The Abdus Salam International Centre for Theoretical Physics

2464-21

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Dead Sea System Tectonics and hazard

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USA

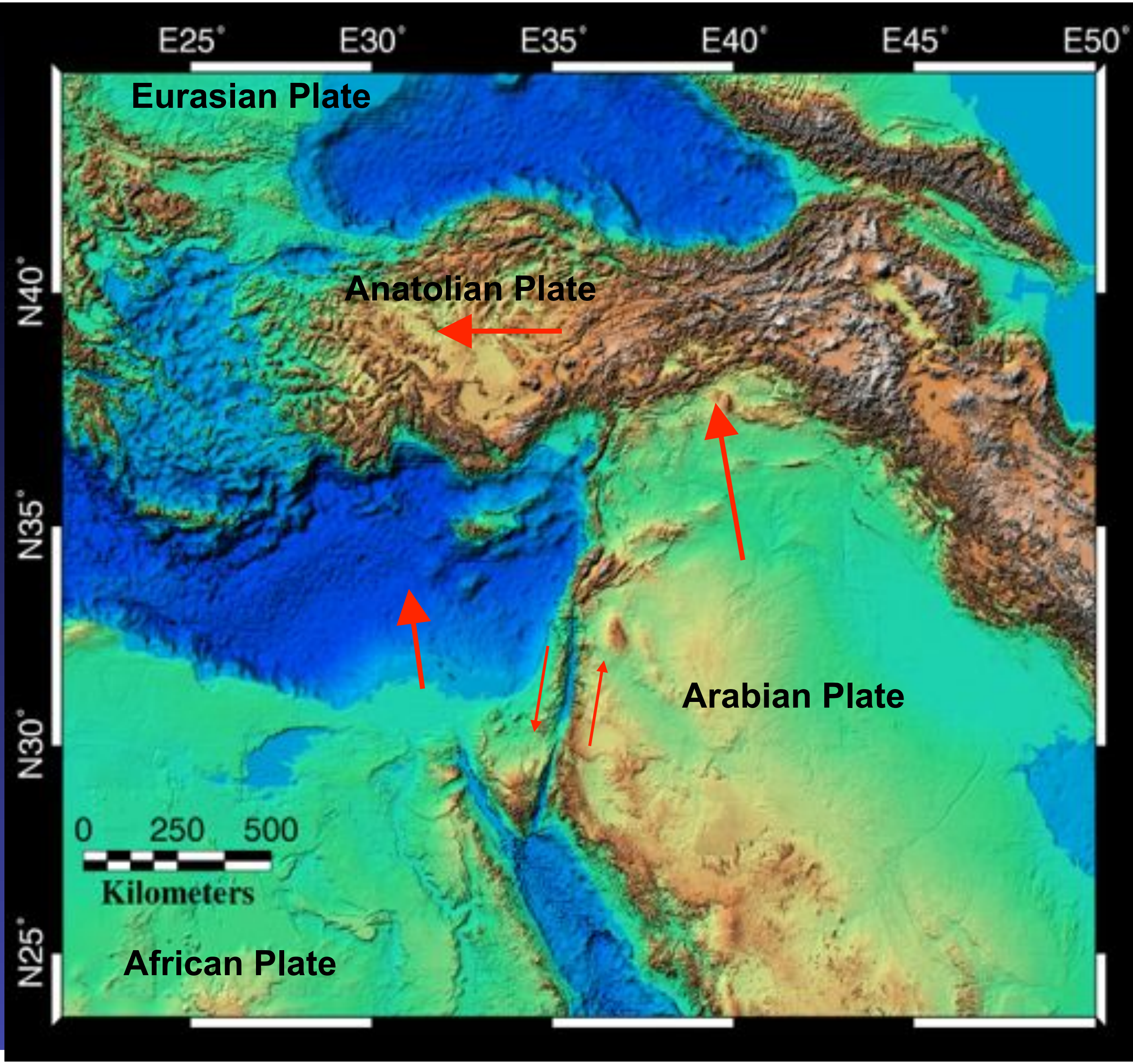
Crustal Deformation and Earthquake Behavior along the Dead Sea Fault System

Illustrations From

Francisco (Paco) Gomez
University of Missouri

Presented by

Robert Reilinger, MIT


E25°
E30°
E35°
E40°
E45°
E50°
N40°
N35°
N30°
N25°
Eurasian Plate
Anatolian Plate
Arabian Plate
African Plate
0 250 500
Kilometers

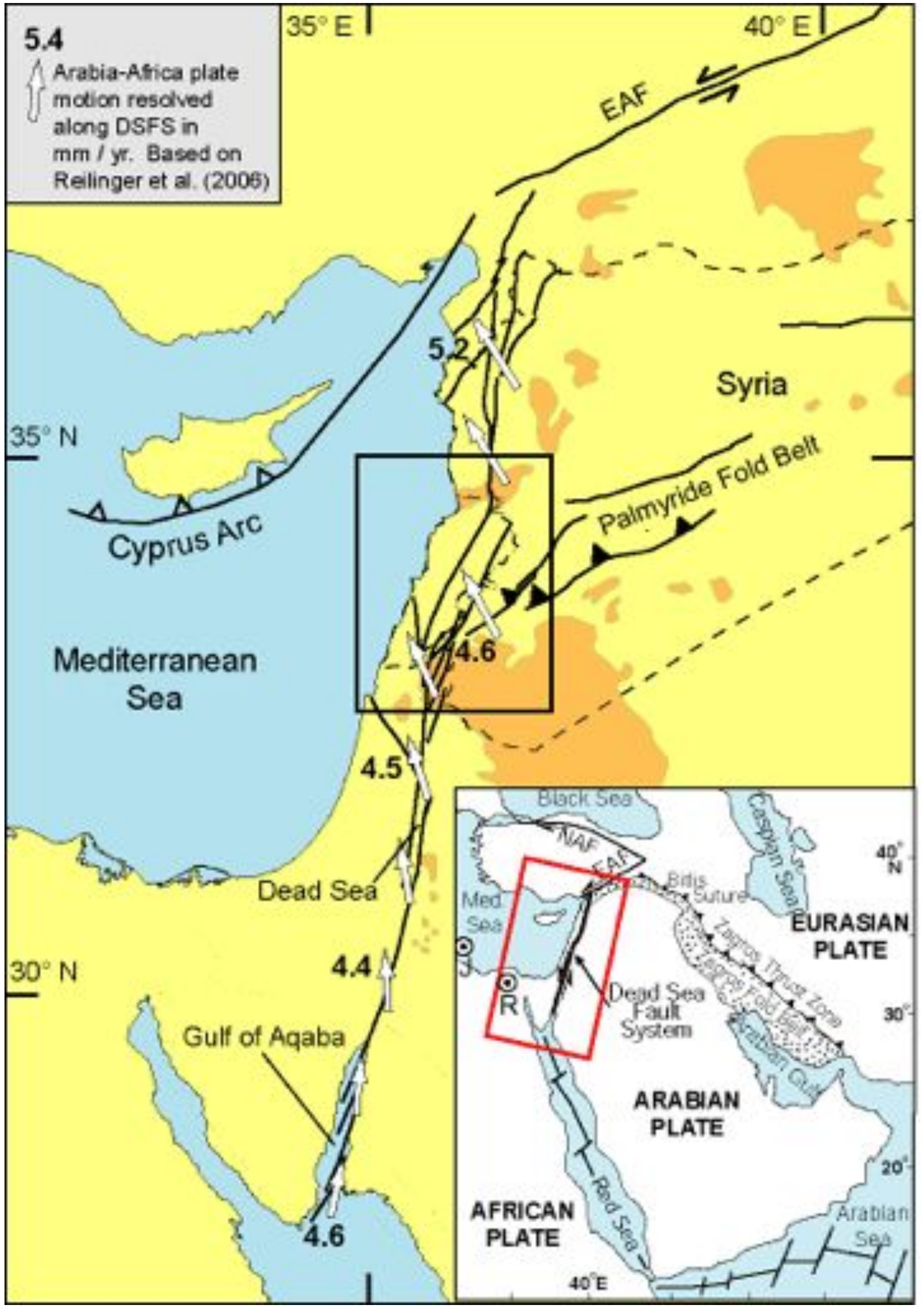
Acknowledgements

- Collaborators:
  - Rob Reilinger, Muawia Barazangi, Mustapha Meghraoui
  - Rani Jaafar , Tony Nemer, Joey Cochran

  - Syria: Syrian National Earthquake Center
  - Lebanese American University
  - Hashemite University (Jordan)

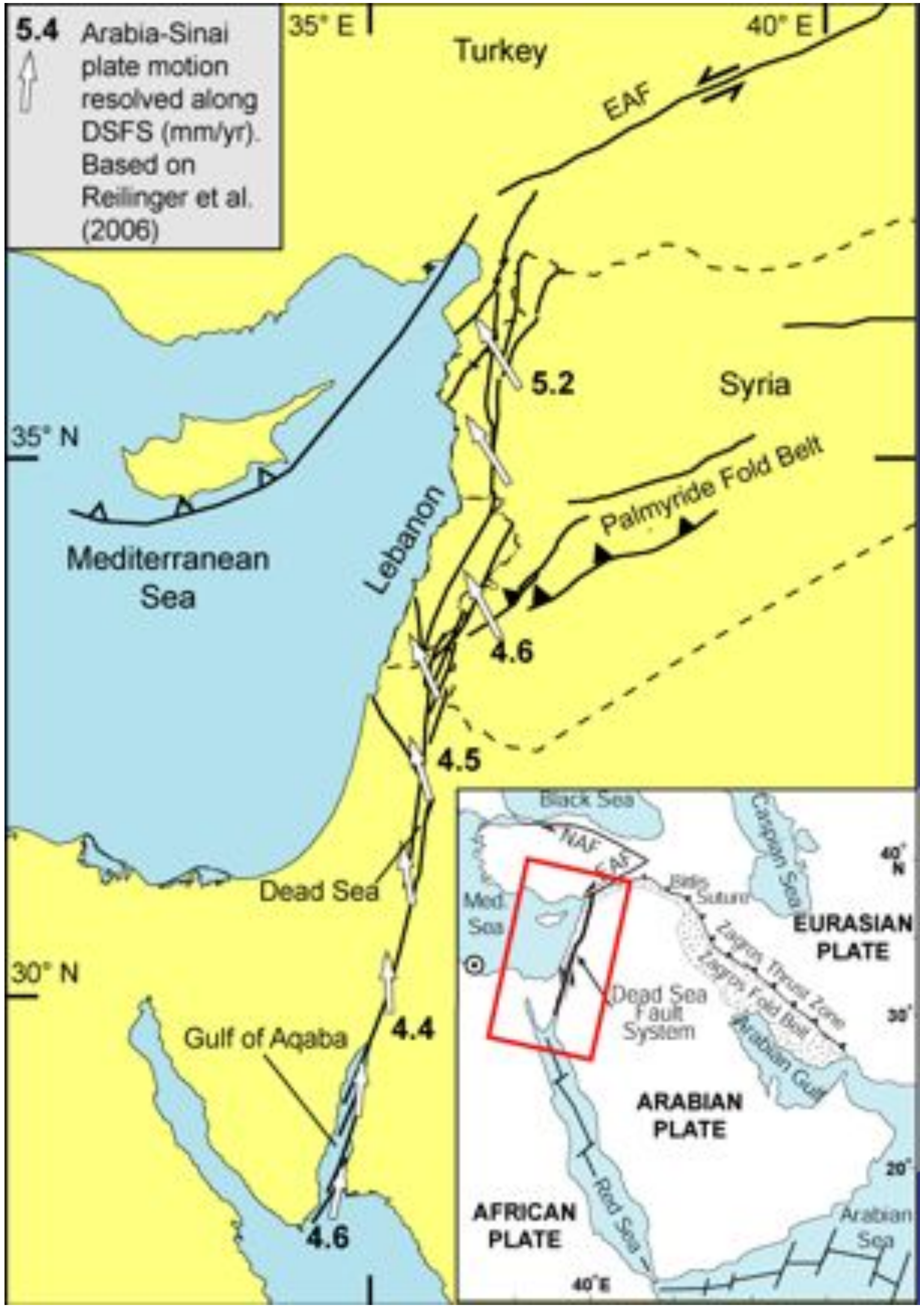
- National Science Foundation, University of Missouri Research Board

- Outline
  - – Why the Dead Sea fault
  - – Where we started (ca. 2000)
  - – Where we are now
    - Paleoseismic & Neotectonic Results
    - A geodetic perspective of the transform
  - – Conclusions



<u>The Main Point</u>: Earthquake Geology vs. Tectonic Geodesy

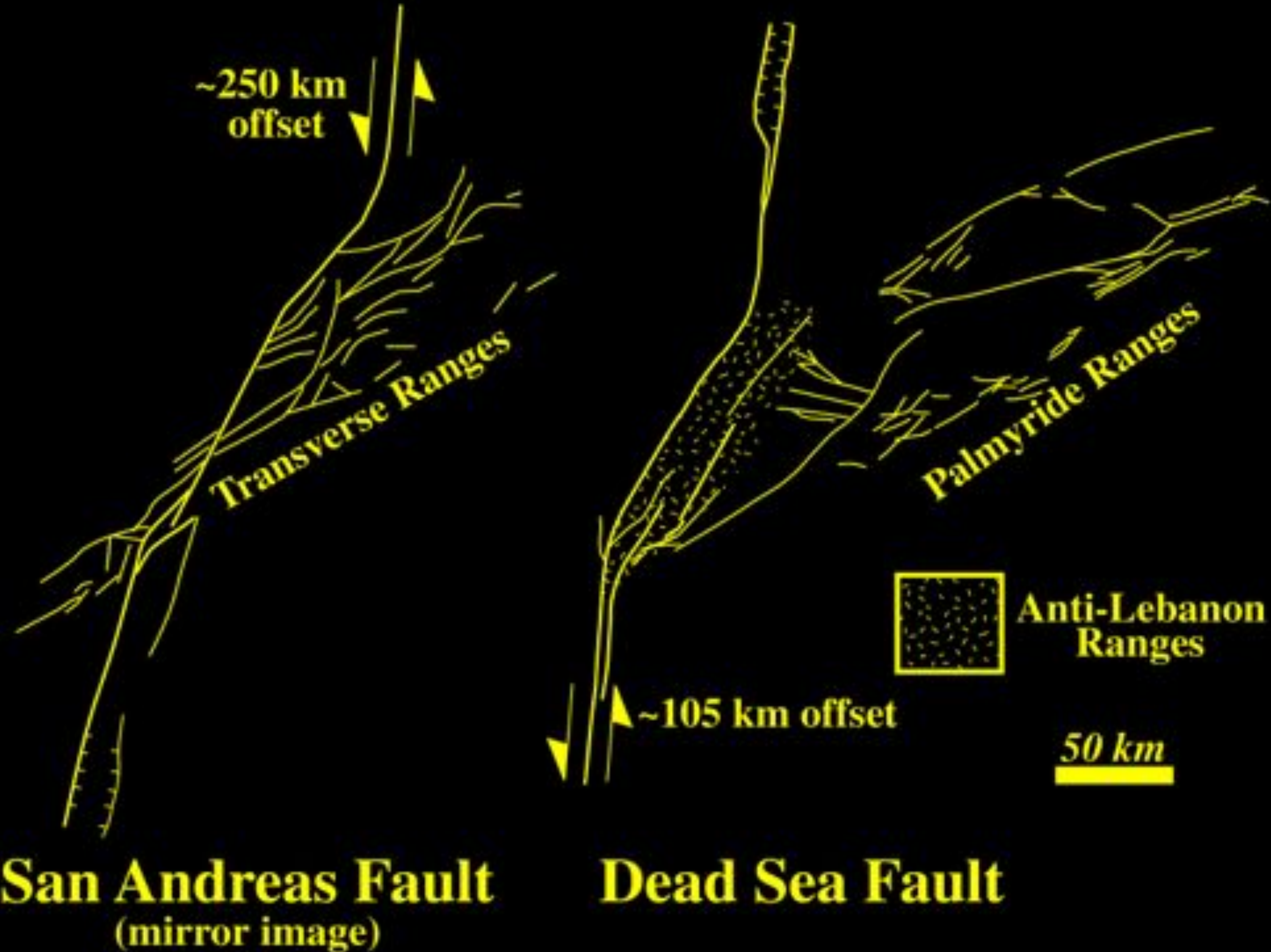
- How does the rate of slip change along strike of the DSF? What do any differences reflect?
- Is the northern DSF convergent, “leaky”, or pure strike-slip?
- Is there internal deformation of Arabia?
- How do GPS velocities compare with Geological slip rates?
- What supports the Syrian Coast Range?



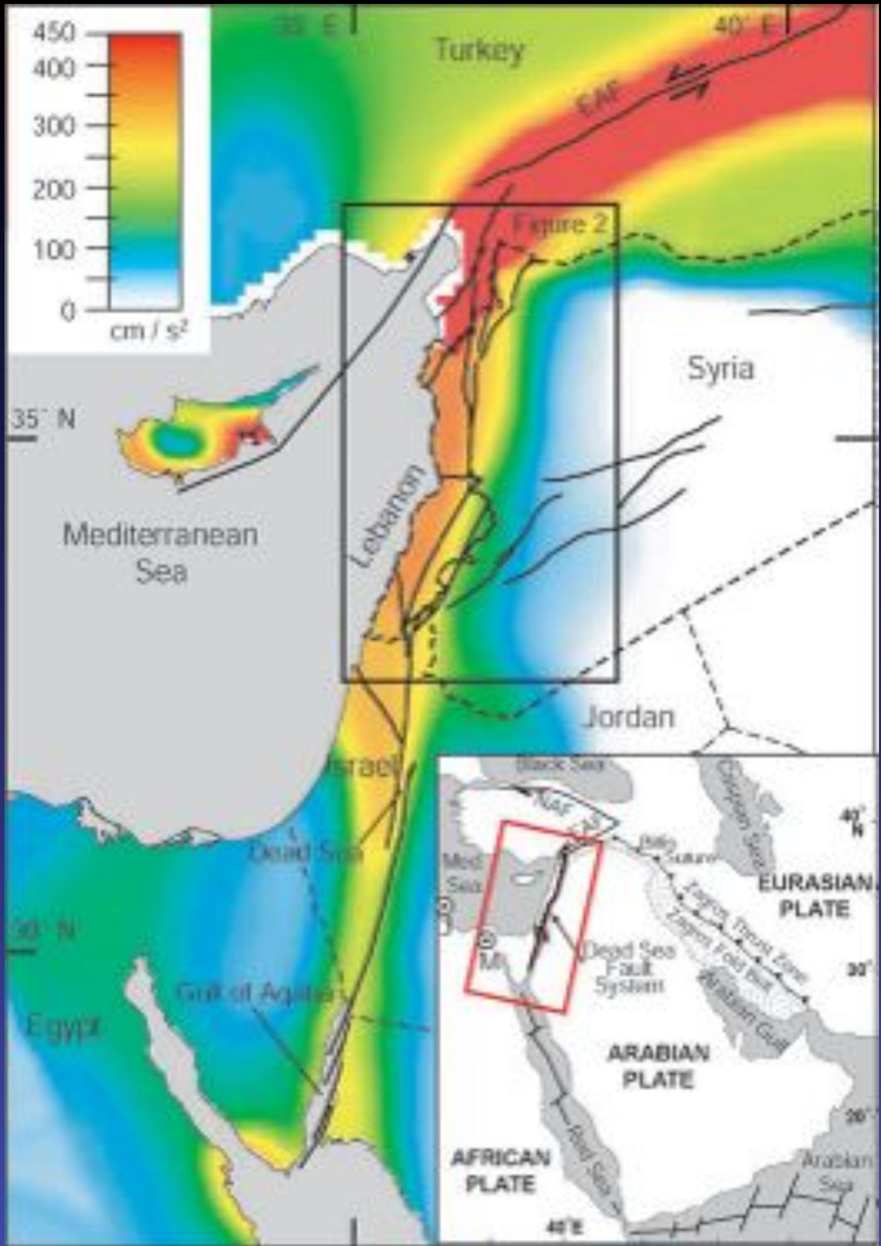
Why the Dead Sea fault?

