SU, M2 GEOP, 2018

Thin-skinned and thick-skinned structural styles in foreland fold-and-thrust belts of some Tertiary orogens

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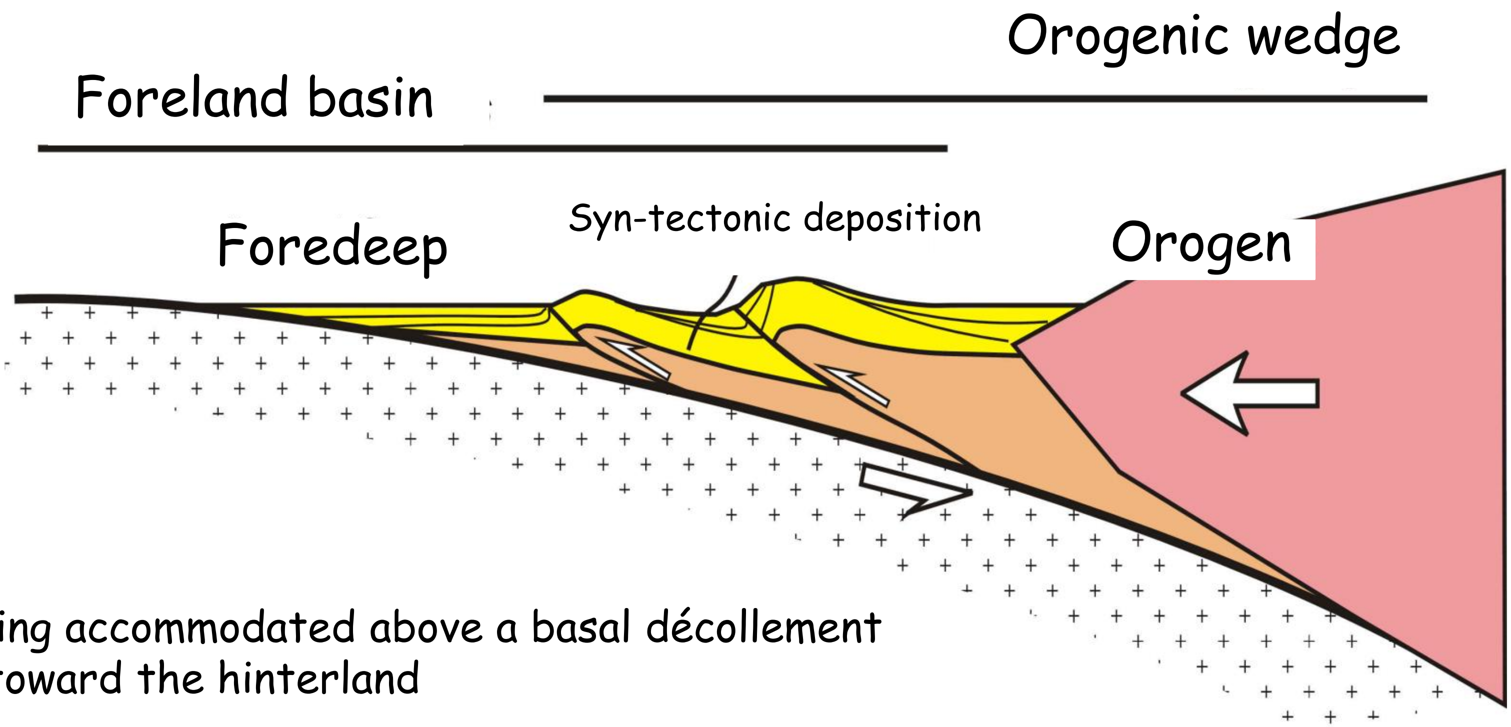
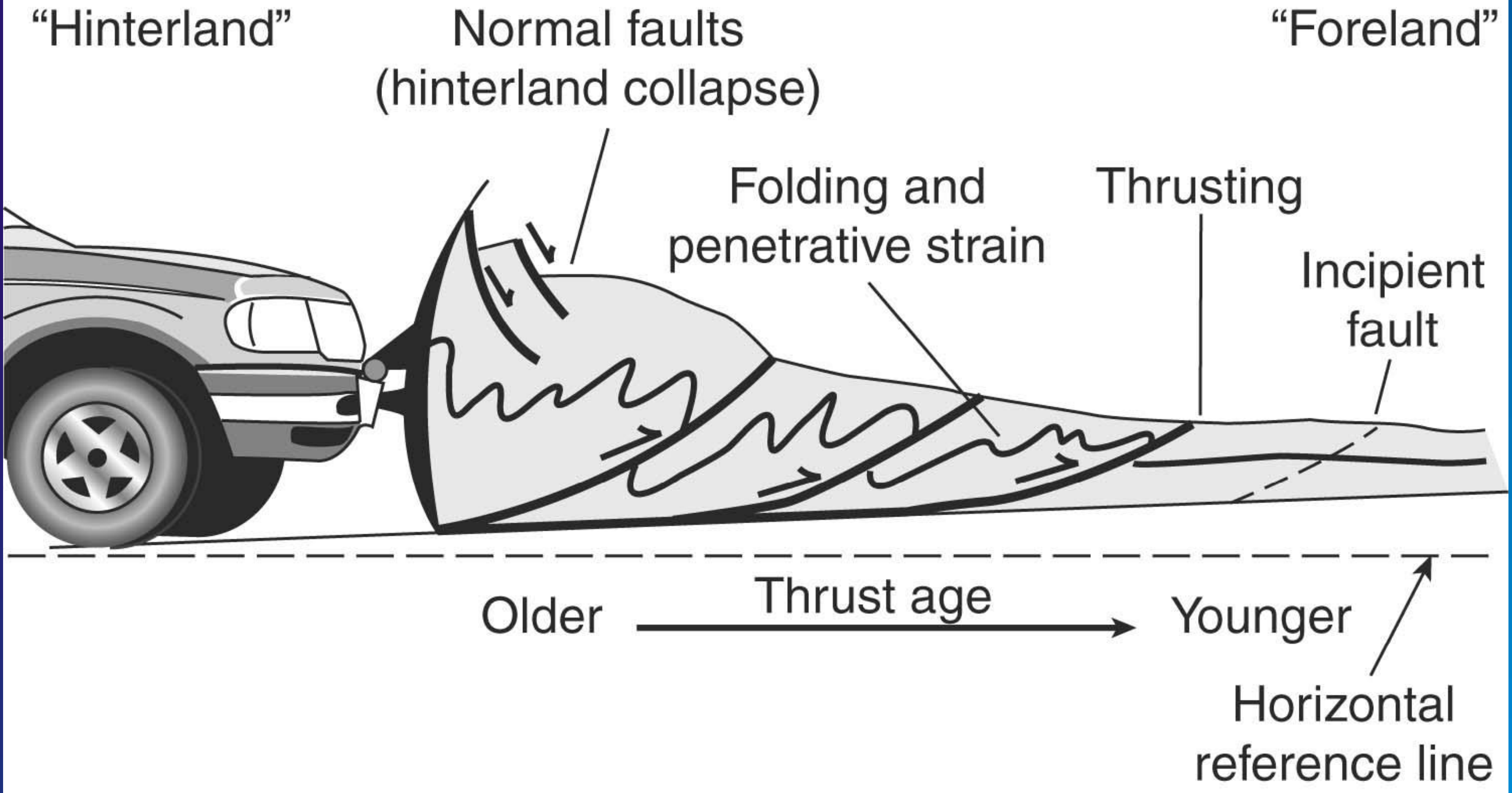
Defining the structural style of fold-and-thrust belts and understanding the controlling factors are necessary steps toward prediction of their long-term and short-term dynamics,
including seismic hazard, and to assess their potential in terms of hydrocarbon exploration.

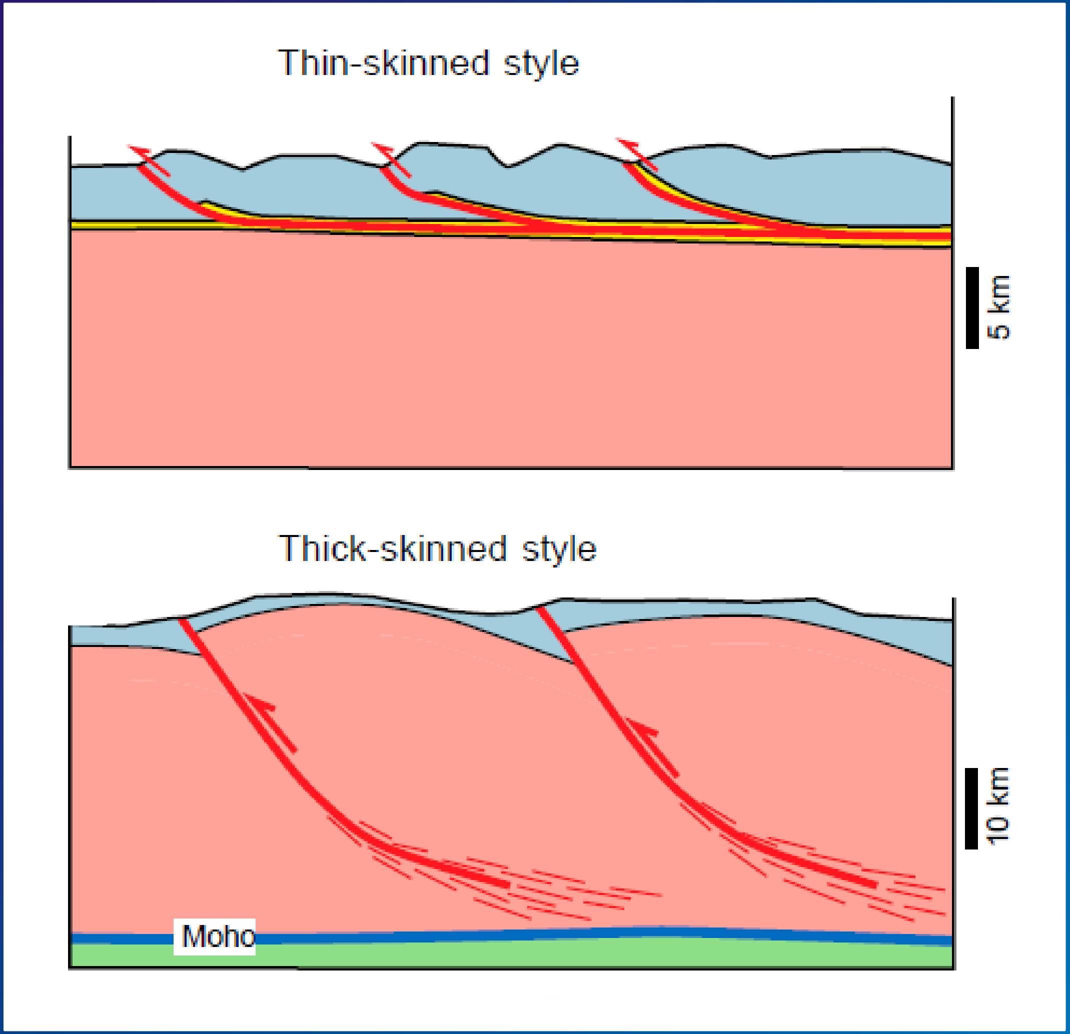


Shortening accommodated above a basal décollement dipping toward the hinterland

Topographic slope and dip of basal décollement define the orogenic wedge


"Hinterland"
Normal faults
(hinterland collapse)
"Foreland"
Folding and
penetrative strain
Thrusting
Incipient
fault
Older
Thrust age
Younger
Horizontal
reference line

(Pfiffner, 2017)



In thick-skinned (i.e., basement-involved) FTBs, shortening involves a significant part of the crust above a deep ductile detachment (≠ thin-skinned)

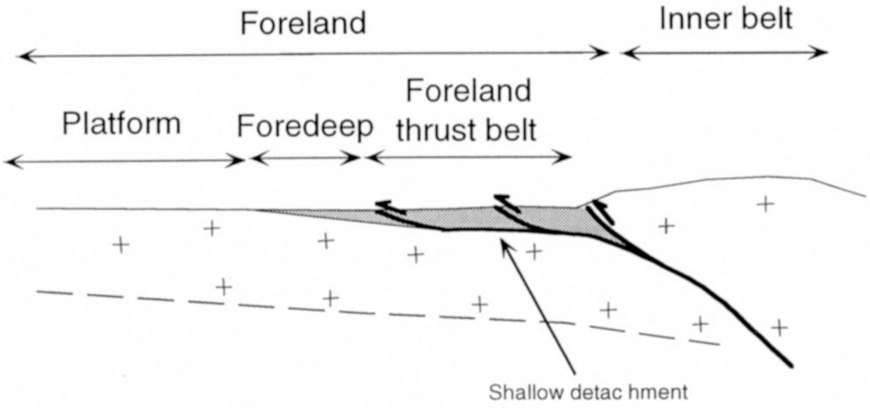
Orogenic forelands may have a complex, polyphase evolution, with implication of different structural styles

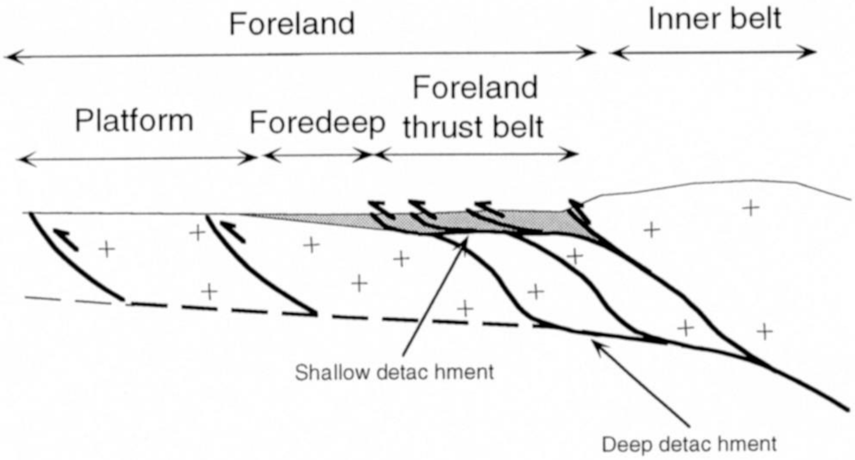
A key process by which basement becomes involved is the inversion of pre-existing extensional faults

Reactivation/inversion of basement faults widespreadly occurs during orogenic evolution of collided passive margins and this process is known to exert a strong control on the evolution of orogens

Basement fault reactivation may induce :

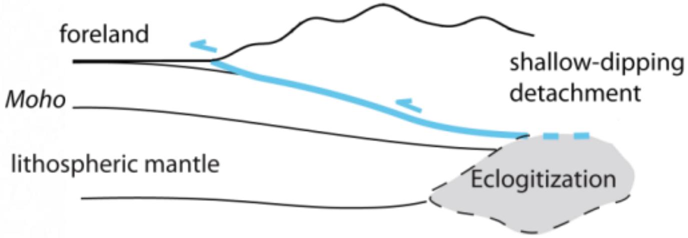
-localization of thrusts and folds in the developing shallow thrust wedge;
-inversion of normal faults and development of crystalline thrust sheets;
- out-of-sequence thrusting and refolding of shallow nappes;
- development of accommodation structures such as lateral ramps;
- development of basement uplifts.

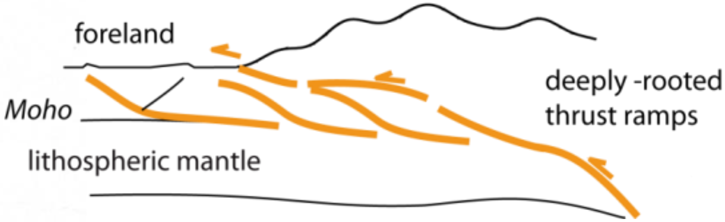




(Lacombe and Mouthereau, 2002)

simple-shear style "subduction"

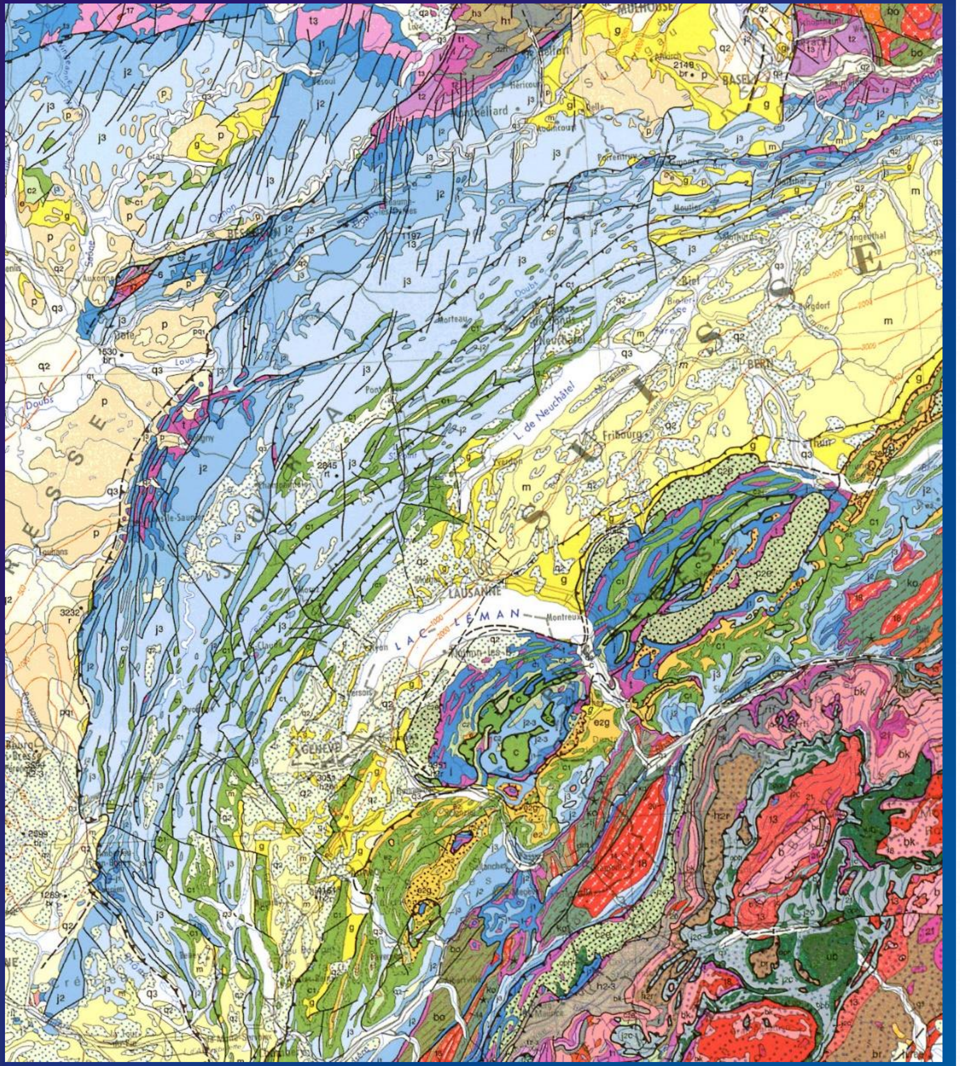


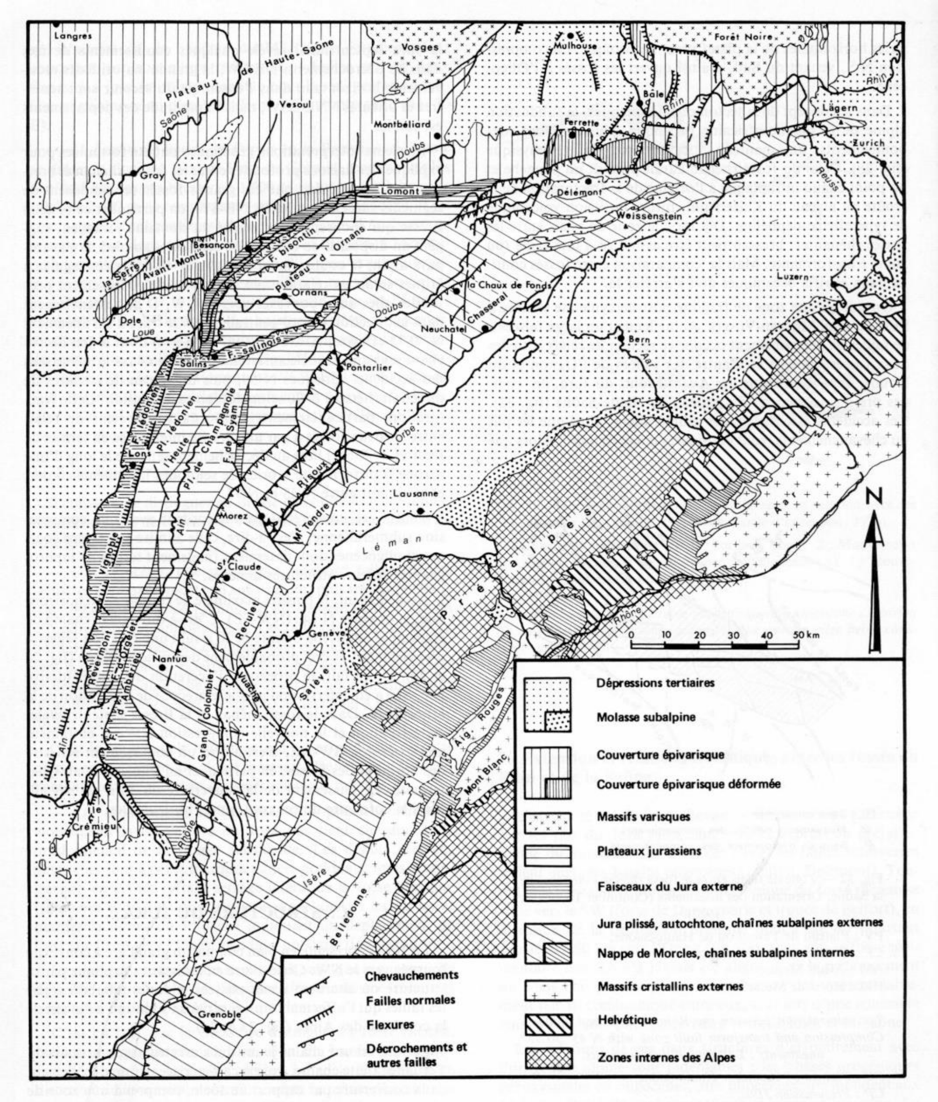


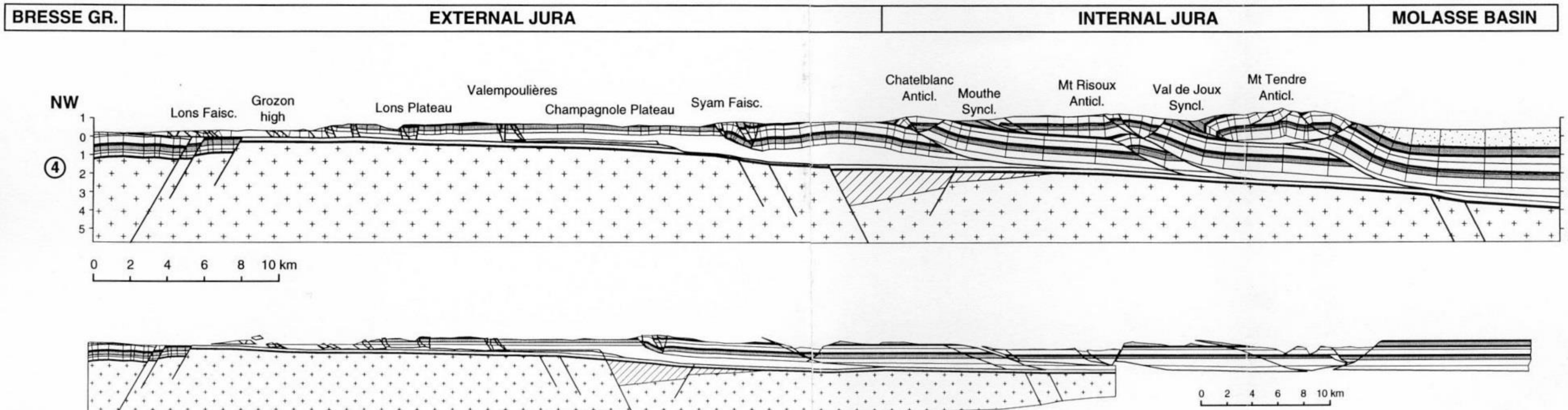
pure-shear style "inversion"

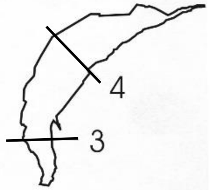
(Mouthereau et al., 2013)

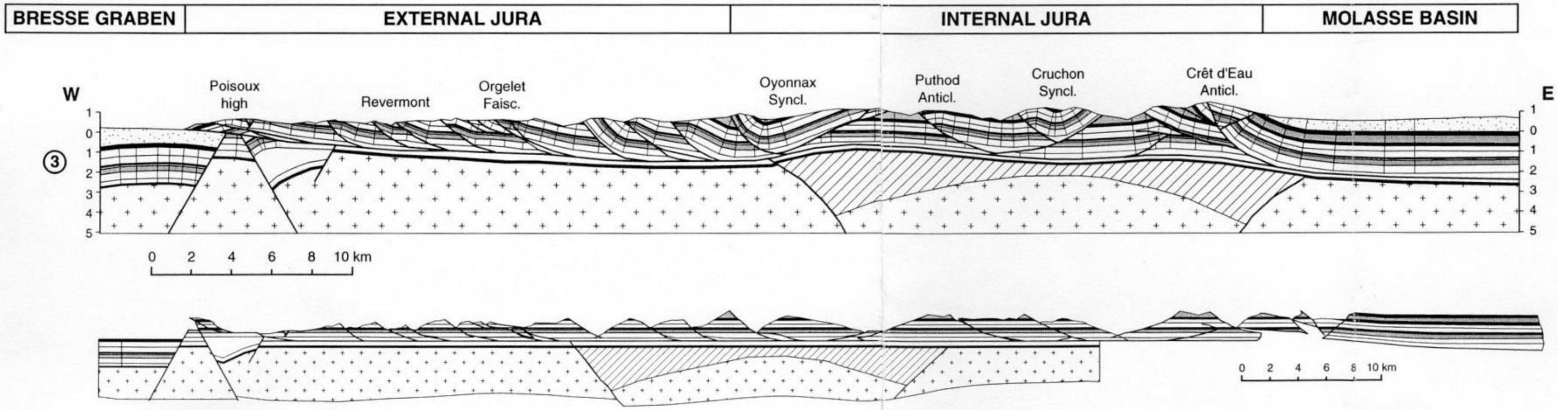
Change from thin-skinned to thick-skinned though time :
the Jura

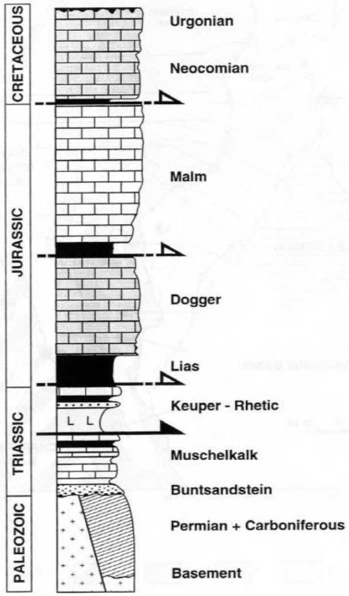

MULHOUSE
BASEL
Montbéliard
BESANÇON
Doubs
Loue
Neuchâtel
L. de Neuchâtel
BERN
Fribourg
Thun
SUISSE
JURA
BRESSE
LAUSANNE
LAC LÉMAN
Montreux
GENÈVE


Langres
Plateaux de Haute-Saône
Vosges
Mulhouse
Forêt Noire
Vesoul
Bâle
Rhin
Lägern
Zurich
Montbéliard
Ferrette
Saône
Gray
Doubs
Lomont
Delémont
Weissenstein
la Serre
Avant-Monts
Besançon
F. bisontin
Plateau d'Ornans
Ornans
La Chaux de Fonds
Chasseral
Neuchatel
Luzern
Dole
Loue
Salins
F. salinois
Pontarlier
Bern
Aar
Lons
F. lédonien
Pl. lédonien
l'Heute
Pl. de Champagnole
F. de Syam
Risoux
Orbe
Lausanne
Morez
Mt Tendre
Léman
Préalpes
Aar
St Claude
Reculet
Vignoble
Revermont
Genève
Nantua
Ain
Grand Colombier
Salève
Aig. Rouges
Mont Blanc
Rhône
Crémieu
Isère
Belledonne
Grenoble
N
0 10 20 30 40 50 km
Dépressions tertiaires
Molasse subalpine
Couverture épivarisque
Couverture épivarisque déformée
Massifs varisques
Plateaux jurassiens
Faisceaux du Jura externe
Jura plissé, autochtone, chaînes subalpines externes
Nappe de Morcles, chaînes subalpines internes
Massifs cristallins externes
Helvétique
Zones internes des Alpes
Chevauchements
Failles normales
Flexures
Décrochements et autres failles



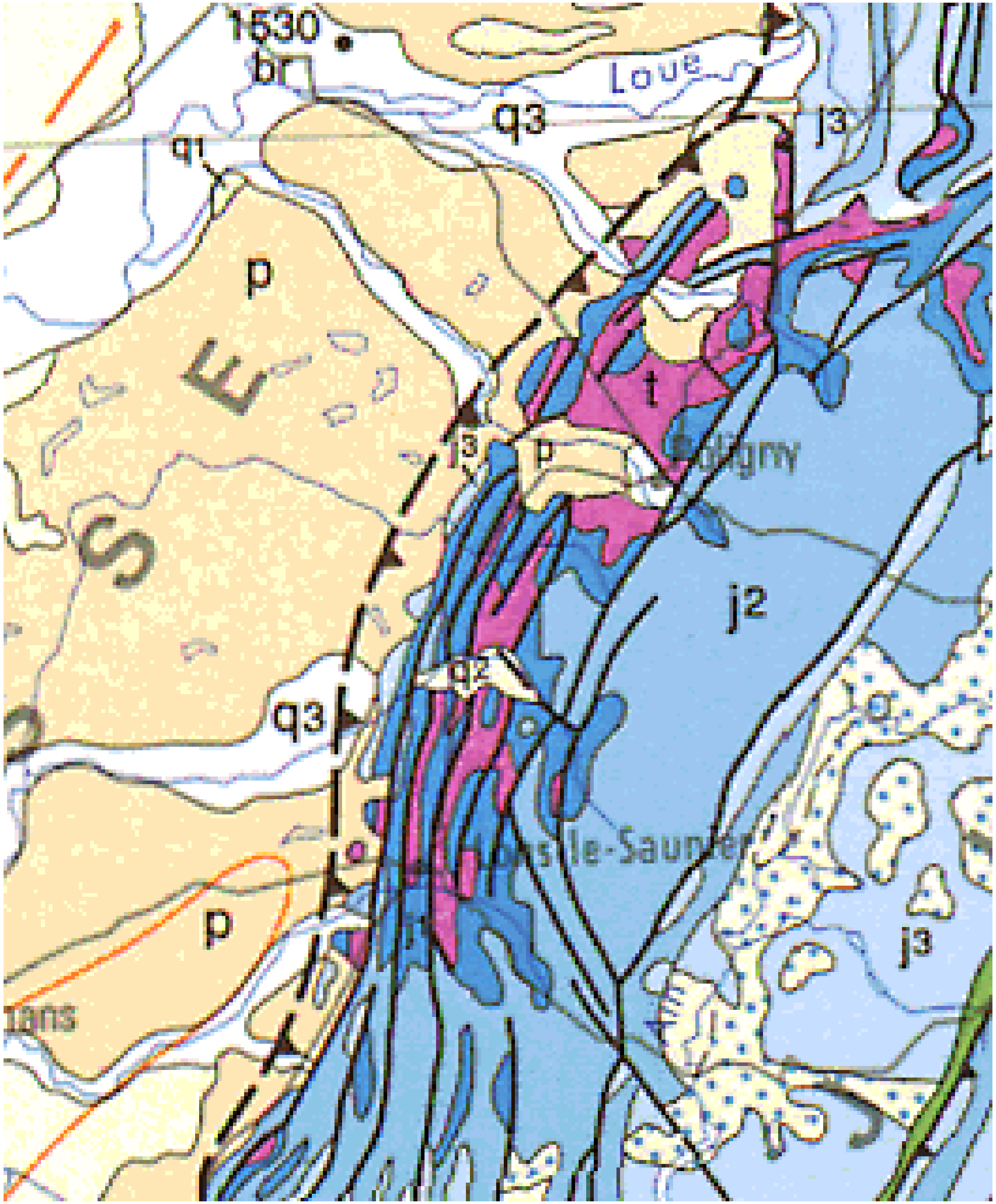






(Philippe, 1995)

Thin-skinned tectonics in the Jura :
a rather short-lived event : 14-10Ma → 4-3Ma


1530
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Loue
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Poligny
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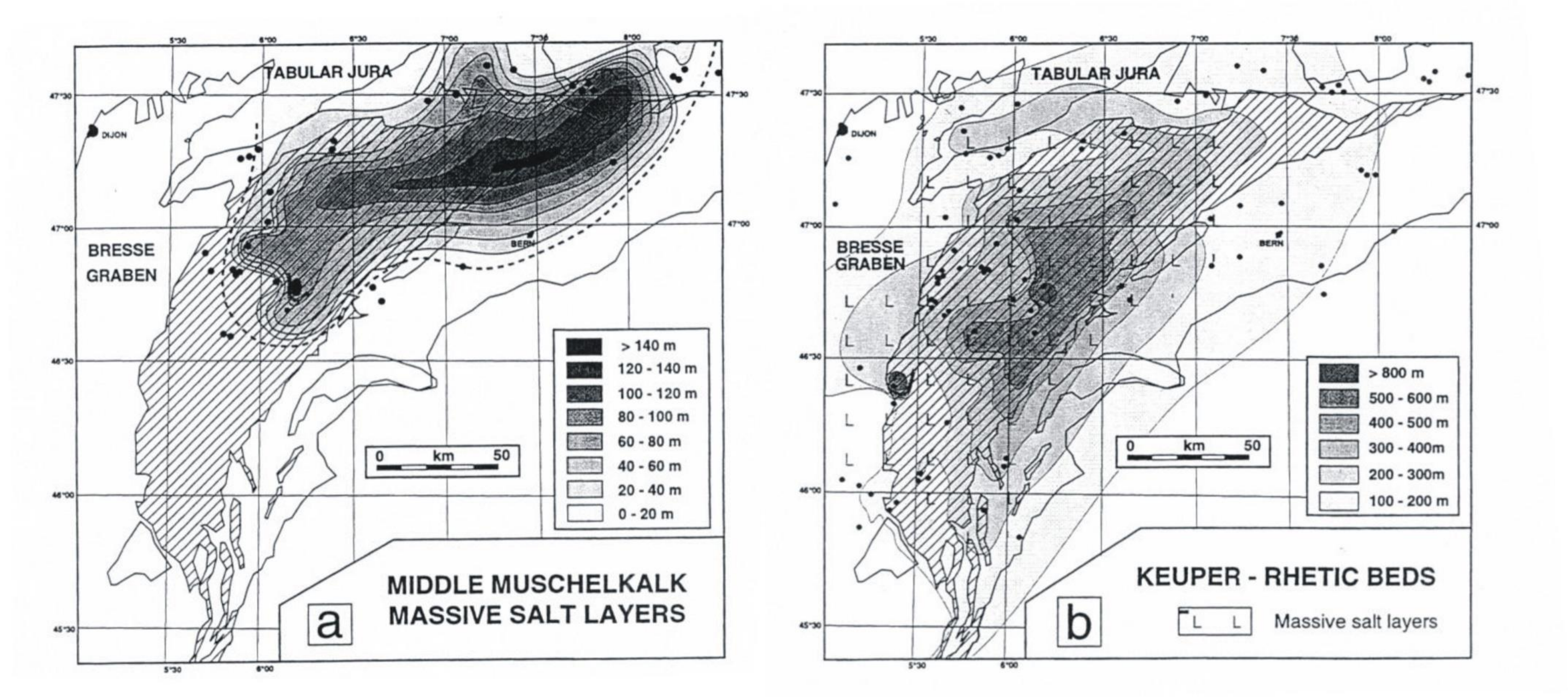
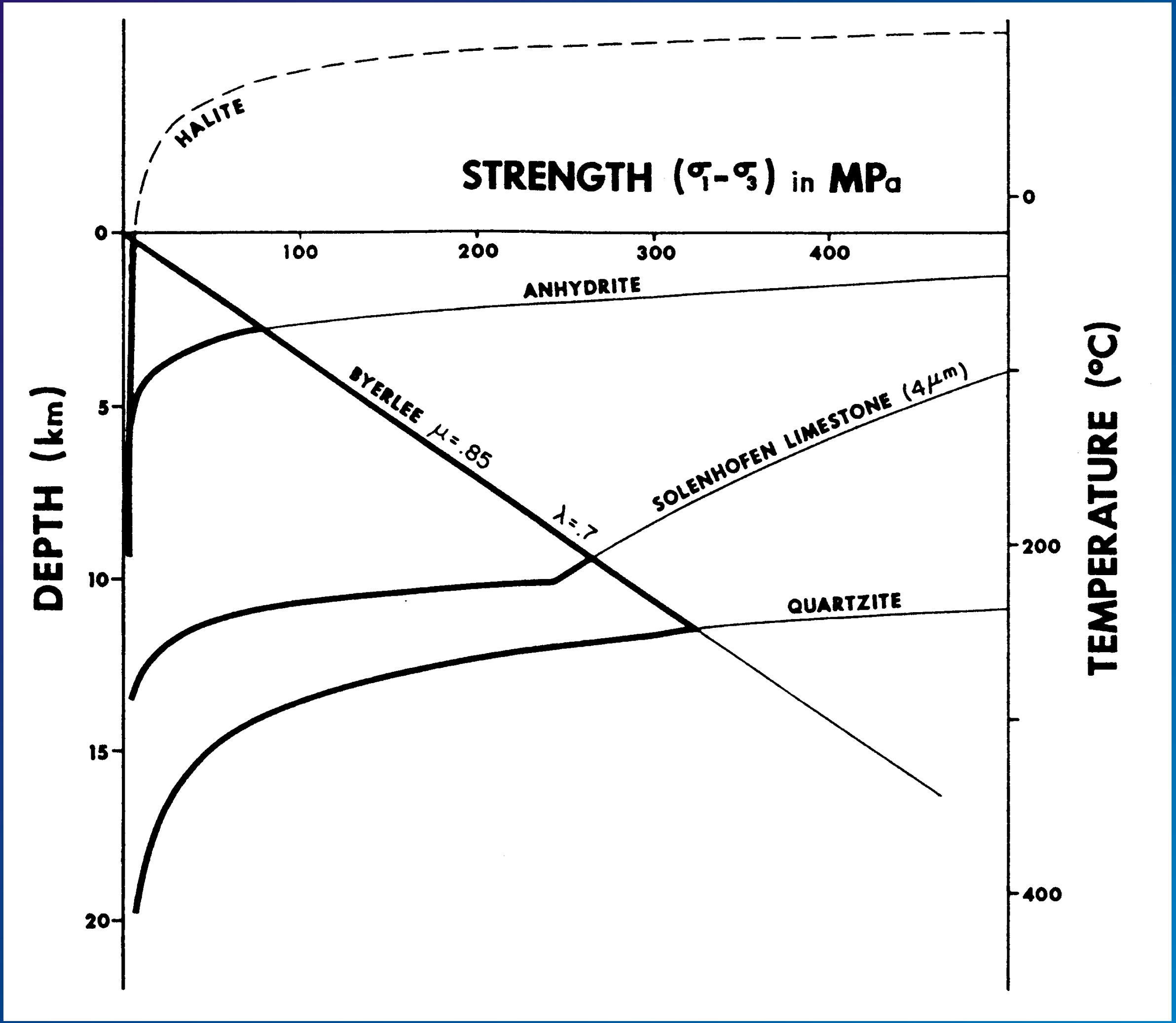
q2
q3
Lons-le-Saunier
p
j3
ans

