KIGAM, 2014

How brittle deformation localizes in the upper continental crust ?
Initiation, geometry and mechanics of brittle faulting in sedimentary rocks and exhuming metamorphic rocks.

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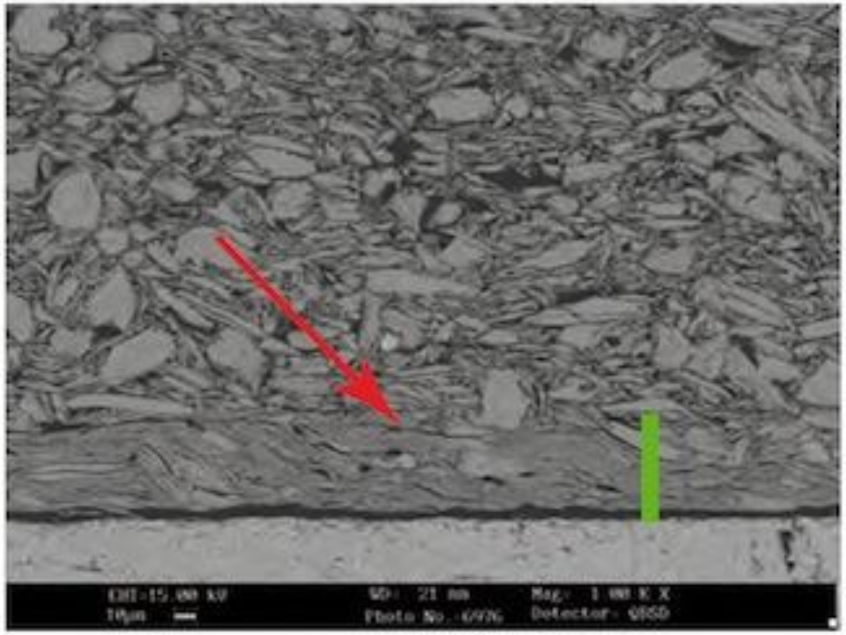
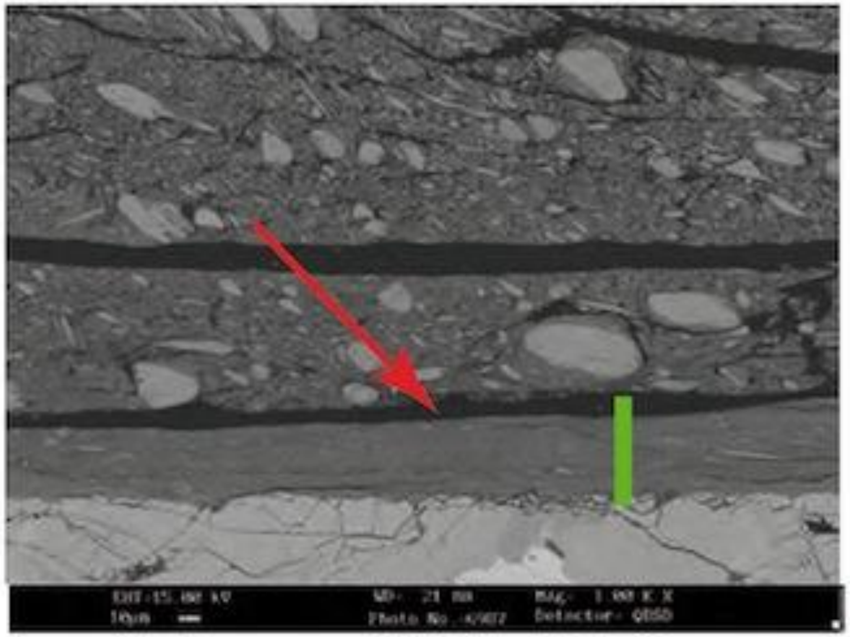
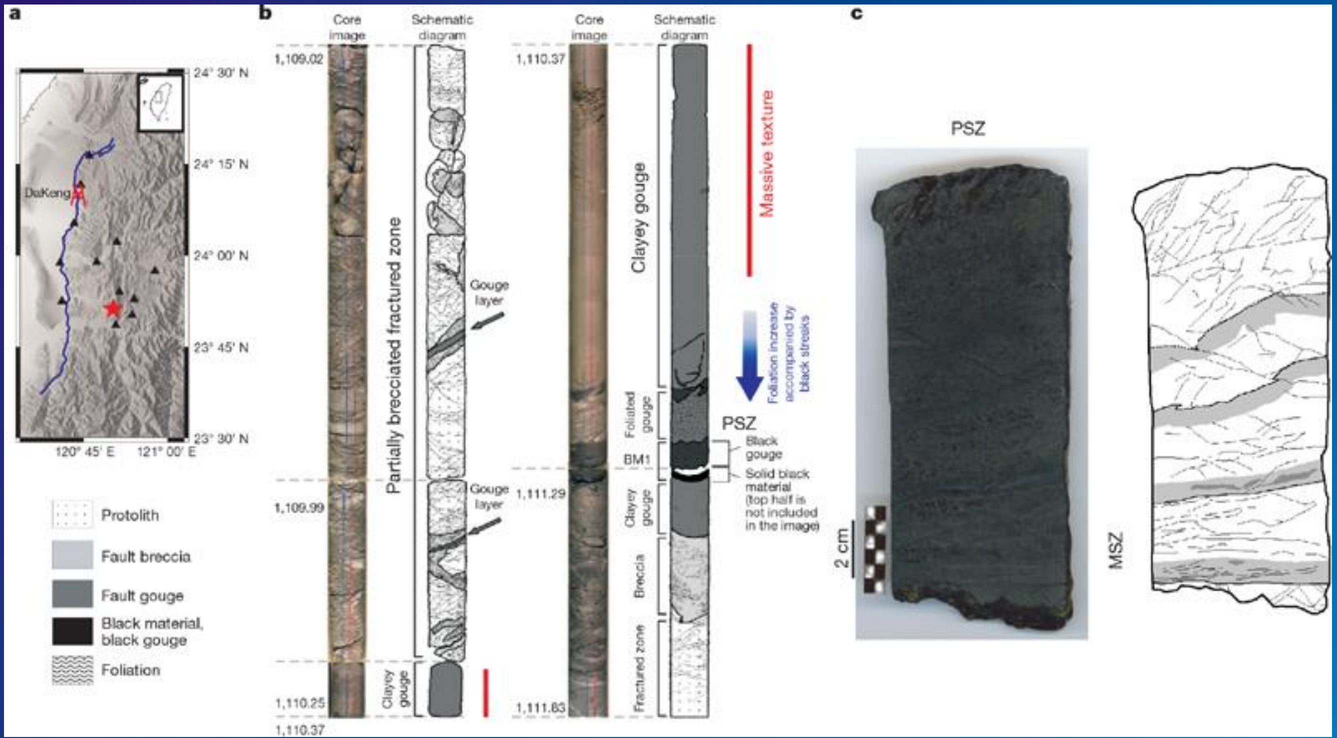
Faults, witnesses of strain localization in the brittle crust





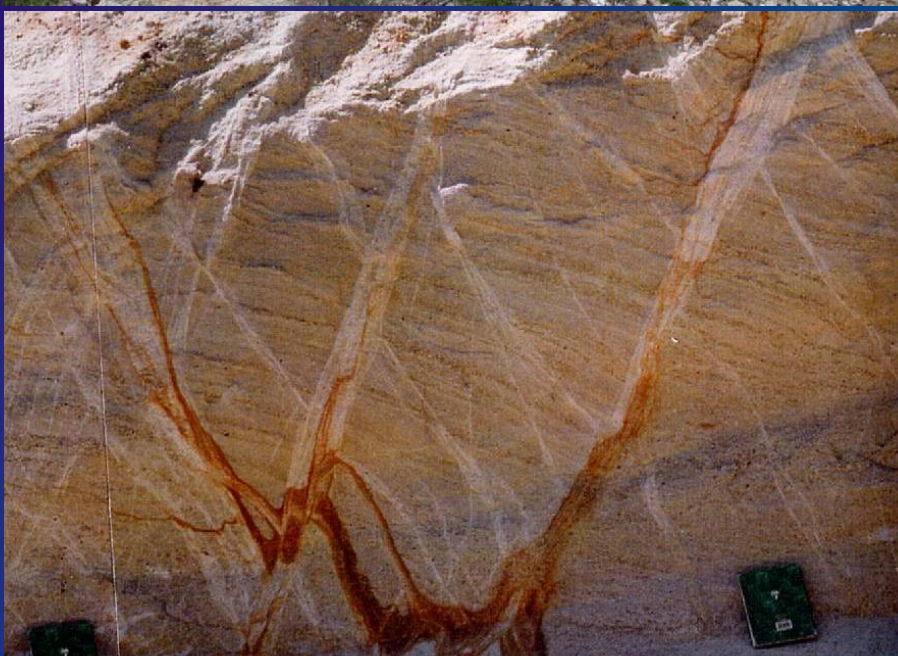

a
b
c
24° 30′ N
24° 15′ N
24° 00′ N
23° 45′ N
23° 30′ N
120° 45′ E
121° 00′ E
DaKeng
Protolith
Fault breccia
Fault gouge
Black material, black gouge
Foliation
Core image
Schematic diagram
1,109.02
1,109.99
1,110.25
1,110.37
1,111.29
1,111.83
Partially brecciated fractured zone
Gouge layer
Clayey gouge
Massive texture
Foliation increase accompanied by black streaks
Foliated gouge
PSZ
Black gouge
BM1
Solid black material (top half is not included in the image)
Breccia
Fractured zone
2 cm
MSZ

Ma et al., 2006

Localization of deformation in the upper crust

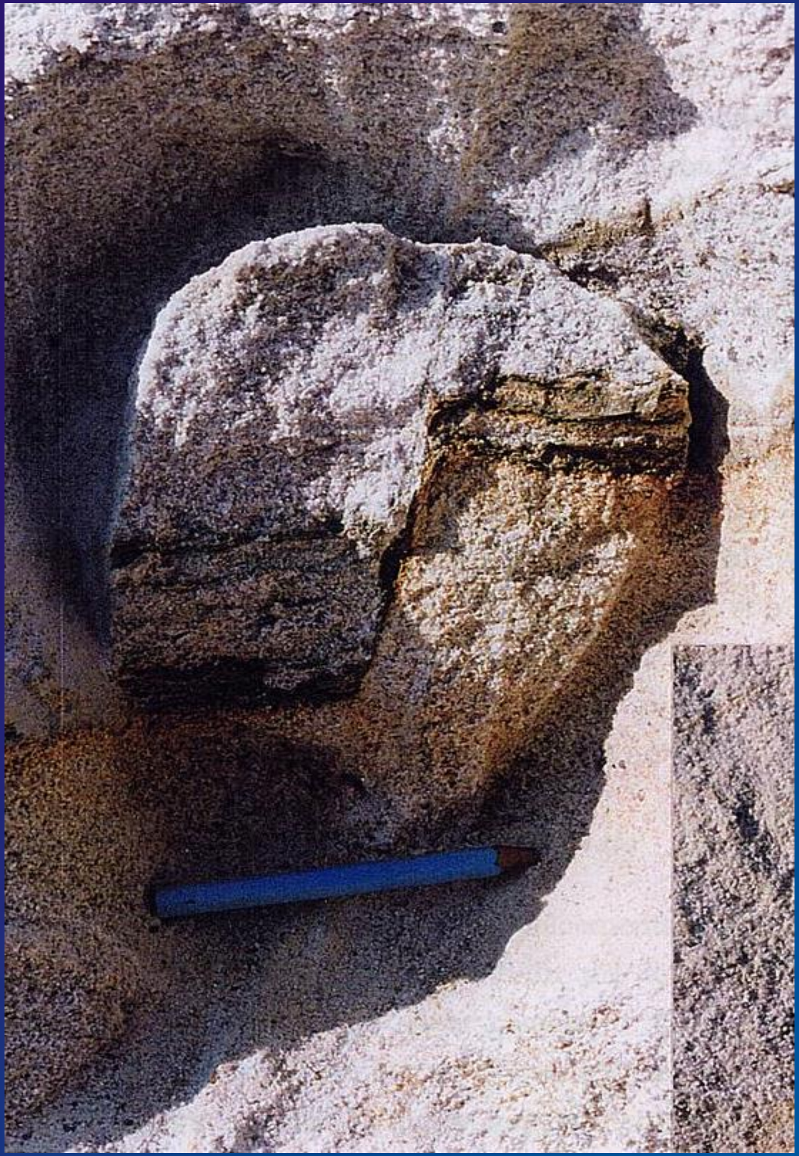
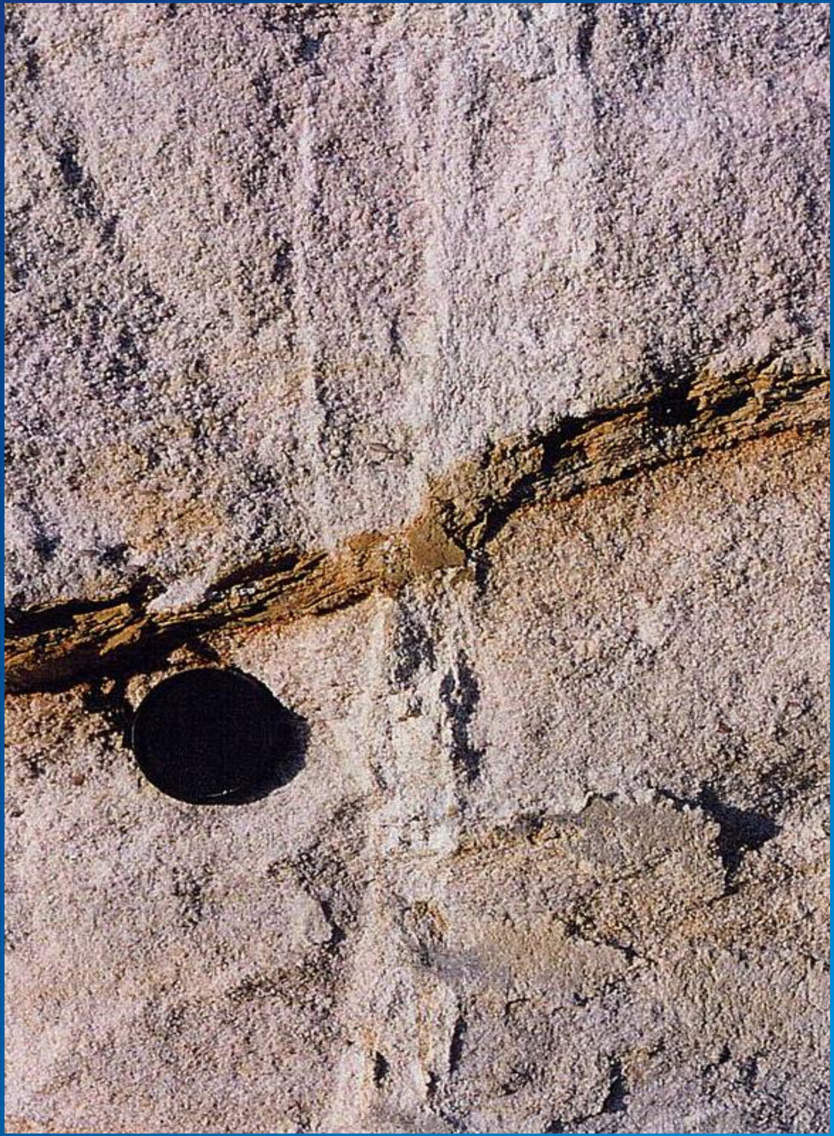

RF5
RF3
10 cm
16
3
2

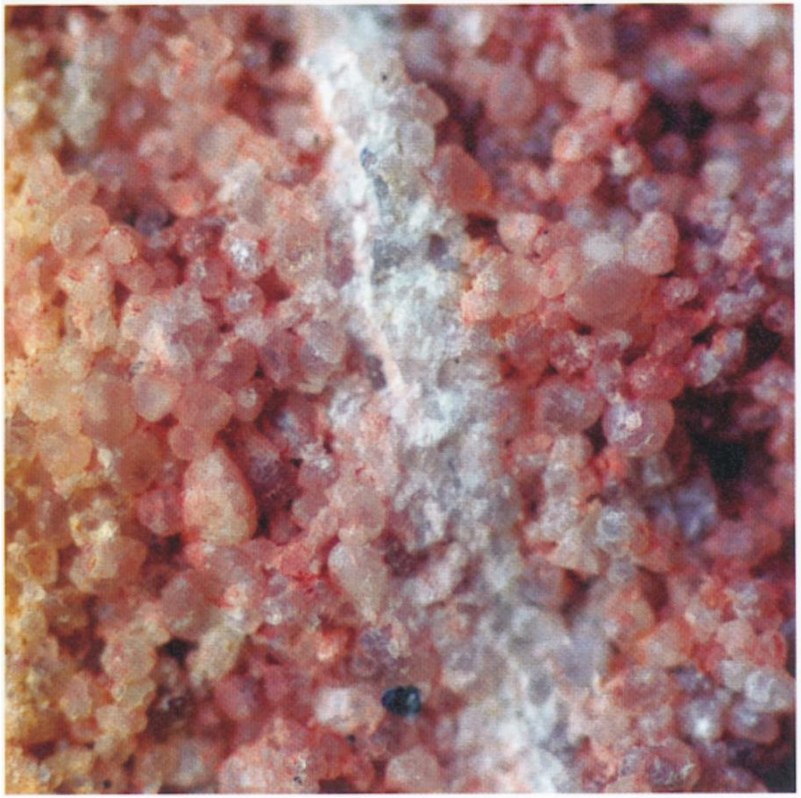
At least 3 different mechanisms of localization

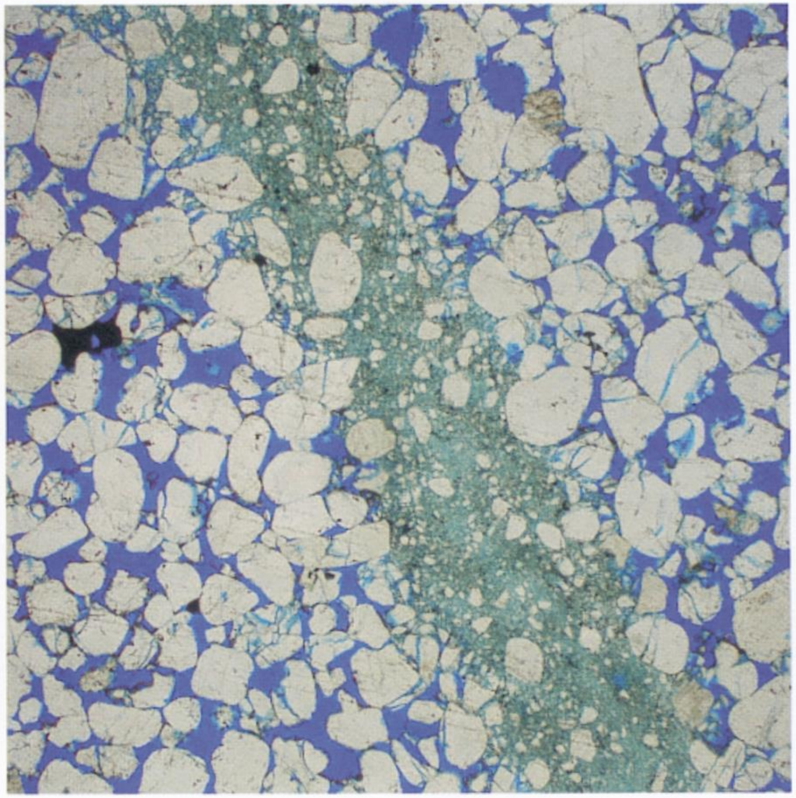


The birth of faults in sedimentary rocks (1) : from deformation bands to faults

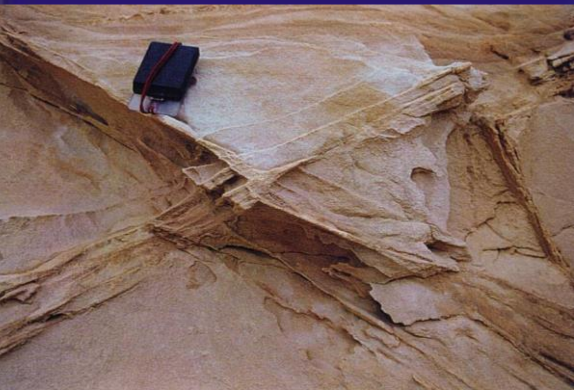

Deformation bands

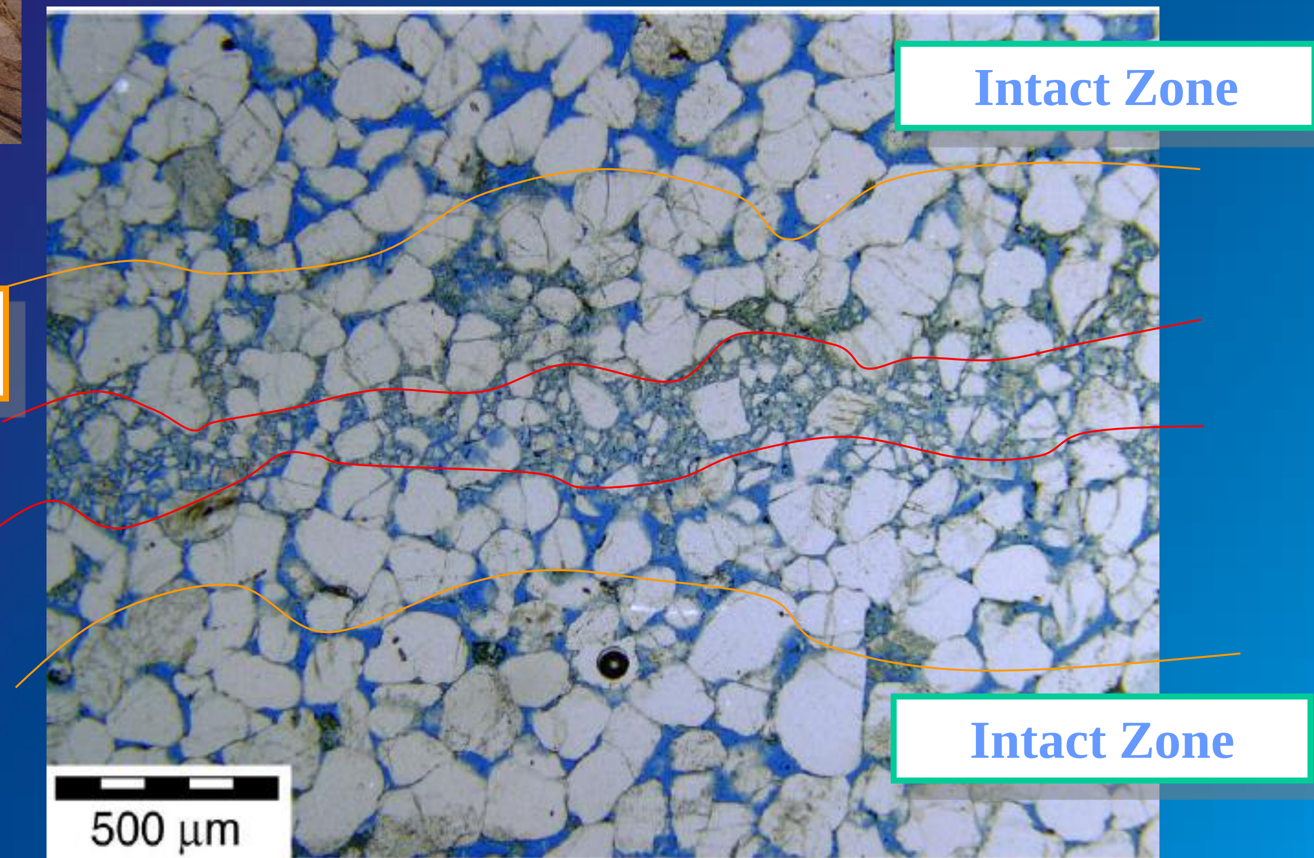







In Fossen, Structural Geology





Grain rotation, compaction, internal fracturing

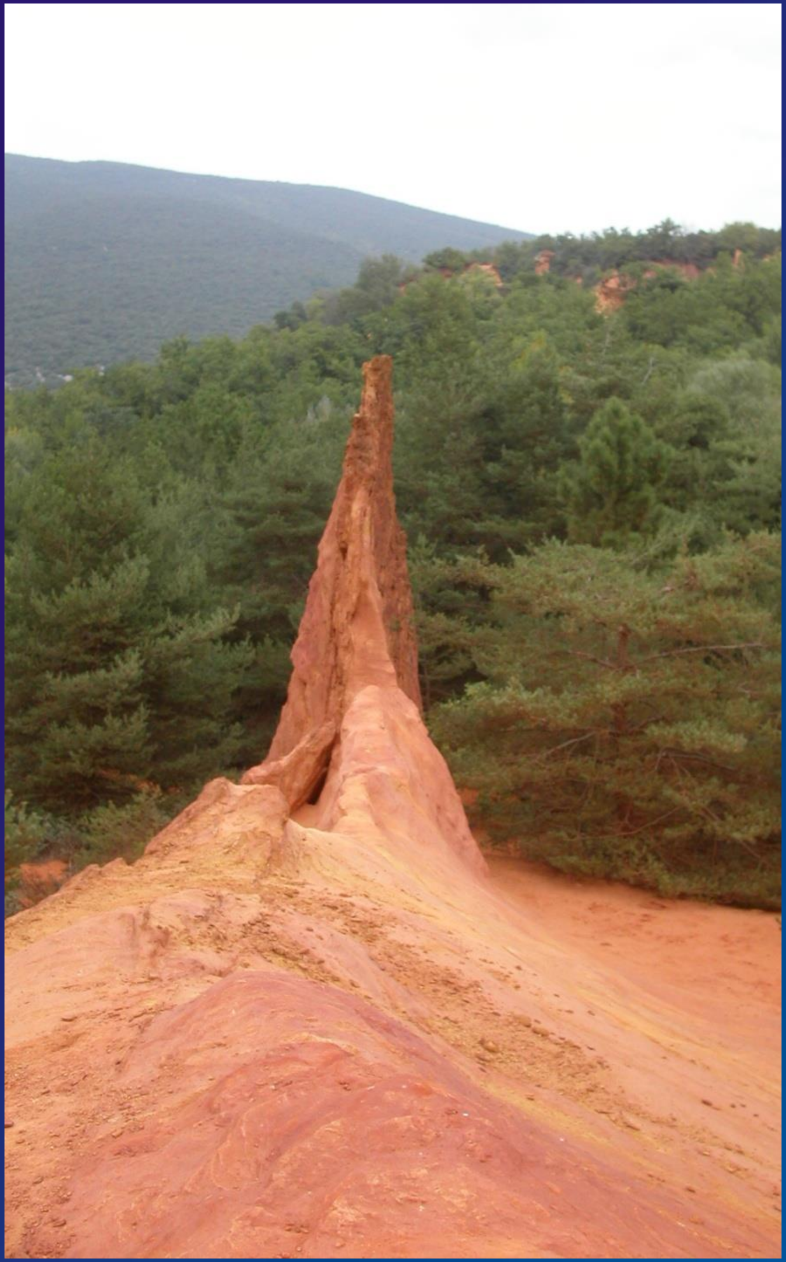
"Deformation band"

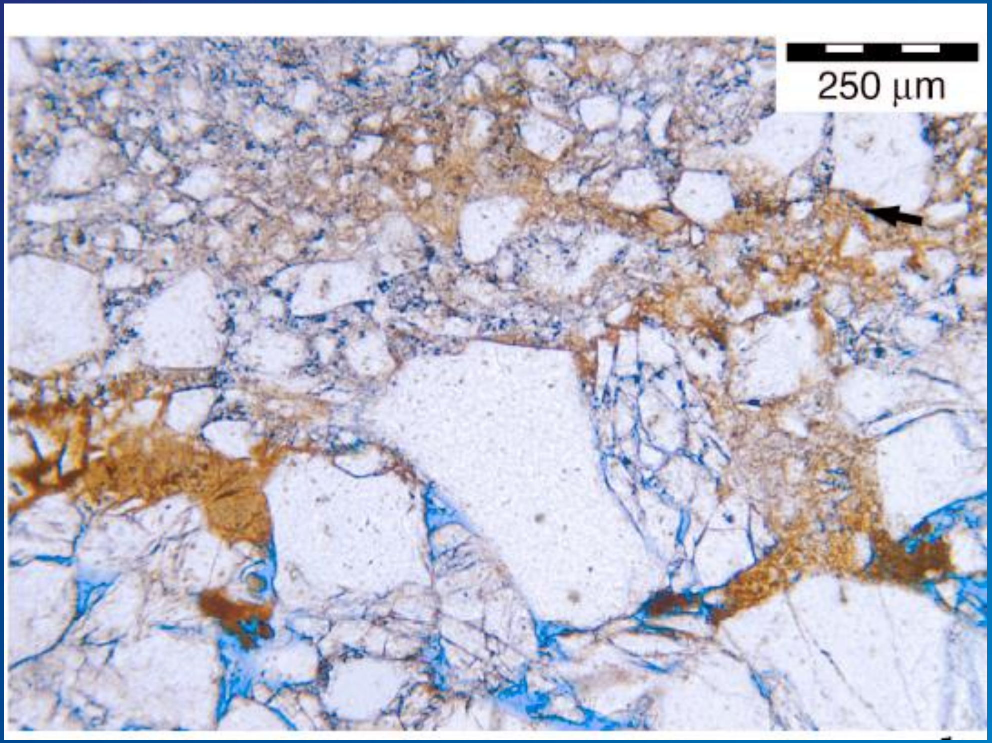
Porosity reduction

Increase of clay content

Increase of the number of contact points

(Du Bernard-Rouchy and Labaume, 2002)

