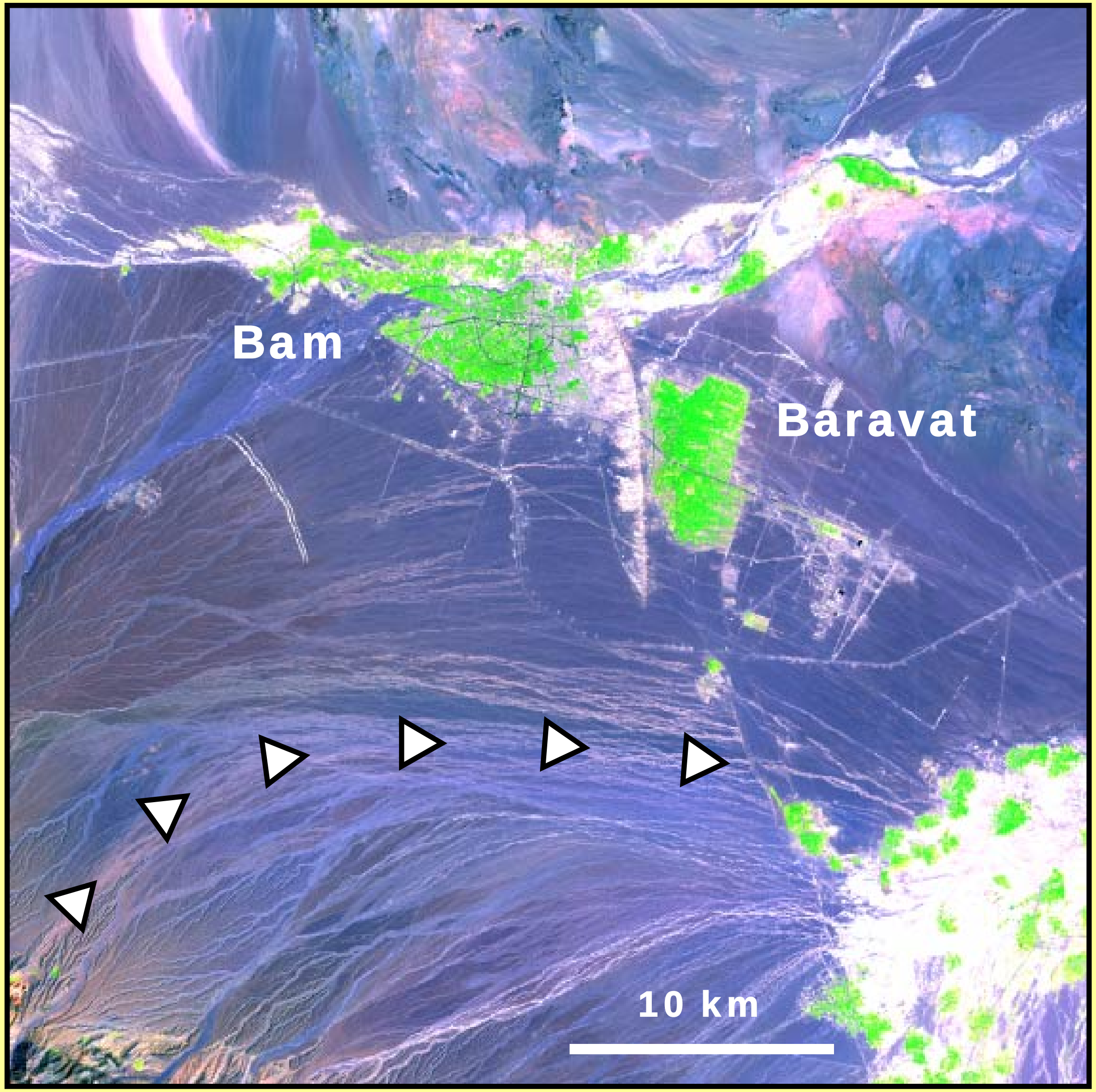

SRTM shaded relief topography

# The Bam area

Main geomorphic features of the Bam area:

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

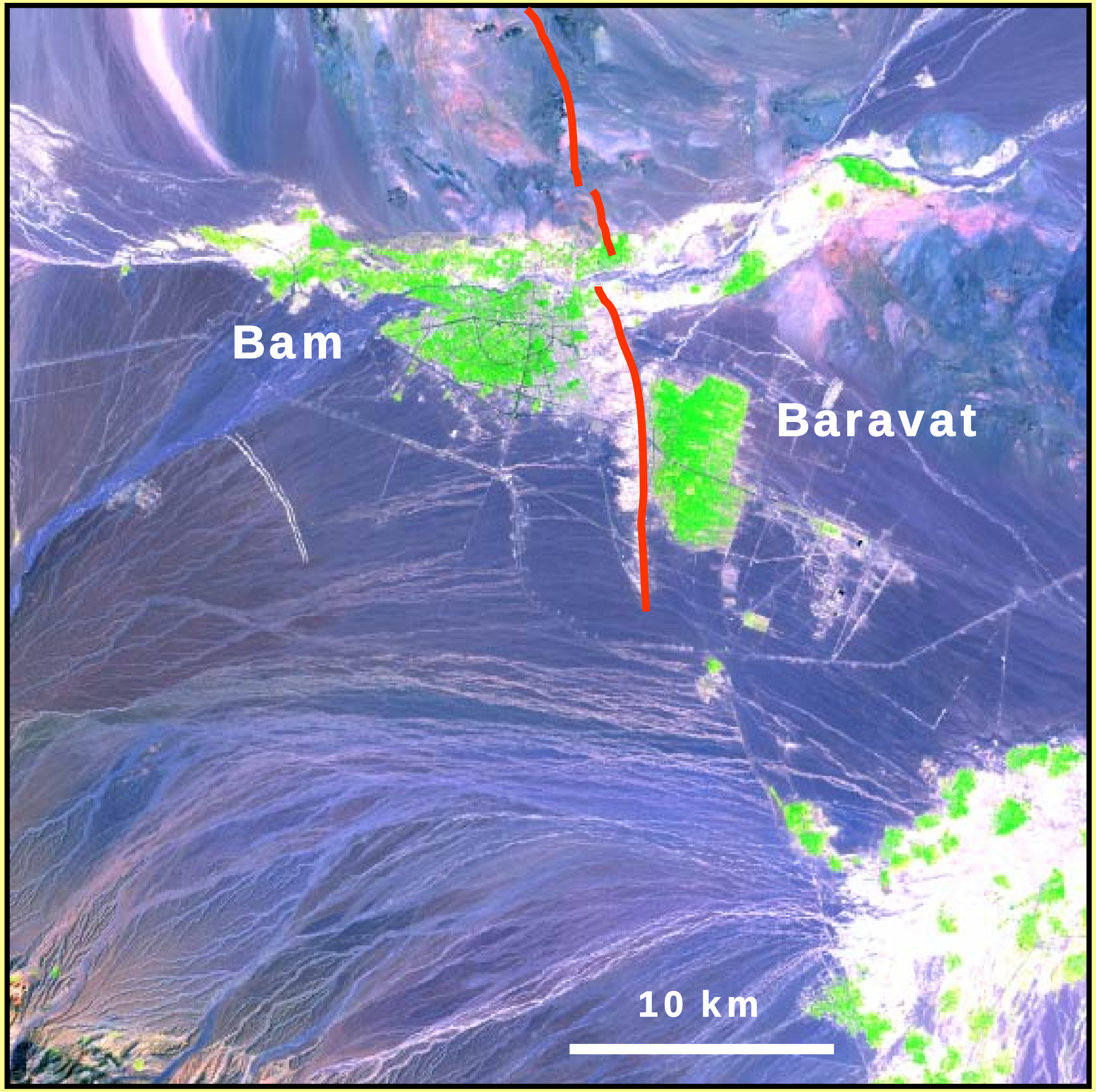
LANDSAT-7 ETM 541 false colour green=vegetation



# The Bam area

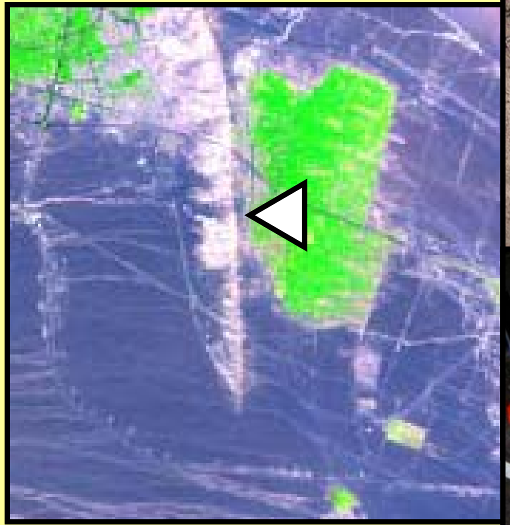
Main geomorphic features of the Bam area:

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



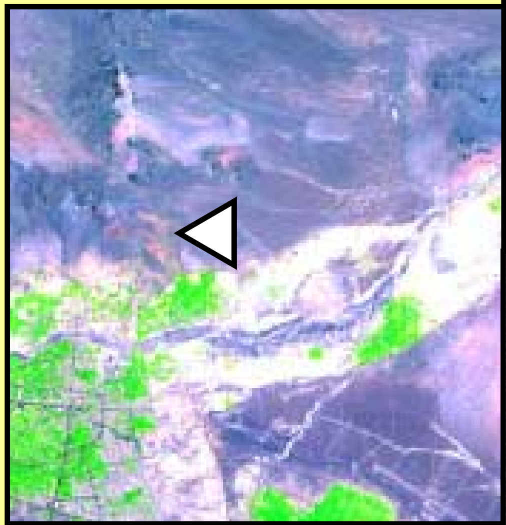

LANDSAT-7 ETM 541 false colour green=vegetation

# 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 ?

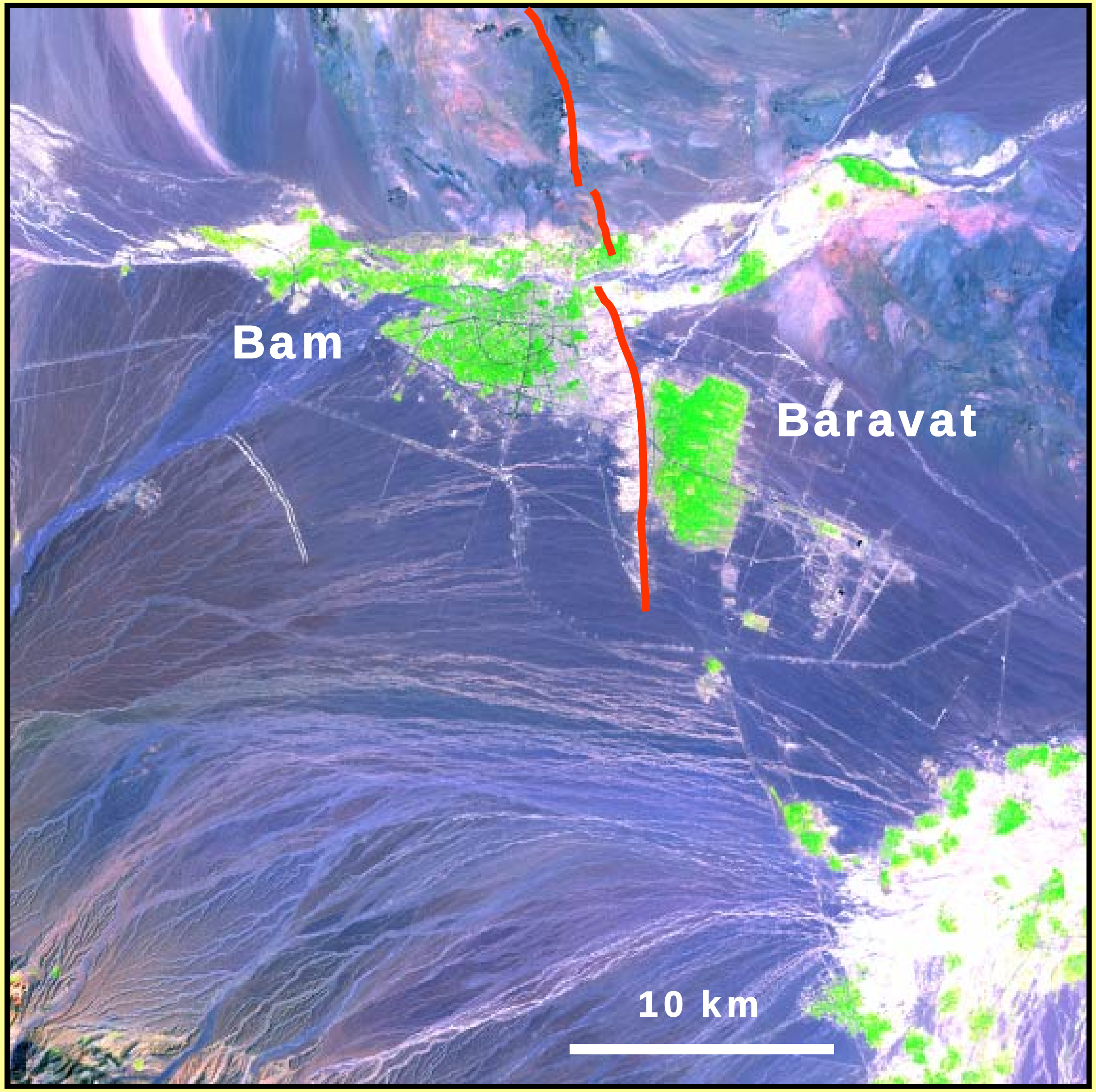
**BUT…**

More damage in Bam than Baravat

Peak vertical acceleration of ~1g in central Bam

Very small surface rupture on Bam fault

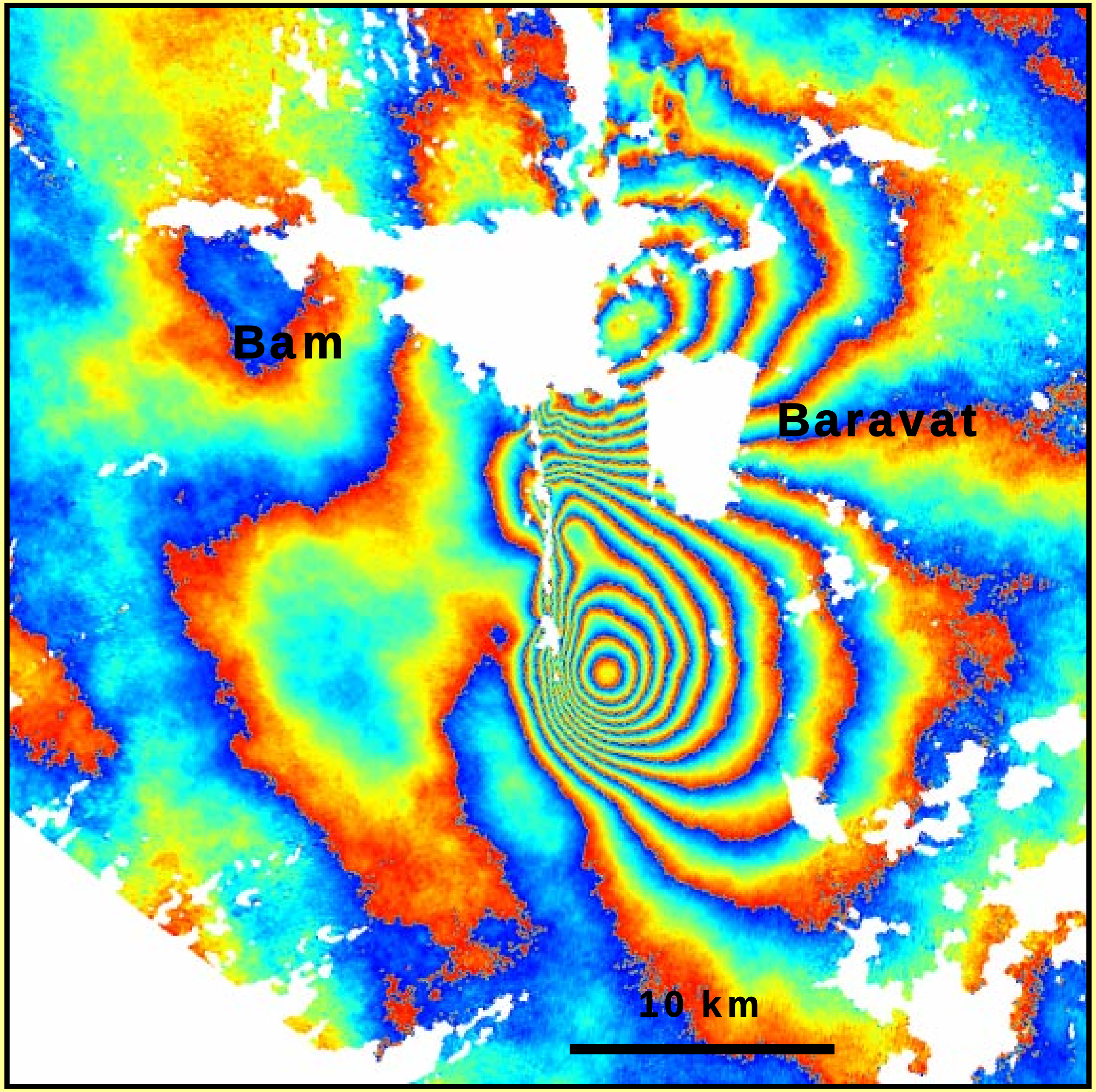
LANDSAT-7 ETM 541 false colour green=vegetation



# Preliminary InSAR data

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

Constructed from Envisat ASAR data released for free by ESA

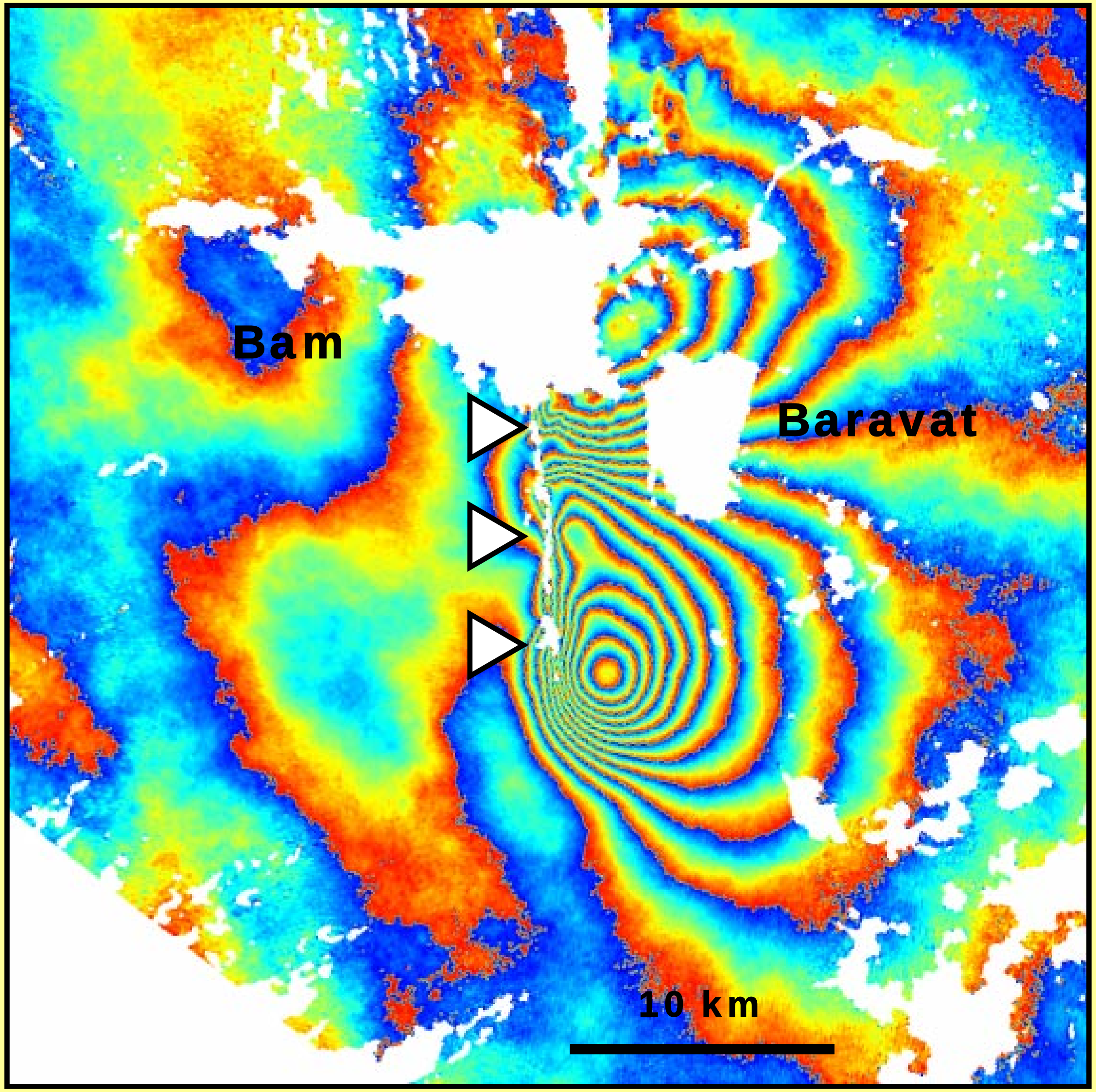


# Preliminary InSAR data

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

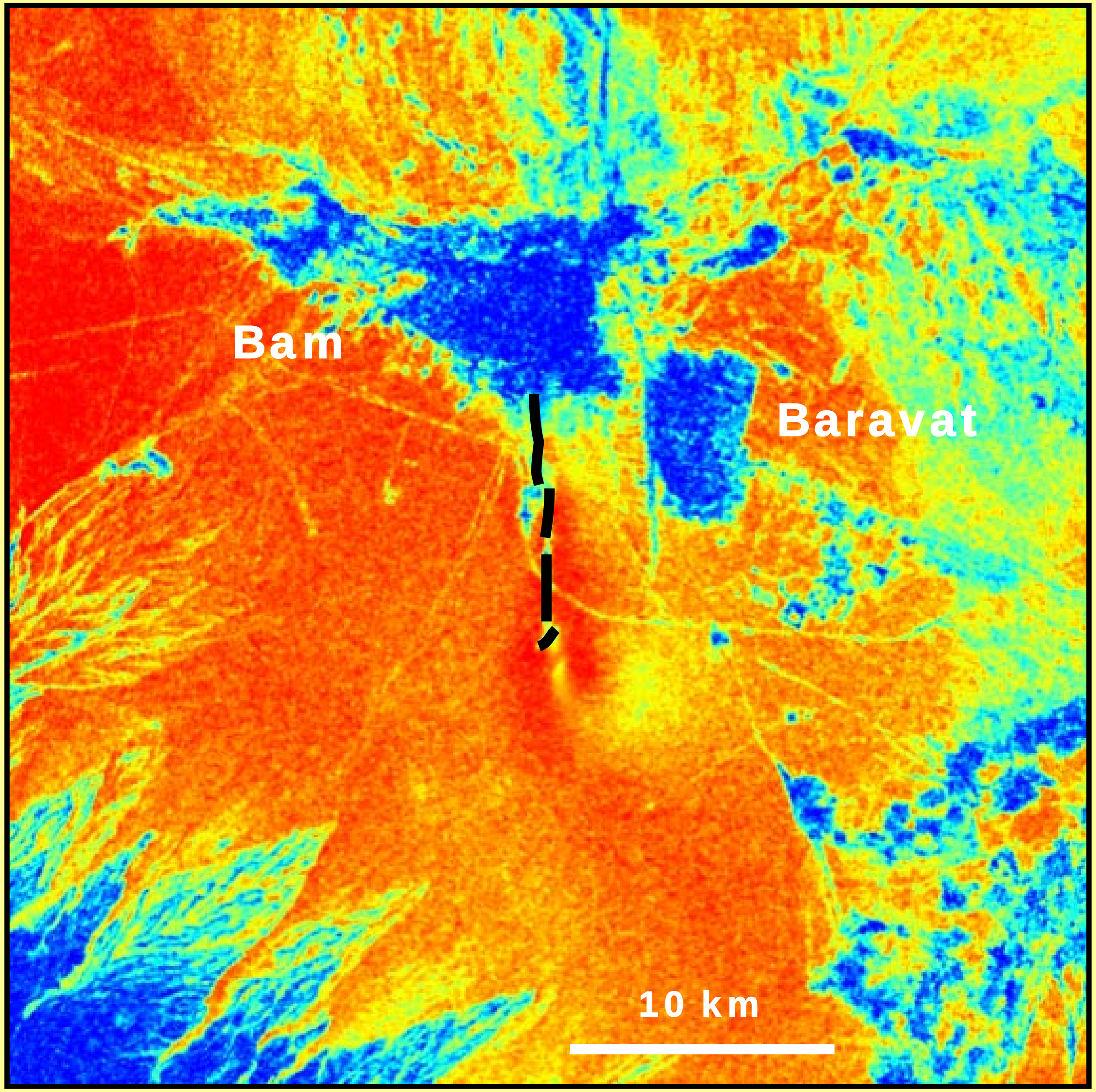


# The Bam earthquake main fault

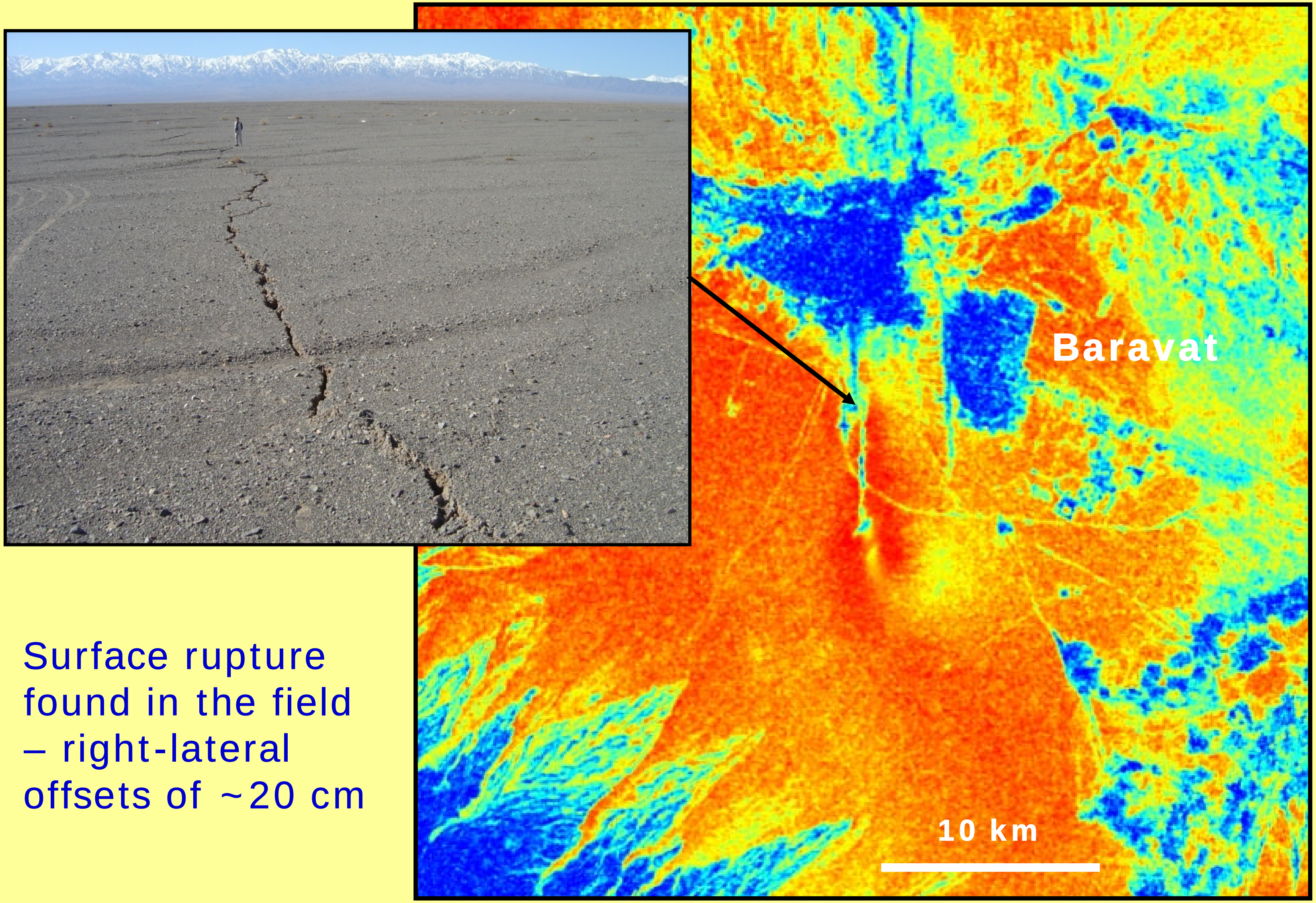
Low coherence indicates vegetation and surface damage