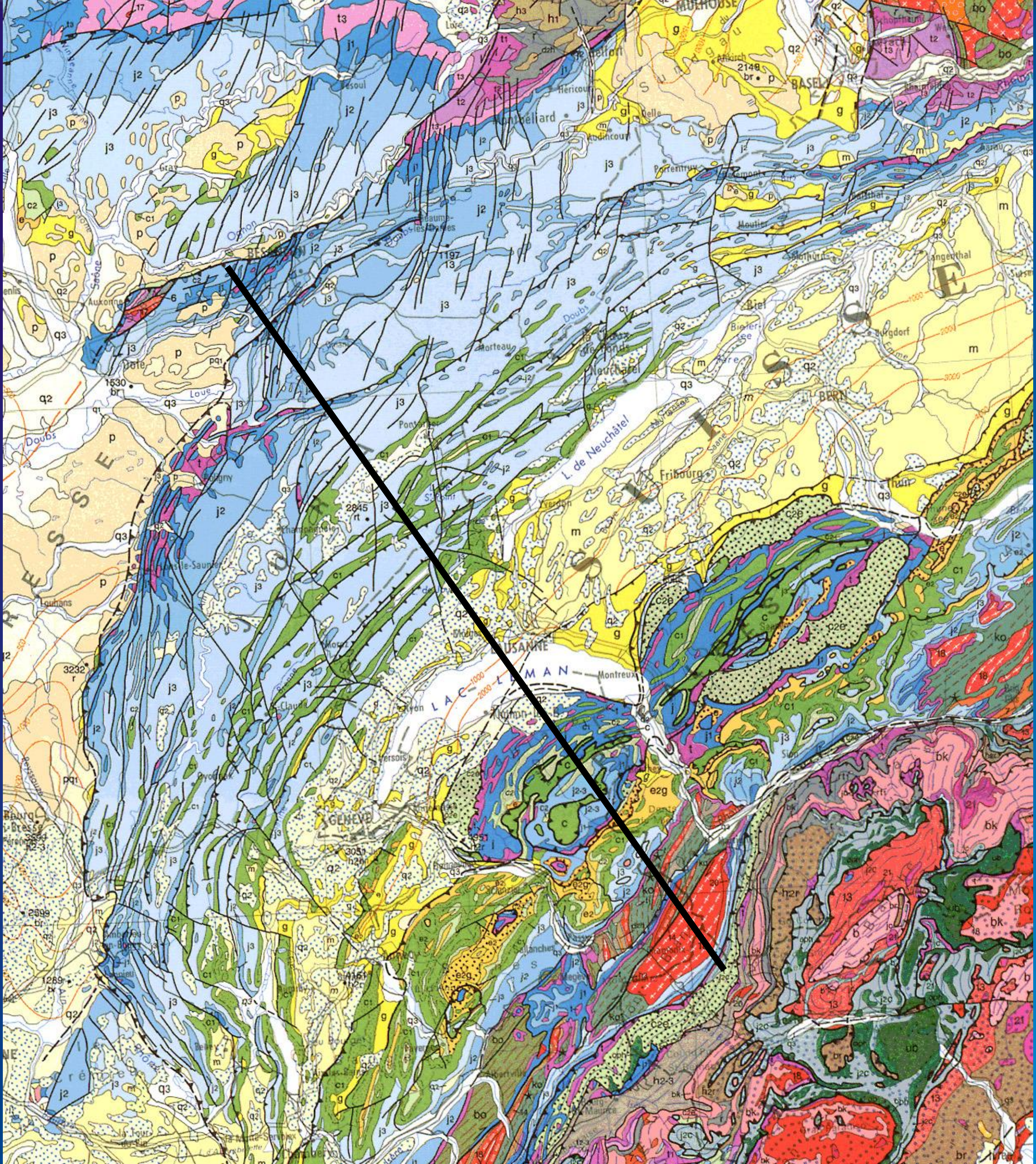
Répartition des évaporites du Trias sous le Jura



(Lienhard, 1984)

Comportement mécanique des évaporites du Trias




MULHOUSE
BASEL
Belfort
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BESANÇON
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Doubs
Saône
Loue
Biel
Burgdorf
Neuchâtel
BERN
L. de Neuchâtel
Fribourg
Thun
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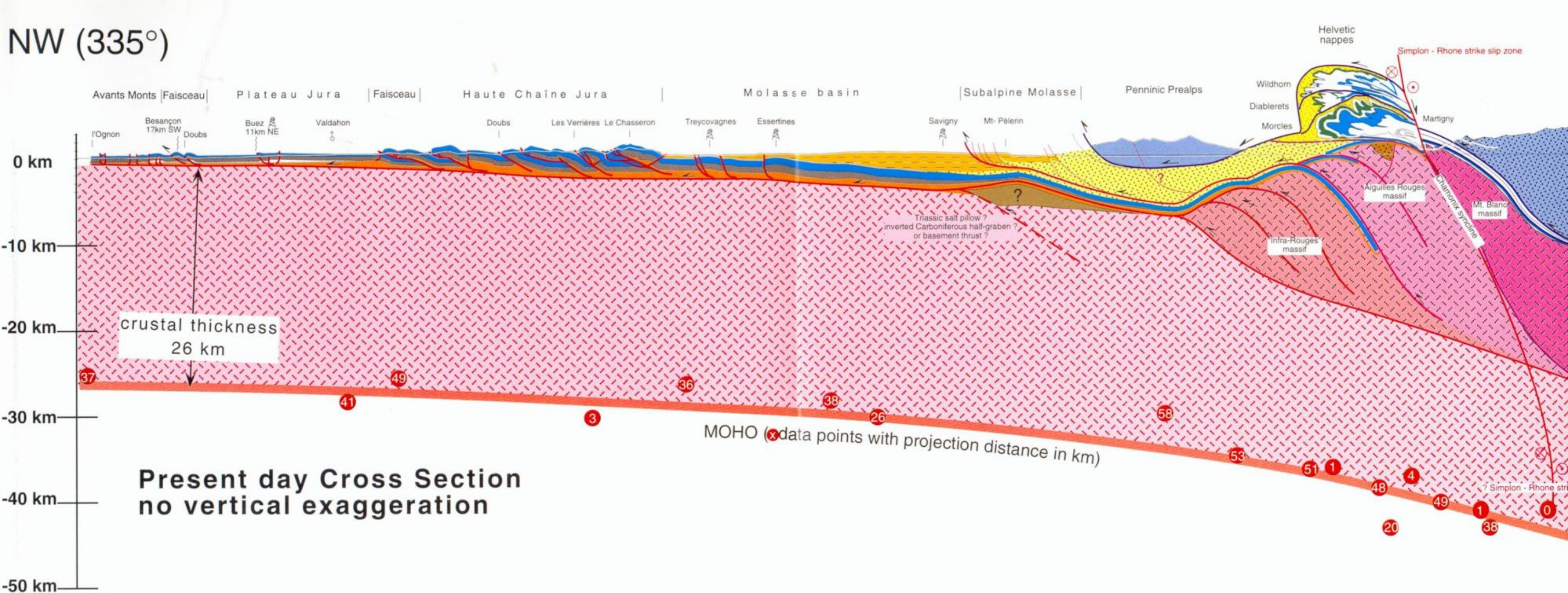
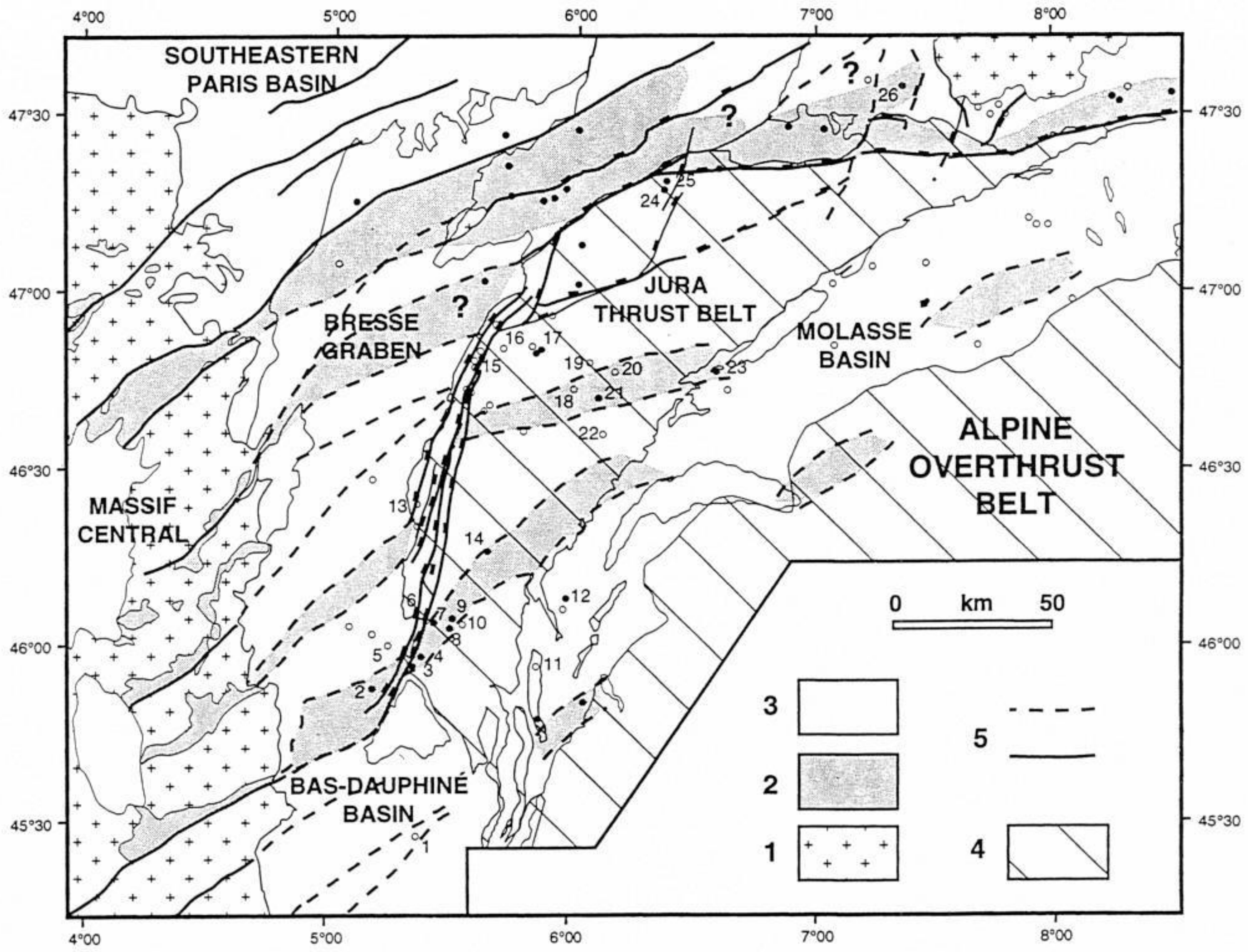
LAC LEMAN
Montreux
Thonon
GENEVE
Sion
Louhans
BRESSE
JURA
SUISSE

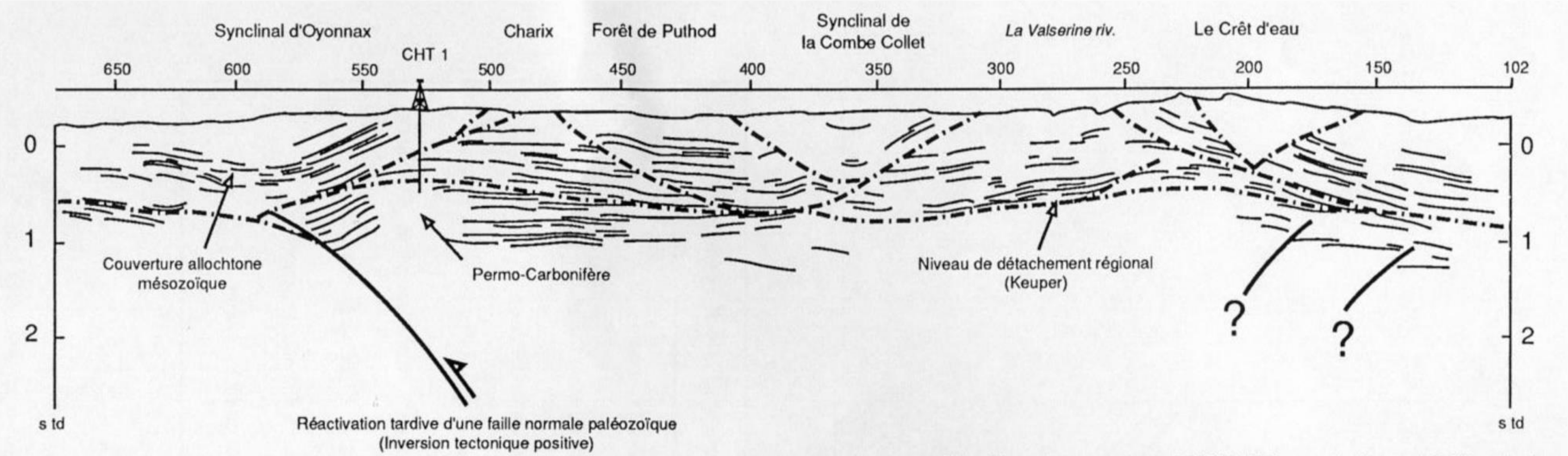


(Burkhard et Sommaruga,1998)

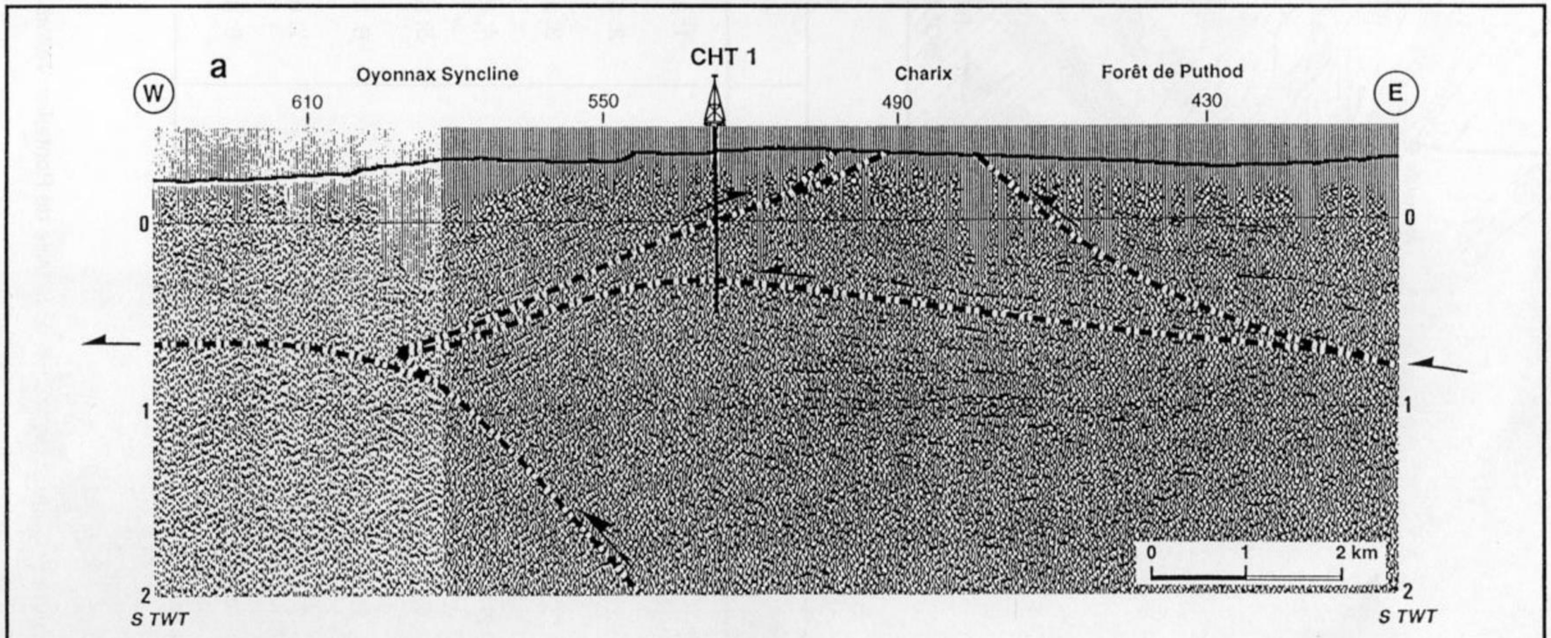


(BRGM, 1980; Truffert et al., 1990)

(Philippe, 1995)

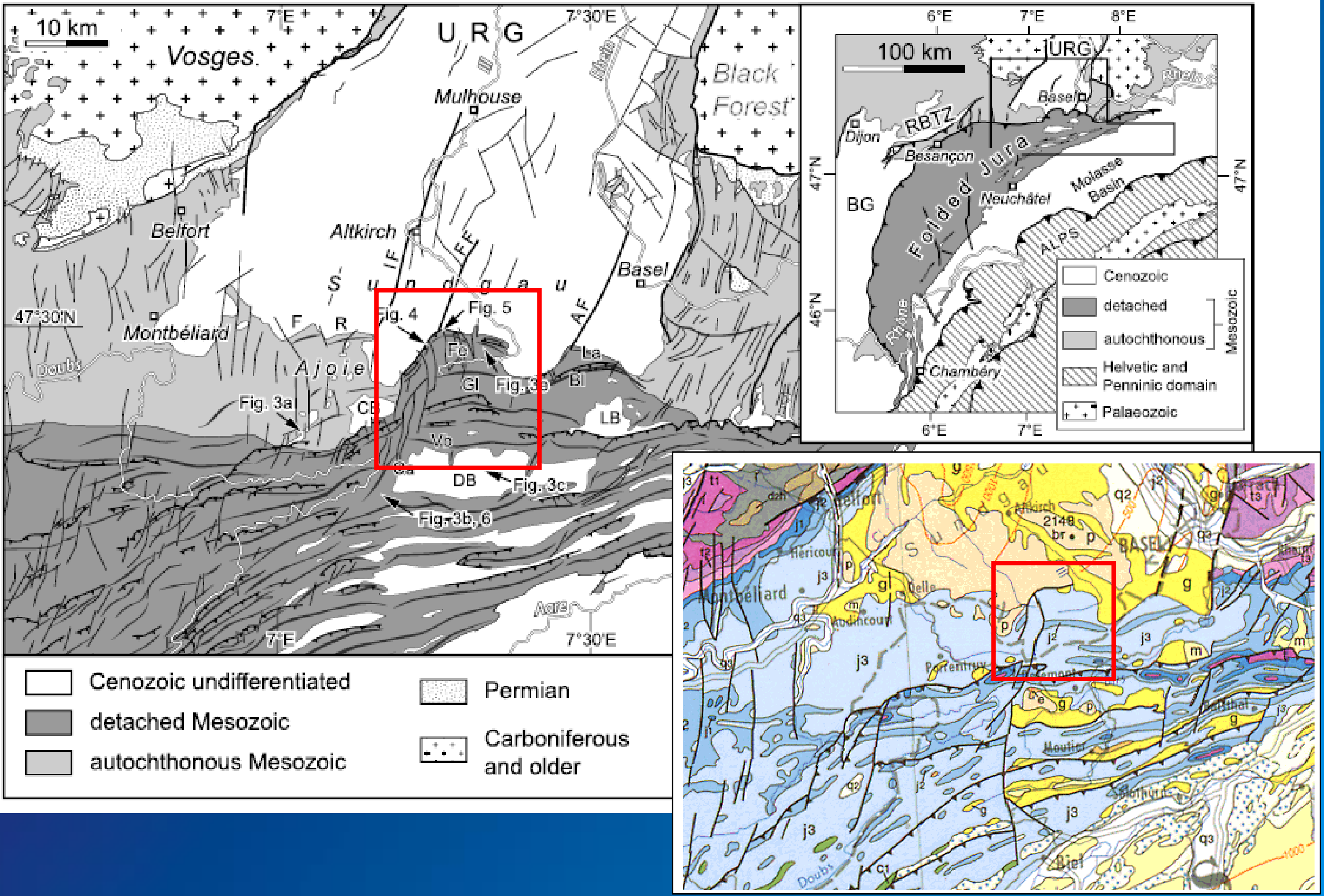


7a: Line-drawing du profil ECORS sous la Haute-Chaîne du Jura.



7b: Vue de détail du profil ECORS Jura-Bresse au niveau du forage CHT 1.

(Ustaszewski and Schmid, 2006)



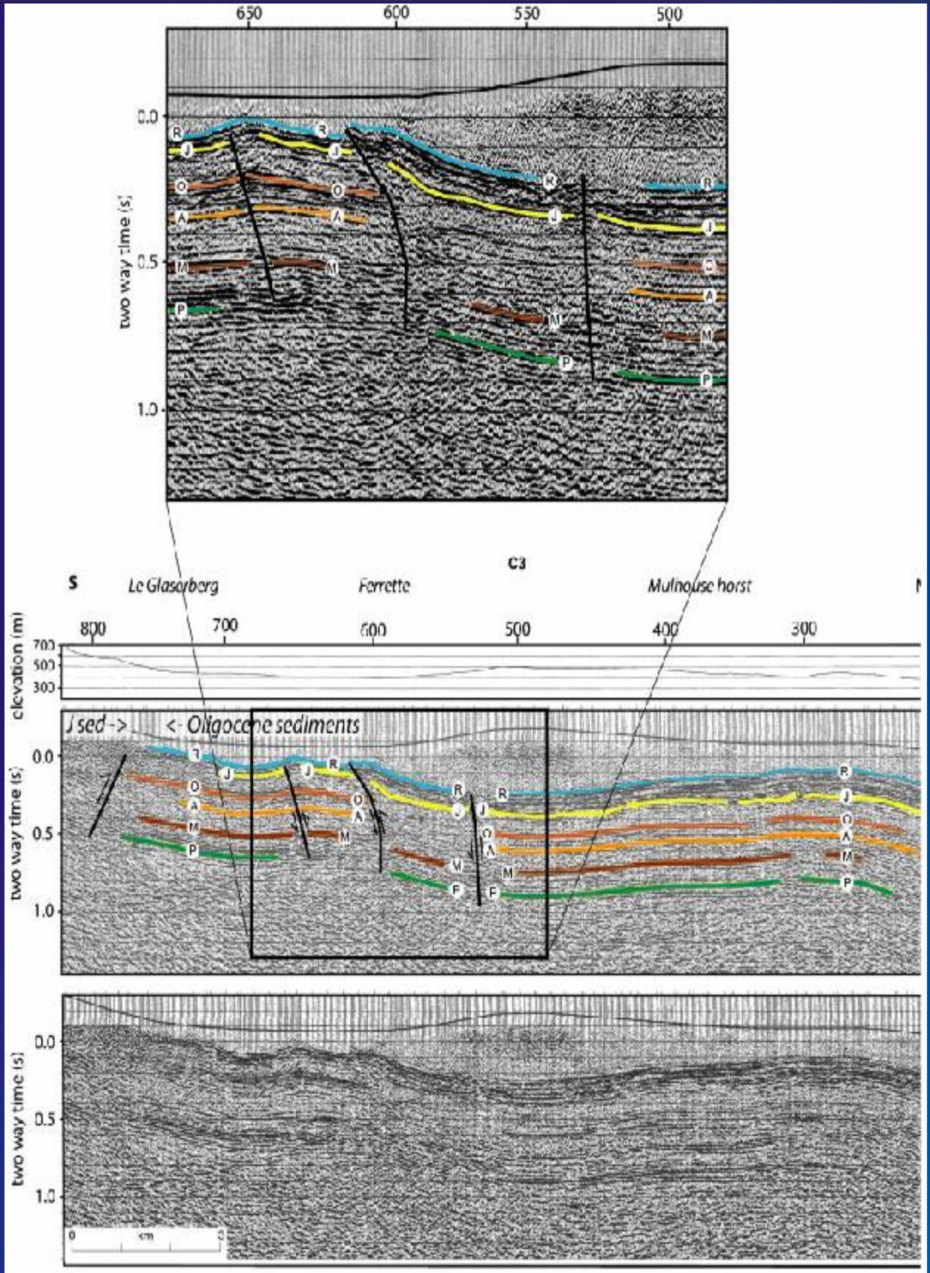


Fig. 3 Uninterpreted and interpreted part of migrated section C3. P, Top Permian; M, Muschelkalk (Triassic); A, Top Aalenian (Jurassic); O, Grande Oolithe (Jurassic); J, Top Jurassic; R, Rupelian. Zero reference is at 350 m above sea-level. Also shown are (1) the ages of the near-surface sediments that suggest thrusting, (2) the surface elevations, (3) the locations of the Ferrette and Le Glaserberg Jura anticlines, and (4) an enlargement of the main faulted area. For location, see Fig. 1.

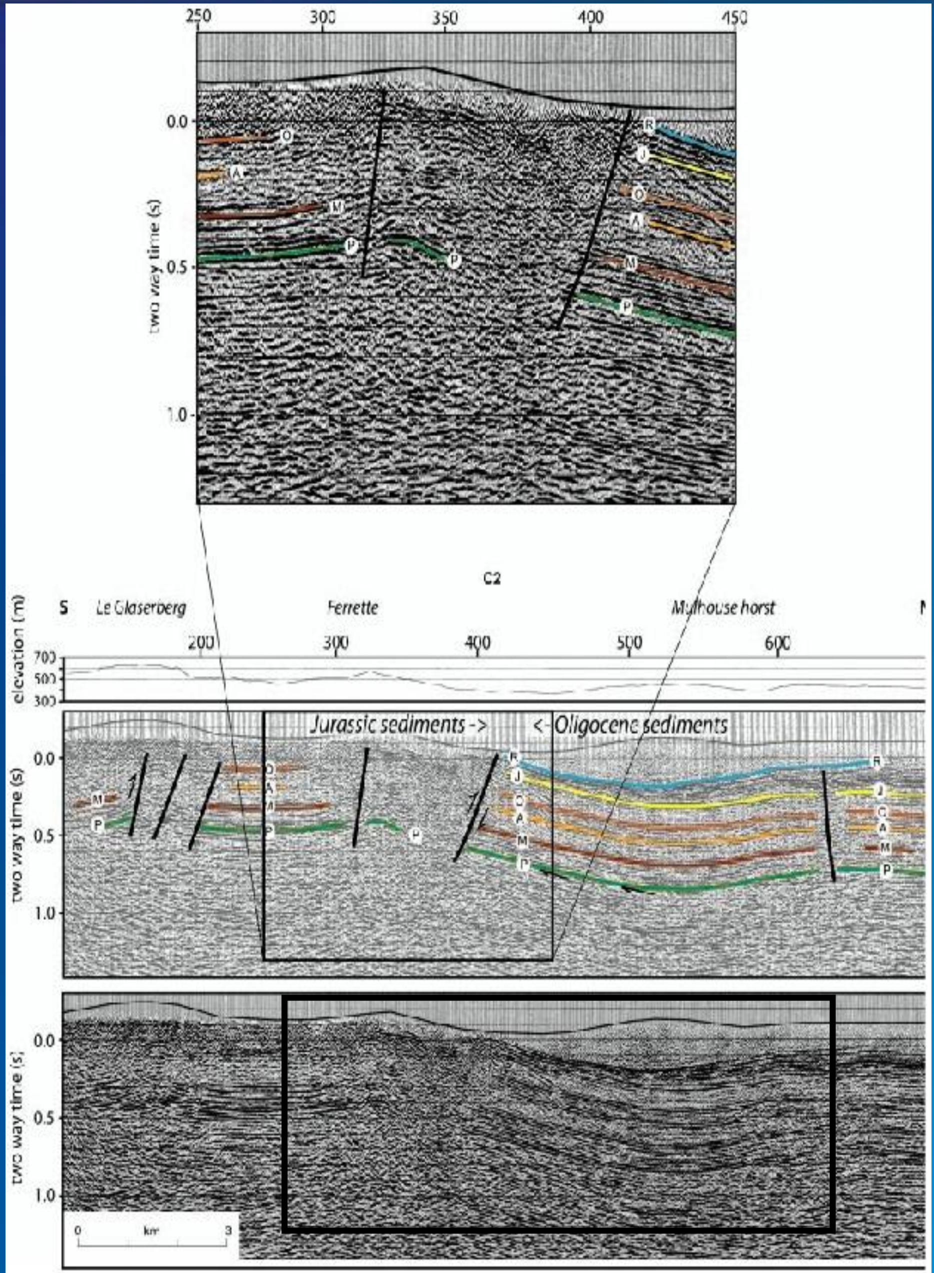
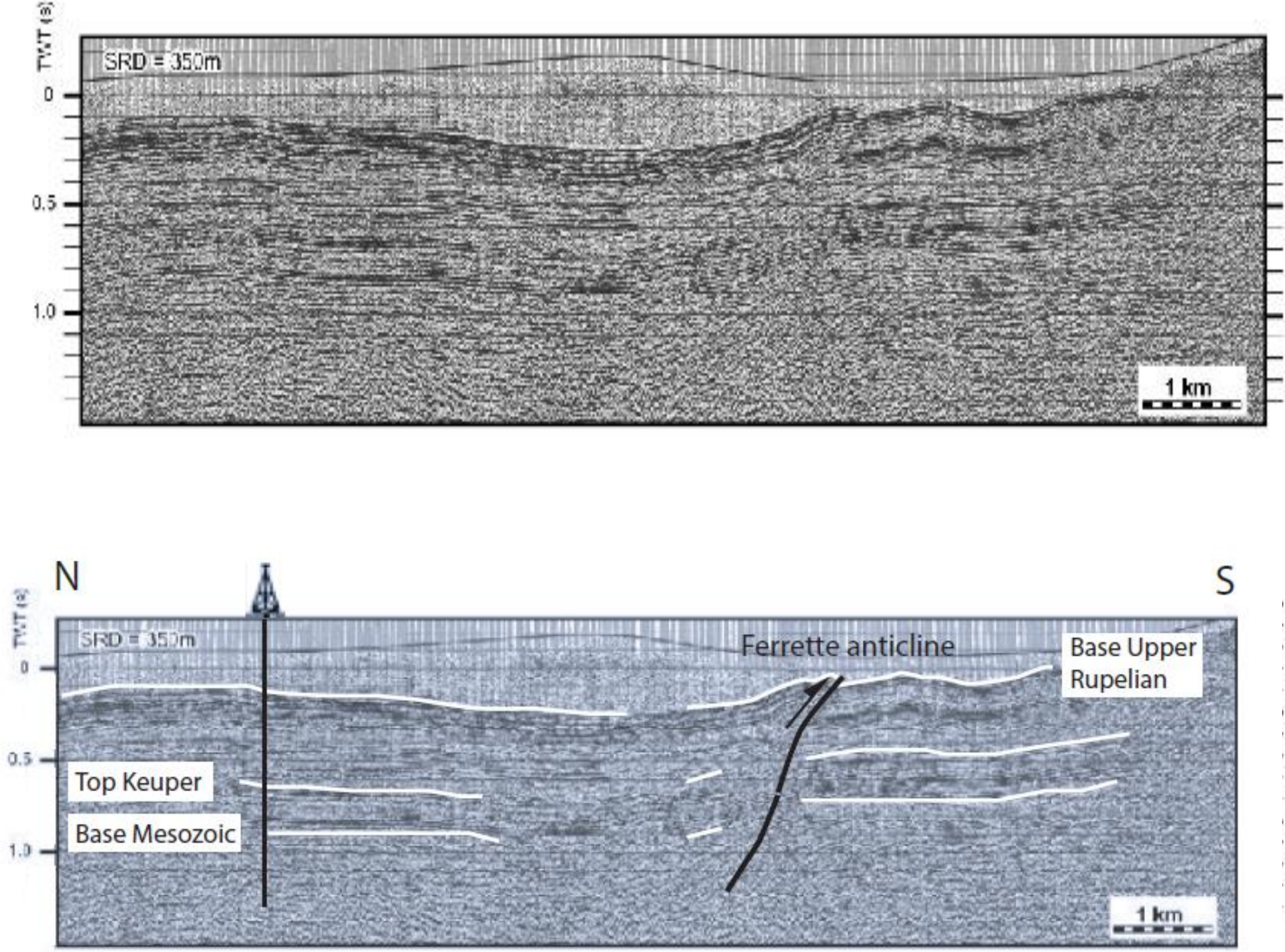


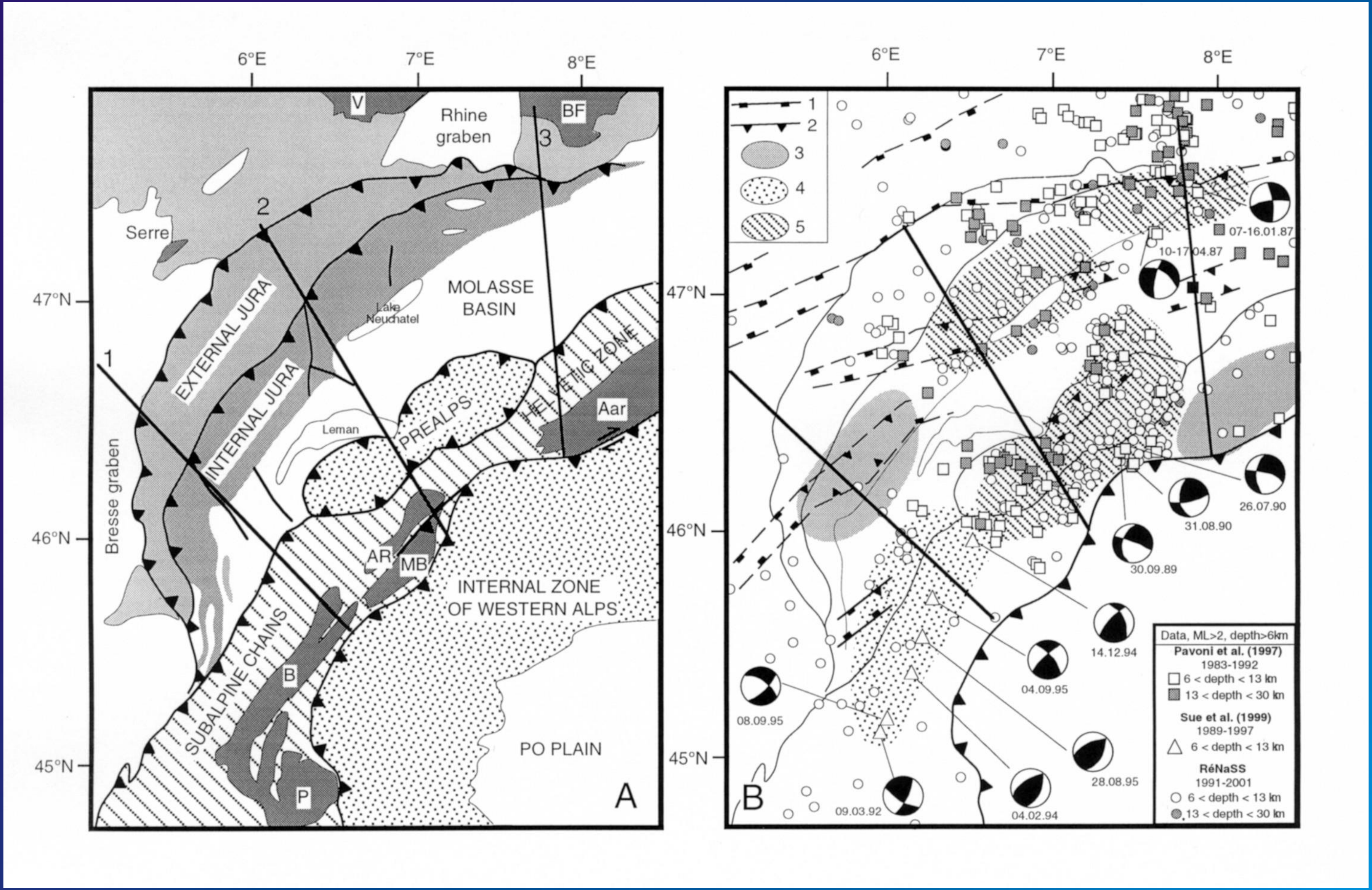
Fig. 2 Uninterpreted and interpreted part of migrated seismic section C2. P, Top Permian; M, Muschelkalk (Triassic); A, Top Aalenian (Jurassic); O, Grande Oolithe (Jurassic); J, Top Jurassic; R, Rupelian. Zero reference is at 350 m above sea-level. Also shown are (1) the ages of the near-surface sediments that suggest thrusting, (2) the surface elevations, (3) the locations of the Ferrette and Le Glaserberg Jura anticlines, and (4) an enlargement of the main faulted area. For location, see Fig. 1.

(Rotstein and Schaming, 2004)

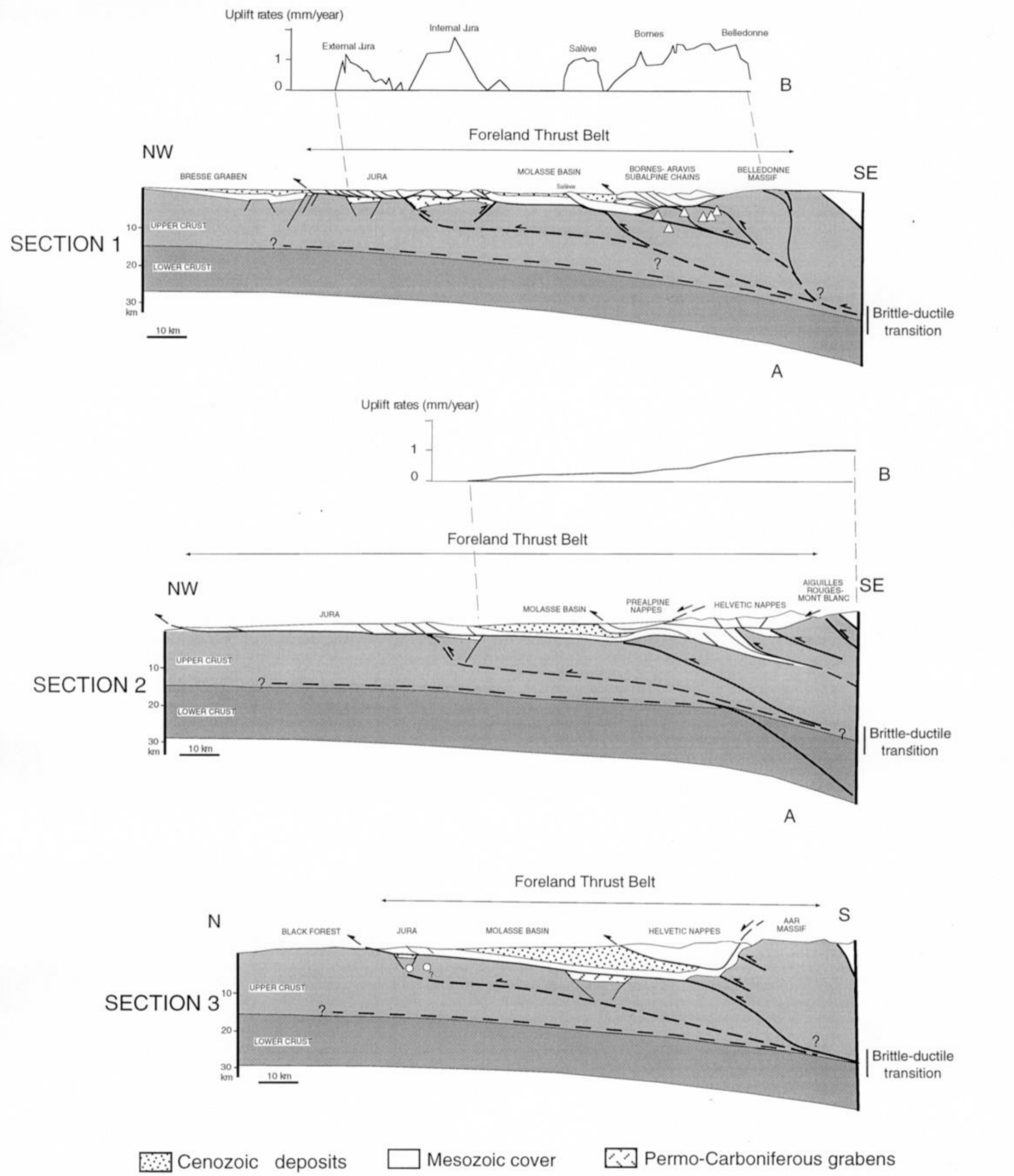


(Ustaszewski and Schmid, 2006)

(Lacombe and Mouthereau, 2002)

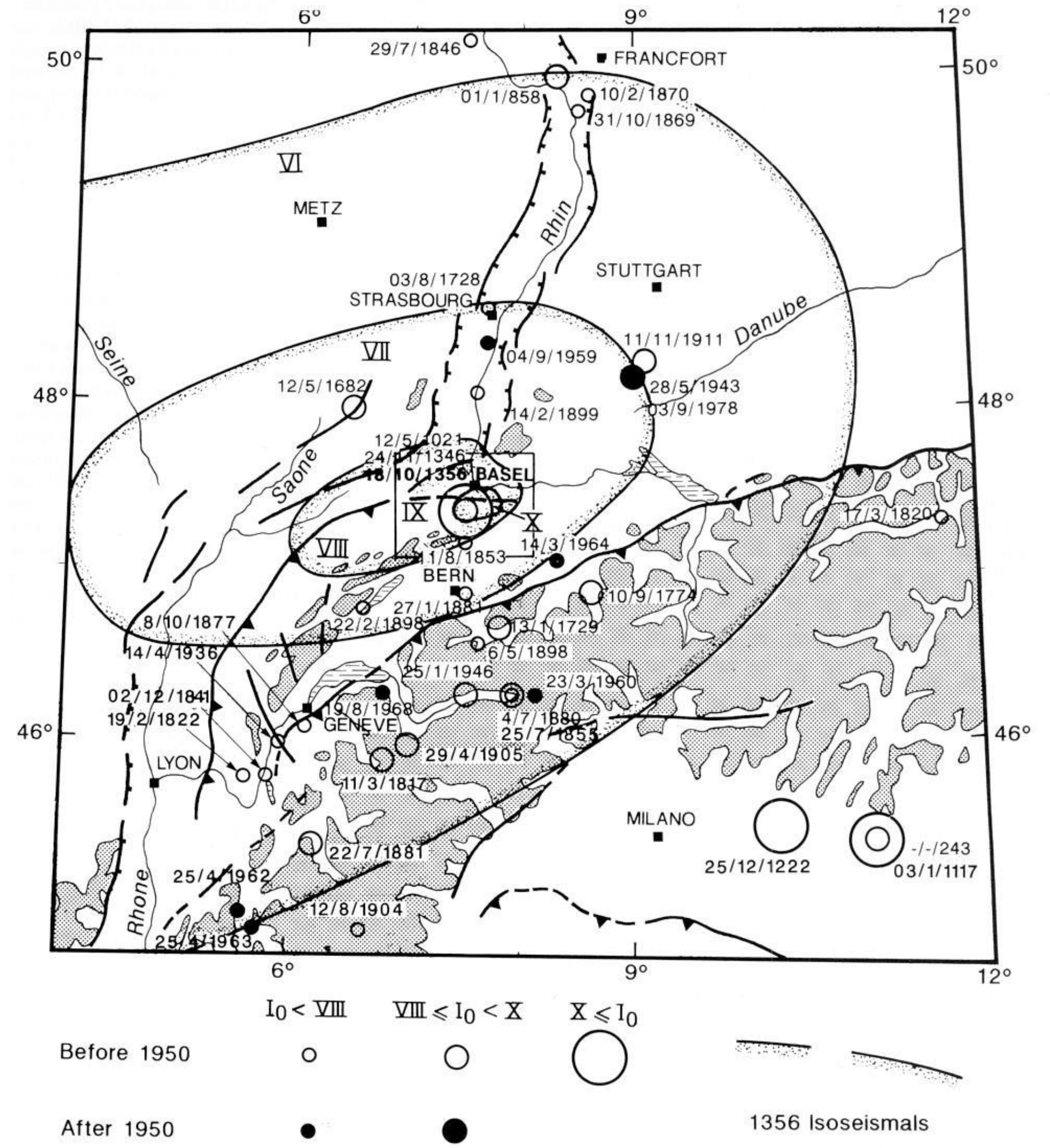


Areas of present-day basement-involved shortening inferred from :
3 : high present-day uplift rates 4 : high present-day uplift rates and seismicity 5 : seismicity

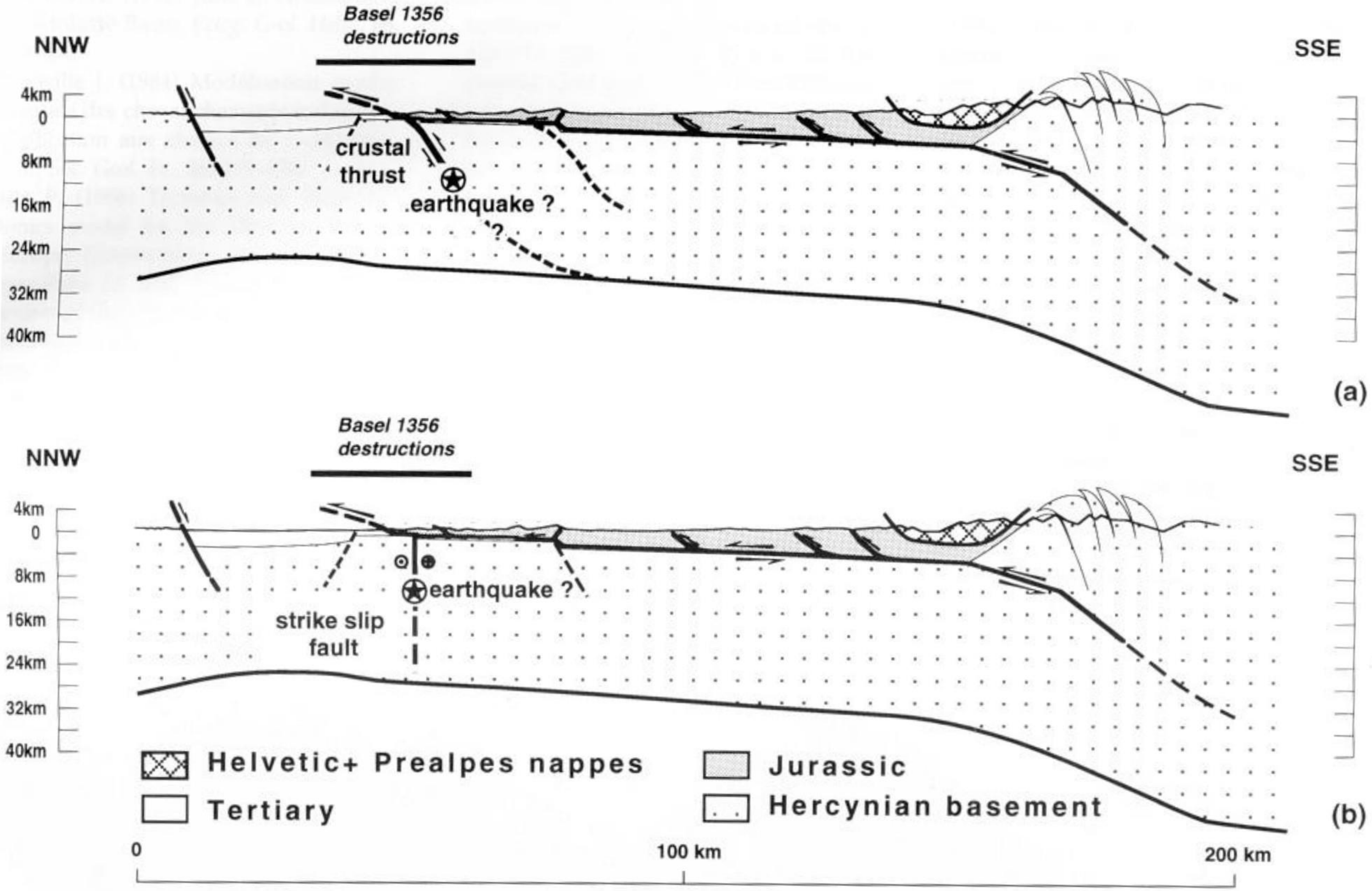


(Lacombe and Mouthereau, 2002)

(Meyer et al., 1994)



. Seismotectonic map of NW Europe and Western Alps. Seismicity, active faults, and elevation contour line 1000 m are from Armijo et al. (1986). Altitudes greater than 1000 m are shaded. Isoseismals of Basel 1356 earthquake are from Mayer-Rosa and Cadiot (1979). Box for Fig. 2b.

