KIGAM, 2014

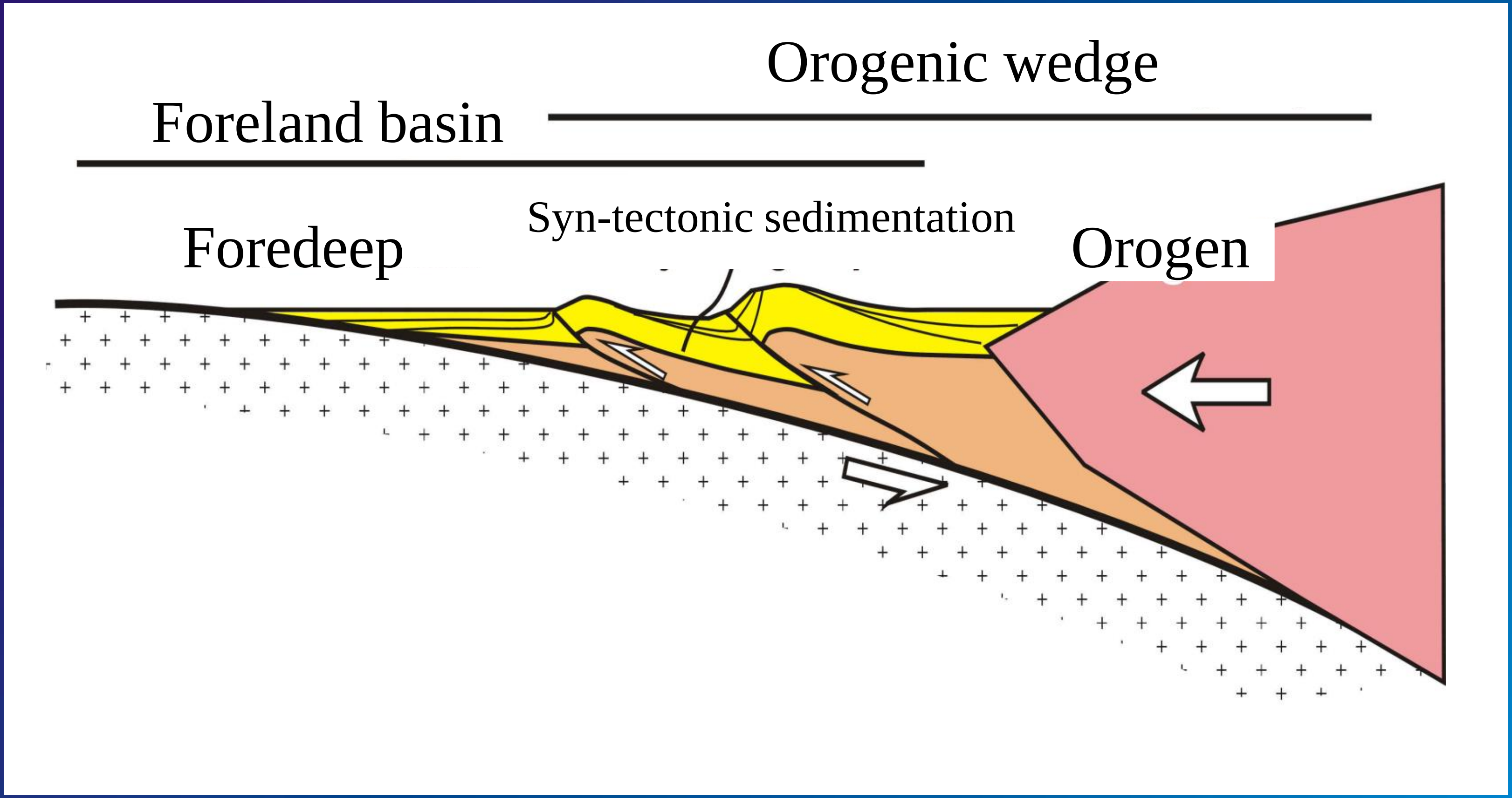
Geometry, kinematics and mechanics of foreland fold-thrust belts (1) : insights from a multisource and multiscale study of the active Zagros fold-thrust belt (Iran).

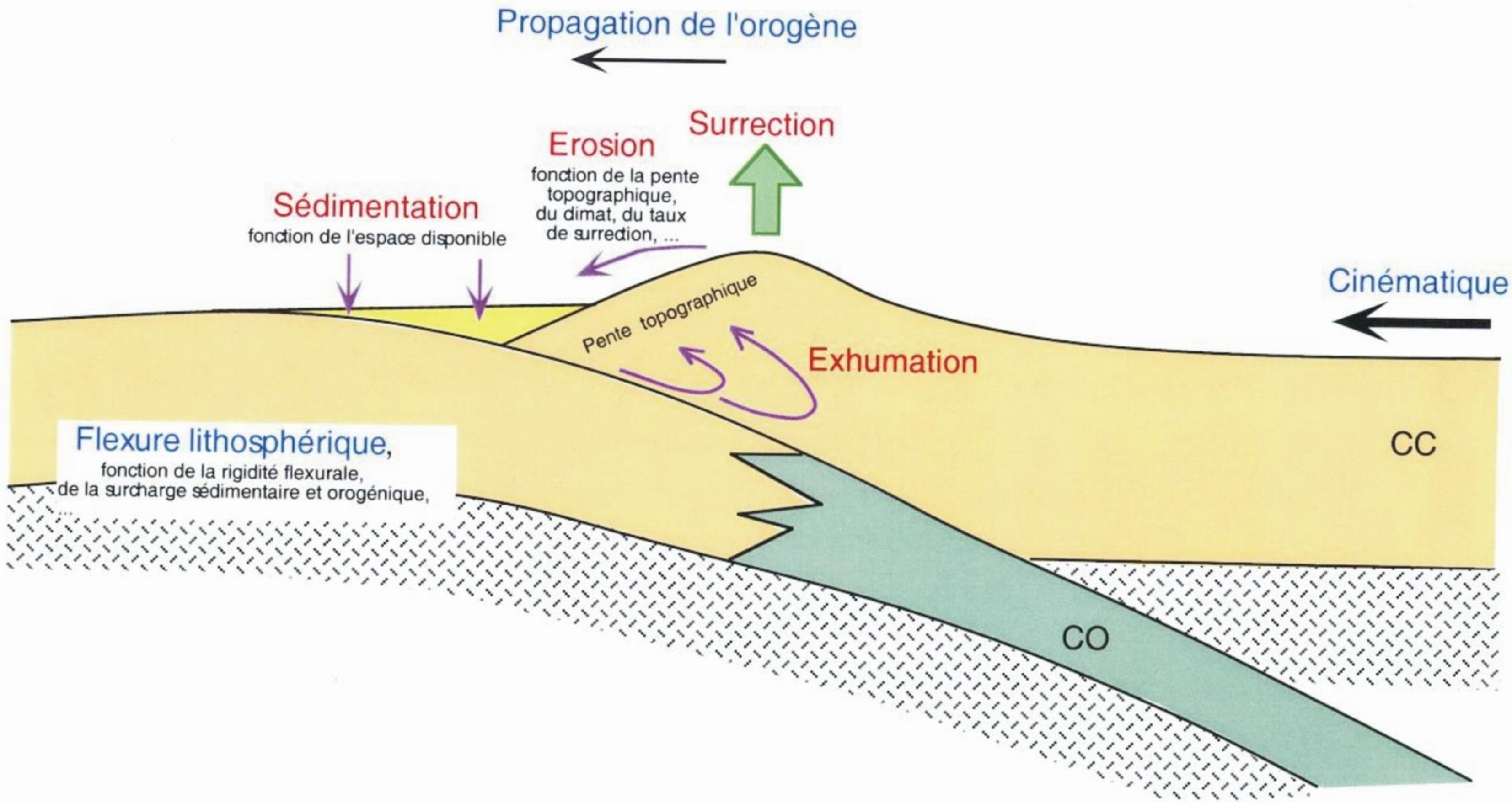
Professor Olivier LACOMBE

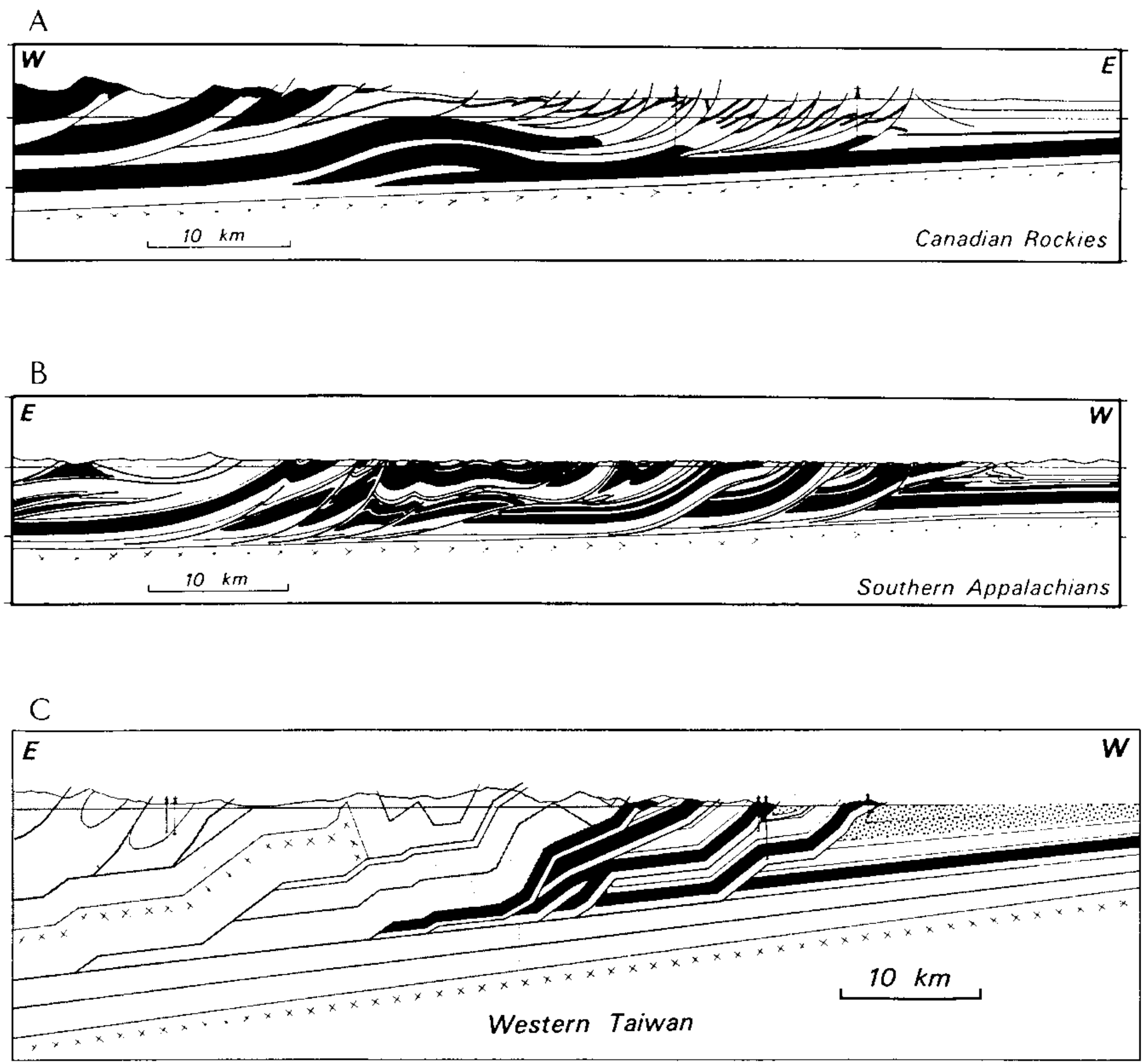
UPMC SORBONNE UNIVERSITÉS

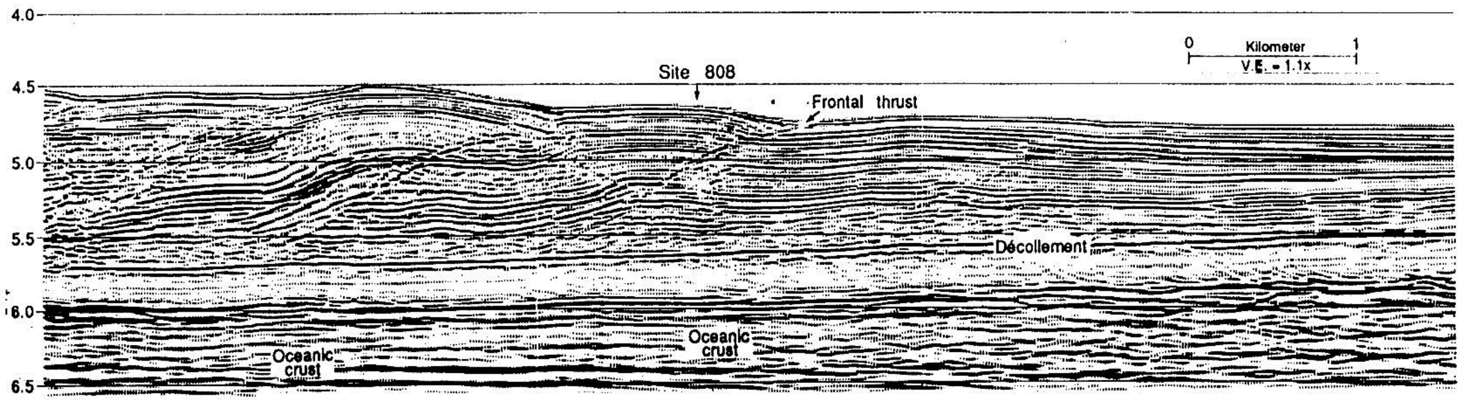
CNRS

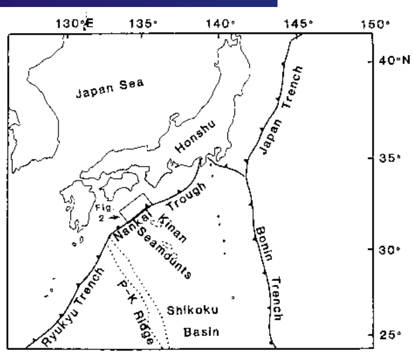
Institut des Sciences de la Terre de Paris
ISTeP SORBONNE UNIVERSITÉS


Orogenic wedge
Foreland basin
Syn-tectonic sedimentation
Foredeep
Orogen

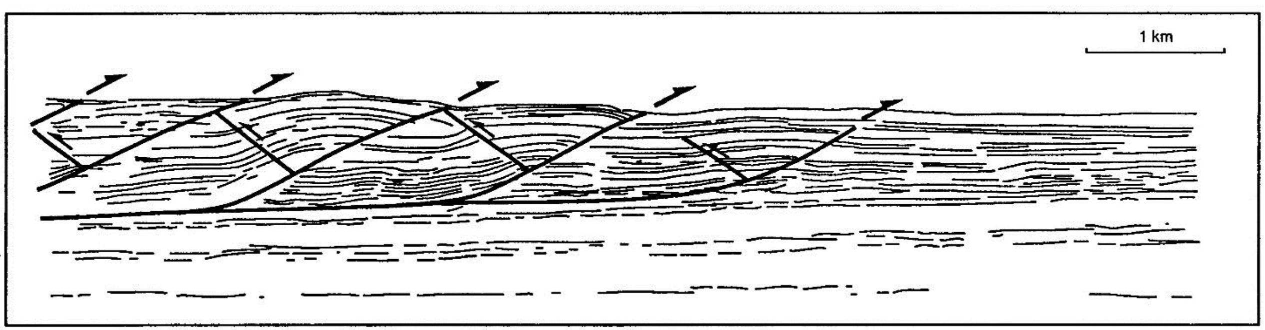

Propagation de l'orogène
Surrection
Erosion
fonction de la pente
topographique,
du climat, du taux
de surrection, ...
Sédimentation
fonction de l'espace disponible
Cinématique
Pente topographique
Exhumation
Flexure lithosphérique,
fonction de la rigidité flexurale,
de la surcharge sédimentaire et orogénique,
...
CC
CO

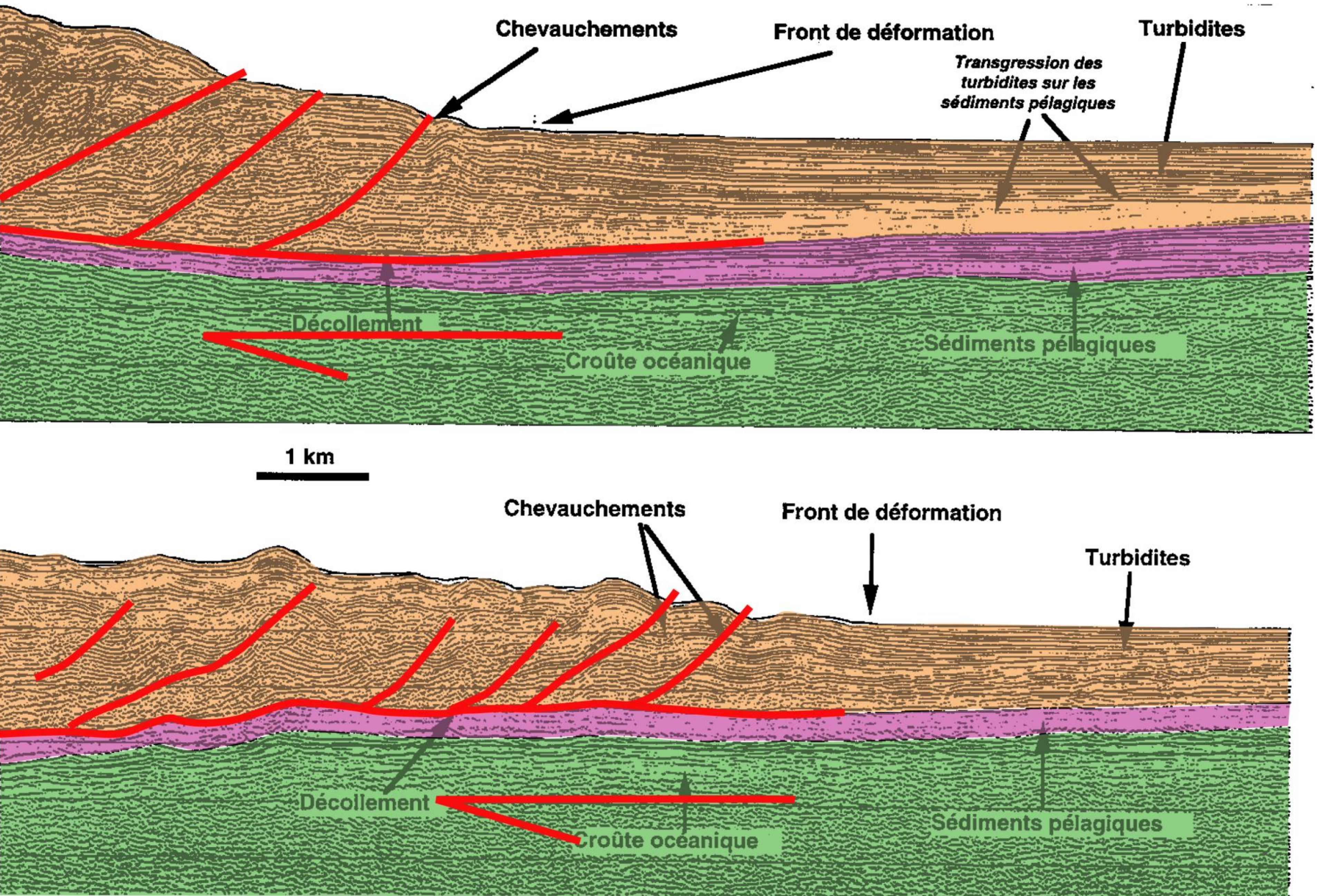

A
W
E
10 km
Canadian Rockies
B
E
W
10 km
Southern Appalachians
C
E
W
10 km
Western Taiwan



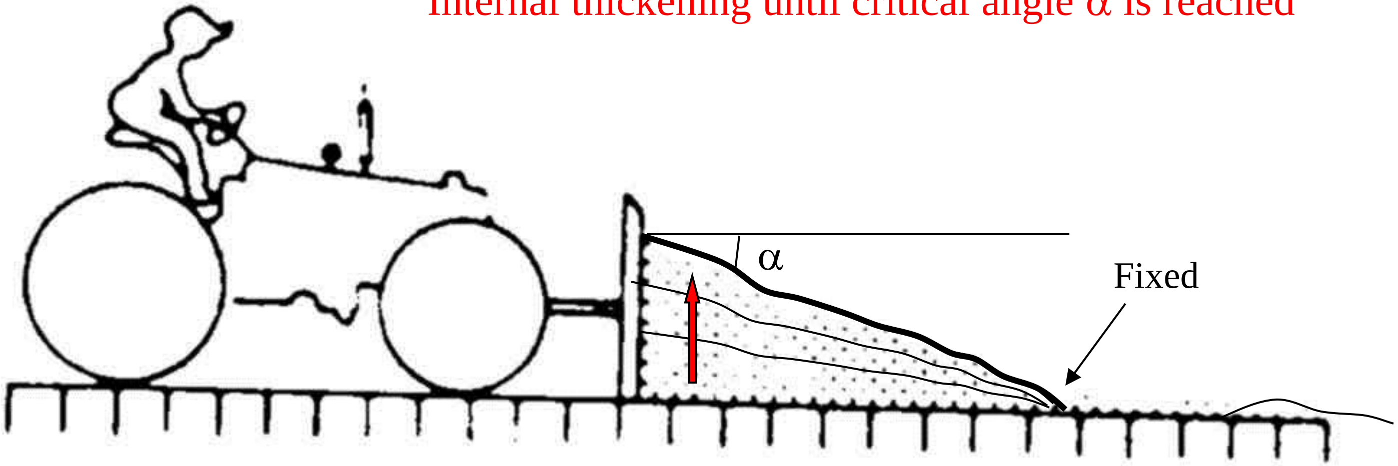


Regional tectonic map showing setting of the Nankai Trough study area (box labeled as Figure 2).

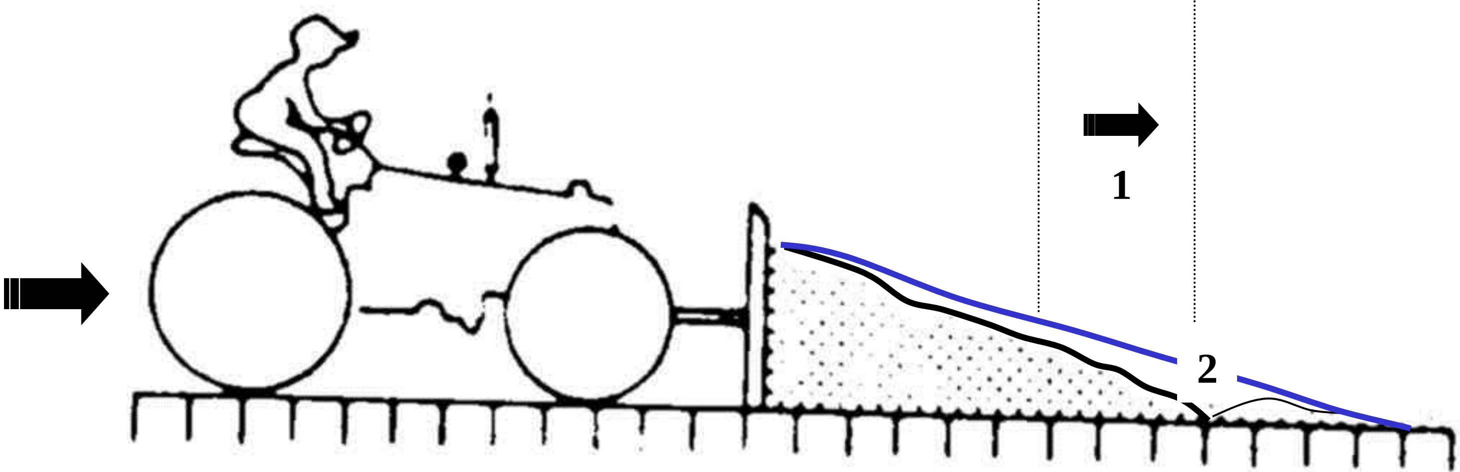


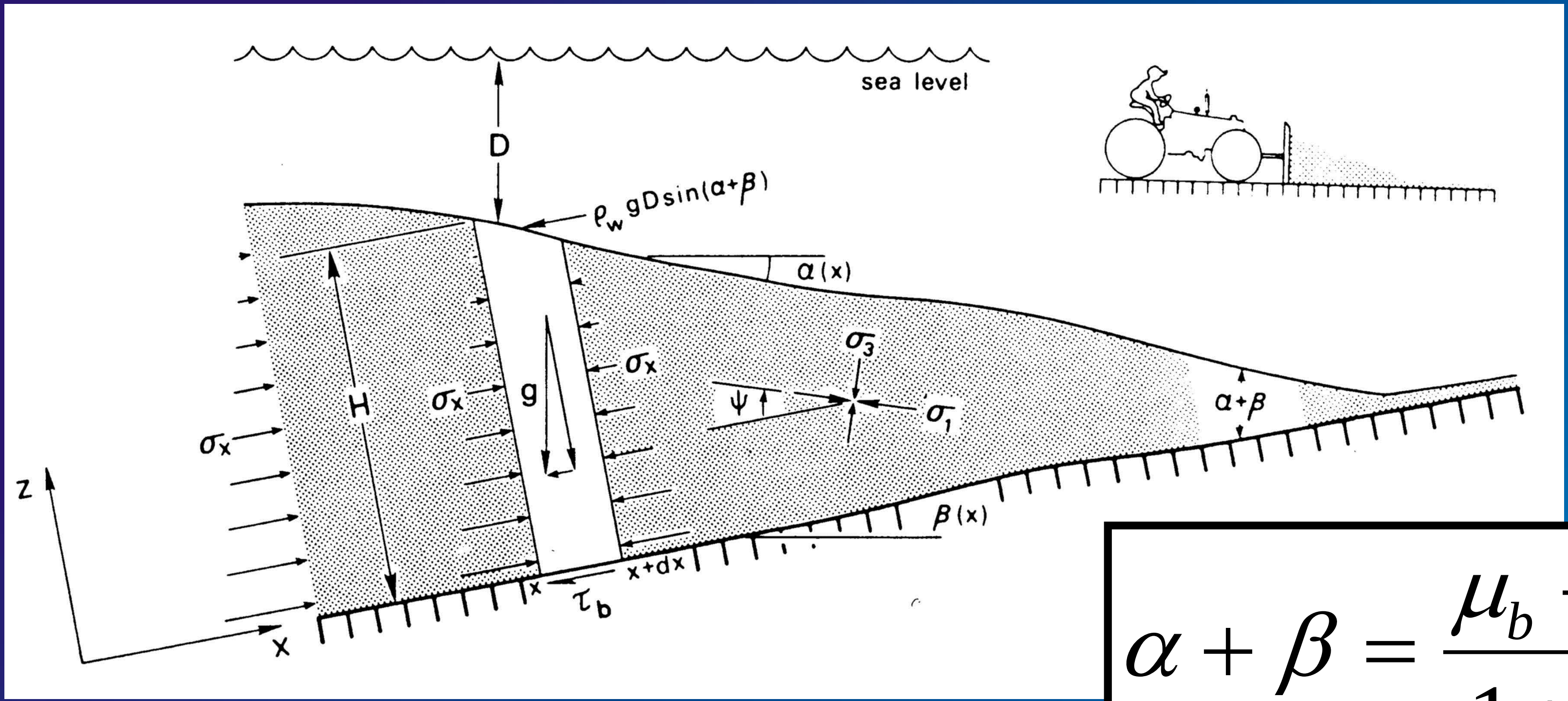

Chevauchements
Front de déformation
Turbidites
Transgression des turbidites sur les sédiments pélagiques
Décollement
Croûte océanique
Sédiments pélagiques
1 km
Chevauchements
Front de déformation
Turbidites
Décollement
Croûte océanique
Sédiments pélagiques

Internal thickening until critical angle α is reached



1. Basal sliding without internal thickening, then
2. New snow is incorporated in the wedge, α is lowered, then
3. The wedge will deform internally until α is reached again, and so on





$$\alpha + \beta = \frac{\mu_b + \beta}{1 + K}$$

$$\rho g H \beta + \rho_w g D(\alpha + \beta) + \tau_b + \frac{d}{dx}\int_0^H \sigma_x dz = 0$$

Weight of overburden

Weight of water

Basal friction

Lateral forces

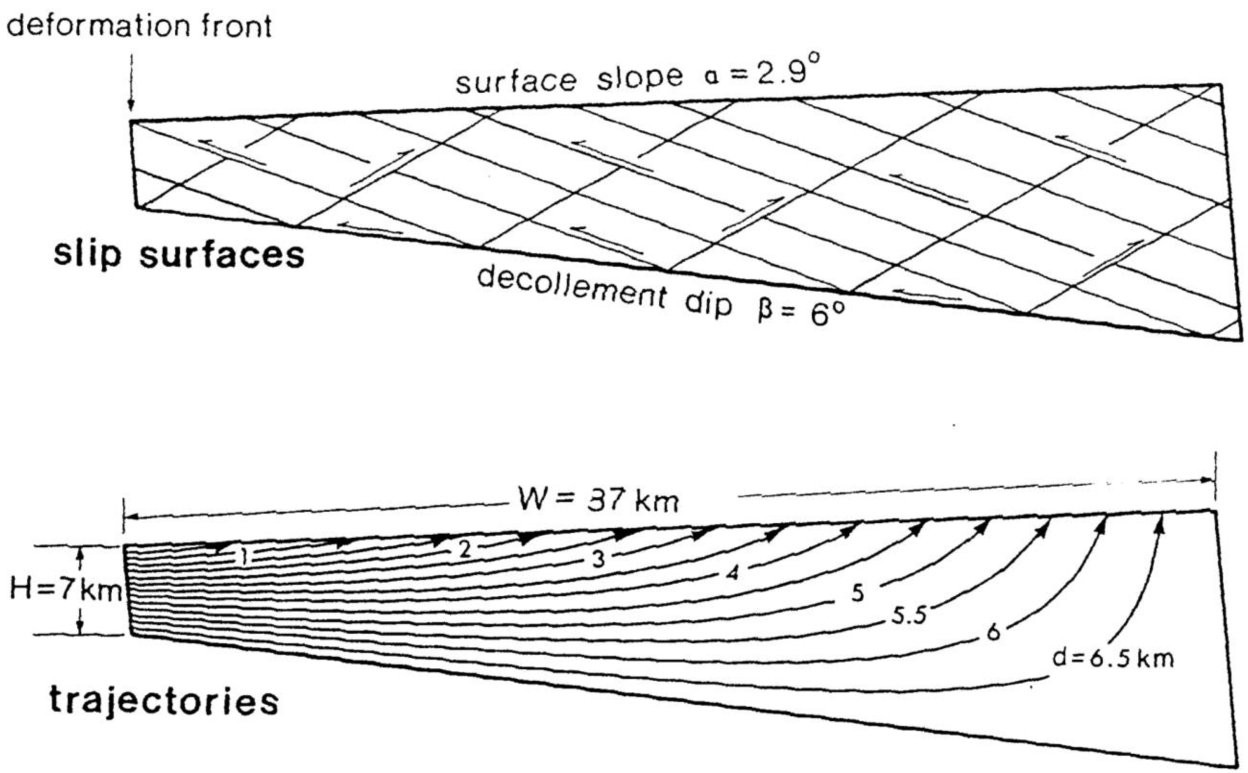
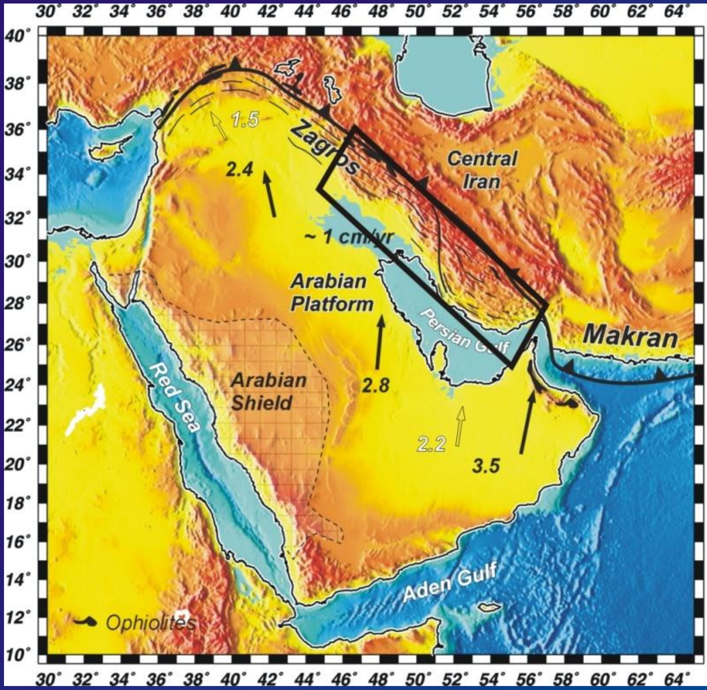
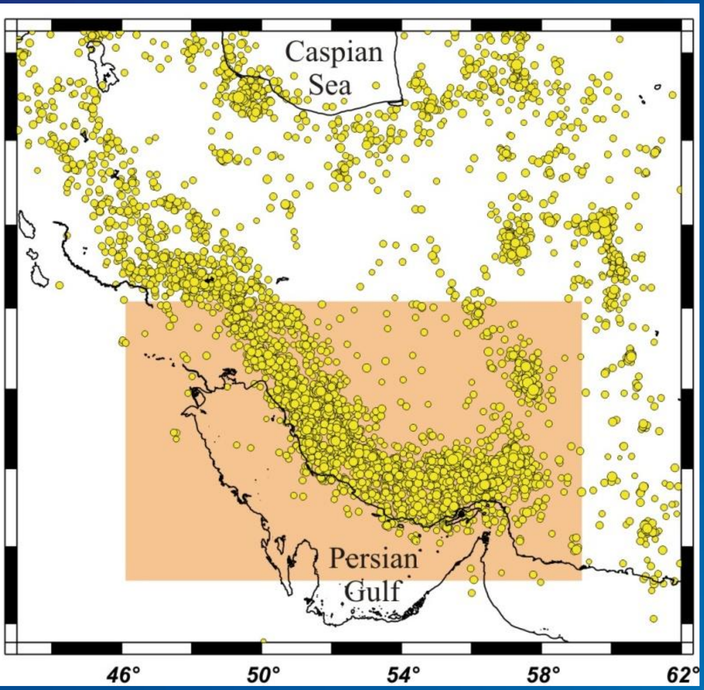


Figure 14. Theoretical slip surfaces and rock trajectories in the critically tapered Taiwan wedge, assuming $\mu = 0.85$.

Dahlen et Suppe, 1988

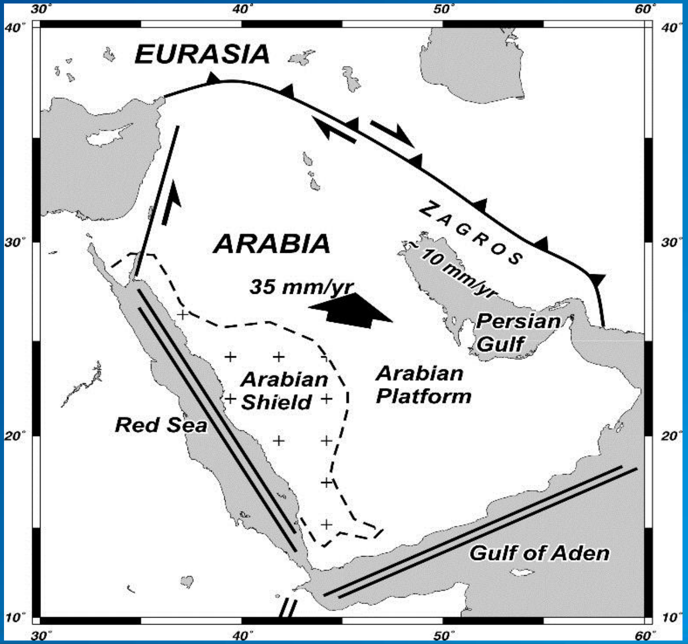
Geodynamic and kinematic setting of the Zagros fold-and-thrust belt

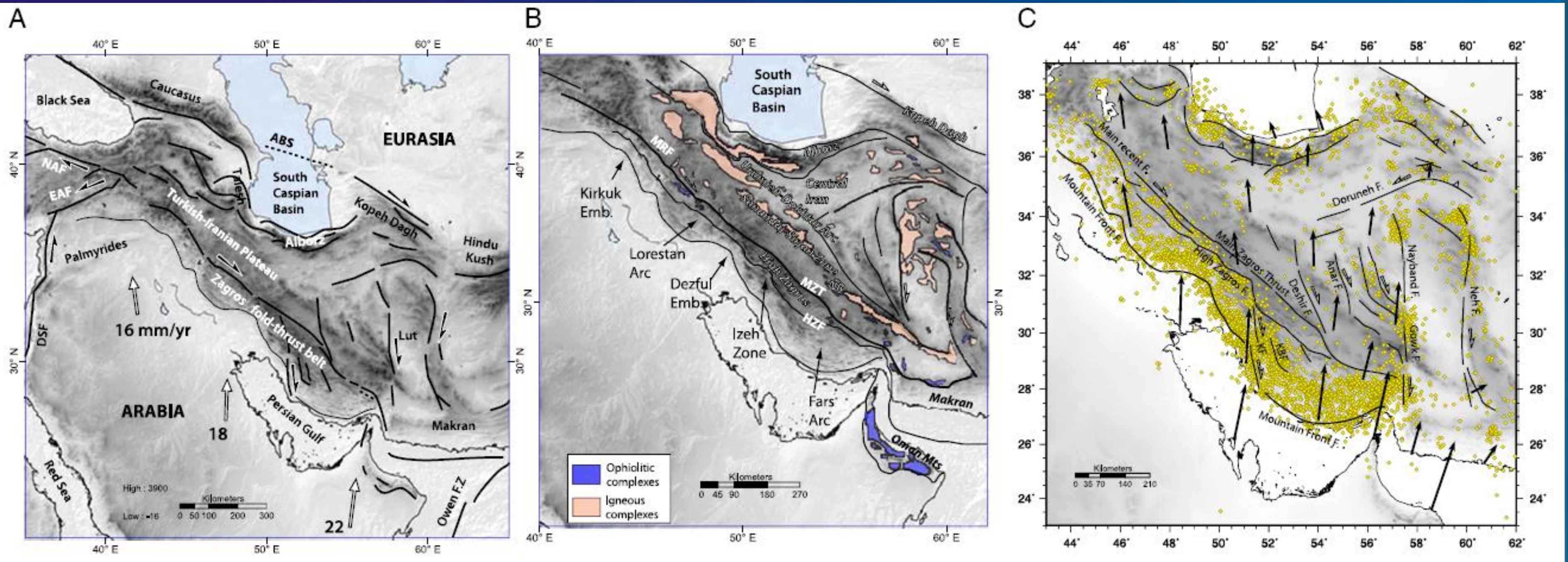




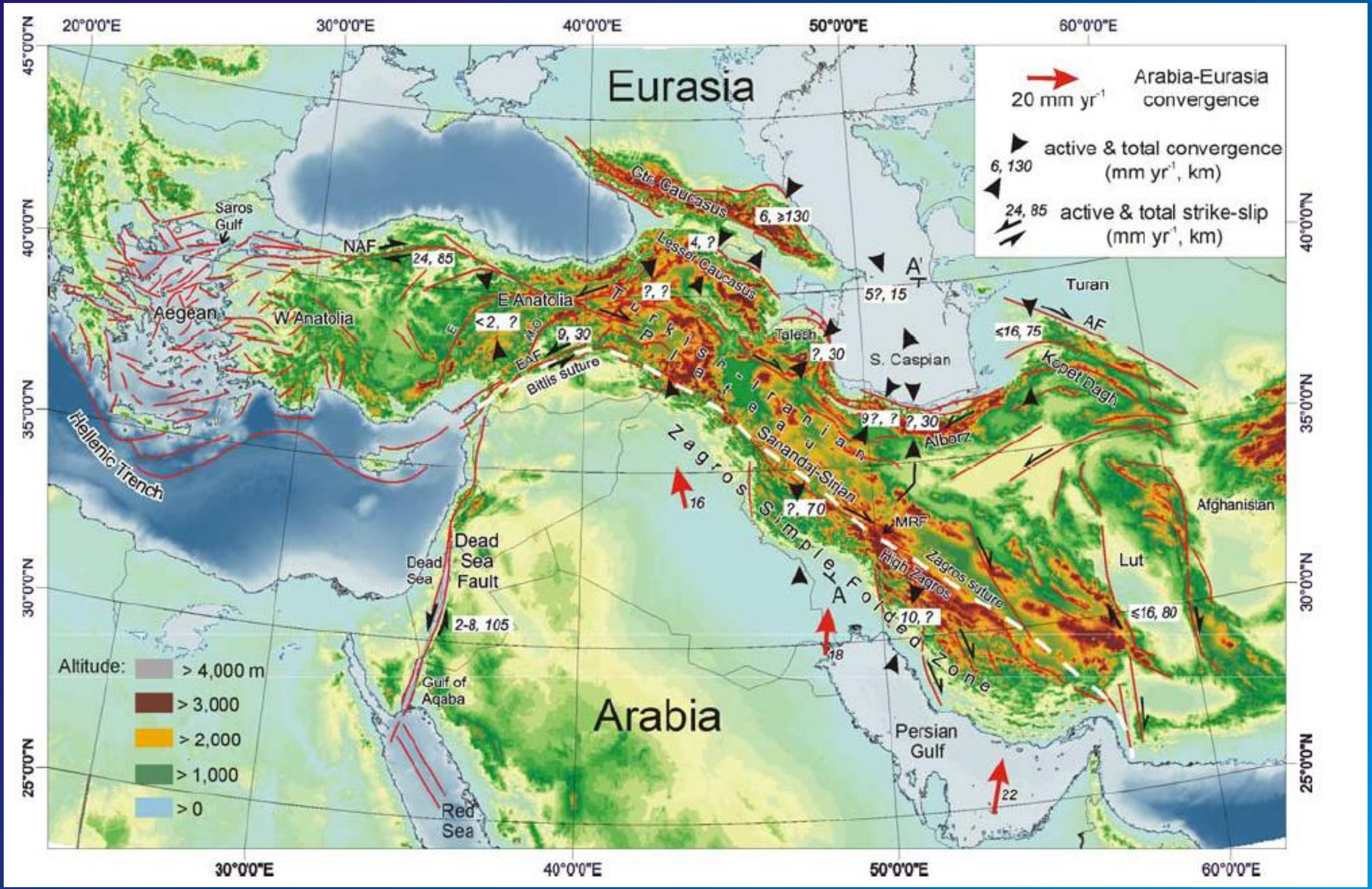
The Zagros belt results from the collision between Arabia and Central Iran, beginning in (Oligo ?)-Miocene times and continuing today.

About one third of the 22-25 mm/yr Arabia-Eurasia convergence is currently accommodated in the Zagros (Vernant et al., 2004)

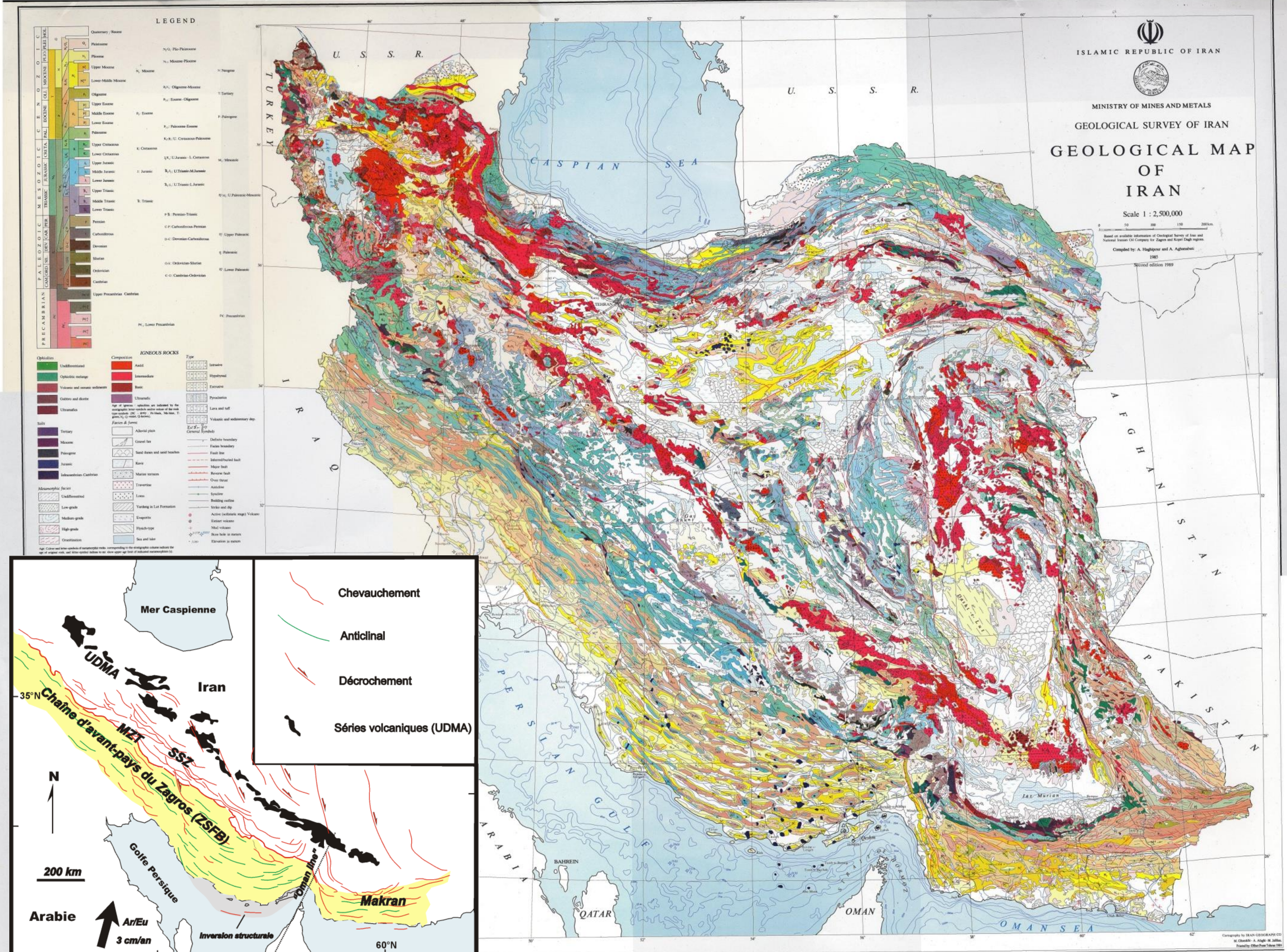




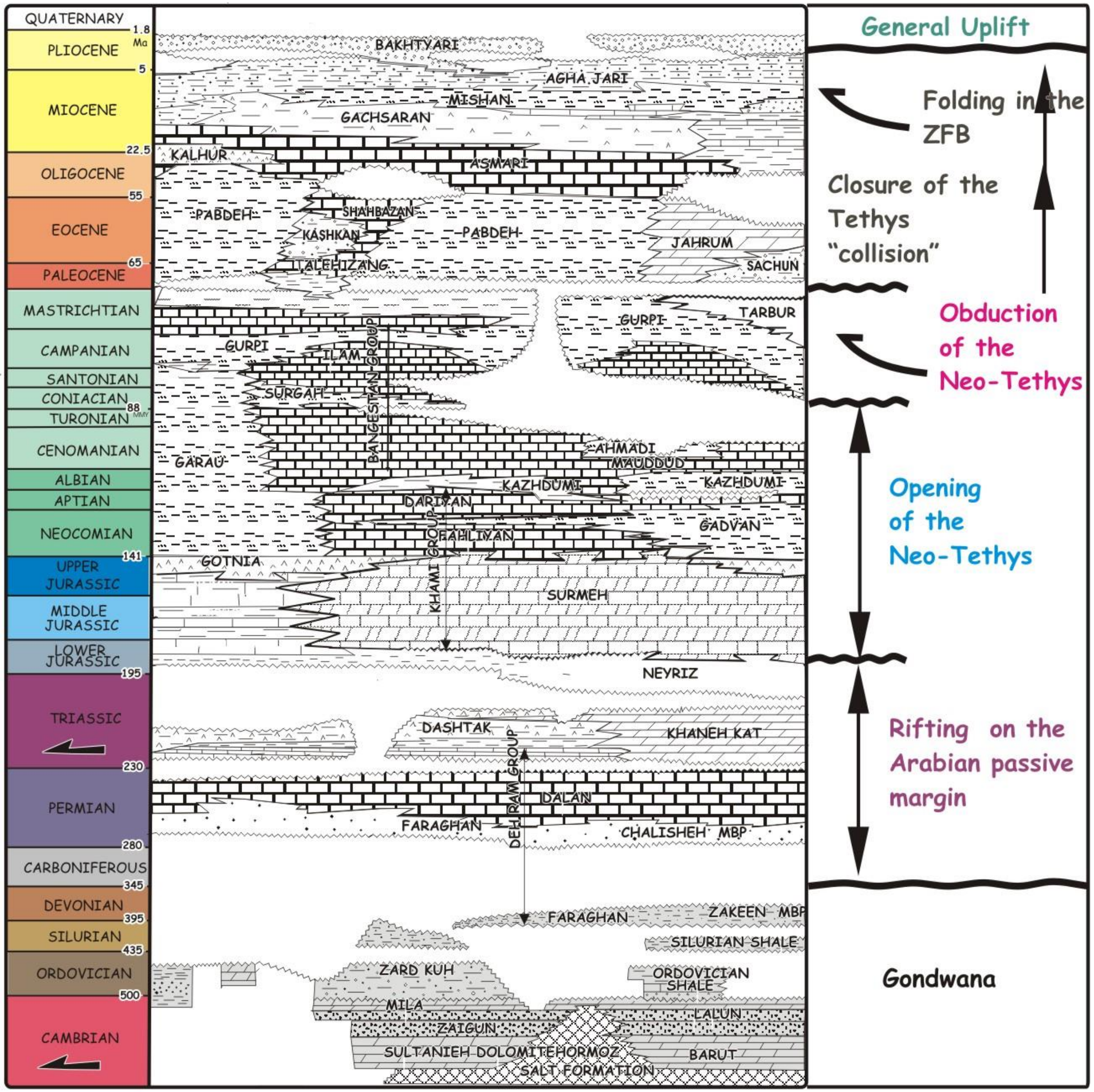
Mouthereau et al. 2012



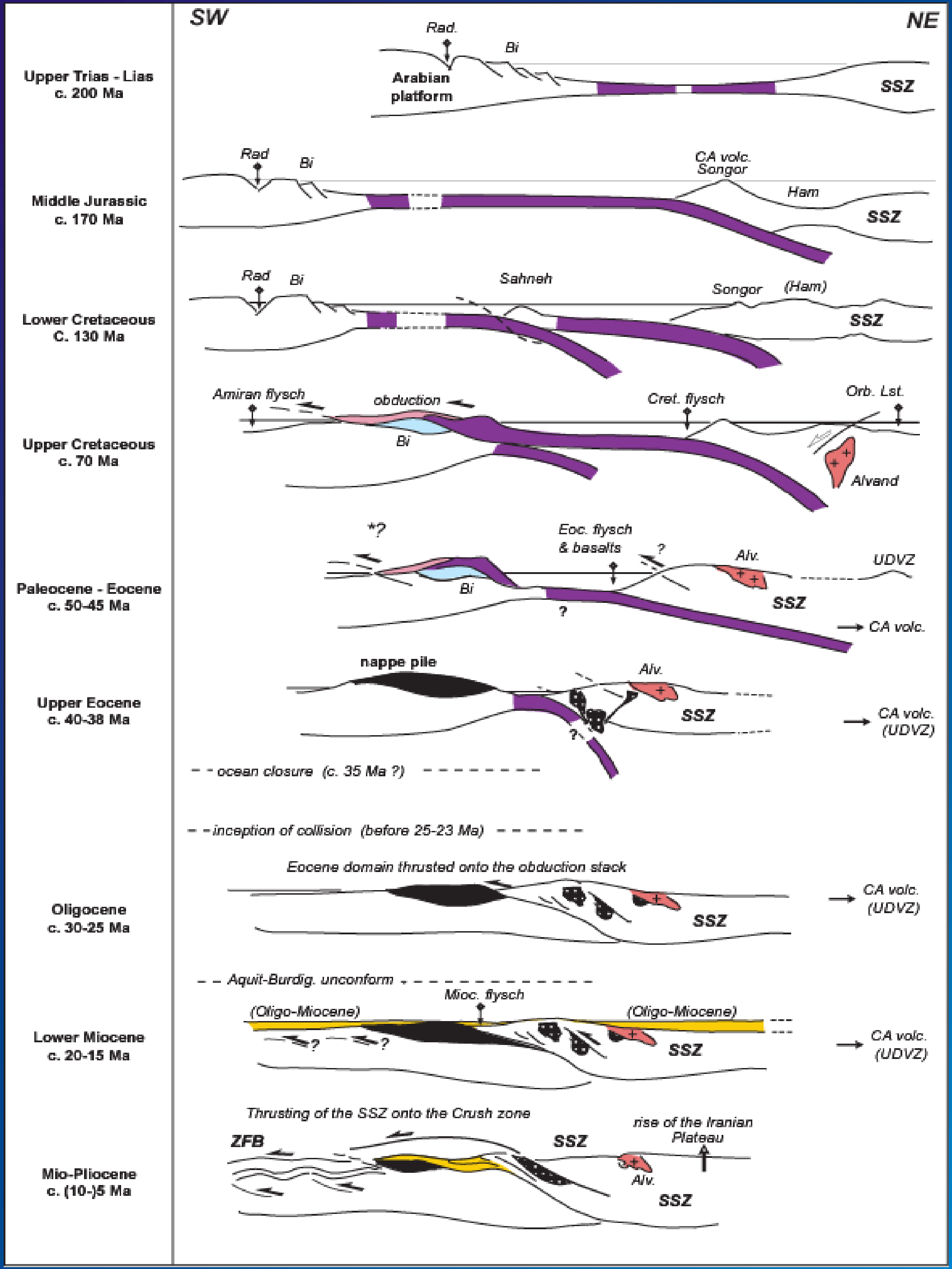
Allen et al. 2004


ISLAMIC REPUBLIC OF IRAN
MINISTRY OF MINES AND METALS
GEOLOGICAL SURVEY OF IRAN
GEOLOGICAL MAP
OF
IRAN
Scale 1 : 2,500,000
Compiled by: A. Haghipour and A. Aghanabati
1985
Second edition 1989
LEGEND
IGNEOUS ROCKS
U. S. S. R.
TURKEY
CASPIAN SEA
IRAQ
AFGHANISTAN
PAKISTAN
PERSIAN GULF
ARABIA
BAHREIN
QATAR
OMAN
OMAN SEA
TEHRAN
Mer Caspienne
UDMA
Iran
35°N
Chaîne d'avant-pays du Zagros (ZSFB)
MZT
SSZ
N
200 km
Golfe Persique
"Oman line"
Makran
Arabie
Ar/Eu
3 cm/an
Inversion structurale
60°N
Chevauchement
Anticlinal
Décrochement
Séries volcaniques (UDMA)

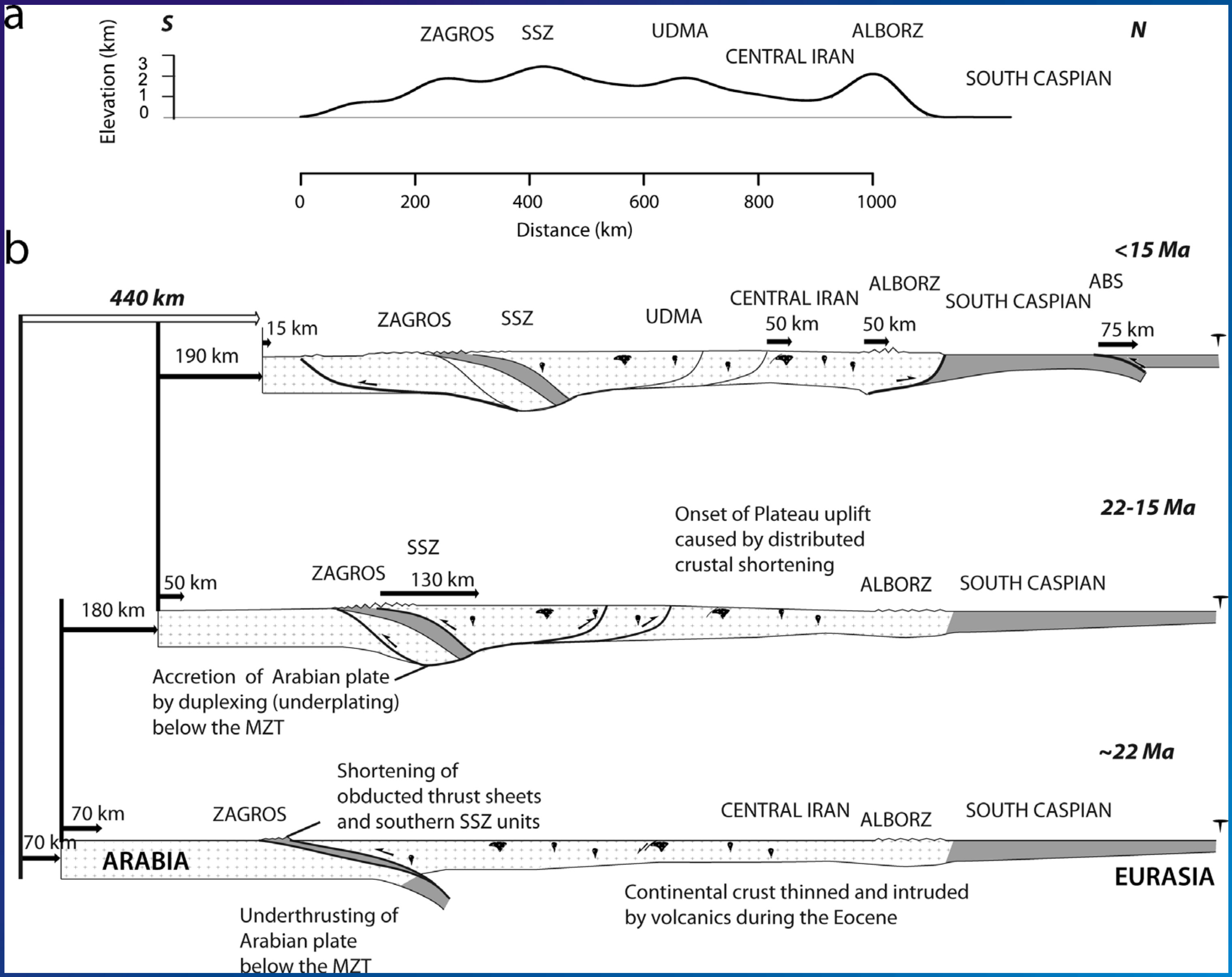
Lithofacies and stratigraphy in the Zagros basin



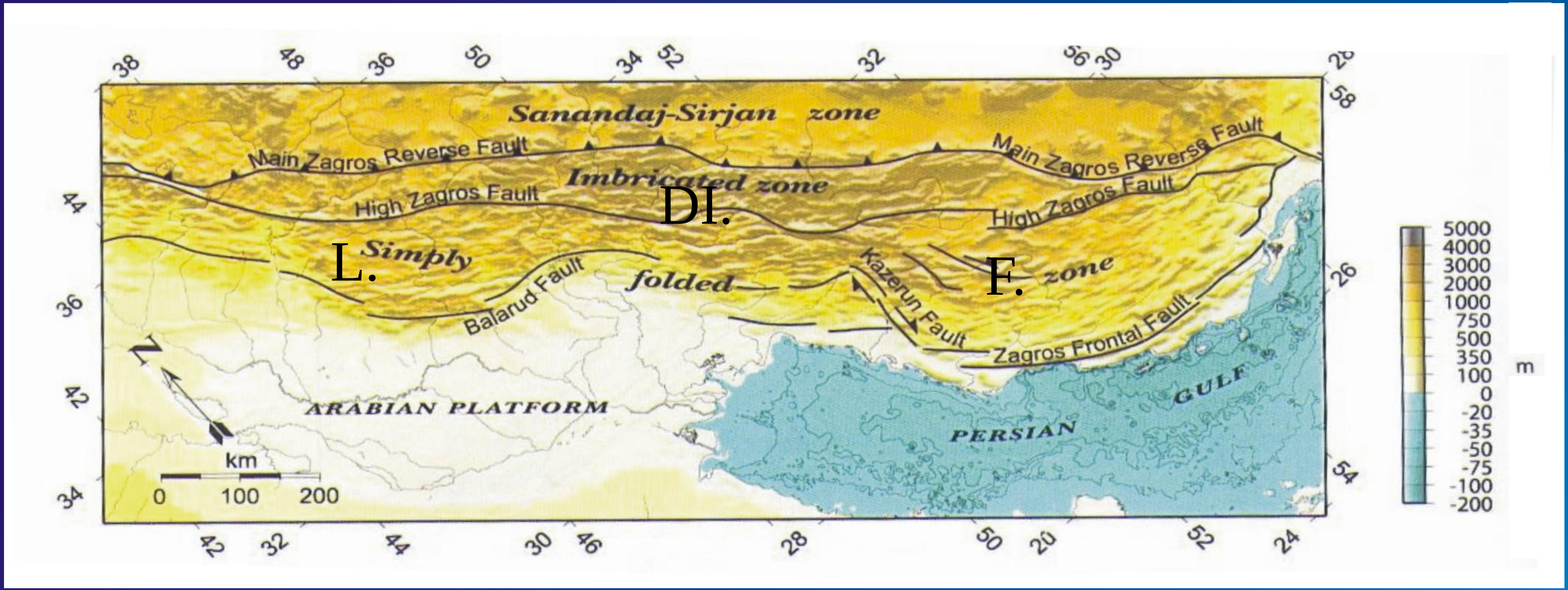
(Agard et al., 2005)