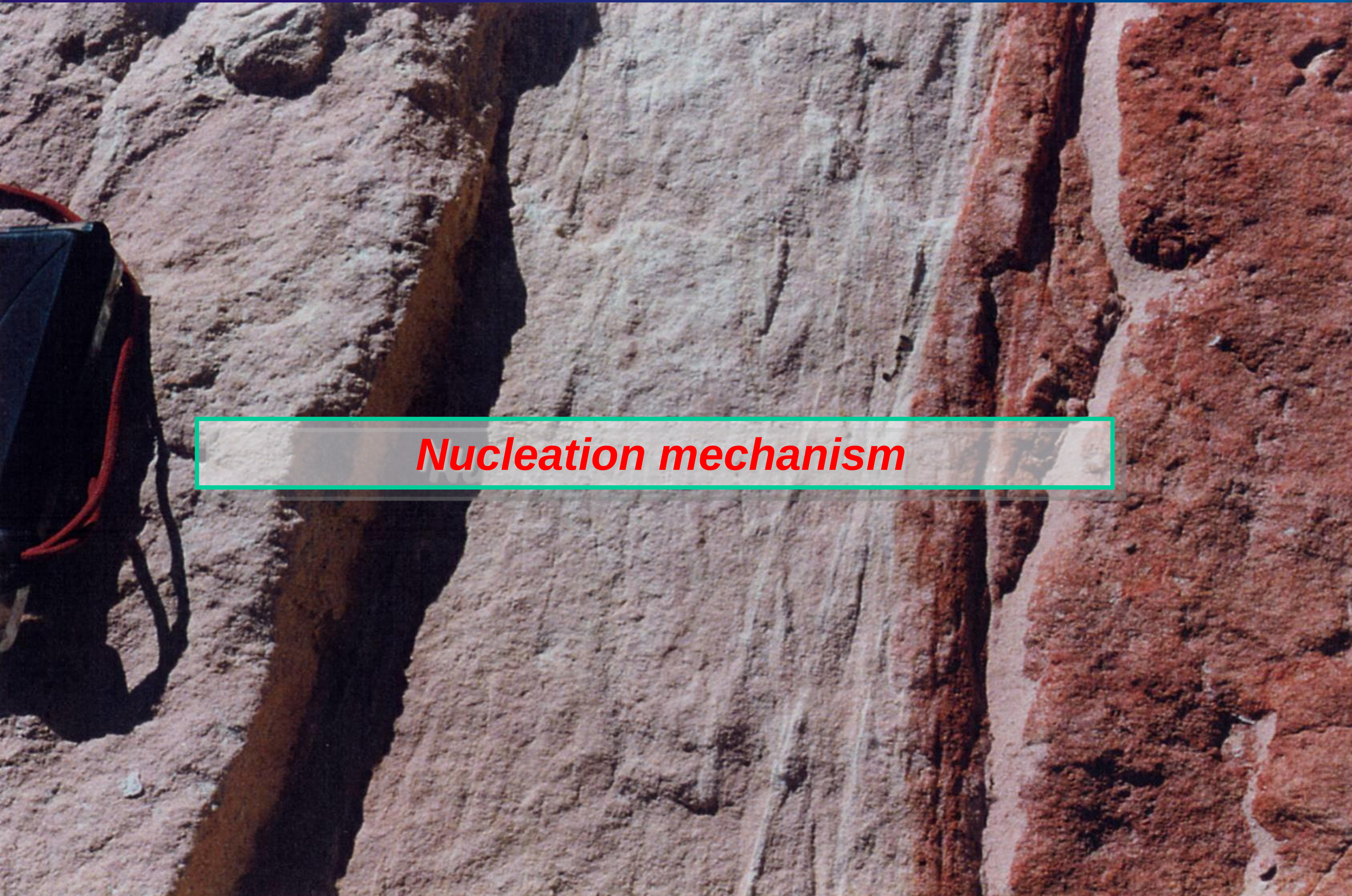


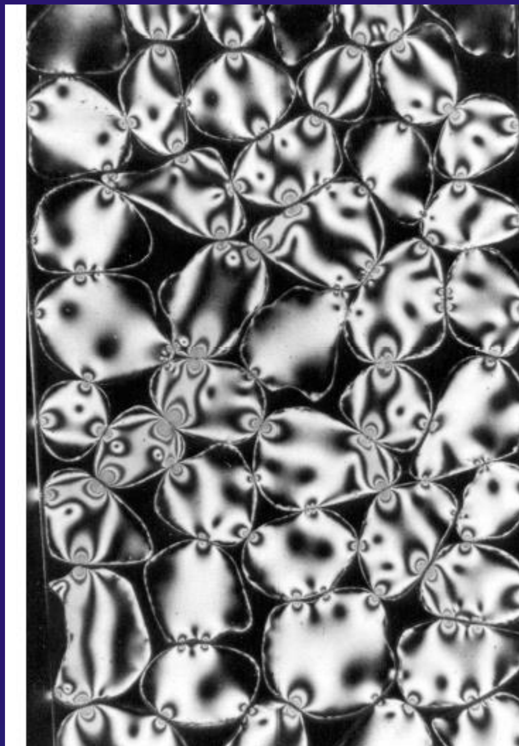


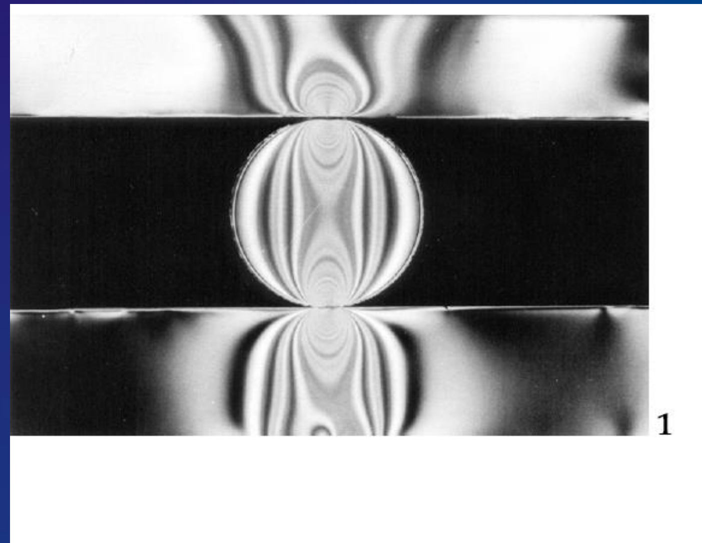
Deformation bands are strong

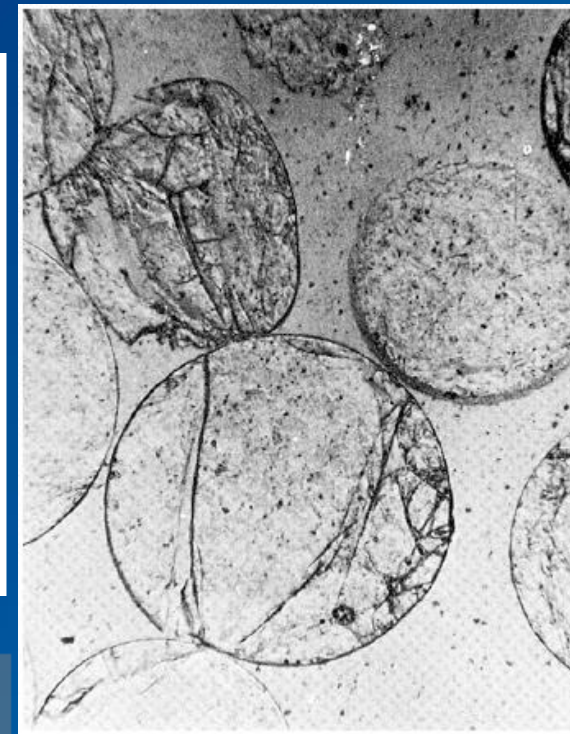
Grain size reduction, porosity reduction, enhanced cementation -> increasing strength compared to surrounding rocks

Nucleation mechanism

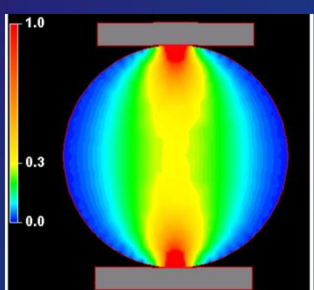


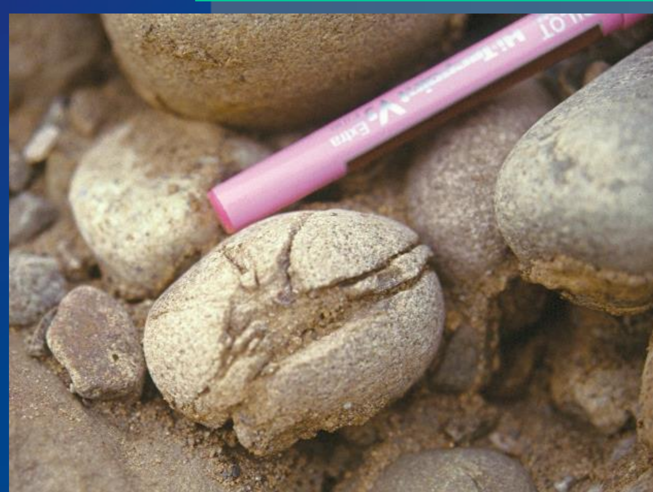


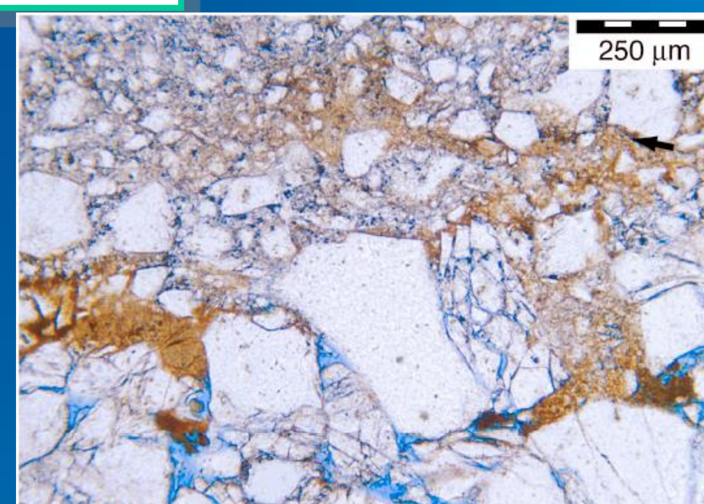




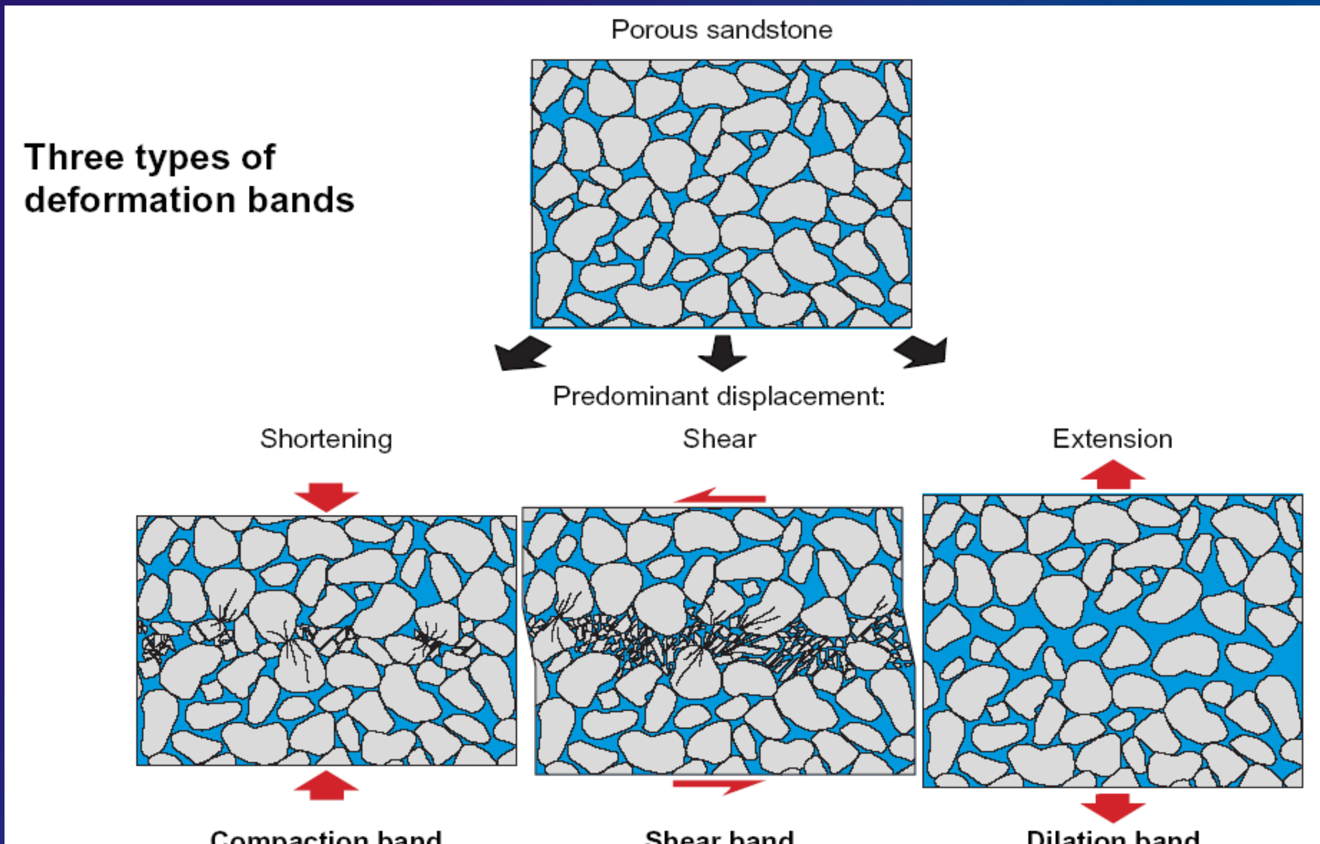
Stress concentrations at contact points



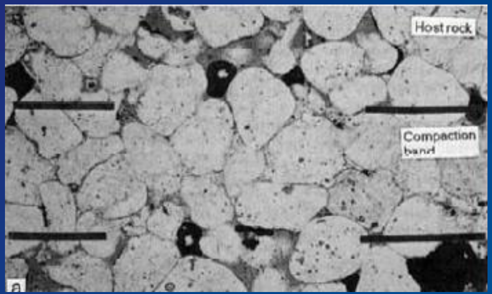


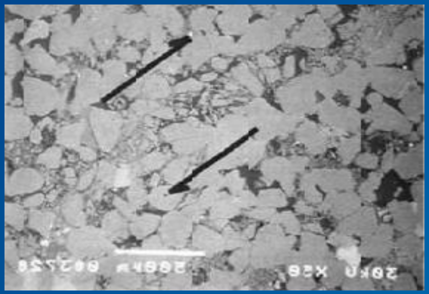


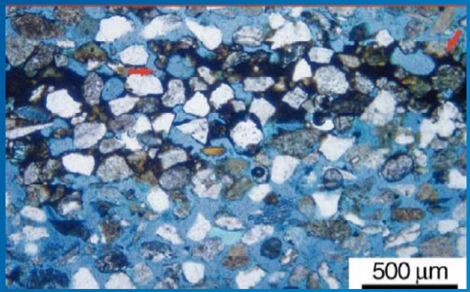
Constitutive grains are free and may be rearranged



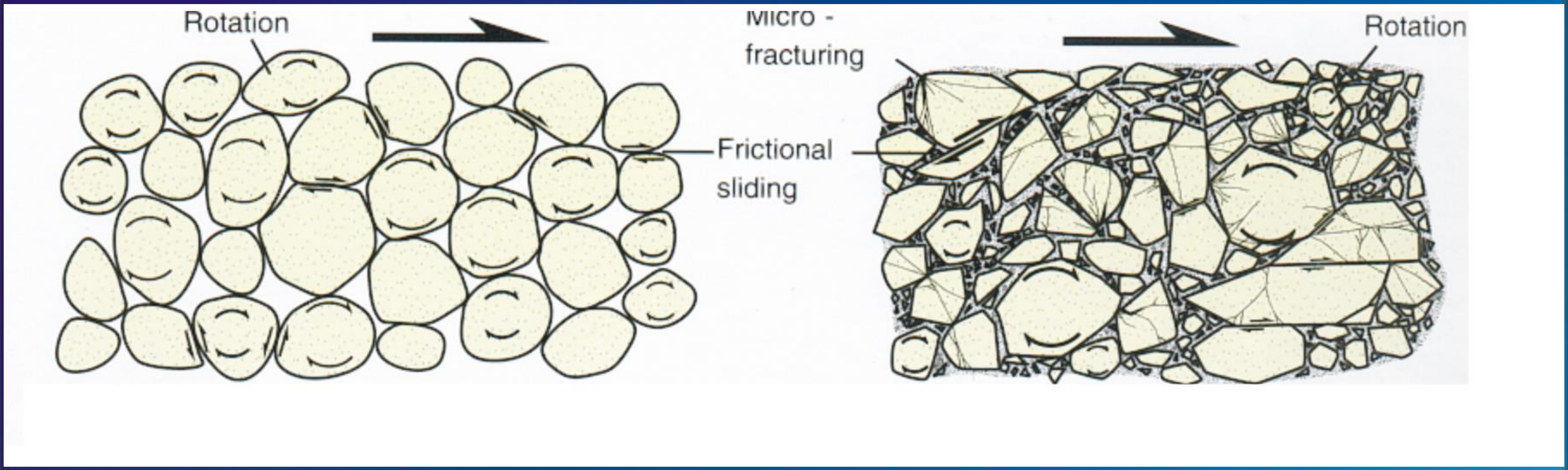
(Mollema and Antonellini, 1996; Aydin, 1978)



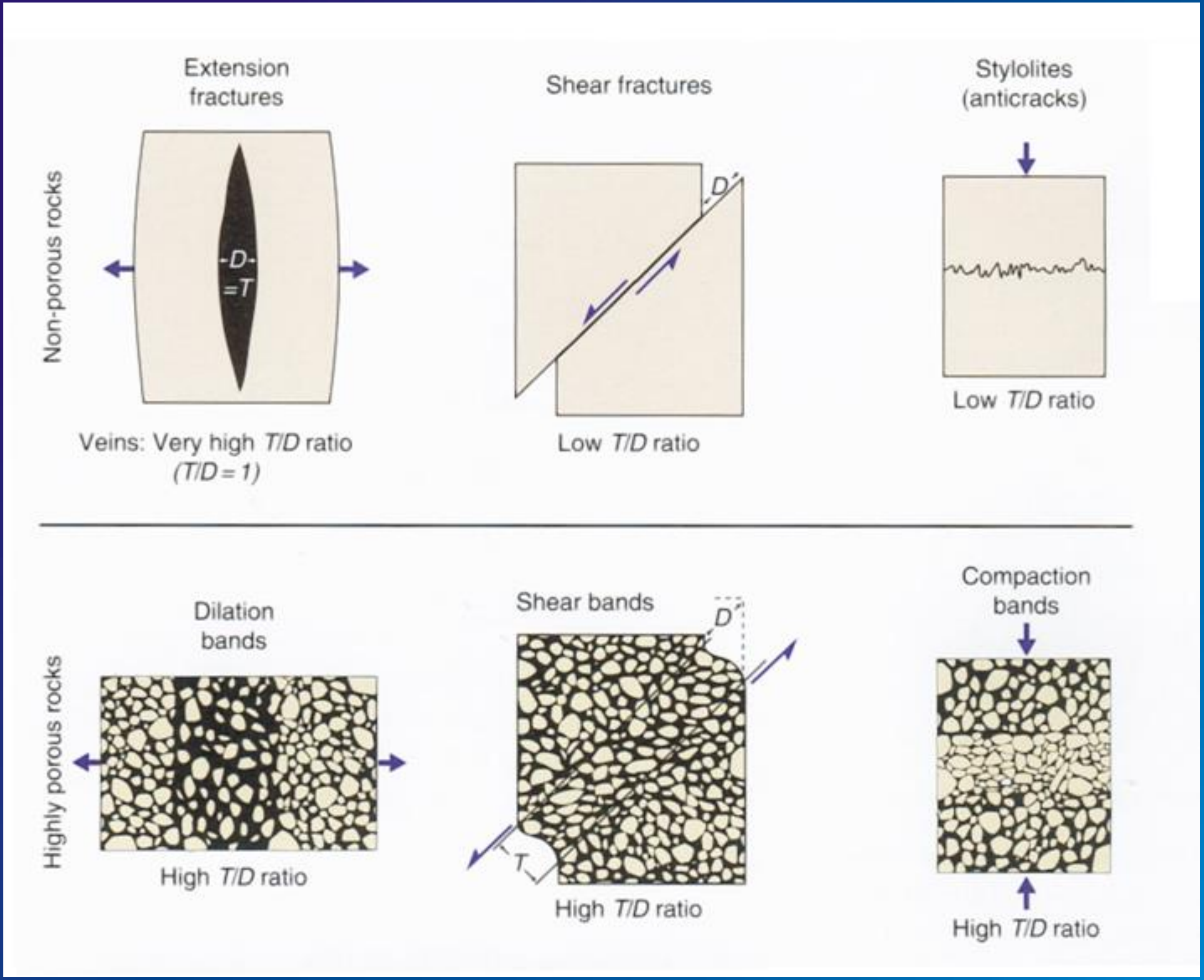




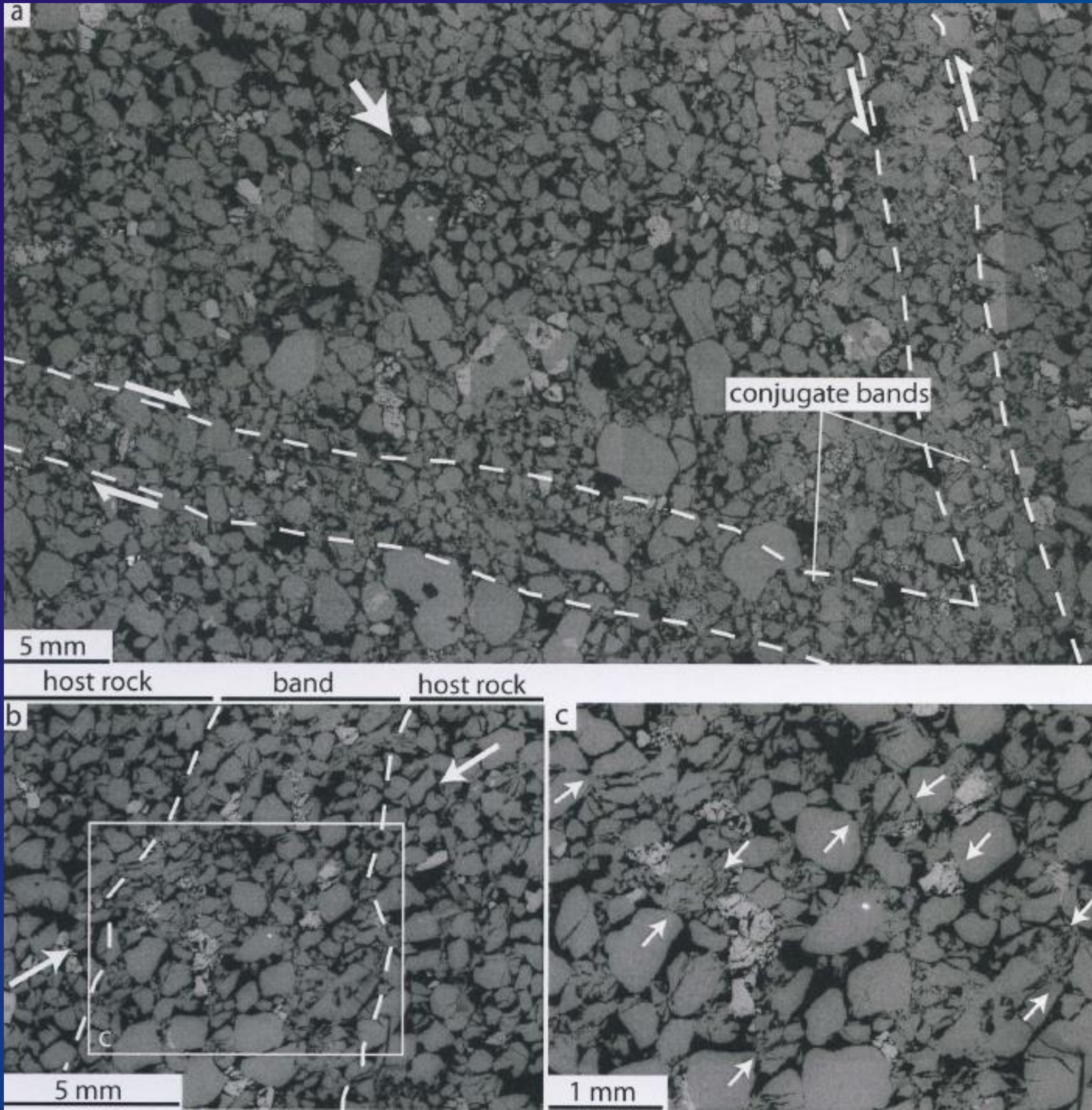
(Du Bernard-Rouchy and Labaume, 2002)



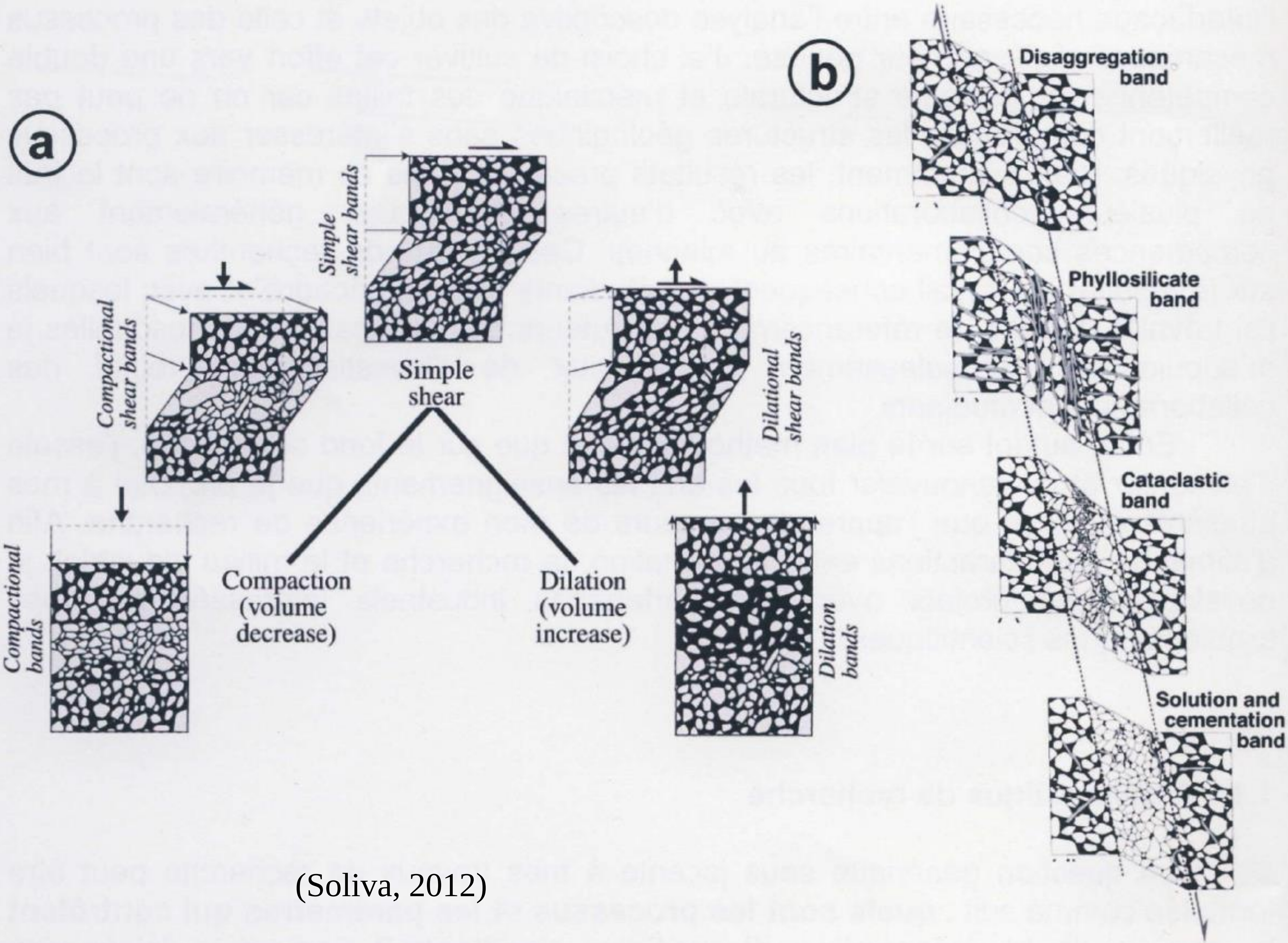
In Fossen, Structural Geology



In Fossen, Structural Geology



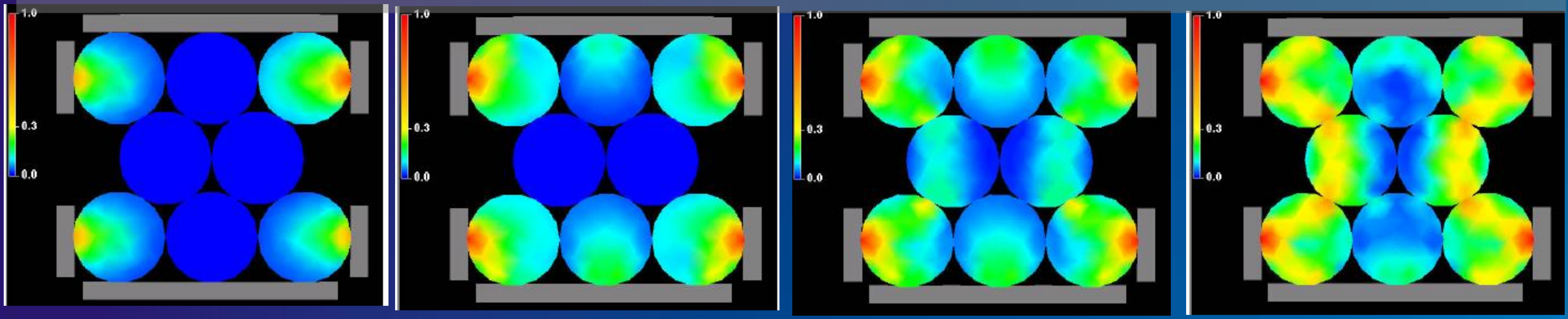
(Soliva, 2012)


a
Simple shear bands
Compactional shear bands
Simple shear
Dilational shear bands
Compactional bands
Compaction (volume decrease)
Dilation (volume increase)
Dilation bands
b
Disaggregation band
Phyllosilicate band
Cataclastic band
Solution and cementation band

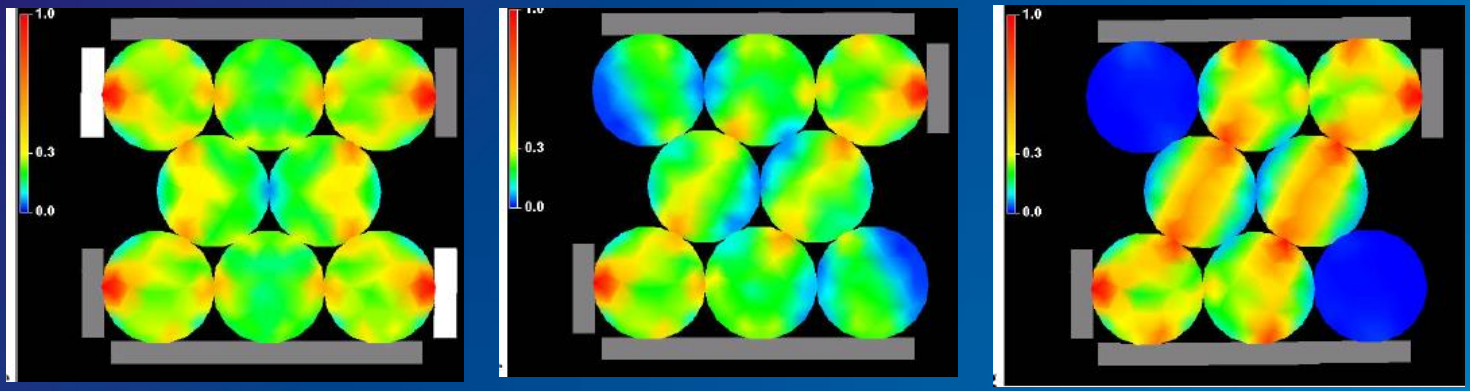
(Soliva, 2012)

- Deformation bands are restricted to highly porous granular media, notably porous sandstones.
- A shear deformation band is a wider zone of deformation than regular shear fractures of comparable displacement.
- Deformation bands do not develop large offsets. Even 100 m long deformation bands seldom have offsets in excess of a few centimeters, while shear fractures of the same length tend to show meter-scale displacement.
- Deformation bands occur as single structures, as clusters, or in zones associated with slip surfaces (faulted deformation bands). This is related to the way that faults form in porous rocks by faulting of deformation band zones

First phase : loading

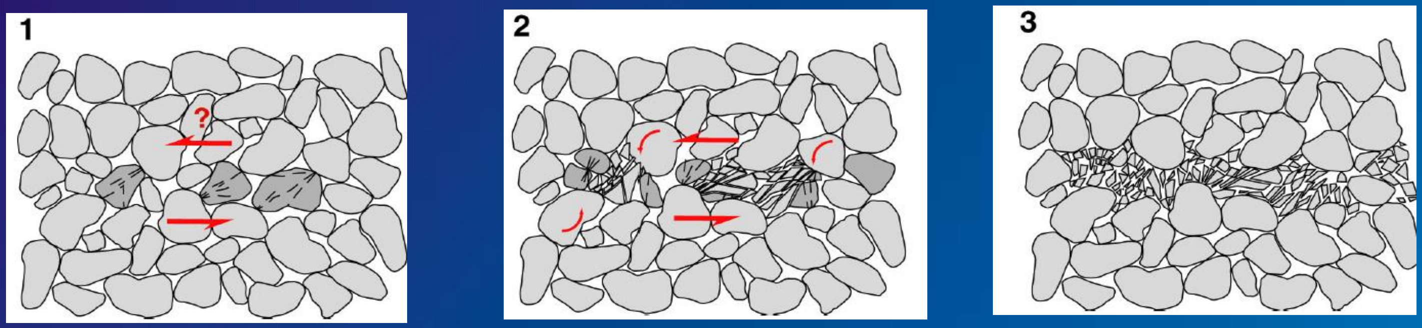


Second phase : desequilibrium



Generation of a band is a unique event

Cataclasis as a mechanism for intragranular fracturing



Rotation and re-organization of grains by compaction put small surfaces in contact.
Stress concentrations on limited surfaces lead to fracturing of grains into smaller ones.

