The Abdus Salam
International Centre
for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2464-14

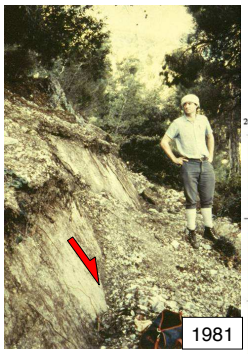
Earthquake Tectonics and Hazards on the Continents

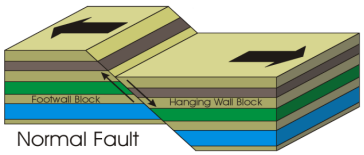
17 - 28 June 2013

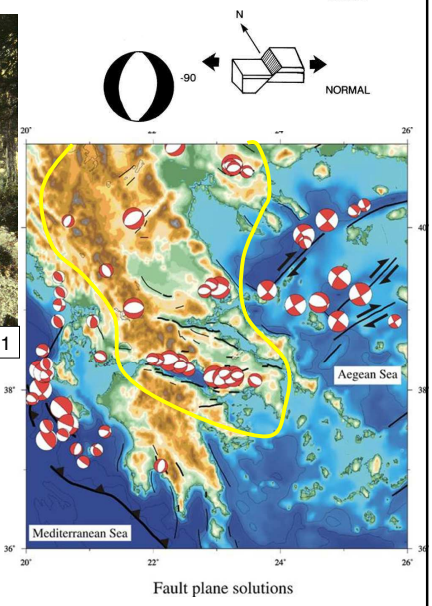
Greece and Africa

J. Jackson
University of Cambridge
UK

Regional extension and normal faulting





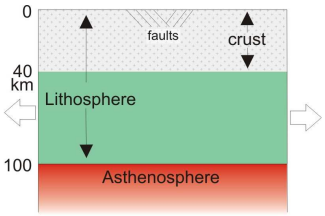


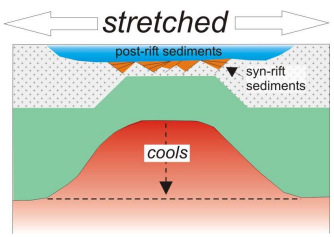
Fault plane solutions

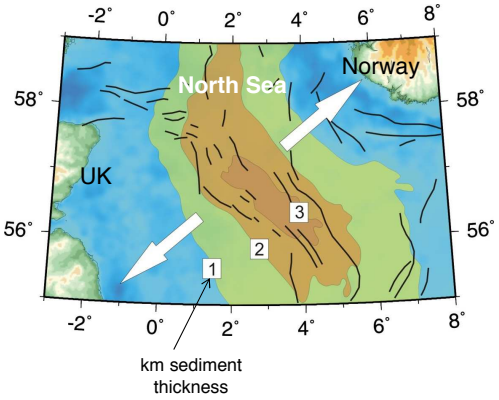
James Jackson

Bullard Laboratories, Cambridge

Normal faulting has produced many sedimentary basins on continents and their margins





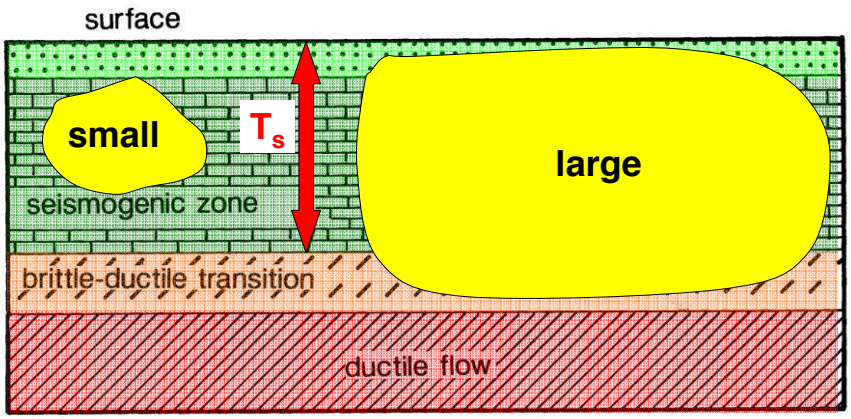


β is the amount of extension = $\frac{\text{original width of the basin}}{\text{stretched width of the basin}}$

D. McKenzie, 1978

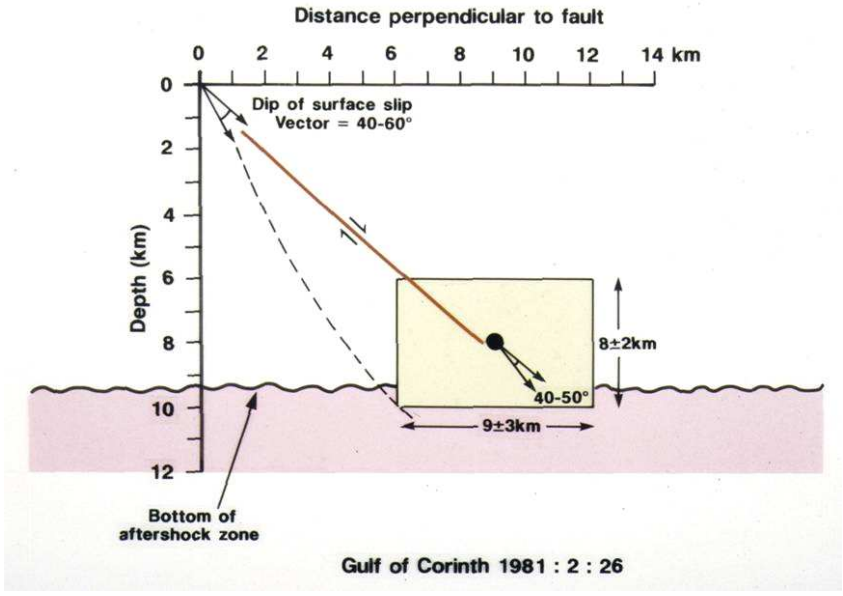
In active extensional regions the normal faulting makes the topography

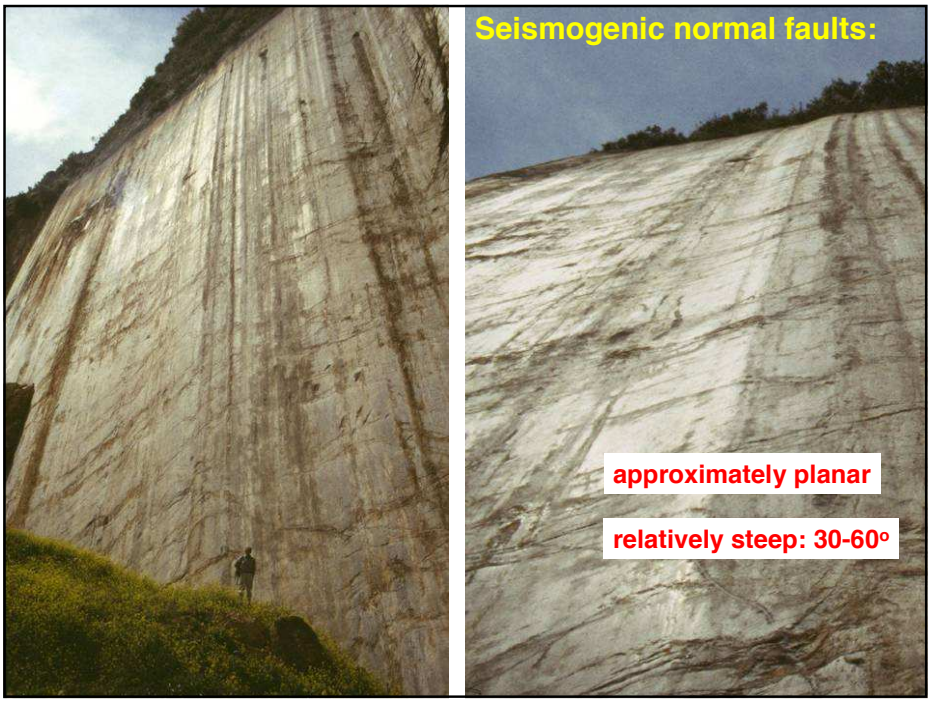
Gulf of Corinth, Greece



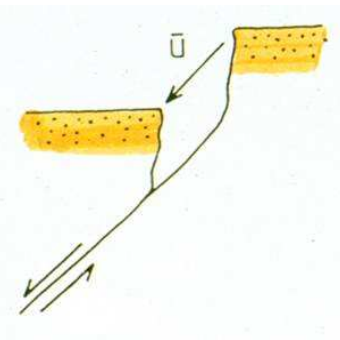
BIG and small faults

C. Scholz

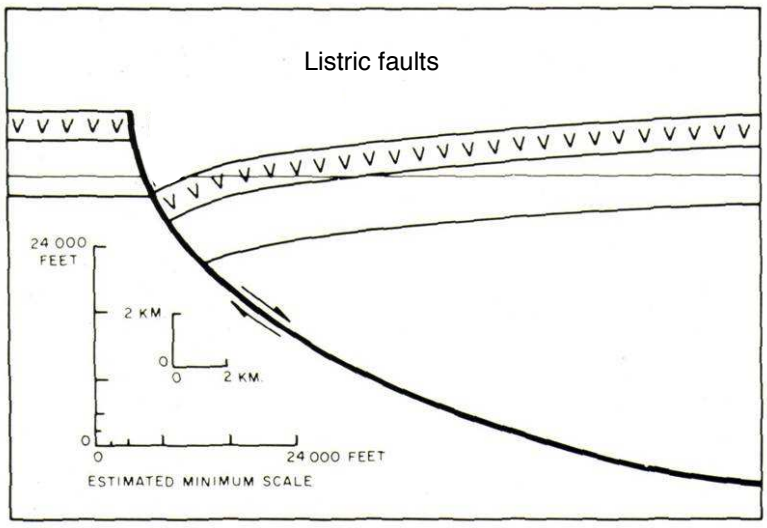



Seismogenic normal faults:
approximately planar
relatively steep: 30-60o

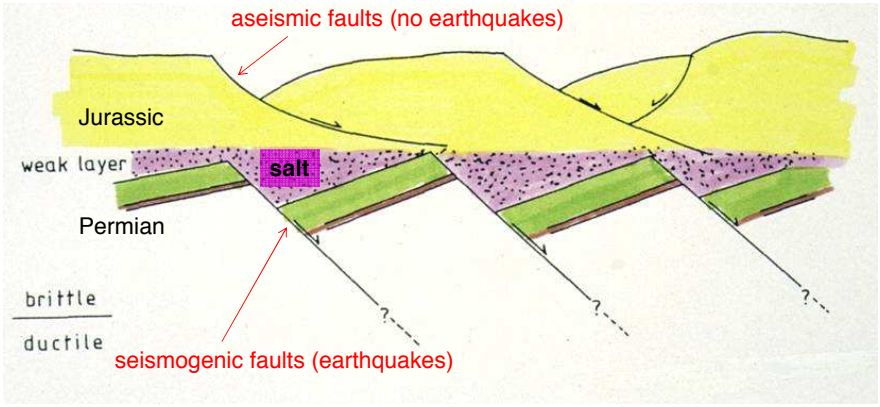

1915 Pleasant Valley Nevada



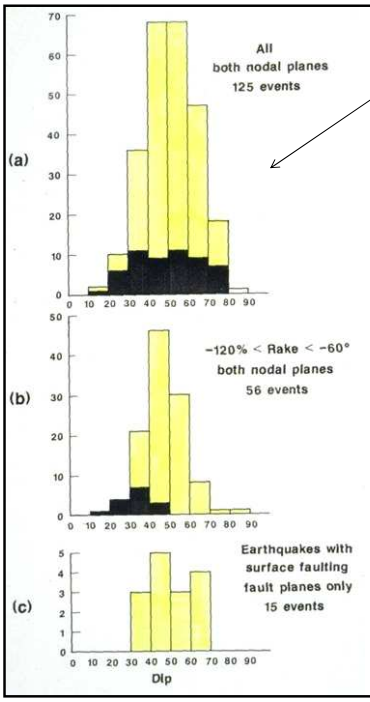
Listric faults



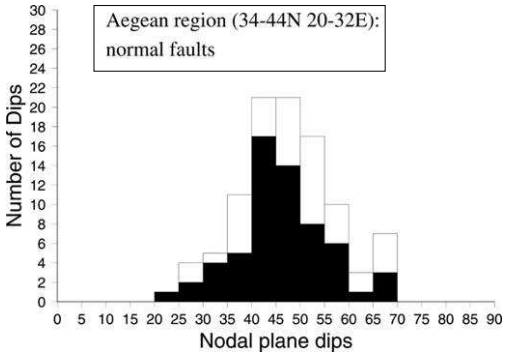
...usually become flat on a weak sedimentary horizon (salt, shale)
... and don't move in earthquakes