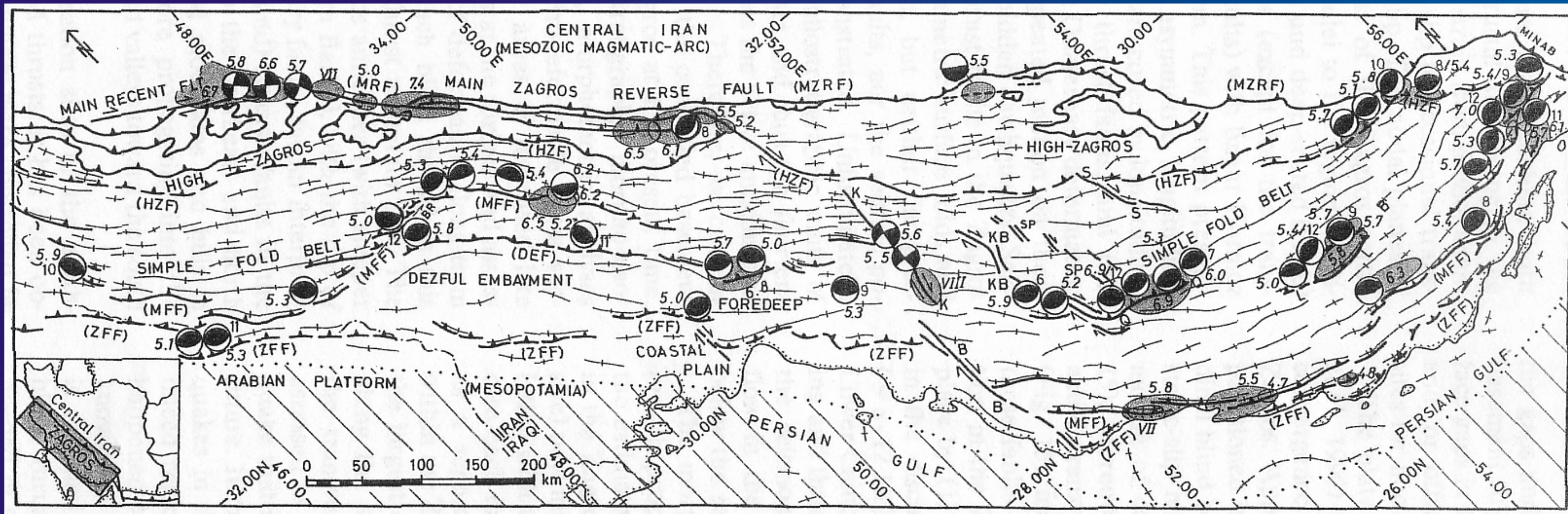
Fars

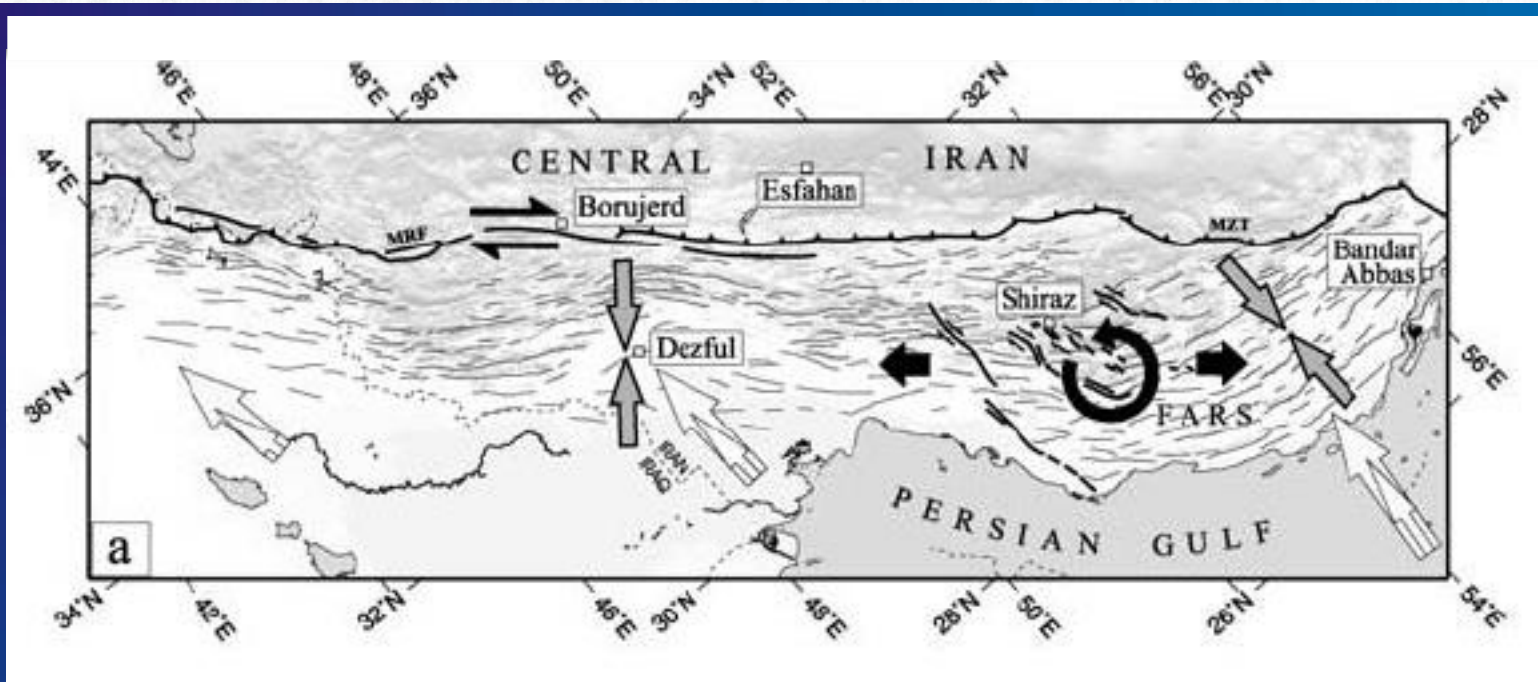


(Mouthereau , 2011)

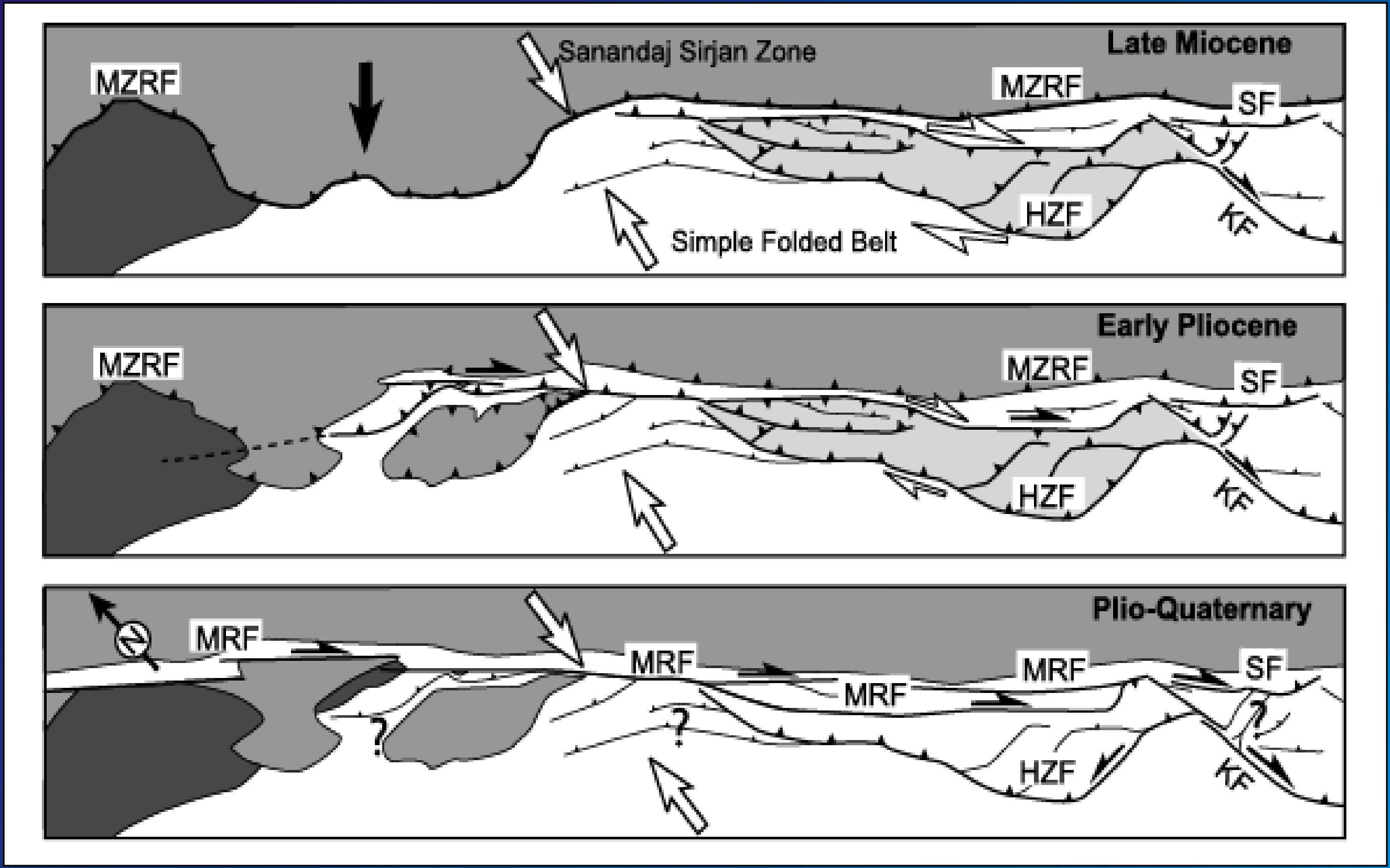


(Berberian, 1995)

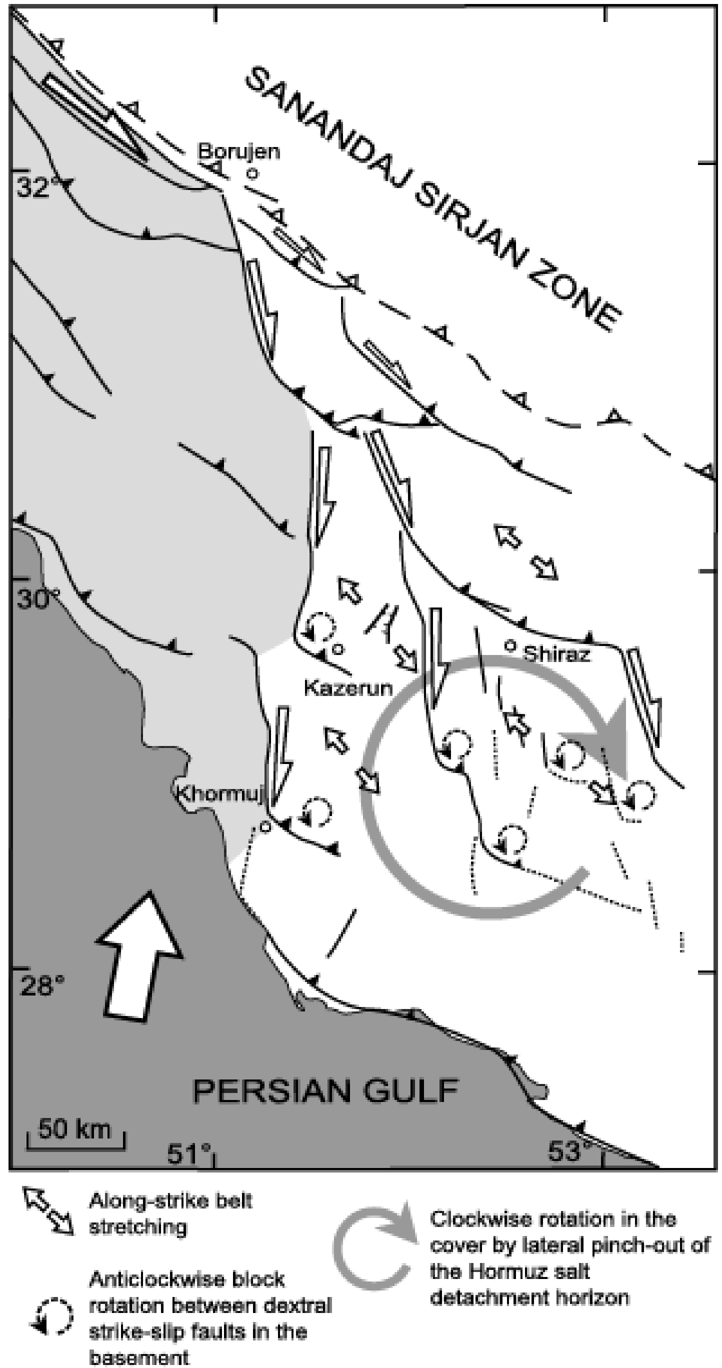




(Berberian, 1995; Talebian and Jackson, 2004)

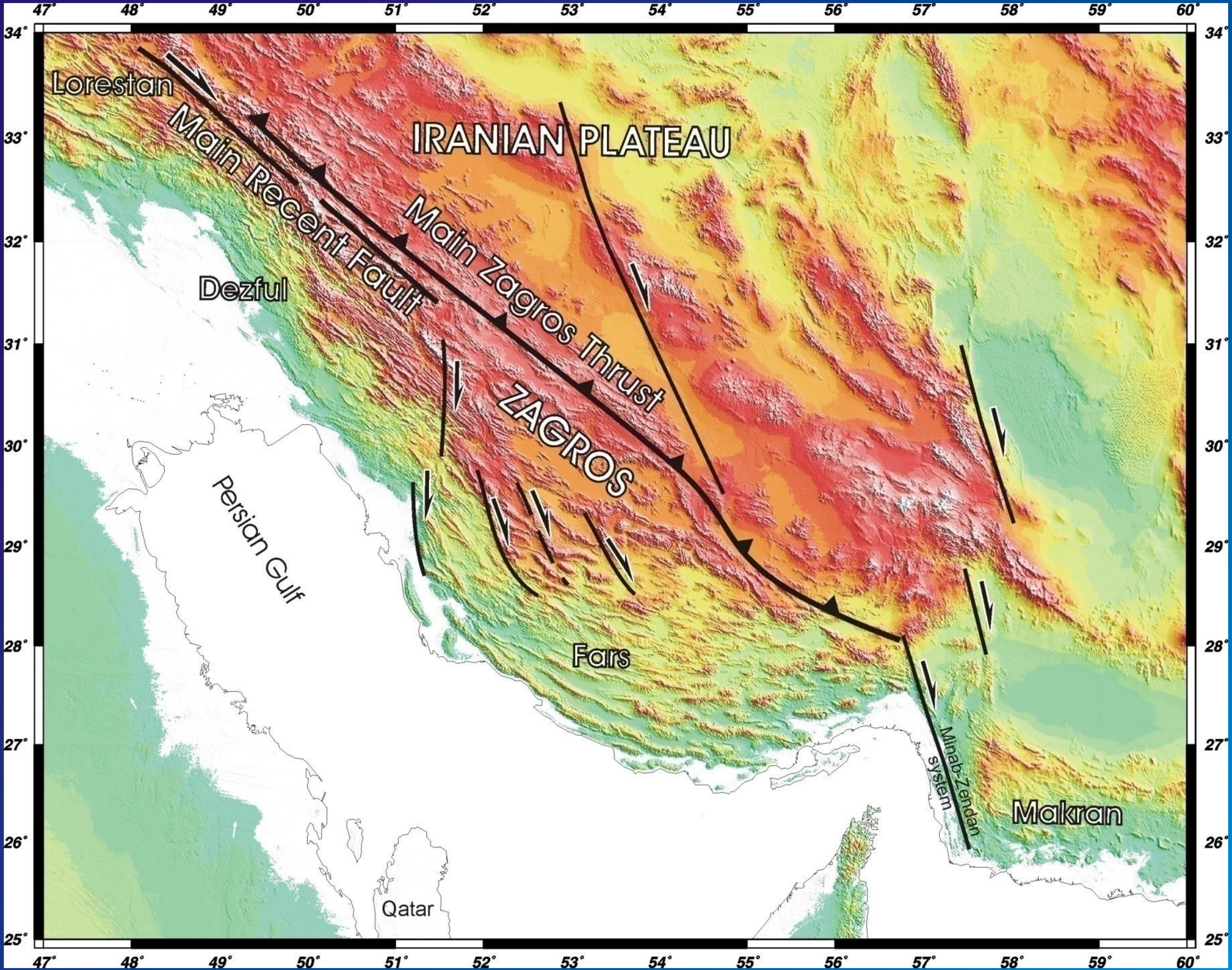


(Authemayou et al., 2006)

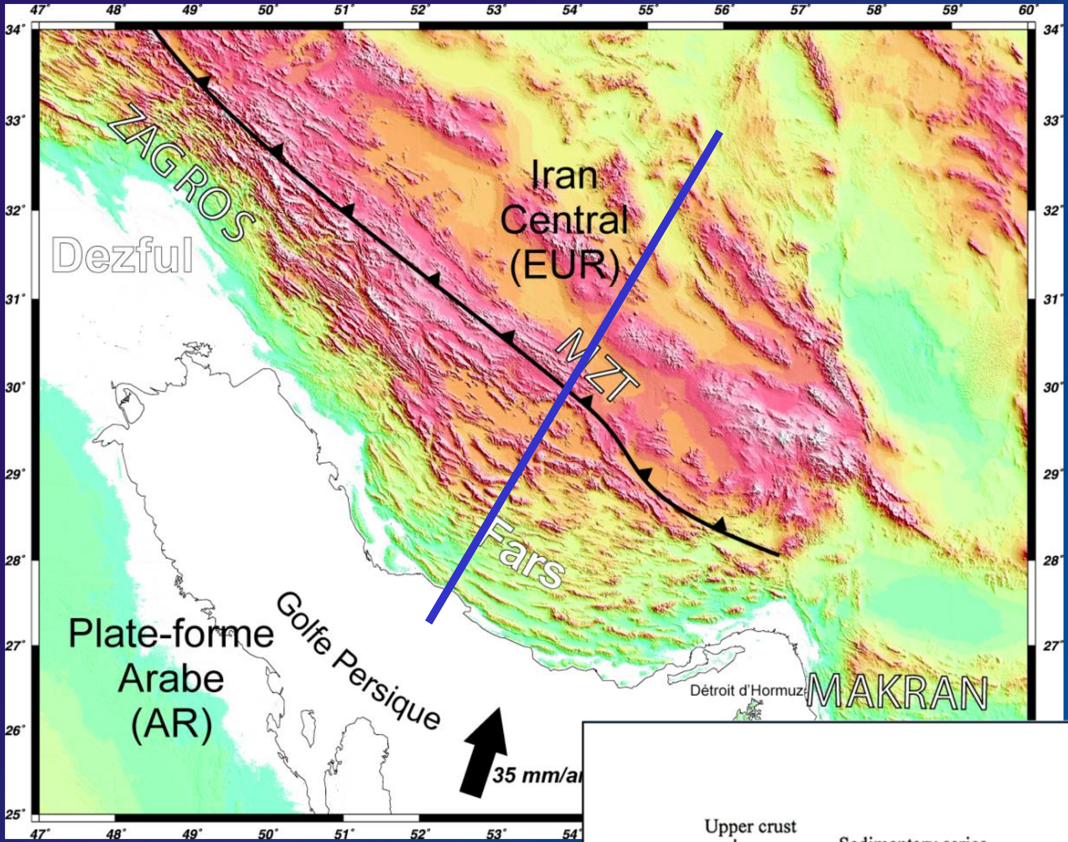


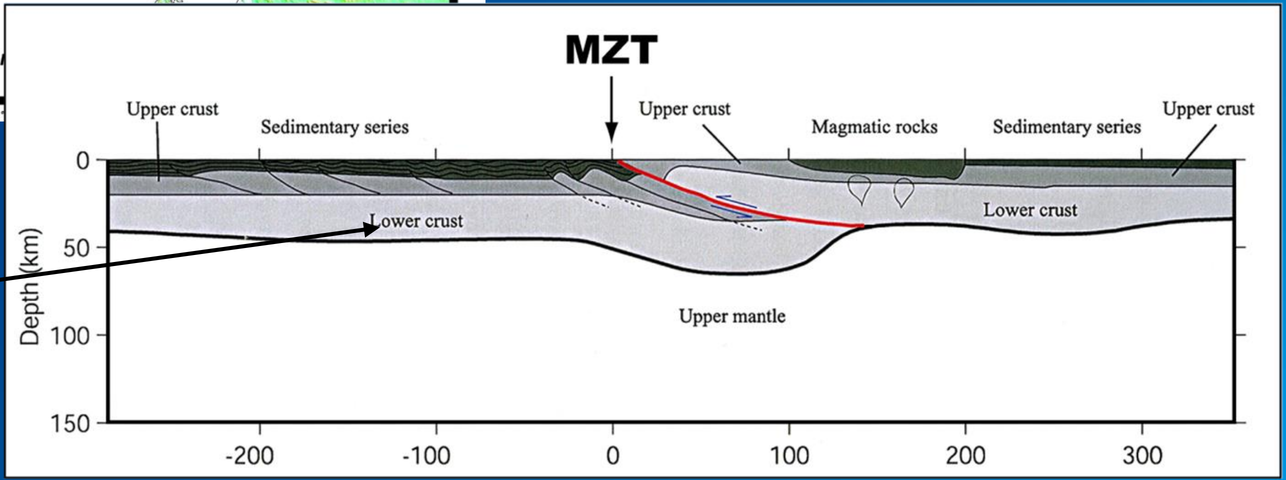
(Authemayou et al., 2006)

Geological setting of the Zagros fold-and-thrust belt



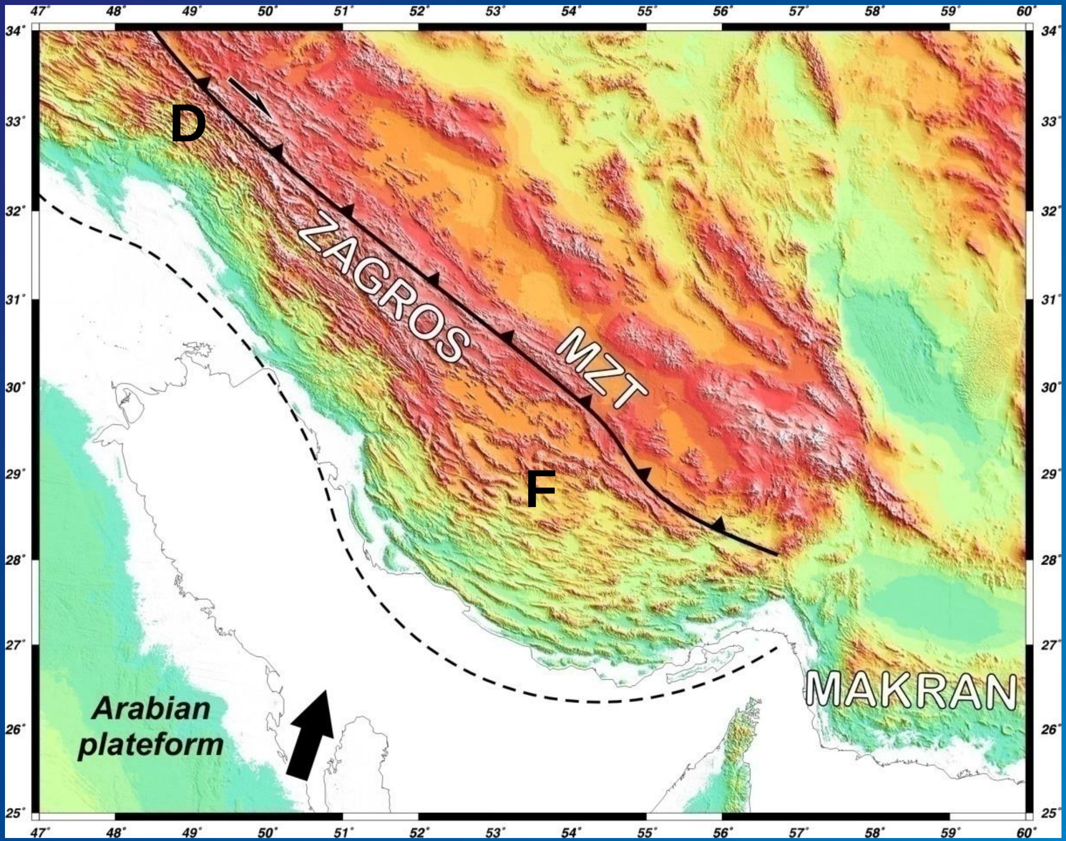
Lorestan
Main Recent Fault
Main Zagros Thrust
IRANIAN PLATEAU
ZAGROS
Dezful
Persian Gulf
Fars
Minab-Zendan system
Makran
Qatar

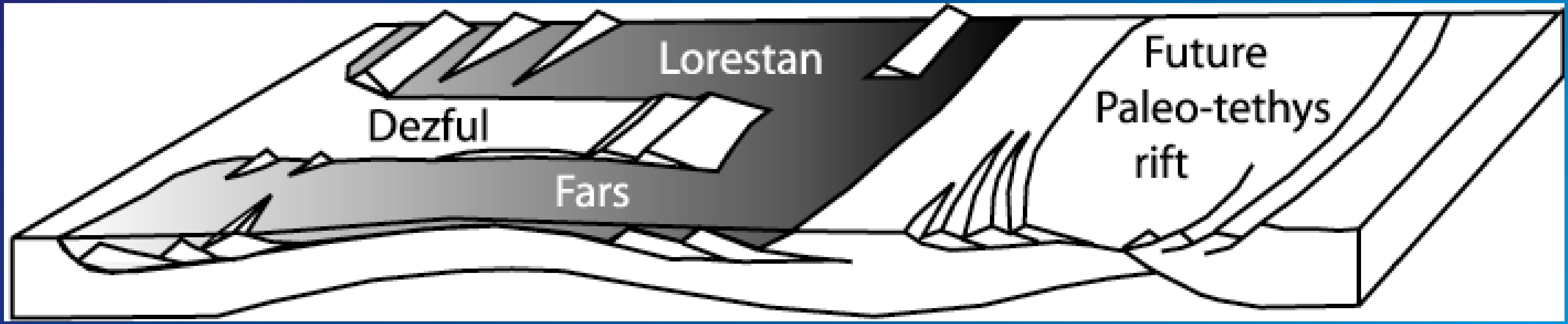




Little thickening below the Zagros

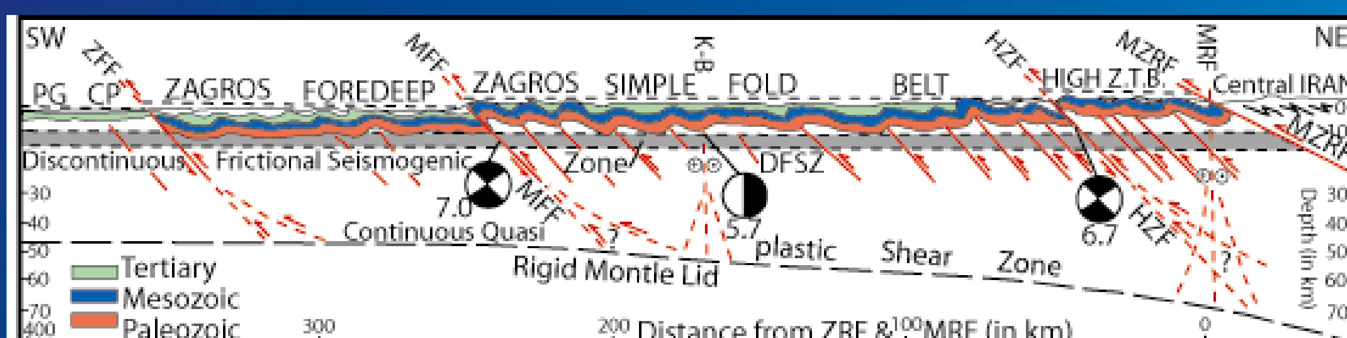
Along-strike segmentation is usually related either to variations in frictional properties of the basal décollement (Cambrian Salts) and/or to the distribution of pre-orogenic basins in the Arabian margin

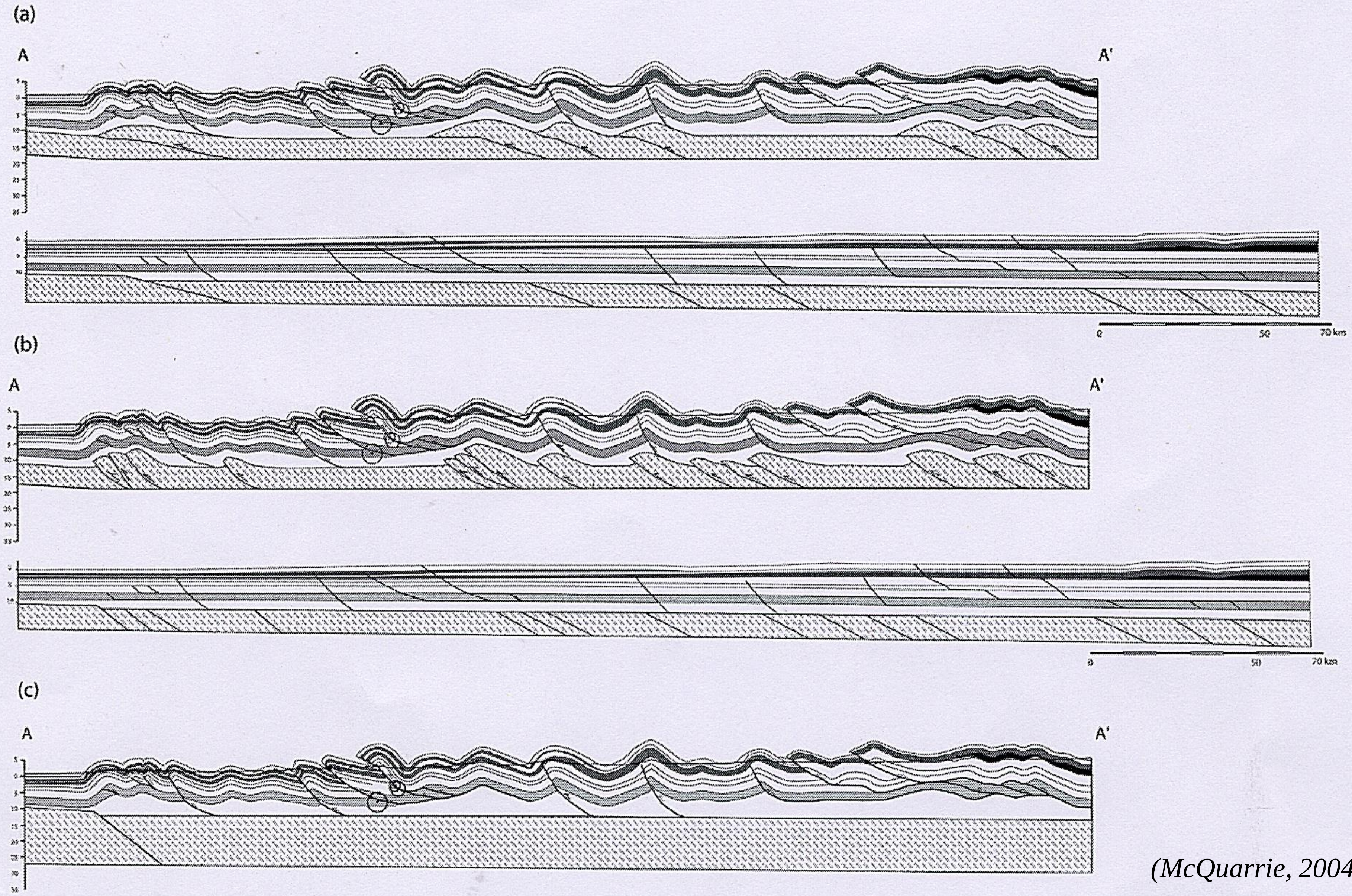




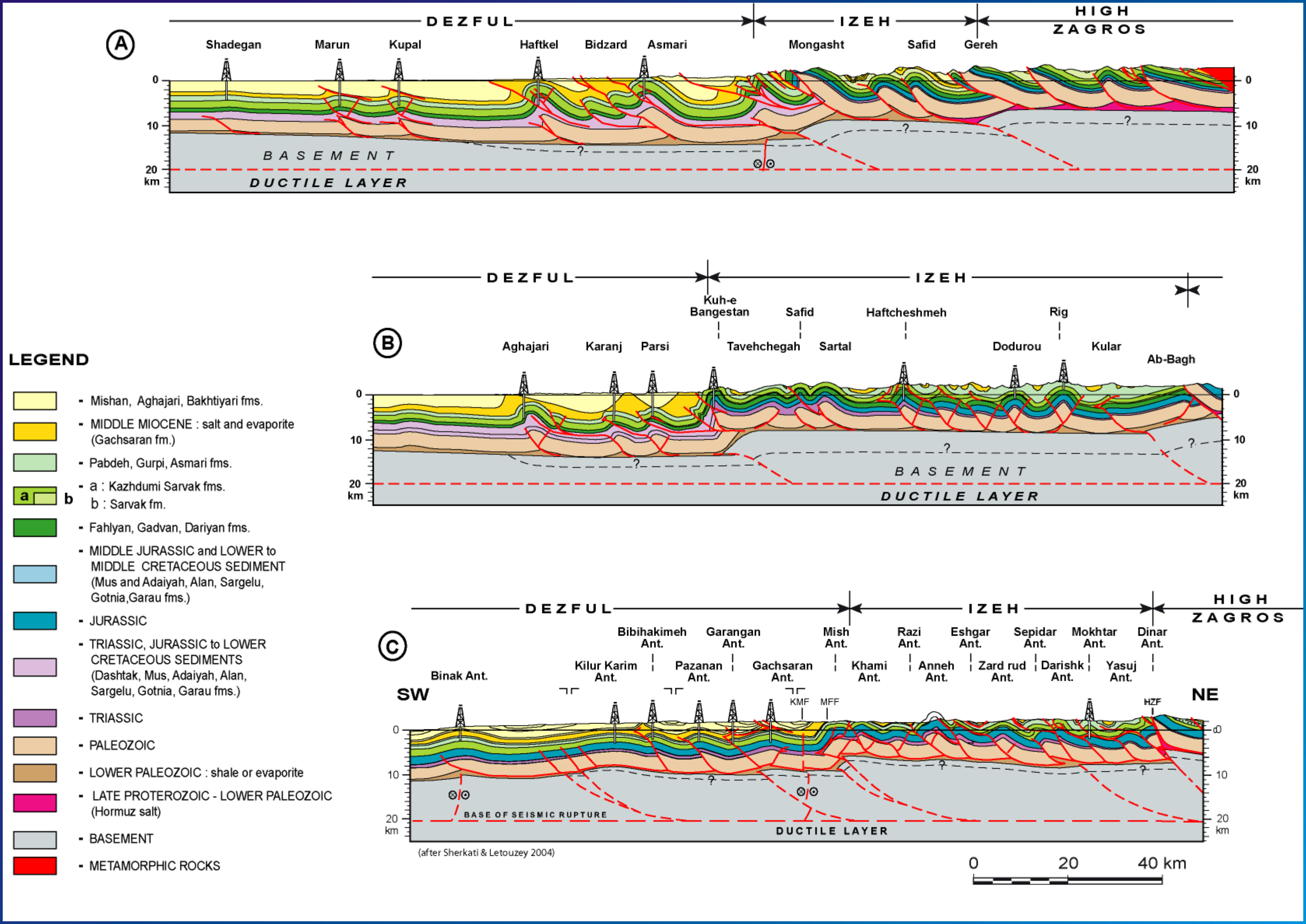
Talbot and Alavi, 1996

(Berberian, 1995)

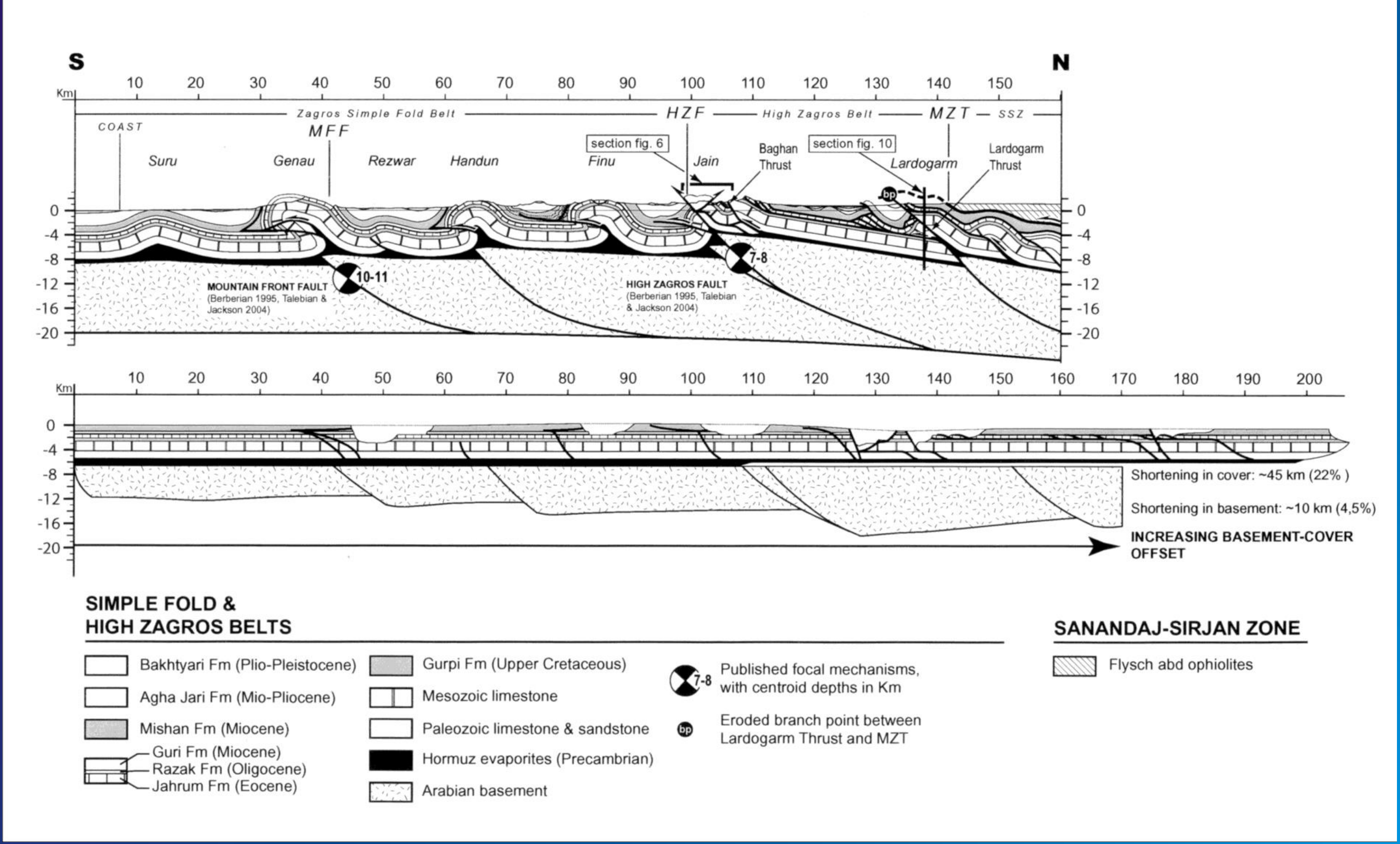




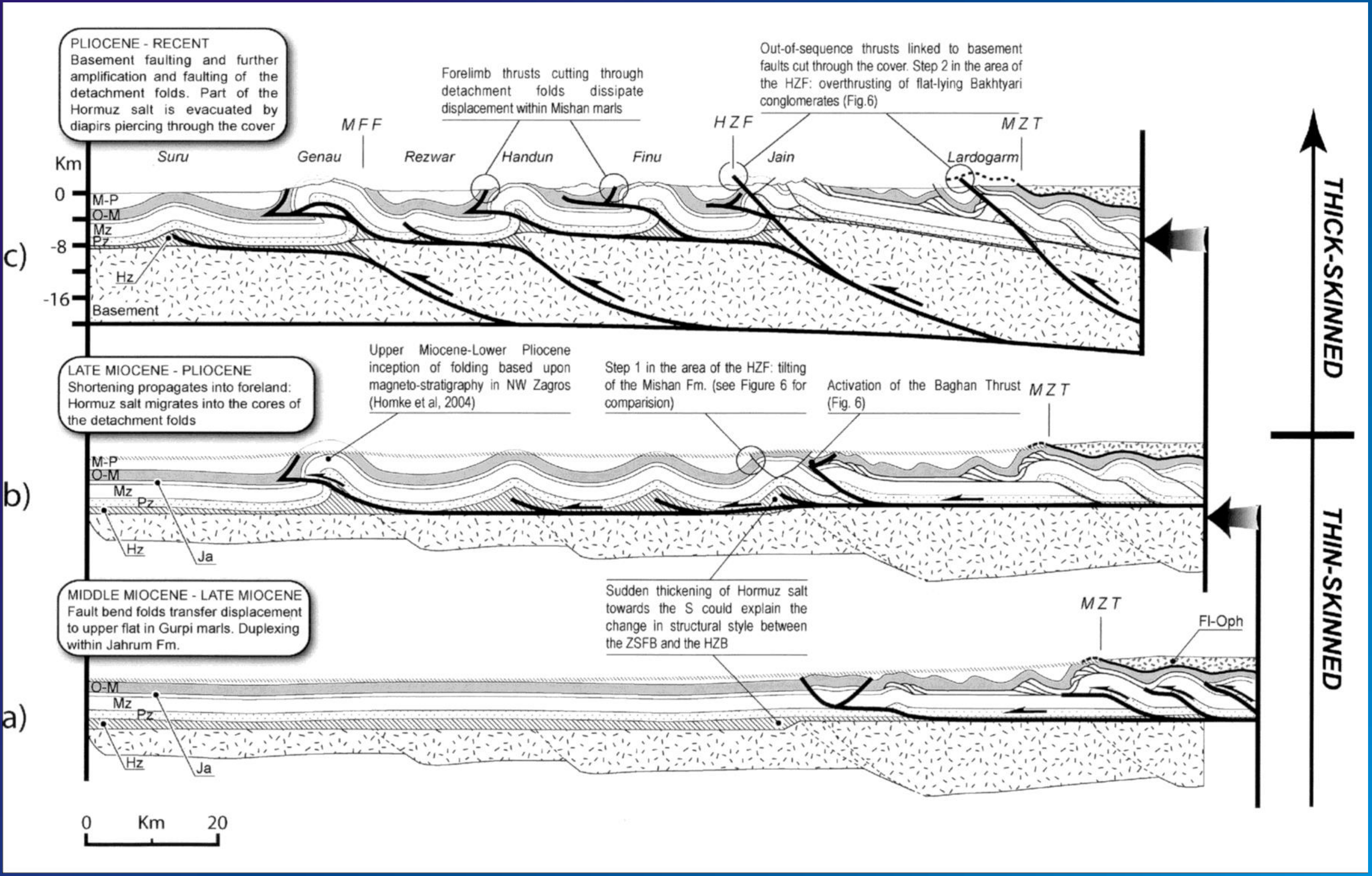
(McQuarrie, 2004)



(Sherkati et al., 2006)

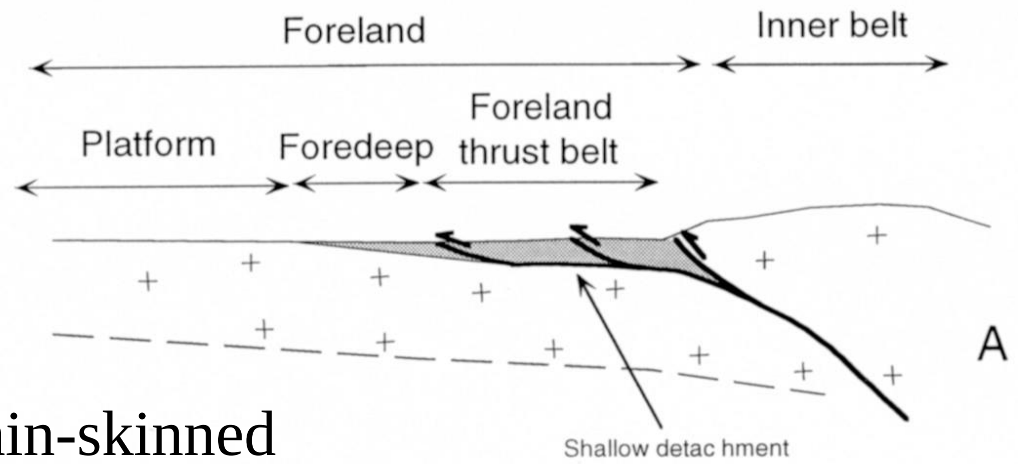


(Molinaro et al., 2005)

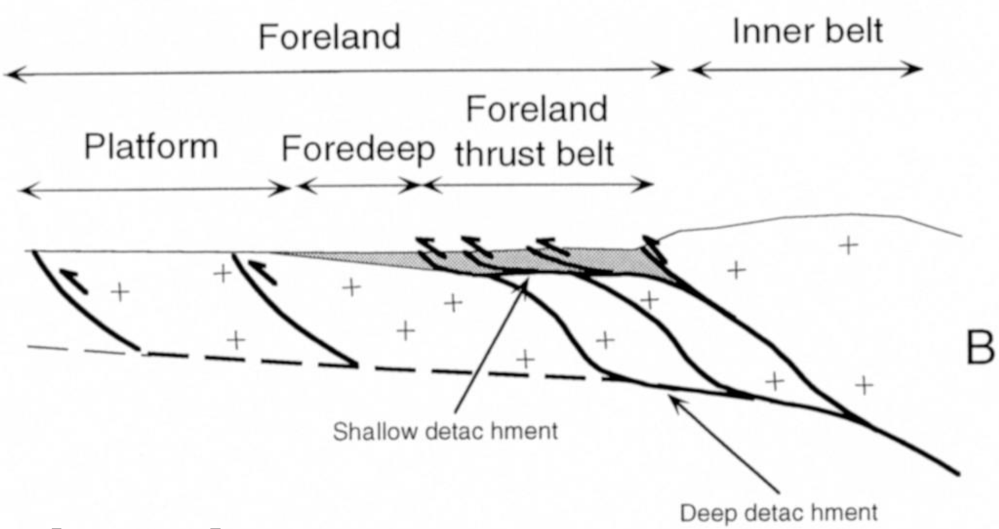


(Molinaro et al., 2005)

(Lacombe and Mouthereau, 2002)

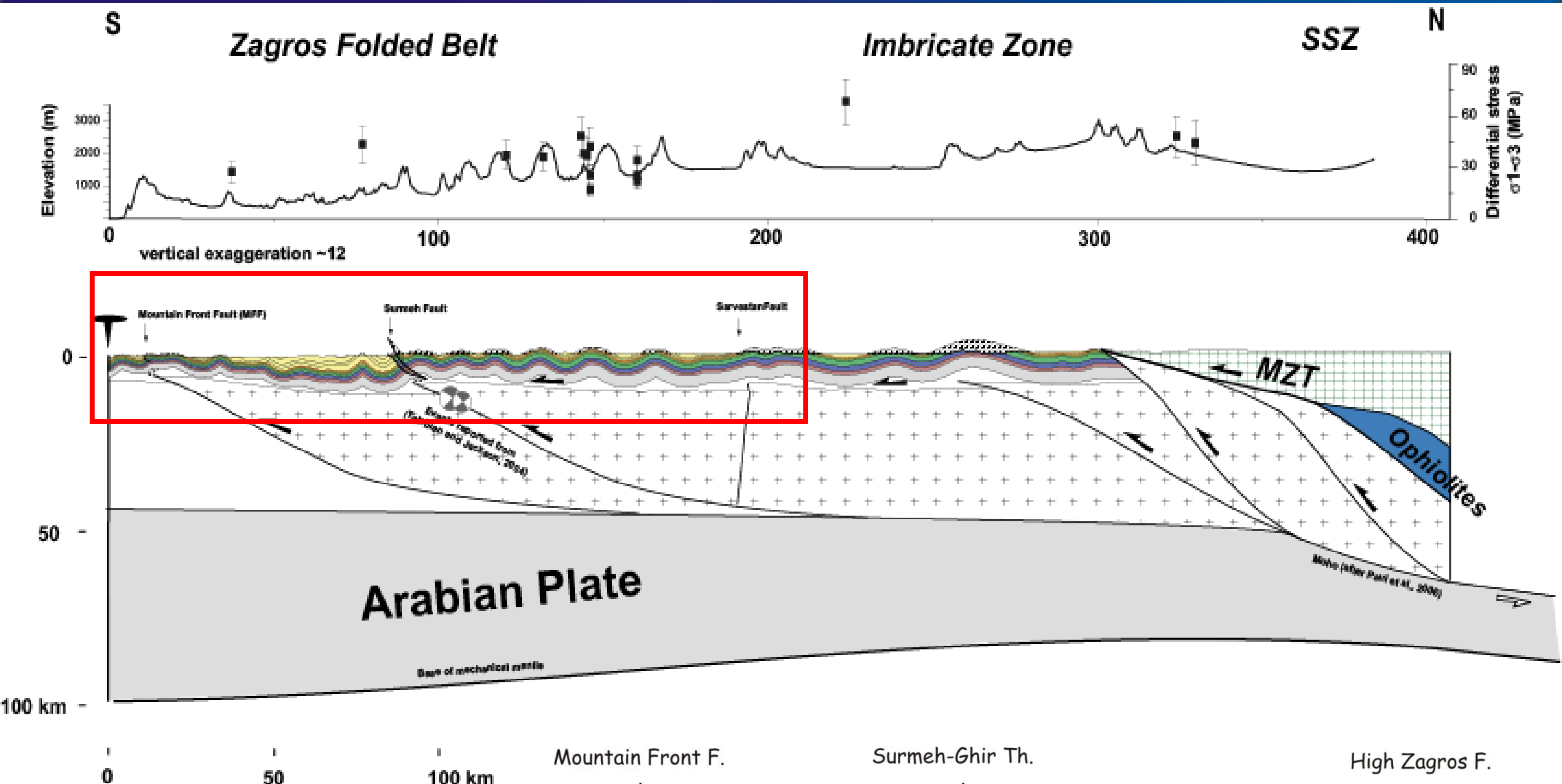


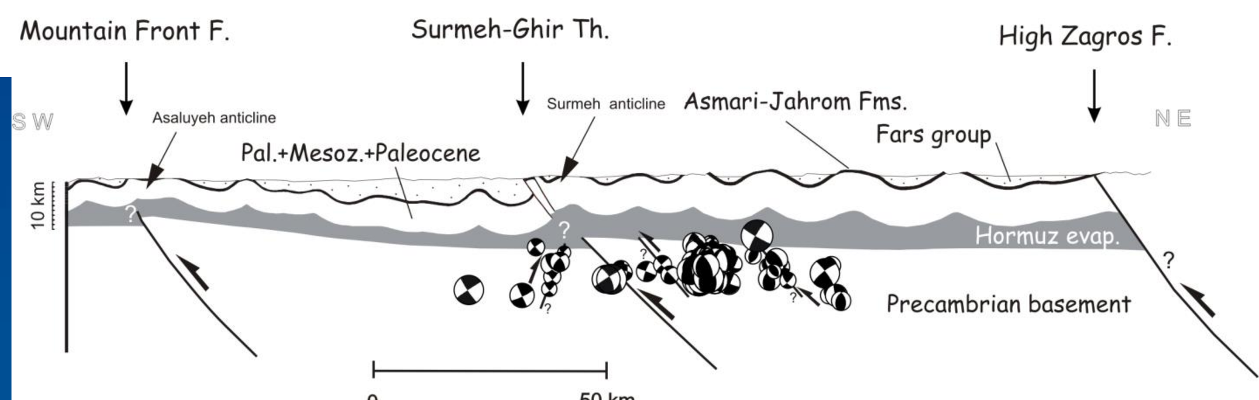
Thin-skinned



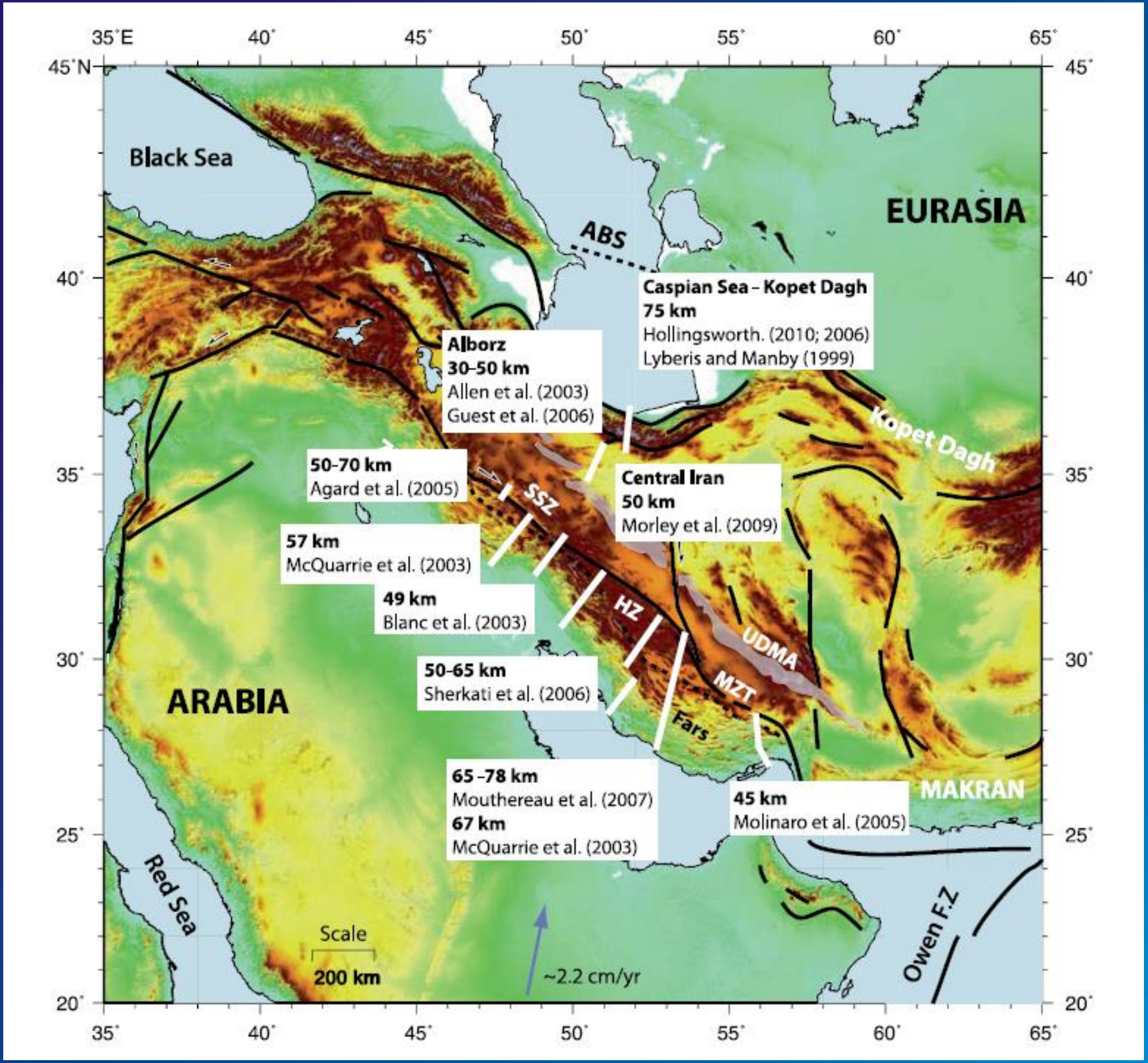
Thick-skinned ?

Thin-skinned + thick-skinned ?

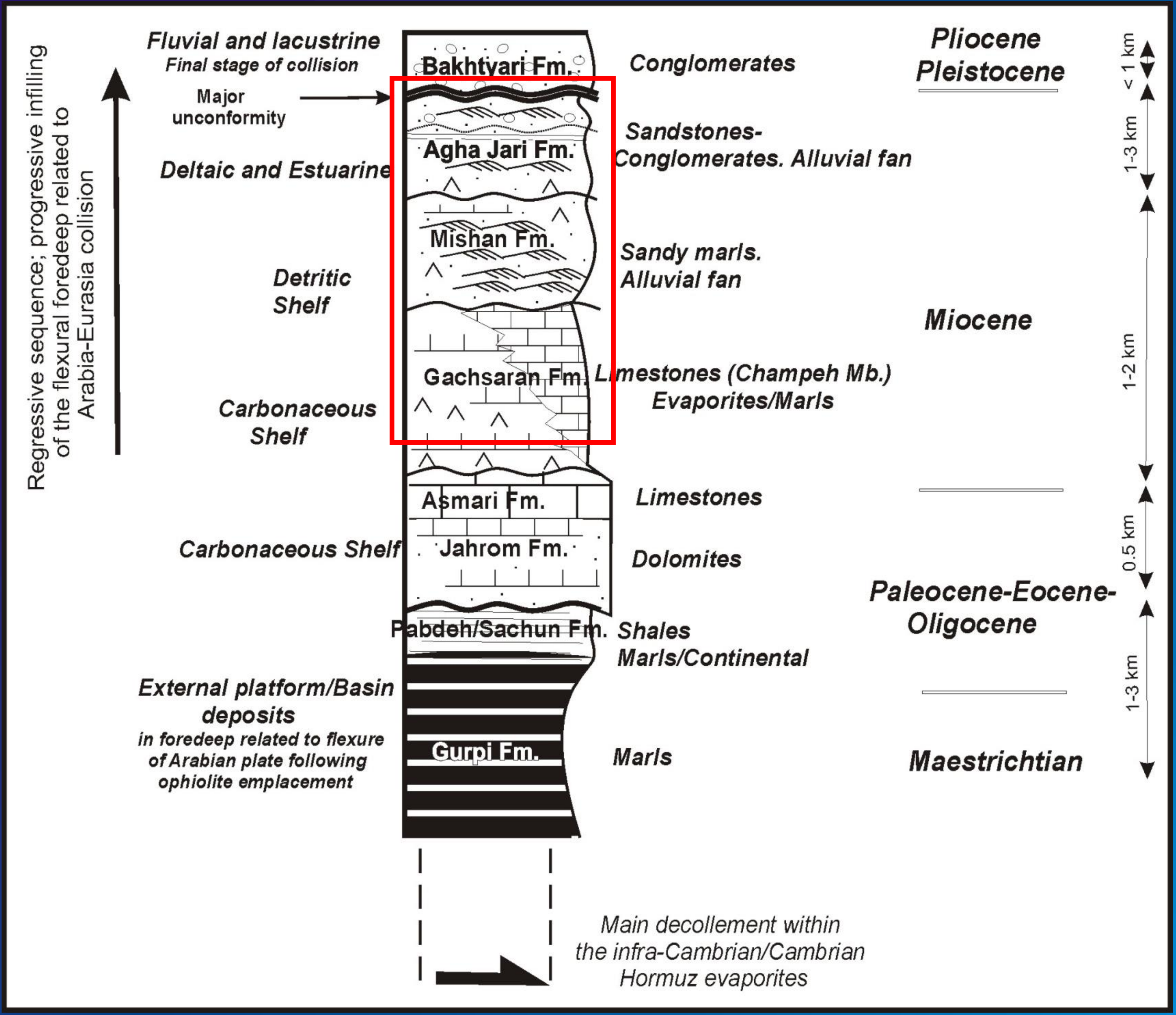




(Mouthereau et al., 2007; Lacombe et al., 2006)



(Mouthereau et al, 2012)



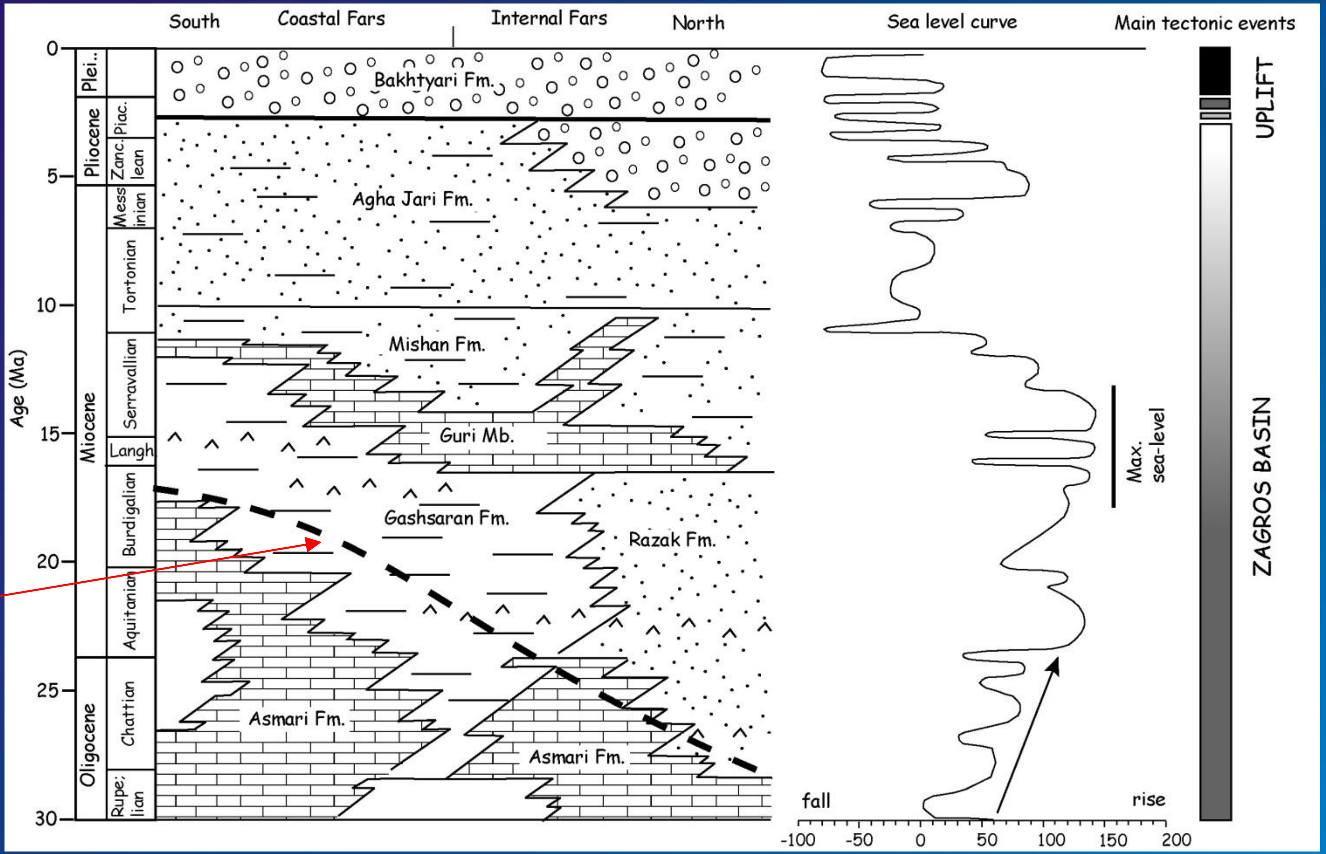
Miocene foreland sequences :

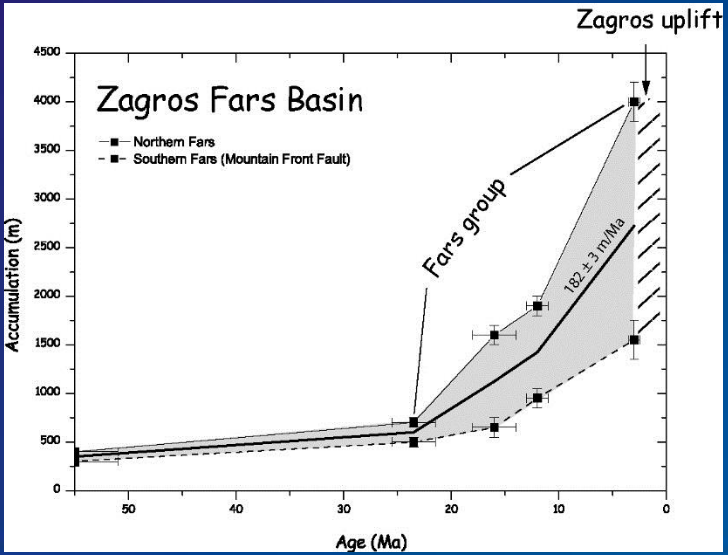
Thick regressive siliciclastic sequence of the Fars Group

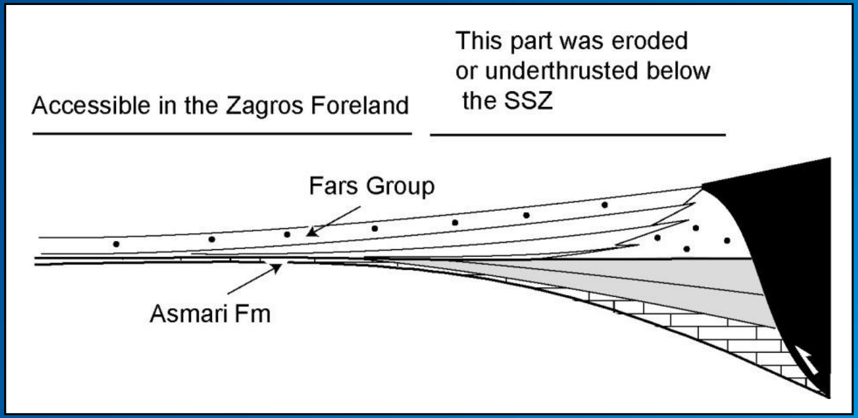
Progressive southward onlap through time

of the shallowing-upward synorogenic deposits (Razak-Gashsaran Fm) onto the carbonates of the Asmari Fm

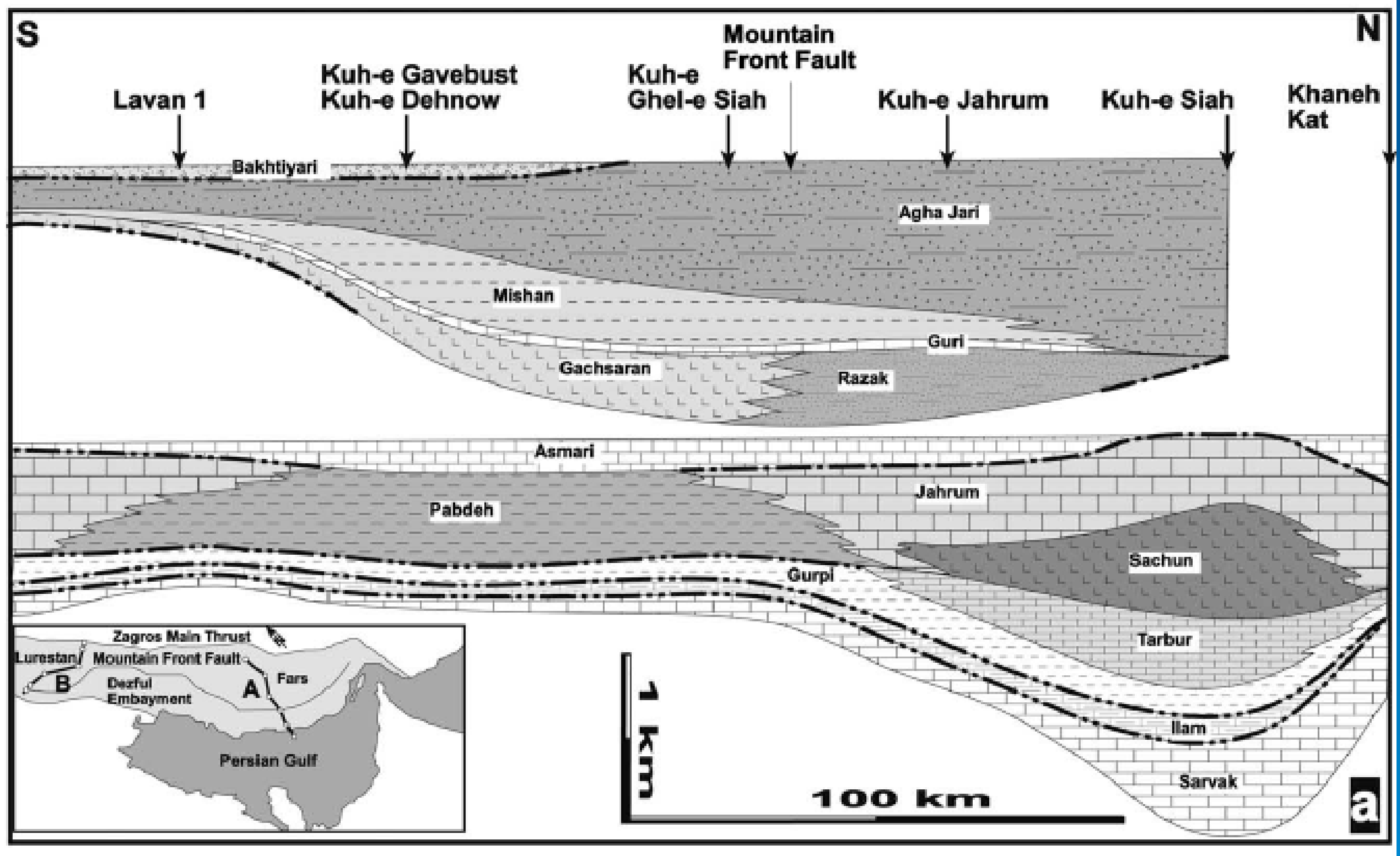
in the context of flexural basin development.