- Along-strike variations on a major plate boundary
- Opportunity to integrate geological and historical observations of past earthquakes
- Implications for regional earthquake hazard
- Analog to other major faults

Dead Sea fault as structural analog to San Andreas fault?



from Chaimov et al. (1992)

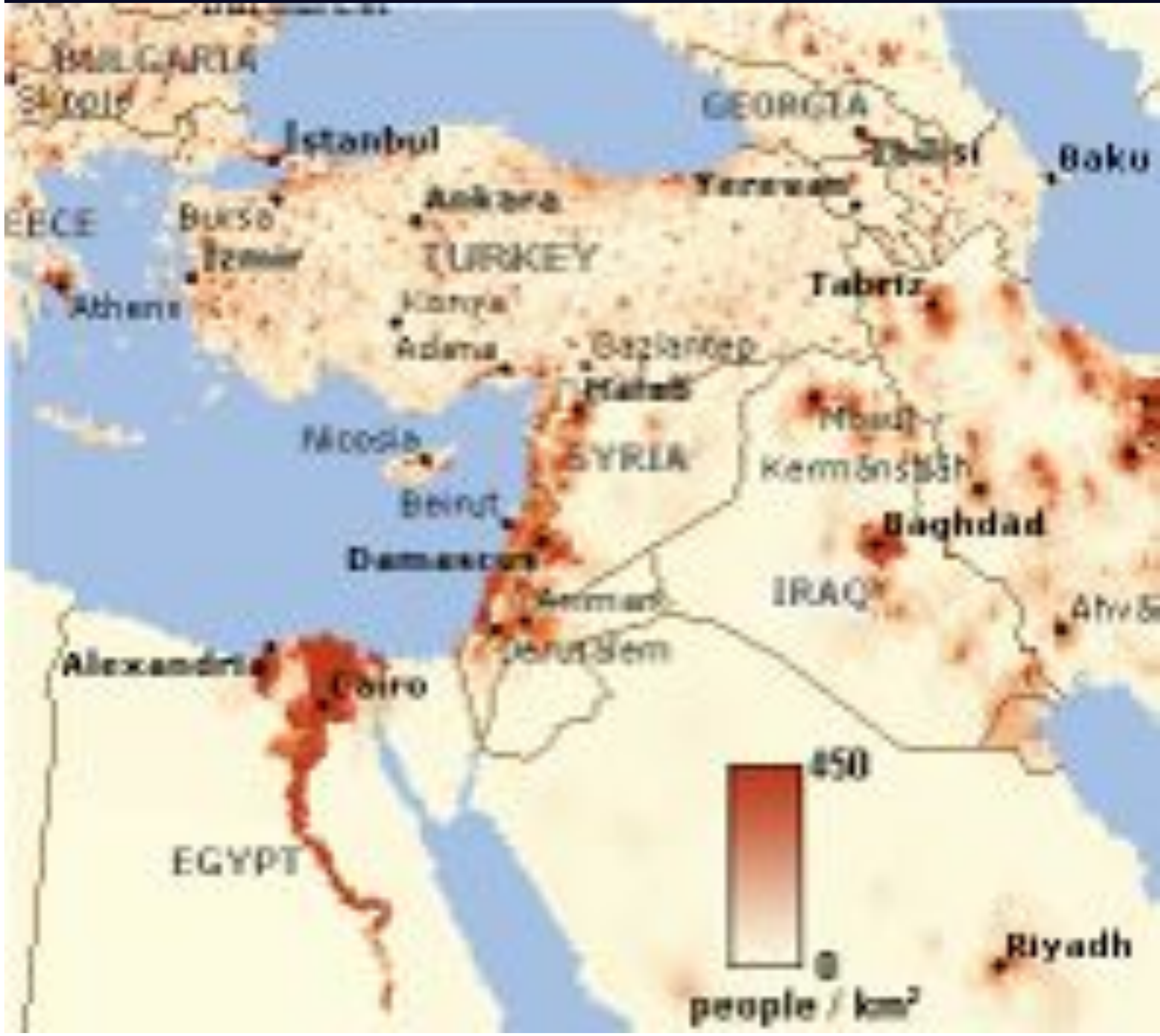


Earthquake Hazard Map

90% chance of ground acceleration exceeding these values during the next 50 years

Note the hazard along the Dead Sea fault system.

Population Density of the Middle East



Note the population along the Dead Sea fault system.

High hazard and significant exposure → High Risk!

A rich cultural history …

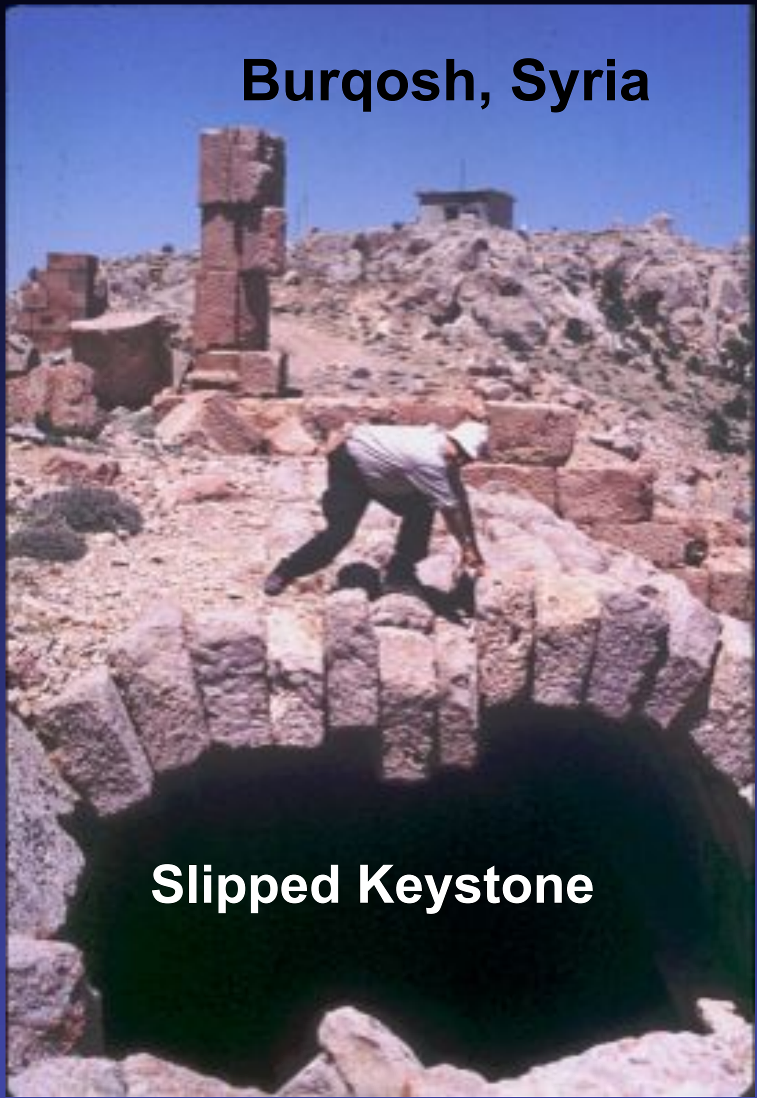
Roman /
Byzantine Era

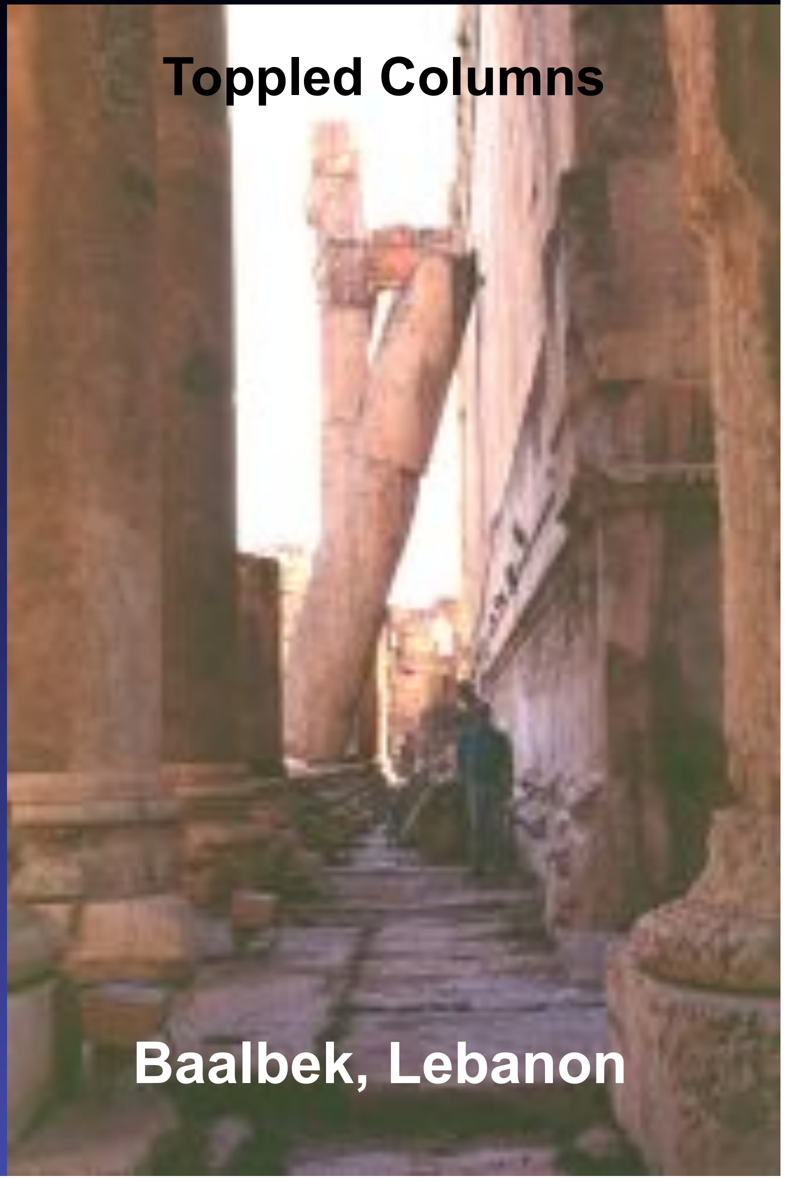
A rich cultural history …

Crusader Era

Earthquake Damage (slipped keystone)

Historical Record of Earthquakes





Limitations of historical records:

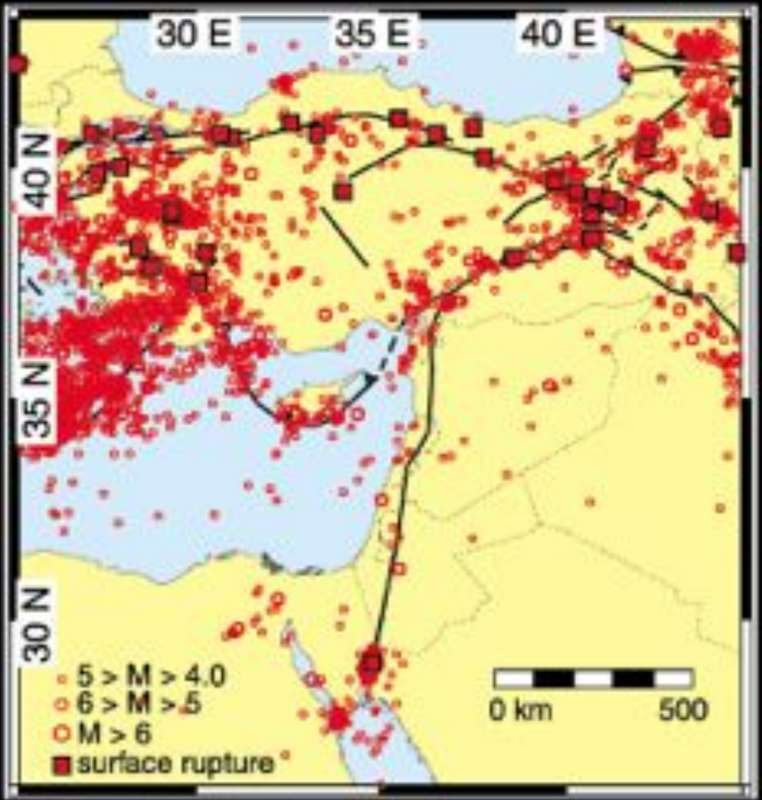
Report of surface rupture is lacking
→ ambiguity of the culprit structure

Example: November 1759 earthquake in the Bekaa Valley

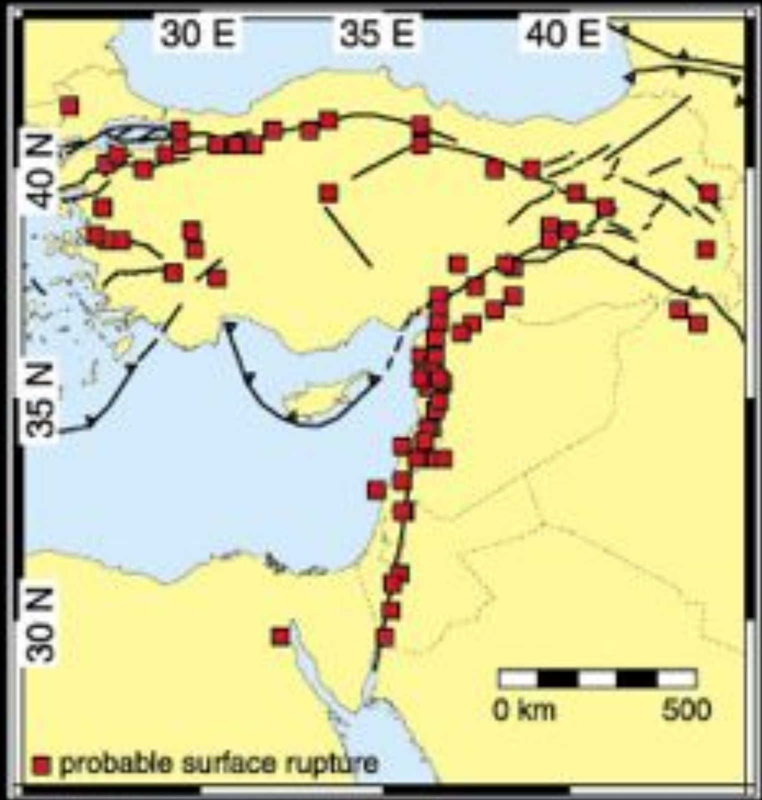
Assumed structure was Yammouneh Fault, but Serghaya fault (eastern Bekaa) is also within the maximum isoseismal zone.

Instrumental vs. Historical Earthquake Records

Instrumental Period (1895 AD - 1997 AD)



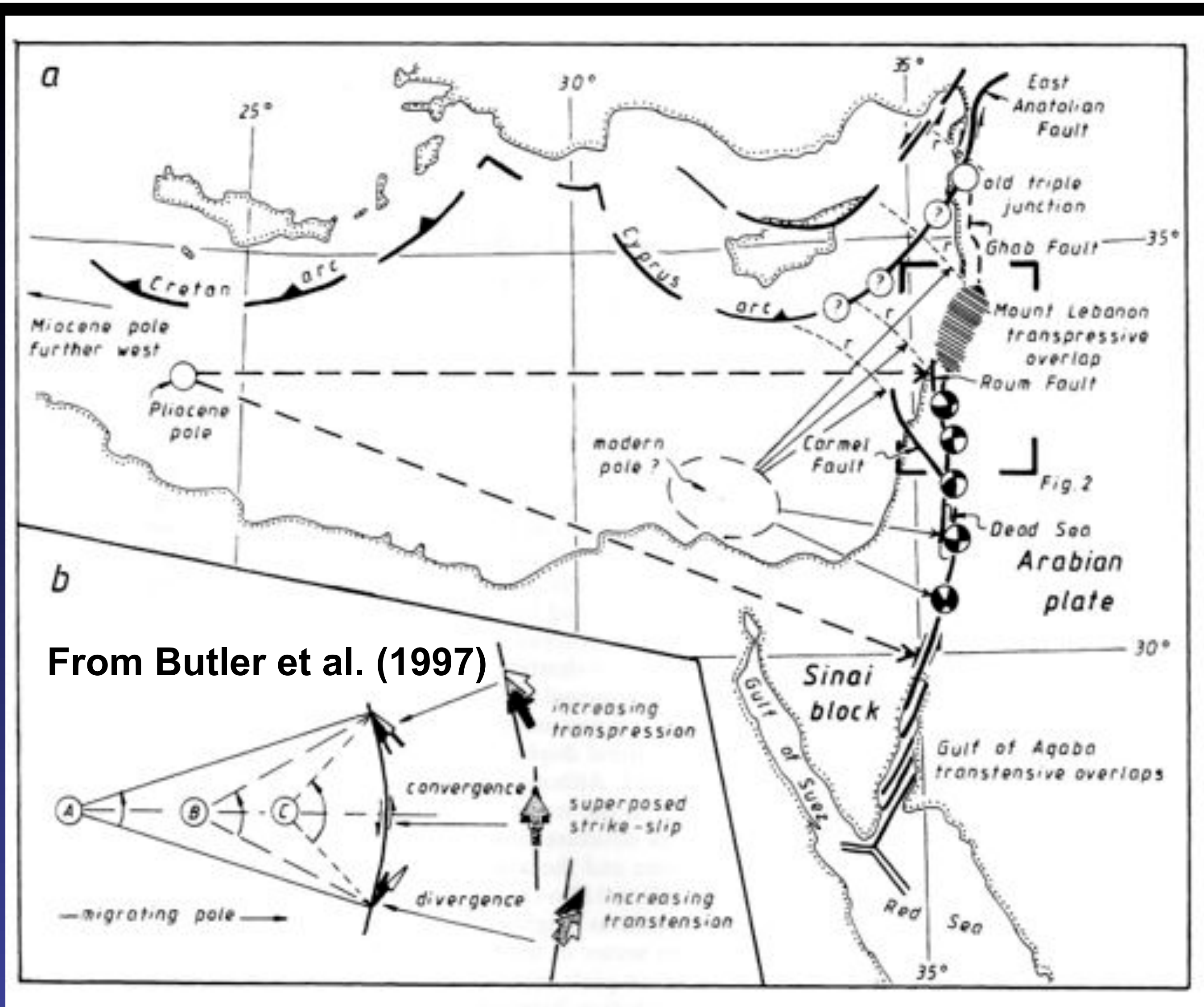
Pre-instrumental Period (1 AD - 1895 AD)



20th century is characterized by quiescence on Dead Sea fault that could be misleading …

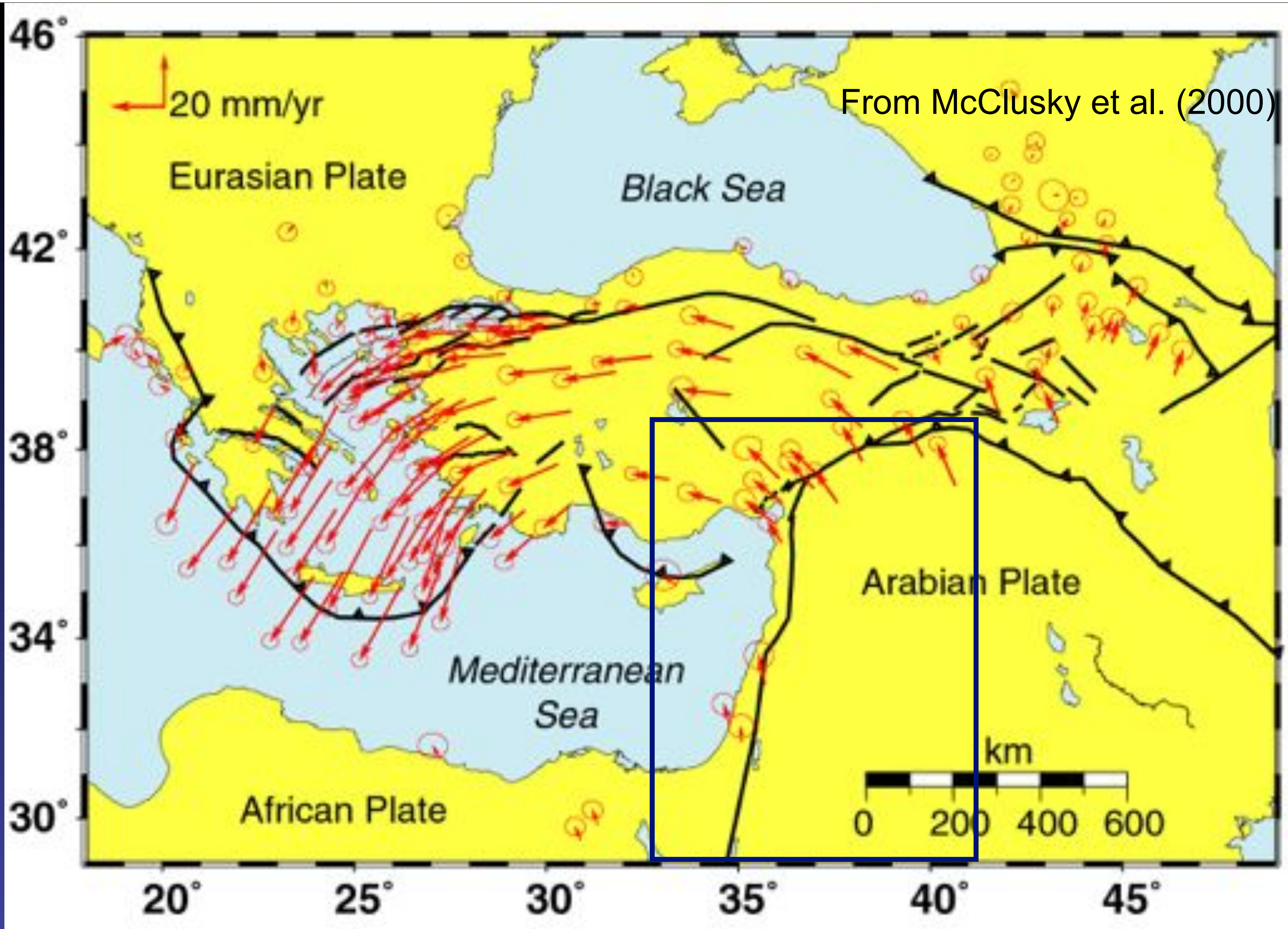
Instrumental seismicity from ISC (1963-1997)

Historical earthquakes from Ambraseys & Jackson (1998), Sbeinati et al. (2005), and Ambraseys et al. (1994)



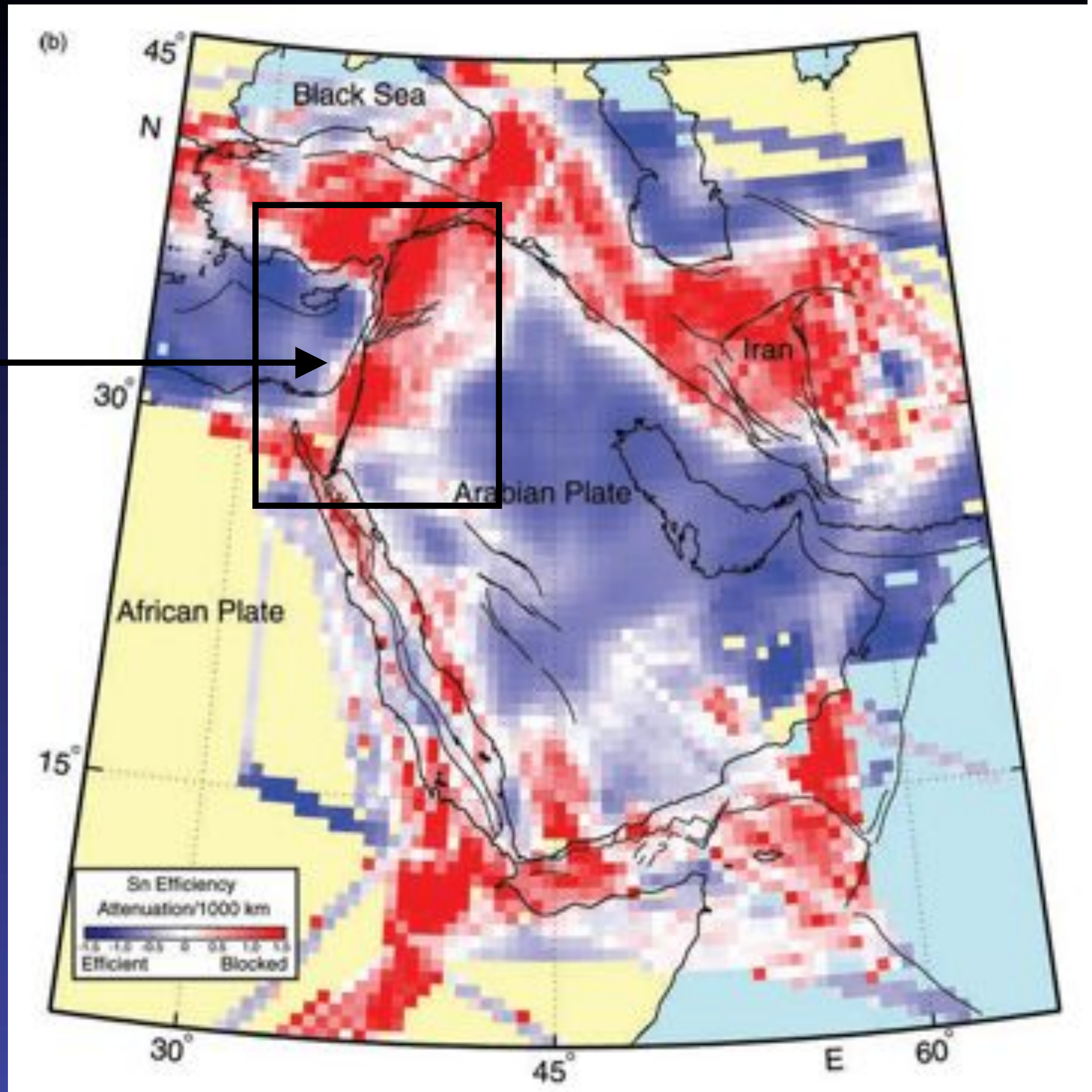
From Butler et al. (1997)

Paucity of seismicity led to some speculation of inactivity of northern Dead Sea fault …



Where we started (GPS velocities, ca. 2000)

Seismic wave propagation studies suggest a weakend lithosphere beneath the DSFS.



