The Abdus Salam
International Centre
for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2464-20

Earthquake Tectonics and Hazards on the Continents

17 - 28 June 2013

Velocity fields, and their application to strain rates, fault slip rates, and hazard estimation

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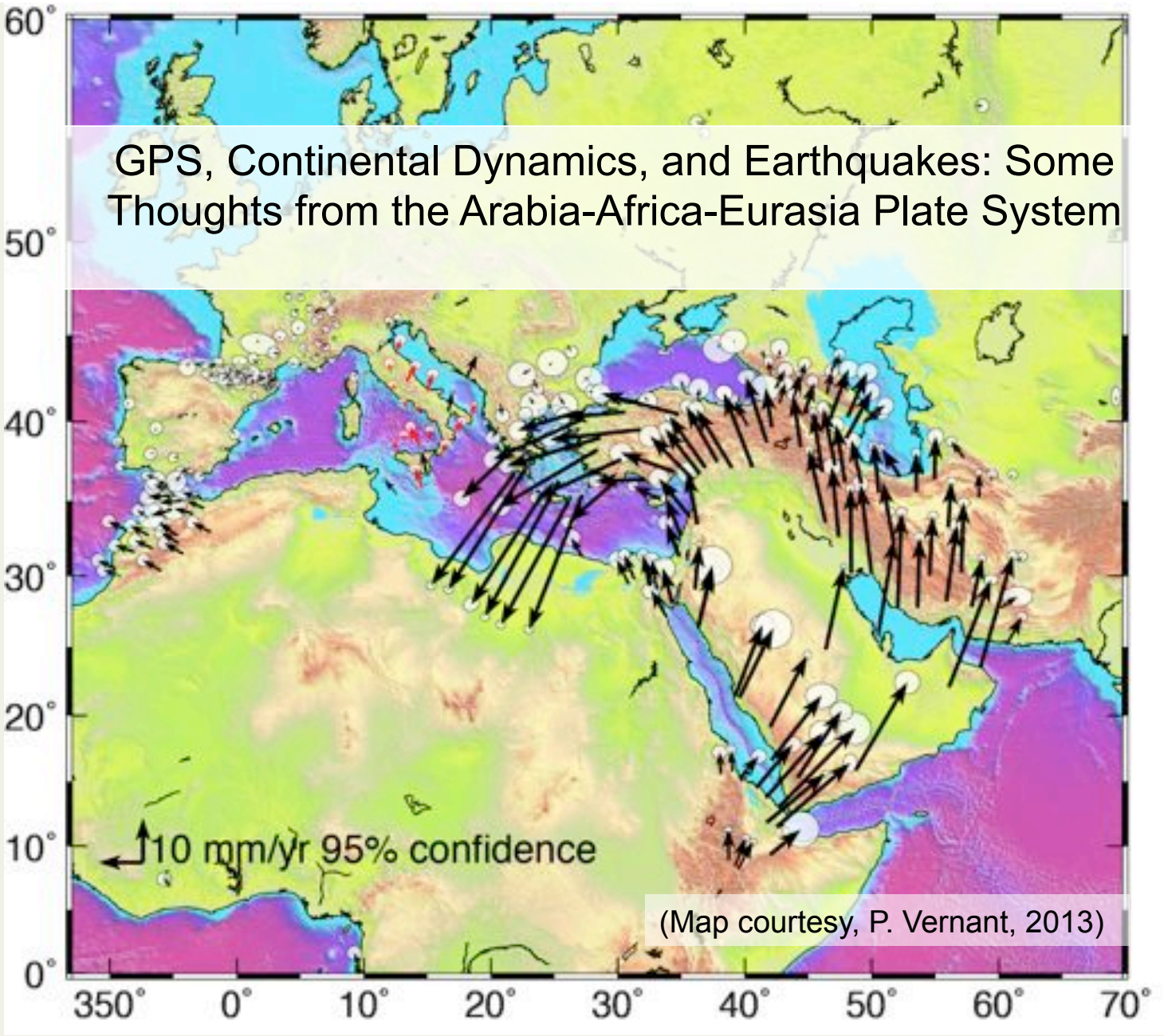
GPS, Continental Dynamics, and Earthquakes: Some Thoughts from the Arabia-Africa-Eurasia Plate System
60°
50°
40°
30°
20°
10°
0°
350°
0°
10°
20°
30°
40°
50°
60°
70°
10 mm/yr 95% confidence
(Map courtesy, P. Vernant, 2013)

Mediterranean-Middle East Crustal Motion Observatory (1988-2013)

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Salah Mahmoud, and K. Sakr, NRIAG, Helwan, Cairo, **Egypt**
Ghebrebrhan Ogubazghi and Berhe Goitom, Asmara Istitute of Tech., Asmara, **Eritrea**
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Demitris Paradissis, Higher Geodesy Laboratory, National Technical University, Athens, **Greece**
Thanasis Ganas, National Observatory, Athens, Athens**, Greece**
Abdullah ArRajehi, King Abdulaziz City for Science and Technology, Riyadh, **Saudi Arabia**
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Driss Ouazar, Ecole Mohammadia des Ingenieurs, Rabat, **Morocco**
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Mohamad Daoud and Abdulmutaleb Alchalbi, National Earthquake Center, Damascus, **Syria**
Semih Ergintav, TUBITAK, MRC, Earth and Marine Sciences Research Institute, Gebze, **Turkey**
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Andriy Dmitrotsa, S.V. Filikov, Crimea Radio Astro. Observatory, Simiez, Crimea, **Ukraine**
Francisco Gomez, Dept of Geological Sciences, University of Missouri, Columbia, MO, **USA**
Rebecca Bendick, Department of Geosciences, University of Montana, Missoula, MT, **USA**
Jamal Sholan, National Seismological Observatory Center, Dahmar, **Yemen**

Red = Provide data from CGPS stations to UNAVCO Open Archive (total # = 32)

Outline

- Introduction: Personal Thoughts from 25 Years of International Collaborations
- GPS Geodesy for Crustal Deformation
- Active Tectonics of the AF-AR-EU Plate System
- Evidence for Plate/Block-Like Behavior
- Elastic Strain Accumulation on Faults

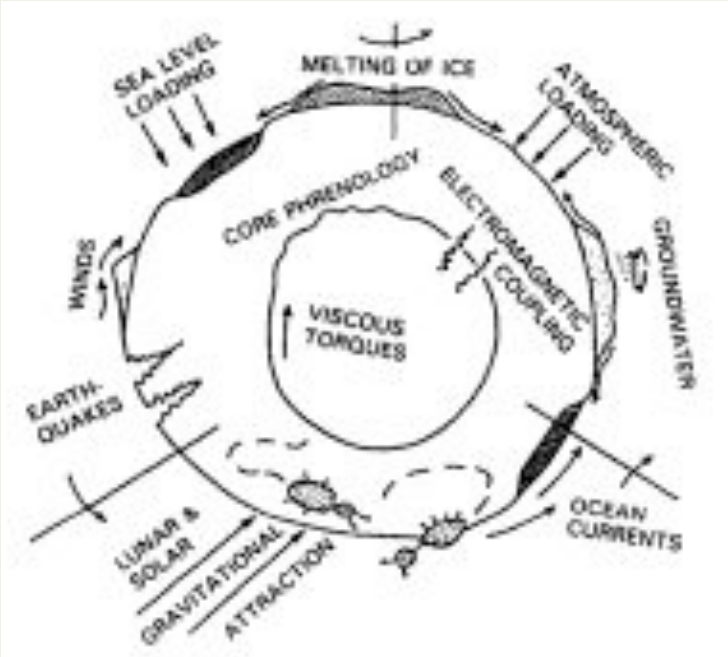
- Earthquake Deformation Cycle

  1999, M_w7.4/7.2, Izmit/Duzce, NAF Earthquakes
  - Inter-Seismic
  - Pre-Seismic (Bouchon et al., 2011; Seismology)
  - Co-Seismic
  - Post-Seismic
  - Induced, Long-Duration Fault Creep??

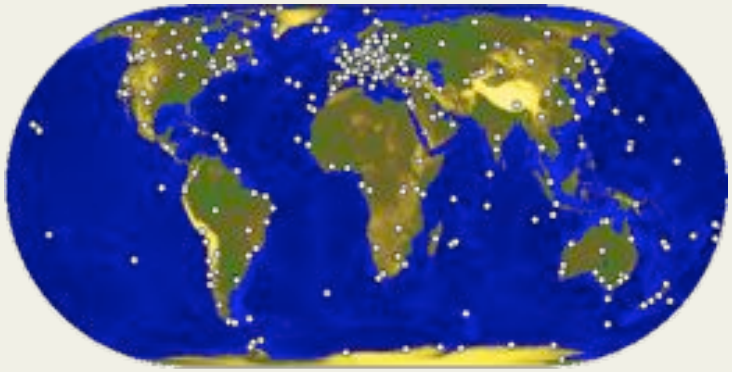
Geodesy

- Geodesy is a scientific discipline that deals with the time varying measurement and representation of the Earth, including it's gravity field, in a 3D space using terrestrial and space borne (GPS, InSAR, GRACE) techniques.

- Tectonic plate motion ✔
- Earthquake deformation ✔
- Earth rotation
- Tidal motion and deformation
- Mass transport and deformation
- Atmospheric properties
- Anthropogenic effects

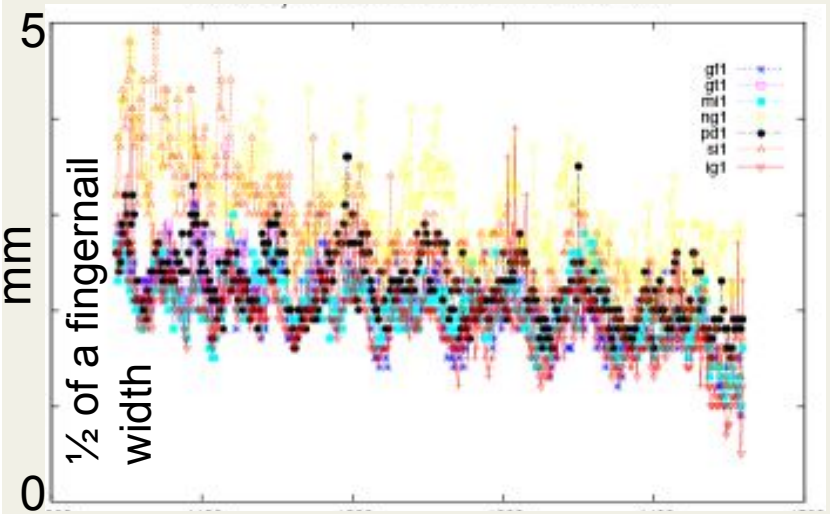


GPS Geodesy

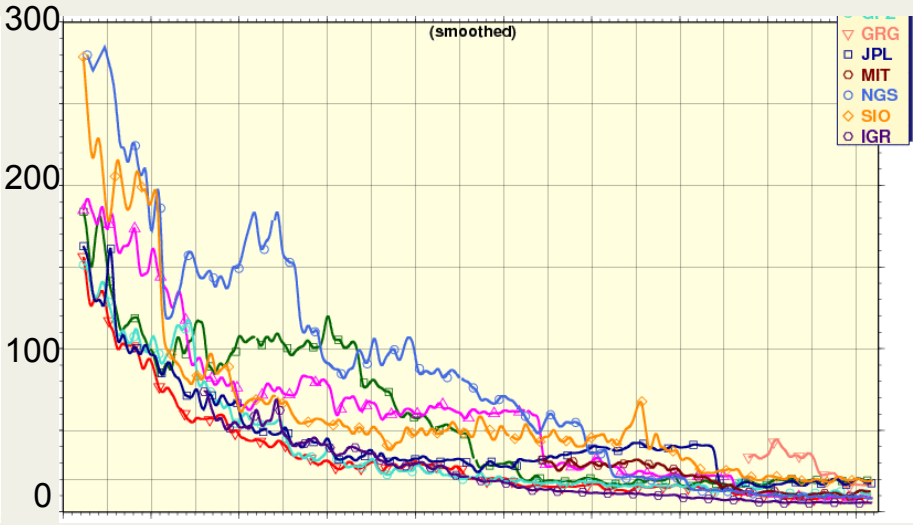


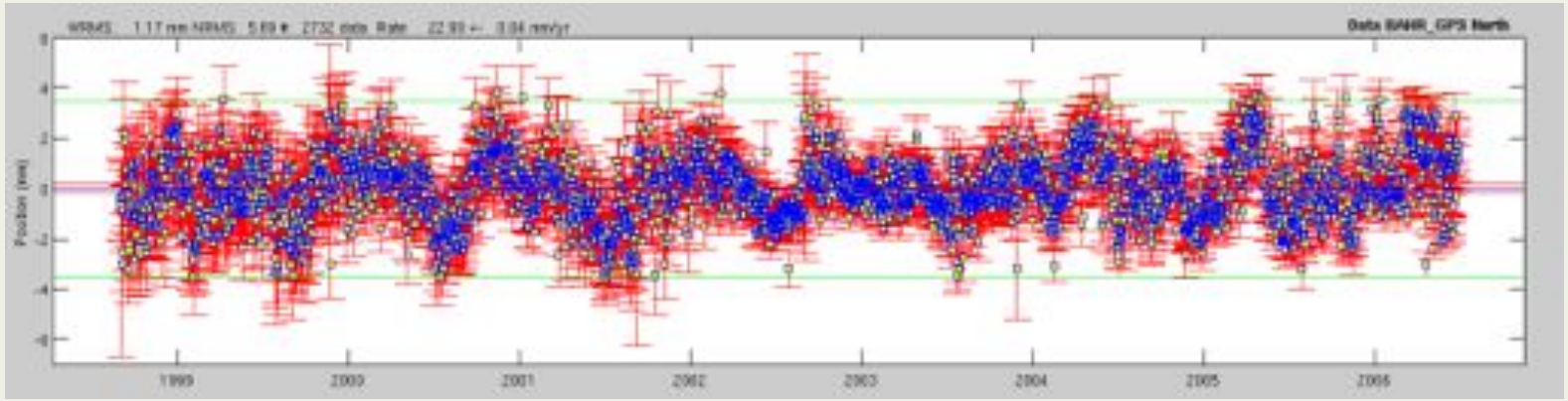
physical models and parameter estimation strategies

East site position uncertainty

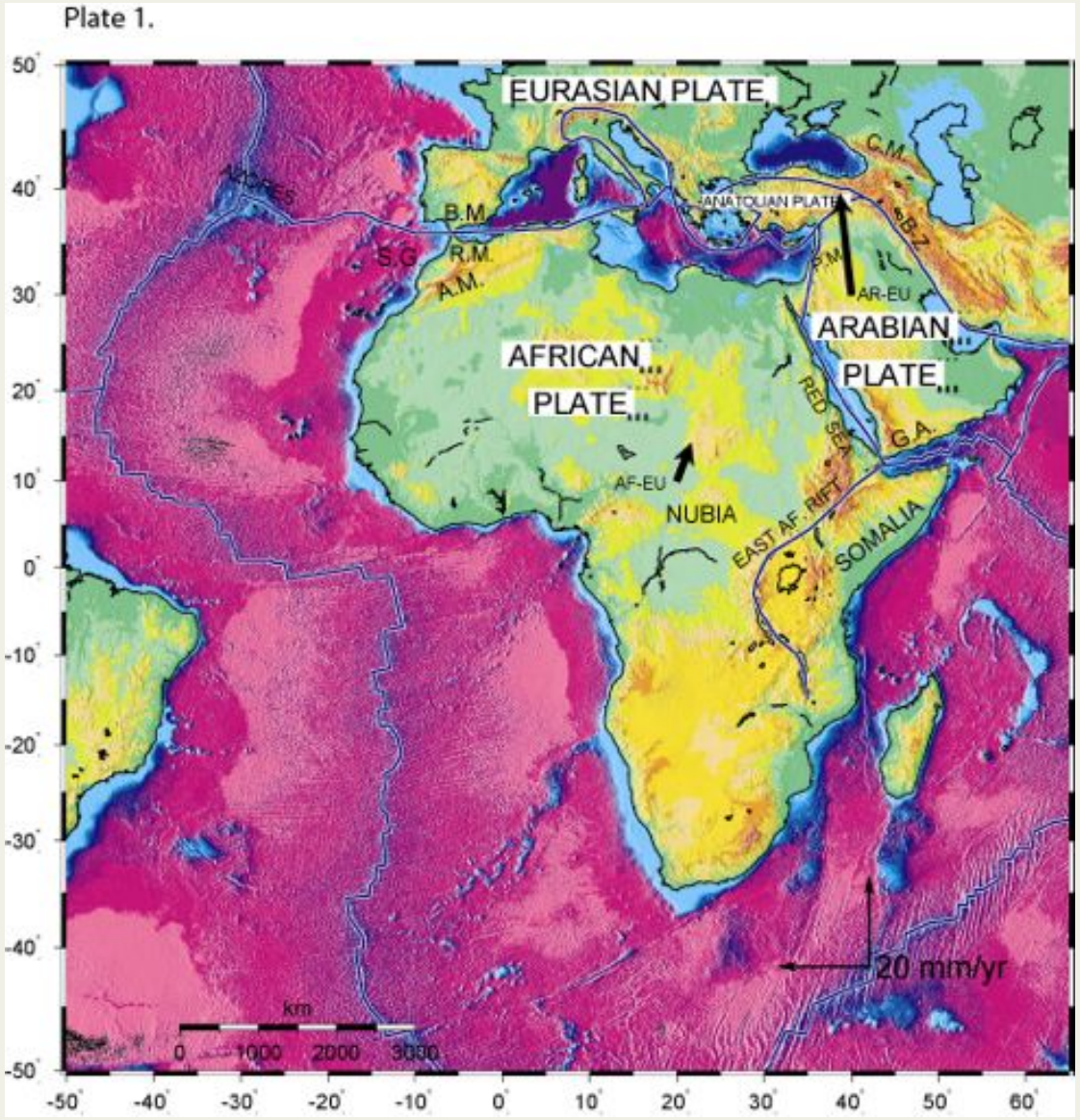


3D GPS satellite position uncertainty

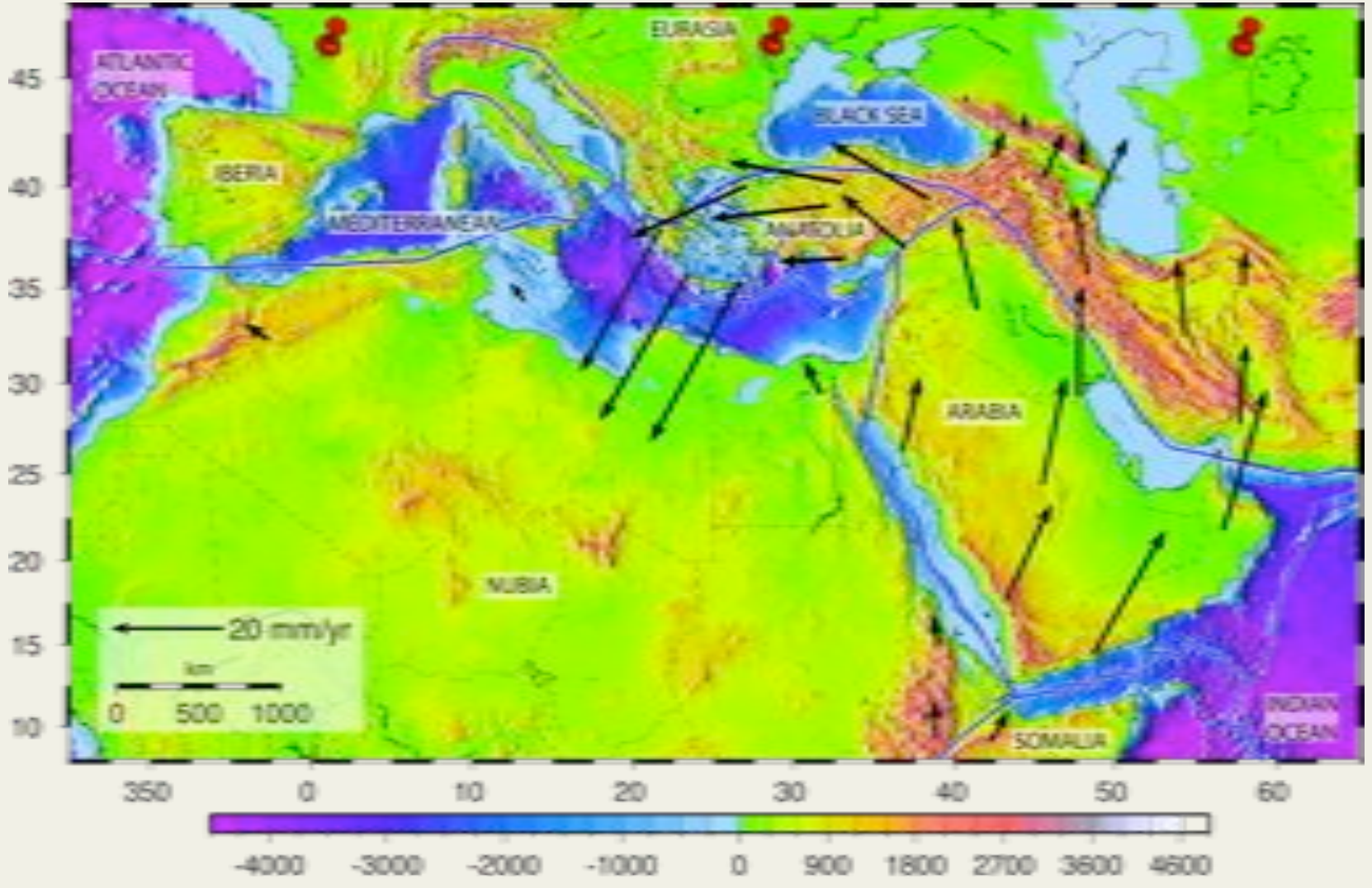



Position (mm)
1999
2000
2001
2002
2003
2004
2005
2006

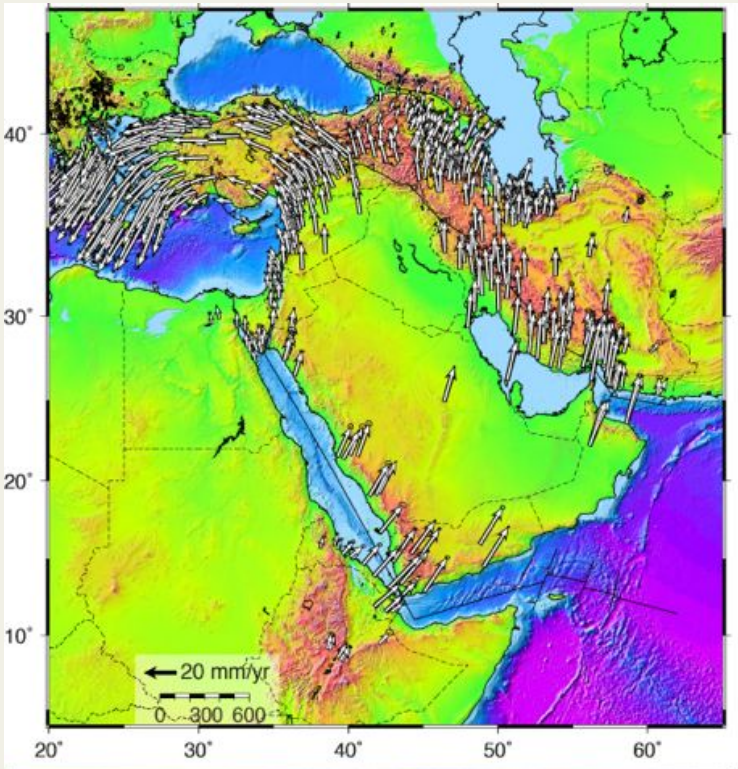
Tectonic Overview



Mediterranean & Middle East Tectonic Overview



Active Tectonics of AF-AR-EU Plate System



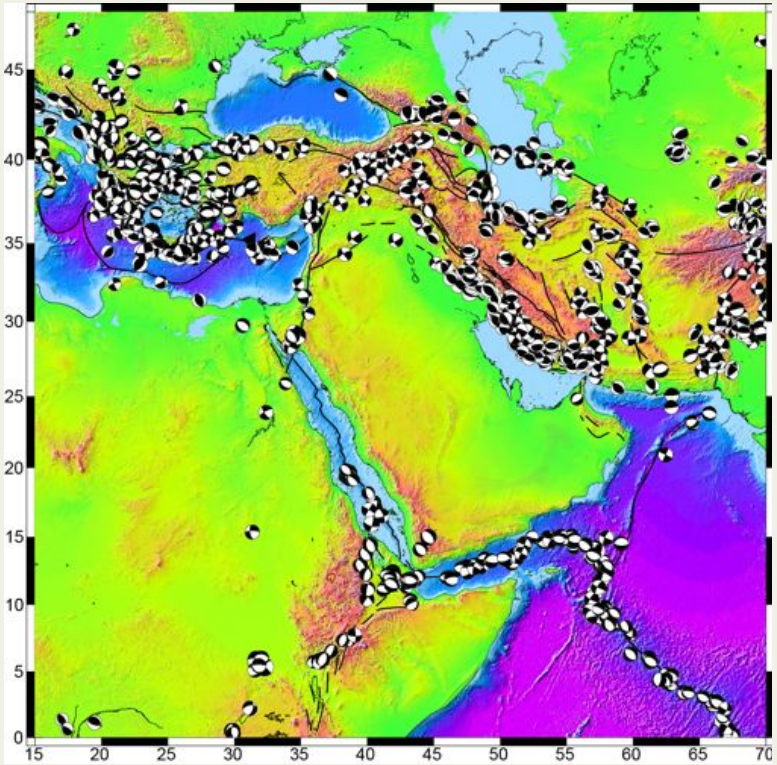
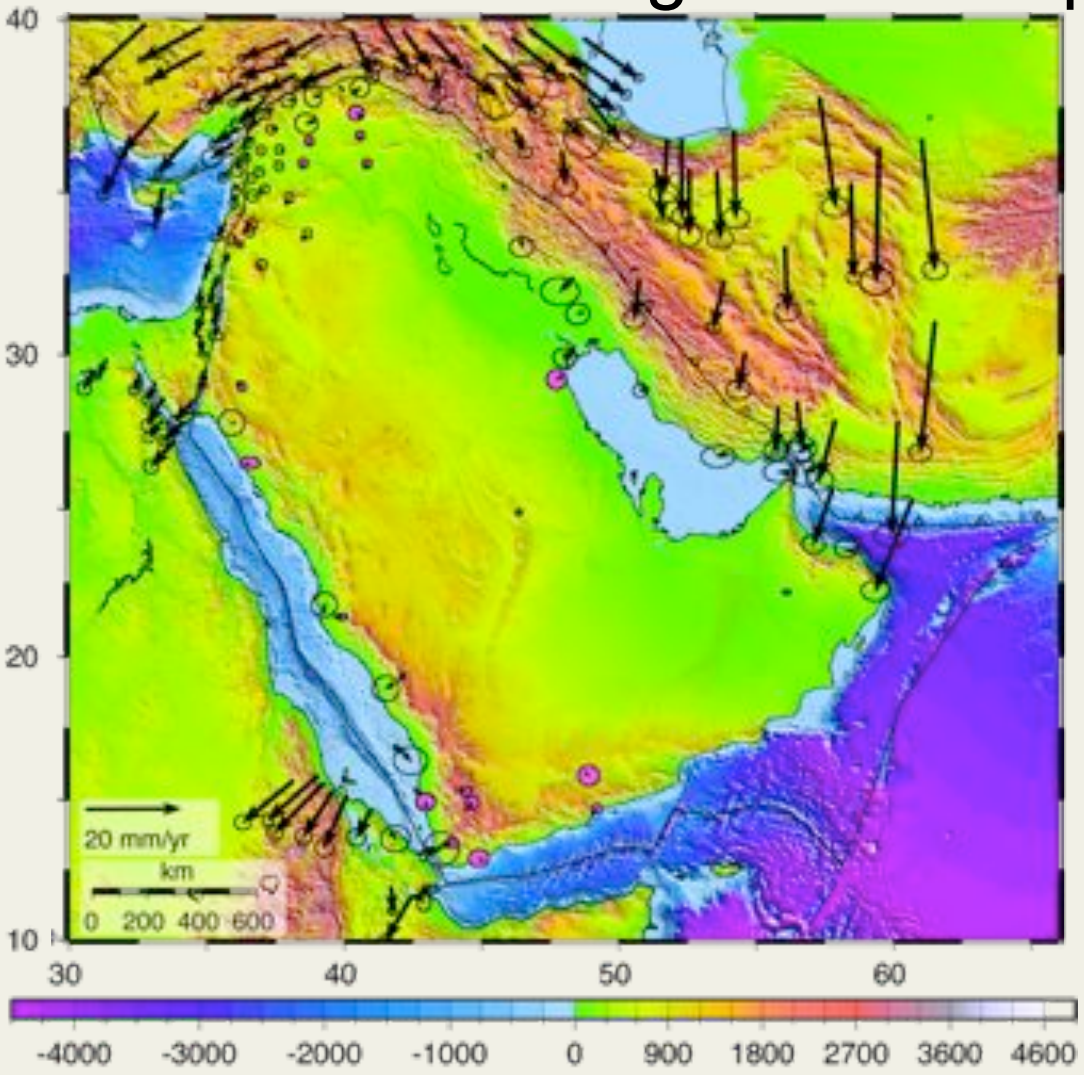


Plate & Block models? (linking regional tectonics to faulting and earthquakes)



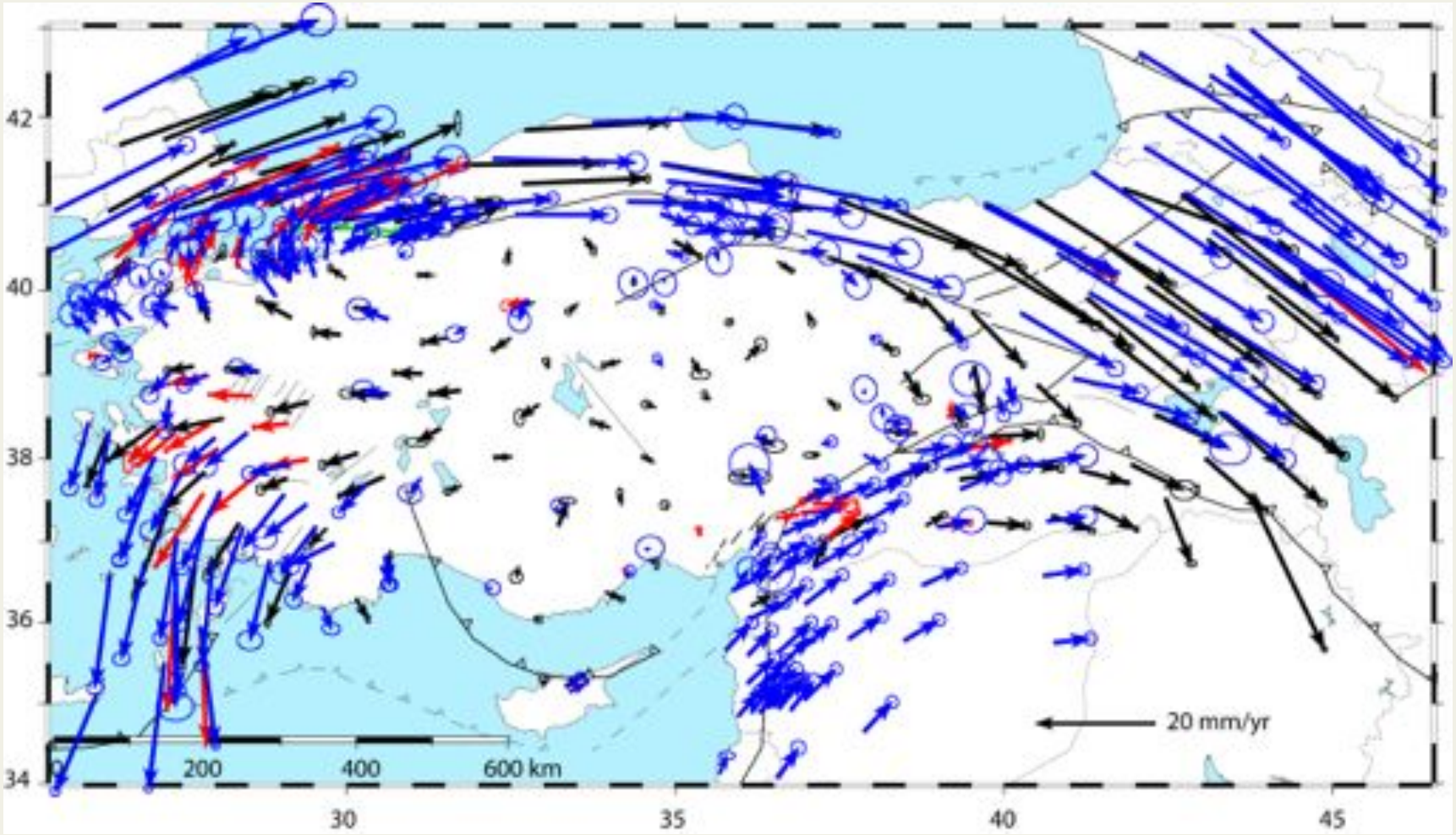
The Assumption:

Crust can be described as discrete blocks or plates whose motion can be modeled as coherent rotations about euler poles? (classic plate tectonic assumption)
(eq cycle time scale?)