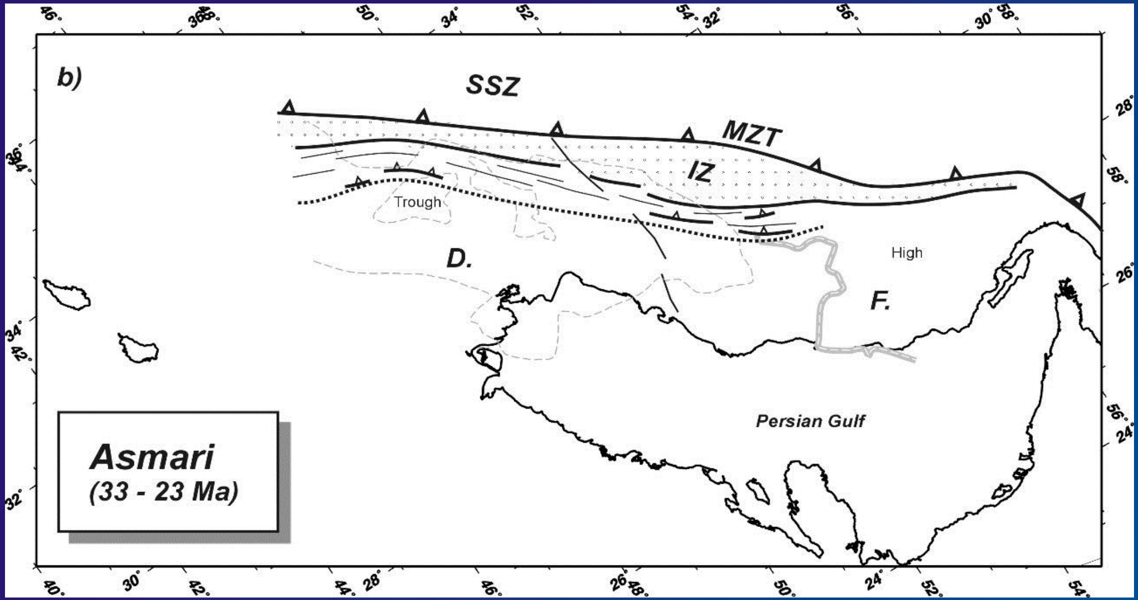


(Mouthereau et al,, 2007)



(Sepher and Cosgrove, 2004)

Oldest folding event recorded in the Fars – Oligocene

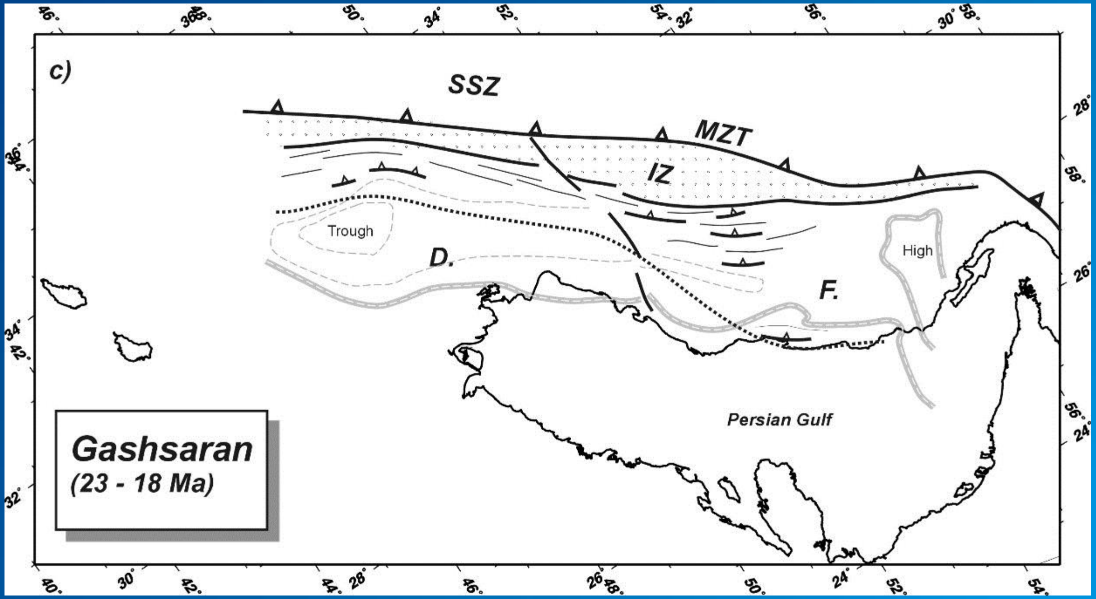


(adapted from Mottiei, 1993)

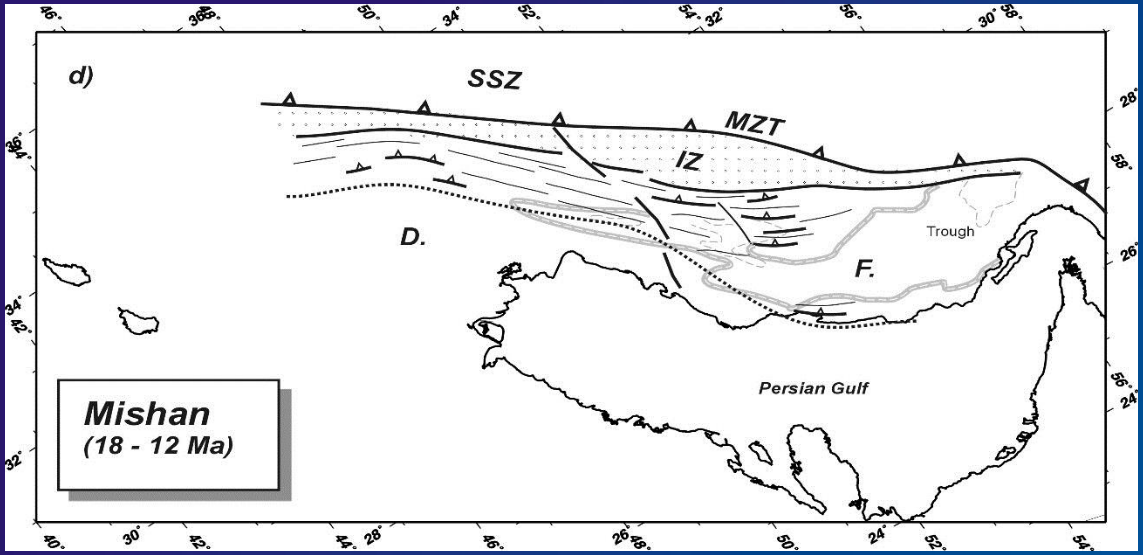
Migration of the collision southward
Maximum subsidence in the Dezful

Initiation of deformation in the southern Fars (Gulf Coast)

Migration of the collision southward
Maximum subsidence parallel to the MZT – the flexural basin was formed



Developement of the upper Fars and active folding near the Gulf Coast
(formation of an intramountain trough)

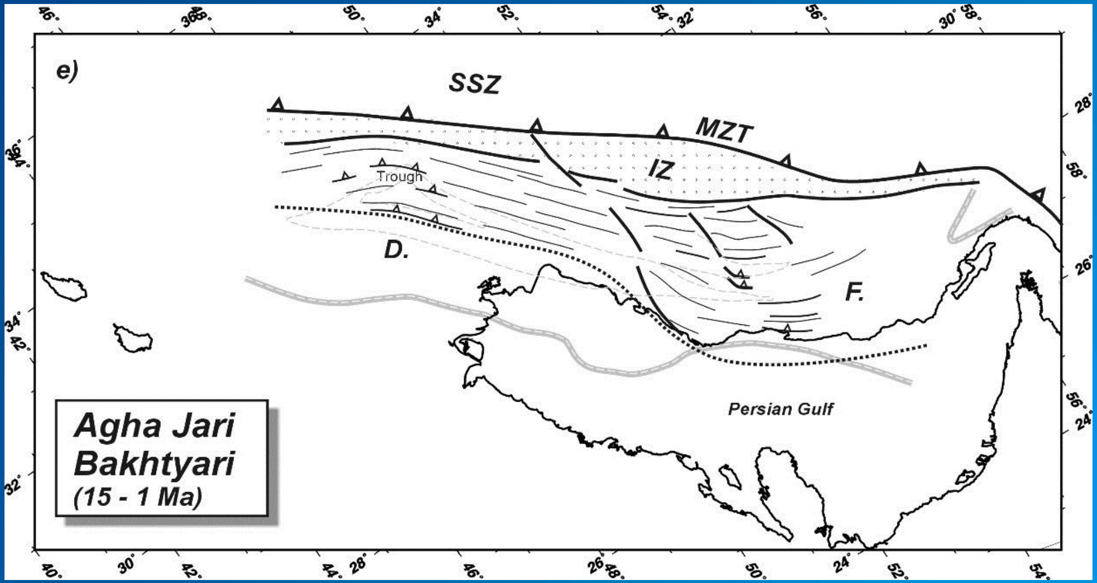


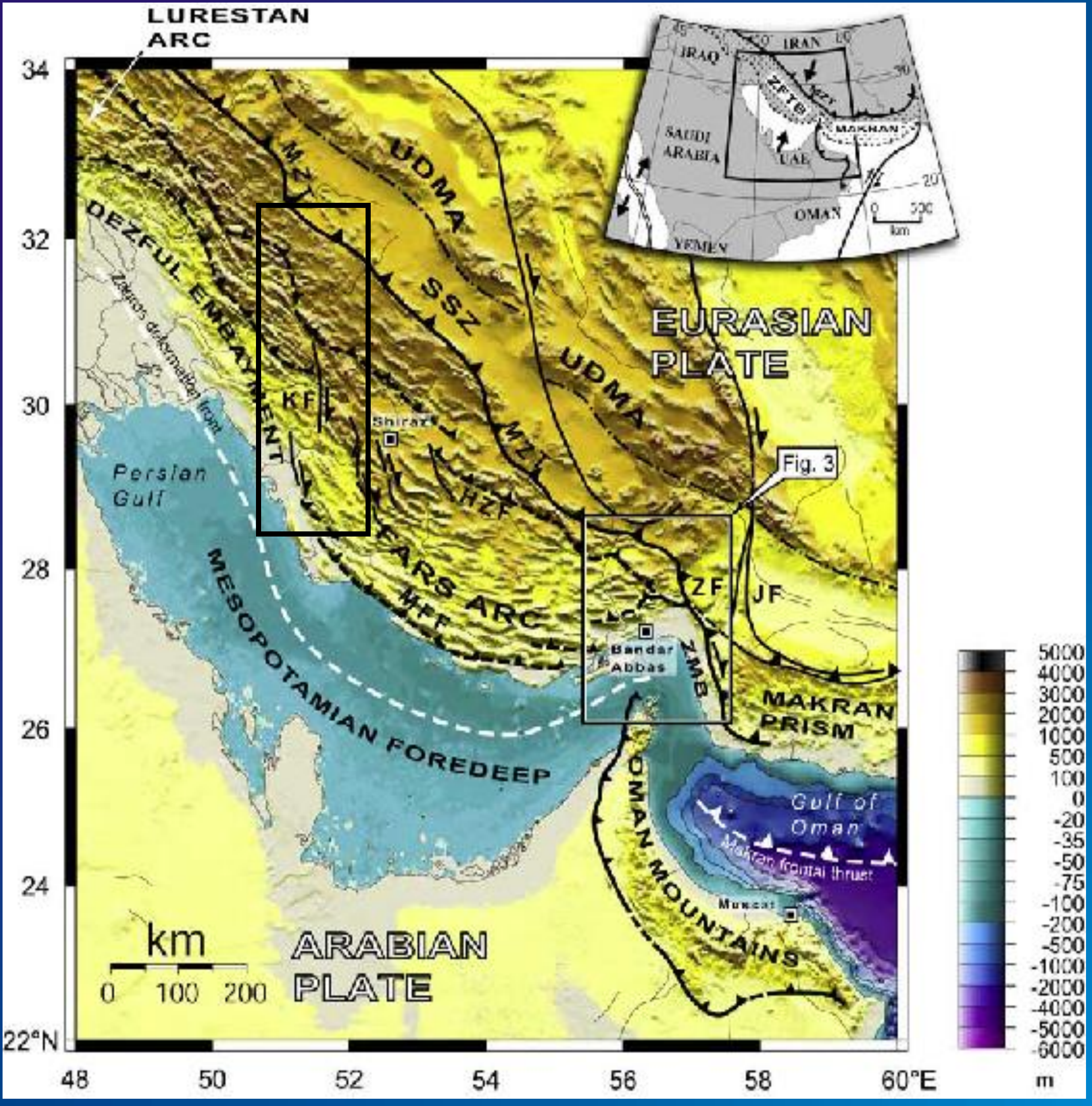
Migration of the collision southward
Maximum subsidence toward a southern trough

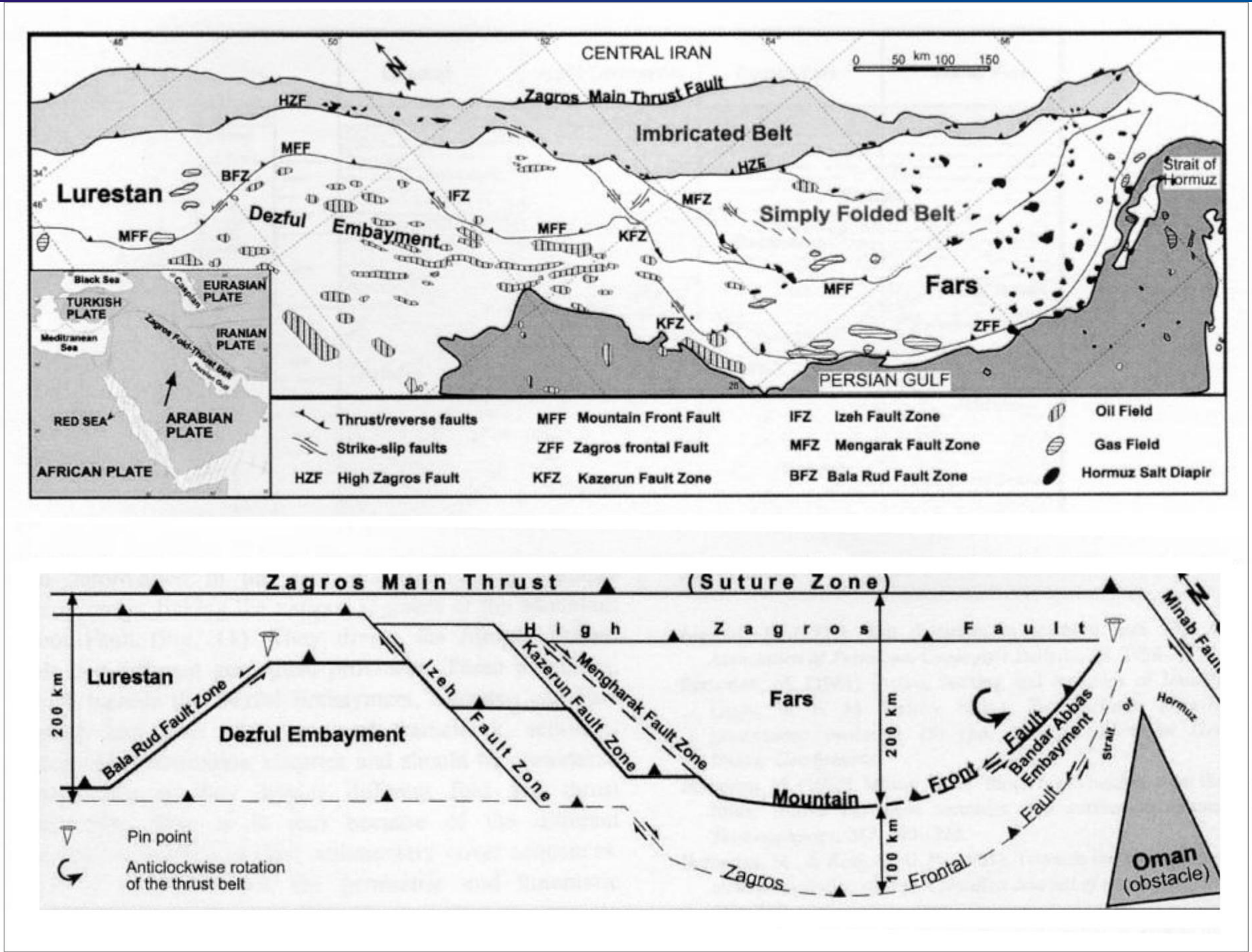
(adapted from Mottiei, 1993)

Renewed subsidence in the Dezful and achievement of the present structure of the ZSFB

Migration of the deformation front toward the Arabian shelf
Maximum subsidence domain propagated into the Arabian shelf consistently

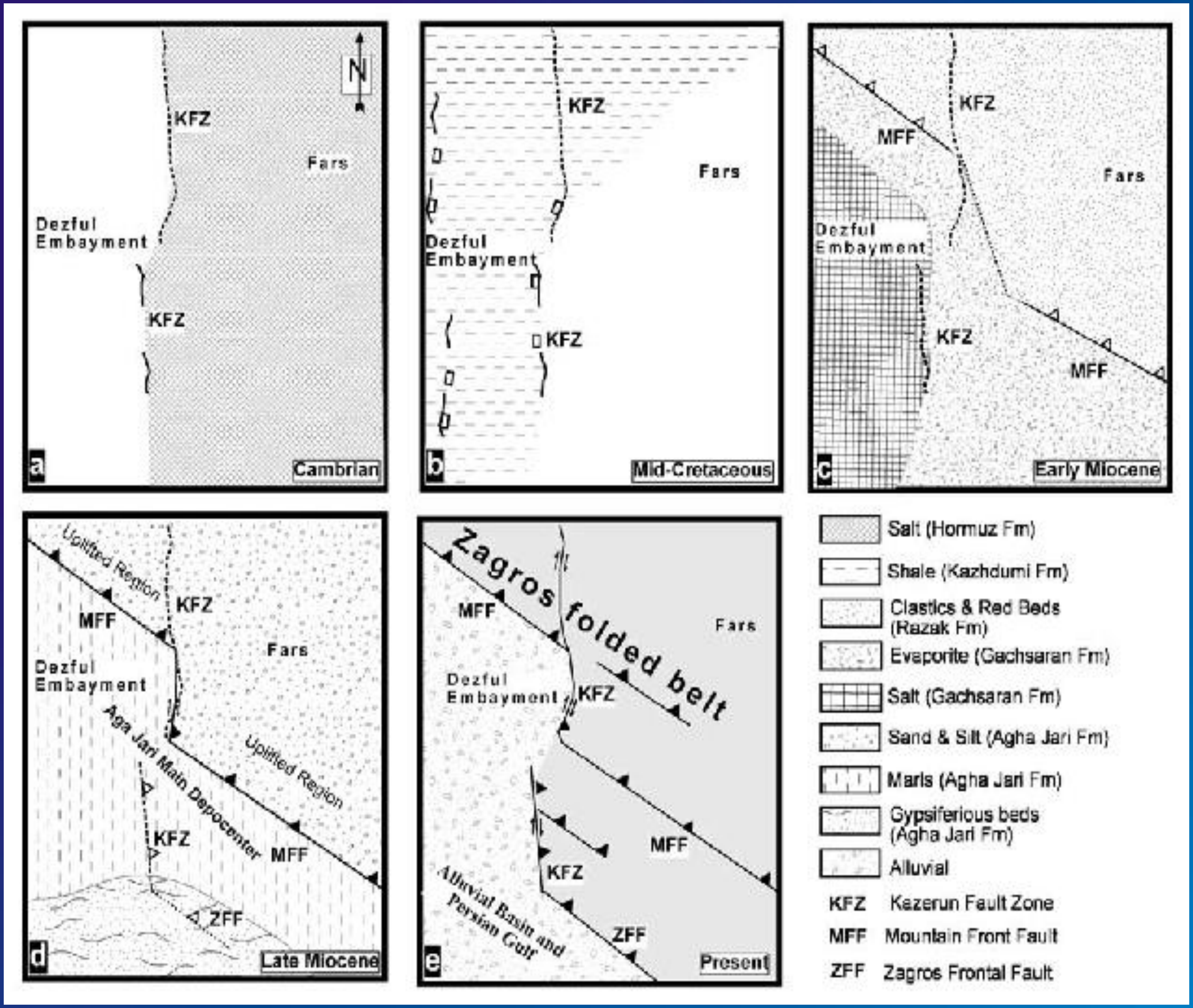



LURESTAN
ARC
DEZFUL EMBAYMENT
Zagros deformation front
MZT
UDMA
SSZ
KF
Shiraz
HZF
EURASIAN
PLATE
Fig. 3
ZF
JF
FARS ARC
MFF
Bandar
Abbas
ZMB
MAKRAN
PRISM
Persian
Gulf
MESOPOTAMIAN FOREDEEP
OMAN MOUNTAINS
Gulf of
Oman
Makran frontal thrust
Muscat
km
0 100 200
ARABIAN
PLATE
IRAQ
IRAN
SAUDI
ARABIA
UAE
OMAN
YEMEN
MAKRAN
ZFTB
34
32
30
28
26
24
22°N
48
50
52
54
56
58
60°E
5000
4000
3000
2000
1000
500
100
0
-20
-35
-50
-75
-100
-200
-500
-1000
-2000
-4000
-5000
-6000
m



(Sepehr and Cosgrove, 2004)

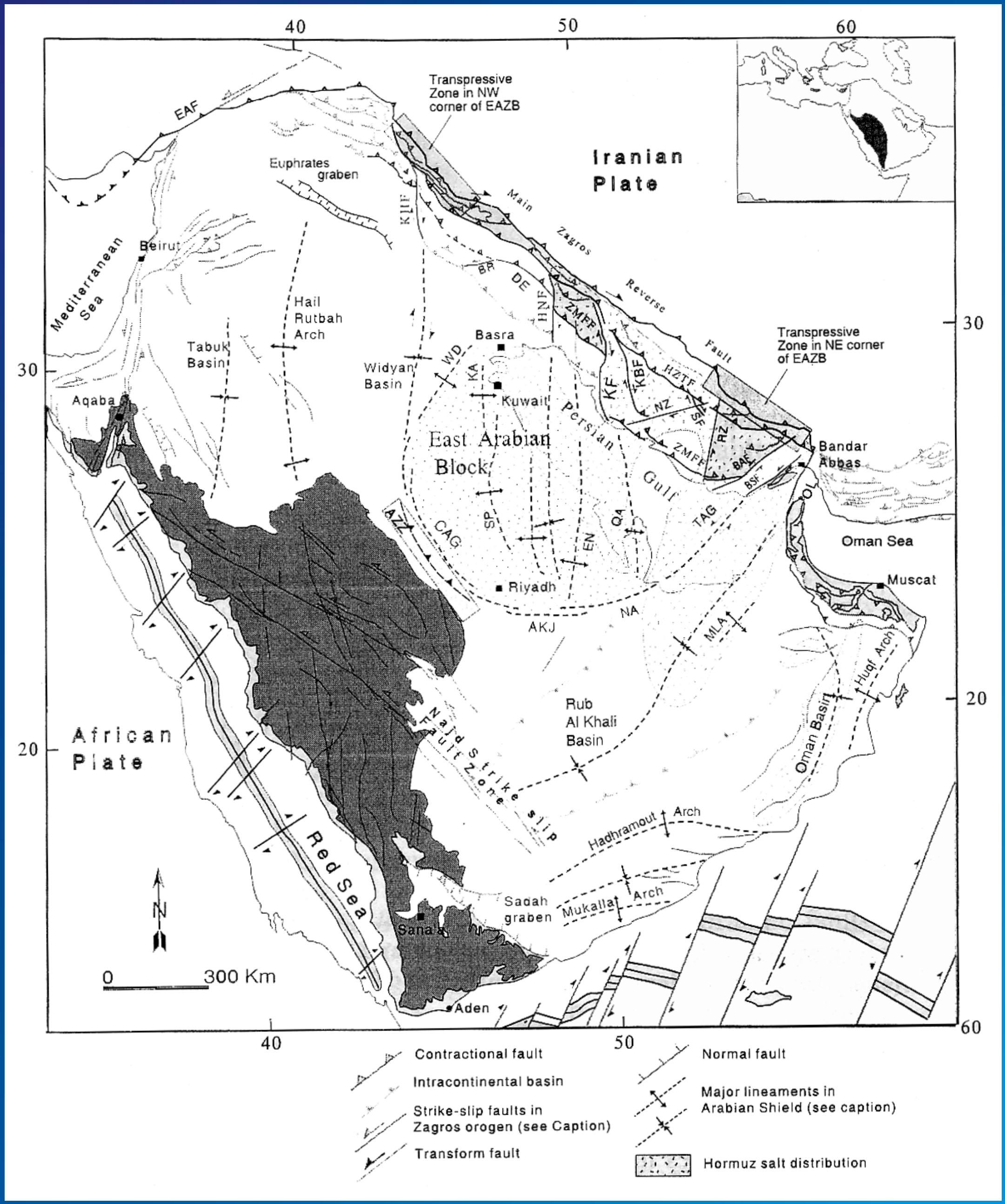
(Sepher and Cosgrove, 2005)

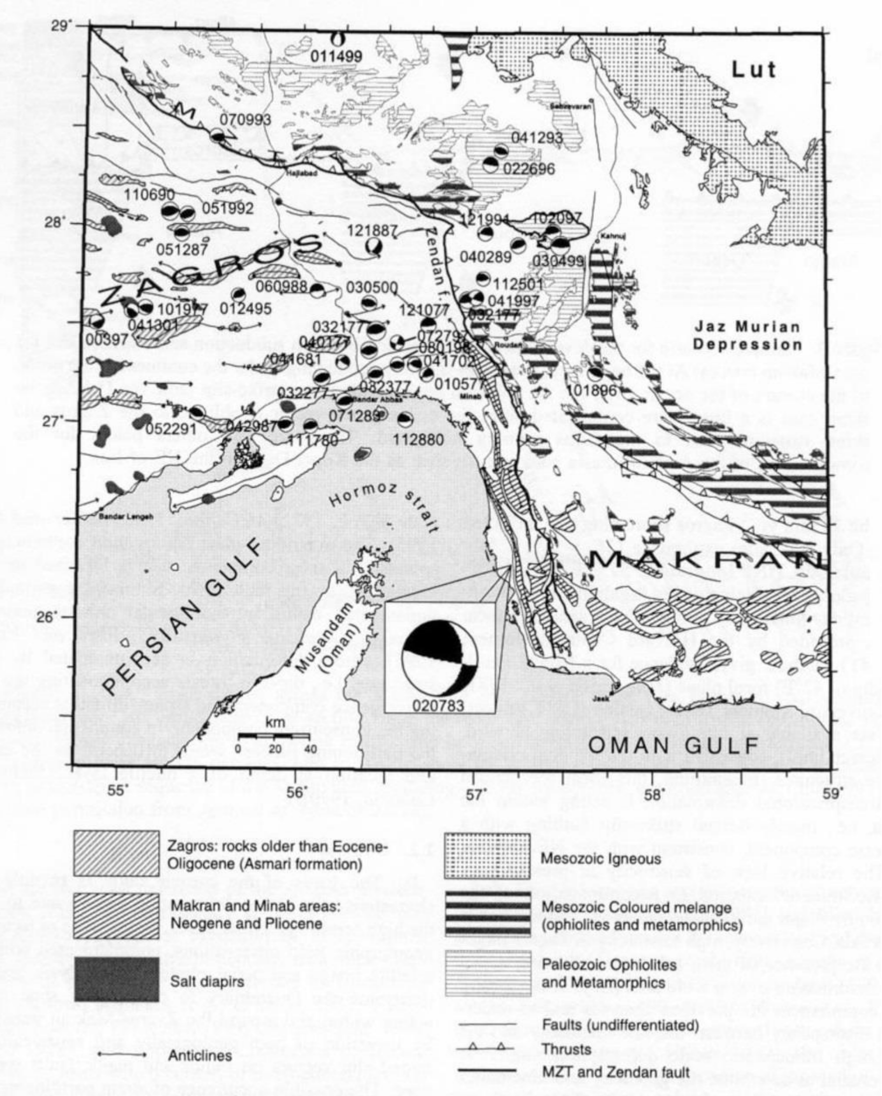


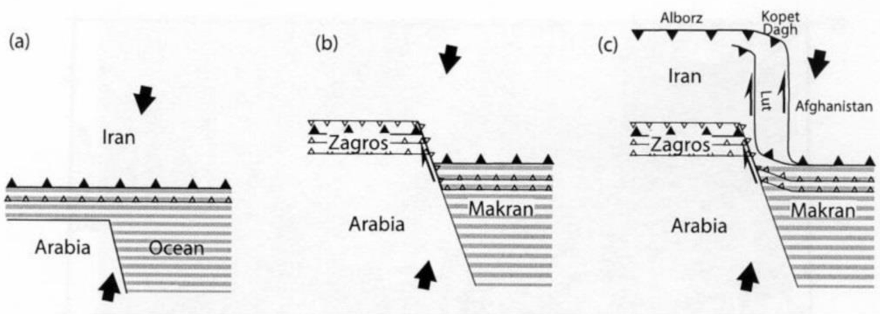
(Sepher and Cosgrove, 2005)

N-S basement faults underlying the Zagros cover inherited from Panafrican orogeny

(Al Laboun, 1986; Beydoun, 1991; Berberian, 1995; Weijermars, 1998; Husseini, 2000; Bahroudi and Talbot, 2003)

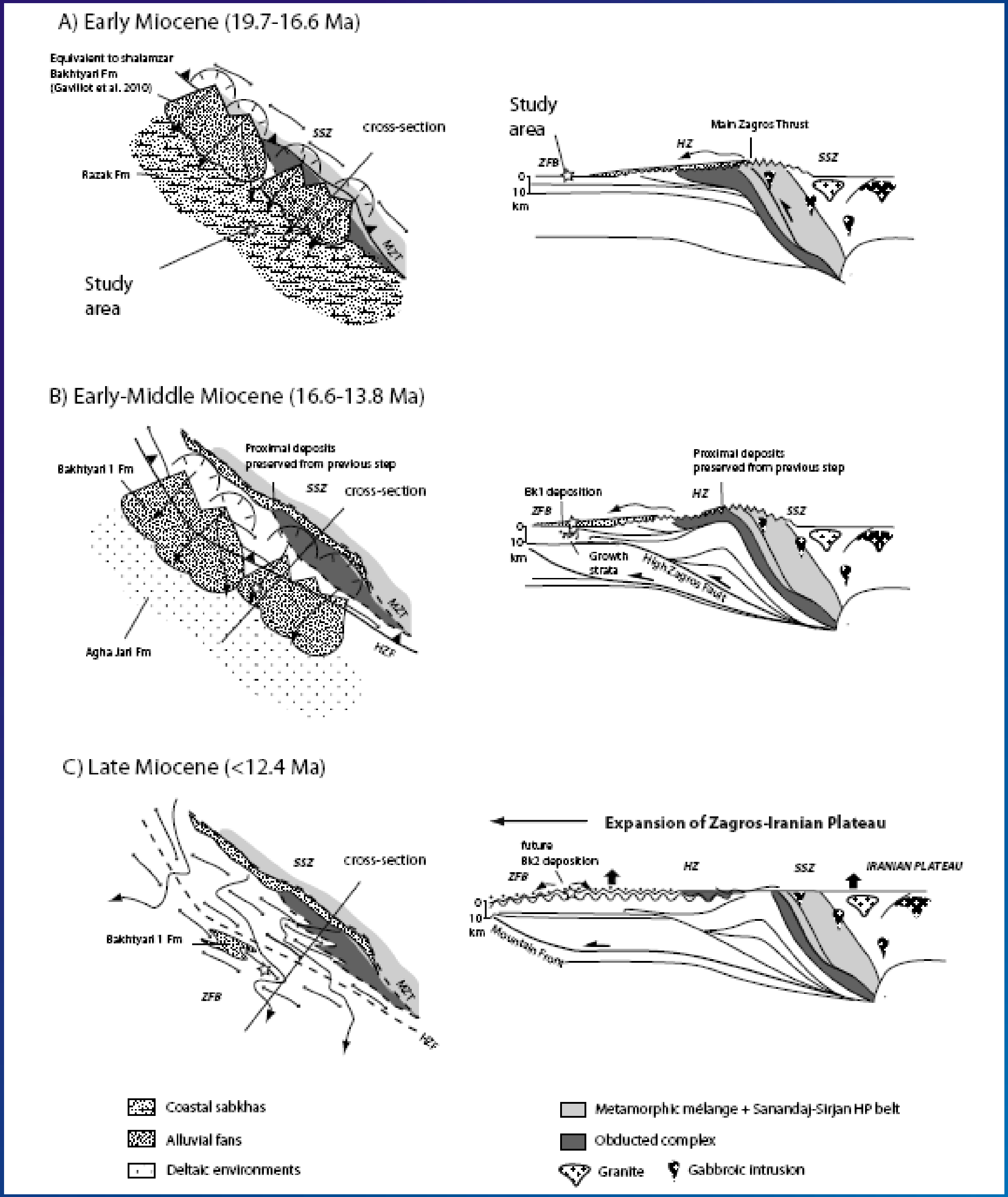






(Regard et al., 2004)

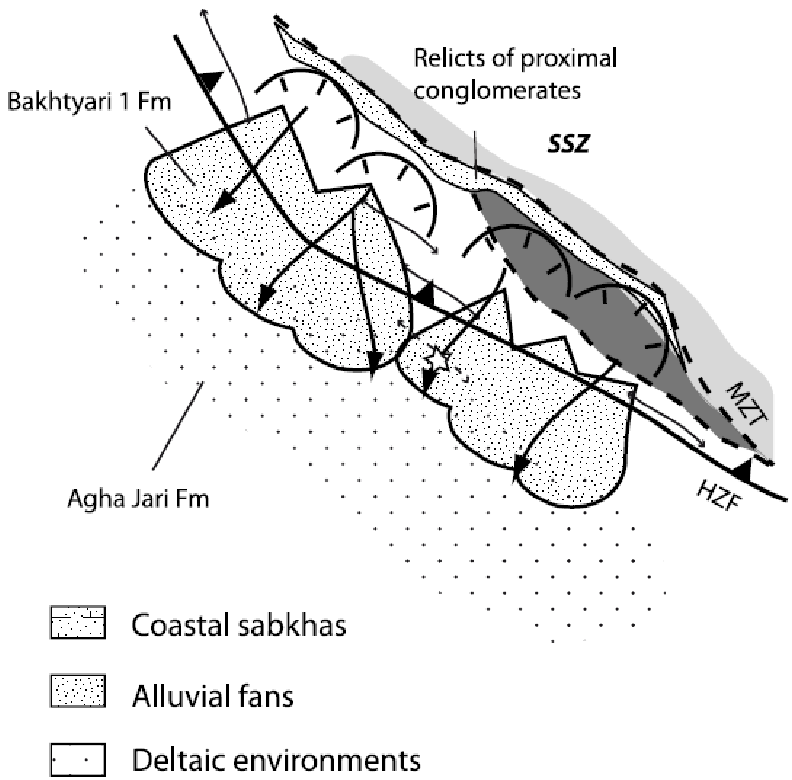
Fars



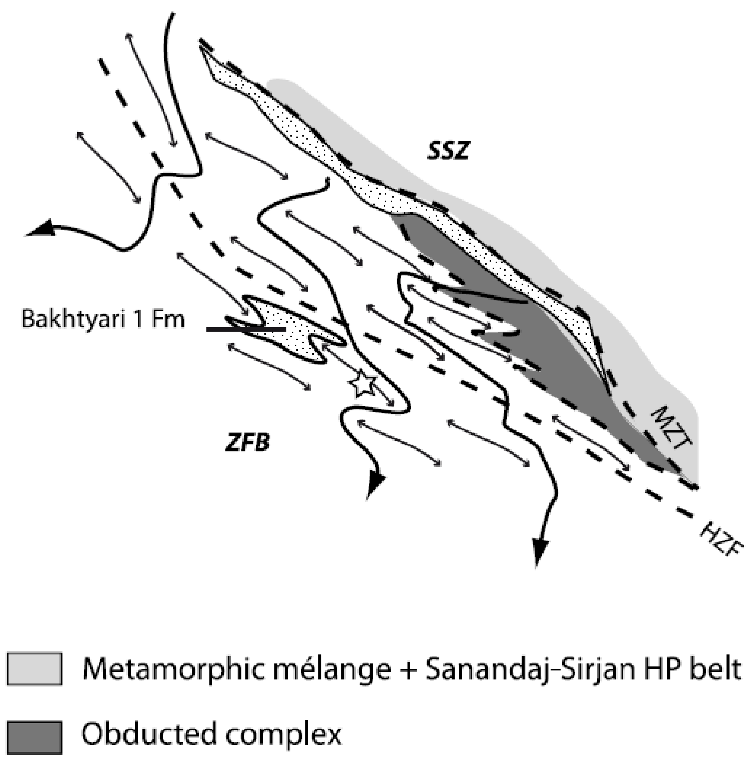
(Khadivi et al., 2012)

Drainage reorganisation from transverse to axial river network

Early-Middle Miocene (16.6-13.8 Ma)

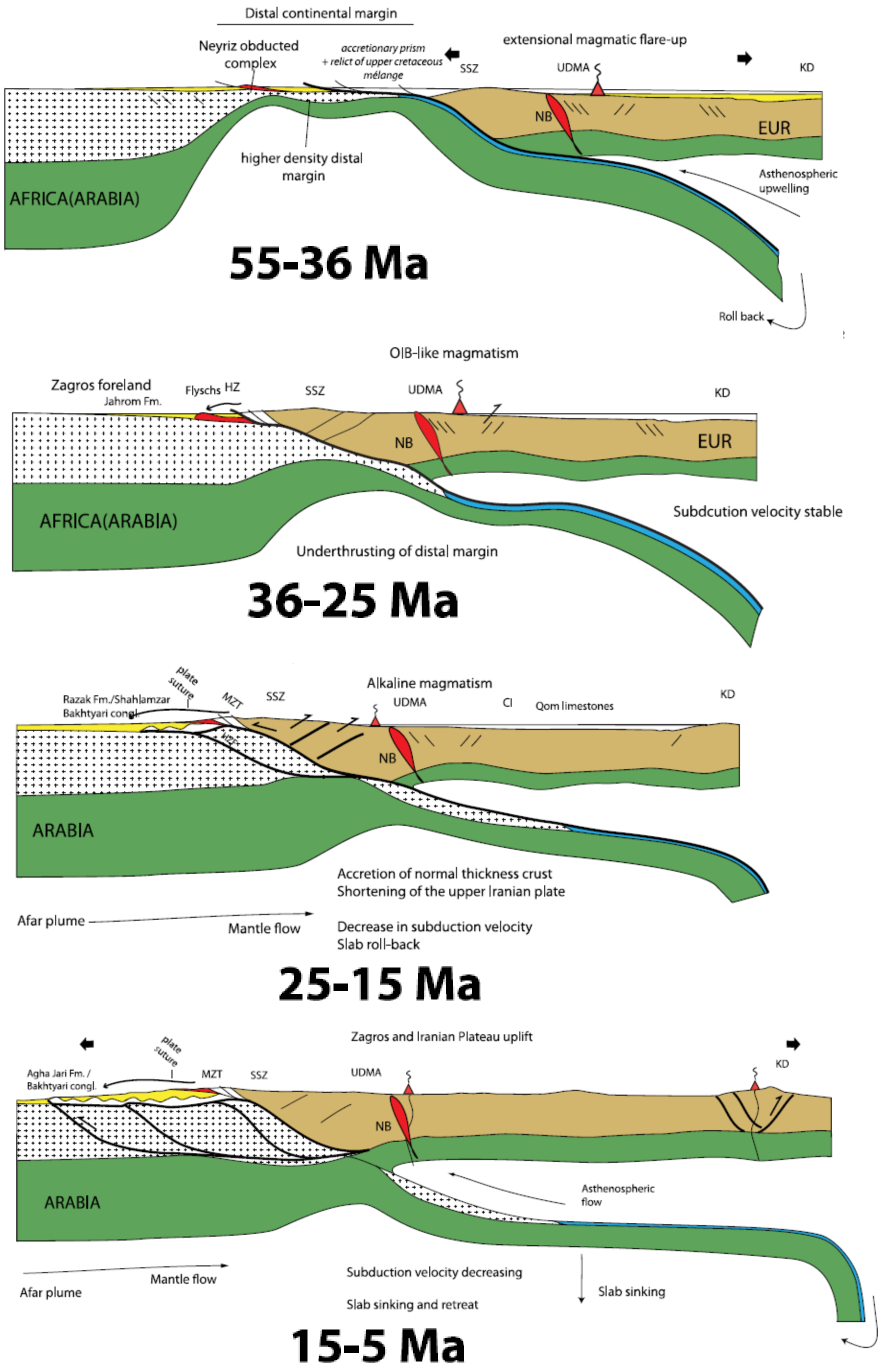


Late Miocene (<12.4 Ma)



(Khadivi et al., 2012)

Central Zagros



- Ophiolites
- Cenozoic deposits
- Oceanic continental crust
- Iranian/Eurasian continental crust
- Arabian continental crust
- Lithospheric mantle

(Mouthereau et al, 2012)

Deformation in the Zagros (1) : folding

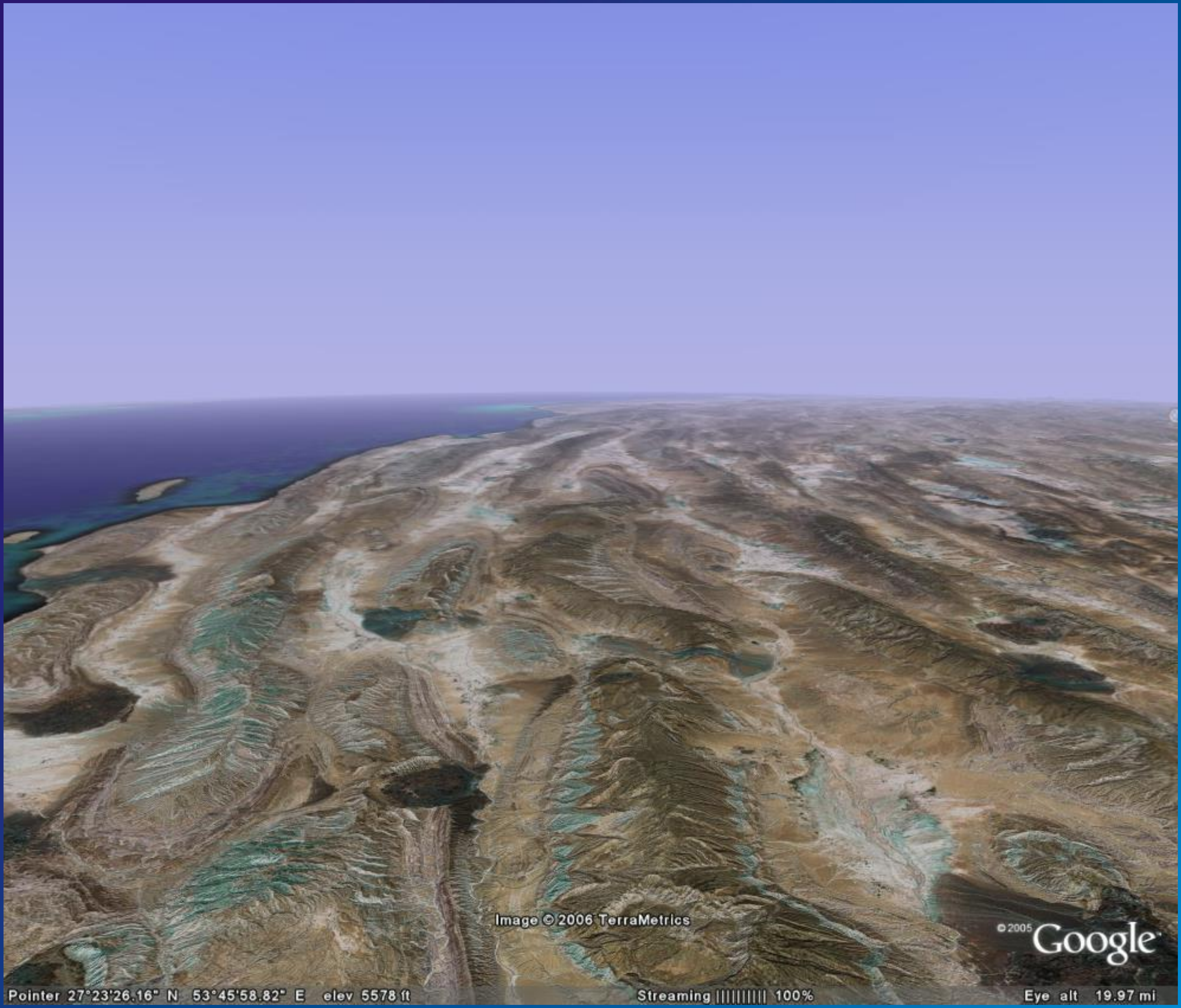
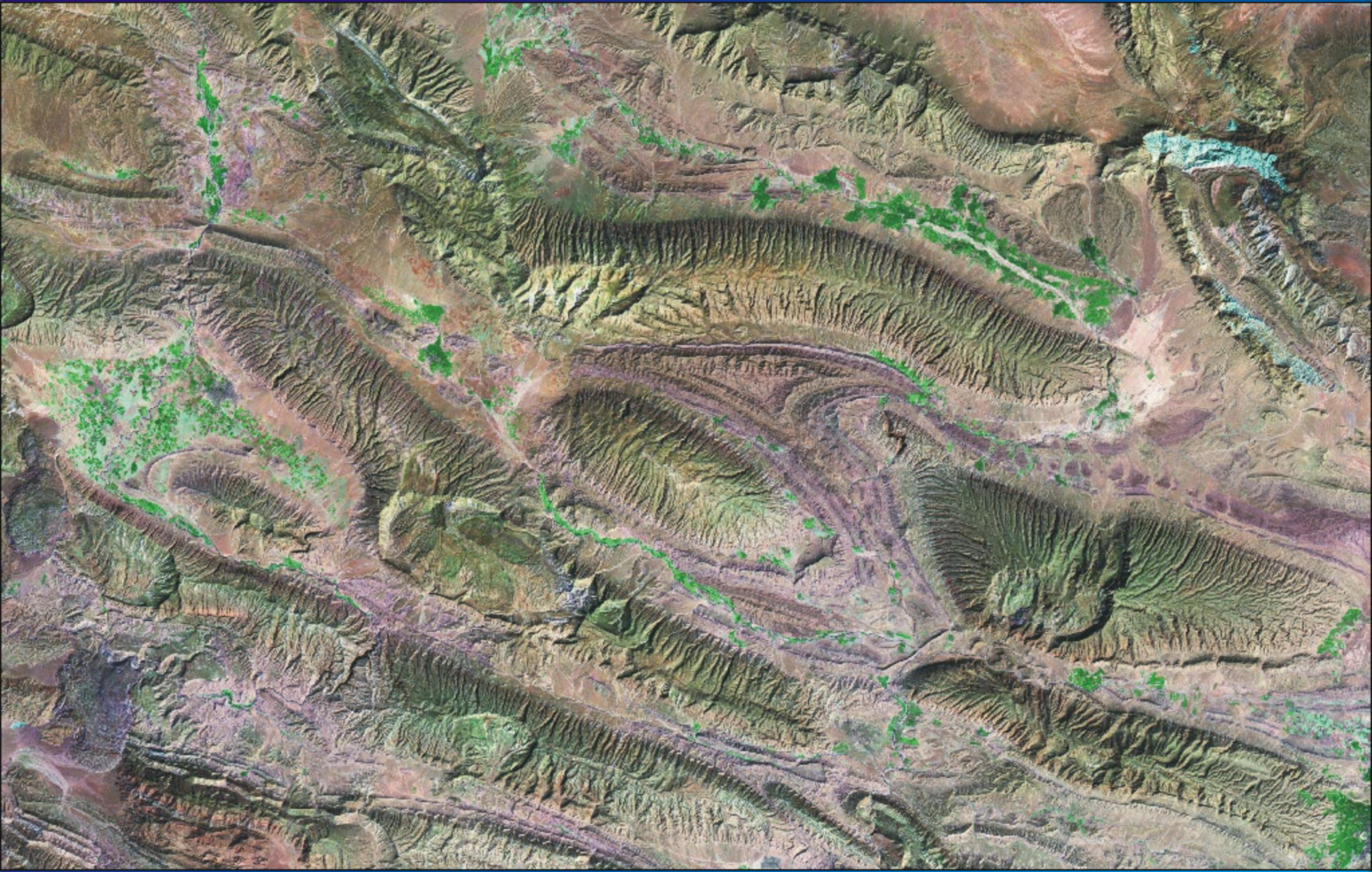
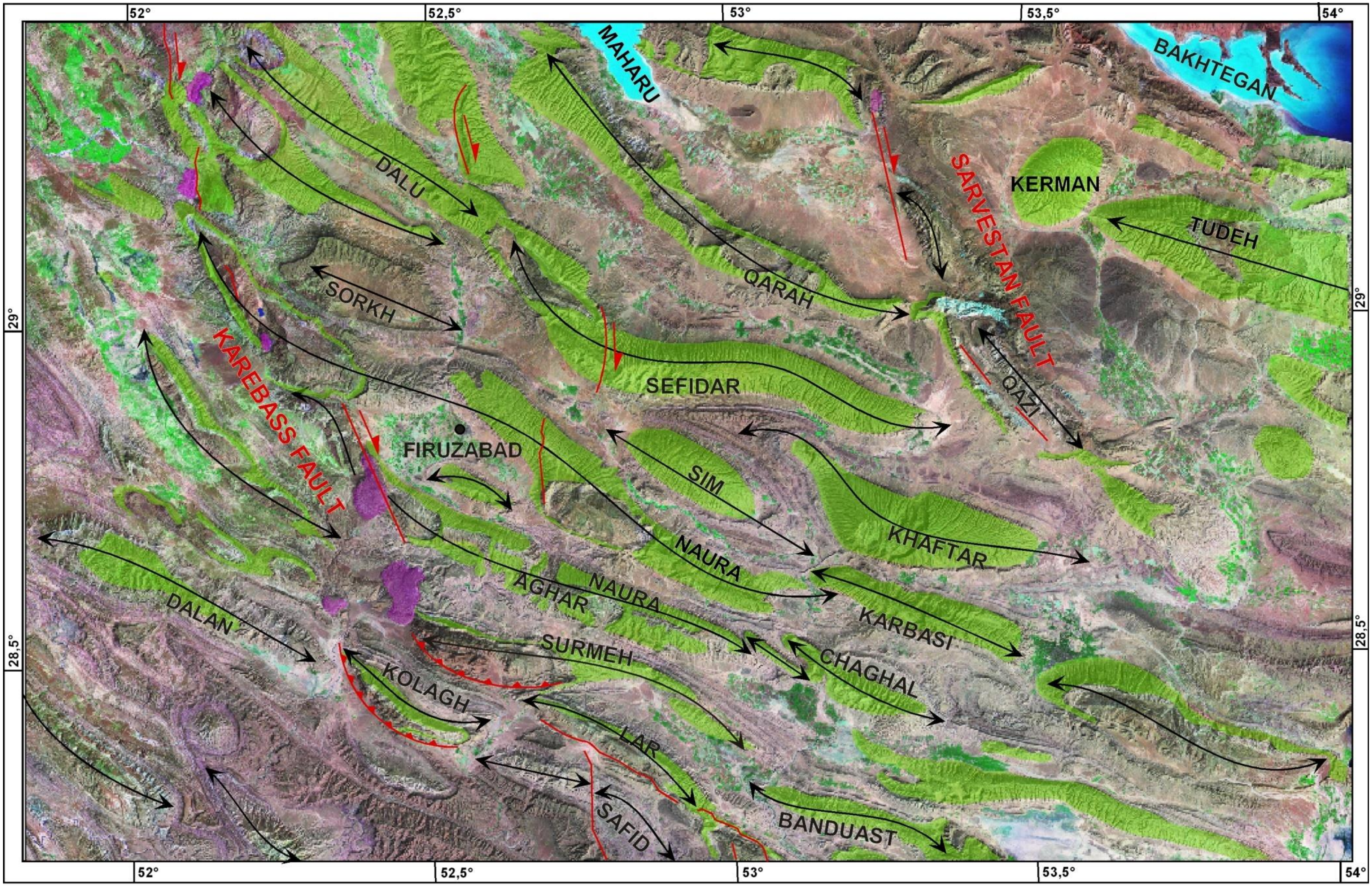


Image © 2006 TerraMetrics
© 2005 Google
Pointer 27°23'26.16" N 53°45'58.82" E elev 5578 ft
Streaming |||||||||| 100%
Eye alt 19.97 mi

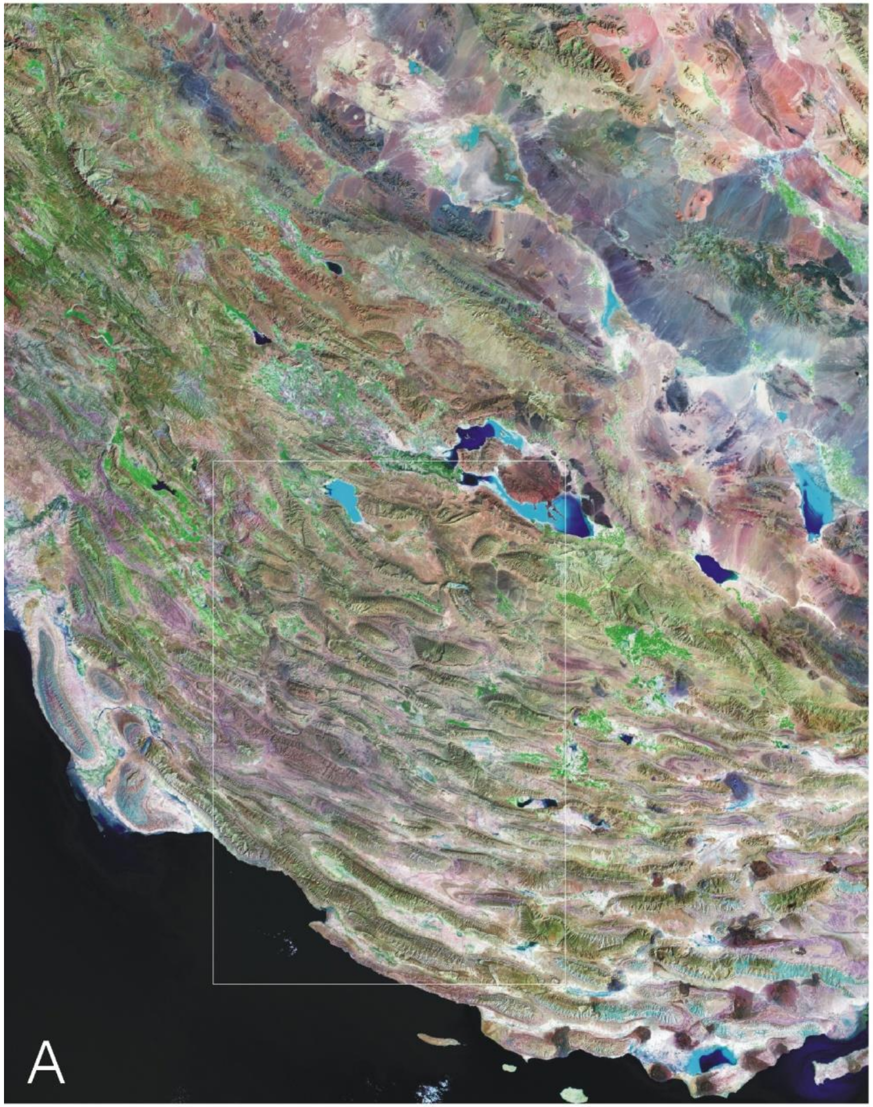


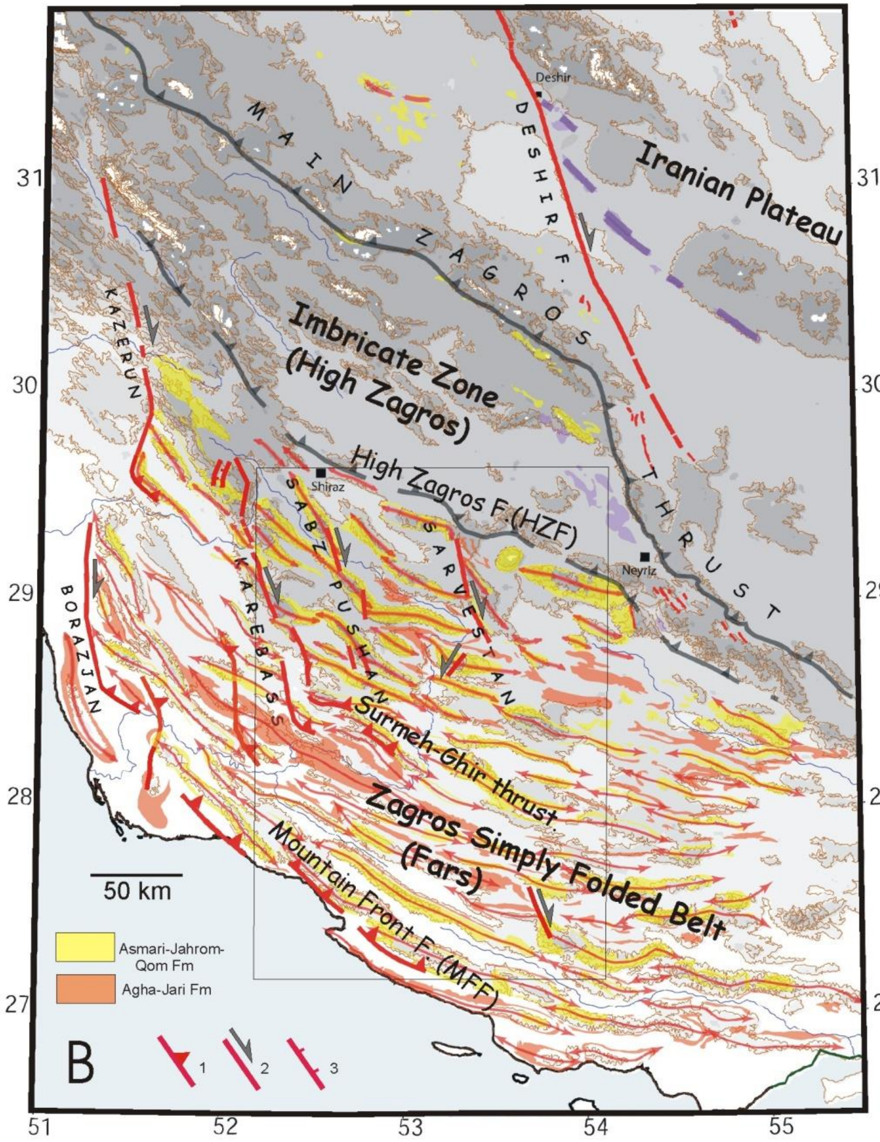


52°
52,5°
53°
53,5°
54°
29°
28,5°
MAHARU
BAKHTEGAN
DALU
KERMAN
SARVESTAN FAULT
TUDEH
QARAH
SORKH
KAREBASS FAULT
SEFIDAR
QAZI
FIRUZABAD
SIM
KHAFTAR
NAURA
AGHAR
NAURA
KARBASI
DALAN
SURMEH
CHAGHAL
KOLAGH
LAR
SAFID
BANDUAST

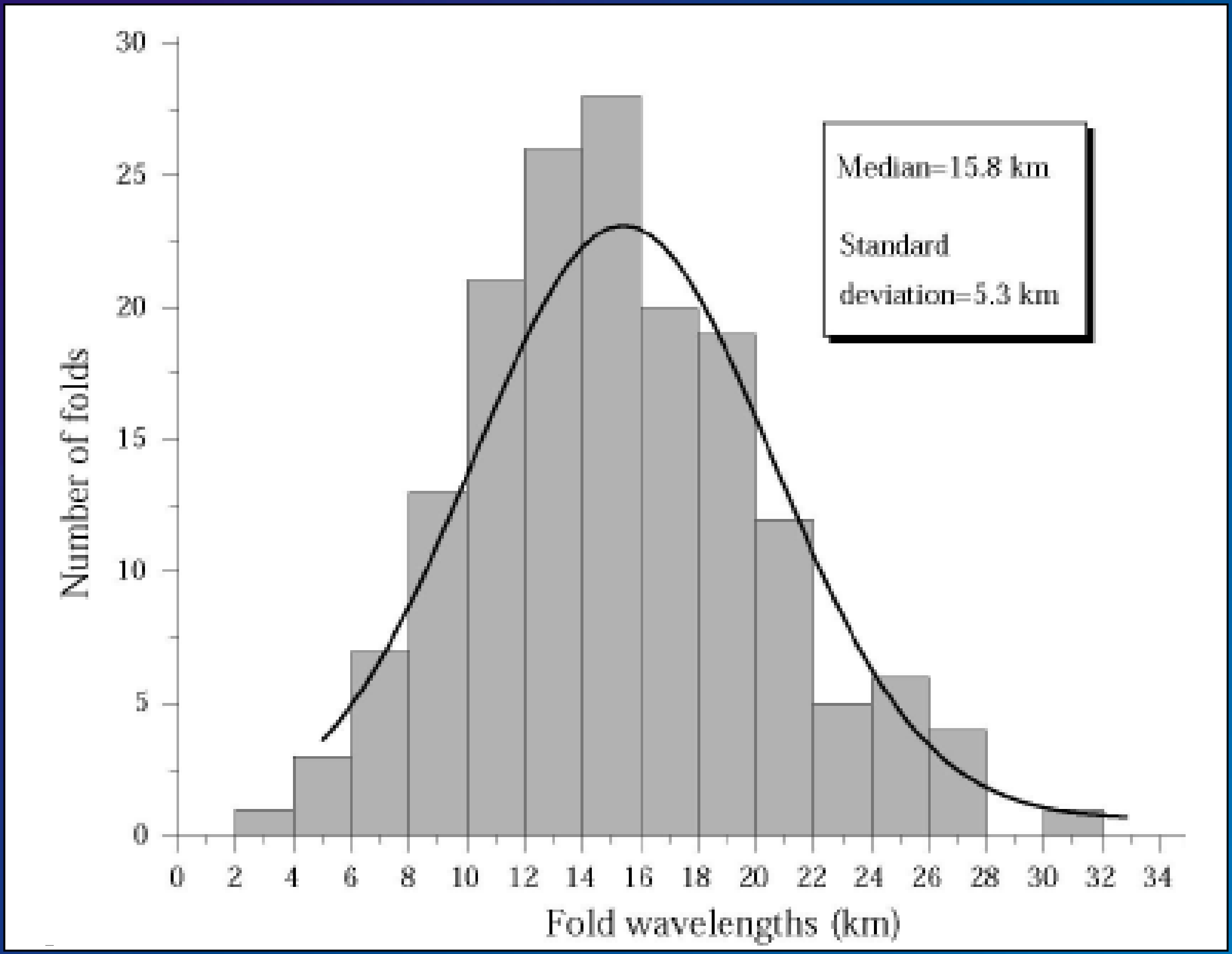
1/80 000

Fars





(Lacombe et al., 2006)

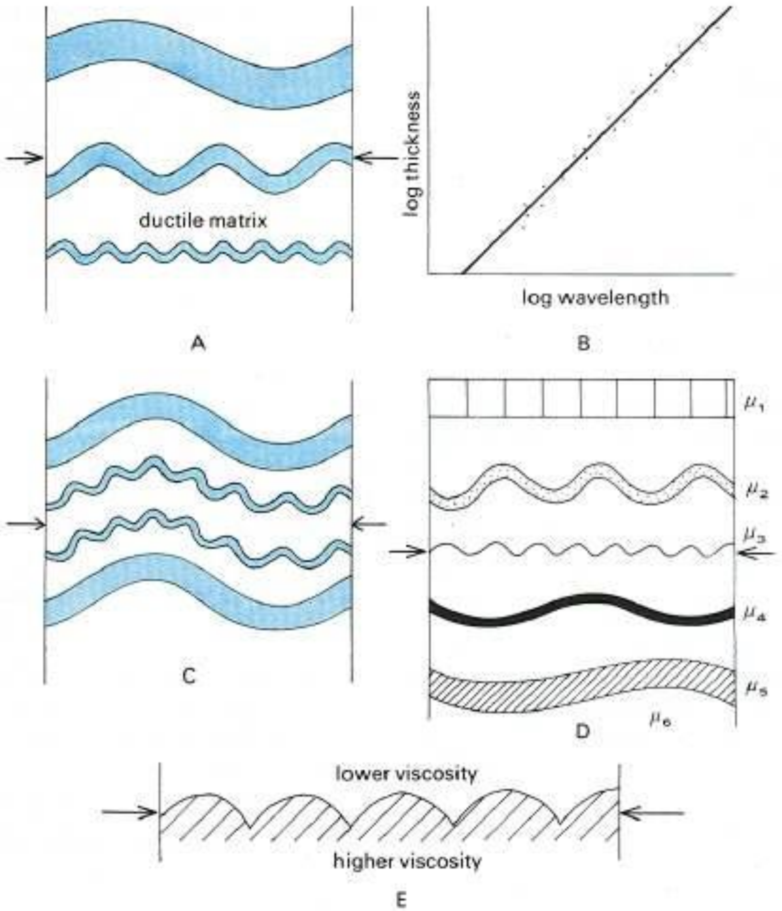


(Mouthereau et al, 2007a, b)

« buckle folds »

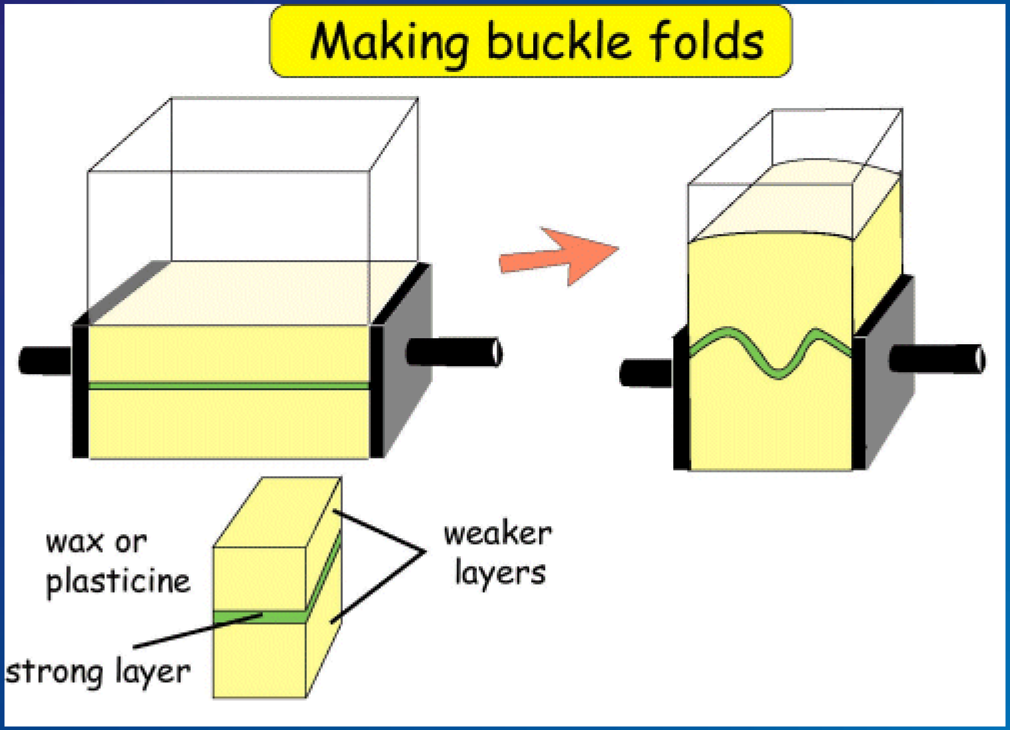
Development of this type of folds requires a significant contrast of competence between the folded strata (elastic or viscous) and the surrounding medium (viscous).