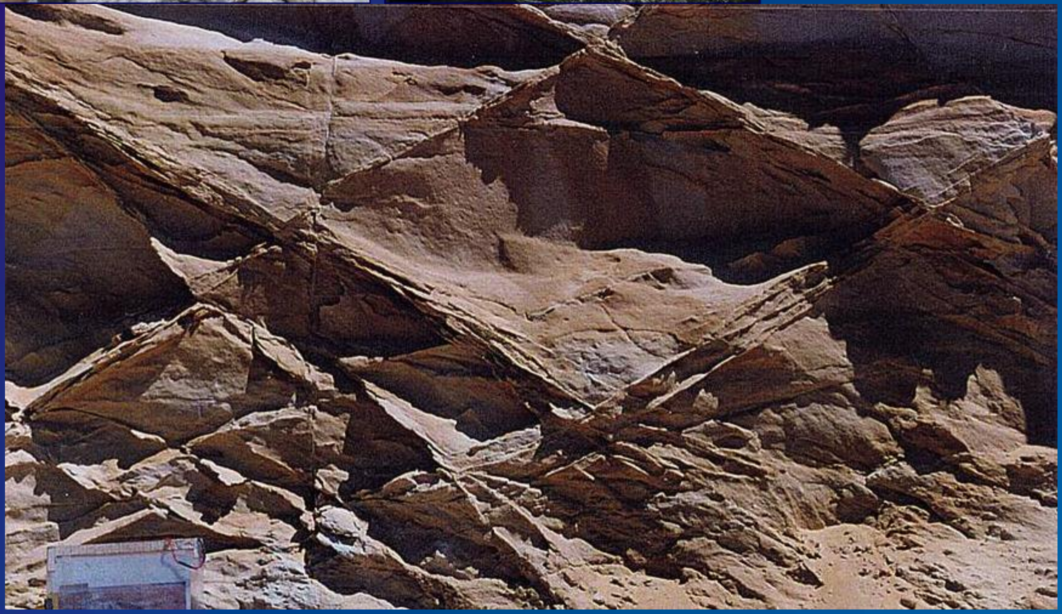
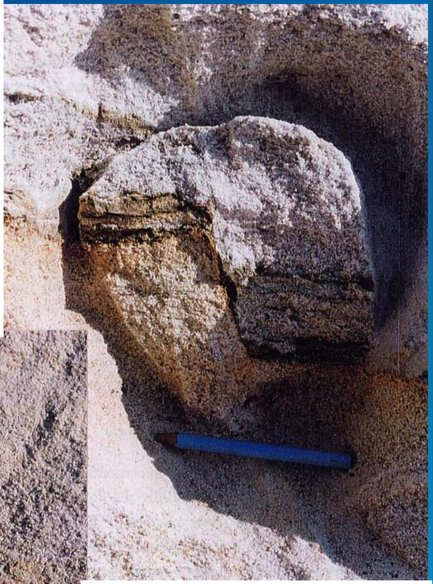
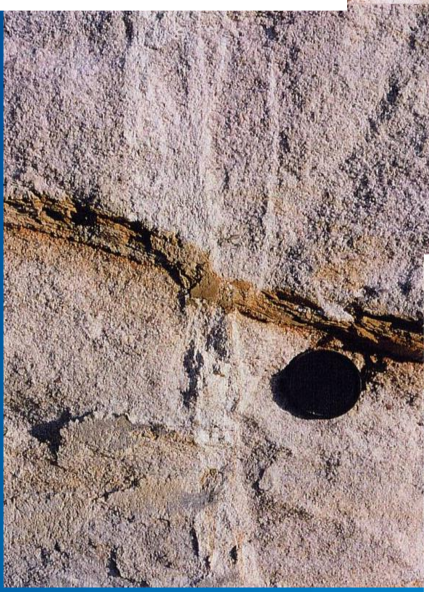
In general, these deformation bands are organized into clusters.

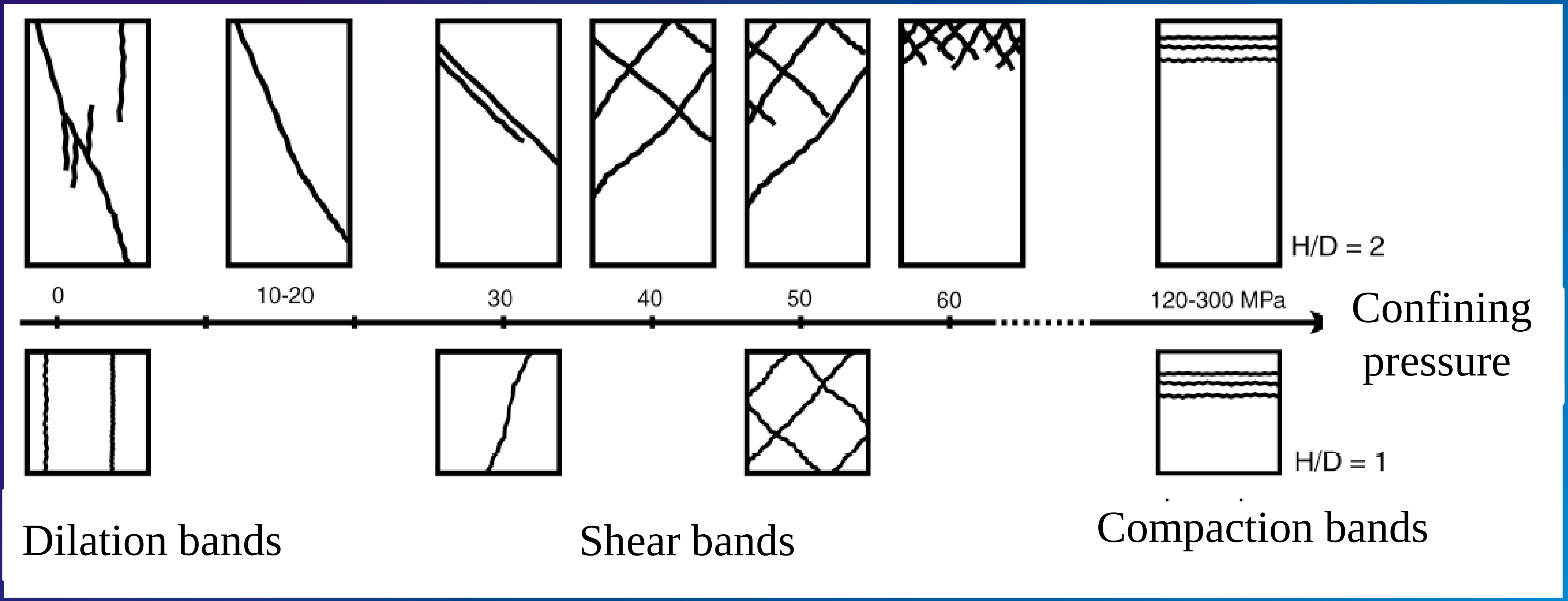
Conditions to form deformation bands

Rock type

This kind of structure is very often encountered in poorly consolidated sands.

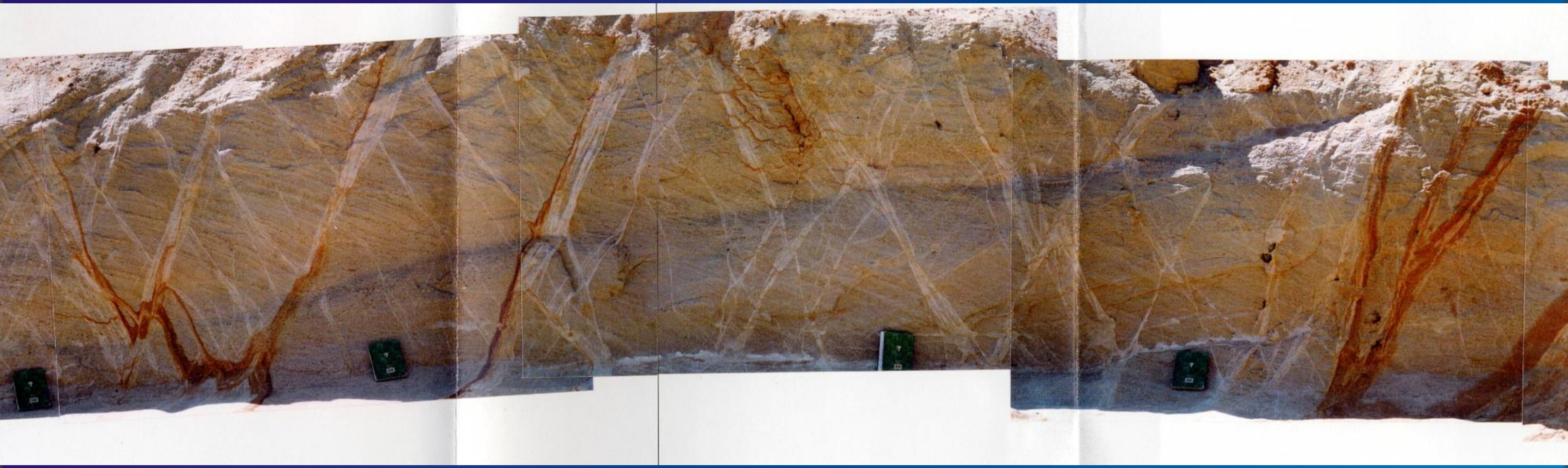


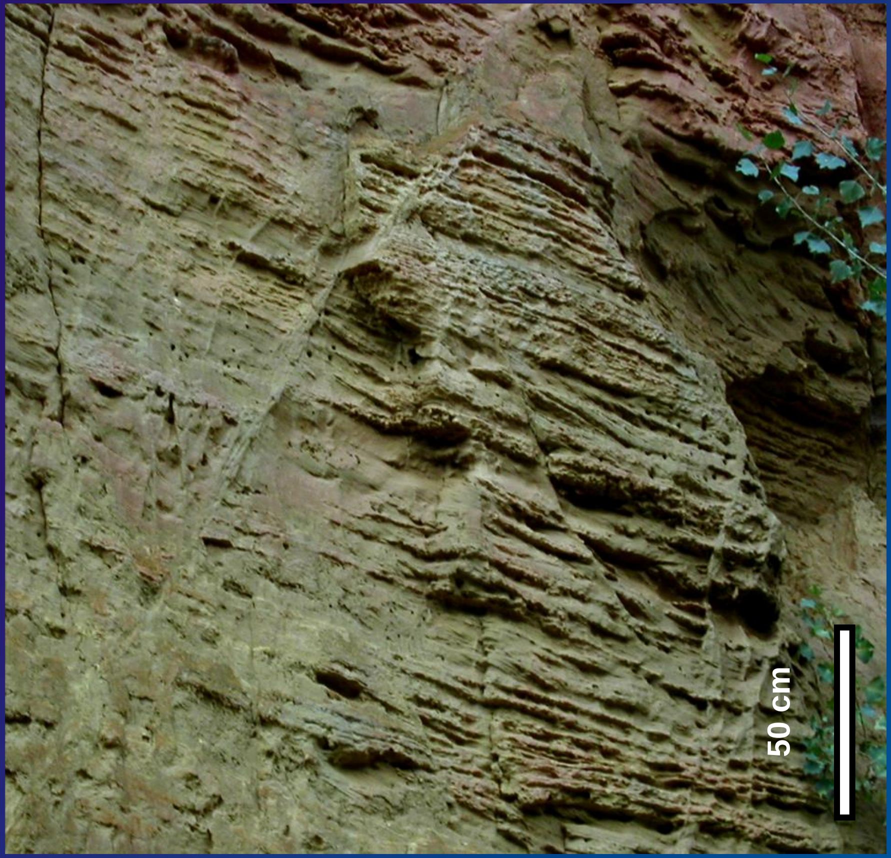


(Bésuelle, 2001)

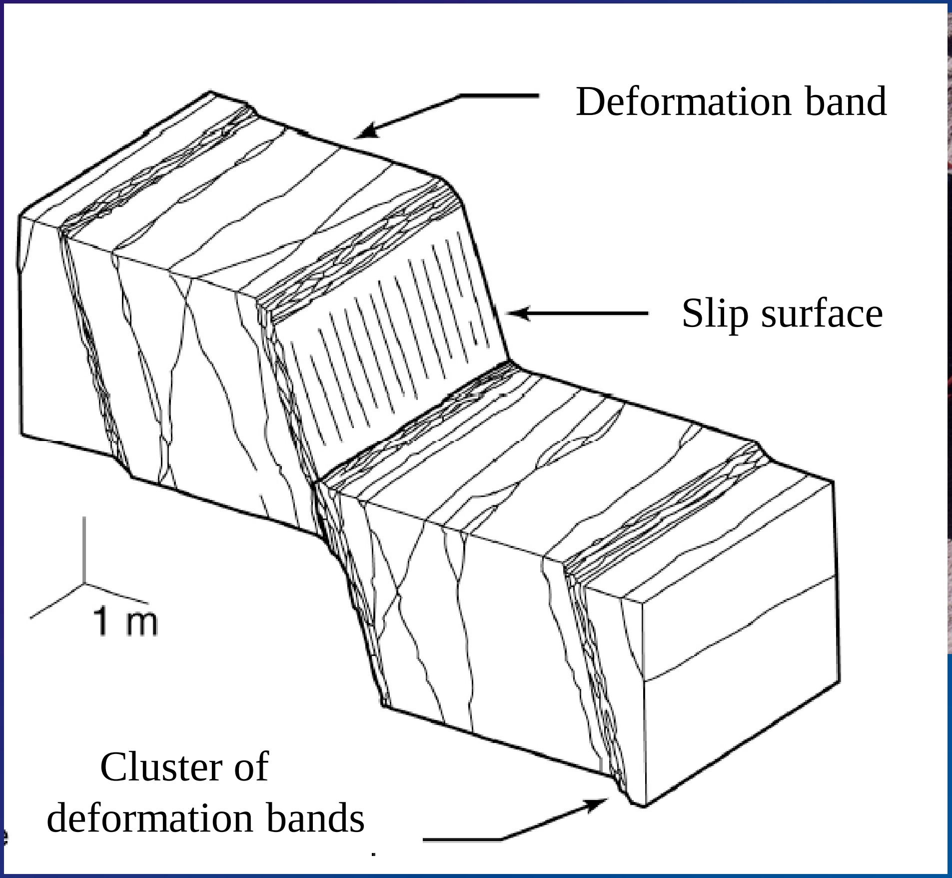
From deformation bands to faults

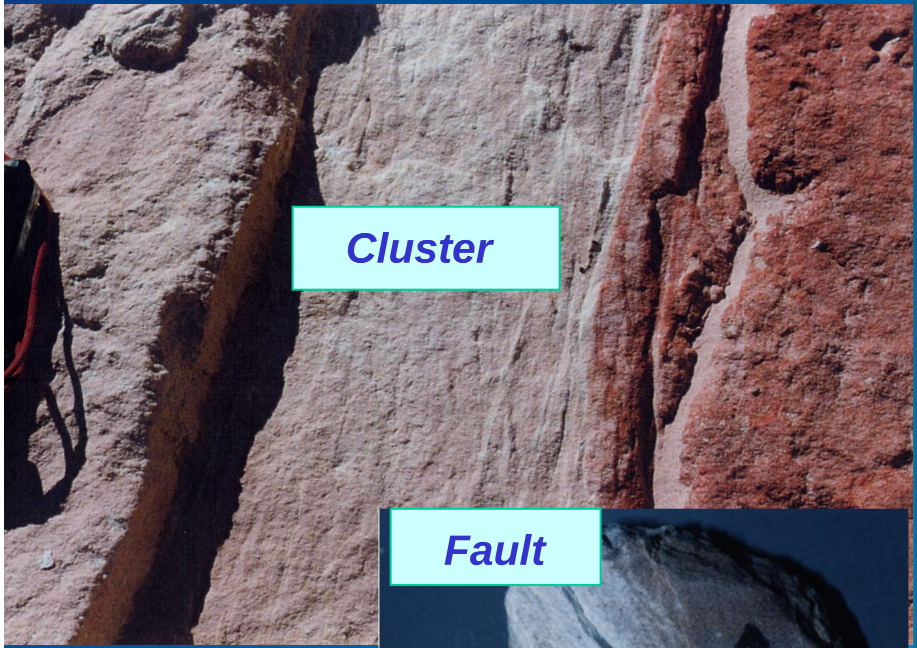


Observation : Significant offsets occur where deformation bands are numerous (clusters)

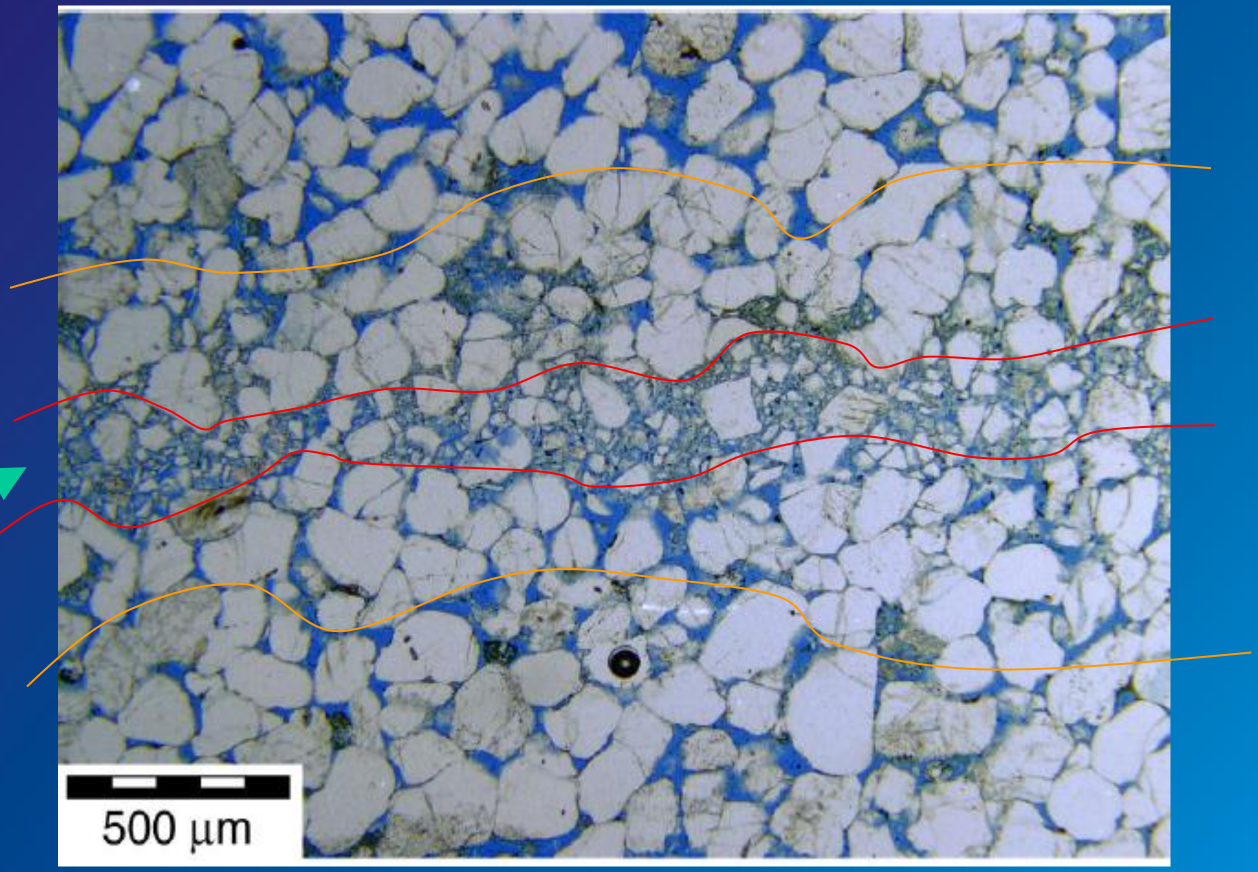

50 cm


Localization of deformation : faulting occurs in cluster zones

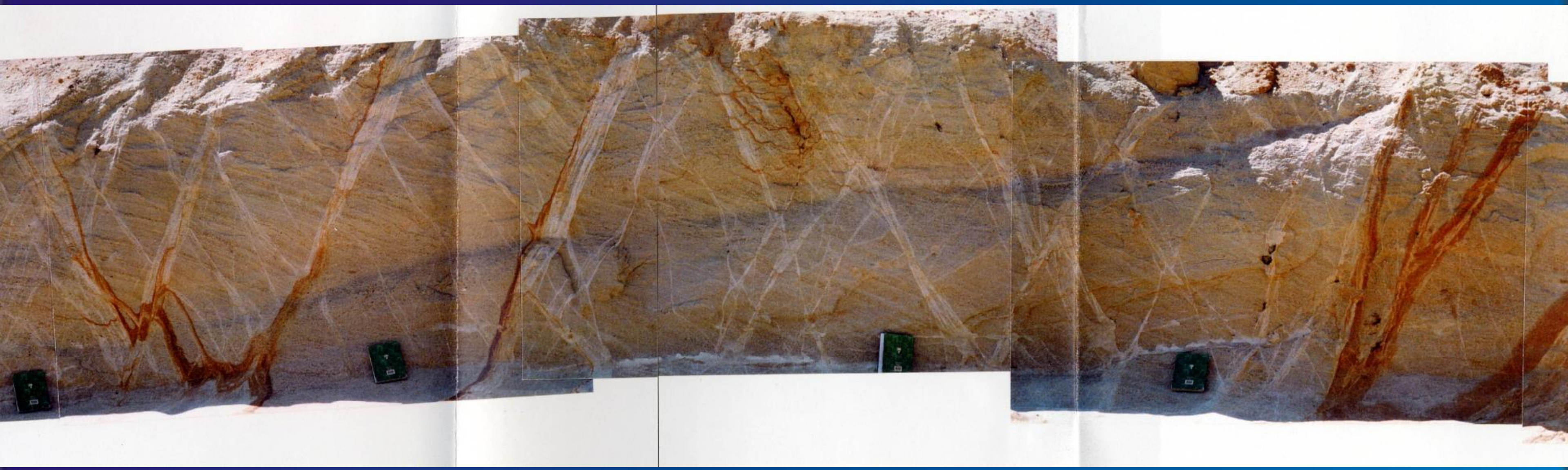




“Hardening”

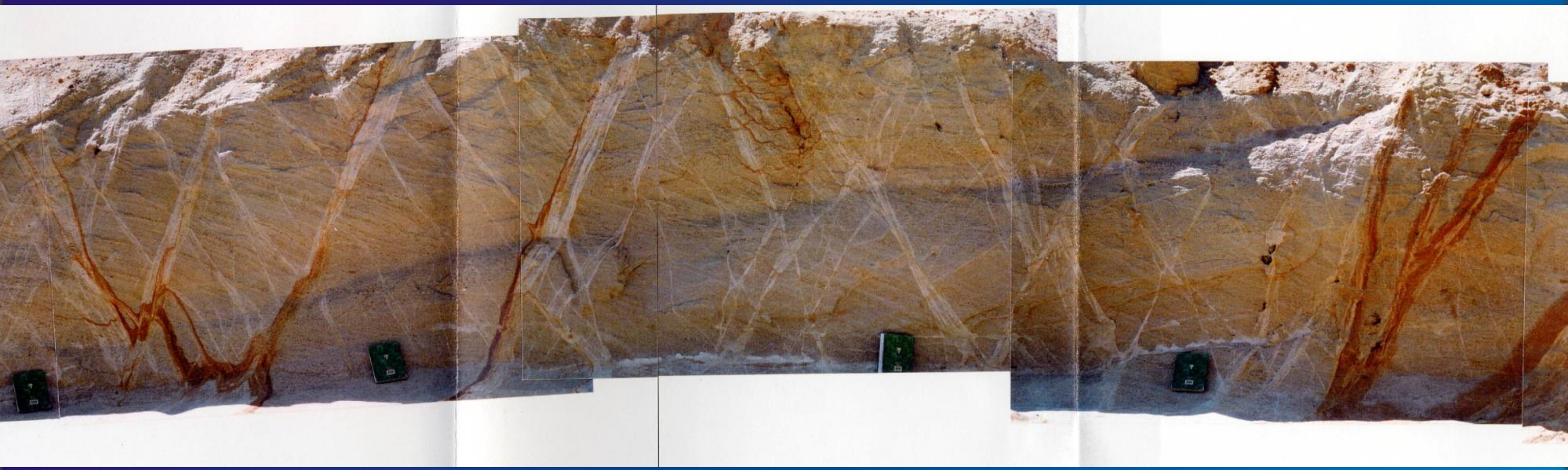


Why to localize deformation here ?



A defomation band is stronger than the surrounding rocks as a consequence of hardening.

As a result, it will no longer accummulate deformation, so it will cause local stress concentrations in its vicinity which will ultimately lead to development of a new deformation band close to it.