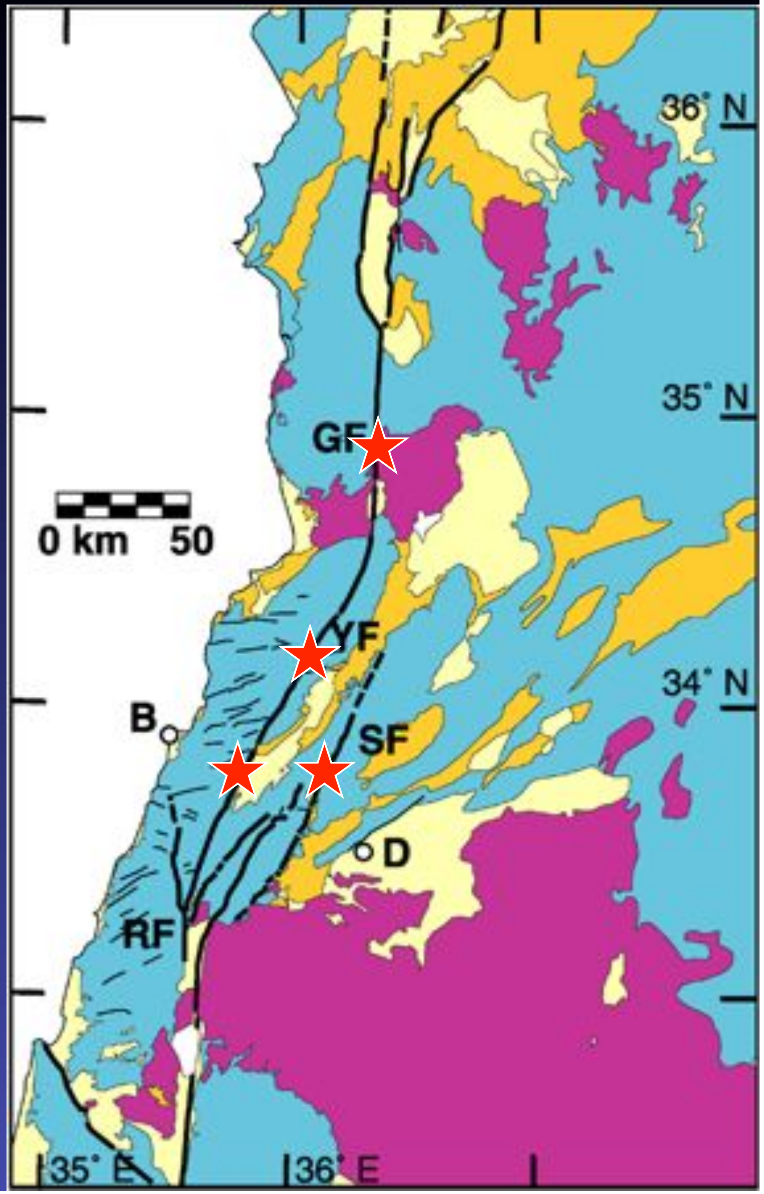
Al Lazki et al., 2004

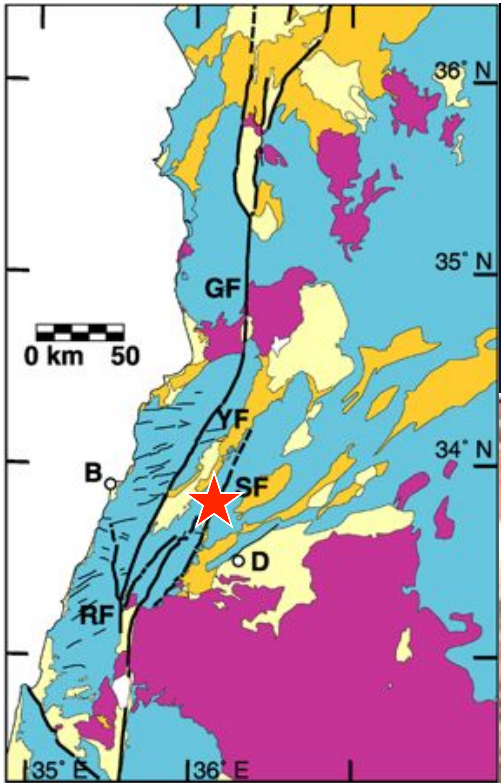
Earthquake Geology

Earthquake Geology

(Focus on the central / northern DSF)

- Examining the main strike-slip faults
  - Yammouneh, Serghaya, & Ghab faults
- The Goals:
  - Where are the active faults?
  - Late Pleistocene / Holocene Slip rates?
  - History of large earthquake recurrence?
    - Frequency?
    - Size?

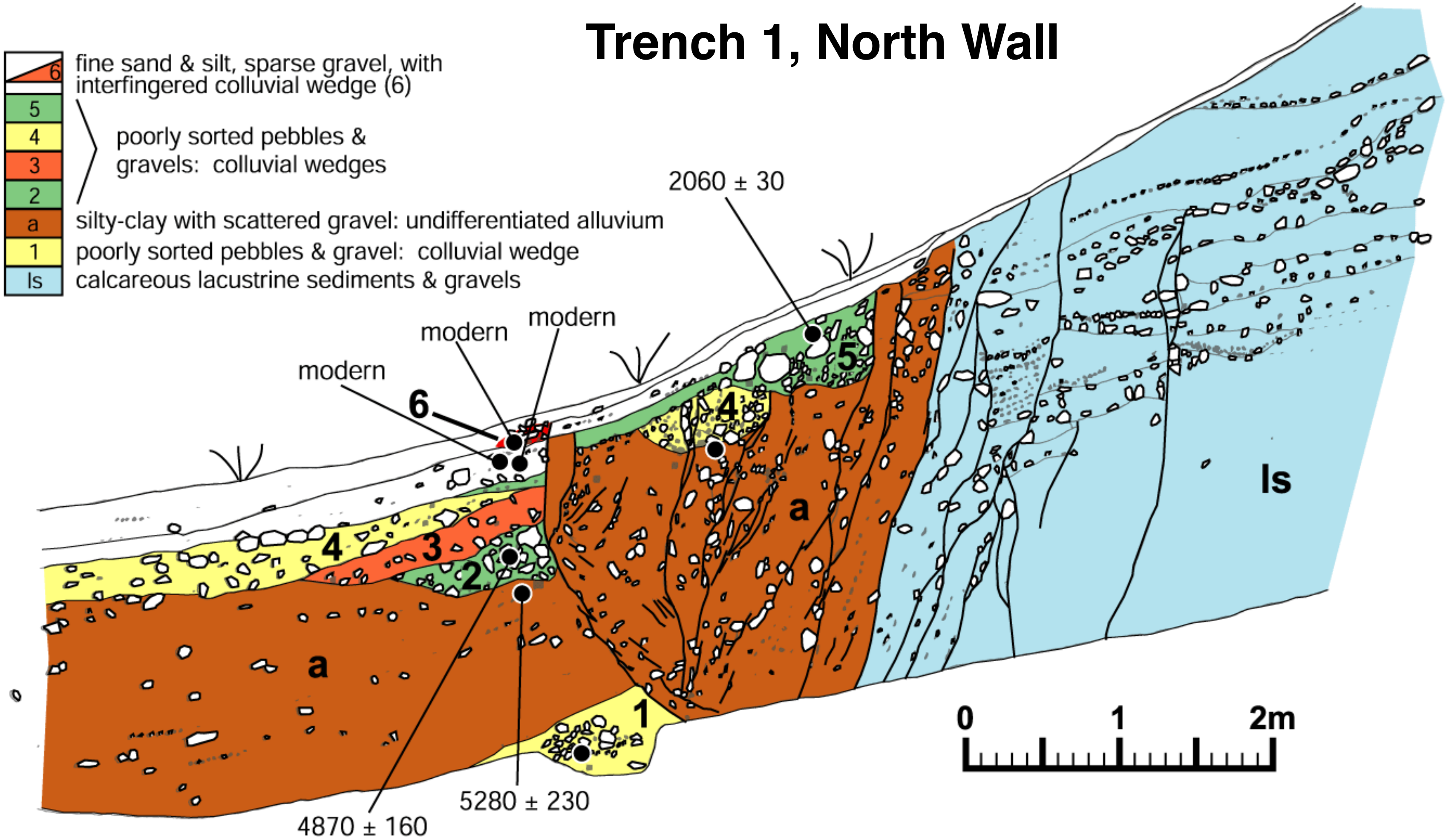




The Serghaya fault branch in western Syria

Previously regarded as inactive since the Pliocene.

Paleoseismic Trenching

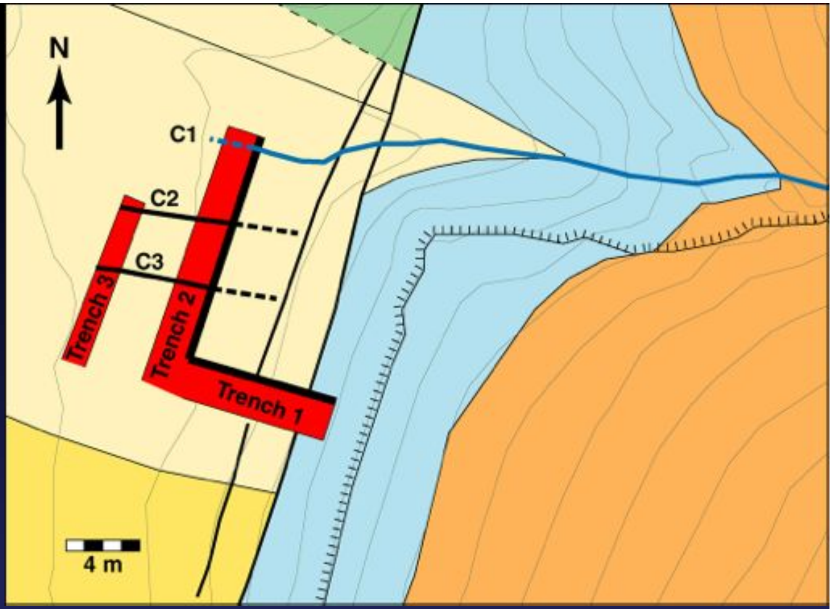


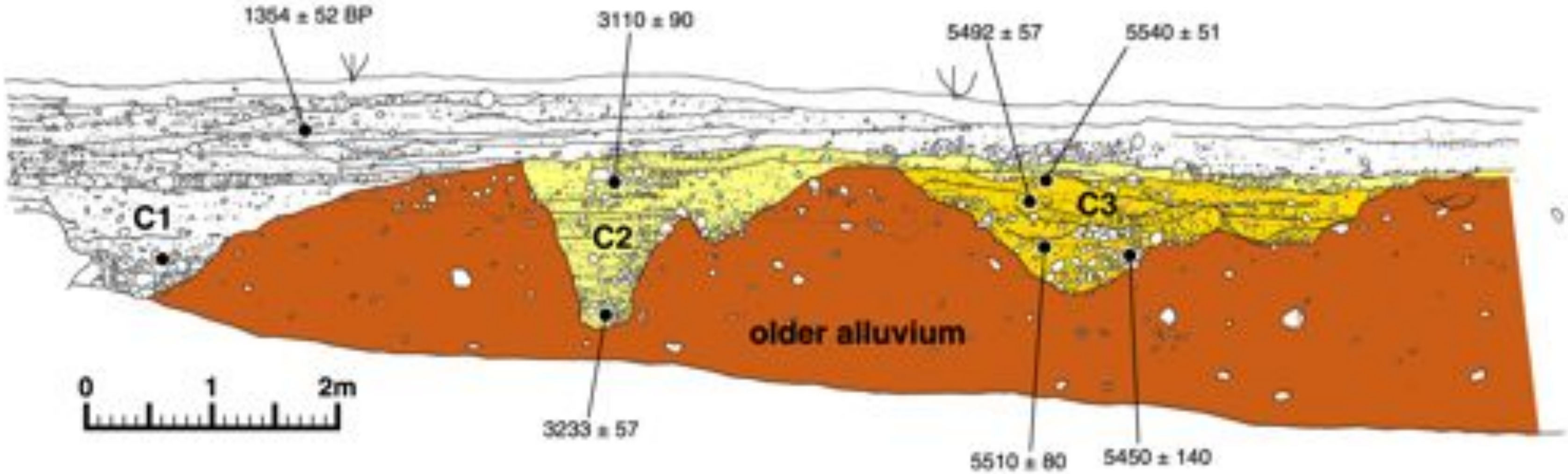
Owing to oblique fault slip, colluvial wedges and buried fault scarps preserve a record of paleo-earthquakes.

(Gomez et al., 2003, GJI)

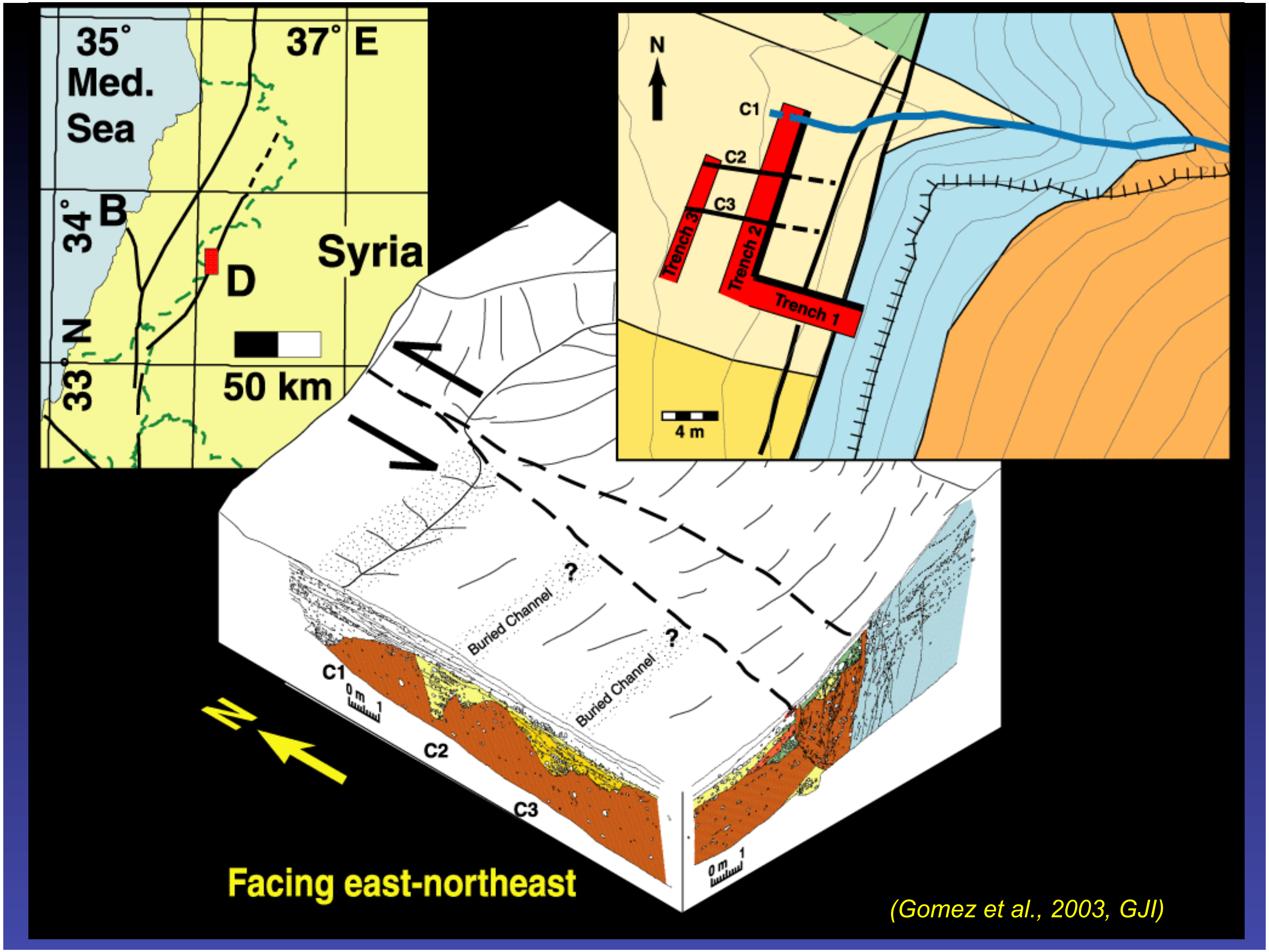
Trench 2, East Wall

Buried channels in trenches parallel to the fault act as piercing points to constrain Holocene offsets.



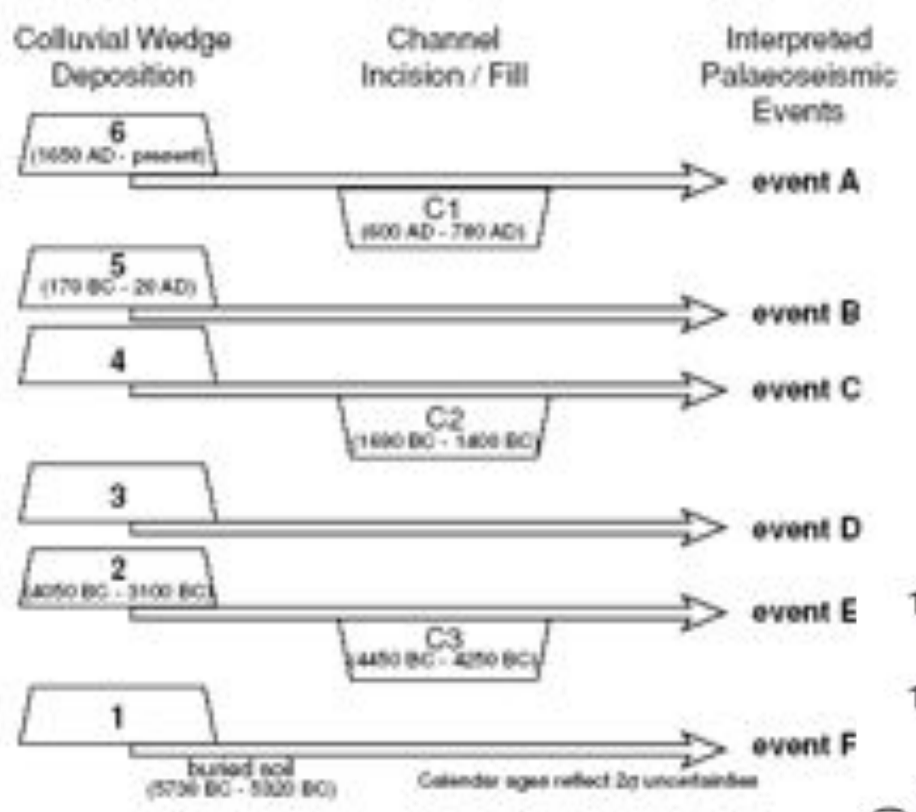


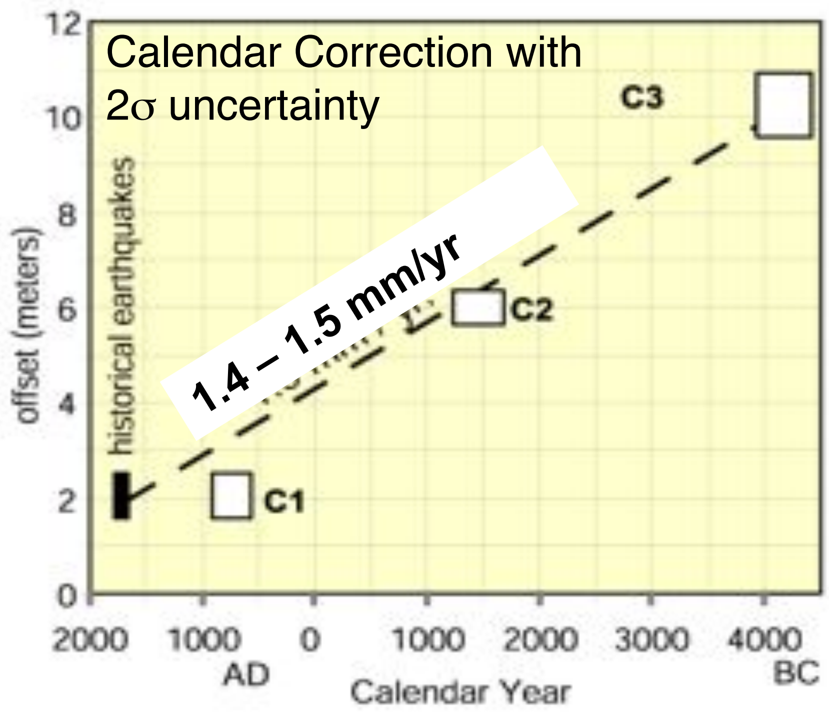
(Gomez et al., 2003, GJI)