In this case, there is a direct relationship between the thickness of the competent strata and the wavelength of folding.

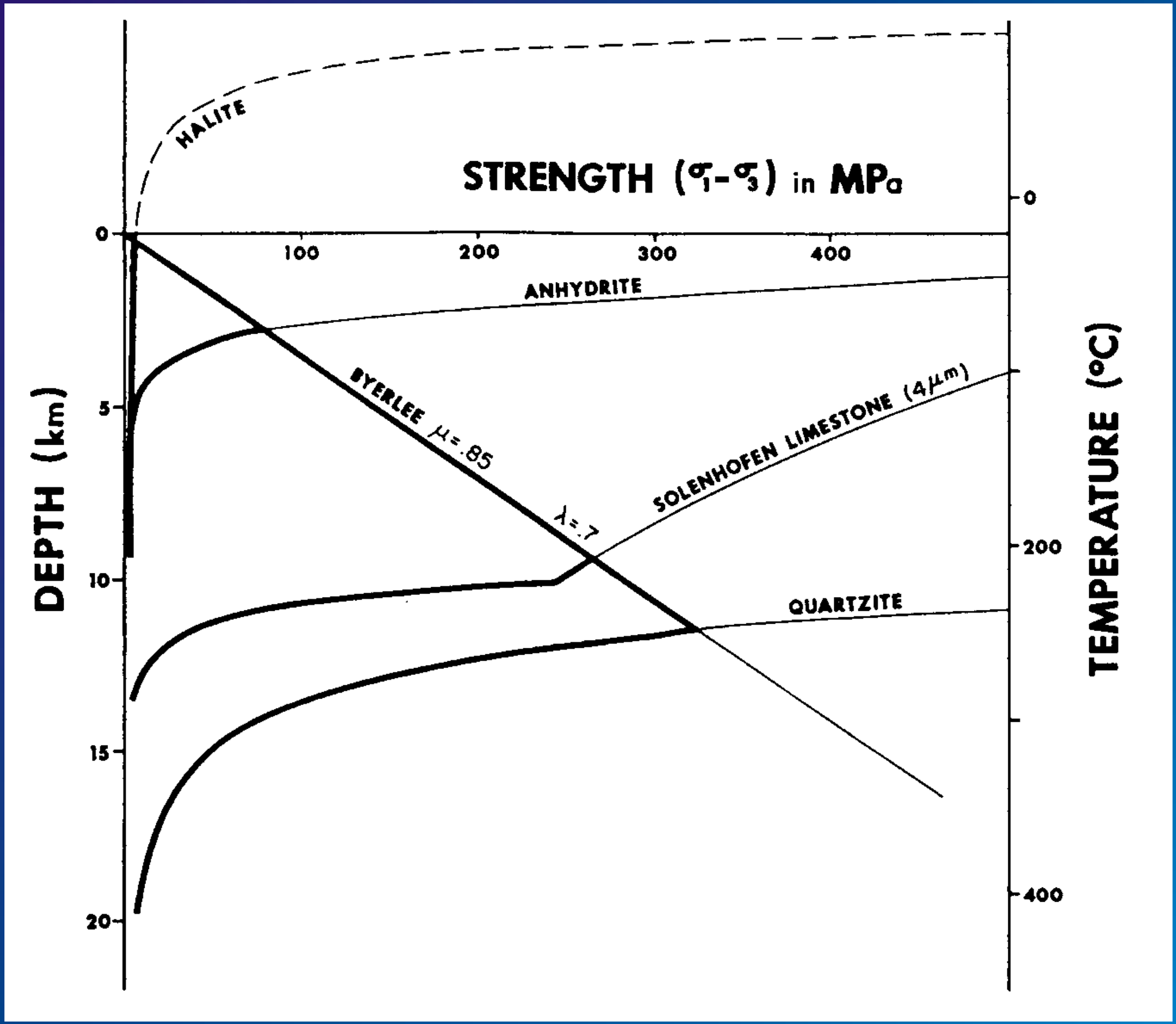


Influence of layer thickness and viscosity contrast on the wavelength of buckle folds. A, B. There is a linear relationship between log layer thickness and log buckle wavelength for widely separated layers of constant viscosity in a ductile matrix of much lower viscosity. C. Buckle folds of different wavelength may be superimposed if the layers are close enough to interfere. D. Buckle folding produced by a number of layers of different viscosity μ_1–μ_5 and different thickness in a ductile matrix of much lower viscosity μ_6. A, C and D are examples of disharmonic folding (see section 3.6). (After Ramberg, H. (1964) *Tectonophysics*, **1**, 307–41.) E. Buckle folding of an interface between two thick layers of contrasting viscosity. The cusps point towards the material of higher viscosity (cf. mullion structure, see section 4.2 and Figure 4.8B).

« buckle folds »
Conditions : « pure shear »



Mechanical behaviour of evaporites



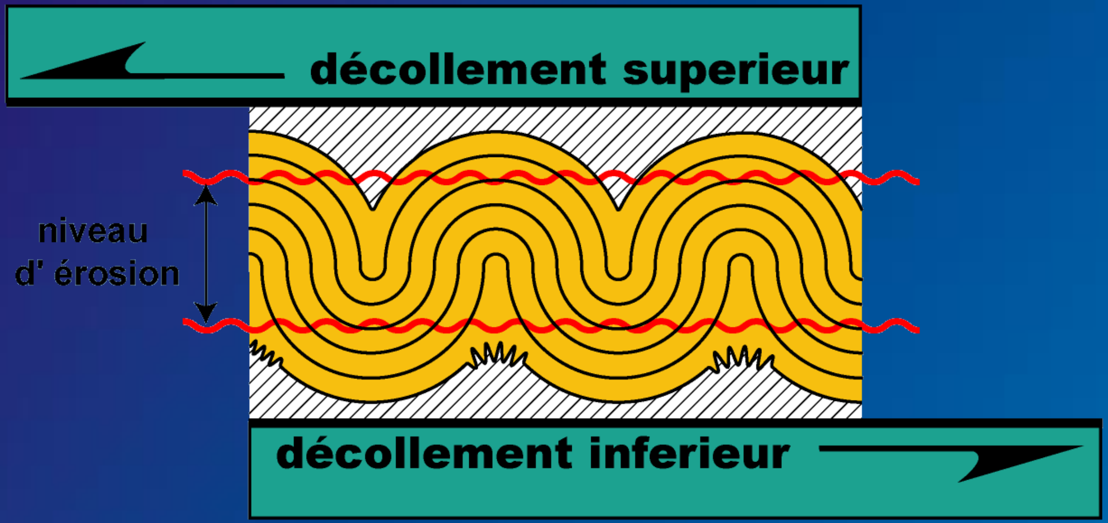
Wavelength Lw for viscous buckling

$$Lw = 2\pi H 6^{-1/3} \sqrt[3]{\eta_l / \eta_m}$$

Initial thickness of competent strata

Viscosity contrast between strata and matrix

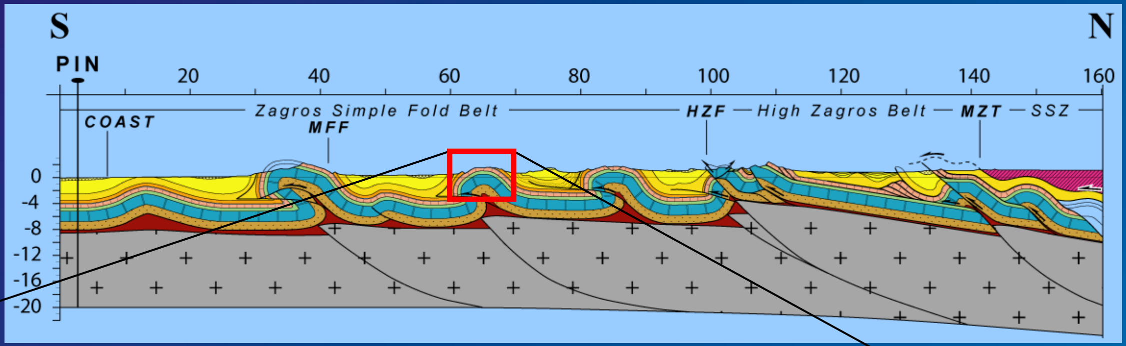
Outcrop scale



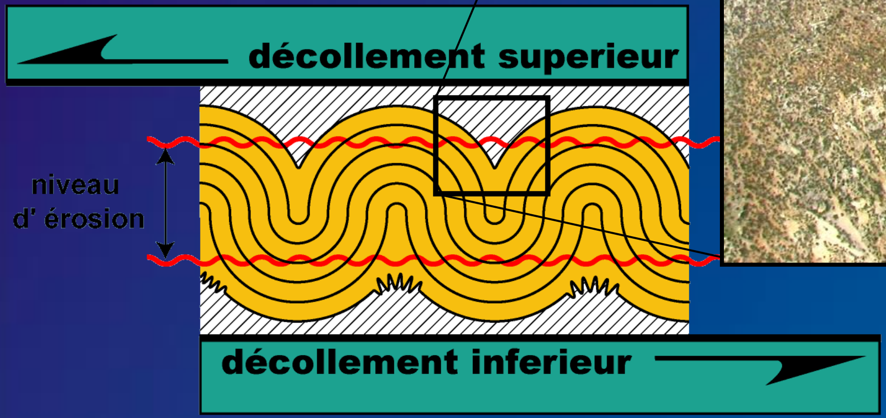
Dahlstrom (1969)

Concentric folding requires 2 décollement levels

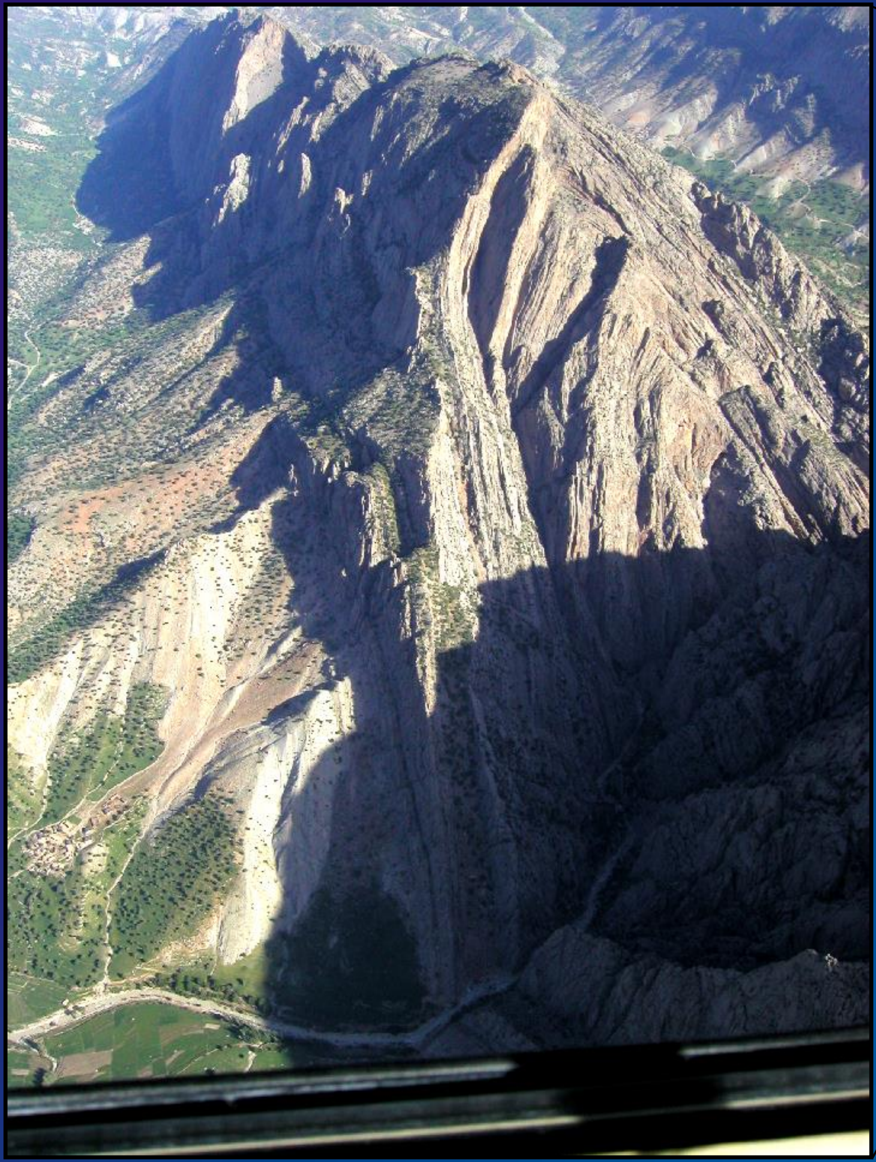
Décollement fold with typical geometry (eastern Zagros) (Molinaro, 2004)

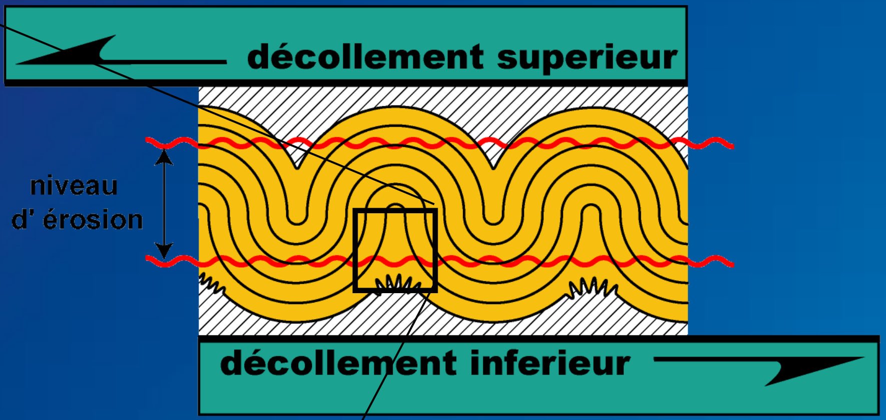


Syncline located just below the upper décollement (Gachsaran evaporites) (Sherkati, 2004)

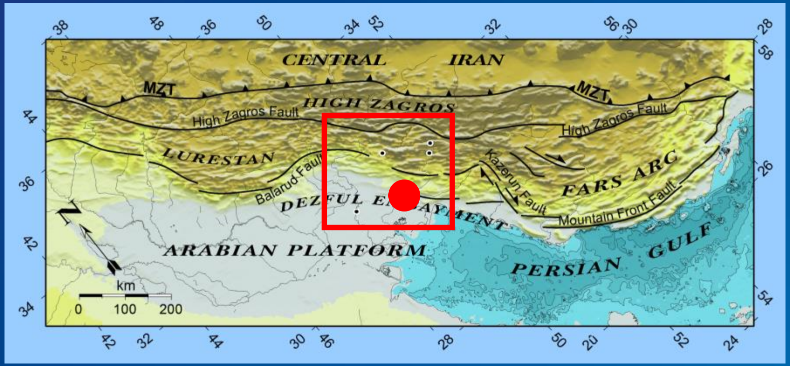


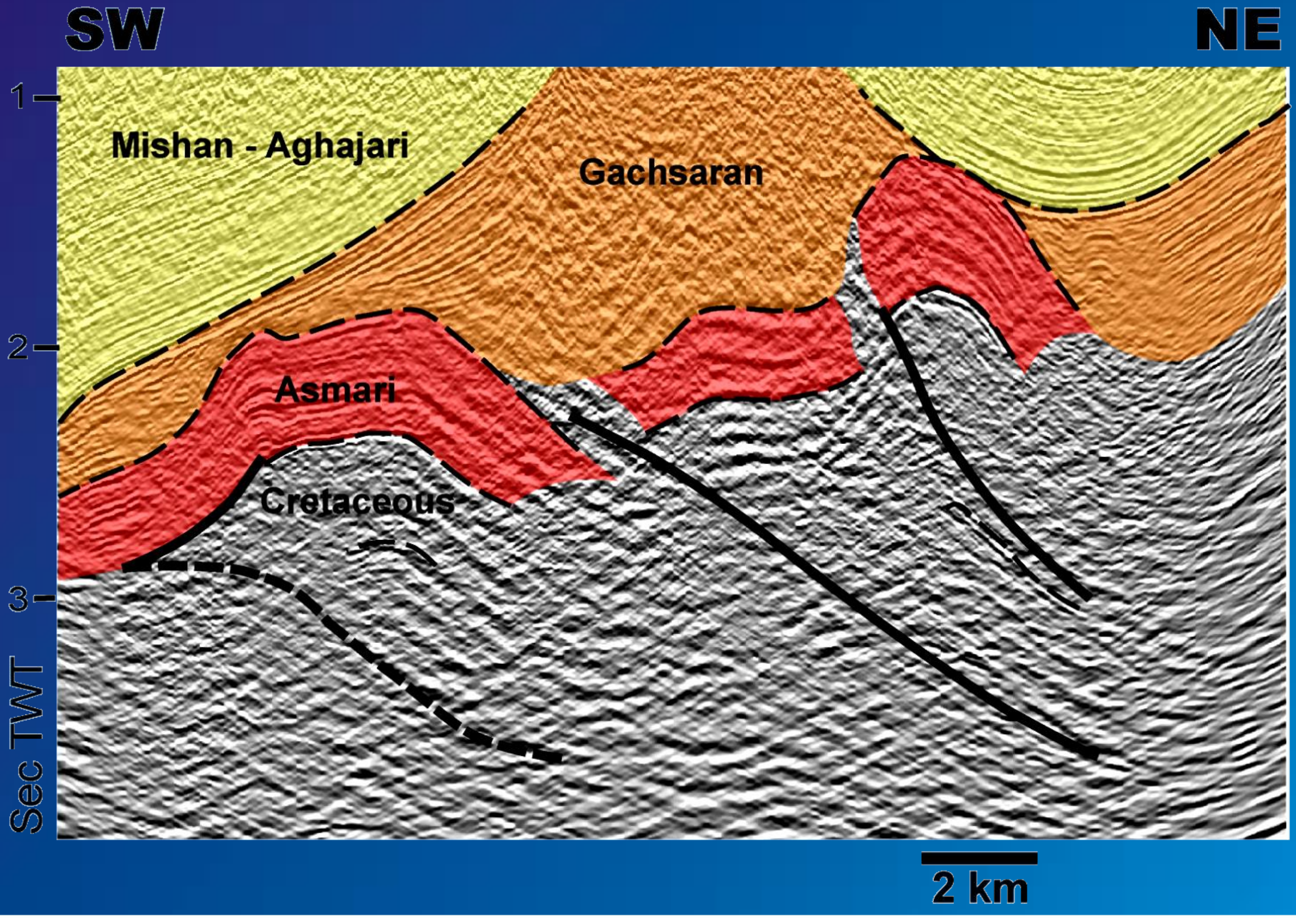
Anticline located just above the lower décollement (Kadjumi Fm) (Sherkati, 2004)

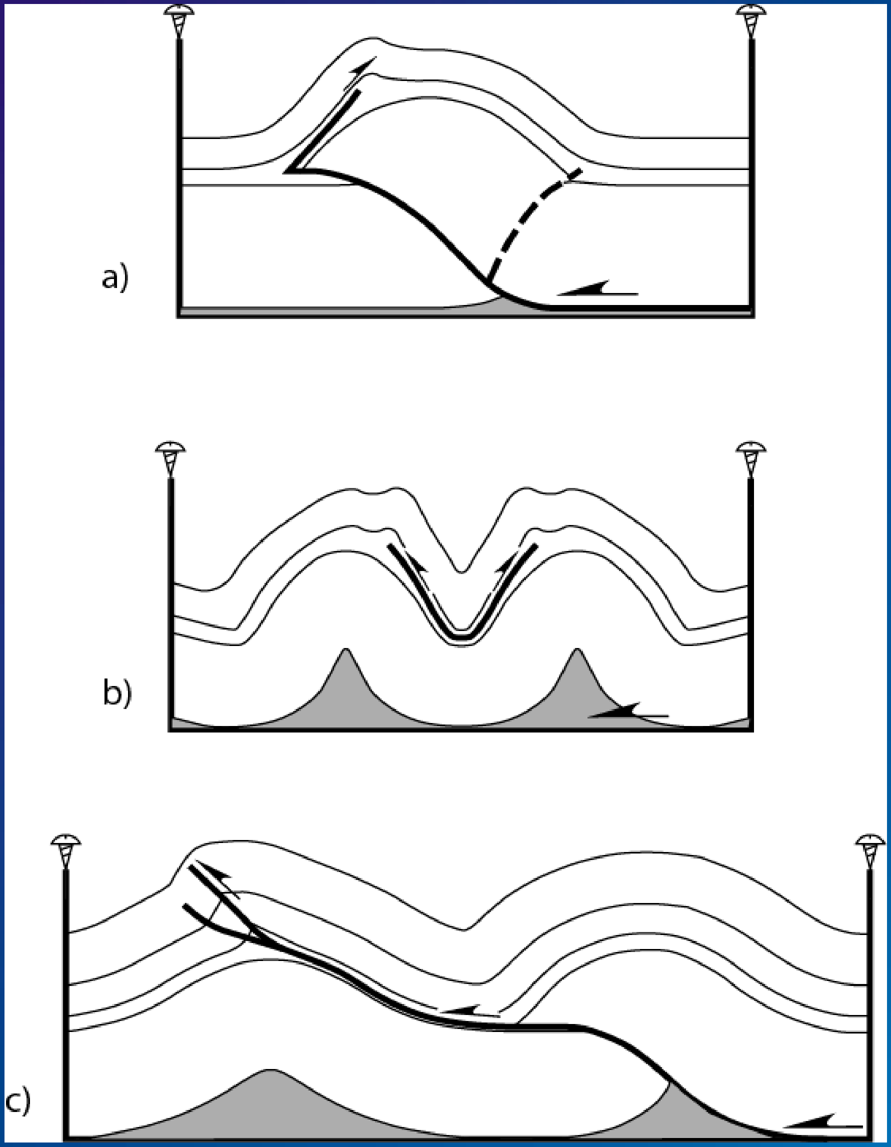




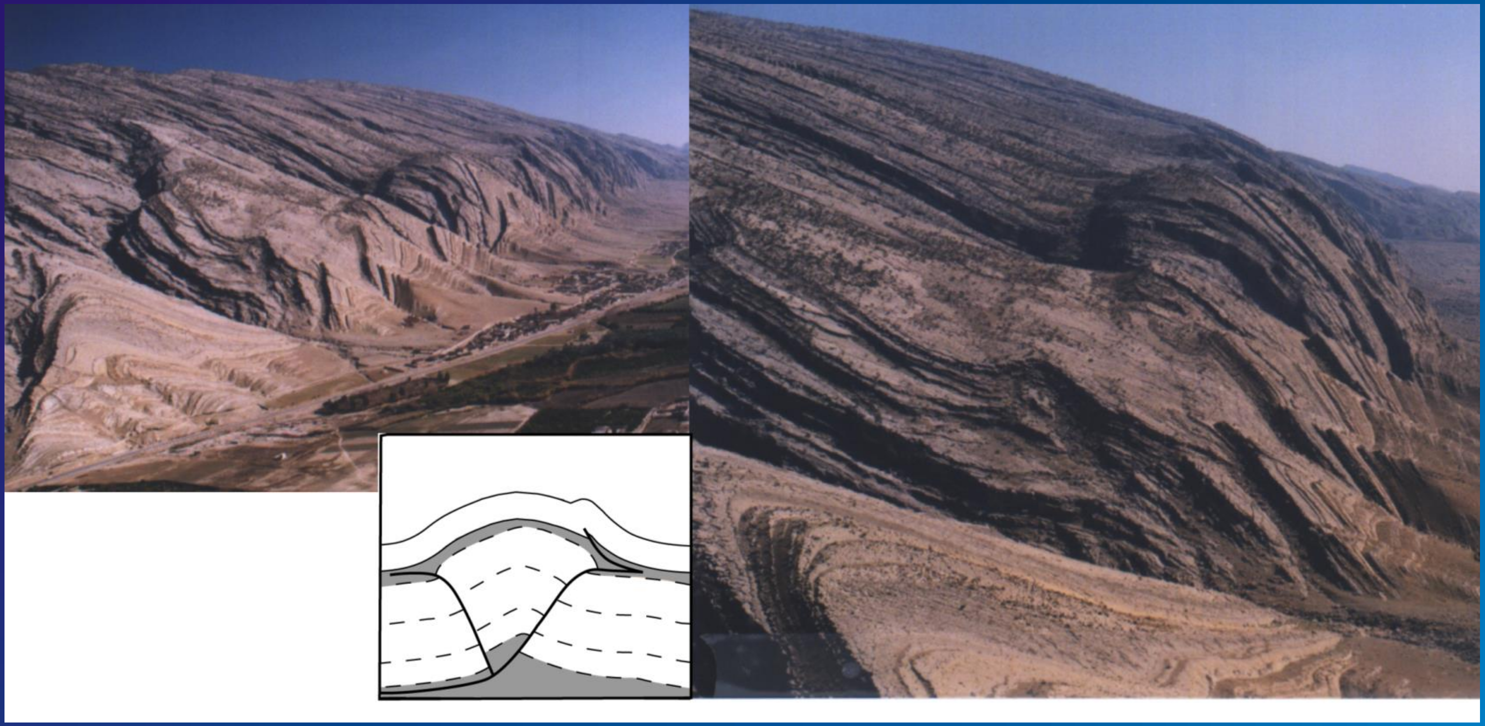
Complete decoupling across upper décollement (Gachsaran salt) (Sherkati, 2004)







Role of intermediate décollement levels
a) et b): « rabbit-ear » folds
c): transmission of deformation from one fold to the other



Example of « rabbit-ear » fold (central Zagros)

Courtesy of D. Frizon de Lamotte

Fars

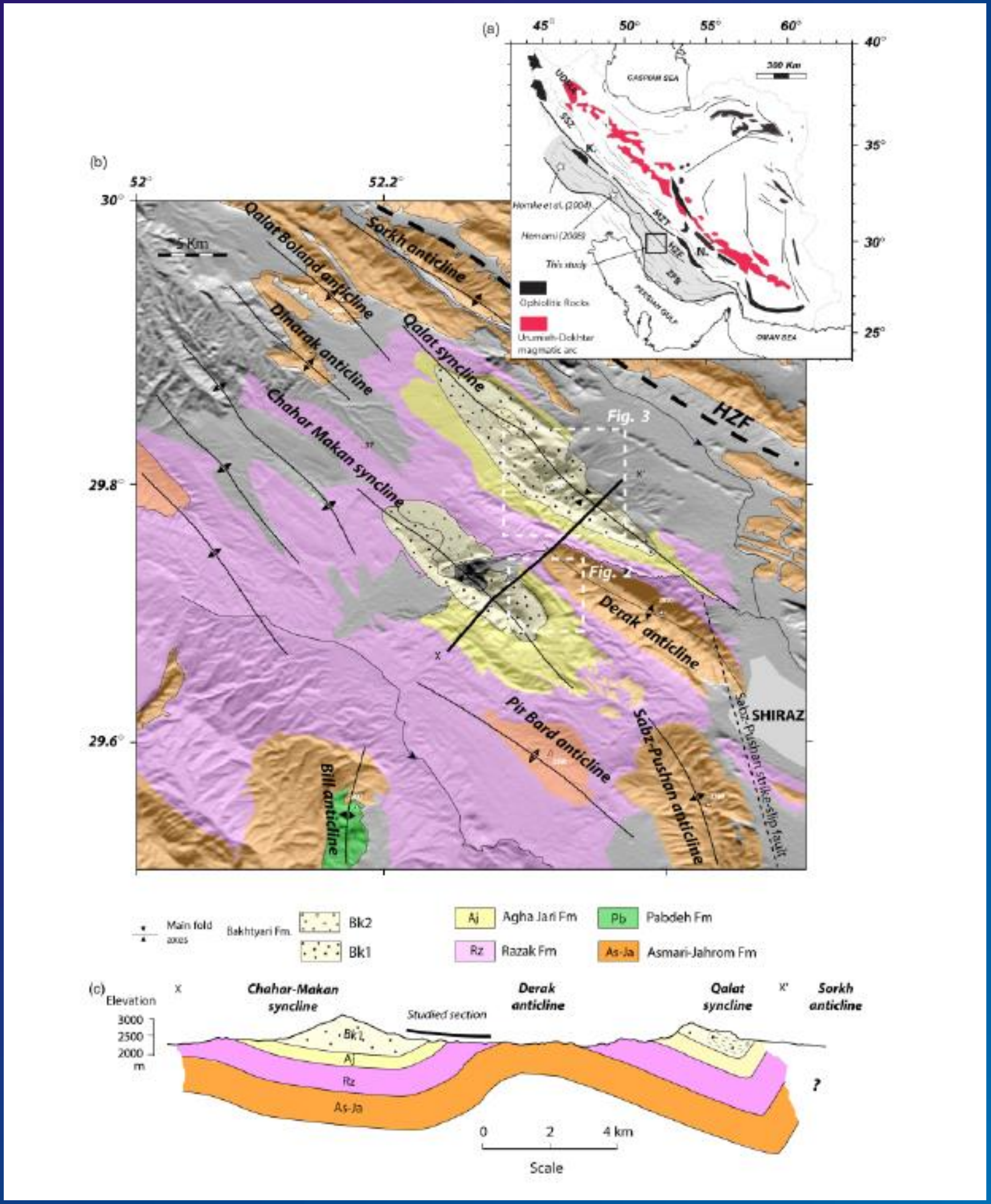
Upper Miocene : growth strata within upper Agha Jari Fm

Fars

Plio-Pleistocene : Major post-folding unconformity

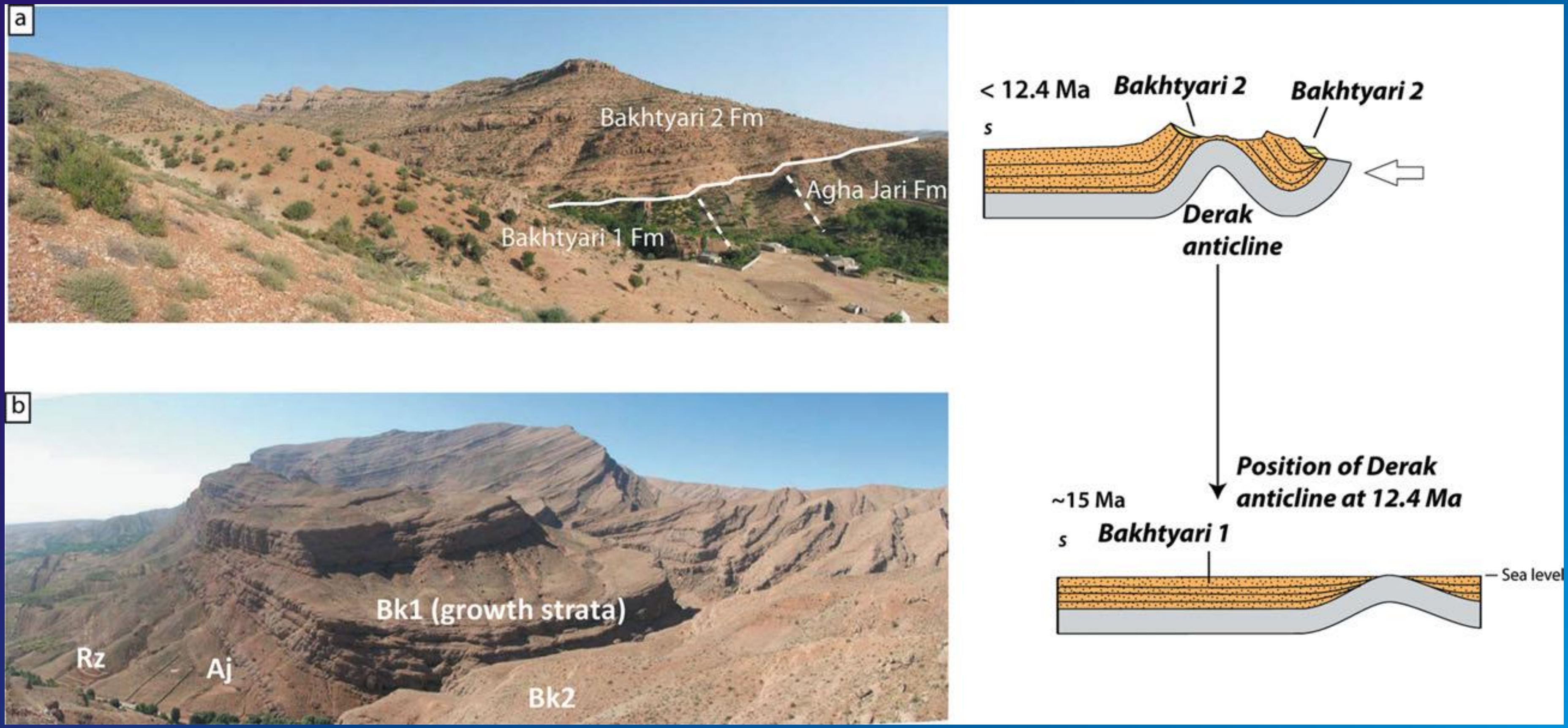
Regional uplift after deposition of Agha Jari Fm.

Fars



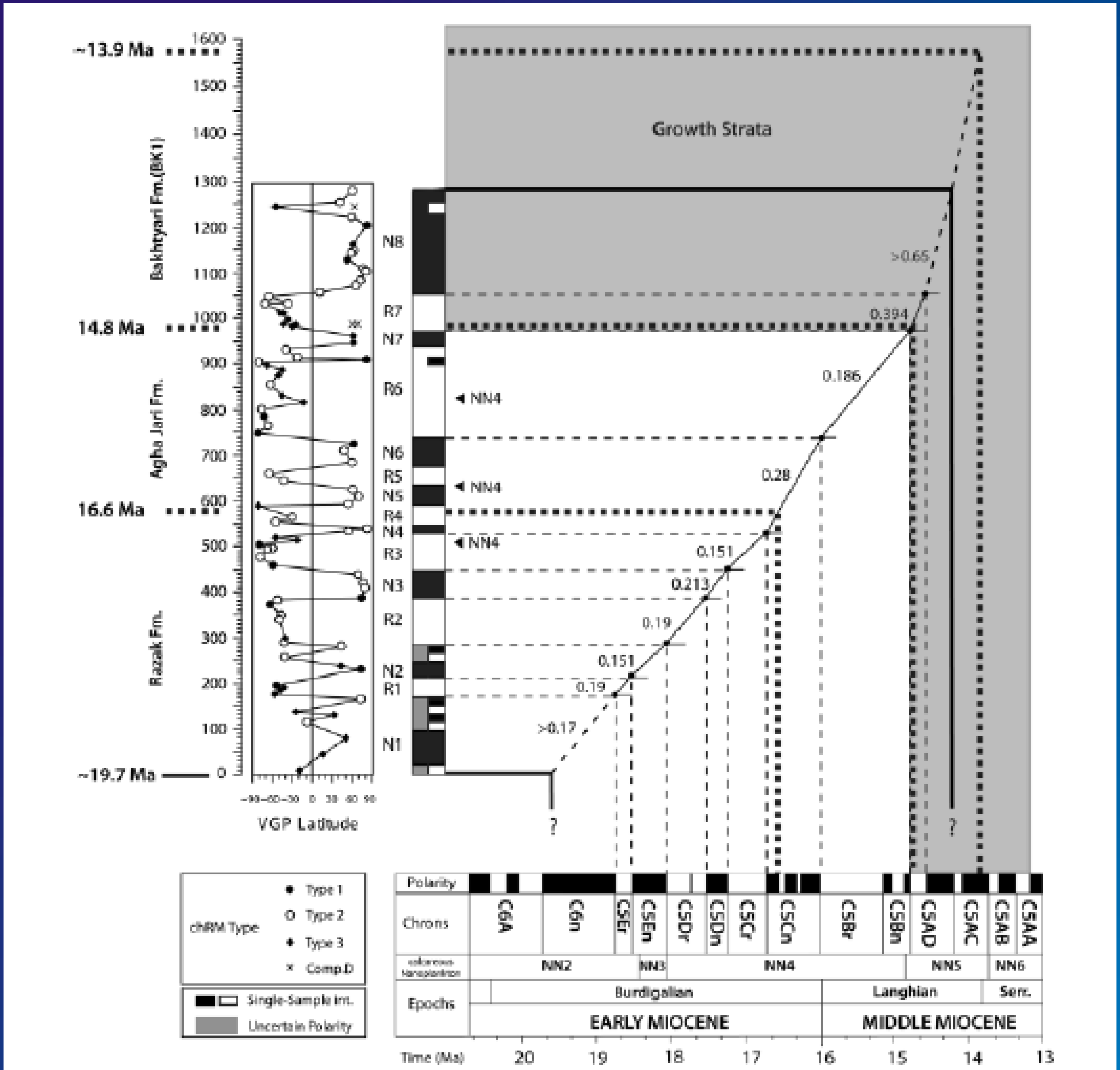
(Khadivi et al., 2010)

Fars

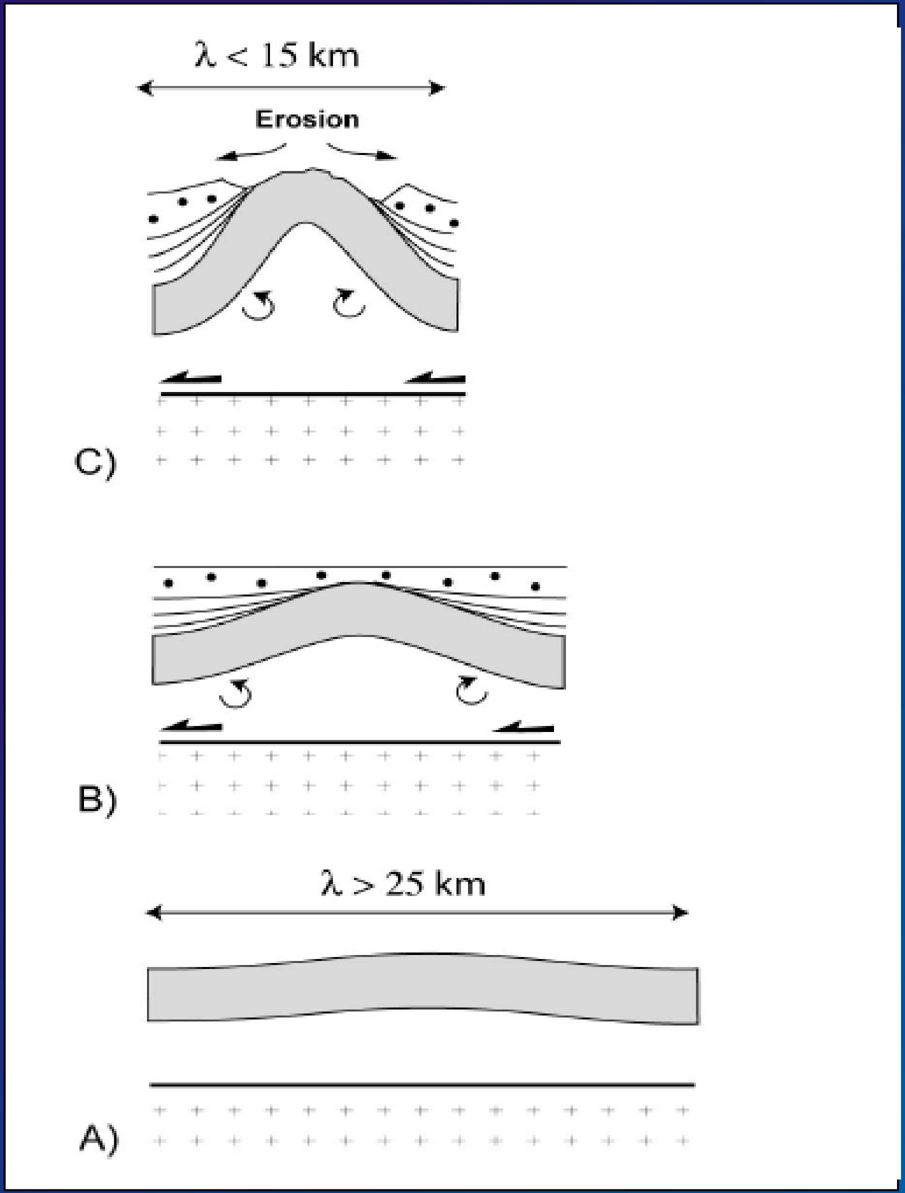


(Khadivi et al., 2010)

Fars



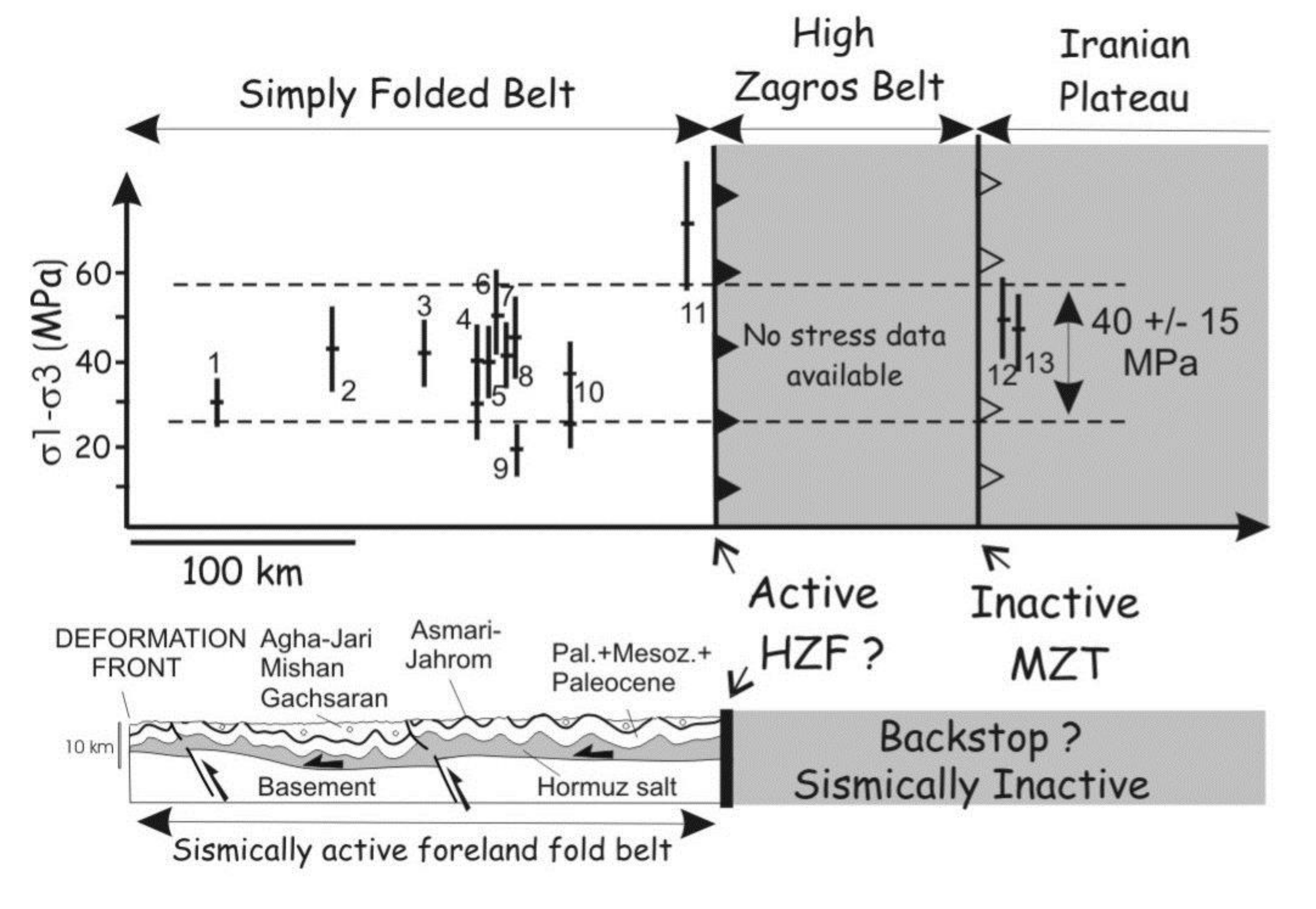
(Khadivi et al., 2010)



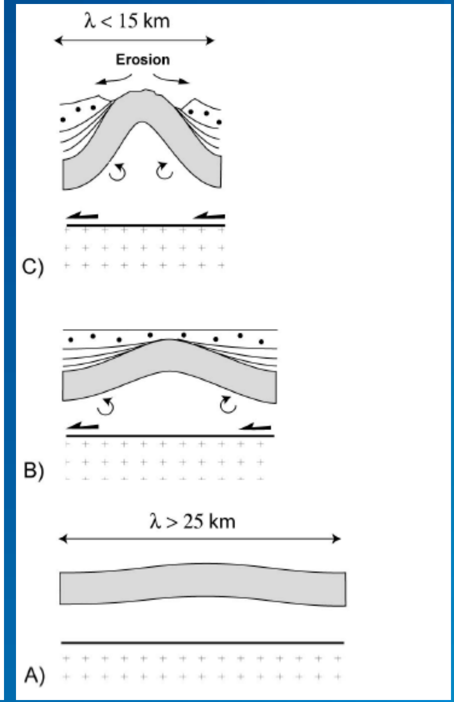
- Overall homogeneous fold wavelength;
- Homogeneously distributed shortening across the Simply Folded Belt;
- Initial rapid fold growth rate, then decrease relative to foreland subsidence;
- Folding under low differential stresses :

→ Buckling of the competent cover above the Hormuz salt

(Mouthereau et al., 2007)



(Lacombe et al., 2007)



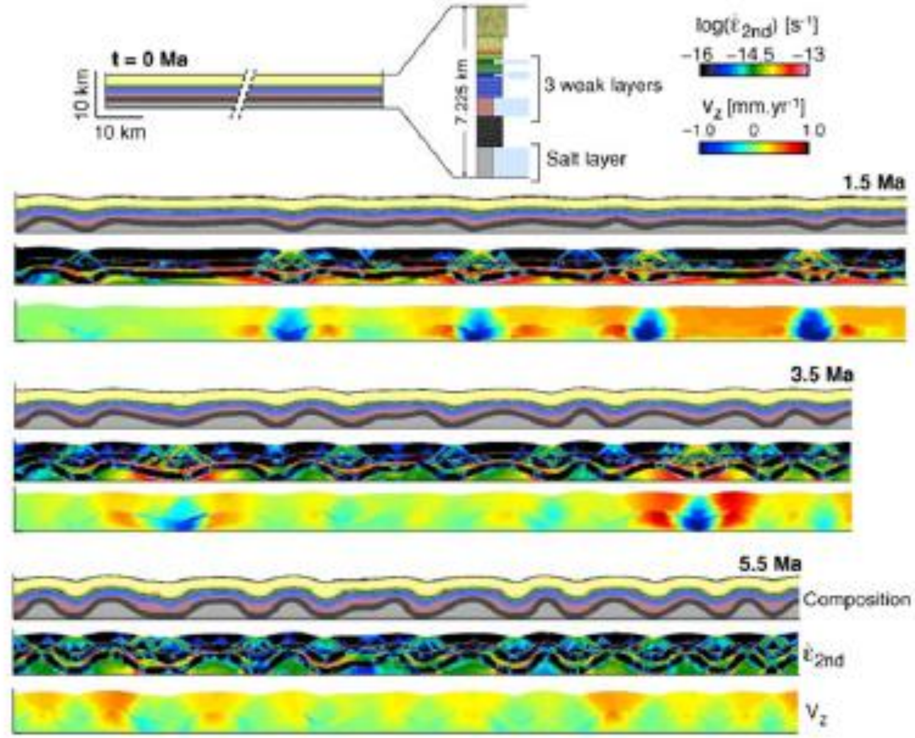
The relative homogeneity of differential stresses agrees with the homogeneously distributed shortening across the SFB, where no deformation gradient toward the backstop is observed in contrast to classical fold-thrust wedges

Both pre- and post-folding differential stresses are low --> folding likely occurred at low stresses; this favours pure-shear deformation
and buckling of sedimentary rocks rather than brittle tectonic wedging.

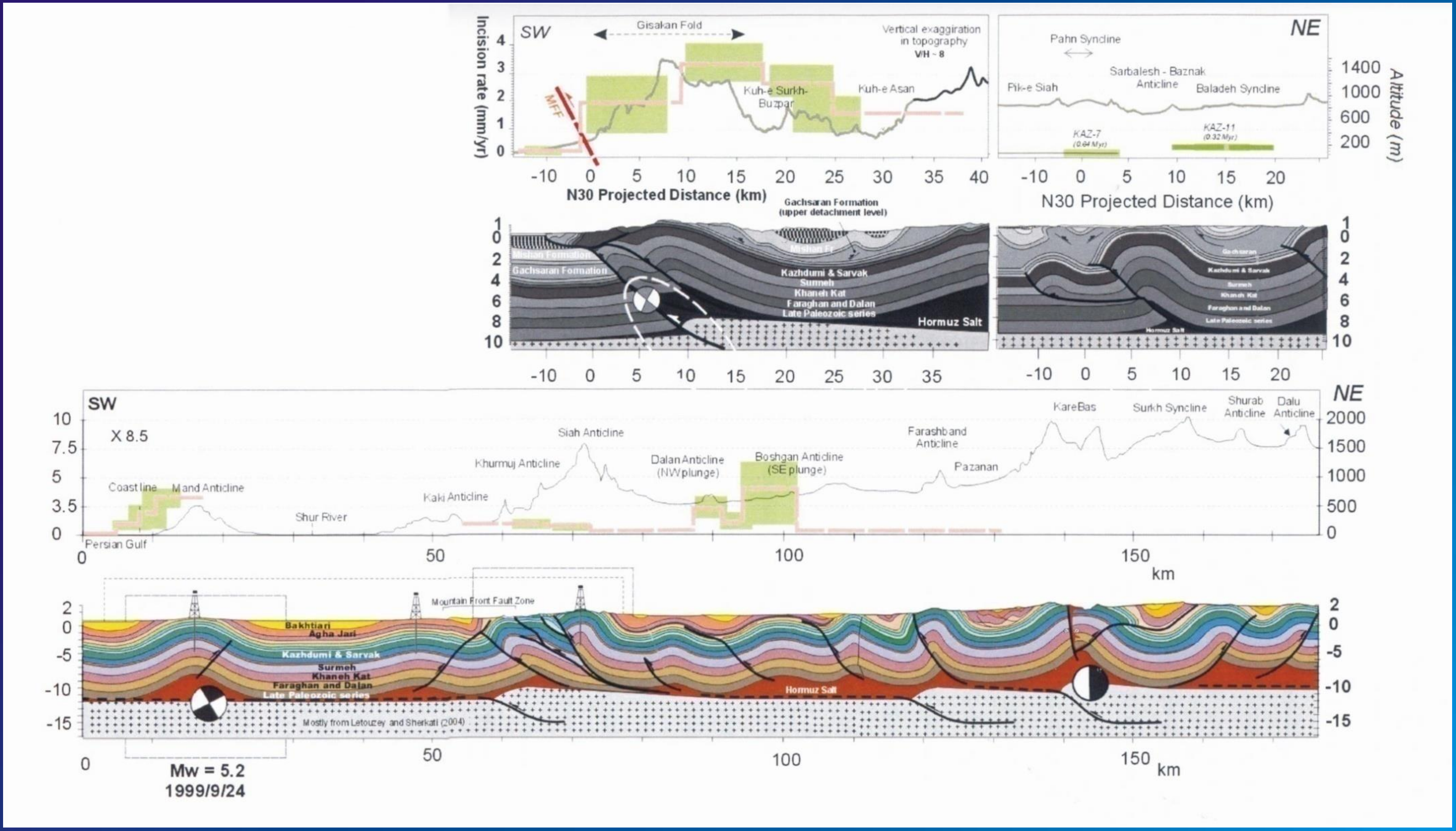
Mechanism of cover folding

Stratigraphy and mechanical layering (Fars region)

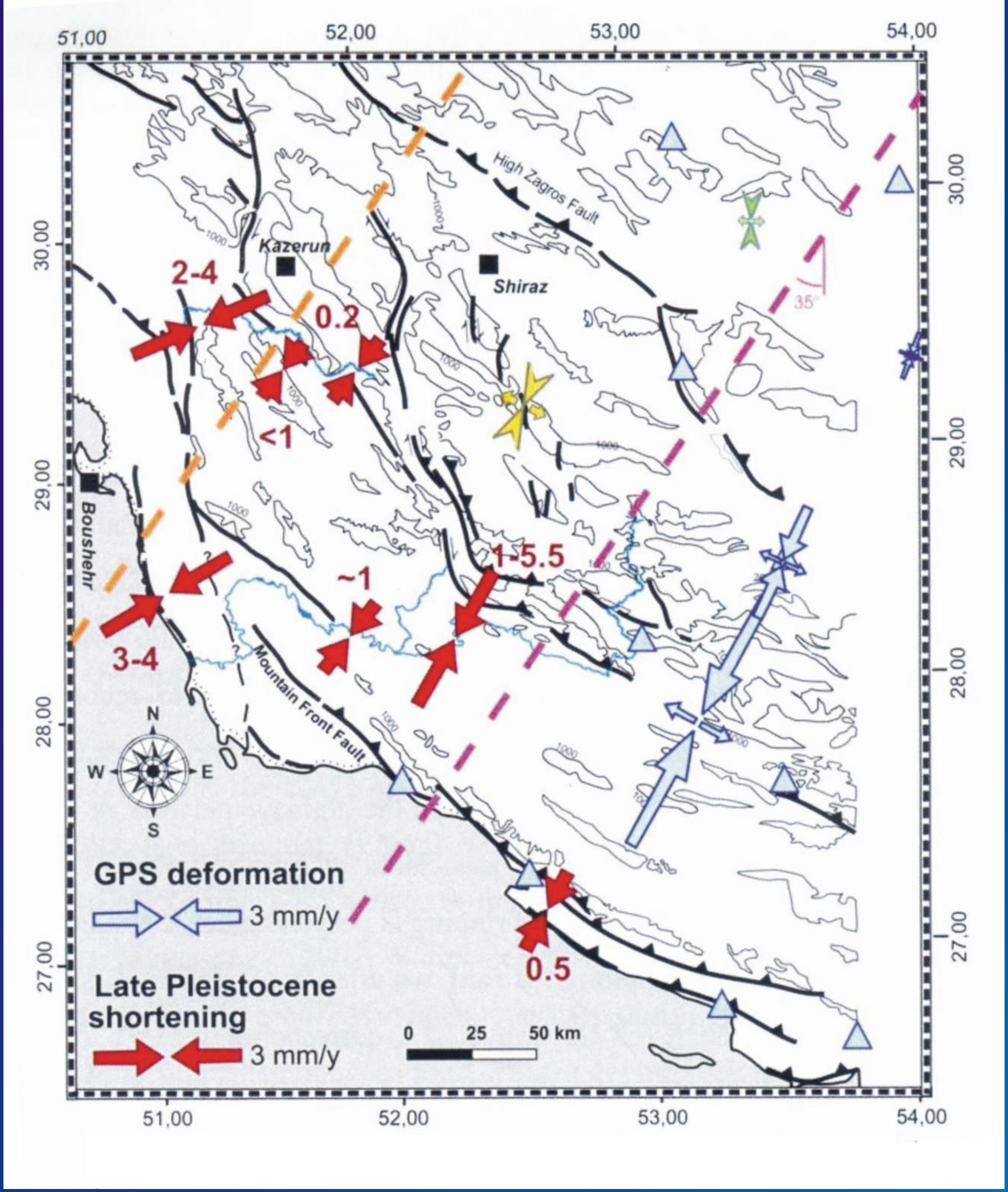
Mechanical modelling of cover folding



(Yamato et al., 2011)



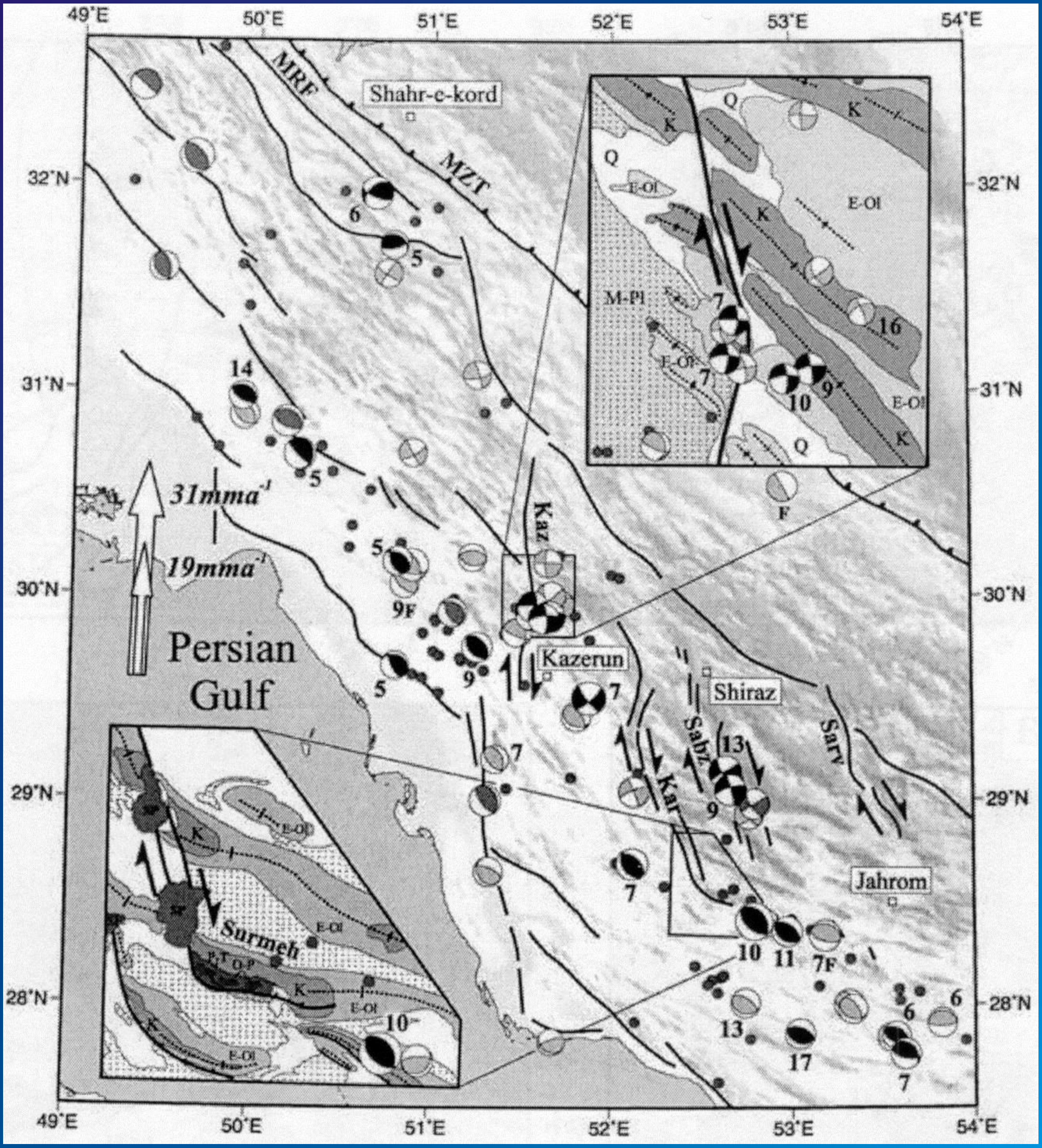
(Oveisi, PhD thesis, 2007)



Outer folds accommodate most of current shortening in the Zagros.
Their growth over the last My can be accounted for either by thin-skinned tectonics, or by the activity of underlying basement faults.
Cover and basement are mostly decoupled : this is in agreement with superimposed thin- and thick-skinned tectonics styles.