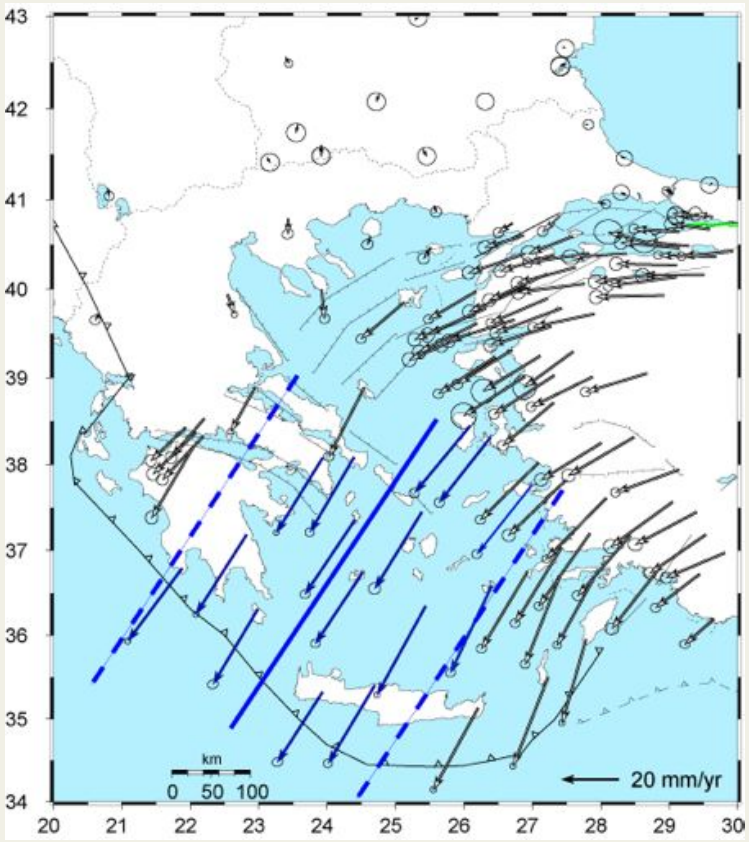
Alternative:
The crust is a continuum and can be modeled as a thin viscous / plastic shell?
(Geologic time scale?)

Anatolian “Plate”

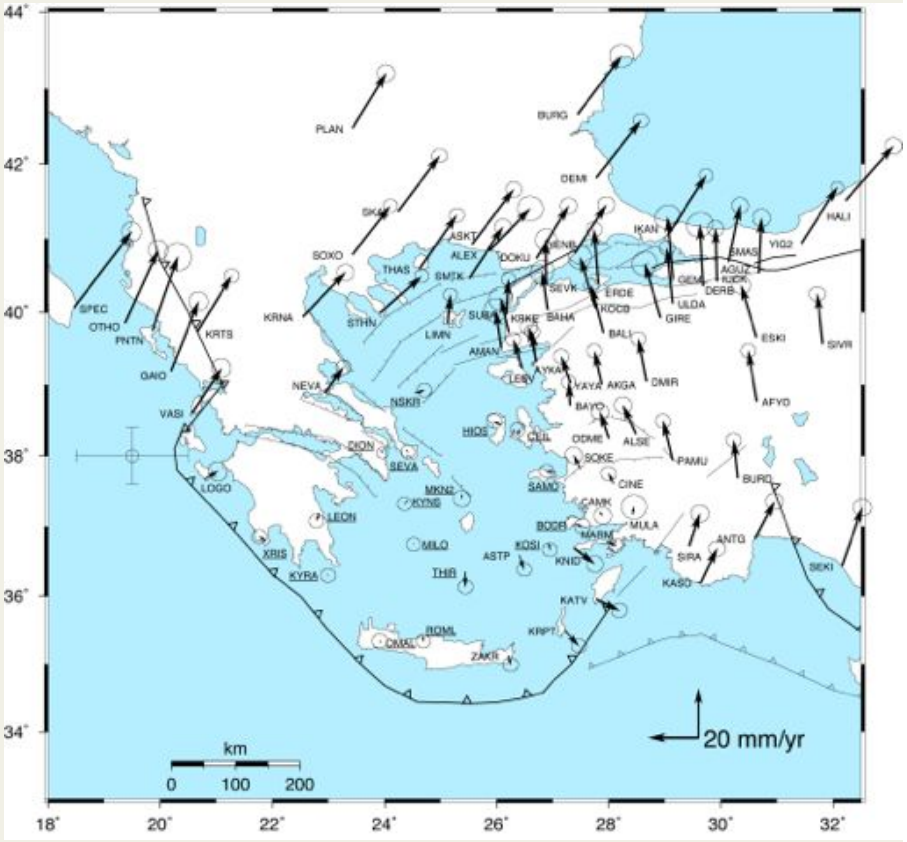
(from McClusky et al., 2010)



Coherent present-day motion of Aegean



Eurasia-fixed



Aegean-fixed

Pre-NAF Aegean extension/post-NAF coherent translation toward trench

Caucasus/Eastern Turkey Plateau

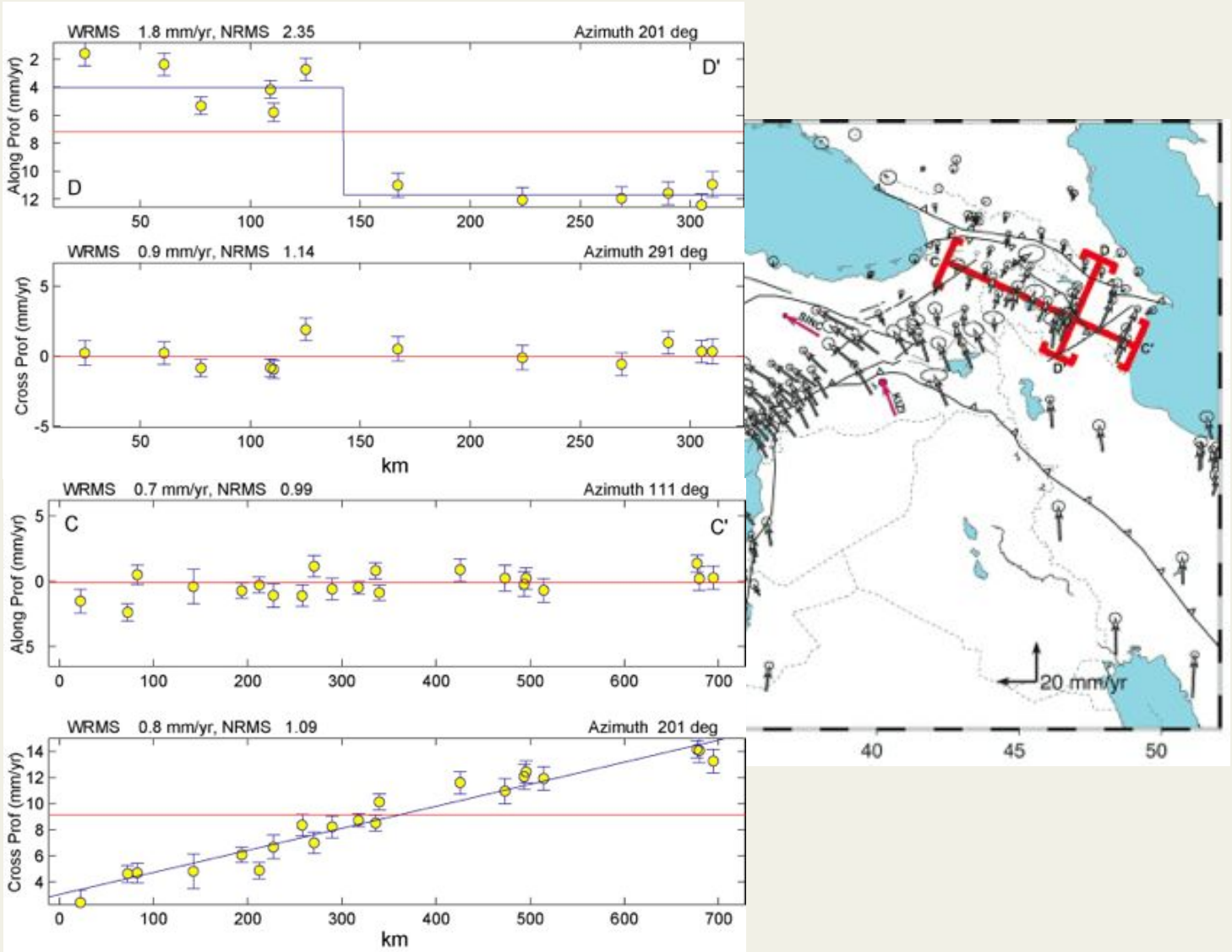


Plate Boundary Deformation (NAF)

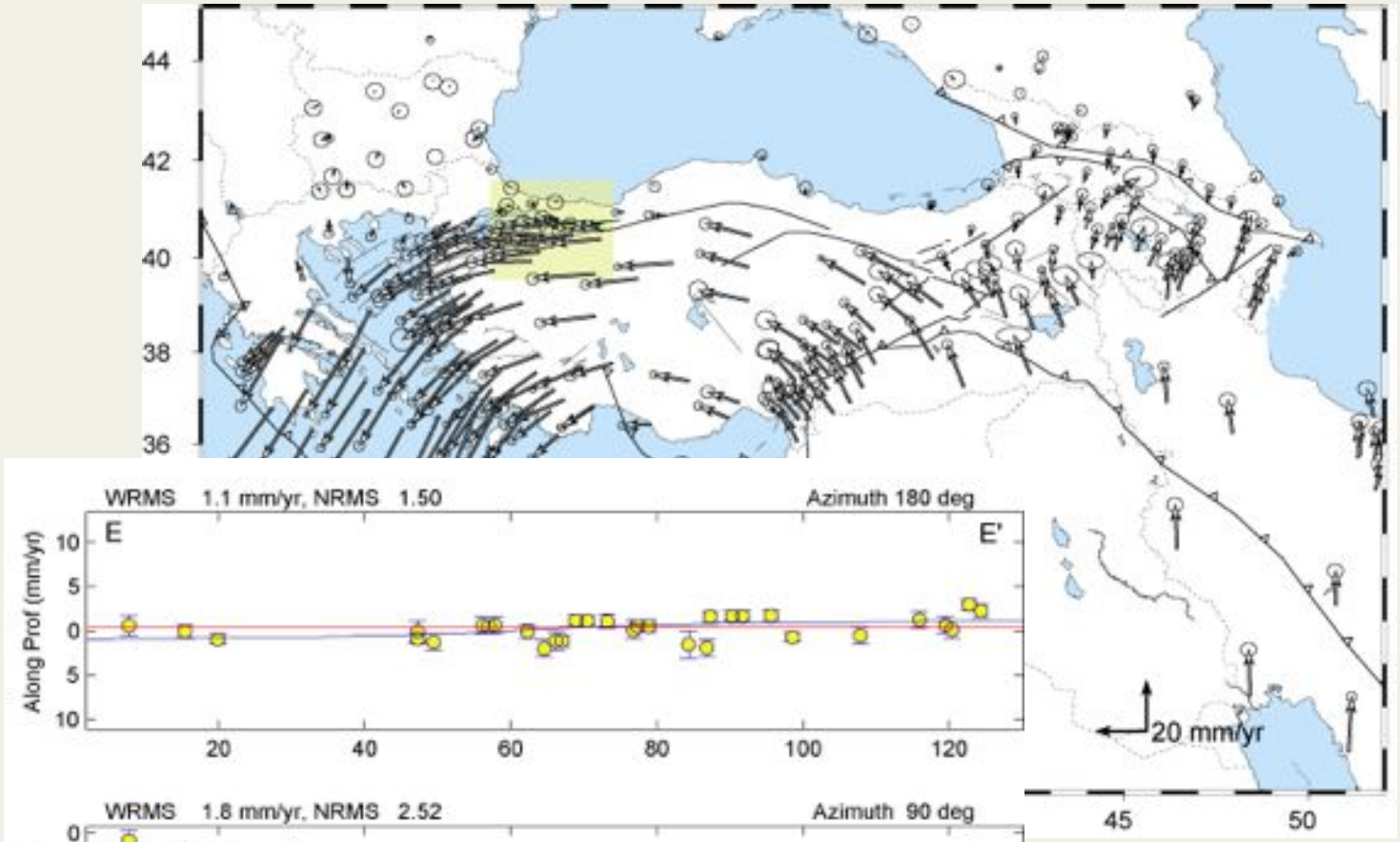


Plate Boundary Deformation (EAF)

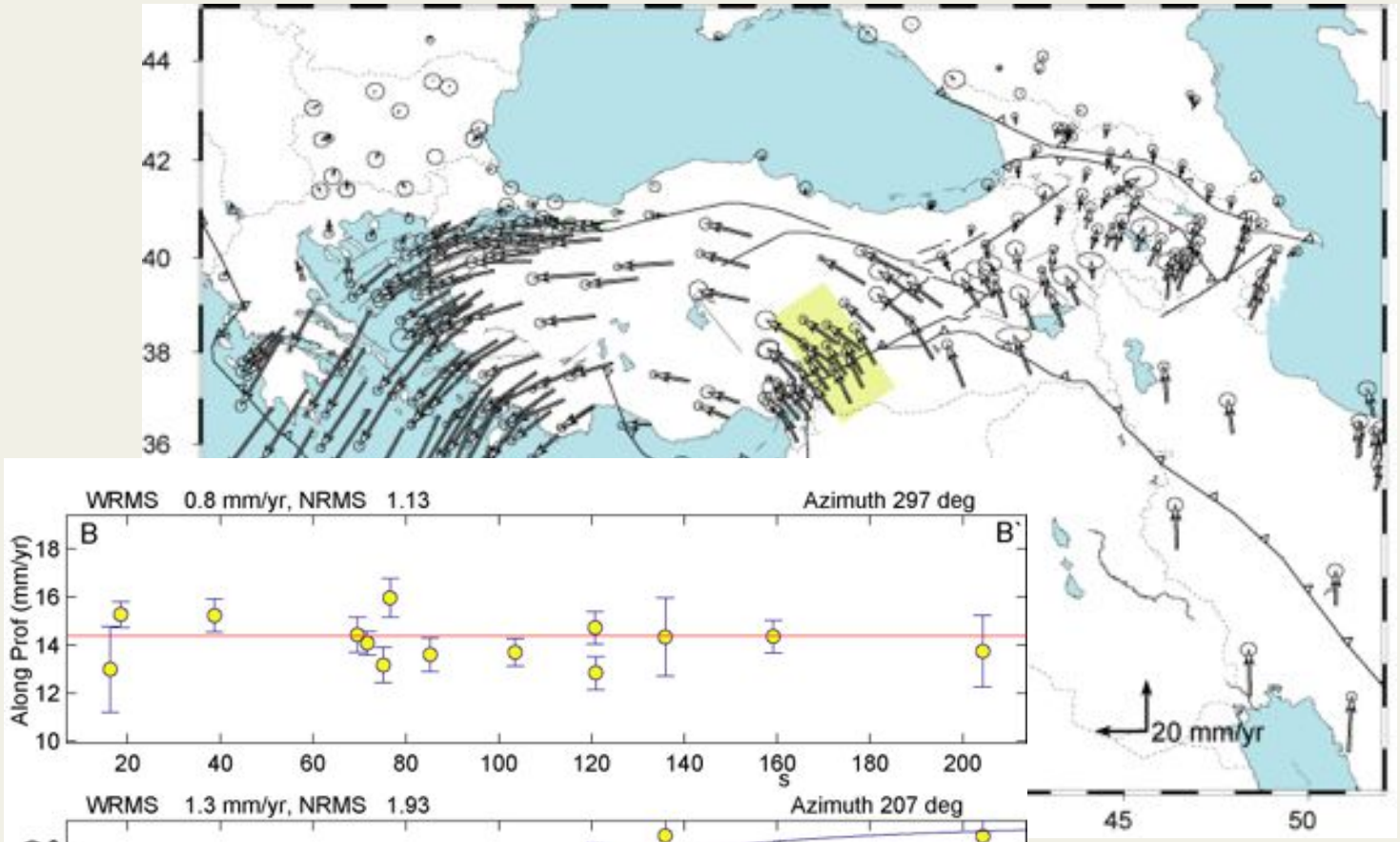
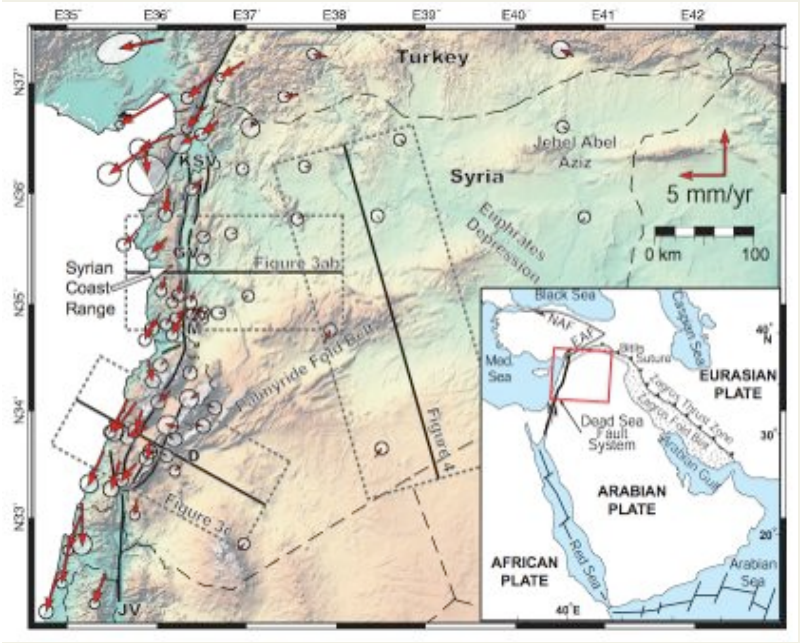
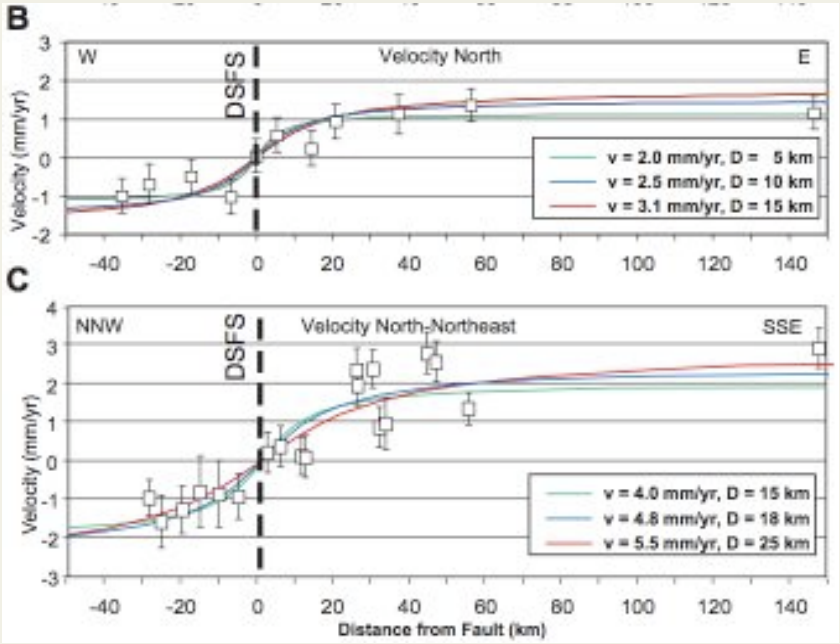


Plate Boundary Deformation (DSF)

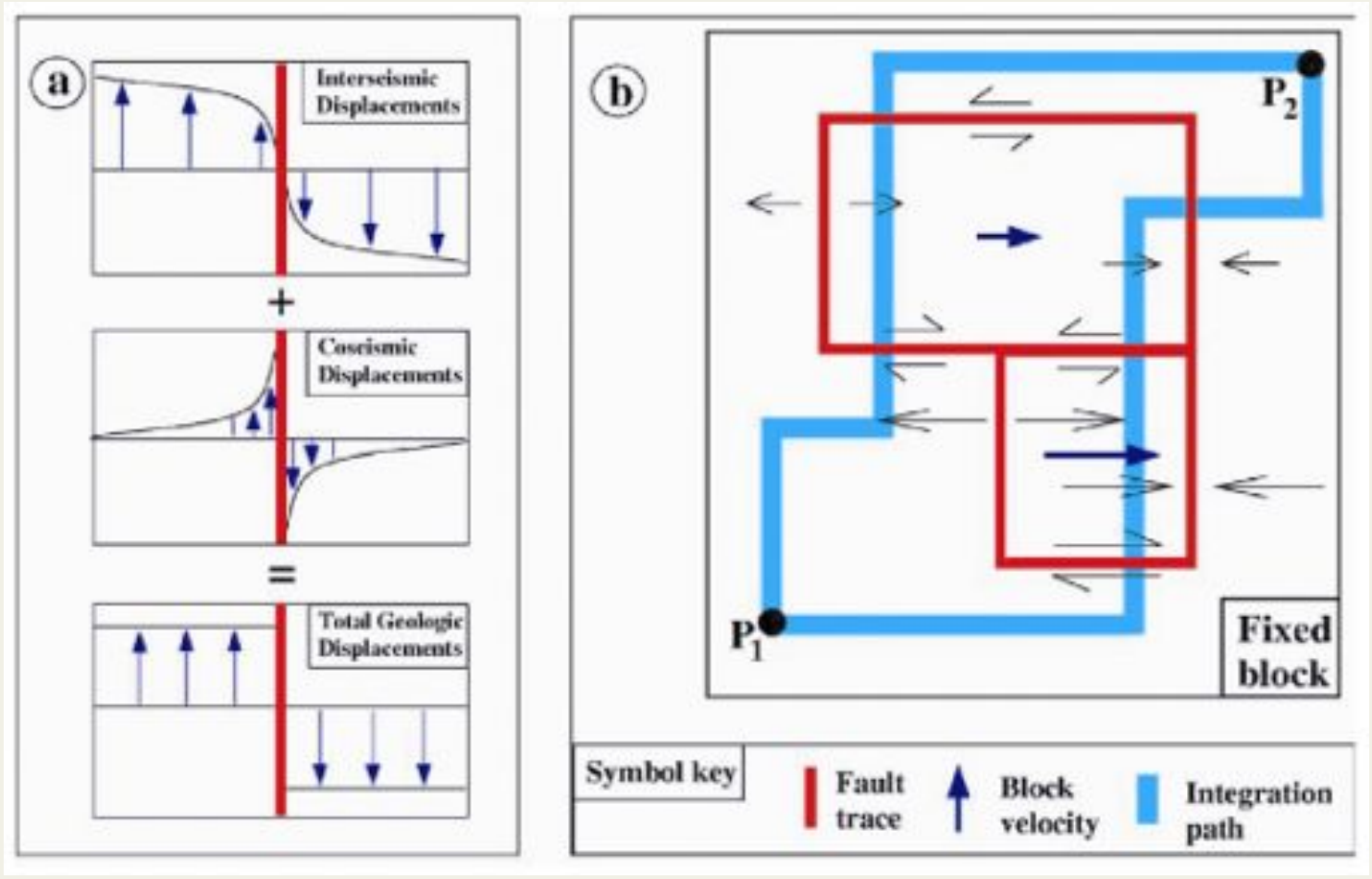
(from Alchalbi et al., 2010)



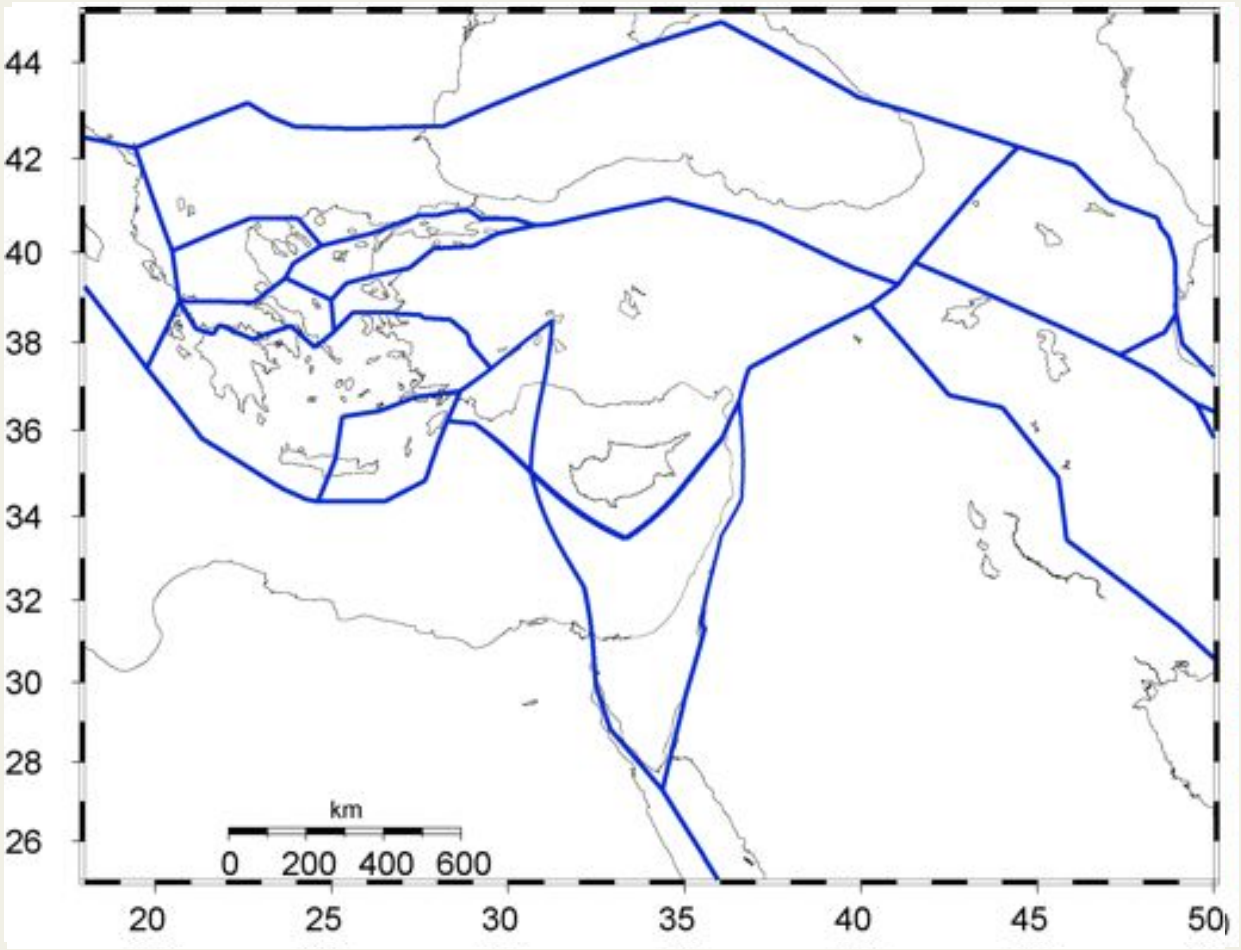


Block Model Schematic

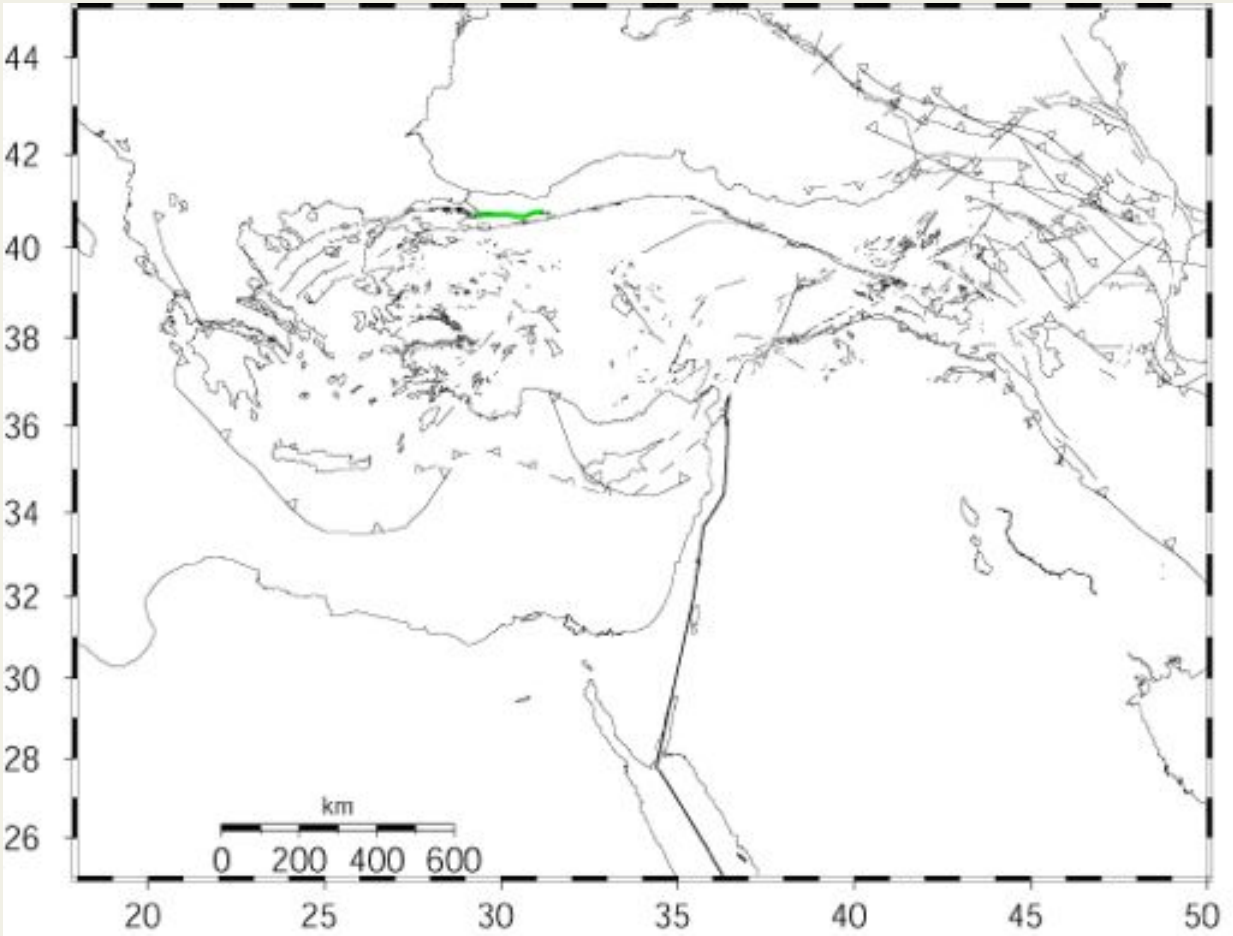
(from Meade et al., 2003)