- individual deformation bands

Hardening

Domain/scale of localized deformation bands

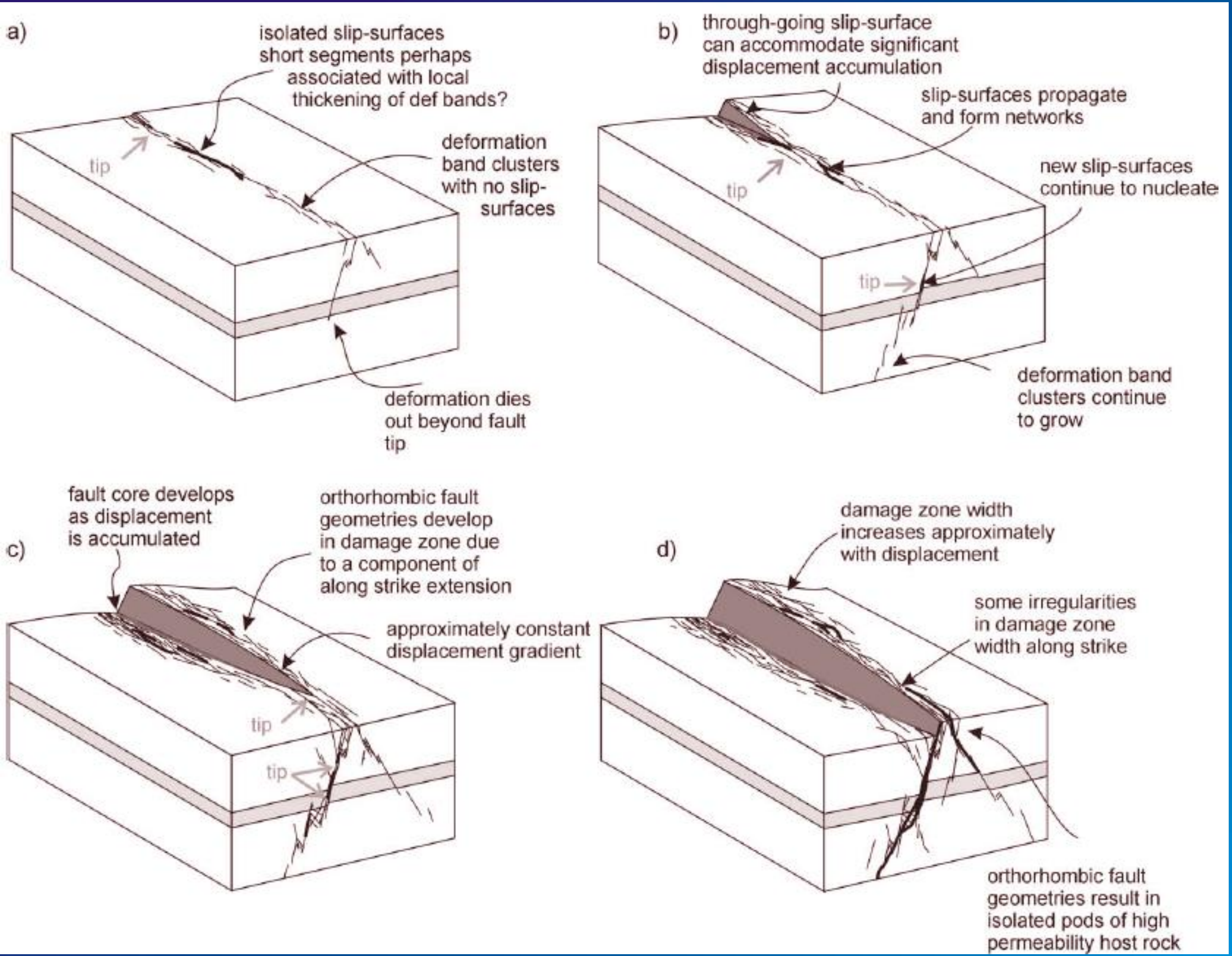
- Significant offset only in or close to clusters

- Localization of shearing in a zone of maximum offset

Softening

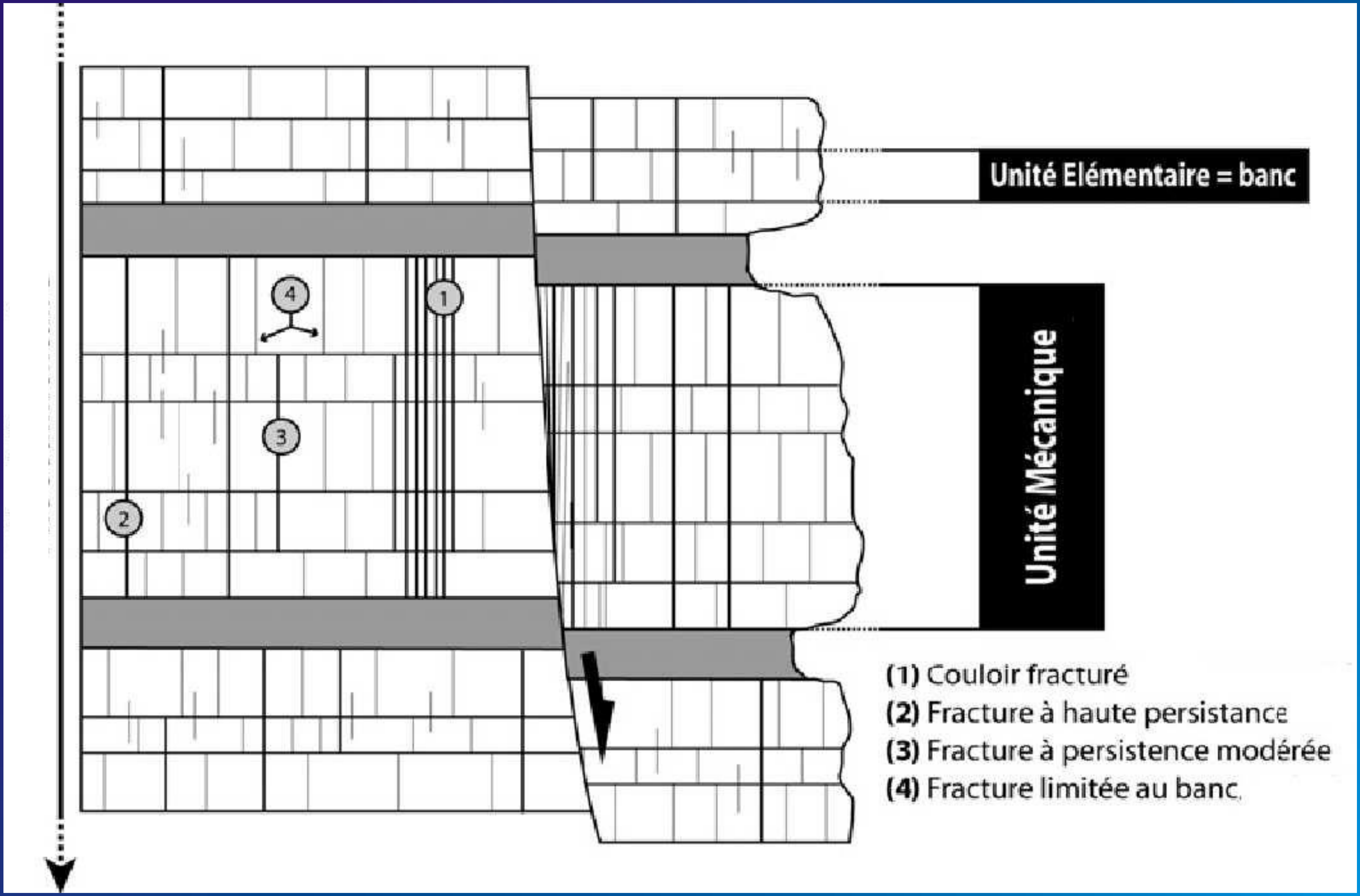
Domain/scale of sub-seismic to seismic fault

ε increase



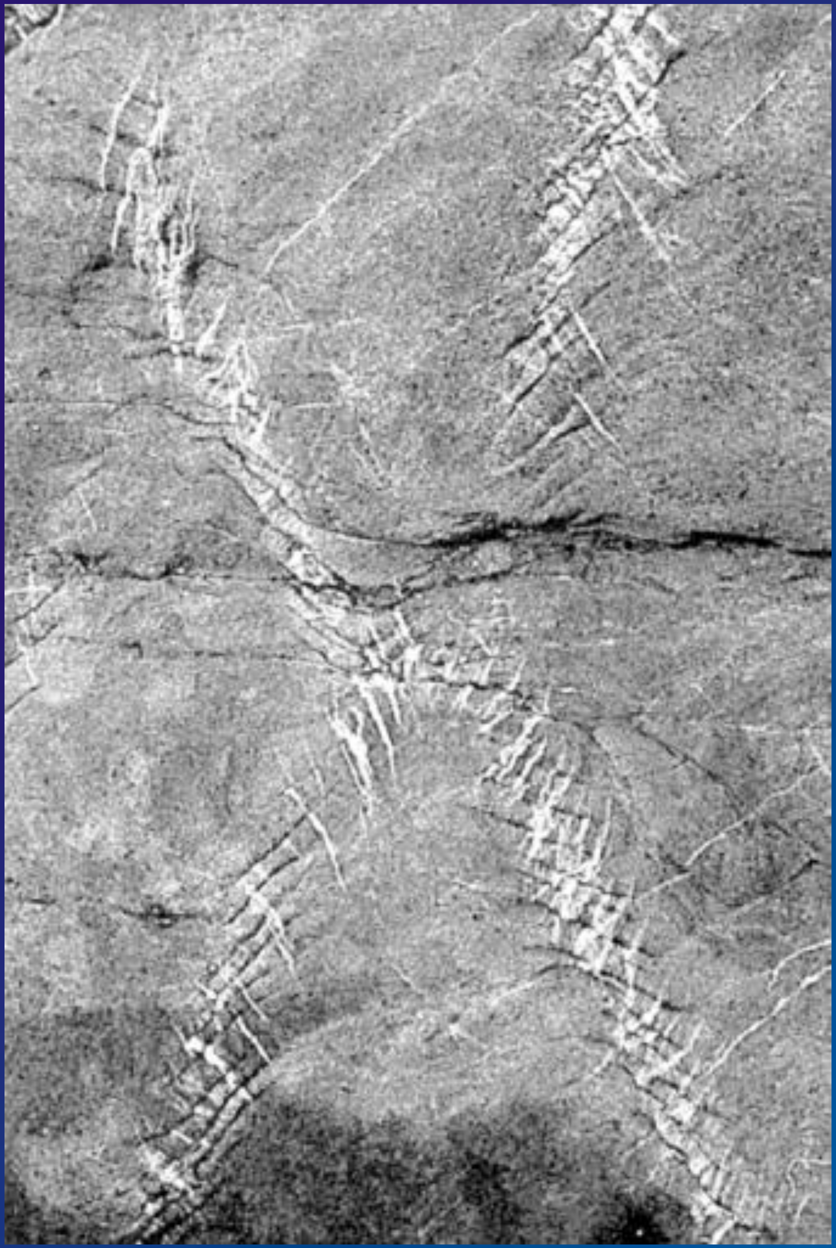
Shipton and Cowie, 2001

The birth of faults in sedimentary rocks (2) : from diffuse fractures to faults

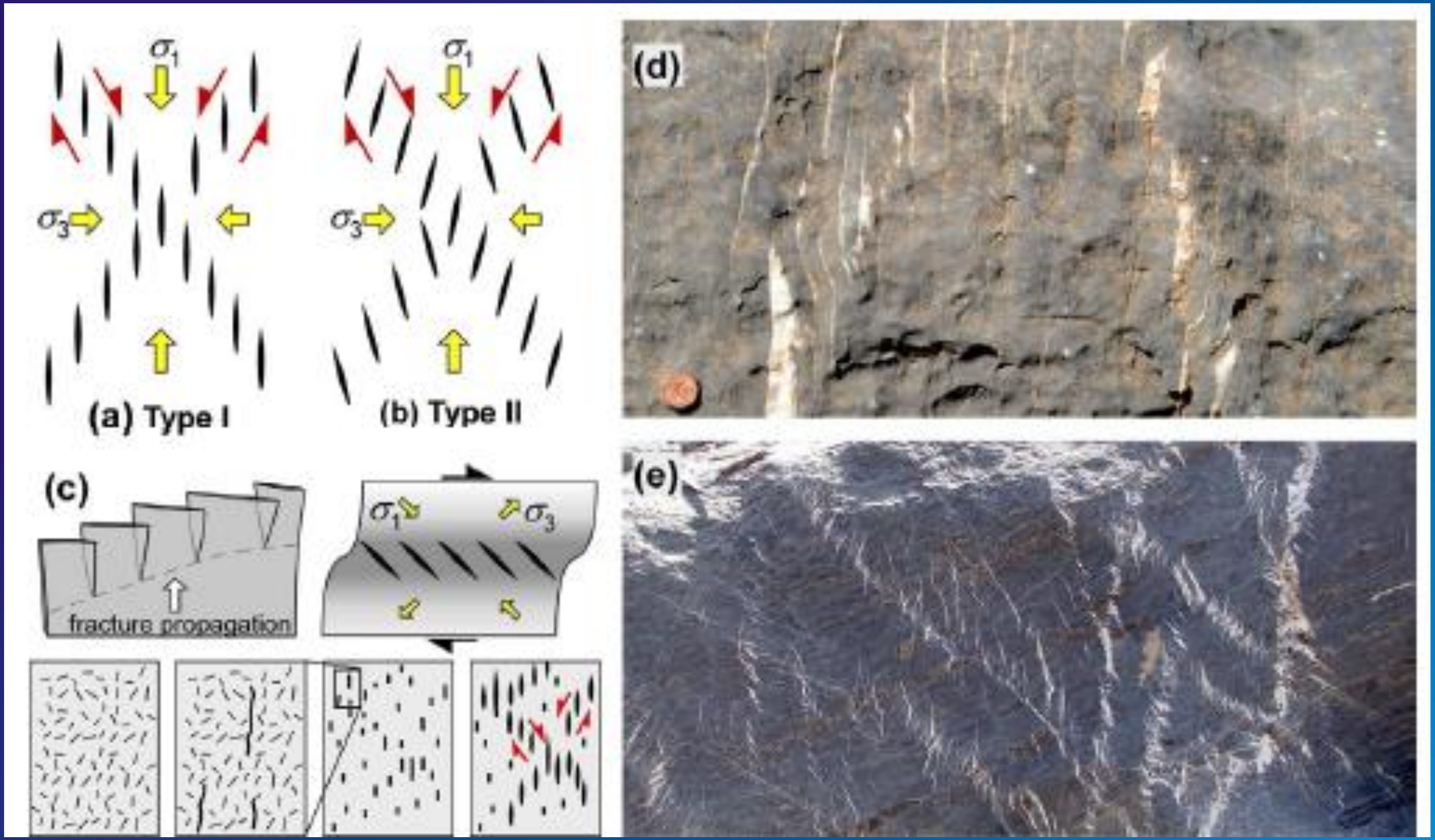

Unité Elémentaire = banc
4
1
3
2
Unité Mécanique
(1) Couloir fracturé
(2) Fracture à haute persistance
(3) Fracture à persistence modérée
(4) Fracture limitée au banc.

(Jorand, 2012)

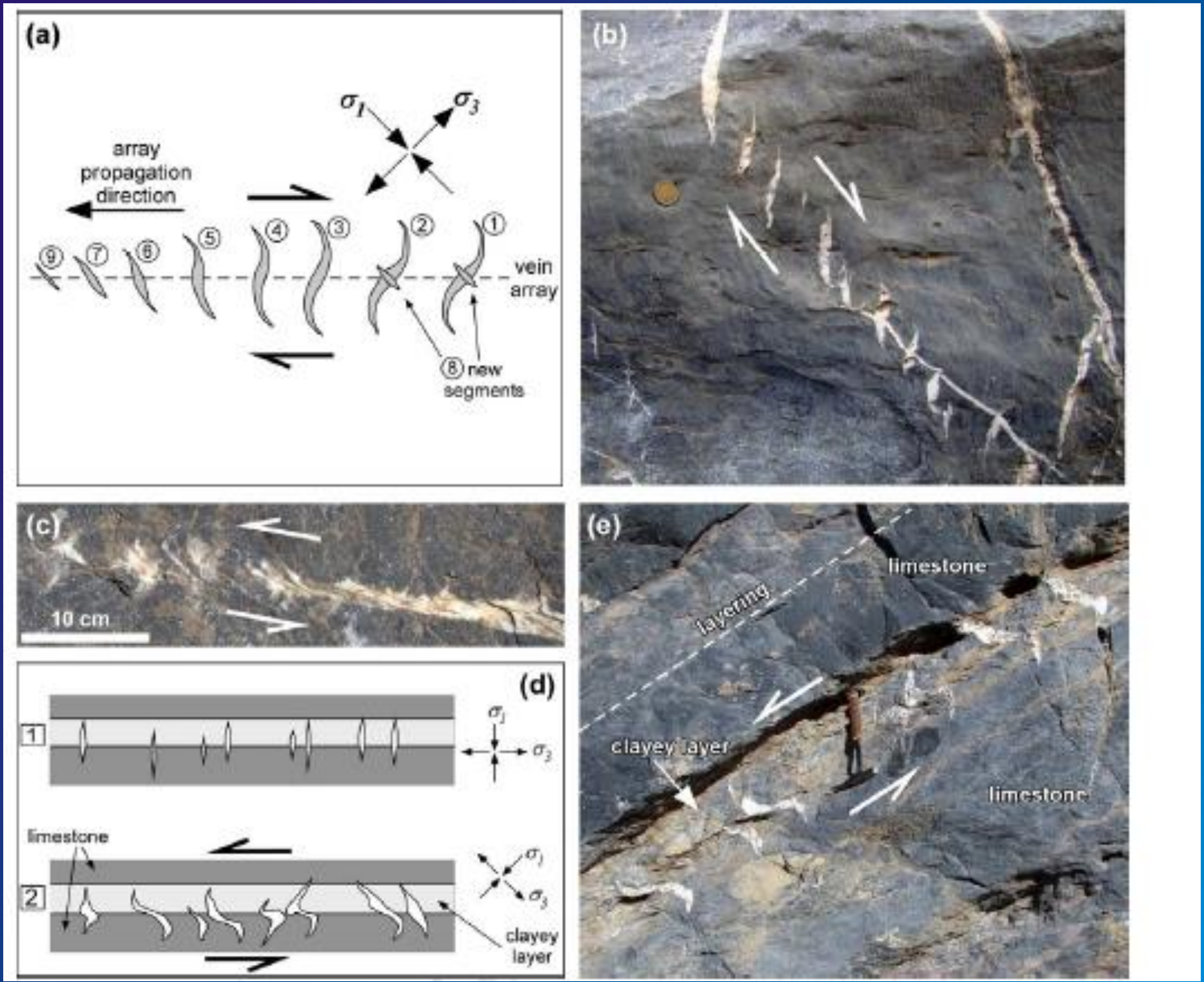
What is the mechanism of localization by fracturing?



En echelon pattern



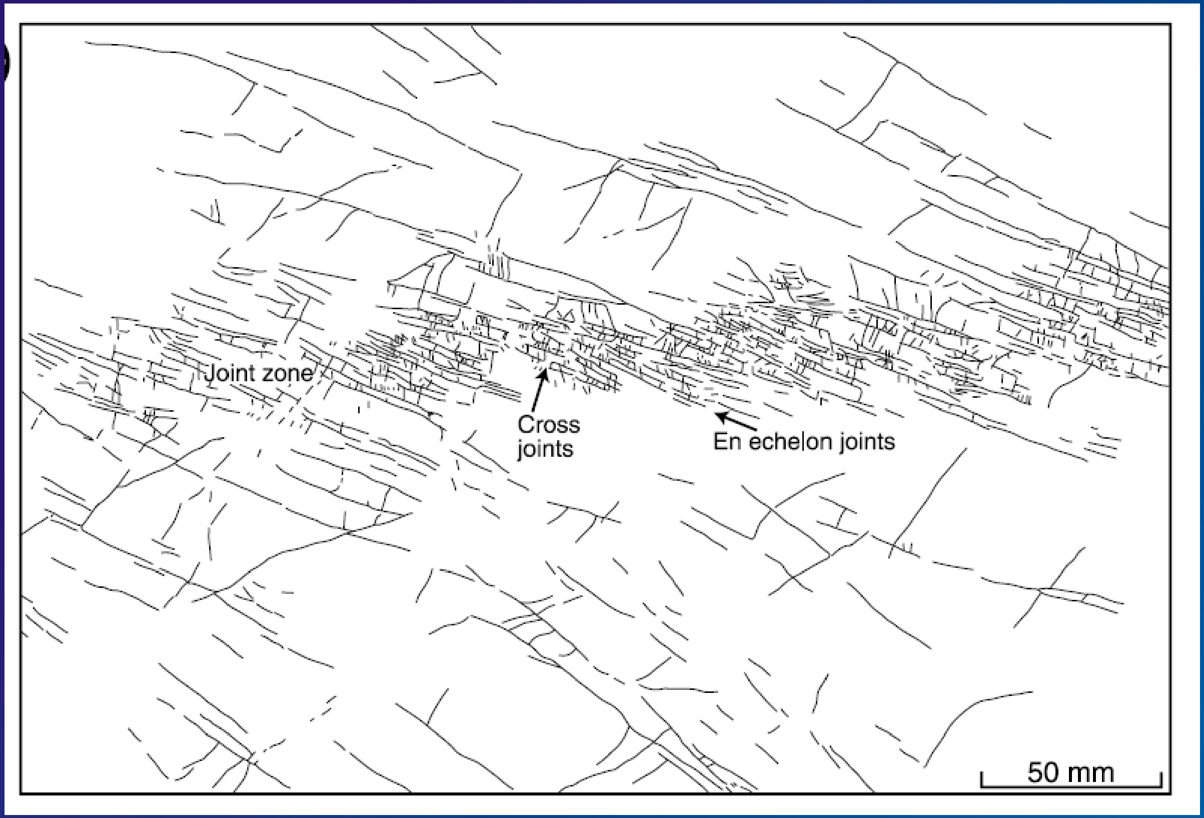
(Bons et al., 2012)

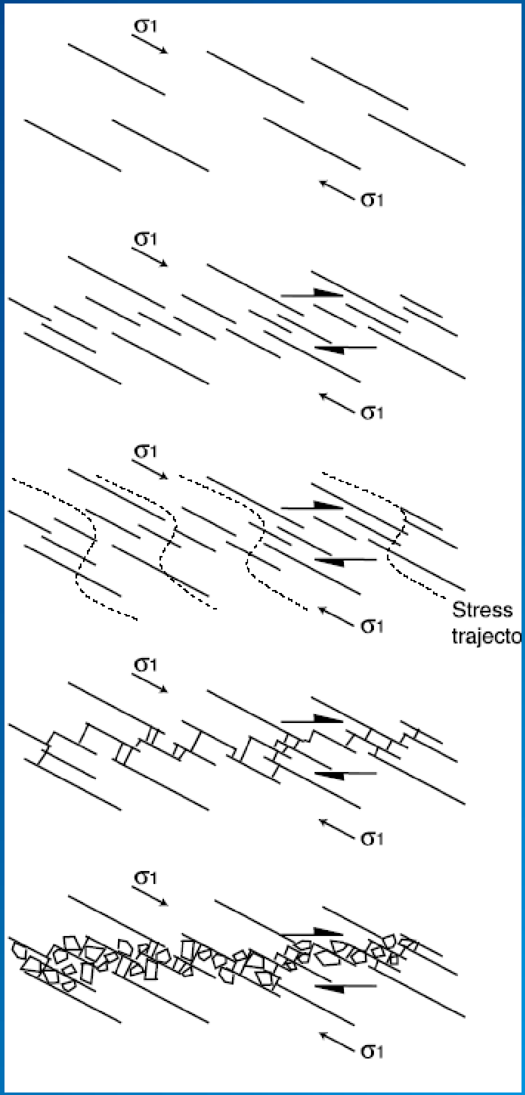


(Bons et al., 2012)

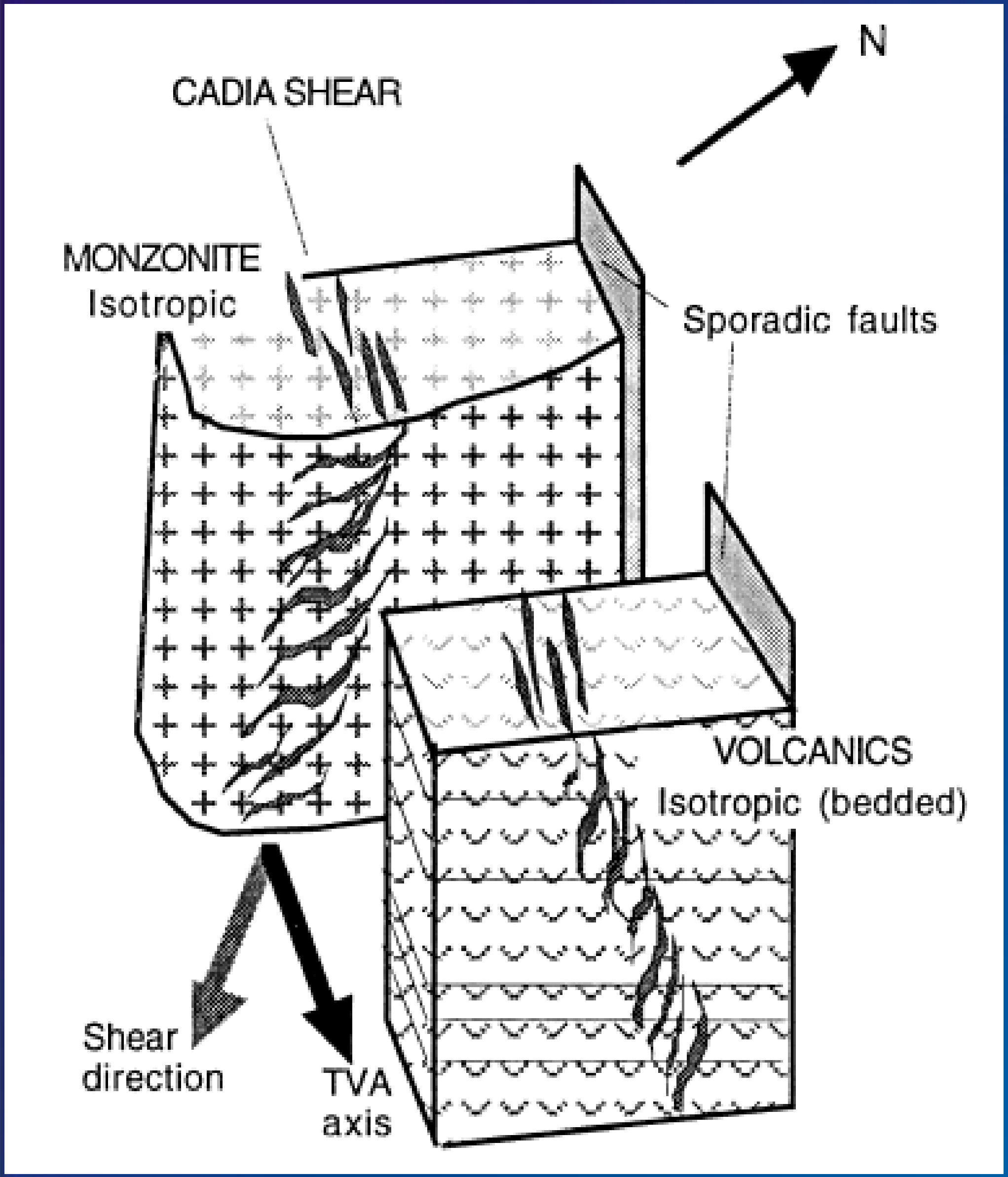
Sub-parallel fractures with large overlap

Sub-parallel fractures with large overlap





Crider and Peacock, 2004



limits

Not so easy to reconstruct a fractured domain in 3D !

En échelon fracture pattern : maturation

A through-going fault may nucleate in the pre-fractured zone, with or without progressive deformation of joints

Whole deformation remains consistent with a unique stress field

How to study fault initiation ?

- Focus on faults with small amounts of slip because they presumably illustrate faults in their early stages
- Study of their termination zones in order to determine the styles of fault initiation.
- Use of space as a proxy for time since structures at and around the fault tips that are presumed to represent the earliest stages of fault development, and structures behind the tips, toward the centre of the fault, that are presumed to represent later stages.

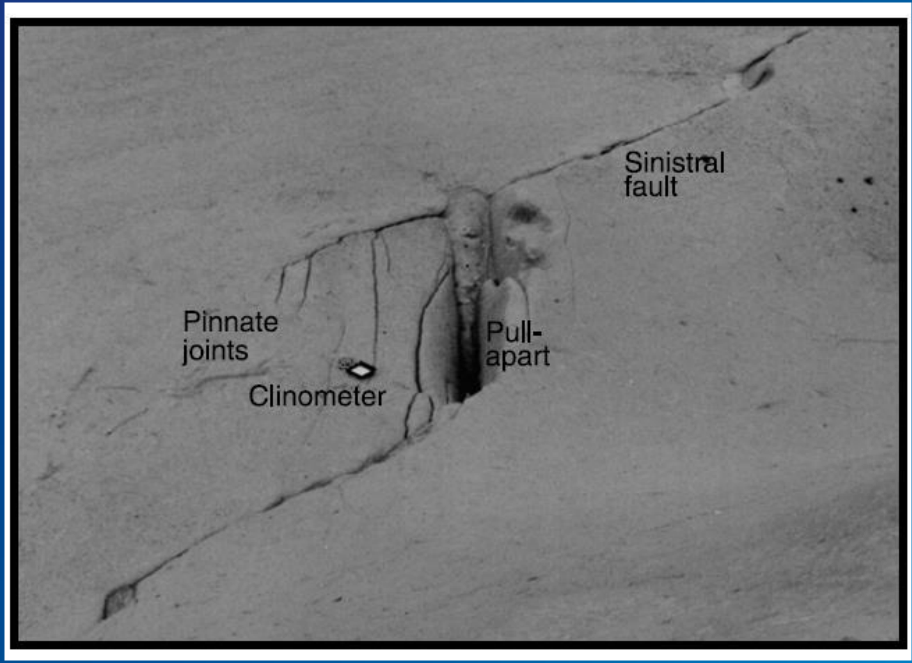
- Three styles of fault initiation:

- initiation from pre-existing structures (formed during an earlier event; e.g., joints)
- initiation with precursory structures (formed earlier in the same deformation event; e.g., joints, veins, solution seams, shear zones)
- Initiation as continuous shear zones.

A common scenario involves fault initiation by shear along pre-existing or precursory structures, which become linked by differently orientated structures, as stresses are perturbed within the developing fault zone; a through-going fault finally develops.