schematic cartoon of southern North Sea during Jurassic extension

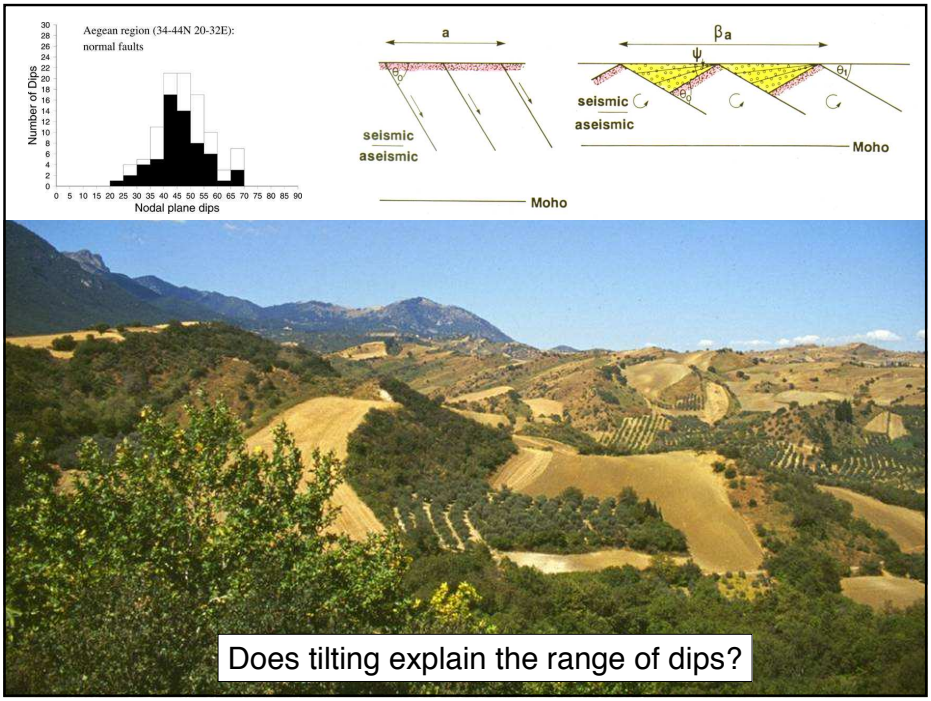


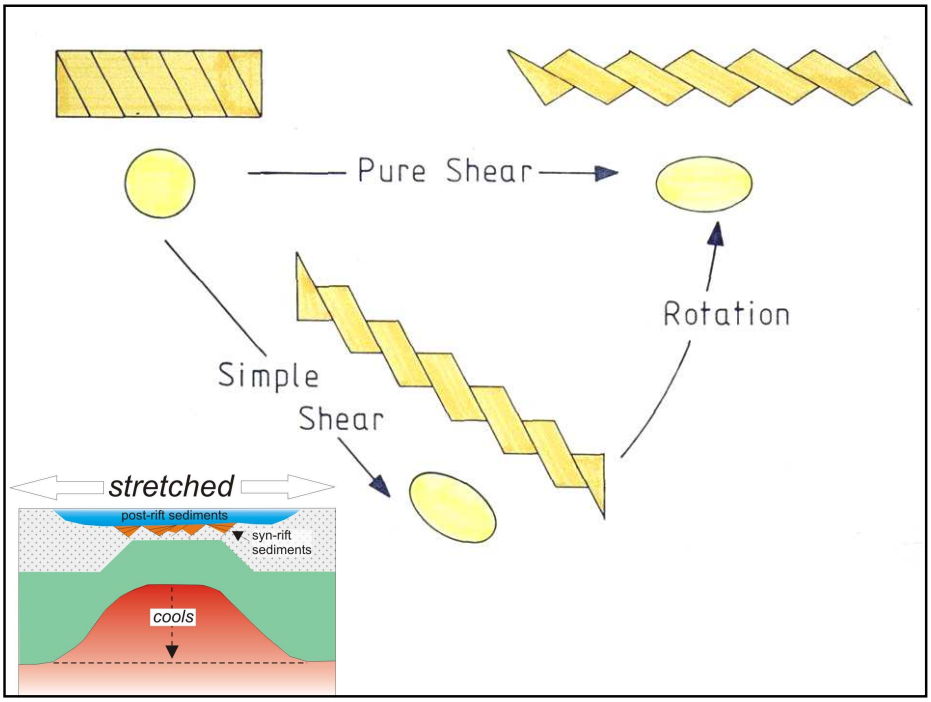
nodal plane dips from fault-plane solutions of large (Mw>5.5) normal-faulting earthquakes on continents



BIG active normal faults dip in the range 30-60°

Jackson & White 1989

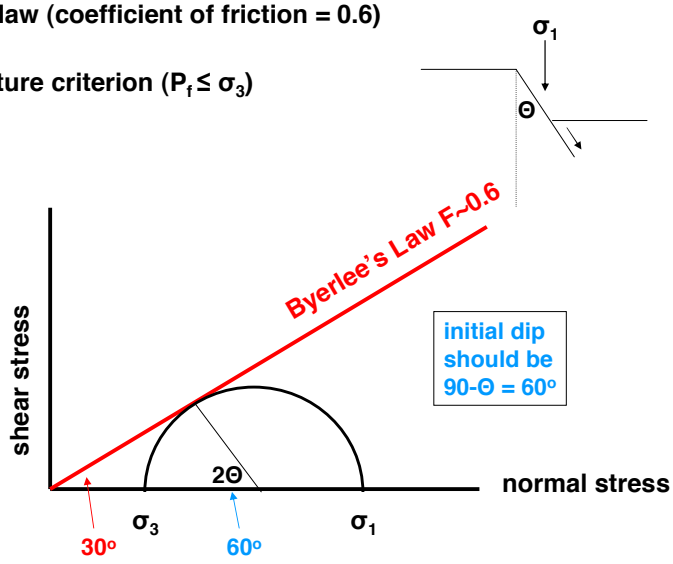

Aegean region (34-44N 20-32E):
normal faults
Number of Dips
Nodal plane dips
a
seismic
aseismic
Moho
βa
ψ
θ1
θ2
seismic
aseismic
Moho
Does tilting explain the range of dips?


Pure Shear
Rotation
Simple
Shear
stretched
post-rift sediments
syn-rift
sediments
cools

1. Anderson's criteria (principal stresses vertical and horizontal)

2. Byerlee's law (coefficient of friction = 0.6)

3. Hydrofracture criterion ($P_f \leq \sigma_3$)



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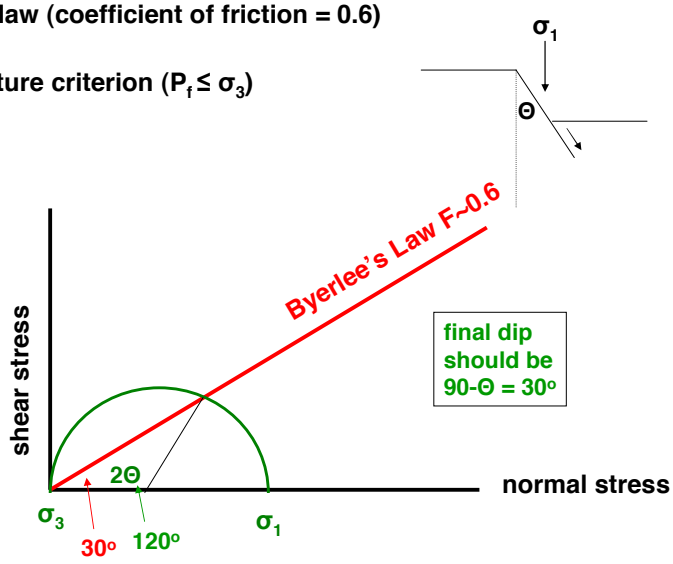
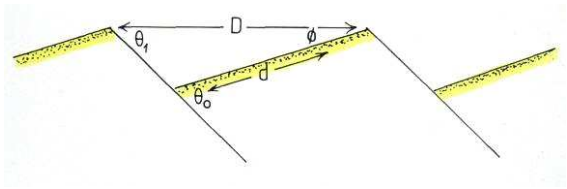




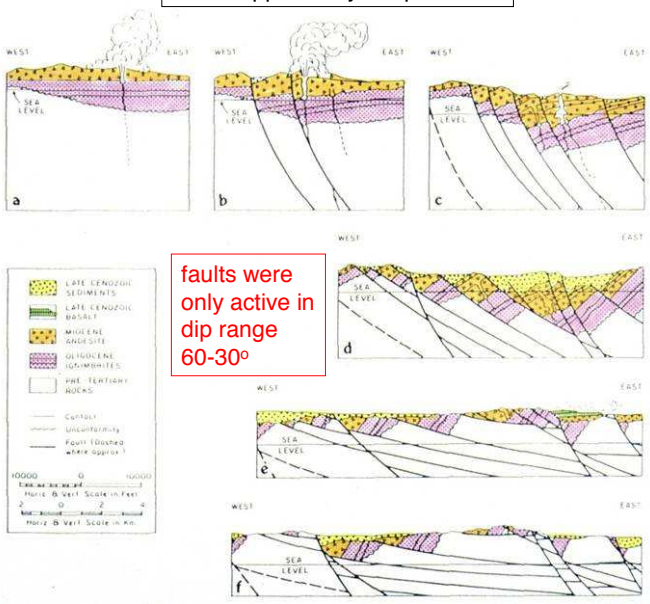
$$\frac{d}{\sin\theta_1} = \frac{D}{\sin\theta_o}$$

$$\beta = \frac{D}{d} = \frac{\sin\theta_o}{\sin\theta_1} = \frac{\sin(\theta_1 + \phi)}{\sin\theta_1}$$

β is the amount of extension = original width of the basin / stretched width of the basin

Rotating from fault dip 60° to 30° gives β = 1.7

what happens beyond β = 1.7?

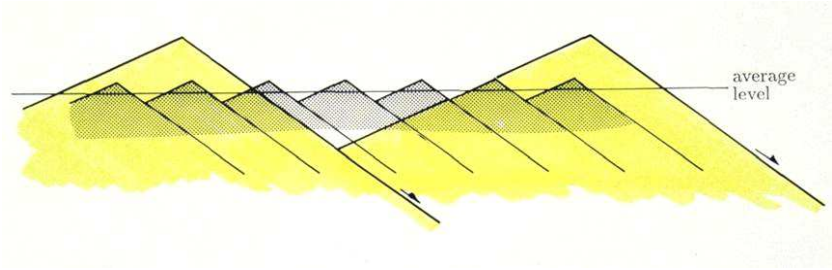


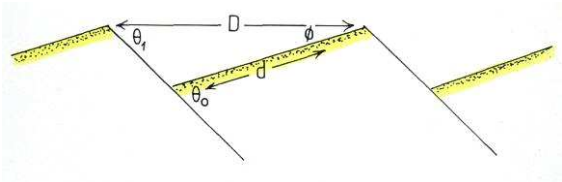
faults were only active in dip range 60-30°

total extension = $\beta_1 \times \beta_2 \times \ldots$ ...

Yerrington Nevada

Proffett, 1977, GSA Bulletin





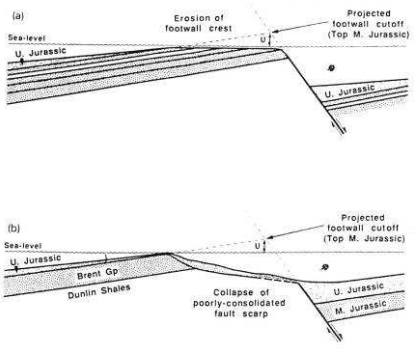
$$\frac{d}{\sin\theta_1} = \frac{D}{\sin\theta_o}$$

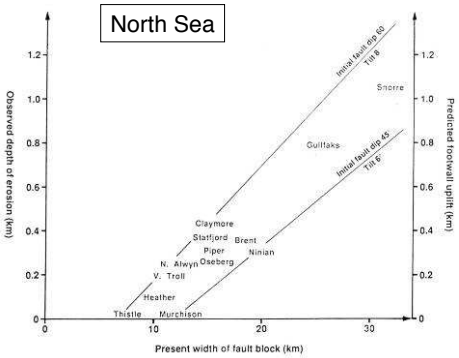
amount of extension (β) is related to tilting

$$\beta = \frac{D}{d} = \frac{\sin\theta_o}{\sin\theta_1} = \frac{\sin(\theta_1 + \phi)}{\sin\theta_1}$$