Interferometric coherence
Red = high
Blue = low

Constructed from Envisat ASAR data released for free by ESA

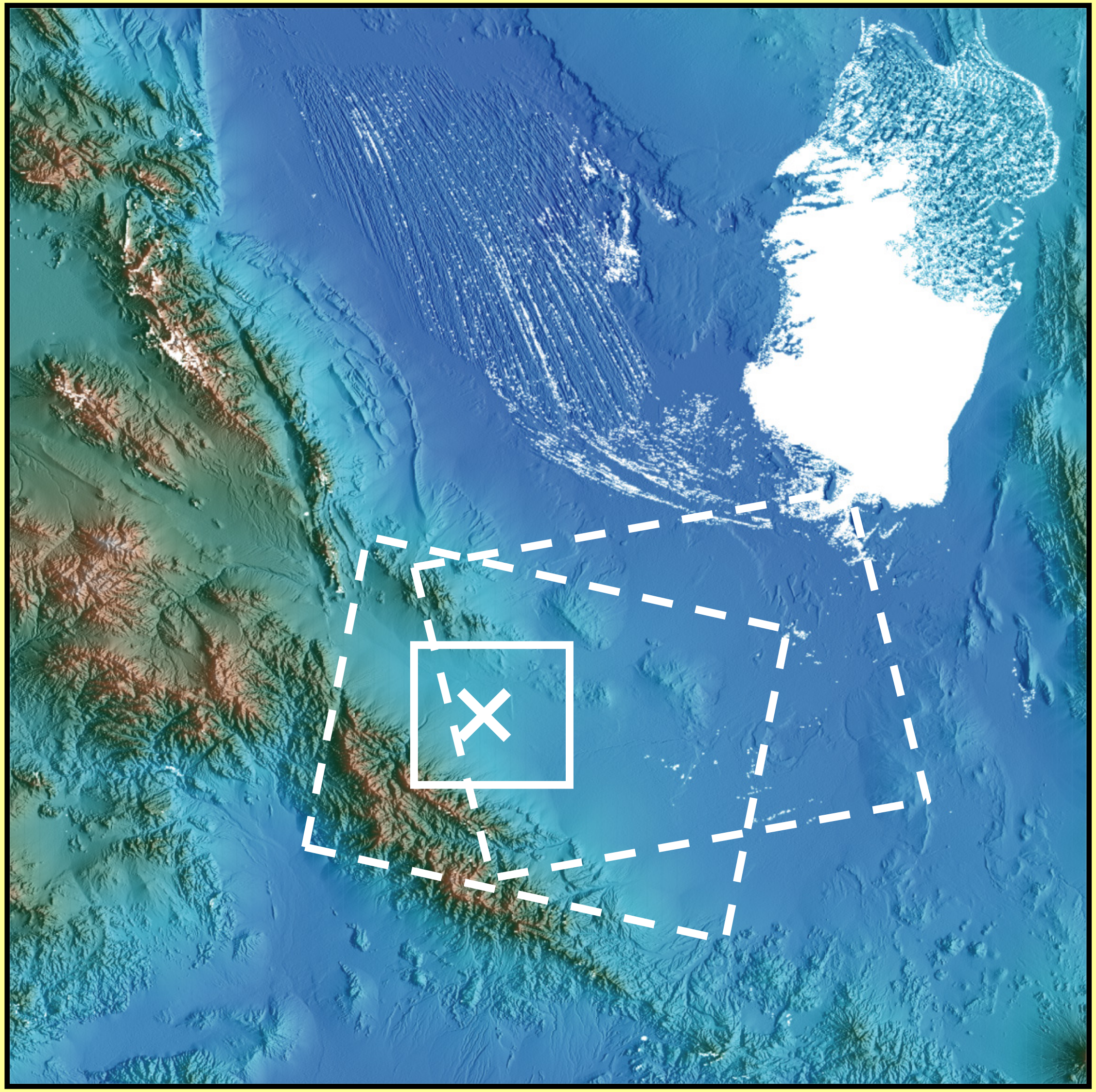


# The Bam earthquake main fault




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

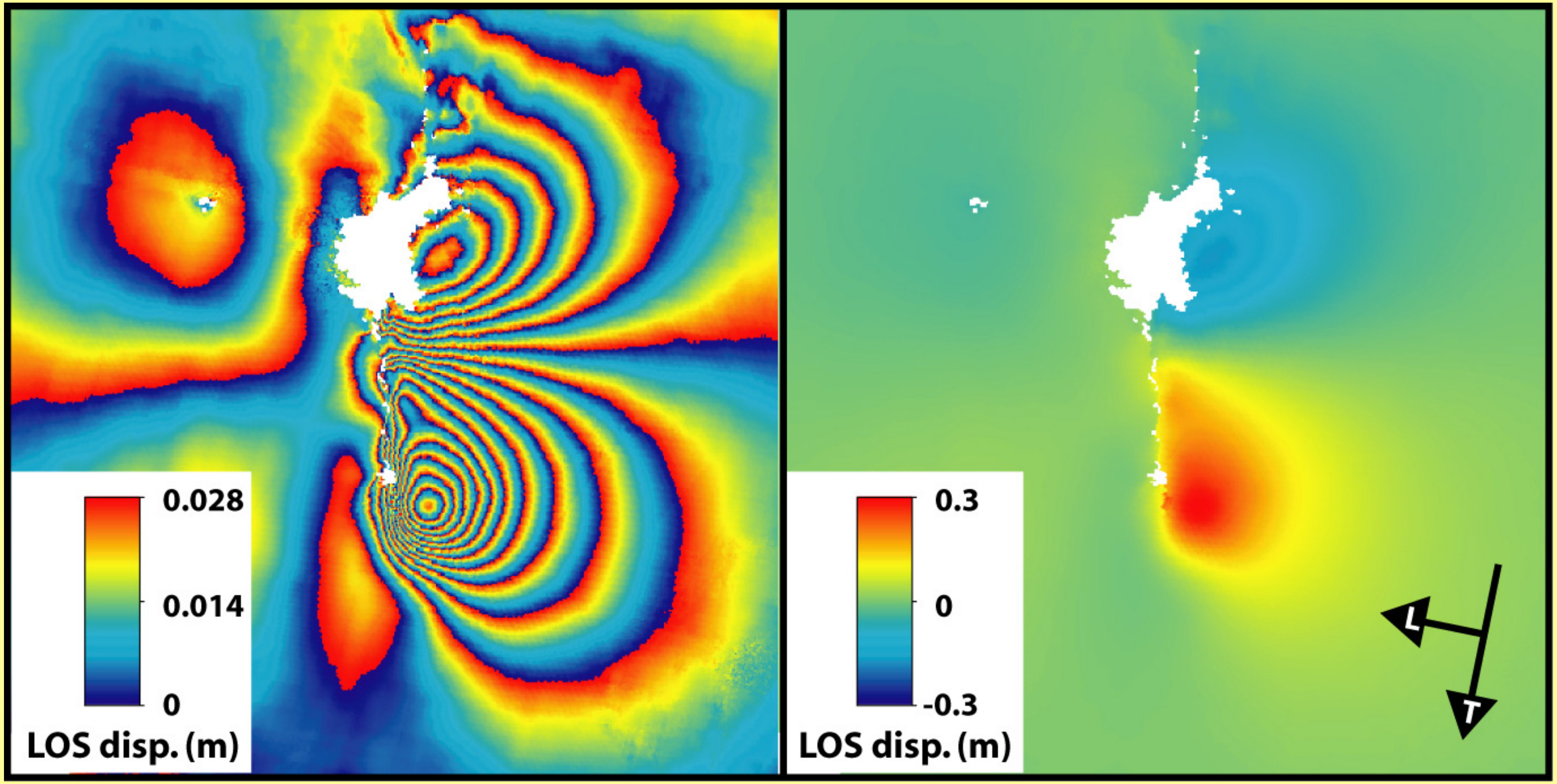
# ASAR data for the Bam earthquake



SRTM shaded-
relief topography

# Descending track interferogram

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

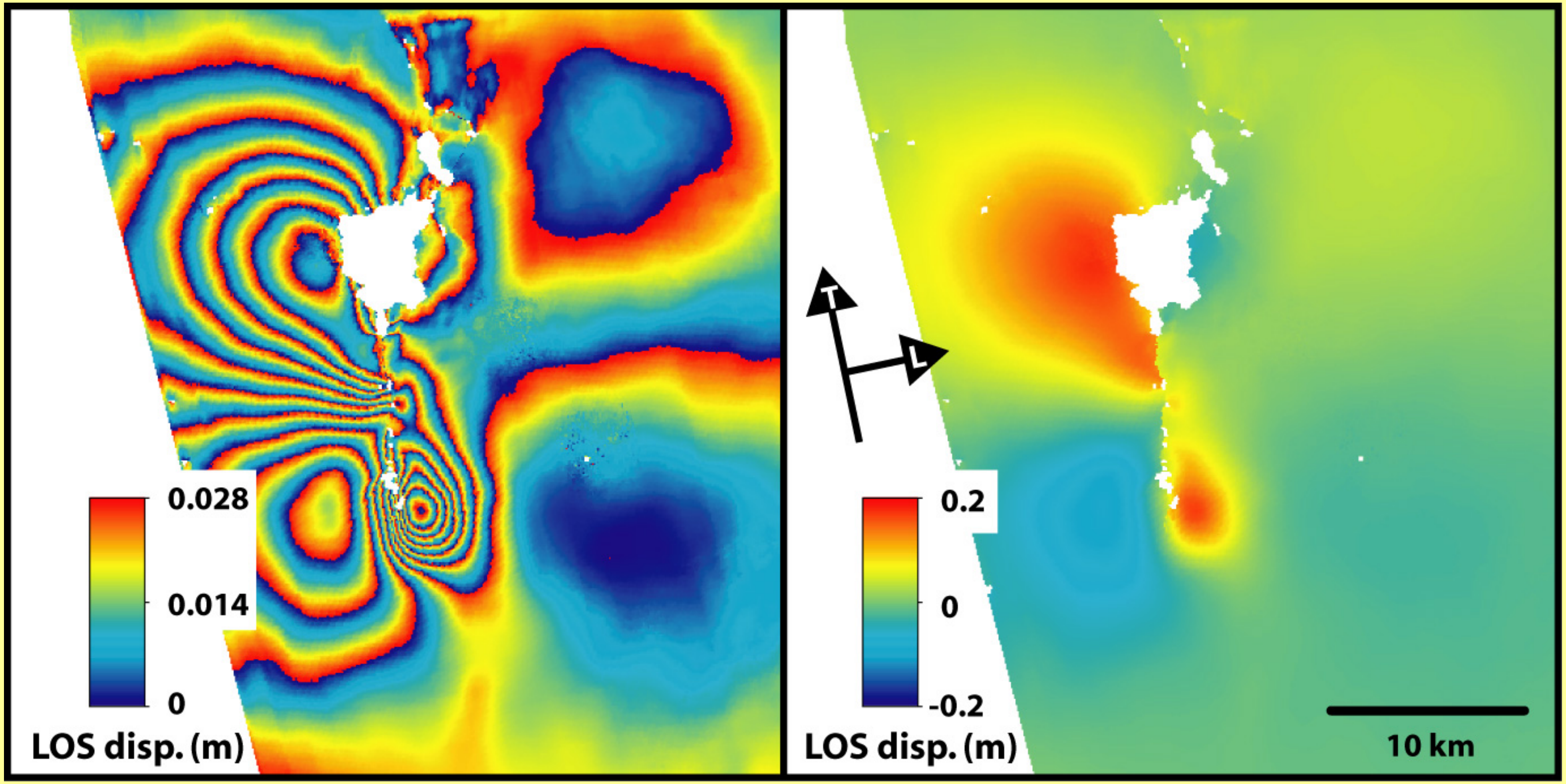



Wrapped

Unwrapped