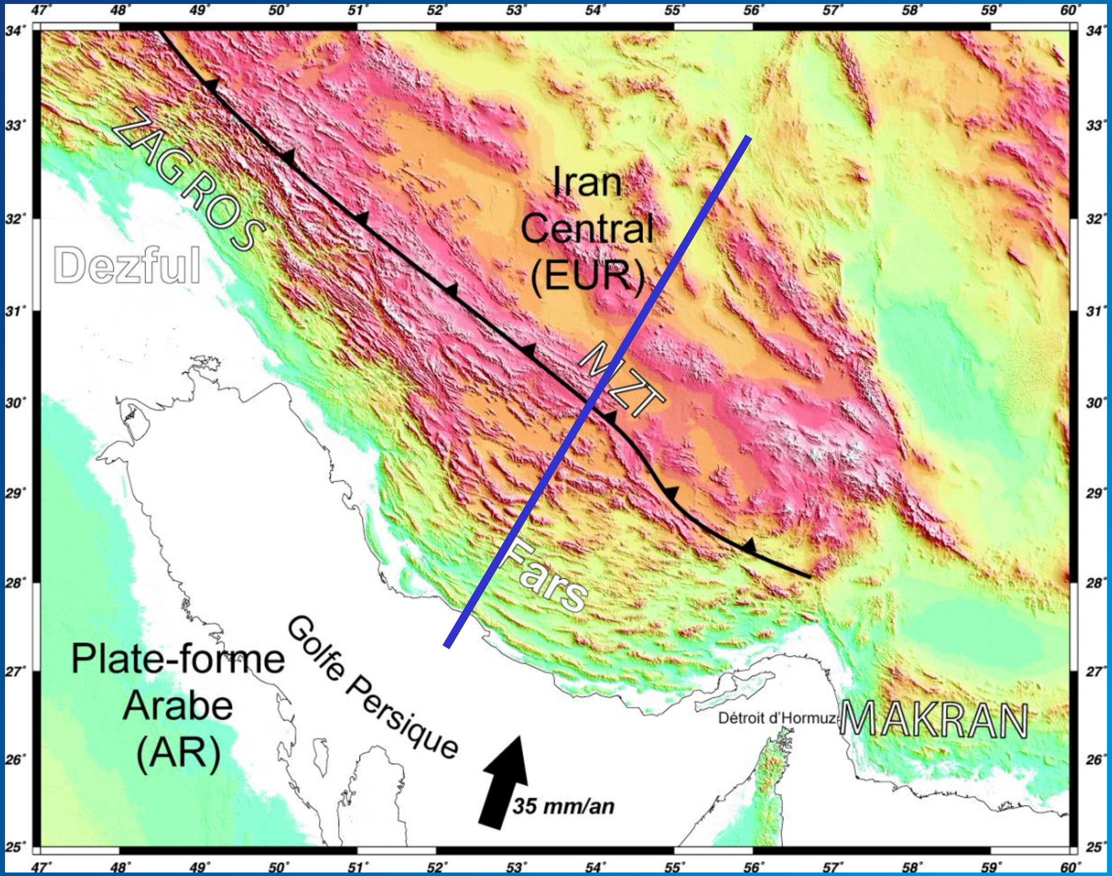


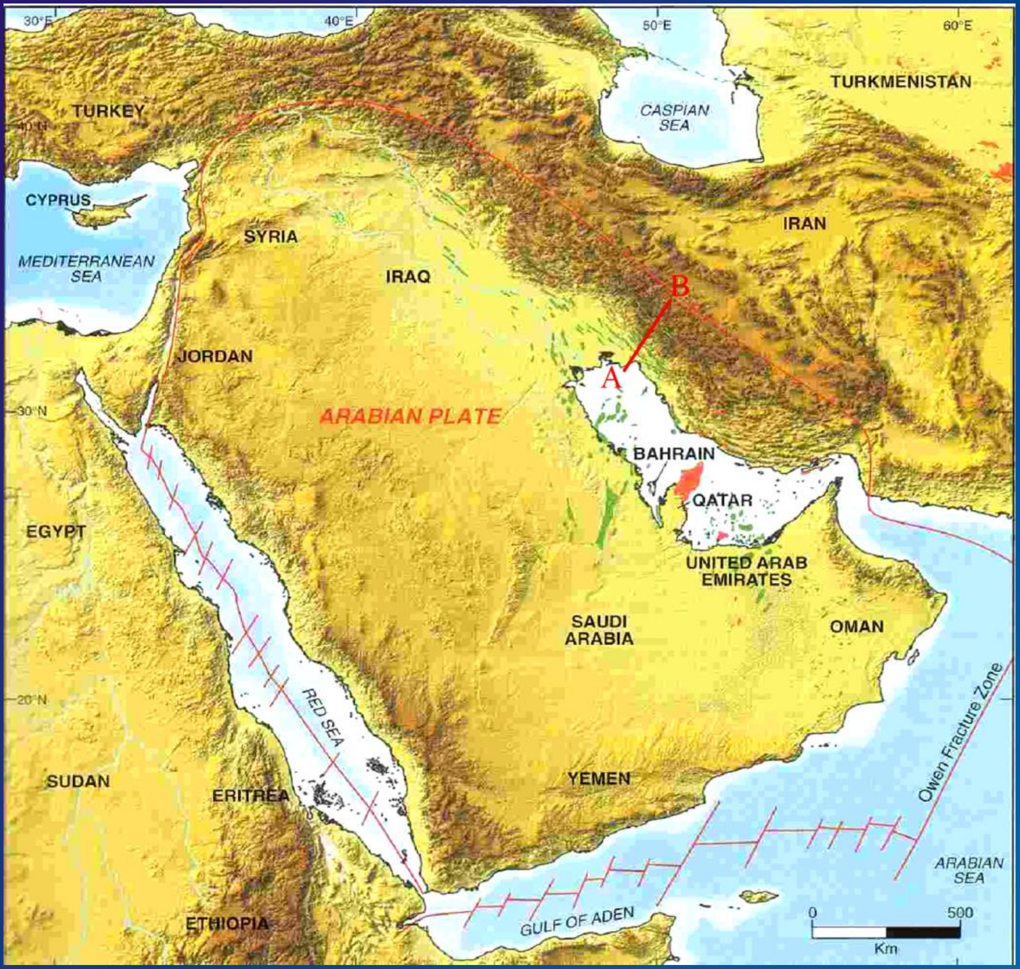
Plausible fault plane geometries for the Basel 1356 earthquake. (a) reactivation of a basement thrust fault beneath the detachment; (b) reactivation of a basement strike-slip fault beneath the detachment.

(Meyer et al., 1994)

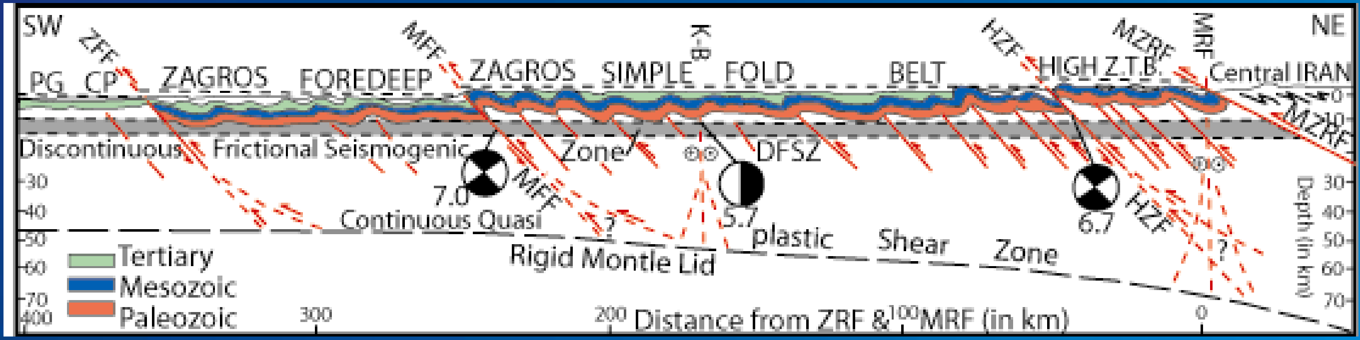
Superimposed thin-skinned and thick-skinned tectonic styles :
the Zagros

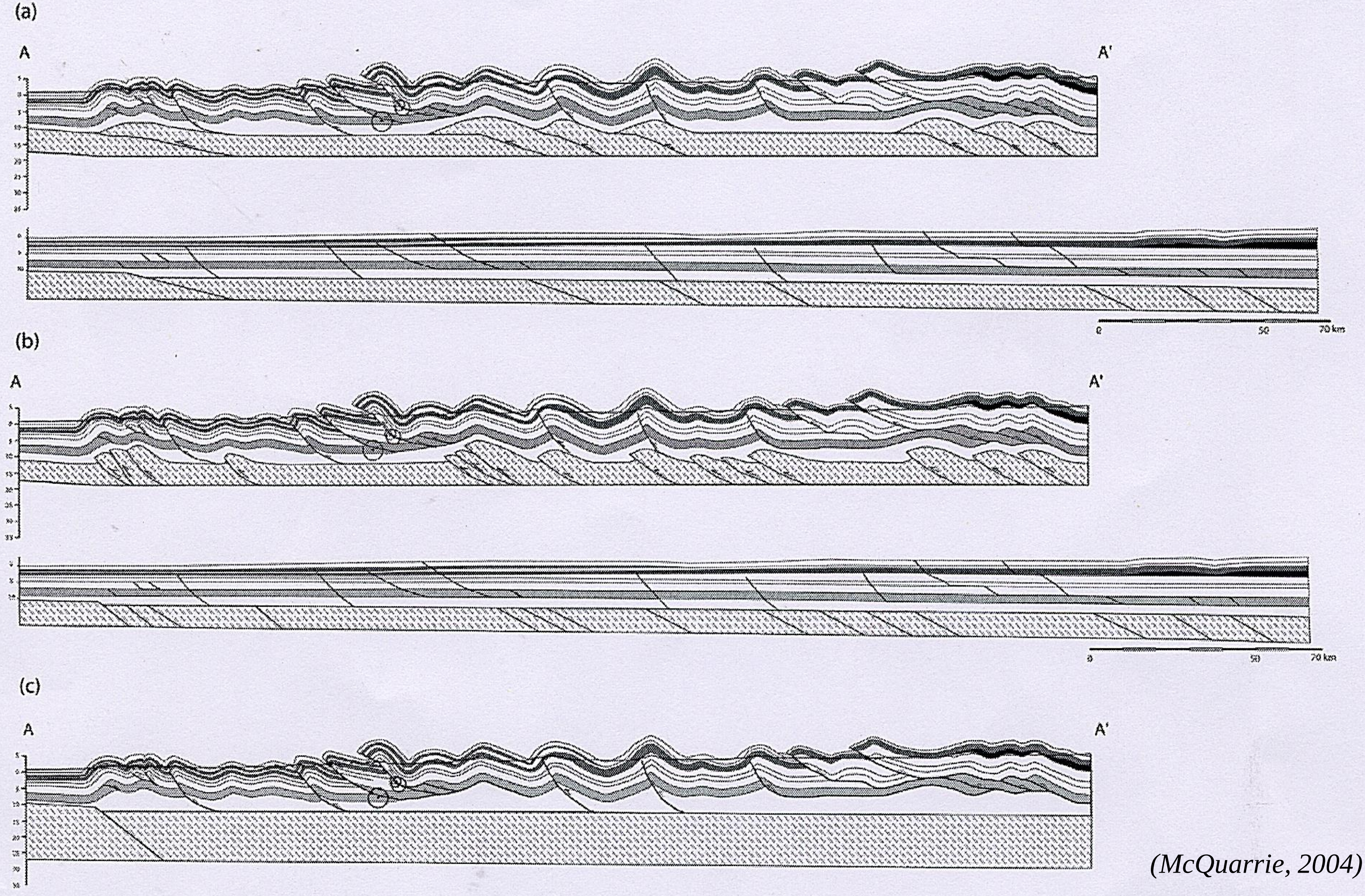
Zagros : Neogene/ongoing collision between Arabia and Central Iran



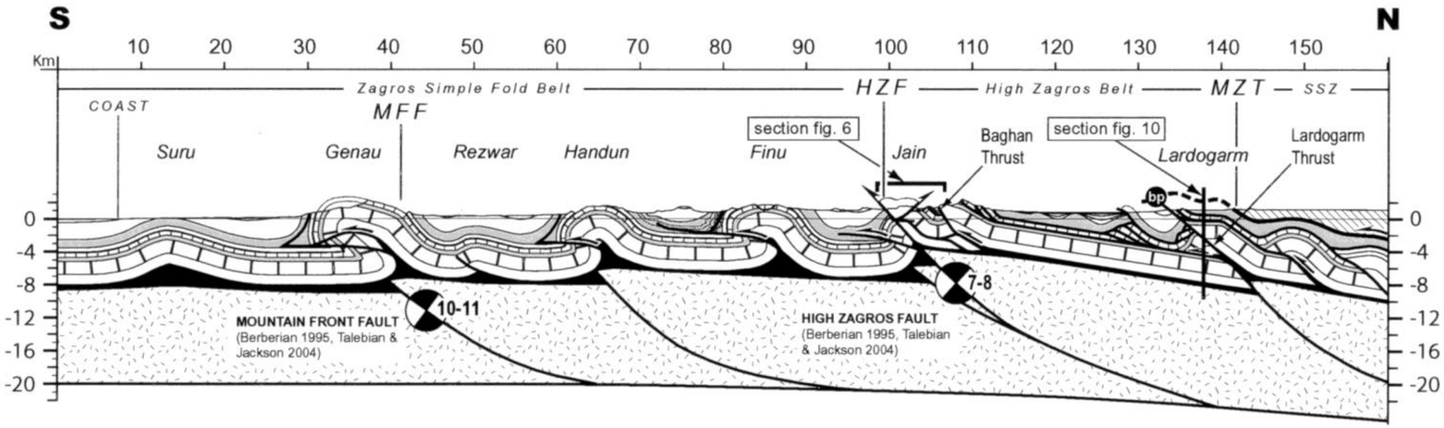


(Berberian, 1995)

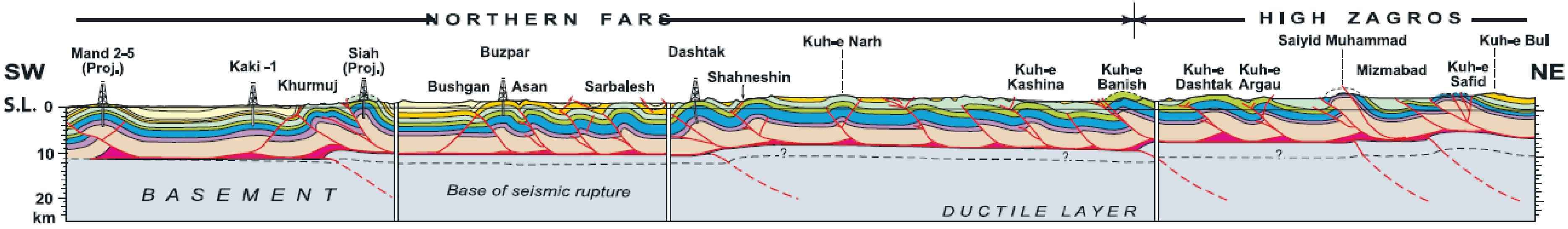




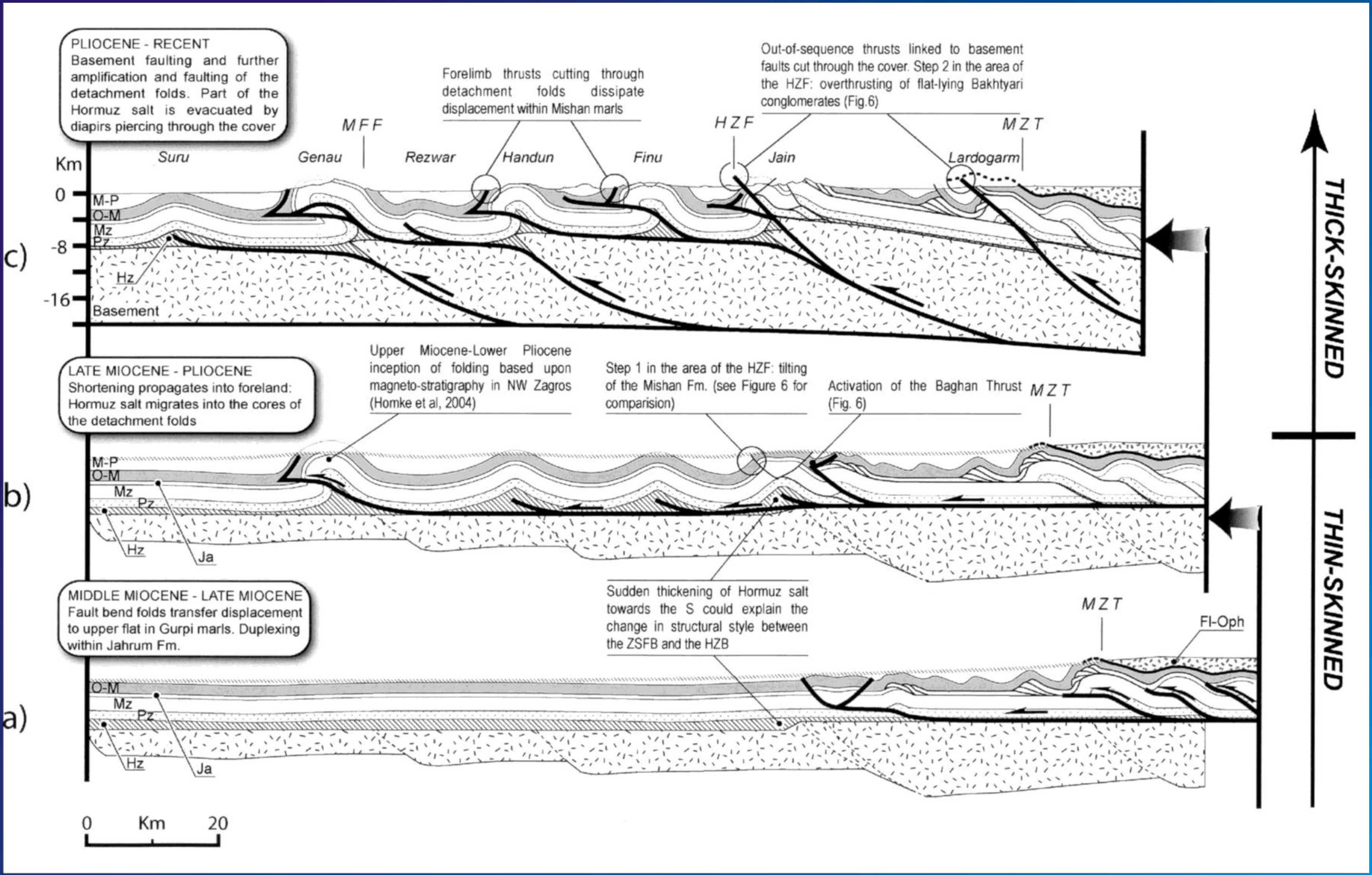
(McQuarrie, 2004)



Molinaro et al., 2005)



(Sherkati et al., 2006)



PLIOCENE - RECENT
Basement faulting and further amplification and faulting of the detachment folds. Part of the Hormuz salt is evacuated by diapirs piercing through the cover

Forelimb thrusts cutting through detachment folds dissipate displacement within Mishan marls

Out-of-sequence thrusts linked to basement faults cut through the cover. Step 2 in the area of the HZF: overthrusting of flat-lying Bakhtyari conglomerates (Fig.6)

LATE MIOCENE - PLIOCENE
Shortening propagates into foreland: Hormuz salt migrates into the cores of the detachment folds

Upper Miocene-Lower Pliocene inception of folding based upon magneto-stratigraphy in NW Zagros (Homke et al, 2004)

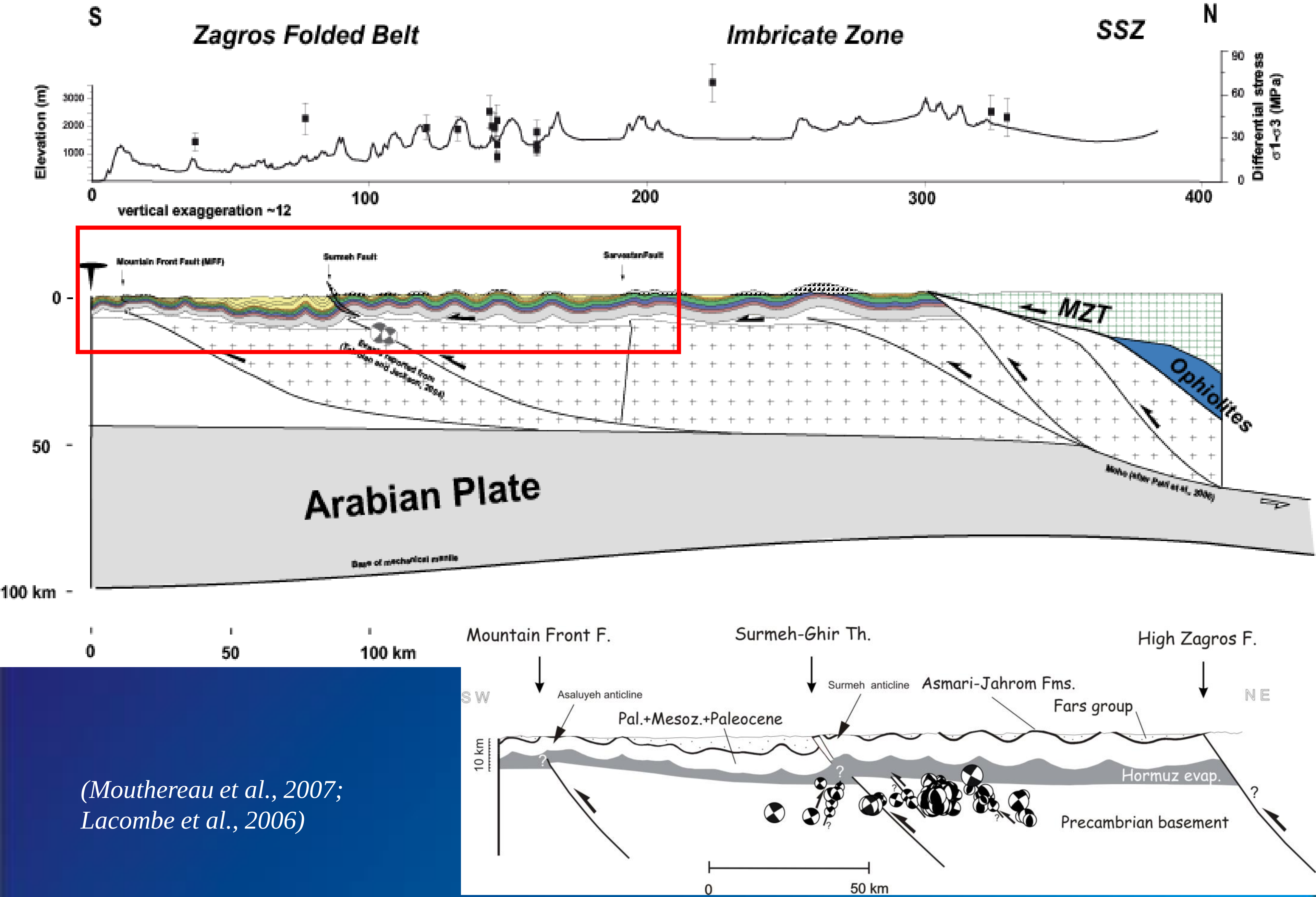
Step 1 in the area of the HZF: tilting of the Mishan Fm. (see Figure 6 for comparision)

Activation of the Baghan Thrust (Fig. 6)

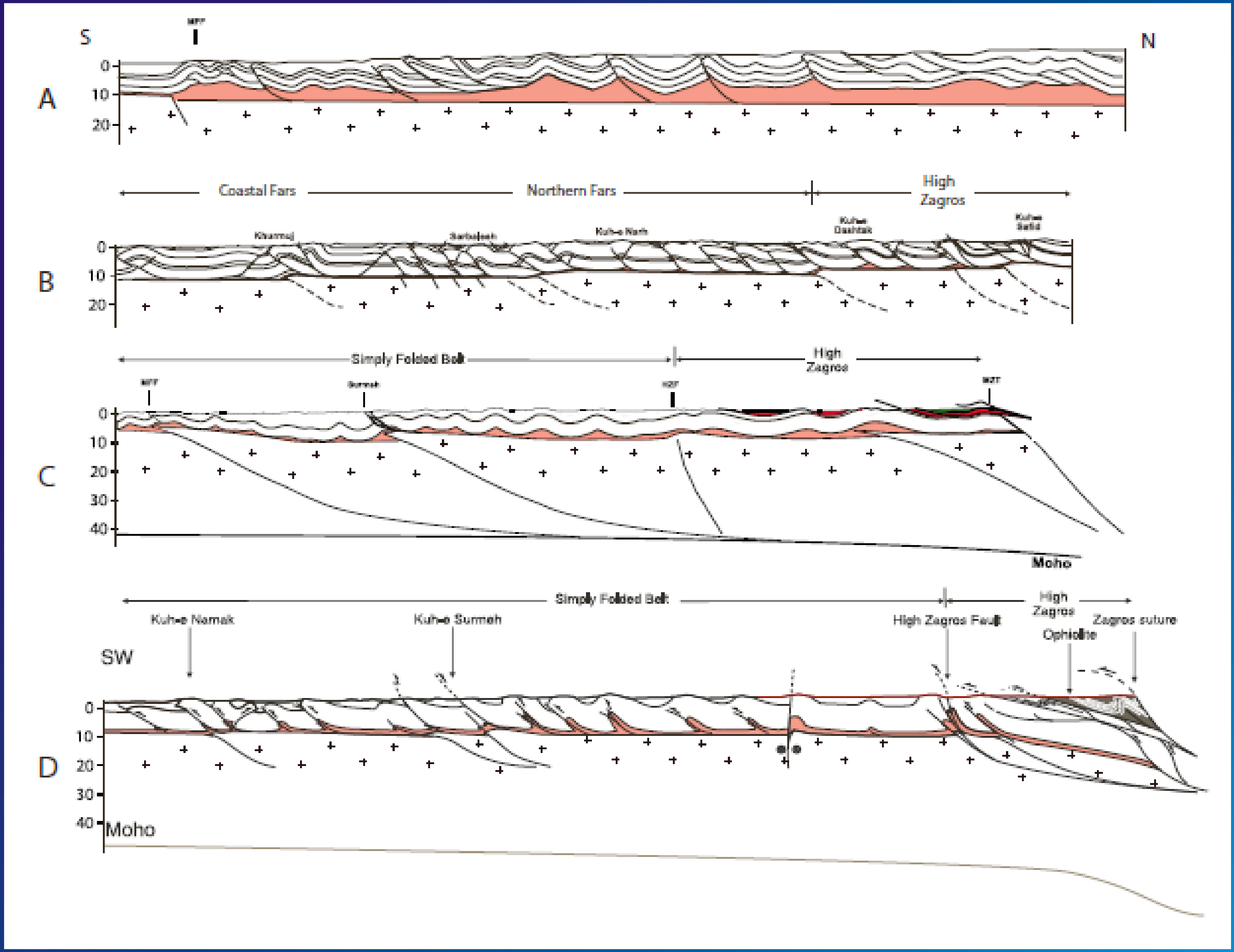
MIDDLE MIOCENE - LATE MIOCENE
Fault bend folds transfer displacement to upper flat in Gurpi marls. Duplexing within Jahrum Fm.

Sudden thickening of Hormuz salt towards the S could explain the change in structural style between the ZSFB and the HZB

(Molinaro et al., 2005)

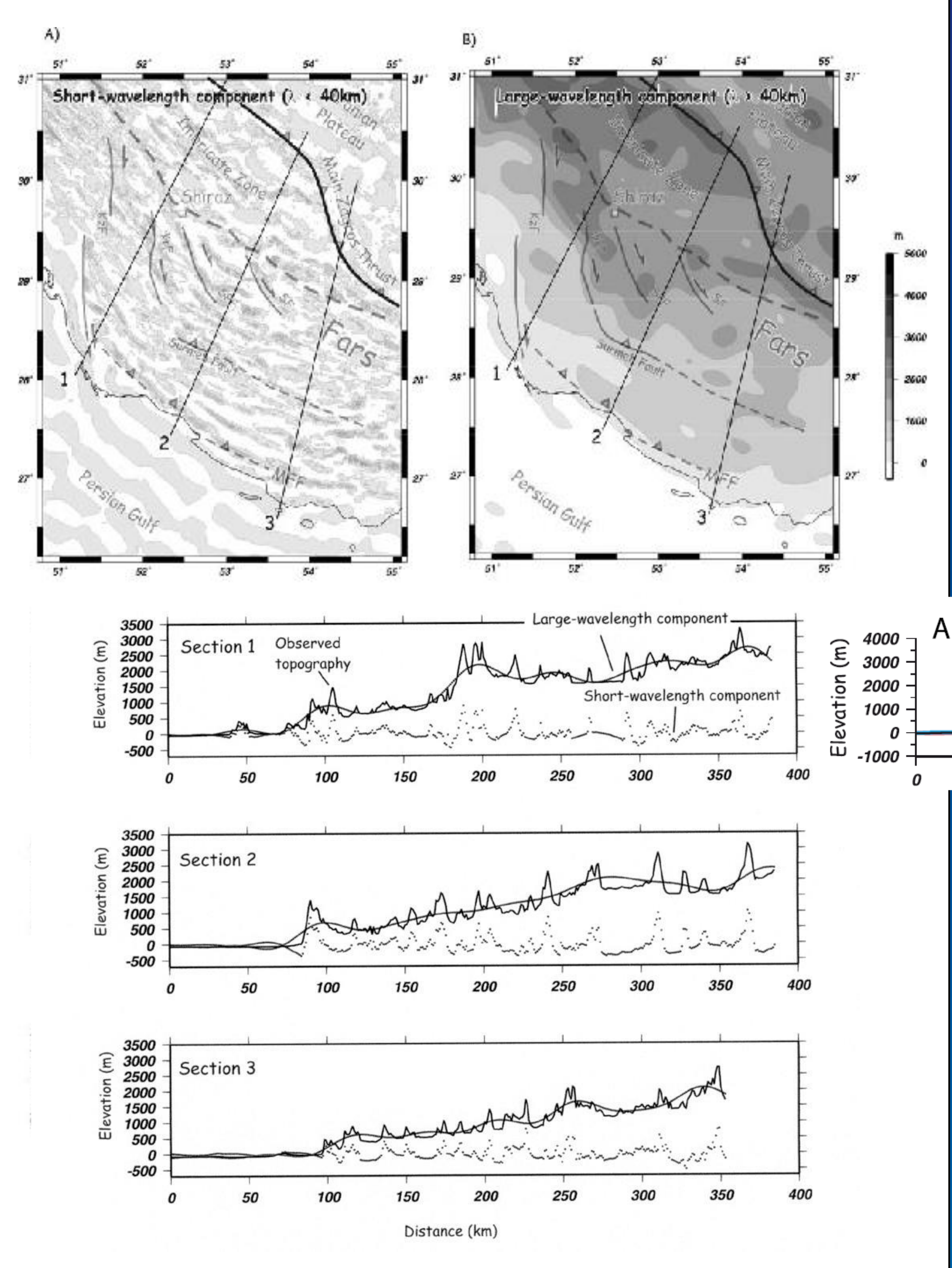


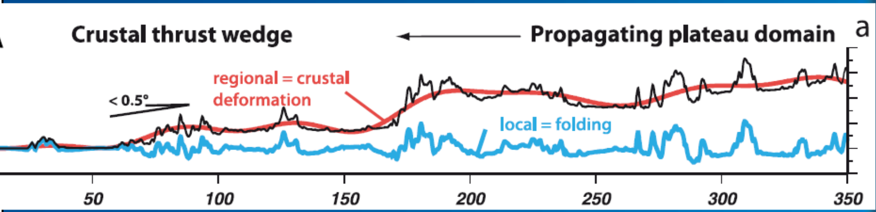
(Mouthereau et al., 2007; Lacombe et al., 2006)



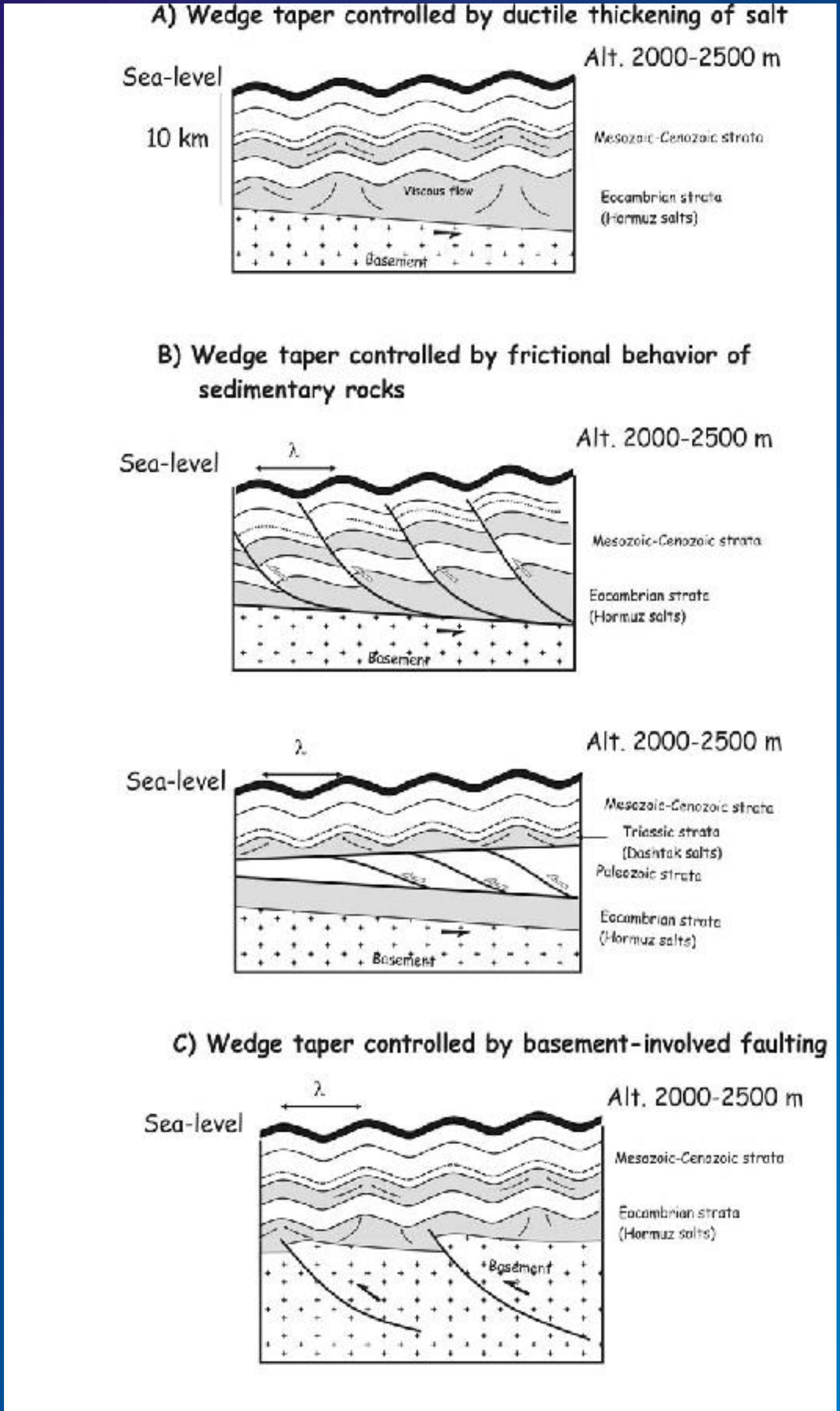
(Lacombe and Bellahsen, 2016)