… but topography is related to block width

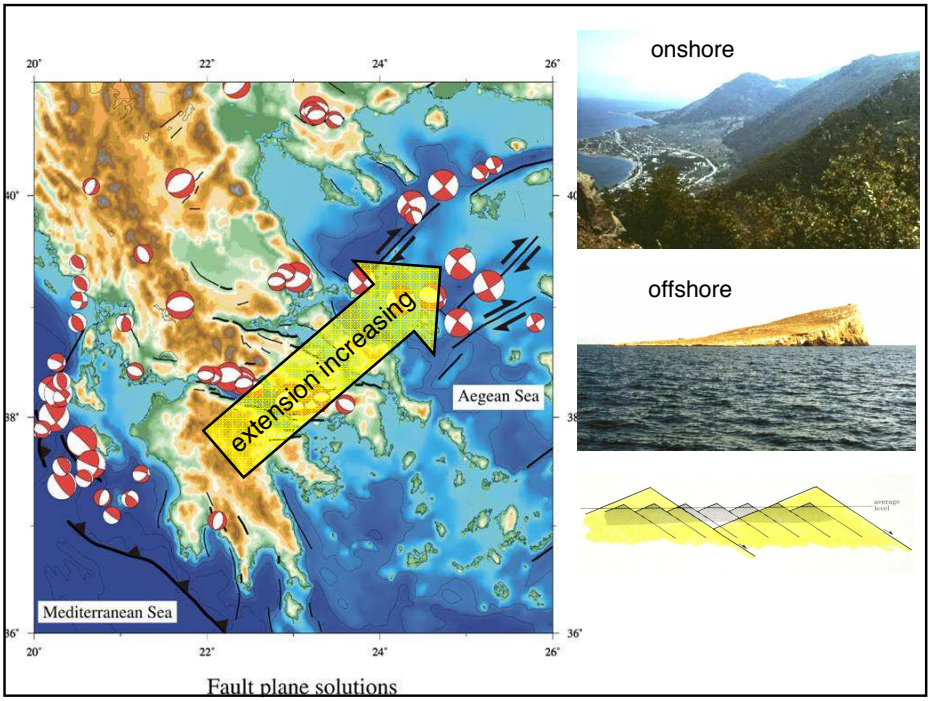
Predicting vertical motions from tilting and block size





big blocks stick up and are eroded (unconformities)
small blocks drown

G. Yielding, J. Geol. Soc. London, 1990



Fault plane solutions

LARGE EARTHQUAKE-GENERATING NORMAL FAULTS IN:

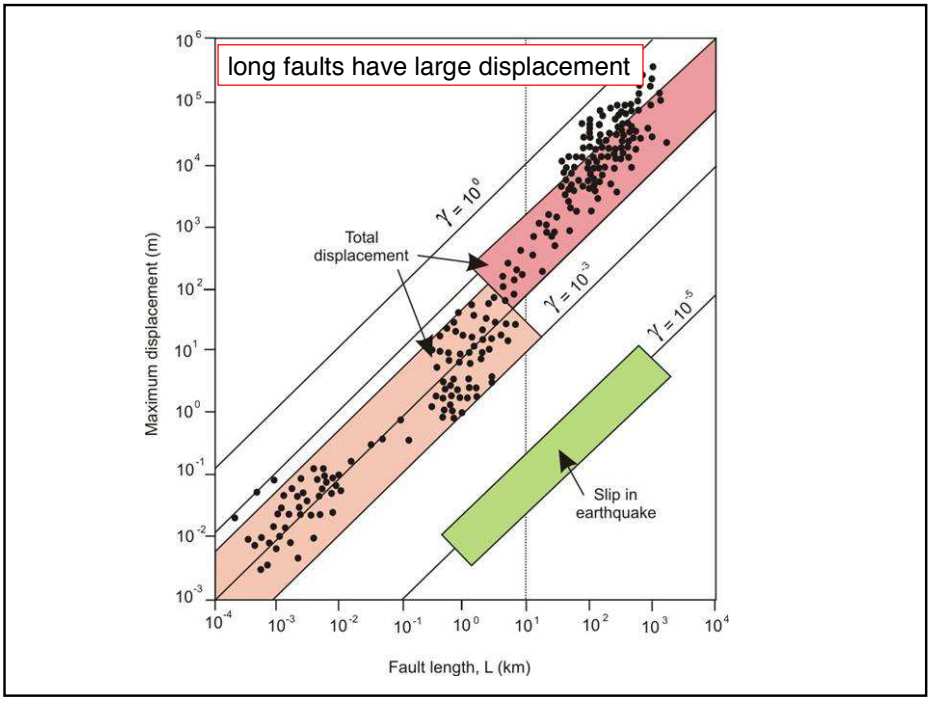
Greece	Turkey	Italy
Gulf of Suez	Tibet	N. & S. China
Western U.S.A.	most of E. Africa	New Zealand

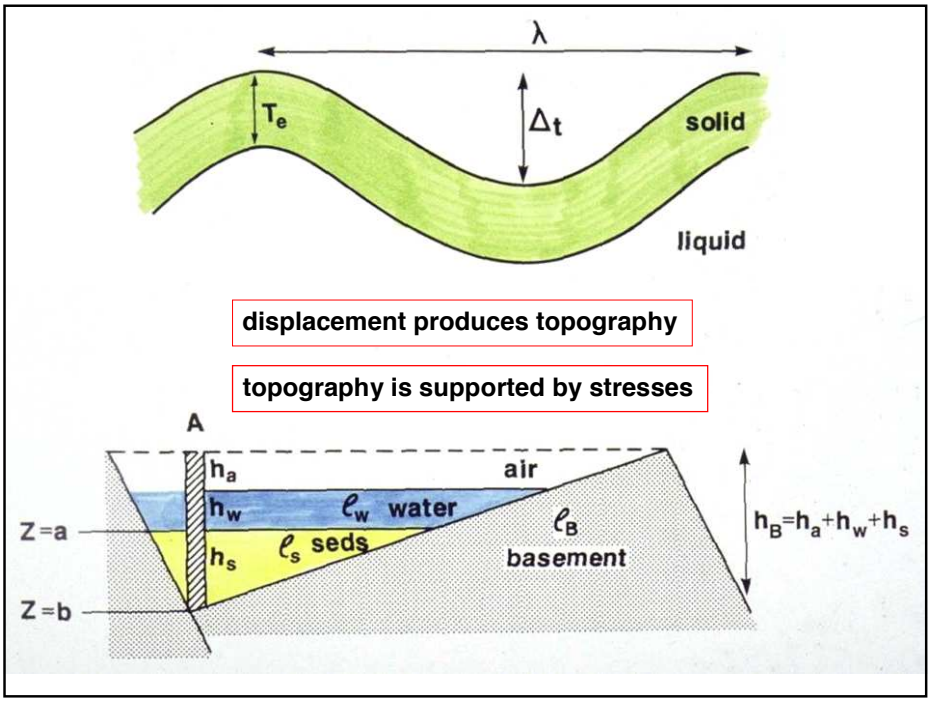
ALL LOOK THE SAME!

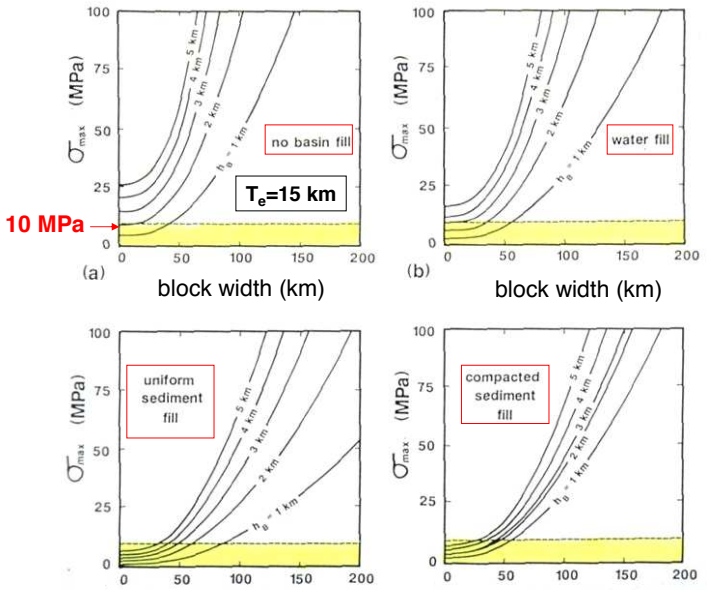
- Confined to top 10–15 km of crust
- Probably planar in cross-section
- Dip in the range ~30–65°
- Maximum segment lengths of <~ 30 km
- Graben widths of <~ 30 km

what controls maximum fault length and graben width?

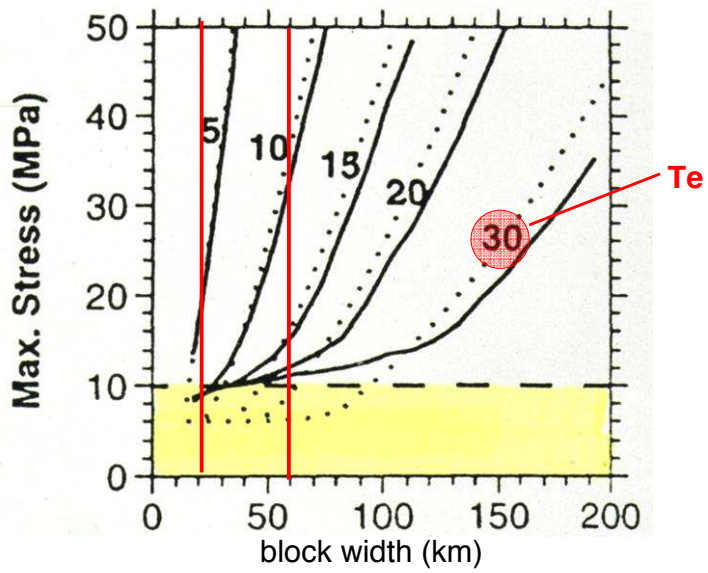
Jackson & White 1989


long faults have large displacement
Maximum displacement (m)
Fault length, L (km)
Total displacement
γ = 10^0
γ = 10^-3
γ = 10^-5
Slip in earthquake


λ
Te
Δt
solid
liquid
displacement produces topography
topography is supported by stresses
A
ha
air
hw
ℓw water
hs
ℓs seds
ℓB
basement
Z=a
Z=b
hB=ha+hw+hs