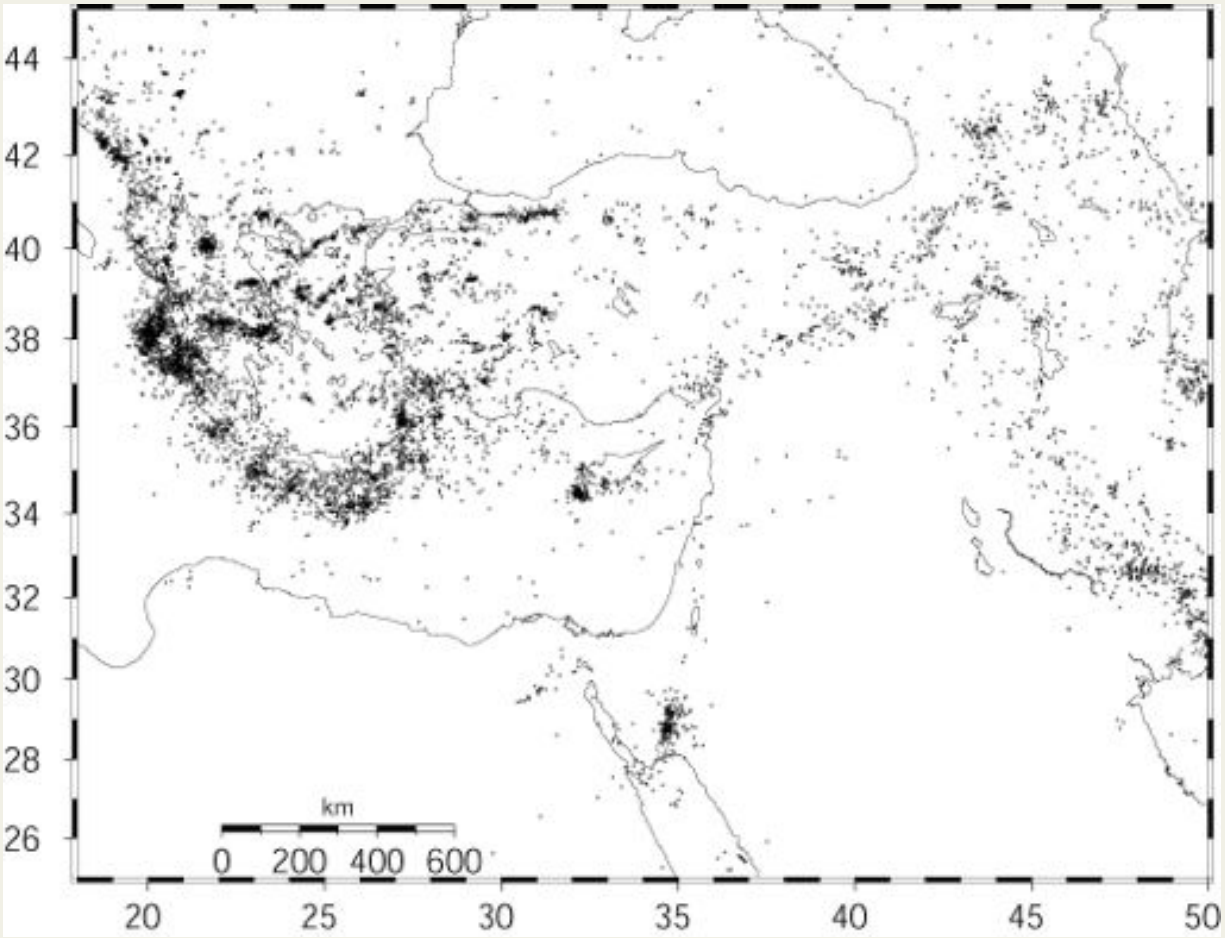
Building Block Model Boundaries



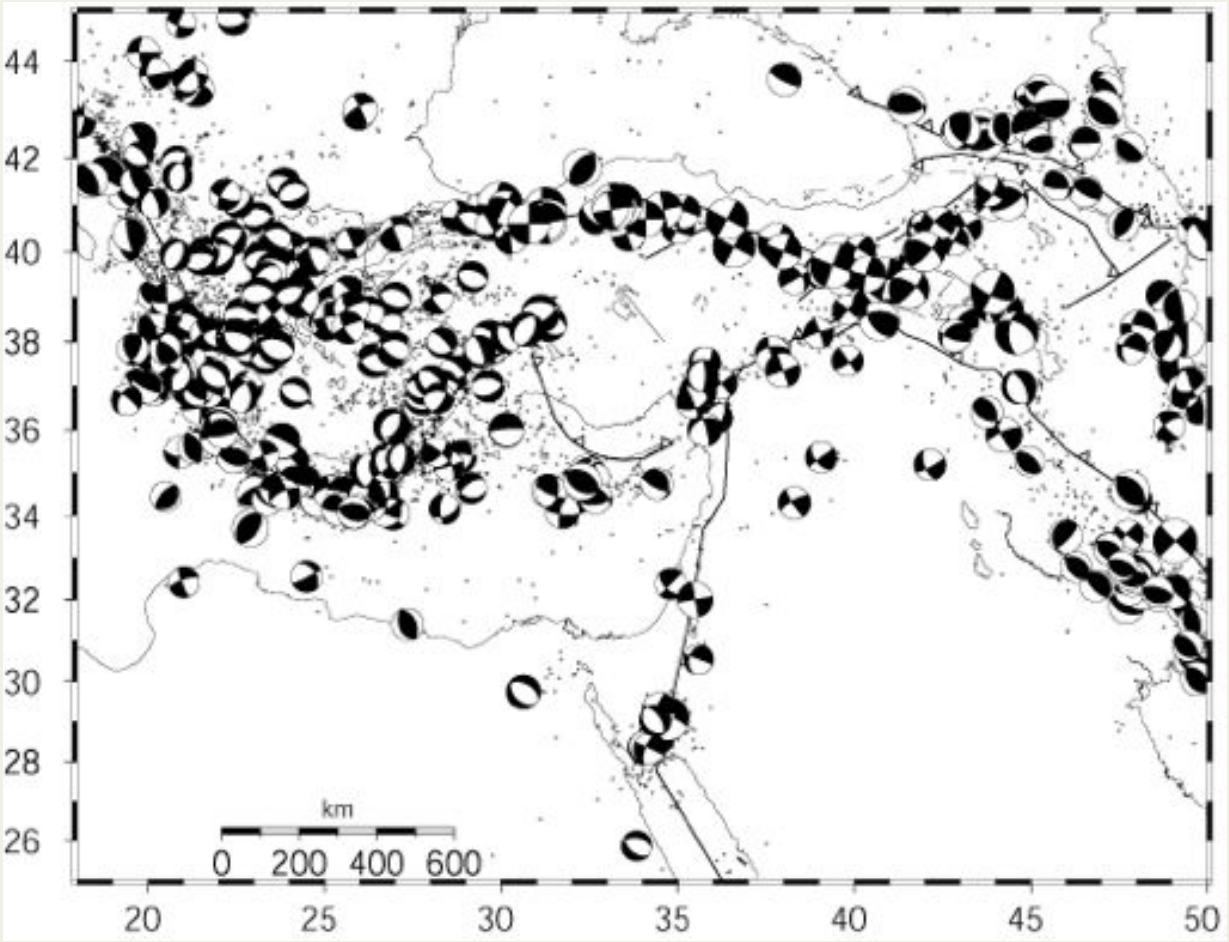
Building Block Model Boundaries



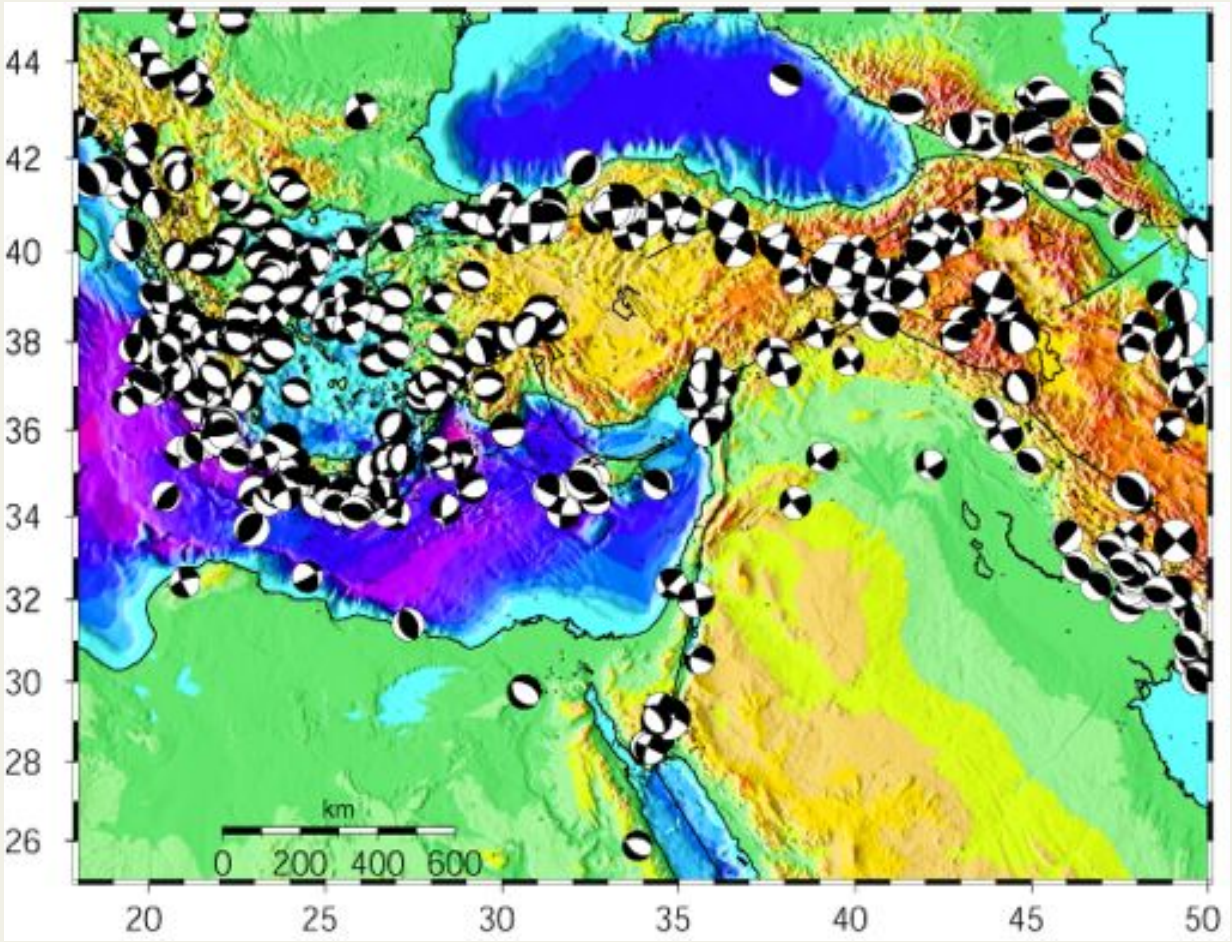
Building Block Model Boundaries



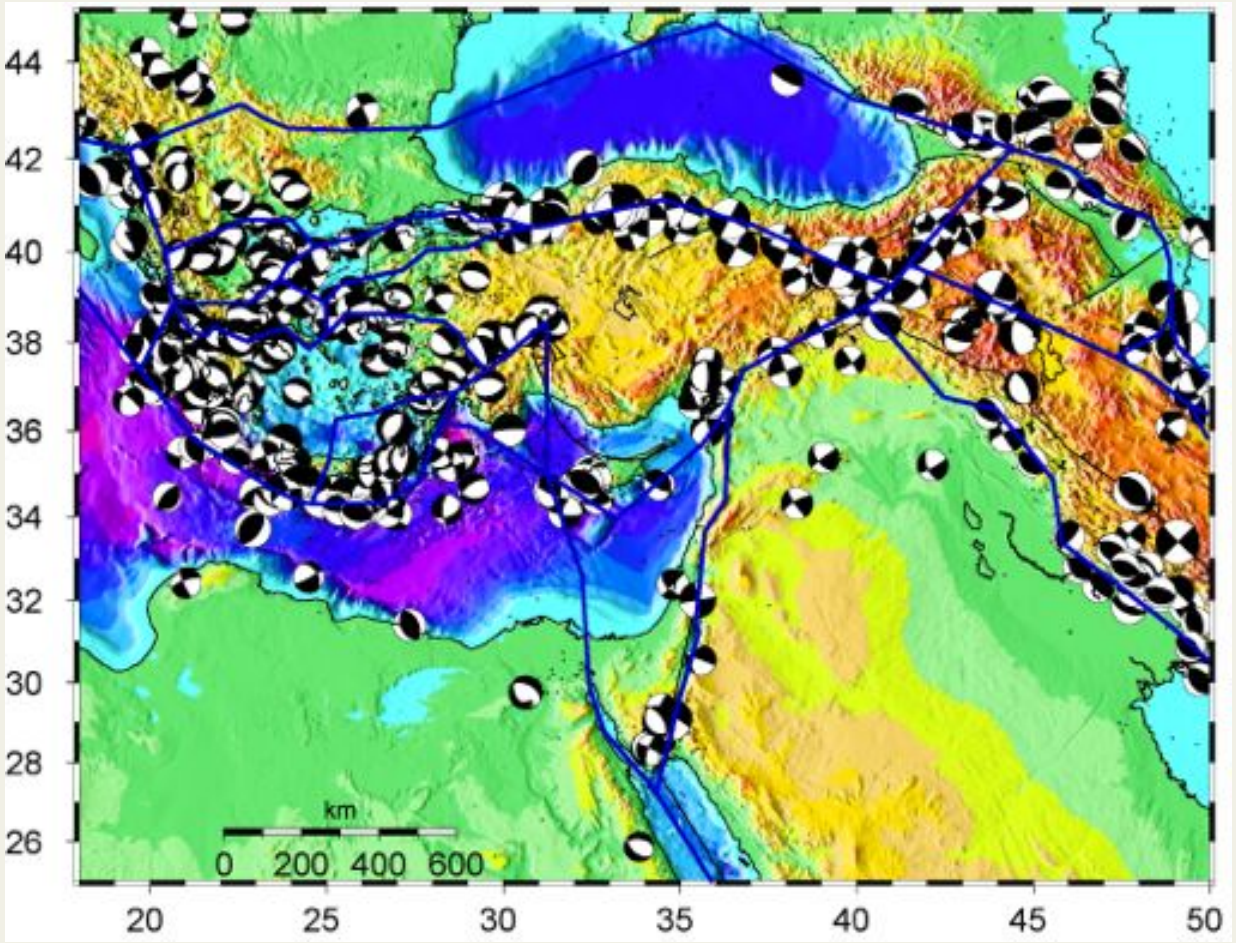
Building Block Model Boundaries



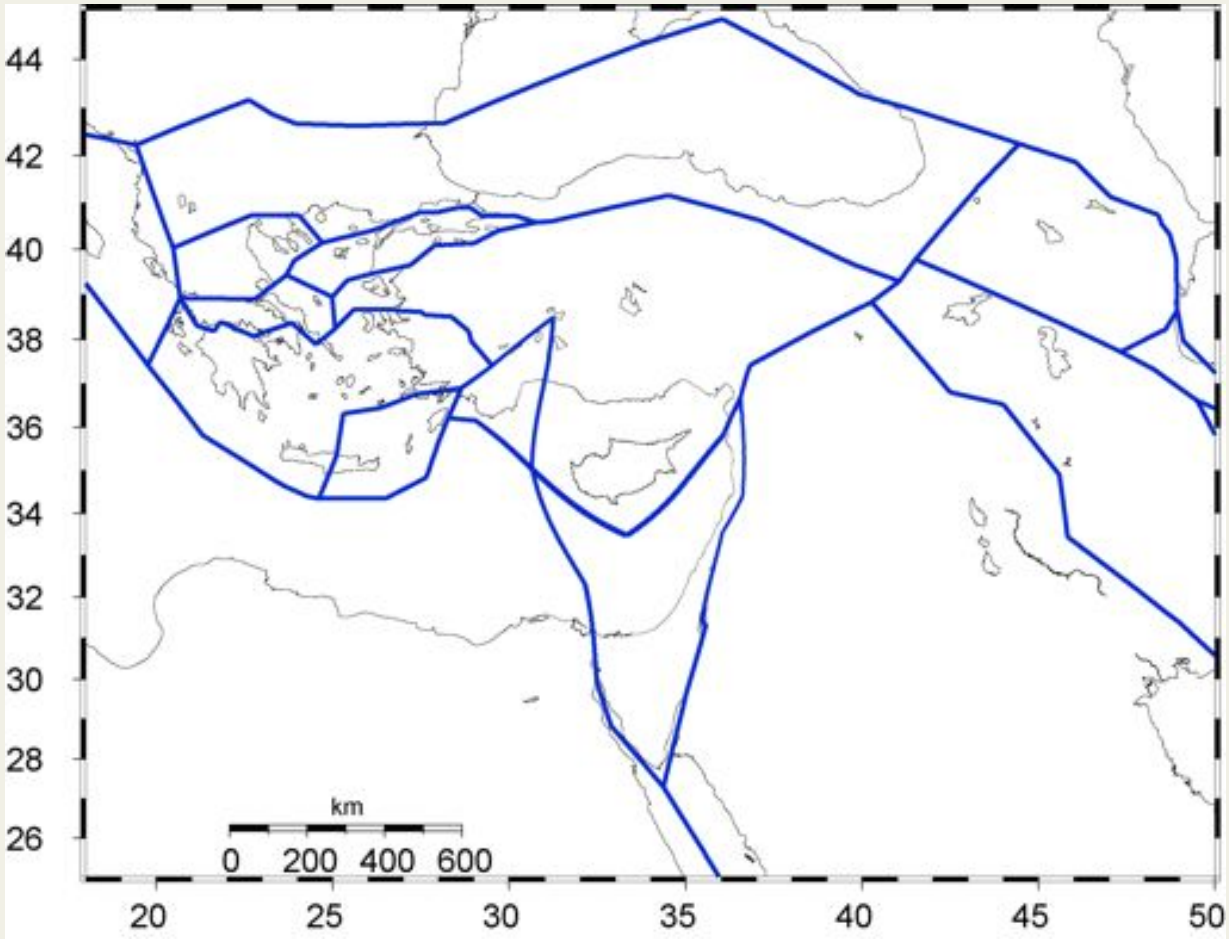
Building Block Model Boundaries



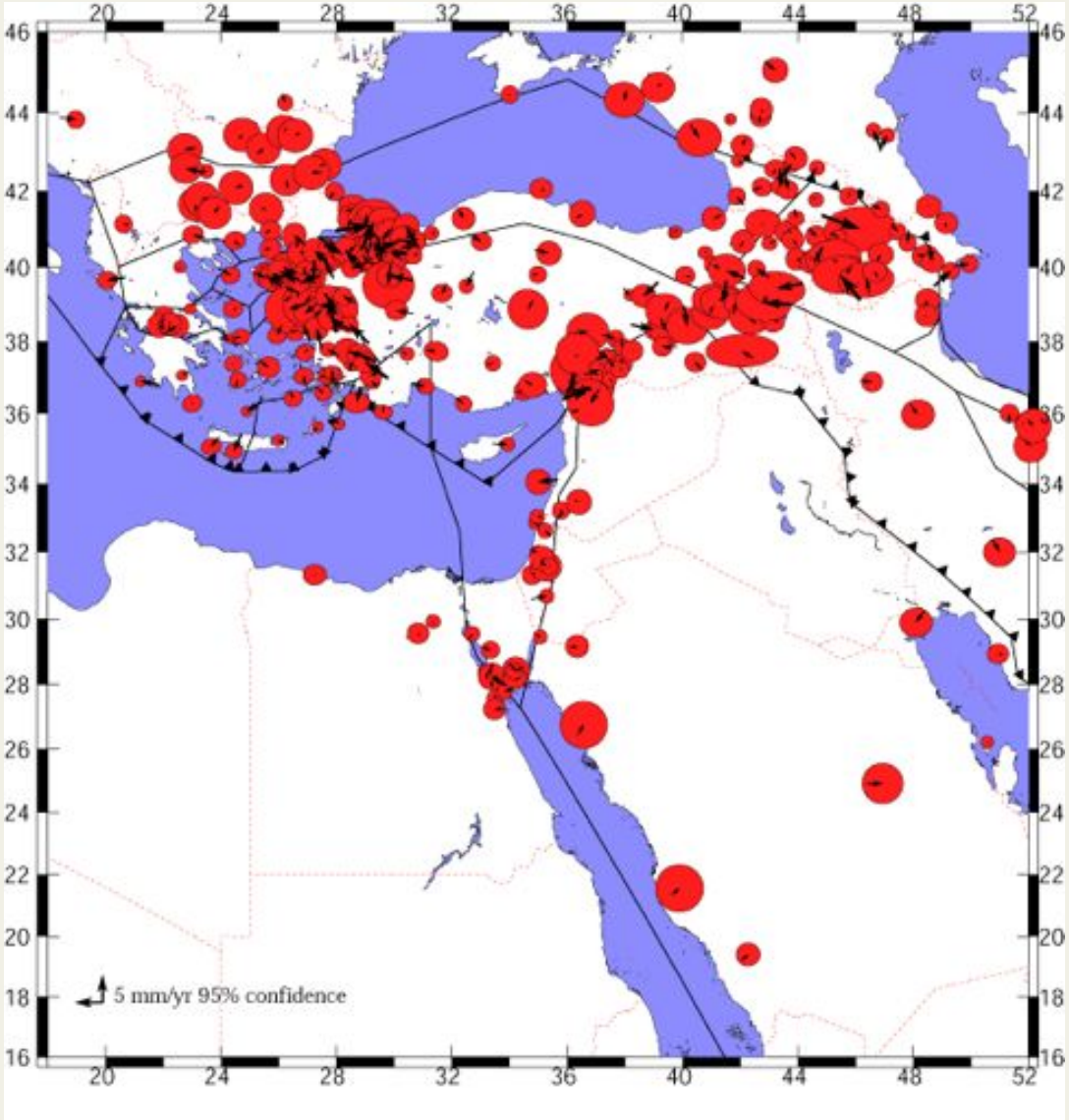
Building Block Model Boundaries



Building Block Model Boundaries



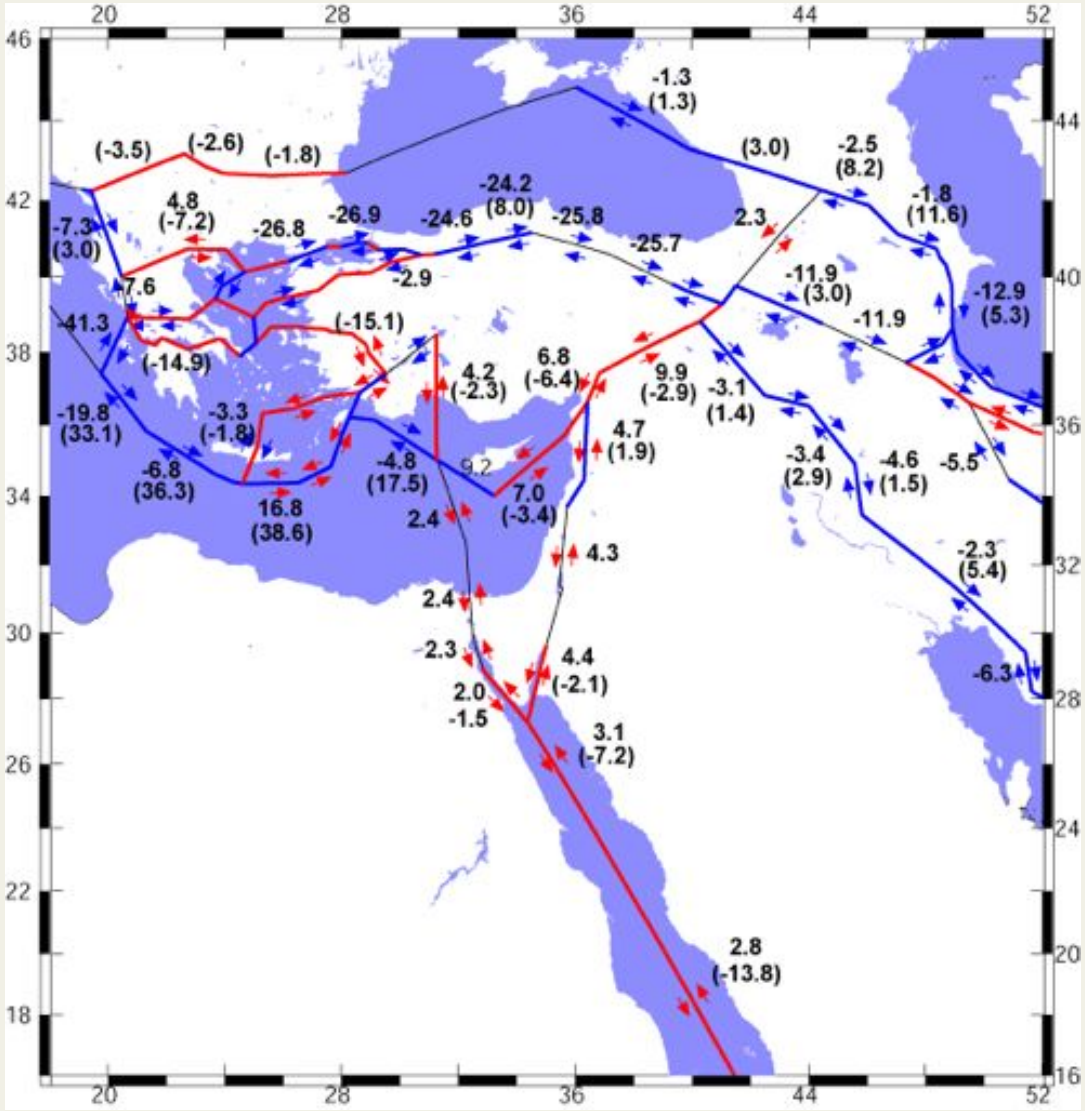
Minimize Residual Velocities



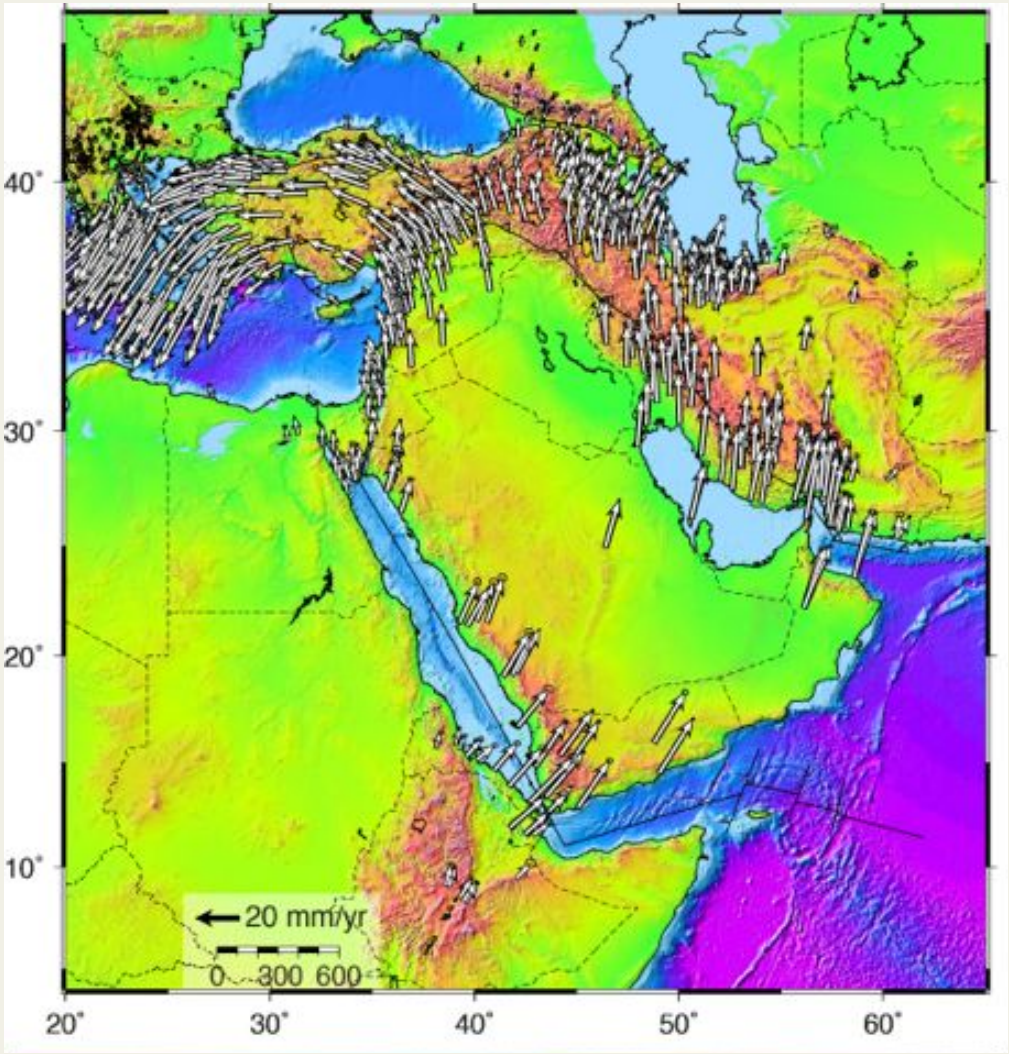
Estimate Slip Rates

Critical assumptions:

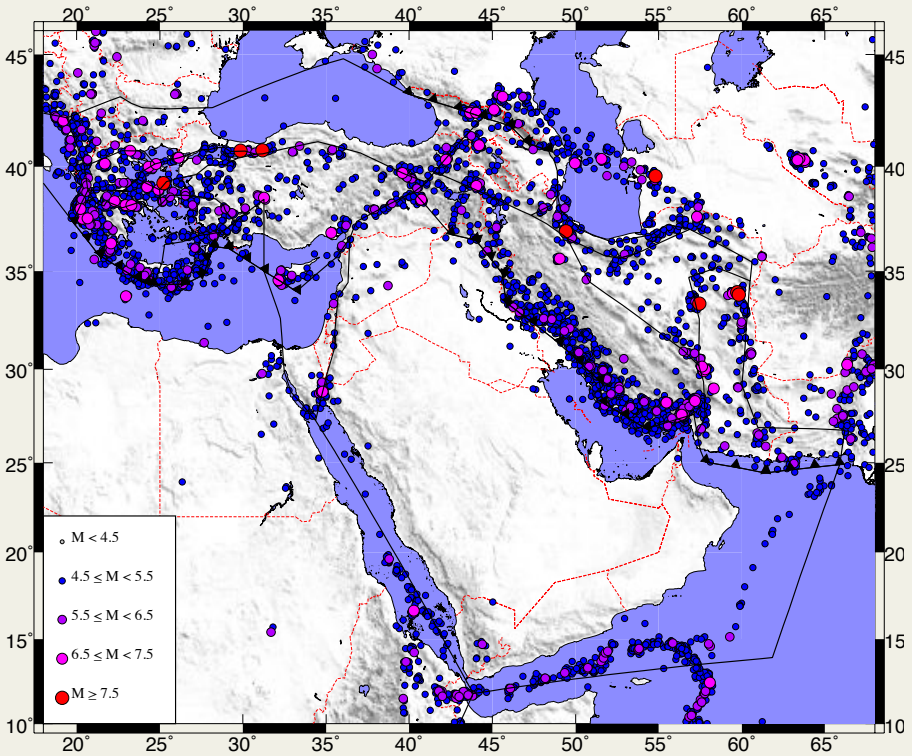
1- No internal deformation of blocks.
2- No missing blocks.