Analysis of topography



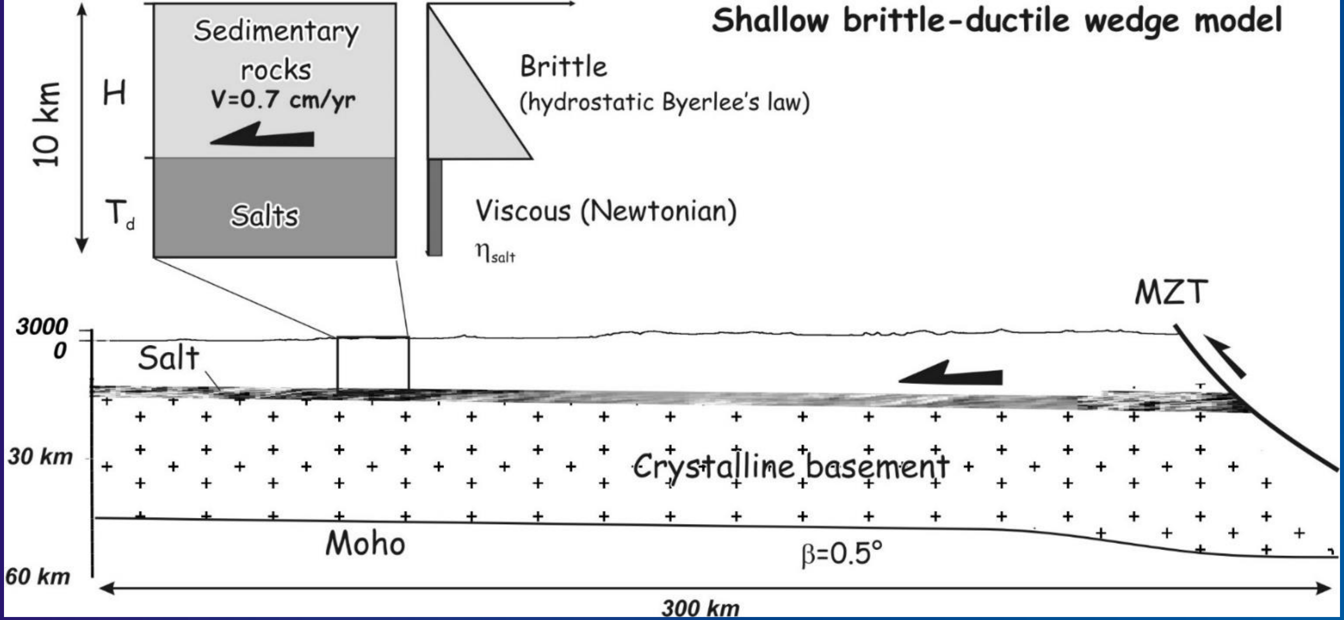


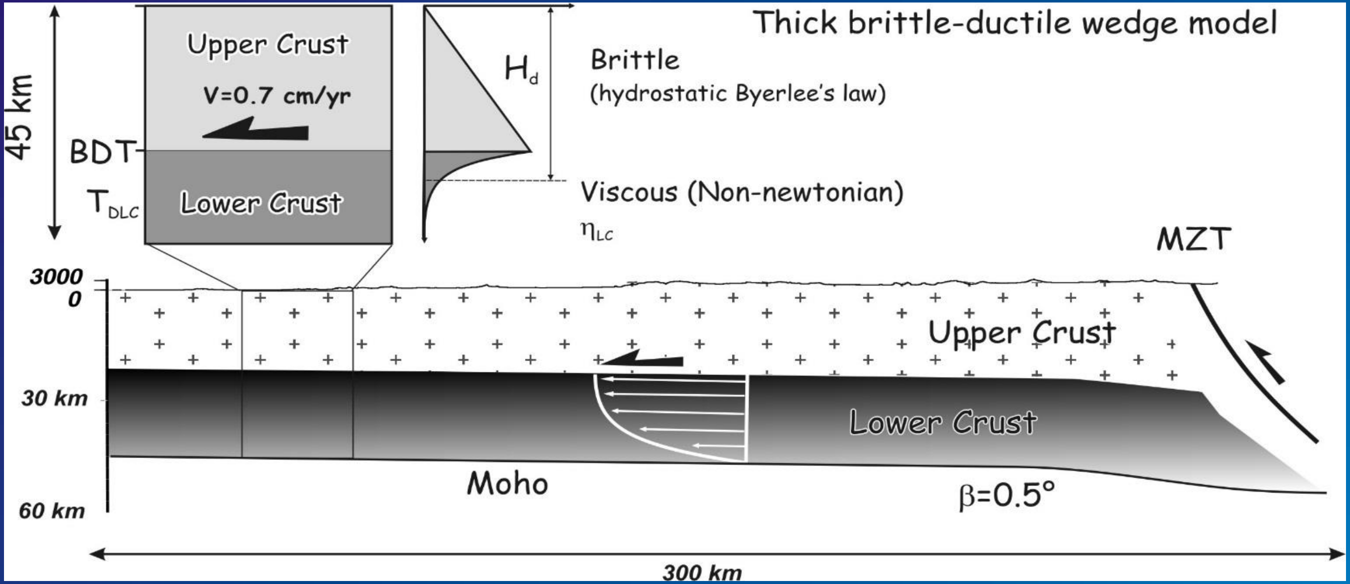
(Mouthereau et al., 2006, 2012)



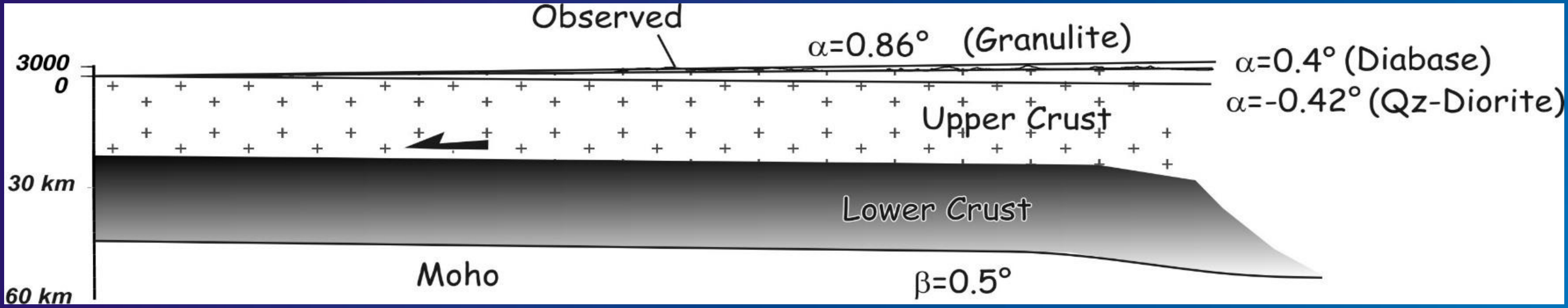
(Mouthereau et al.,2006)

Analytical modelling of the Zagros wedge





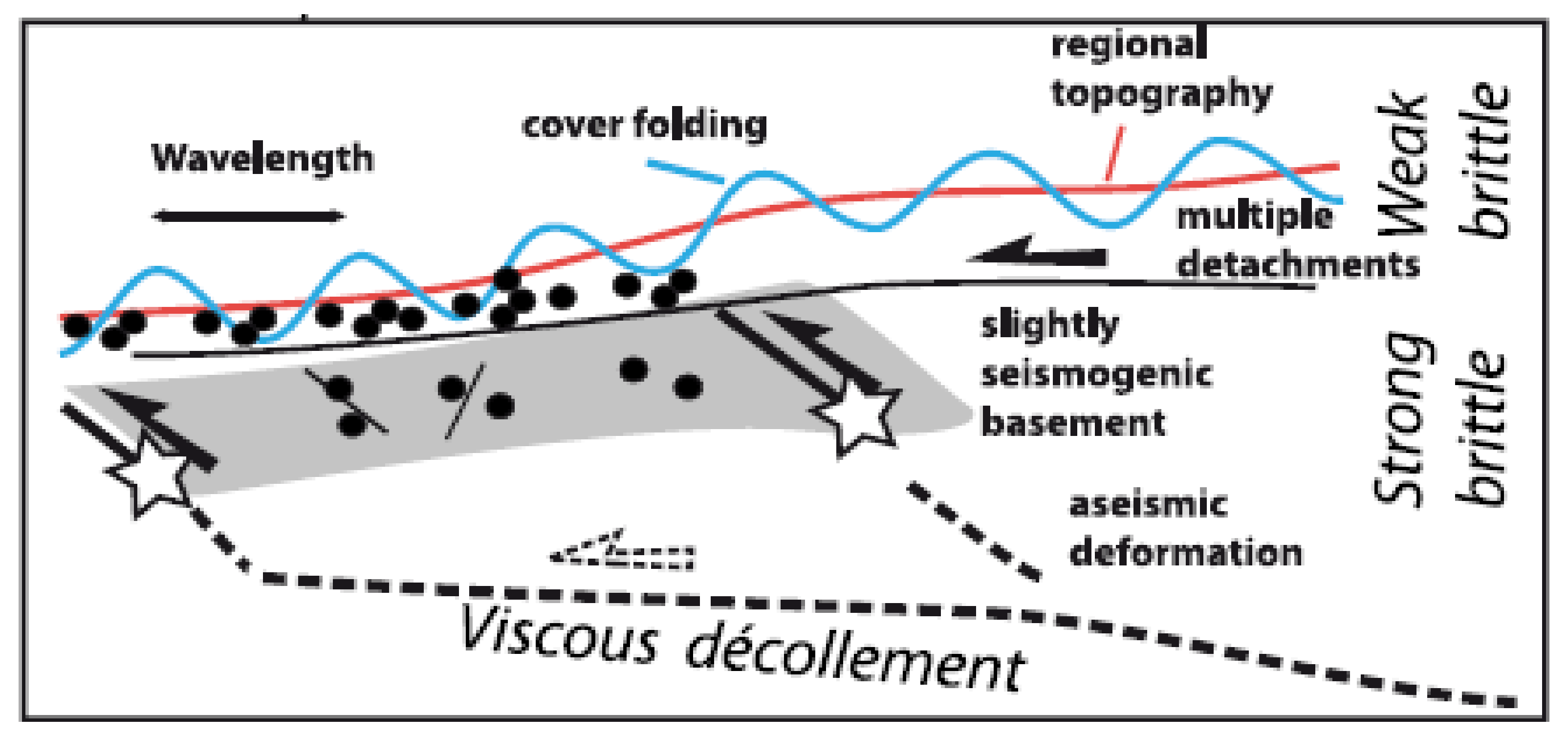
(Mouthereau et al., 2006)



Salt is unable to sustain topography.

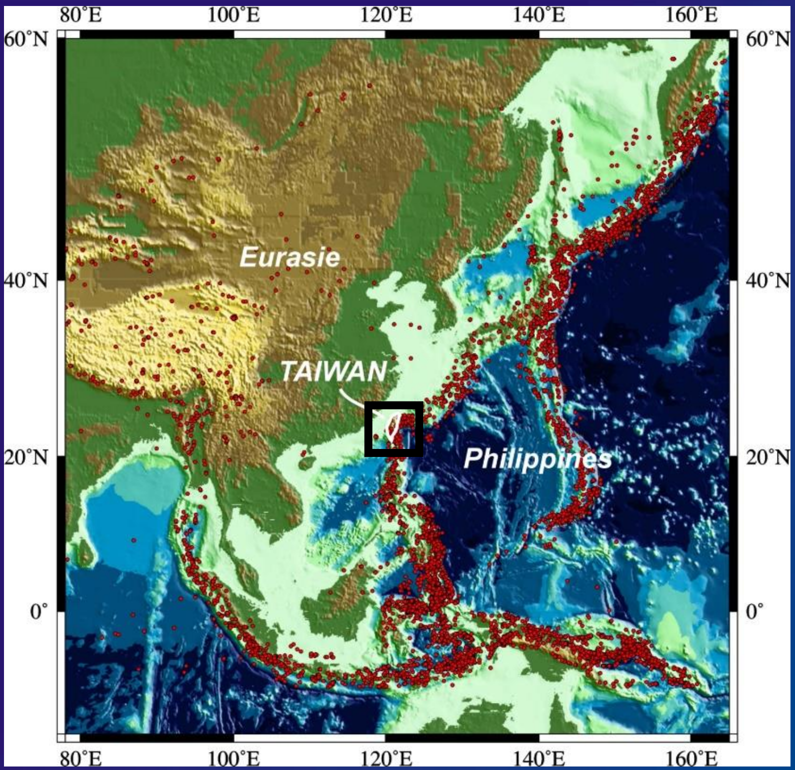
Only a model of critically-tapered brittle-viscous wedge involving the crystalline basement reproduces the observed topographic slopes across the Fars

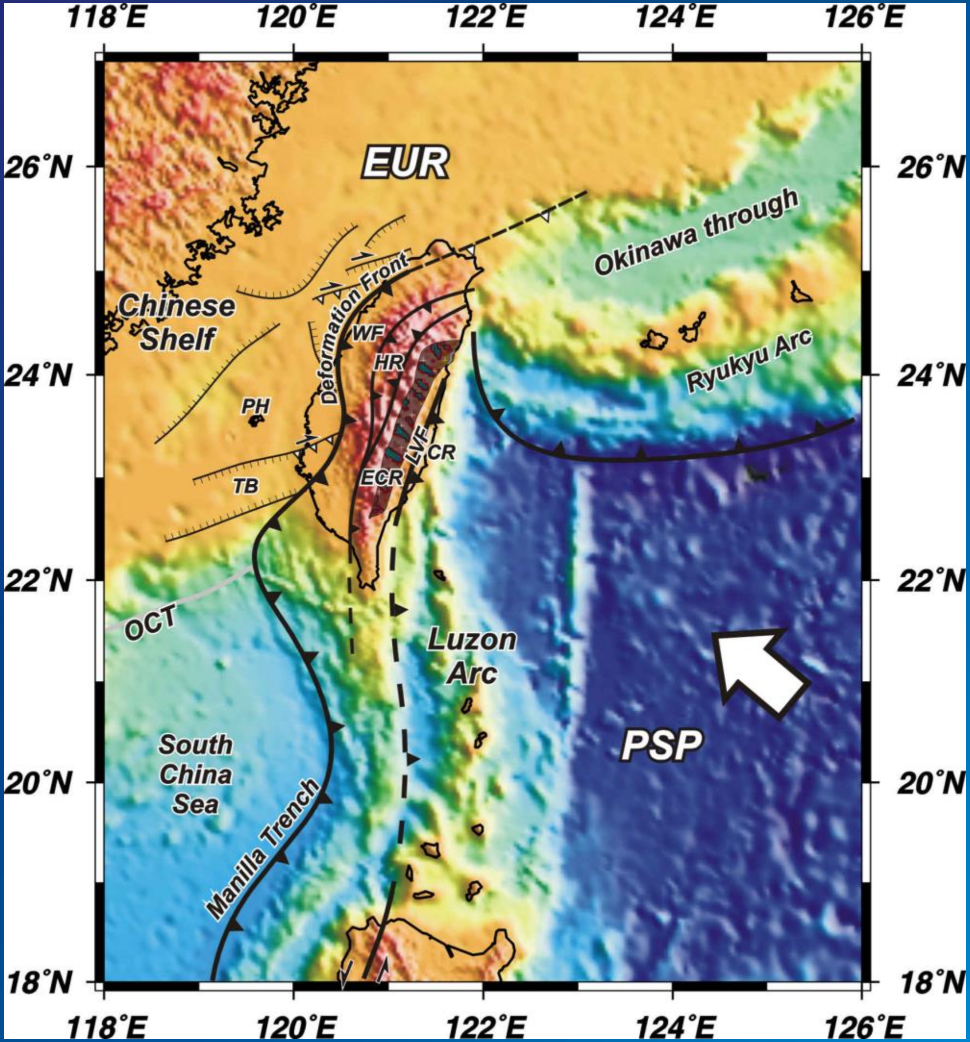
(Mouthereau et al., 2006)

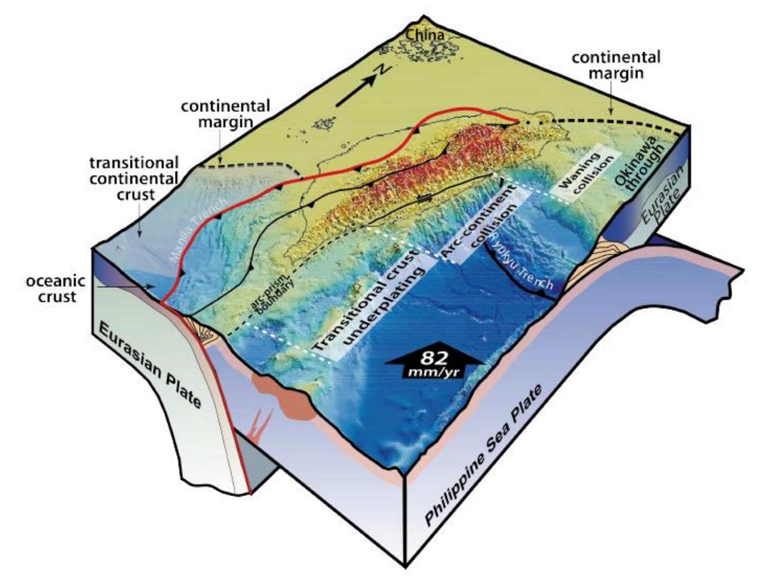


(Mouthereau et al., 2012)

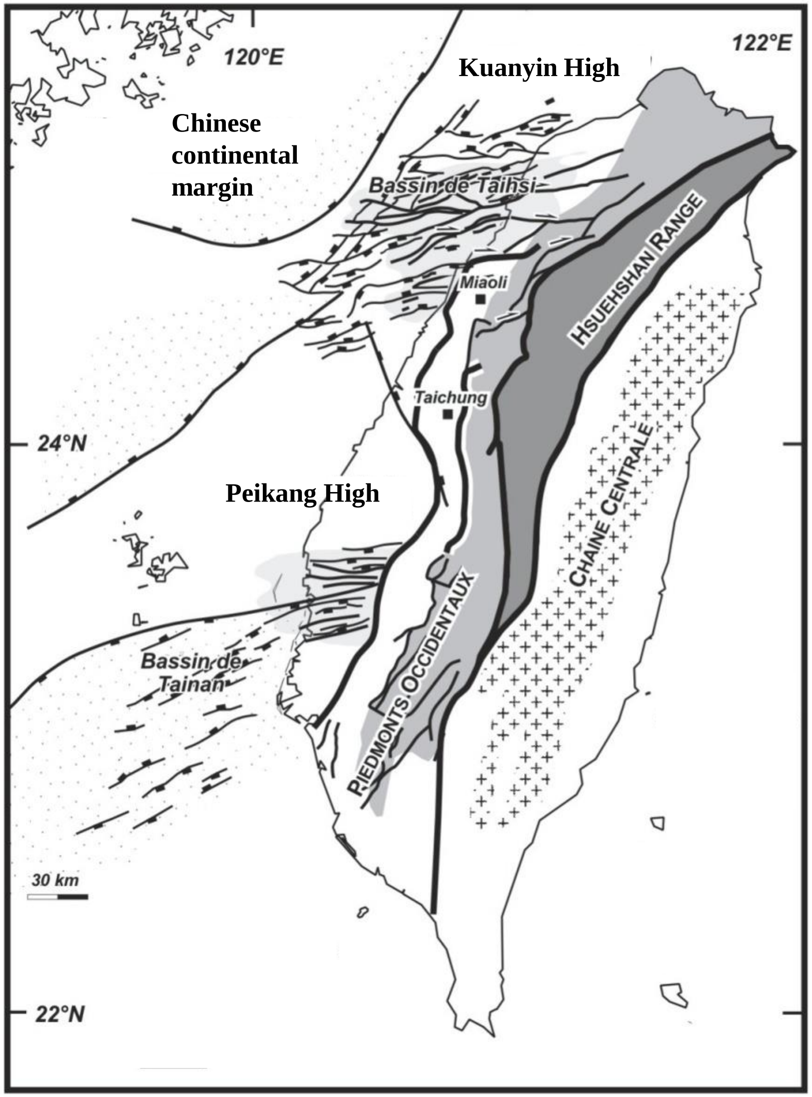
Lateral variations of structural style :
Taiwan

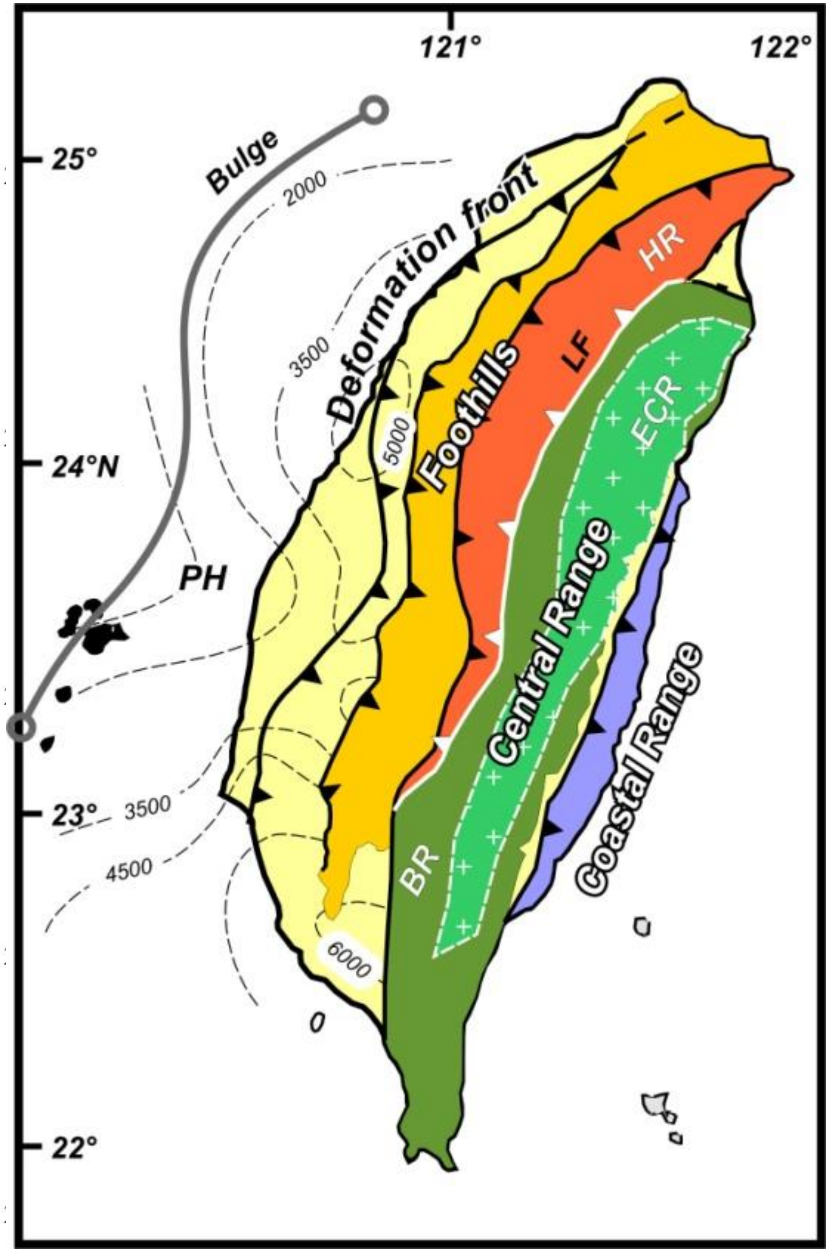






Plio-Pleistocene oblique arc-continent collision between the N-S Luzon volcanic arc and the ENE chinese continental passive margin that underwent Eocene–Oligocene rifting and subsequent spreading associated with the opening of the South China Sea, as well as later Miocene extensional events.


120°E
122°E
Kuanyin High
Chinese continental margin
Bassin de Taihsi
Miaoli
Taichung
Hsuehshan Range
Chaine Centrale
24°N
Peikang High
Piedmonts Occidentaux
Bassin de Tainan
30 km
22°N

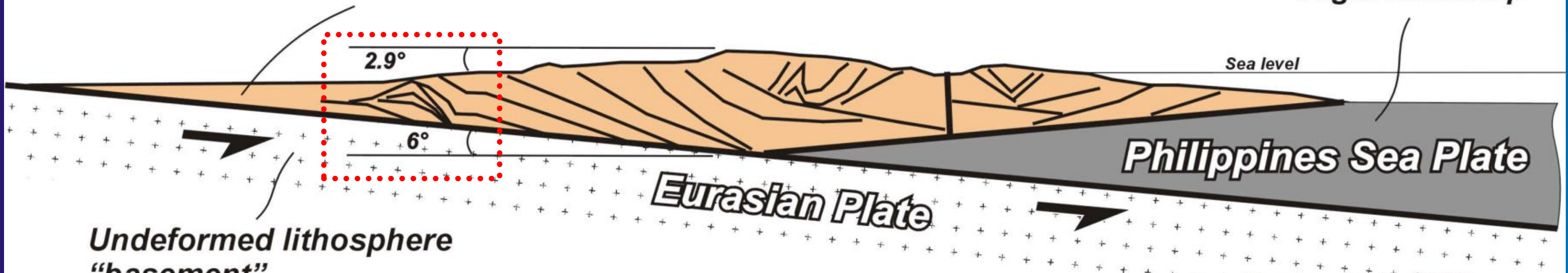

121°
122°
25°
Bulge
2000
Deformation front
HR
3500
LF
ECR
Foothills
5000
24°N
PH
Central Range
Coastal Range
3500
23°
4500
BR
6000
0
22°

Steady critical wegde model for Taiwan

Critically tapered wegde
(with thin-skinned approximation)

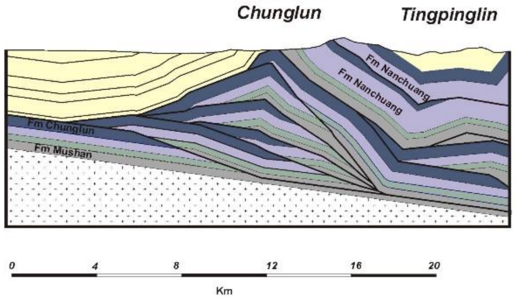
Eurasian sediments are scraped off and deformed into the Taiwan orogen

Rigid backstop



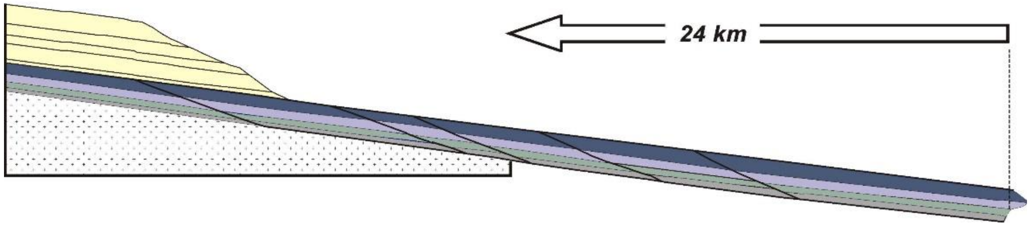
Undeformed lithosphere “basement”

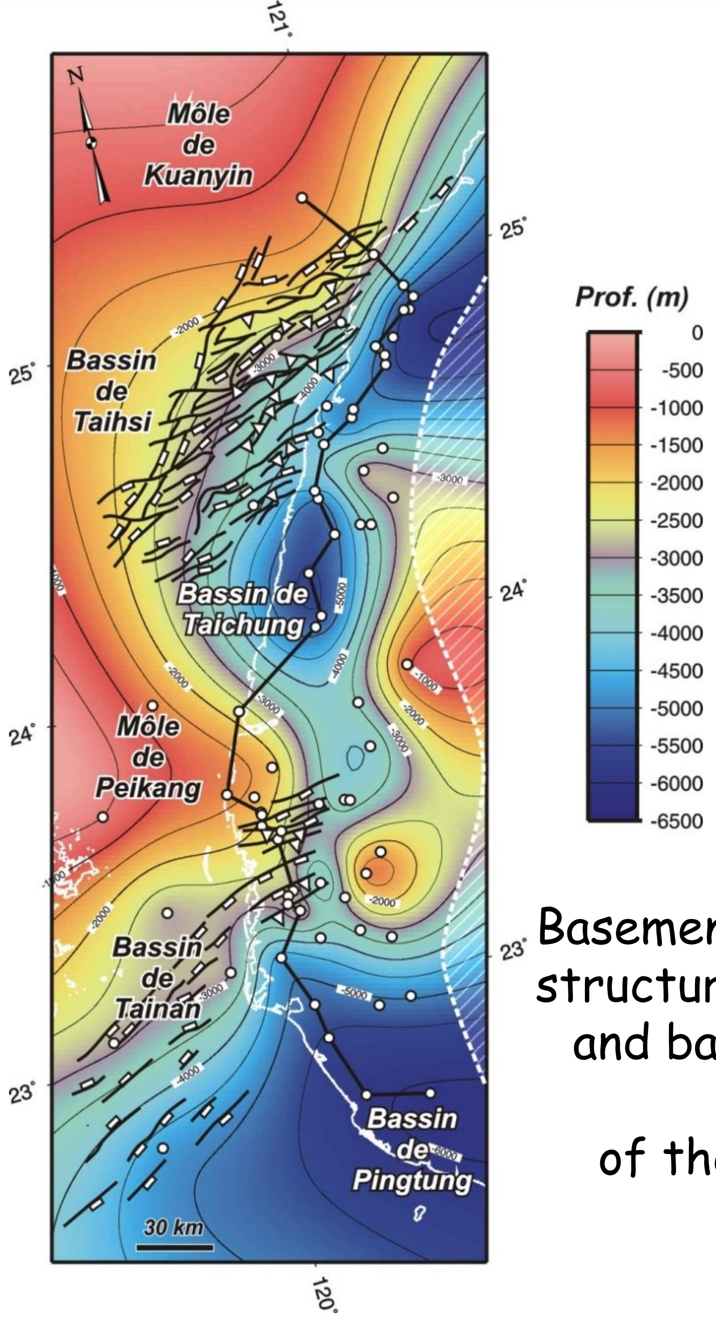
Davis et al., 1983
Suppe, 1981
Barr and Dahlen, 1990



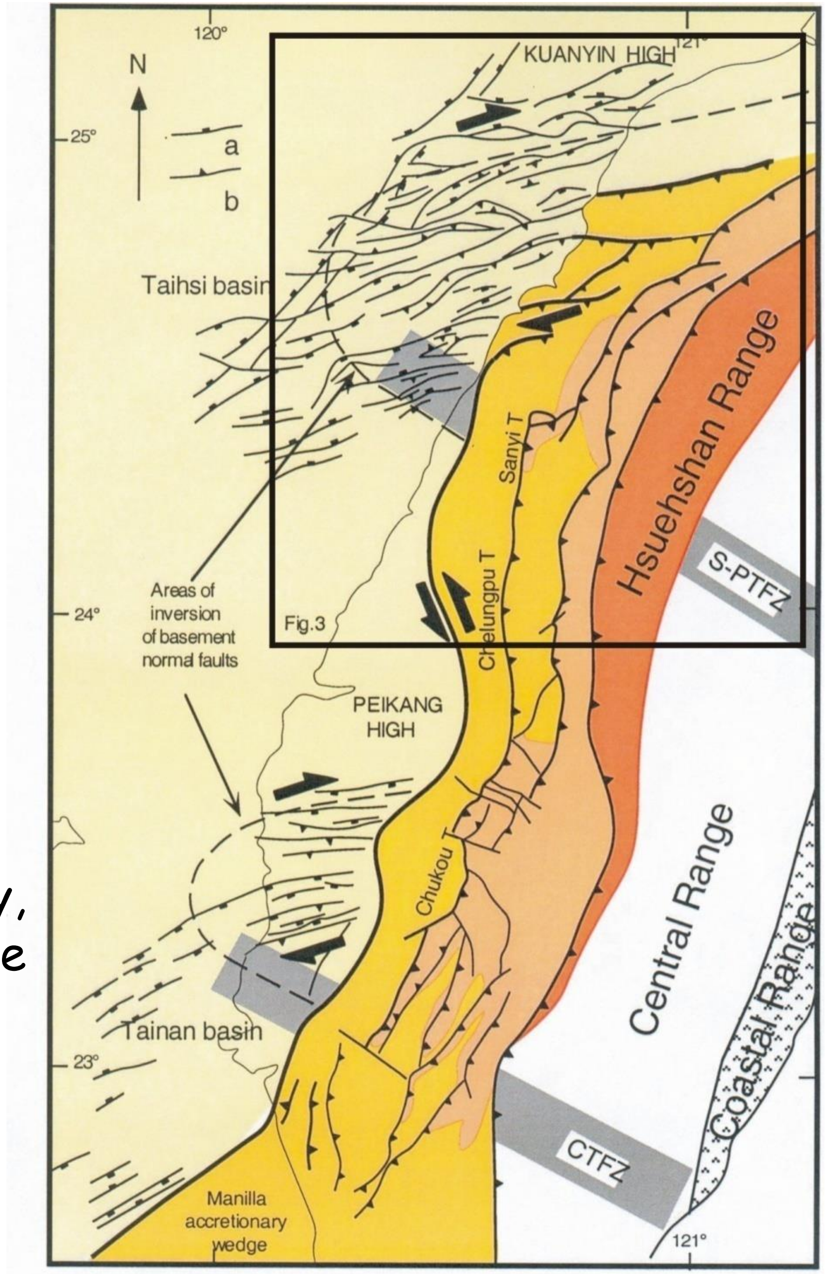
Thin-skinned hypothesis

Large shortening
of the sedimentary cover





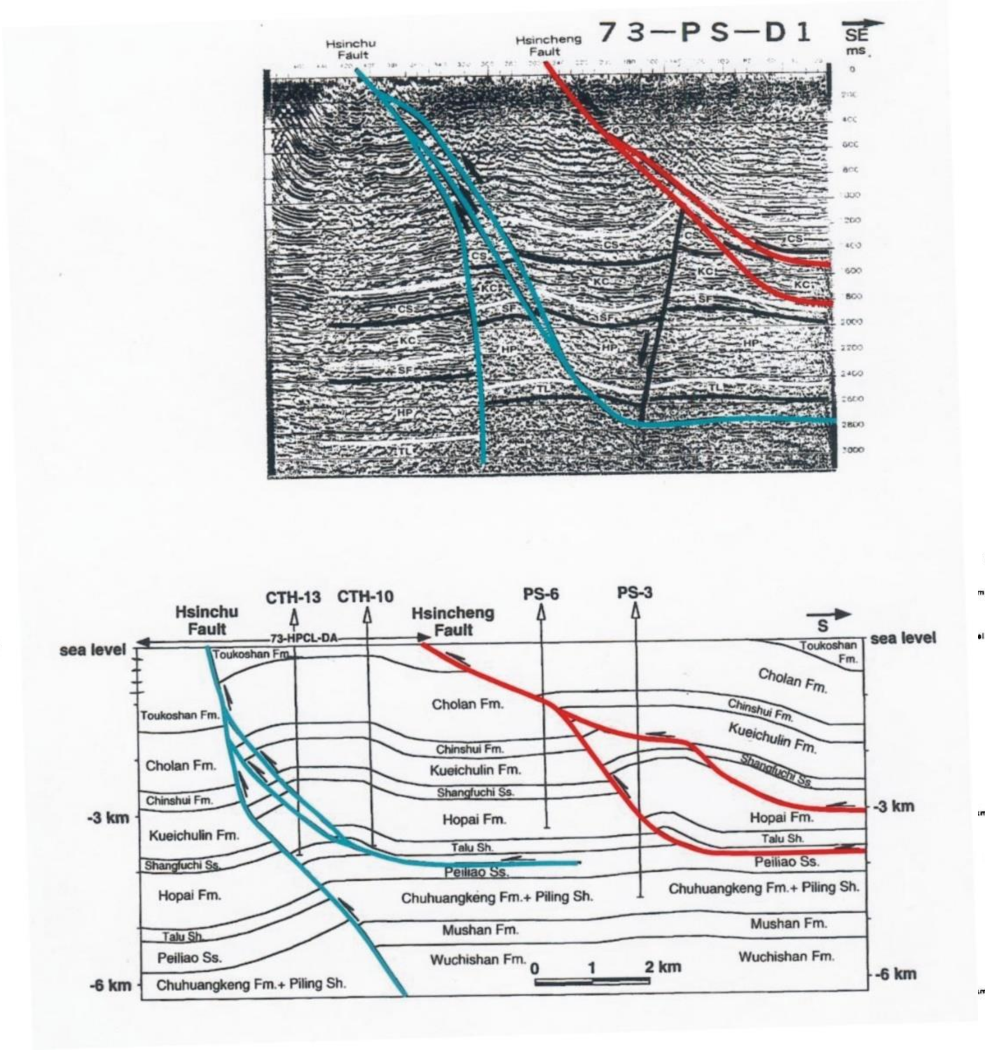
Basement topography, structural inheritance and basin inversion south of the basement highs

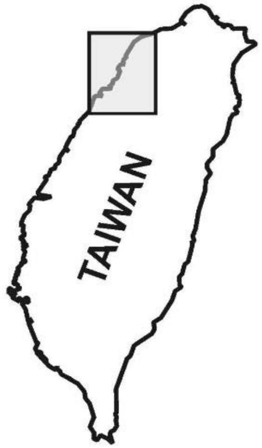


(Mouthereau et al., 2002)

(Lacombe and Mouthereau, 2002)

2 very different visions of the structural style in northern Taiwan





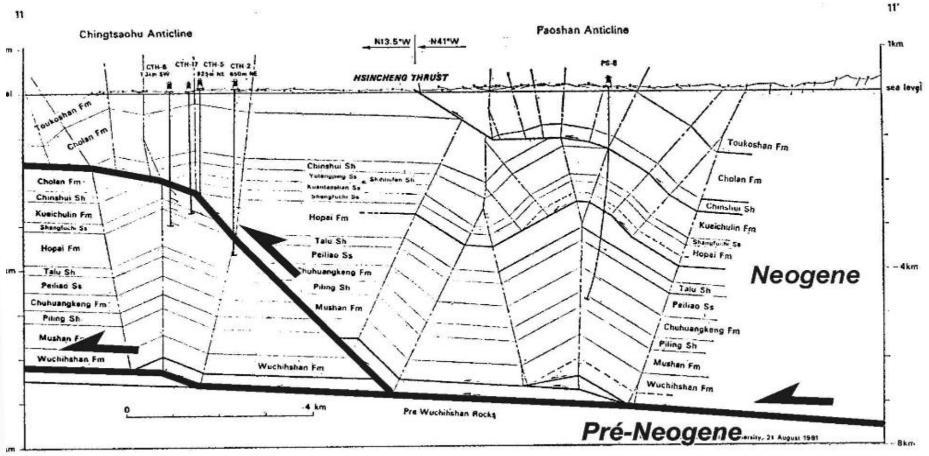
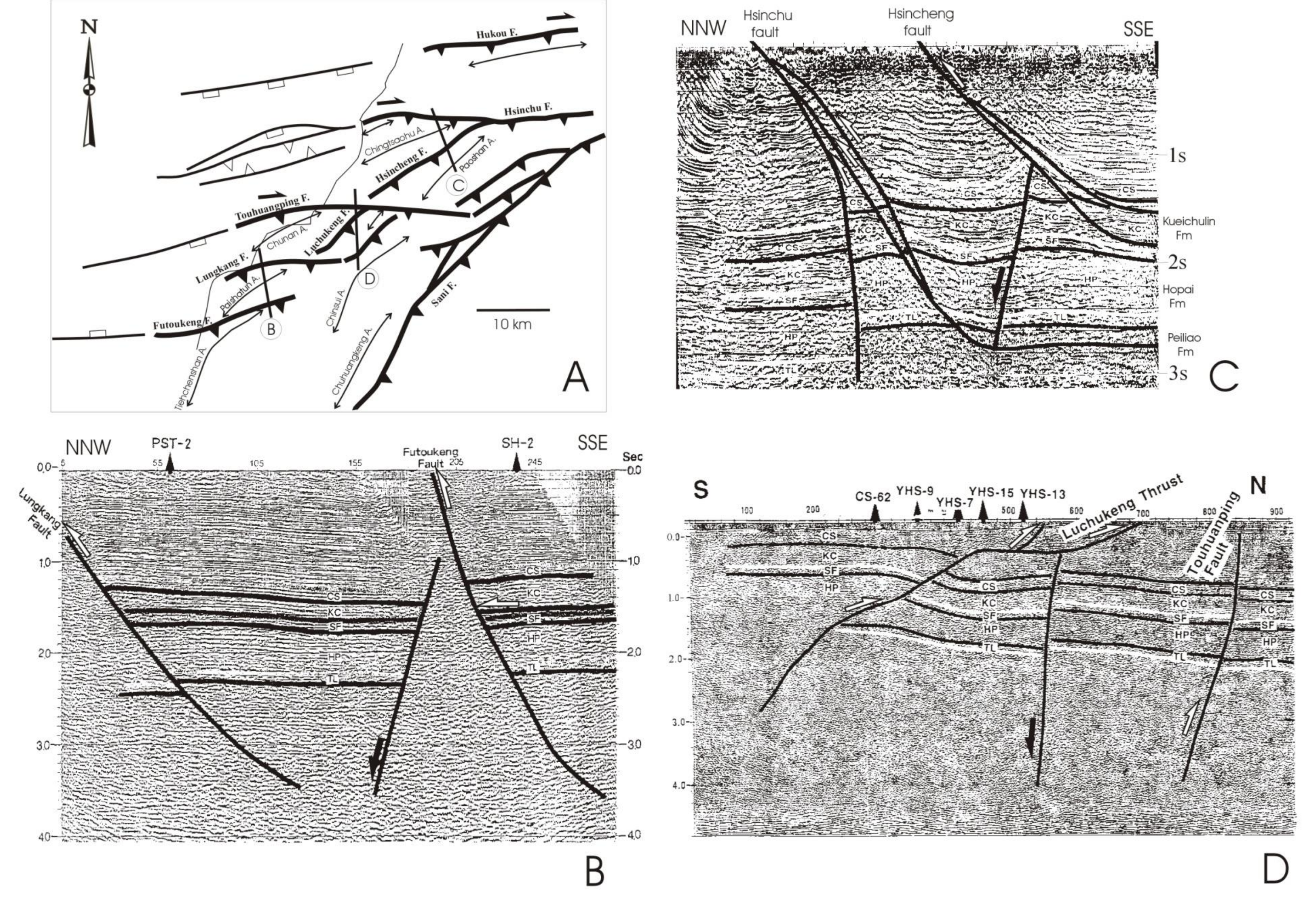


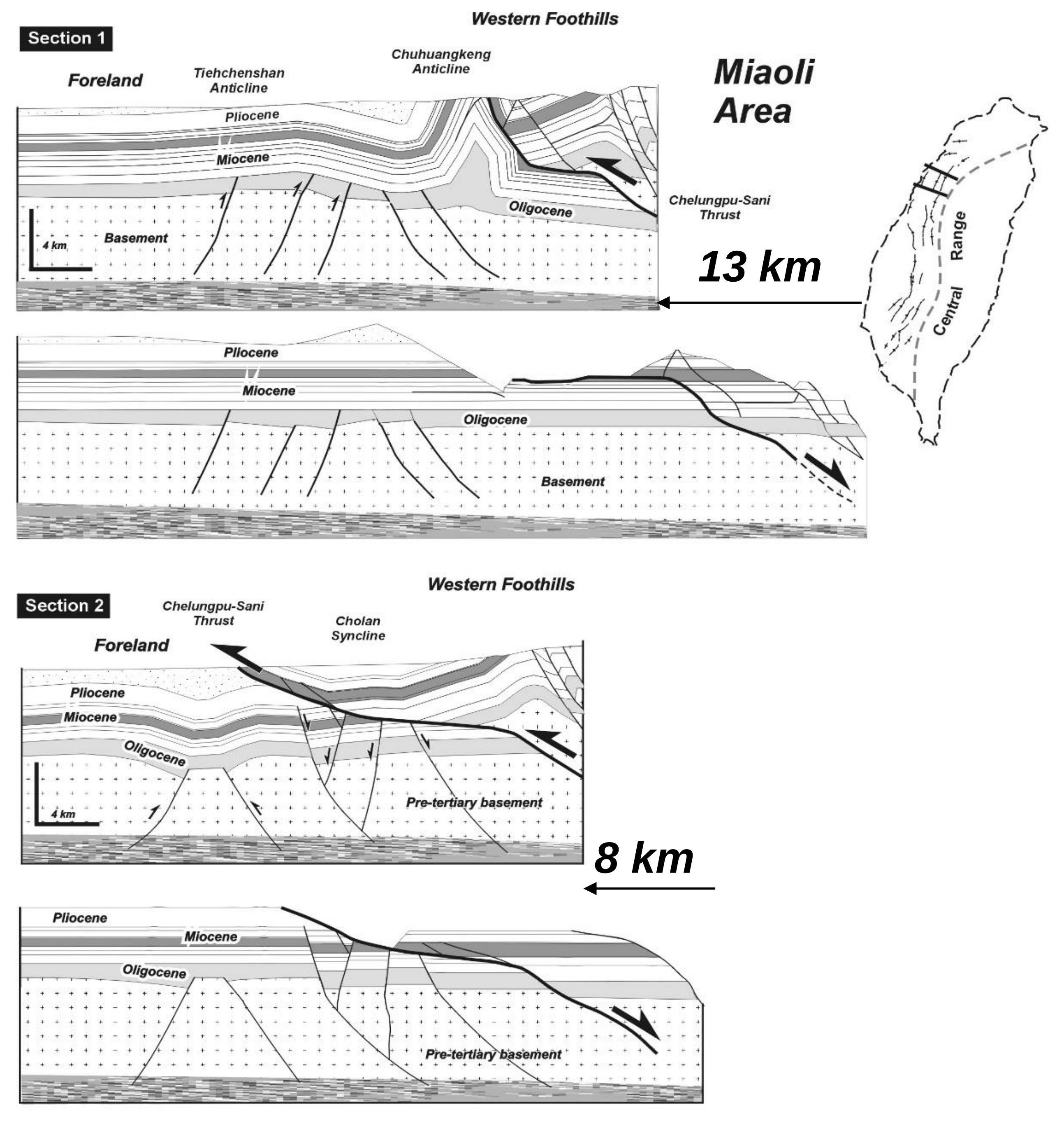
Figure 2. Structural interpretation through section 11-11′ in the northern part of the Miaoli-Hsinchu area.