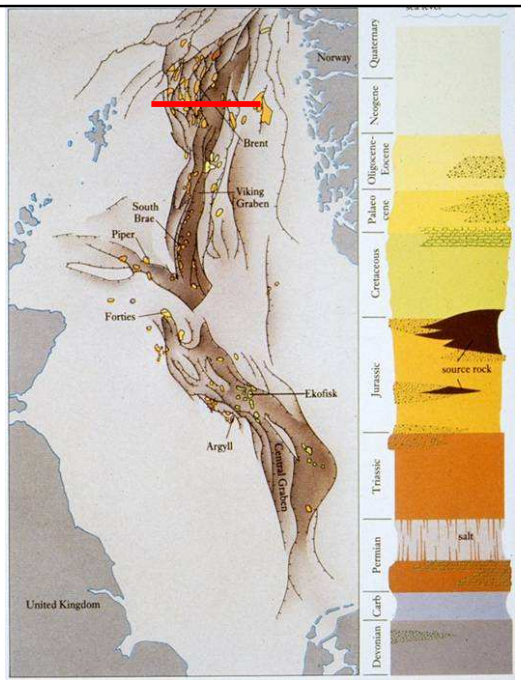


stresses required to support tilting increase rapidly with block width

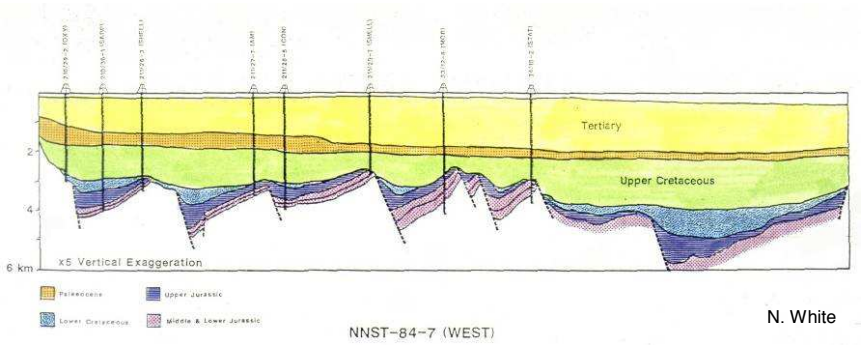


...but stresses ***reduce*** as elastic thickness (Te) increases

A. Foster & F. Nimmo



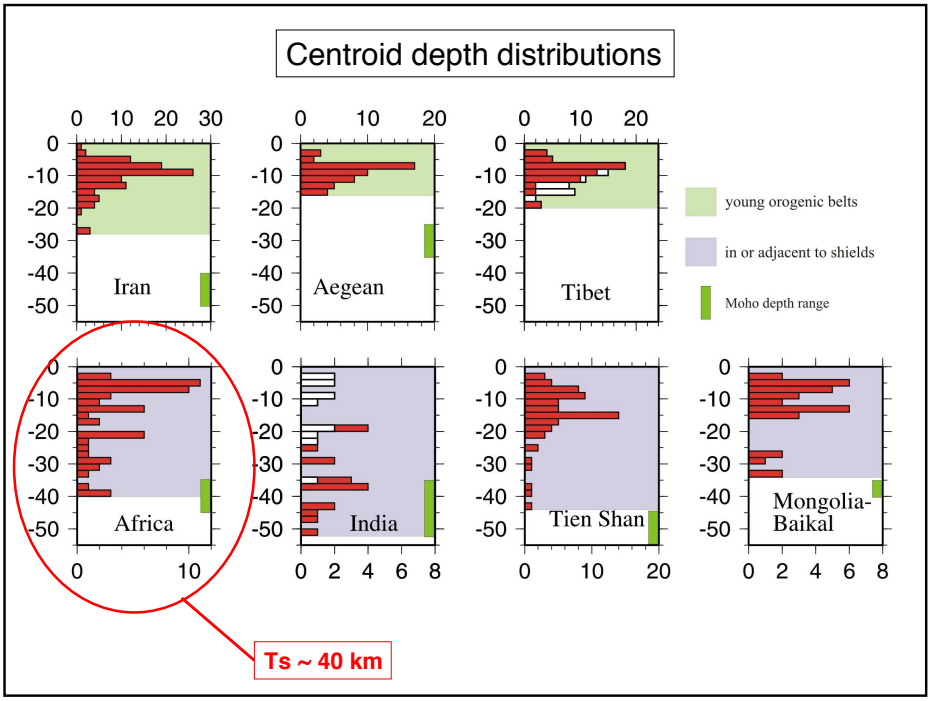
10 km

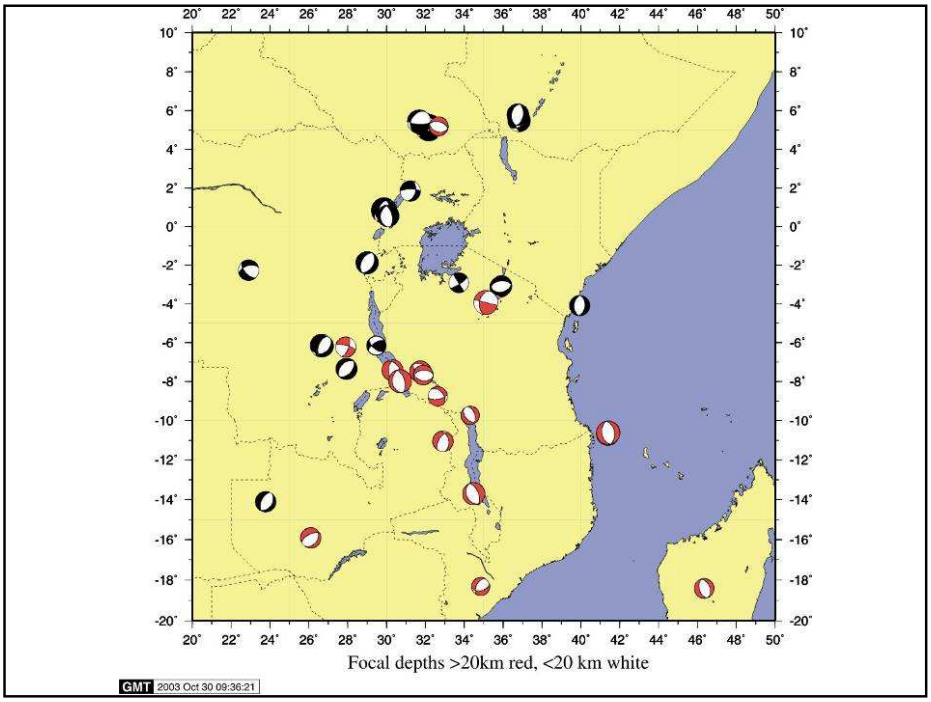


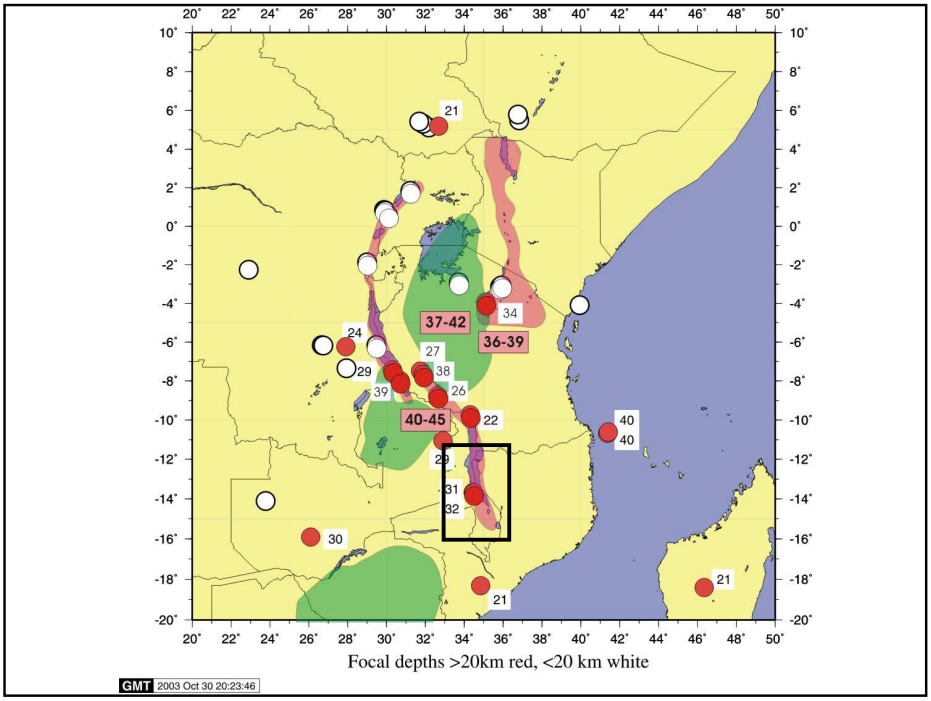
N. White

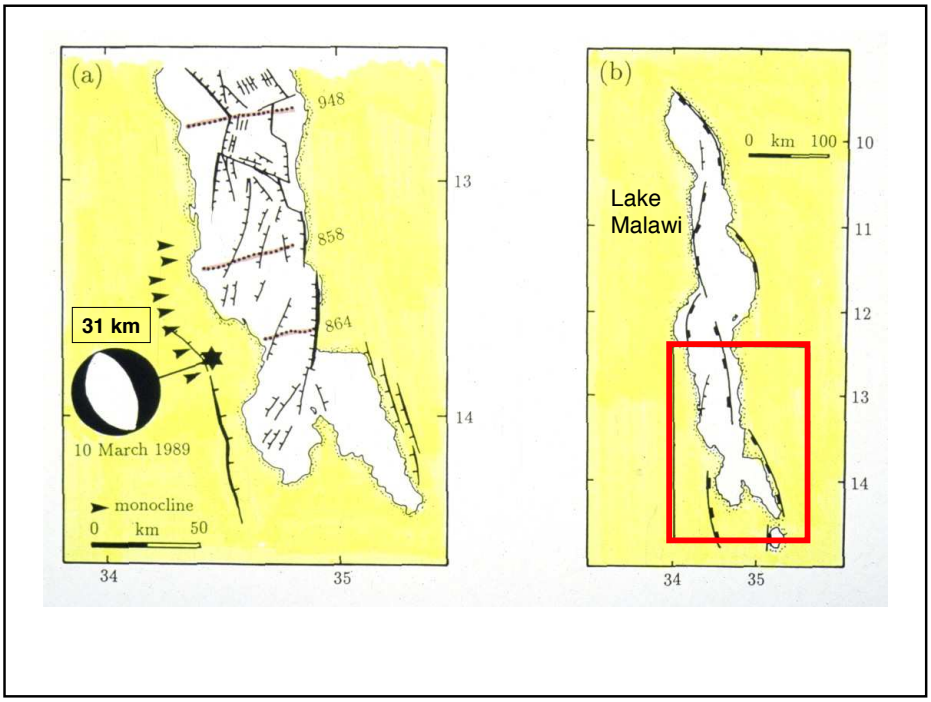
Tilted blocks ***up to 25 km in width***
can be supported by stresses of ***10MPa or less***
(i.e. the stress drops in earthquakes)
for a ***normal elastic thickness of 10-15 km***

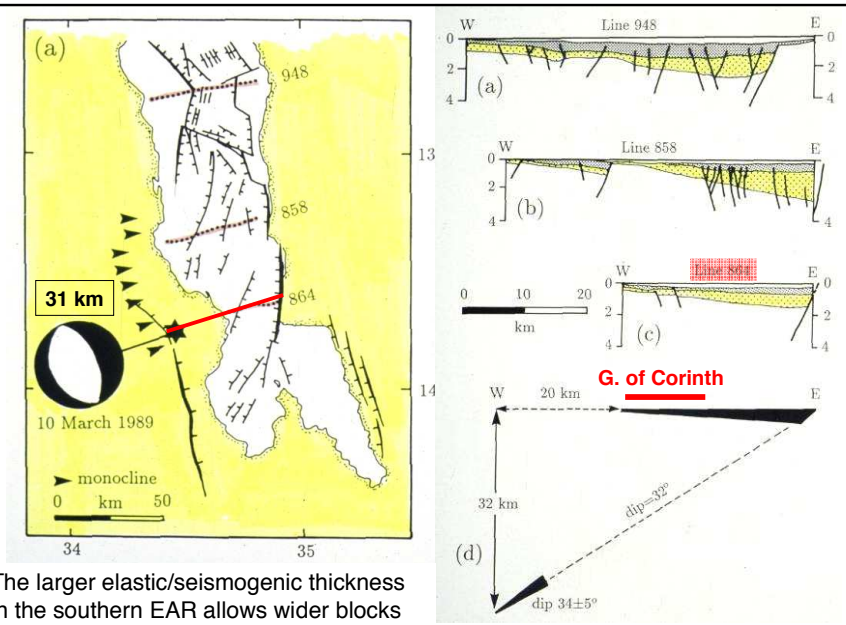
...so what about the southern East Africa Rift?


Centroid depth distributions
Iran
Aegean
Tibet
Africa
India
Tien Shan
Mongolia-
Baikal
young orogenic belts
in or adjacent to shields
Moho depth range
Ts ~ 40 km


Focal depths >20km red, <20 km white
GMT 2003 Oct 30 09:36:21


37-42
36-39
40-45
Focal depths >20km red, <20 km white
GMT 2003 Oct 30 20:23:46


(a)
948
858
864
31 km
10 March 1989
monocline
0 km 50
(b)
0 km 100
Lake
Malawi

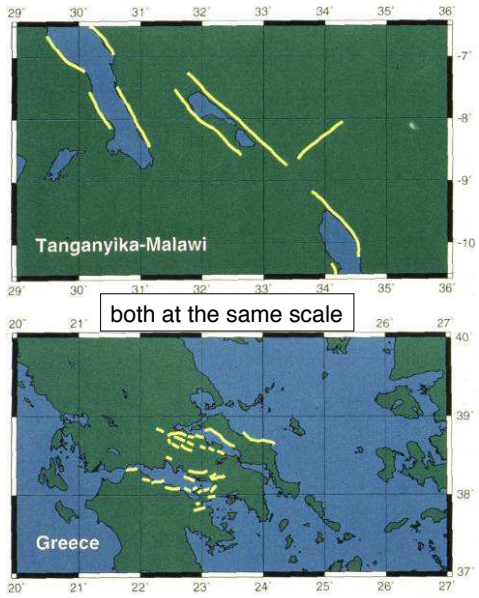


The larger elastic/seismogenic thickness in the southern EAR allows wider blocks and longer faults