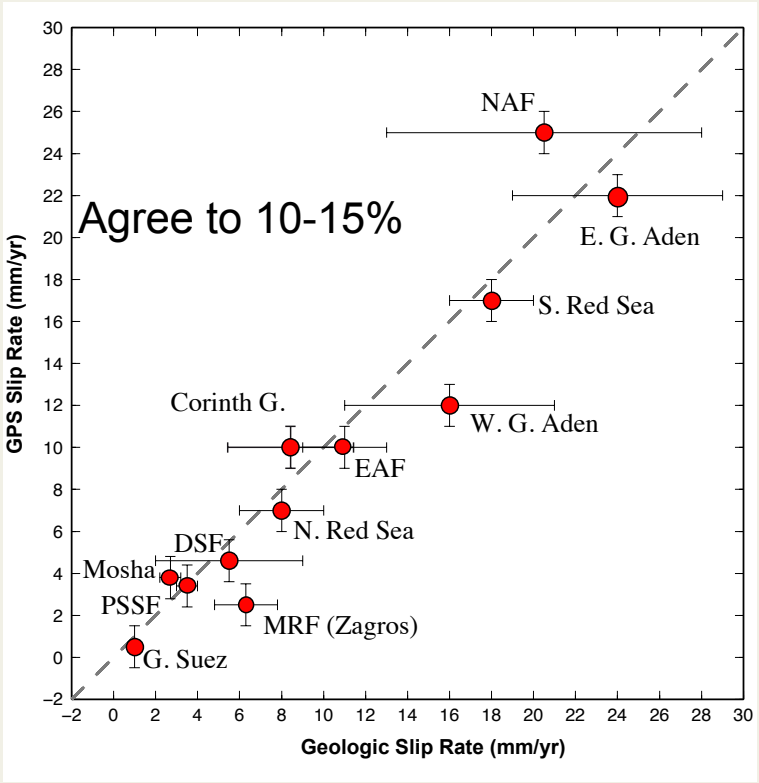


GPS and Geologic Plate Motions and Deformation



Geodetic vs. Geologic and Plate Tectonic Rates

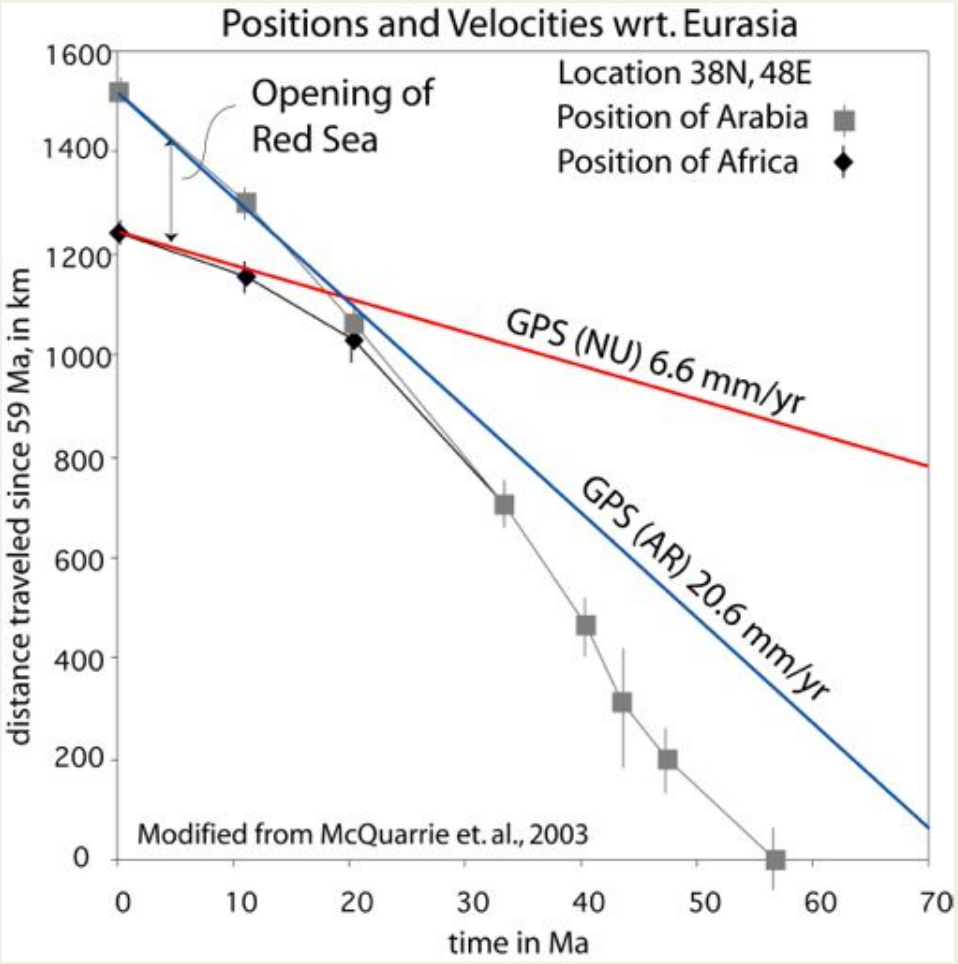




EULER VECTORS

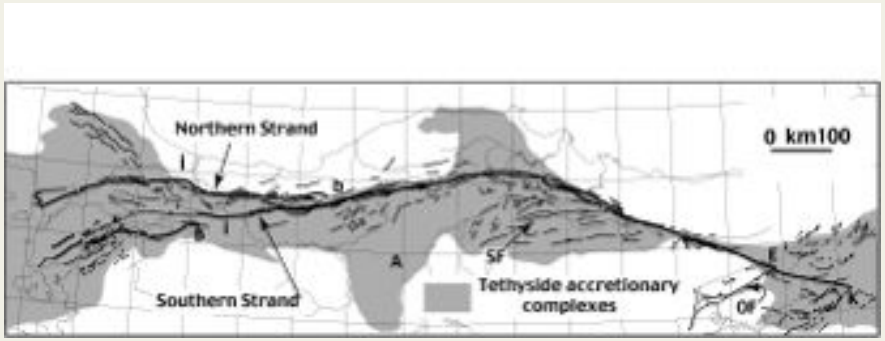
Lat (°N)	Long. (°E)	Rate (°/Ma ccw)	Ref
31.7 ± 0.2	24.6 ± 0.3	0.37 ± 0.01	JGR 06
32.8 ± 1.2	23.8 ± 2.7	0.39 ± 0.05	DeMets et al. (2010)

GPS and NU/AR-EU Plate Motions

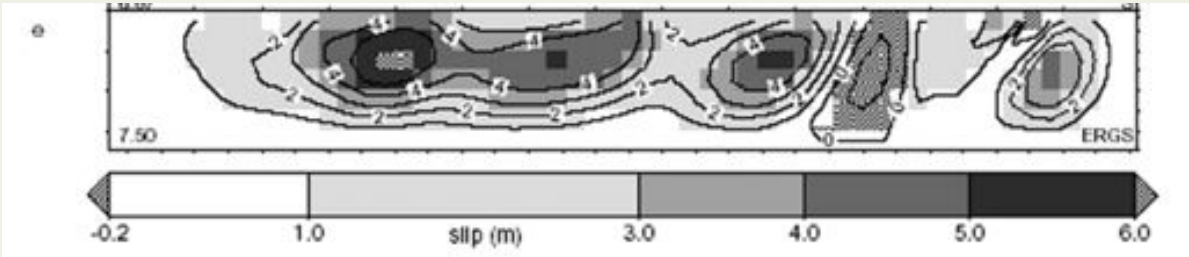


AR-EU no significant change since at least 20 Ma and NU-EU since 11 Ma

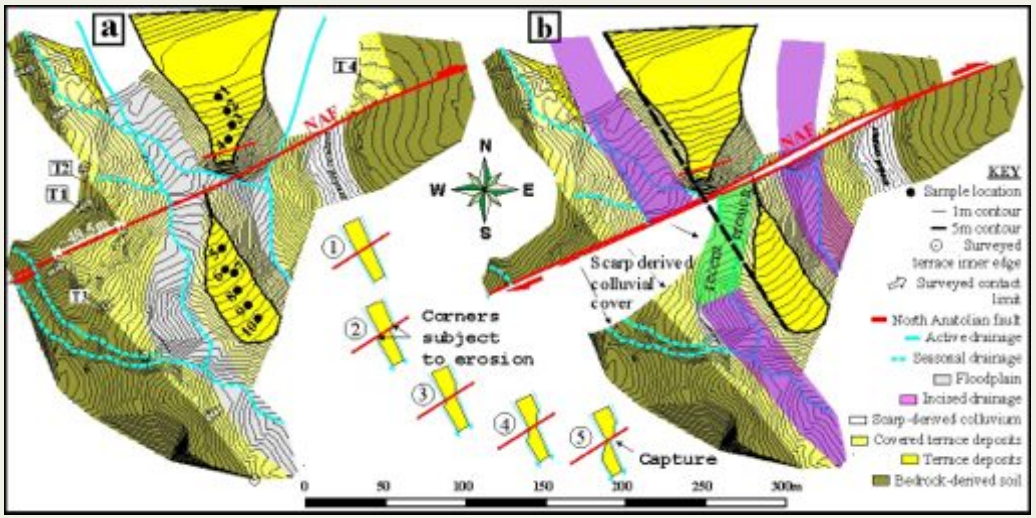
Surface vs. Slip at Depth



North Anatolian Fault “keirogen”, Sengor et al. (2004)



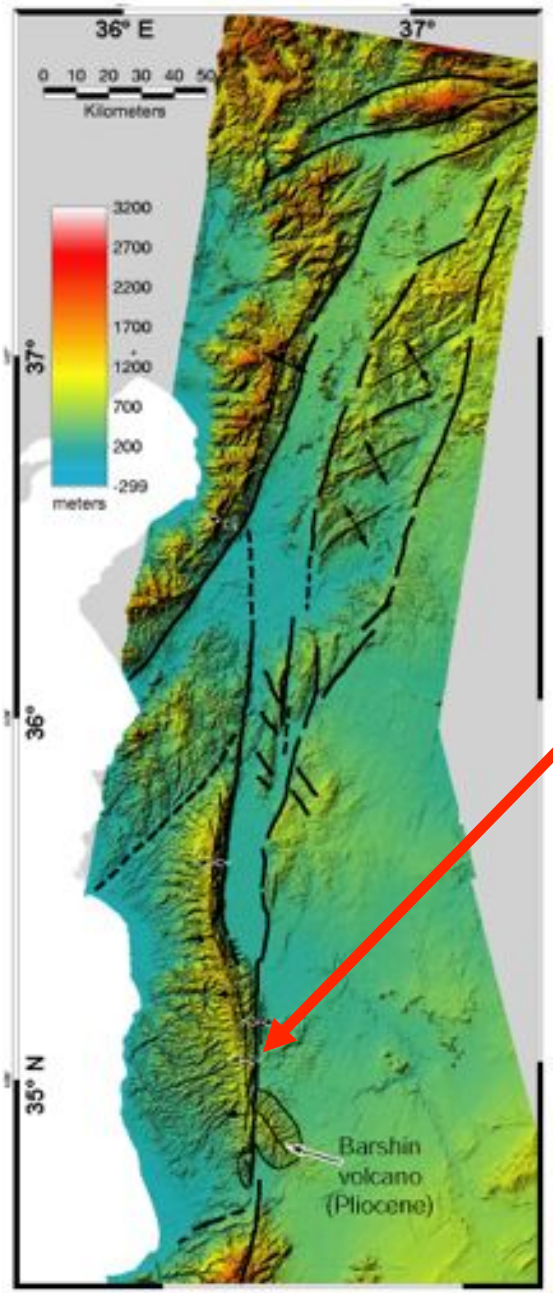
Izmit EQ slip, Feigl et al. (2002)

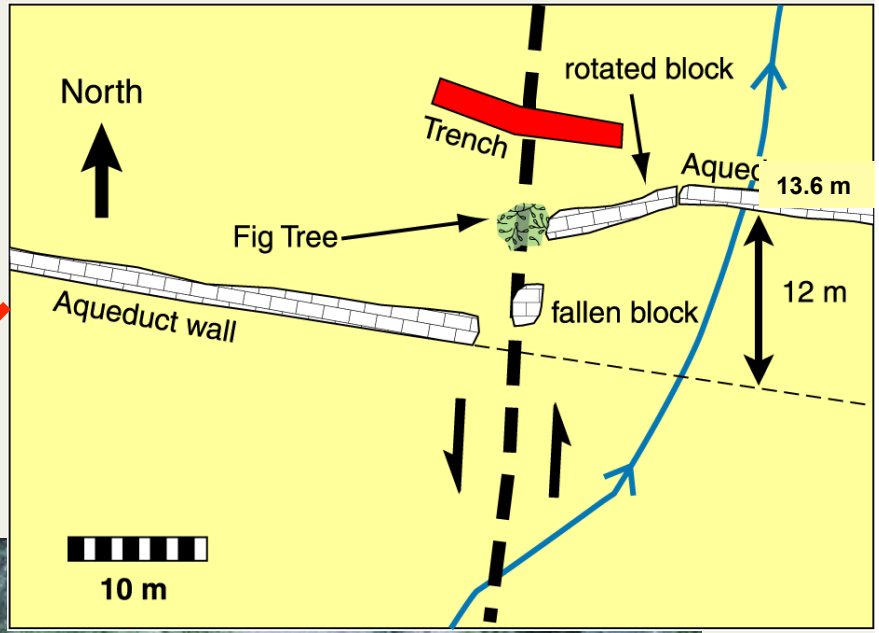


Geology fault slip rate estimated using surface offsets and dates:
~ 20 ± 5 mm/yr
Kozaci et al. (2007)

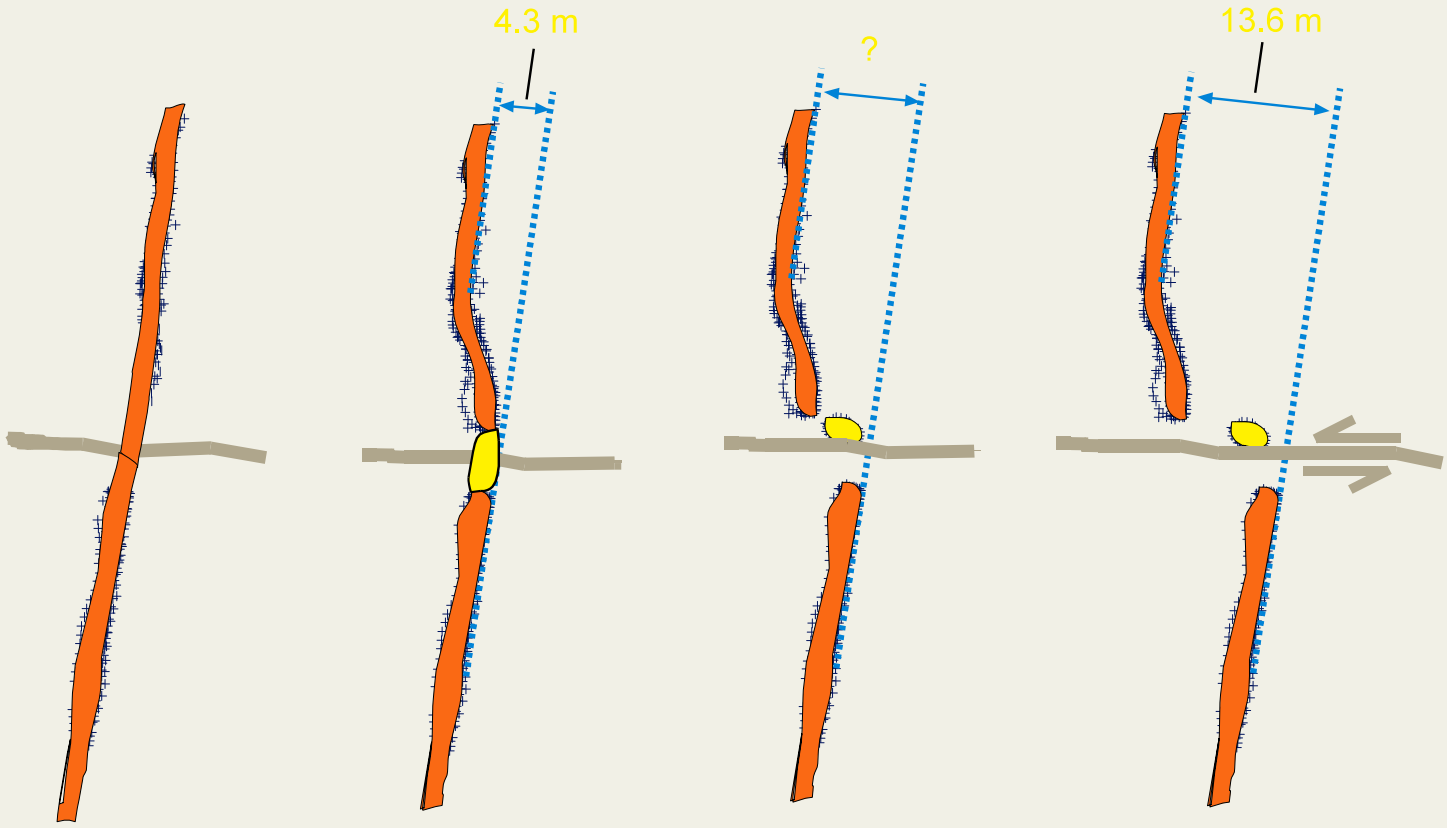
Geodetic fault slip rate from elastic block model :
~ 24 ± 2 mm/yr
DIFFERENT?

Northern Dead Sea Fault



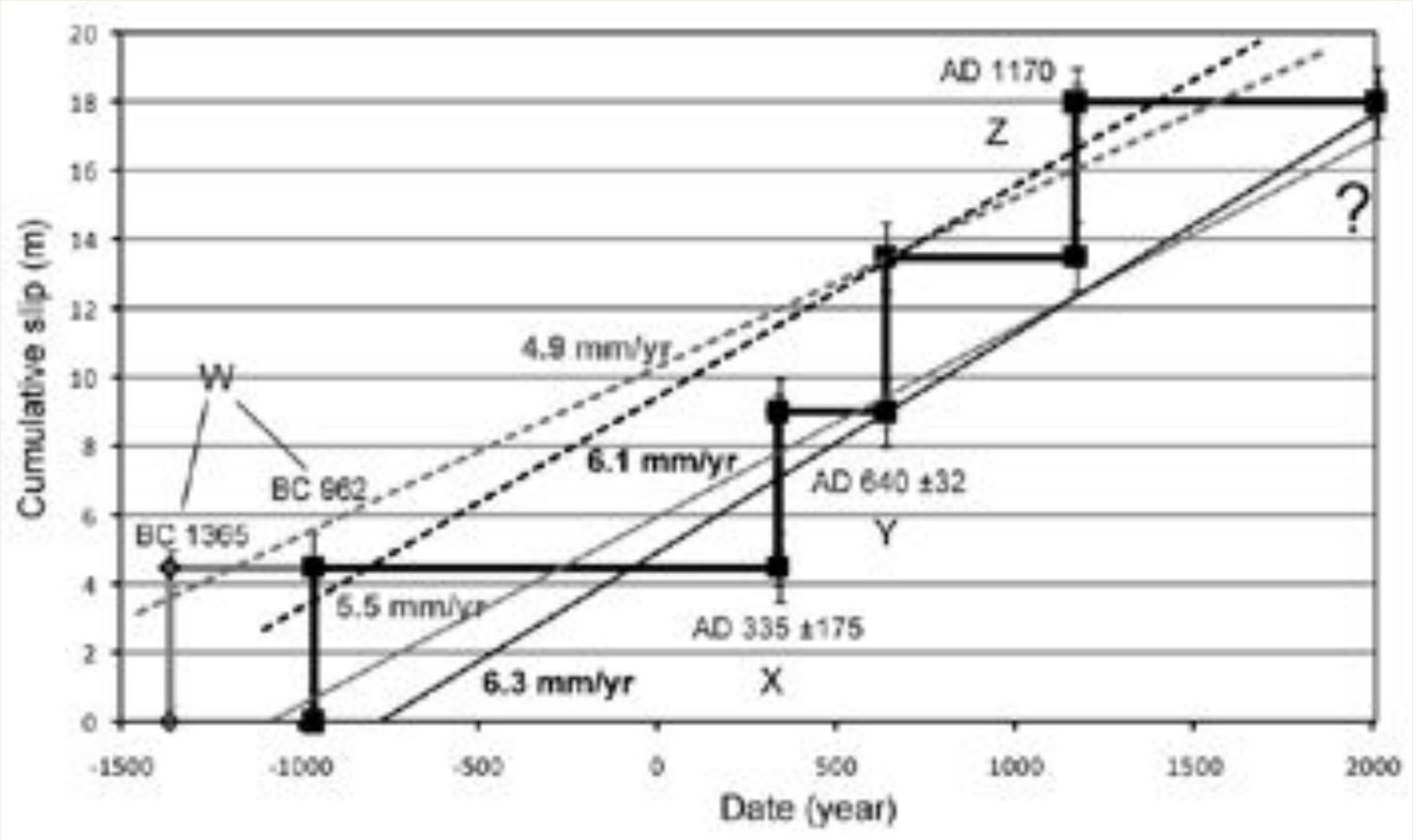


Al Harif aqueduct - Faulting episodes



Sbeinati et al. (2010)

Paleoseismic Slip Rate for Northern DSF?

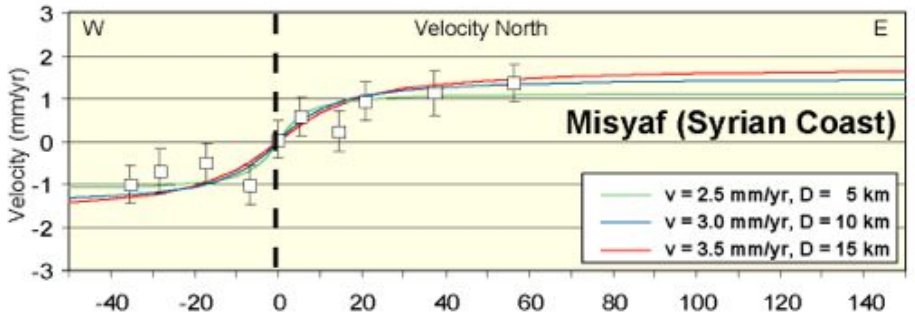


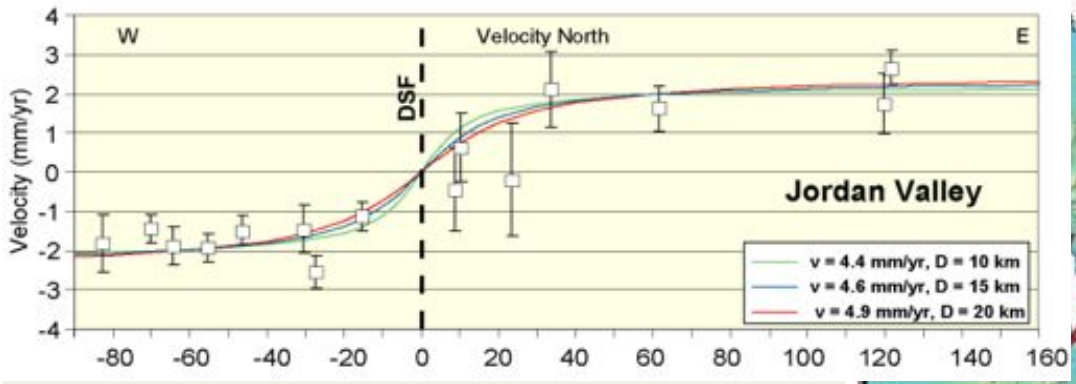
This seems a bit fast?

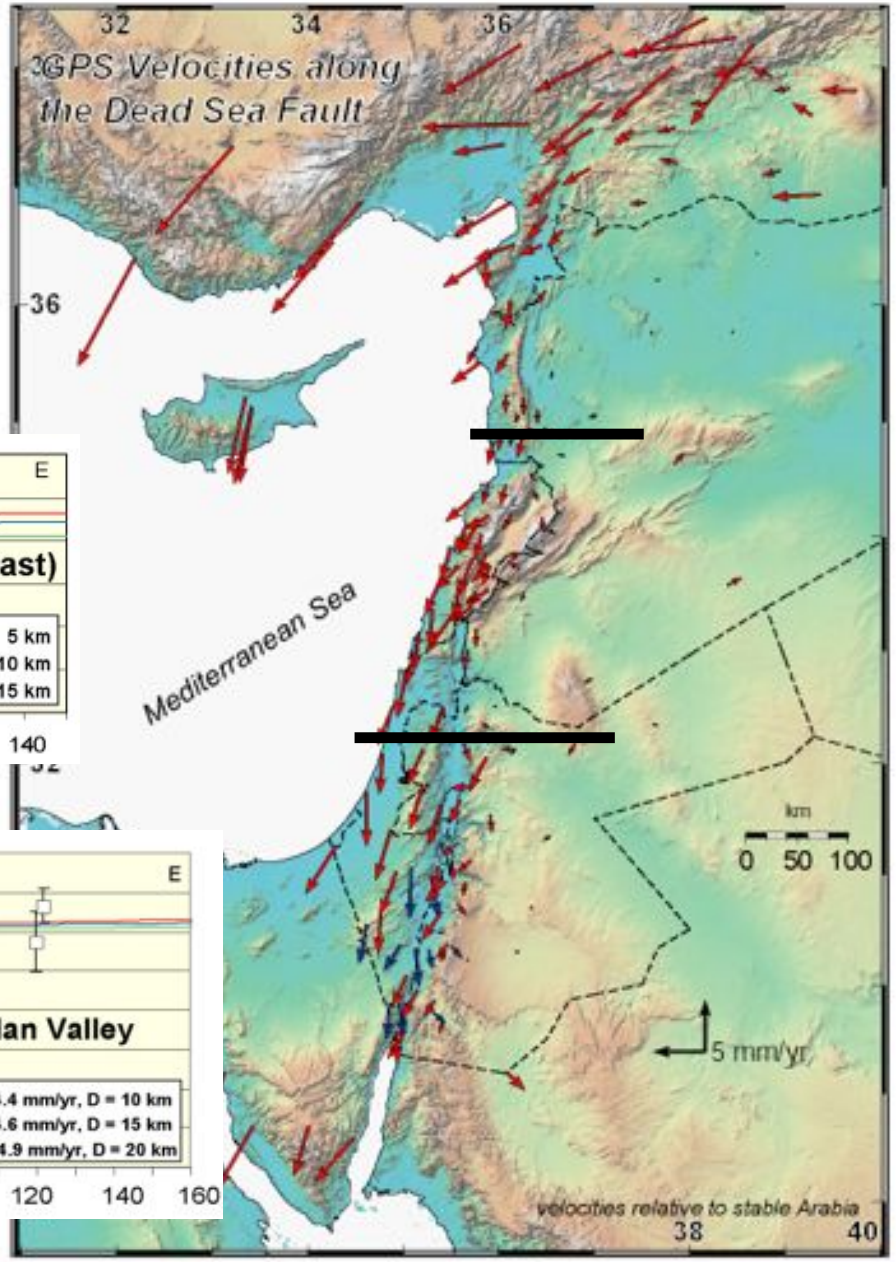
Note: Displacement for 1,000-1400 BC event is assumed.

(Sbeinati et al., 2010)

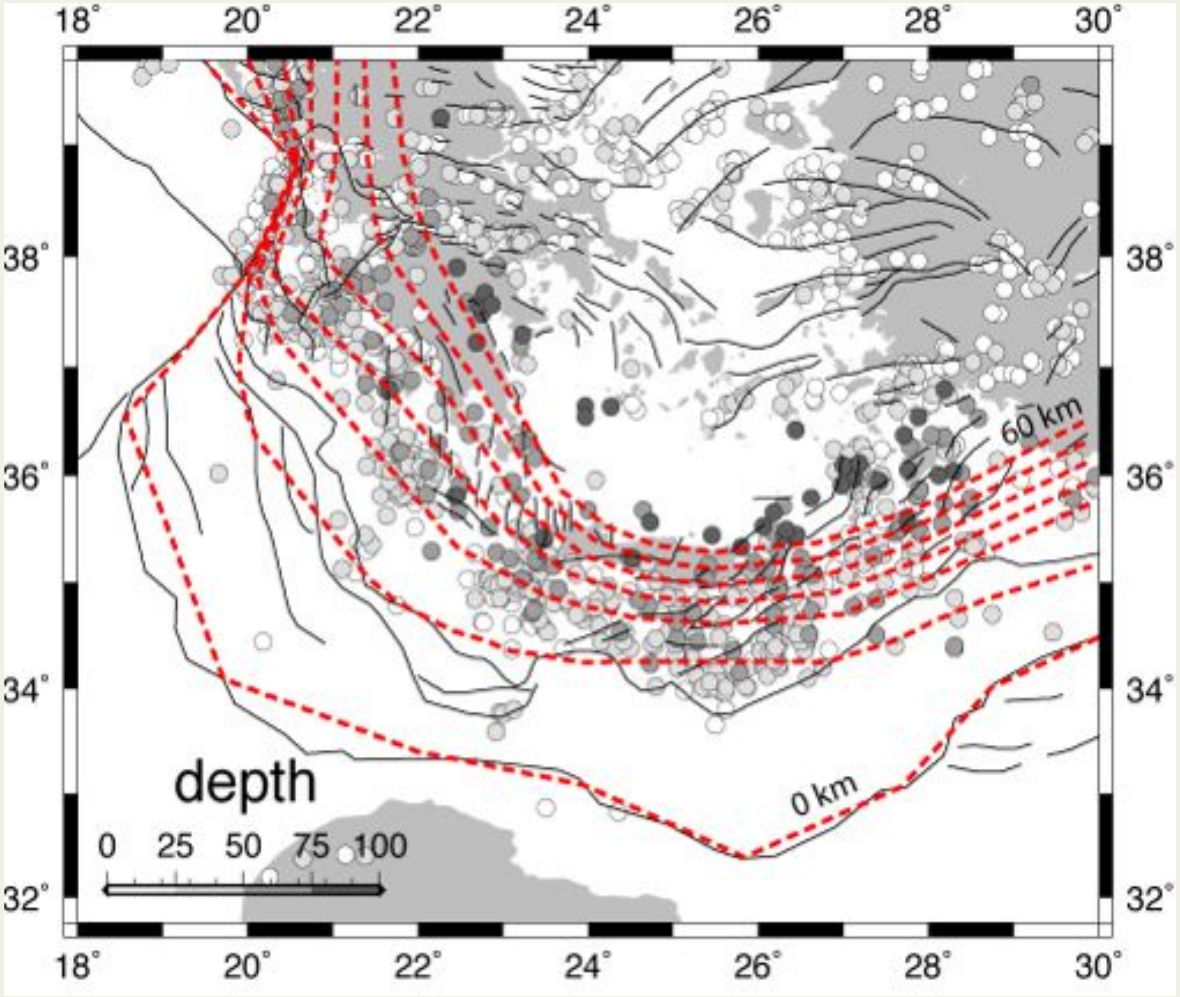
- GPS slip-rate and along-strike change in velocities?!





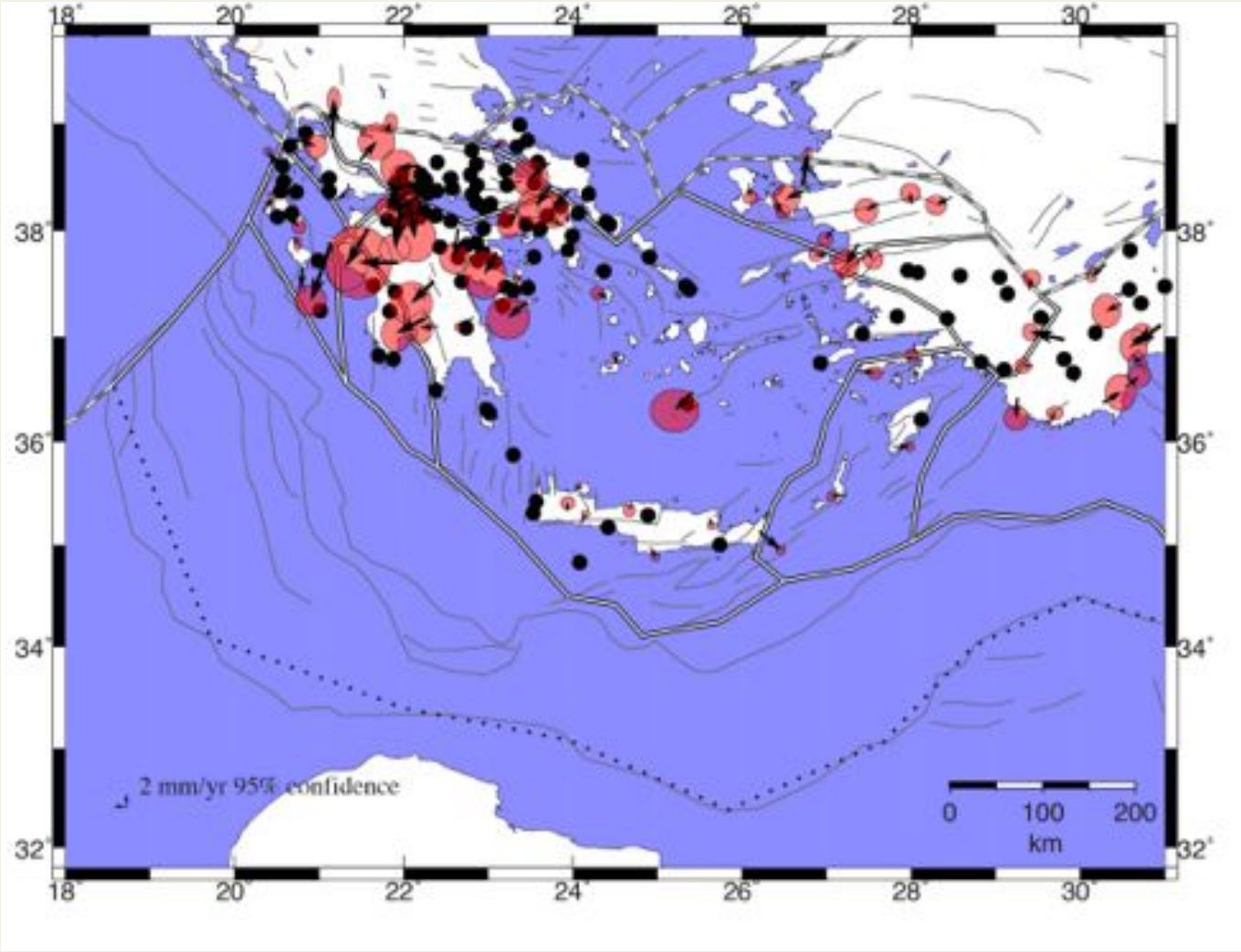


Strain Accumulation on the Hellenic Arc

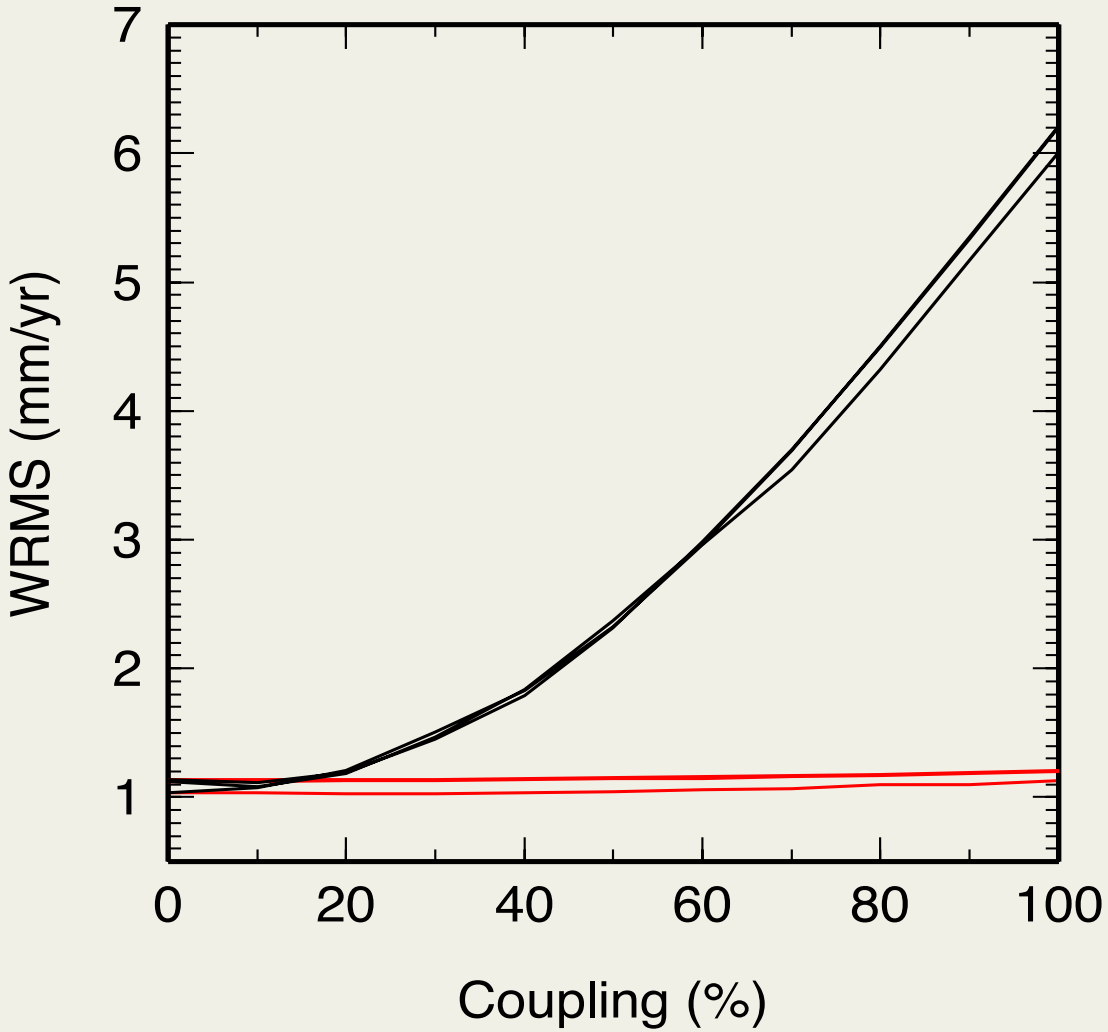


Aegean/SW Turkey Block Model

(from Vernant et al., 2013)