(Gomez et al., 2003, GJI)

Slip Rate and Holocene Earthquakes on Serghaya Fault

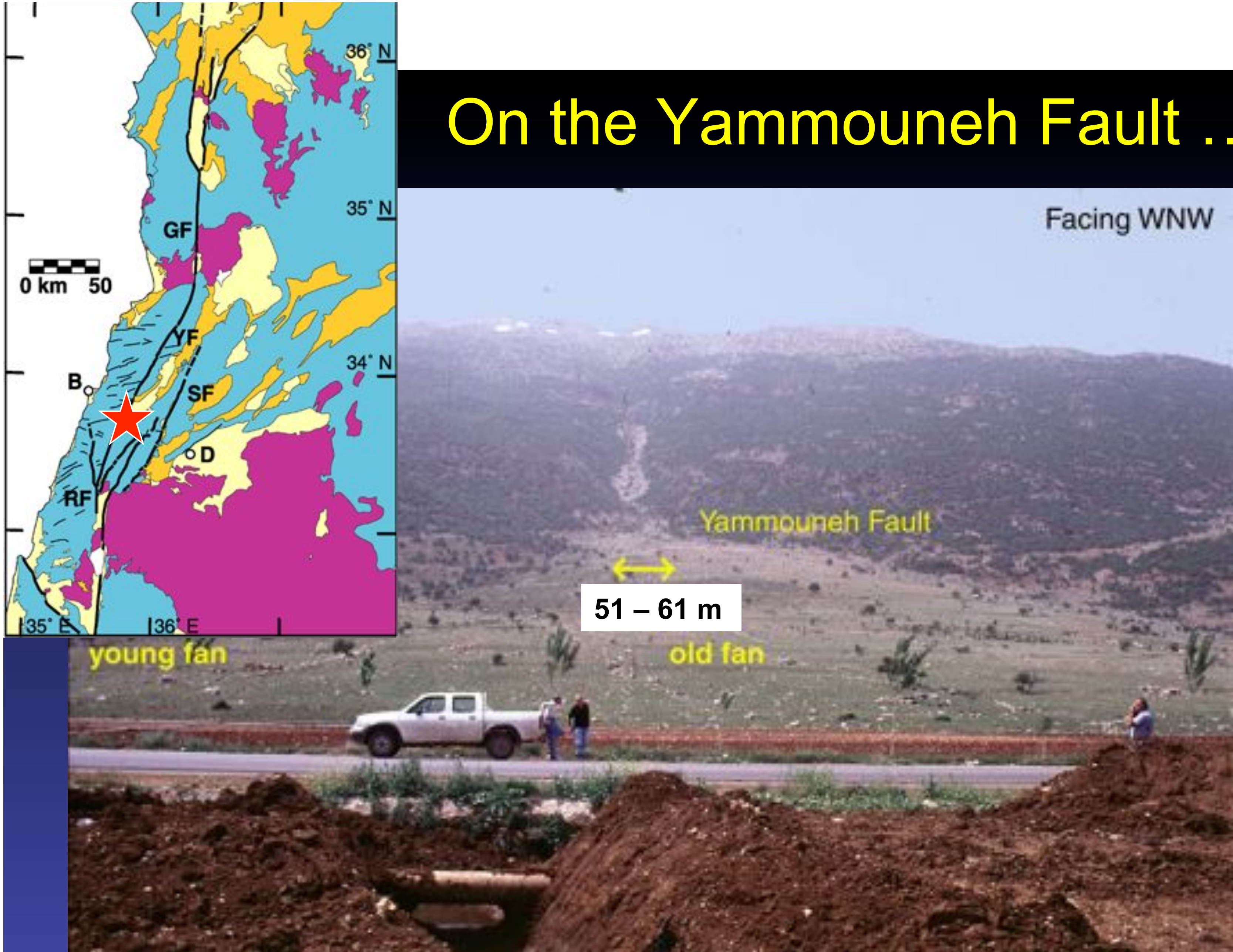




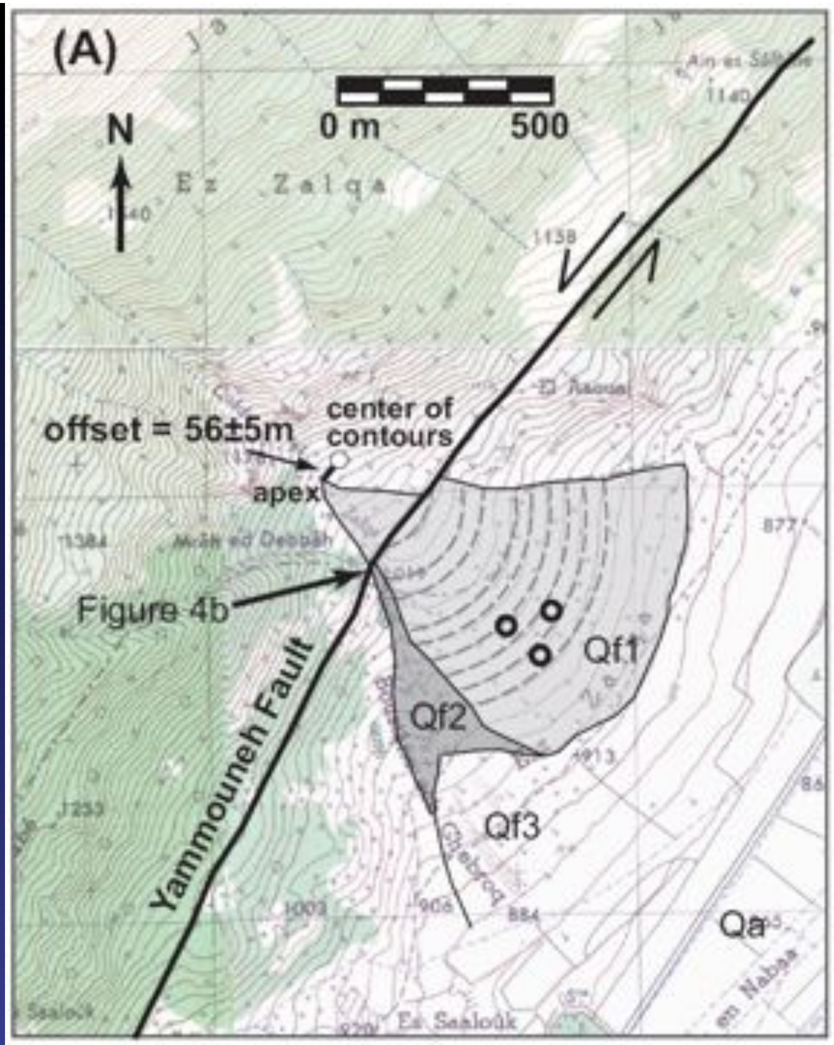
Not too bad for a fault originally believed to be inactive for the past 2 – 3 million years!

Gomez et al. (JGSL 2001; GJI 2003)

On the Yammouneh Fault …

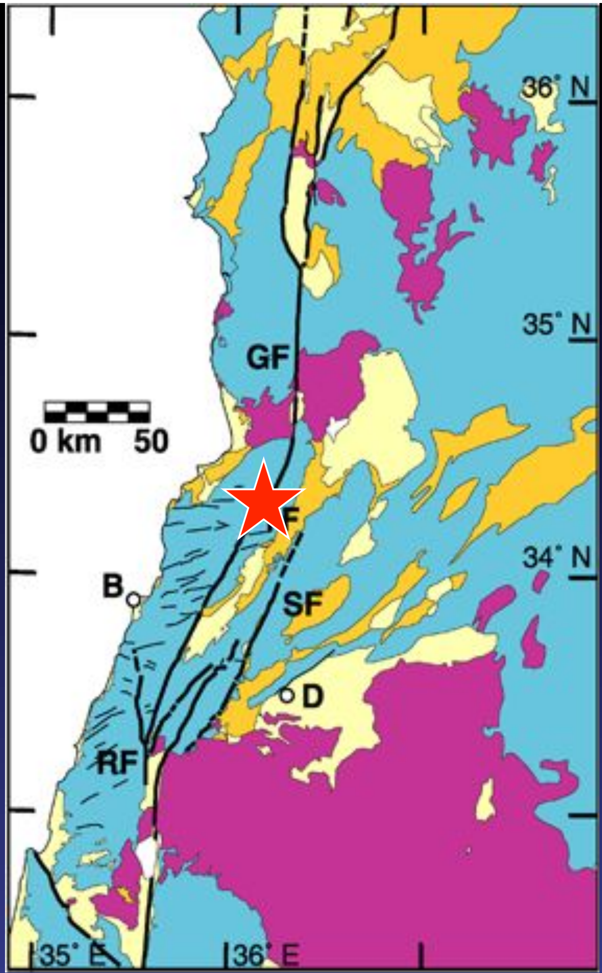


- Holocene slip rate for Yammouneh fault from a faulted alluvial fan

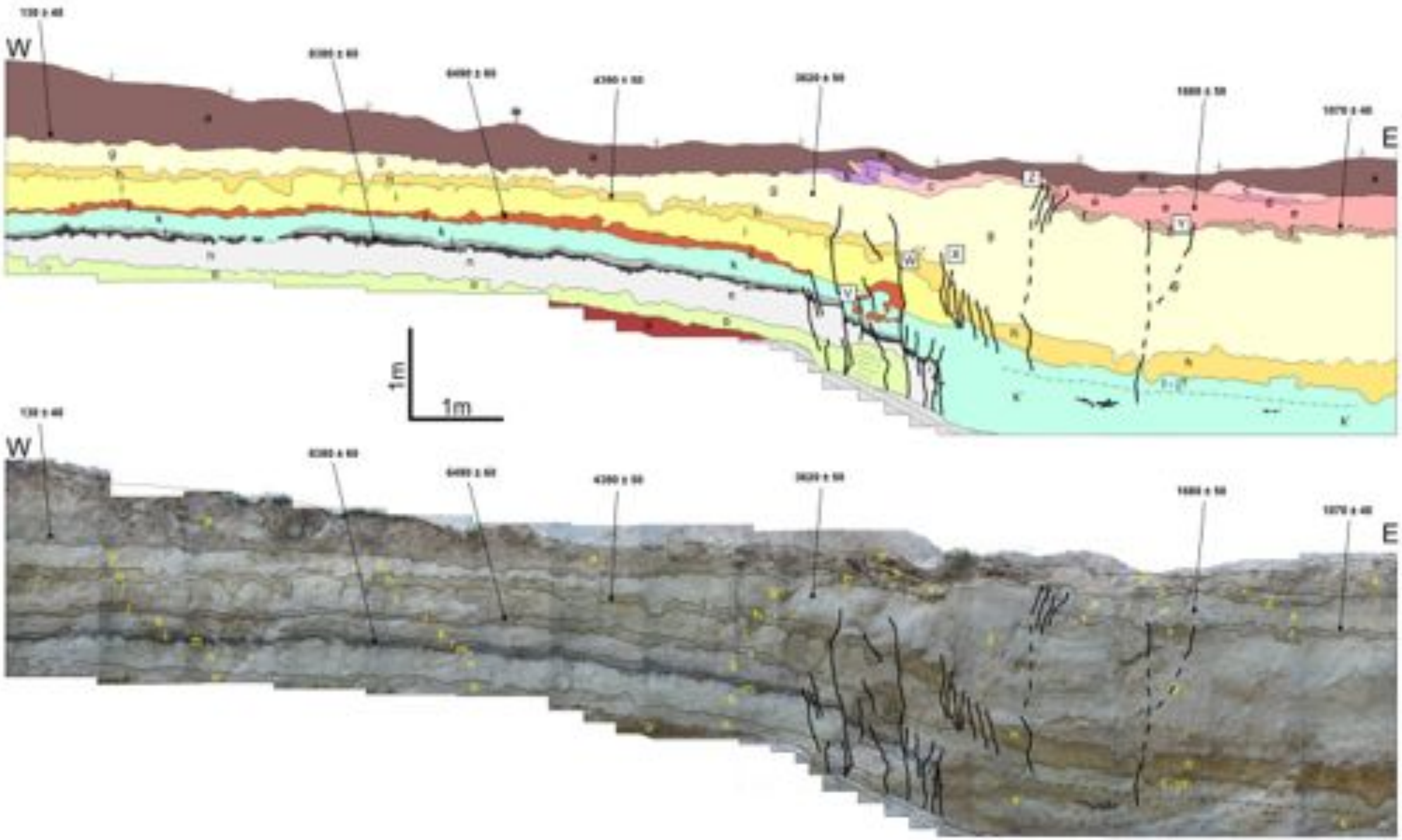


- Offset can be estimated using the fan morphology
  - 51 – 61 meters (ignore the number on the previous slide)
- Age of the abandoned fan surface is determined using cosmogenic Cl-36 ages
  - 9.8 – 11.7 Ka
- Suggested slip rate ~3.9 – 5.2 mm/yr.

(Gomez et al., 2007, GSL Spec. Pub.290)



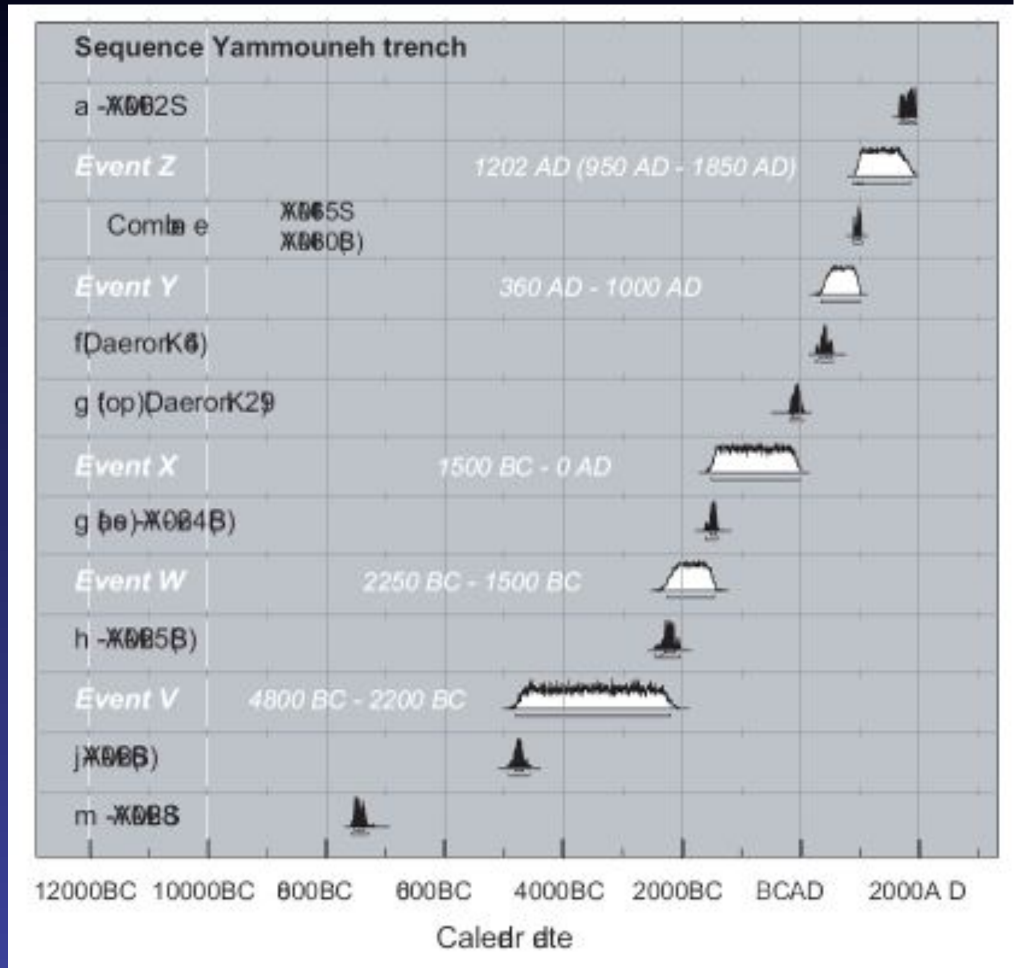
- Sometimes, the fault is more subtle, but still detectable at the surface …
- Paleoseismic trench study along the northern Yammouneh fault.



- 5 events in the past 5 – 6 thousand years
- (see also Daeron et al., 2005)

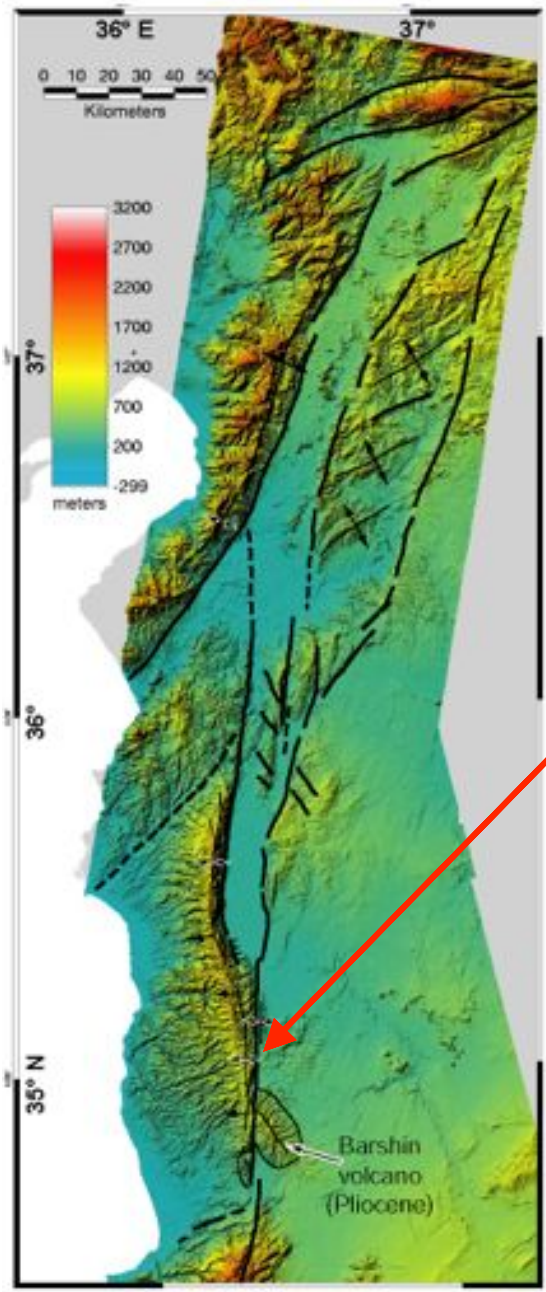
(Nemer et al., 2008)

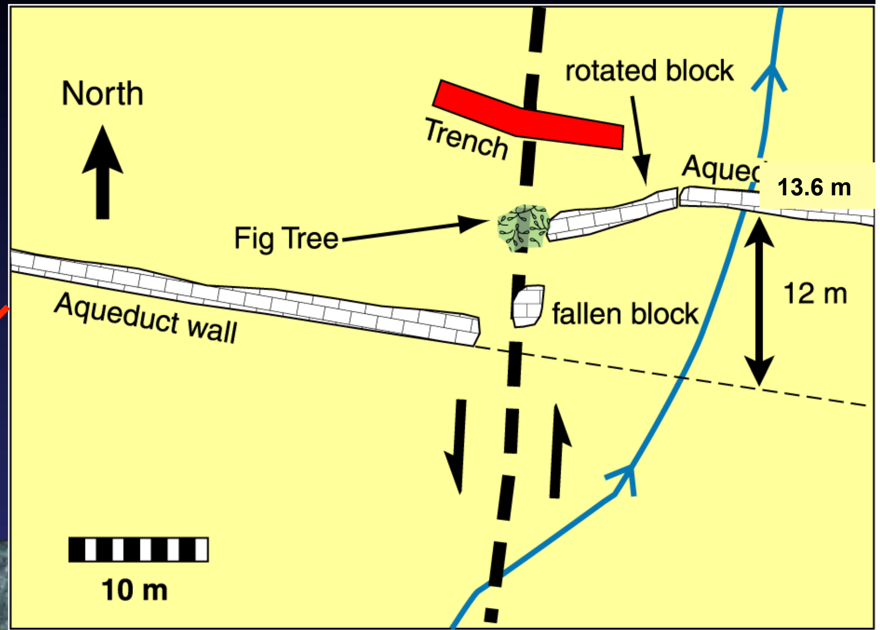
- Average recurrence period of ~1000 years
- Last event is the historically documented earthquake in 1202 AD