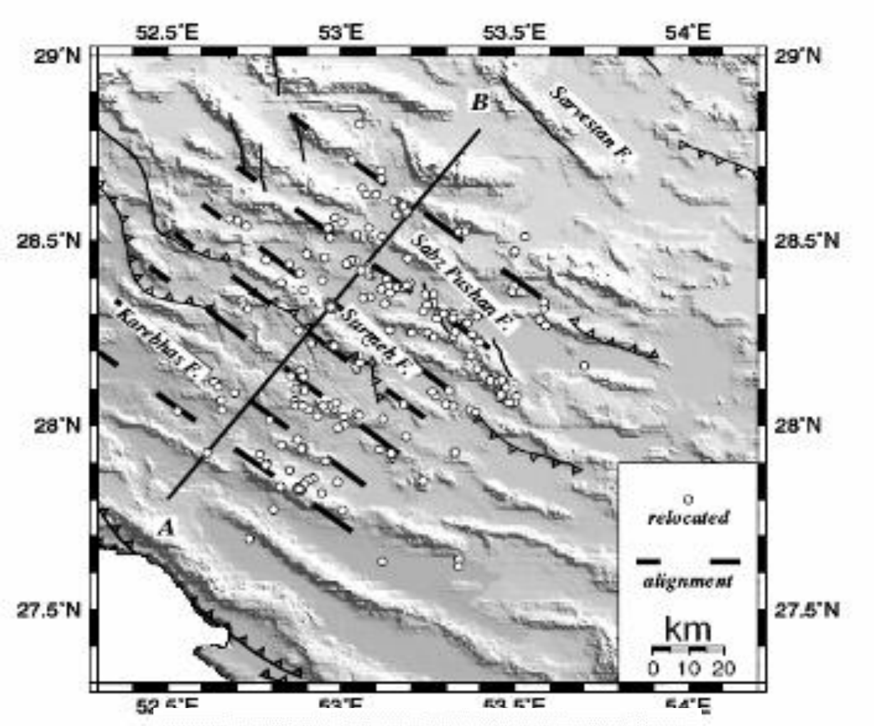
(Oveisi, PhD thesis, 2007)

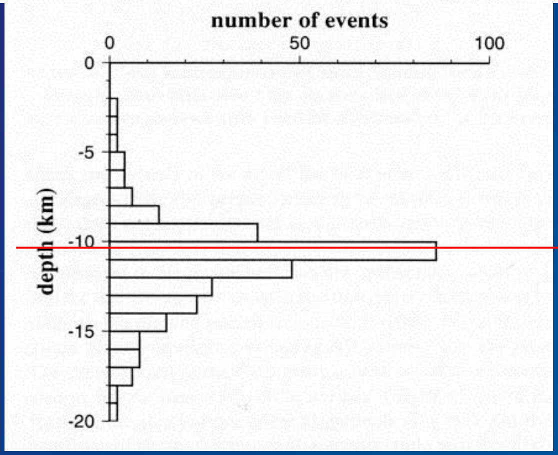
Deformation in the Zagros (2) : earthquakes and seismic faulting

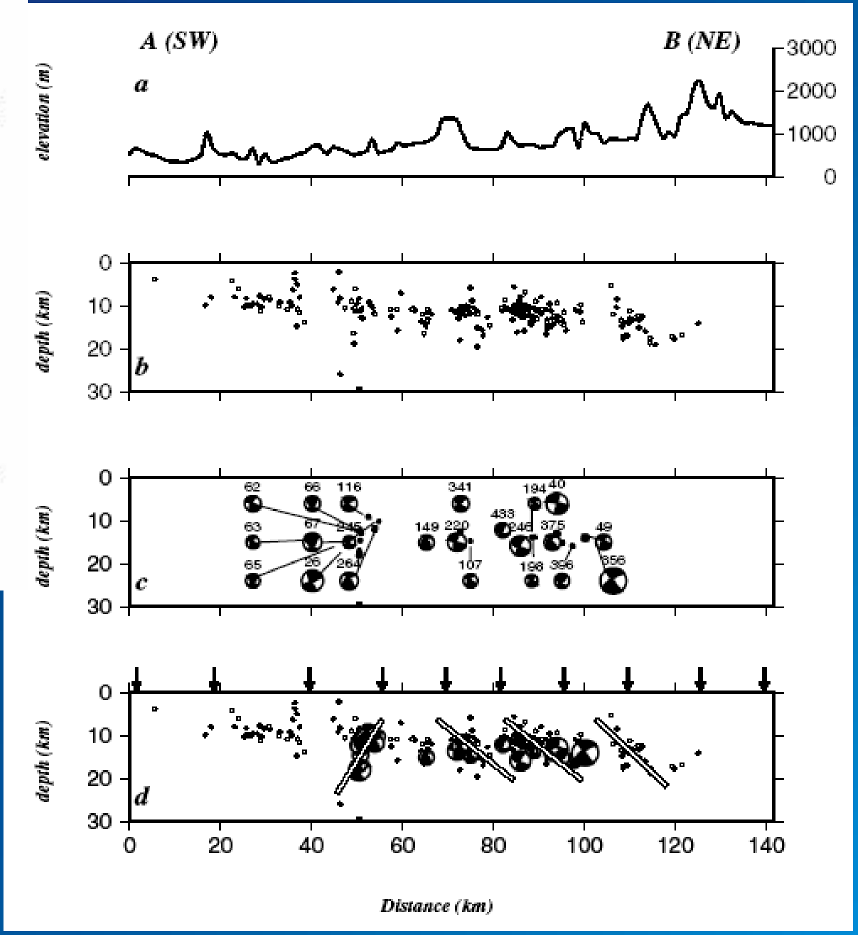


(Talebian and Jackson, 2004)

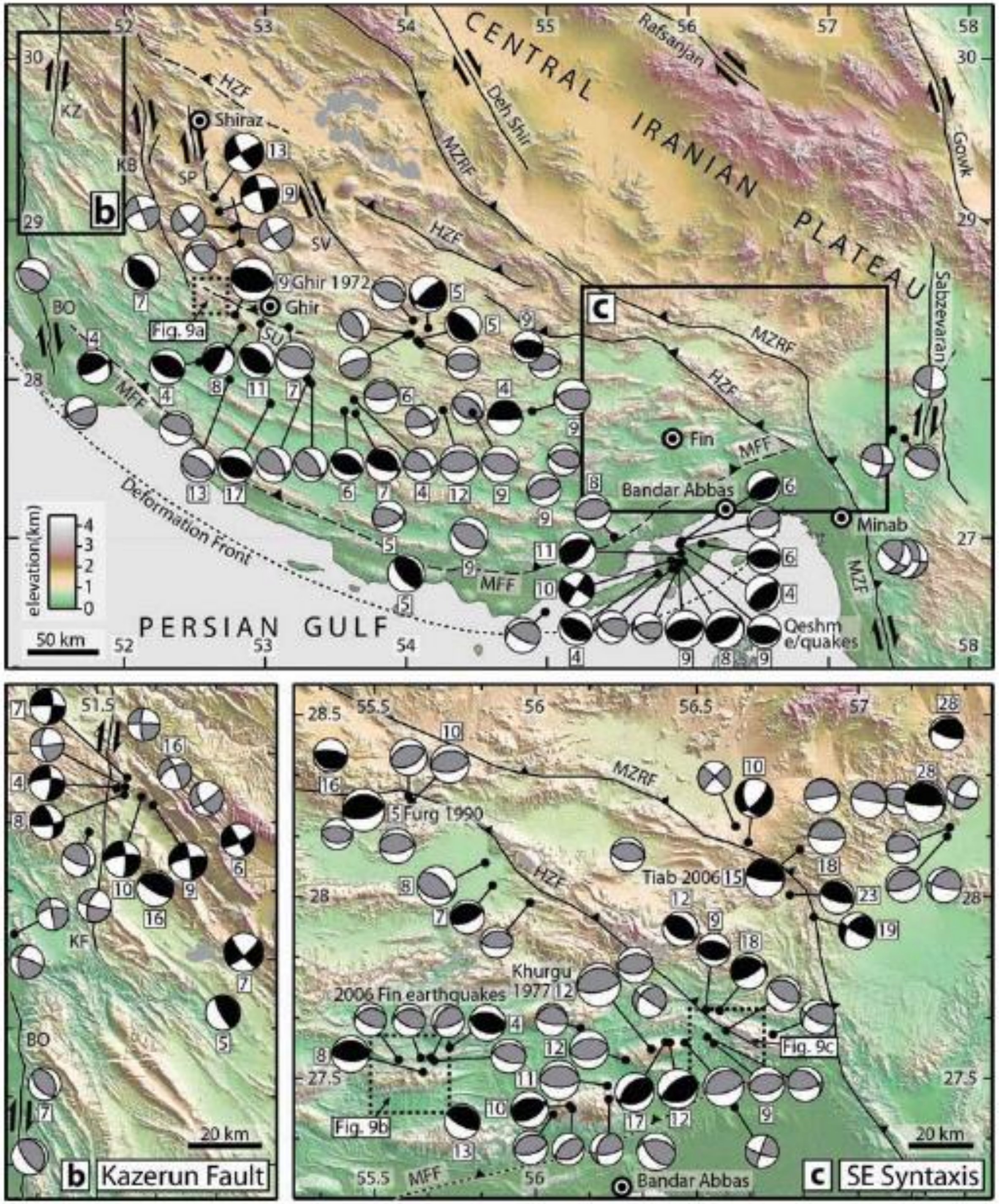
Localization of basement faults using microseismicity



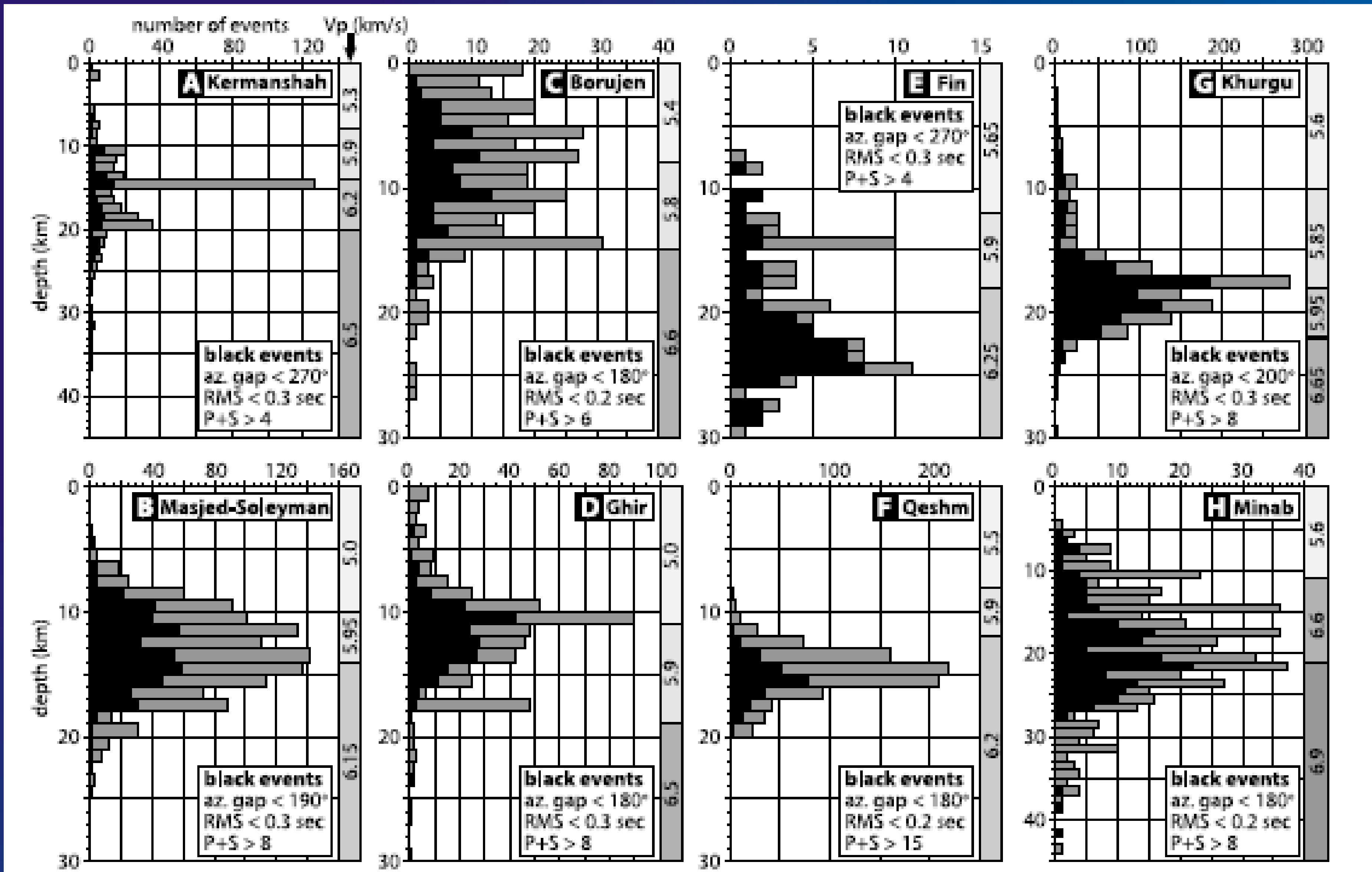




(Tatar et al. 2004).

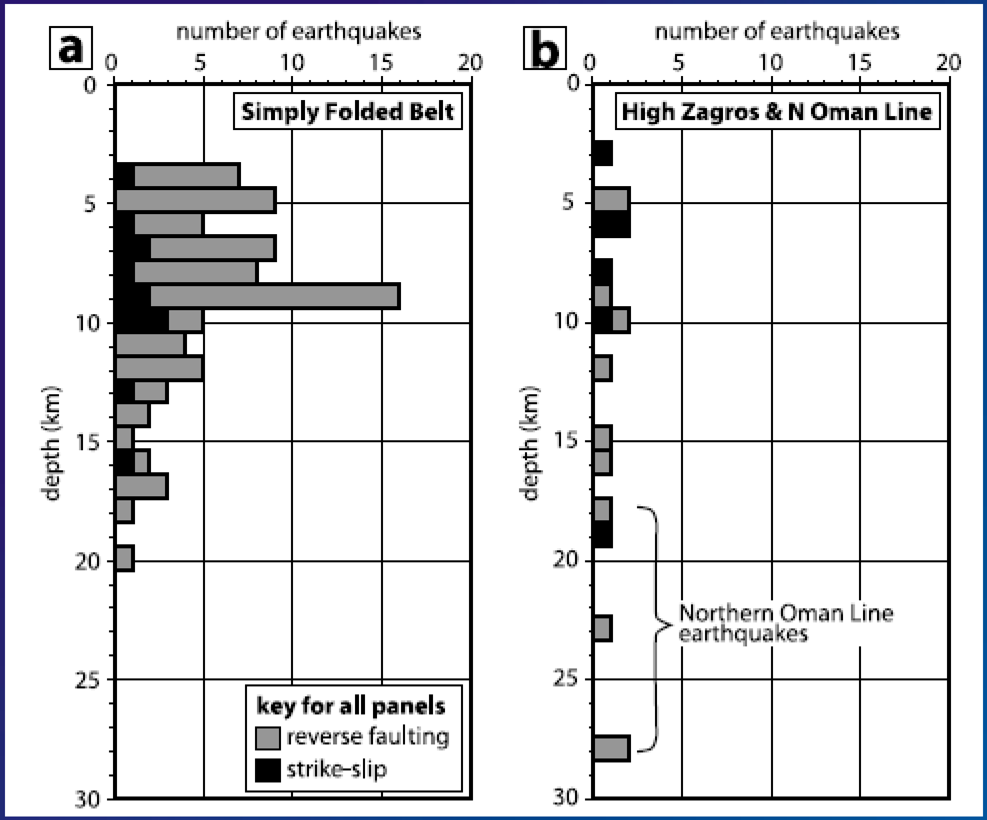


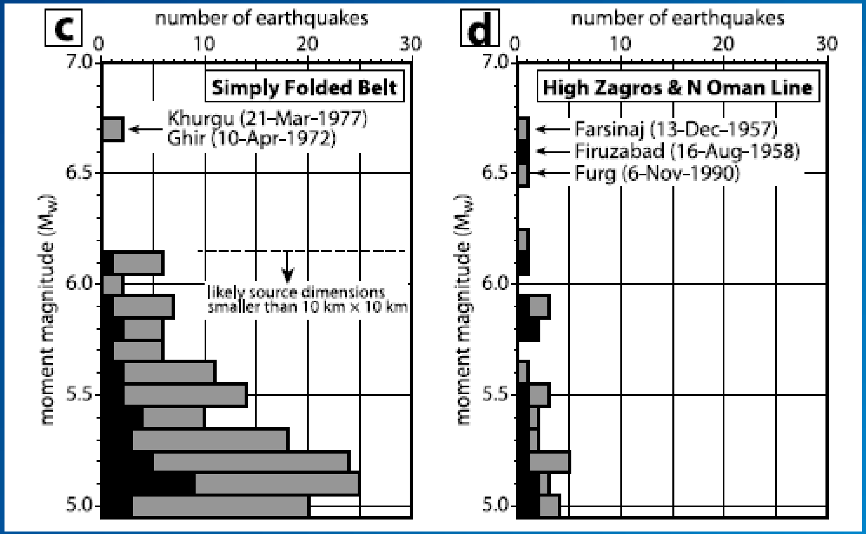
(Nissen et al., 2011)



(Nissen et al., 2011)

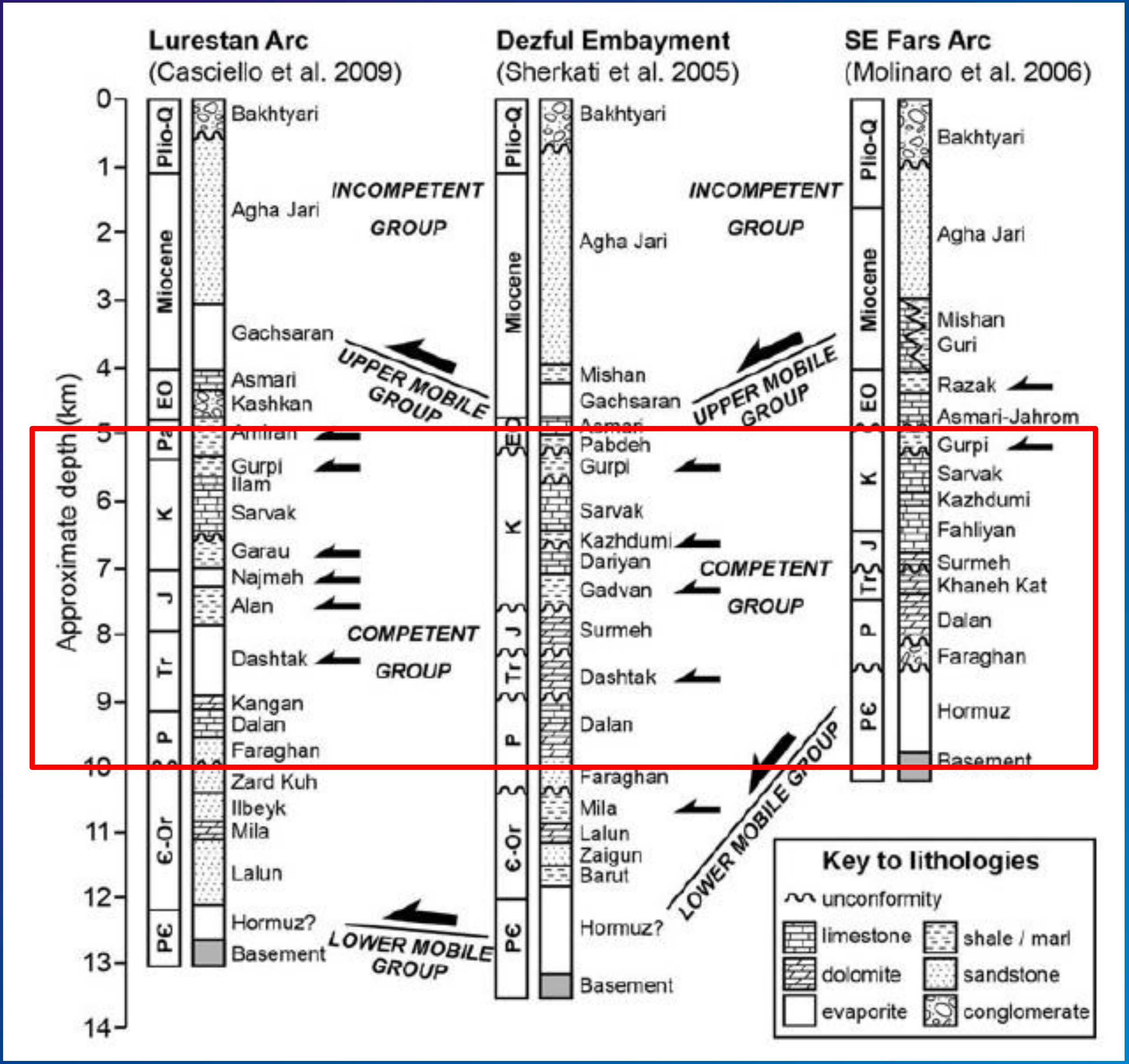
Microseismicity



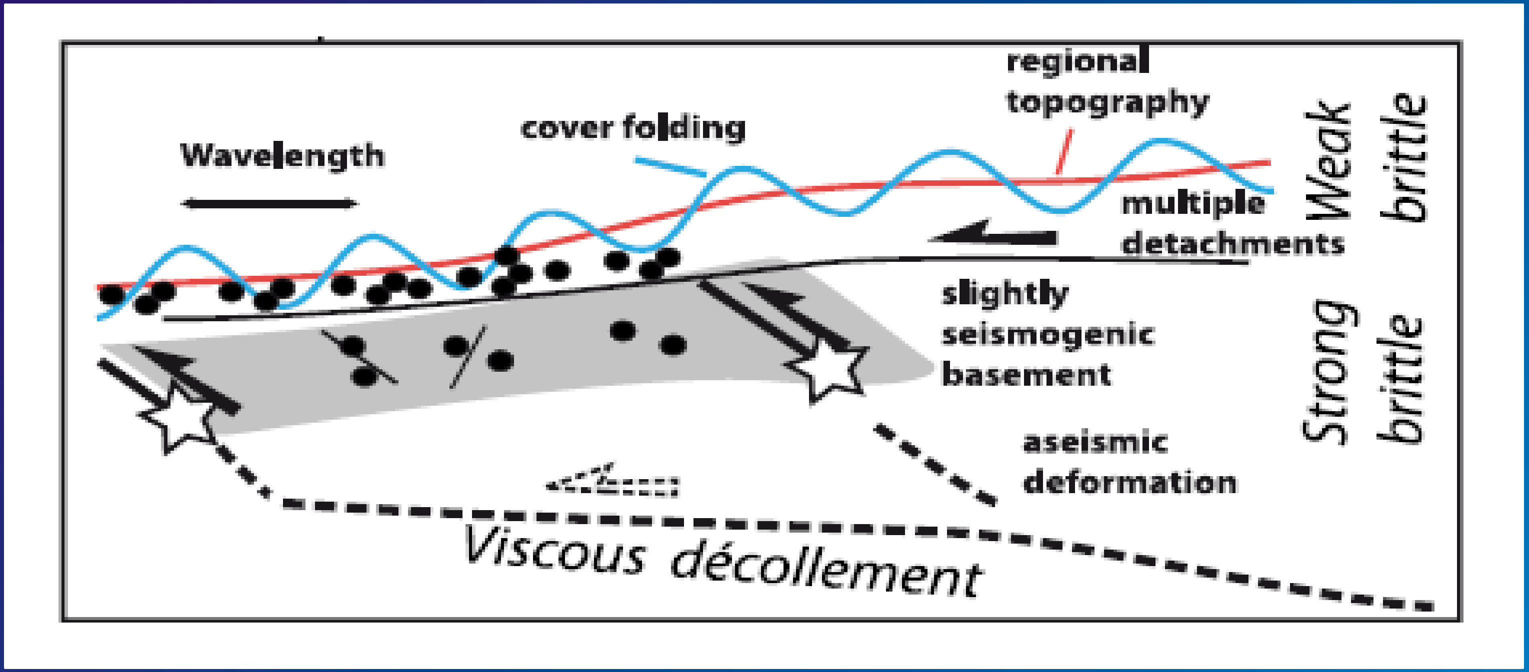


teleseismically recorded earthquakes

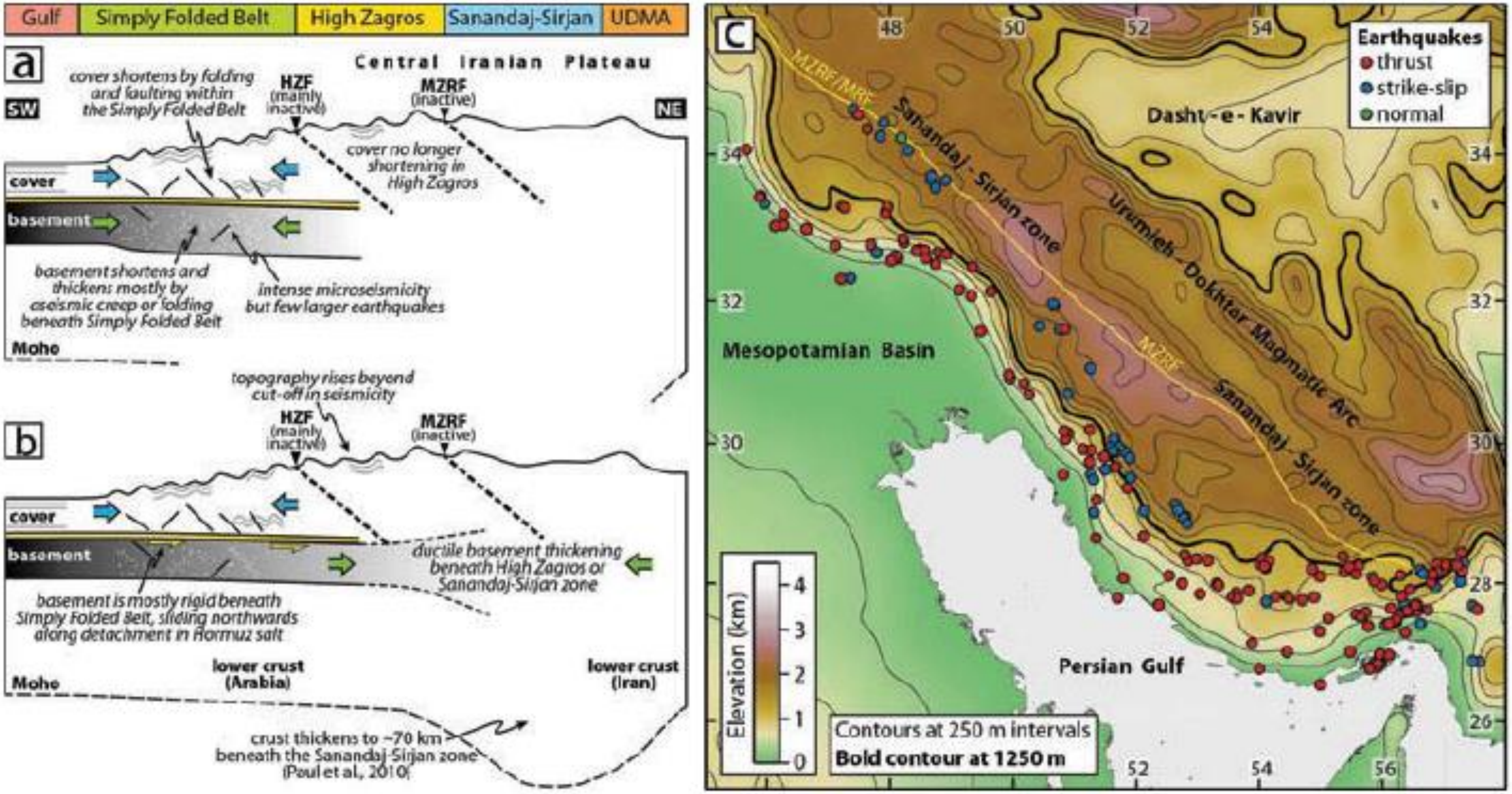
(Nissen et al., 2011)



(Nissen et al., 2011)



(Mouthereau et al., 2012)



(Nissen et al., 2011)

Deformation in the Zagros (3) : meso-scale fracturing

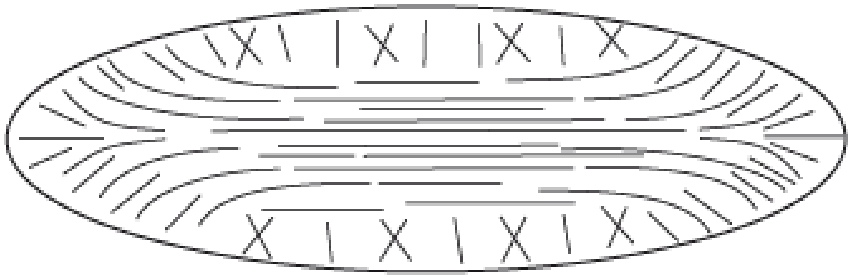
The study of fracture patterns and their possible genetic relationships to cover folding is of key importance in the Zagros.

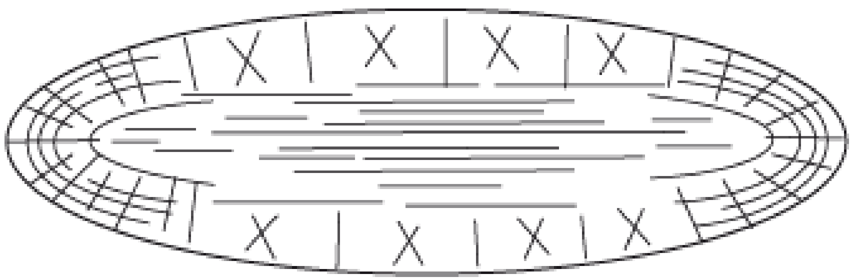
Several giant oil fields are found, especially in the Dezful Embayment

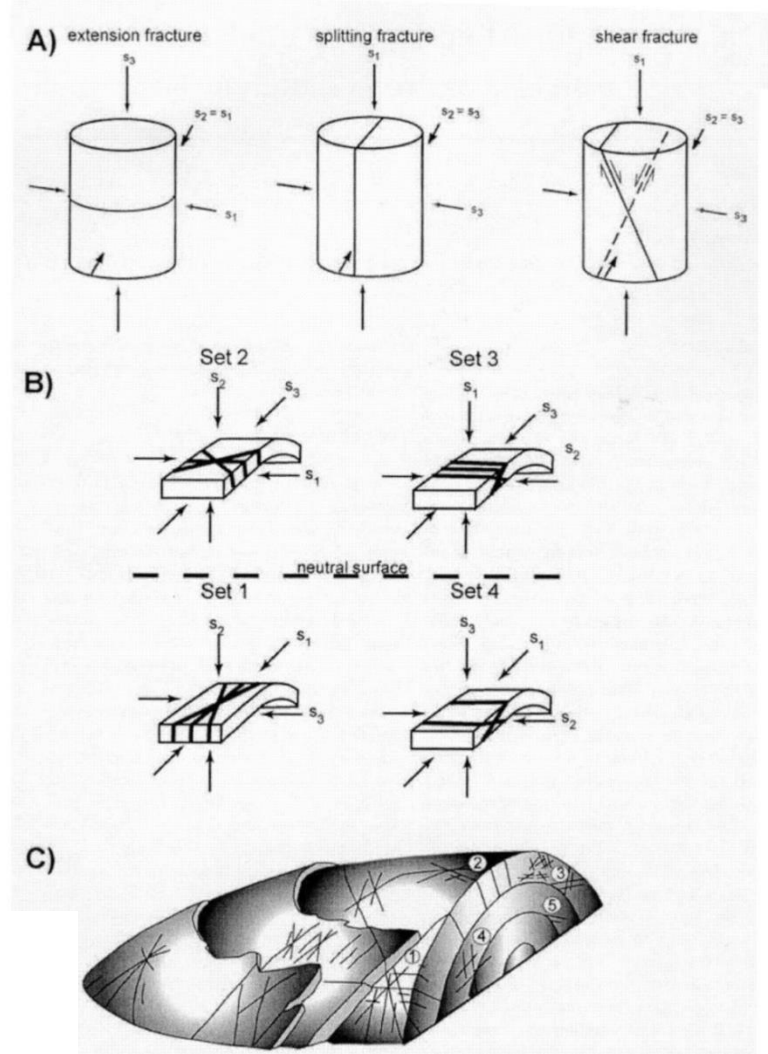
The Asmari Formation is an Oligocene–Early Miocene platform carbonate which is the most prolific oil reservoir in Iran, and it is commonly regarded as a classic fractured carbonate reservoir, with production properties that depend strongly on the existence of fracture networks

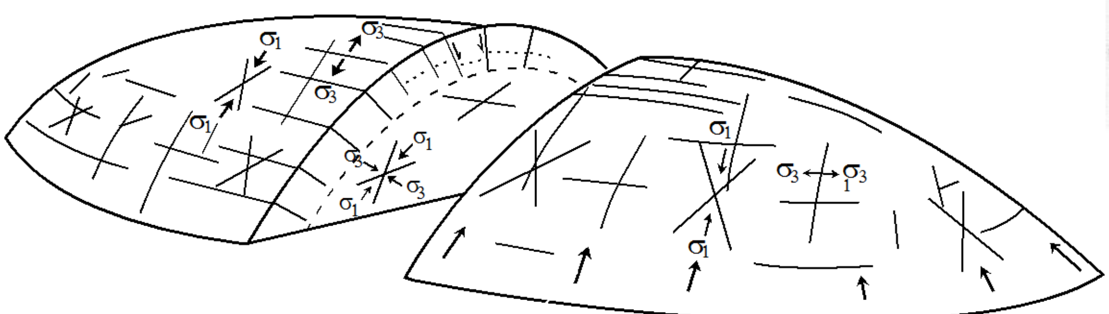
Fold geometry and kinematics have for a long time been recognized as the most important factors that control fracturing. Stearn & Friedman (1972) proposed a pioneering classification of fold-related fractures, including an axial extensional set running parallel to the fold axis, a cross-axial extensional set oriented perpendicular to the fold axis and two sets of conjugate shear fractures oblique to the fold axis with their obtuse angle intersecting the trend of the fold axis.

Since then, numerous studies have attempted to relate the development of meso-structures to either the structural domains of the fold or to quantitatively estimated curvature of strata

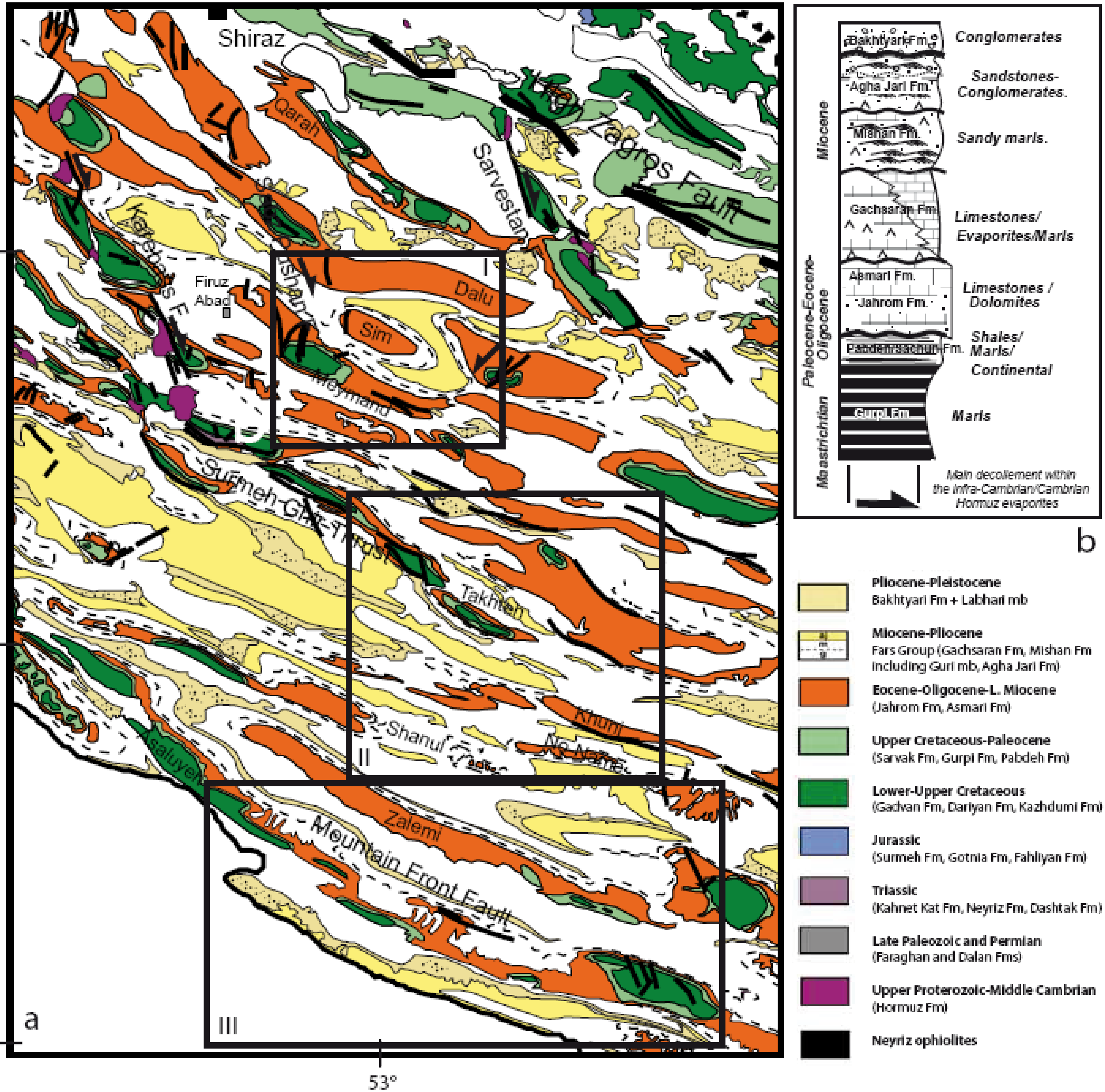




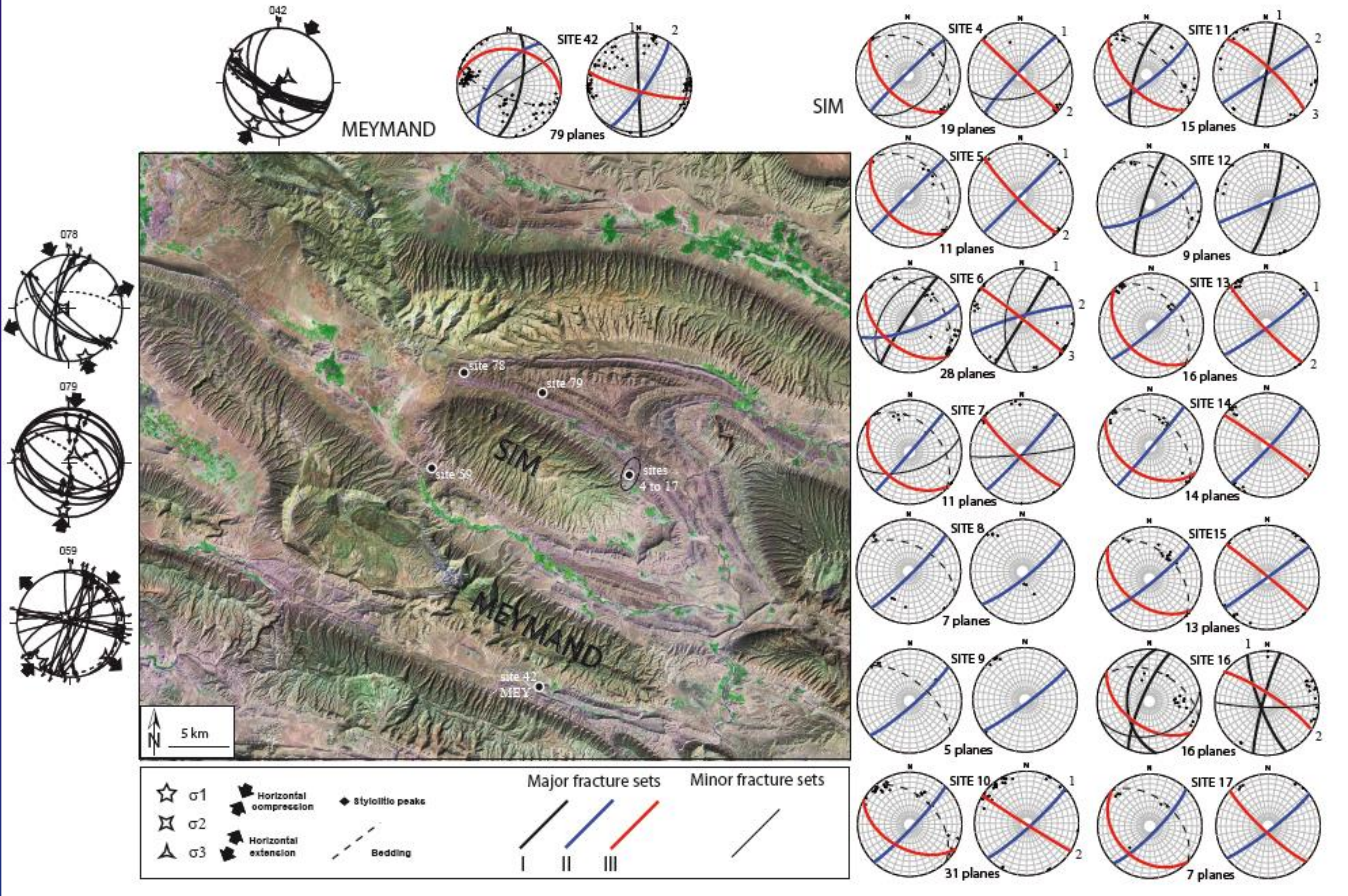




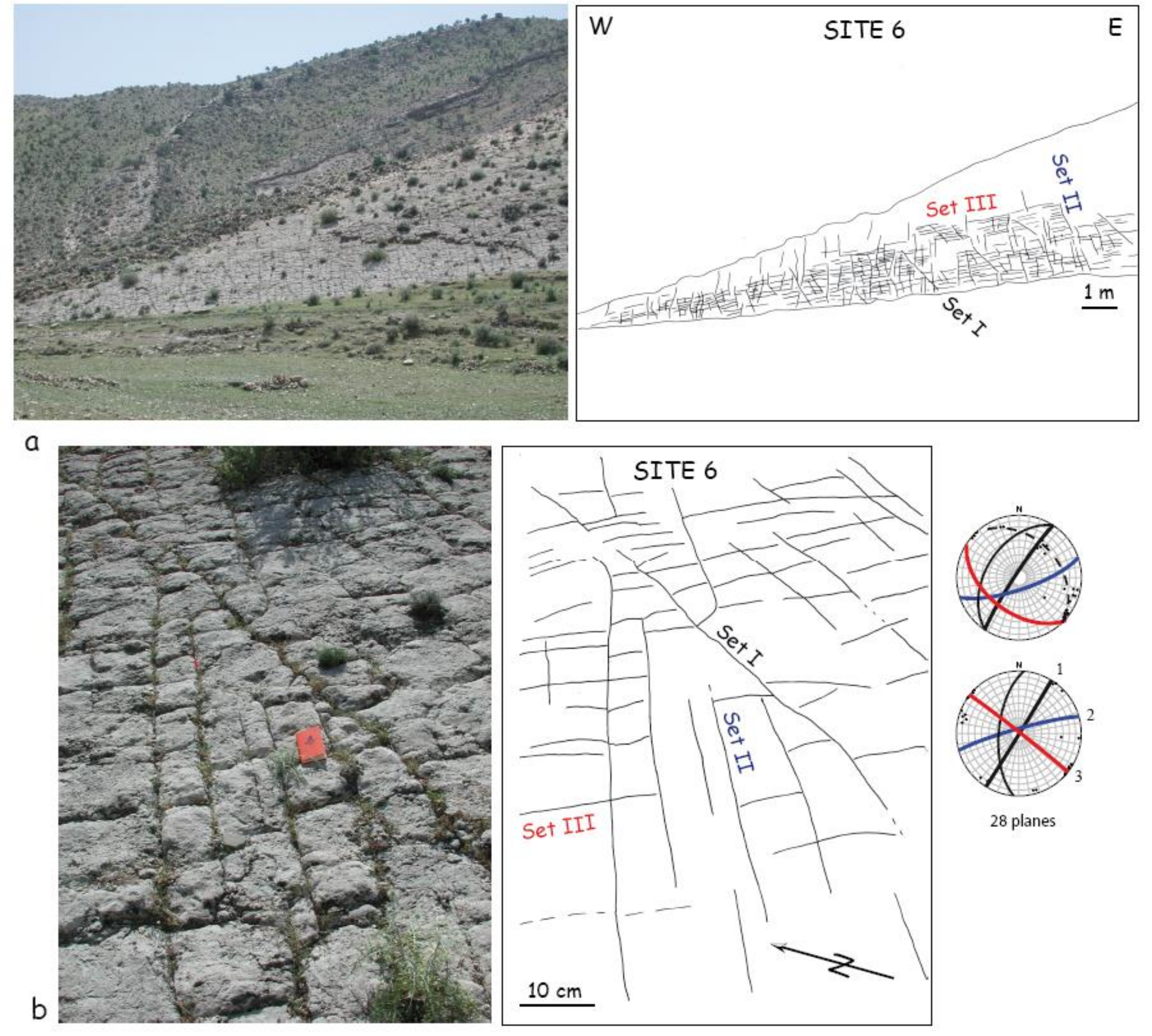
Slip direction



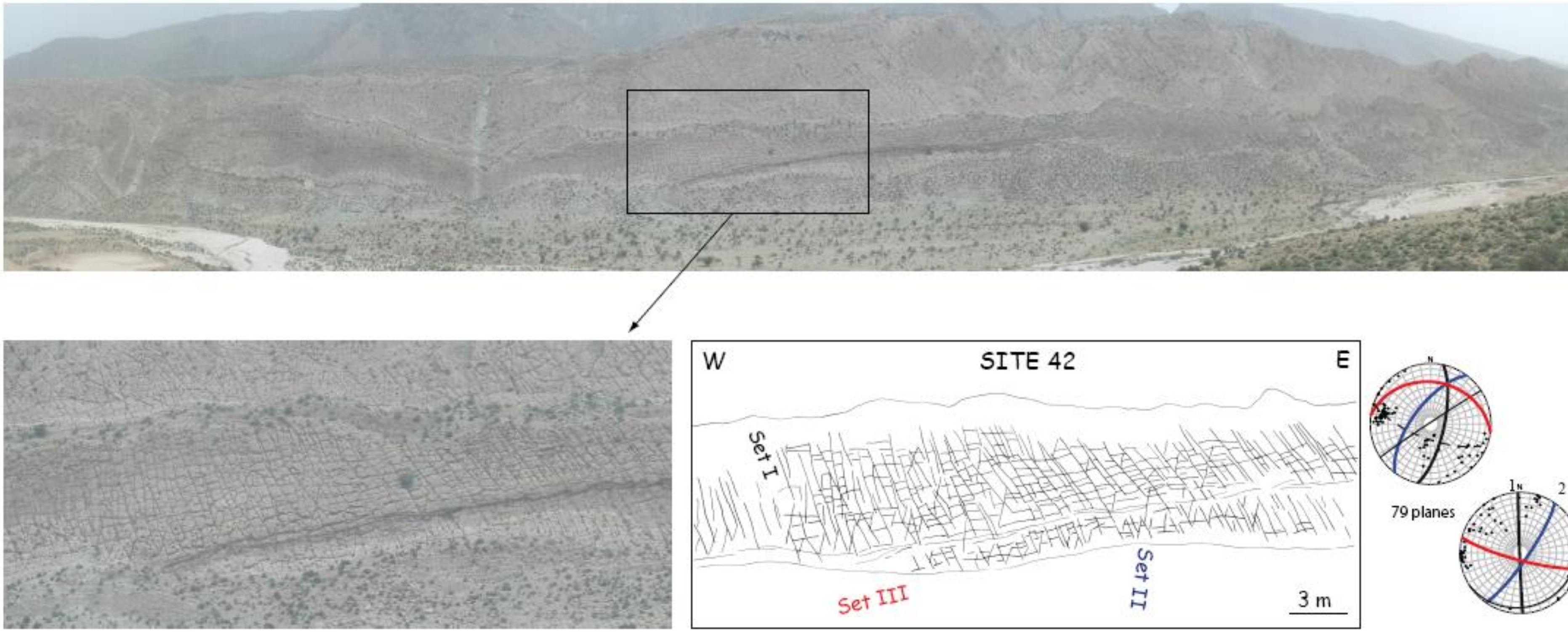
Shiraz
Qarah
Sarvestan
Zagros Fault
Karehbas F.
Firuz Abad
Dalu
Sim
Meymand
Surmeh-Ghir Thrust
Takhten
Khuni
Shanul
Zalemi
Asaluyeh
Mountain Front Fault
I
II
III
a
29°
28°
27°
53°
Bakhtyari Fm.
Conglomerates
Agha Jari Fm.
Sandstones-Conglomerates.
Miocene
Mishan Fm.
Sandy marls.
Gachsaran Fm.
Limestones/Evaporites/Marls
Paleocene-Eocene-Oligocene
Asmari Fm.
Jahrom Fm.
Limestones / Dolomites
Pabdeh/Sachun Fm.
Shales/ Marls/ Continental
Maastrichtian
Gurpi Fm.
Marls
Main decollement within the Infra-Cambrian/Cambrian Hormuz evaporites
b
Pliocene-Pleistocene
Bakhtyari Fm + Labhari mb
Miocene-Pliocene
Fars Group (Gachsaran Fm, Mishan Fm including Guri mb, Agha Jari Fm)
Eocene-Oligocene-L. Miocene
(Jahrom Fm, Asmari Fm)
Upper Cretaceous-Paleocene
(Sarvak Fm, Gurpi Fm, Pabdeh Fm)
Lower-Upper Cretaceous
(Gadvan Fm, Dariyan Fm, Kazhdumi Fm)
Jurassic
(Surmeh Fm, Gotnia Fm, Fahliyan Fm)
Triassic
(Kahnet Kat Fm, Neyriz Fm, Dashtak Fm)
Late Paleozoic and Permian
(Faraghan and Dalan Fms)
Upper Proterozoic-Middle Cambrian
(Hormuz Fm)
Neyriz ophiolites



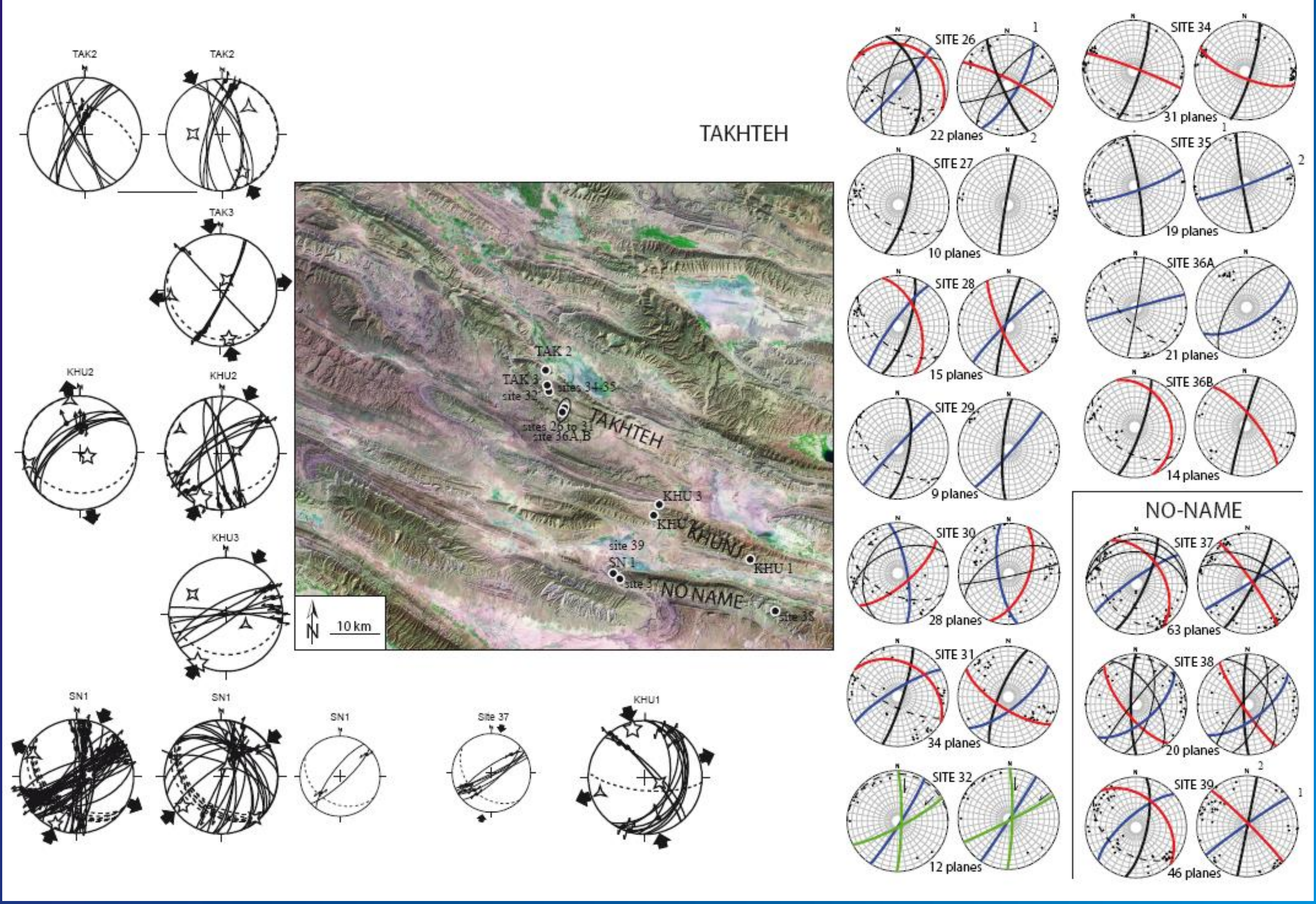
(Lacombe et al., 2011)



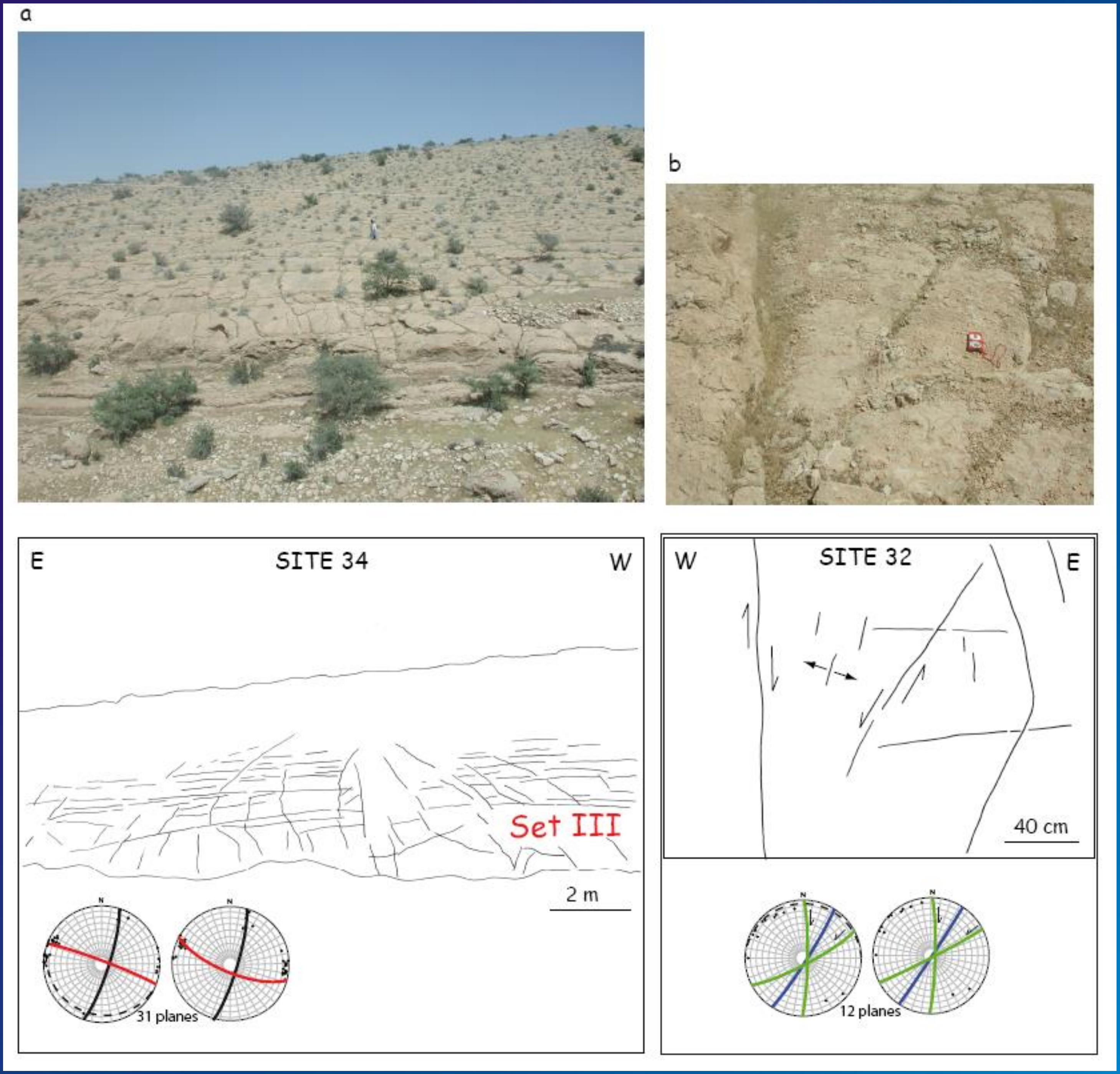
(Lacombe et al., 2011)



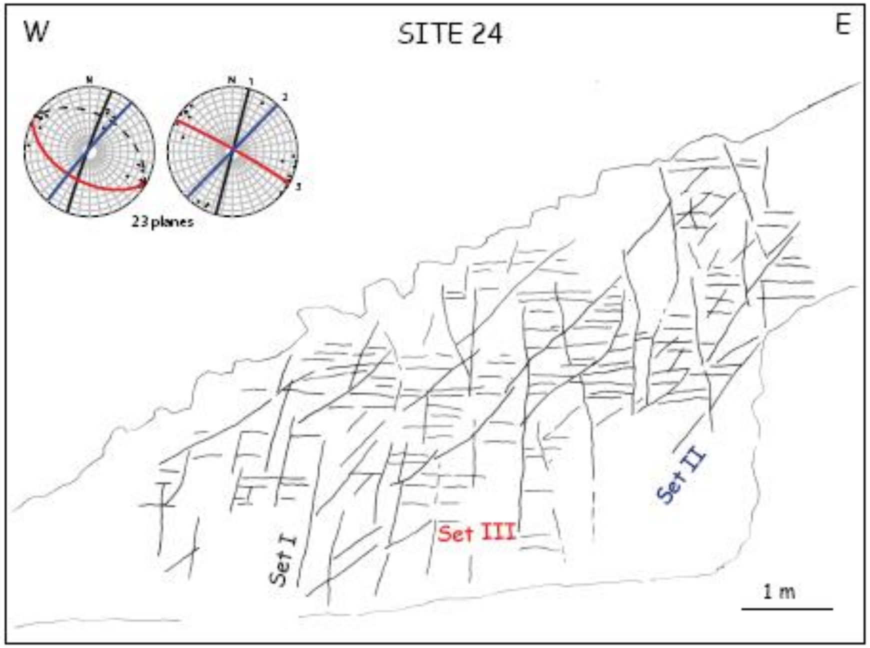
(Lacombe et al., 2011)



(Lacombe et al., 2011)



(Lacombe et al., 2011)



(Lacombe et al., 2011)

3 major sets in all the domains considered :

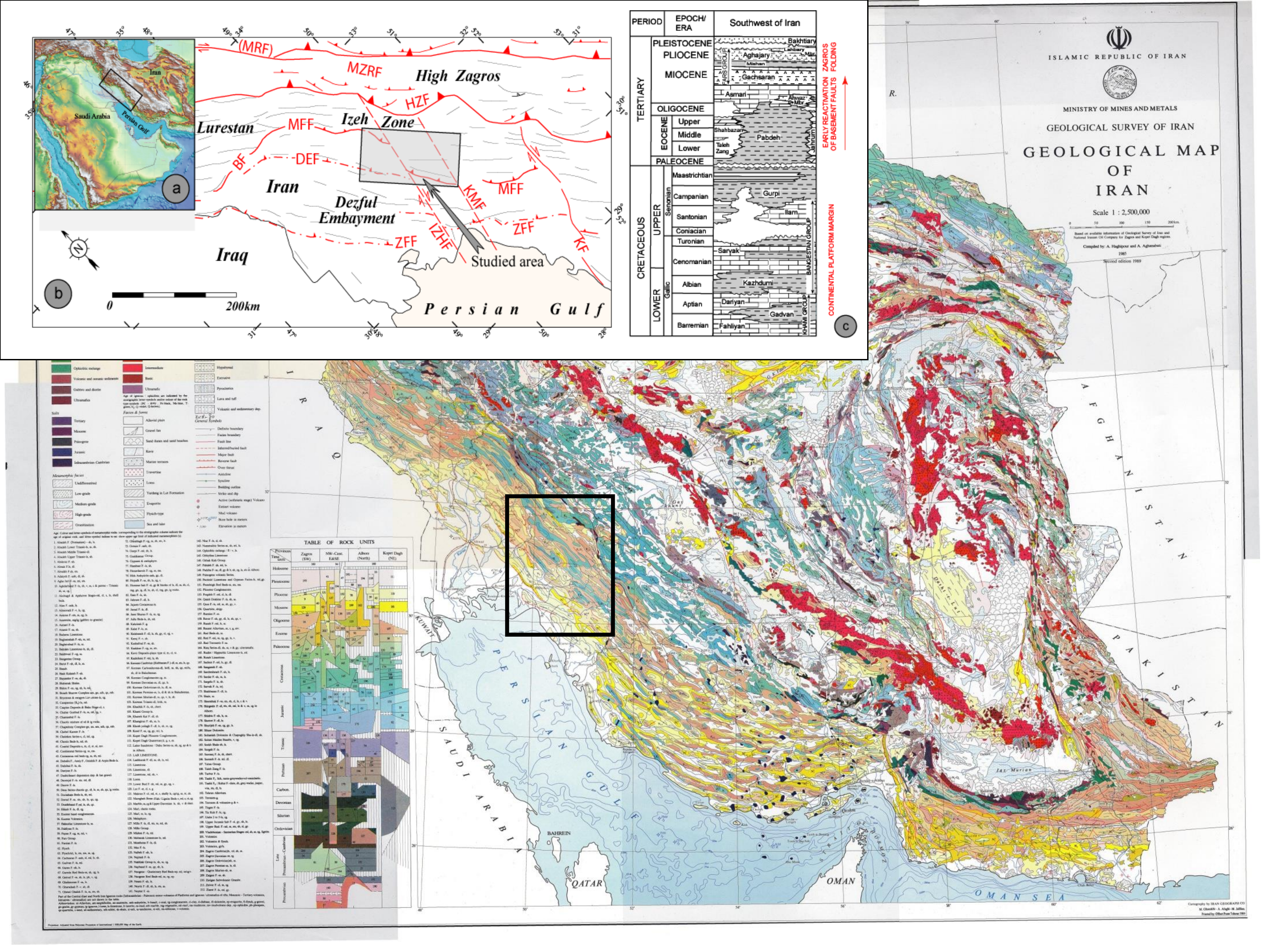
Set I is generally bed-perpendicular, and trends N–S to N020–030 after unfolding.
Set II is also bed-perpendicular, and strikes NE to ENE (N040 to N070) after unfolding.
Set III is bed-perpendicular and trends almost always parallel to the local fold axis (E–W to NNW–SSE, mainly WNW–ESE).