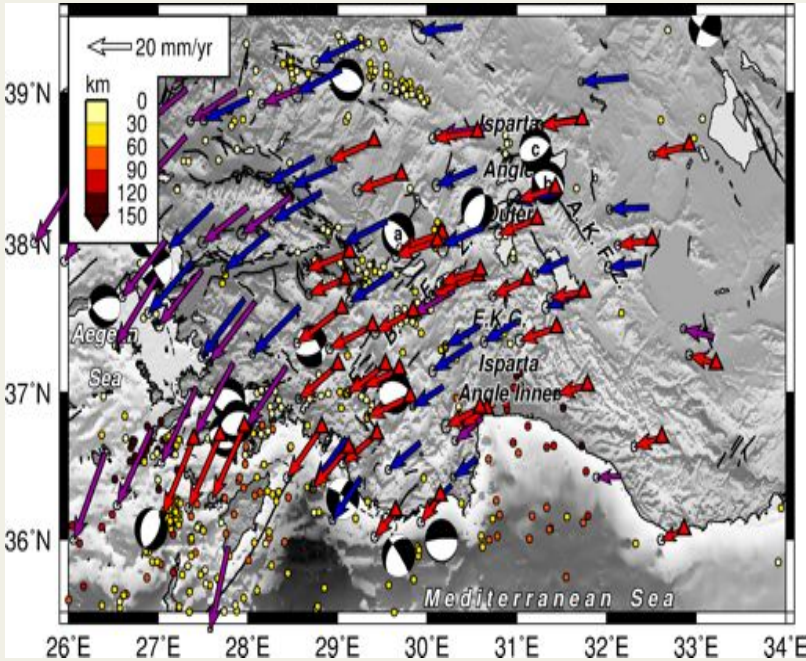


Coupling on Hellenic interface

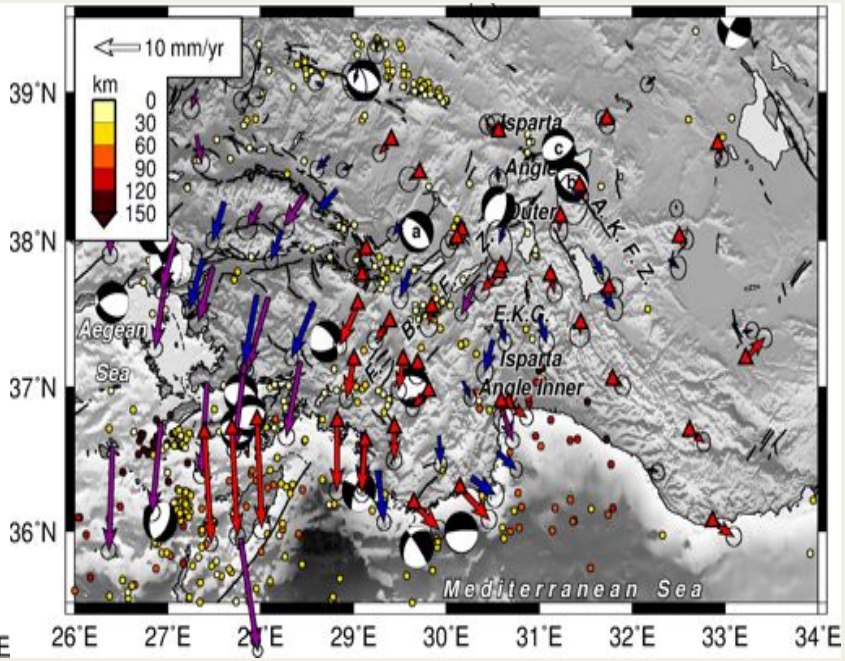


SW Anatolia Motion Towards Cyprus Arc

Eurasia-fixed



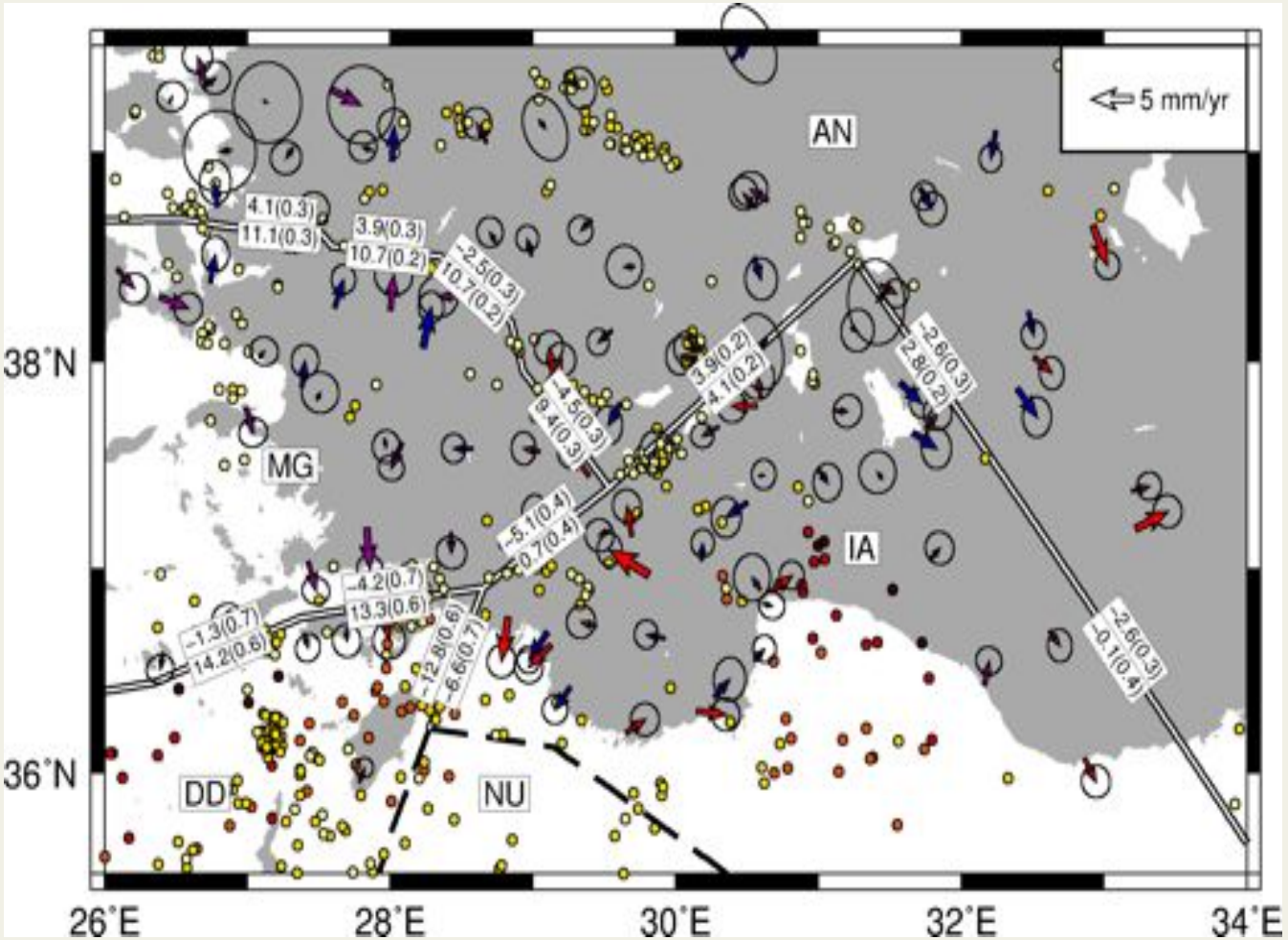
Anatolia-fixed



As the Aegean, SW Turkey is moving (extending) towards the offshore trench system

(from Tiryakioğlu et al., 2013)

Block Model for Isparta Angle

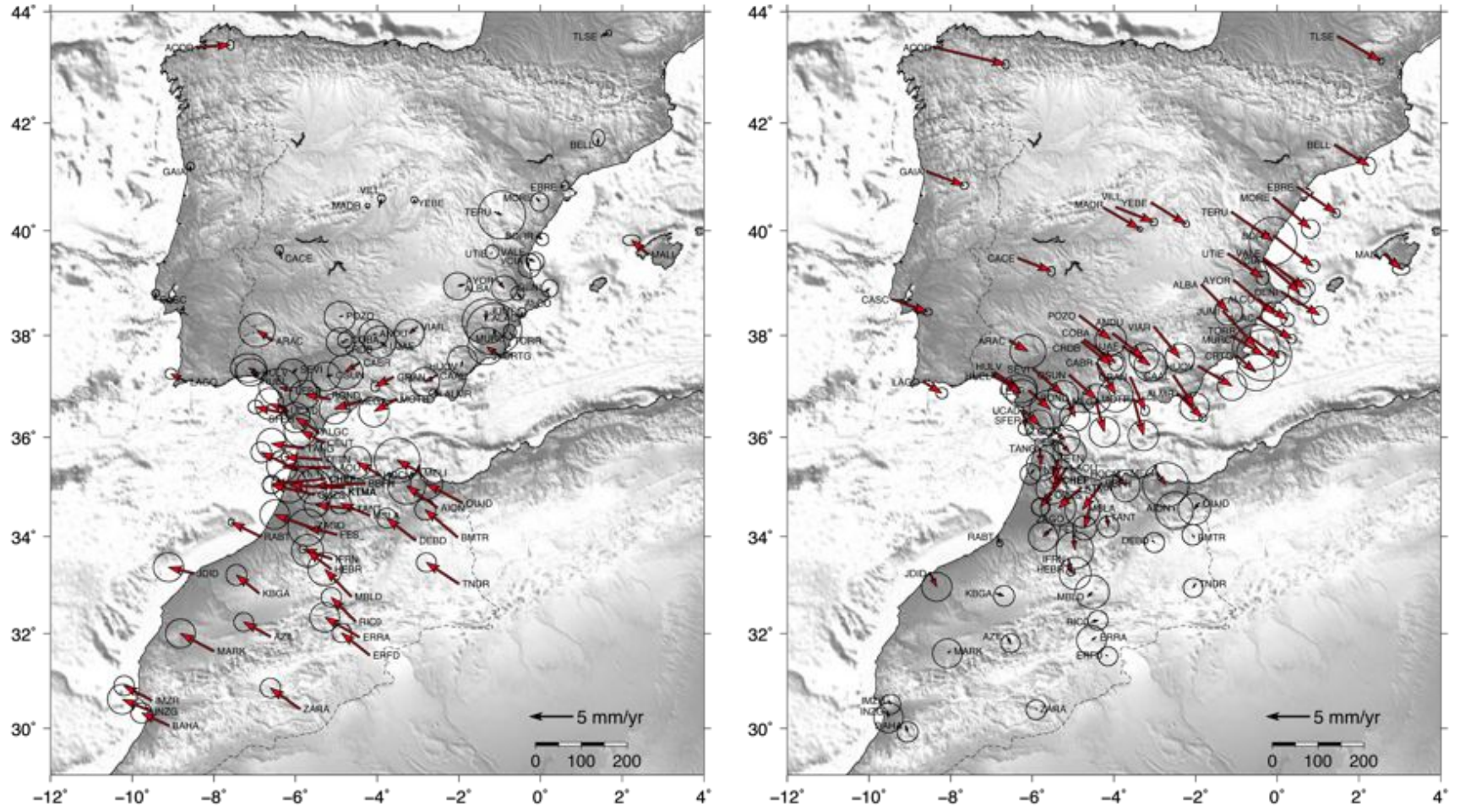


(from Tiryakioğlu et al., 2013)

W. Mediterranean

GPS Velocities wrt Eurasia

GPS Velocities wrt Africa

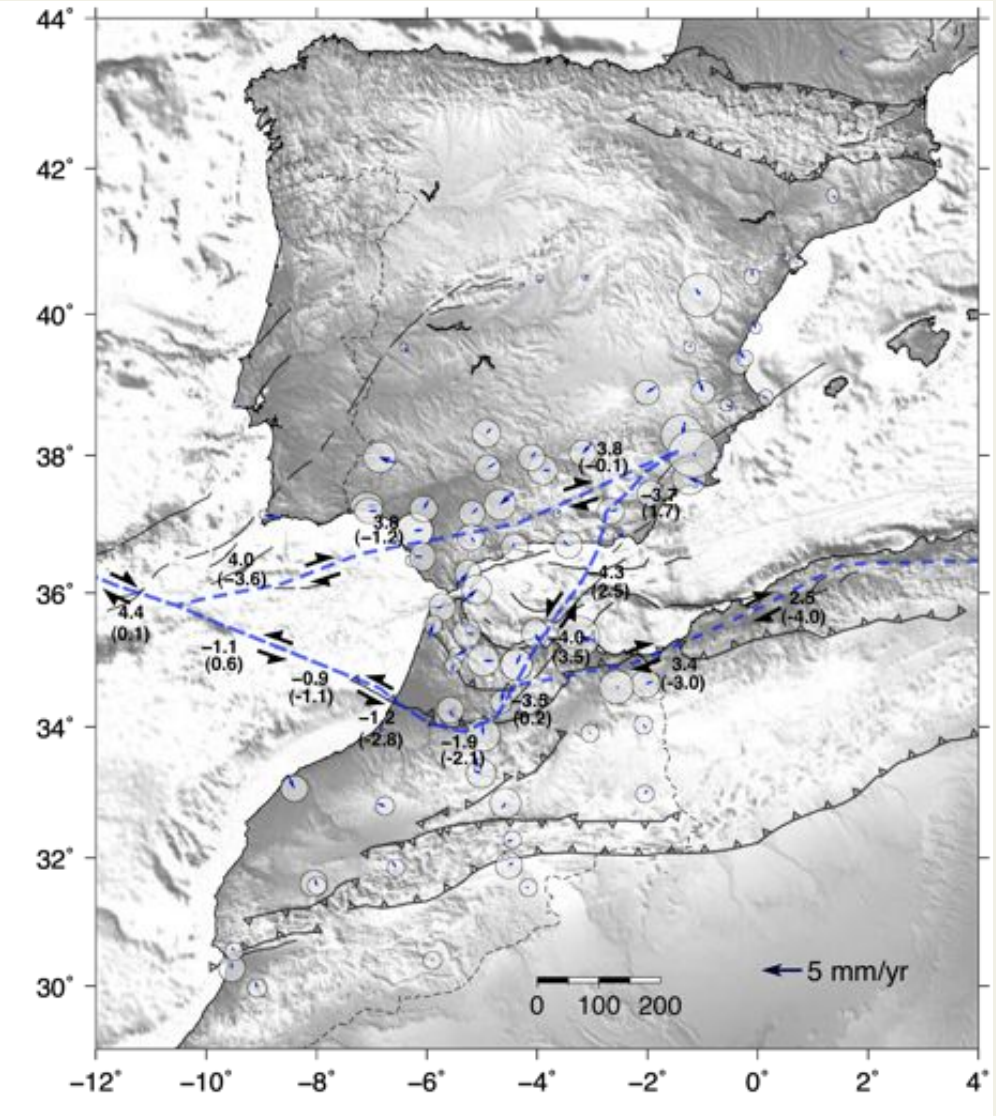


(from Koulali et al., 2011)

GPS Kinematics of W Mediterranean

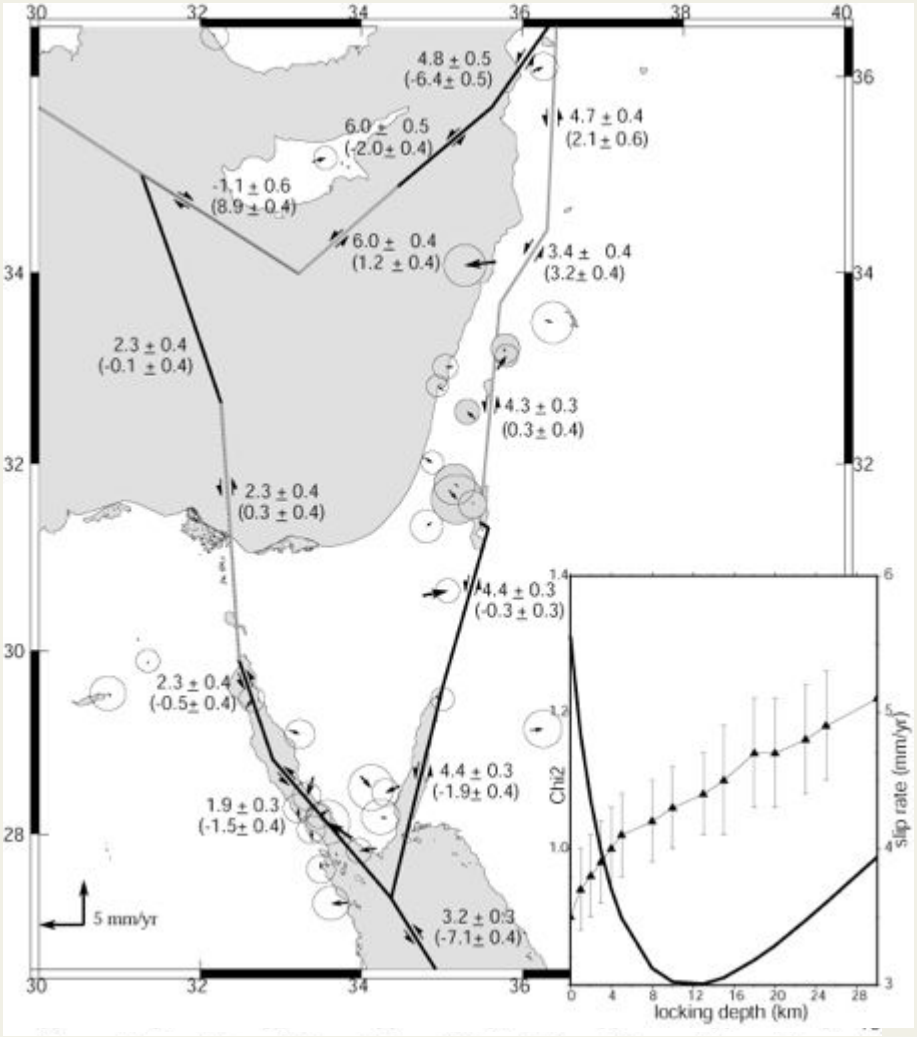
Block model residuals;
West translation and clockwise rotation

(from Koulai et al., 2011)



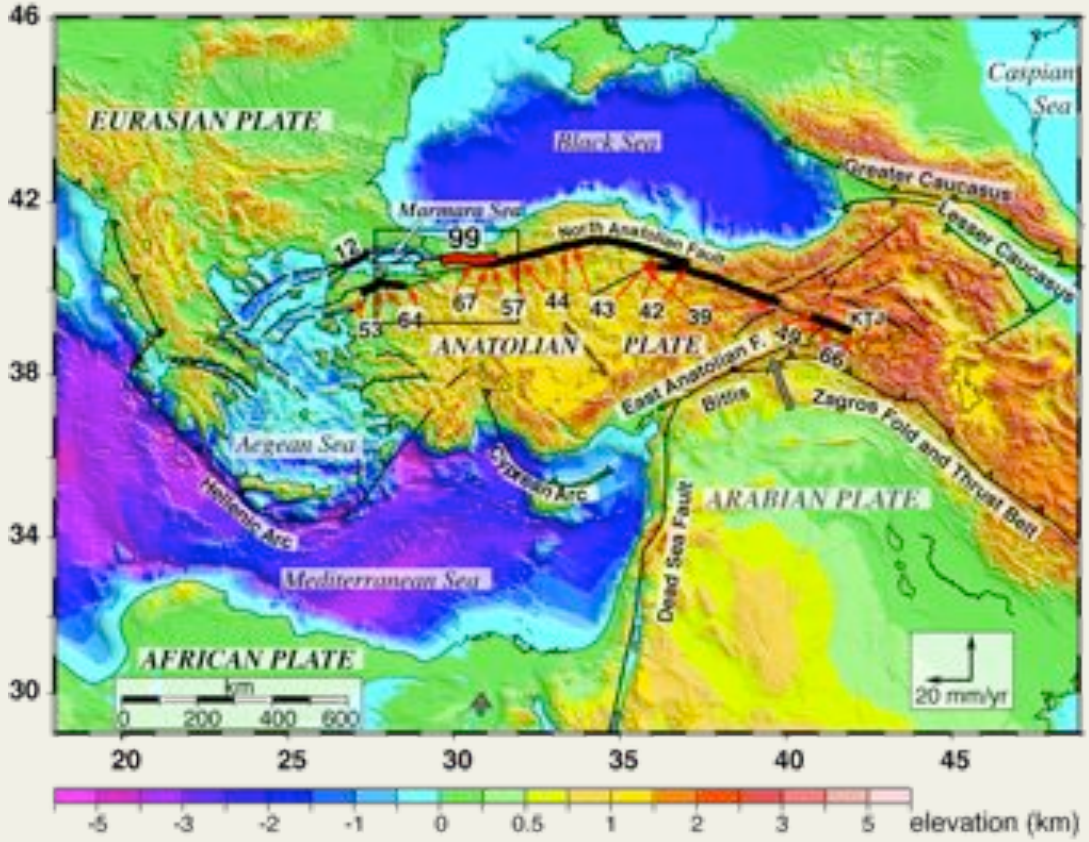
Sinai “Block”

(from Mahmoud et al., 2005)



Part II: Earthquake Cycle

20th Century NAF Earthquakes
What can we learn about the seismic cycle?

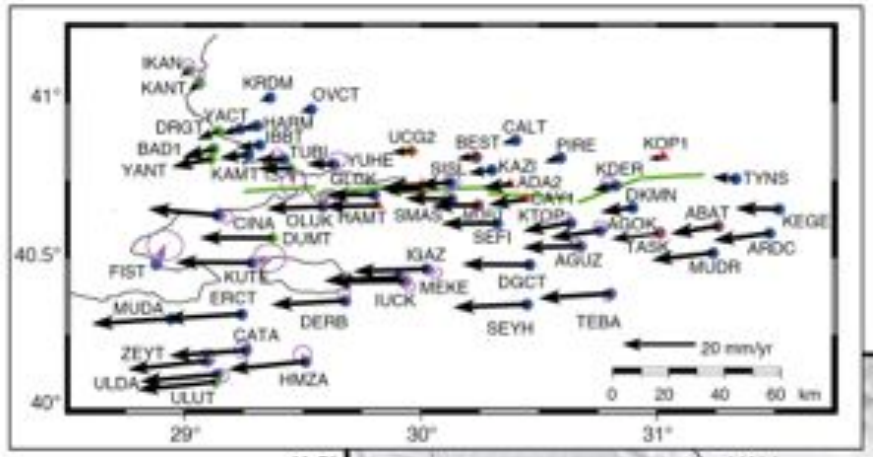


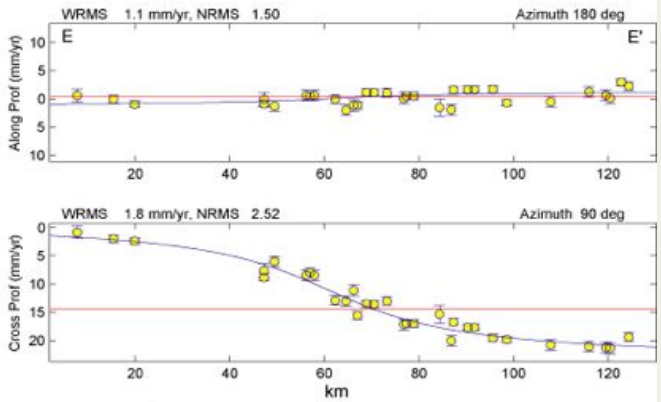
NAF: 1300 km long, ~10 M_w7 EQ's in the 20 century, ~15M people live within 50 km of the fault trace.

Izmit/Duzce EQ Sequence

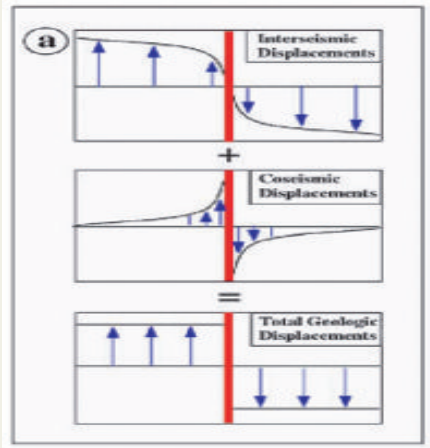
- Izmit M_w7.6 Aug 17th 1999 @ ~ 03:00 local
  - Rupture length 150 km
  - Hypo-central depth ~17 km
  - Damage ~$10B US
  - Segmented vertical fault plane
  - Up to 5 m right lateral strike slip motion
  - Killed ~30,000
- Duzce M_w7.2 Nov 12th 1999 @ ~19:00 local
  - Rupture length 80 km
  - Hypo-central depth ~15 km
  - Segmented south dipping fault plane
  - Killed ~1000

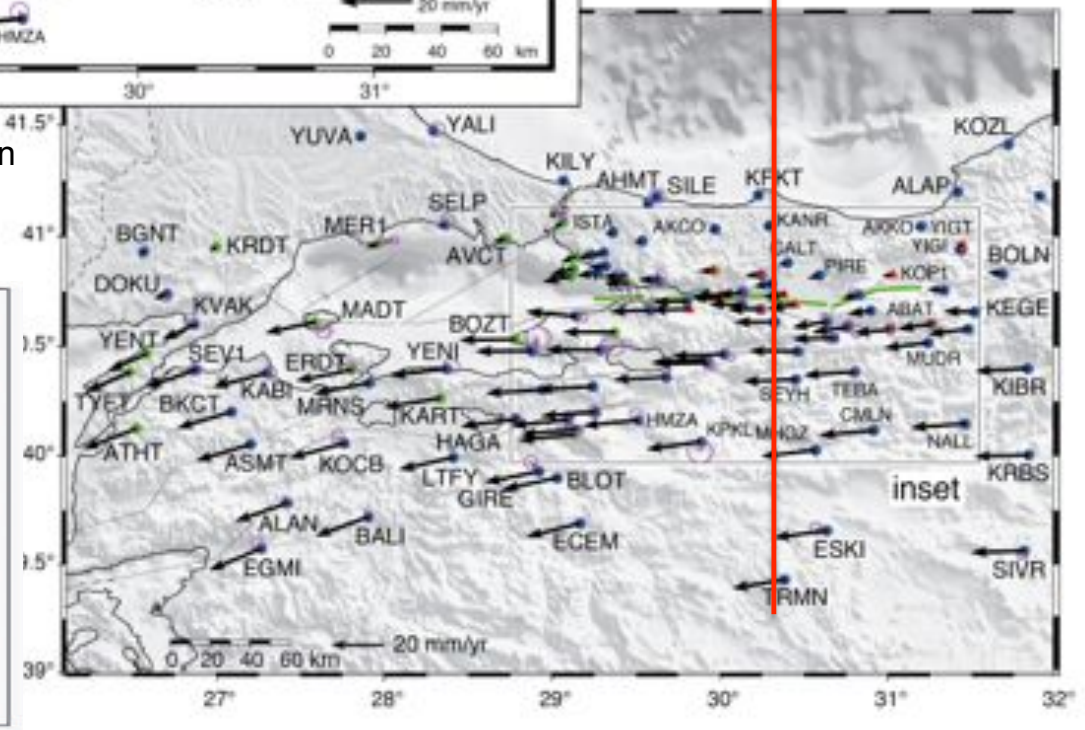
Inter-Seismic Strain Accumulation



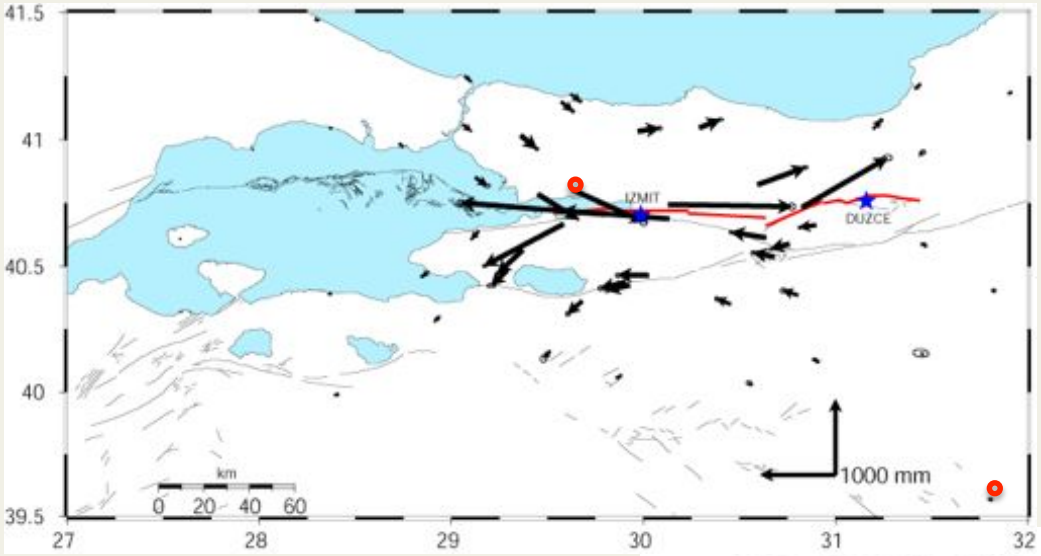


Interseismic site motion modeled using elastic block model……





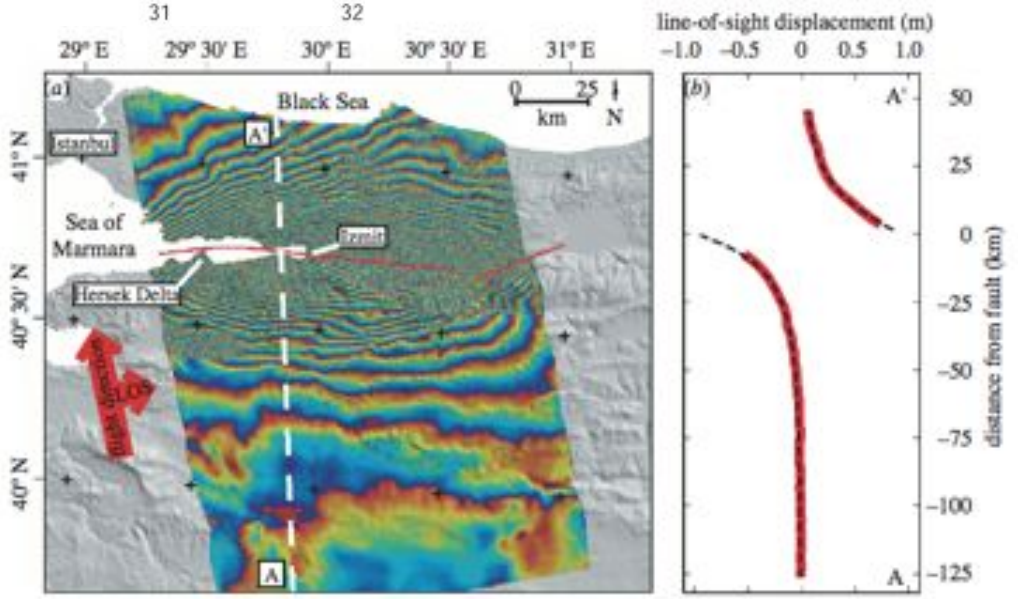
Izmit EQ Co-Seismic Displacements



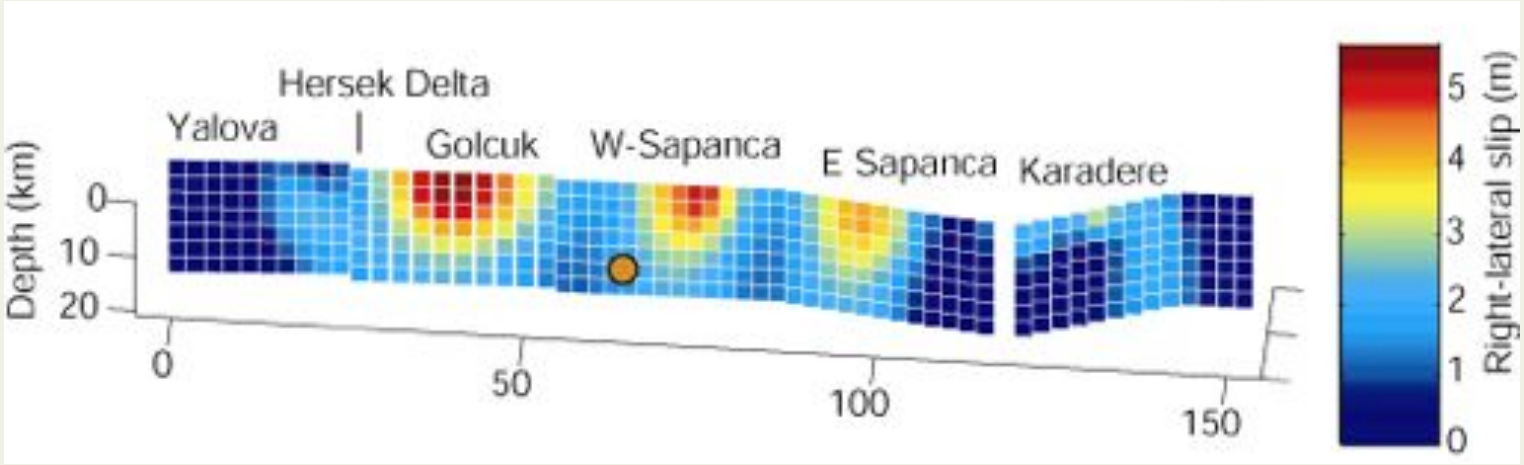
GPS

InSAR

(Interferometric Synthetic Aperture Radar)

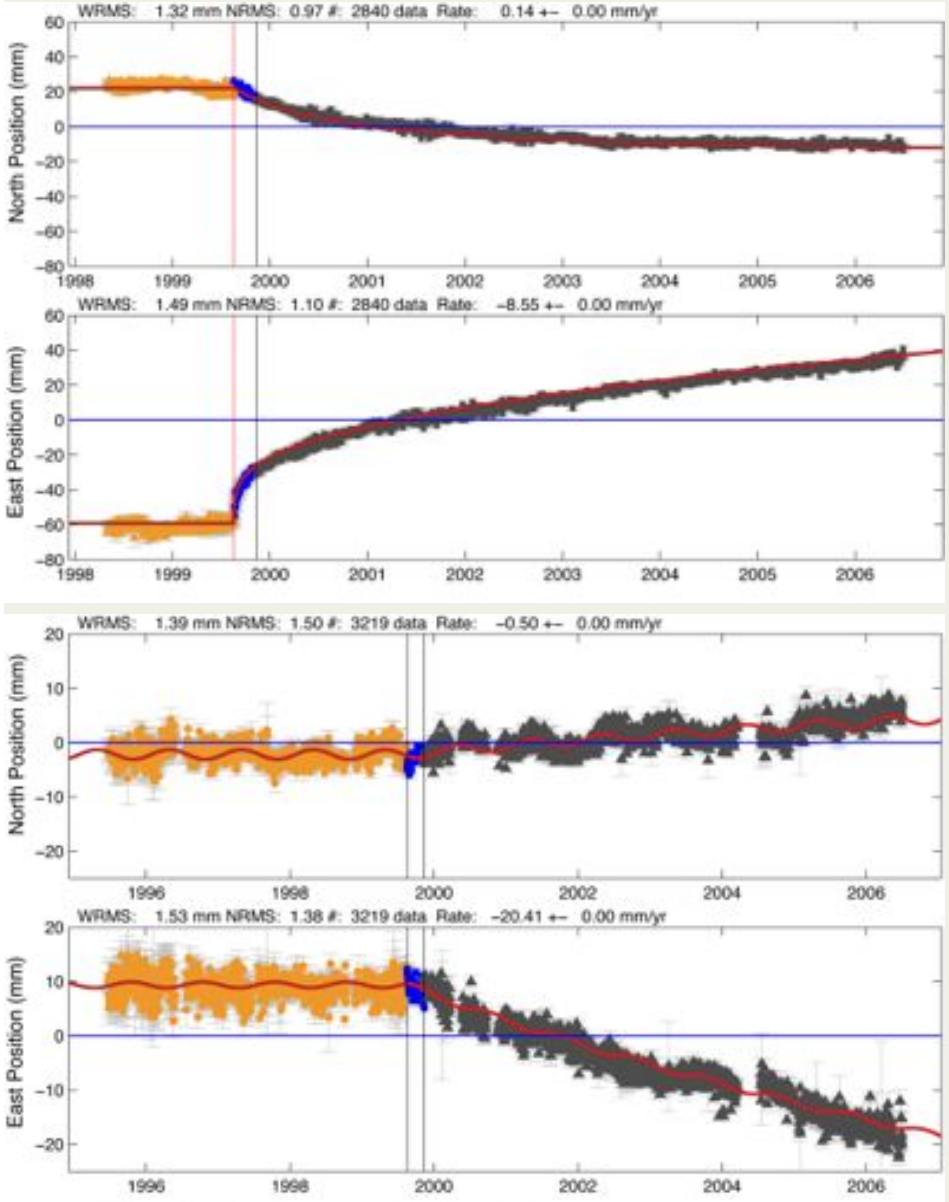


Izmit EQ Coseismic Fault Slip Distribution

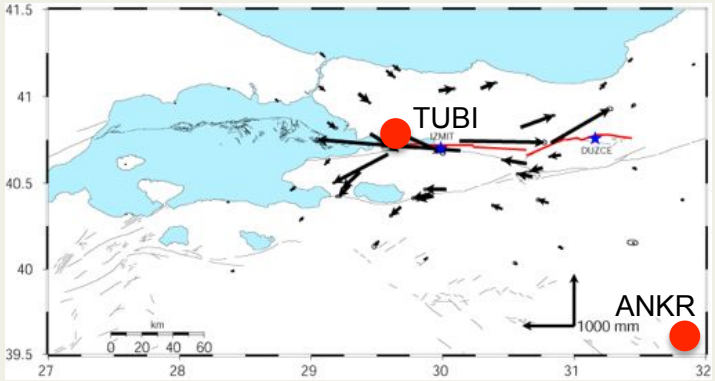


(Reilinger, *et al., 2000* Science).