Crider and Peacock, 2004

En échelon fracture pattern : maturation



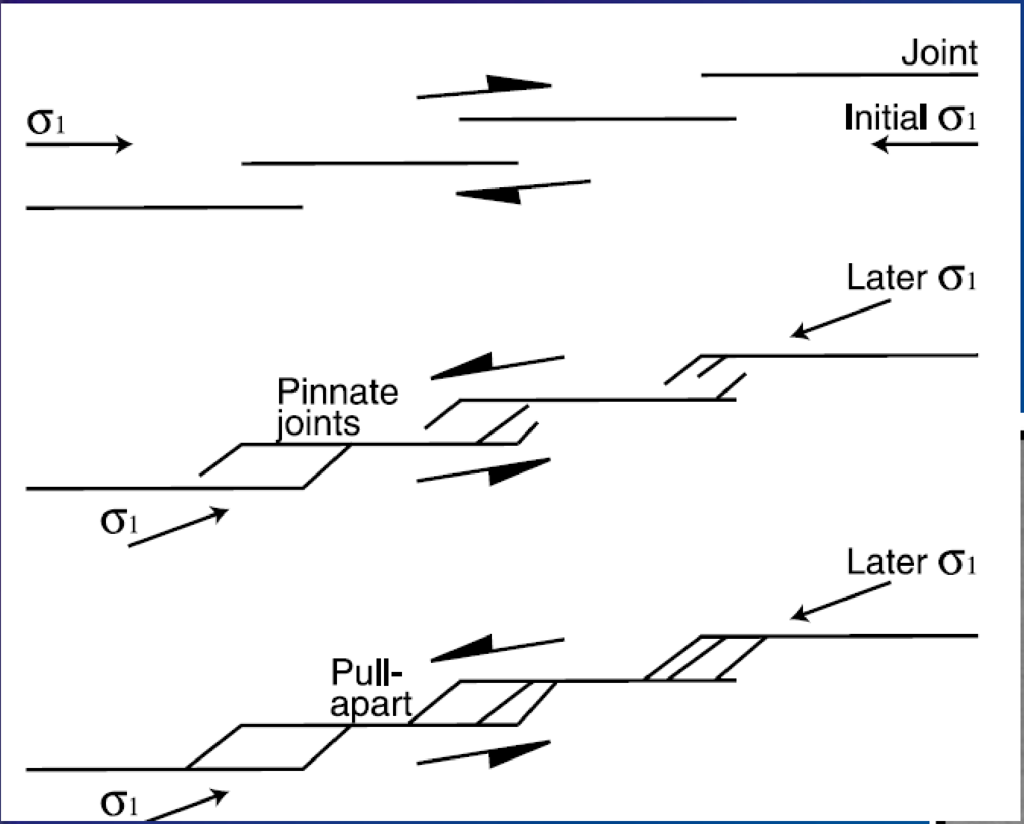
Crider and Peacock, 2004

Complexity :

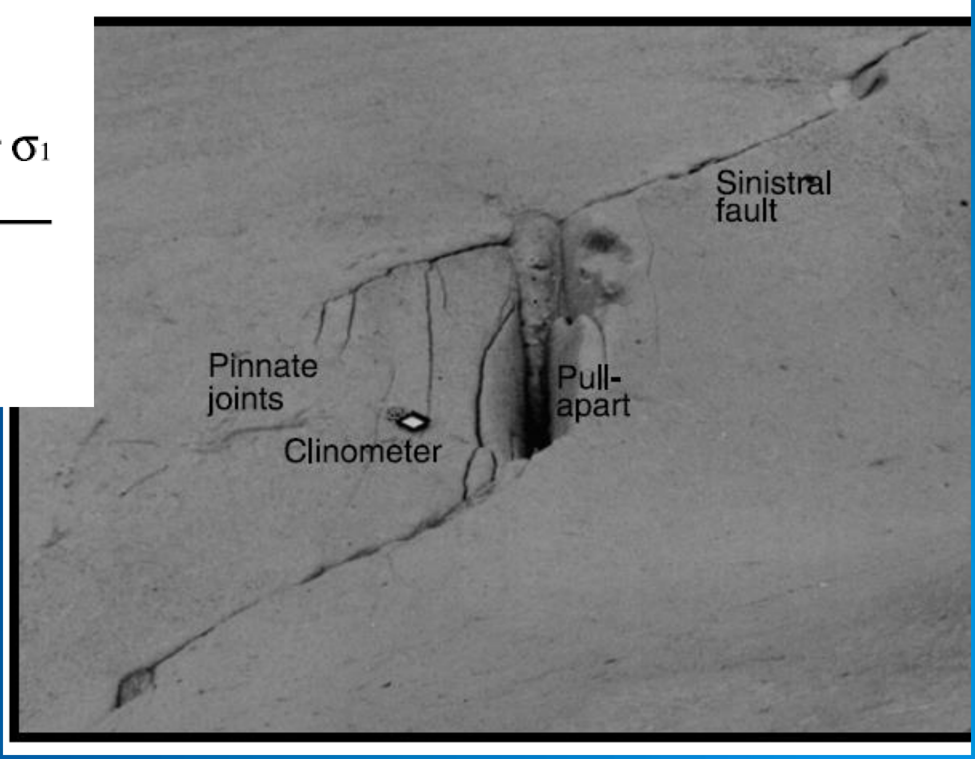
A number of field observations show shearing of previous joints, leading to secondary compressional or extensional jogs

Deformation is inconsistent with a unique stress field

Shearing of en echelon fracture pattern

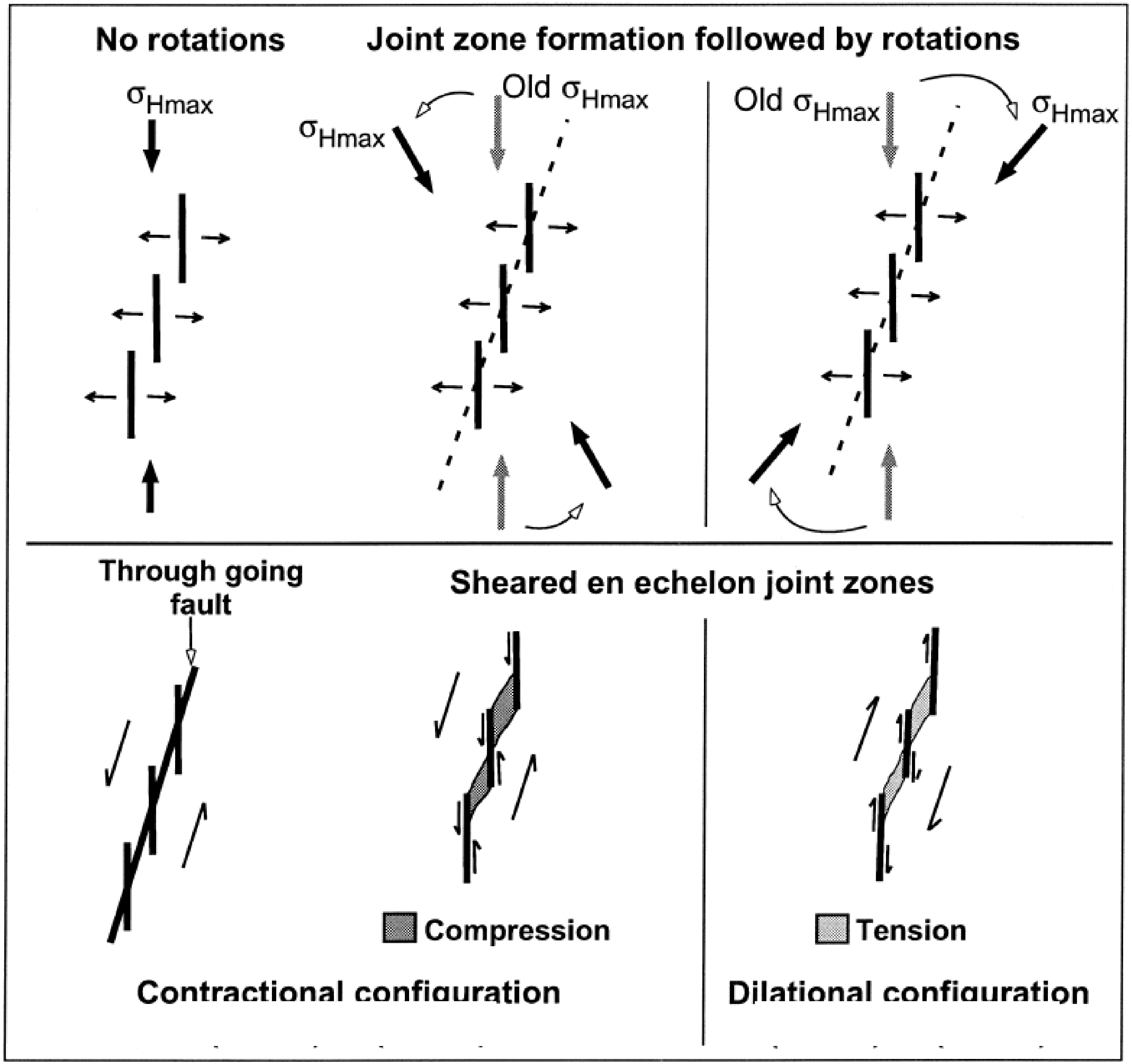


Crider and Peacock, 2004



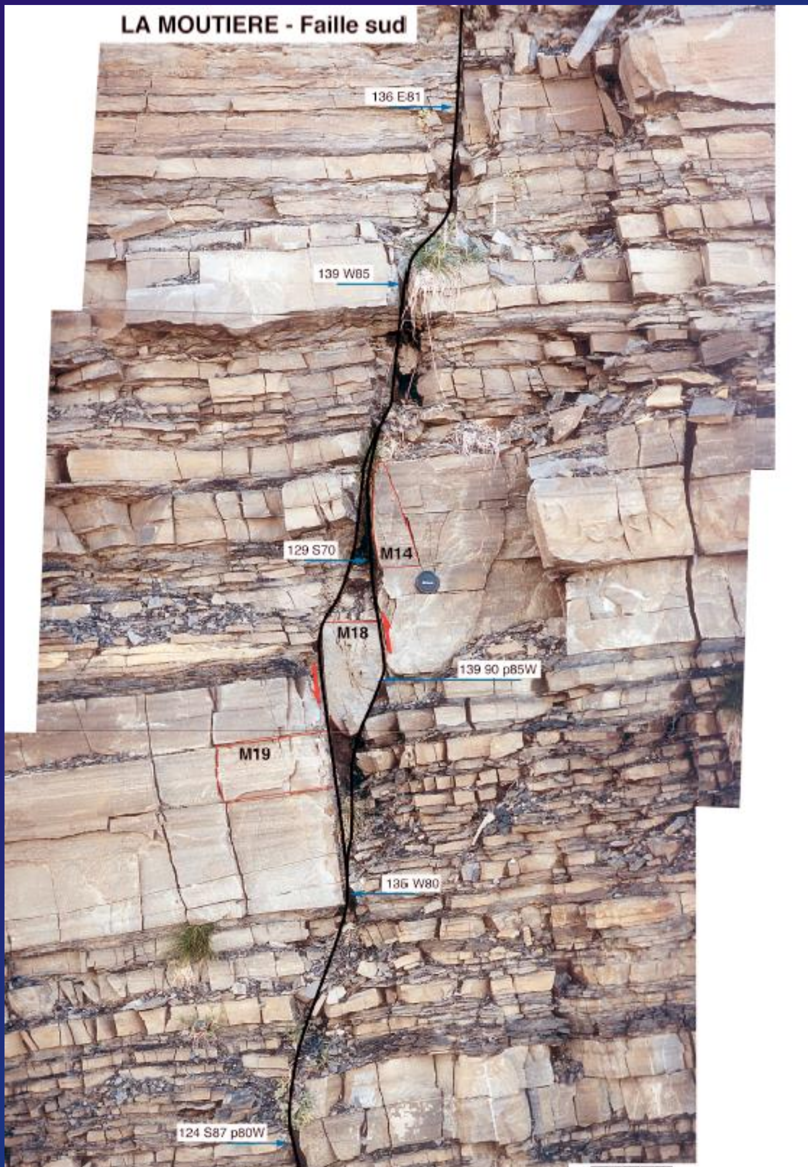
Complexity :

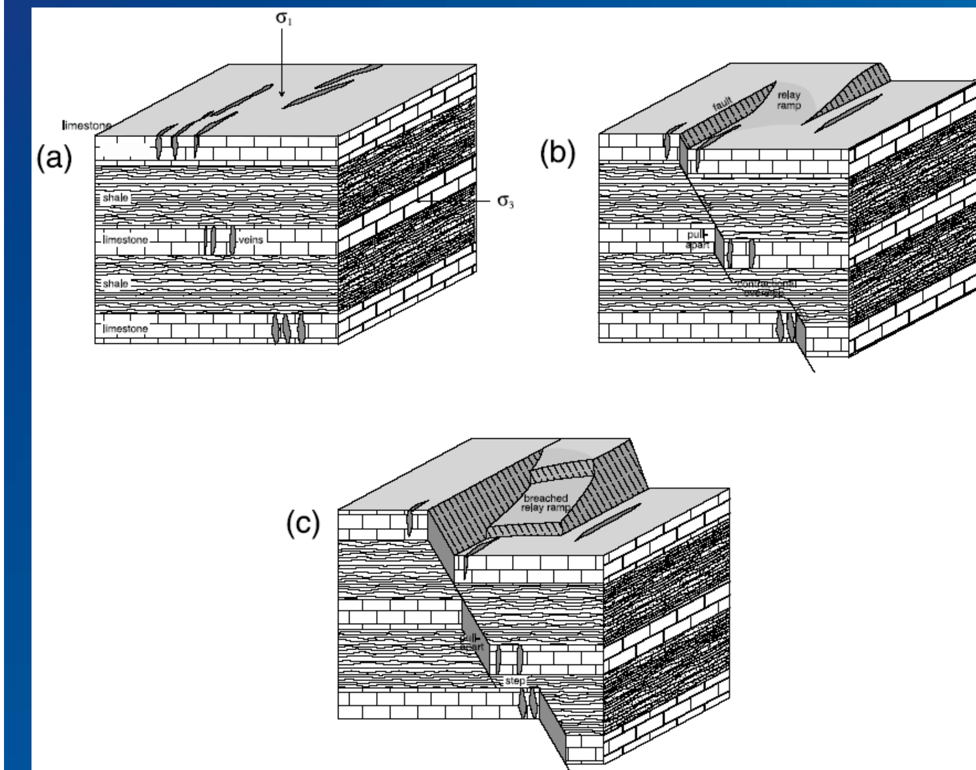
Requires stress rotation



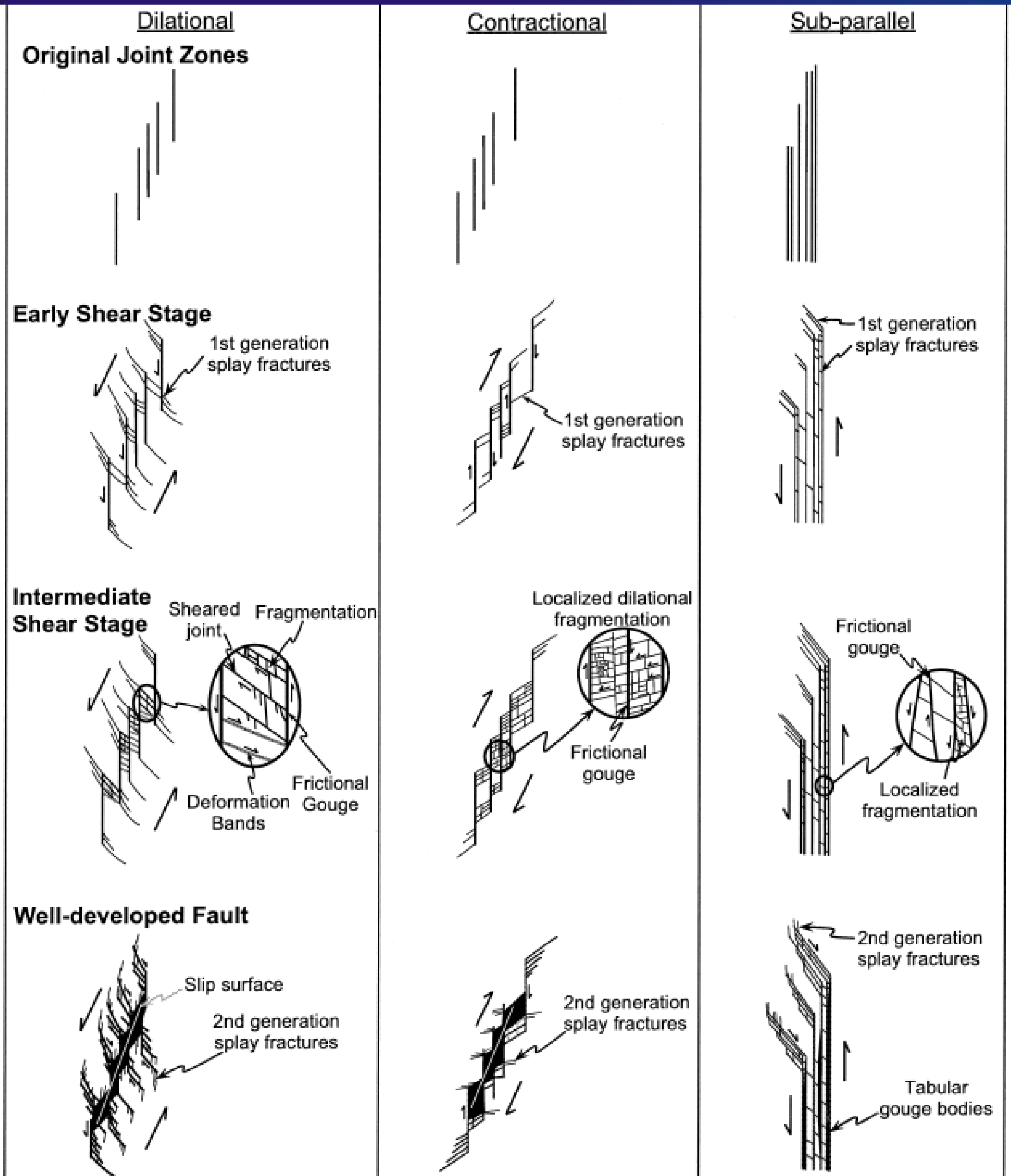
No rotations
Joint zone formation followed by rotations
σ_{Hmax}
Old σ_{Hmax}
σ_{Hmax}
Old σ_{Hmax}
σ_{Hmax}
Through going fault
Sheared en echelon joint zones
Compression
Tension
Contractional configuration
Dilational configuration

Influence of bedding





Crider and Peacock, 2004



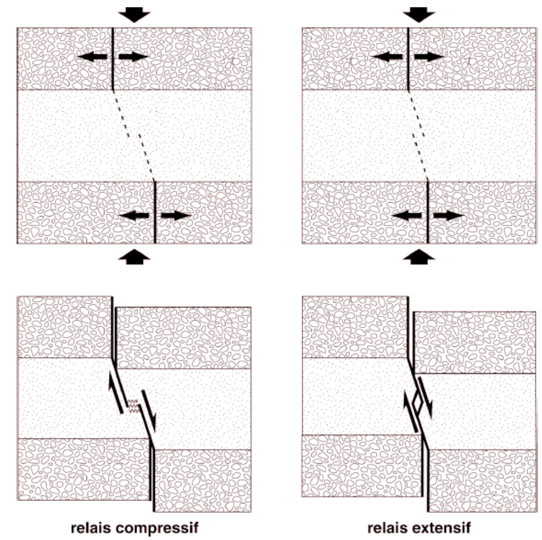
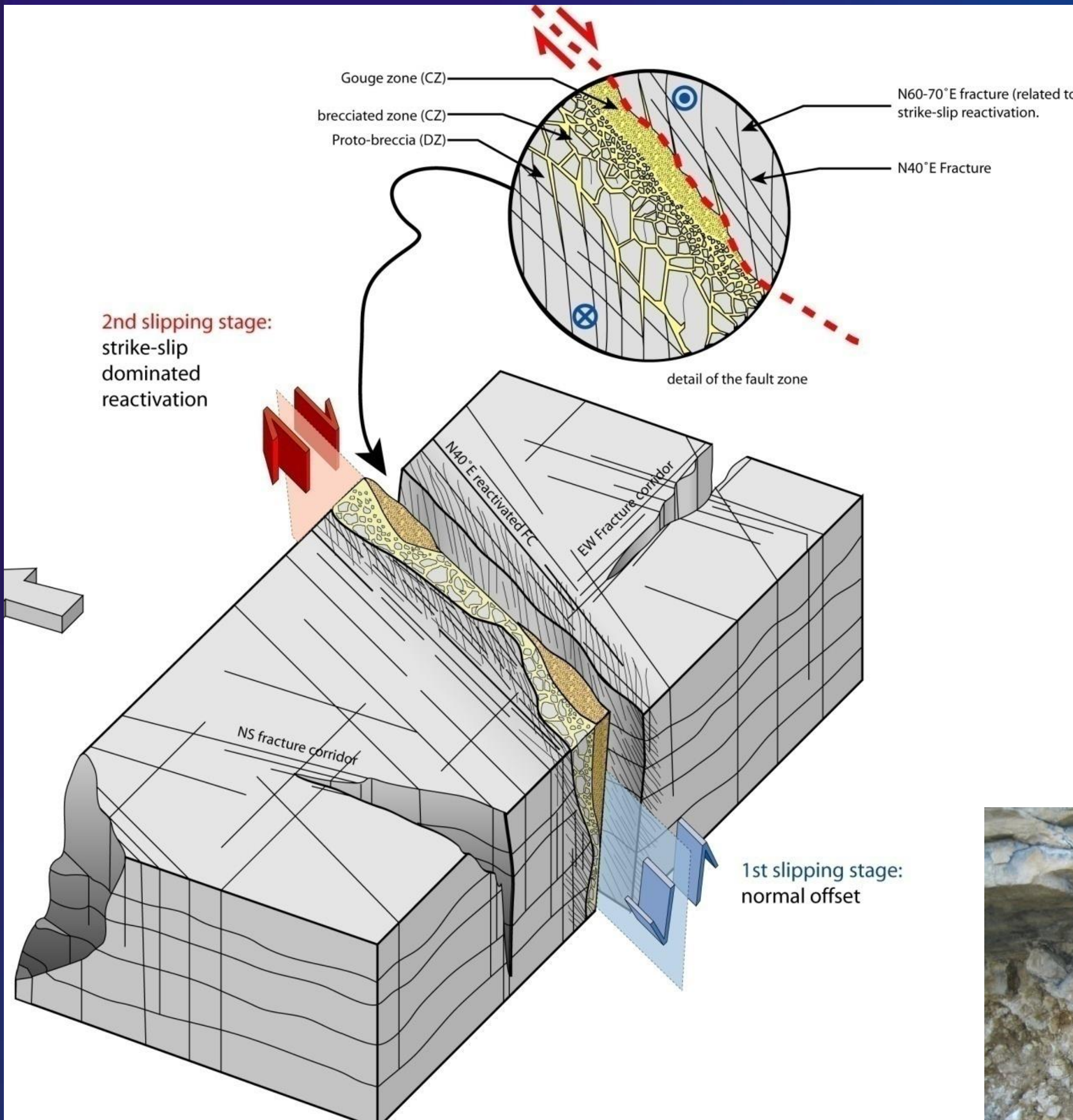


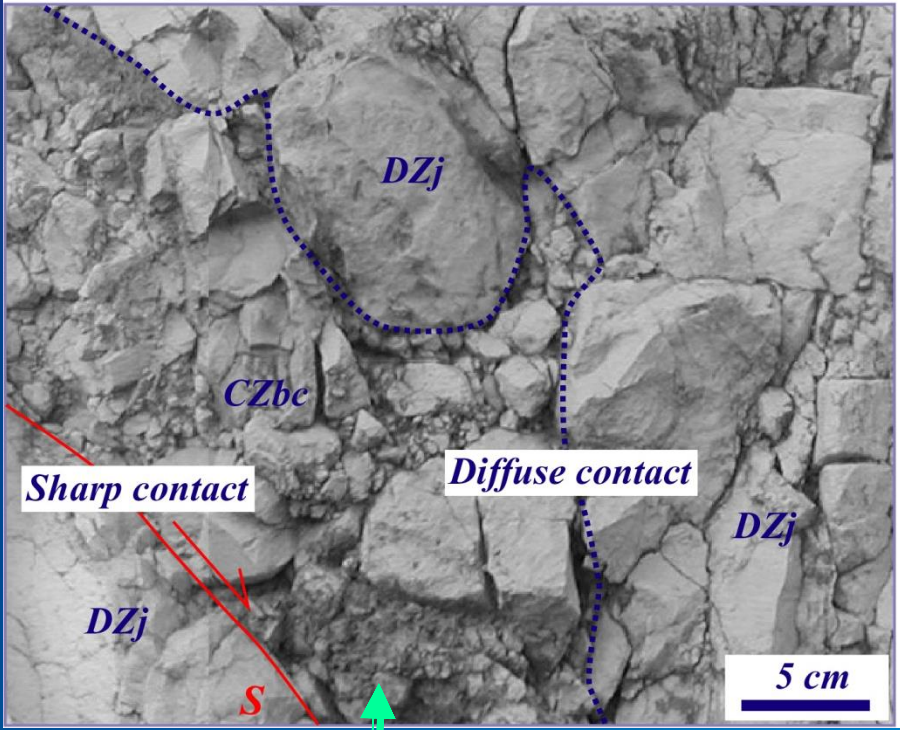
Figure IV-54 : Schématisation des relais pouvant se développer lors de la propagation des bandes cisaillantes qui connectent les fractures de mode I. Dans le cas d'un relais compressif, des stylolithes indiquent une dissolution dans la zone de relais alors que dans le cas d'un relais extensif, un petit "pull-appart" se développe entre les bandes cisaillantes.

The fault plane is ultimately made of numerous dip irregularities

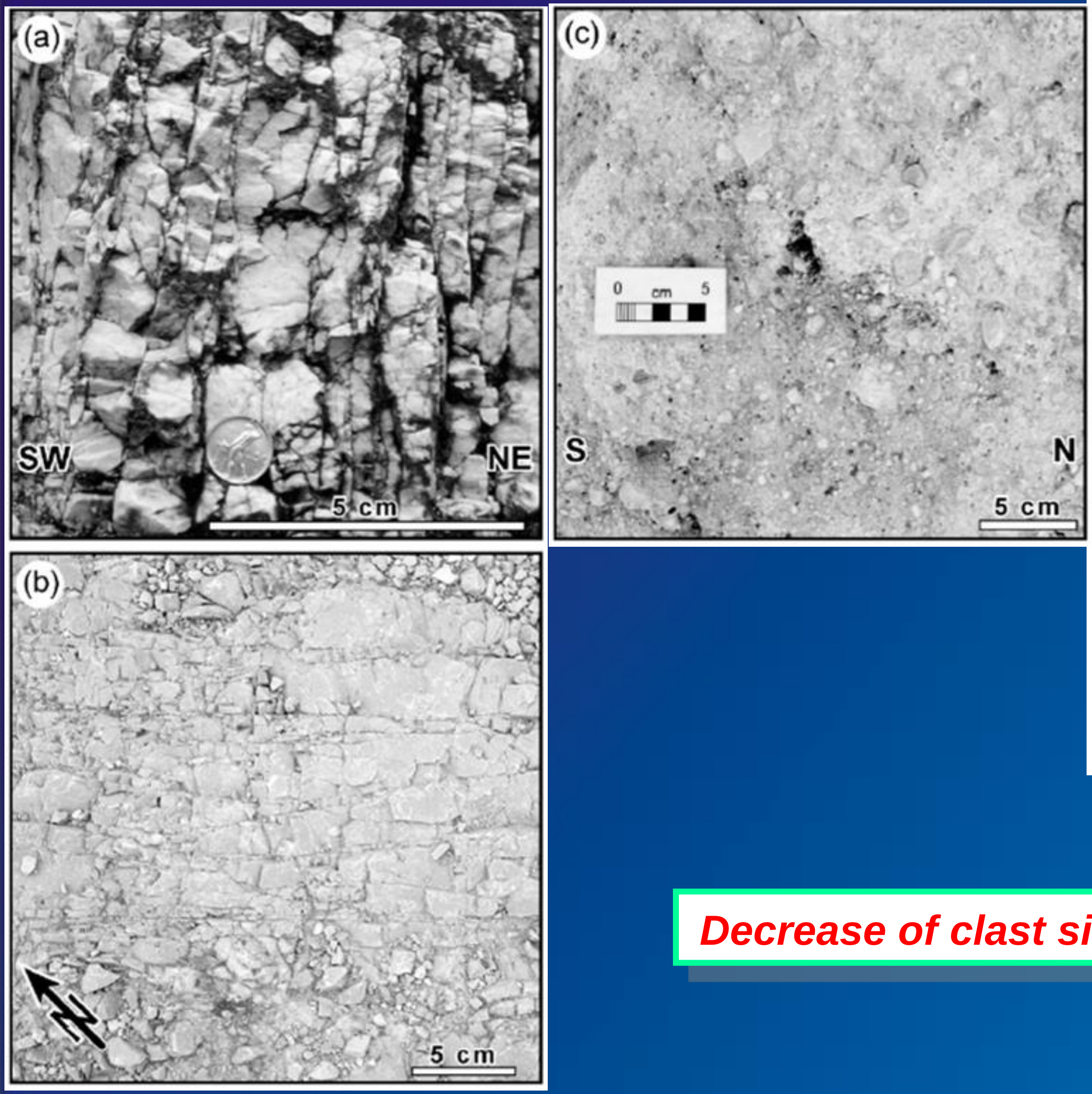

Development of the fault zone

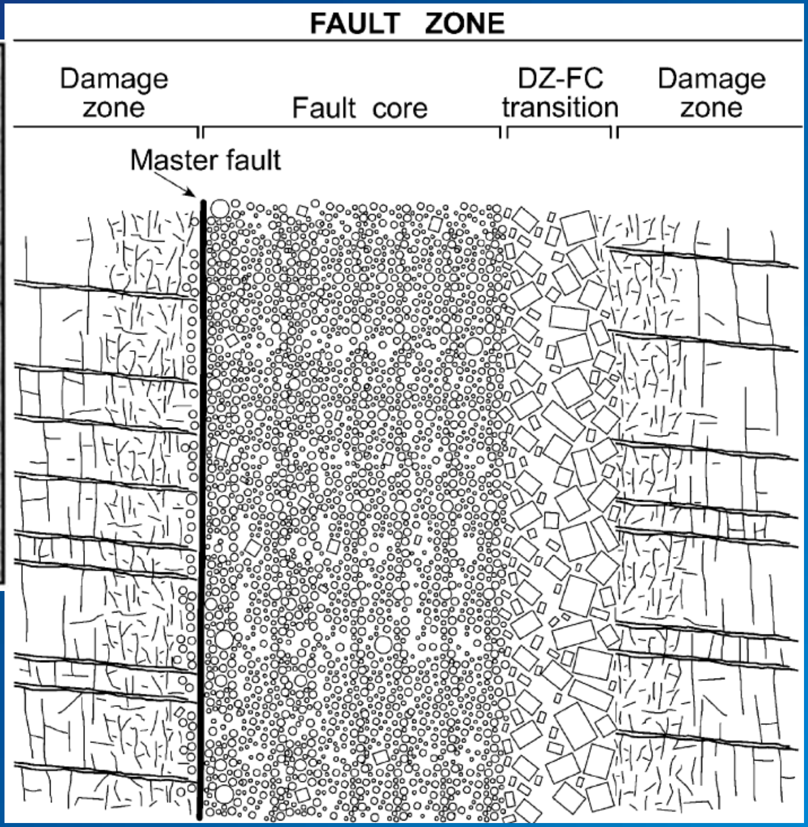


DuBernard-Rouchy, 2002

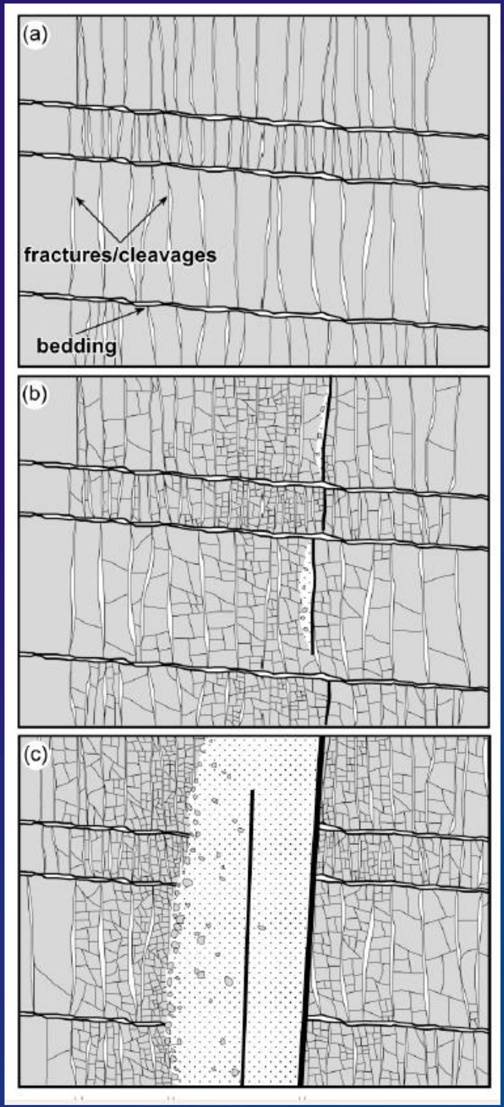


- Jointing can not explain such fracturing !