# Ascending track interferogram

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



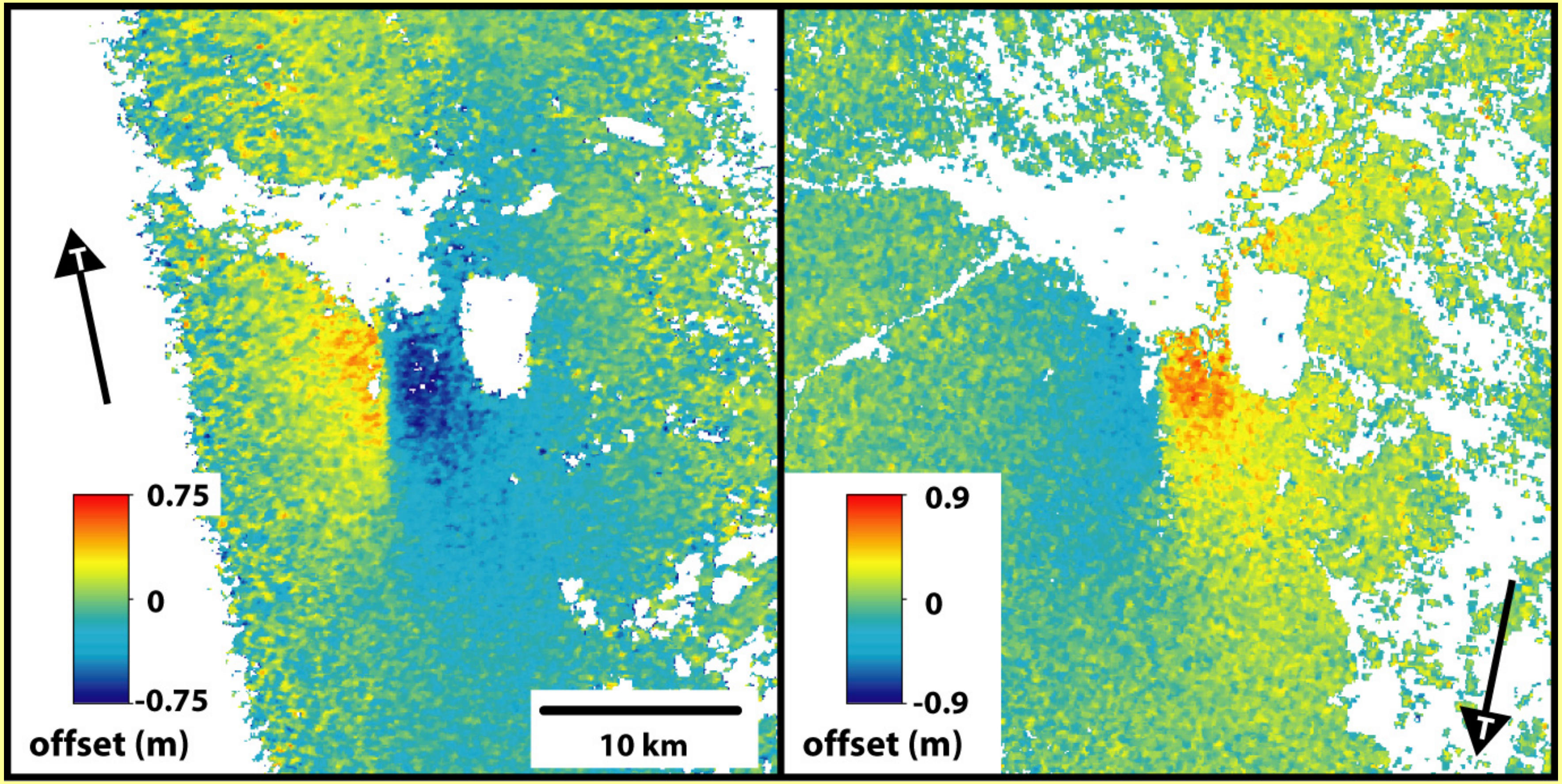

Wrapped

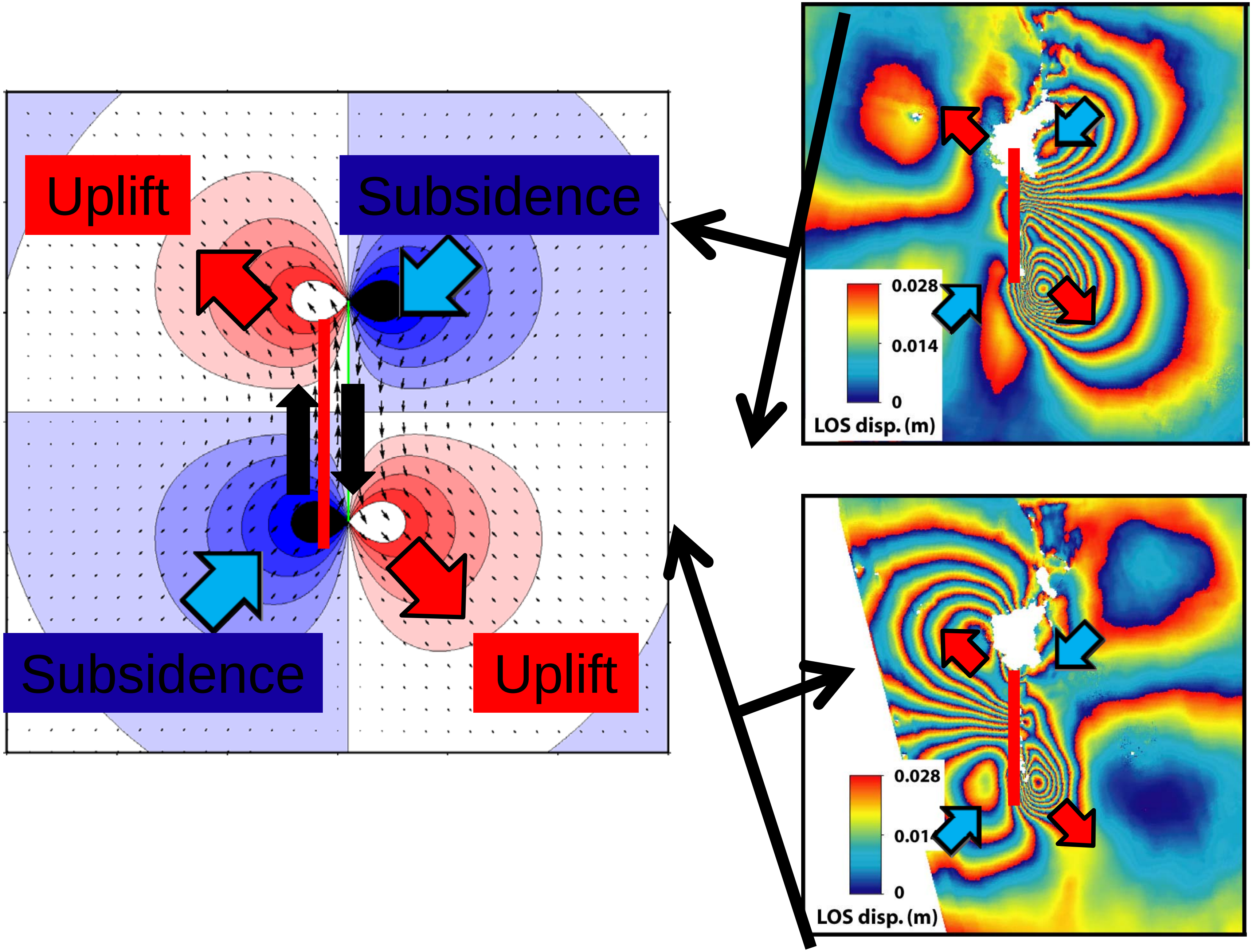
Unwrapped

# Azimuth offsets

Ascending

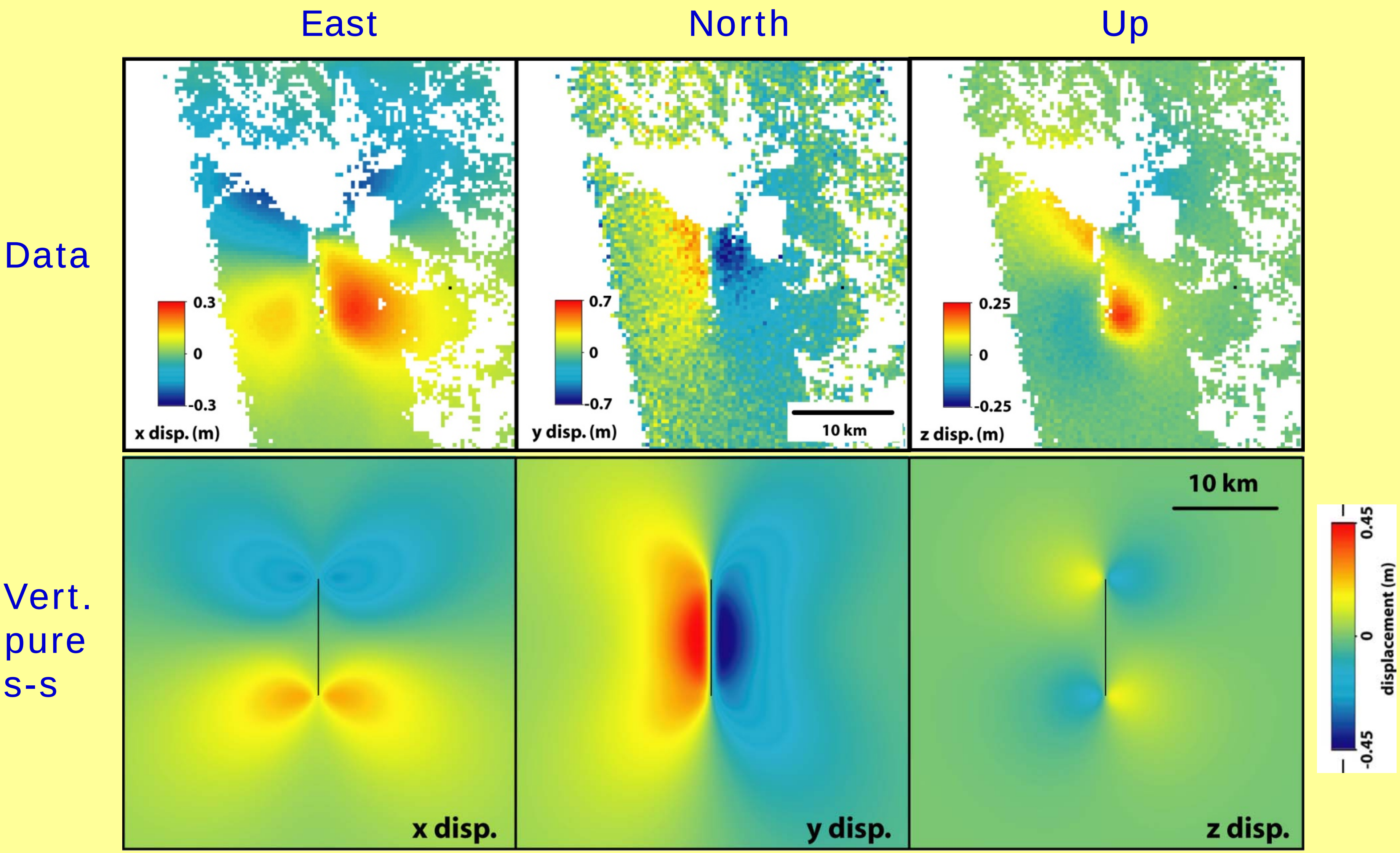
Descending





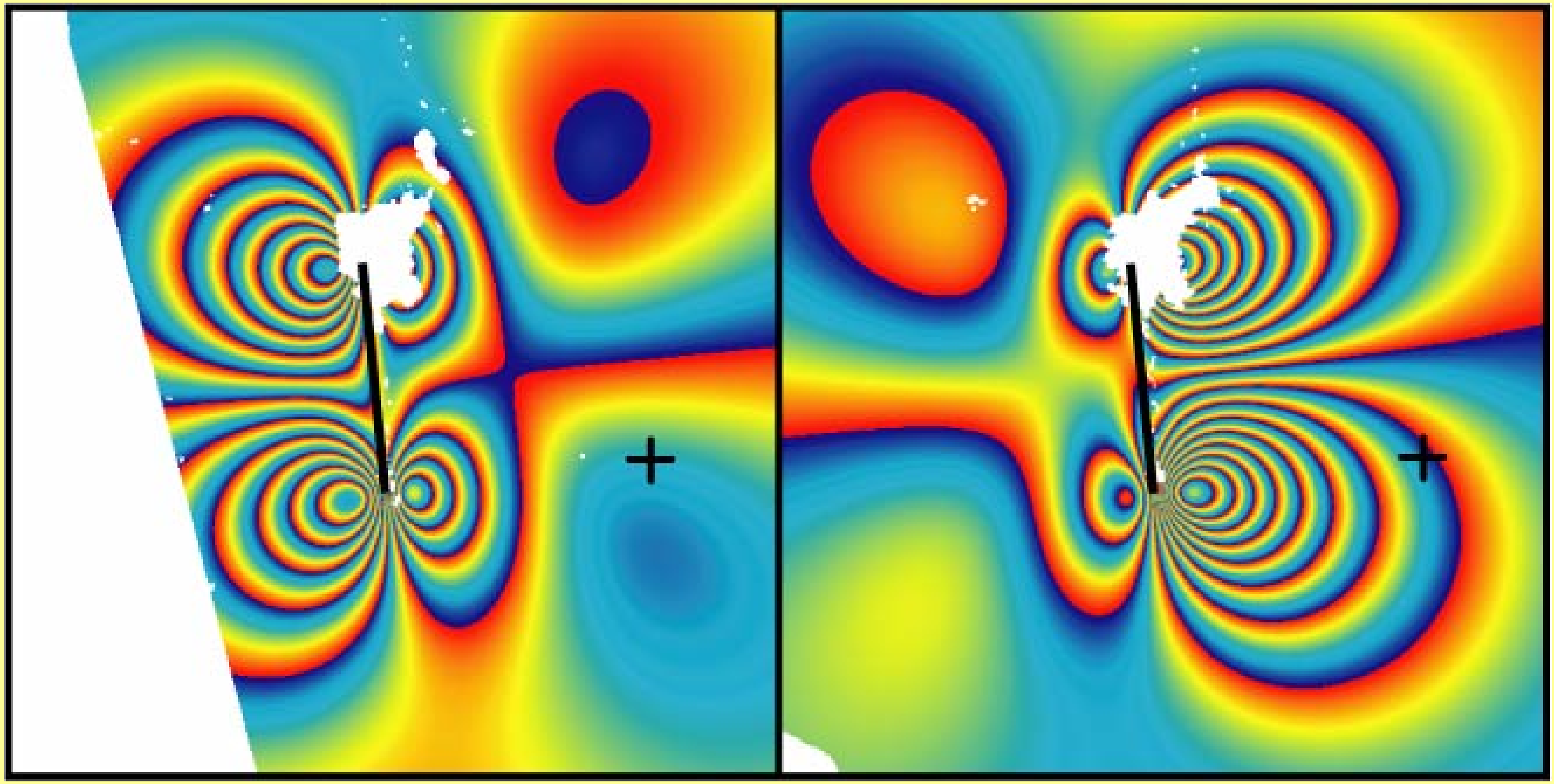
Uplift
Subsidence
Subsidence
Uplift
0.028
0.014
0
LOS disp. (m)
0.028
0
LOS disp. (m)

# Bam earthquake 3D displacements



# Single fault, uniform-slip model

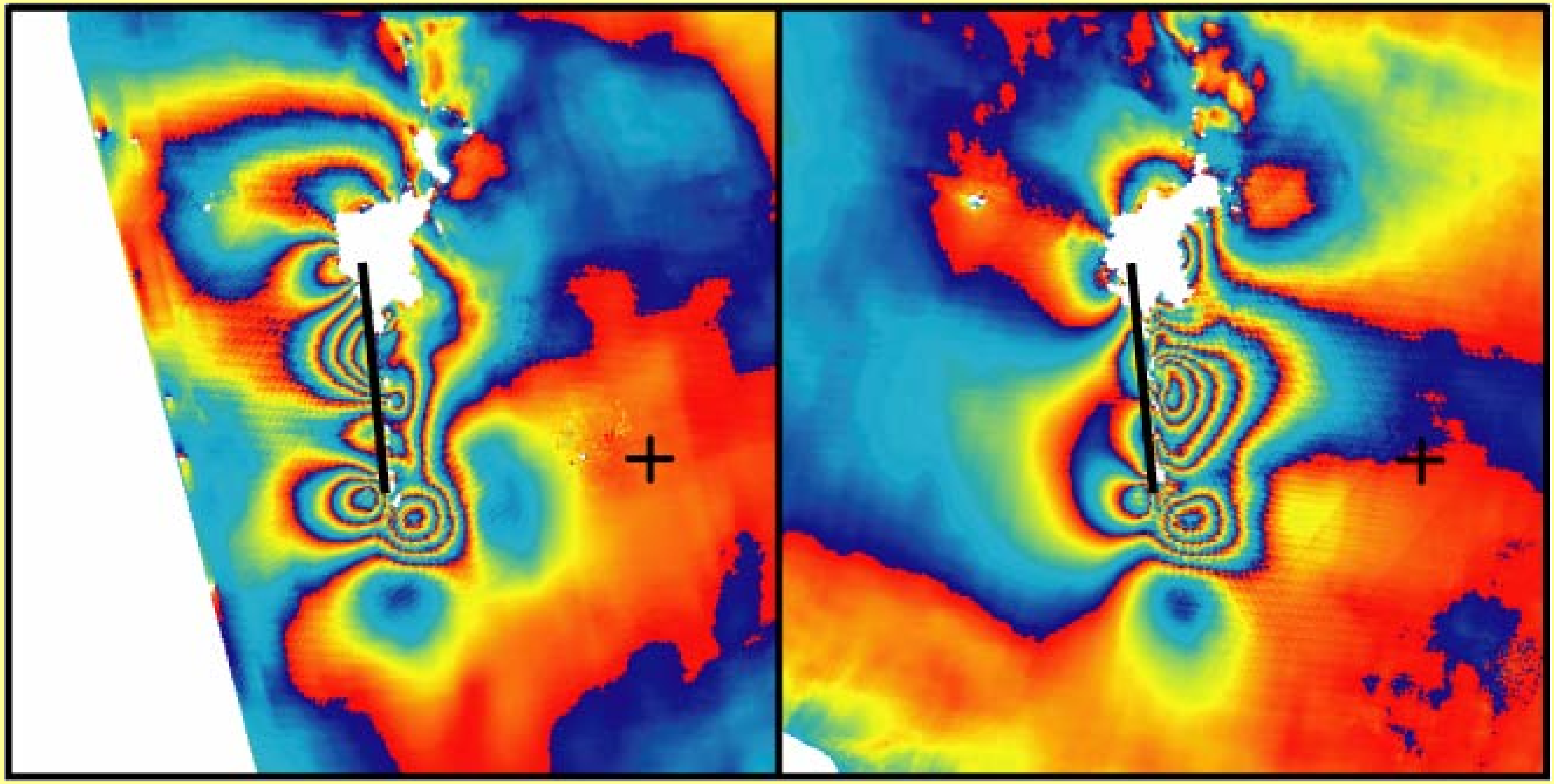
About 2m slip on 12 km long fault in top 10 km of crust