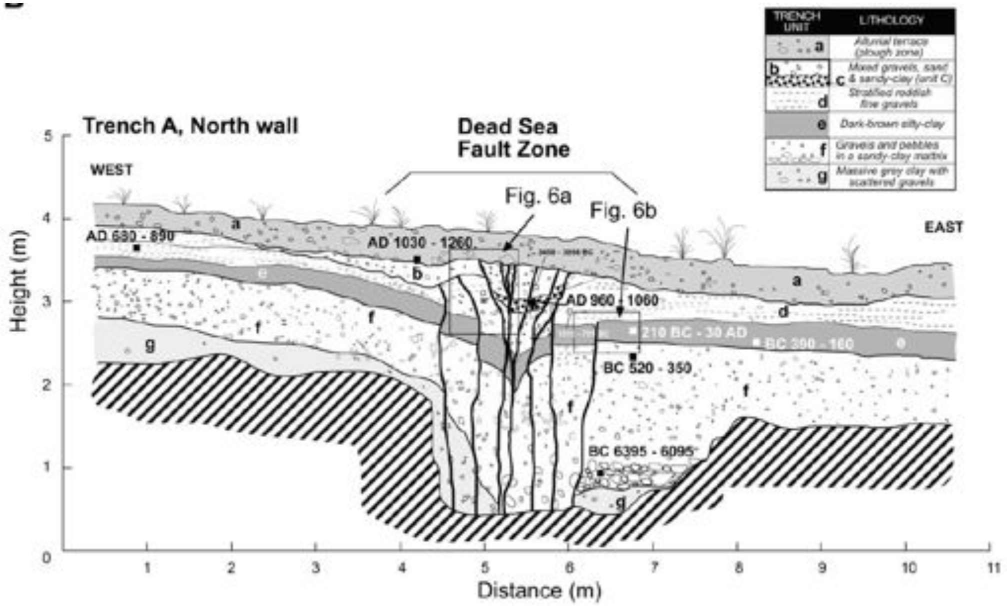


(Nemer et al., 2008)

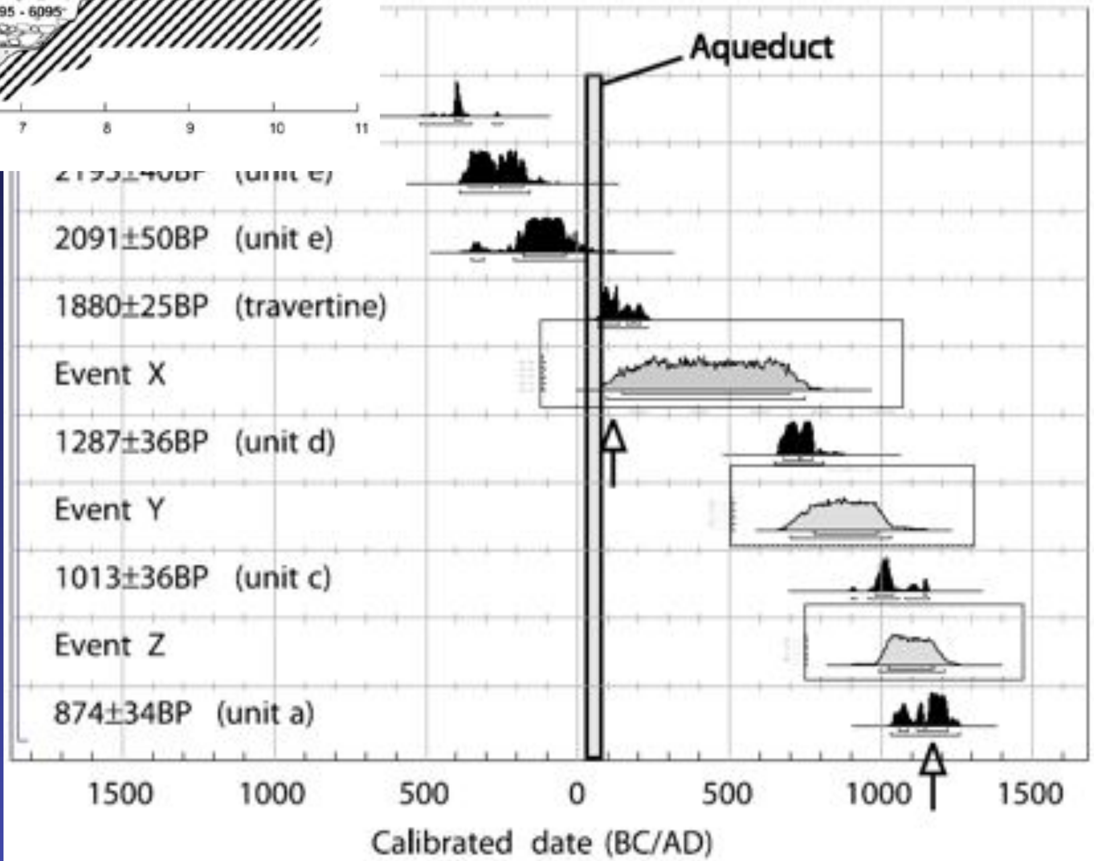
Northern Dead Sea Fault







Meghraoui et al. (EPSL, 2003)
Seinati et al. (GSA SP, 2010)

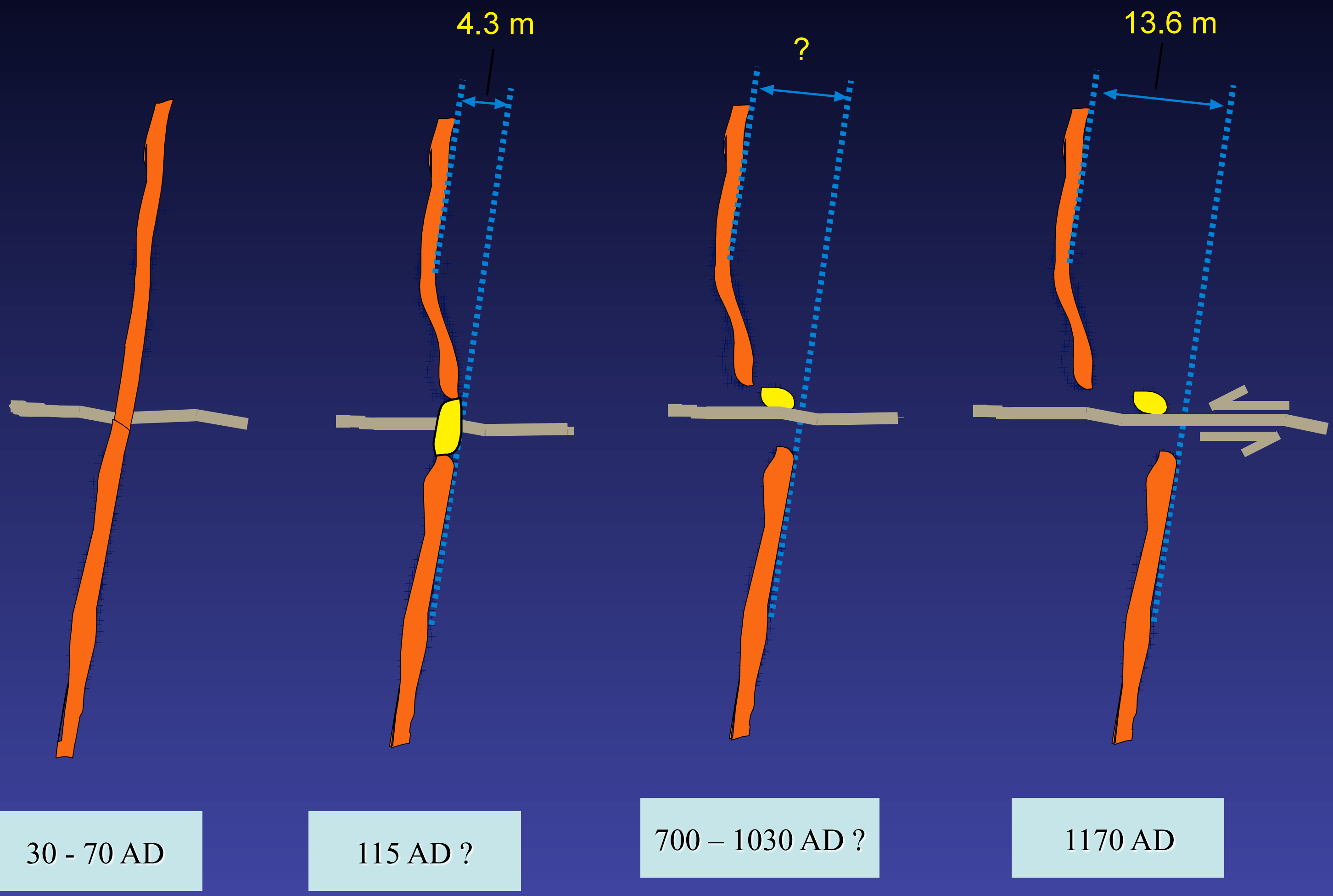


3 events during 1st millenium

No earthquake during prior 500 years

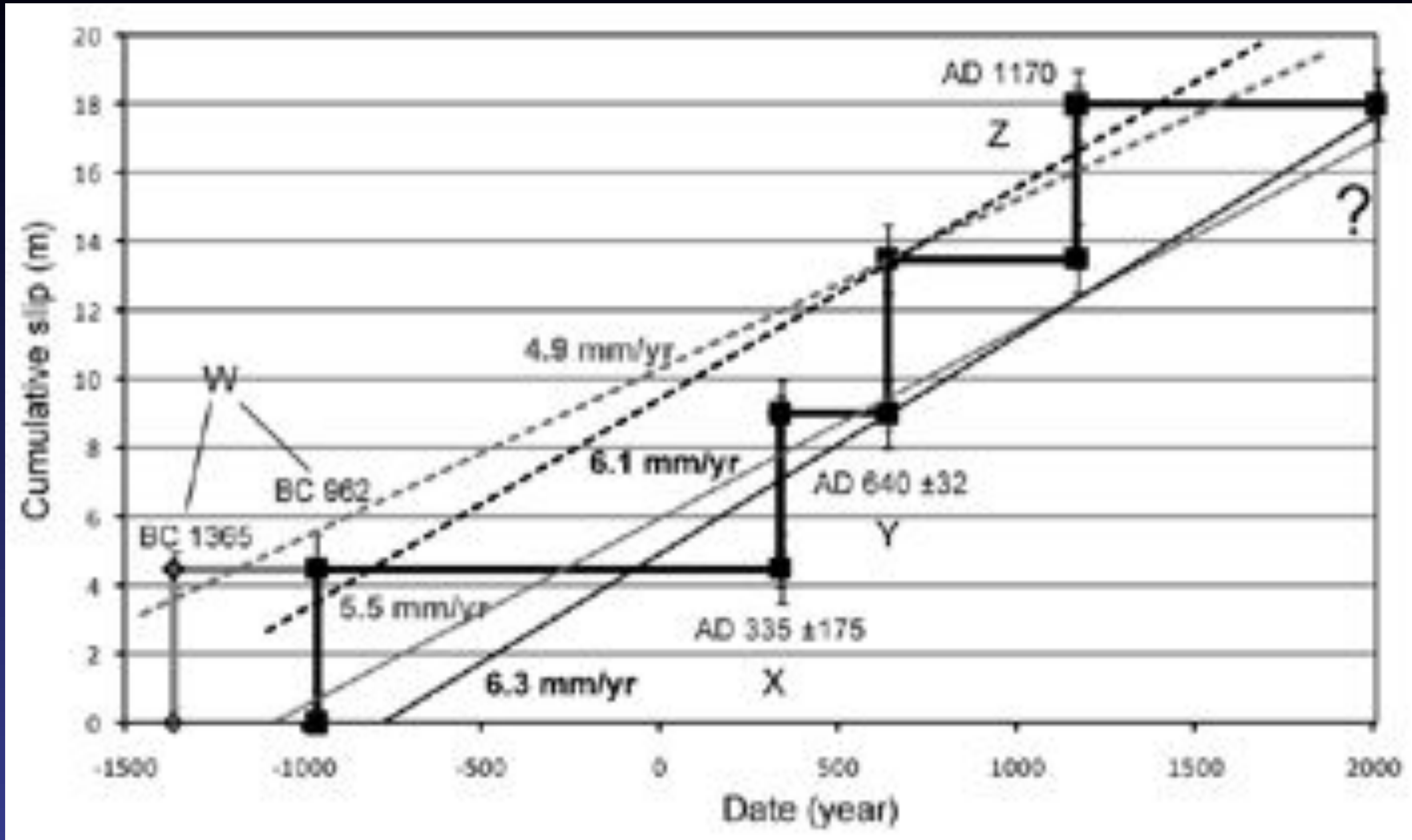
No earthquake since 1170 AD (historical record)

Al Harif aqueduct - Faulting episodes



Sbeinati et al. (2010)

Paleoseismic Slip Rate for Northern DSF?

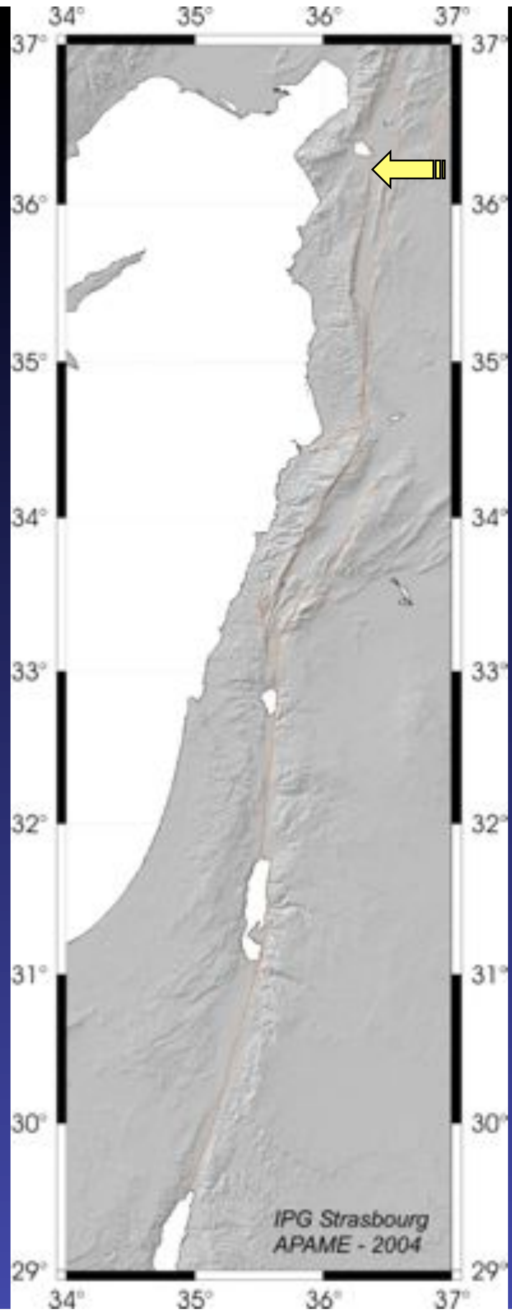


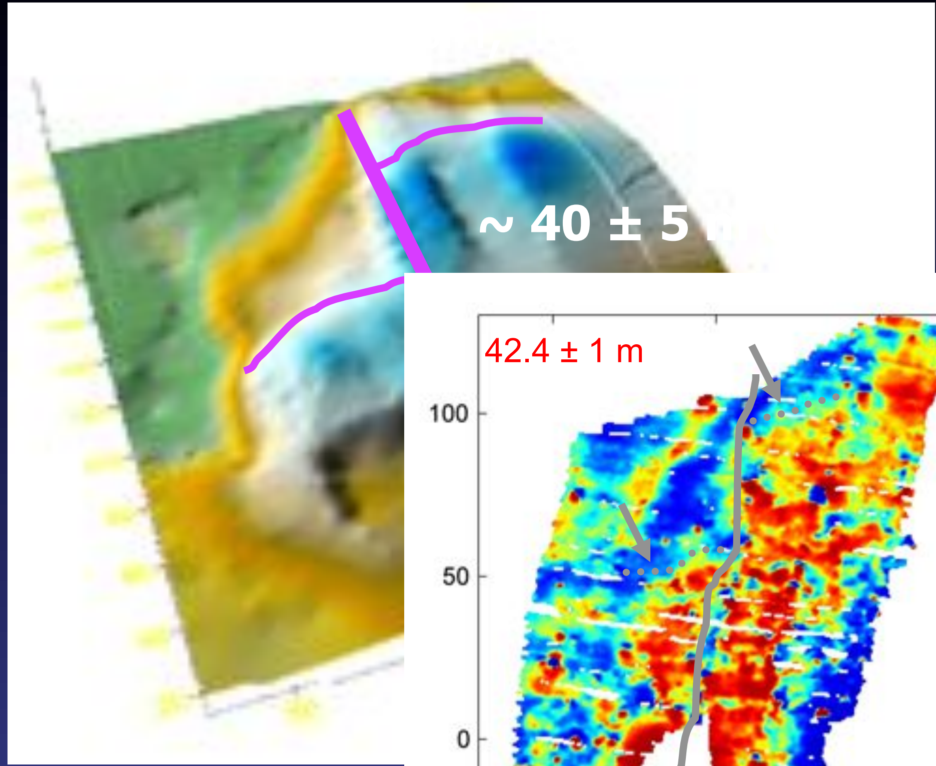
This seems a bit fast?

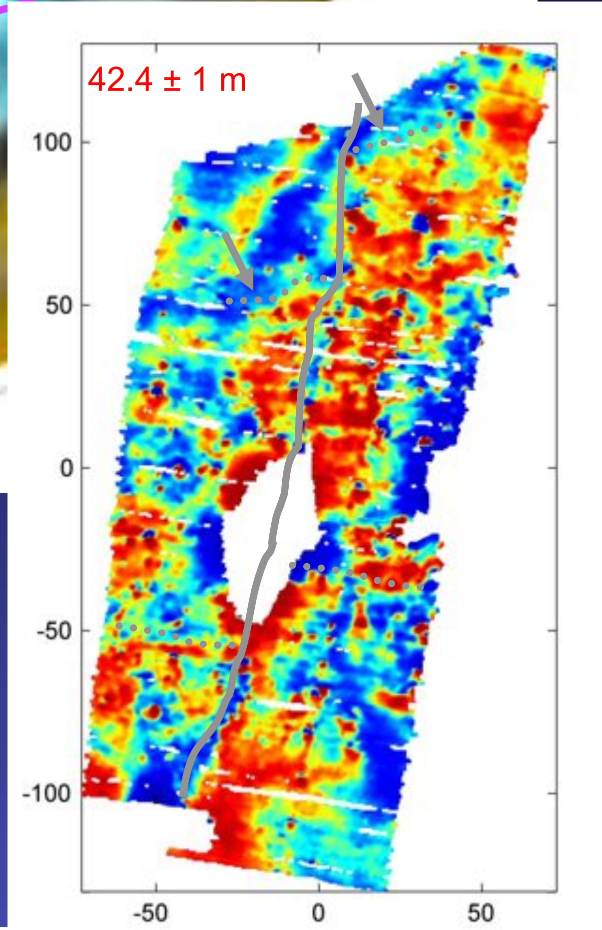
Note: Displacement for 1,000-1400 BC event is assumed.

(Sbeinati et al., 2010)

Faulted Tell site Sicantarla







Magnetic Survey
6 – 8 Ka
Sr ~ 5.3 – 7.1 mm/yr
(Altunel et al., 2006)

Earthquake Geology (partial summary)

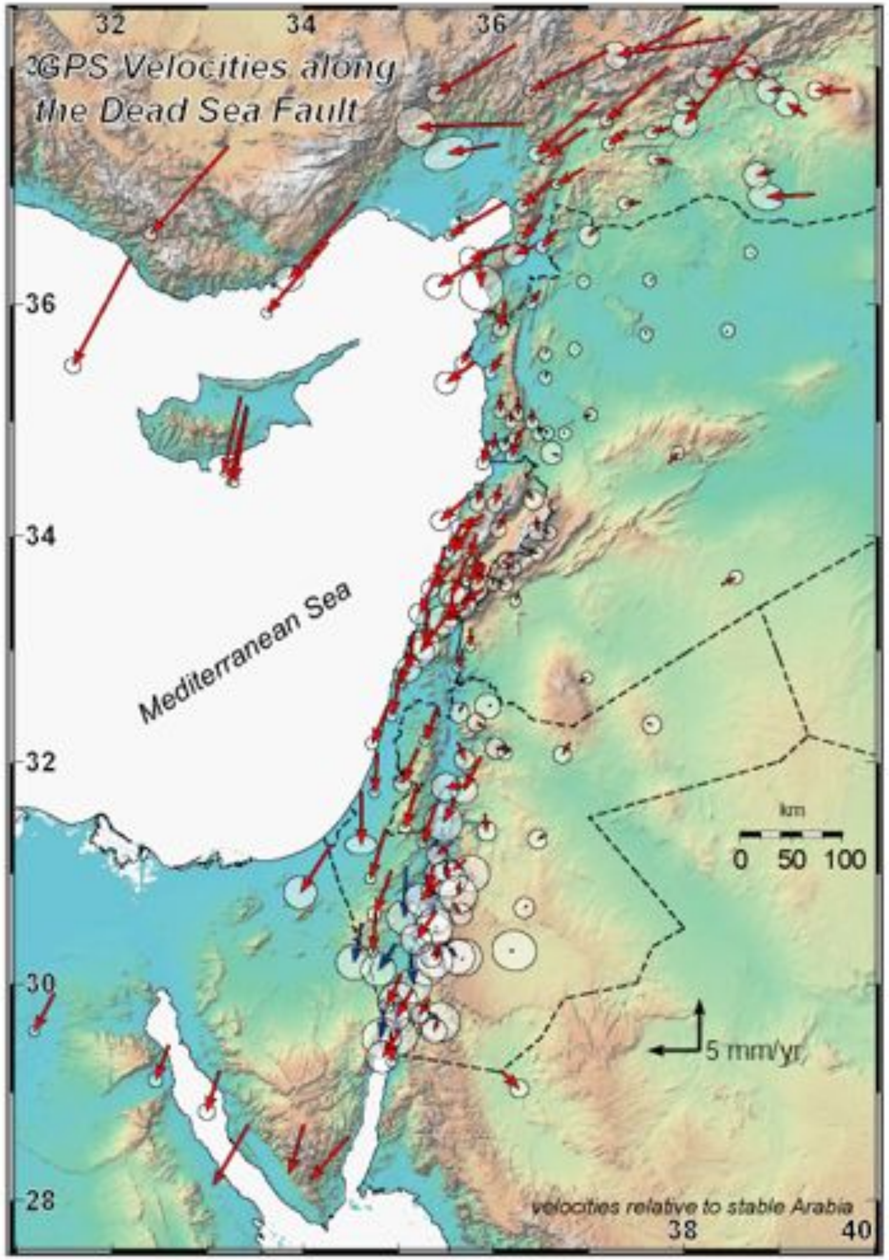
- Northern DSF (Meghraoui et al., 2003; Sbeinati et al., 2010)
    - Slip rate: 4.1 – 7.0 mm/yr
    - EQ behavior: temporal clustering
- Central DSF
  - Serghaya fault (Gomez et al., 2003)
    - Slip rate: 1.3 – 1.5 mm/yr
    - EQ behavior: quasi-periodic
  - Yammouneh fault (Nemer et al., 2008; Daeron et al. 2006)
    - Slip rate: 3.9 – 5.2 mm/yr
    - EQ behavior: quasi-periodic
- Southern DSF
  - Jordan Valley:
    - Slip rate: 4.9 – 6.0 mm/yr (Ferry et al., 2007, 2011)
  - Wadi Araba
    - Slip rate: 3.9 – 5.0 mm/yr (Klinger et al., 2000; Niemi et al., 2001; Lebeon et al., 2012)