Set III fractures trending parallel to the fold axis and observed in most sites are interpreted as extensional axial fractures generated in response to the fold outer arc extension, hence typically fold-related.

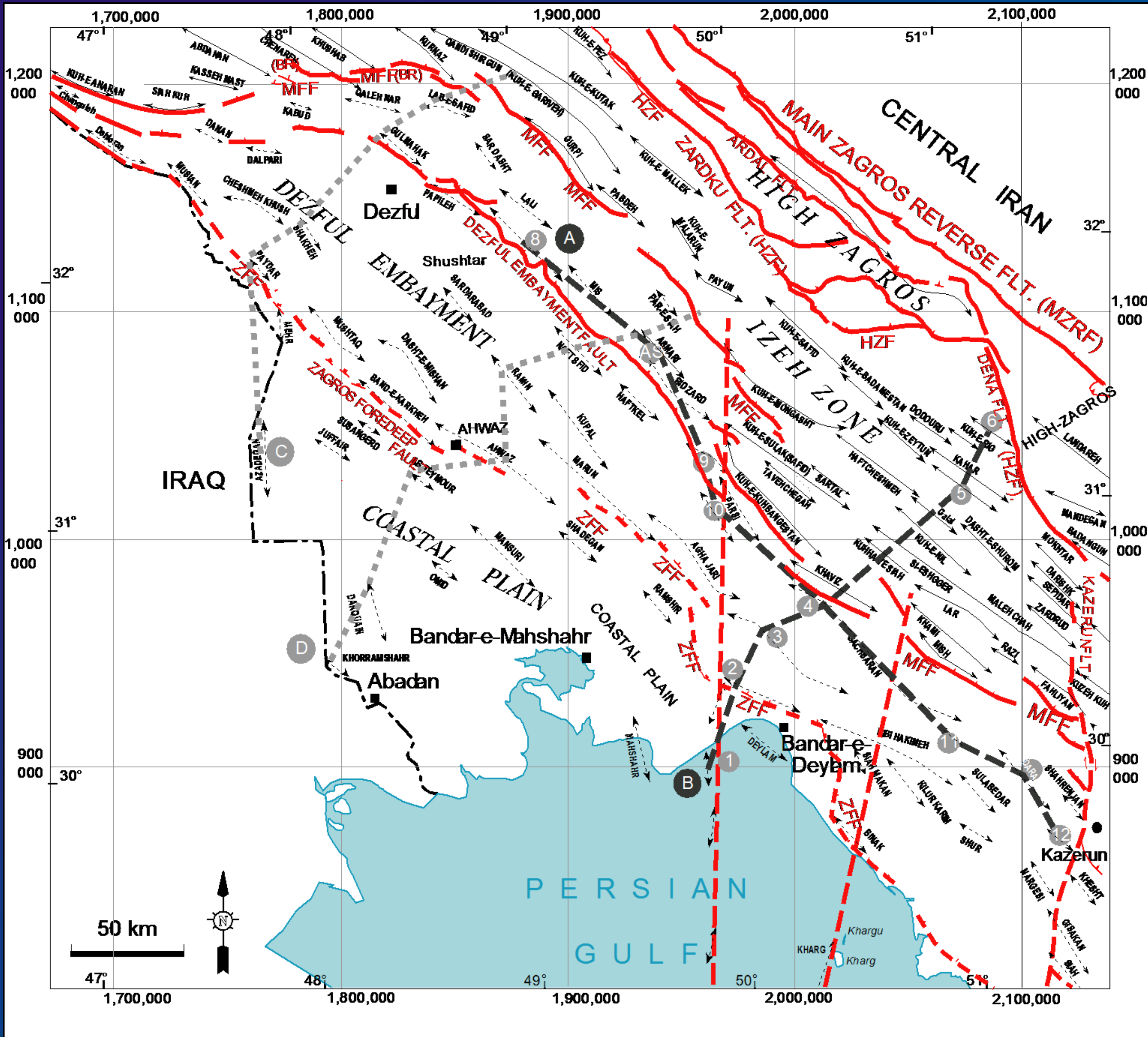
Fracture sets, either bed-perpendicular (in most cases) or not strictly perpendicular, against which fractures of set III abut,were considered pre-tilting (or possibly syn-tilting if perpendicular to the fold axis, i.e. cross-axial).

Among pre-tilting fractures, the distinction between pre-folding and early-folding fractures is based on the kinematic consistency with folding. While an early folding set formed during LPS in a consistent stress field (i.e. a fold-related extensional cross-axial set or oblique shear fracture set), a pre-folding set also predates bed tilting but may have originated in a differentstress field (unrelated to folding).

Post-folding fractures are theoretically observed in a sub-vertical attitude and they cut across the tilted strata irrespective of the geometry of the fold if they originated from a later, different stress field. In our study, post-folding fracture sets have in their present attitude a trend similar to that of the early-folding fractures of set I after unfolding. They possibly reflect a late (post-tilting) stage of fracture development during late fold tightening.



(MRF)
MZRF
High Zagros
HZF
MFF
Izeh Zone
Lurestan
BF
DEF
Iran
Dezful
Embayment
KMF
MFF
ZFF
IZHF
ZFF
KF
Iraq
Studied area
Persian Gulf
0
200km
a
b
Iran
Saudi Arabia
Persian Gulf
PERIOD
EPOCH/ ERA
Southwest of Iran
TERTIARY
PLEISTOCENE
PLIOCENE
MIOCENE
OLIGOCENE
EOCENE
Upper
Middle
Lower
PALEOCENE
CRETACEOUS
UPPER
Senonian
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
LOWER
Gallic
Albian
Aptian
Barremian
Bakhtiary
Lahbary
Aghajary
Mishan
Gachsaran
Asmari
Ahwaz Mbr.
Shahbazan
Pabdeh
Jahrum
Taleh Zang
Gurpi
Ilam
Sarvak
Kazhdumi
Dariyan
Gadvan
Fahliyan
BANGESTAN GROUP
KHAMI GROUP
EARLY REACTIVATION OF BASEMENT FAULTS
ZAGROS FOLDING
CONTINENTAL PLATFORM MARGIN
c
ISLAMIC REPUBLIC OF IRAN
MINISTRY OF MINES AND METALS
GEOLOGICAL SURVEY OF IRAN
GEOLOGICAL MAP
OF
IRAN
Scale 1 : 2,500,000
Second edition 1989
TABLE OF ROCK UNITS
IRAQ
KUWAIT
PERSIAN GULF
SAUDI ARABIA
BAHREIN
QATAR
OMAN
OMAN SEA
AFGHANISTAN
PAKISTAN



1,700,000
1,800,000
1,900,000
2,000,000
2,100,000
47°
48°
49°
50°
51°
1,200 000
1,100 000
1,000 000
900 000
32°
31°
30°
CENTRAL IRAN
MAIN ZAGROS REVERSE FLT. (MZRF)
HIGH ZAGROS
ZARDKU FLT. (HZF)
ARDAL FLT.
HZF
MFF
MFF(BR)
(BR)
IZEH ZONE
DENA FLT. (HZF)
HIGH-ZAGROS
DEZFUL EMBAYMENT
DEZFUL EMBAYMENT FAULT
ZAGROS FOREDEEP FAULT
ZFF
KAZERUN FLT.
COASTAL PLAIN
IRAQ
Dezful
Shushtar
AHWAZ
Bandar-e-Mahshahr
KHORRAMSHAHR
Abadan
Bandar-e-Deylam
Kazerun
Khargu
Kharg
KHARG
PERSIAN GULF
50 km
A
B
C
D
1
2
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4
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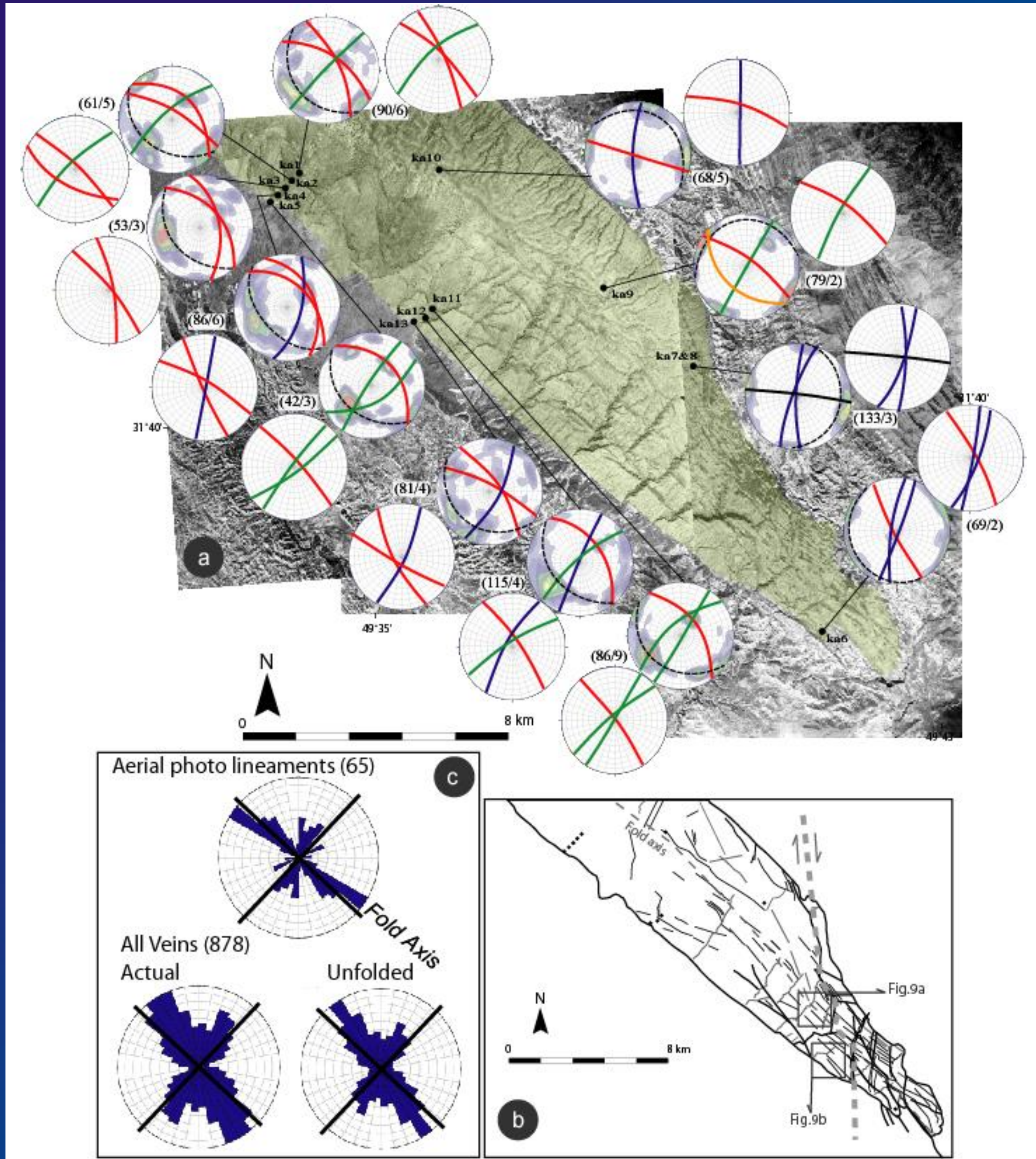
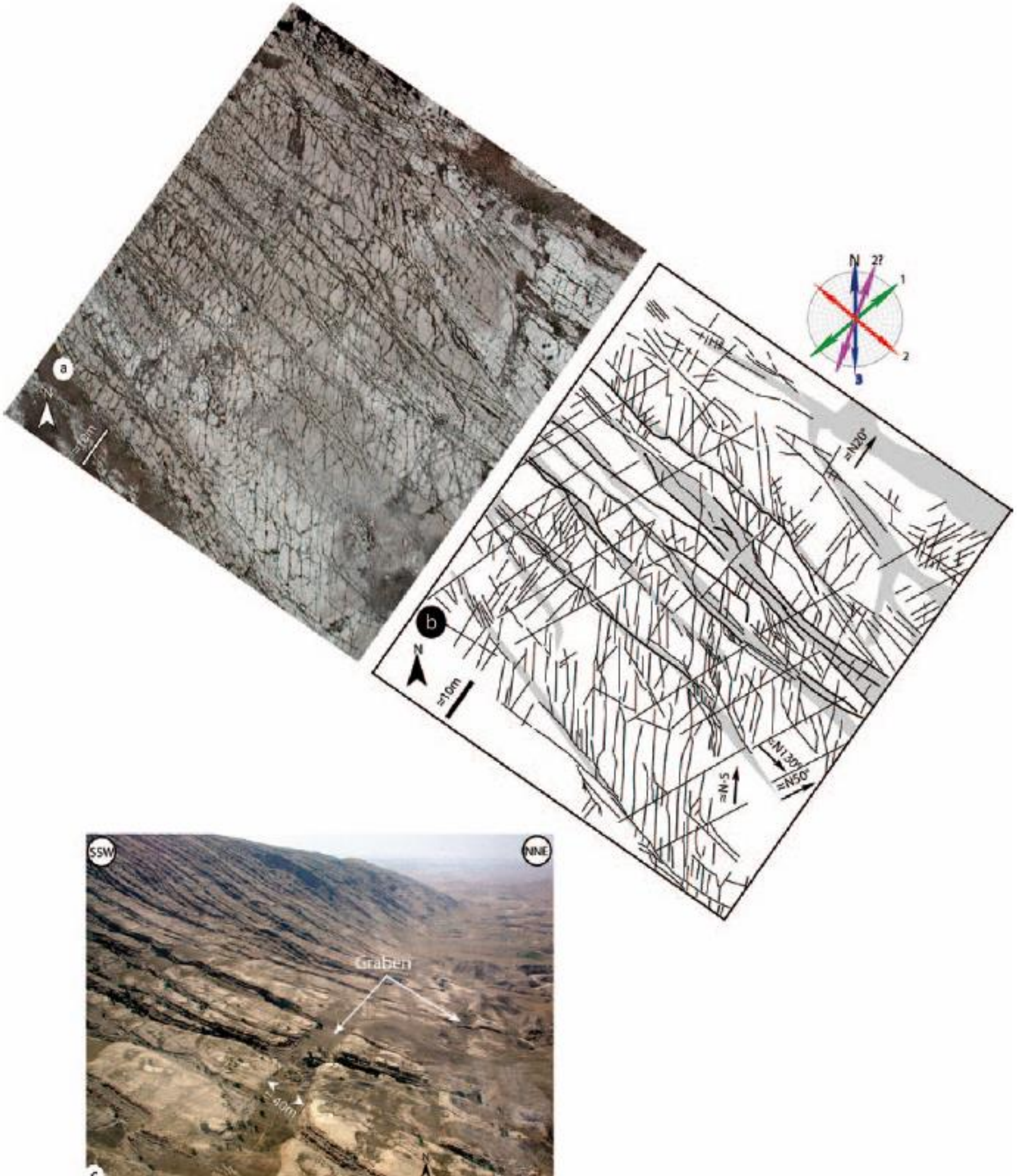
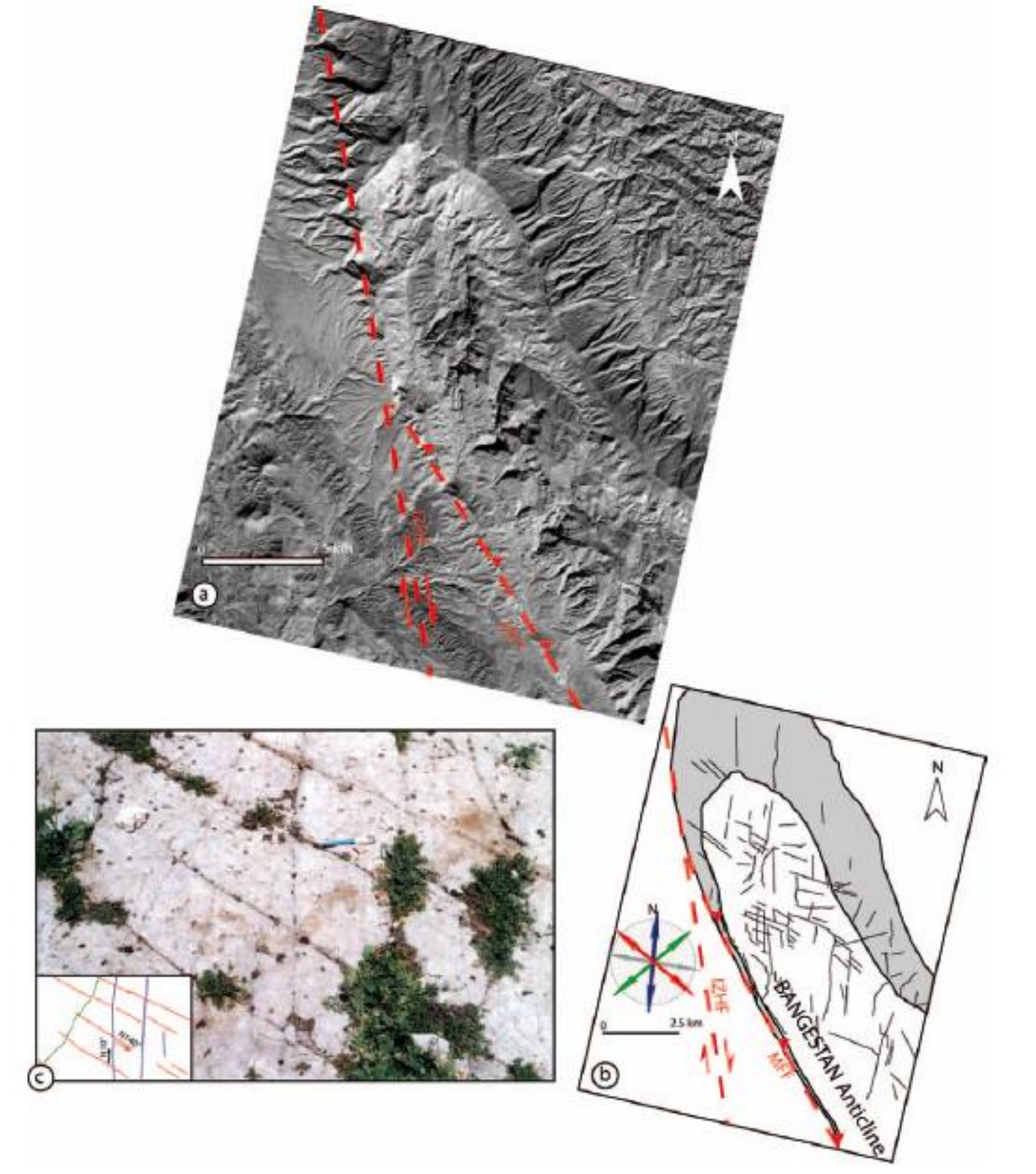
9
10
11
12



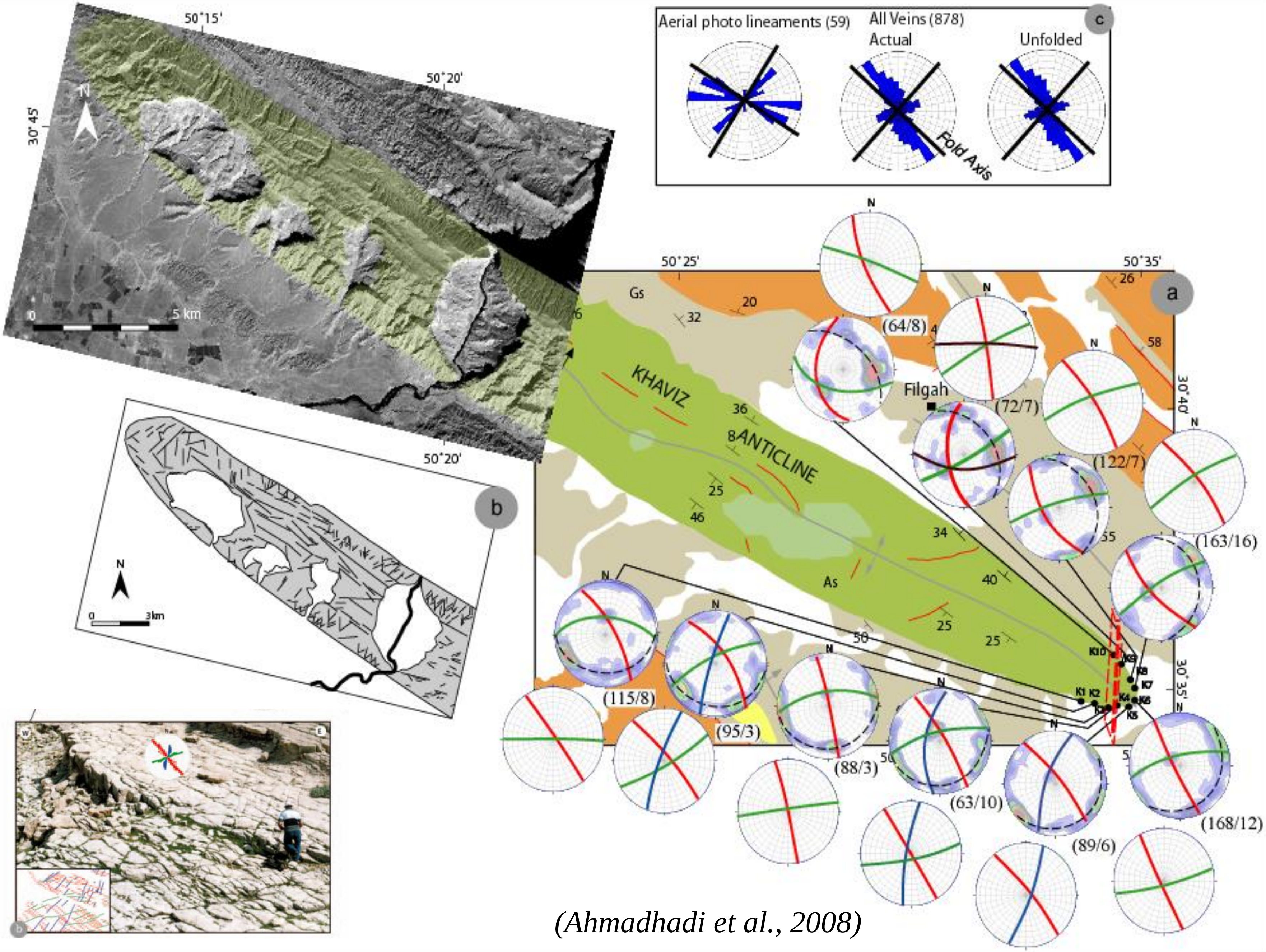
(Ahmadhadi et al., 2008)



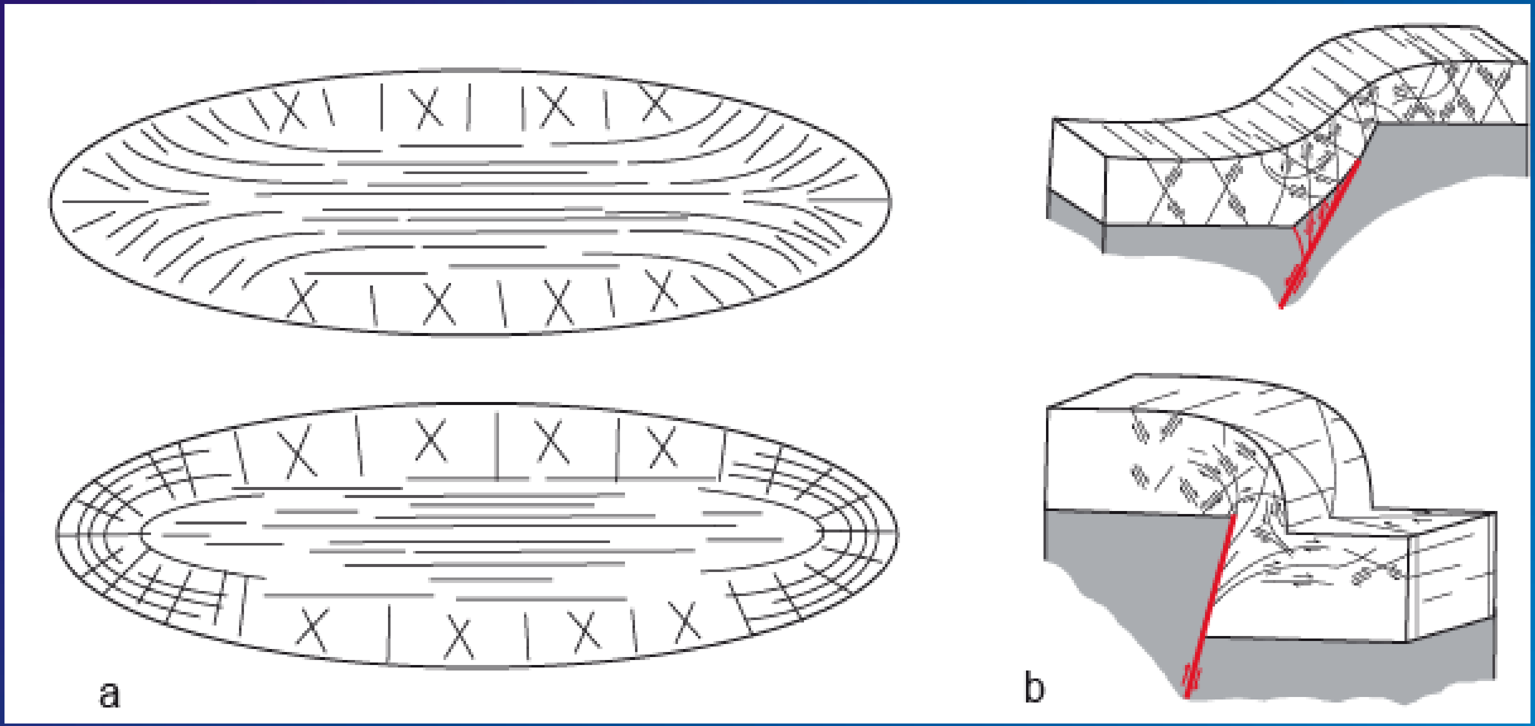
(Ahmadhadi et al., 2007)

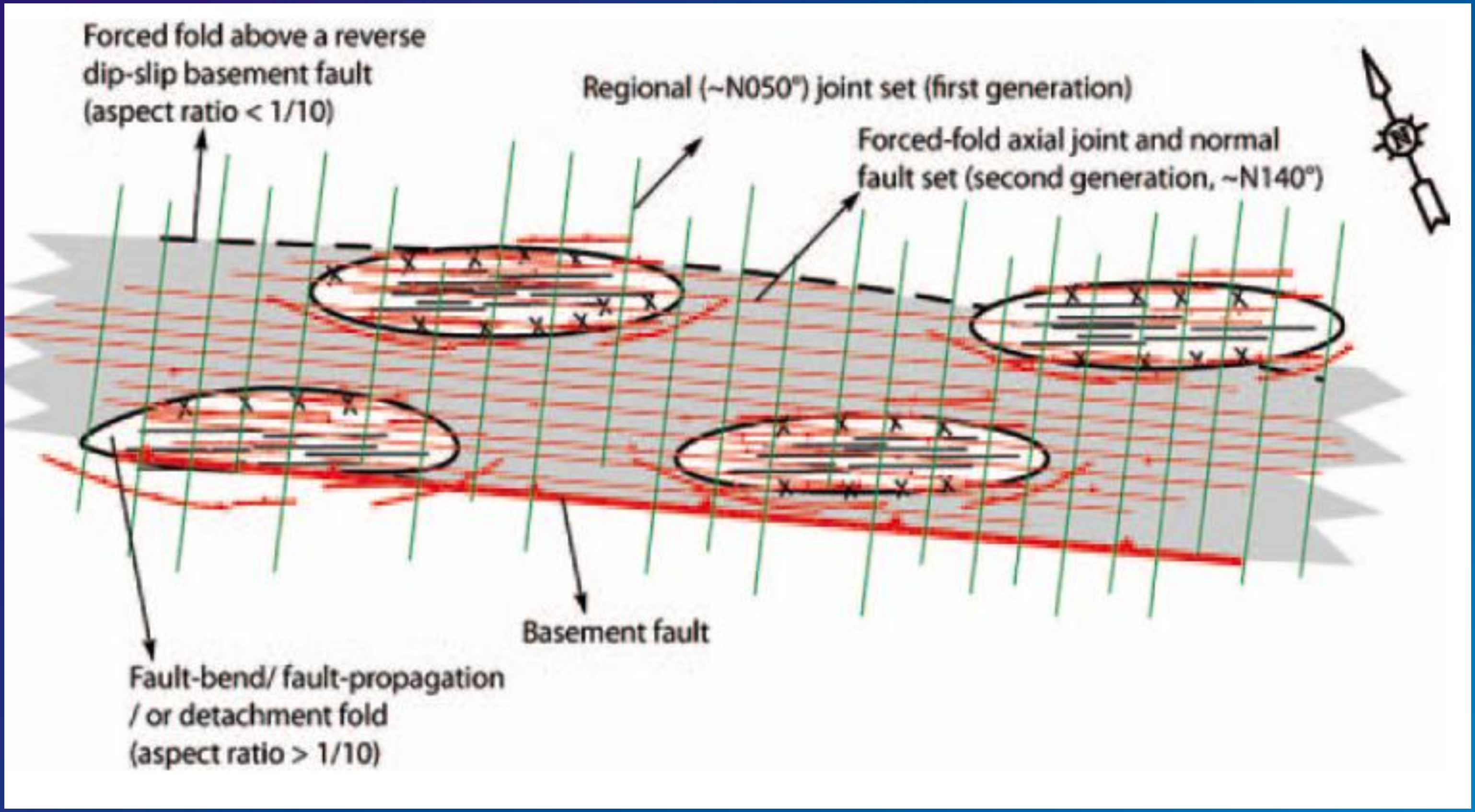


(Ahmadhadi et al., 2007)



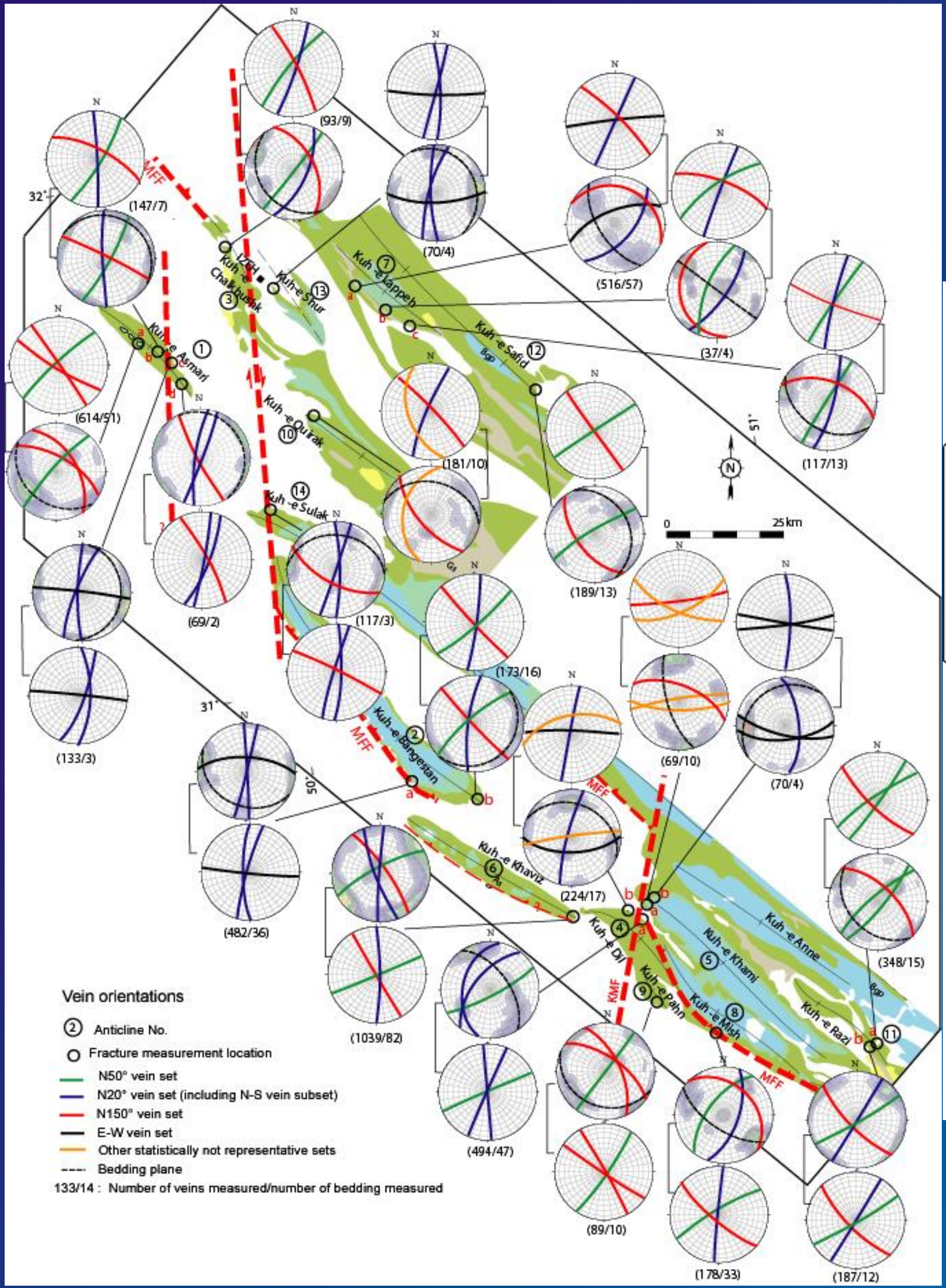
(Ahmadhadi et al., 2008)

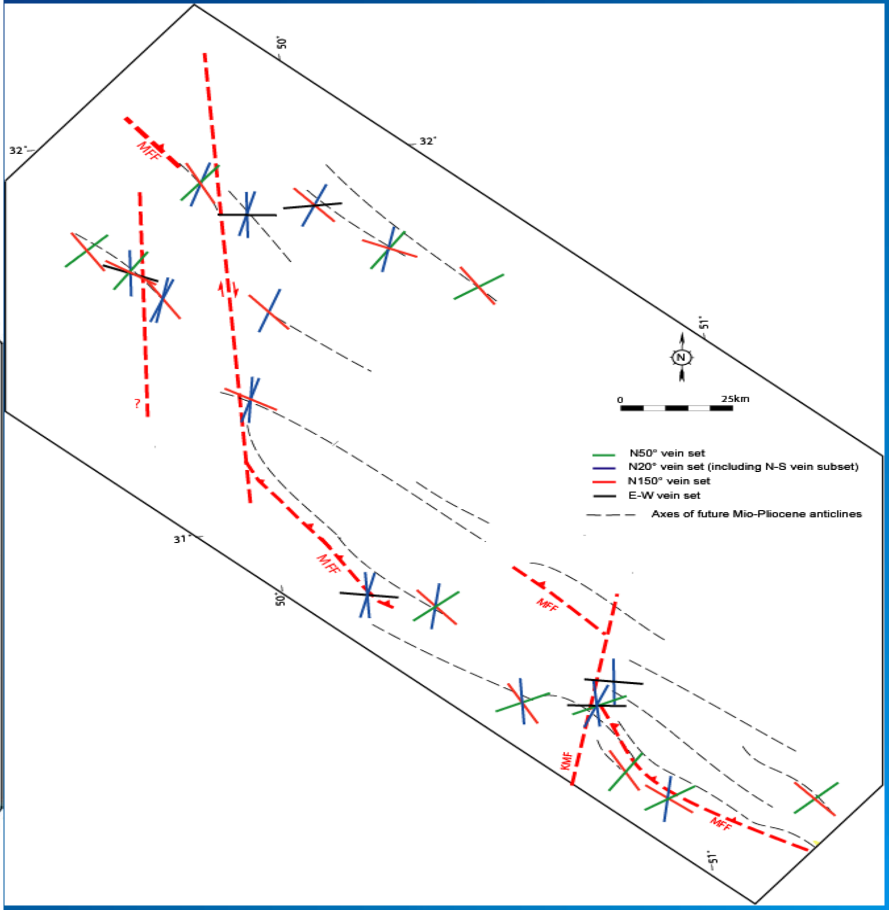

a
b



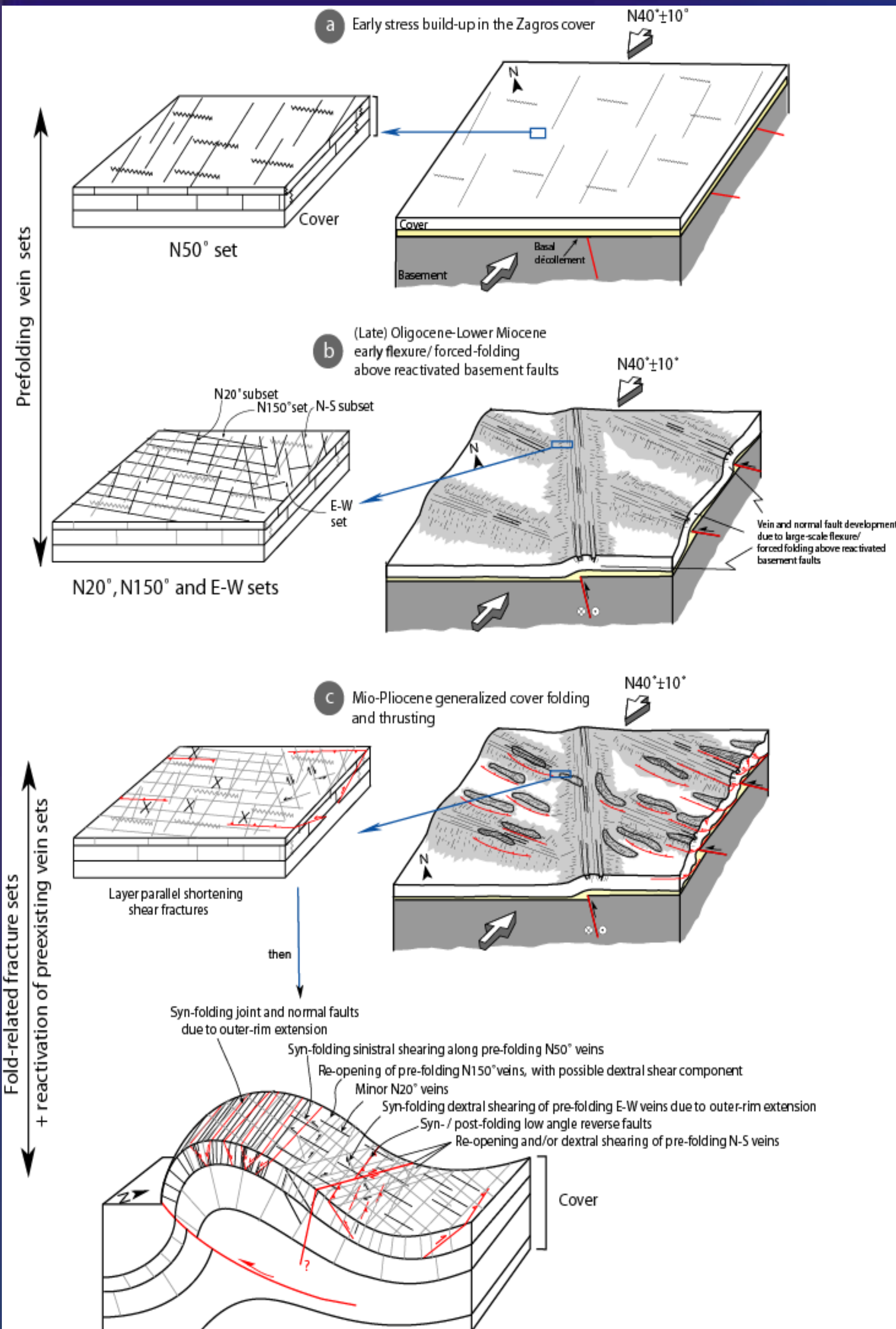
(Ahmadhadi et al., 2007)

Specific occurrence of some prefolding vein sets in the vicinity of basement faults

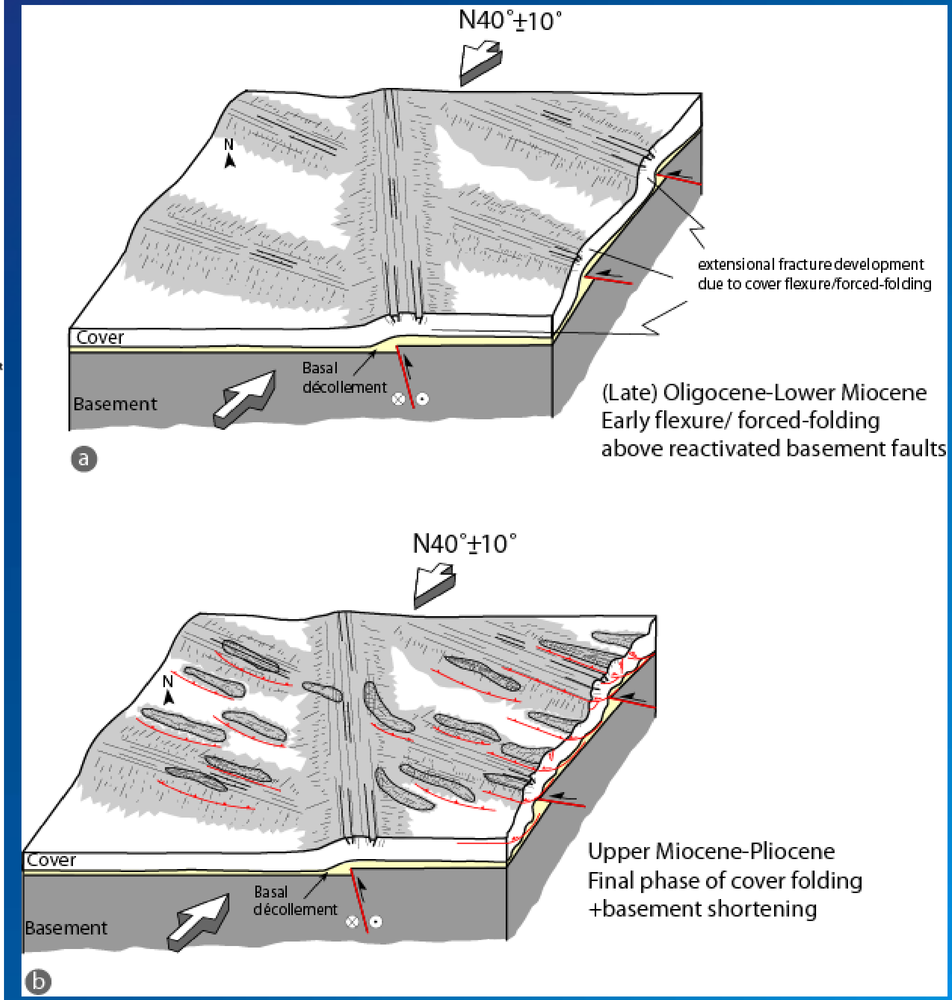




(Ahmadhadi et al., 2008)



Onset of stress build-up

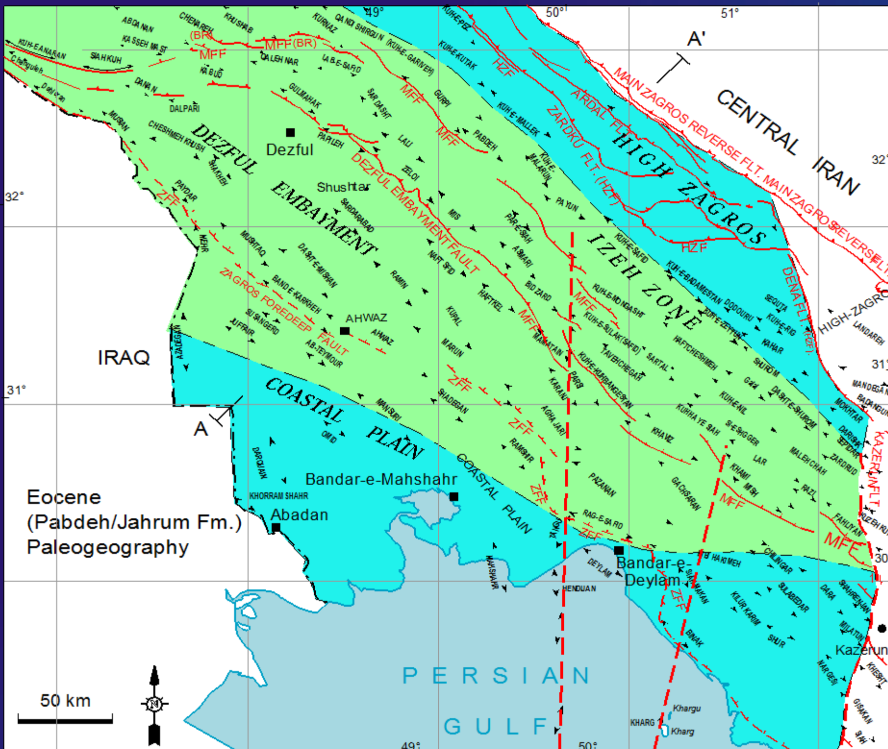


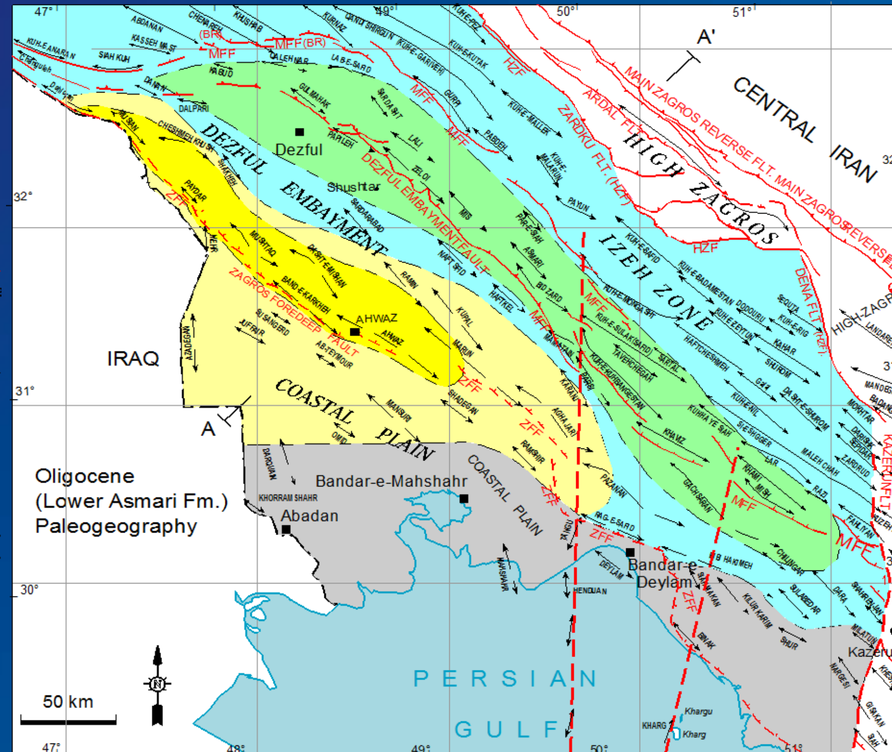
(Ahmadhadi et al., 2007; Ahmadhadi et al., 2008)

Basement structures and early basement block movements may therefore have an impact on fracture development in the overlying cover rocks.

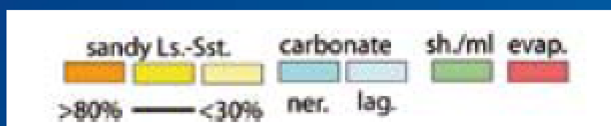
The occurrence of some local compressional trends and related fracture sets was partly controlled by underlying deep-seated basement faults in the Zagros region. The transmission of orogenic stress through the faulted crystalline basement of the Zagros was probably heterogeneous and complex; deformation propagated in an irregular fashion through the basement and the cover leading to local stress perturbations, hence to a complex directional distribution and chronology of fractures in the cover.

Such a complexity should be taken into account in further studies of folded and fractured reservoirs.



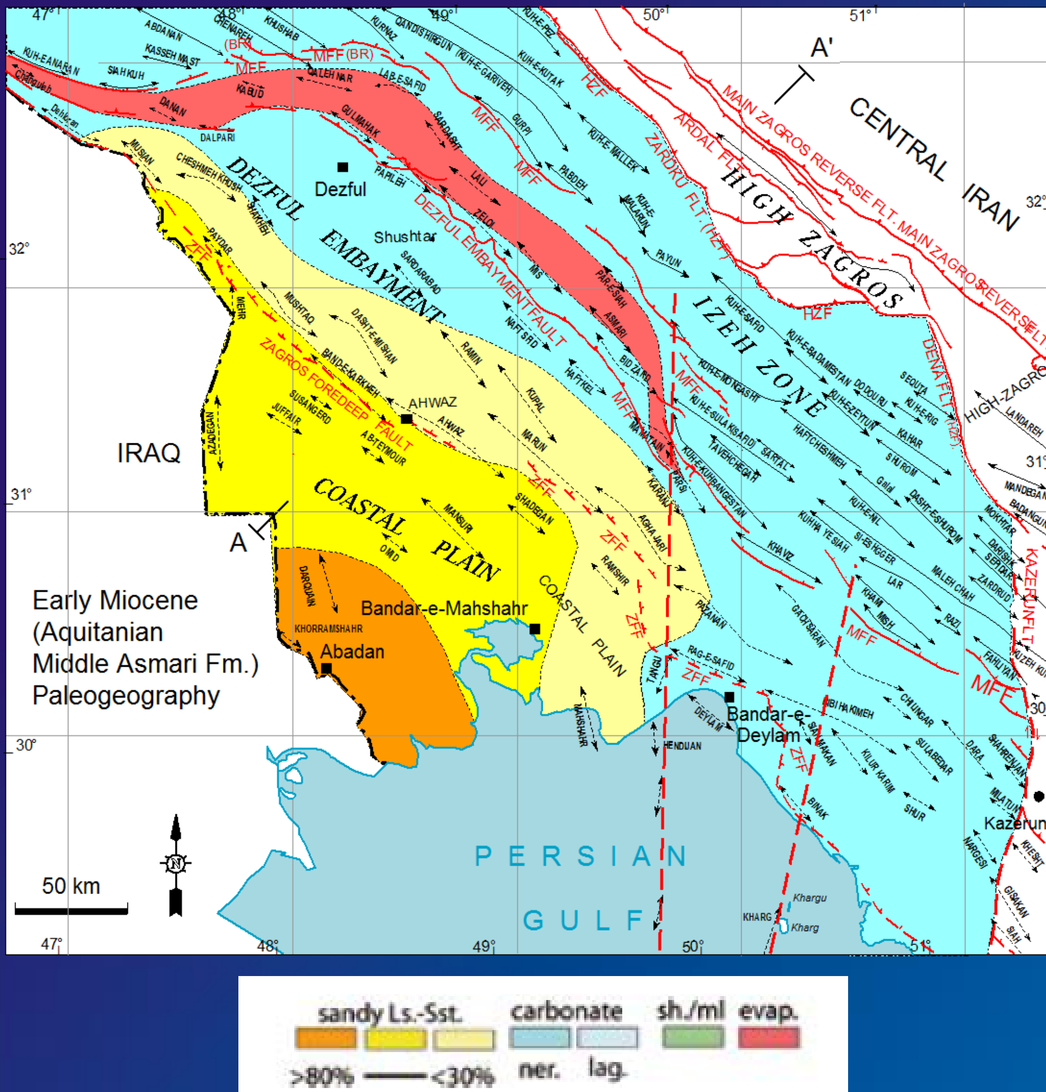


(Ahmadhadi et al., 2007)



During Eocene times, the Pabdeh basin covered a wide area from the south of the High Zagros fault toward the Zagros Foredeep Fault.

During the Lower Oligocene, progressive basin restriction and sedimentary flux progradation toward the depocenter of the previous Pabdeh basin - between the MFF to the north and the ZFF to the south - following the progradation of the carbonate platform and clastic facies of the Lower Asmari Formation suggest that the NW-SE trending basement faults were presumably reactivated

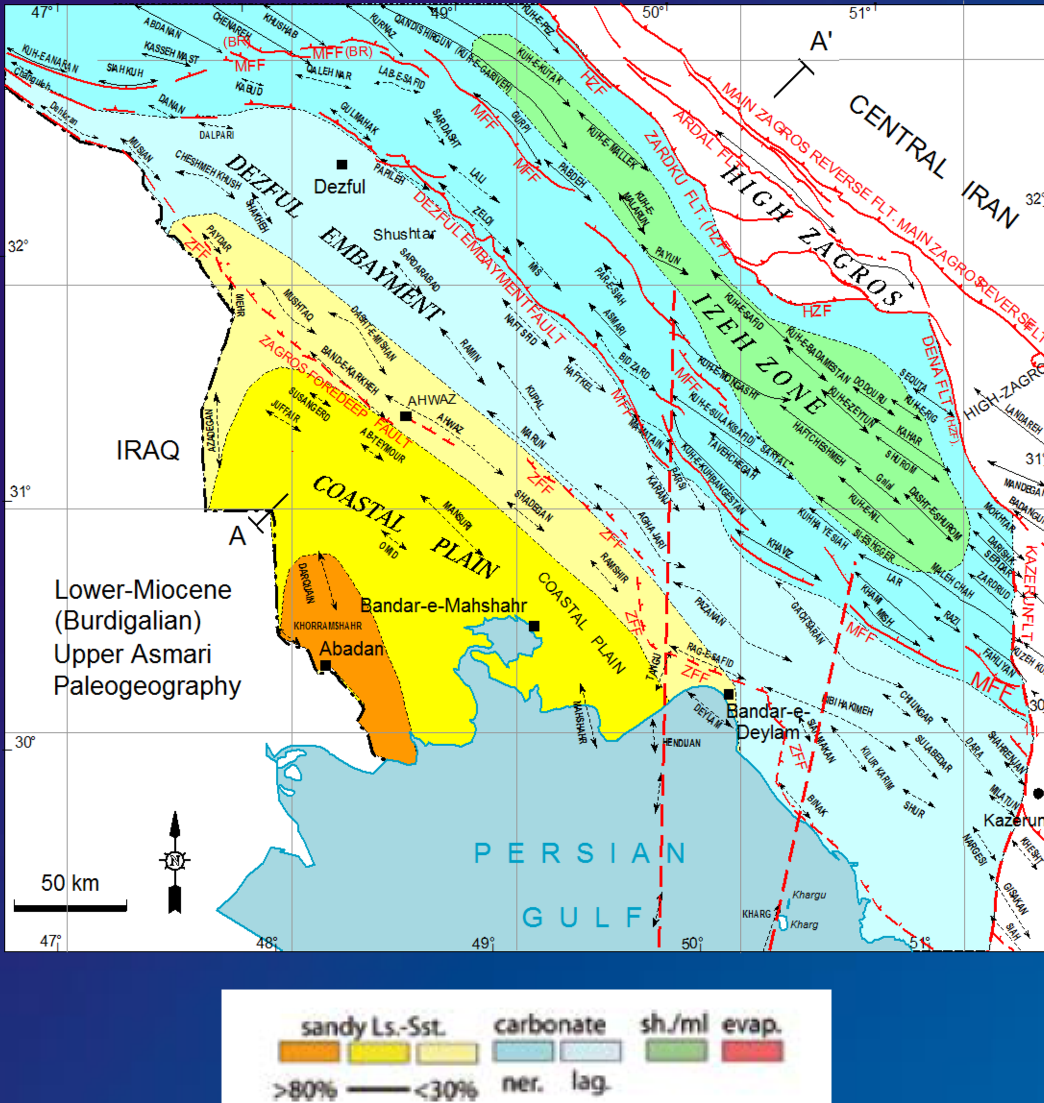


(Ahmadhadi et al., 2007)

The development of a long narrow evaporitic intra-basin (Kalhur Member) during the latest Oligocene-early Lower Miocene likely indicate an abrupt facies change (both laterally and vertically)

→ difficult to interpret simply by eustasy or any sedimentological process alone, without any tectonic control.

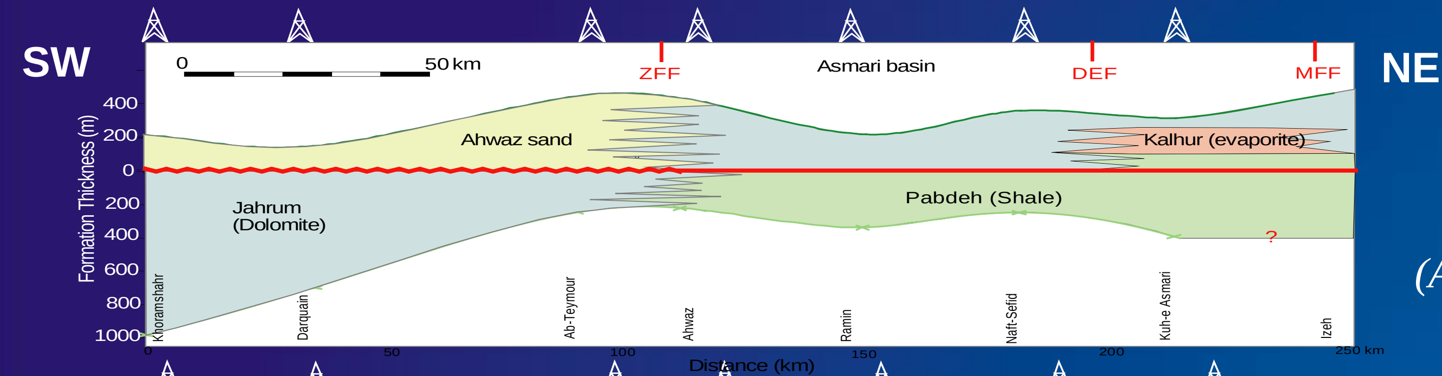
Rather :
the localization of this intra-basin between the MFF to the north and the DEF to the south and the abrupt facies change from marls to evaporites suggests a direct relation between this restricted lagoon intra-basin and deep-seated basement faults.