Izmit/Duzce EQ Postseismic Deformation



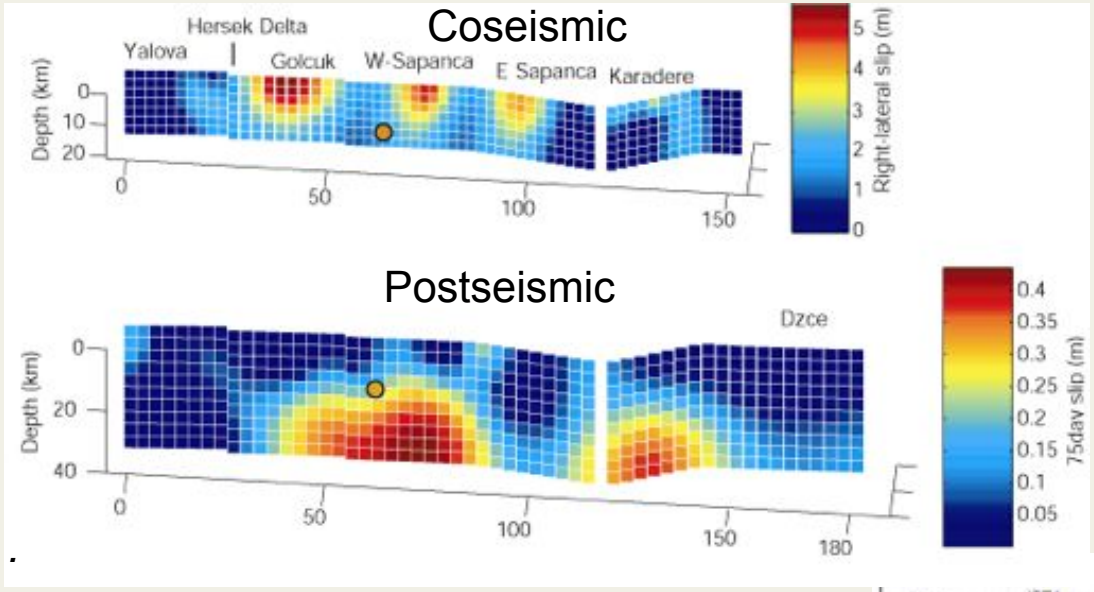
TUBI (near-field)
Deformation appears to have both short and long decay times



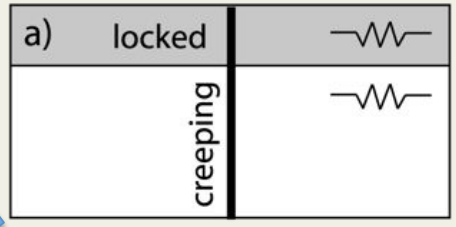
ANKR (far-field)
Post-seismic deformation appears to have a very long decay time

(from Ergintav et al., 2009)

Fault Plane Afterslip (a) or Viscoelastic Relaxation (b)?

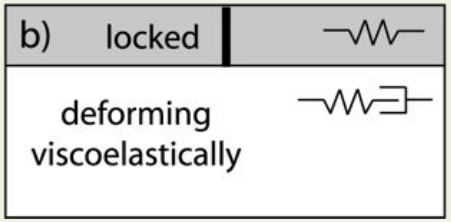


Elastic After-slip

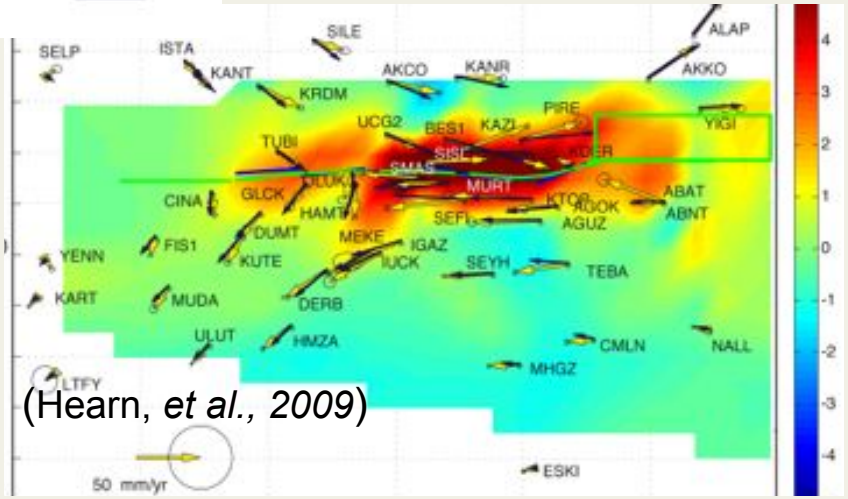


Fits early post-seismic deformation best.

Viscoelastic Relaxation

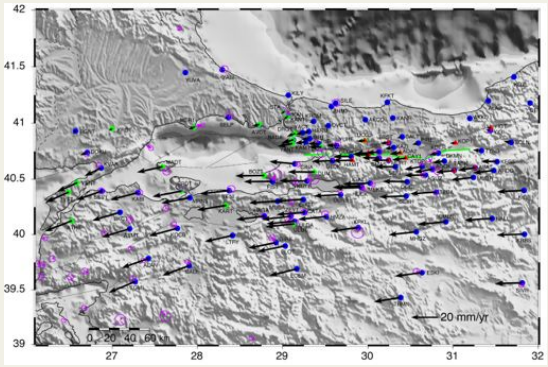


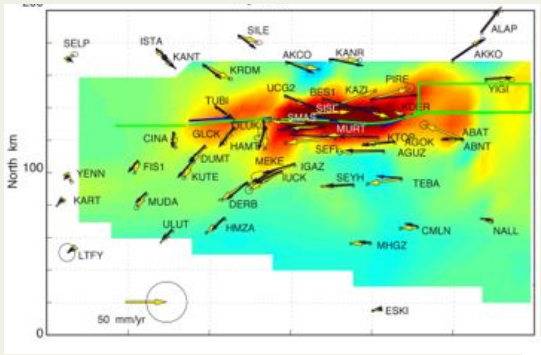
Fits all stages of post-seismic deformation well.



(Hearn, *et al., 2009*)

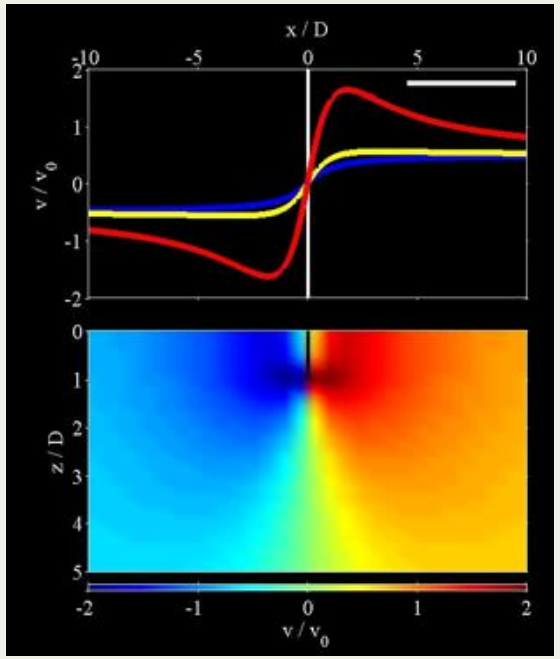
Unifying Inter-Seismic and Post-Seismic deformation models: Fitting the Entire Seismic Cycle (from E. Hetland)



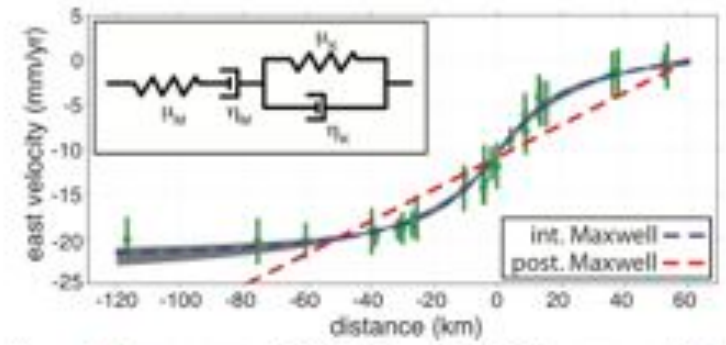


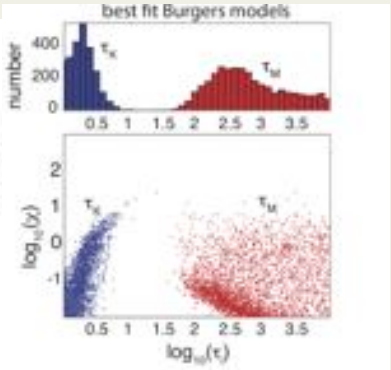
Elastic

Viscoelastic



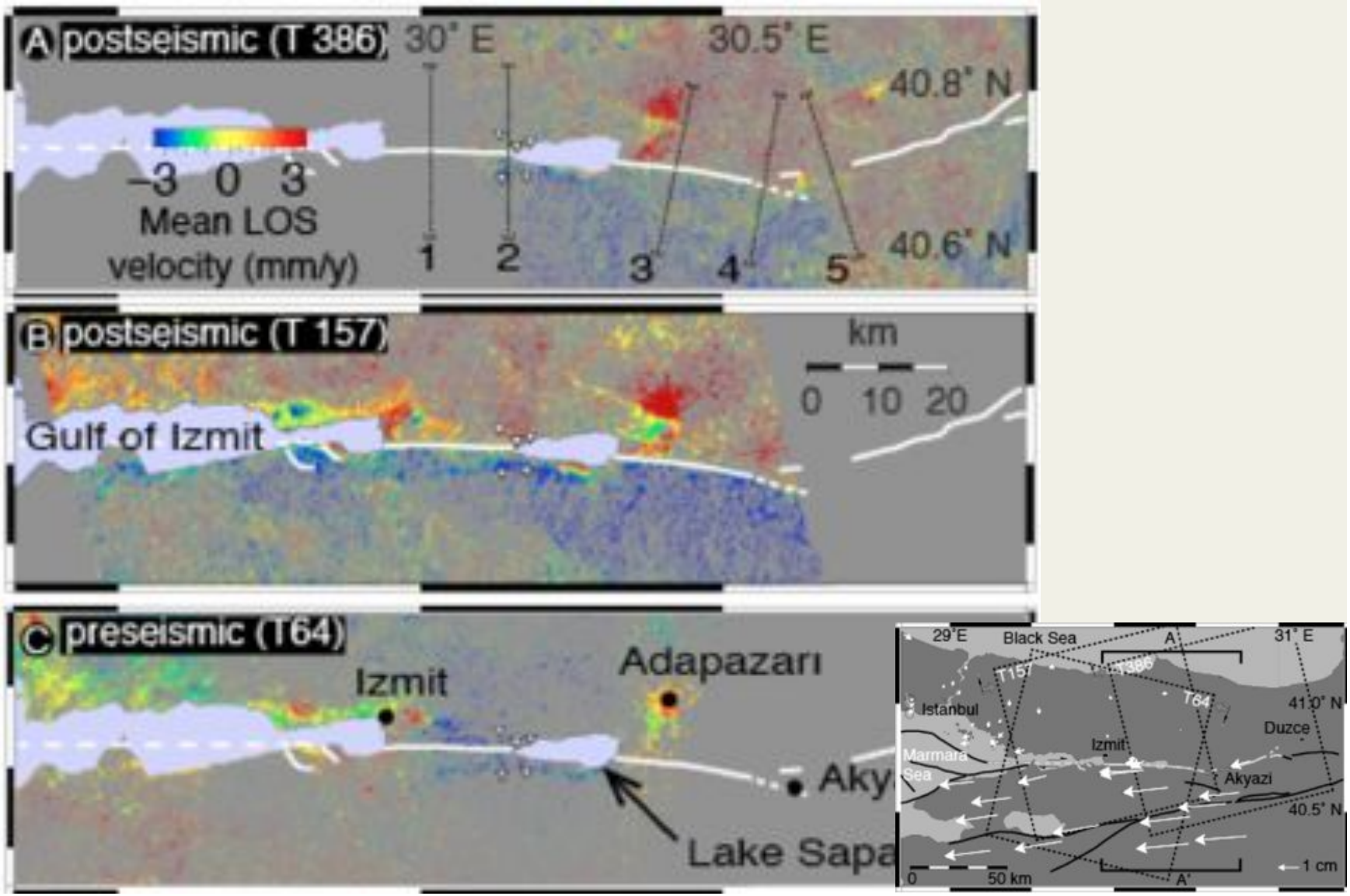
Bi-viscous rheology





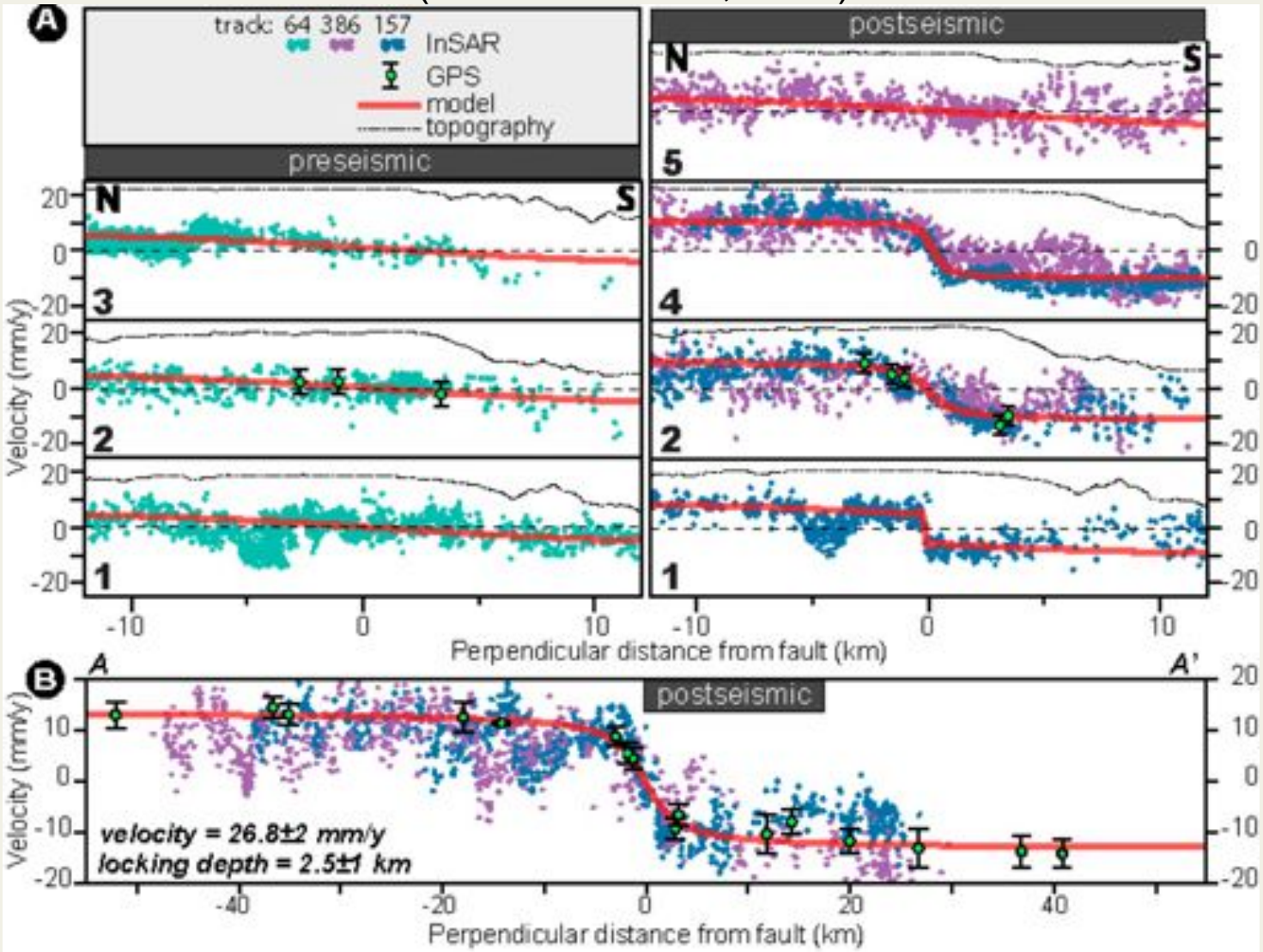
After-Slip to Fault Creep?

(from Cakir et al., 2012)



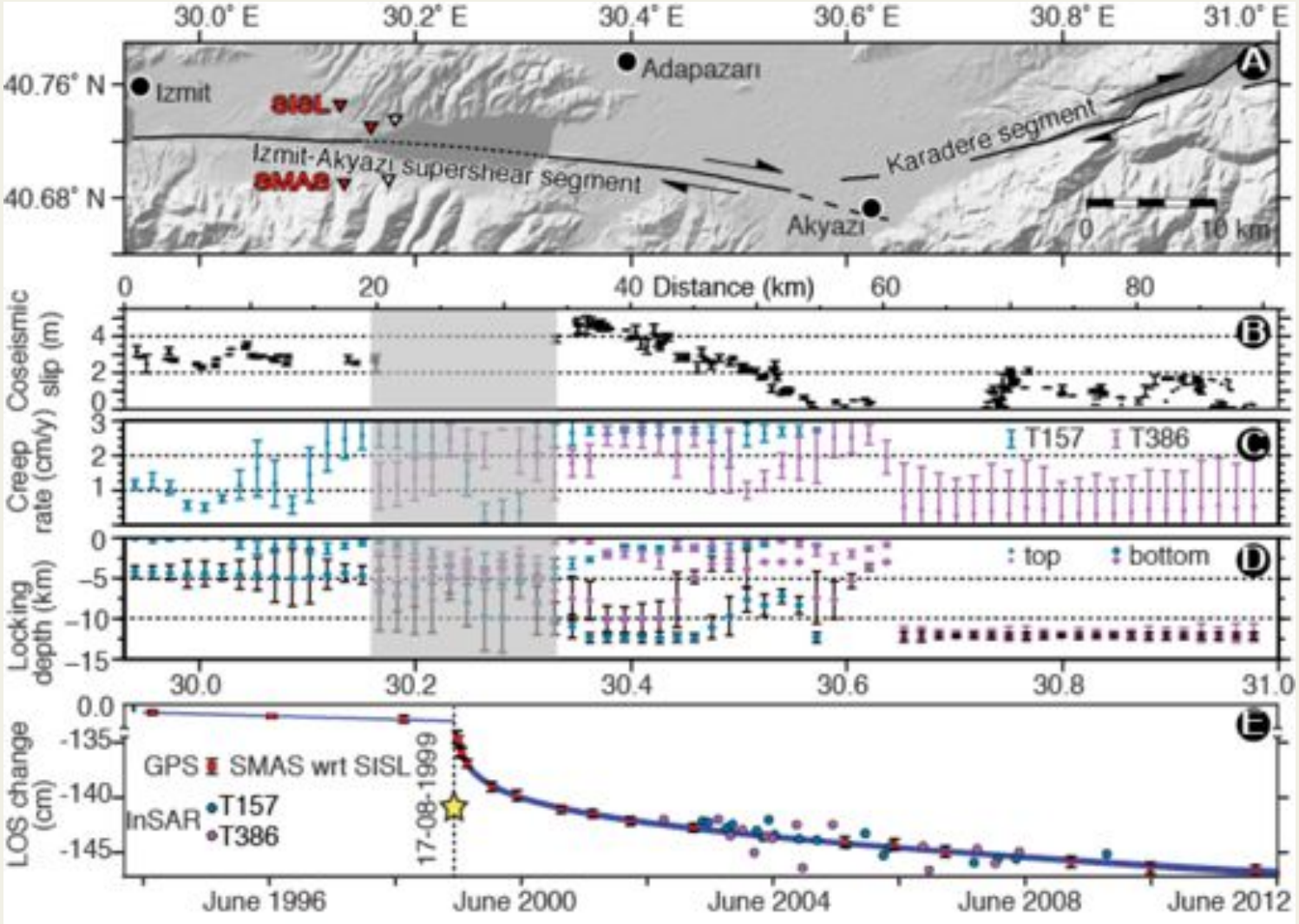
Post-Seismic Trans-NAF Profile

(from Cakir et al., 2012)



Near-Field GPS Network

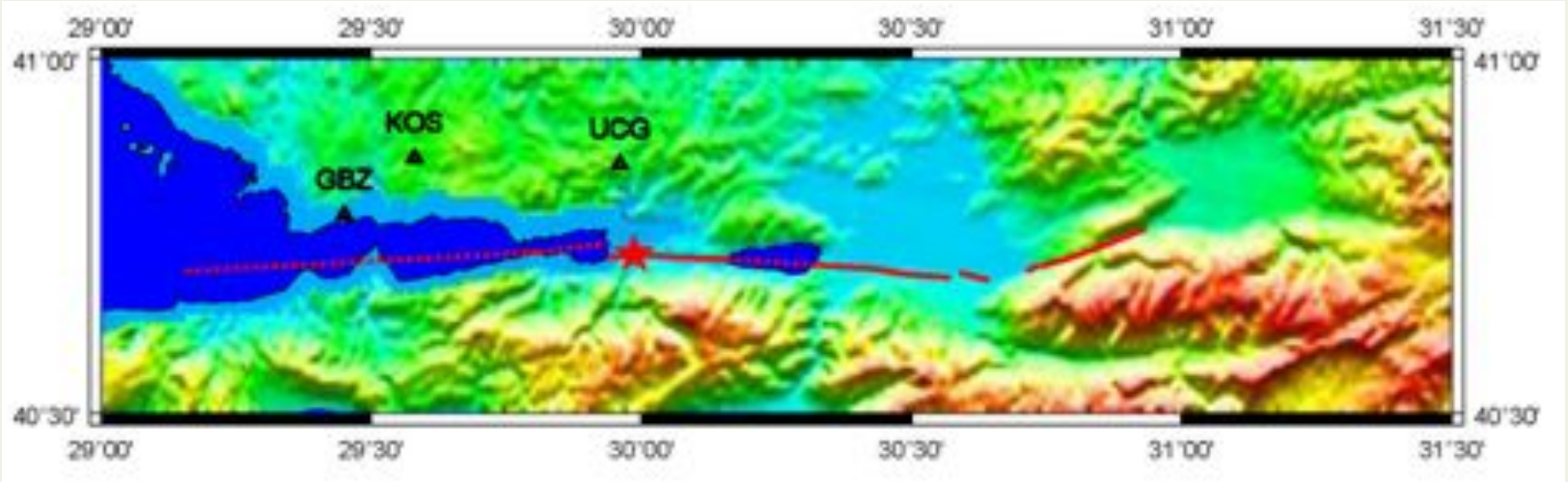
(from Cakir et al., 2012)



Precursory Fault Slip

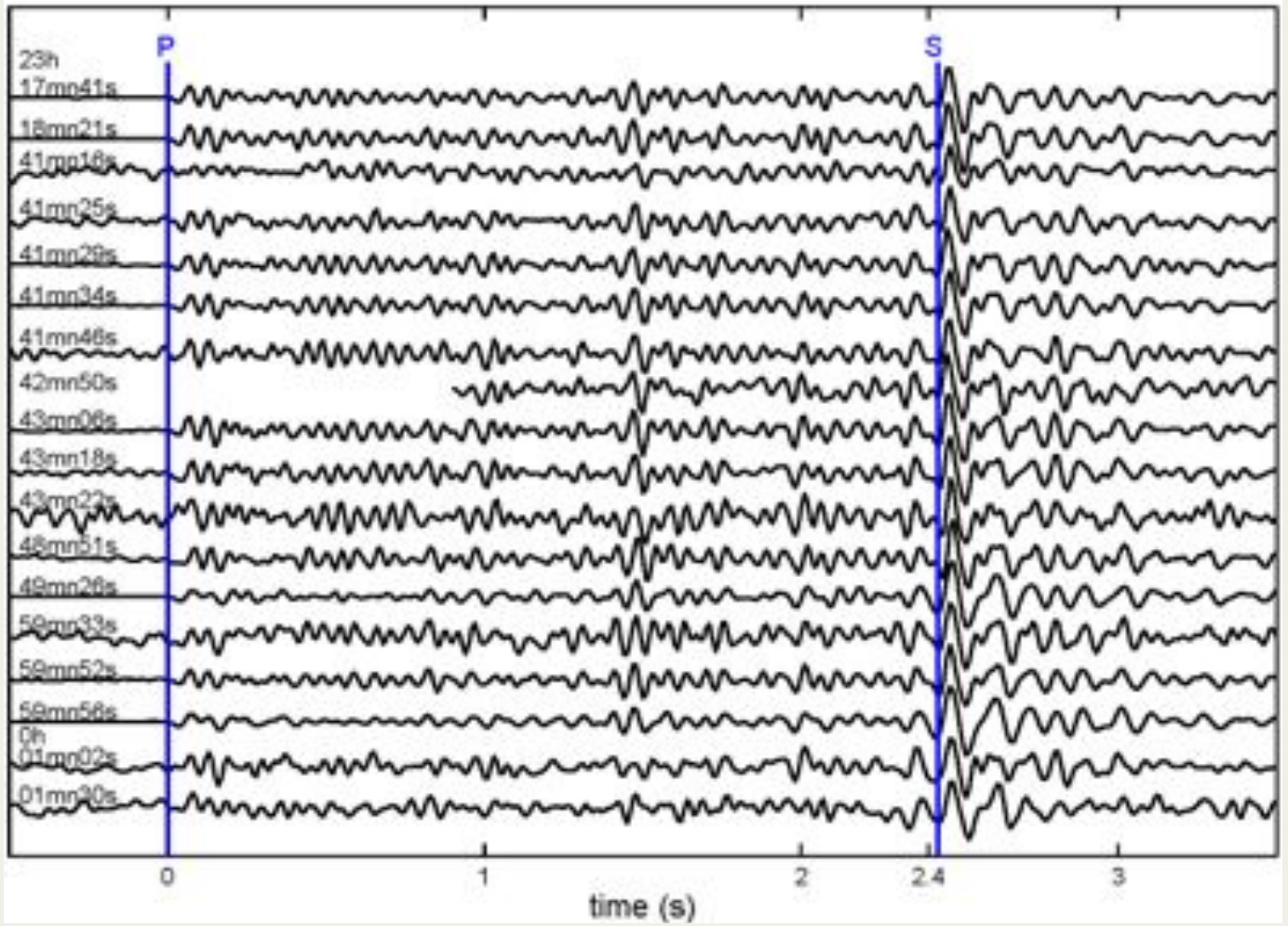
The Izmit Rupture and the Closest Stations to the Epicenter

(courtesy, Michel Bouchon, 2013)



18 Pre-Earthquake Shocks in 40 Minutes Before EQ

(Bouchon et al., 2011)



Izmit Nucleation

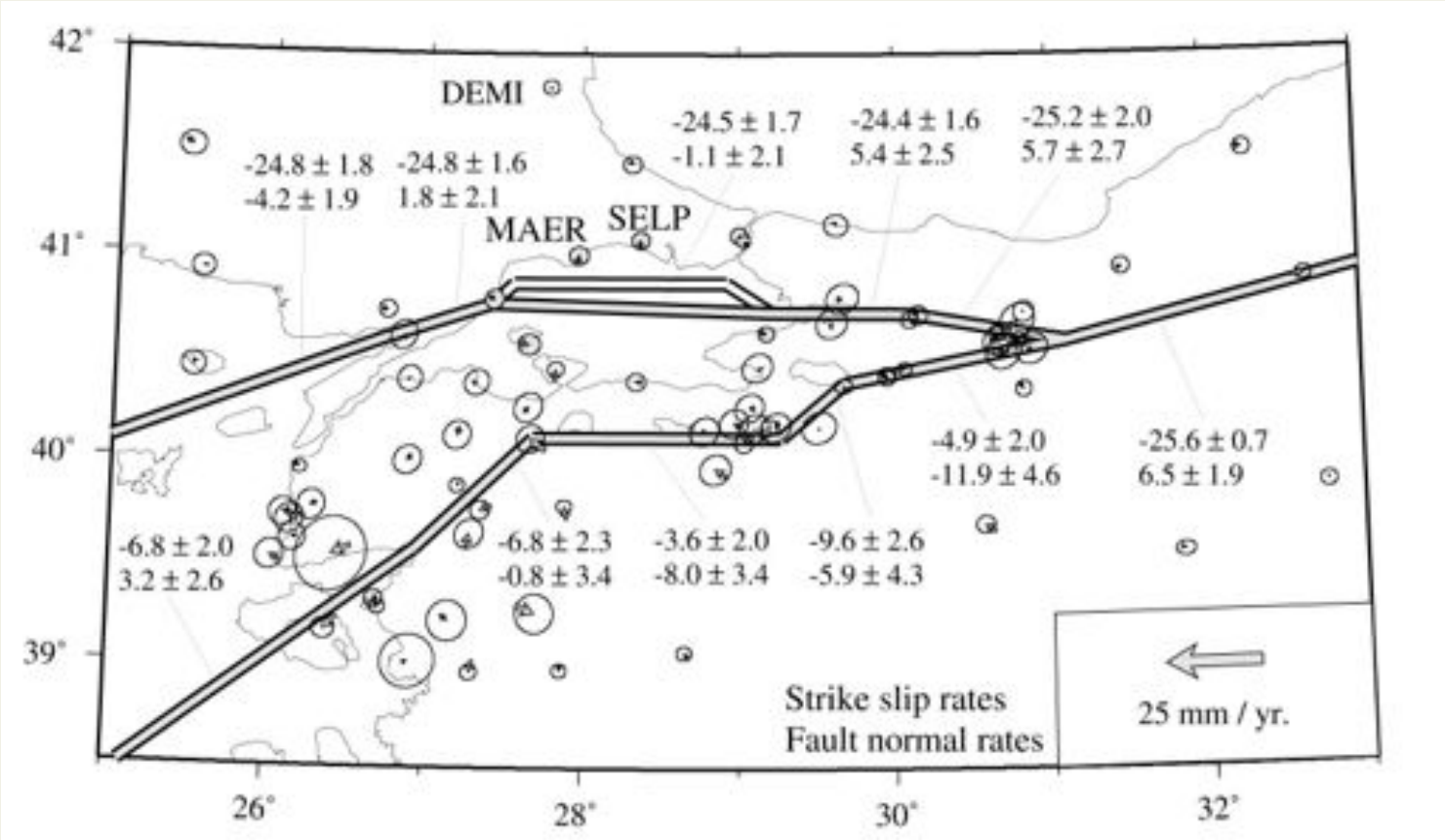
(courtesy, Michel Bouchon, 2013)

Observation: During the 44 minutes that precede the earthquake, the hypocentral area emits an unsual signal, never seen before: a seismic vibration which repeats itself over and over sometimes only a few seconds apart. These bursts become more frequent as the time of the earthquake approaches. They are accompanied by a continuous low-frequency seismic noise.