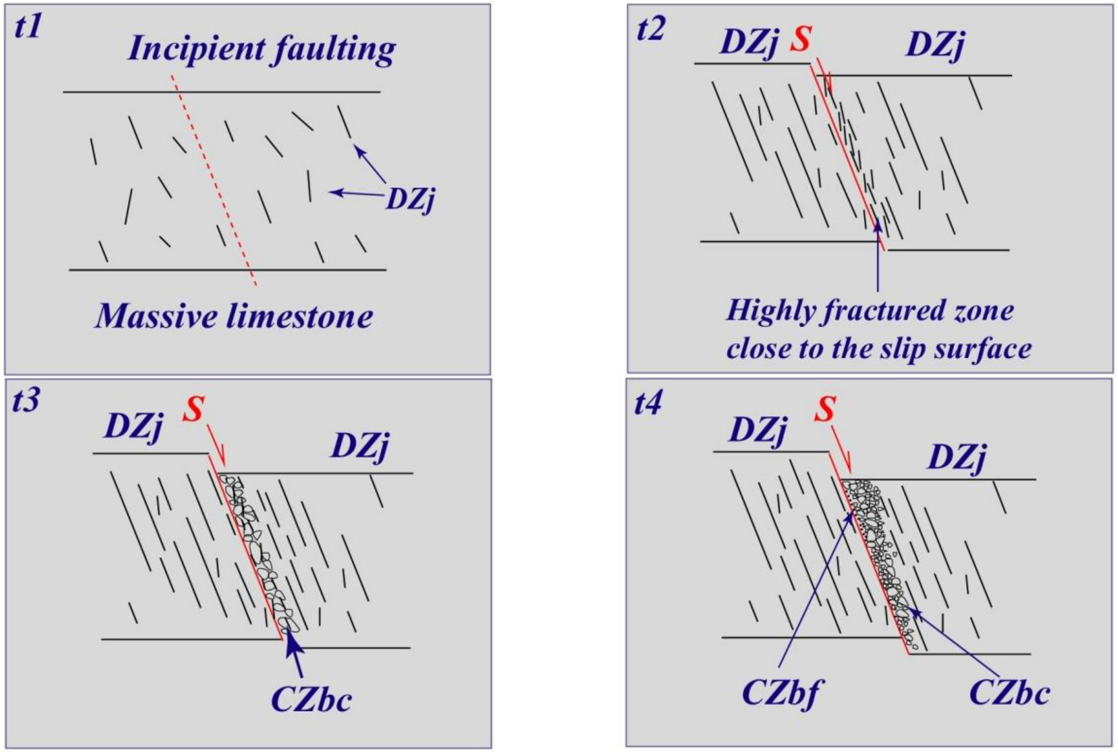




Decrease of clast size, bloc pulverization,



Scenario for fault initiation & propagation:



Fault motion induces fracture densification around the fault.
=> Progressively, dislocation of the protolith close to the fault, coarse Breccia (CZbc) formation and fine Breccia (CZbf).

The birth of faults in sedimentary rocks (3) : from pressure solution to faults

Micarelli et al., 2005

Micarelli et al., 2005

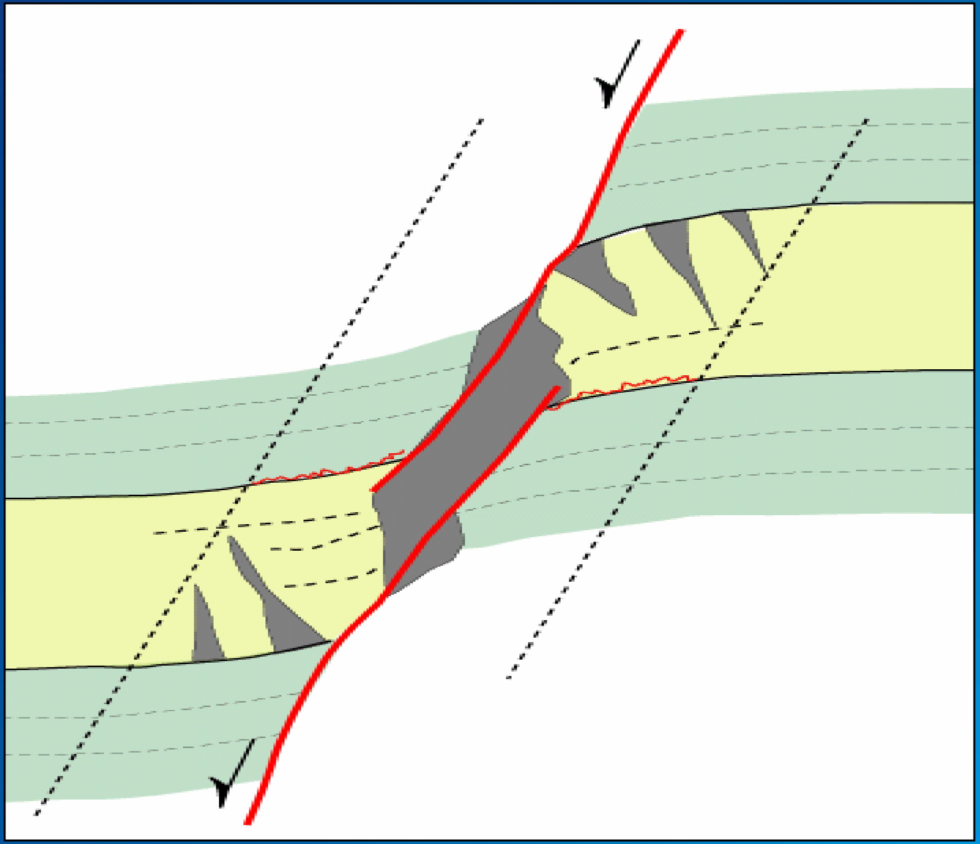
Micarelli et al., 2005

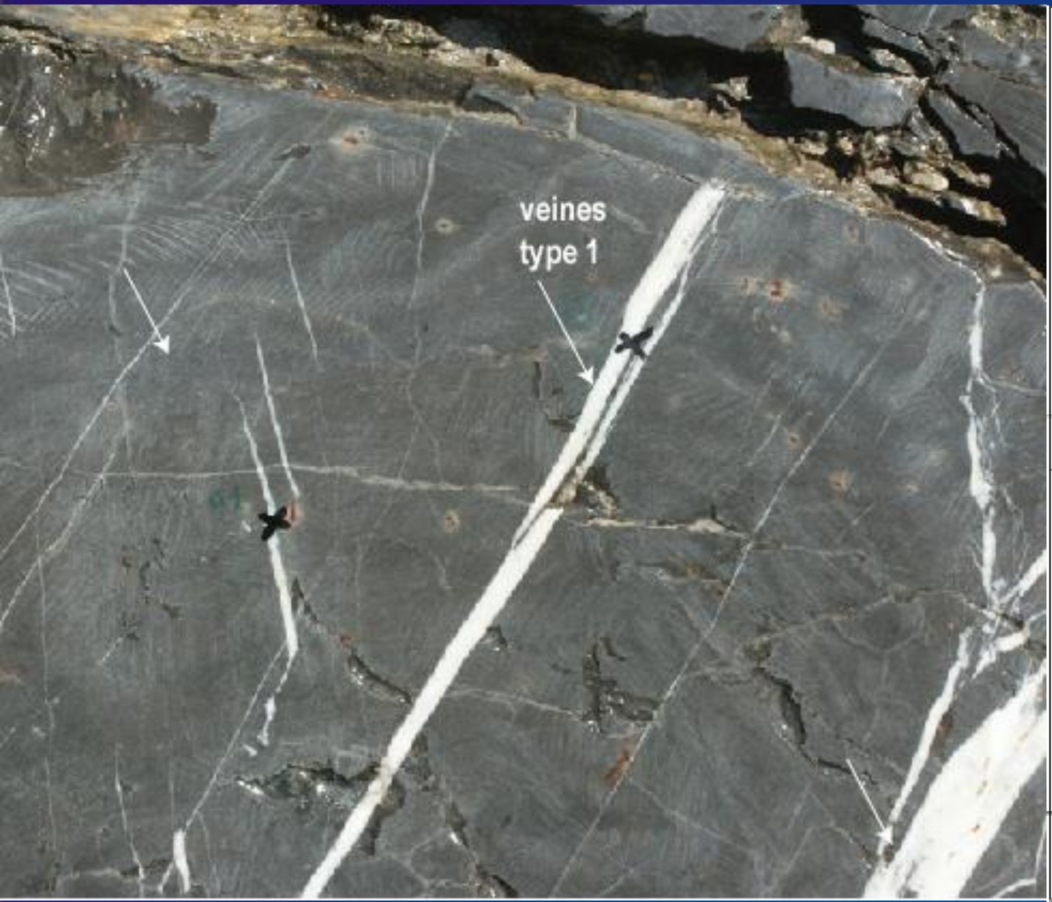
Bed thinning

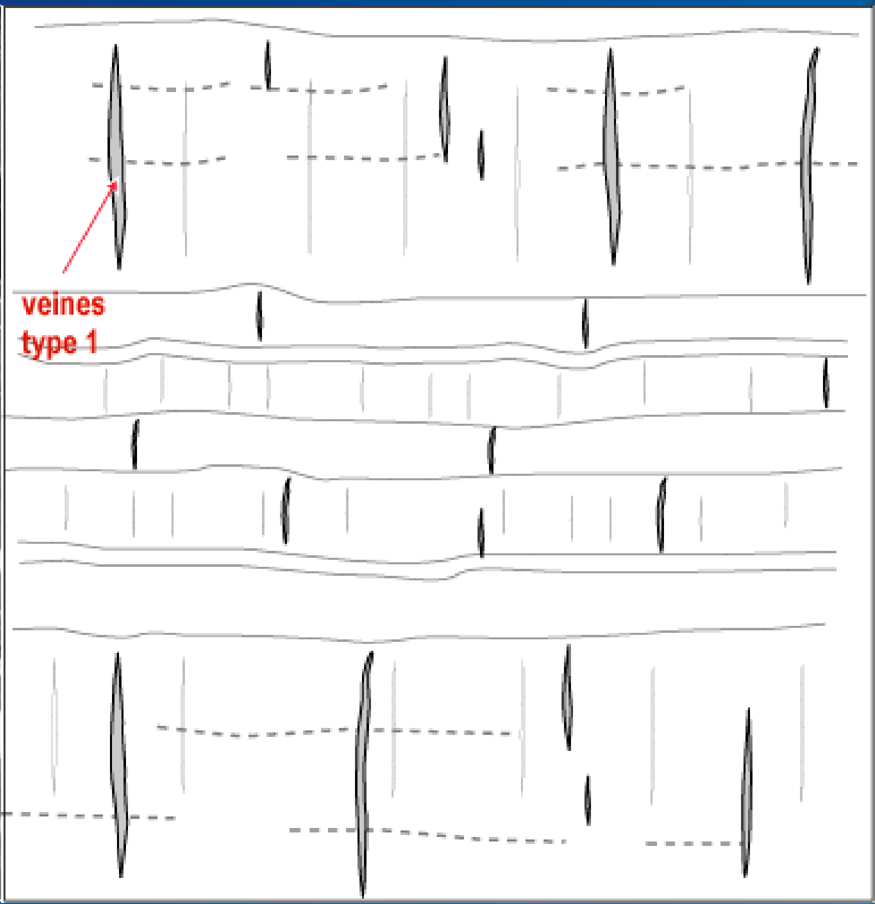
Calcite crystalisation in extensional jogs

Stylolites → dissolution

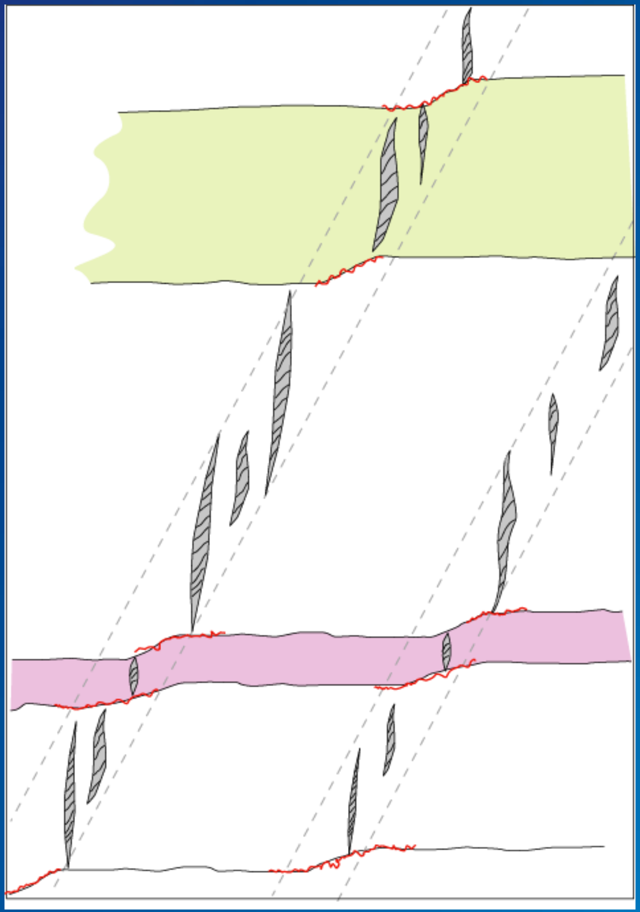
No true sliding …





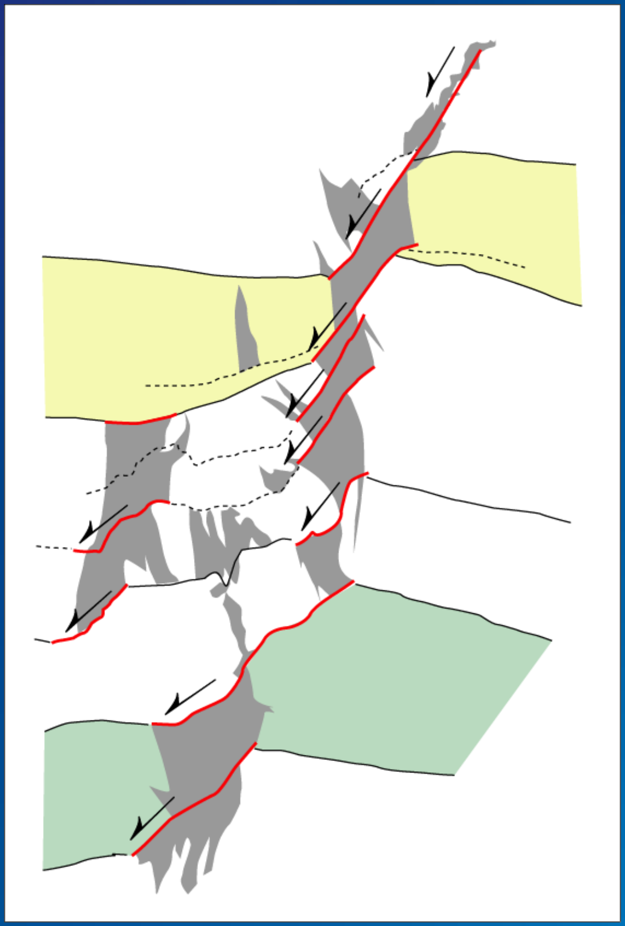


1- distributed deformation : joints



1- distributed deformation : joints

2- Localization initiation : echelon



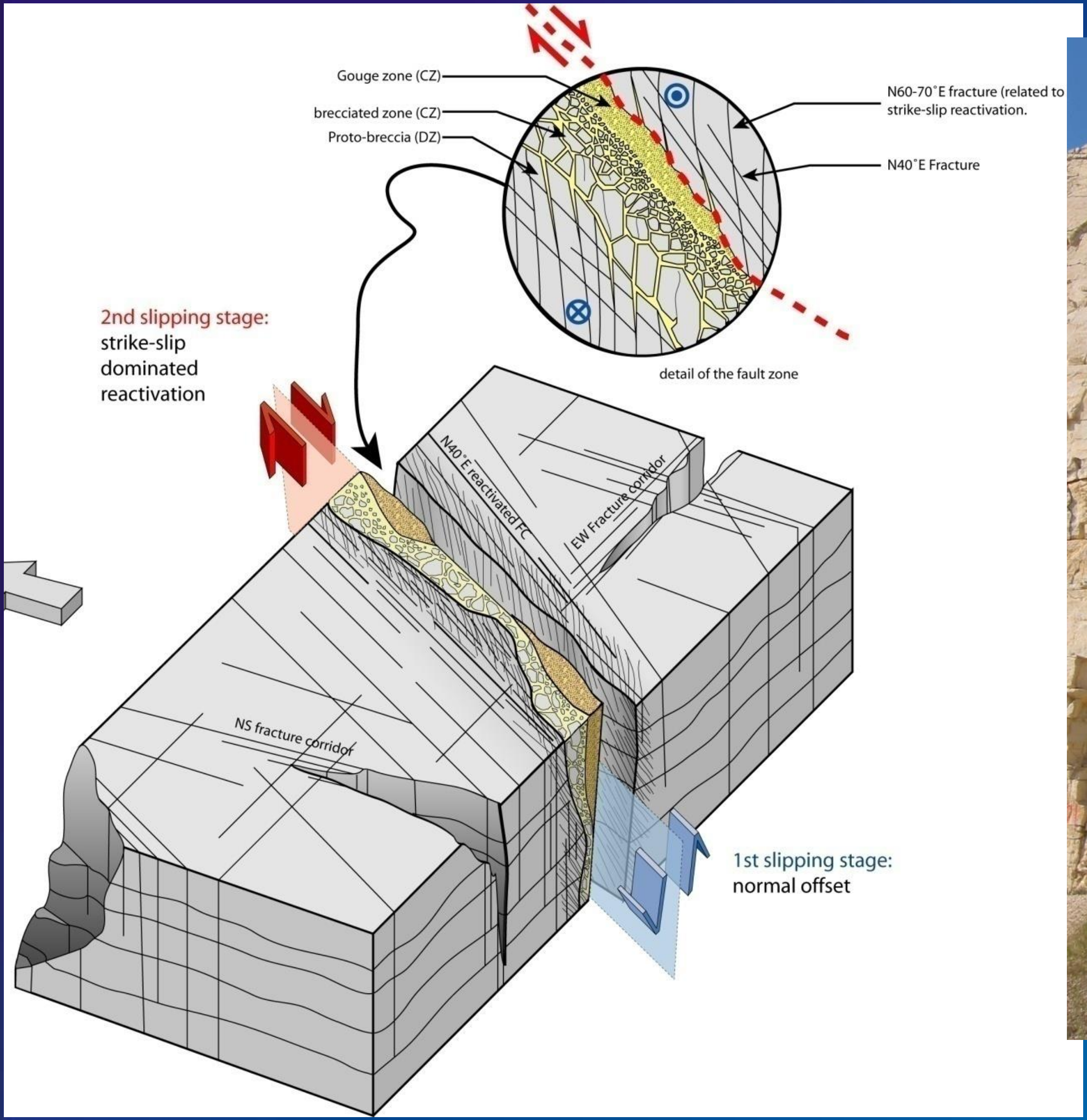
1- distributed deformation : joints

2- Localisation initiation : echelon

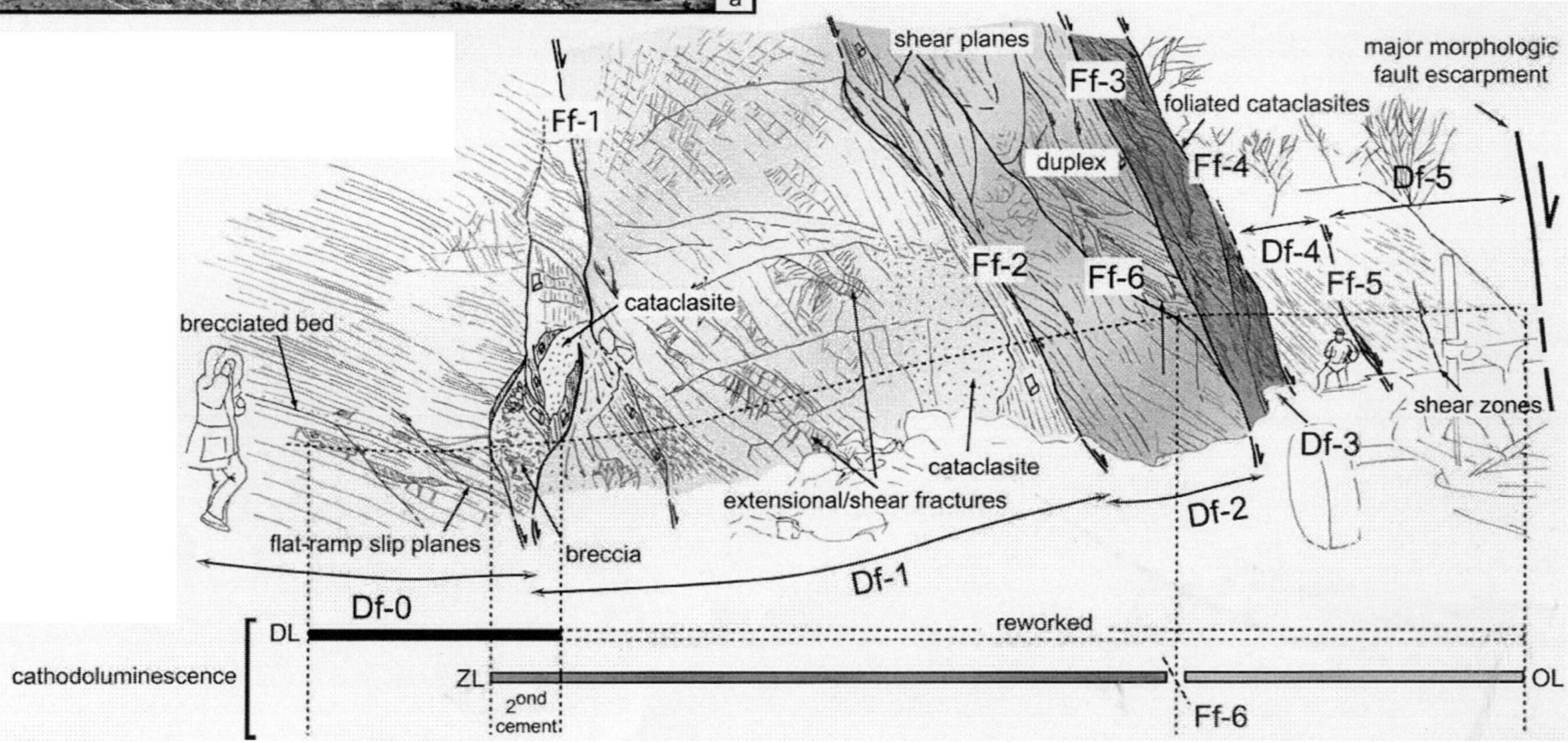
3- Slip Surface : on Stratiform stylolites

Micarelli et al., 2005

Internal structure of faults

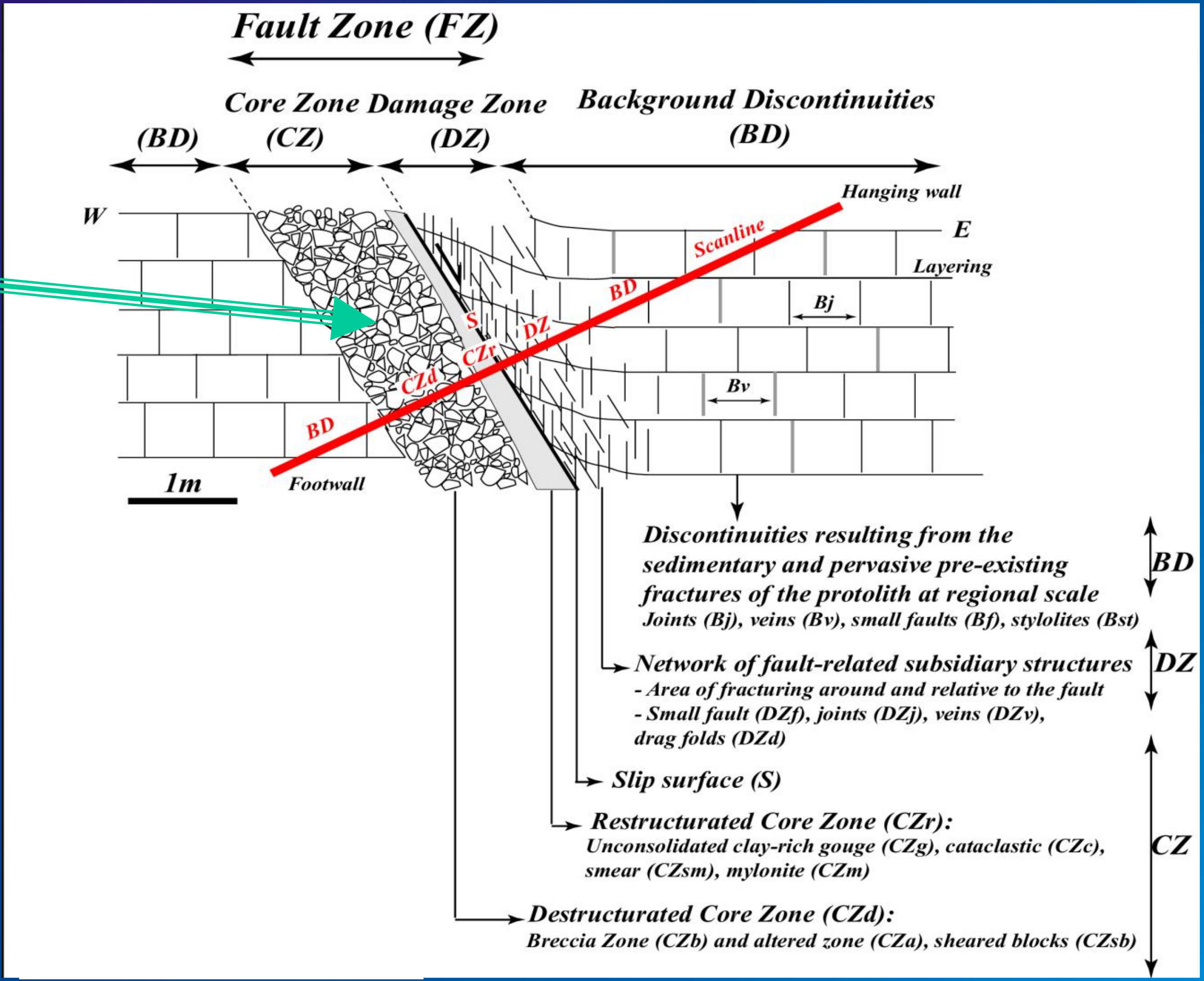


DuBernard-Rouchy, X., 2002



(Bussolotto, PhD thesis, 2010)

- Weakest zone of the FZ



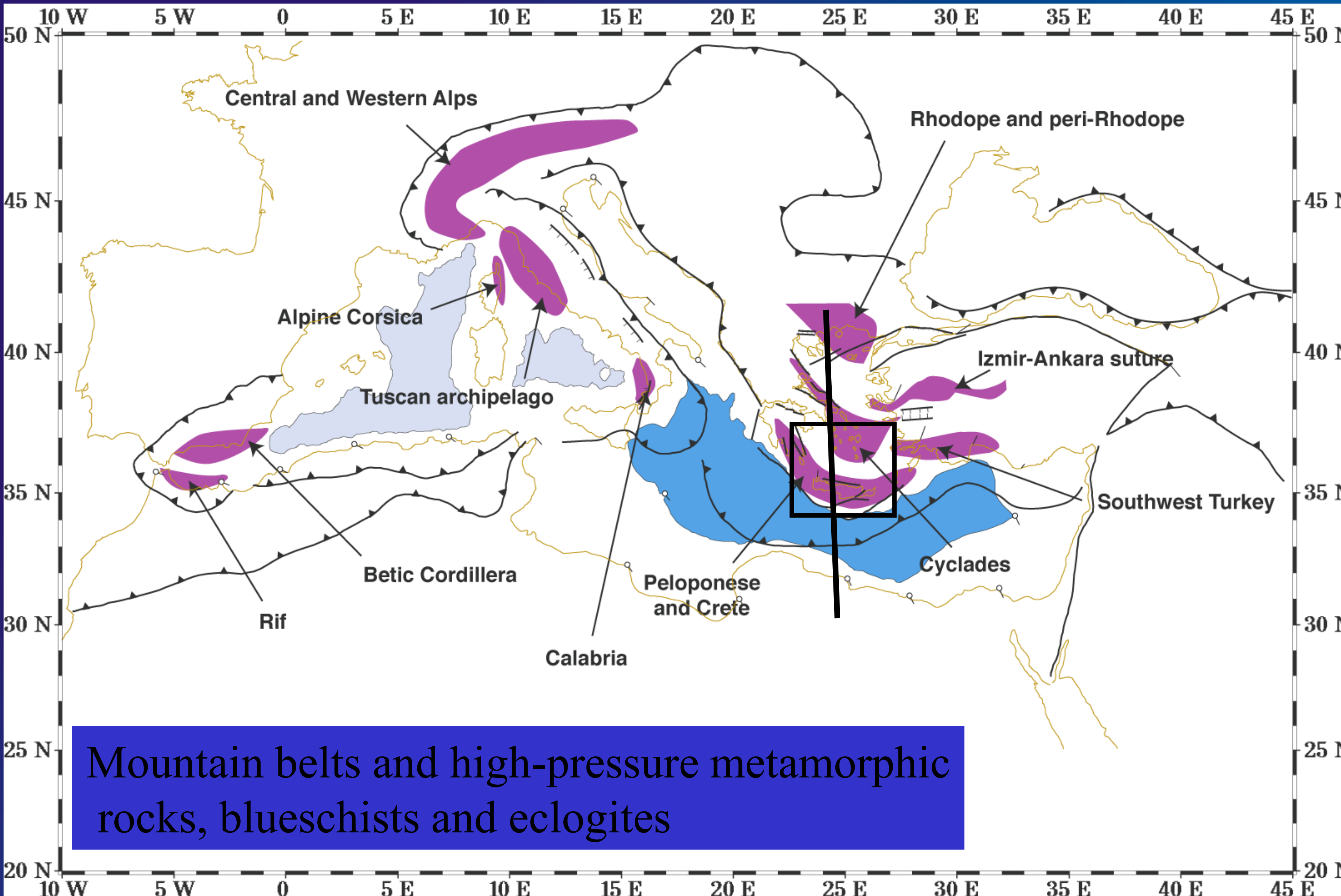
Initiation and geometry of faulting in exhuming metamorphic rocks

An alternative way of studying brittle fault initiation :

Consists of examining how brittle tectonic structures initiate and further develop during exhumation of rocks which previously suffered ductile deformation and metamorphism.