(Yang et al., 1996)

(Namson, 1981)



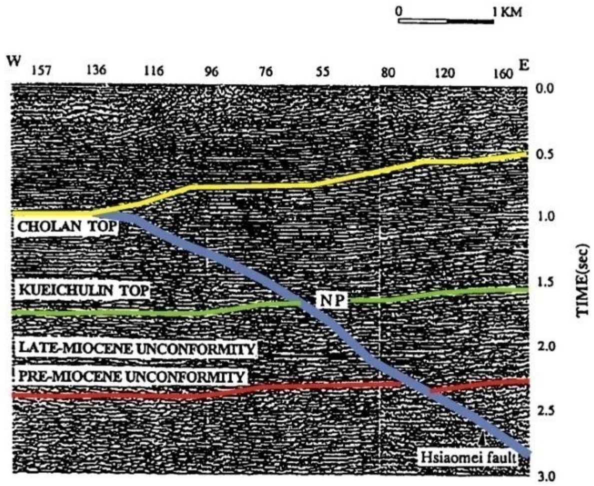
(Lacombe et al., 2003; profiles from Yang et al., 1994, 1996, 1997)

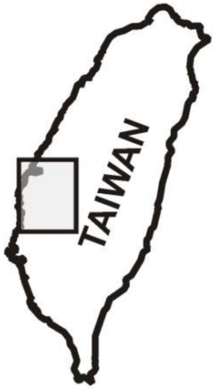


(Mouthereau and Lacombe, 2006)

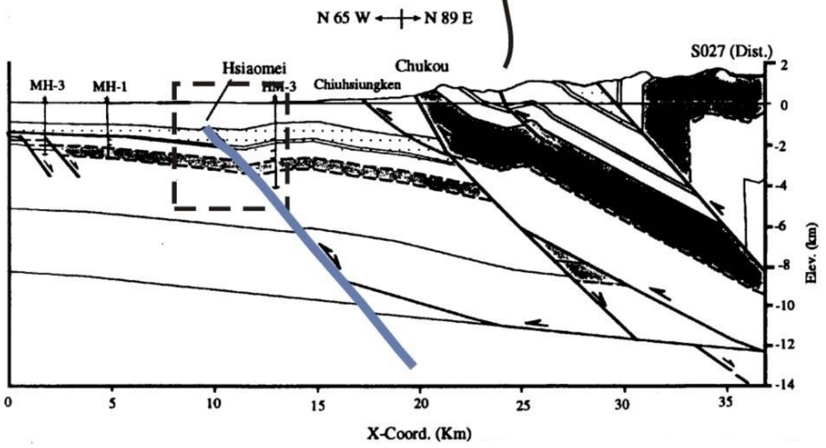
Superimposed decoupling in the sedimentary cover and basement controlled by structural inheritance

2 very different visions of the structural style in central Taiwan

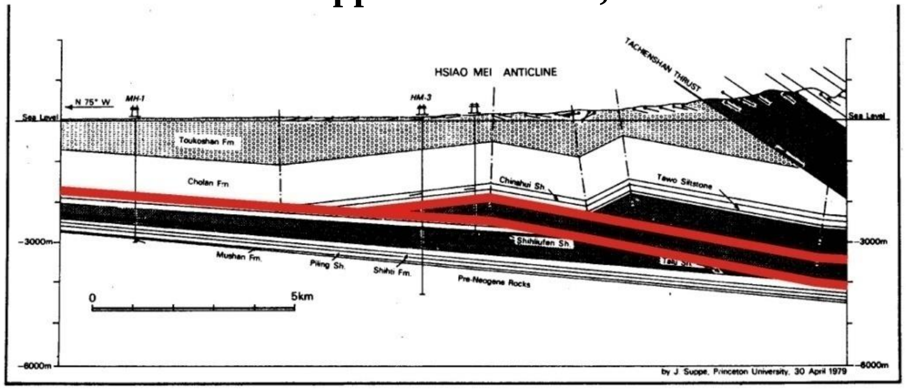


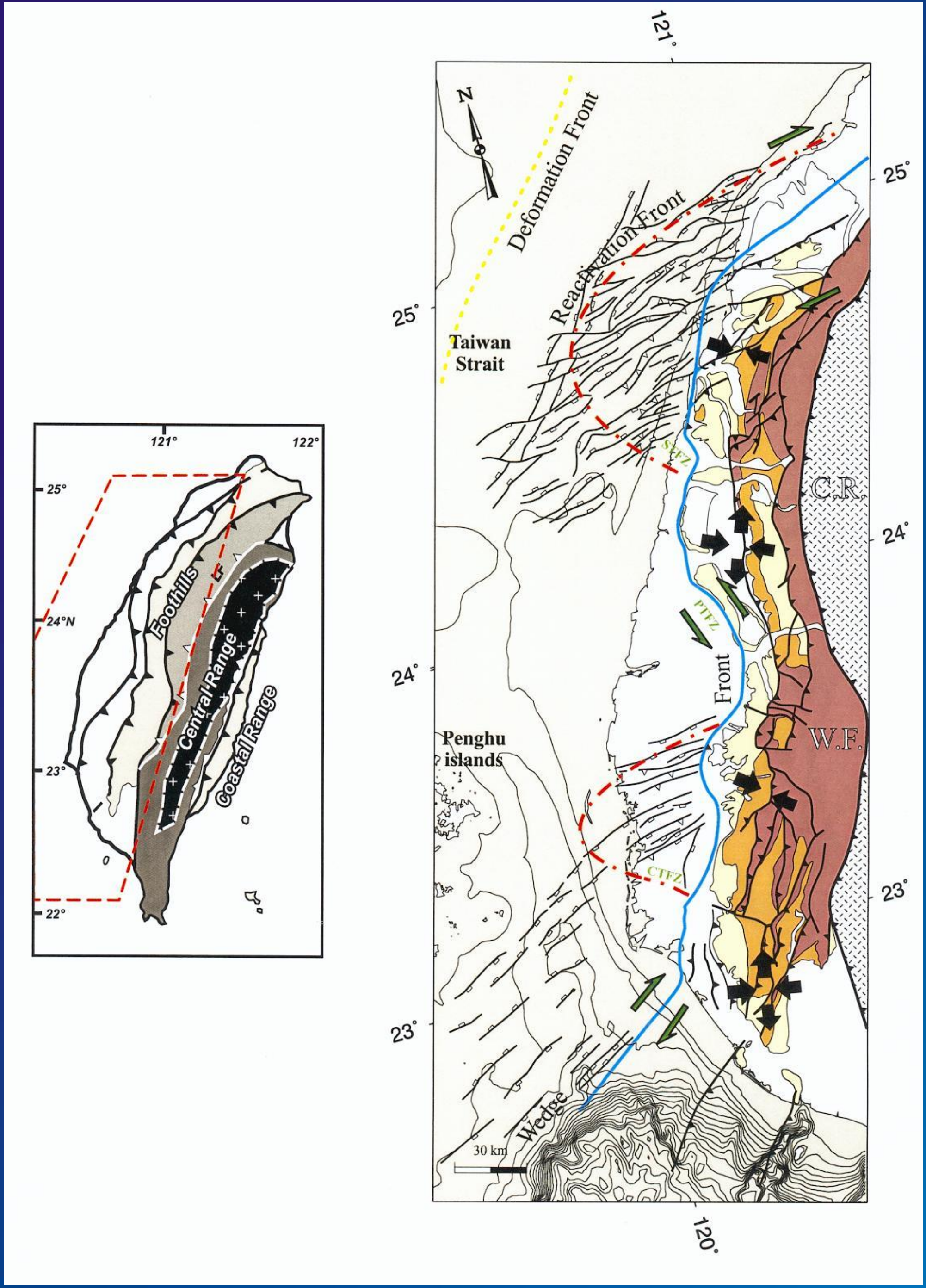


Hung et al., 1999



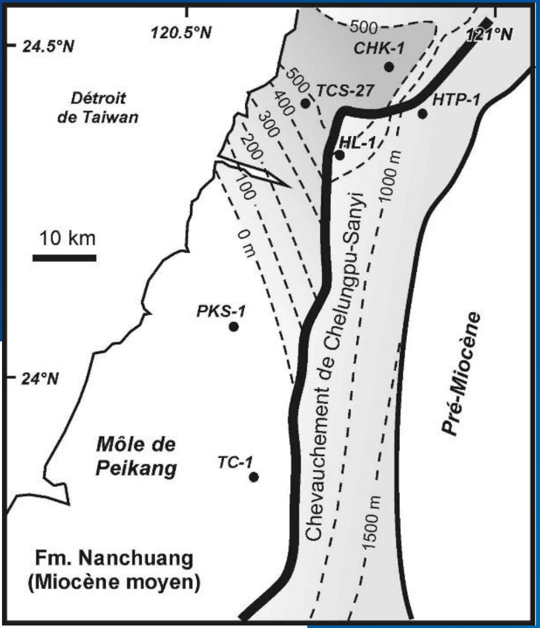
Suppe and Namson, 1979

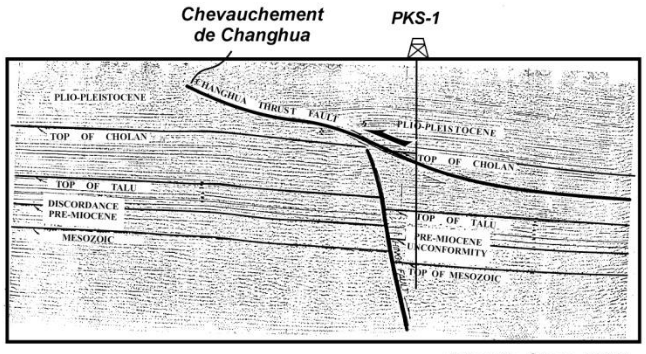




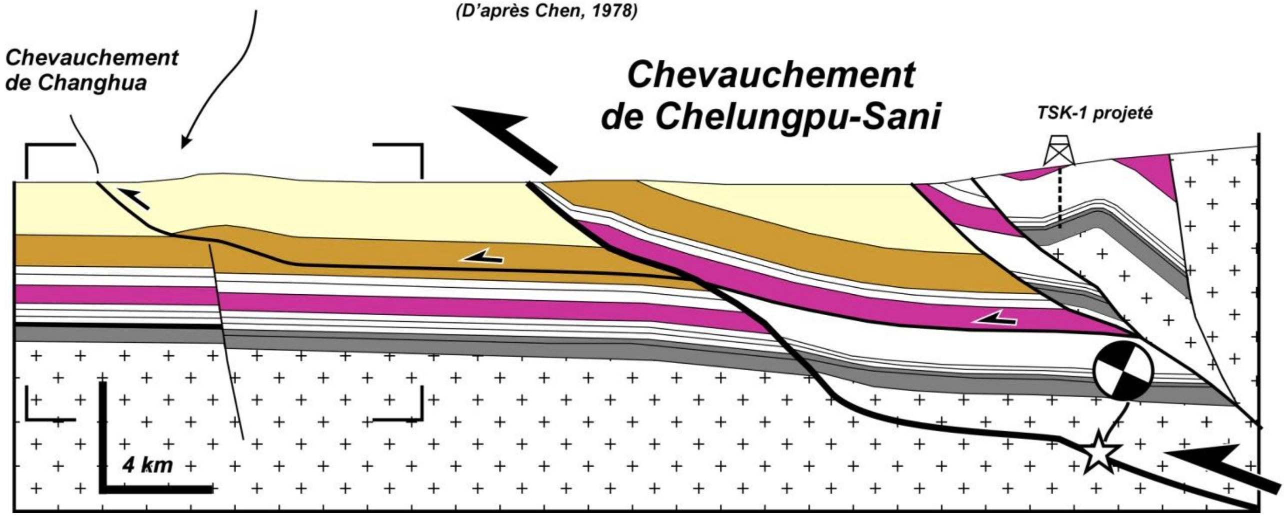
(Mouthereau et al., 2002)

The Chichi earthquake :
initiation of a thrust ramp dipping 30° at 11-12 km which connects to the Chelungpu thrust (an inherited normal fault)





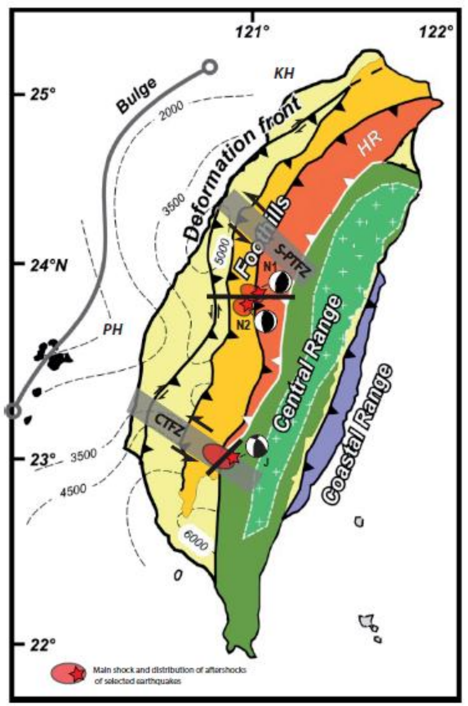
(D'après Chen, 1978)

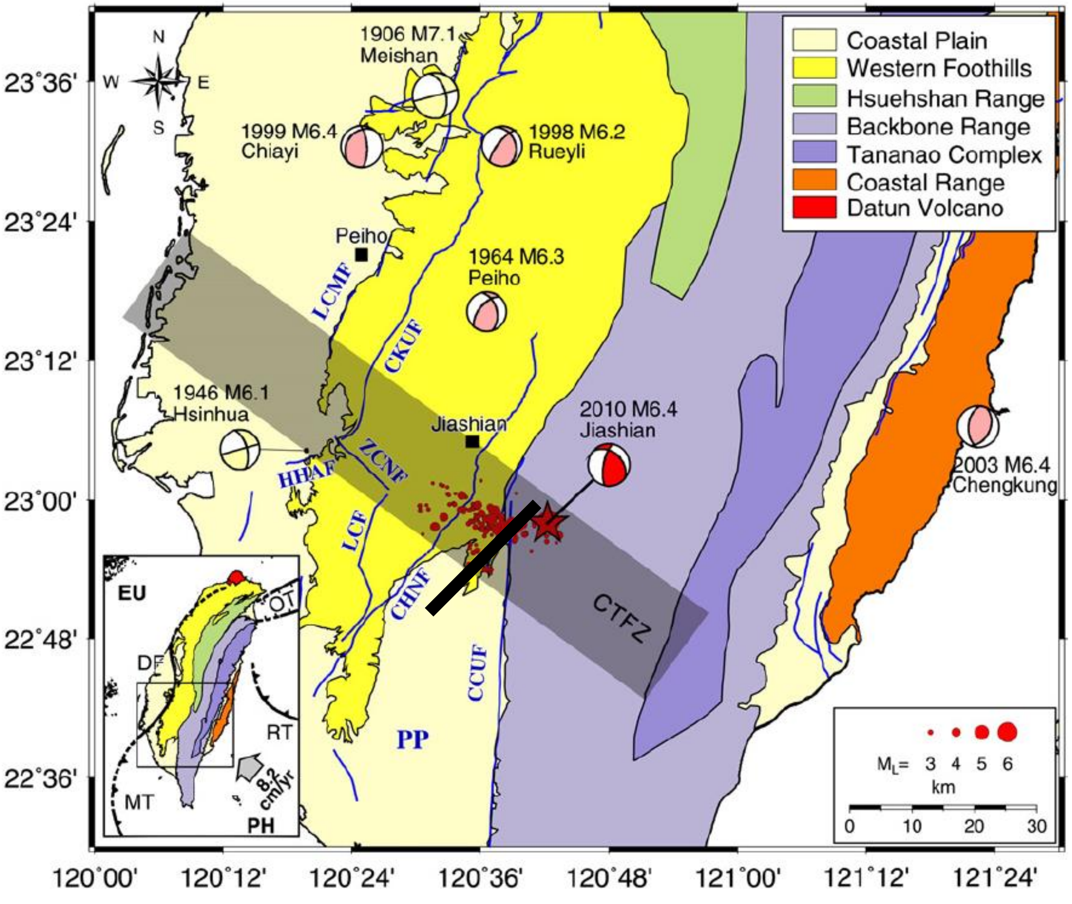


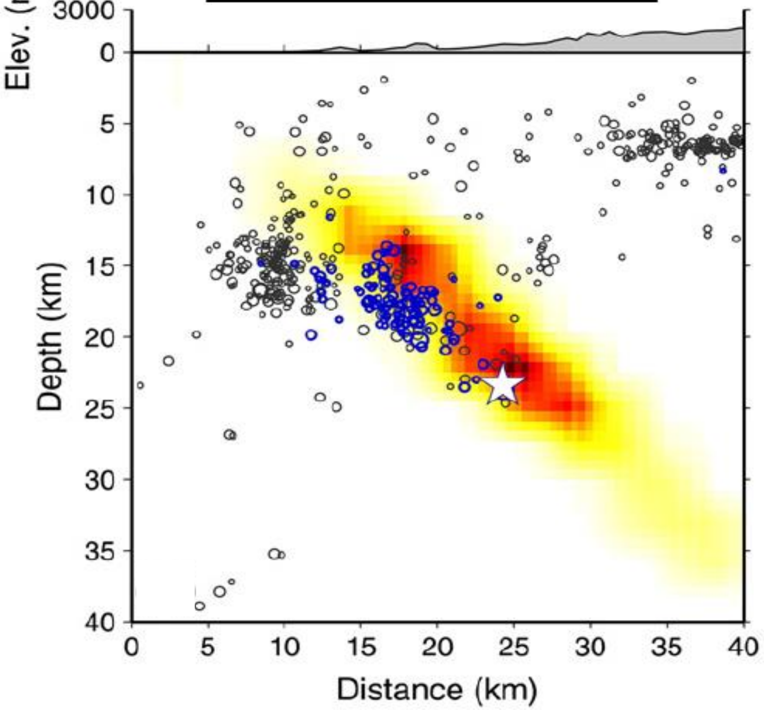
(Mouthereau et al, 2001)

2010 March 4, Mw 6.3 Jia-Shian earthquake

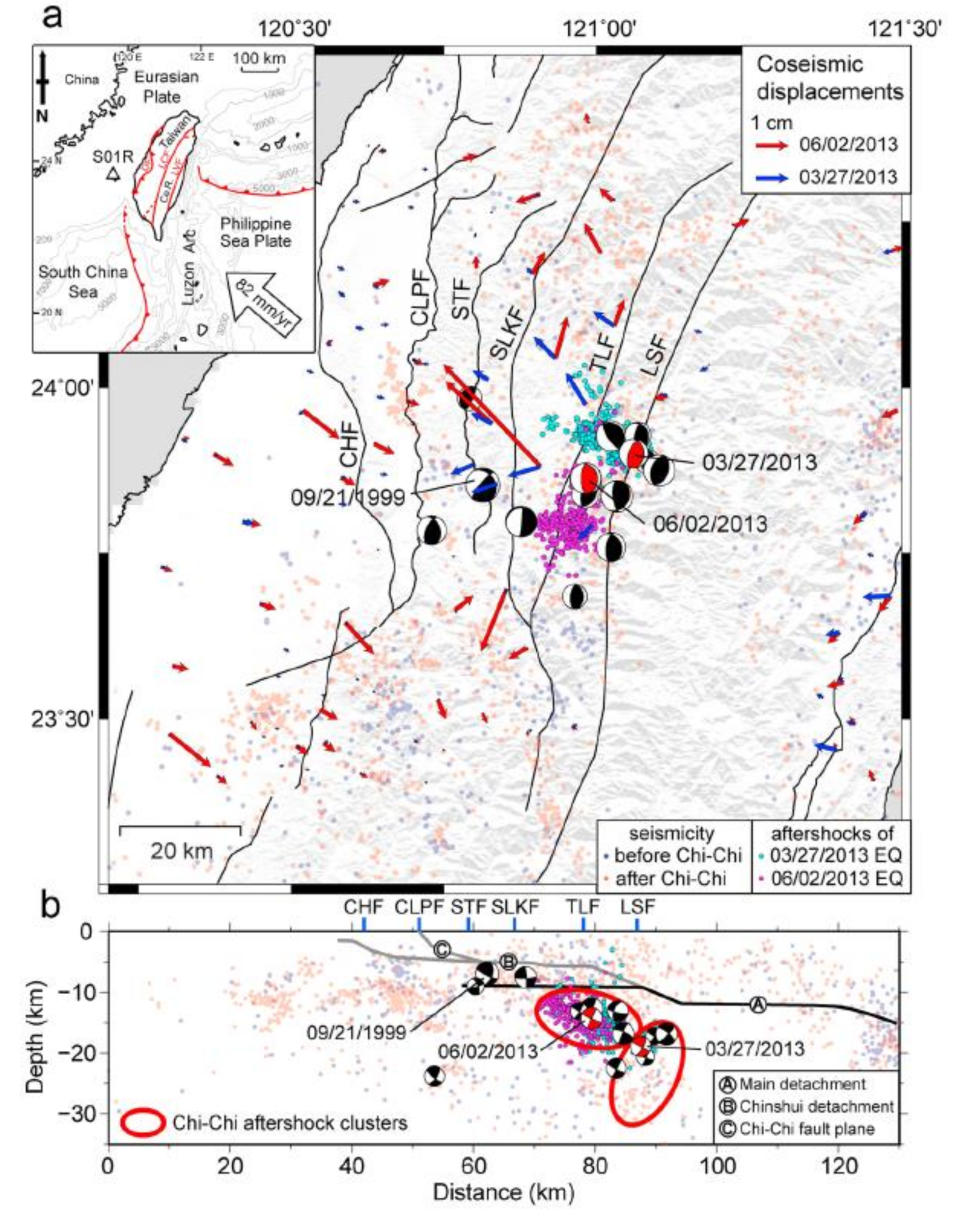
(Rau et al, 2013)





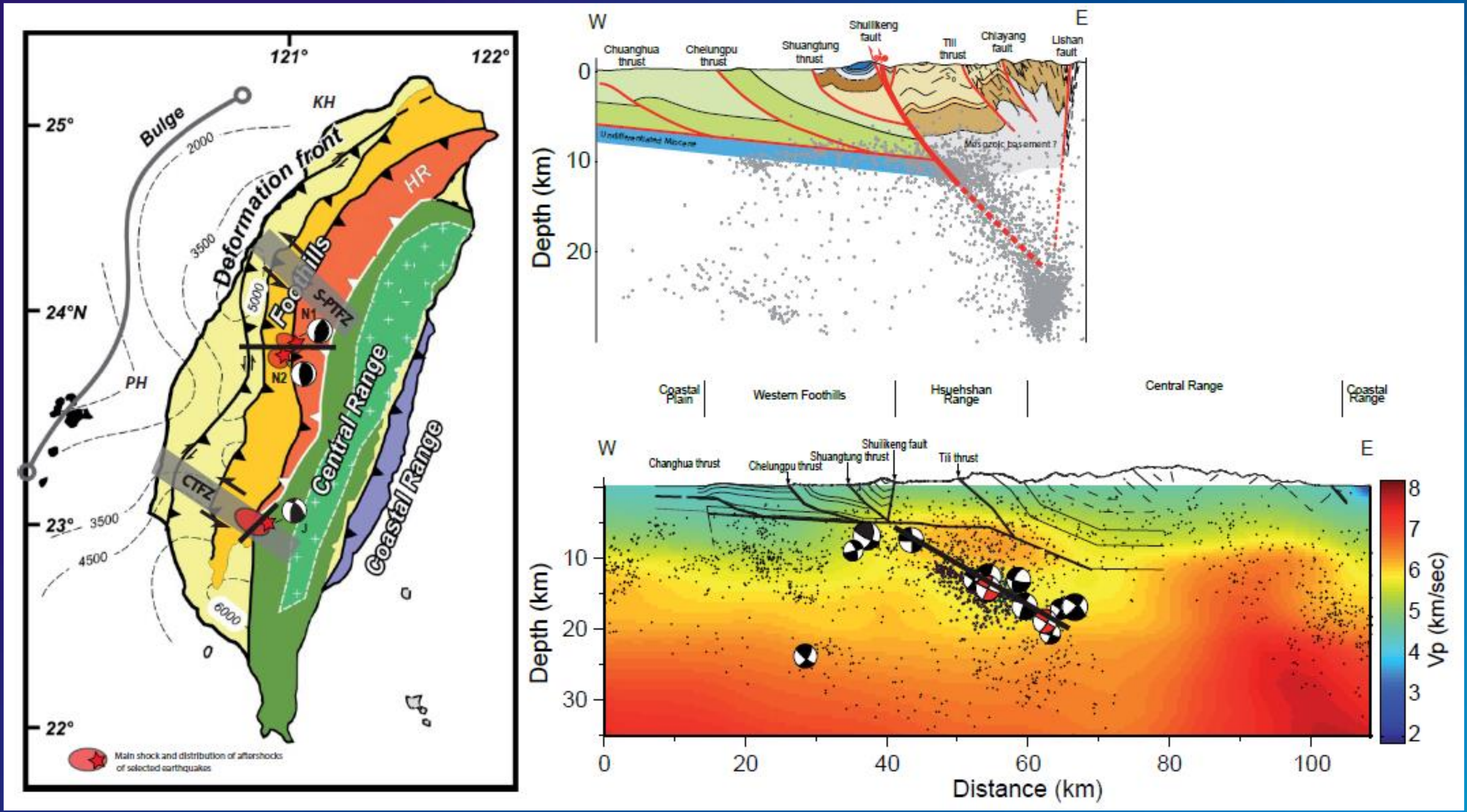


ML 6.2 and ML 6.5
2013 Nantou
earthquakes



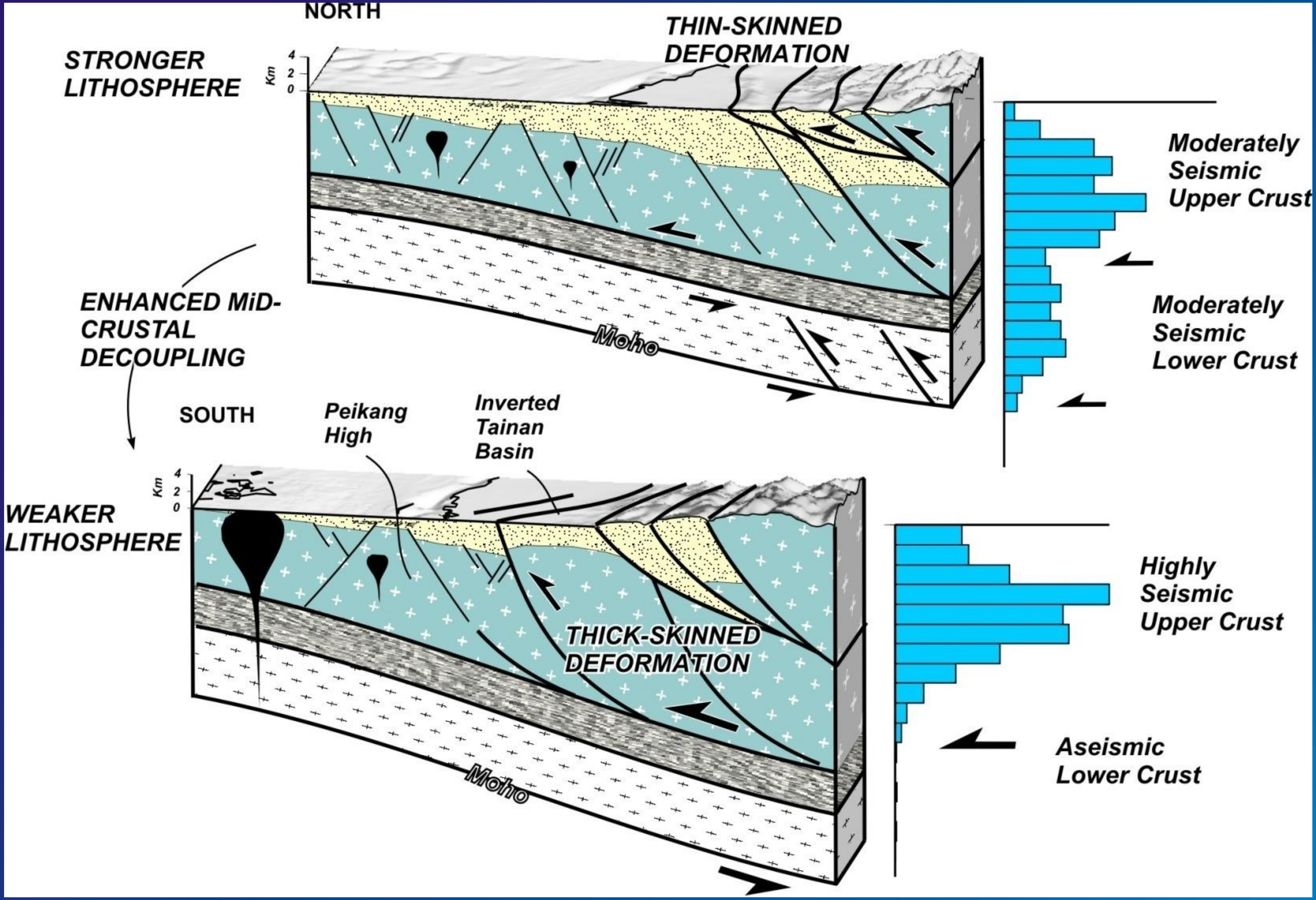
(Chuang et al, 2013)

ML 6.2 and ML 6.5 2013 Nantou earthquakes



(Brown et al., 2012; Chuang et al, 2013)

The earthquakes occur on essentially the same 30° dipping fault plane ramping up from ~20 km depth near a cluster of 1999 Chi-Chi earthquake aftershocks to the shallow detachment and the Chi-Chi fault plane.

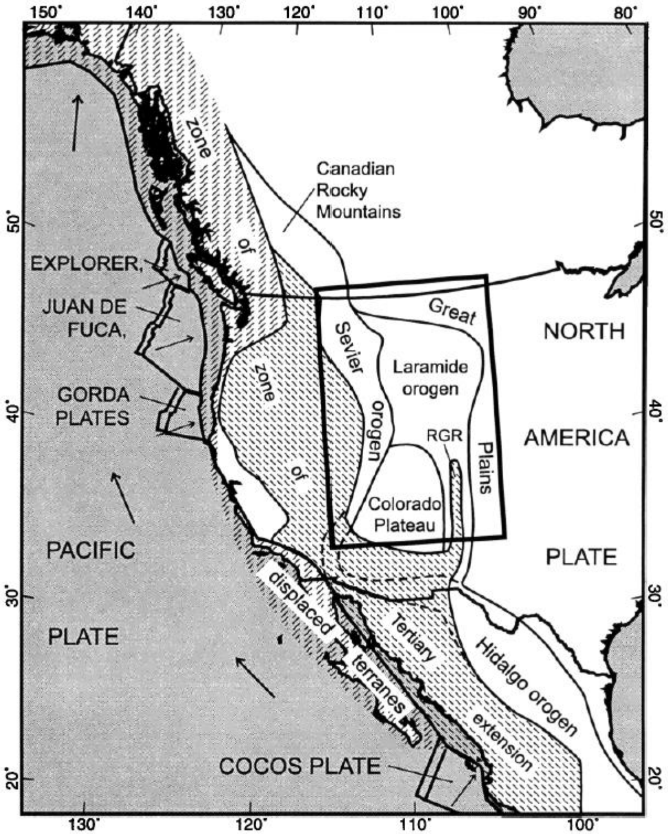


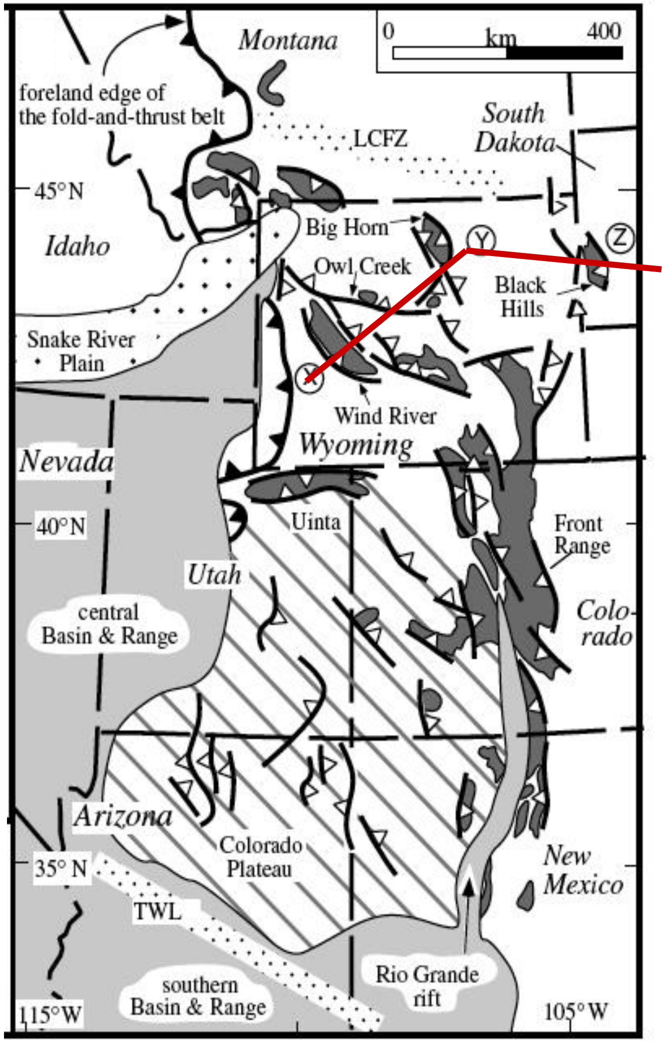
The degree of basement involvement *vs* thin-skinned deformation increases as the lithosphere weakens (rheology of the lower crust)

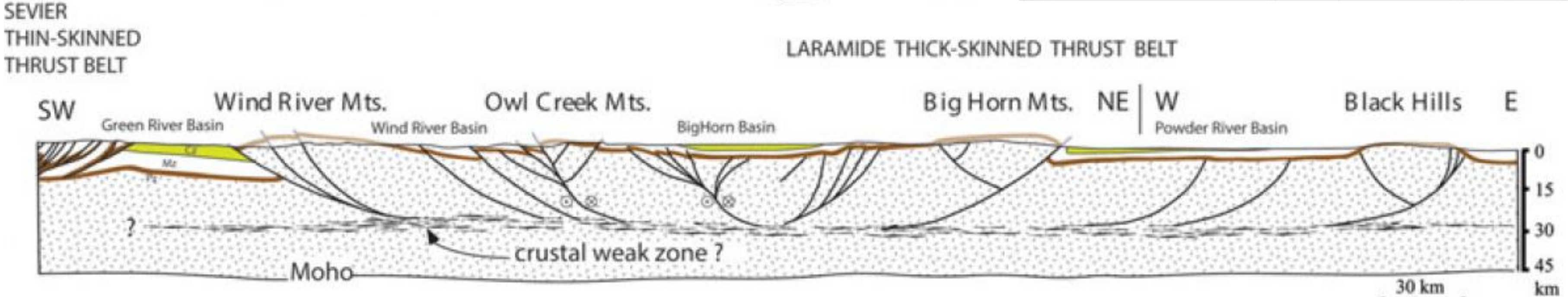
(Mouthereau and Petit, 2003)