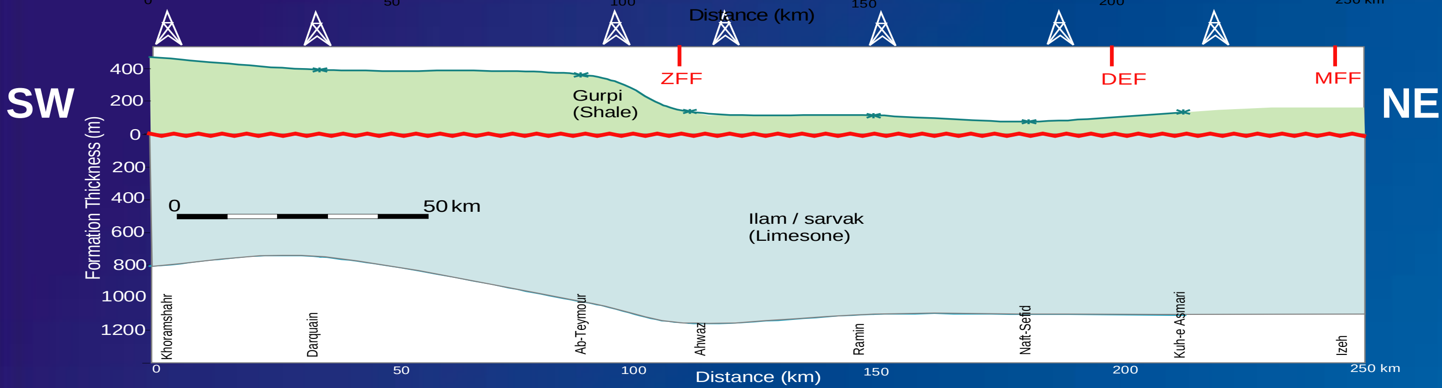
The Ahwaz/Ghar Member delta front, indicated by more than 30% of the sand content of the Asmari carbonate, formed just and parallel to the south of the ZFF.

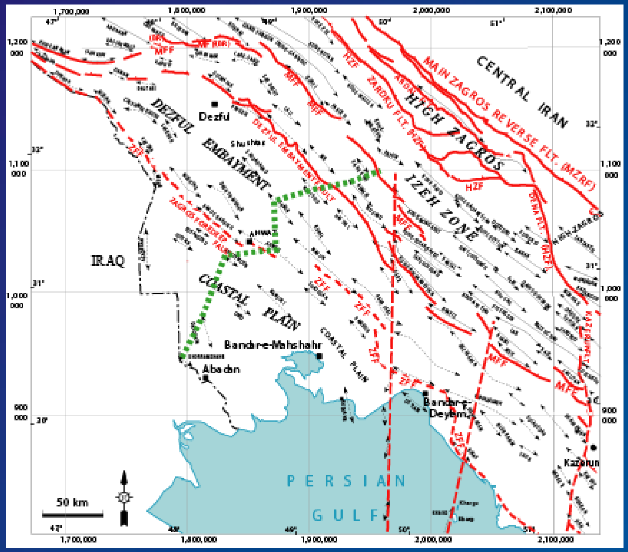
During Burdigalian times, the Upper Asmari carbonates covered the entire basin with a hemipelagic facies toward the northern part of the Mountain Front Fault

(Ahmadhadi et al., 2007)



(Ahmadhadi et al., 2007)





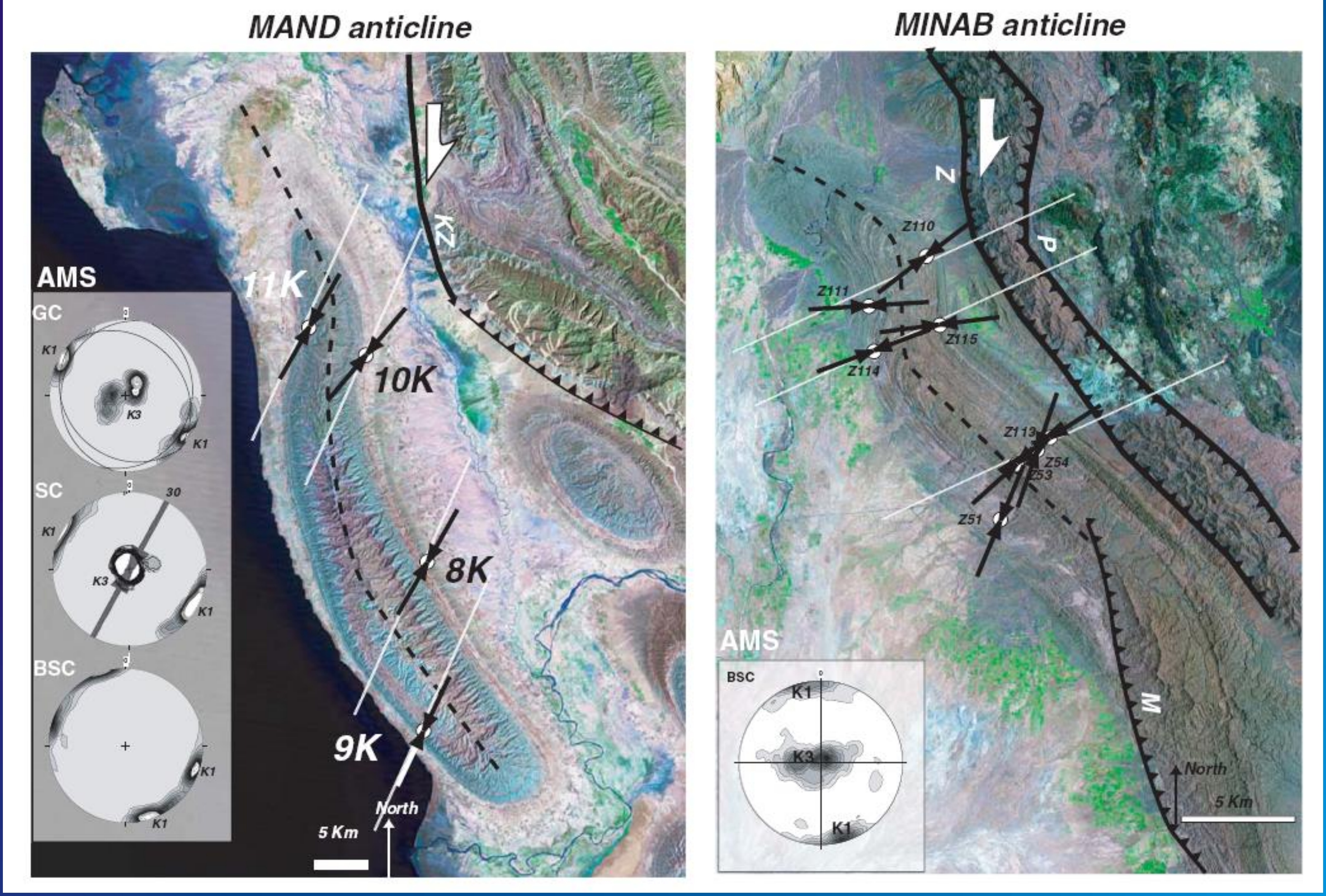
Transect based on the thickness variations of the main lithostratigraphical units (formations) with definite time lines (top and bottom) :

Both thickness and main facies variations within Pabdeh/Jahrum and Asmari formations coincide with the location of the main basement faults; this strongly suggests that these faults were reactivated during Pabdeh/Jahrum and Asmari deposition.

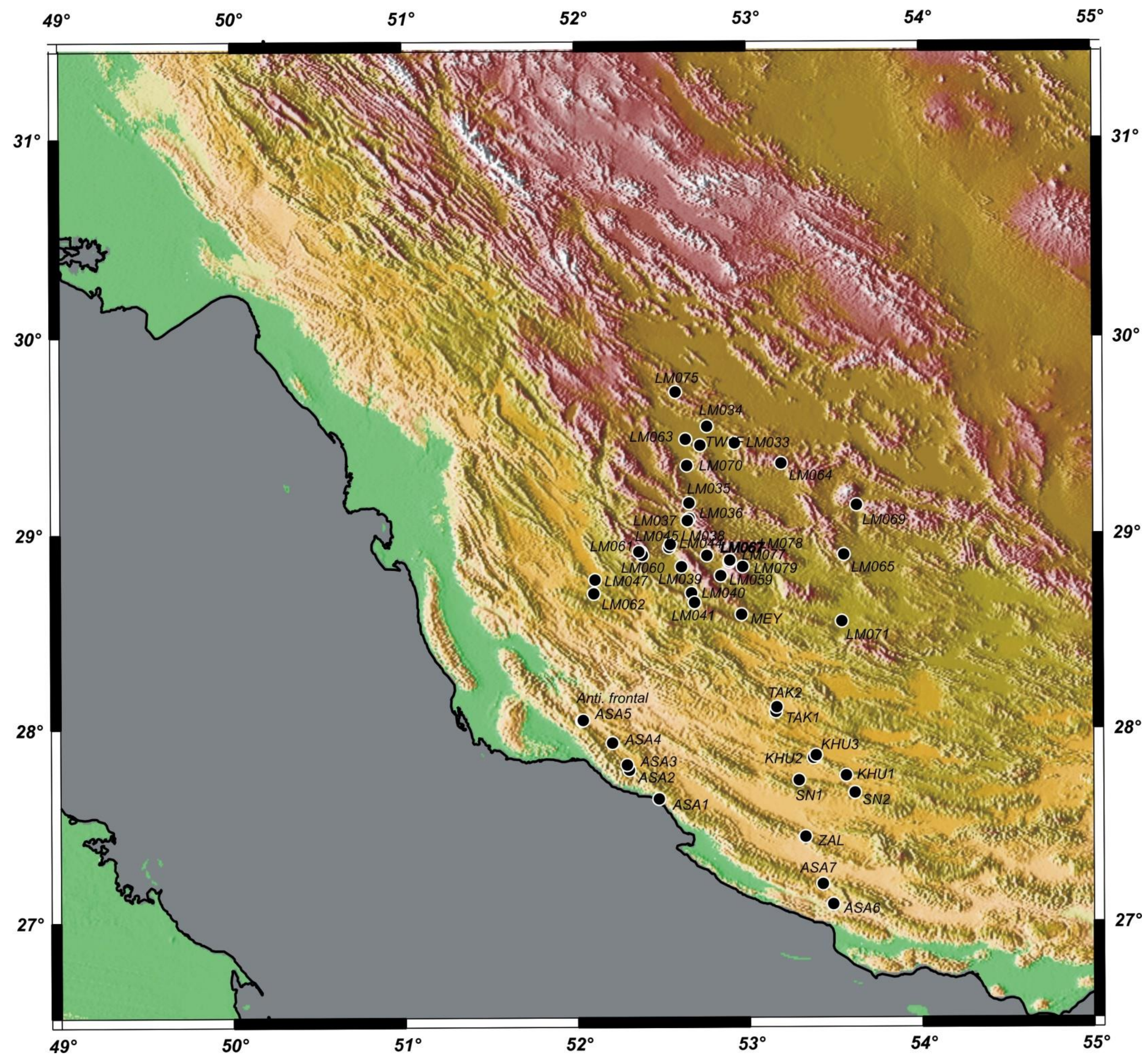
- Facies distribution and sub-basins development in the Central Zagros during Eo (?)-Oligocene-lower Miocene were likely controlled by the compressional reactivation of deep-seated basement faults

- Deformation in the region presumably started as soon as Eocene – Oligocene, with amplification of forced folding during Chattian/Aquitanian (~30 – 22 Ma) and initiation of early vein sets within Asmari Fm

Paleostress/shortening patterns in the Zagros belt : AMS, calcite twins and meso-scale faulting



(Aubourg et al.,2010)



49°
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TWKF
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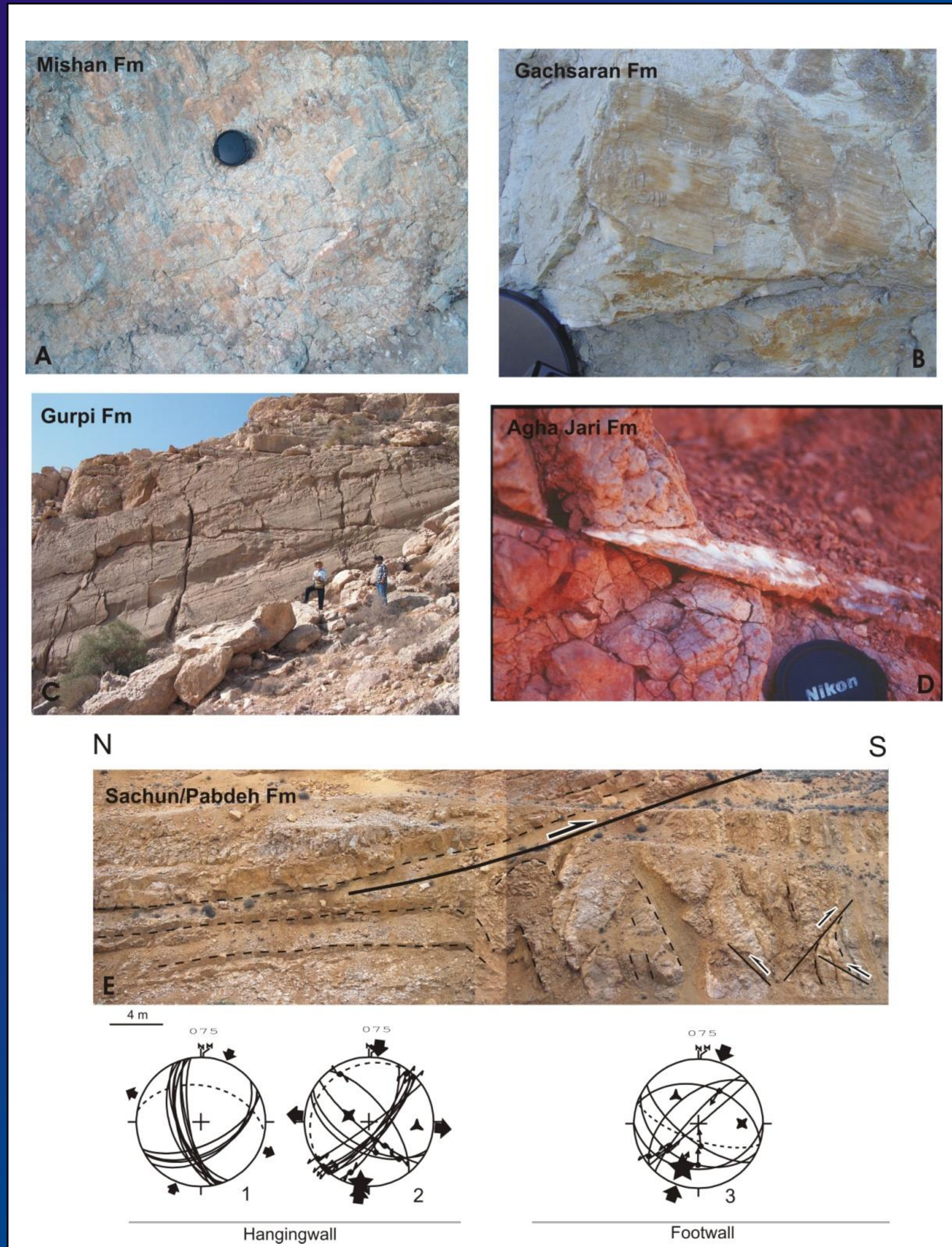
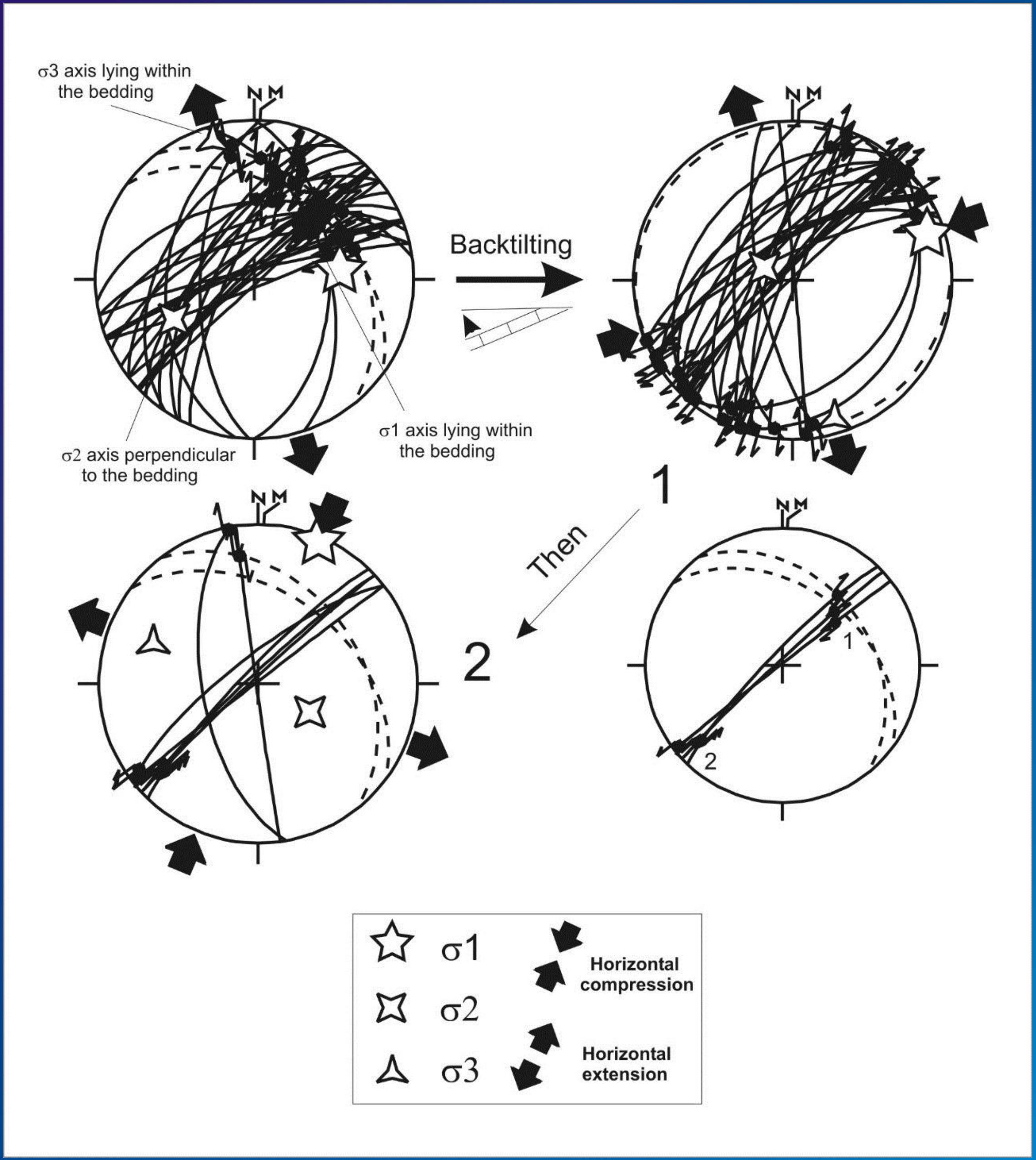
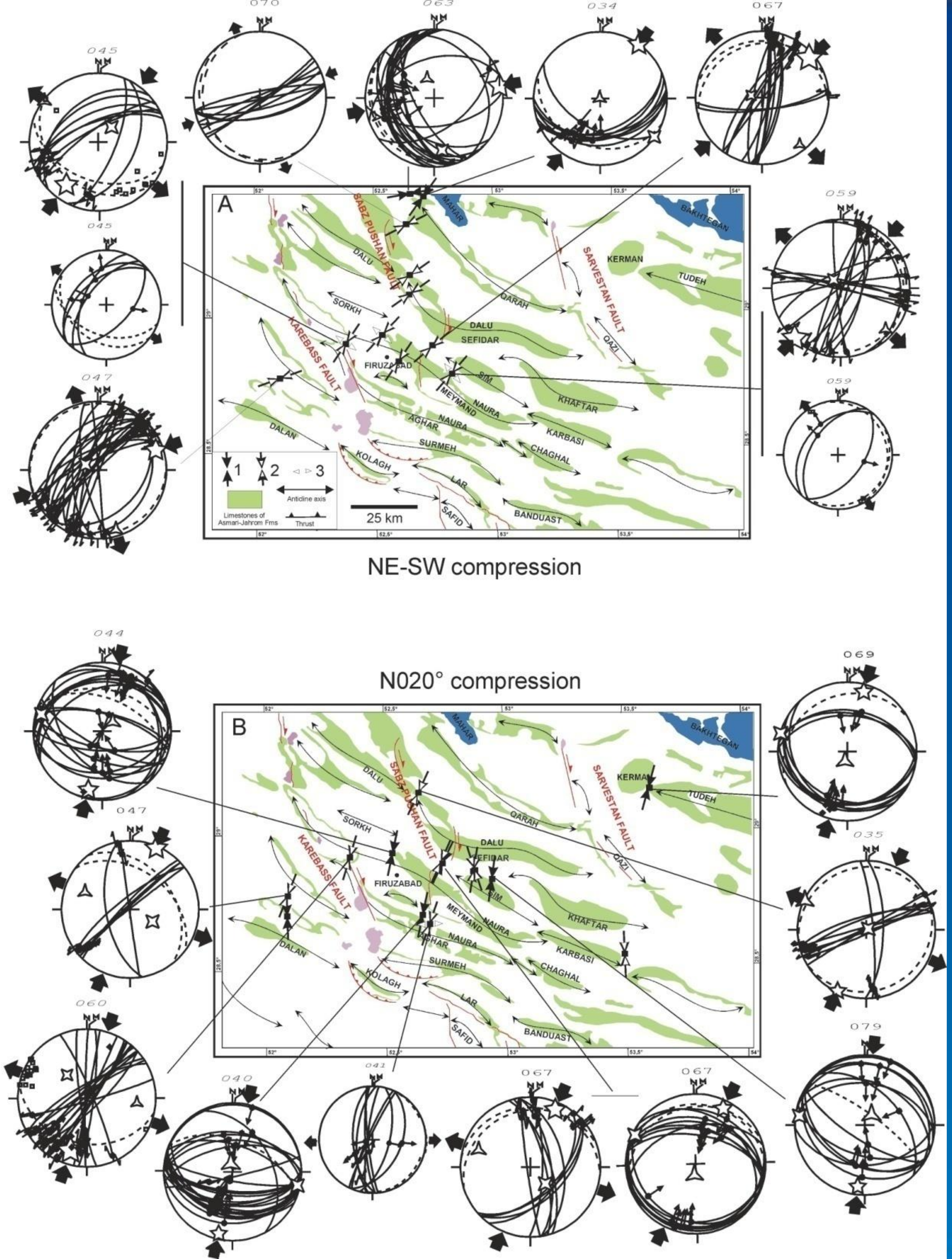
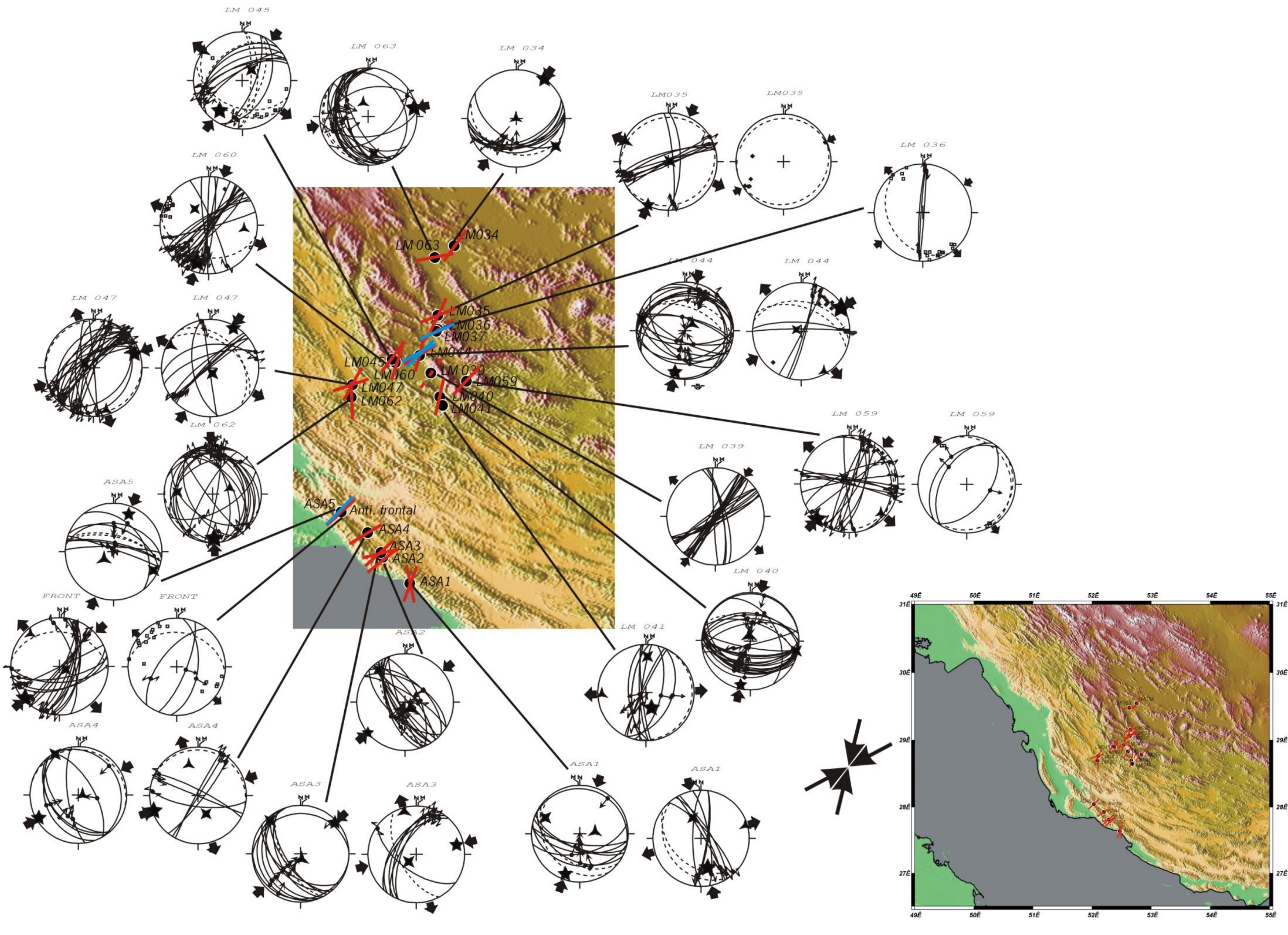
LM070
LM064
LM035
LM036
LM069
LM037
LM045
LM038
LM061
LM044
LM067
LM078
LM077
LM060
LM079
LM065
LM047
LM039
LM059
LM040
LM062
LM041
MEY
LM071
Anti. frontal
ASA5
TAK2
TAK1
ASA4
KHU3
ASA3
KHU2
ASA2
KHU1
SN1
SN2
ASA1
ZAL
ASA7
ASA6


Mishan Fm
A
Gachsaran Fm
B
Gurpi Fm
C
Agha Jari Fm
Nikon
D
N
S
Sachun/Pabdeh Fm
E
4 m
075
1
075
2
075
3
Hangingwall
Footwall


σ3 axis lying within the bedding
N M
Backtilting
σ1 axis lying within the bedding
σ2 axis perpendicular to the bedding
1
Then
2
1
2
σ1
σ2
σ3
Horizontal compression
Horizontal extension



(Lacombe et al.,2006)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LM 034
LM035
LM035
LM 036
LM 060
LM 044
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LM 059
LM 059
LM 039
ASA5
LM 040
FRONT
FRONT
ASA2
LM 041
ASA4
ASA4
ASA3
ASA3
ASA1
ASA1
LM 063
LM034
LM035
LM036
LM037
LM044
LM045
LM060
LM 039
LM059
LM047
LM062
LM040
LM041
ASA5
Anti. frontal
ASA4
ASA3
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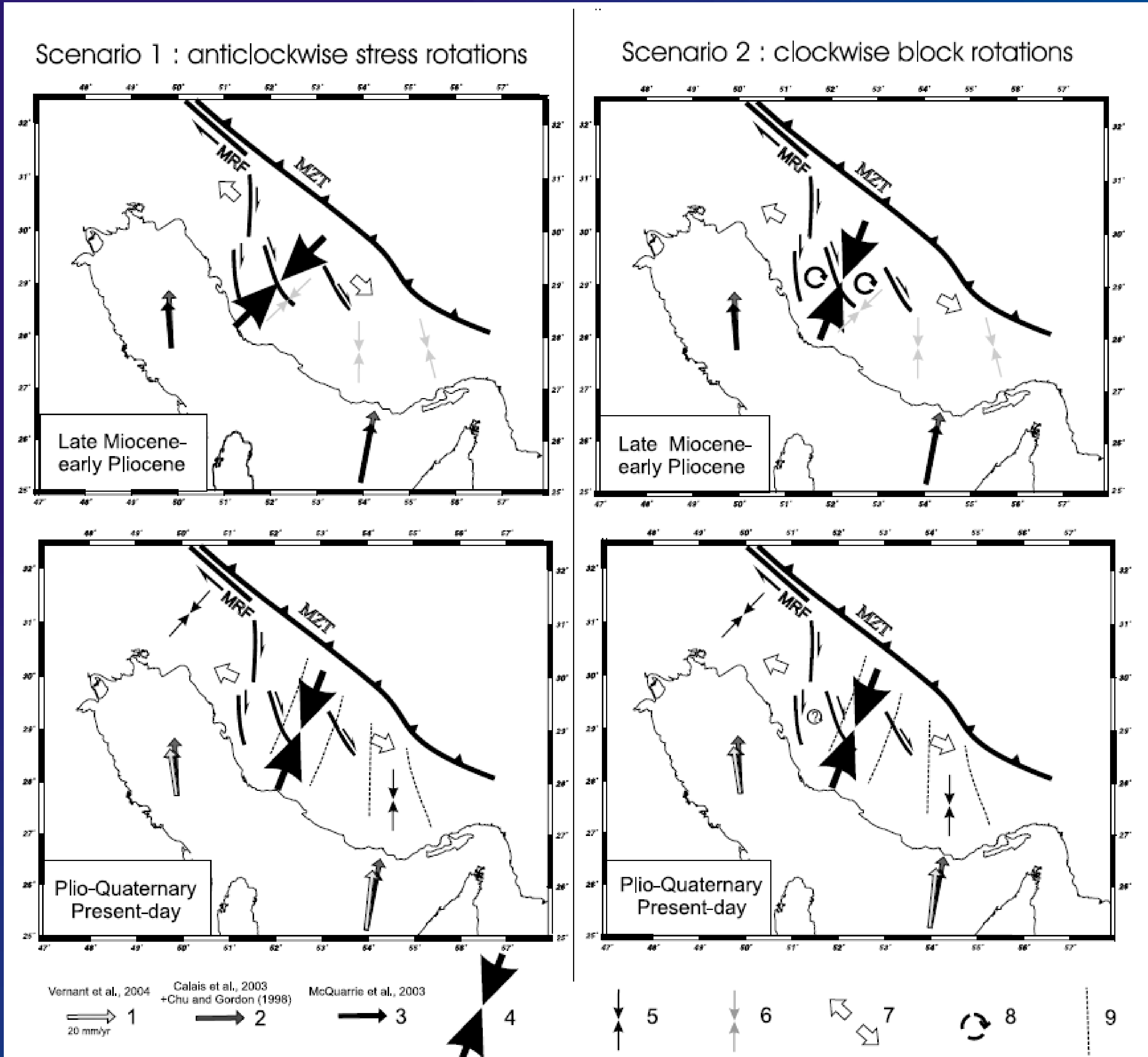
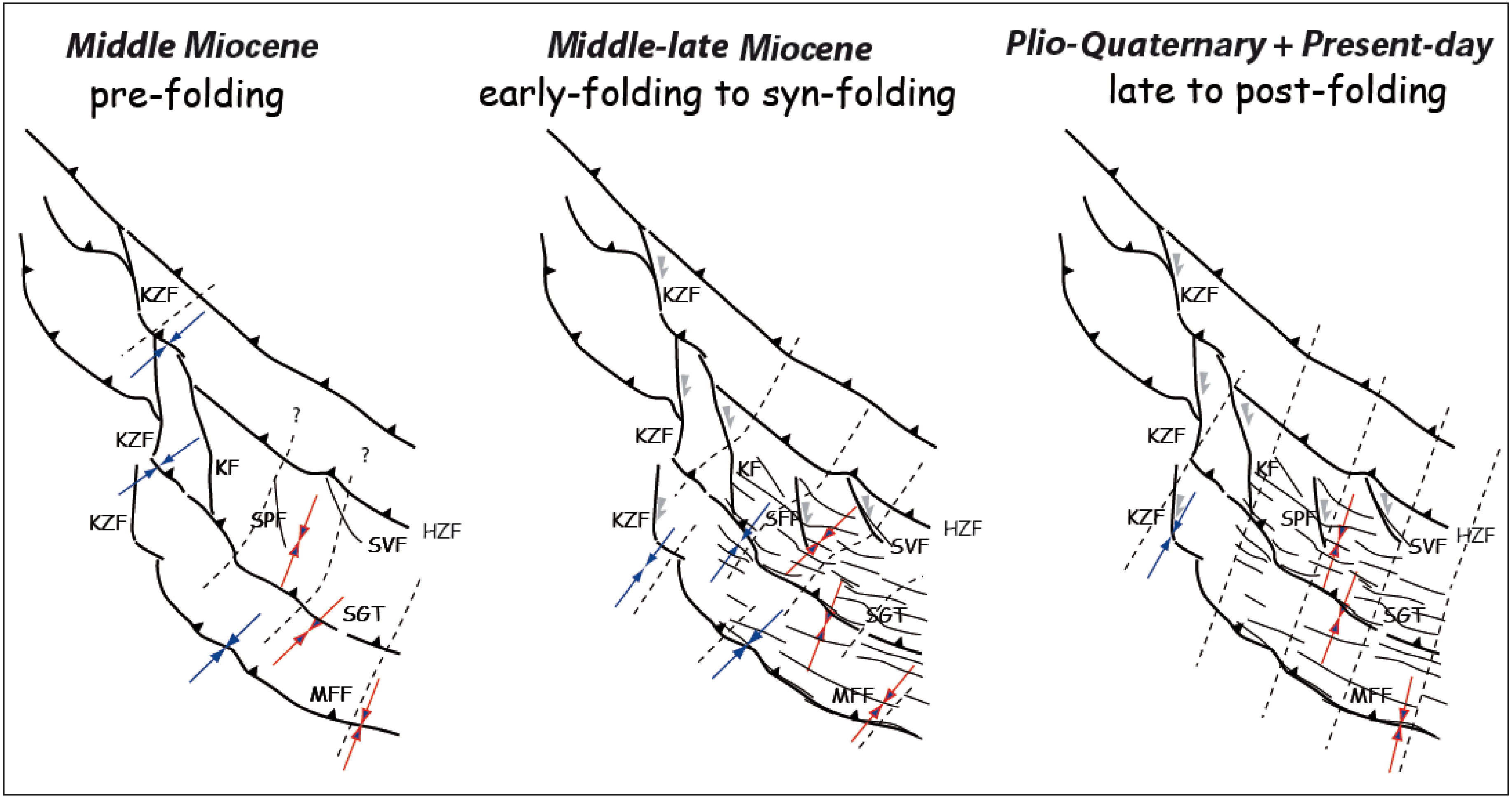
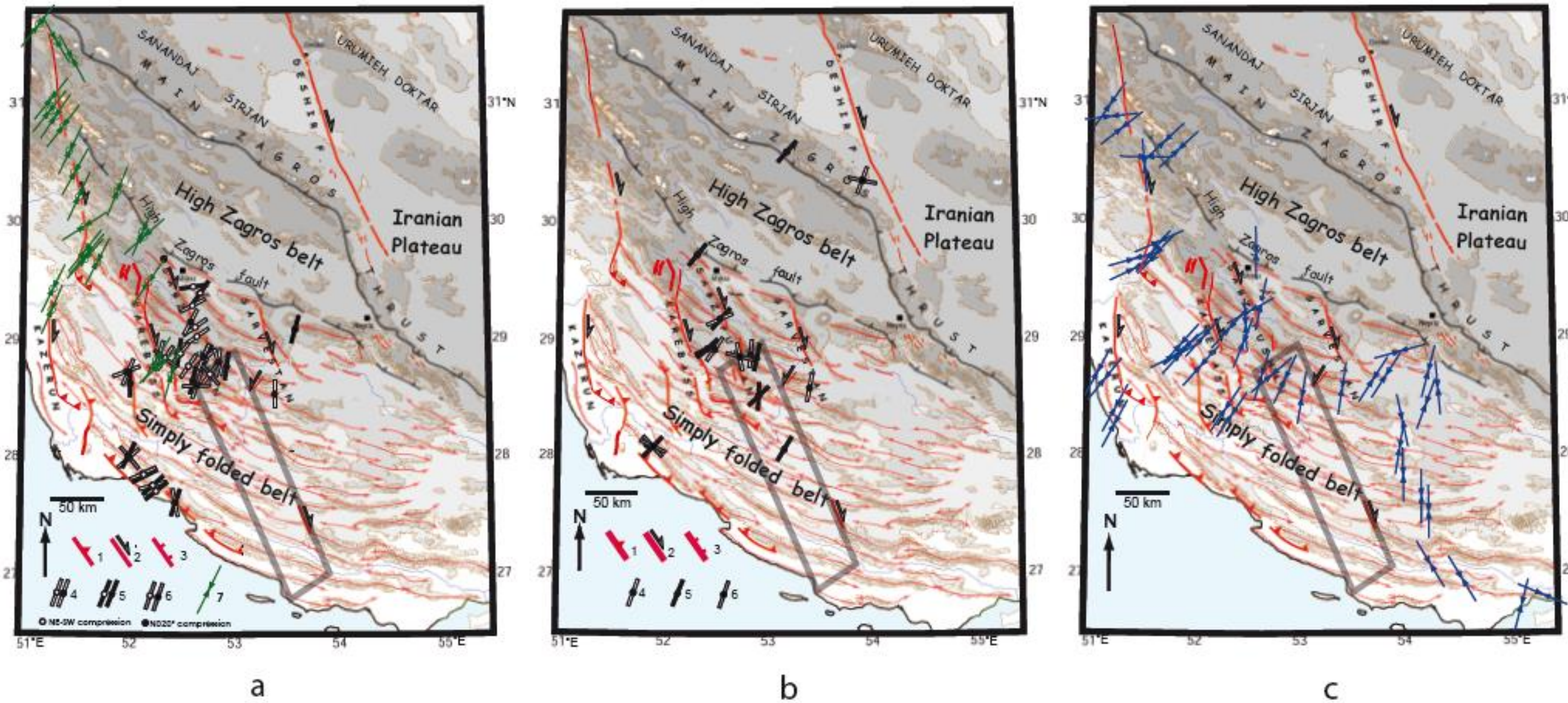
28E
27E



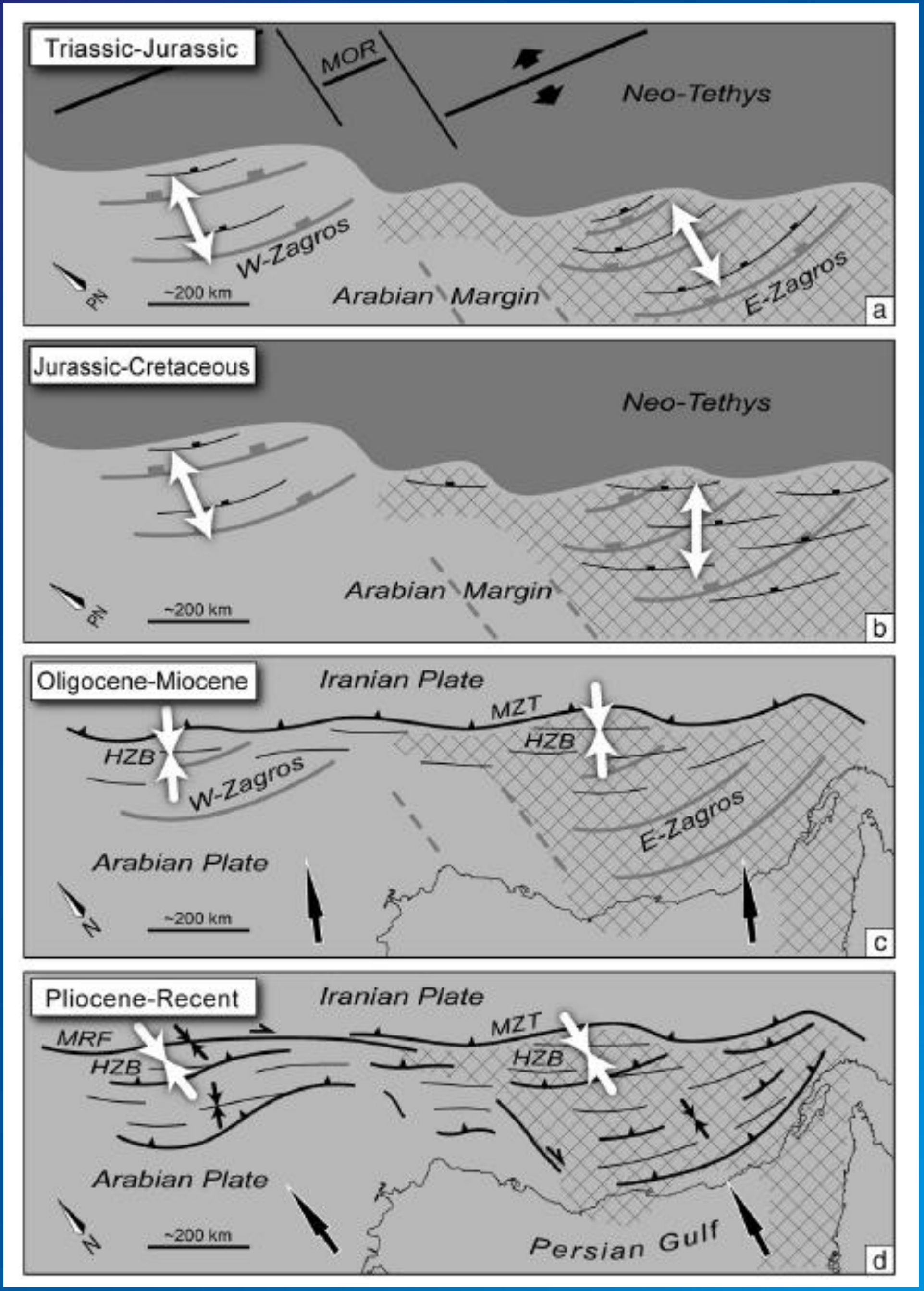
(Lacombe et al., 2006)



(Lacombe et al., 2011)

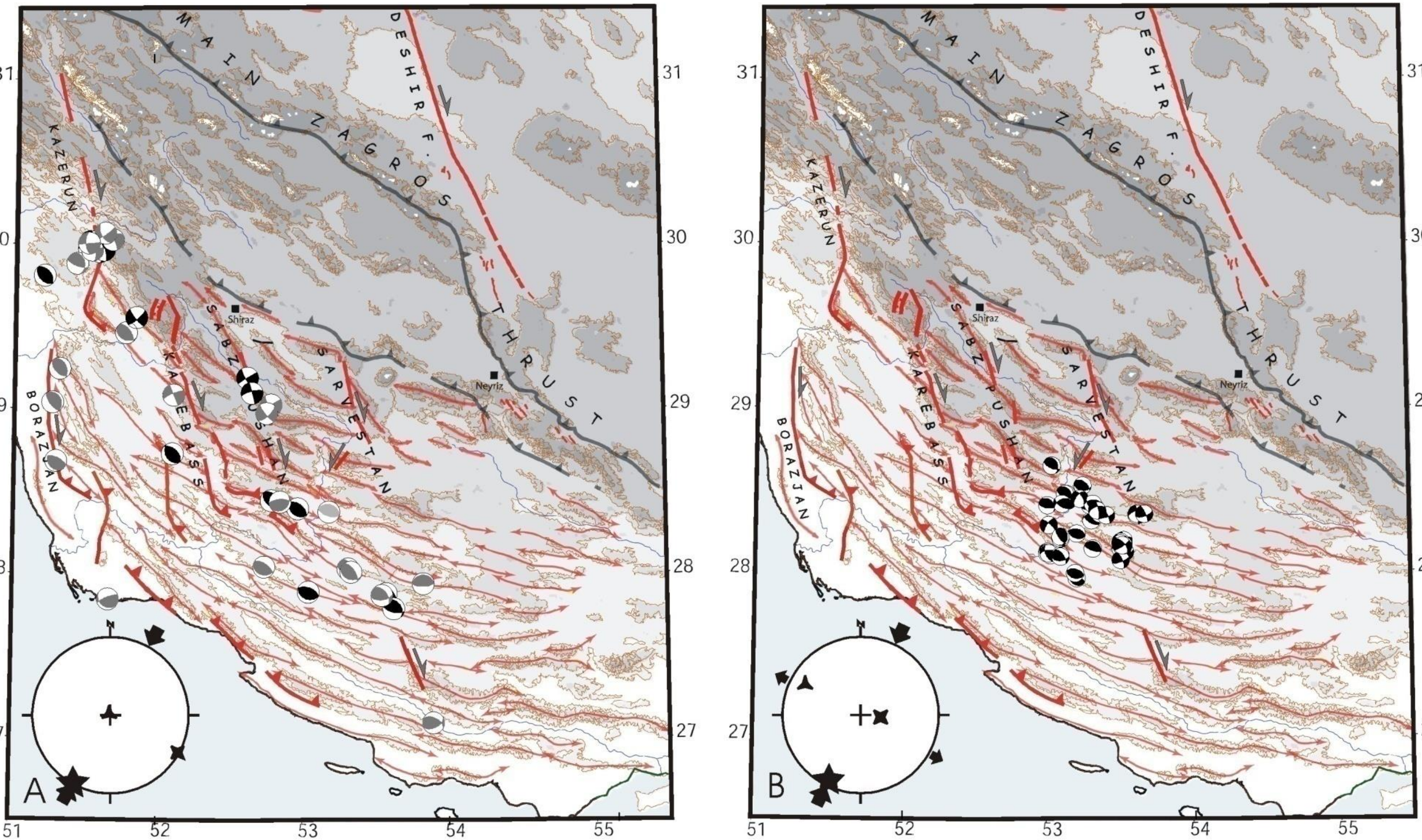


(Lacombe et al., 2011)

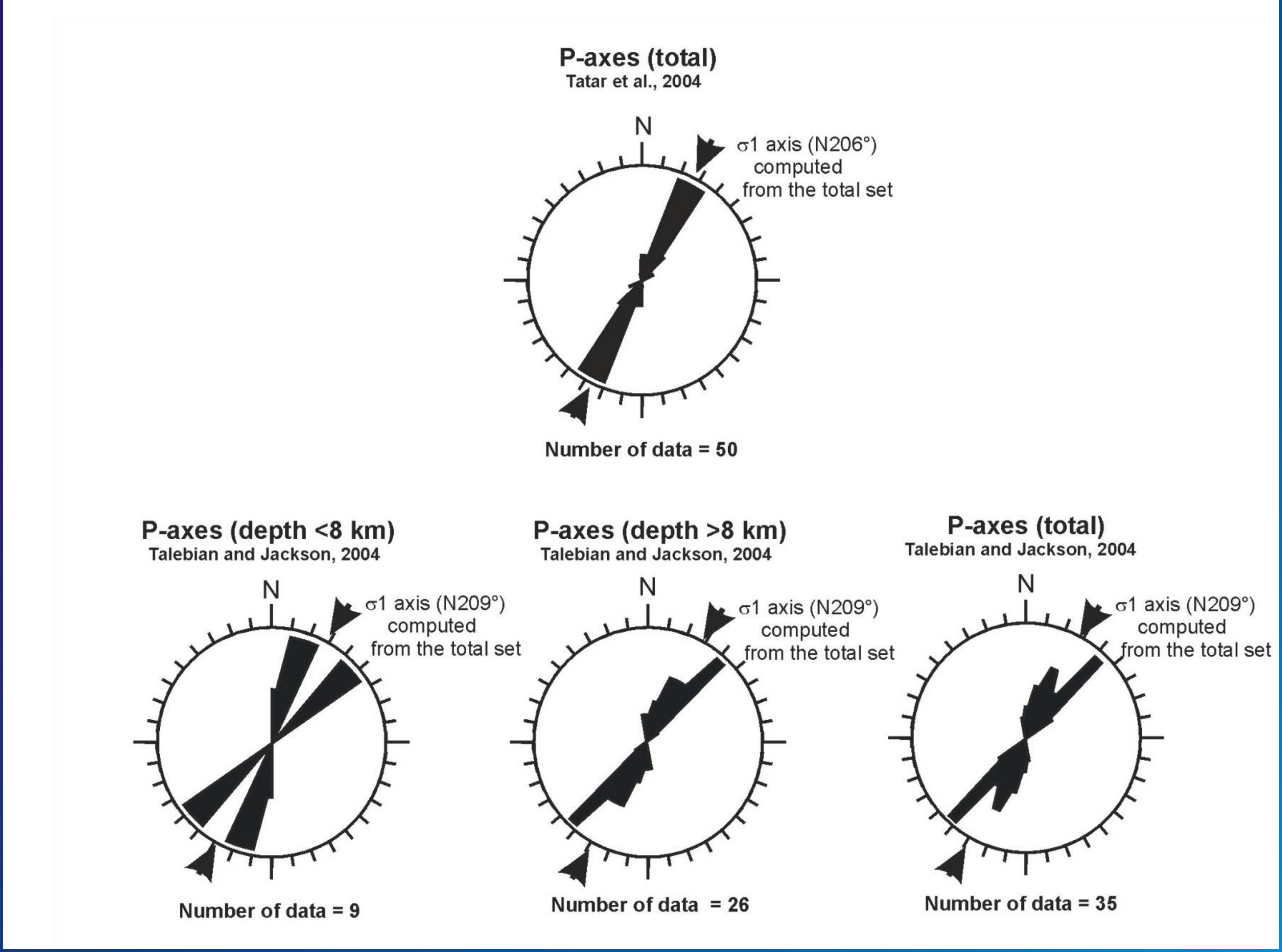


(Navabpour and Barrier, 2012)

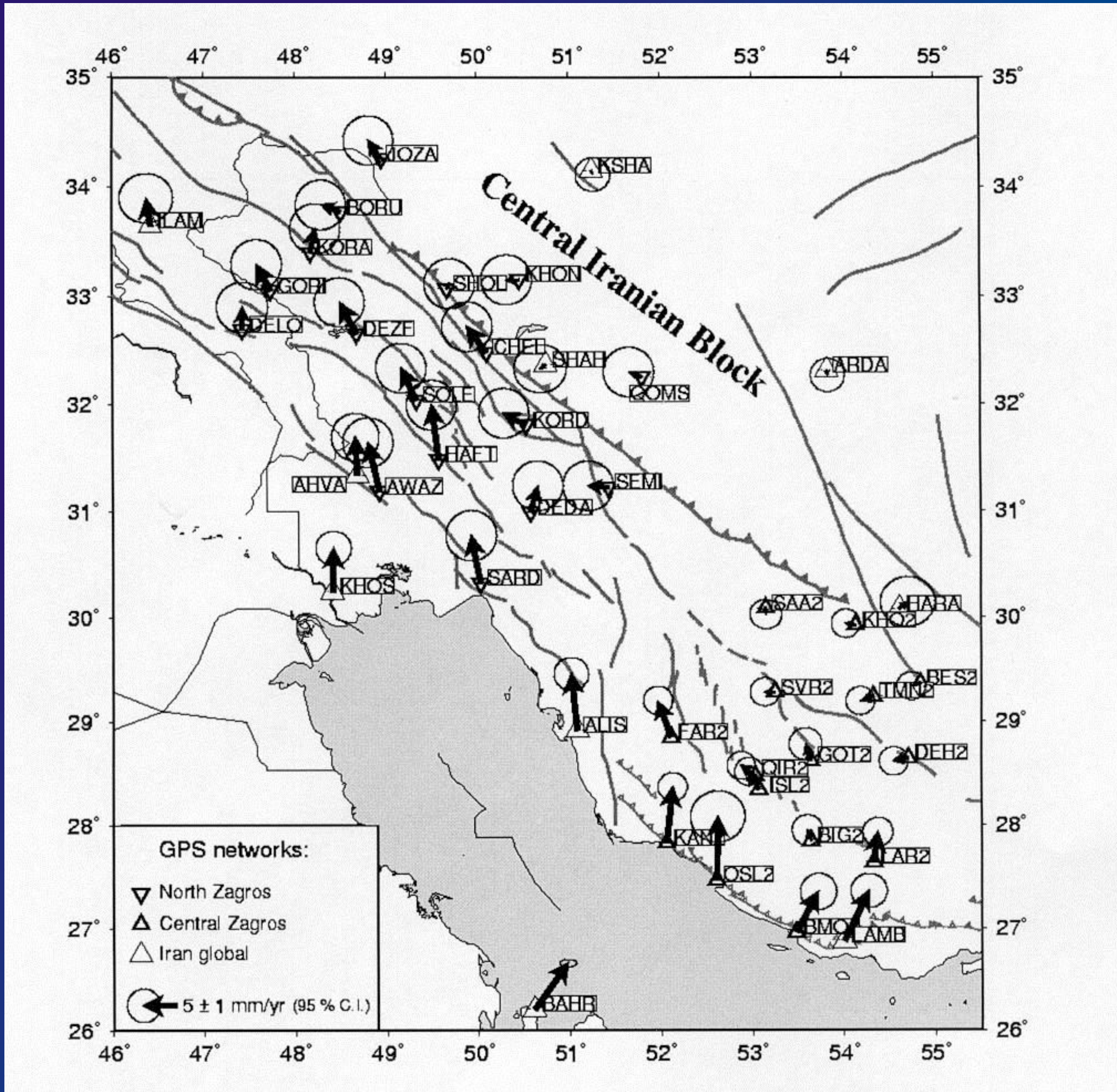
Stress/shortening patterns in the Zagros belt : earthquakes focal mechanisms and GPS measurements



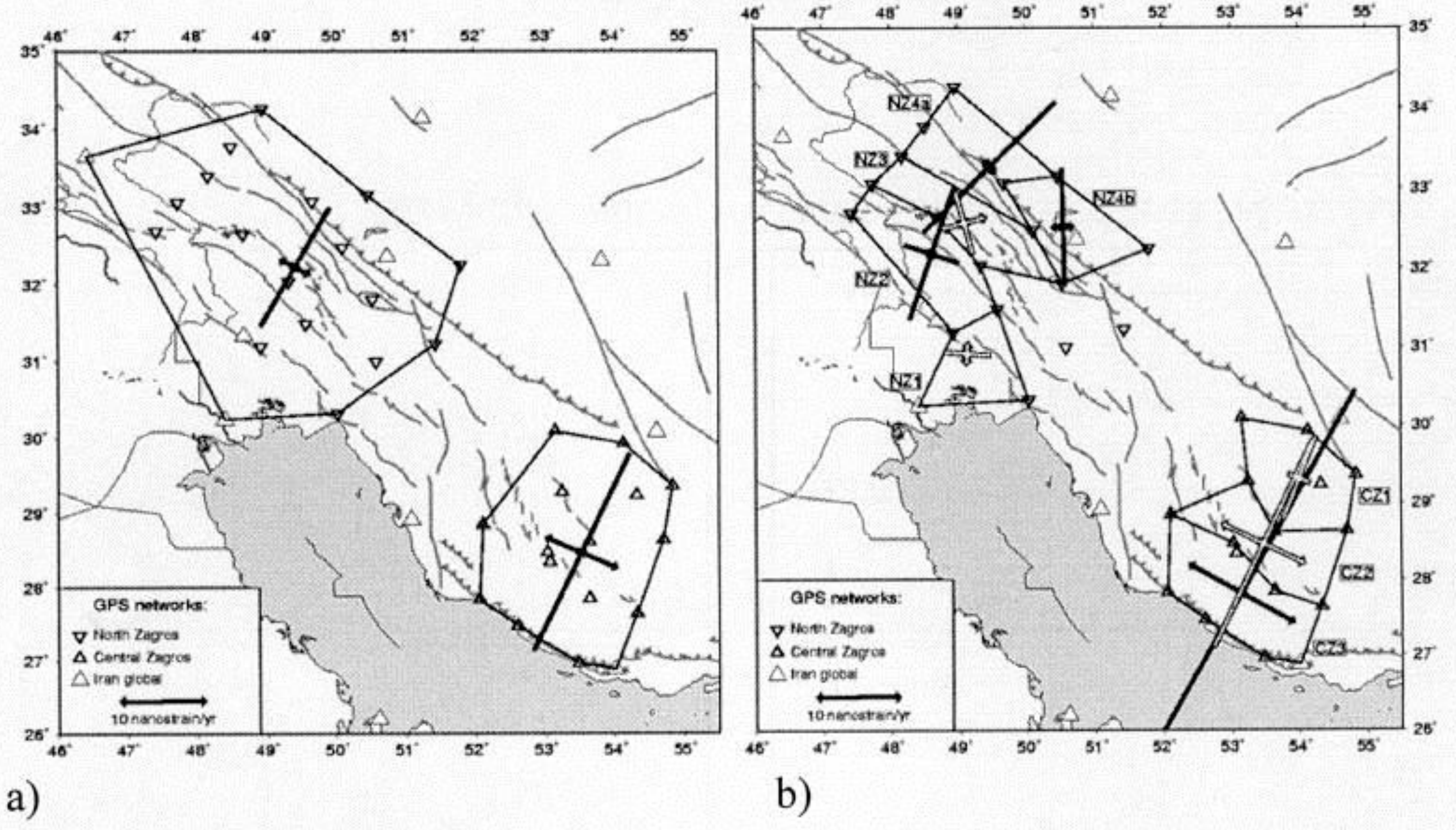
(Lacombe et al.,2006)



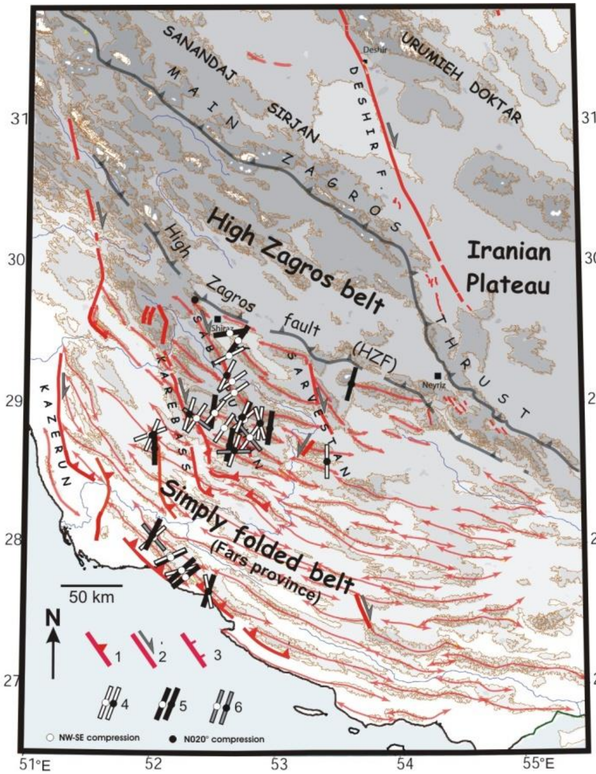
(Lacombe et al.,2006)



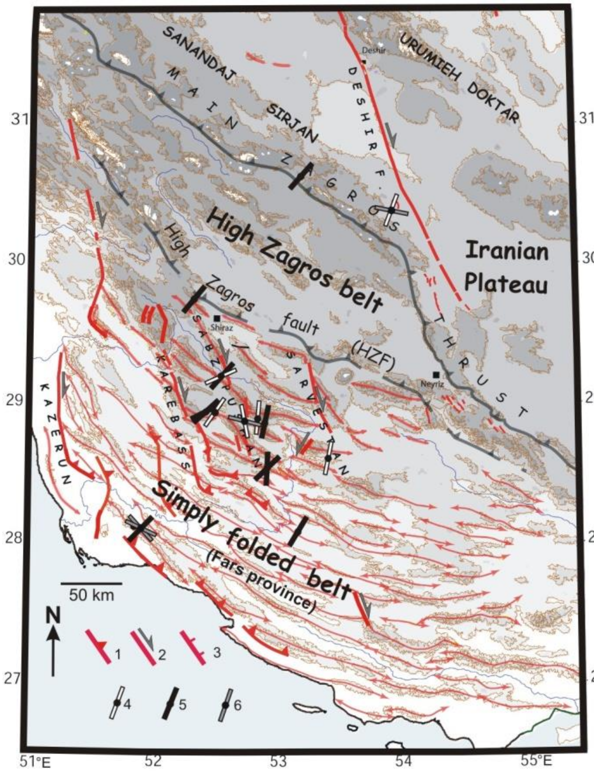
(Walpersdorf et al., 2006)



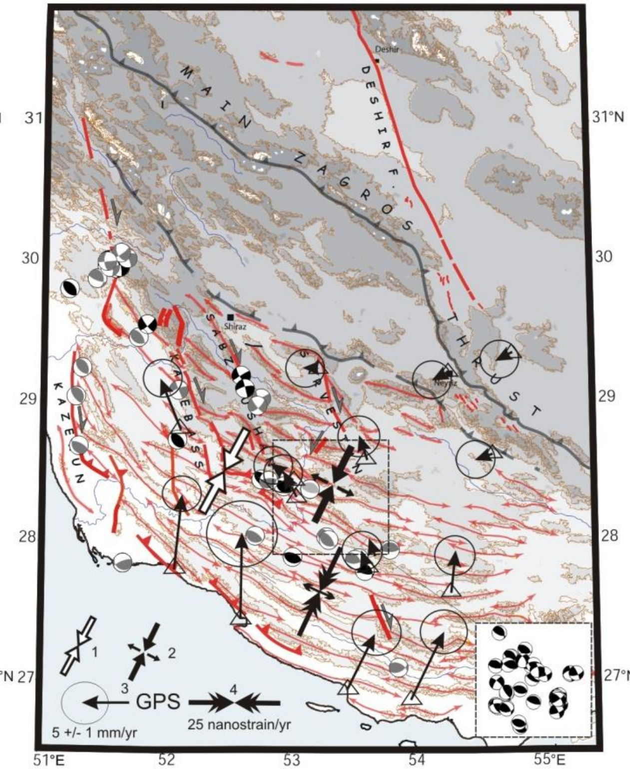
(Walpersdorf et al., 2006)



Neogene compressional trends from fault slip data in the cover (Lacombe et al., 2006)



Neogene compressional trends from calcite twin data in the cover (Lacombe et al., 2007)



Current compressional trends from earthquake focal mechanisms in the basement (Lacombe et al., 2006) and GPS shortening rates (Walpersdorf et al., 2006)

→ Neogene collisional stresses consistenyly recorded at all scales

→ The salt-bearing Hormuz master decollement poorly decouples basement and cover stress fields

- The early stage of reactivation of basement faults likely marks the onset of collisional deformation and intraplate stress build-up in the Zagros basin. Basement-involved deformation started 25–15 Ma and predated the initiation of cover folding.