Interpretation: A patch of the fault located at the bottom of the brittle crust has begun to slip slowly 44 minutes before the earthquake. This phase of slow slip accelerates in time...

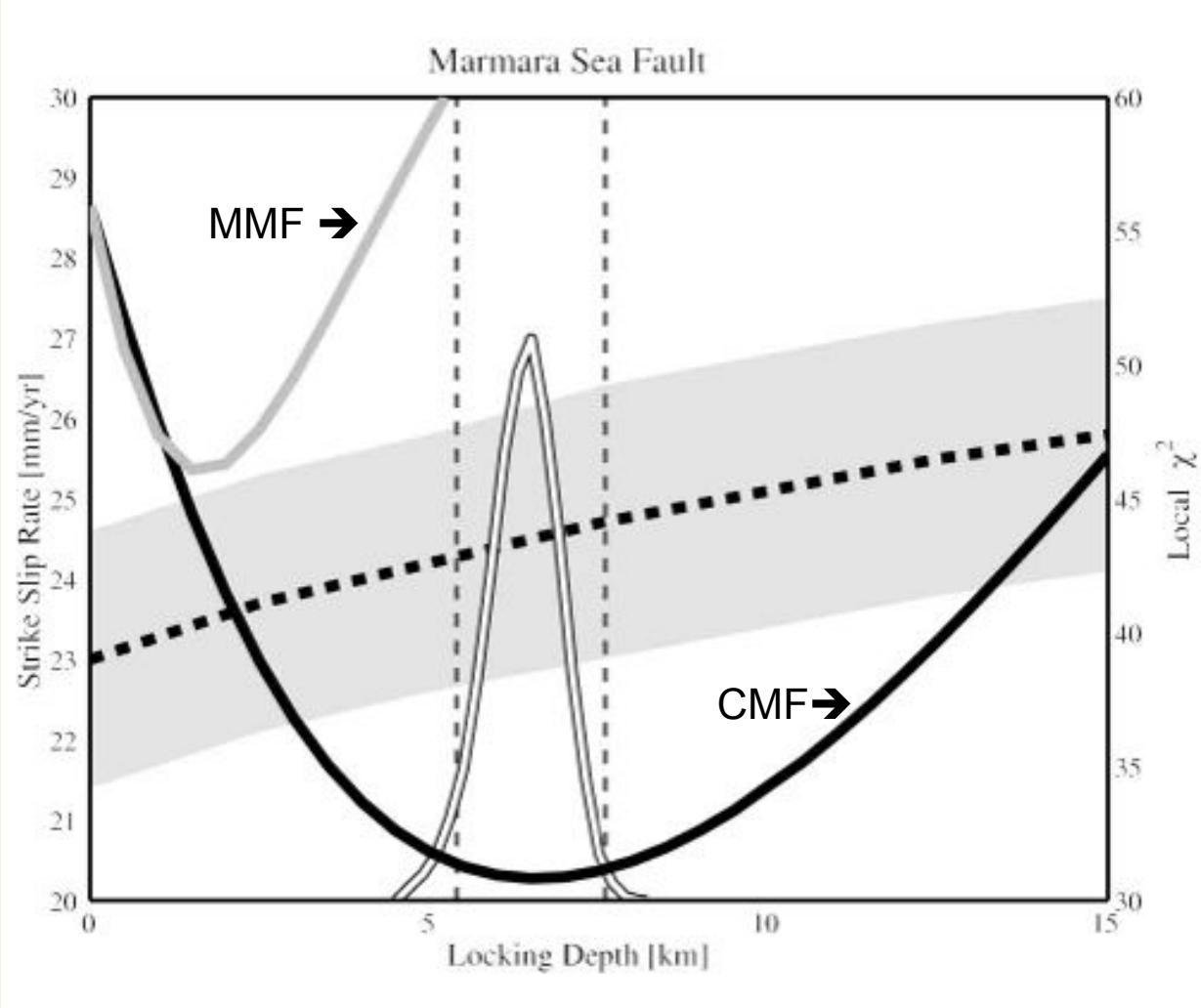
Creep on the Main Marmara Fault?

(from Meade et al., 2003)



Main Marmara Fault Locking Depth

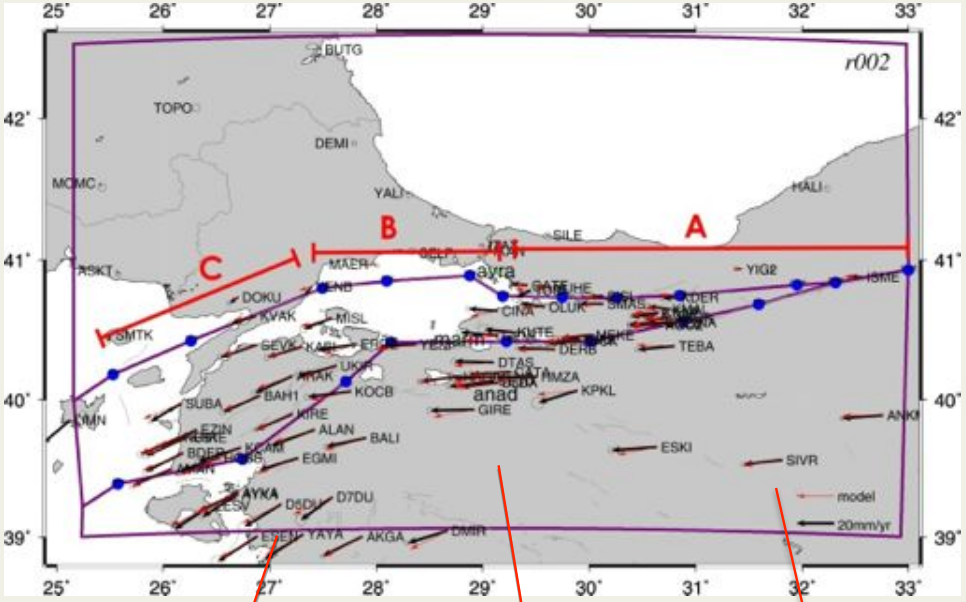
(from Meade et al., 2003)

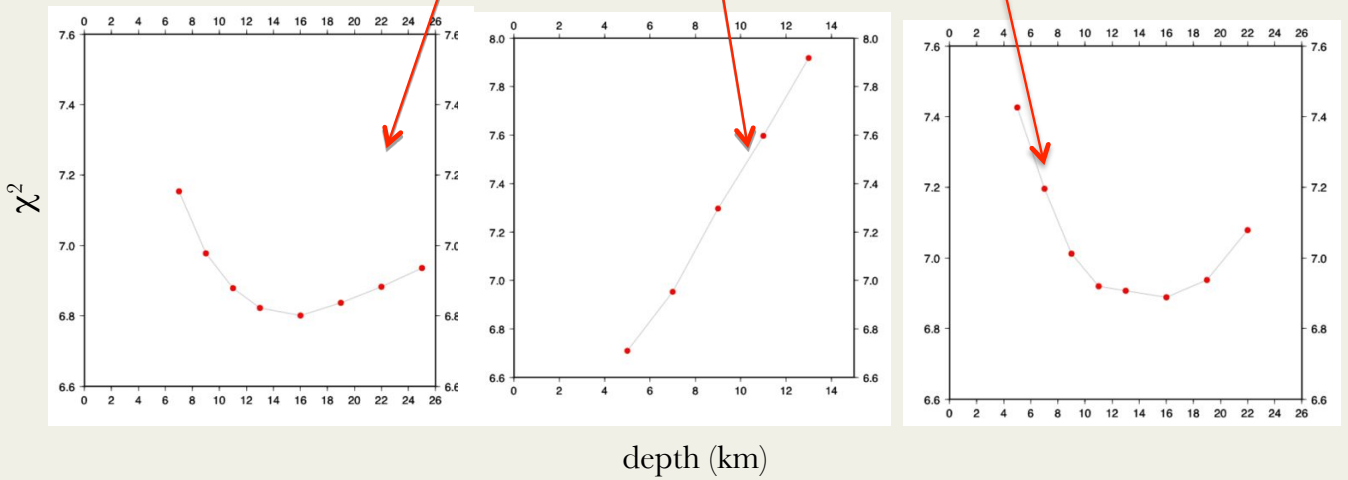


Locking Depth for the MMF

(from S. Ergintav and R. Cakmak)

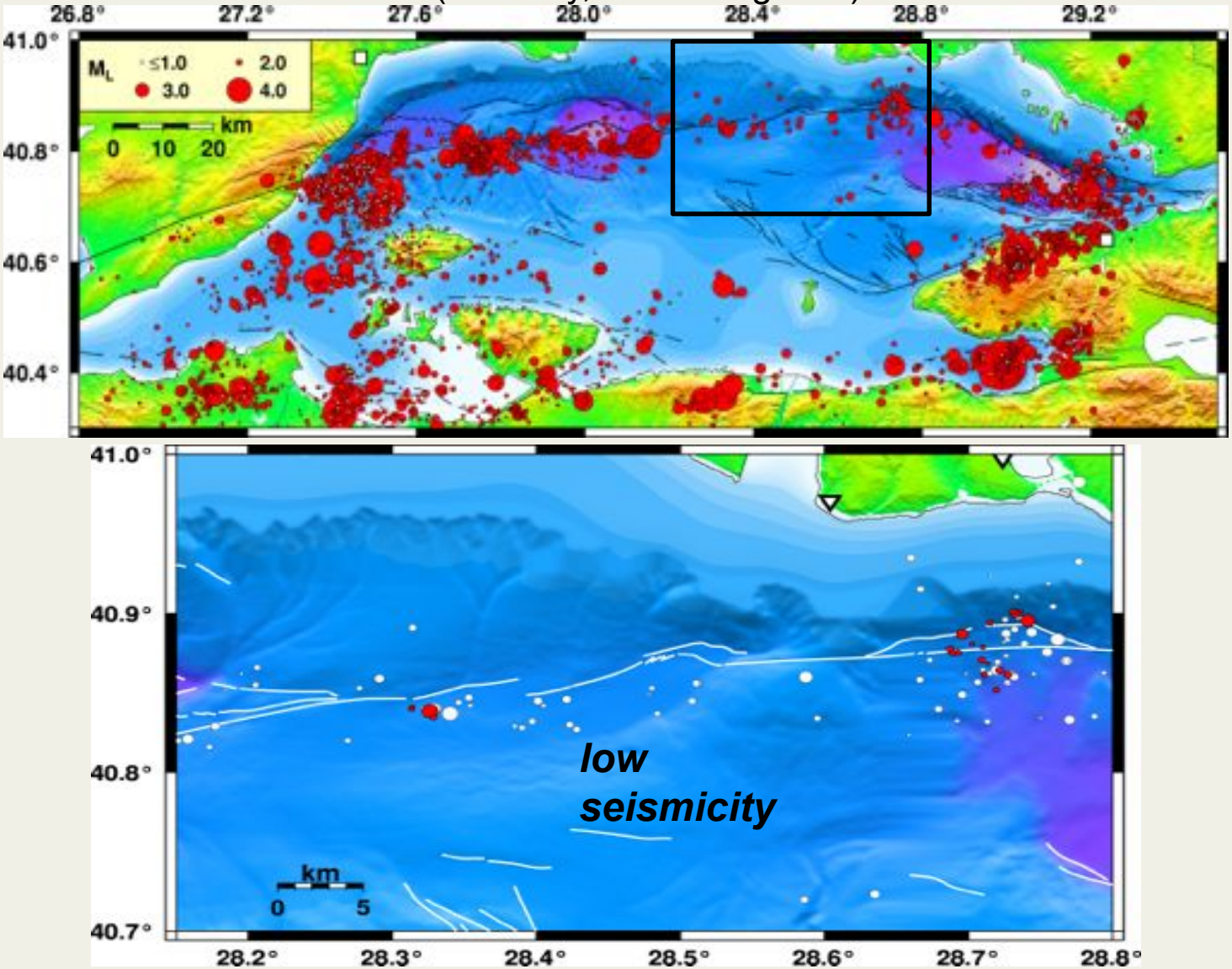
Parameters:
-with same geometry
-by fixing the depth
with 3 kms

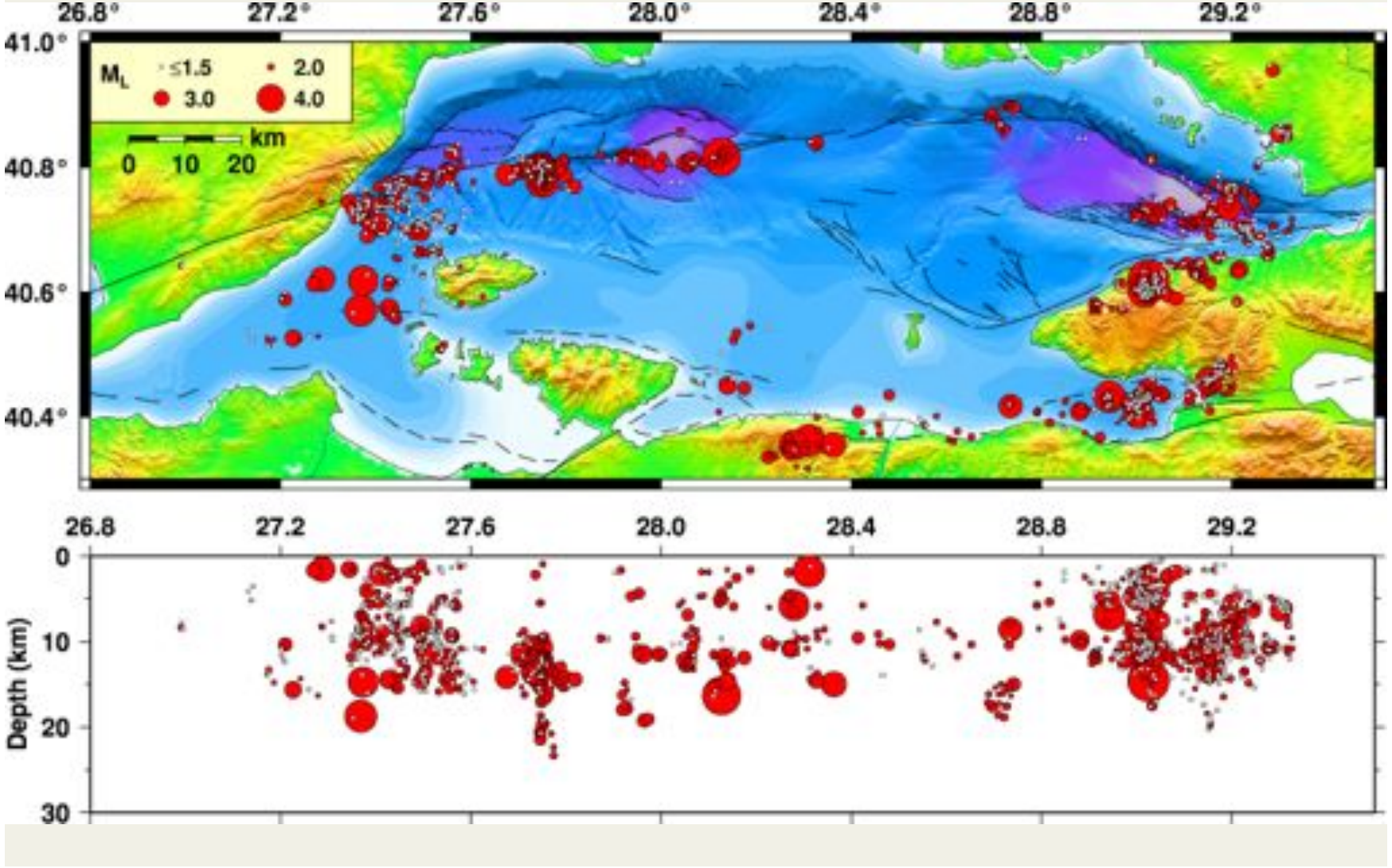




Fully Locked or Creeping?

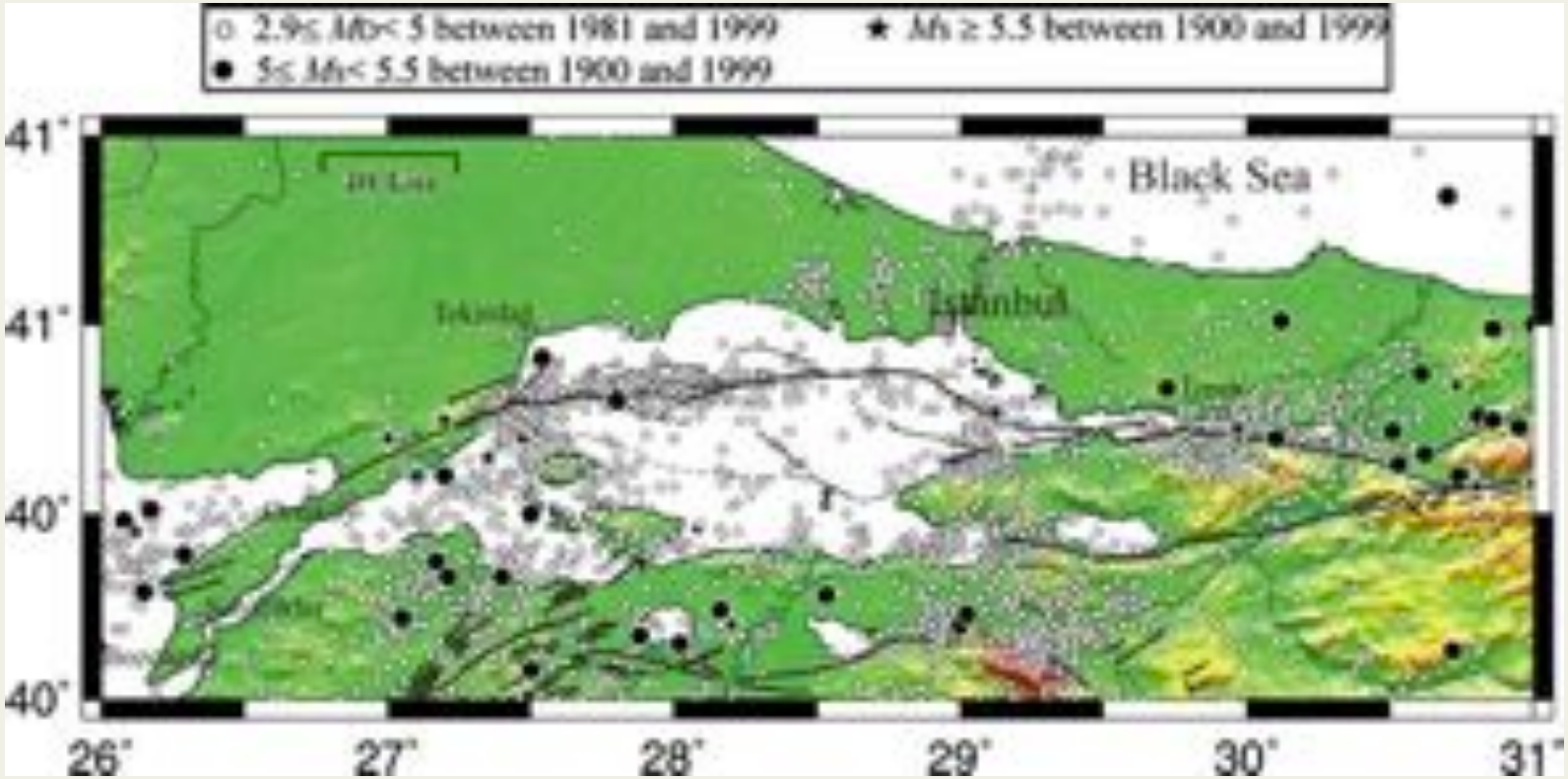
(courtesy, Semih Ergintav)




26.8°
27.2°
27.6°
28.0°
28.4°
28.8°
29.2°
41.0°
40.8°
40.6°
40.4°
M_L
≤1.5
2.0
3.0
4.0
km
0 10 20
26.8
27.2
27.6
28.0
28.4
28.8
29.2
0
10
20
30
Depth (km)

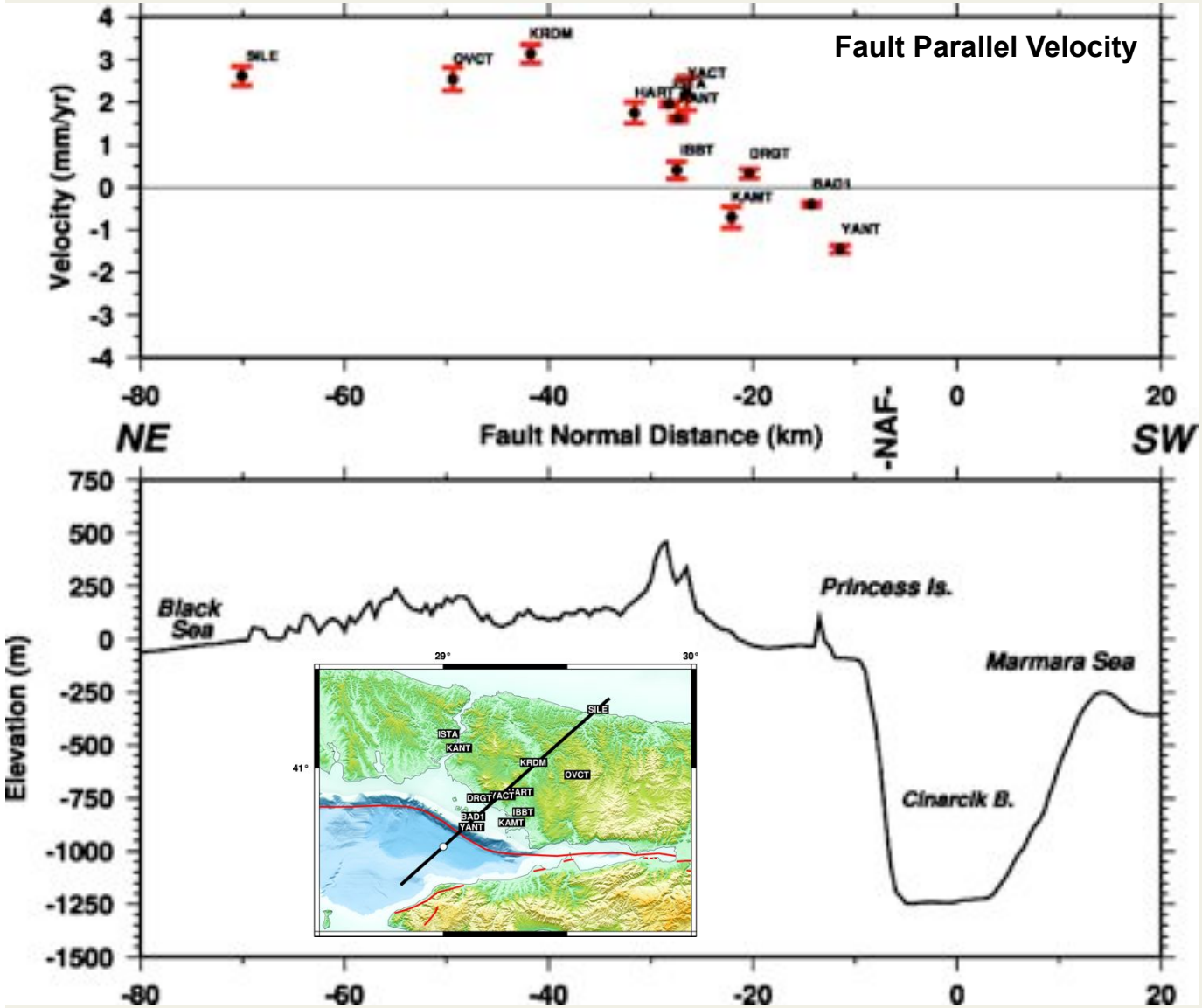
MMF Long-term seismicity

(from Utkucu et al., 2008)



Prince's Islands Fault Strain Accumulation

(courtesy, Semih Ergintav)



Strain Loading is %20 of Interseismic loading before Izmit Eq. in rupture area

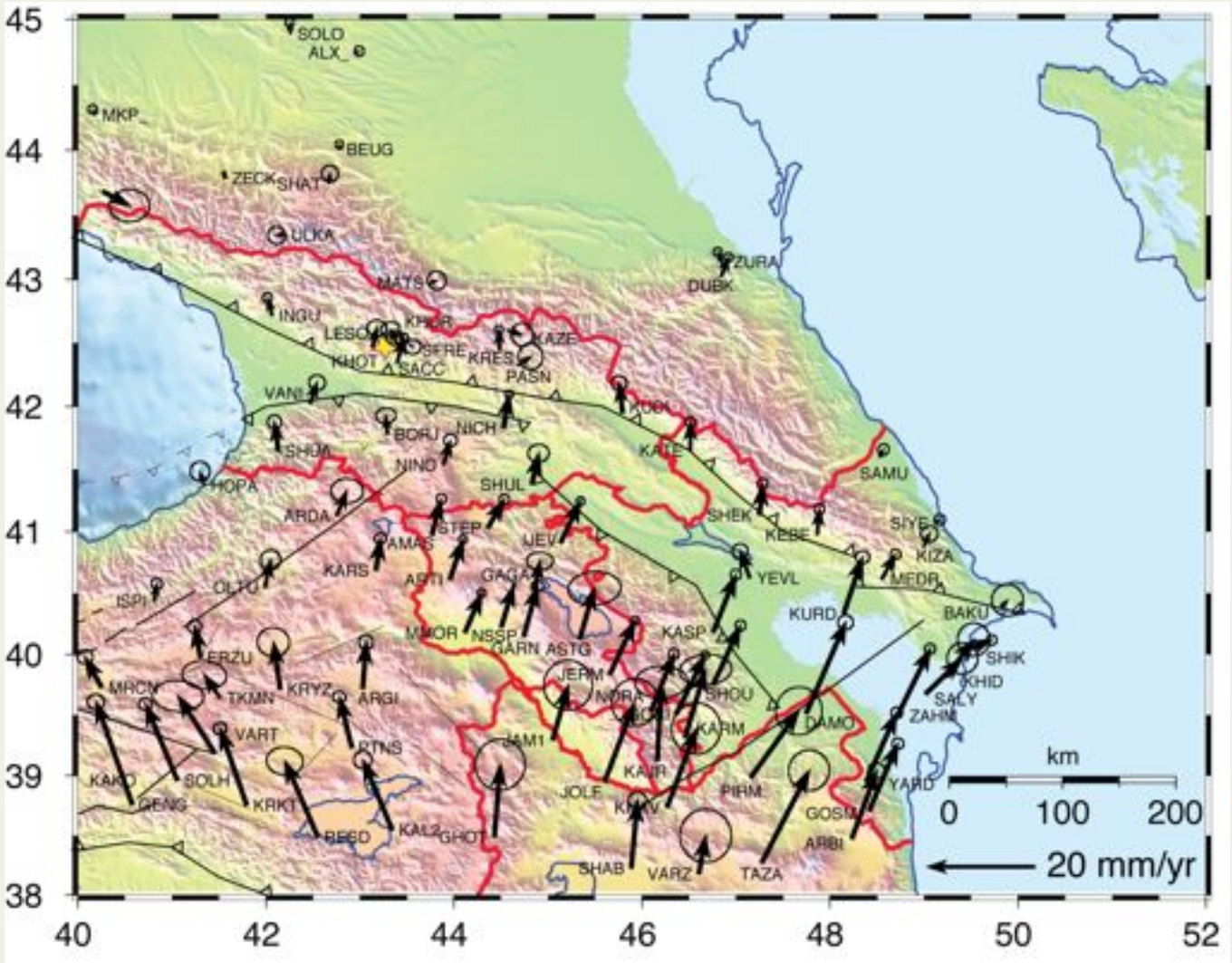
TOO LOW?

a) Creeping/ shallow locking depth

b) Vertical fault and low strain loading (check other branches at the south?)