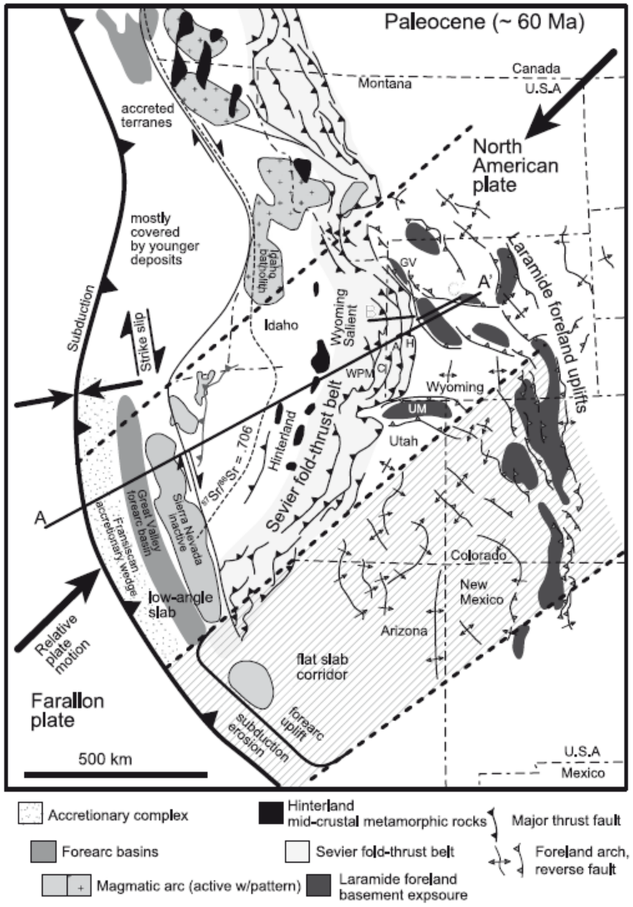
Thick-skinned tectonic style :
the Laramide belt

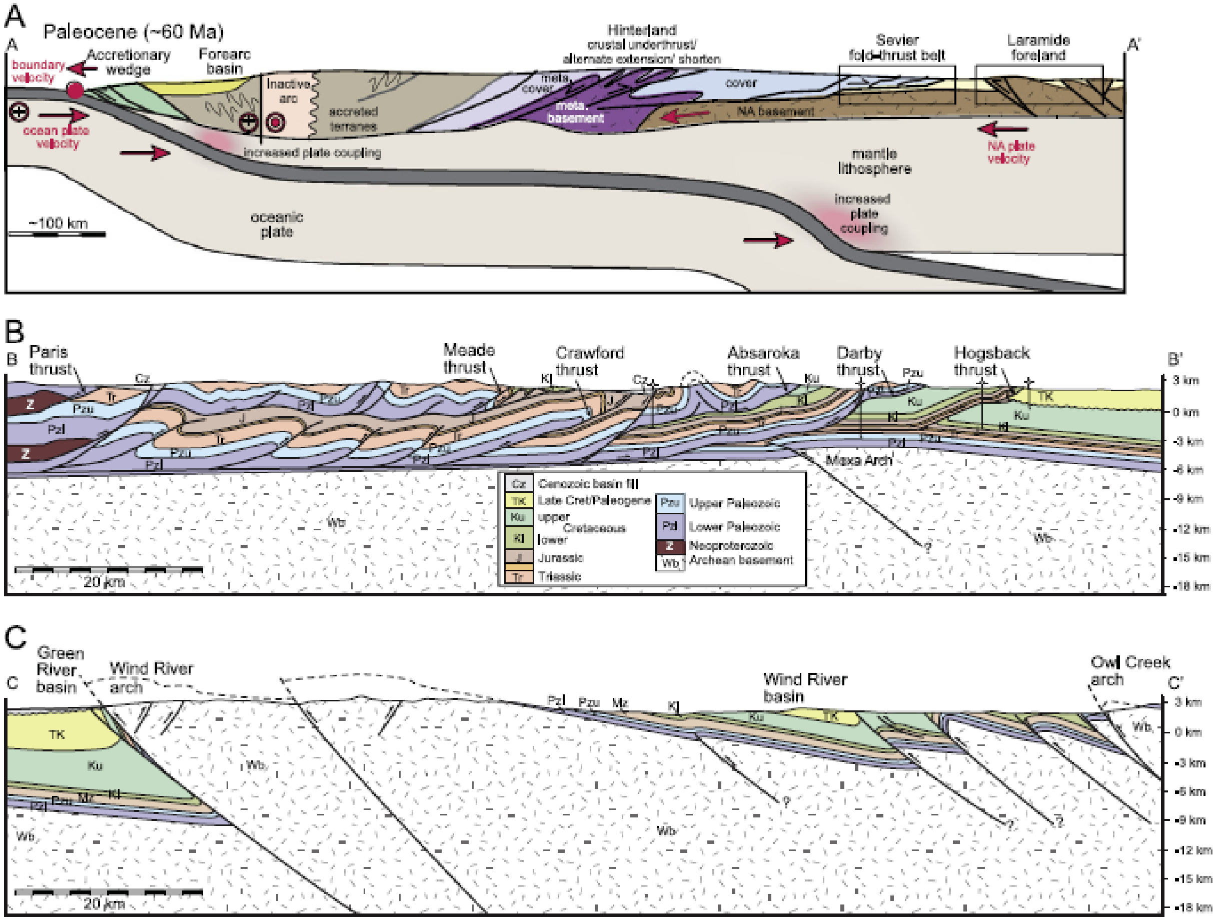

WELCOME TO
WYOMING
FOREVER WEST


150˚
140˚
130˚
120˚
110˚
100˚
90˚
80˚
50˚
40˚
30˚
20˚
zone
of
Canadian Rocky Mountains
EXPLORER,
JUAN DE FUCA,
GORDA PLATES
Great
Sevier
zone
of
orogen
Laramide orogen
RGR
Plains
Colorado Plateau
NORTH
AMERICA
PLATE
PACIFIC
PLATE
displaced
terranes
Tertiary
extension
Hidalgo orogen
COCOS PLATE

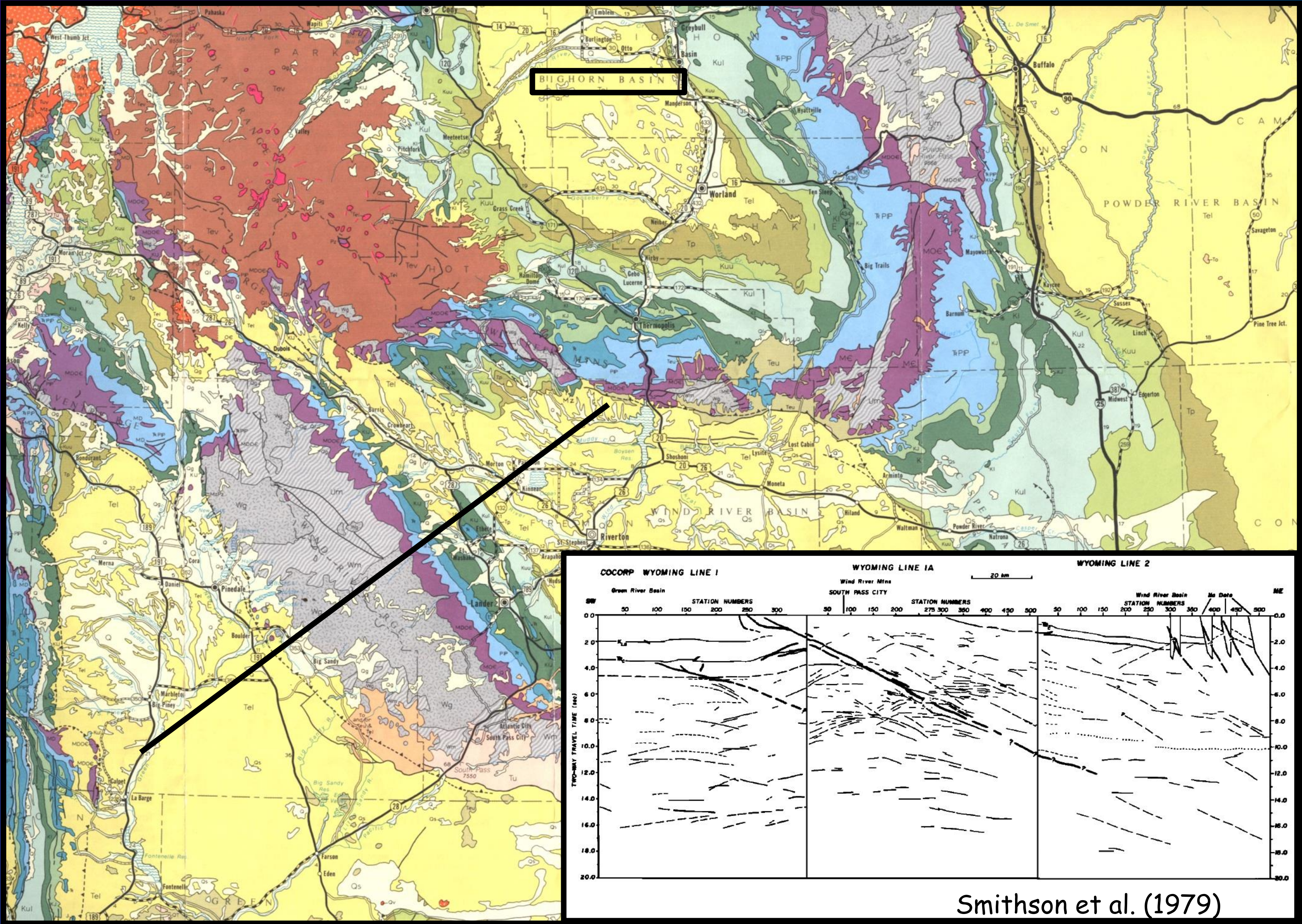

0
km
400
Montana
foreland edge of the fold-and-thrust belt
LCFZ
South Dakota
45°N
Idaho
Big Horn
Owl Creek
Black Hills
Y
Z
X
Snake River Plain
Wind River
Wyoming
Nevada
Uinta
Front Range
40°N
Utah
central Basin & Range
Colo-rado
Arizona
Colorado Plateau
New Mexico
35° N
TWL
southern Basin & Range
Rio Grande rift
115°W
105° W


SEVIER THIN-SKINNED THRUST BELT
LARAMIDE THICK-SKINNED THRUST BELT
SW
Wind River Mts.
Owl Creek Mts.
Big Horn Mts.
NE
W
Black Hills
E
Green River Basin
Wind River Basin
BigHorn Basin
Powder River Basin
Mz
?
crustal weak zone ?
Moho
0
15
30
45
km
30 km



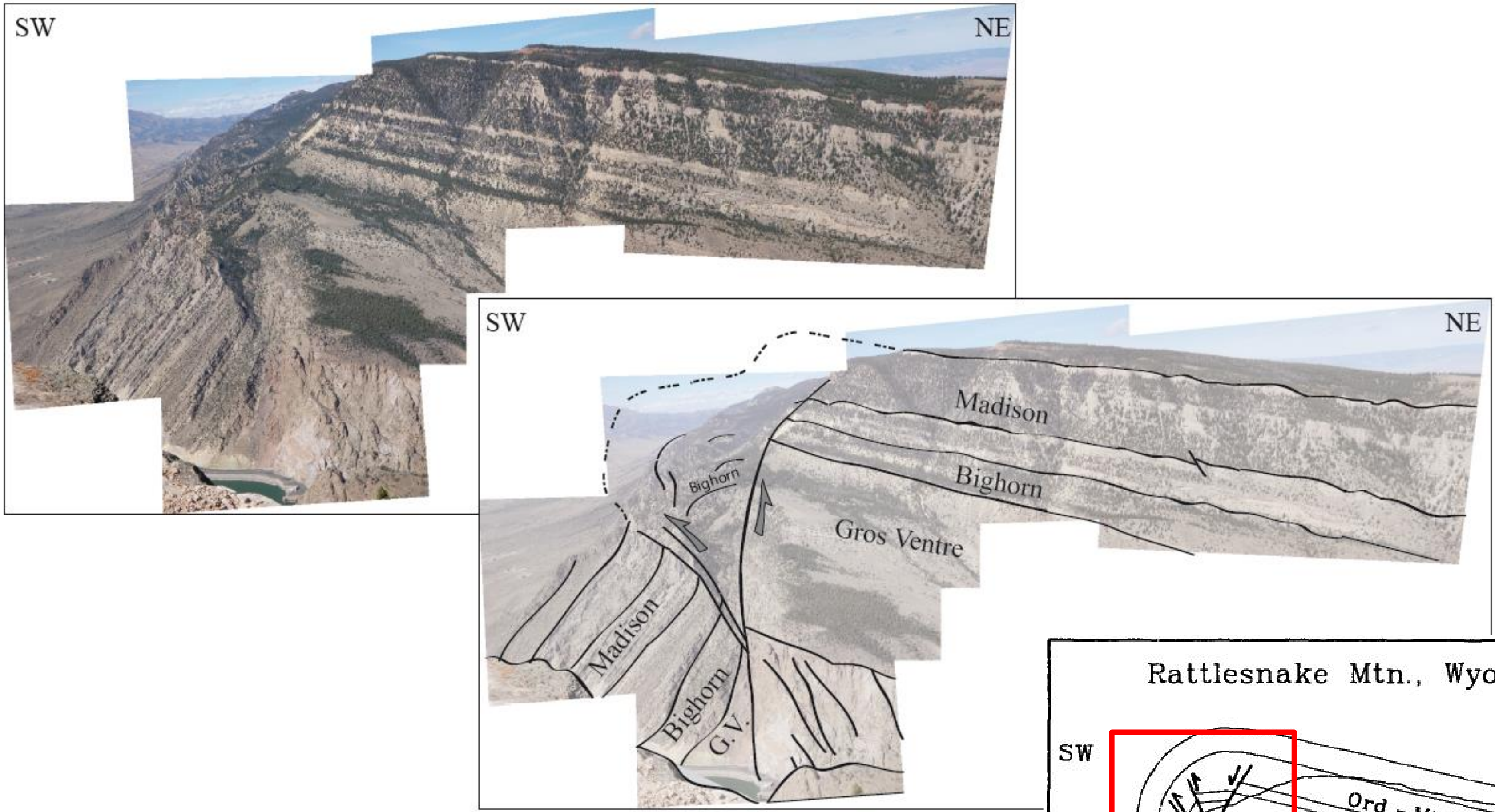


(Weil and Yonkee, 2012)

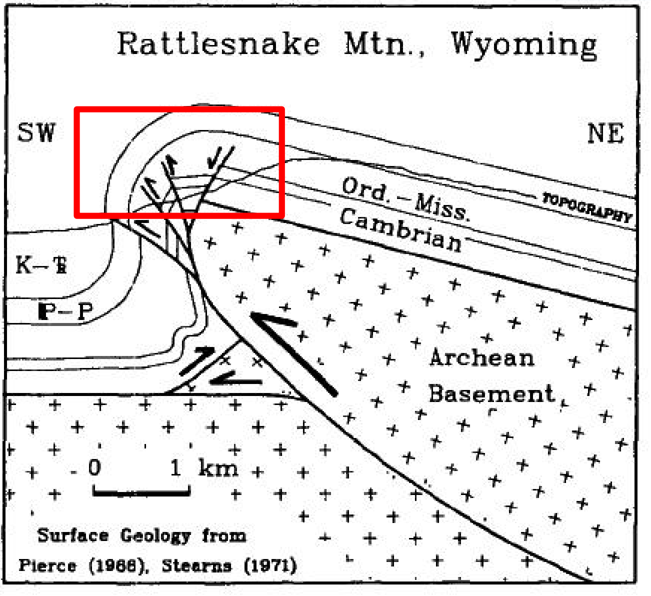


Smithson et al. (1979)


Beartooth Pass 10940
MTNS
Clark
Elk Basin
Deaver
Cowley
Powell
Garland
Byron
Lovell
Ralston
Cody
Wapiti
Emblem
Greybull
Shell
Burlington
Otto
Basin
Manderson
Hyattville
Meeteetse
Pitchfork
Worland
Ten Sleep
Granite Pass 8950
BIGHORN BASIN
Tel
Tp
Kul
Kuu
KJ
Kl
PP
TRPP
MDO
MDOЄ
Ql
Q
Og
Mz
Um
Pz
OLD TRAIL TOWN
Cody Cowboy Village
FREE INTERNET & Continental Breakfast
OPEN
10 km

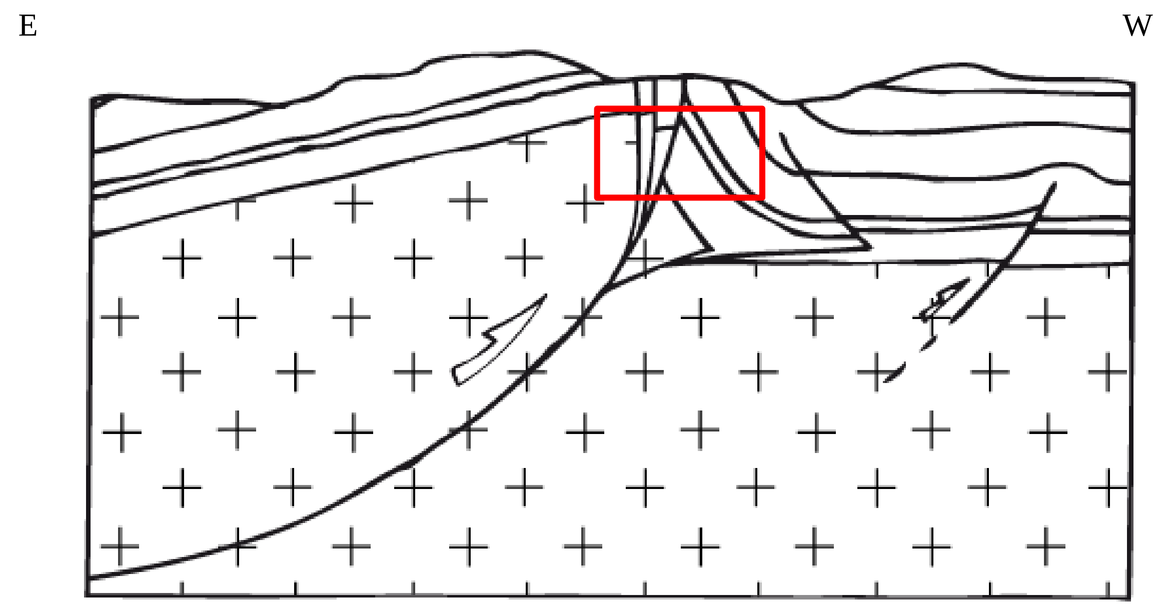


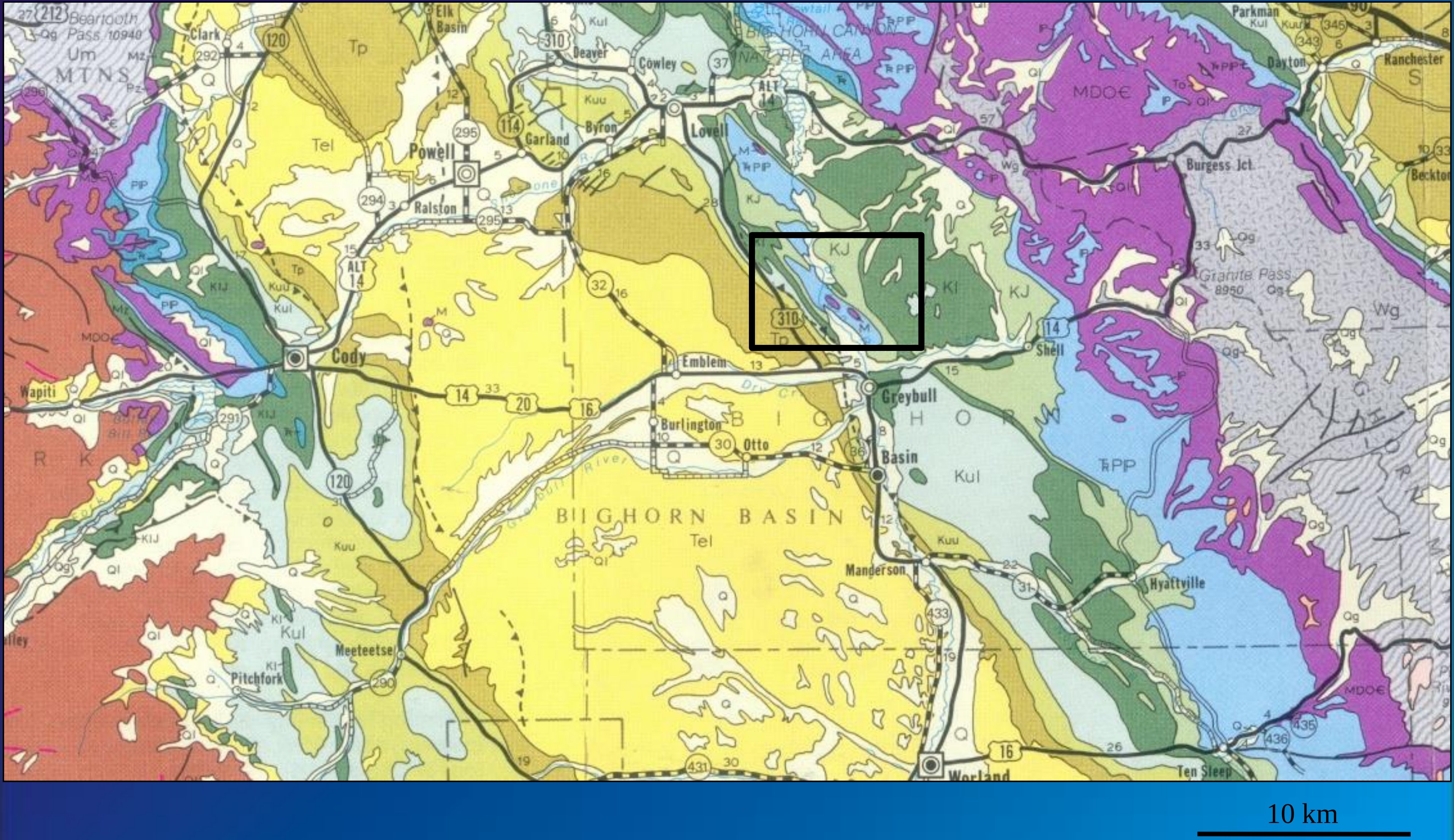
(Beaudoin et al., 2012)

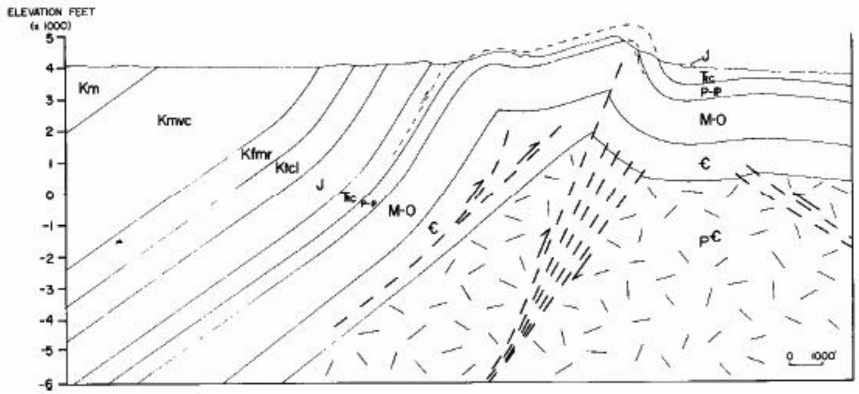


Erslev (1986)

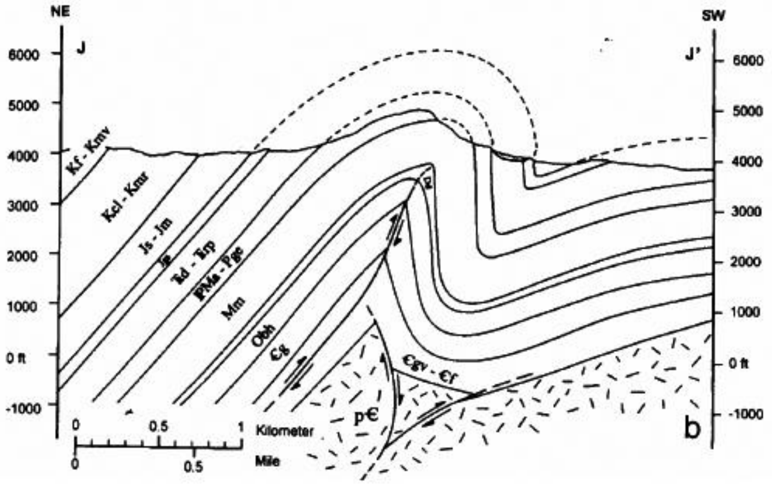

E
W


E
W

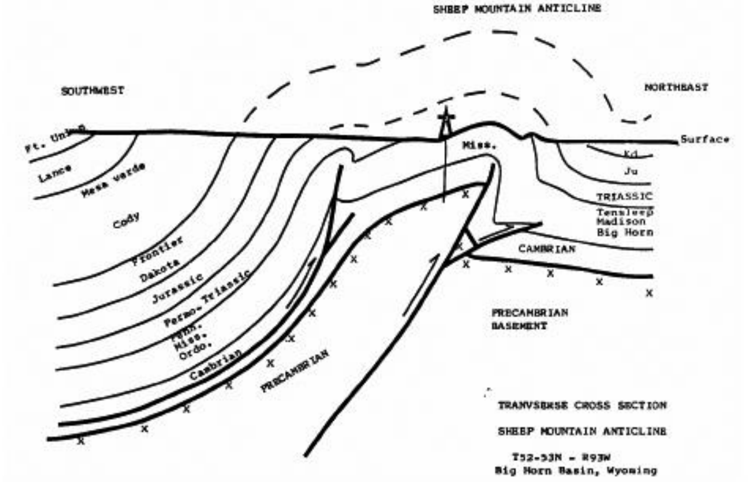

Beartooth Pass 10940
MTNS
Clark
Elk Basin
Deaver
Cowley
Lovell
BIG HORN CANYON NATL REC AREA
Parkman
Dayton
Ranchester
Powell
Garland
Byron
Ralston
Burgess Jct
Granite Pass 8950
Cody
Emblem
Shell
Greybull
Wapiti
Burlington
Otto
Basin
BIGHORN BASIN
Manderson
Hyattville
Meeteetse
Pitchfork
Worland
Ten Sleep
Tp
Tel
Kul
Kuu
KJ
Kl
KlJ
MDO€
Wg
TRPP
PP
Qg
Ql
Q
M
10 km



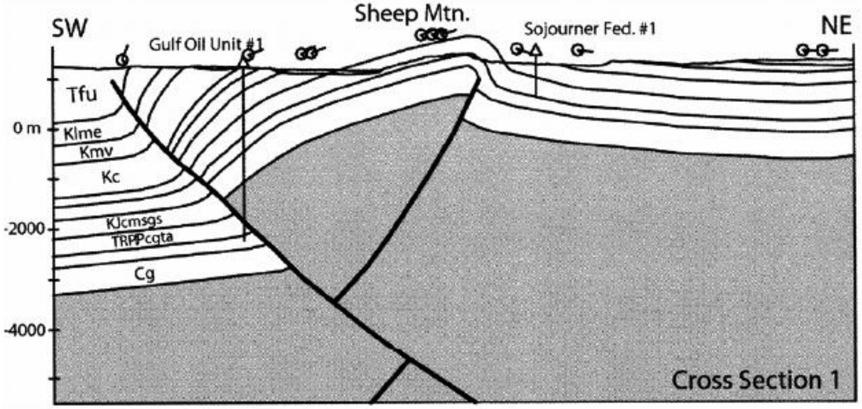
SW–NE trending cross section through Sheep Mountain anticline from Hennier and Spang, 1983. Bedding dips and Formation contacts are constrained by surface mapping and geologic markers from exploration wells. Hennier and Spang postulate a relatively undeformed basement with multiple thrust planes in an overall wedge shaped geometry to generate folding in the overlying sediments.



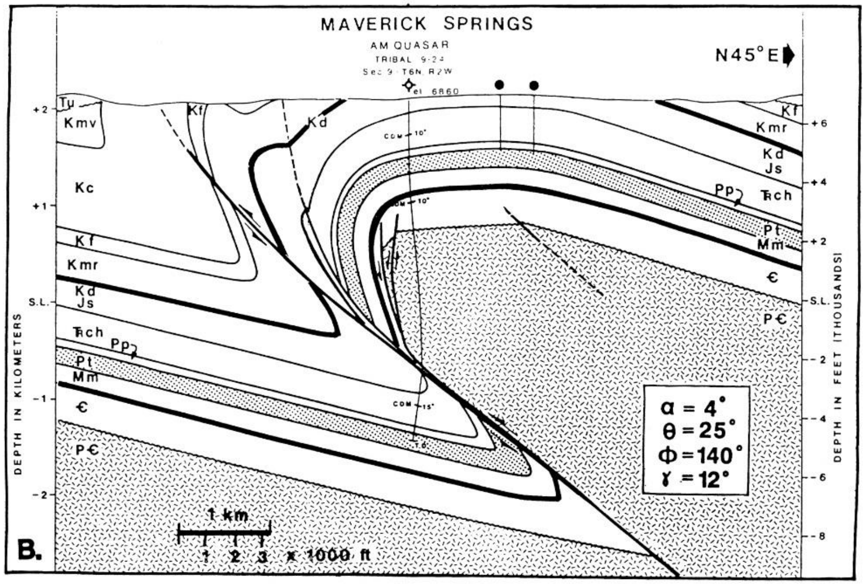
SW-NE trending cross-section through Sheep Mountain anticline from Forster et al., 1996. Bedding dips and Formation are constrained by surface mapping and geologic markers from exploration wells. A wedge shaped fault zone is hypothesized as the mechanism by which overlying strata fold.

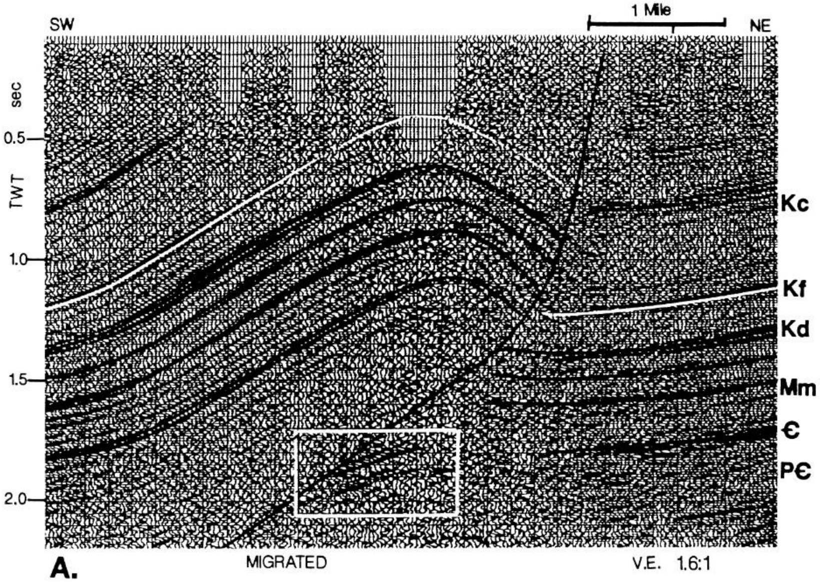


SW-NE trending cross-section through Sheep Mountain anticline from Brown, 1984. Geological constraints are not given, but are most likely surface dips and formation markers from wells. Brown proposes substantial basement folding and a wedge shaped fault zone beneath the forelimb of Sheep Mountain.

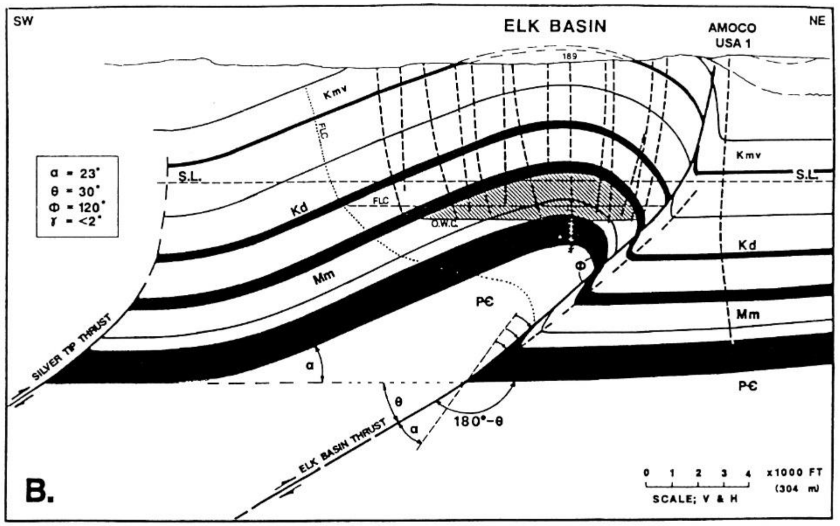


SW-NE trending cross-section through Sheep Mountain anticline from Stanton and Erslev, 2002. Geological constraints are surface dips, formation markers from wells, and three 2D seismic profiles. Stanton and Erslev propose a moderately folded basement. Their kinematic modeling suggests that the Rio thrust fault slipped after slip along the fault beneath Sheep Mountain Anticline had already uplifted the fold.

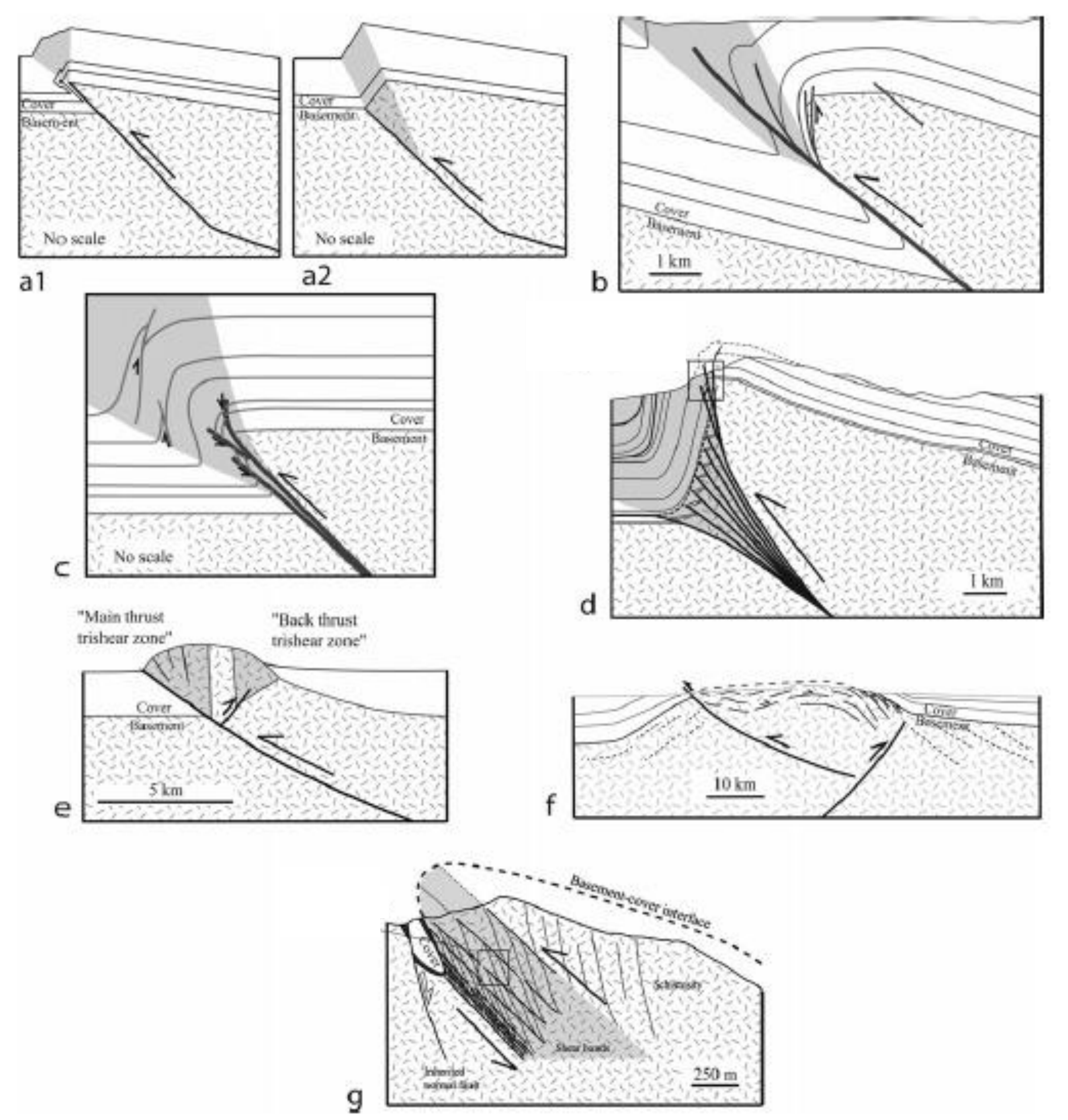




Stone (1993)



Elk Basin anticline, a mature thrust fold. A: Time-migrated, interpreted seismic profile (600% dynamite, 1969; modified from Weitzel, 1985). TWT is two-way traveltime. B: Structural cross section (see Fig. 15 C) showing well control, common Paleozoic oil pool (diagonally lined with oil-water contact (O.W.C.), a fault-limited chord (FLC) at the base of the Dakota (Kd) horizon, and values for the various angles (modified from Stone, 1983a). S.L. is sea level.



(Lacombe and Bellahsen, Geological Magazine,2016)

The mechanical response of the basement rocks and the overall fold geometry are highly dependent on :

-P and T conditions during deformation

-nature and orientation of the pre-deformation fabric of the basement rocks

-competence of the cover rocks

-degree of coupling of folded strata with basement blocks.

Basement can be deformed through :

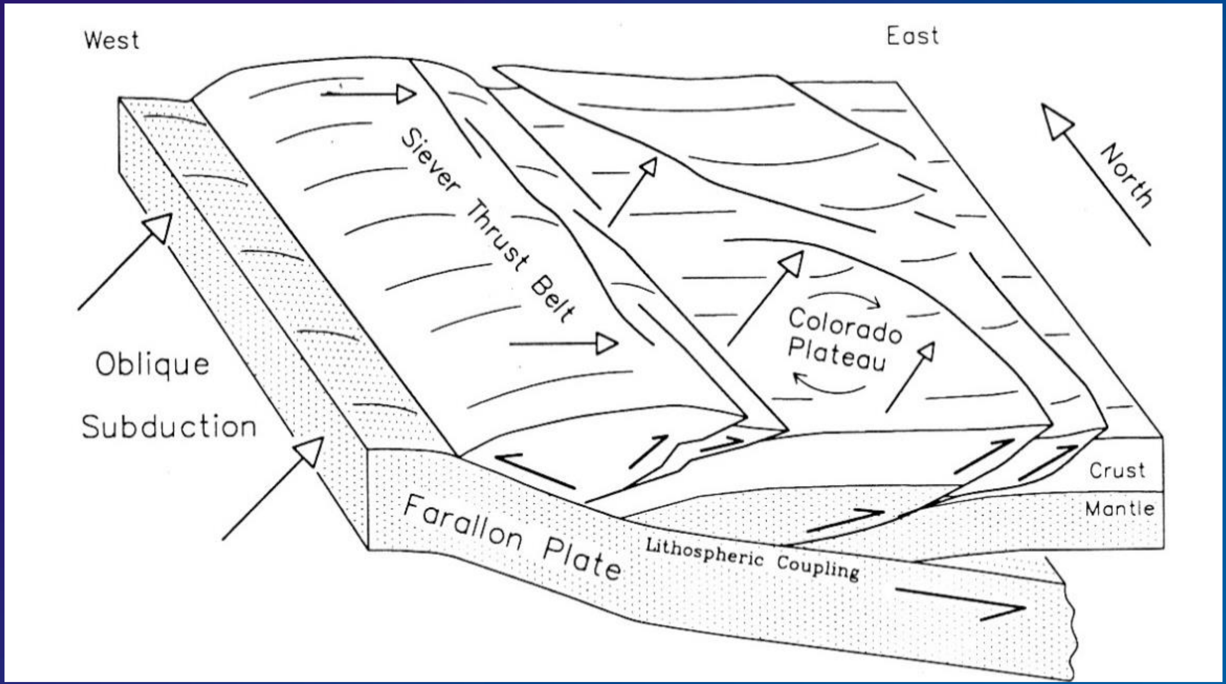
-slip on sets of closely spaced fractures

-flexural slip on pre-existing foliation oriented sub-parallel to bedding

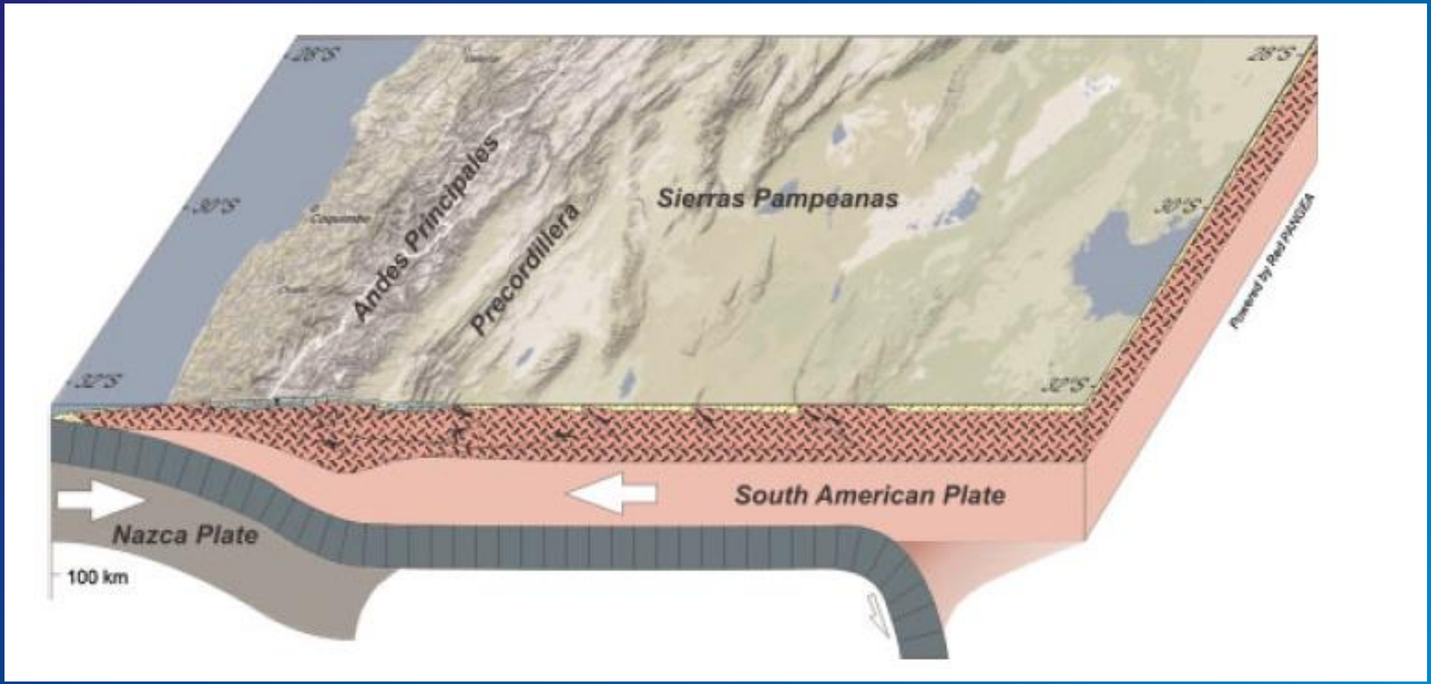
-axial surface-parallel slip on foliation favourably oriented for simple shearing parallel to the master fault

-pervasive cataclasis.