- This indicates far-field stress transmission from the Arabia-Central Iran plate boundary since late Oligocene-early Miocene , and therefore efficient mechanical coupling between the Arabian and Eurasian plates since that time.

- The transmission of stress through the pre-fractured Arabian crystalline basement was however heterogeneous and complex, so the deformation front propagated in an irregular fashion through the basement and the cover.

- The sequence of deformation includes early inversion of basement faults, then more or less nearly coeval thin-skinned and thick-skinned tectonics.

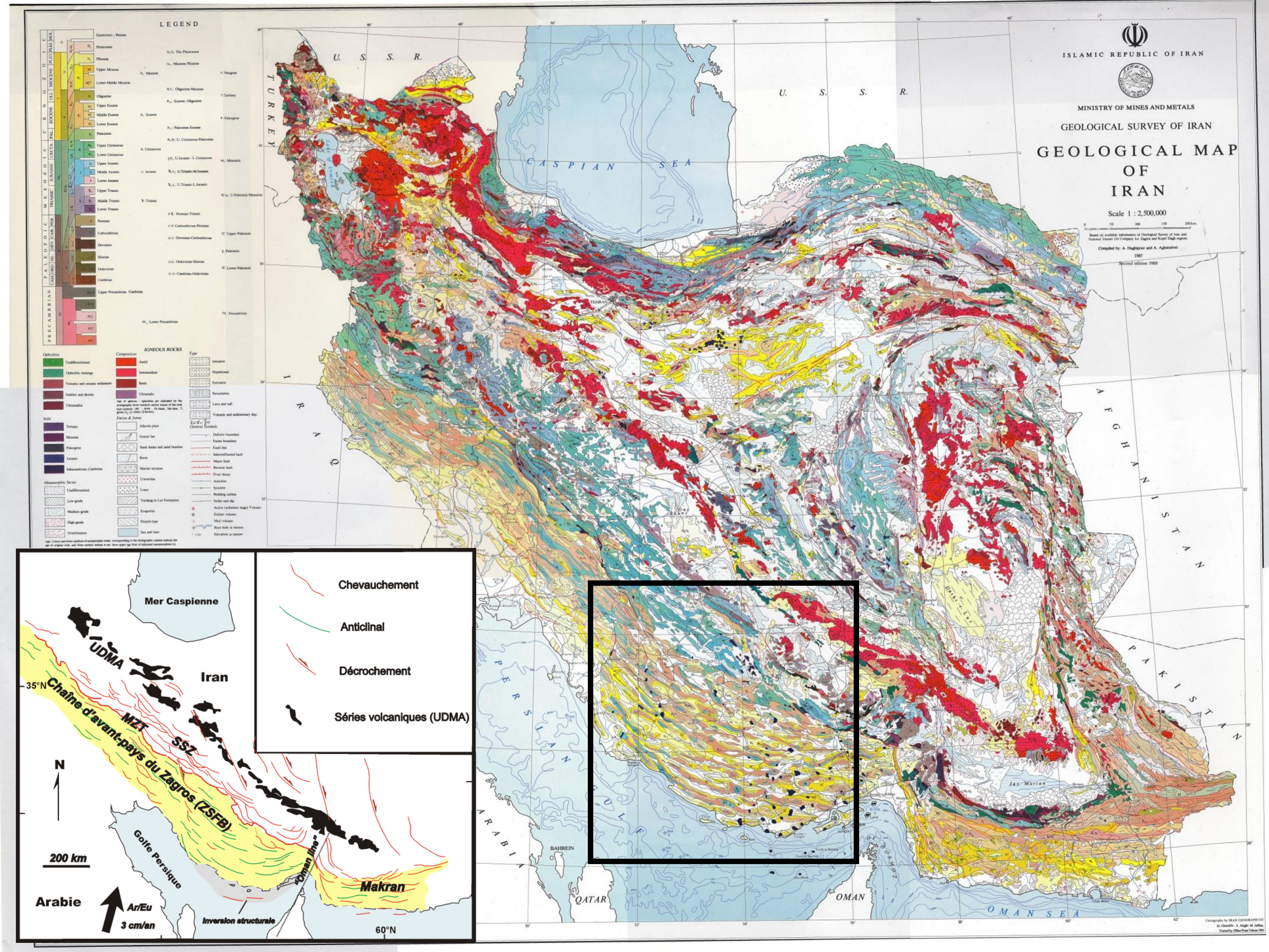
- Beyond regional implications, this study also puts emphasis on the need of carefully considering pre-folding fracture development related to early reactivation of basement faults in models of folded-fractured hydrocarbon reservoirs.

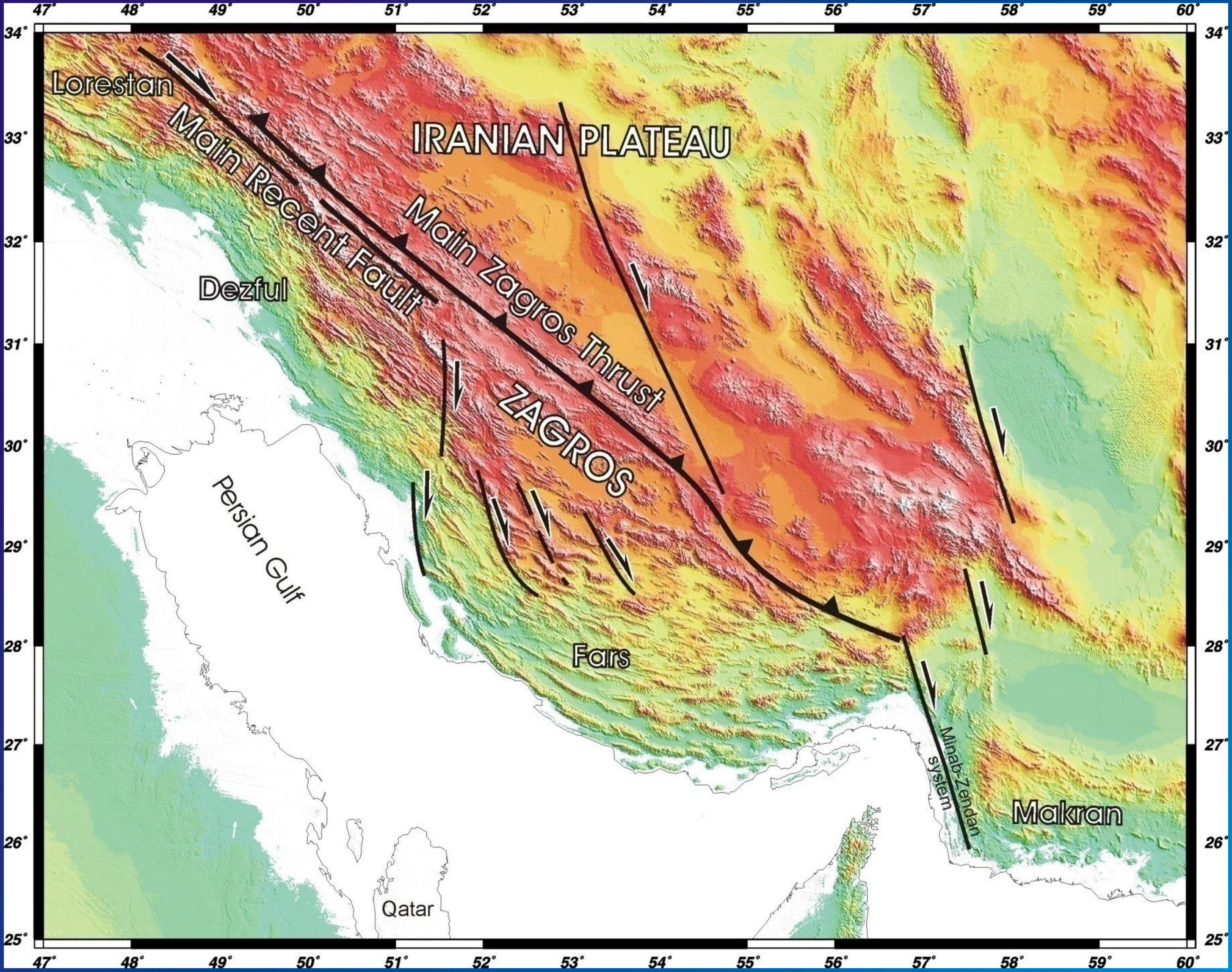
In contrast to other seismic regions of Iran (Alborz, Kopet Dagh), the seismicity in the Zagros is abundant but of low magnitude (only small to moderate earthquakes).

The comparison of seismic and geodetic strain rates indicates mainly aseismic deformation in the Zagros (Masson et al., 2005).

Cover is mainly decoupled from the basement (Hormuz salt); stress transfer from the basement to the cover may however occur during increasing strain rate (i.e., few large earthquakes).

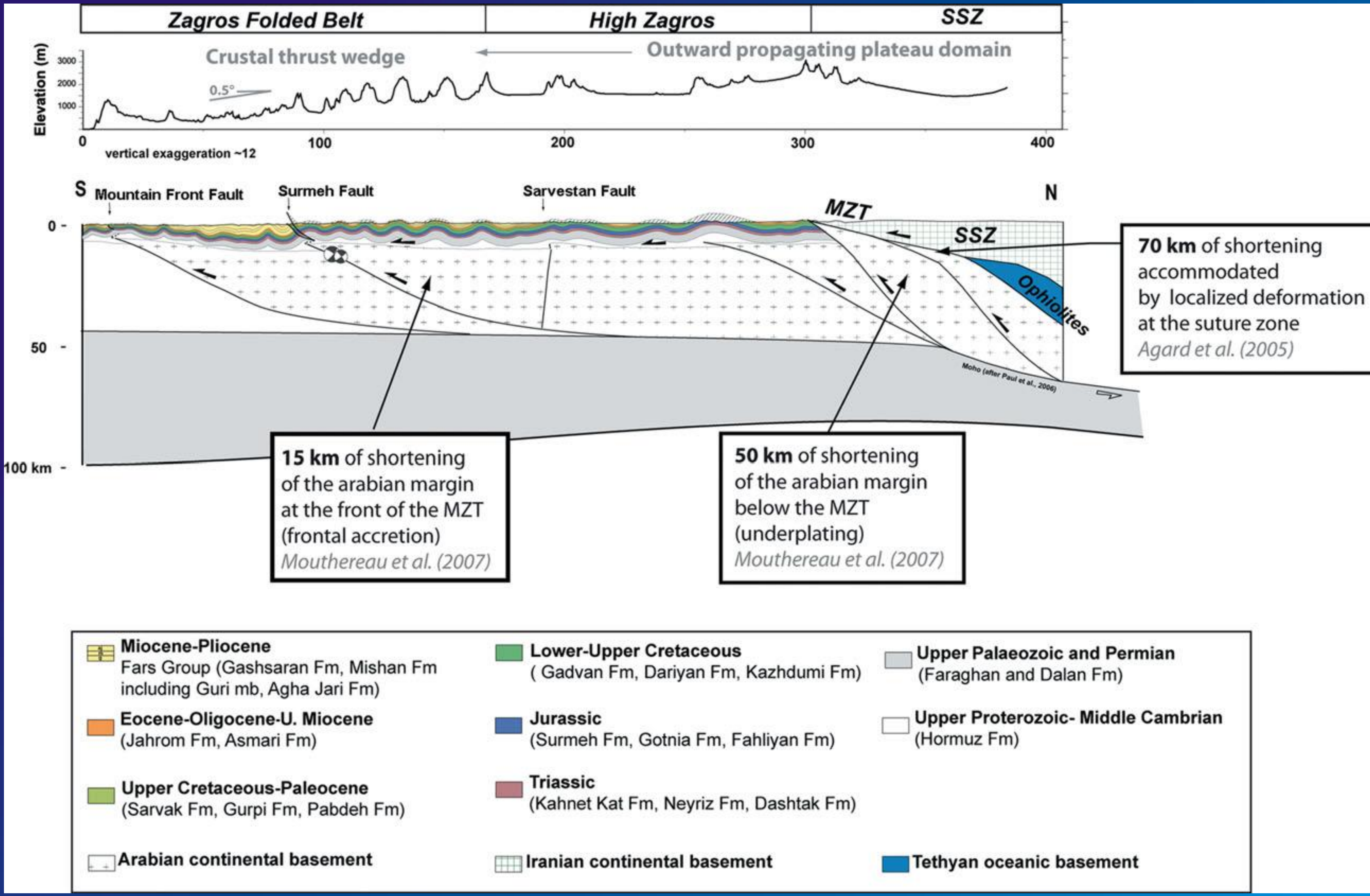
Crustal rheology, mechanics of folding and the building of topography in the Zagros


ISLAMIC REPUBLIC OF IRAN
MINISTRY OF MINES AND METALS
GEOLOGICAL SURVEY OF IRAN
GEOLOGICAL MAP OF IRAN
Scale 1 : 2,500,000
LEGEND
IGNEOUS ROCKS
U. S. S. R.
TURKEY
CASPIAN SEA
IRAQ
AFGHANISTAN
PAKISTAN
PERSIAN GULF
ARABIA
QATAR
BAHREIN
OMAN
OMAN SEA
Mer Caspienne
UDMA
Iran
35°N
Chaîne d'avant-pays du Zagros (ZSFB)
MZT
SSZ
N
200 km
Golfe Persique
"Oman line"
Makran
Arabie
Ar/Eu
3 cm/an
Inversion structurale
60°N
Chevauchement
Anticlinal
Décrochement
Séries volcaniques (UDMA)

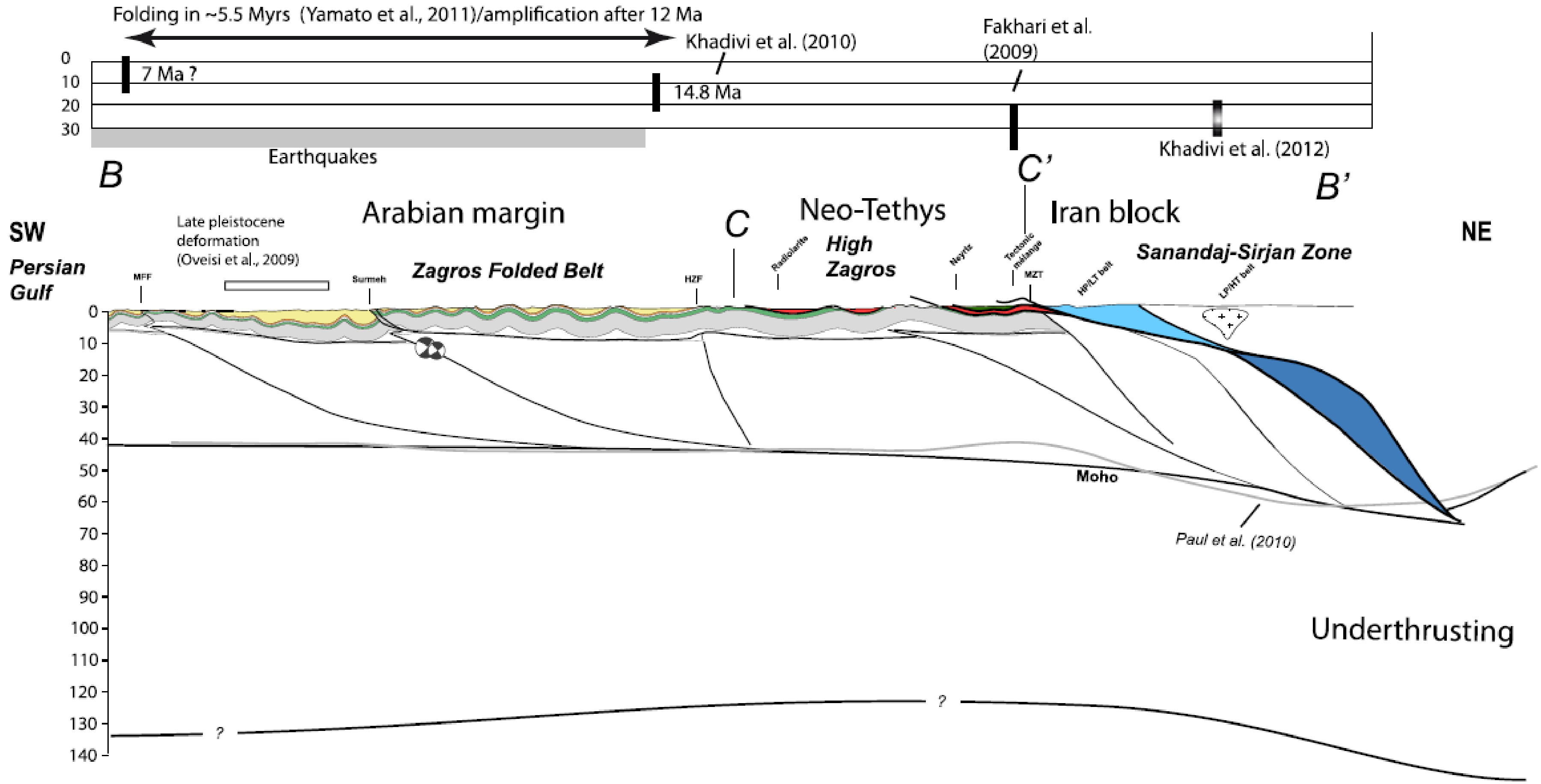


Lorestan
Main Recent Fault
Main Zagros Thrust
IRANIAN PLATEAU
Dezful
ZAGROS
Persian Gulf
Fars
Minab-Zendan system
Makran
Qatar

Fars

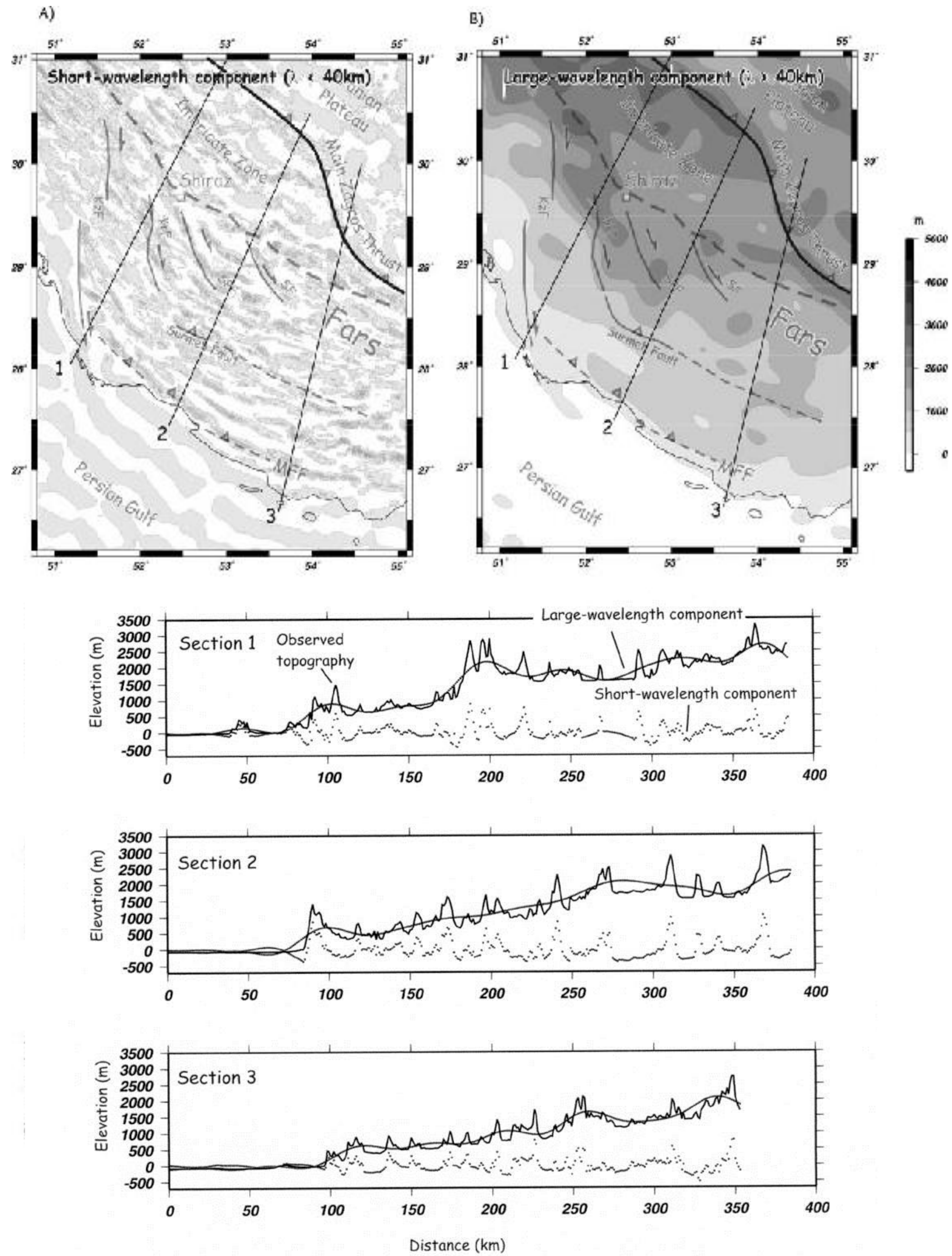


(Mouthereau, 2011)

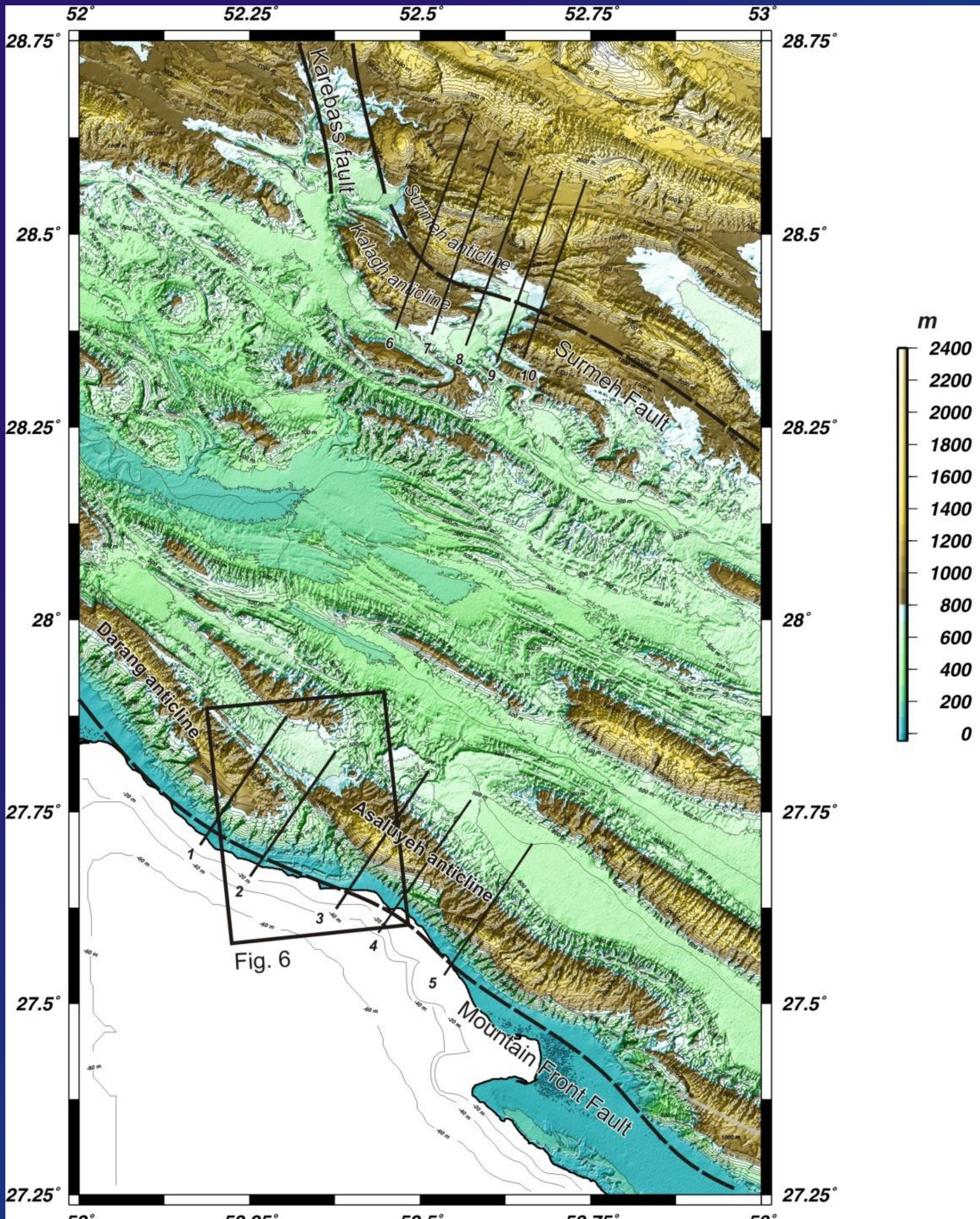


(Mouthereau et al., 2012)

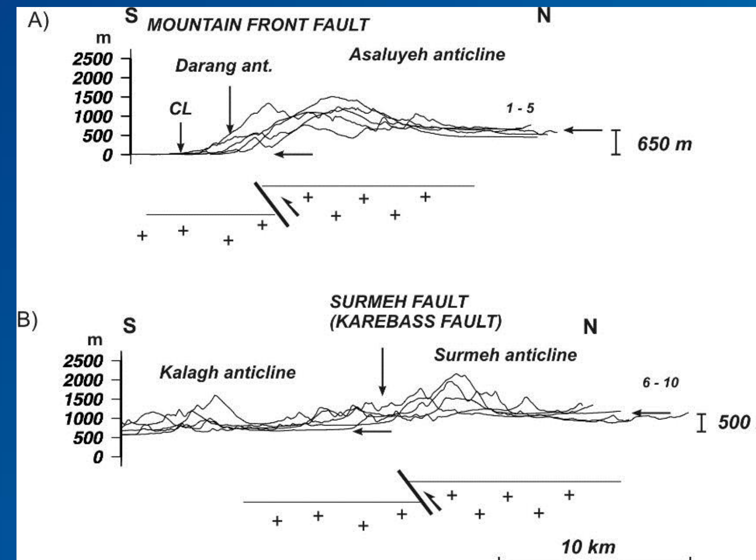
Analysis of topography



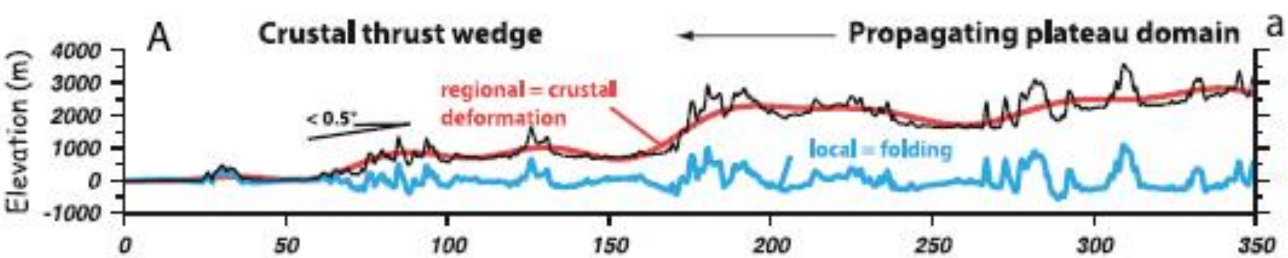
(Mouthereau et al., 2006)

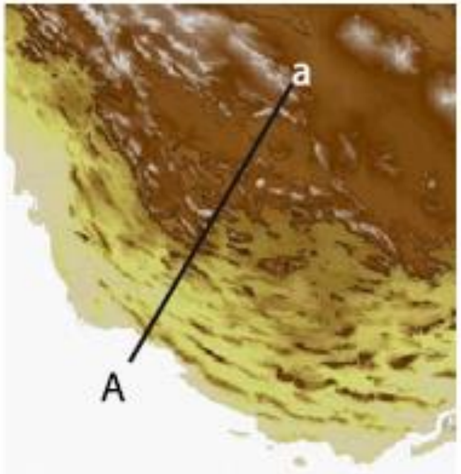


(Mouthereau et al.,2006)

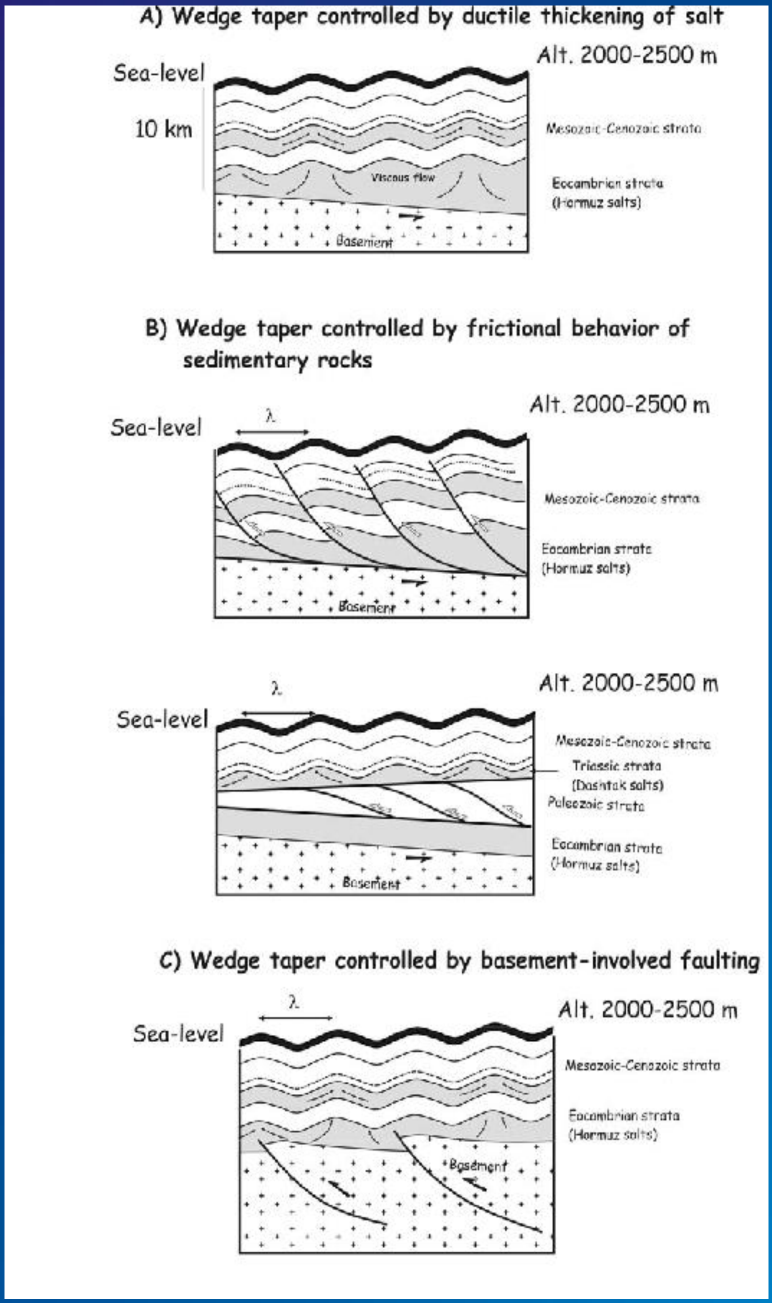


Wavelength components of the topography (Fars region, central Zagros)





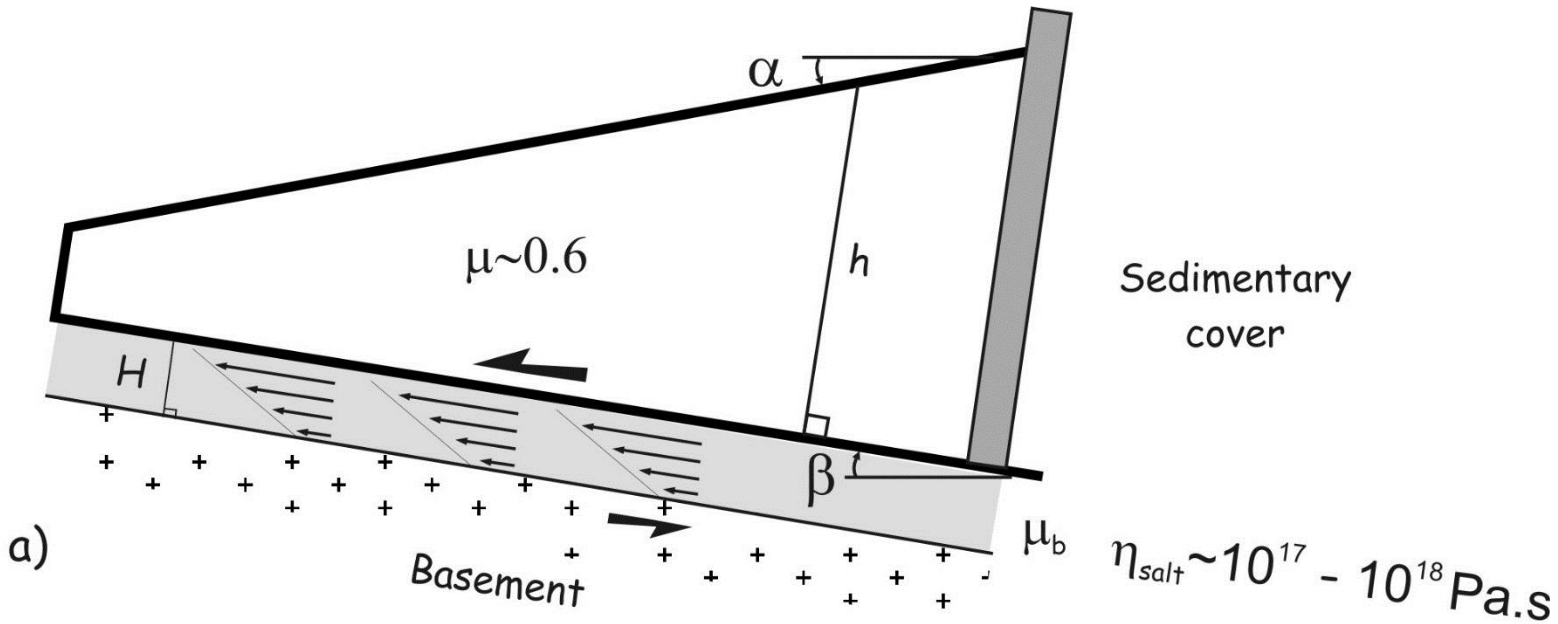
Mouthereau et al. 2012



(Mouthereau et al.,2006)

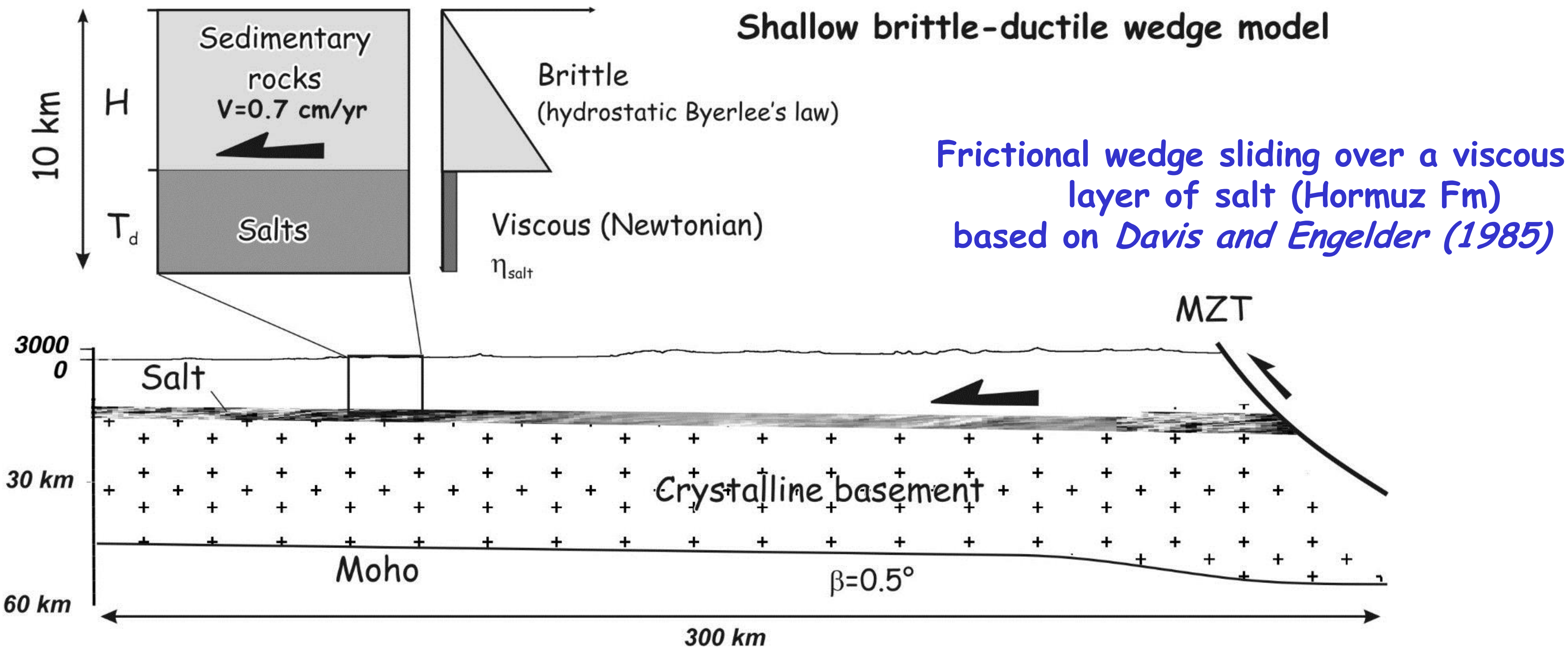
Wedge modelling

$$\alpha + \beta = \frac{\mu_b + \beta}{1 + K}$$



(Mouthereau et al.,Geophys. J. Int., 2006)

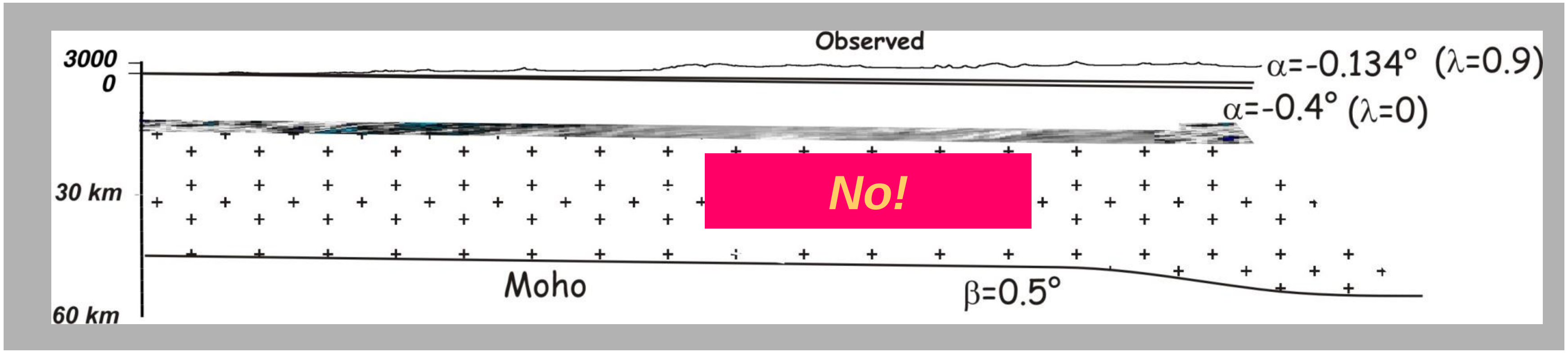
Salt/cover wedge assumption



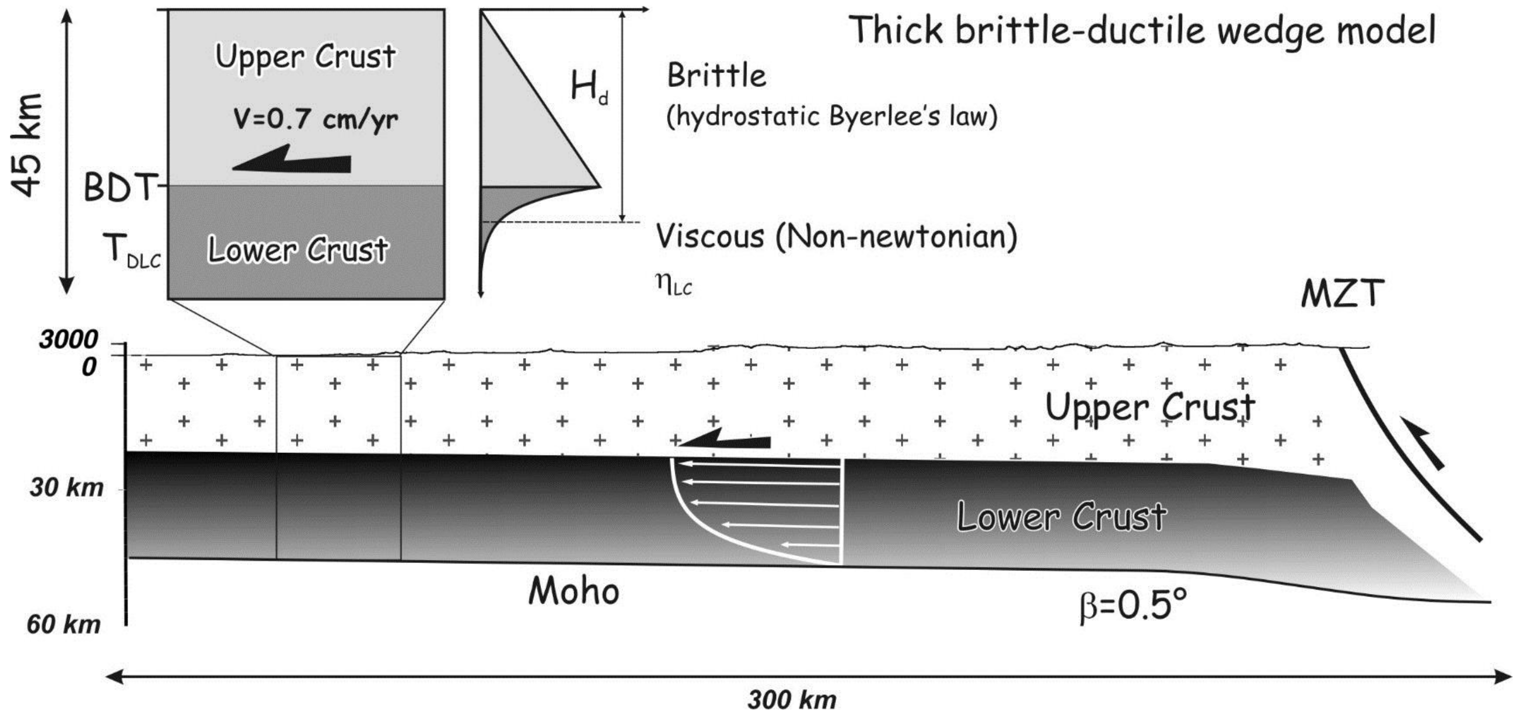
Frictional wedge sliding over a viscous layer of salt (Hormuz Fm) based on *Davis and Engelder (1985)*

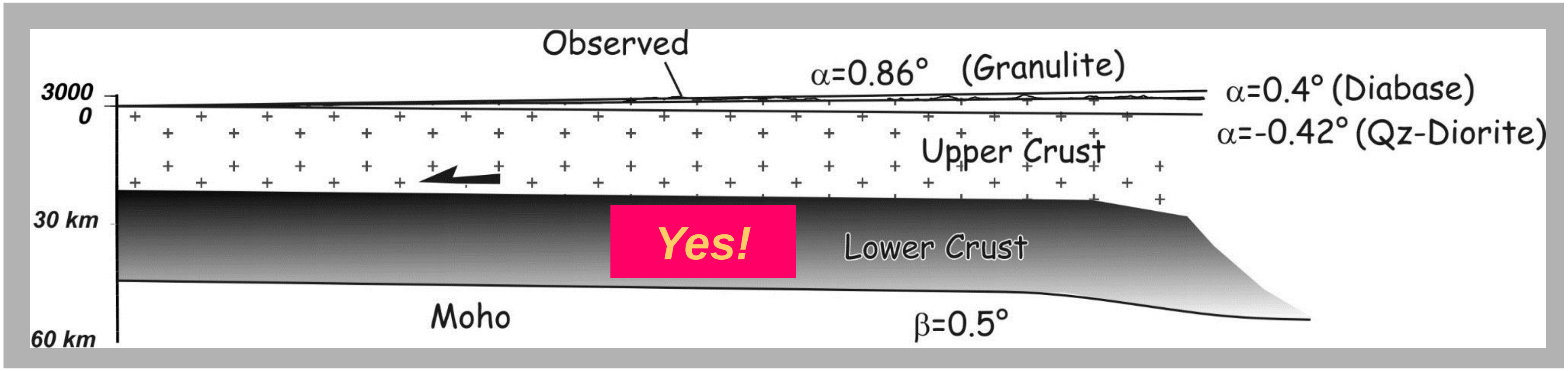
Viscosities 10^{17} to 10^{18} Pa.s (higher bounds)
Internal friction angles 30-40°

Salt thickness 0.5-1-2 km
Variable pore fluid ratio

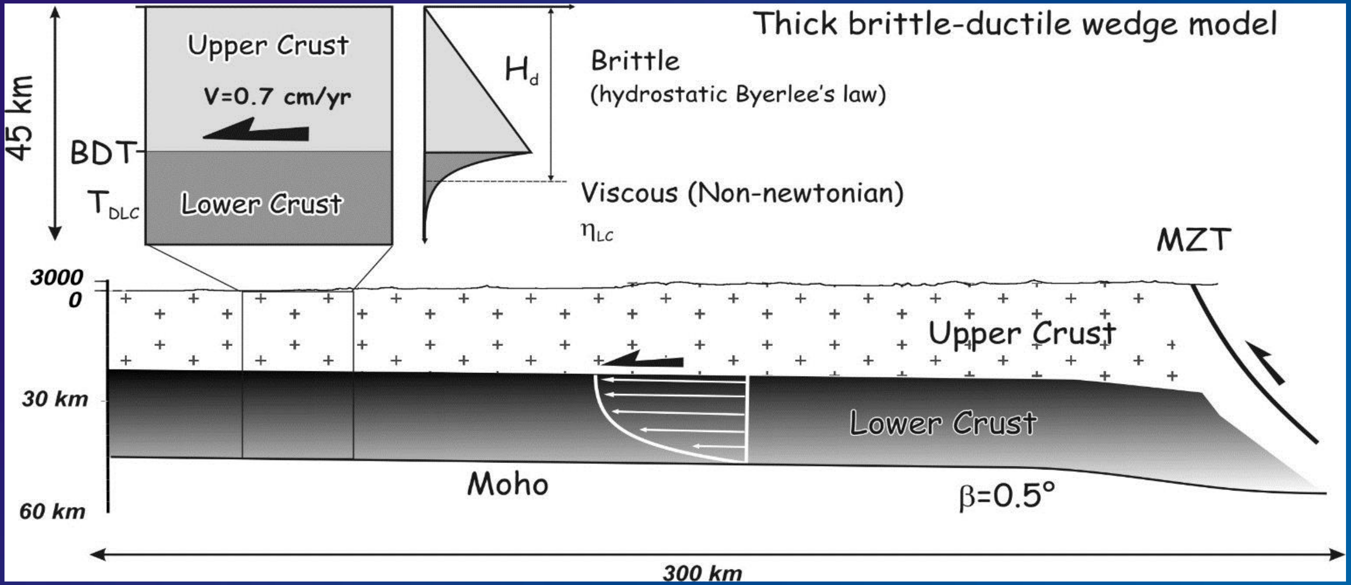


Crustal wedge assumption

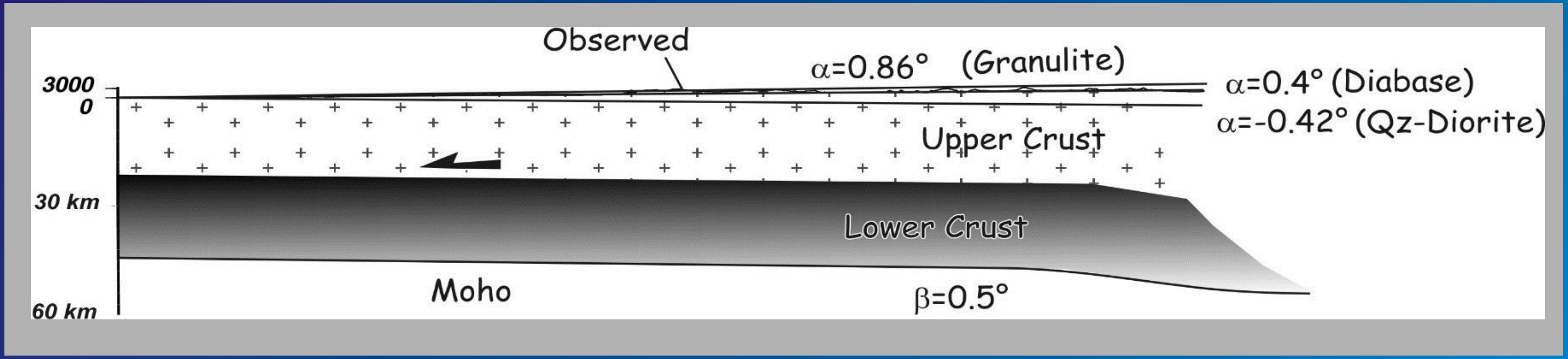




Such a model involving a granulitic lower crust with sufficient viscosity is able to reproduce the observed topography

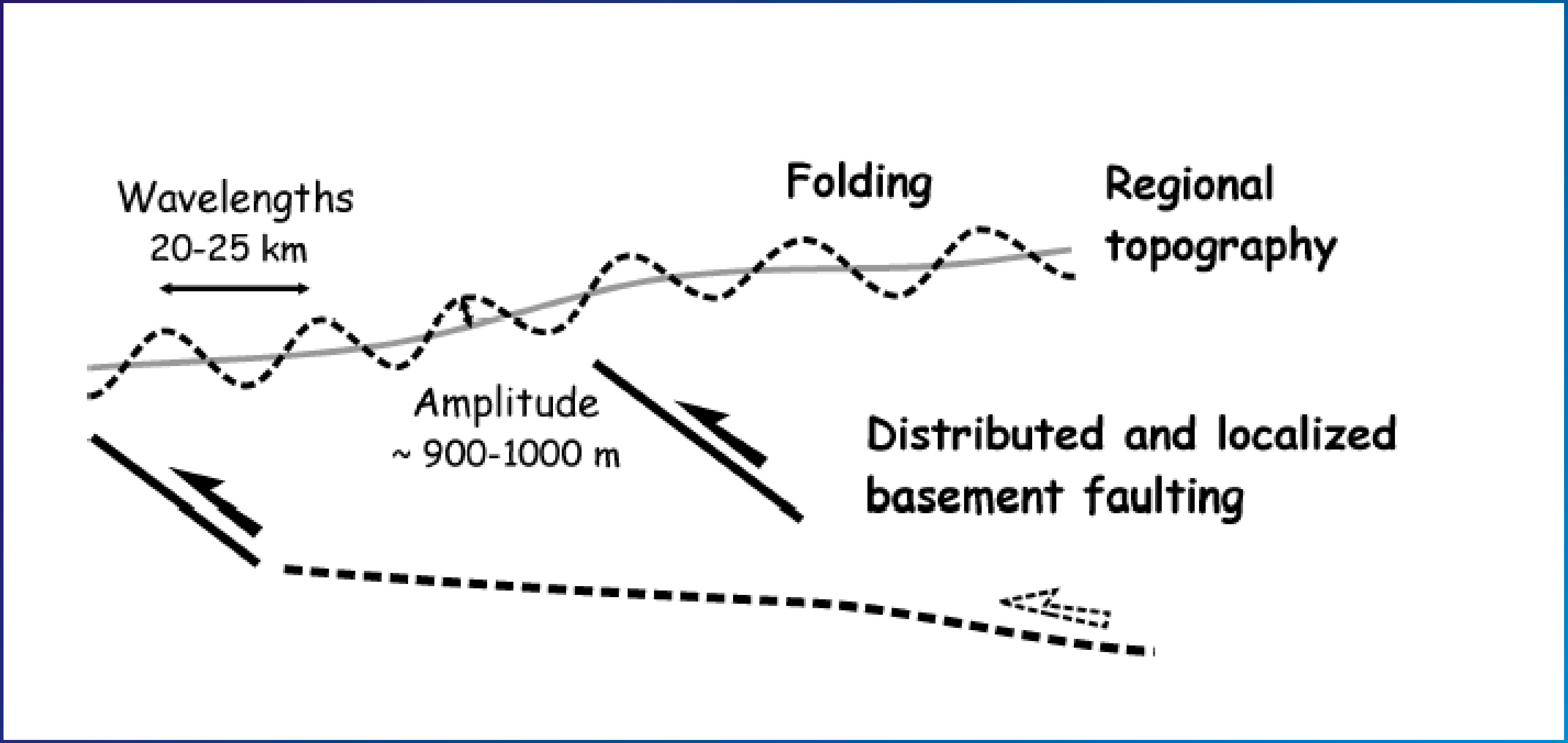


(Mouthereau et al., 2006)

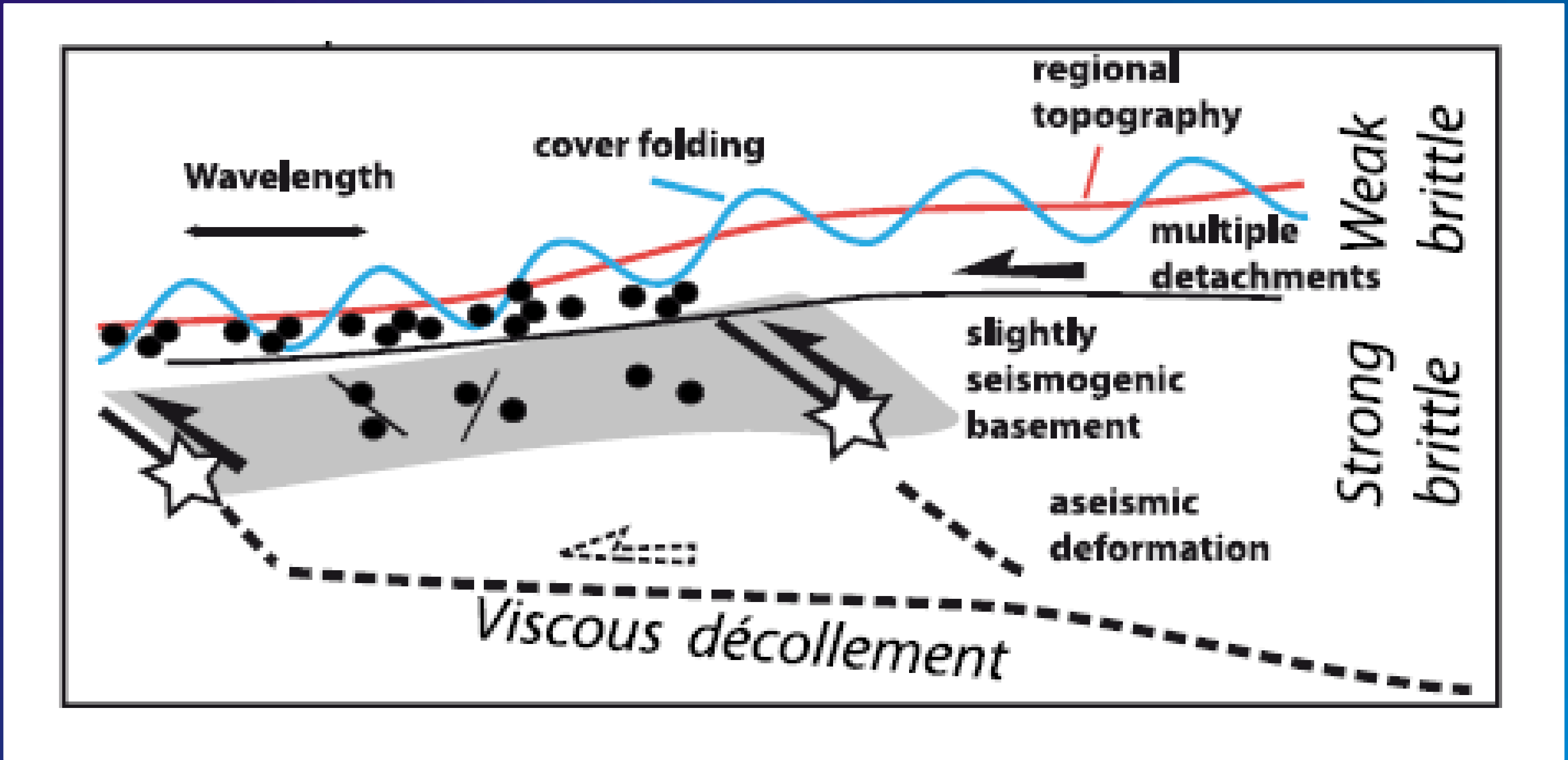


Analytical modelling of the Zagros wedge

→ salt is unable to sustain topography; only a model of critically-tapered brittle–viscous wedge involving the crystalline basement reproduces the observed topographic slopes across the Fars



(Mouthereau et al., 2007)

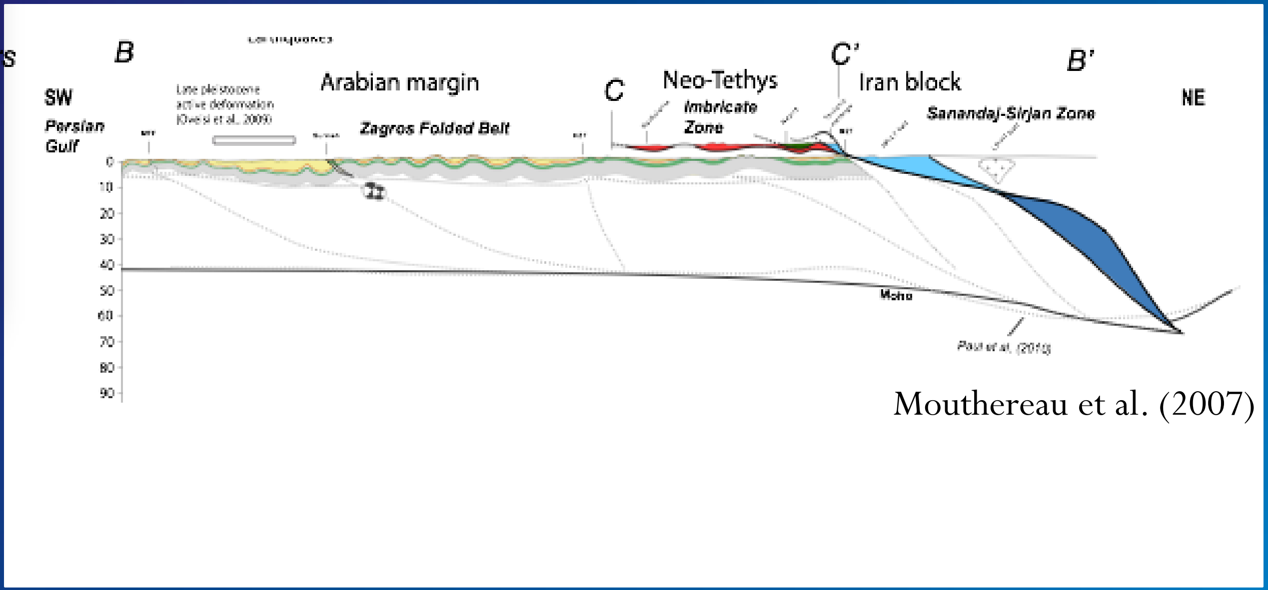


(Mouthereau et al., 2012)

Zagros = superimposed thin-skinned and thick-skinned tectonics

Zagros : inverted Mesozoic rifted margin

Shortening : ~37 %

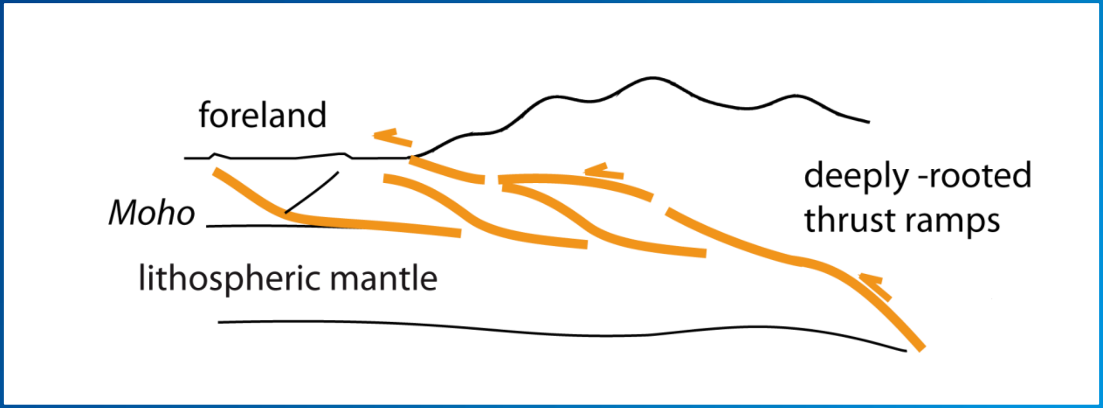


Mouthereau et al. (2007)

Convergence 7km/Ma
Erosion rate <2 km/Ma

style thick-skinned
"pure-shear"

Decoupling within middle-lower crust
h ~ 15-20 km




Thank you for your attention…

Suggested readings :

Ahmadhadi F., Daniel J.M., Azzizadeh M. & Lacombe O., 2008, Evidence for pre-folding vein development in the Oligo-Miocene Asmari Formation in the Central Zagros Fold Belt, Iran**.** **Tectonics**, 27, TC1016

Lacombe O., Mouthereau F., Kargar S. & Meyer B., 2006, Late Cenozoic and modern stress fields in the western Fars (Iran) : implications for the tectonic and kinematic evolution of Central Zagros. **Tectonics**, 25, TC1003

Lacombe O., Bellahsen N. & Mouthereau F., 2011, Fracture patterns in the Zagros Simply Folded Belt (Fars): New constraints on early collisional tectonic history and role of basement faults. In "Geodynamic evolution of the Zagros", O. Lacombe, B. Grasemann and G. Simpson eds, **Geological Magazine**, 148, 940-963

Mouthereau F., Lacombe O. & Meyer B., 2006, The Zagros Folded Belt (Fars, Iran) : constraints from topography and critical wedge modelling, **Geophys. J. Int**., 165(1), 336-356

Mouthereau F., Tensi J., Bellahsen N., Lacombe O., Deboisgrollier T. & Kargar S., 2007, Tertiary sequence of deformation in a thin-skinned/thick-skinned collision belt : the Zagros Folded Belt (Fars, Iran). **Tectonics**, 26, TC5006

Mouthereau F., Lacombe O. & Verges J., 2012. Building the Zagros collisional orogen: timing, strain distribution and the dynamics of Arabia/Eurasia plate convergence. **Tectonophysics**, 532-535, 27-60

Talebian, M.& Jackson J.A. , 2004. A reappraisal of earthquake focal mechanisms and active shortening in the Zagros mountains of Iran, **Geophys. J. Int.**,156, 506 – 526.