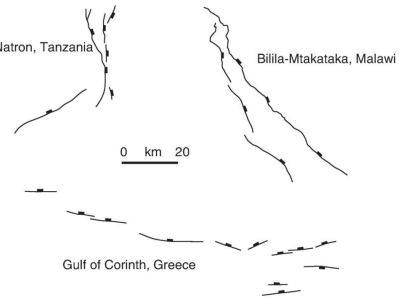
Mta Wa Mbu, Tanzania

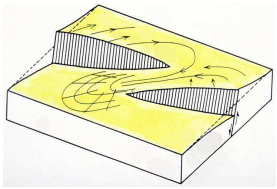
Bilila-Mtakataka, Malawi

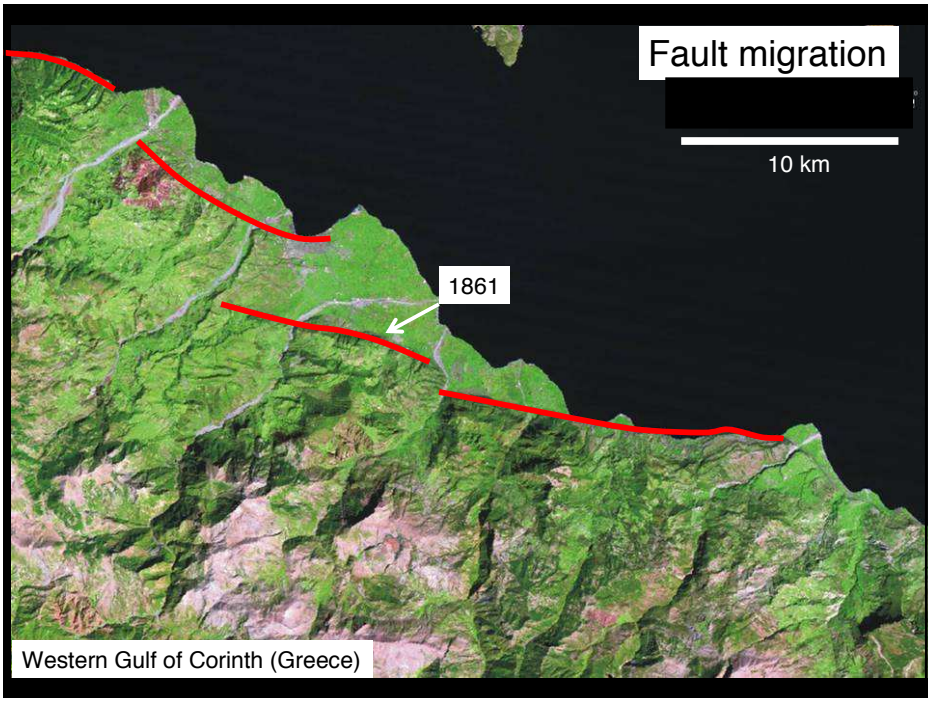
Scale of fault segmentation

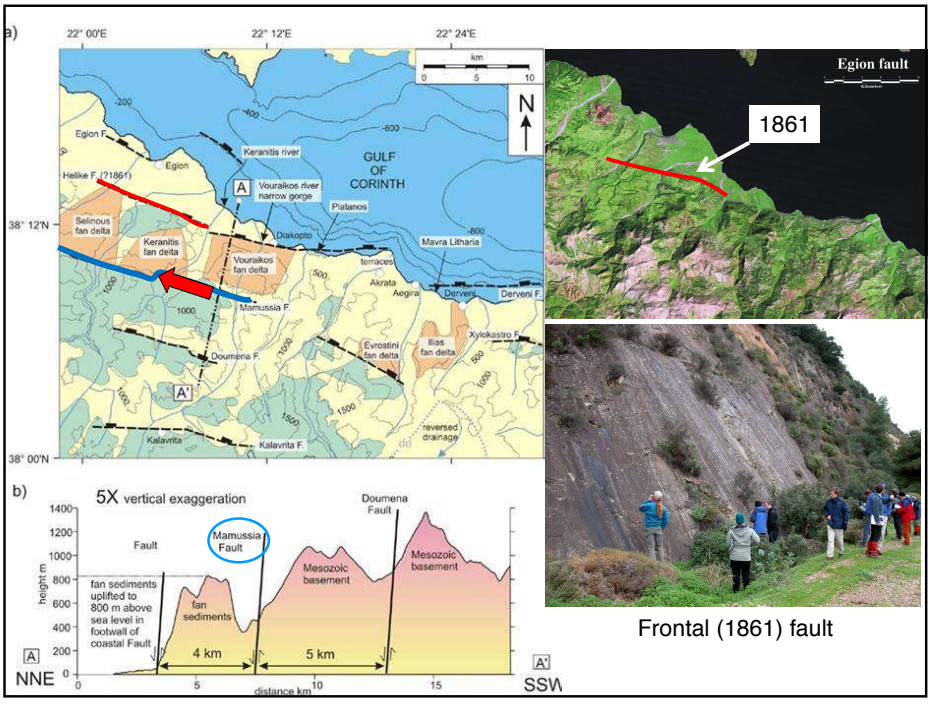


both at the same scale

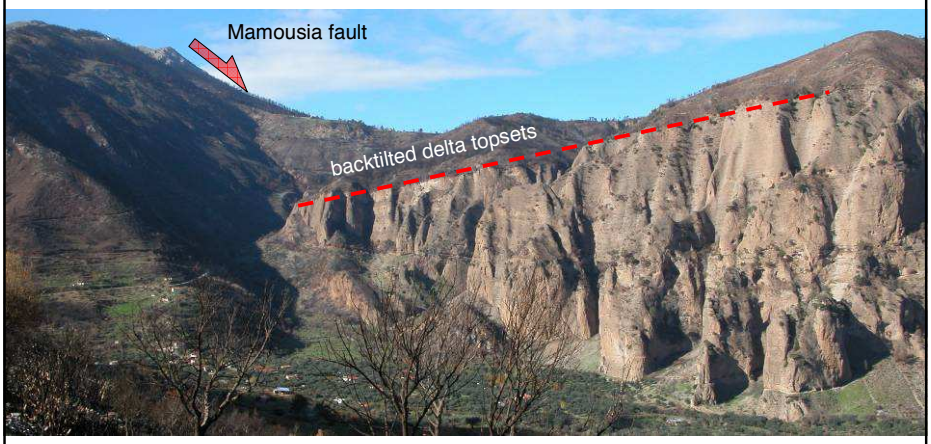




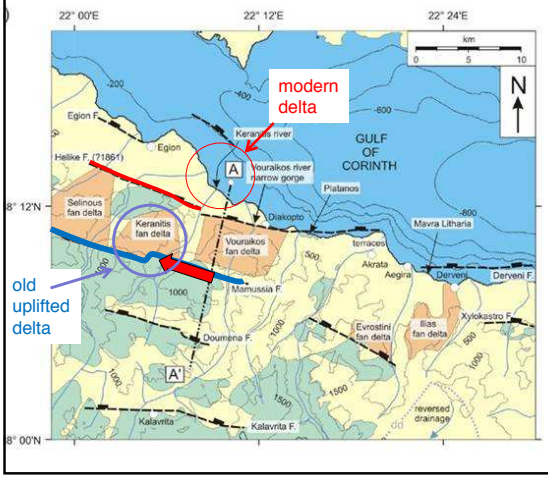

Fault migration
10 km
1861
Western Gulf of Corinth (Greece)

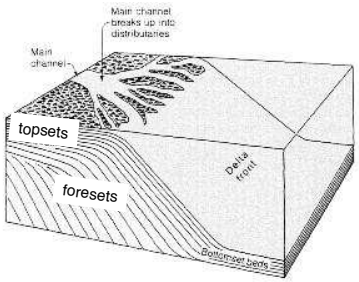

a)
22° 00'E
22° 12'E
22° 24'E
38° 12'N
38° 00'N
GULF OF CORINTH
Egion F.
Helike F. (?1861)
Egion
Keranitis river
Vouraikos river narrow gorge
Platanos
Diakopto
Selinous fan delta
Keranitis fan delta
Vouraikos fan delta
terraces
Akrata
Aegira
Derveni
Derveni F.
Mavra Litharia
Mamussia F.
Doumena F.
Evrostini fan delta
Ilias fan delta
Xylokastro F.
Kalavrita
Kalavrita F.
reversed drainage
N
b)
5X vertical exaggeration
Fault
Mamussia Fault
Doumena Fault
Mesozoic basement
fan sediments uplifted to 800 m above sea level in footwall of coastal Fault
fan sediments
4 km
5 km
height m
distance km
NNE
SSW
Egion fault
1861
Frontal (1861) fault