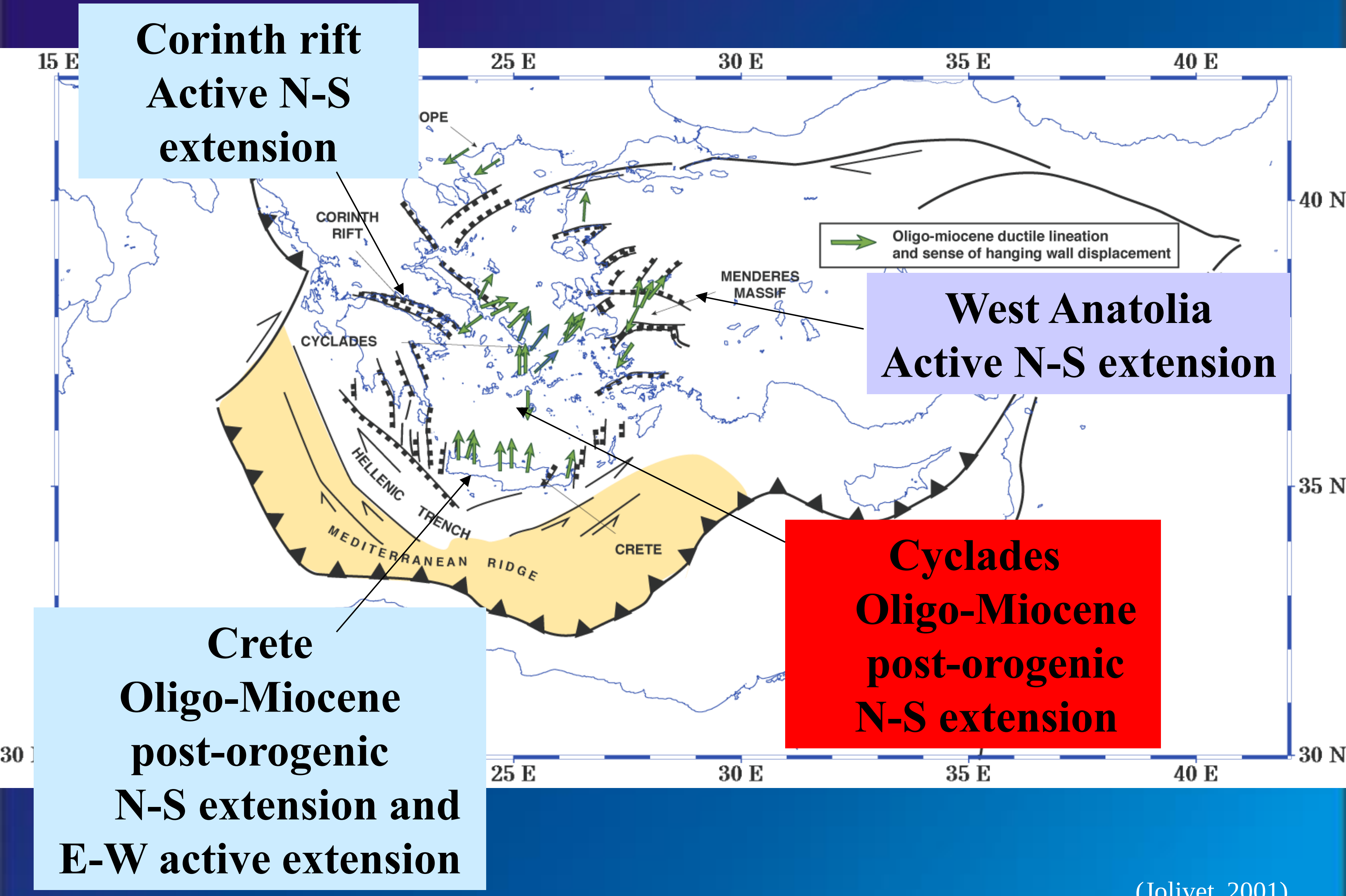
Rocks passing through the ductile-brittle transition during their way back to the surface record, and therefore potentially document, the initial localization of brittle deformation in a previously ductile material that exhibits foliation and ductile shear zones but devoid of true brittle pre-existing discontinuities.

This allows the description of the succession of events that ultimately lead to localization and development of brittle faults. Provided that the kinematics of the system does not change during rock exhumation, one can thus take advantage of the fact that (micro)structures evolve in type while the regional structure enters the brittle domain, for instance during syn-exhumation cooling.

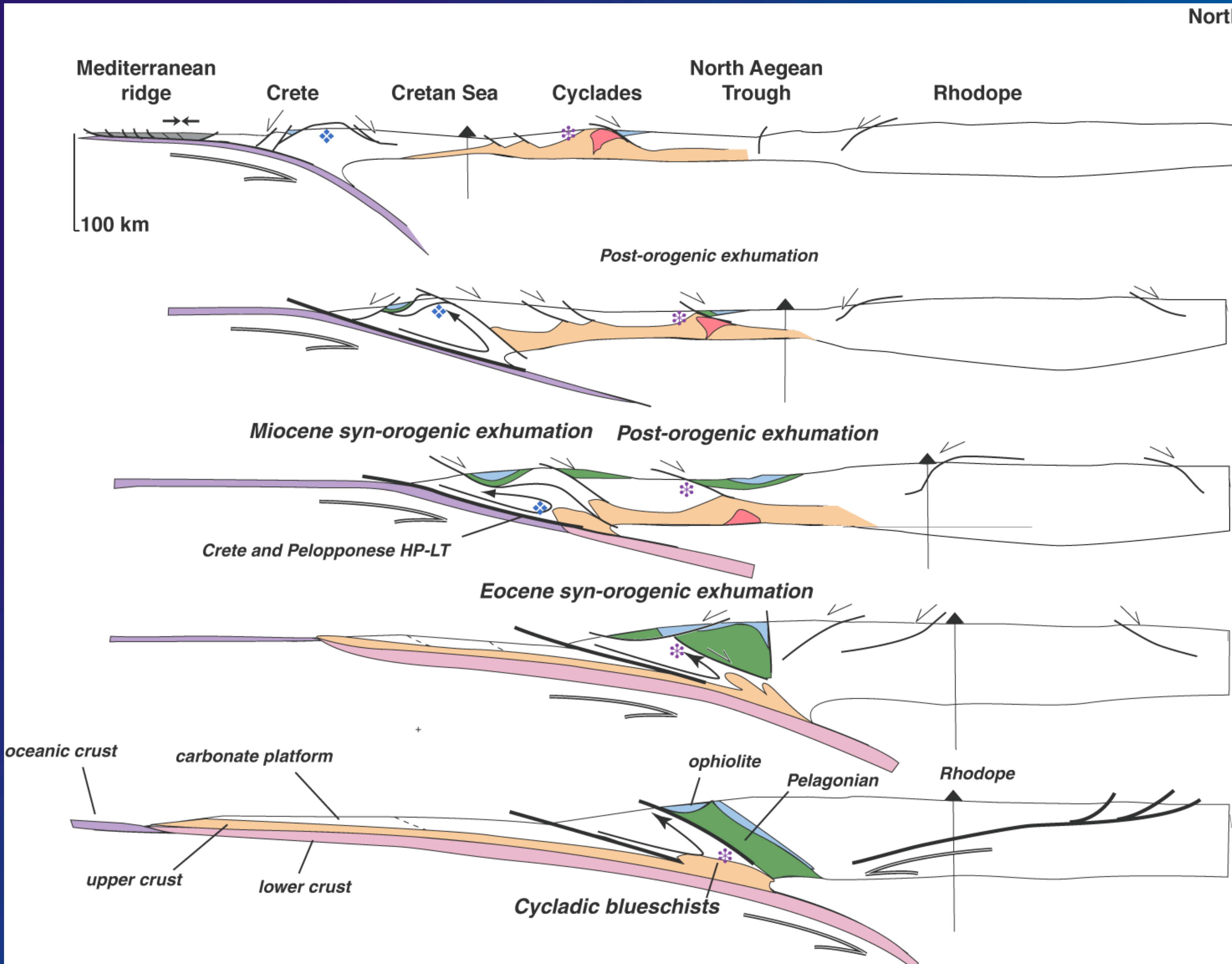


Mountain belts and high-pressure metamorphic rocks, blueschists and eclogites

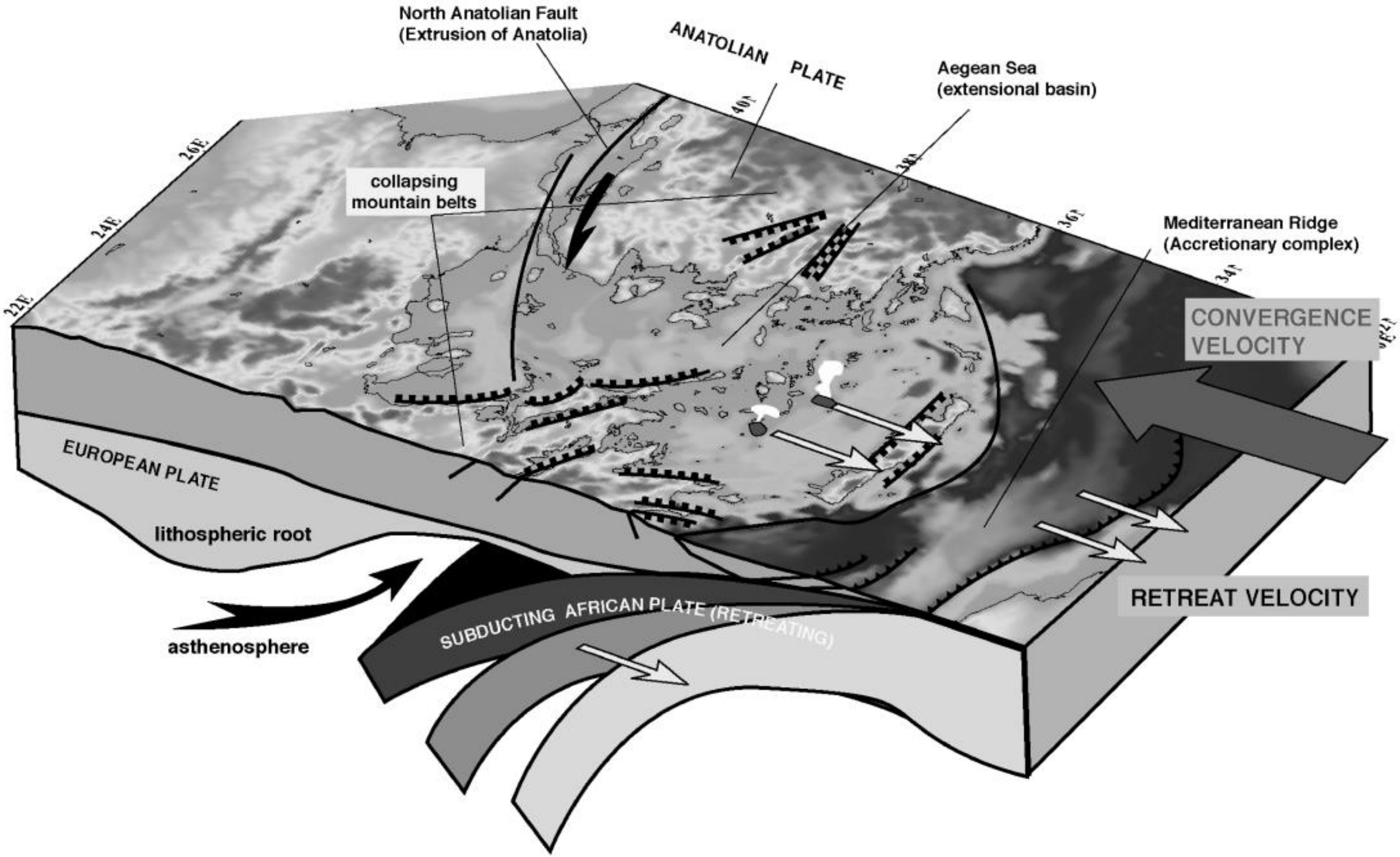
(Jolivet et al., 2003)



(Jolivet, 2001)

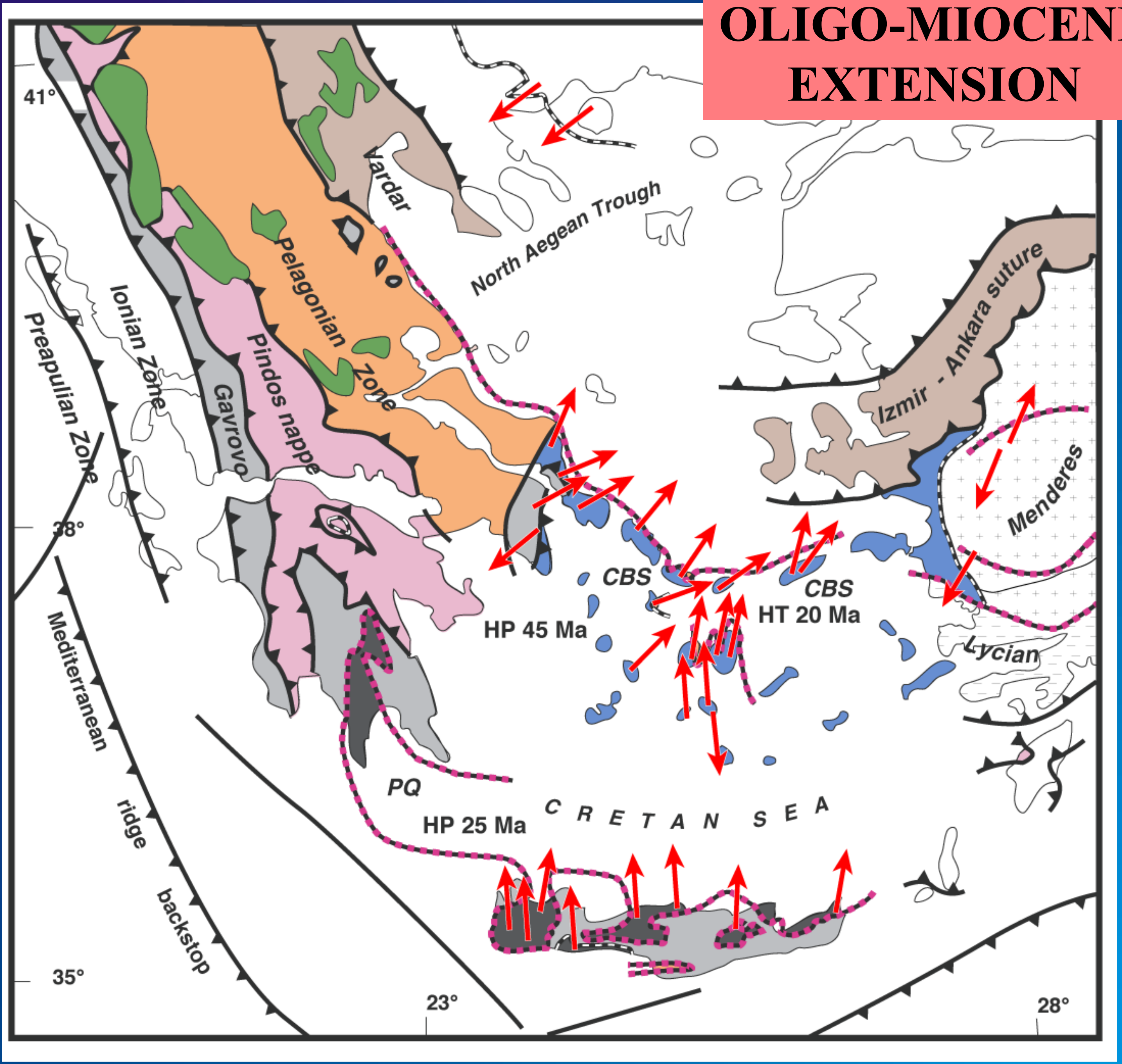


(Jolivet et al., 2003)

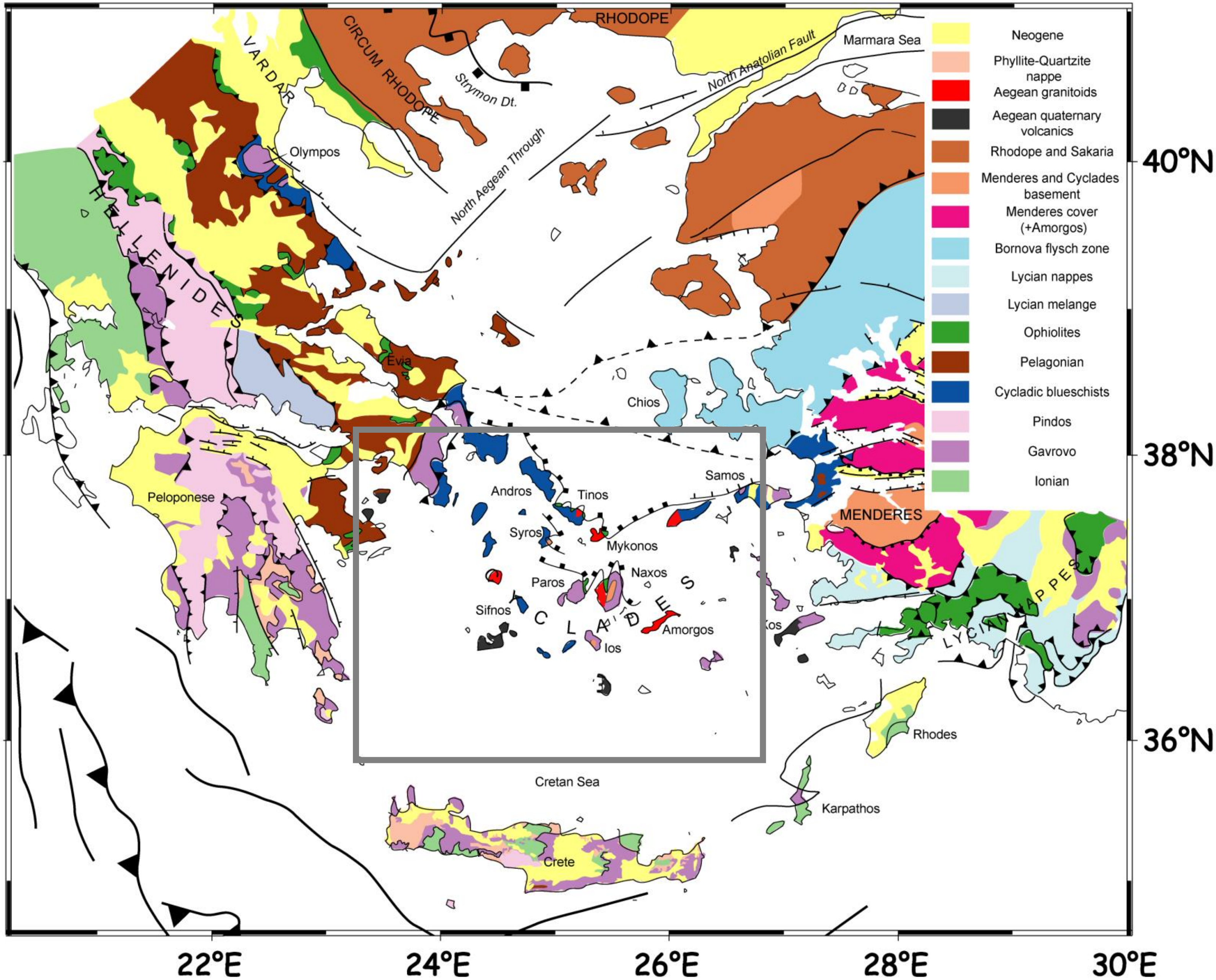


(Jolivet et al., 2004)

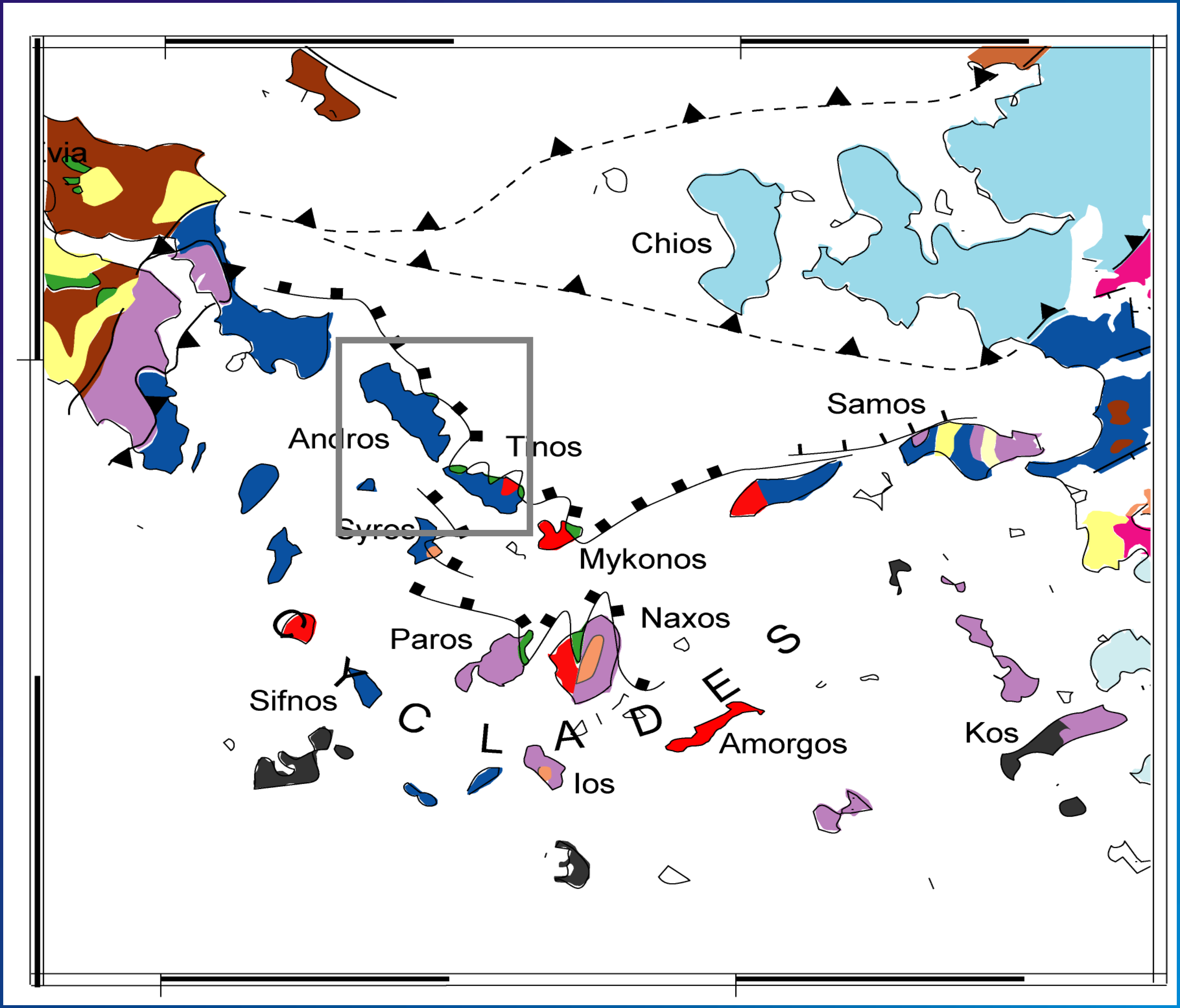
OLIGO-MIOCENE EXTENSION



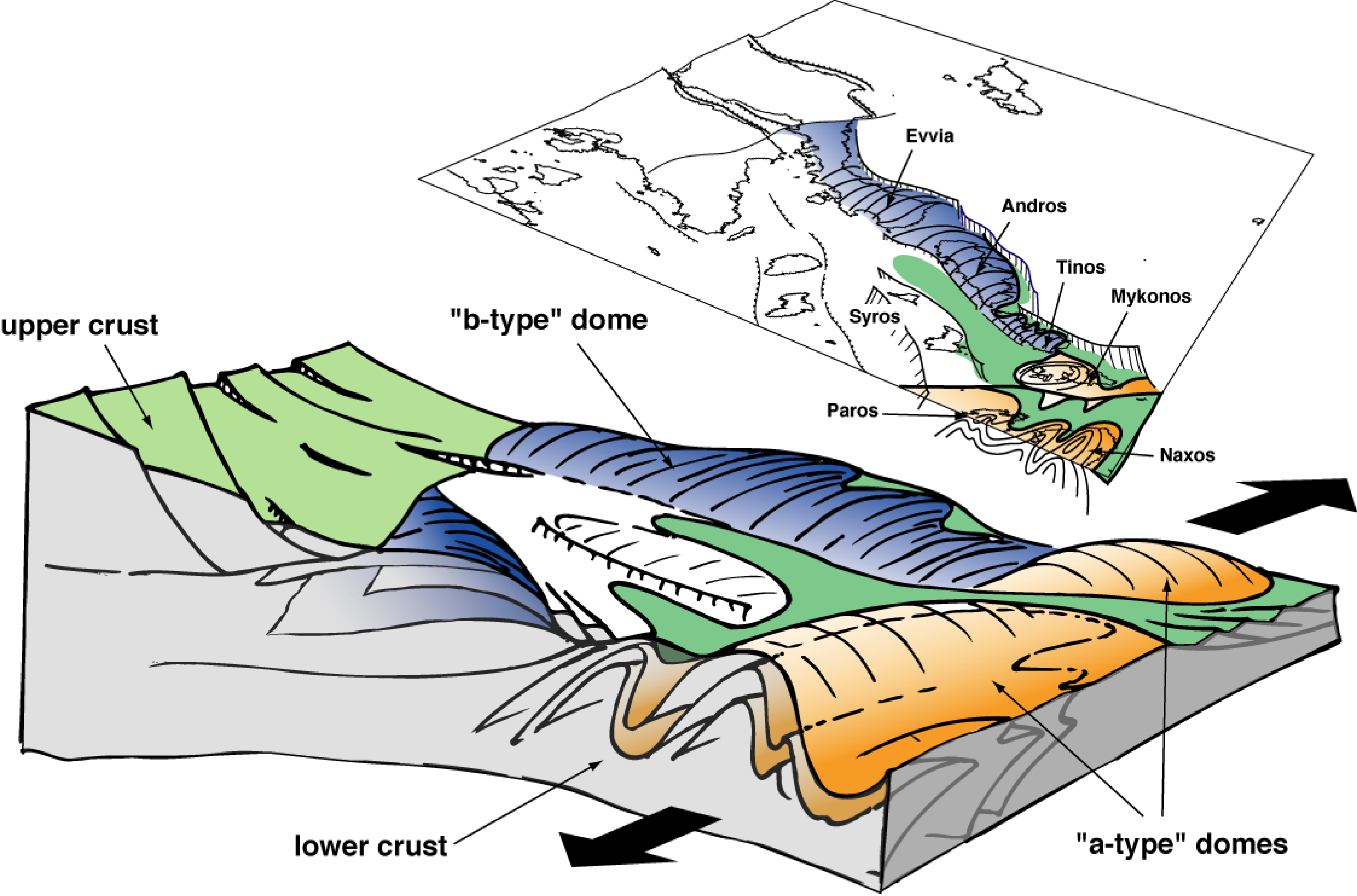
(Courtesy of L. Jolivet)