Ascending model Descending model

# Single fault model

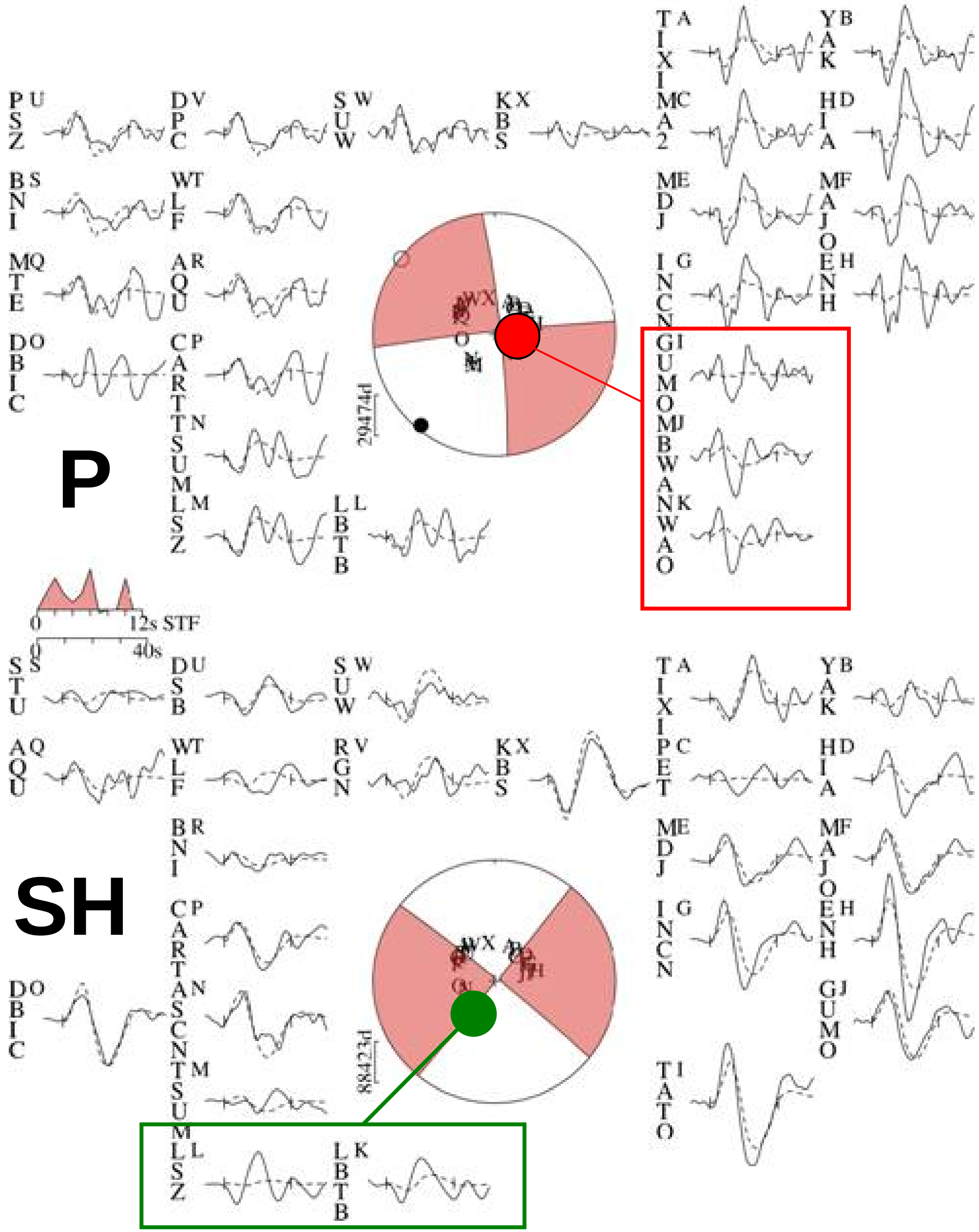
Large residuals, especially in SE quadrant (rms = 25 mm)