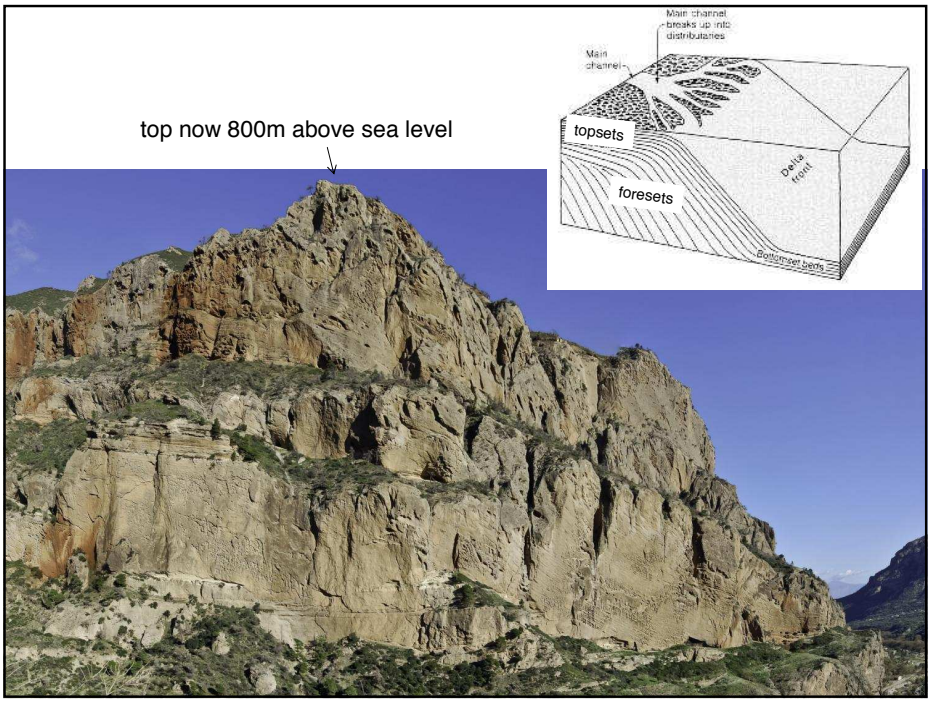

Mamousia fault

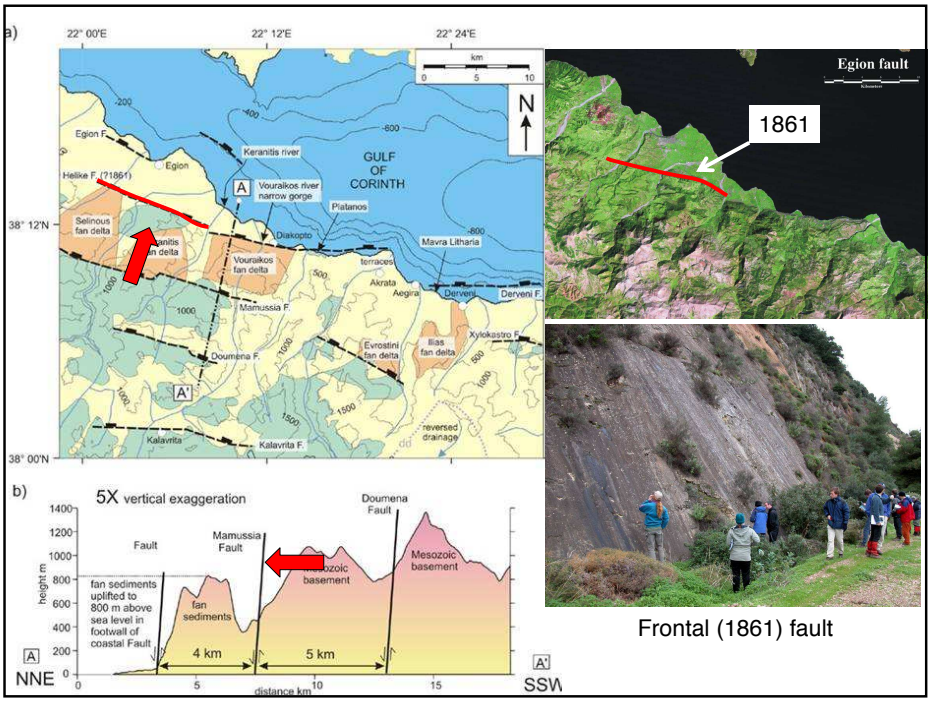

Mamousia fault
backtilted delta topsets

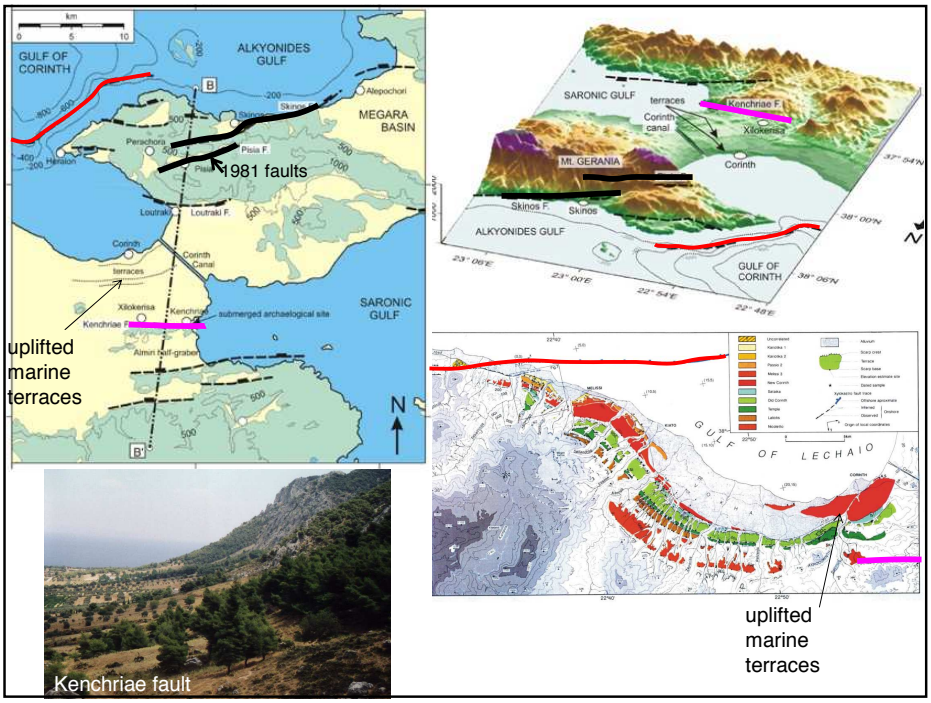

Mamousia fault
topsets
foresets

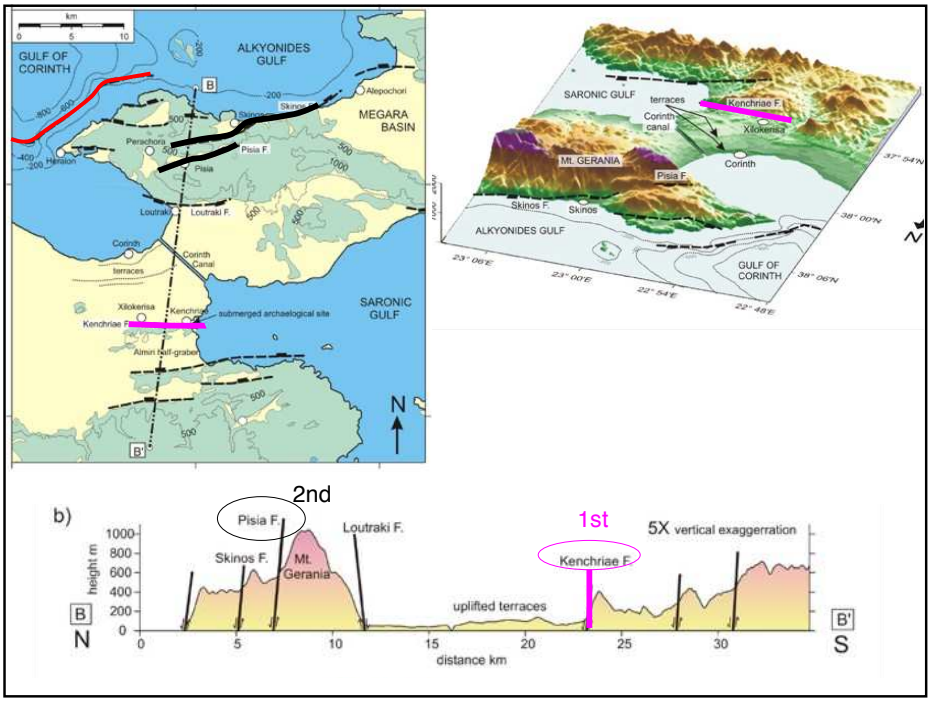

22° 00'E
22° 12'E
22° 24'E
km
0
5
10
N
modern delta
old uplifted delta
GULF OF CORINTH
Egion F.
Egion
Helike F. (?1861)
Keranitis river
Vouraikos river narrow gorge
A
A'
Platanos
Diakopto
Selinous fan delta
Keranitis fan delta
Vouraikos fan delta
terraces
Akrata
Aegira
Derveni
Derveni F.
Mamoussia F.
Doumena F.
Evrostini fan delta
Ilias fan delta
Xylokastro F.
Kalavrita
Kalavrita F.
reversed drainage
Mavra Litharia
8° 12'N
8° 00'N

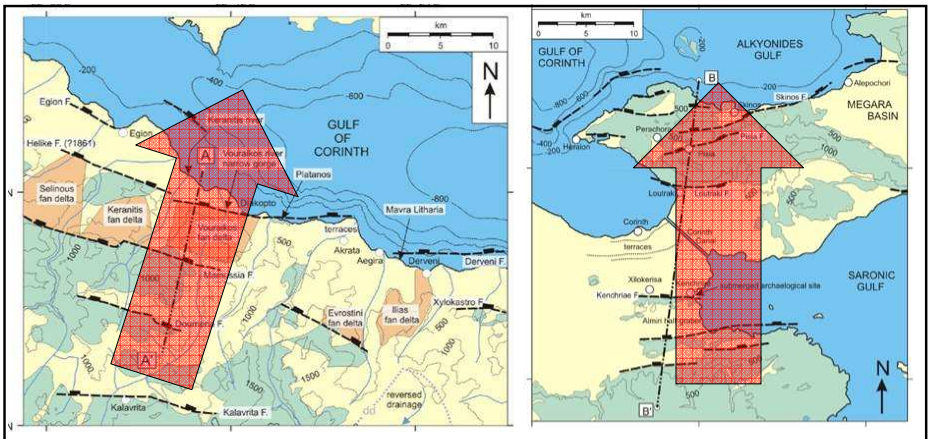

Main channel breaks up into distributaries
Main channel
topsets
foresets
Delta front
Bottomset beds


top now 800m above sea level
Main channel breaks up into distributaries
Main channel
topsets
foresets
Delta front
Bottomset beds


a)
22° 00'E
22° 12'E
22° 24'E
38° 12'N
38° 00'N
km
0 5 10
N
Egion F.
Helike F. (?1861)
Egion
Keranitis river
Vouraikos river narrow gorge
GULF OF CORINTH
Platanos
Diakopto
Mavra Litharia
Selinous fan delta
Vouraikos fan delta
terraces
Akrata
Aegira
Derveni
Derveni F.
Mamussia F.
Doumena F.
Evrostini fan delta
Ilias fan delta
Xylokastro F.
reversed drainage
Kalavrita
Kalavrita F.
A
A'
b)
5X vertical exaggeration
Doumena Fault
Mamussia Fault
Fault
Mesozoic basement
fan sediments uplifted to 800 m above sea level in footwall of coastal Fault
fan sediments
4 km
5 km
height m
distance km
NNE
SSW
Egion fault
1861
Frontal (1861) fault


GULF OF CORINTH
ALKYONIDES GULF
MEGARA BASIN
SARONIC GULF
1981 faults
uplifted marine terraces
Kenchriae fault
SARONIC GULF
terraces
Corinth canal
Kenchriae F.
Xilokerisa
Mt. GERANIA
Corinth
Skinos F.
Skinos
ALKYONIDES GULF
GULF OF CORINTH
GULF OF LECHAIO
uplifted marine terraces

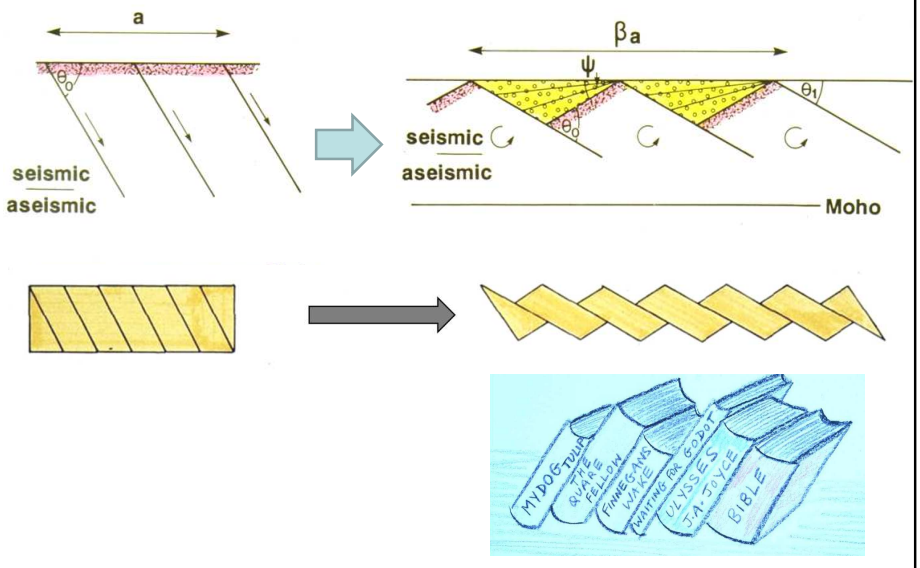

GULF OF CORINTH
ALKYONIDES GULF
MEGARA BASIN
SARONIC GULF
SARONIC GULF
terraces
Corinth canal
Kenchriae F.
Xilokerisa
Mt. GERANIA
Pisia F.
Corinth
Skinos F.
Skinos
ALKYONIDES GULF
GULF OF CORINTH
b)
2nd
Pisia F.
Loutraki F.
1st
5X vertical exaggerration
Skinos F.
Mt. Gerania
Kenchriae F.
uplifted terraces
height m
distance km
B
N
B'
S



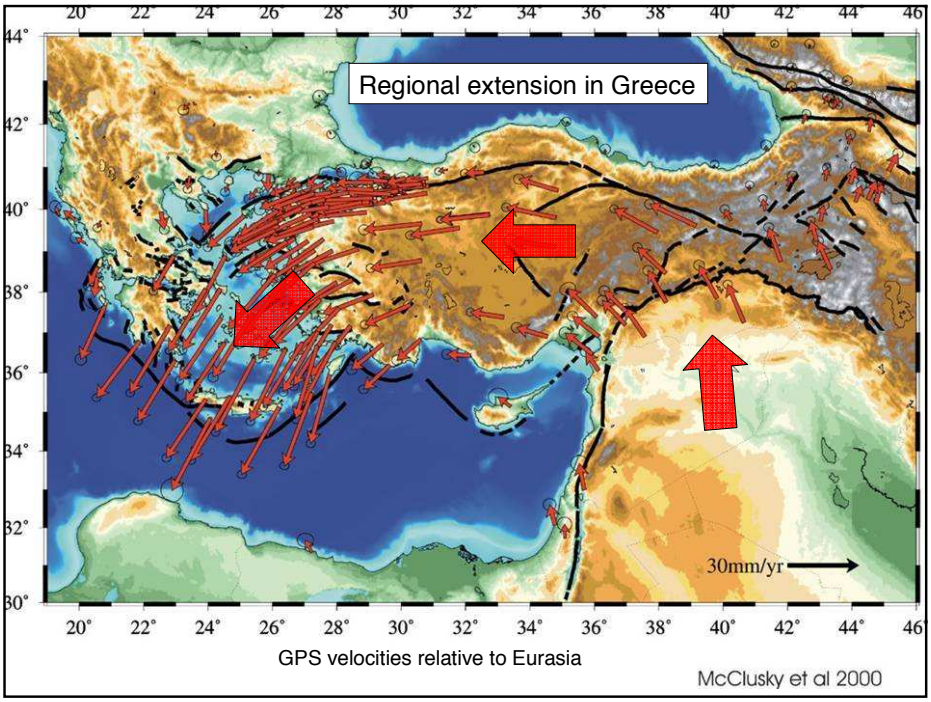
In both places ***faulting has migrated into the hanging wall***.

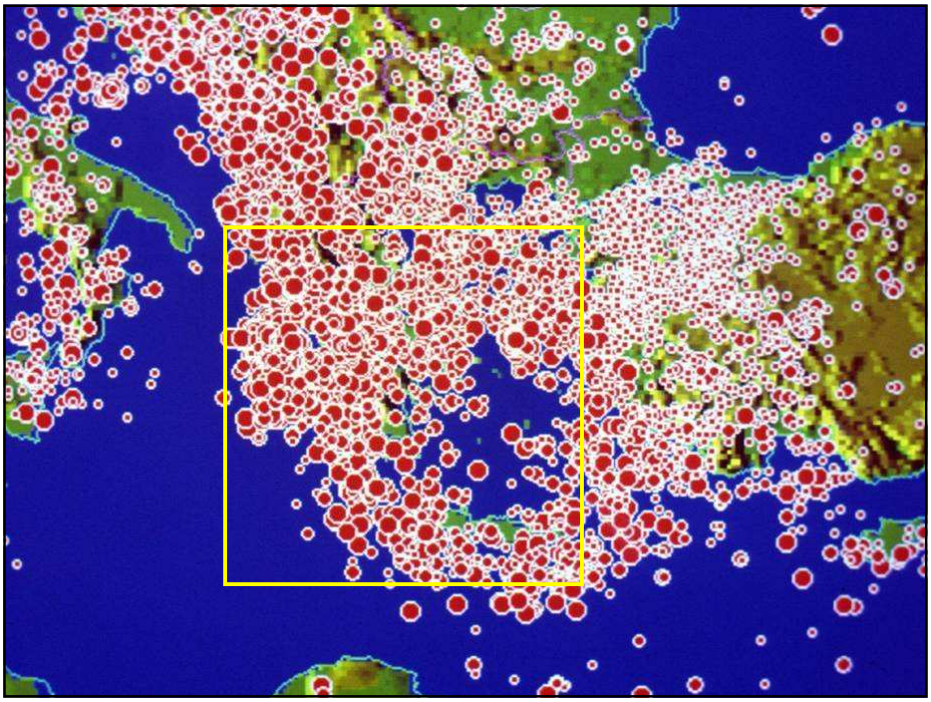
Is this common?

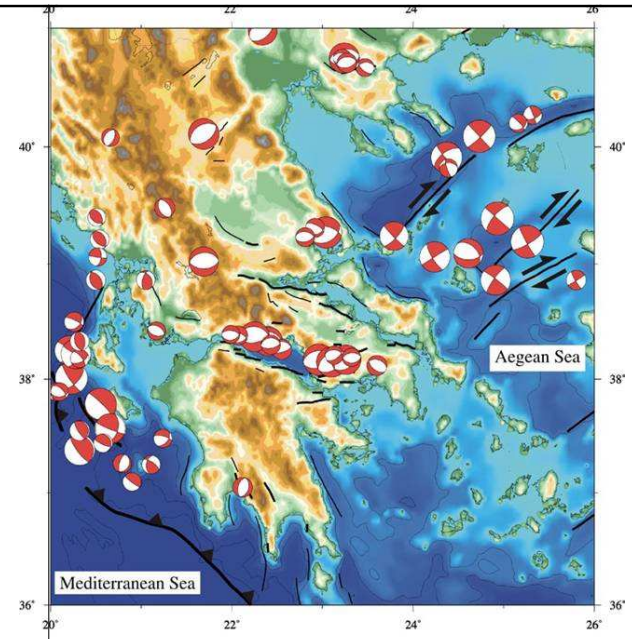
How could you tell, without a reference (sea) level?
(e.g in Nevada, Italy, Tibet, East Africa)



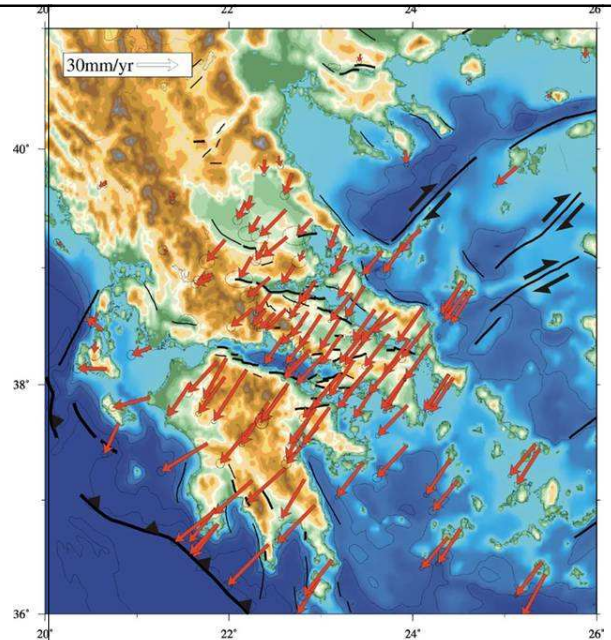
Is domino (bookshelf) faulting simultaneous?
or sequential?