Tectonic Geodesy

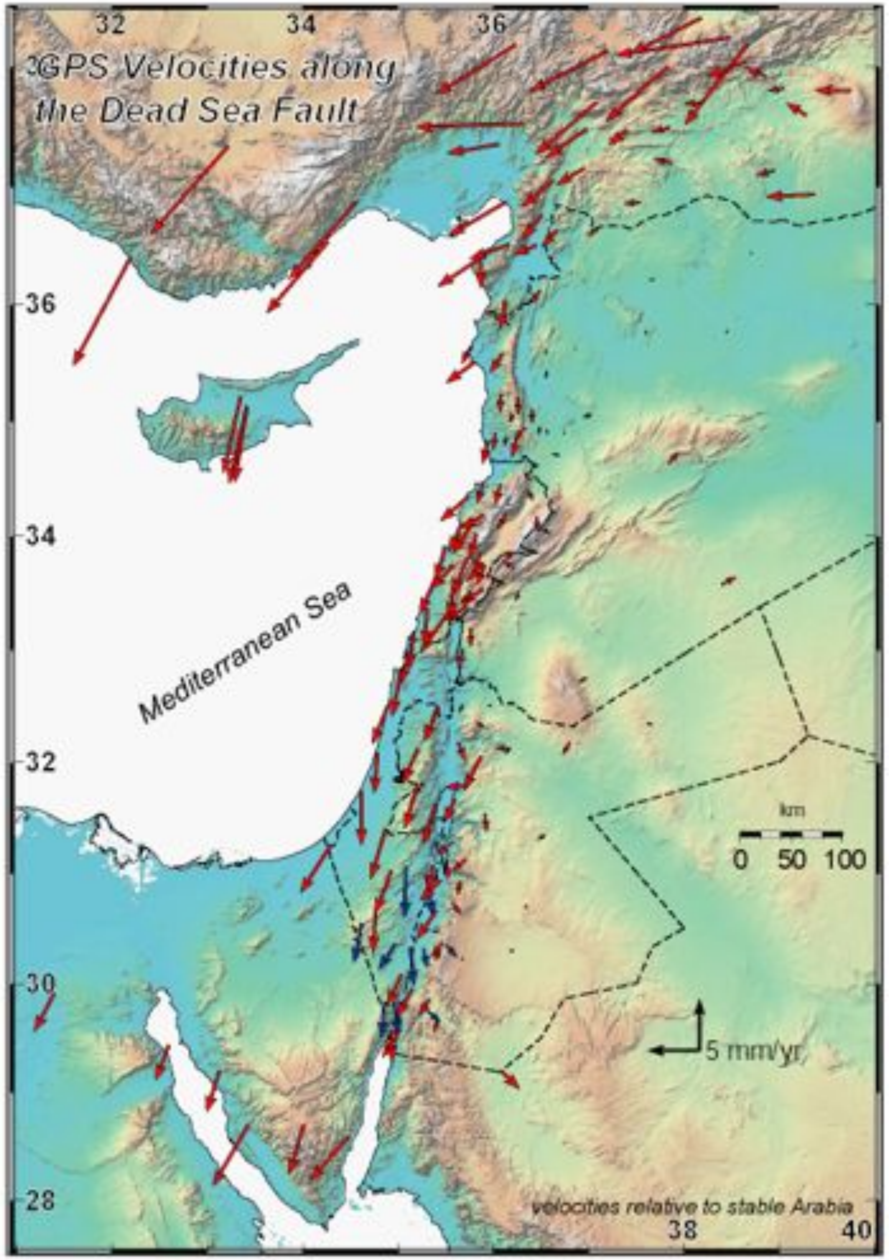
GPS Observations for the DSFS

- Syria (Alchalbi et al., 2009)
  - 3 survey campaigns: 2000, 2007, 2008
  - 1 CGPS (2001 – present); 3 2008 – present
- Lebanon (Jaafar, 2008)
  - 7 (+½) survey campaigns: 2002 – 2010
  - 1 CGPS (2002 – present)
- Jordan (Abu Rajab et al., in review)
  - 5 survey campaigns: 2005 – 2010
  - 4 CGPS (2005 – present)
- Plus, regional CGPS data
- Plus, other data from MIT & collaborators (especially Turkey, Egypt)

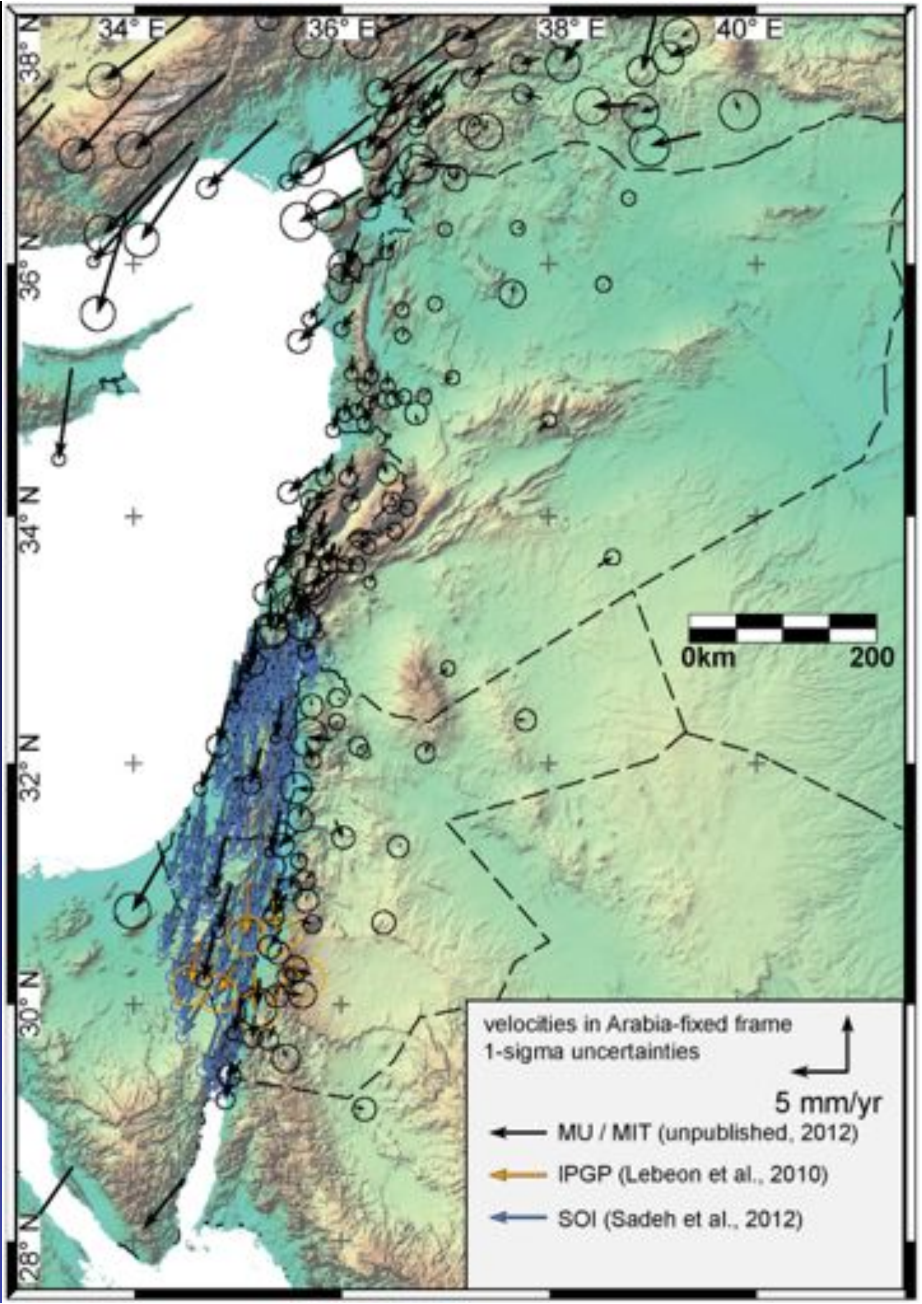
- Uncertainties
  - 8+ years (Syria, Lebanon): 1σ < 0.5 mm/yr
  - 6 years (Jordan, some Lebanon): 1σ < 0.6 mm/yr
  - 5 years (Jordan, some Lebanon): 1σ ~ 0.8 mm/yr
- Along-strike change in velocities?!

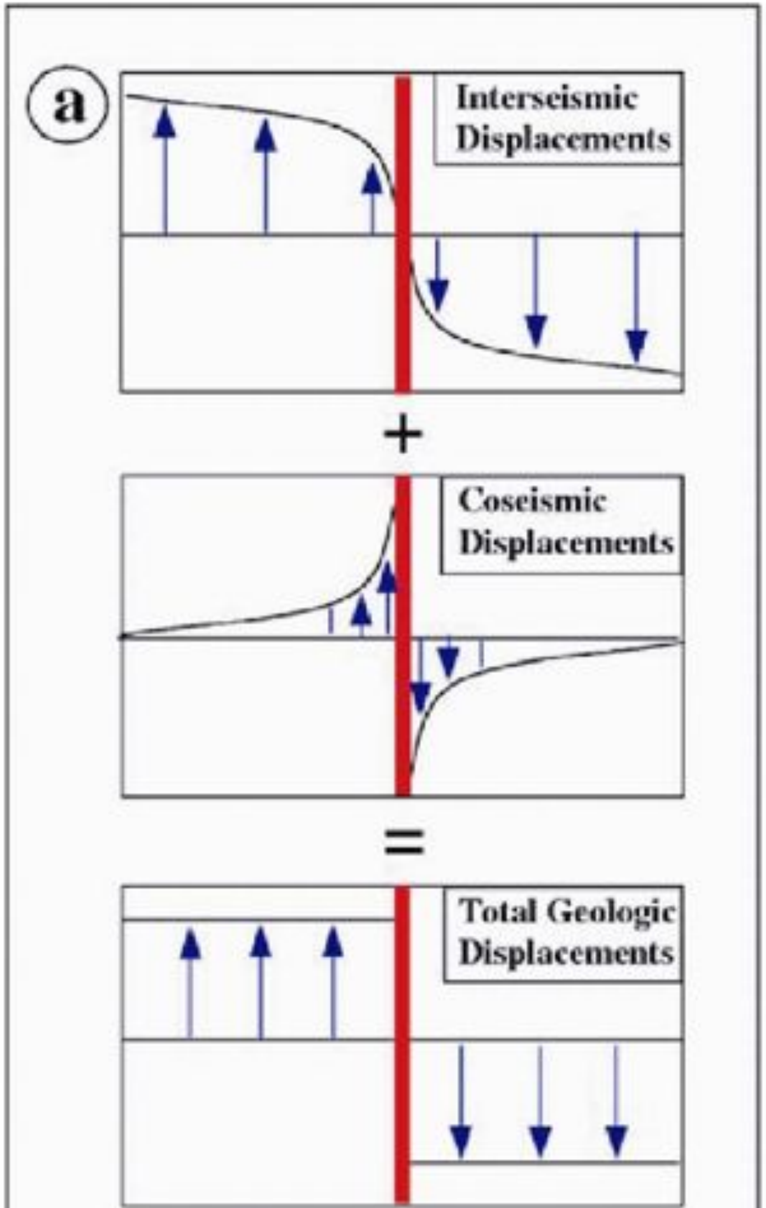


- Uncertainties
  - 8+ years (Syria, Lebanon): 1σ < 0.5 mm/yr
  - 5 years (Jordan, some Lebanon): 1σ < 0.8 mm/yr
  - 3 years (Jordan, some Lebanon): 1σ ~ 1 mm/yr
- Along-strike change in velocities?!



Comprehensive GPS velocity map of the Dead Sea fault system





From Meade et al. (2002)

The Earthquake Cycle

(a simplified view)

- Recall Elastit Rebound …
- Fault is locked during "interseismic" period
  - strain accumulates near fault
  - Locations at distance move
- During earthquake
  - strain is released
  - areas near the fault catch up with those away from fault

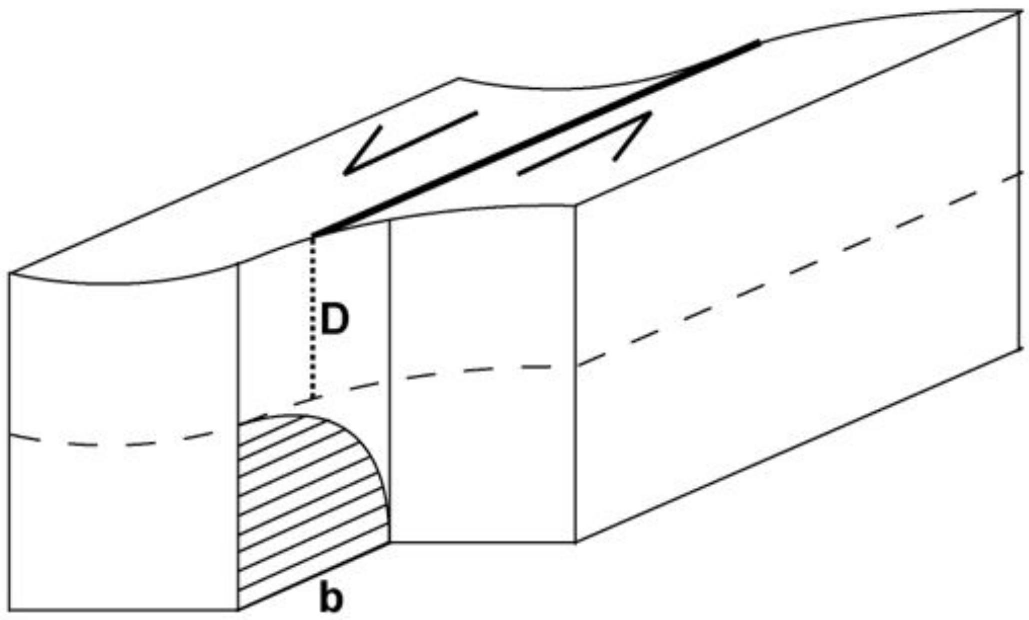
1-D Elastic Dislocation Model for Strain Accumulation

- x = distance from fault
- v = velocity at distance x
- b = long-term (deep) slip rate
- D = locking depth

$$v(x) = \frac{b}{\pi}\arctan\left(\frac{x}{D}\right)$$

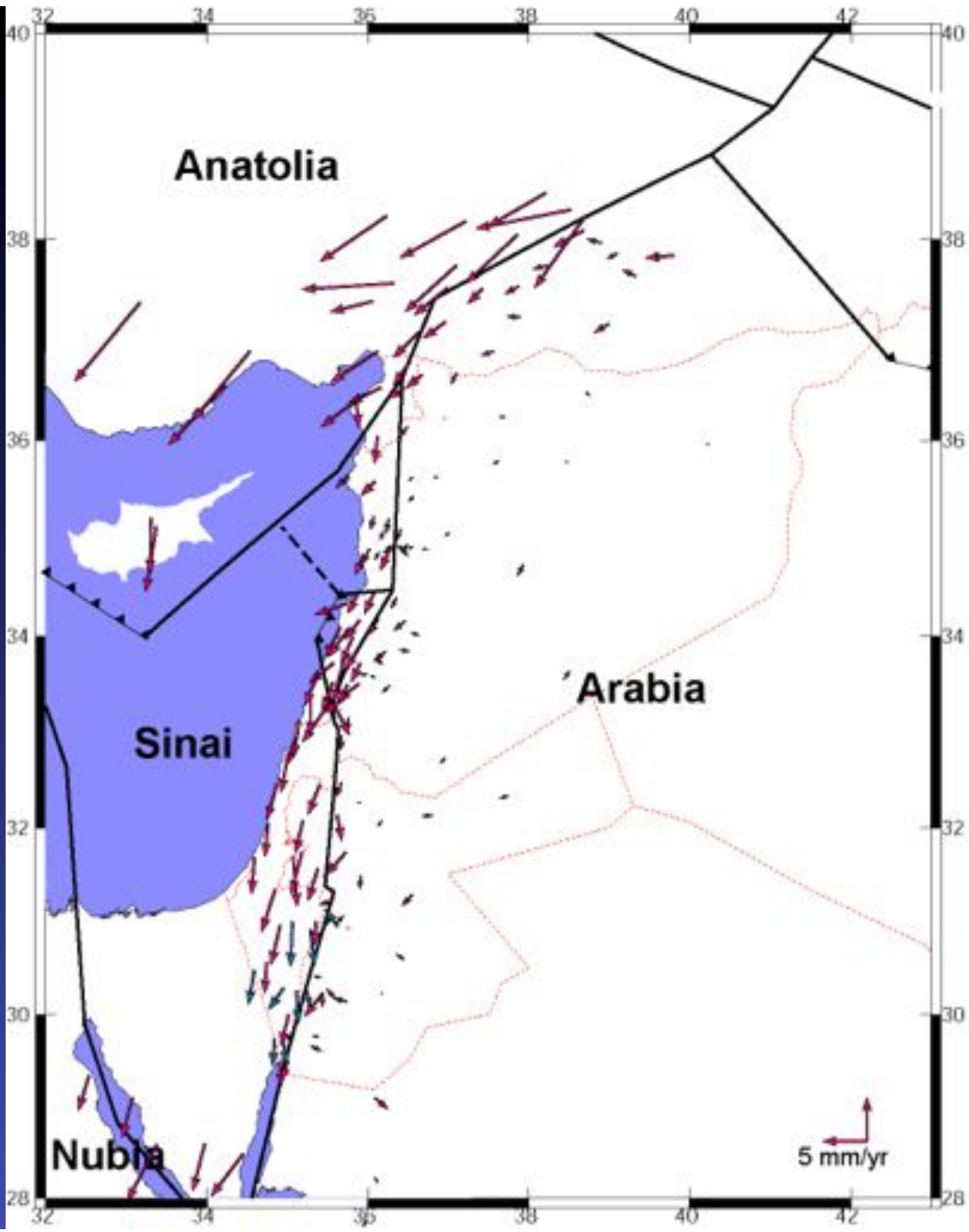
After Savage & Burford (1974)

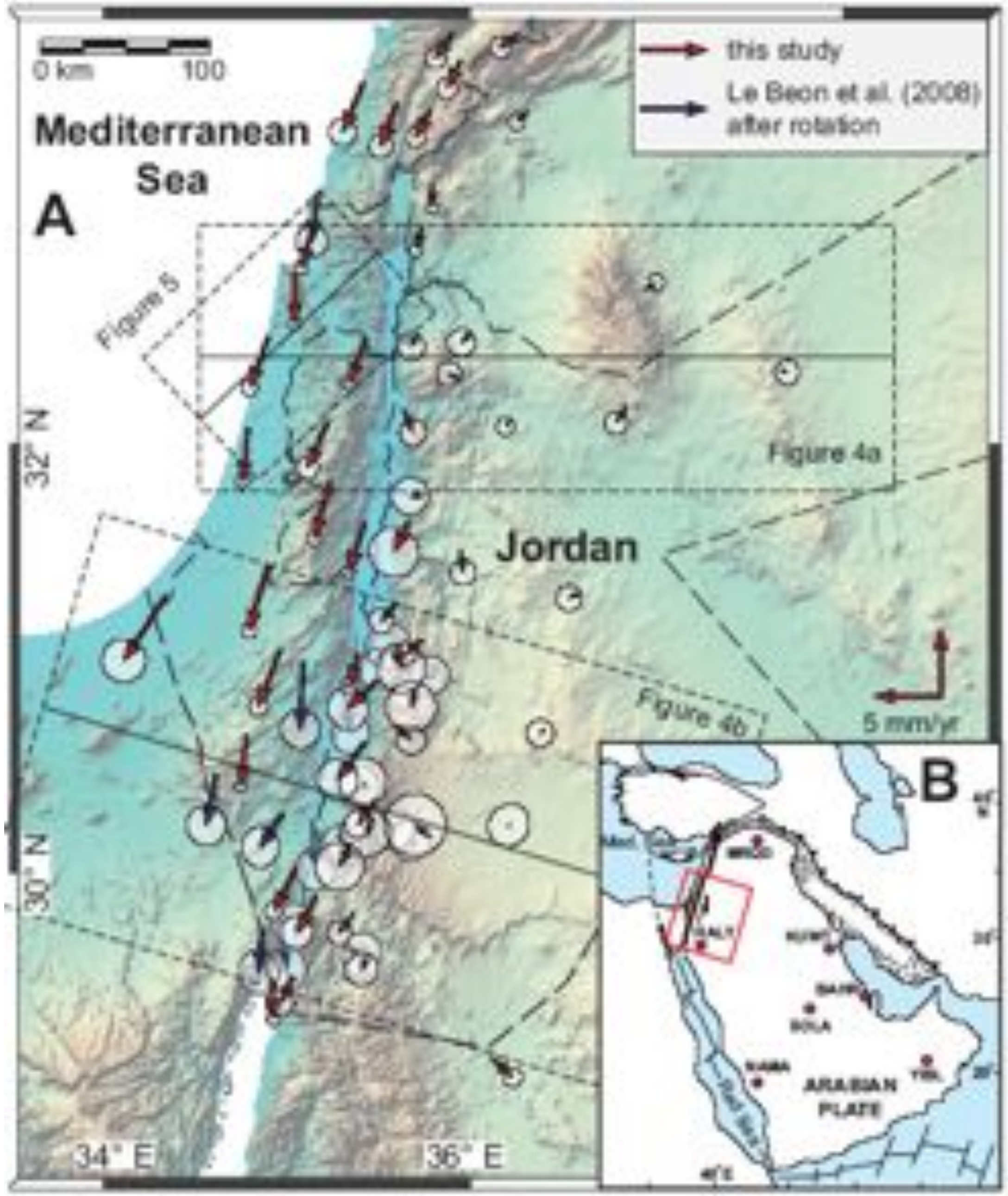
- 2-D solutions are also possible (e.g., Okada, 1986)