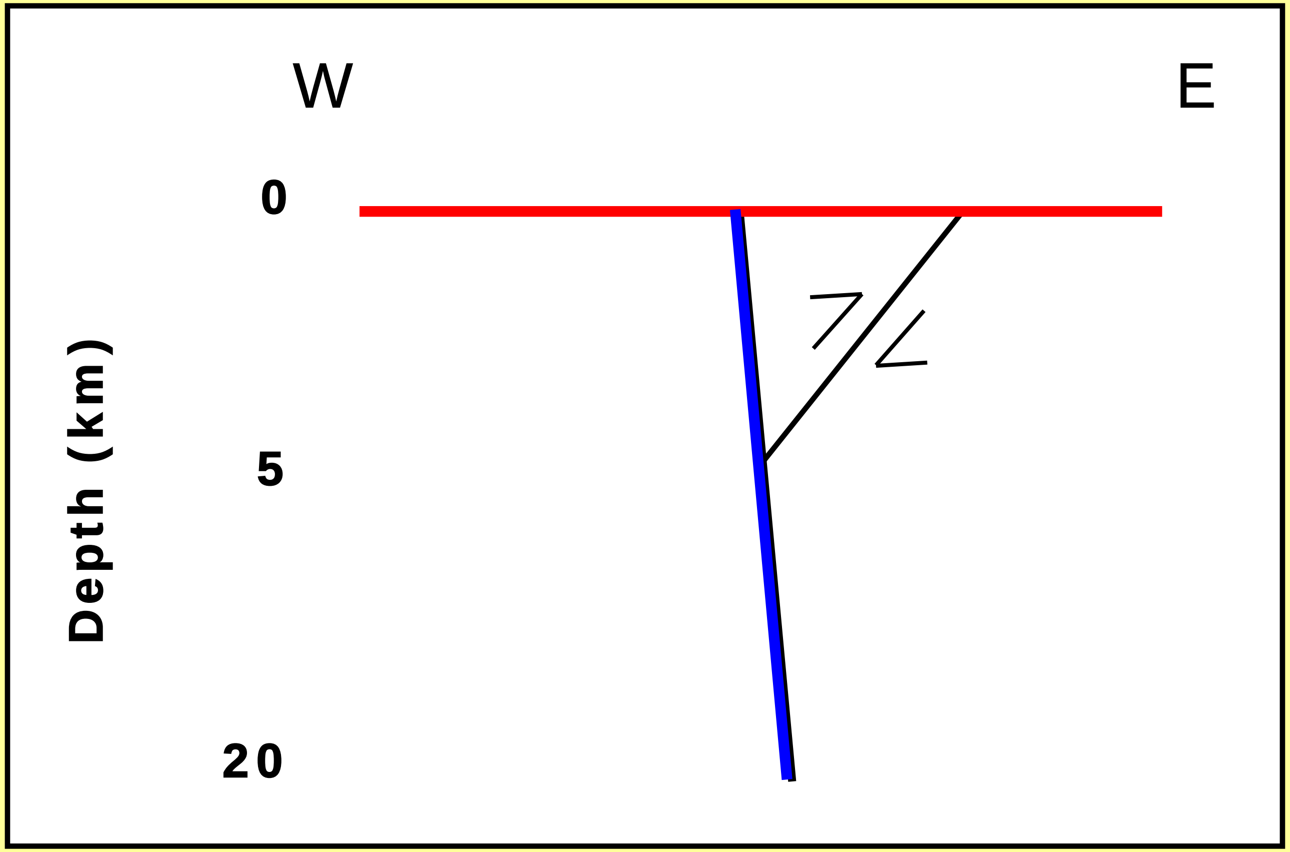
Ascending residual Descending residual

Bam 031226: single source

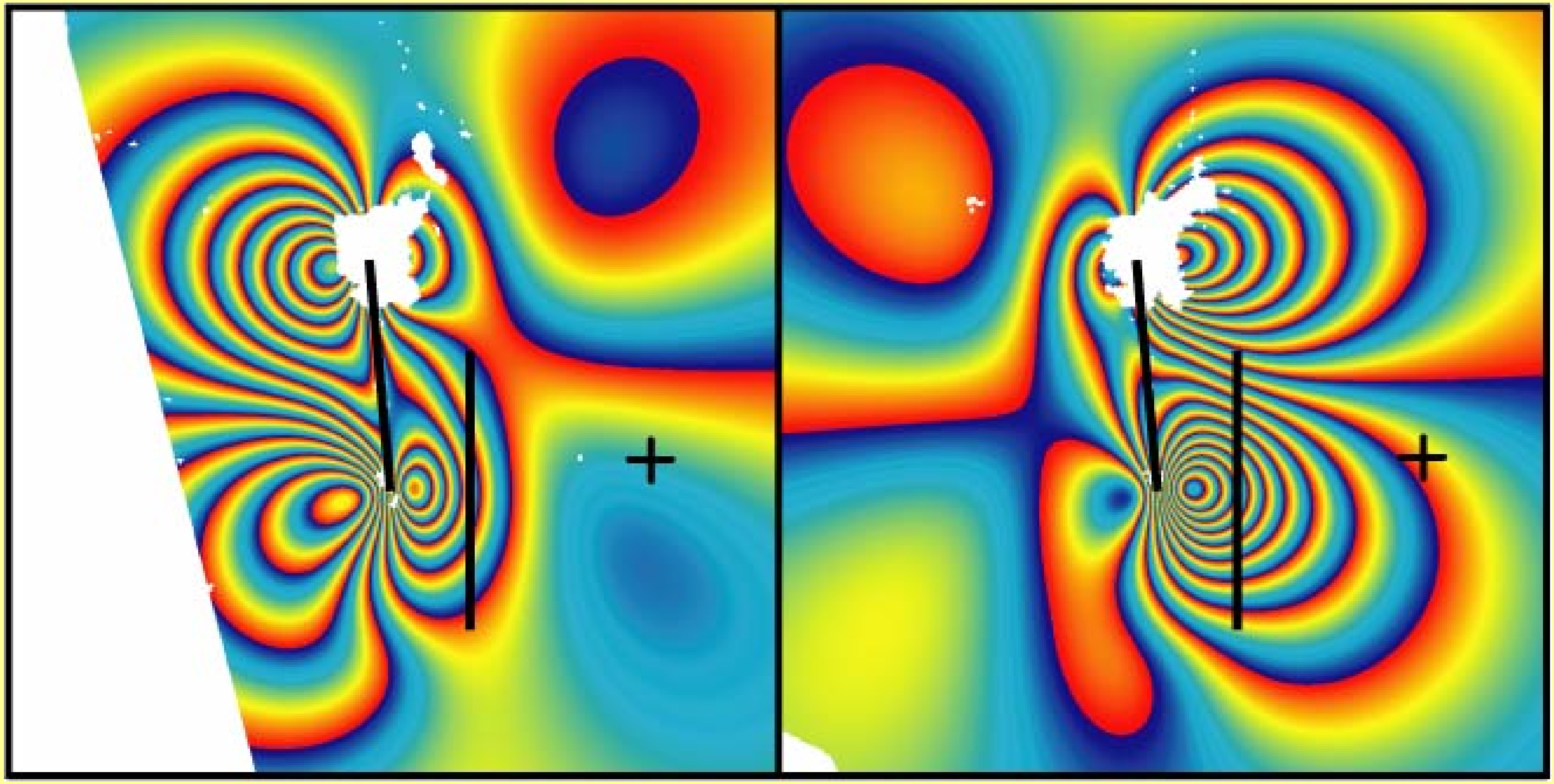
354/86/182/6/7.6E18



# Two fault model



# Two fault model (uniform slip)

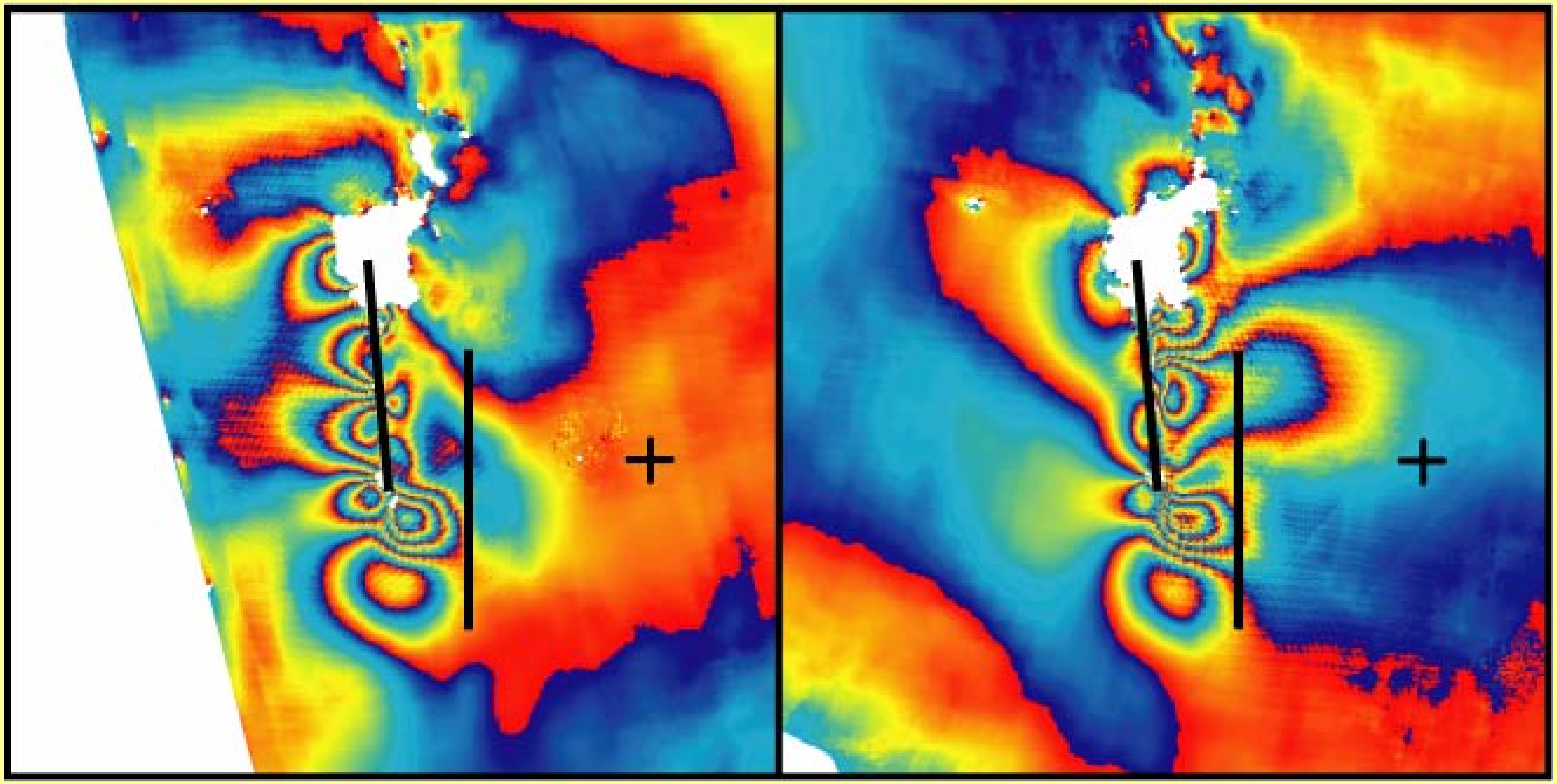


Ascending model

Descending model

# Two fault model (uniform slip)

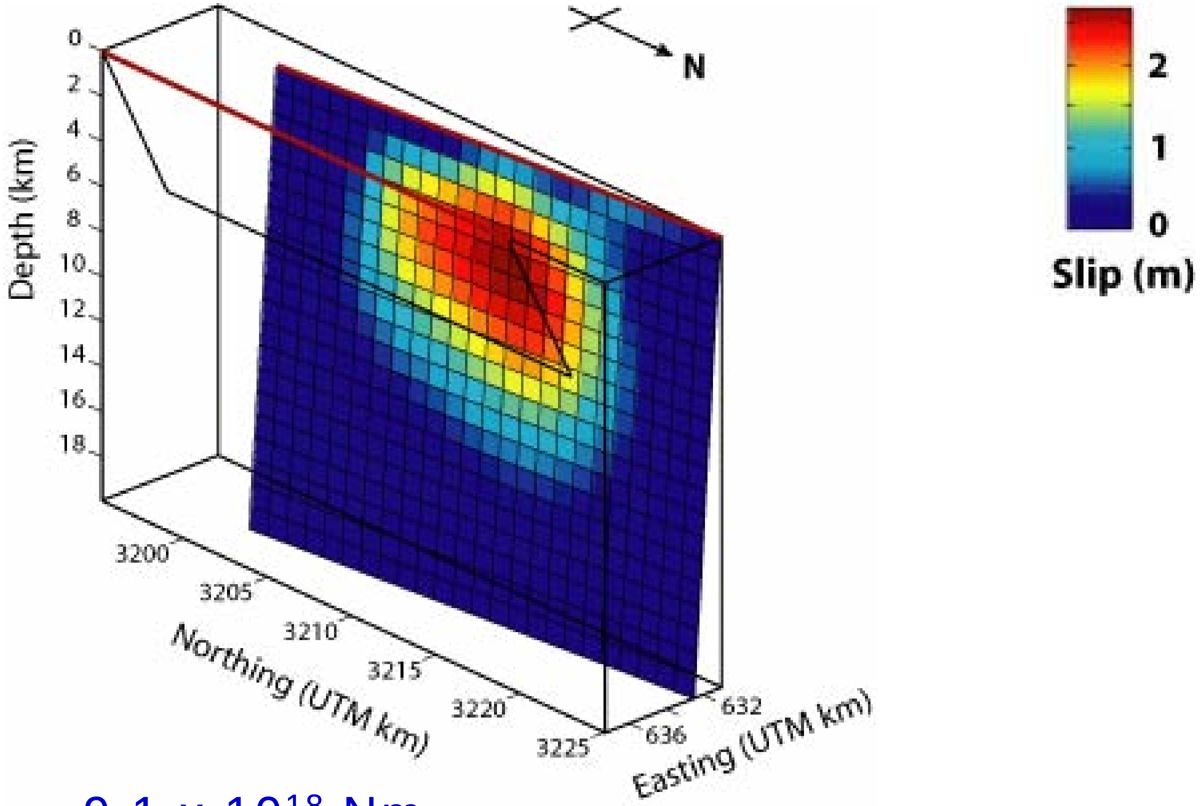
Improved fit in SE quadrant (rms = 17 mm)