Regional extension in Greece
30mm/yr
GPS velocities relative to Eurasia
McClusky et al 2000

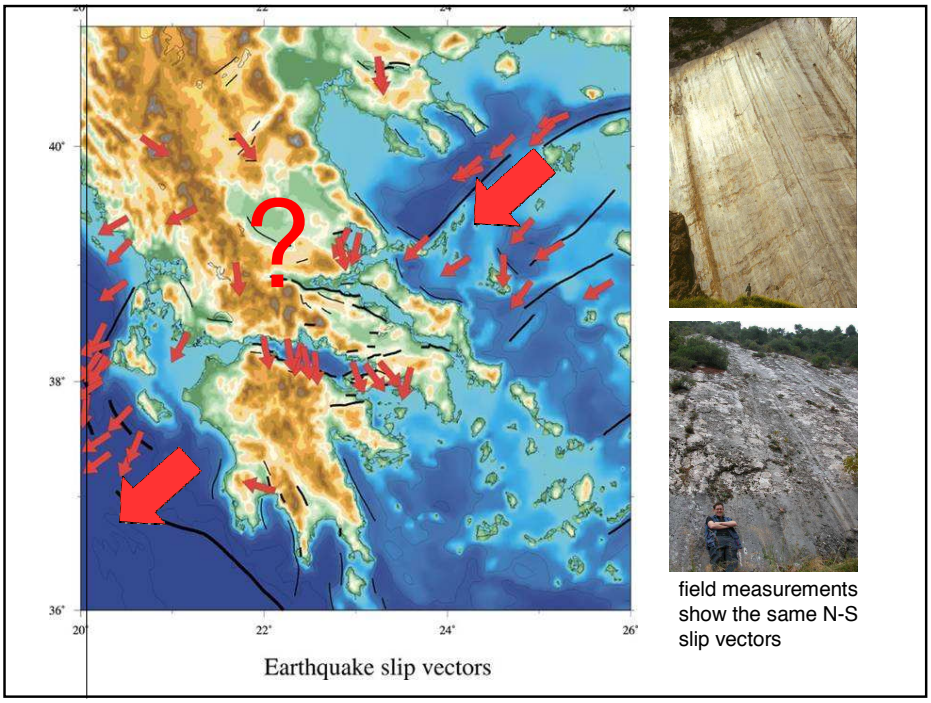


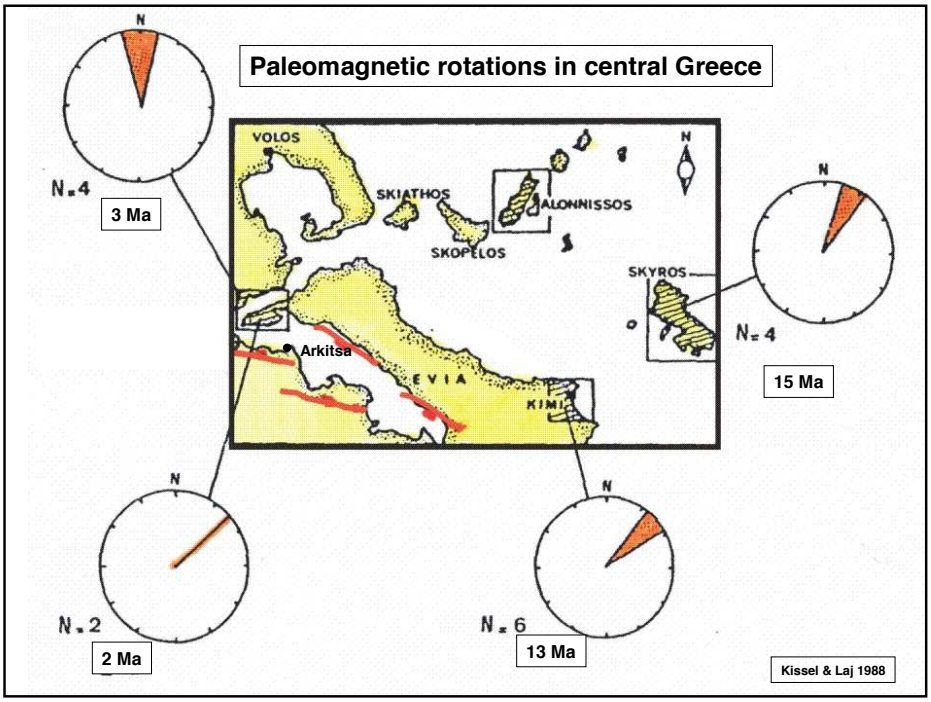


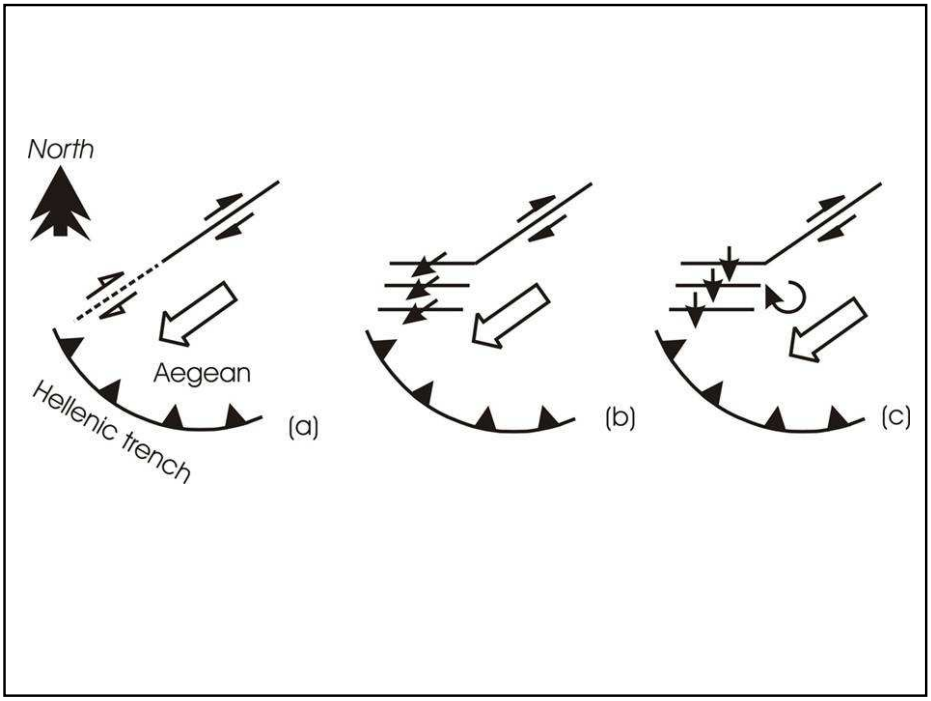
Fault plane solutions

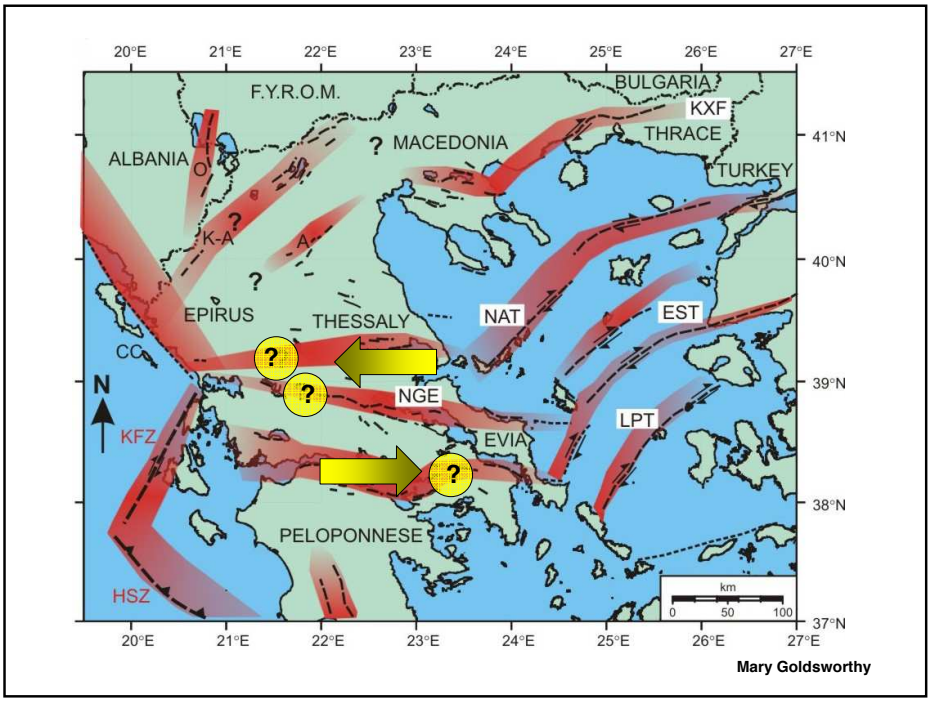


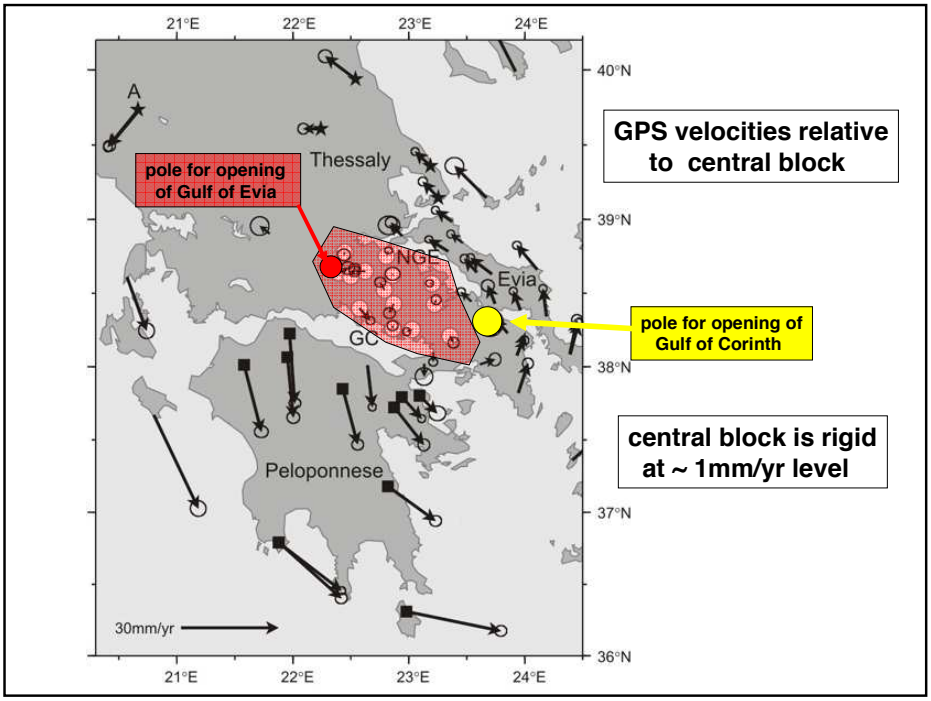
GPS velocities relative to Eurasia

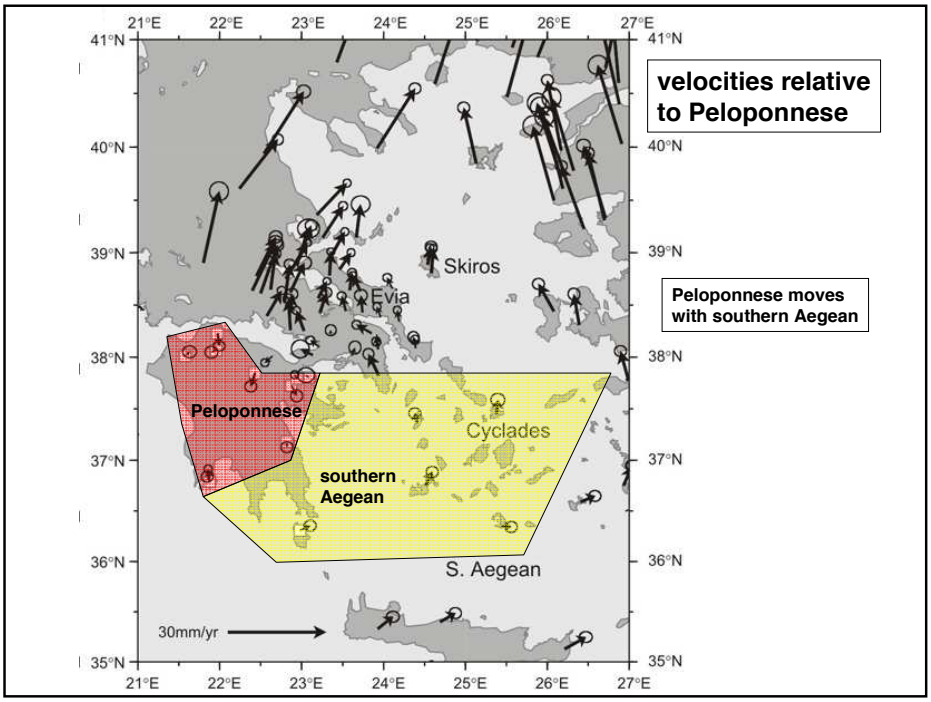

40°
38°
36°
20°
22°
24°
26°
?
Earthquake slip vectors
field measurements show the same N-S slip vectors