Block Model

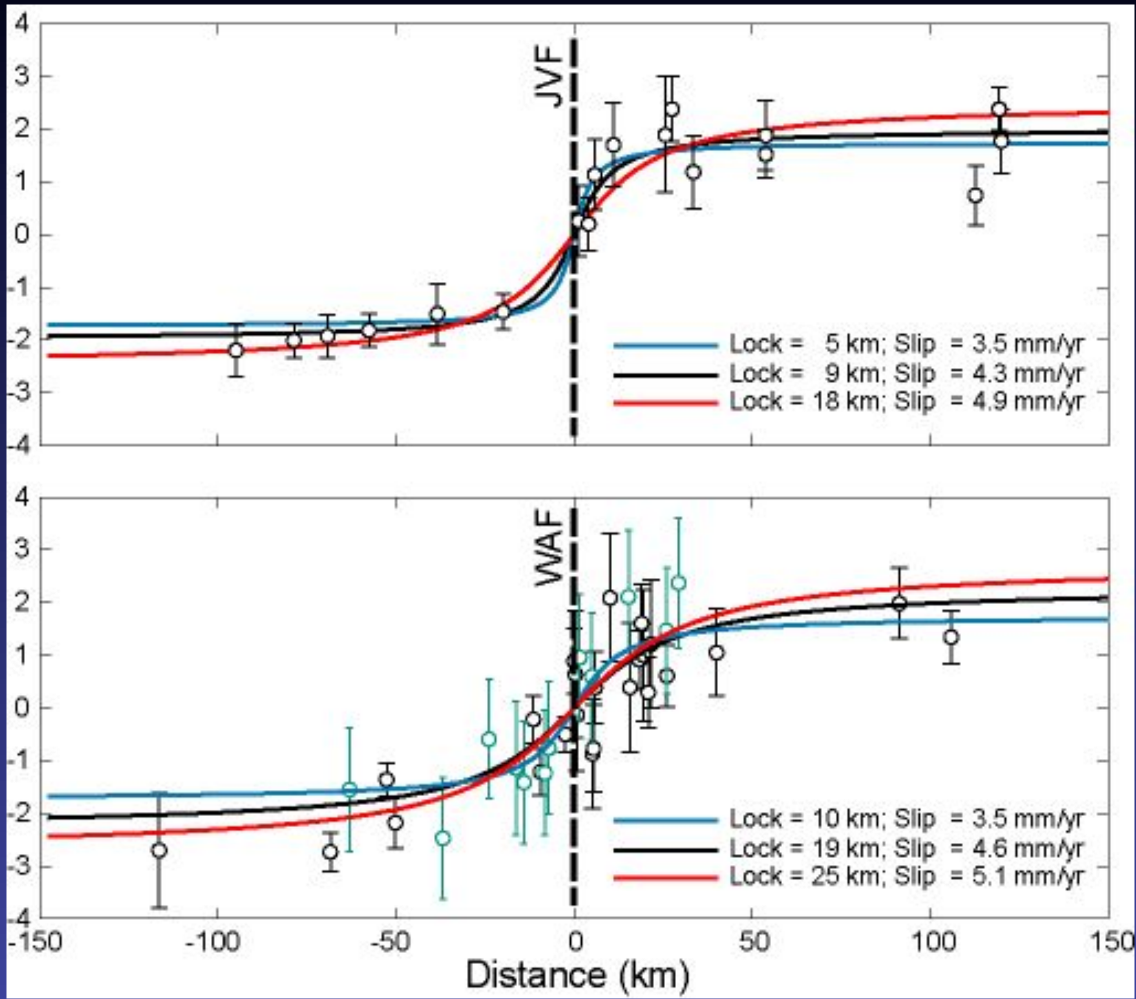
- Divide E. Mediterranean region into elastic blocks bounded by locked faults
- Accounts for deformations from fault bends and terminations (following Meade & Loveless, 2009)
- Two variations:
  - NE Sinai coherent
  - NE Sinai broken

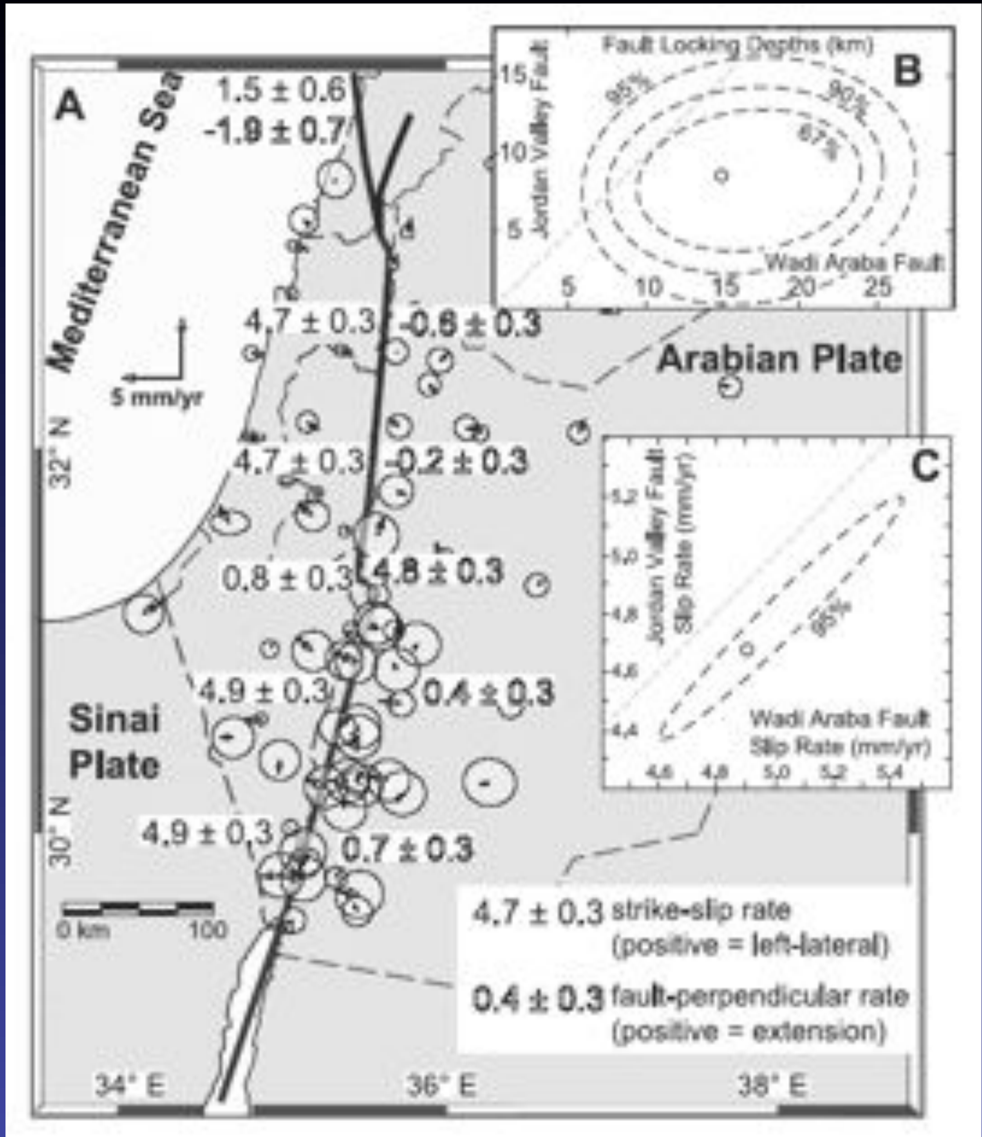




(Al-Tarazi et al., 2011)

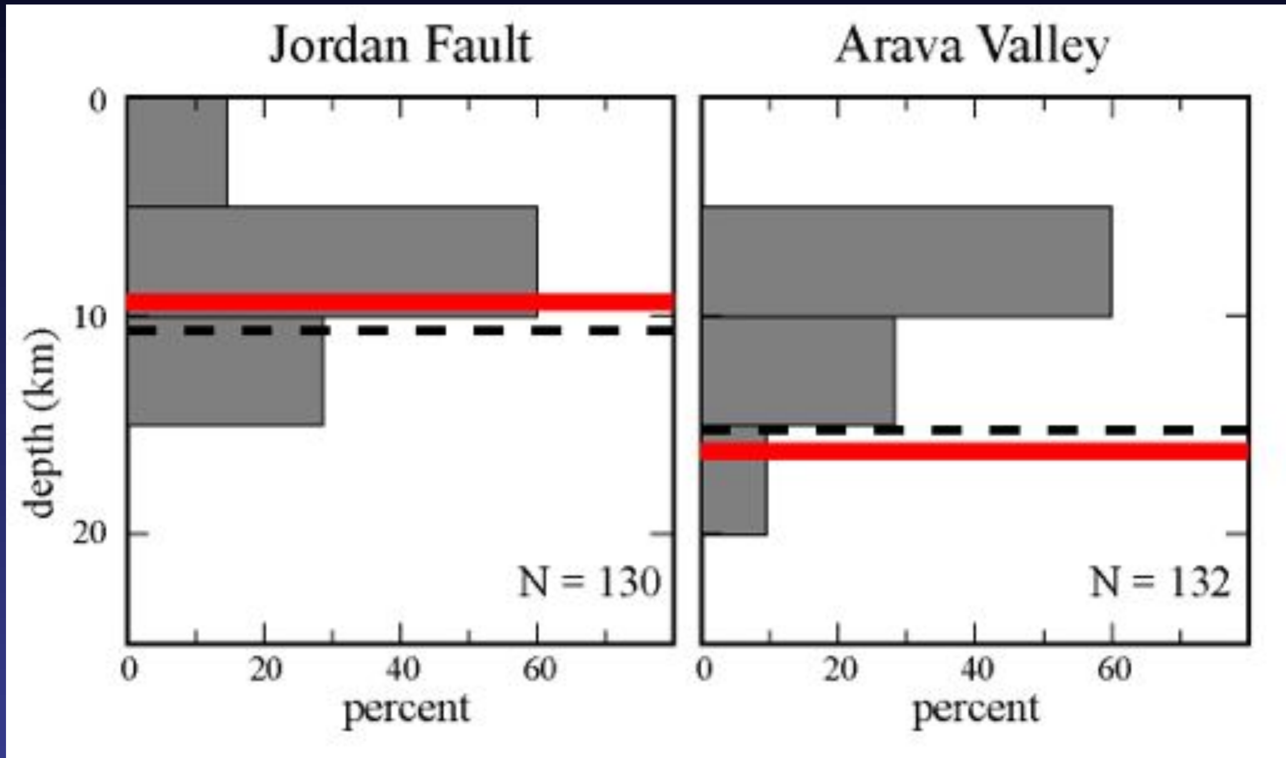
Profiles across the southern DSFS





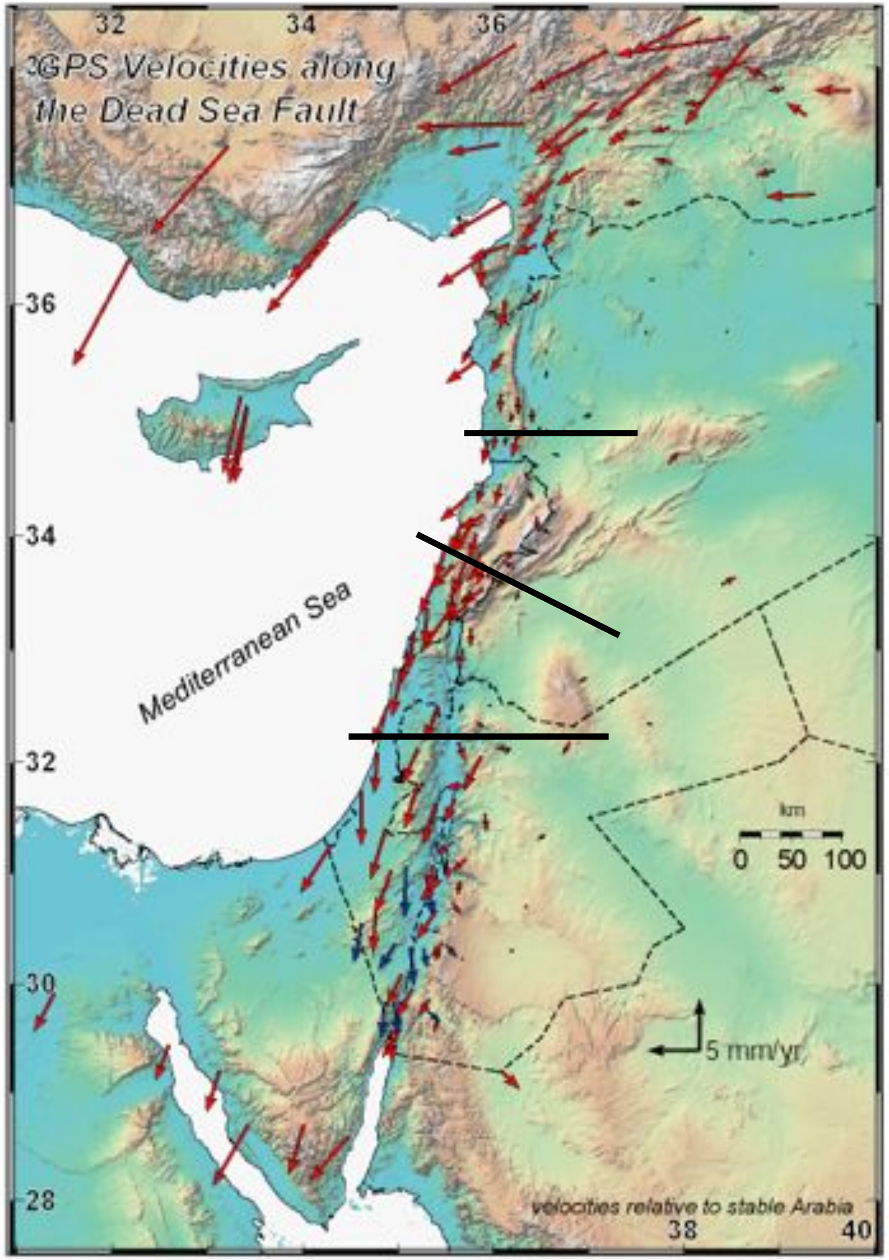
(Al Tarazi et al., 2011)

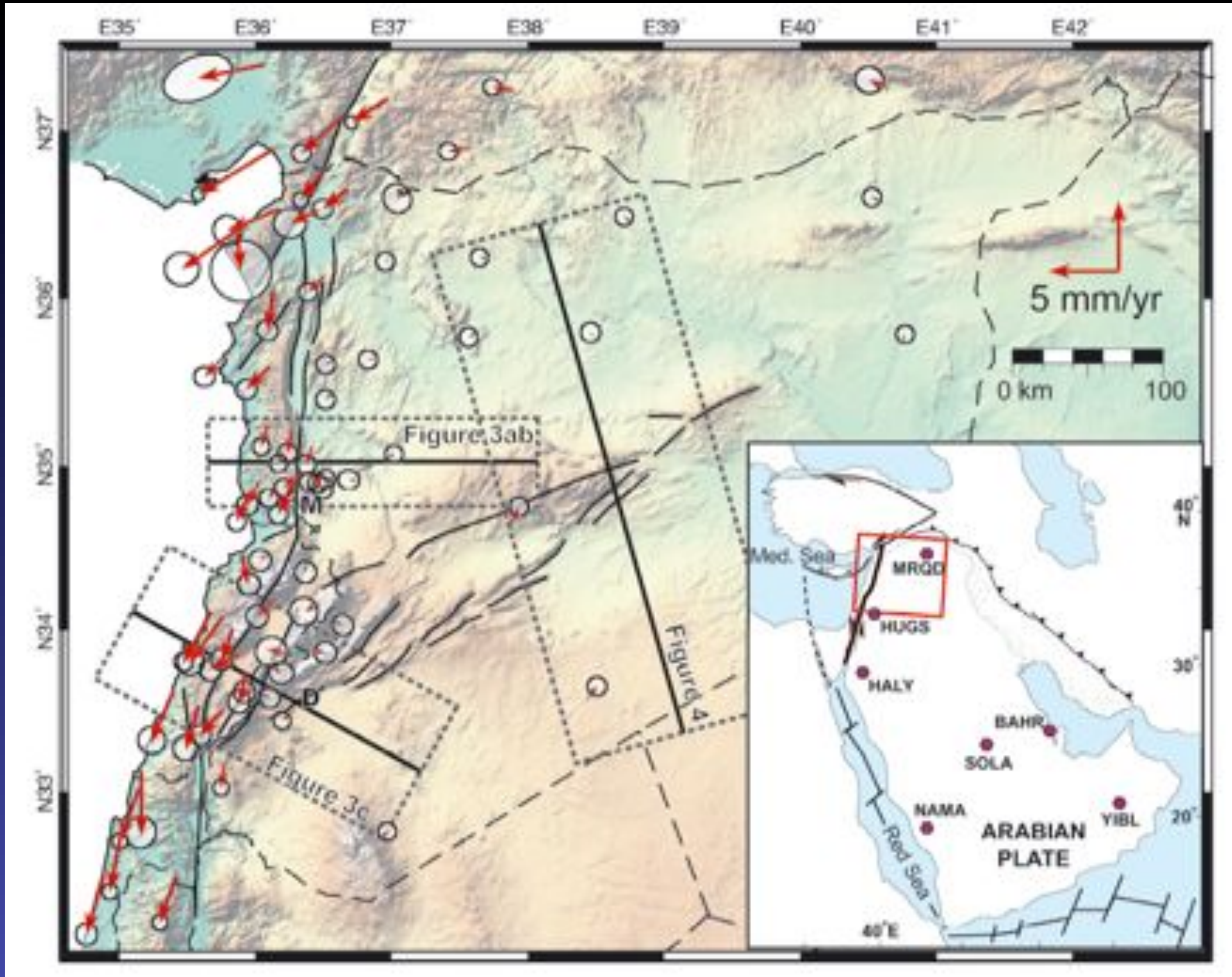
Seismicity along the southern DSF



Dashed black line = 95% cut-off for seismic moment (Sadeh et al., 2012)
Solid red line = geodetic locking depth (Al Tarazi et al., 2011; Cochran, 2013)

- Along-strike change in velocities?!
- Examination of 3 profiles





E35°
E36°
E37°
E38°
E39°
E40°
E41°
E42°
N37°
N36°
N35°
N34°
N33°
5 mm/yr
0 km
100
Figure 3ab
Figure 3c
Figure 4
M
D
Med. Sea
MRGD
HUGS
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BAHR
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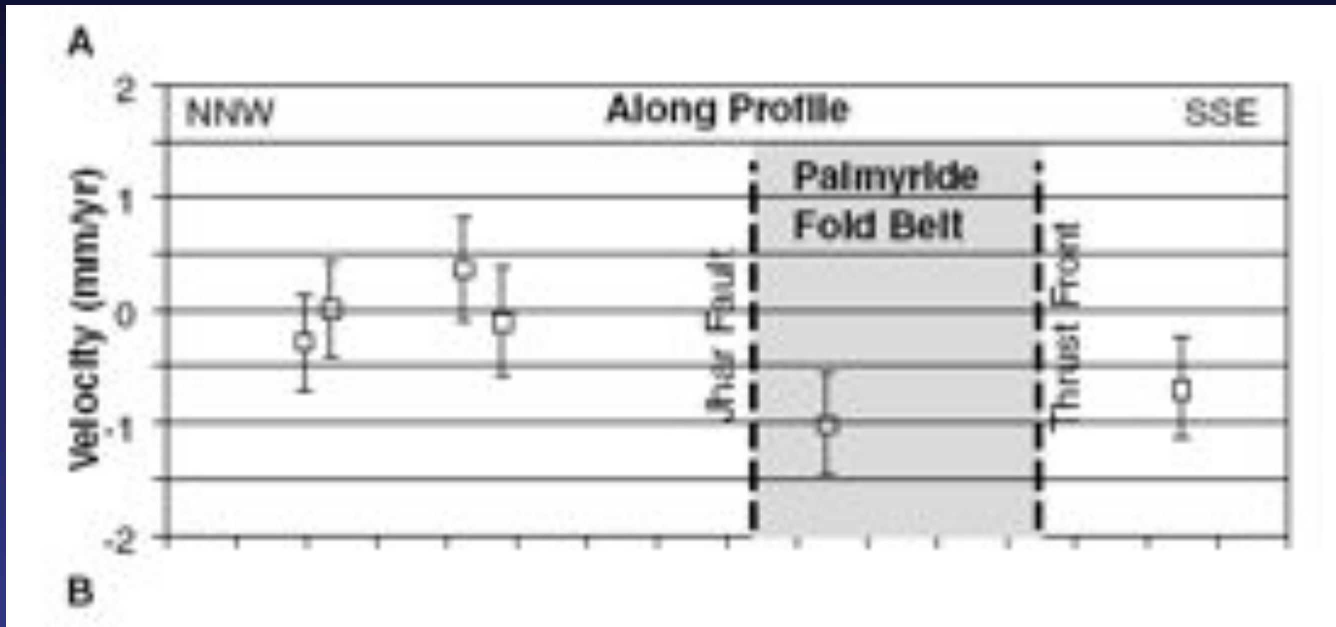
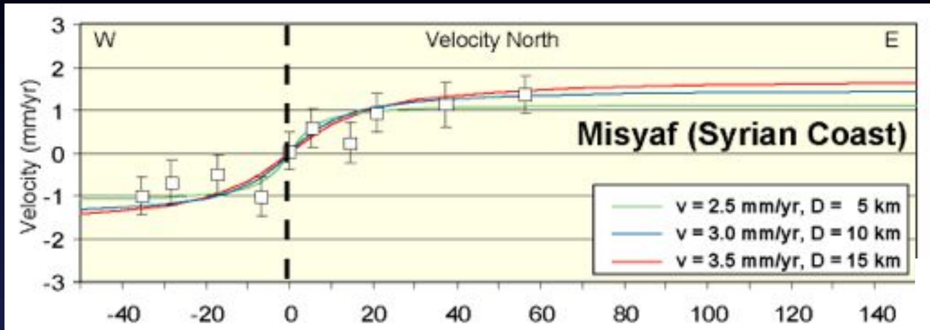
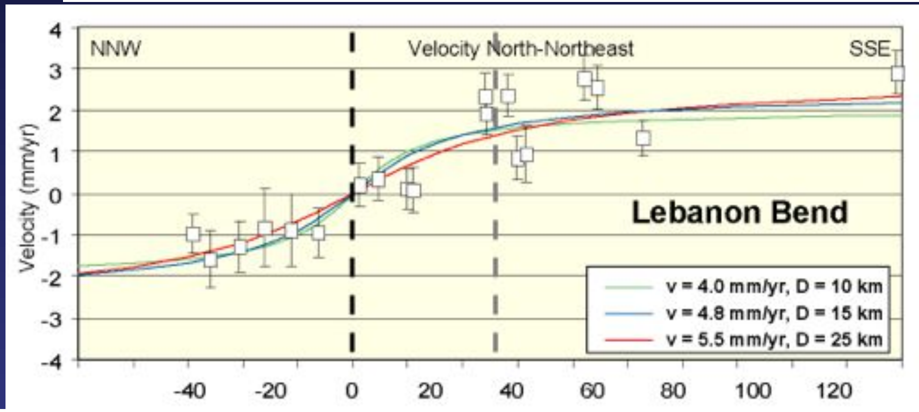
ARABIAN
PLATE
Red Sea
40°N
30°
20°
40°E