Ascending residual

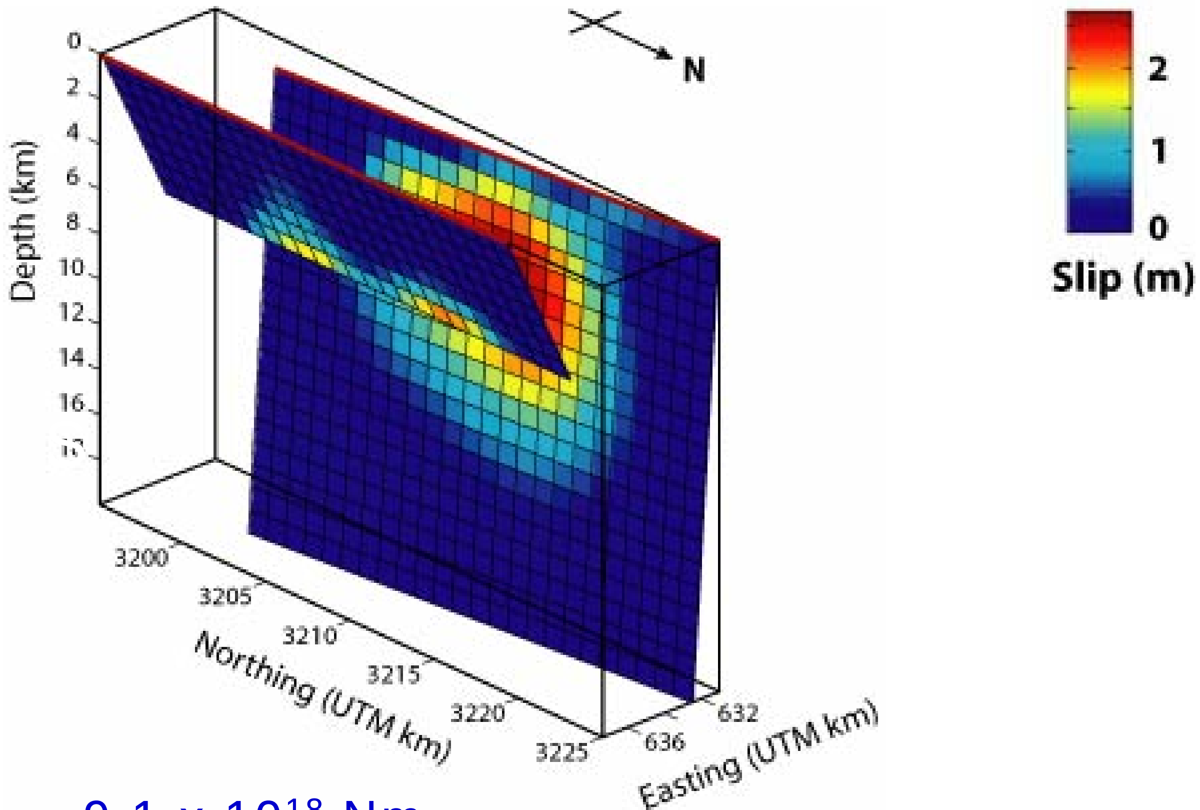
Descending residual

# Variable slip model




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

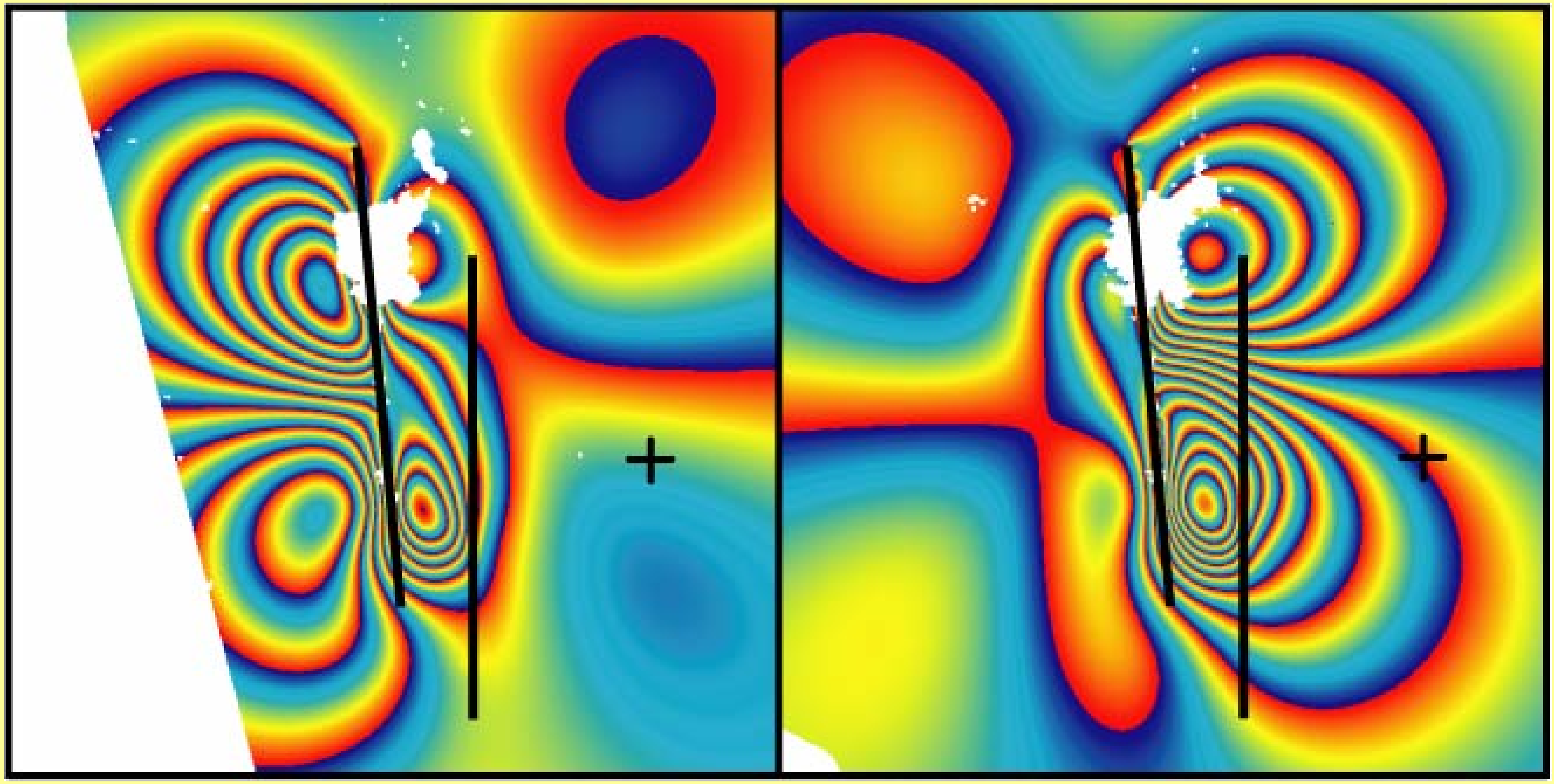
# Variable slip model




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

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

# Variable slip model

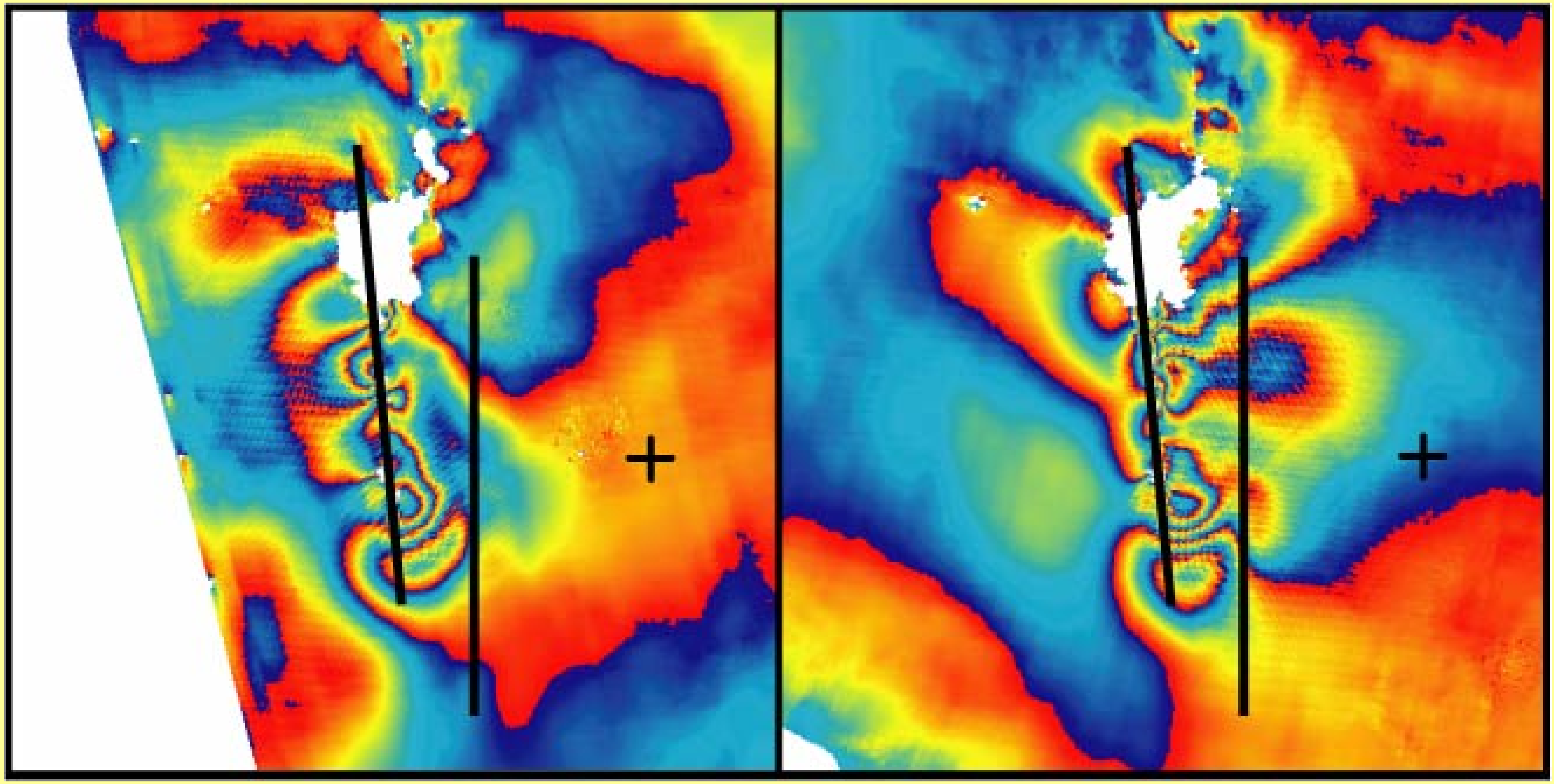


Ascending model

Descending model

# Variable slip model

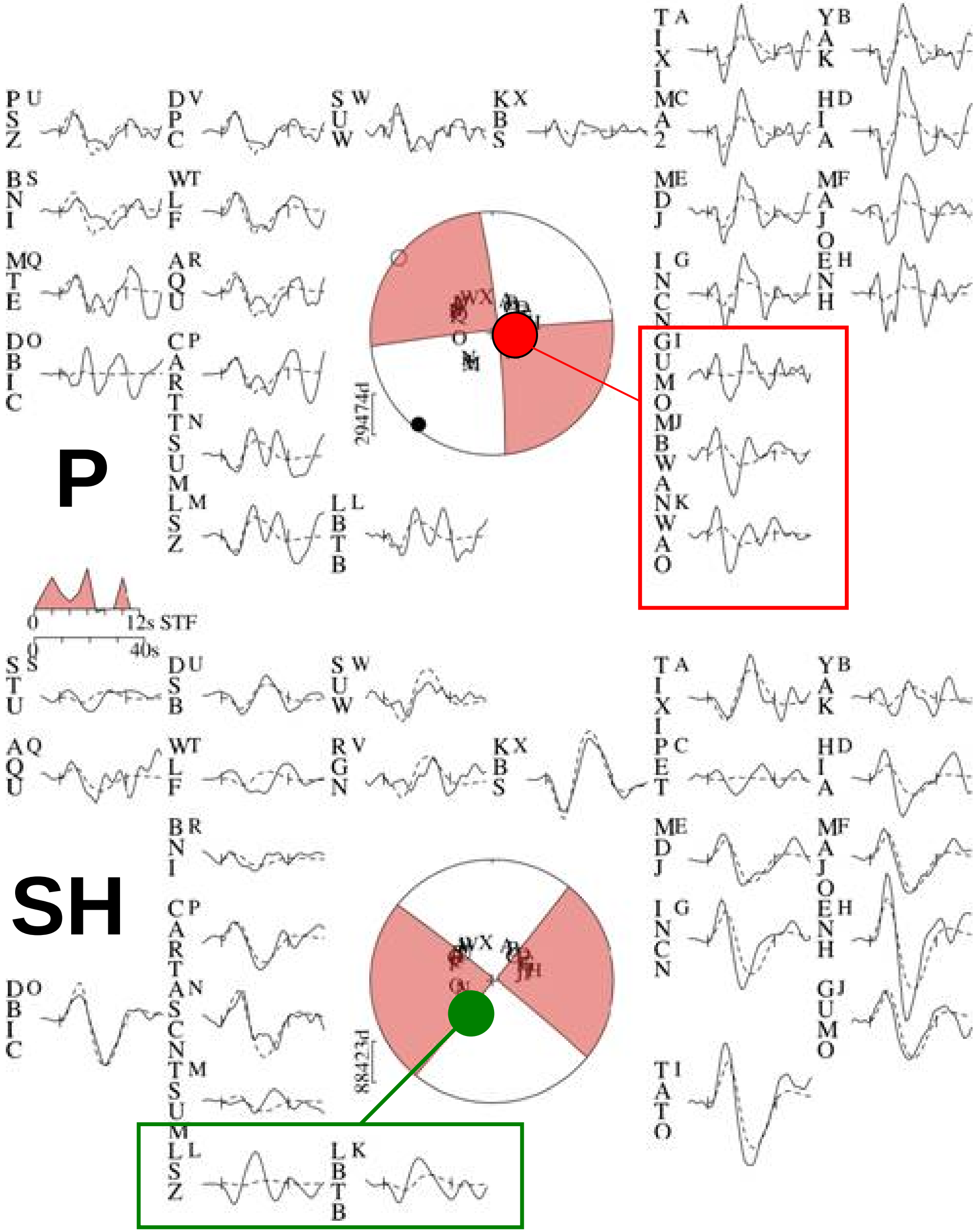
Significantly improved fit (rms = 13 mm)



Ascending residual　　　　Descending residual

Bam 031226: single source

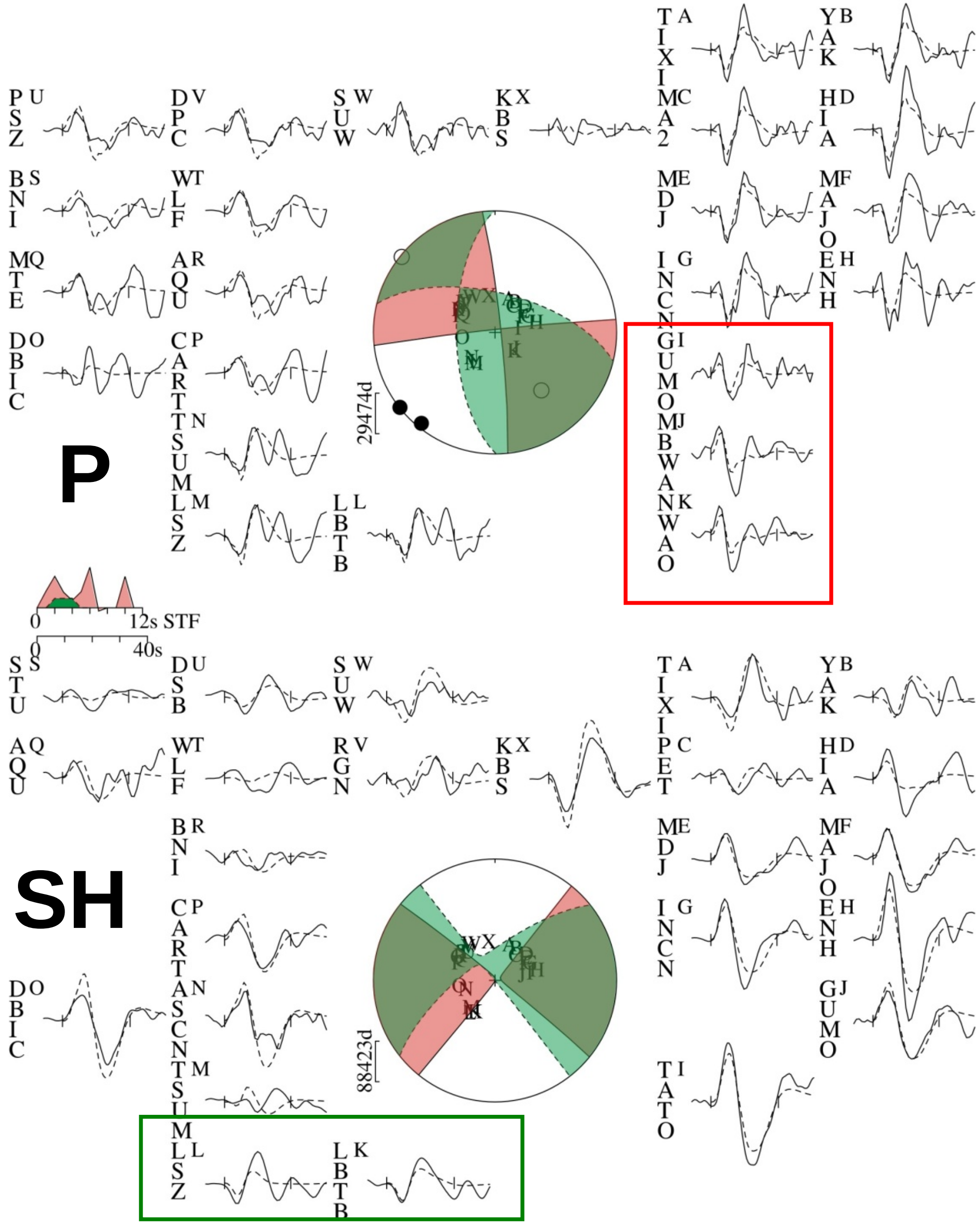
354/86/182/6/7.6E18

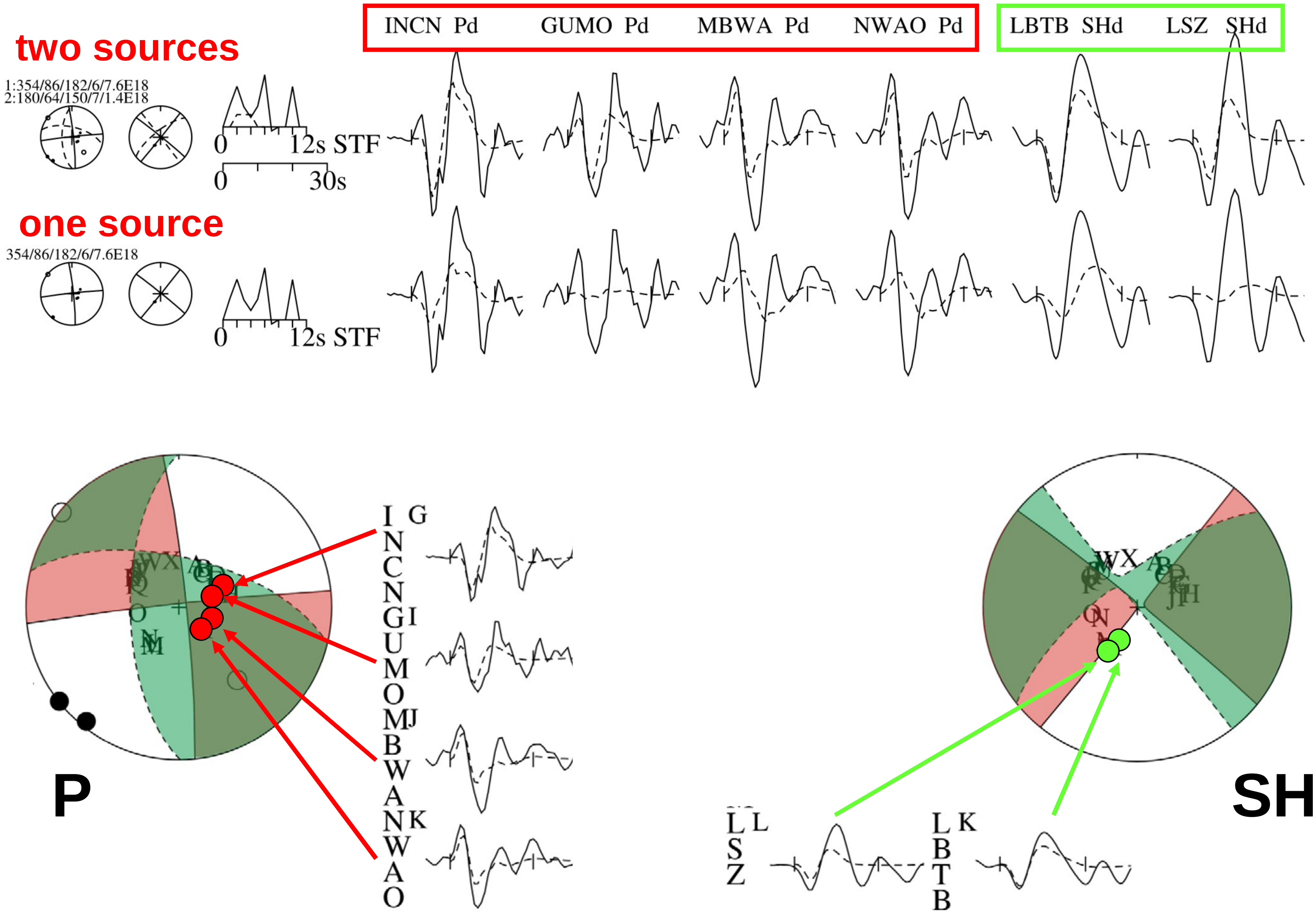


Bam 031226: two sources

1: 354/86/182/6/7.6E18

2: 180/64/150/7/1.4E18





two sources
1:354/86/182/6/7.6E18
2:180/64/150/7/1.4E18
0
12s STF
0
30s
one source
354/86/182/6/7.6E18
0
12s STF
INCN Pd
GUMO Pd
MBWA Pd
NWAO Pd
LBTB SHd
LSZ SHd
G
INCN
I
GUMO
J
MBWA
K
NWAO
P
L
LSZ
K
LBTB
SH