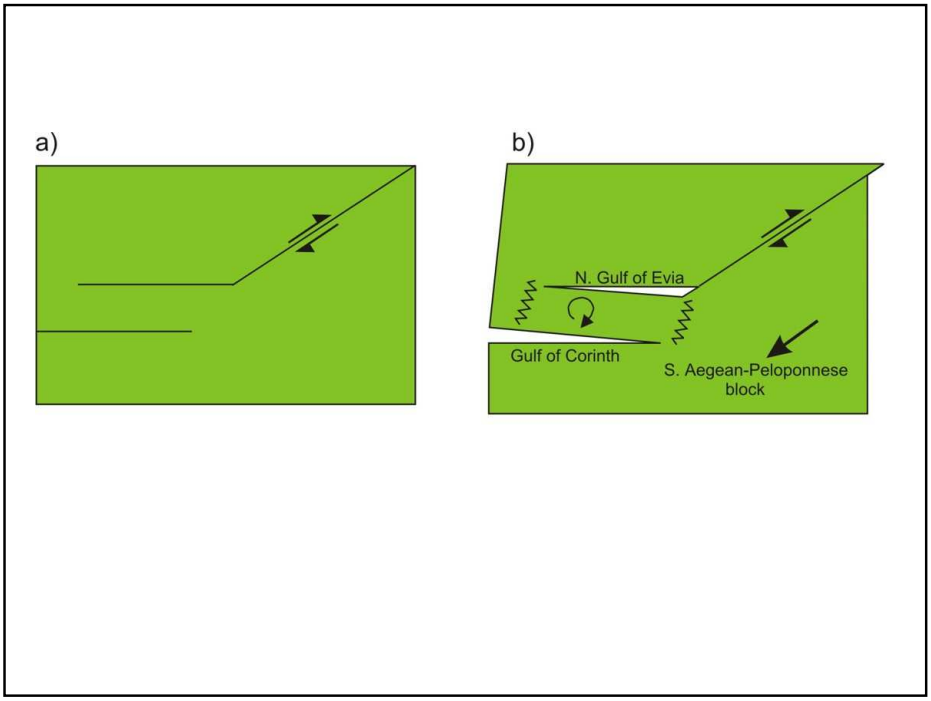

Paleomagnetic rotations in central Greece
N
N=4
3 Ma
VOLOS
SKIATHOS
SKOPELOS
ALONNISSOS
SKYROS
Arkitsa
EVIA
KIMI
N=4
15 Ma
N=2
2 Ma
N=6
13 Ma
Kissel & Laj 1988

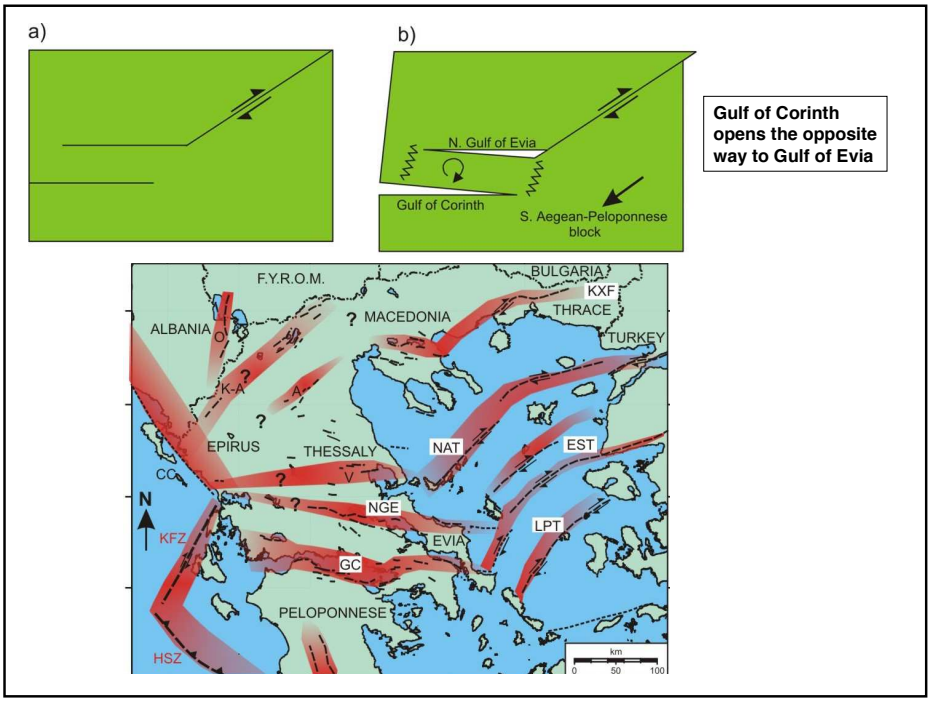

North
Aegean
Hellenic trench
(a)
(b)
(c)

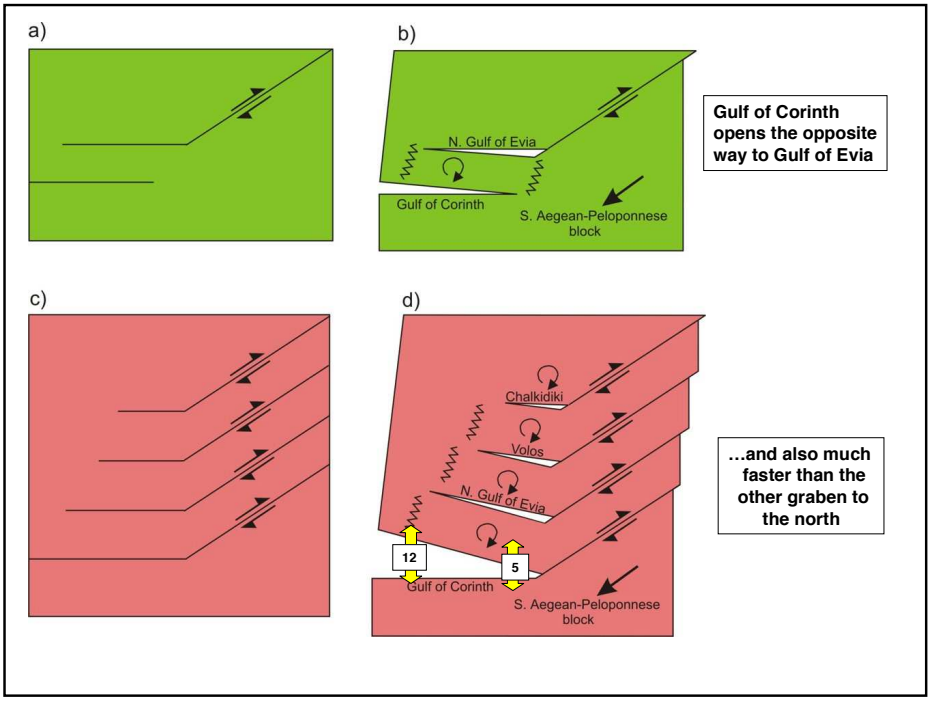

20°E
21°E
22°E
23°E
24°E
25°E
26°E
27°E
41°N
40°N
39°N
38°N
37°N
F.Y.R.O.M.
BULGARIA
KXF
THRACE
TURKEY
? MACEDONIA
ALBANIA
O
K-A
A
?
EPIRUS
THESSALY
NAT
EST
CC
?
?
NGE
LPT
N
KFZ
EVIA
?
PELOPONNESE
HSZ
km
0
50
100
Mary Goldsworthy


21°E
22°E
23°E
24°E
40°N
39°N
38°N
37°N
36°N
A
Thessaly
pole for opening of Gulf of Evia
NGE
Evia
GC
Peloponnese
30mm/yr
GPS velocities relative to central block
pole for opening of Gulf of Corinth
central block is rigid at ~ 1mm/yr level


21°E
22°E
23°E
24°E
25°E
26°E
27°E
41°N
40°N
39°N
38°N
37°N
36°N
35°N
Skiros
Evia
Peloponnese
Cyclades
southern Aegean
S. Aegean
30mm/yr
velocities relative to Peloponnese
Peloponnese moves with southern Aegean


a)
b)
N. Gulf of Evia
Gulf of Corinth
S. Aegean-Peloponnese block


a)
b)
N. Gulf of Evia
Gulf of Corinth
S. Aegean-Peloponnese block
Gulf of Corinth opens the opposite way to Gulf of Evia
F.Y.R.O.M.
BULGARIA
KXF
THRACE
TURKEY
ALBANIA
MACEDONIA
K-A
EPIRUS
THESSALY
NAT
EST
CC
NGE
LPT
KFZ
EVIA
GC
PELOPONNESE
HSZ
N
km
0
50
100



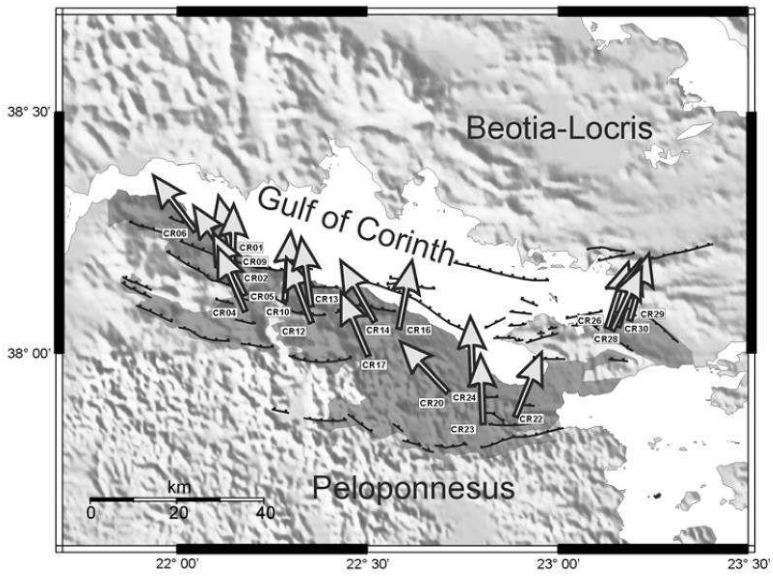


Figure 8. Tilt-corrected paleomagnetic declinations (all transferred to normal polarity) along the Corinth and Megara basin. The arrow represents one site.

Mattei et al 2004

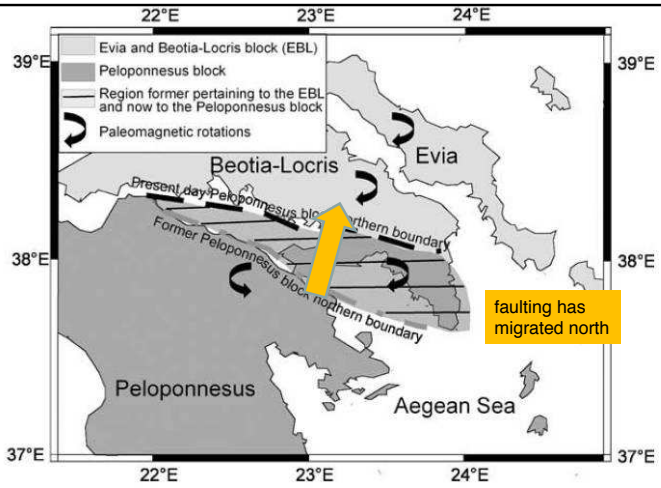


Figure 11. Evolution of the Peloponnesus-Evia block boundary as deduced by paleomagnetic and GPS data. The clockwise paleomagnetic rotations measured in the Megara basin suggest that such a region (hatched region in the plot) rotated clockwise during Plio-Pleistocene times, coherently with the Evia block. Conversely, GPS data show that the Megara basin now belongs to the slow rotating Peloponnesus block, implying a recent reorganization of the deformation belt separating the two crustal domains.

Mattei et al 2004