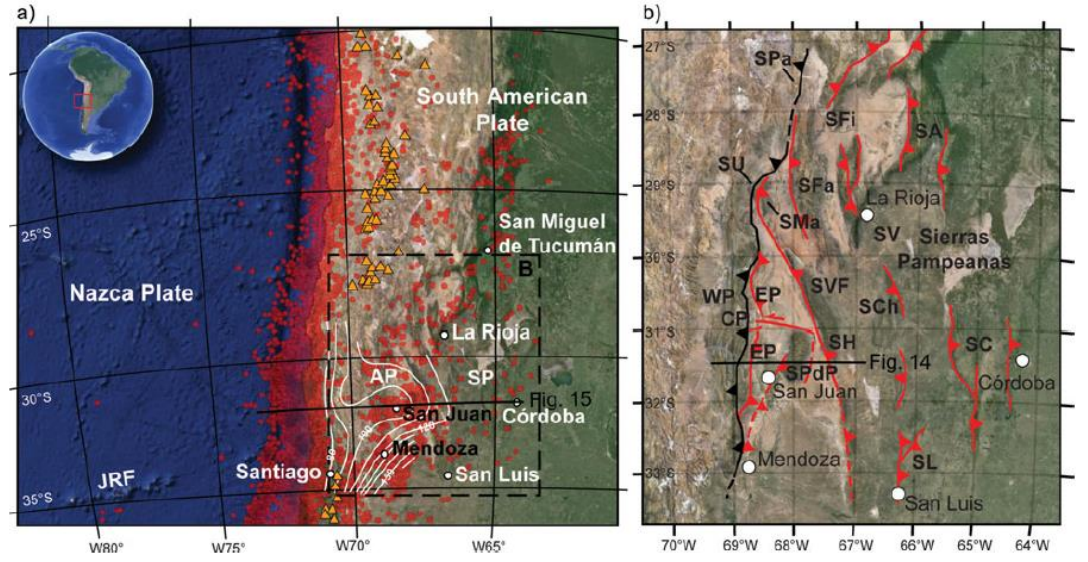
Alternatively, the curved attitude of the basement–cover interface may only mimic true basement folding. Several mechanisms may account for such folding of cover rocks without folding of basement rocks, such as basement fault zones containing wedges of cataclastic material.

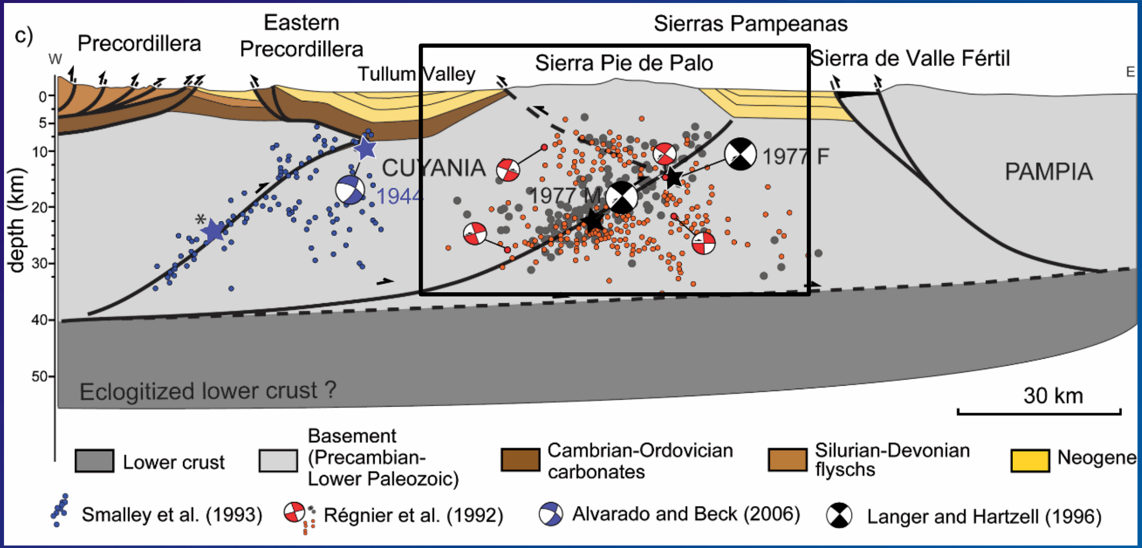


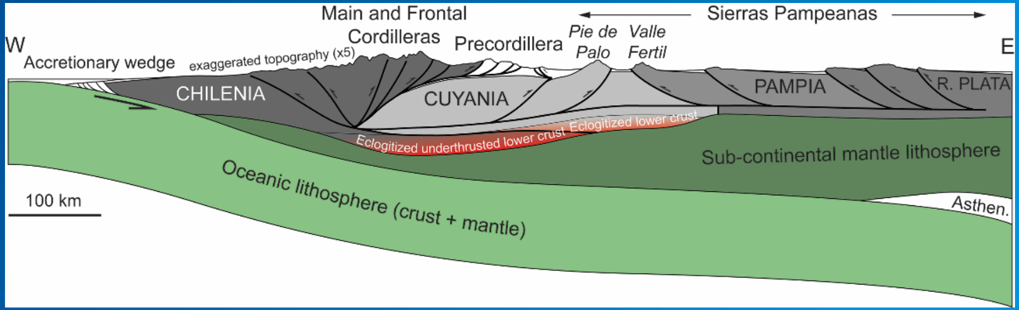
Erslev, 1993



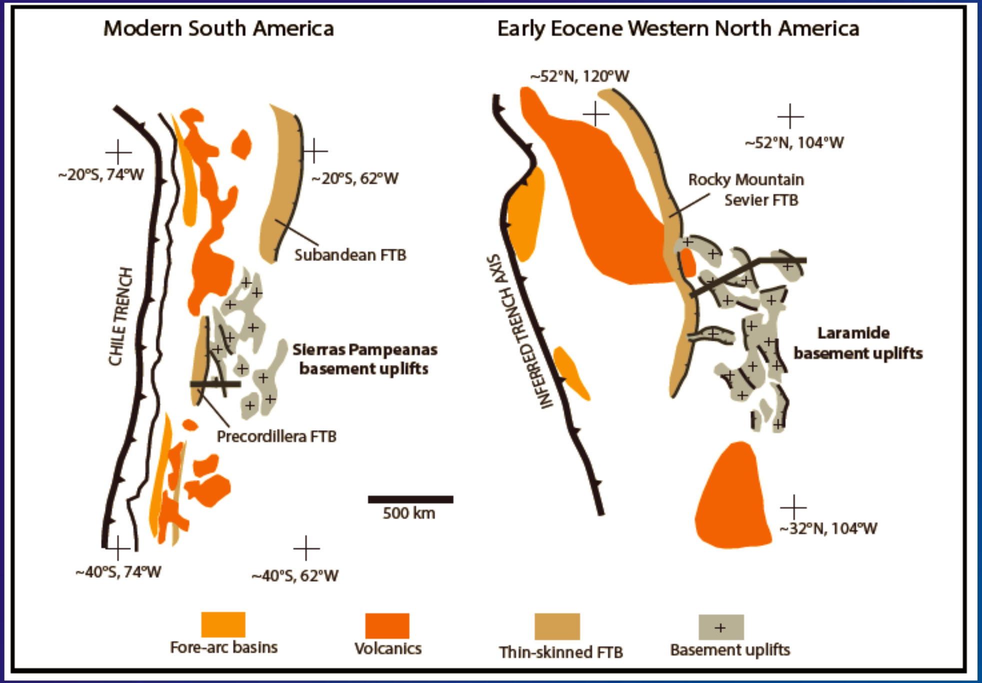
Ramos, 2010



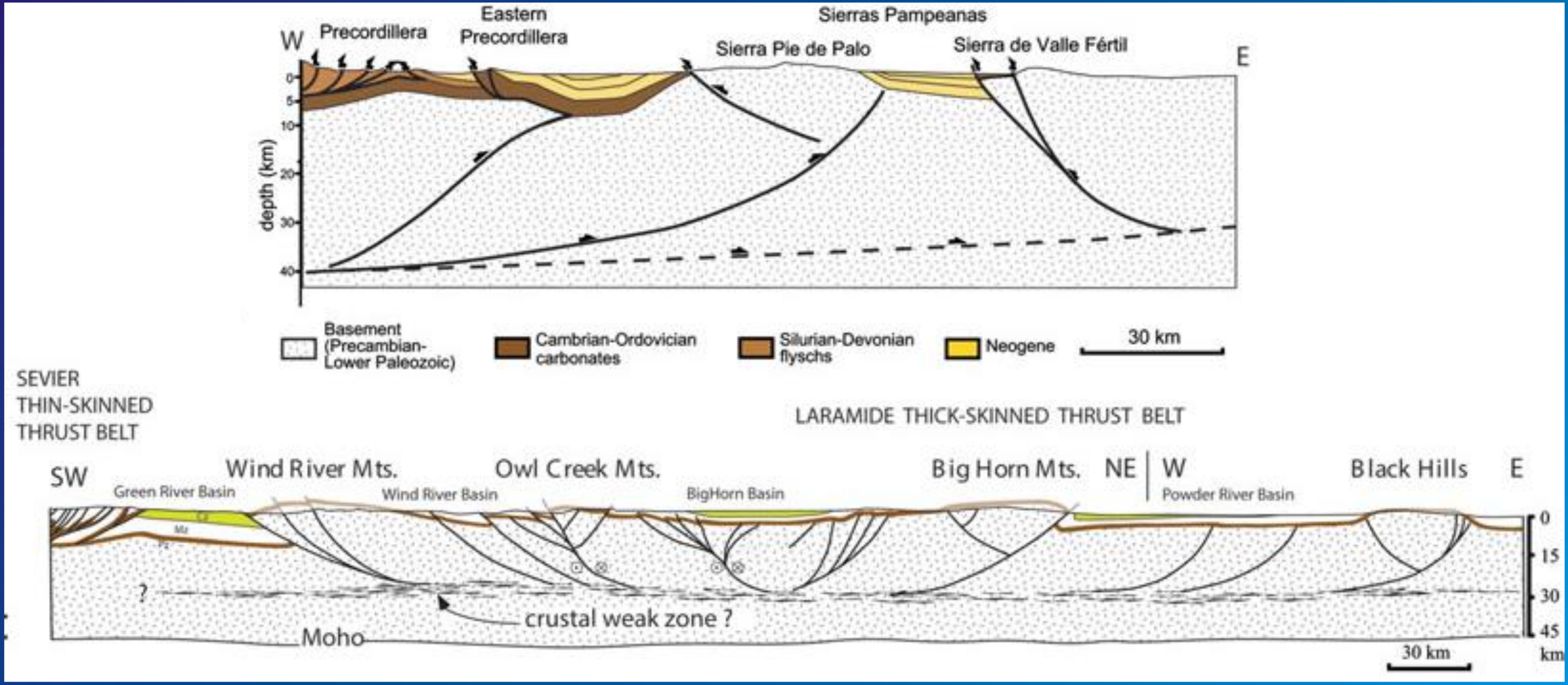


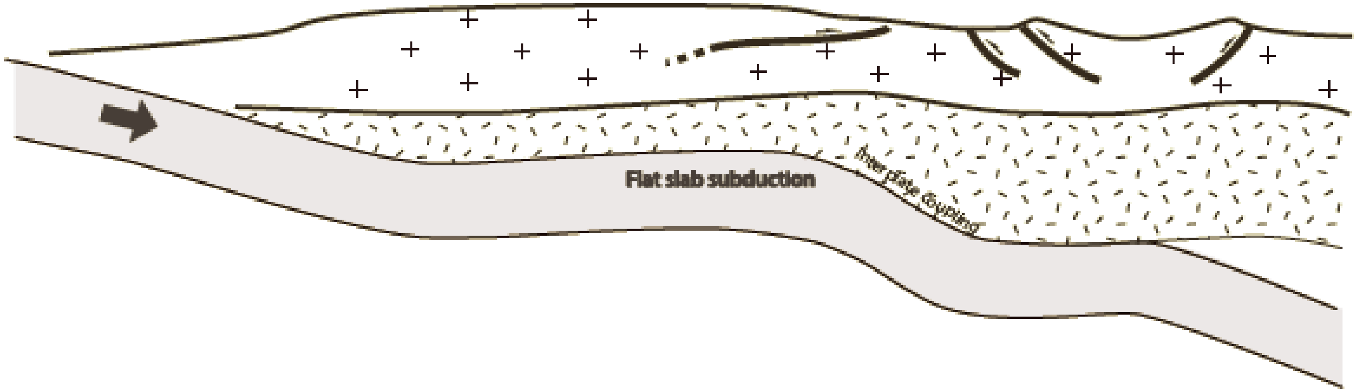


(Bellahsen et al., 2016)

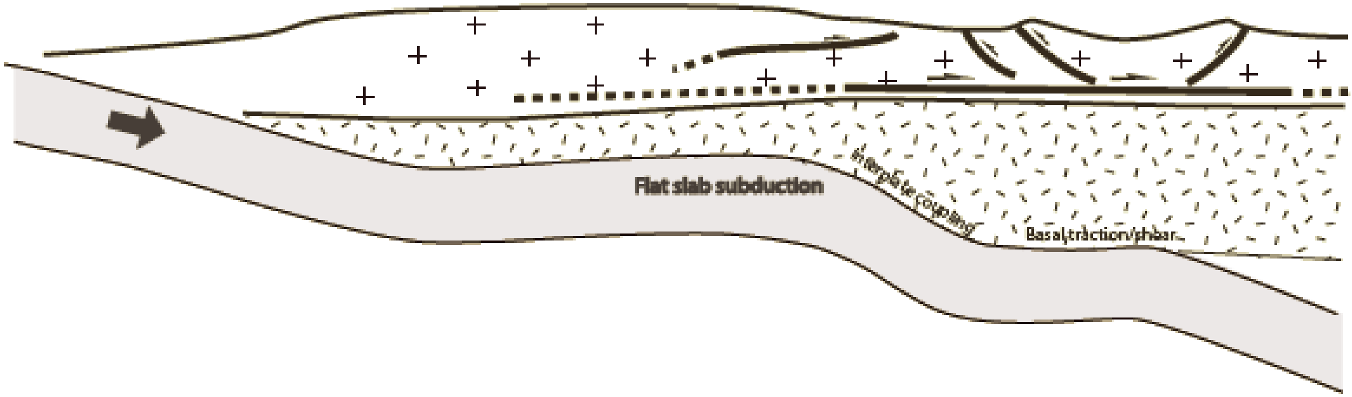


(Lacombe and Bellahsen, 2016)

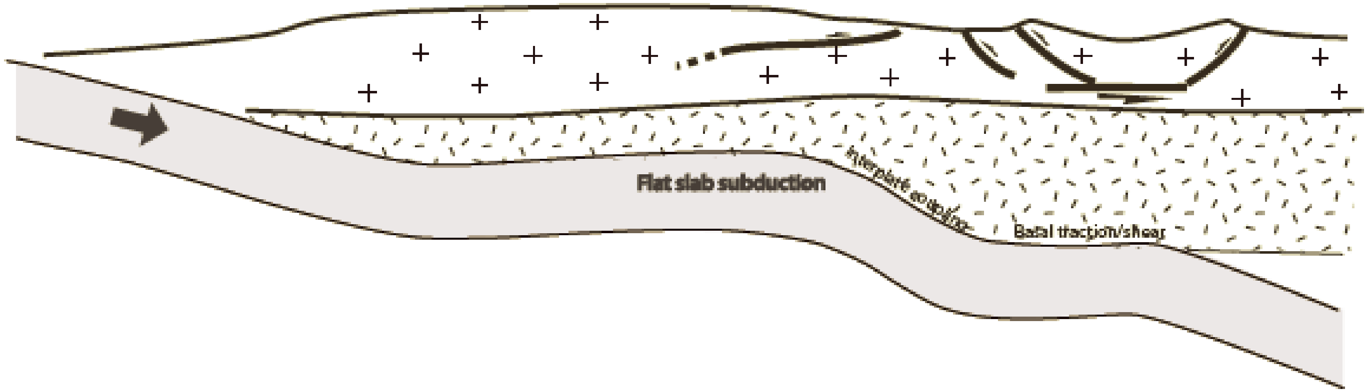




Crustal faults and biharmonic folding of the upper plate lithosphere (crust/mantle)



Crustal buckling and detachment

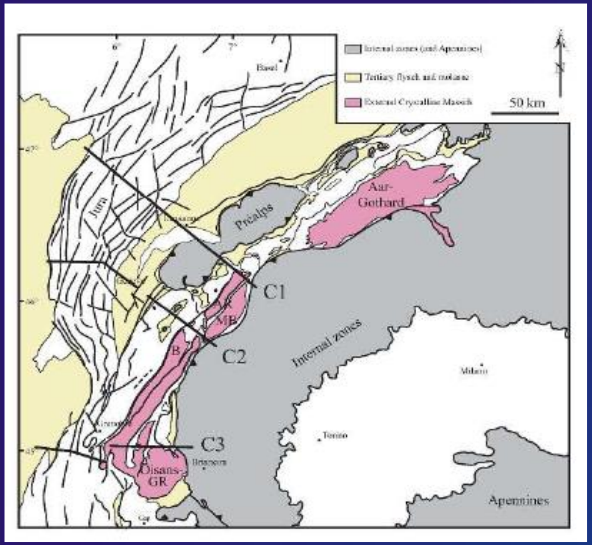


Sub-crustal shear

(Lacombe and Bellahsen, 2016)

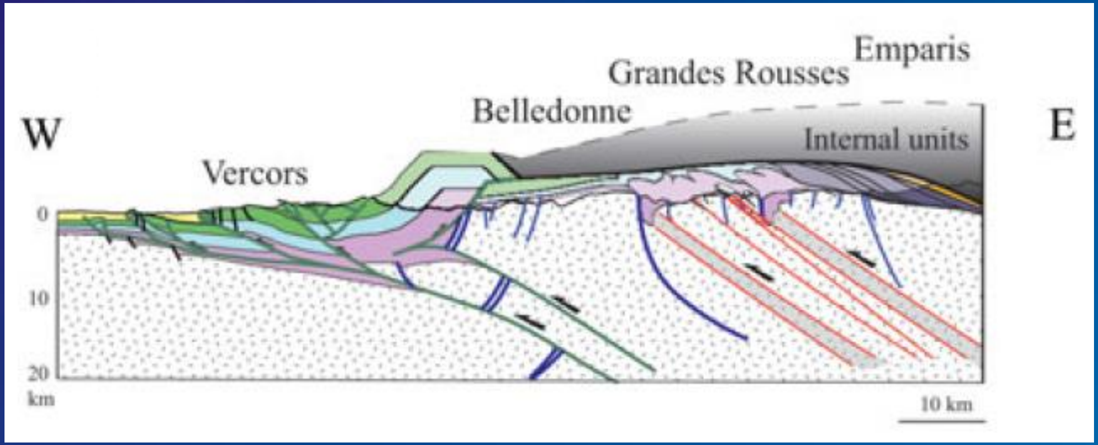
Along-strike variations of basement-involved shortening : the Western Alps

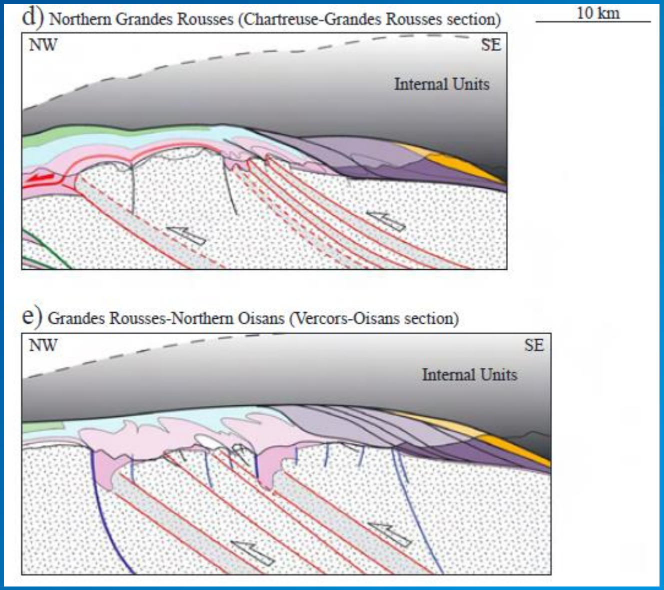
Oisans



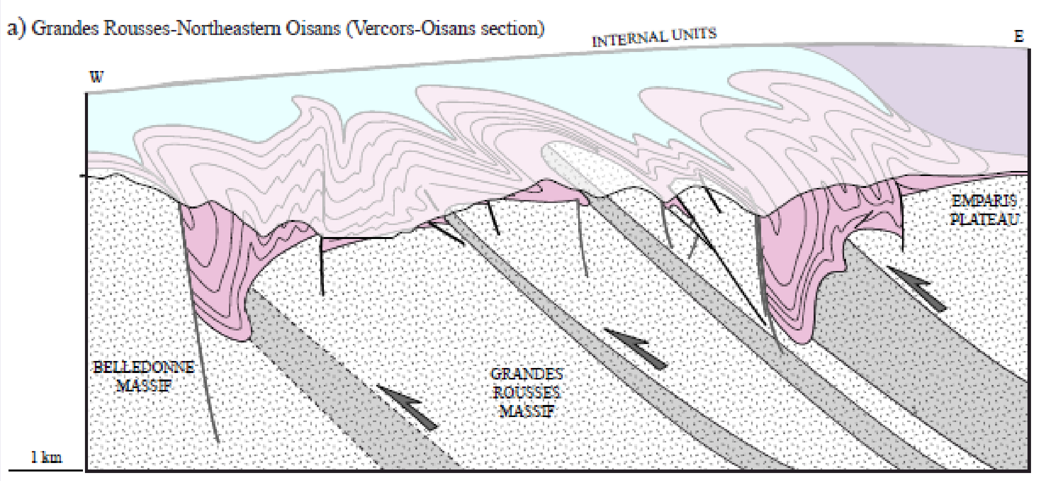
Oligocene : basement was shortened in a distributed way by accretion and thrust stacking below the wedge (distributed underplating) without wedge widening

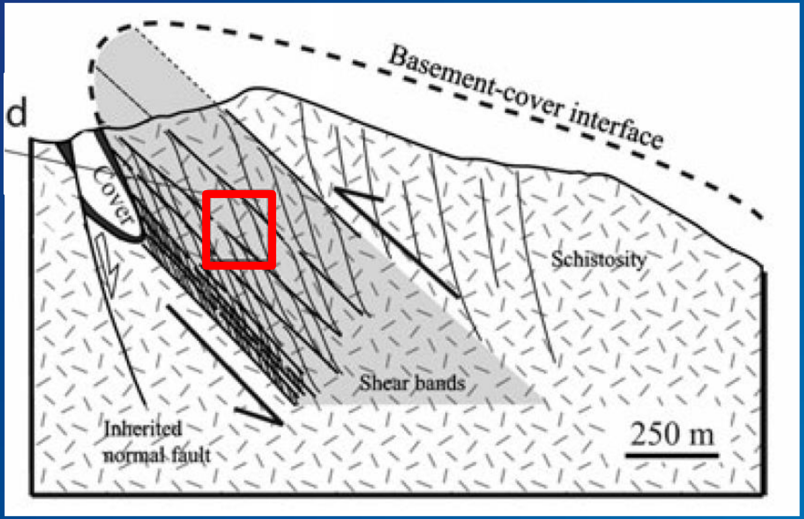
Miocene : deformation localized on the frontal ramp that activated the Vercors shallow decollement (frontal accretion hence orogenic wedge widening).

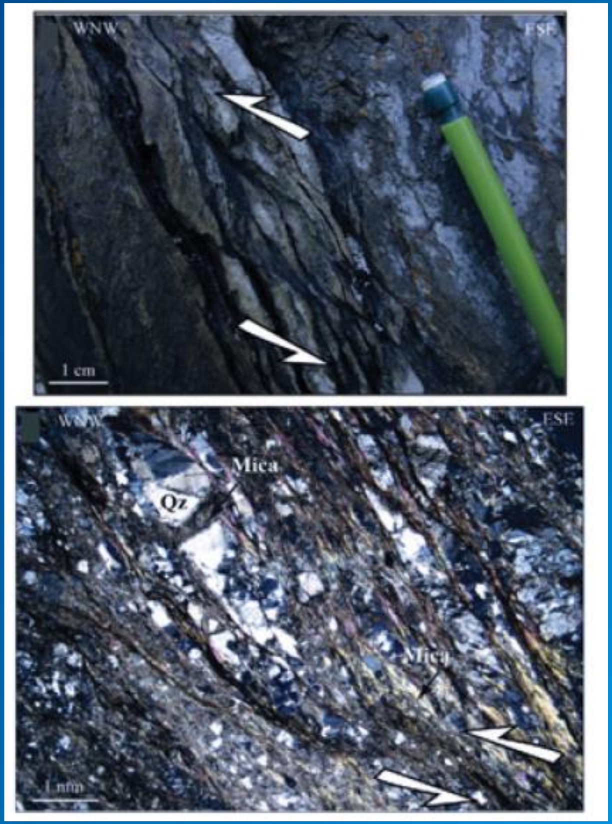




(Bellahsen et al., 2014)





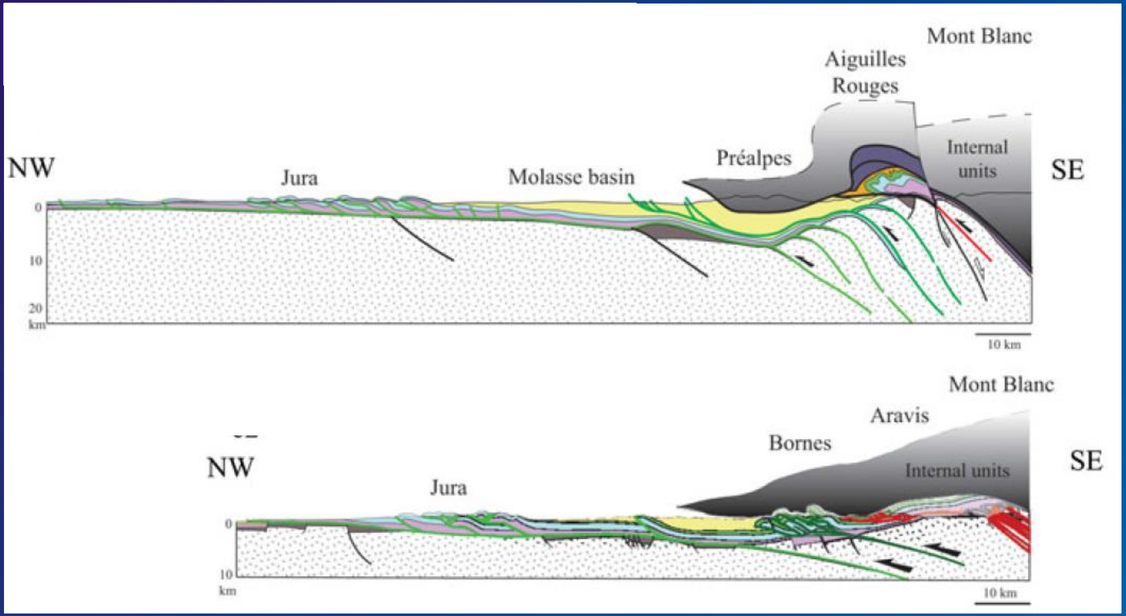


(Lacombe and Bellahsen, 2016)

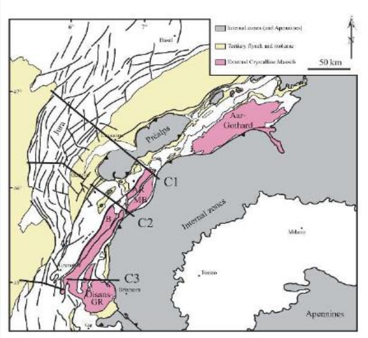
Mont Blanc-Aiguilles Rouges :

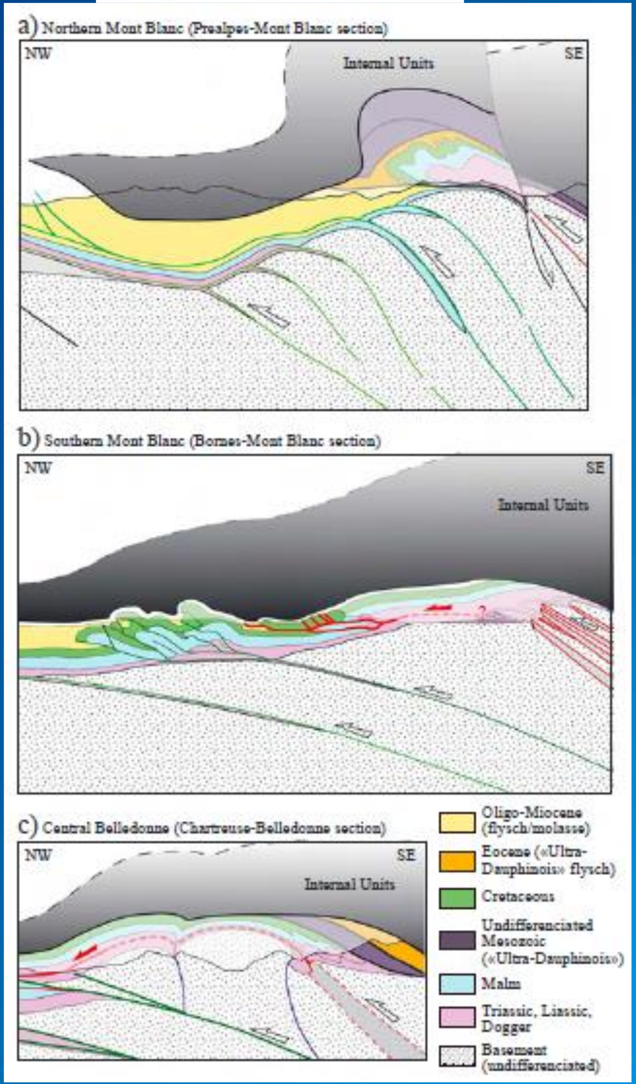
Oligo-Miocene : basement shortened by underplating below the internal units

Miocene -early Pliocene : basement units were still underplated (lower Aiguilles Rouges) while a very wide cover domain was accreted in frontal parts (e.g., Jura and Molasse Basin) with the activation of large basement thrusts.



(Bellahsen et al., 2014)



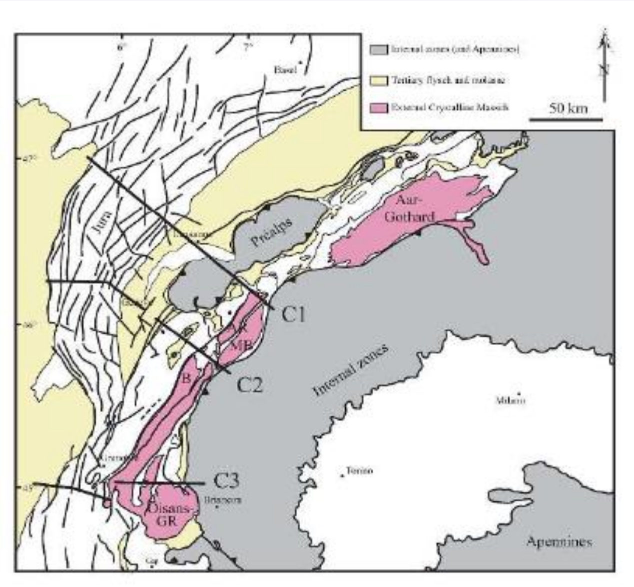


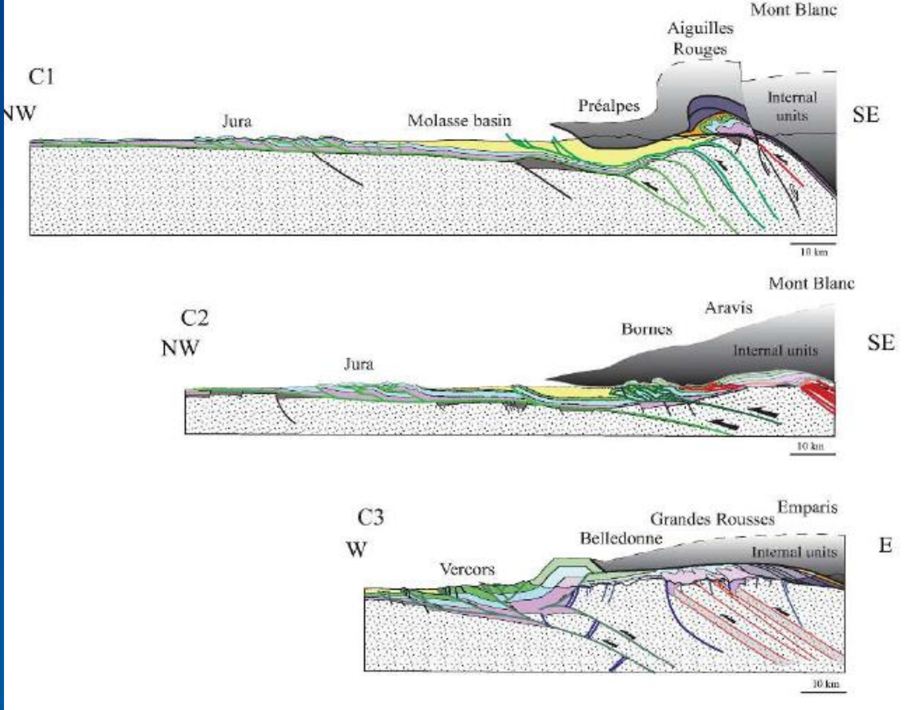
Localization and style of basement-involved deformation varies along the strike of the western Alpine arc.

Both the amount of shortening (km) and shortening (%) across the entire external zone increase from the Oisans section to the Mont Blanc section.

The increase of the amount of shortening is most likely due to a wider inherited Mesozoic basin in the North (Ultra-Helvetic/Valaisan).

The increase of the shortening probably has a rheological explanation. Along the Mont Blanc section, basement shortening remains localized, leading to stacking of basement slices. while it is distributed far toward the foreland along the Oisans section; this can be related to the rheology of the crust during collision, the more buried and thermally weakened crust at the latitude of the Mont Blanc (400°C, 5kb) being more prone to localized shortening at the orogen-scale.