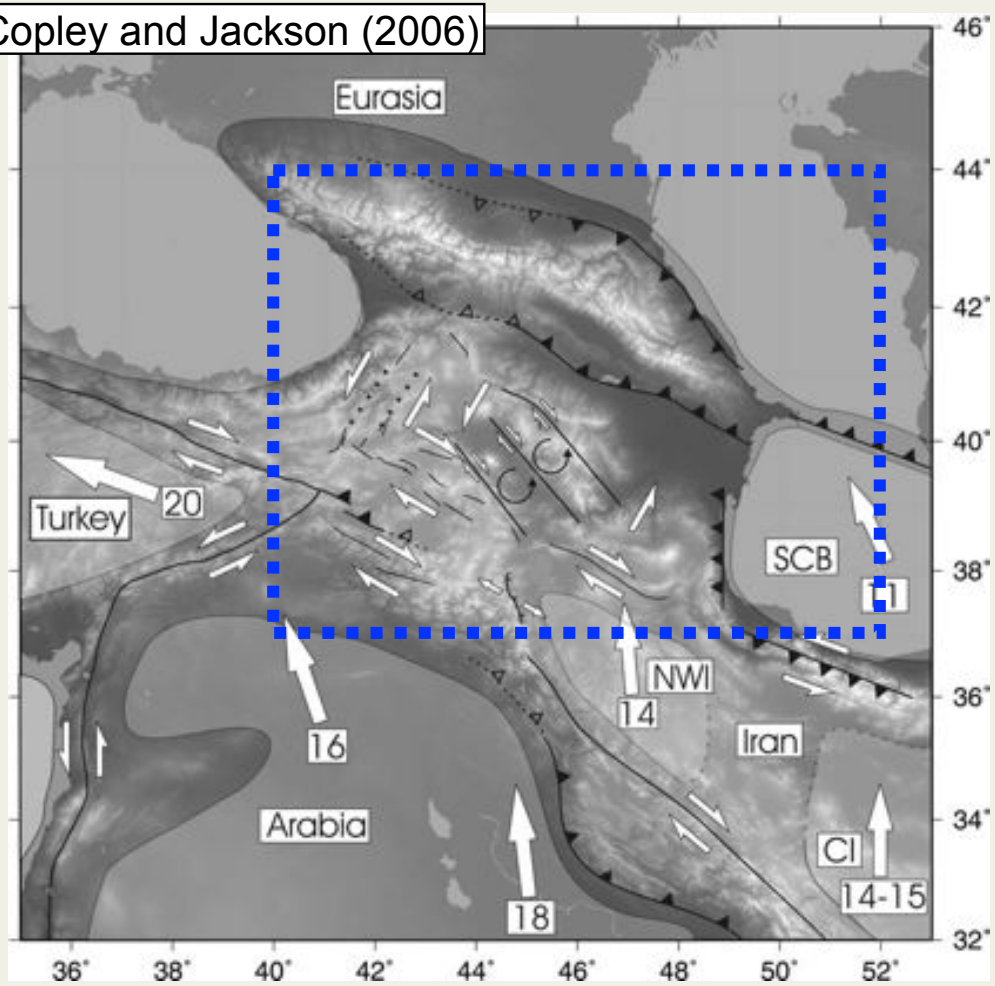
c) Fault has dip

Caucasus/E Turkey Deformation and Earthquake Hazards



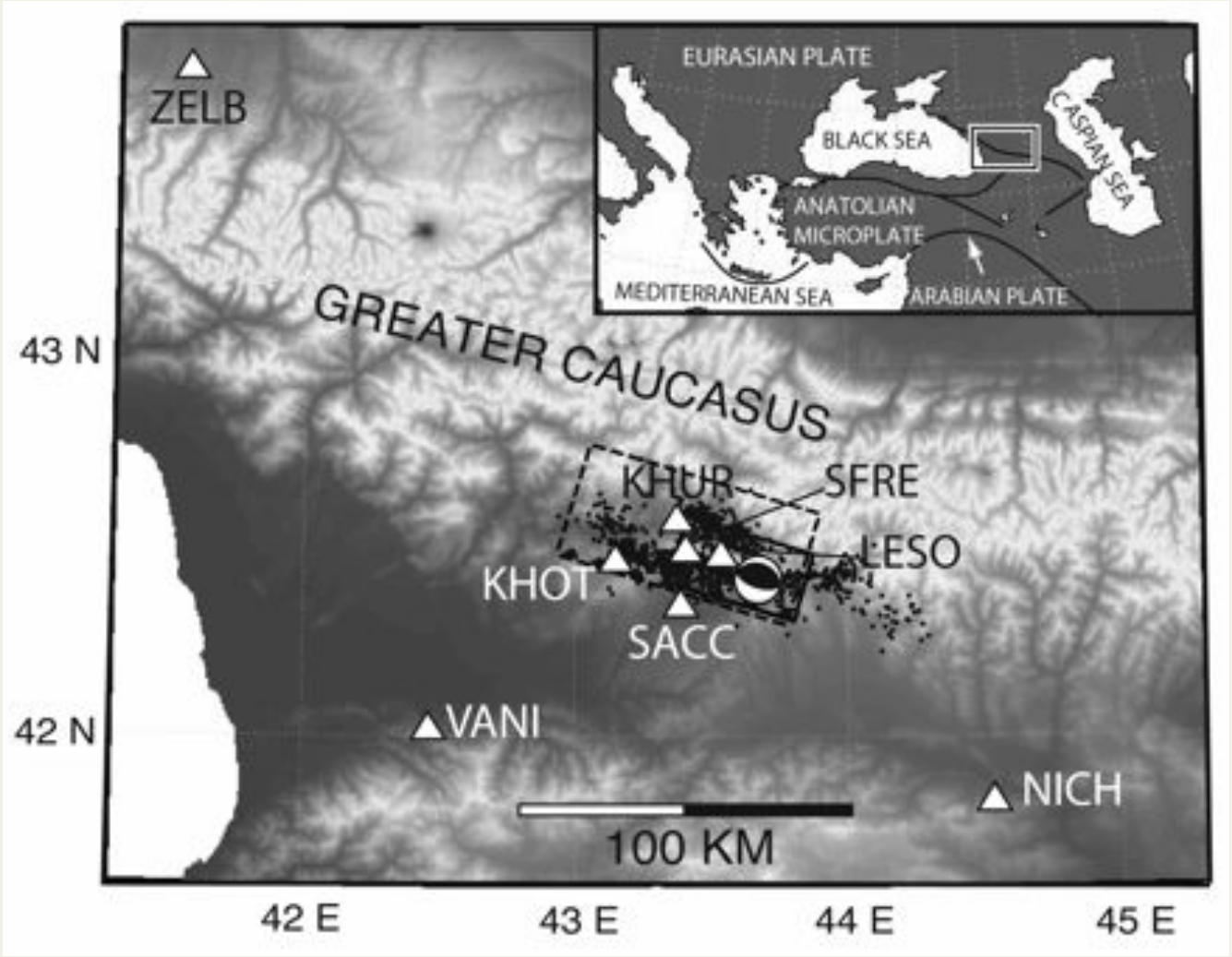
The Arabia collision zone

Copley and Jackson (2006)

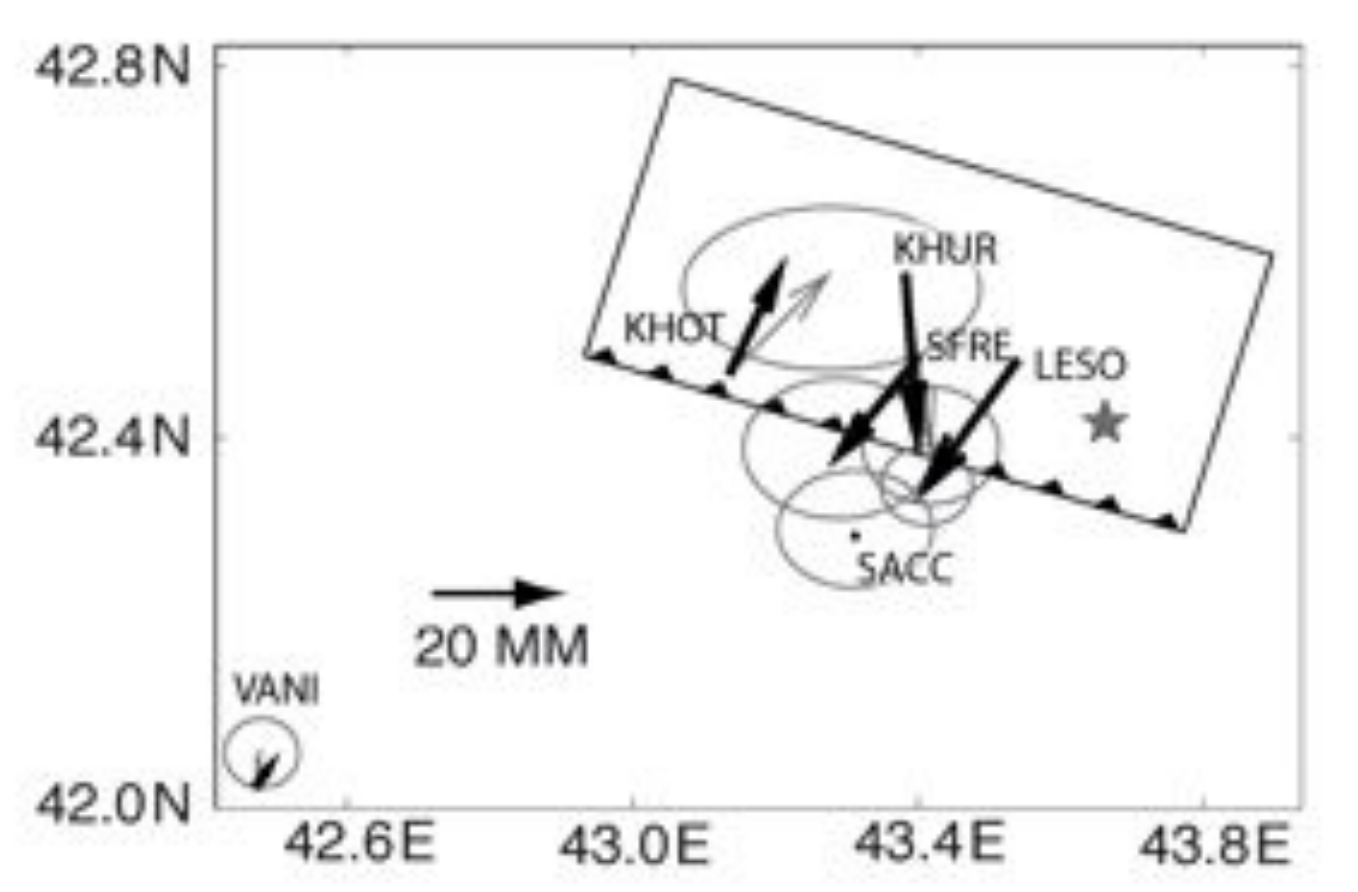


1991, M=7.0 Racha, Georgia EQ

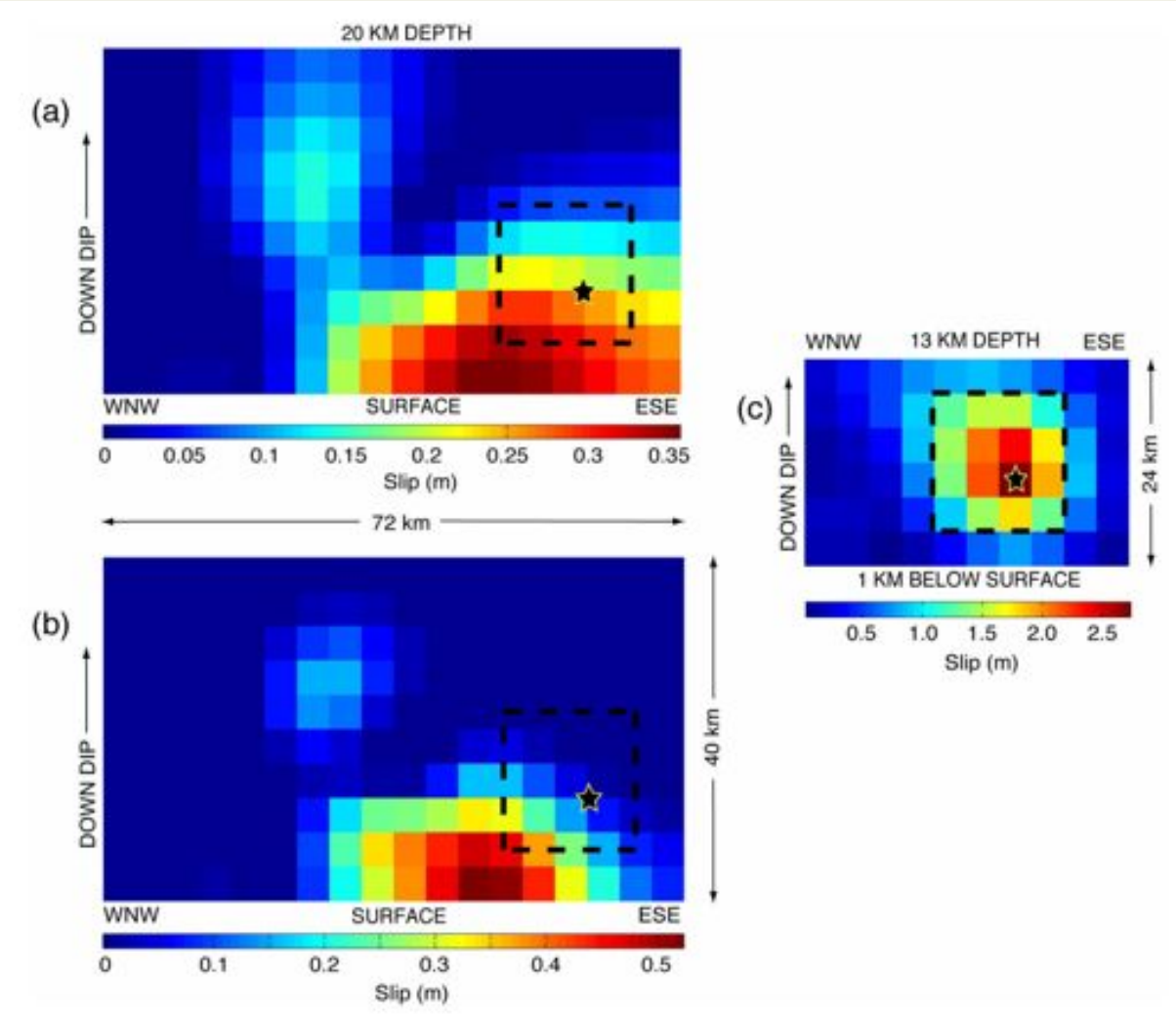
(from Podgorski et al., 2007)



Racha Post-seismic motions (1991-1994)

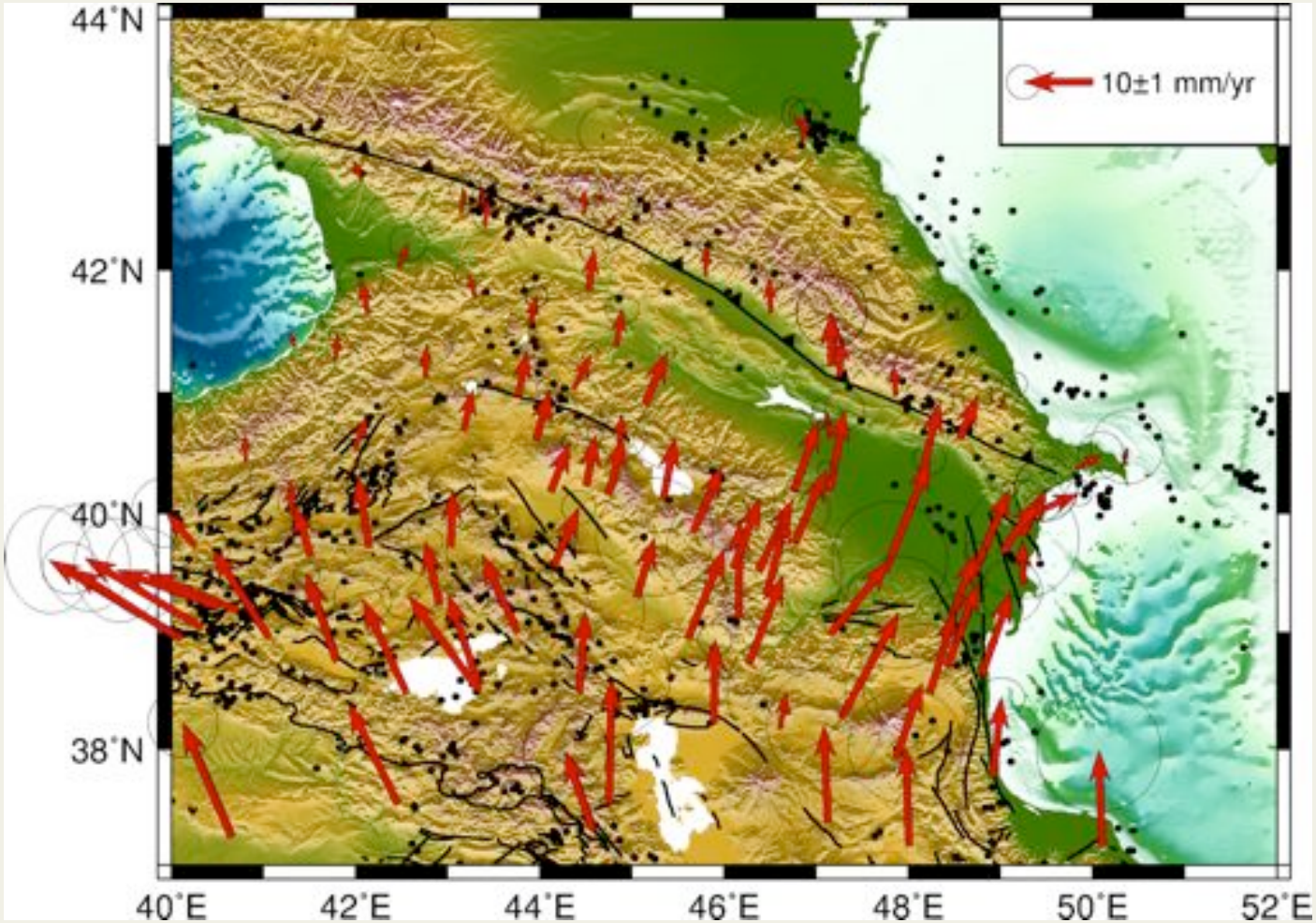


Modeled post-seismic fault slip



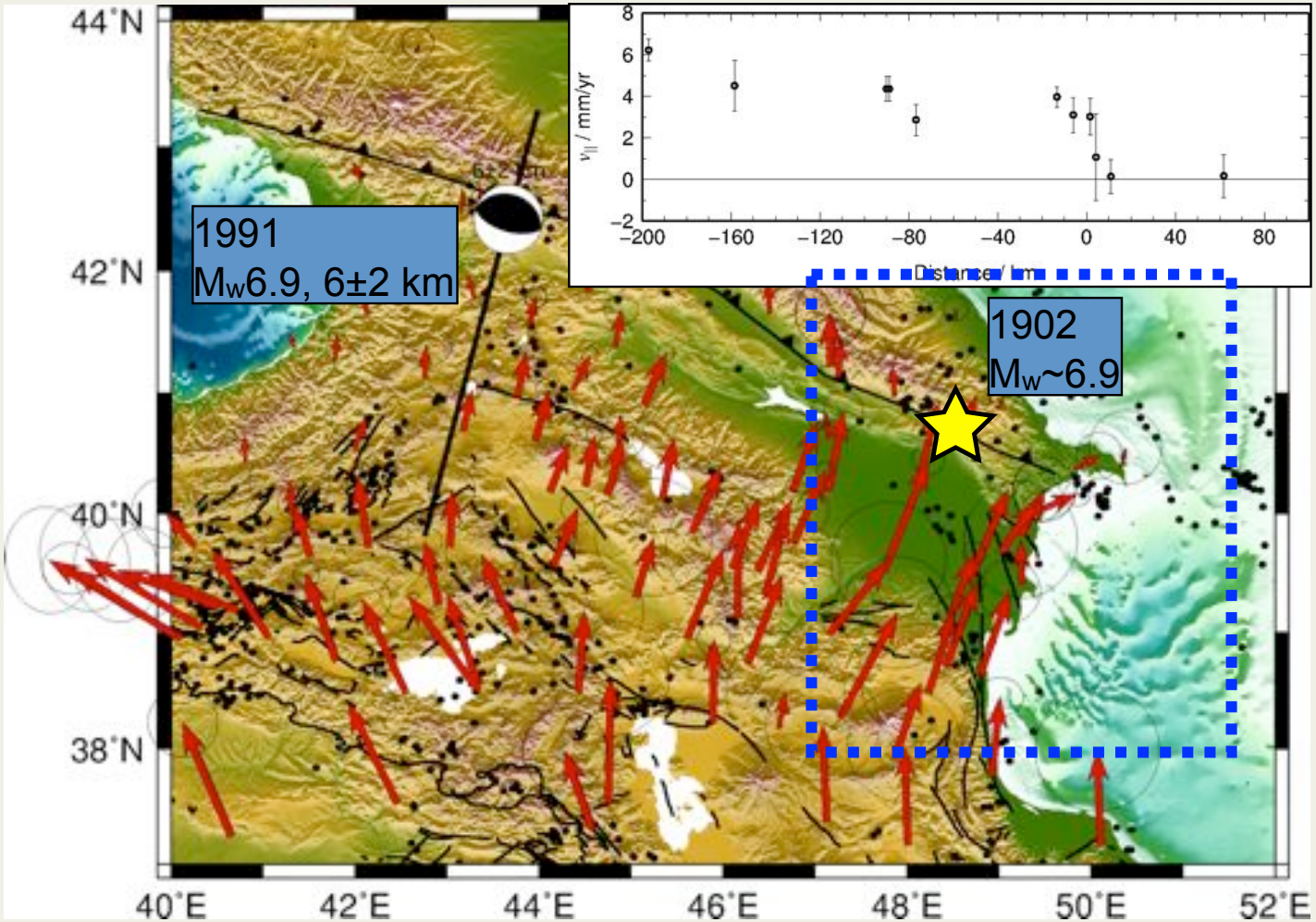
The Caucasus

(from Kadirov et al., 2012)

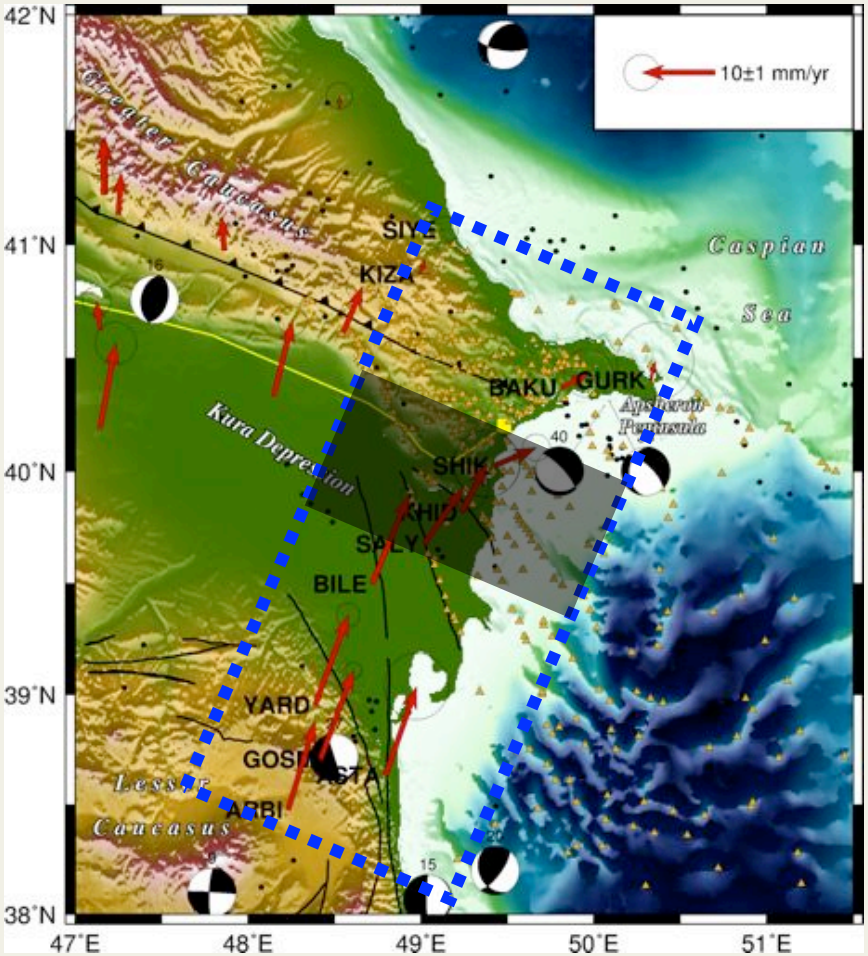


The Caucasus

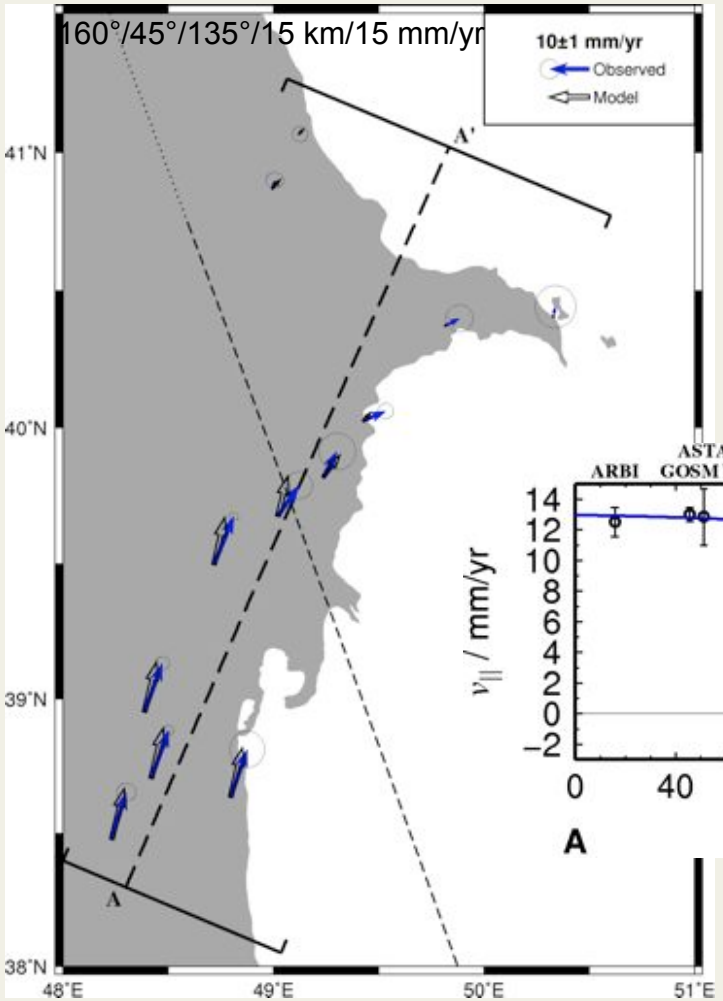
(from Kadirov et al., 2012)

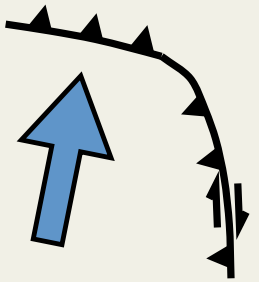


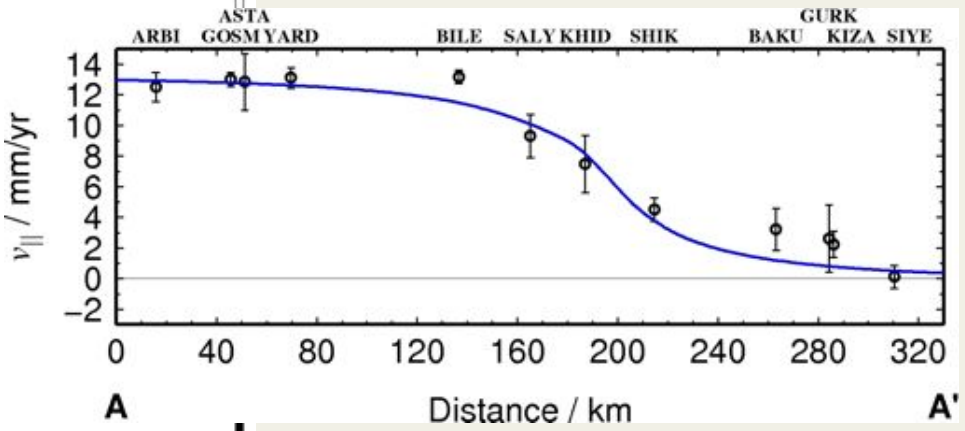
Updated and expanded GPS



An Illustrative Model

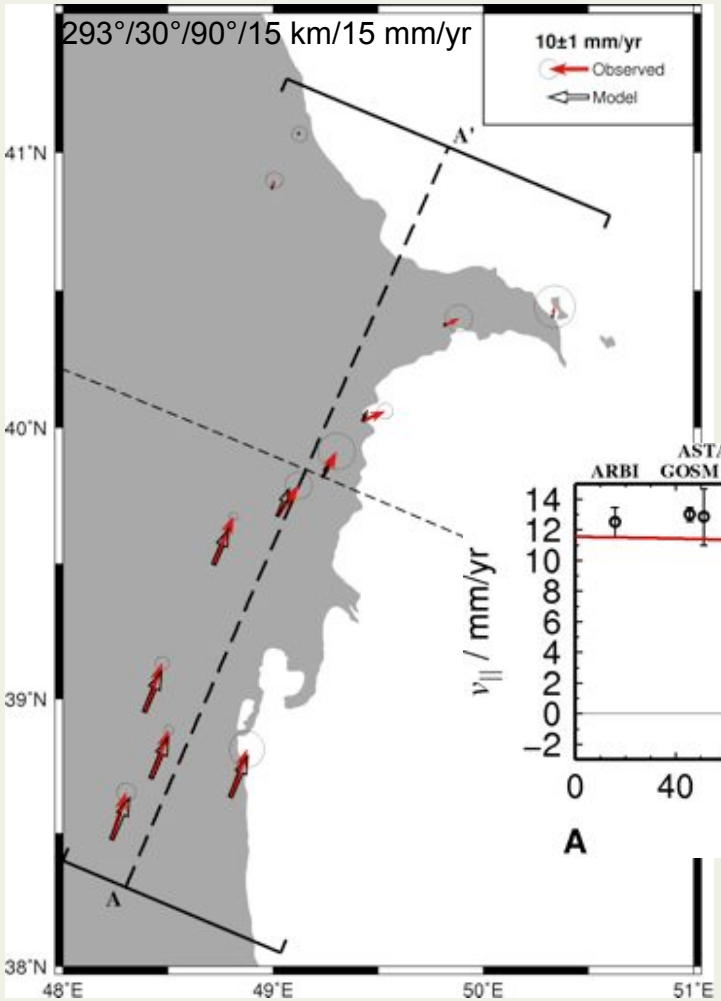


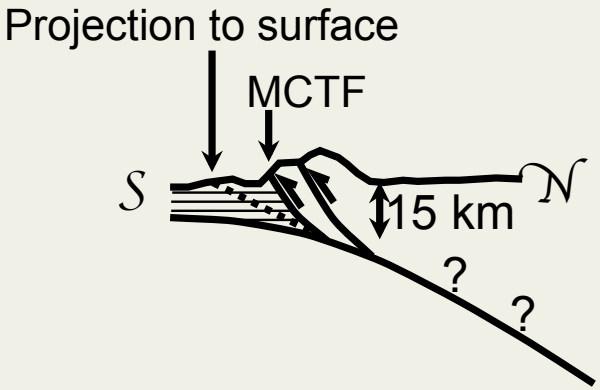


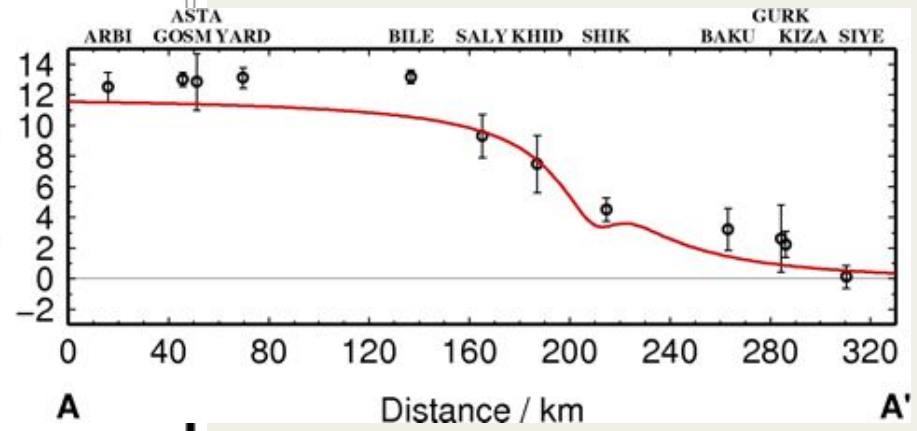


WRMS(N = 12) = 1.6 mm/yr

An Illustrative Model

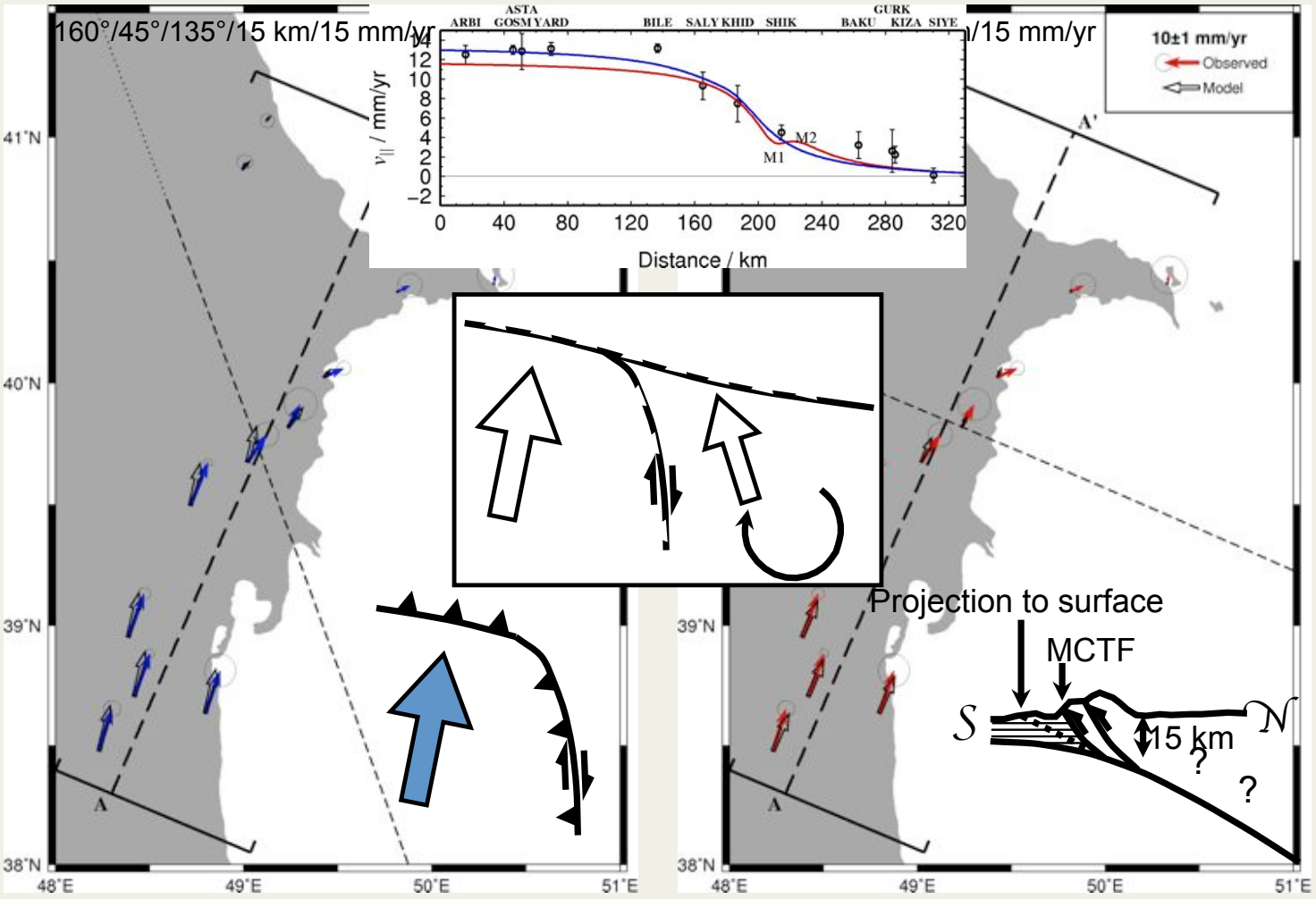






WRMS(N = 12) = 2.0 mm/yr

An Illustrative Model



Baku Earthquake Hazards Caveats/Conclusions

- A large N-S strain rate exists along the Caspian Sea coast in Azerbaijan
  - ~ 10 mm/yr over 150 km (~ 67 nanostrain/yr)
- Evidence of large, shallow, earthquakes nearby but accommodation of strain near Baku (population and industry) remains unclear
- Elastic dislocation models of proposed faults in the area can fit the data BUT...
  - It is likely too simplistic given decoupling and anelastic deformation
  - Full block model approach for better determination of boundaries
- Concern for energy industry and large population centers not necessarily aware of or prepared for a potentially destructive earthquake