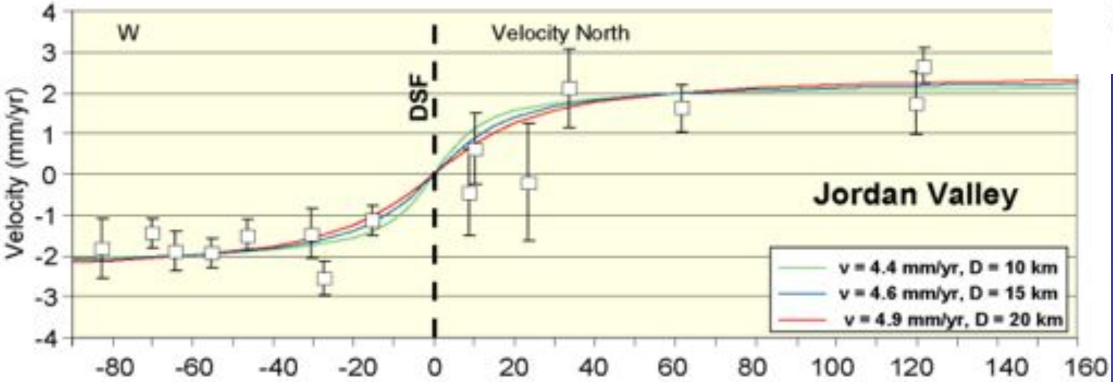


Suggestion of some shortening across the Palmyride fold belt – maximum of up to 1 mm/yr. (Alchalbi et al., 2010)

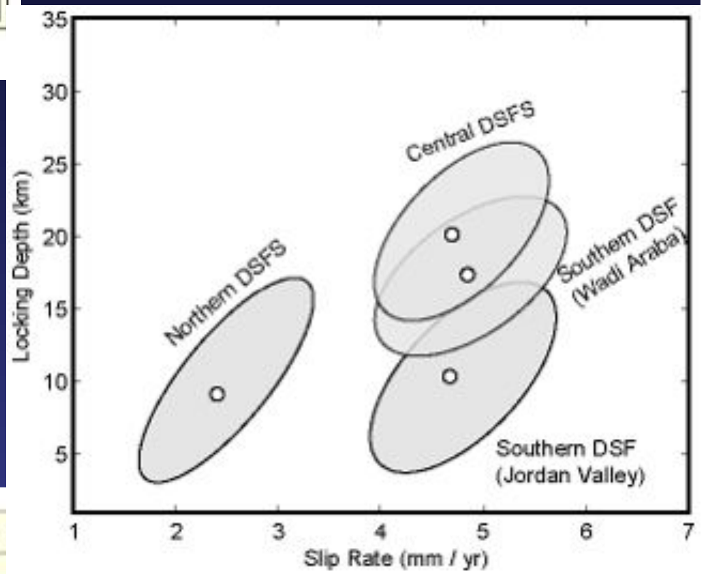
Southern & Central vs. Northern DSF







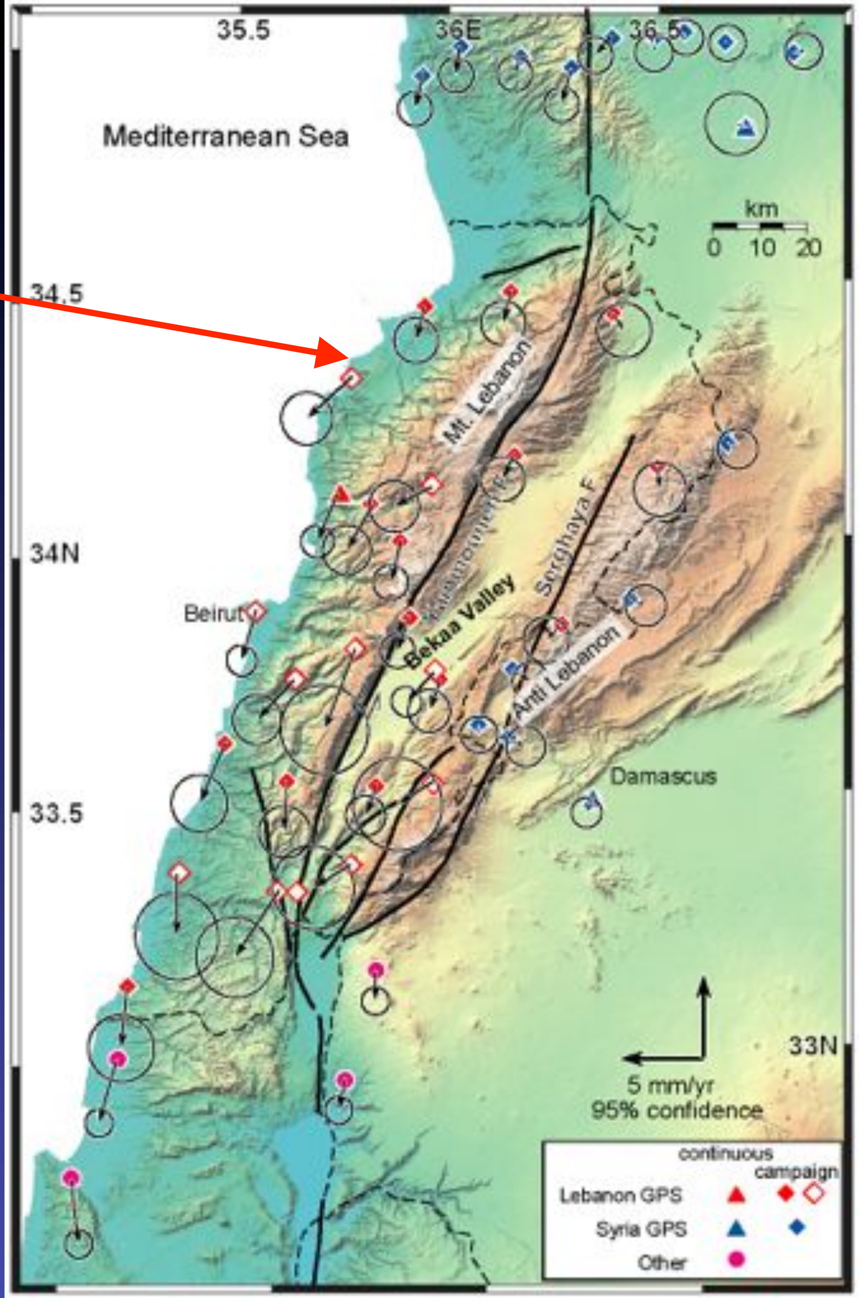
North DSF is statistically distinct!



Central & South DSF consistent with geology

- Velocity decrease occurs in northern Lebanon

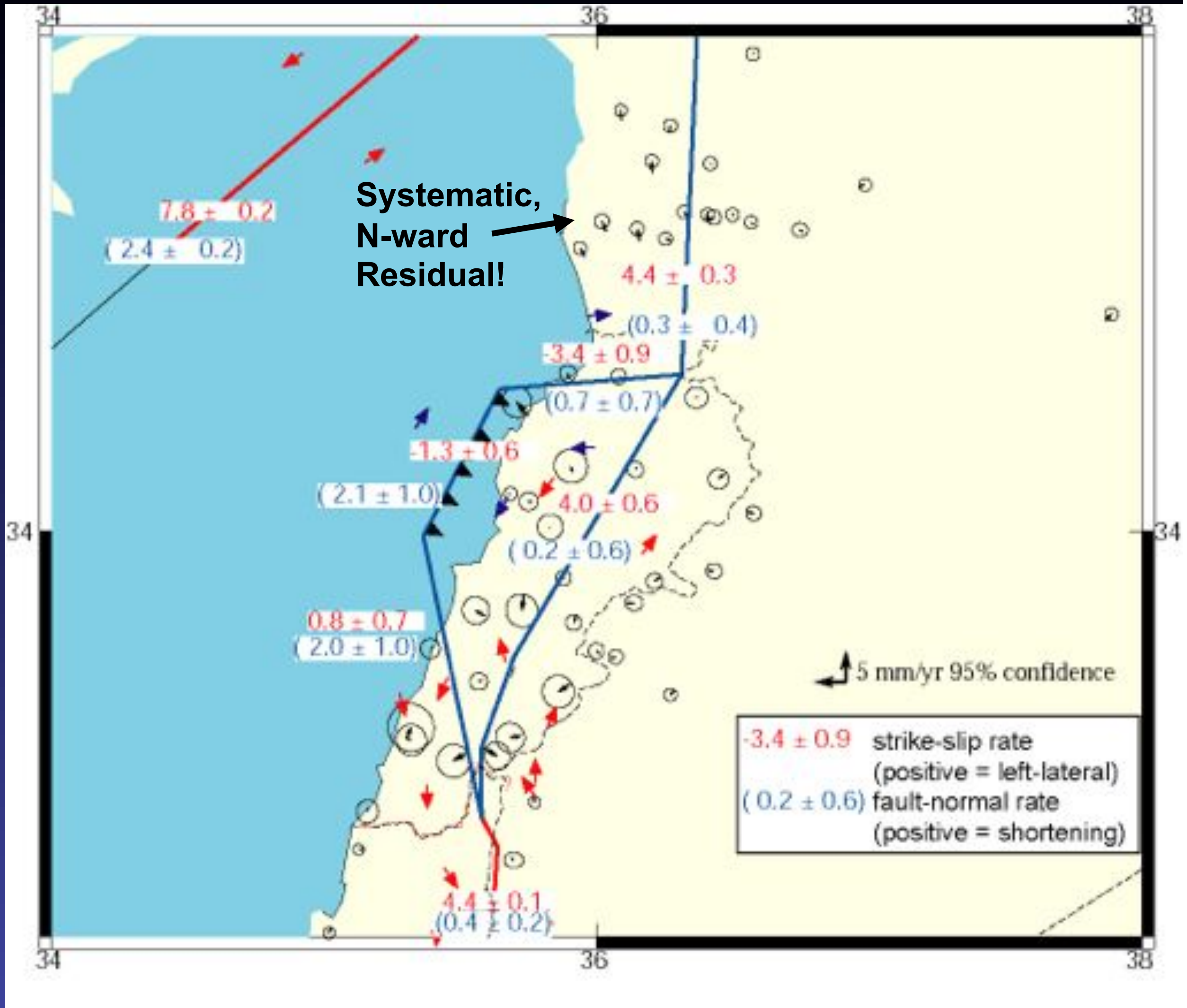
- This velocity gradient occurs within the Sinai plate



- Slip rates in Lebanon lower than profiles – 2-D models are better suited than profiles, here

- Simplified thrust fault: ~1.7 mm/yr shortening (2.1 mm/yr on 30 degree fault)

- But, the model doesn't fit NW Syria well – what if we break the Sinai Plate?



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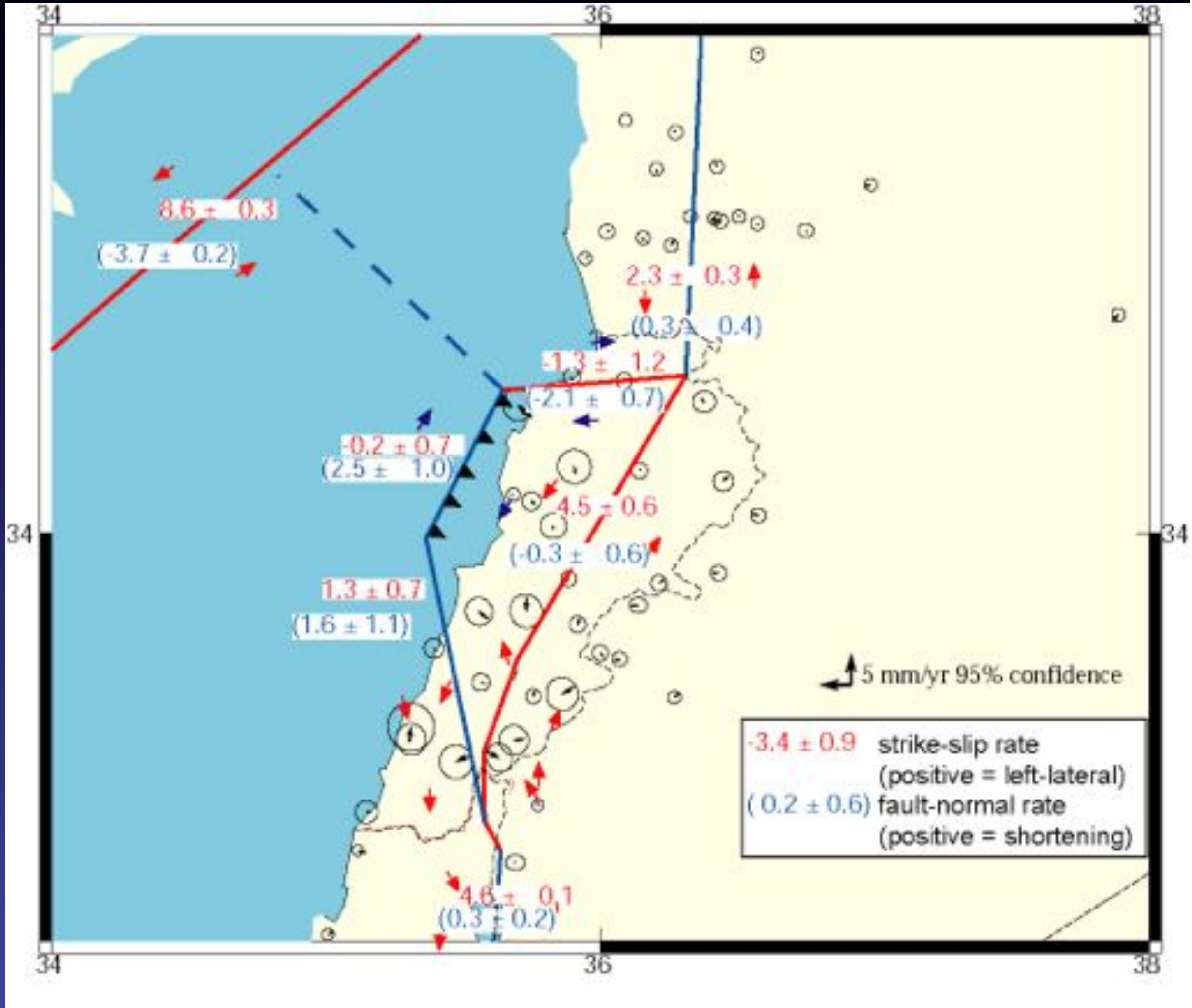
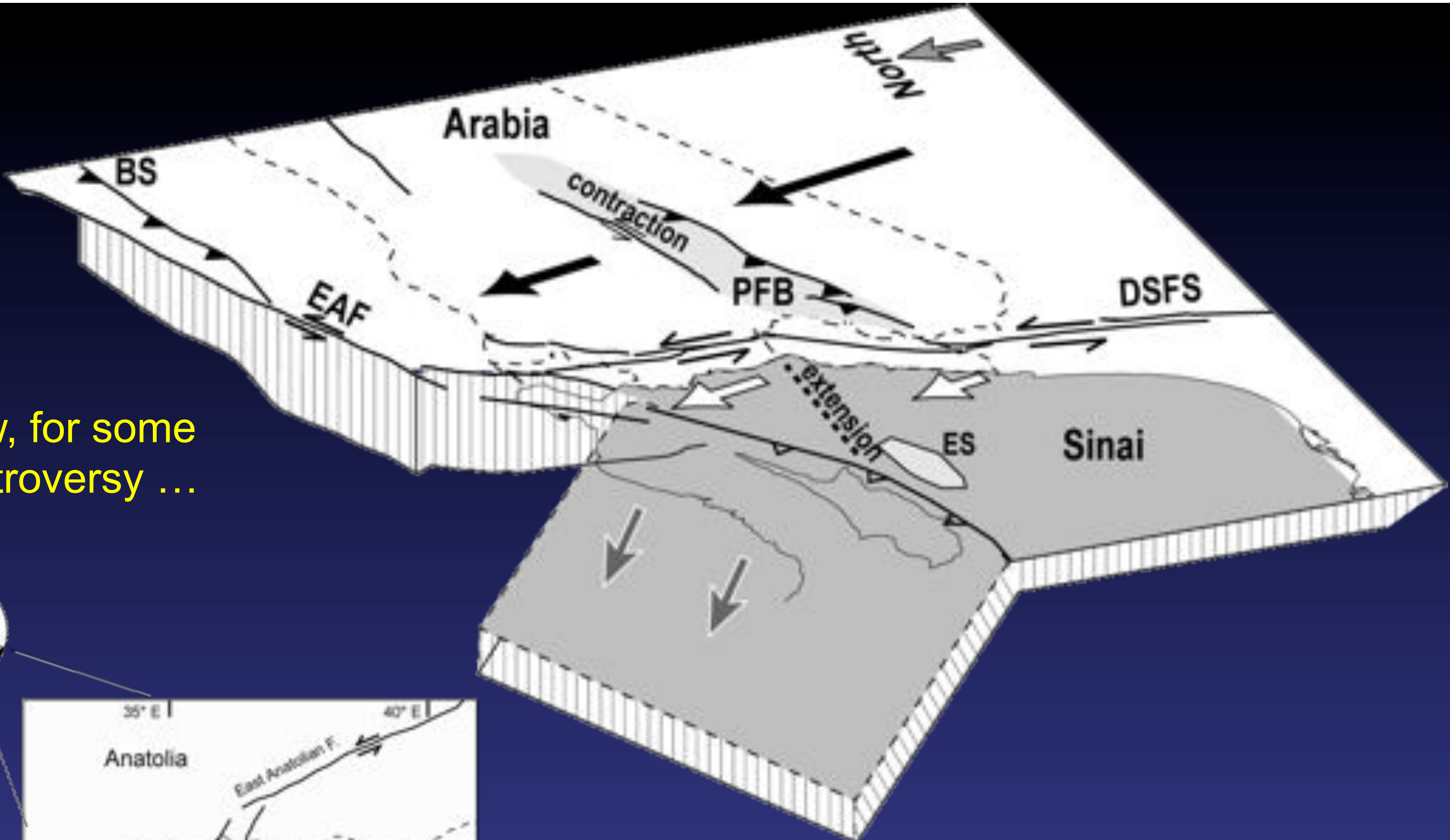
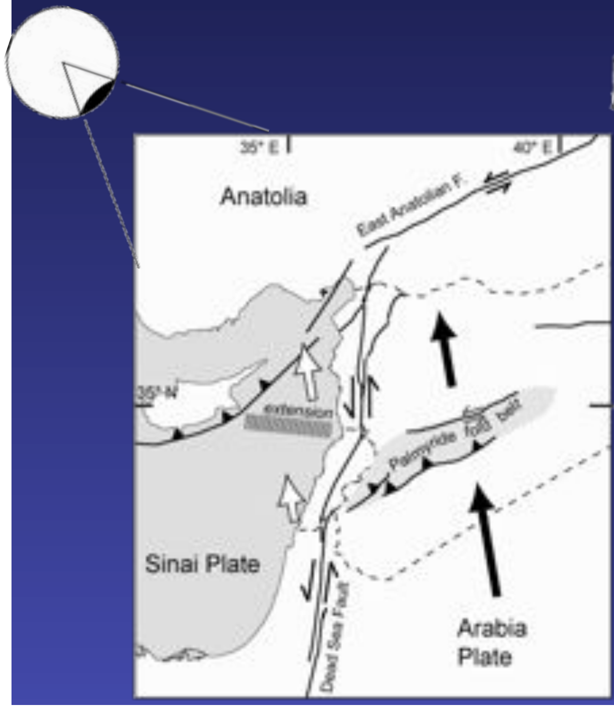


But, DO NOT take the 'fault' In this model literally – perhaps diffuse extension / stretching in Sinai Plate?



Now, for some controversy …



Perhaps the NE Sinai plate is partially broken from the main plate

If so, perhaps subducted oceanic lithosphere pulls the plate –i.e., NE Sinai converges with Anatolia faster than the main part of Sinai

Could this be caused by Eratosthenes Seamount?

Conclusions

- A comprehensive view of near-field geodetic deformation is now available for the DSFS – a result of international cooperation
- GPS showing some surprises – DSFS is not as simple as we thought
- Geological and geodetic slip rates are generally consistent – except northern DSF!
- Only about 1/2 of the slip is ‘transferred’ through the LRB – it’s not a simple restraining bend
- Much of the expected shortening is not present within the Lebanese Restraining Bend – is it offshore? (elastic block model)
- Is plate tectonic approximation appropriate for NE Sinai plate?