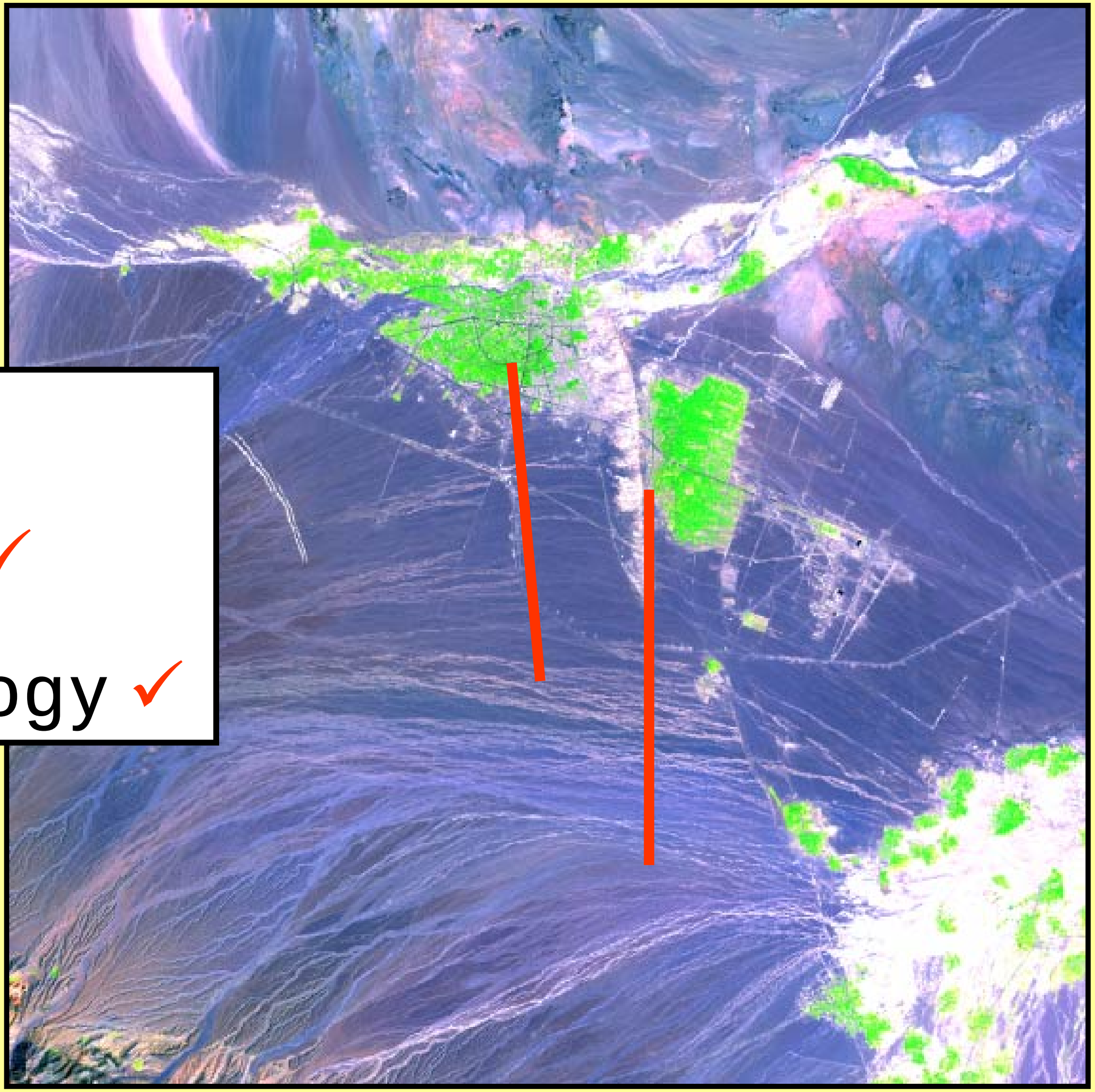
# Two fault model

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

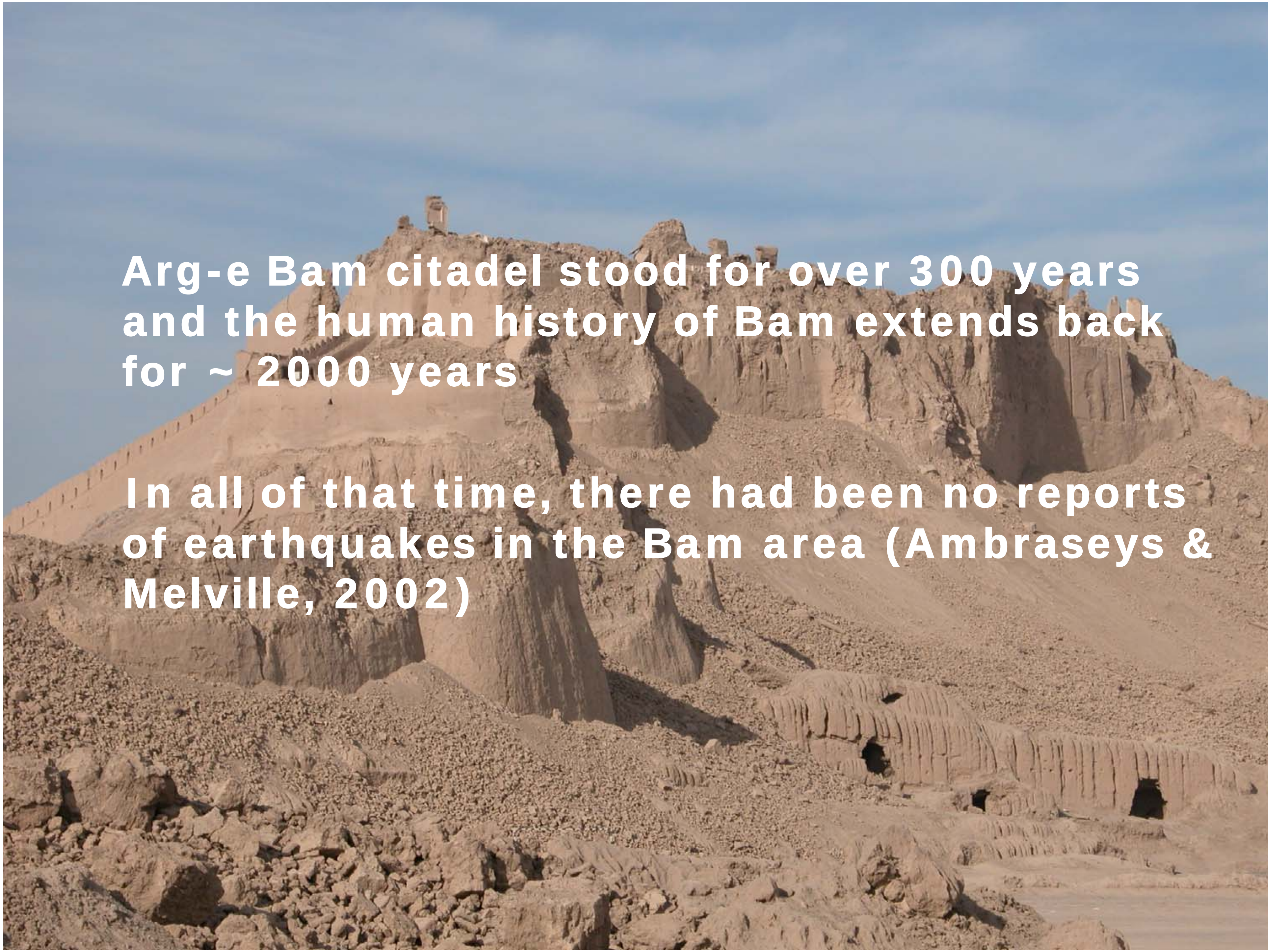
Geodesy ✓

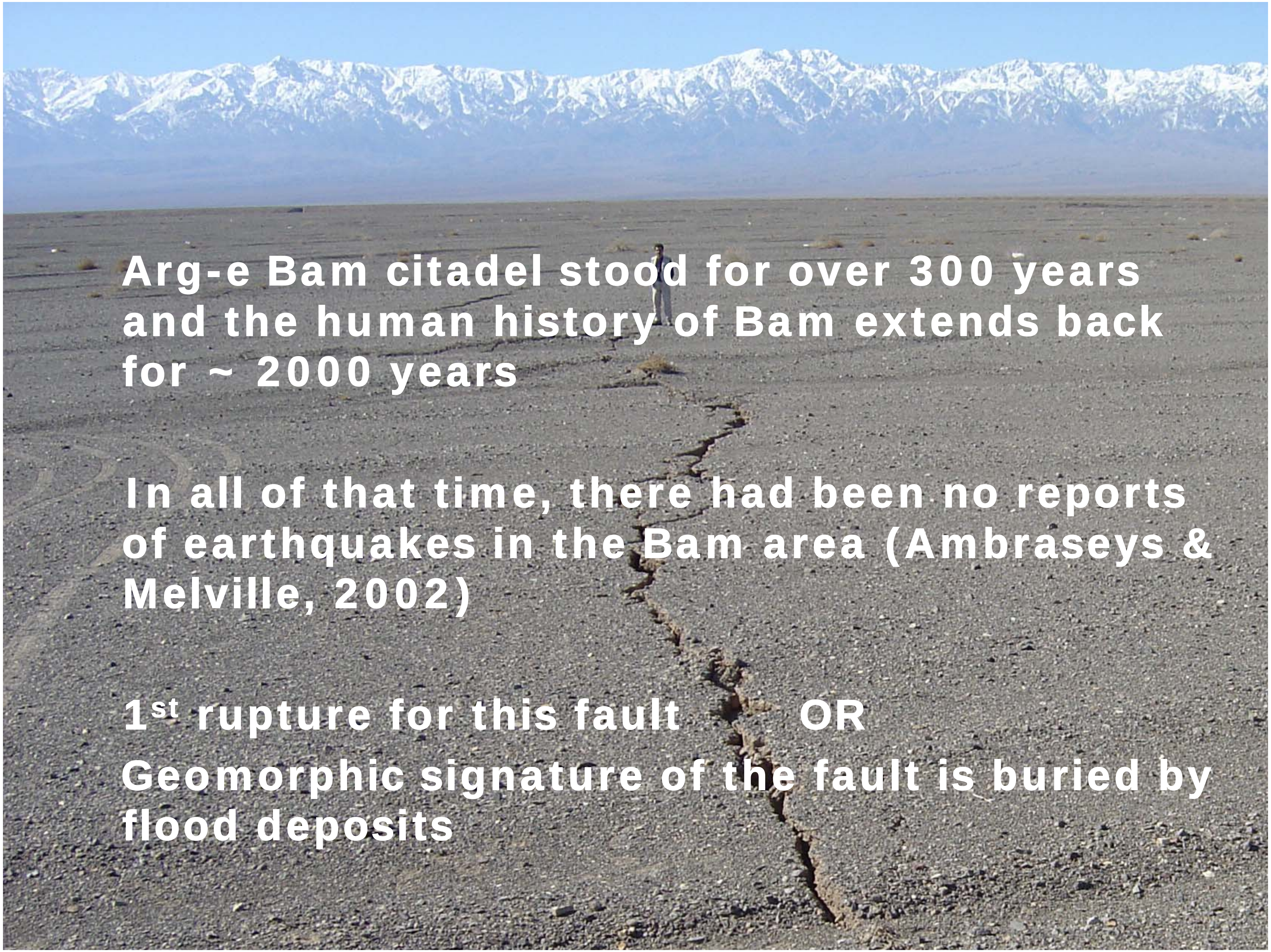
Seismology ✓

Geomorphology ✓

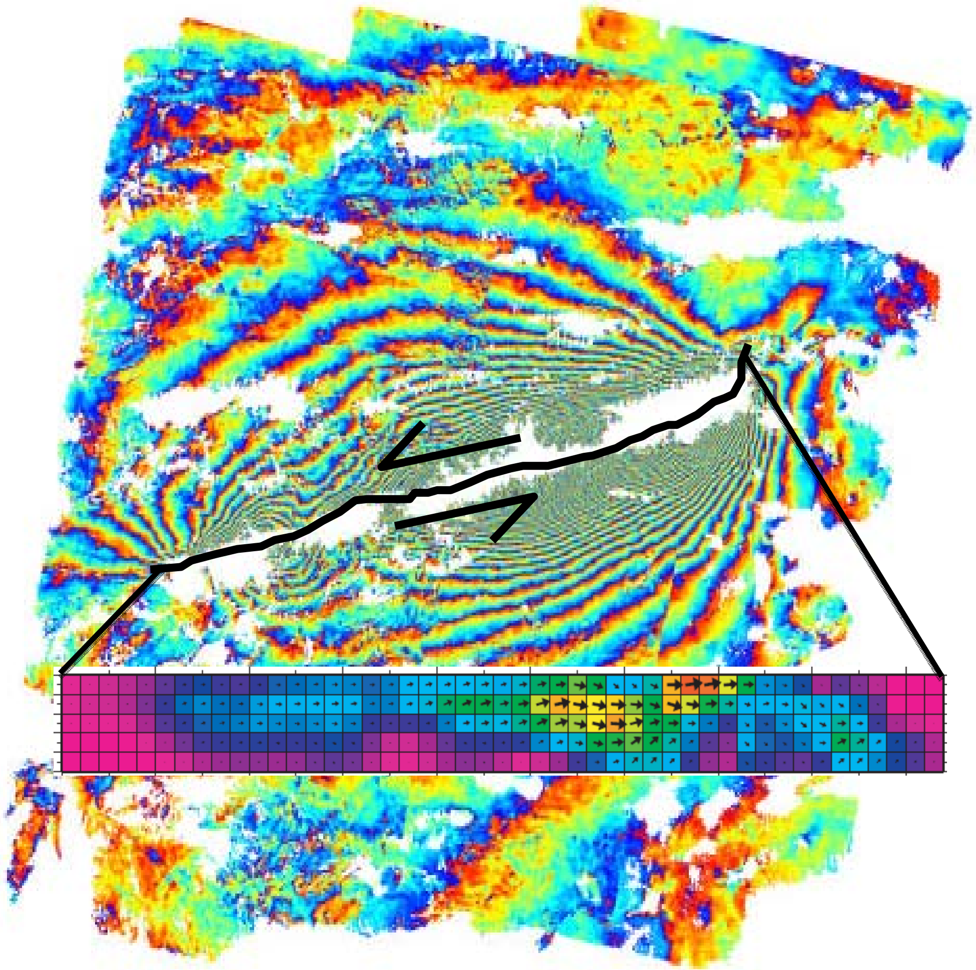


LANDSAT-7 ETM
541 false colour
green=vegetation


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

# Coseismic deformation - Summary



**Current Capability**

- Map deformation fields for most damaging earthquakes on the continents.
- Identify responsible faults
- Estimate slip models.
- Assess impact on future hazard .

**What could be done?**

- Routine analysis of **ALL** damaging earthquakes, c.f. Harvard CMT.
- Real-time assessment of causative fault and likely damage area.
- Near-real time assessment of future hazard (aftershocks + triggered quakes).

**Why are we not doing this already?**

- Data.
- Method Development.
- Manpower.