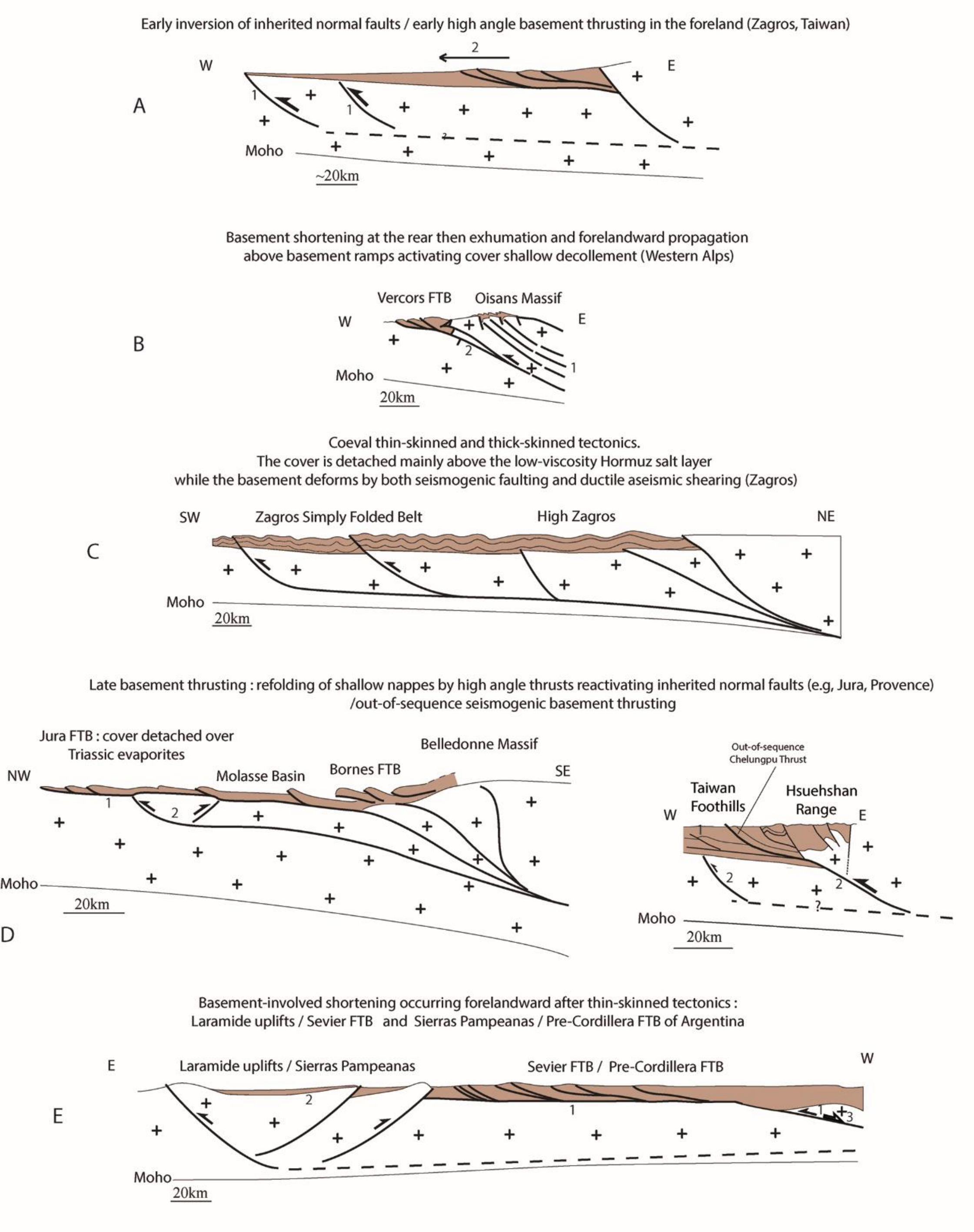




(Bellahsen et al., 2014)

Sequence of deformation in fold-and-thrust belts

Sequence of thick-skinned versus thin-skinned tectonics in FTBs



Early inversion of inherited normal faults / early high angle basement thrusting in the foreland (Zagros, Taiwan)

Basement shortening at the rear then exhumation and forelandward propagation above basement ramps activating cover shallow decollement (Western Alps)

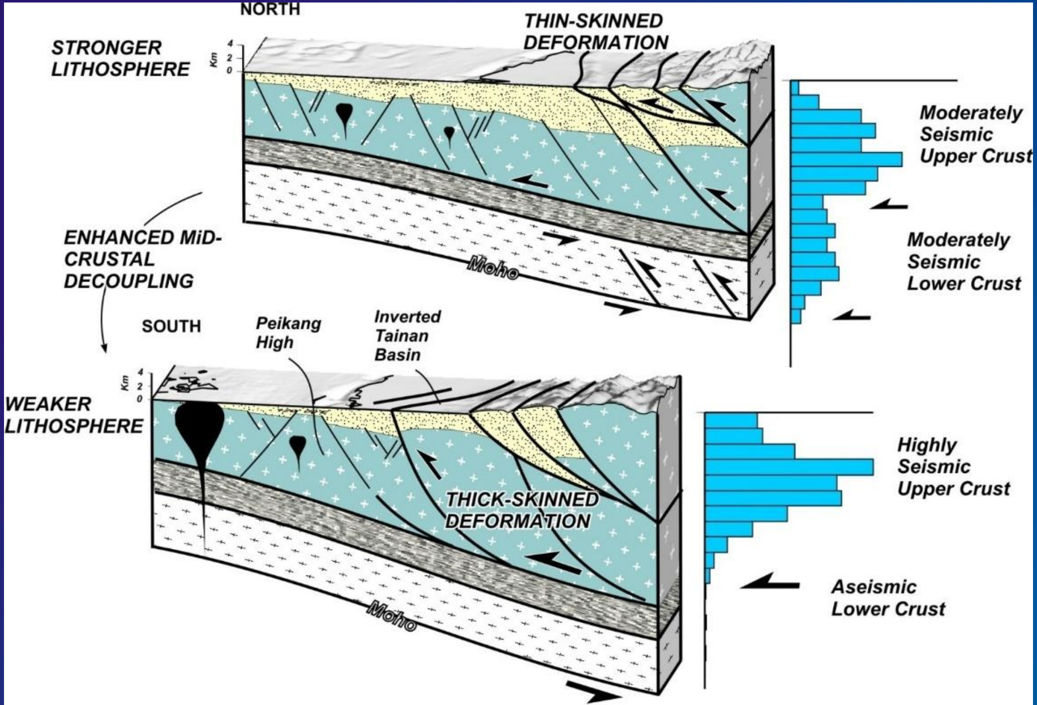
Coeval thin-skinned and thick-skinned tectonics. The cover is detached mainly above the low-viscosity Hormuz salt layer while the basement deforms by both seismogenic faulting and ductile aseismic shearing (Zagros)

Late basement thrusting : refolding of shallow nappes by high angle thrusts reactivating inherited normal faults (e.g, Jura, Provence) /out-of-sequence seismogenic basement thrusting

Basement-involved shortening occurring forelandward after thin-skinned tectonics : Laramide uplifts / Sevier FTB and Sierras Pampeanas / Pre-Cordillera FTB of Argentina

(Lacombe and Bellahsen, 2016)

Some first-order rheological controls of the structure of fold-and-thrust belts

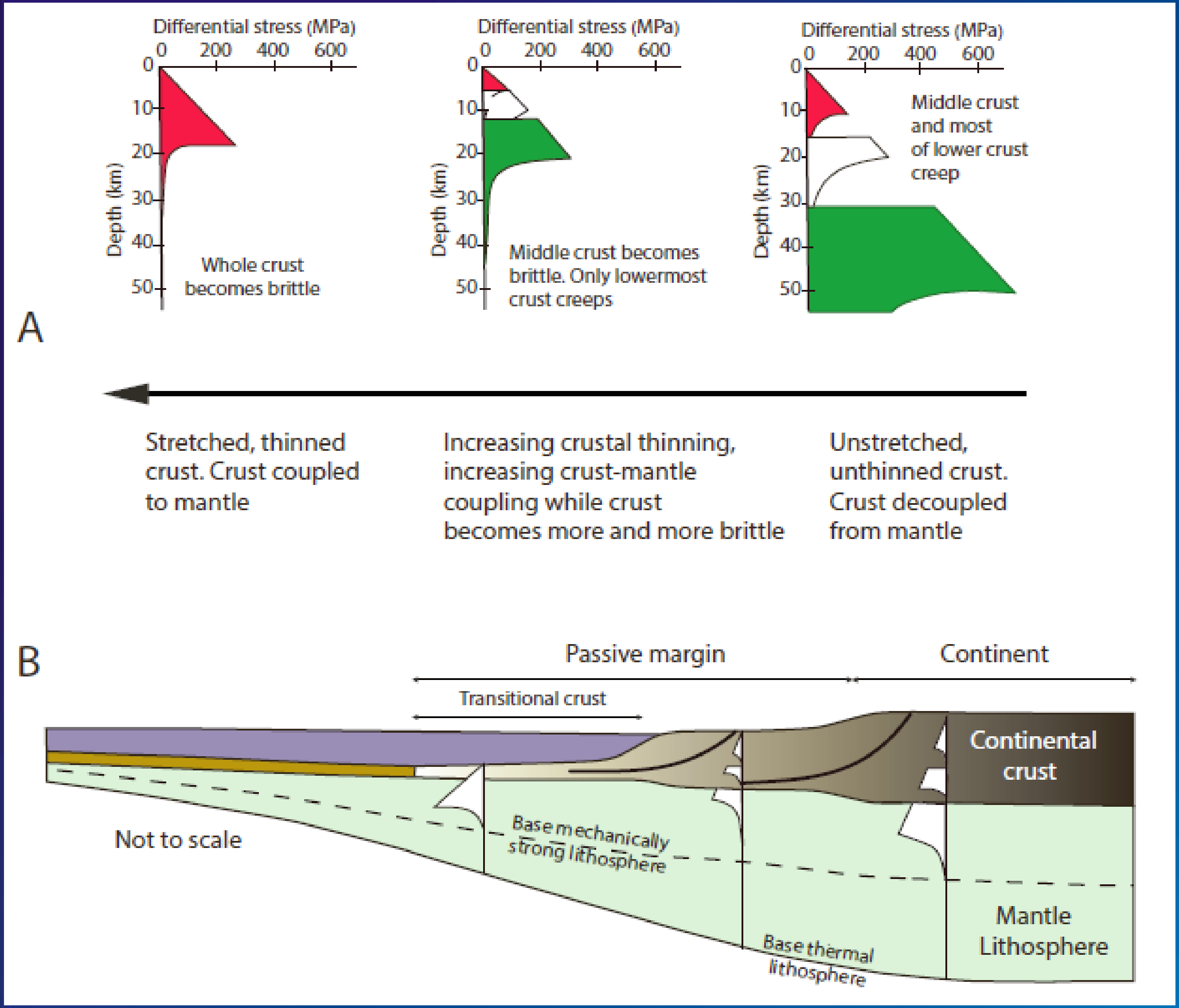


Correlation between spatial variations of the flexural rigidity of the lithosphere and the nature and amount of foreland deformation has been suggested for the Andes FTB and Taiwan.

Regions with low Te correlate with thick-skinned deformation whereas regions with high Te correlate with thin-skinned deformation : a strong lithosphere is less easily deformed so that shortening is localized in a narrow zone at shallow depth, while a weaker lithosphere enables crust-mantle decoupling and shortening of the whole crust.

The local increase of plate coupling and inhomogeneities in a prefractured margin as in Taiwan can affect the rigidity of the layered continental lithosphere, supporting a mechanical relationship between its strength and the structural style.

Differential stretching of the lithosphere modifies its rheological properties which will subsequently control deformation style during collision.



As the crust thins and cools during progressive rifting, the reduction in overburden pressure and temperature makes the rocks which originally deformed by plastic creep gradually become more prone to brittle failure.

The result is that the initial weak zones in the middle crust and deep crust disappear and that the entire crust becomes brittle.

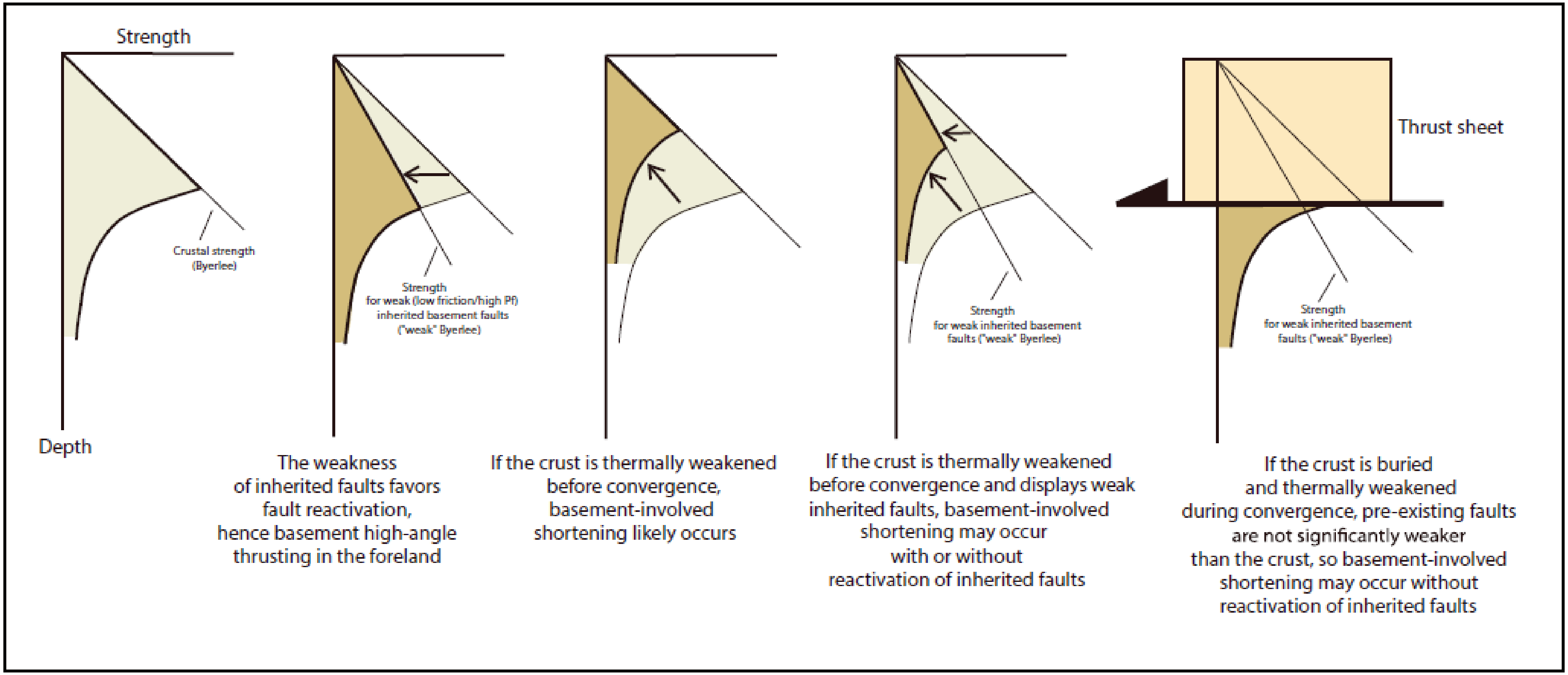
The important consequences of the progressive embrittlement of originally ductile rocks during lithospheric extension are (1) that lateral flow or displacement of particular layers within the crust should become progressively more difficult as rifting proceeds, and (2) that the upper crust becomes coupled to the mantle.

(Reston and Manatschal, 2011; Cloetingth et al., 2005)

Passive margins are key players in the collisional processes as the arrival of their proximal, poorly thinned parts into the subduction zone mark the onset of collision.

For thick-skinned FTBs that developed from former passive margins, the occurrence of weak mechanical layers within the proximal margin lithosphere (the middle and most of the lower crust are expectedly ductile) may explain that contractional deformation be distributed within most of the crust, giving rise to basement- involved tectonic style.

In contrast, because these weak crustal levels are usually lacking in distal parts of the margins as a result of thinning, these stronger lithospheric domains are more prone to localized deformation in a continental subduction style.



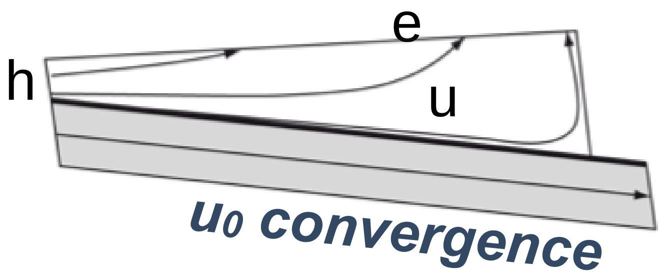
The weakness of inherited faults favors fault reactivation, hence basement high-angle thrusting in the foreland

If the crust is thermally weakened before convergence, basement-involved shortening likely occurs

If the crust is thermally weakened before convergence and displays weak inherited faults, basement-involved shortening may occur with or without reactivation of inherited faults

If the crust is buried and thermally weakened during convergence, pre-existing faults are not significantly weaker than the crust, so basement-involved shortening may occur without reactivation of inherited faults

(Lacombe and Bellahsen, 2016)



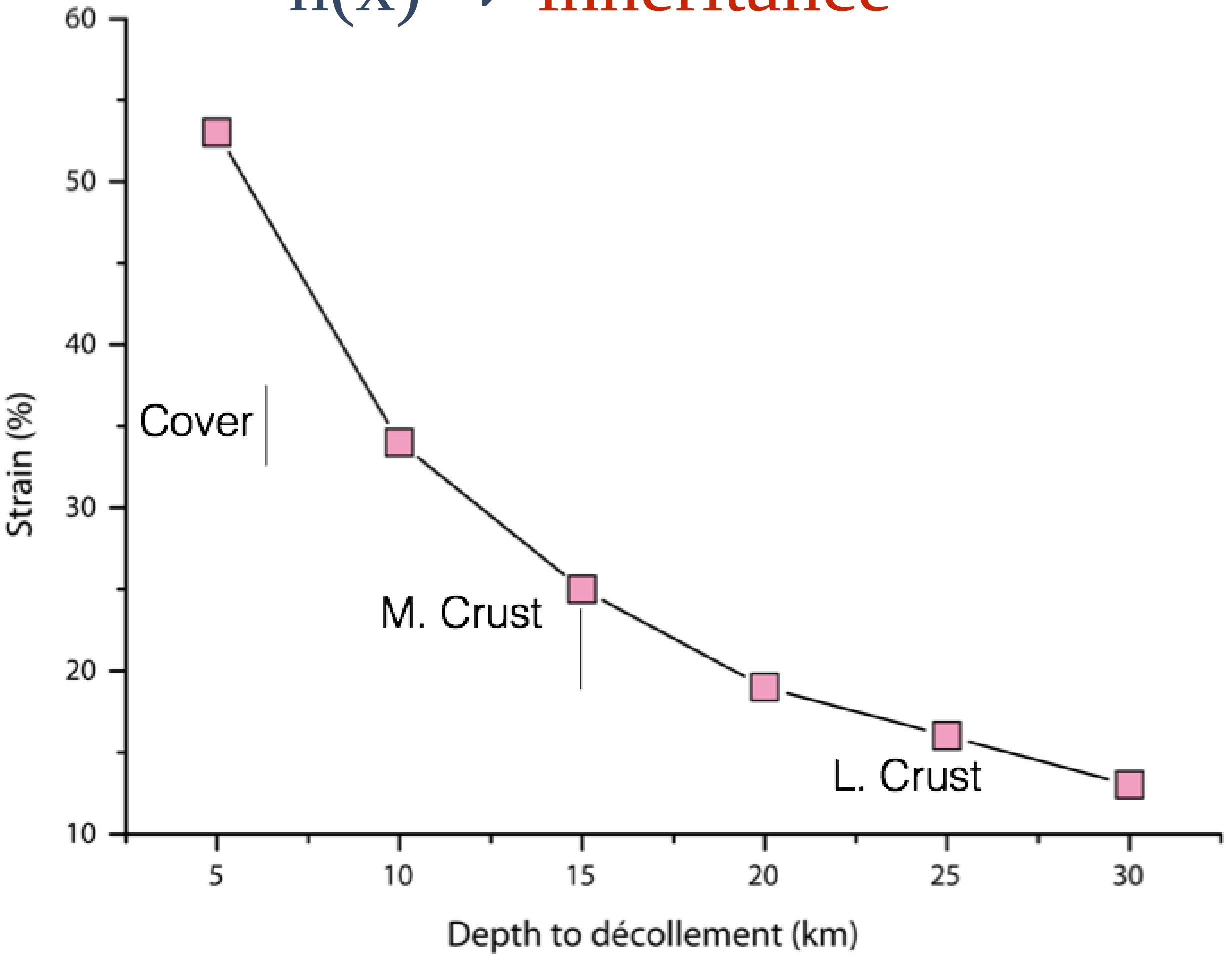
Displacement

Erosion

$$u(x,z)=\frac{1}{h(x)}\int_0^x \varepsilon(x)\,dx$$

Accreted thickness

h(x) ⇨ inheritance

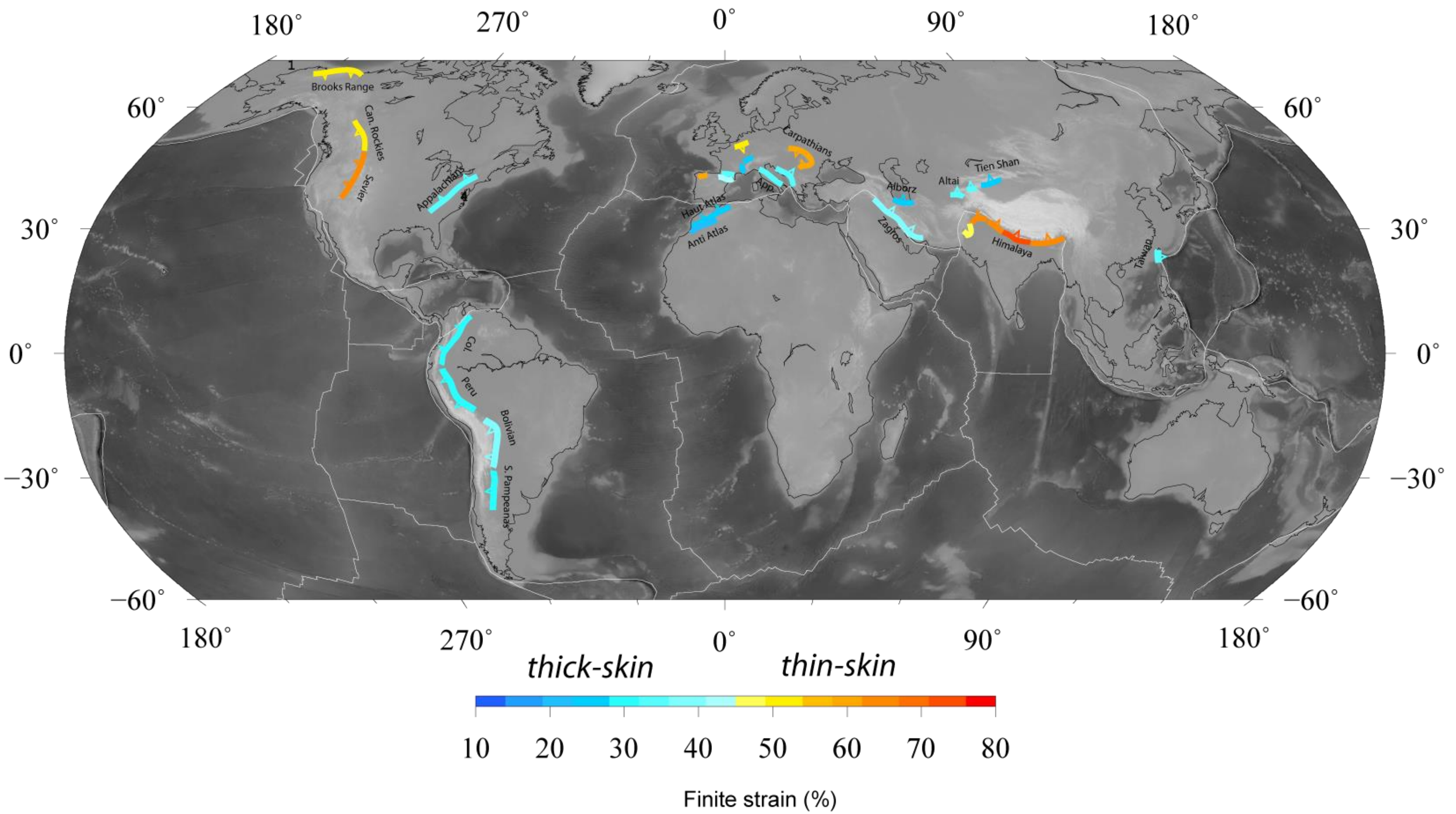


Shortening
→DL/L (%)

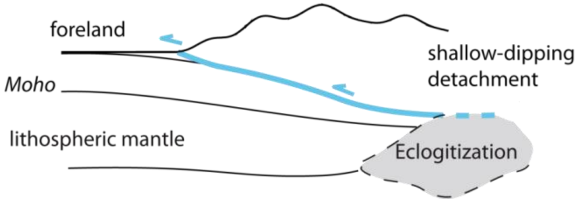
Linear erosion
0 →5.5 km/Myr

Convergence =
4.6 km/Myr

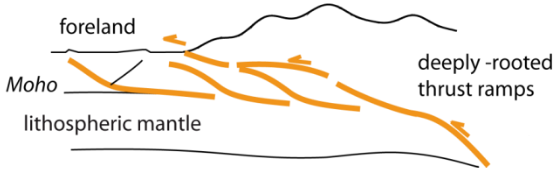
Décollement → 3°



h < 10 km



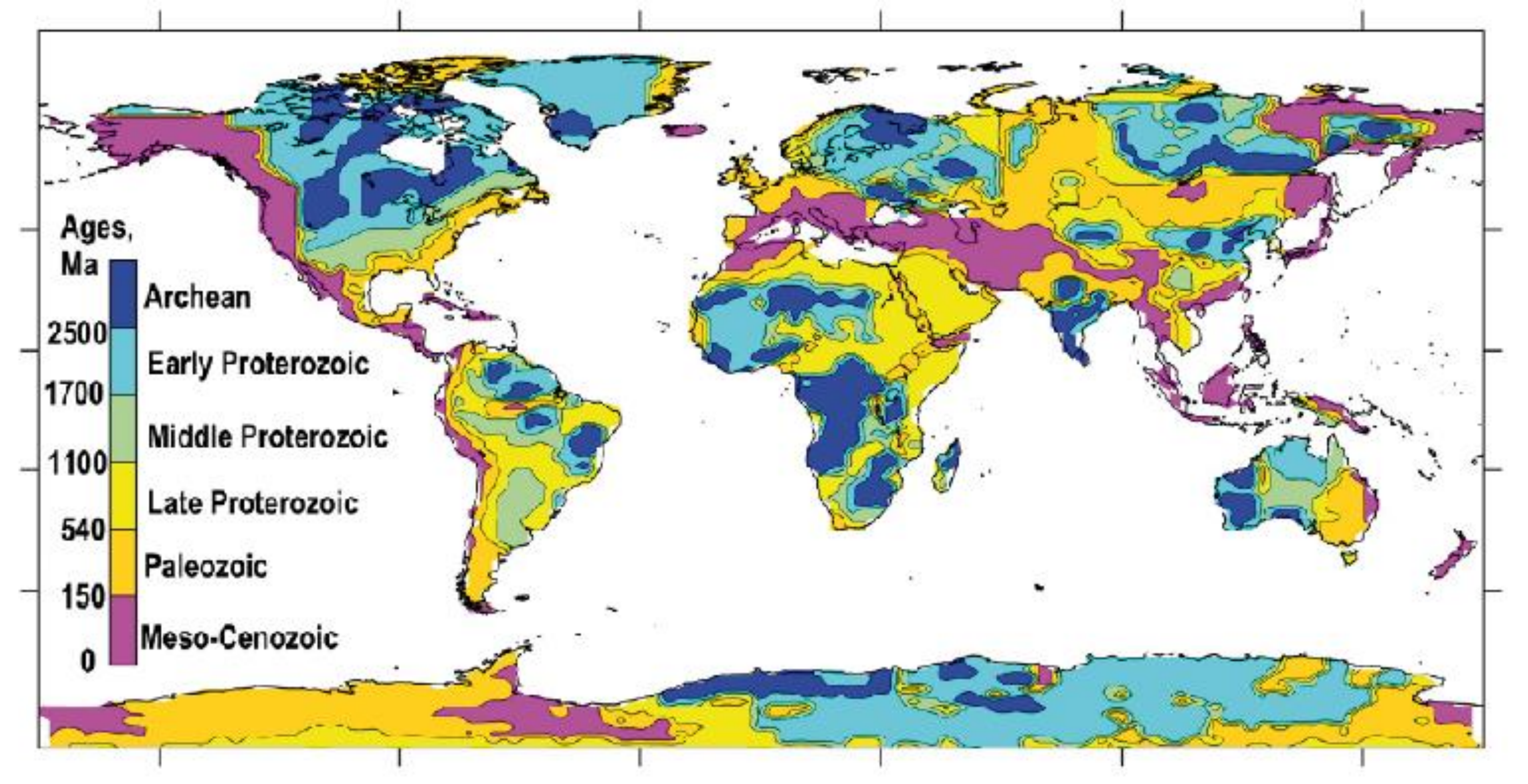
h > 15-20 km



Thin-skinned
~40-75%

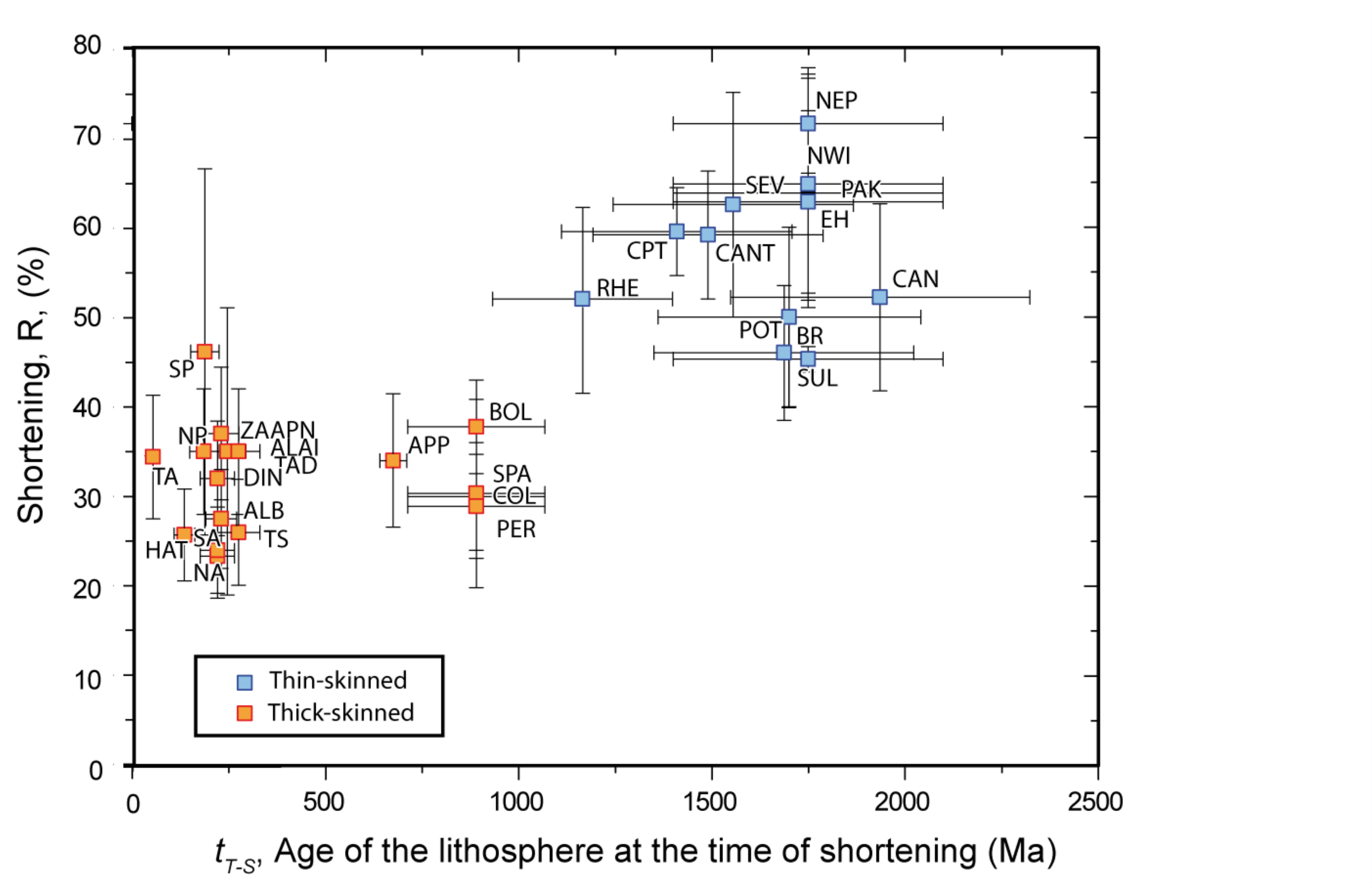
Thick-skinned
~20-40%

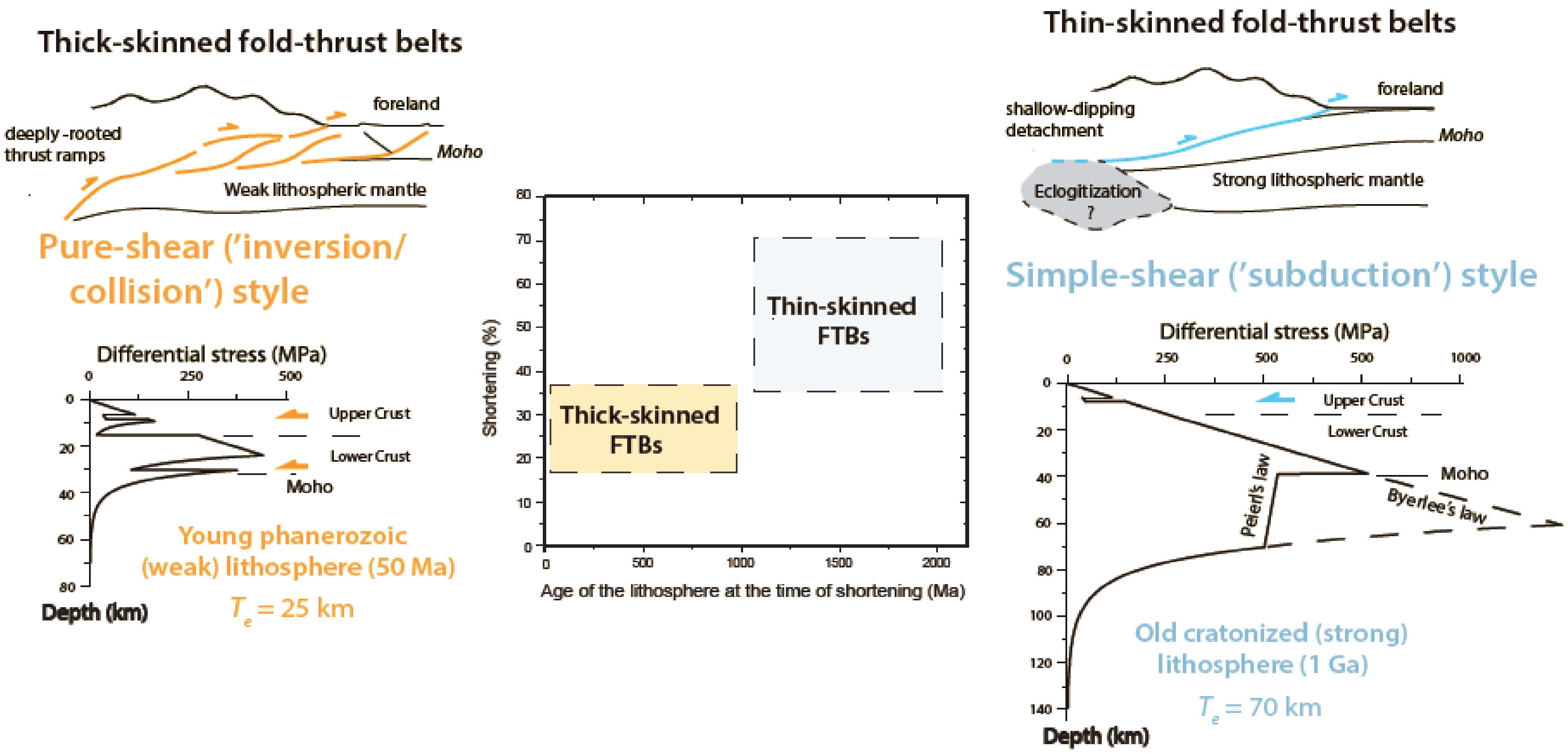
Thermotectonic age of continents
= age of the last tectono-magmatic event



Artemieva (2006)

Mouthereau et al. (2013)





(Lacombe and Bellahsen, 2016)

Conclusions

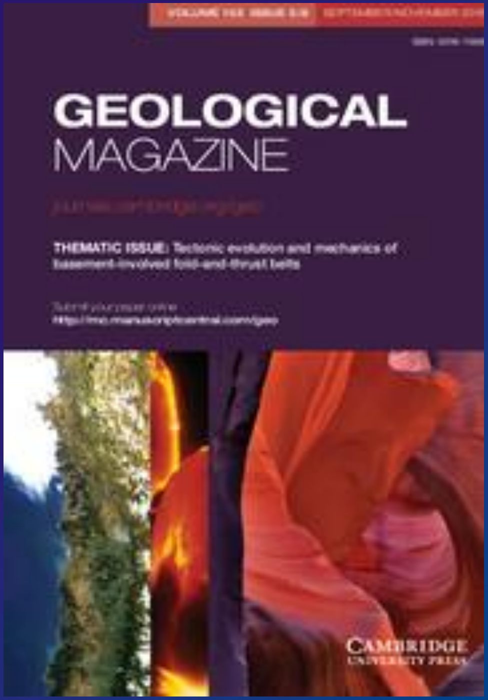
1. There are increasing lines of evidence of basement-involved shortening in FTBs, even in the 'archetypal' thin-skinned belts. This basement involvement is often associated with basement inversion tectonics.

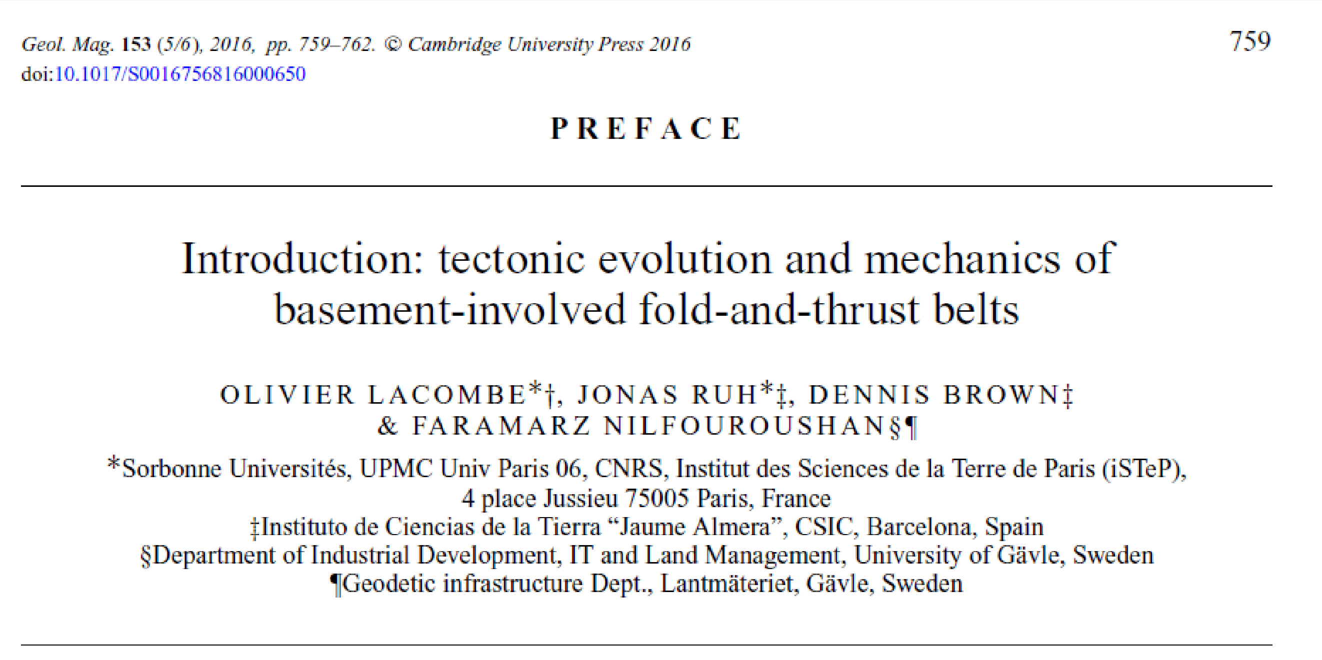
2. The pre-orogenic deformation of the basement may control the geometry, kinematics and mechanics of FTBs, either at the scale of the whole belt (e.g., belt curvature, segmentation and along-strike variations of structural styles, sequence of deformation, localization of contractional deformation and % of shortening) or at the scale of tectonic units (reactivation of inherited basement faults, basement-cored folding).

In some cases however, inherited basement (normal) faults are not reactivated whereas newly-formed compressional shear zones develop, which brings into question the bulk rheology of the crust vs the rheology of preexisting fault zones available for reactivation.

3. In basement-involved, thick-skinned FTBs, shortening is distributed throughout thewhole crust and is usually lower than in their thin-skinned counterparts, which likely requires/reflects a specific thermo-mechanical behavior of the underlying lithosphere (e.g, hot and young, hence weak). In FTBs resulting from inversion of former proximal passive margins, basement thrusting that occurs in a rather localized way in their inner parts requires structural inheritance and/or a hot crustal temperature either inherited from a recent (pre- orogenic) rifting event or resulting from syn-orogenic underthrusting and heating.

4. Basement-involvement in FTBs raises the question of the way the orogen is mechanically coupled to the foreland and how orogenic stresses are transmitted through the heterogeneous basement of the foreland/plate interior. Development of thick-skinned belts within cratons remains somewhat enigmatic and likely requires specific boundary conditions (strong interplate coupling, such as provided by flat-slab subduction) ensuring efficient transmission of stresses (crustal/lithospheric stress guide) and propagation of deformation in the pro- and retro-foreland by crustal/lithospheric buckling or deep crustal decollement, in addition to local structural and/or possible physical/compositional weakening.





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PREFACE

Introduction: tectonic evolution and mechanics of basement-involved fold-and-thrust belts

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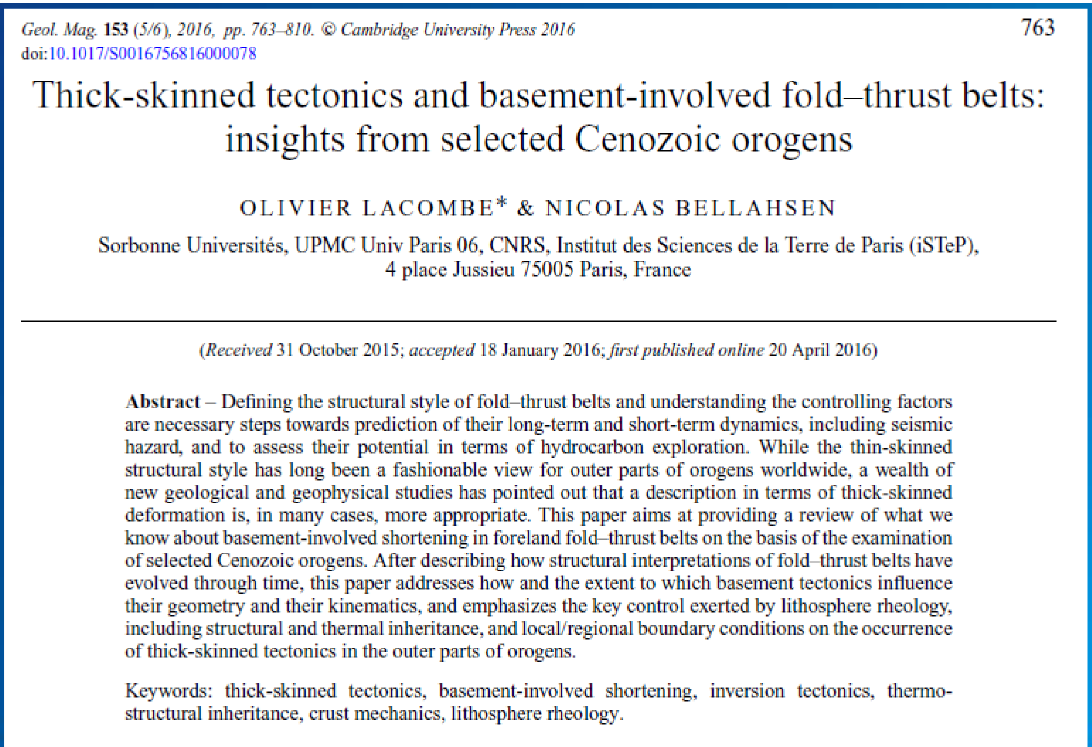

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Thick-skinned tectonics and basement-involved fold–thrust belts: insights from selected Cenozoic orogens

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Abstract – Defining the structural style of fold–thrust belts and understanding the controlling factors are necessary steps towards prediction of their long-term and short-term dynamics, including seismic hazard, and to assess their potential in terms of hydrocarbon exploration. While the thin-skinned structural style has long been a fashionable view for outer parts of orogens worldwide, a wealth of new geological and geophysical studies has pointed out that a description in terms of thick-skinned deformation is, in many cases, more appropriate. This paper aims at providing a review of what we know about basement-involved shortening in foreland fold–thrust belts on the basis of the examination of selected Cenozoic orogens. After describing how structural interpretations of fold–thrust belts have evolved through time, this paper addresses how and the extent to which basement tectonics influence their geometry and their kinematics, and emphasizes the key control exerted by lithosphere rheology, including structural and thermal inheritance, and local/regional boundary conditions on the occurrence of thick-skinned tectonics in the outer parts of orogens.

Keywords: thick-skinned tectonics, basement-involved shortening, inversion tectonics, thermo-structural inheritance, crust mechanics, lithosphere rheology.