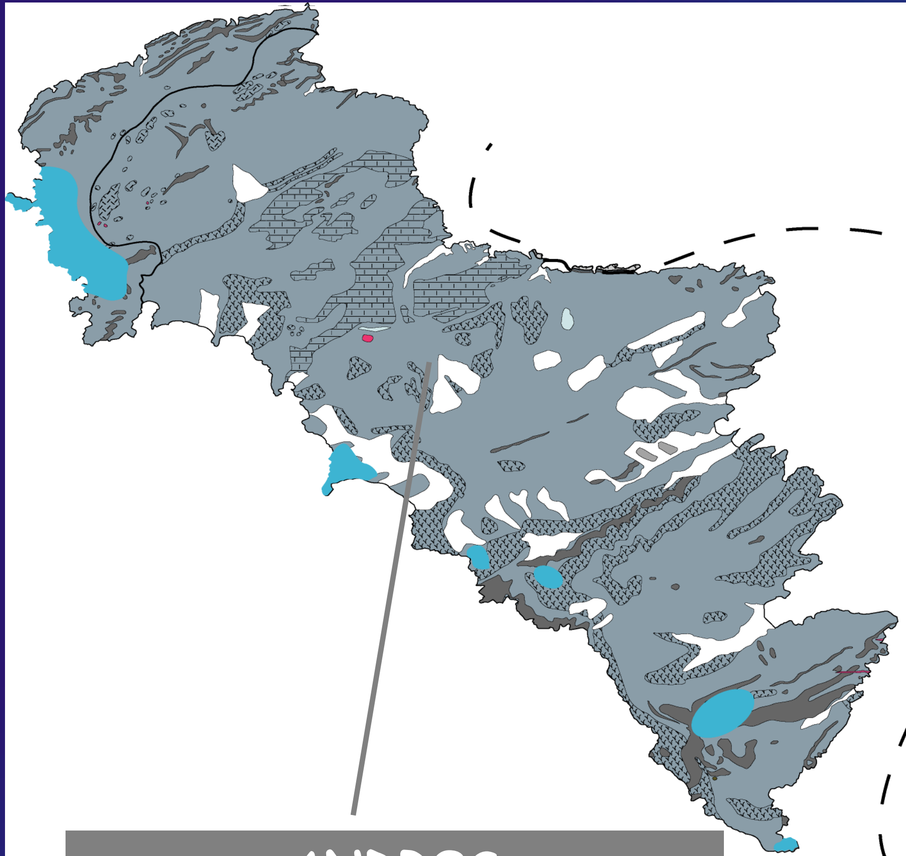
(Courtesy of L. Jolivet)

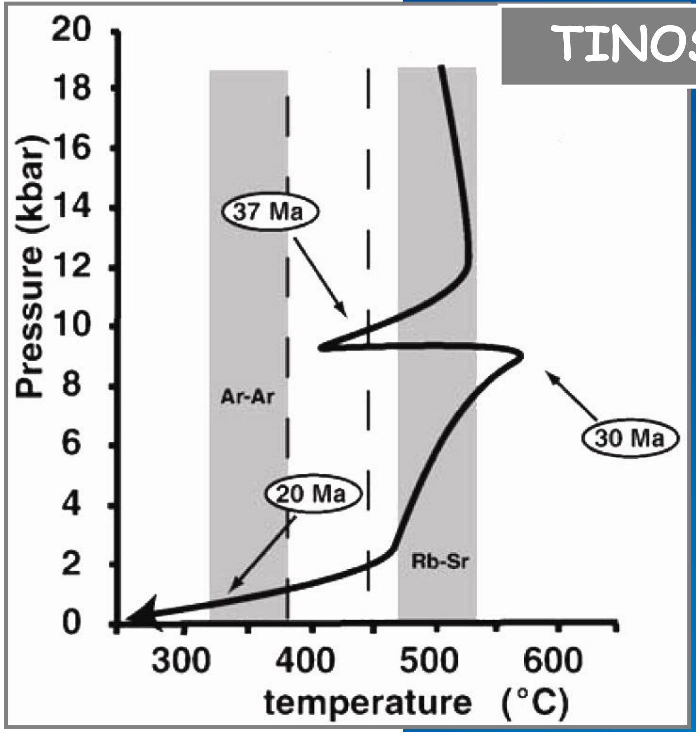


(Courtesy of L. Jolivet)



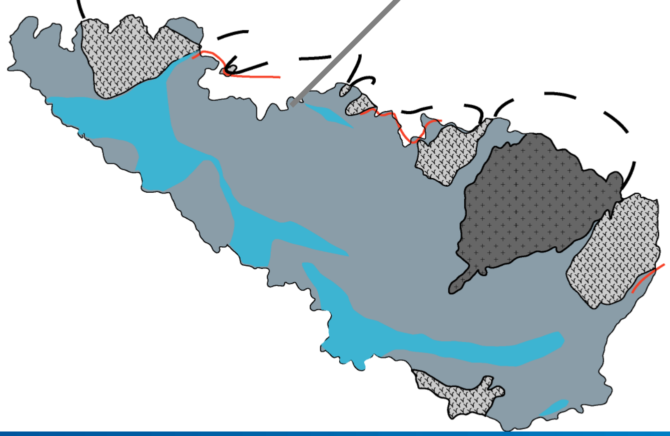
(Jolivet et al., 2004)





TINOS

Parra *et al*, Lithos, 2002

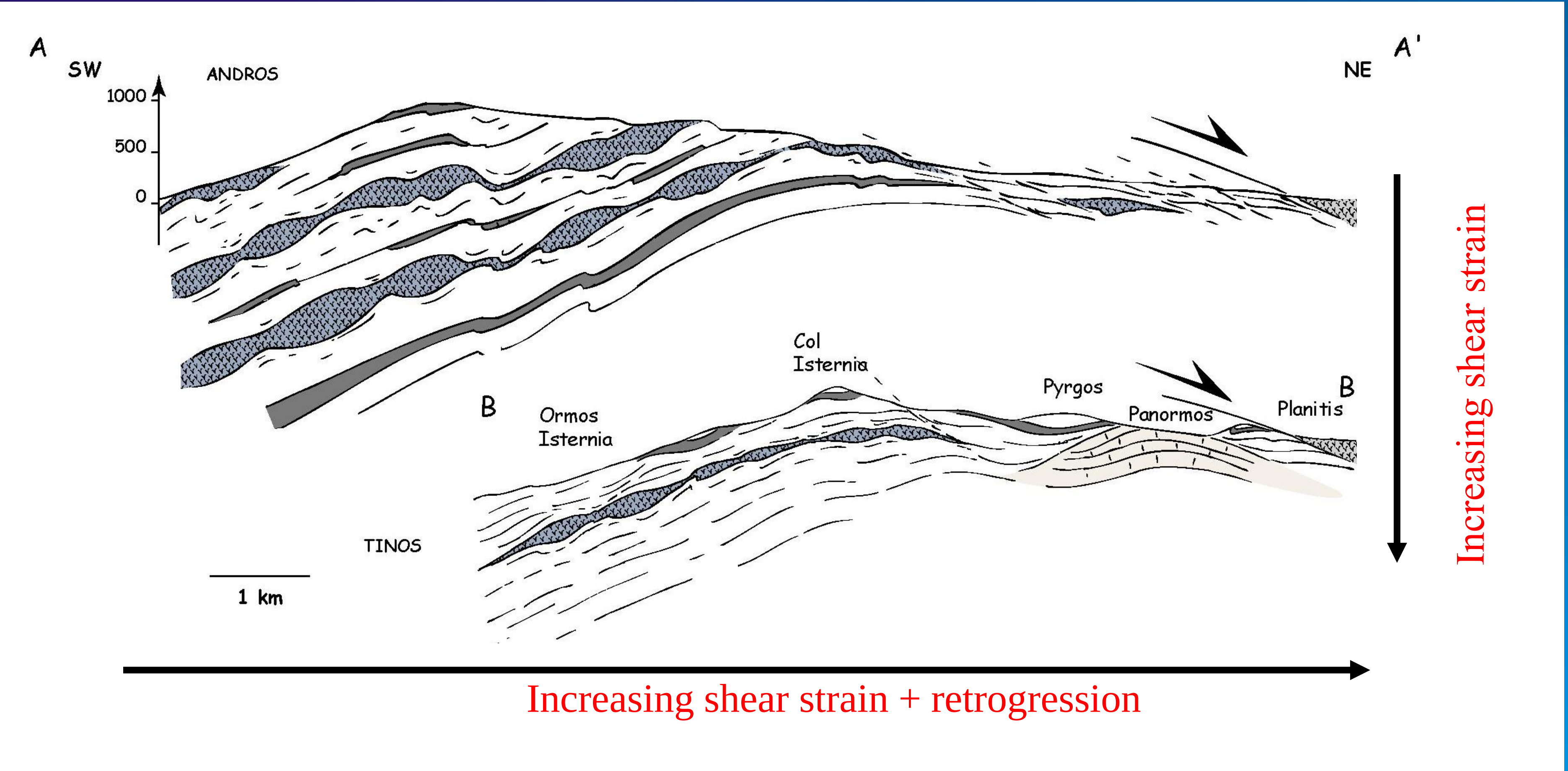


ANDROS

Peak P-T conditions:

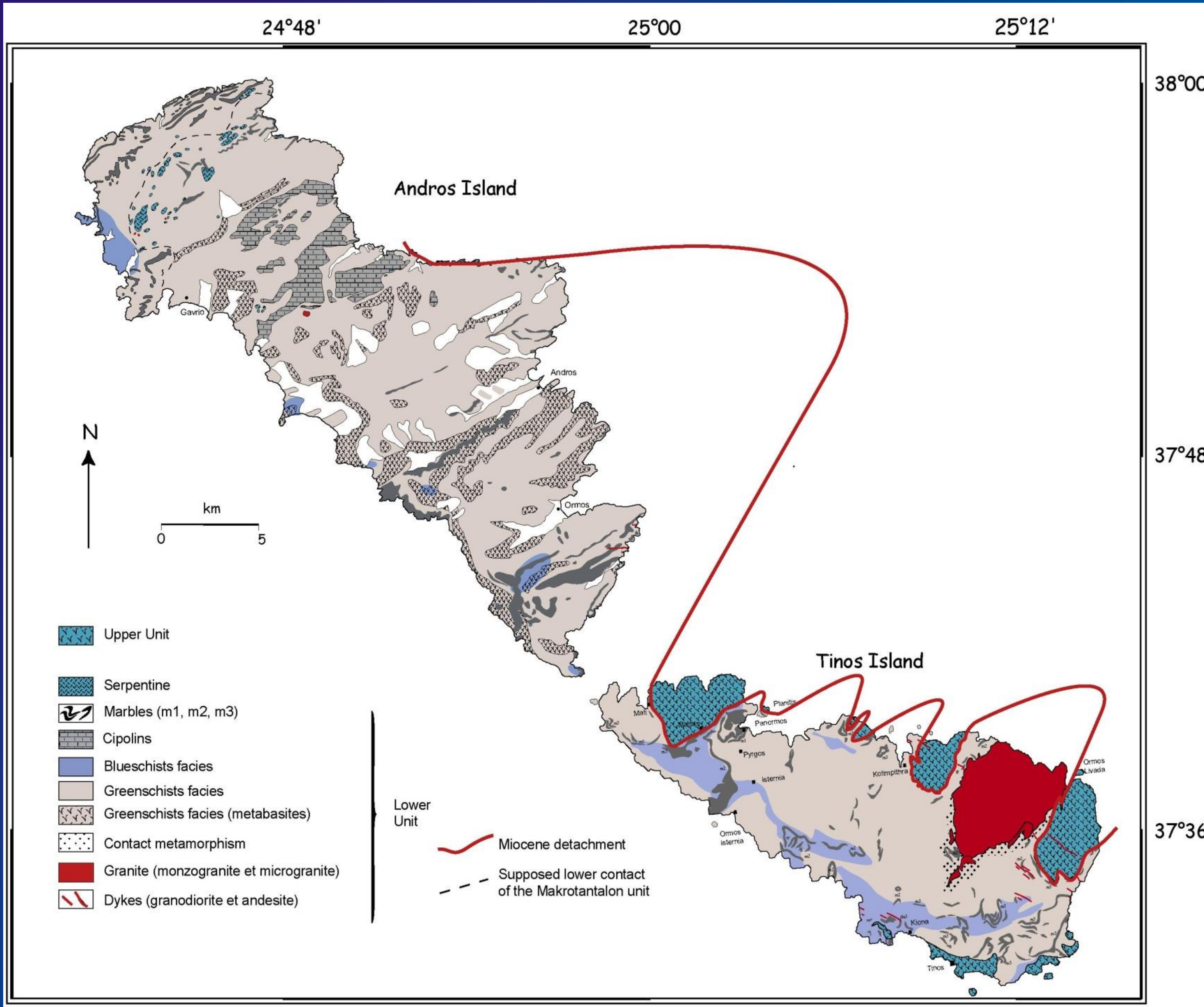
T: 450-500°C - P > 10Kbar

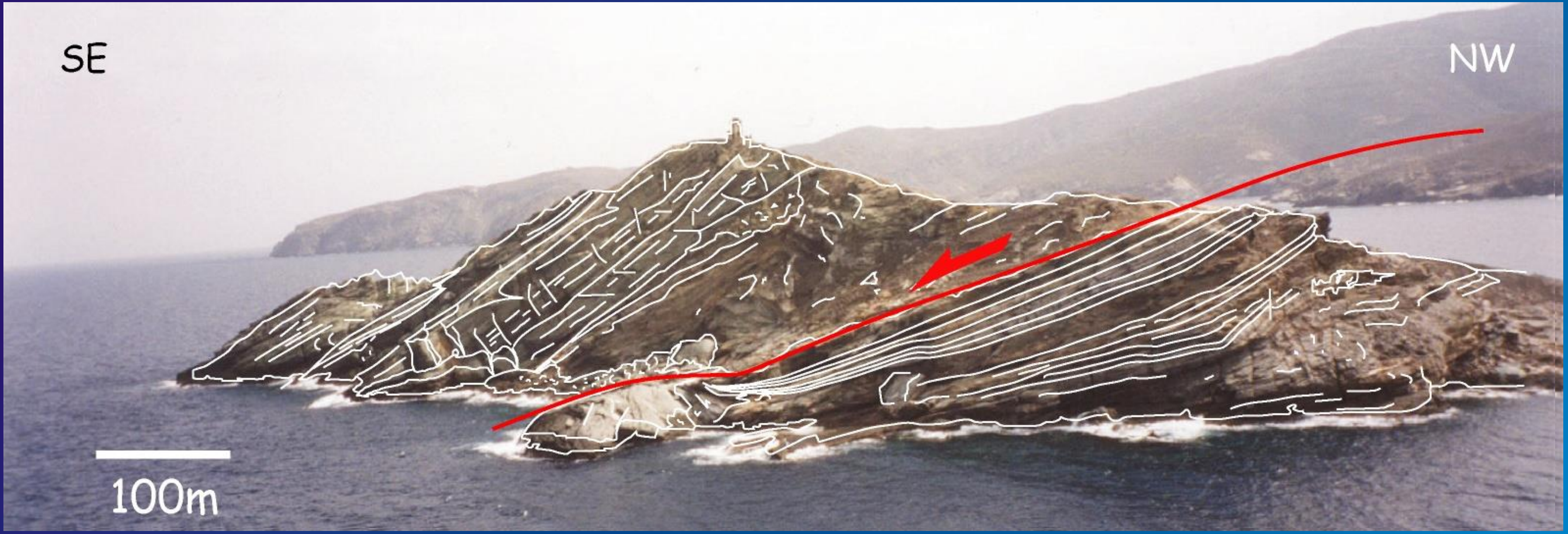
Lower unit :
Alternating metabasites, marbles and metapelites
Relics of HP metamorphism



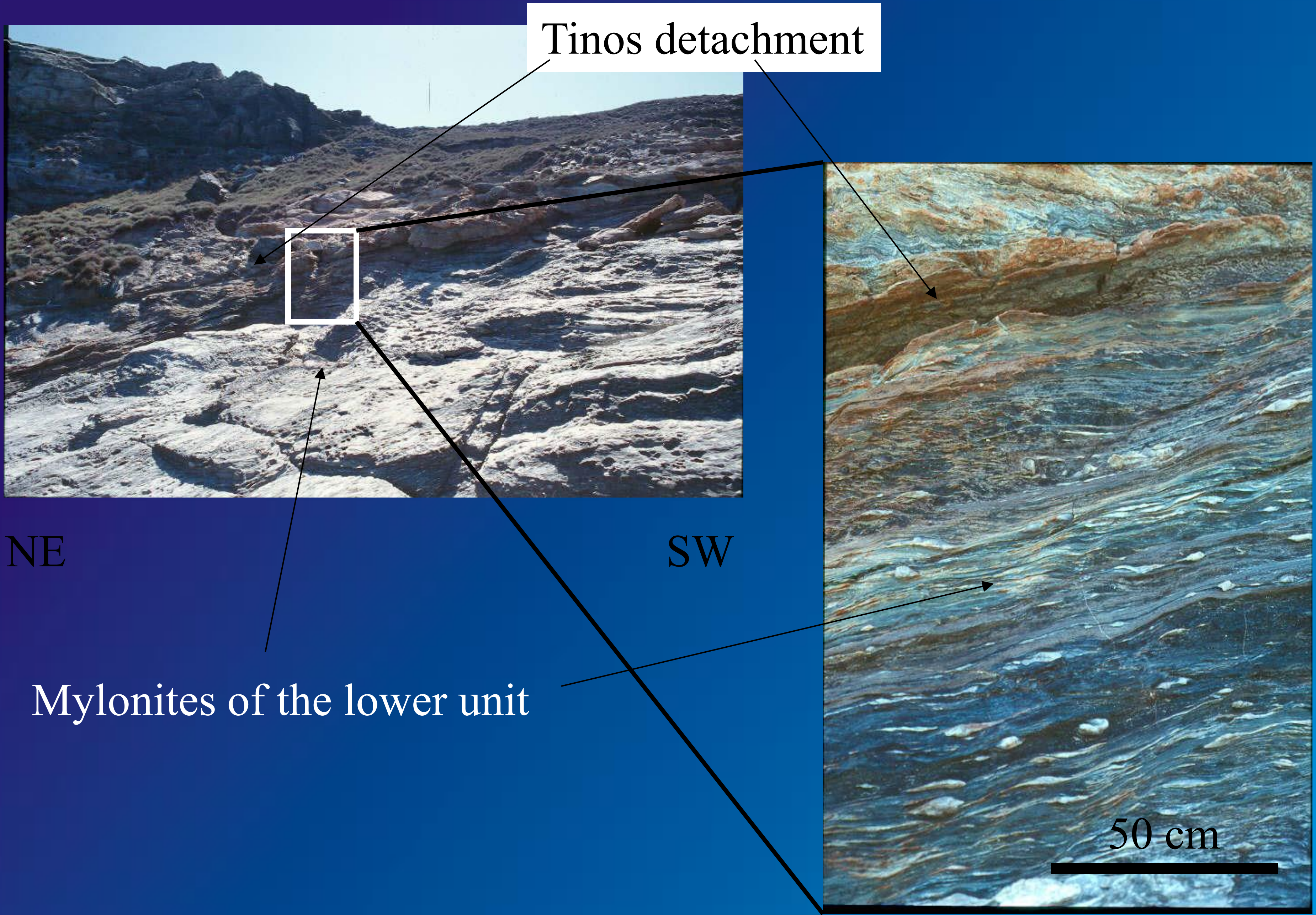
Upper unit :
serpentinites, metagabbros.
No HP metamorphism

The Tinos-Andros 'metamorphic core complex' :
An upper unit and a lower unit separated by a detachment

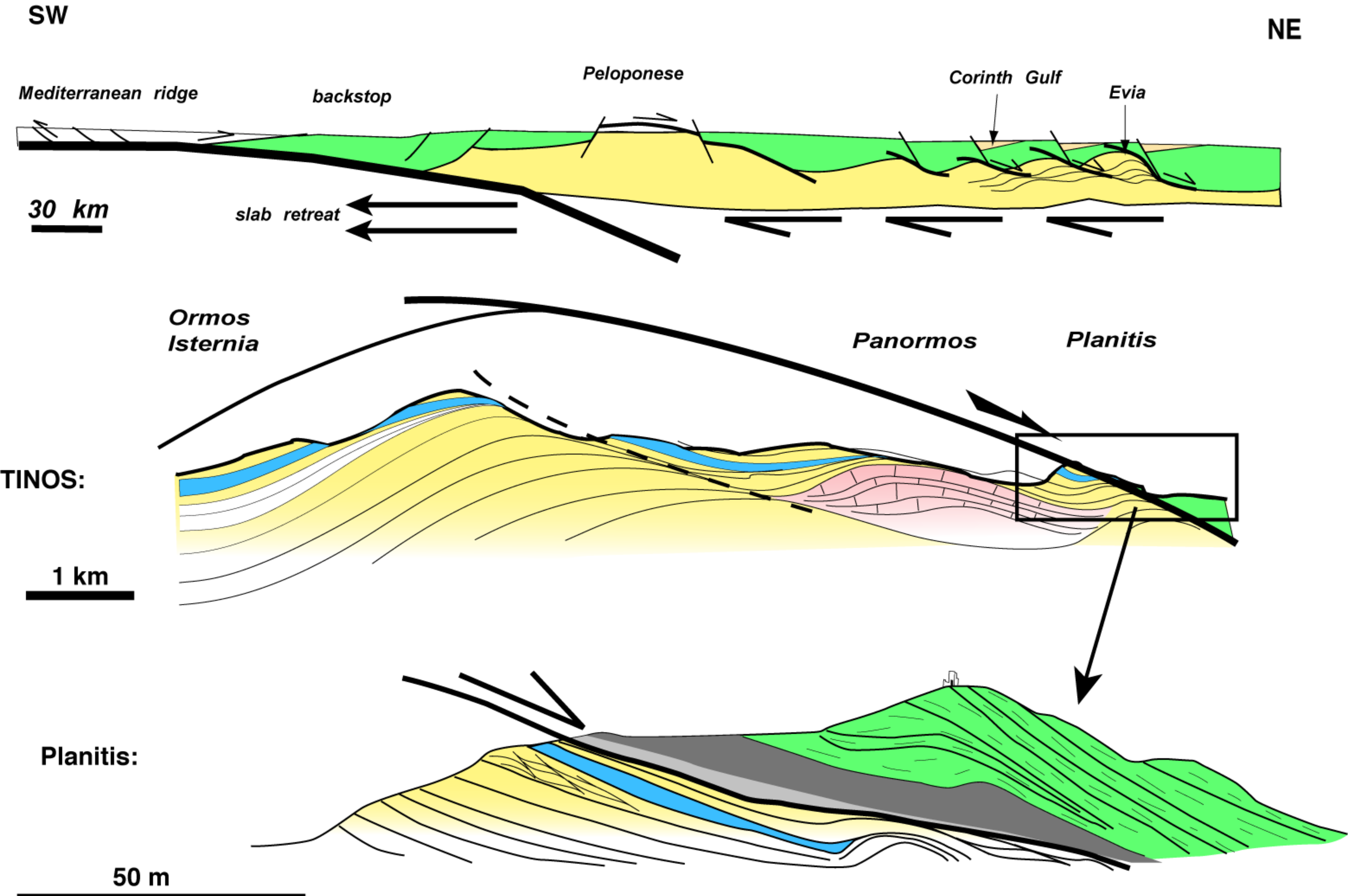




**The detachment :
Planitis, Tinos**



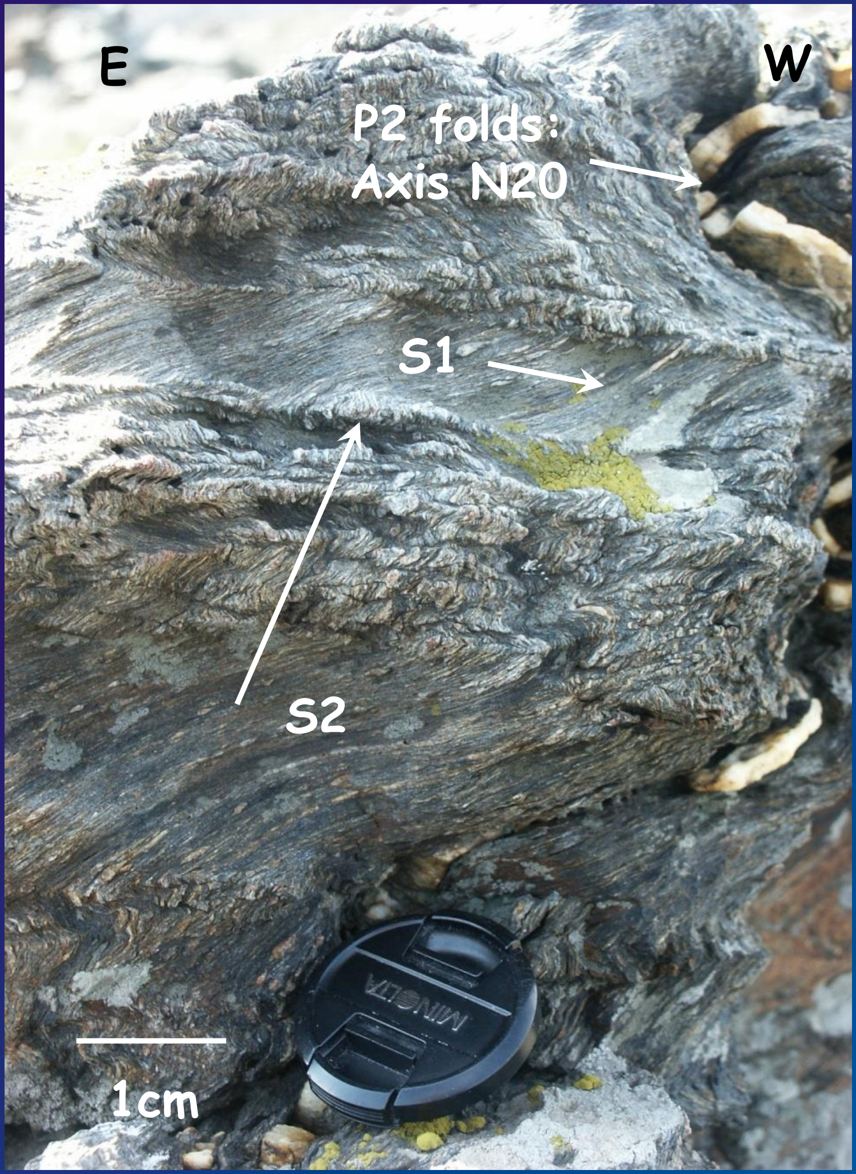
Tinos detachment
NE
SW
Mylonites of the lower unit
50 cm



(Courtesy of L. Jolivet)

The upper unit

Ductile to brittle continuous evolution and sequence of deformation



(Mehl et al.,2005)

Initiation of sheath folds


MINOLTA

BOUDINAGE

Every scale

BOUDINAGE

Every scale

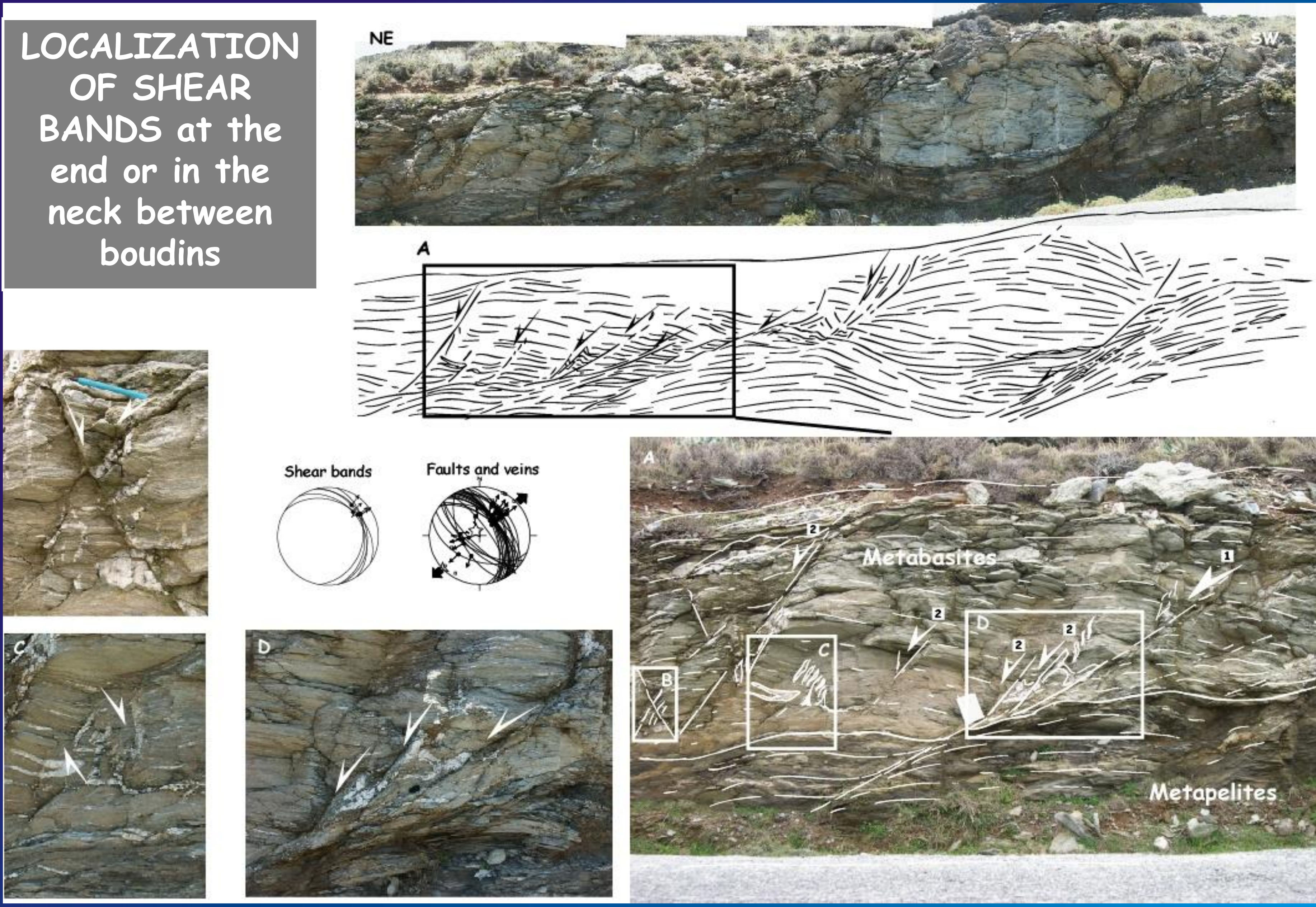

10cm


1cm

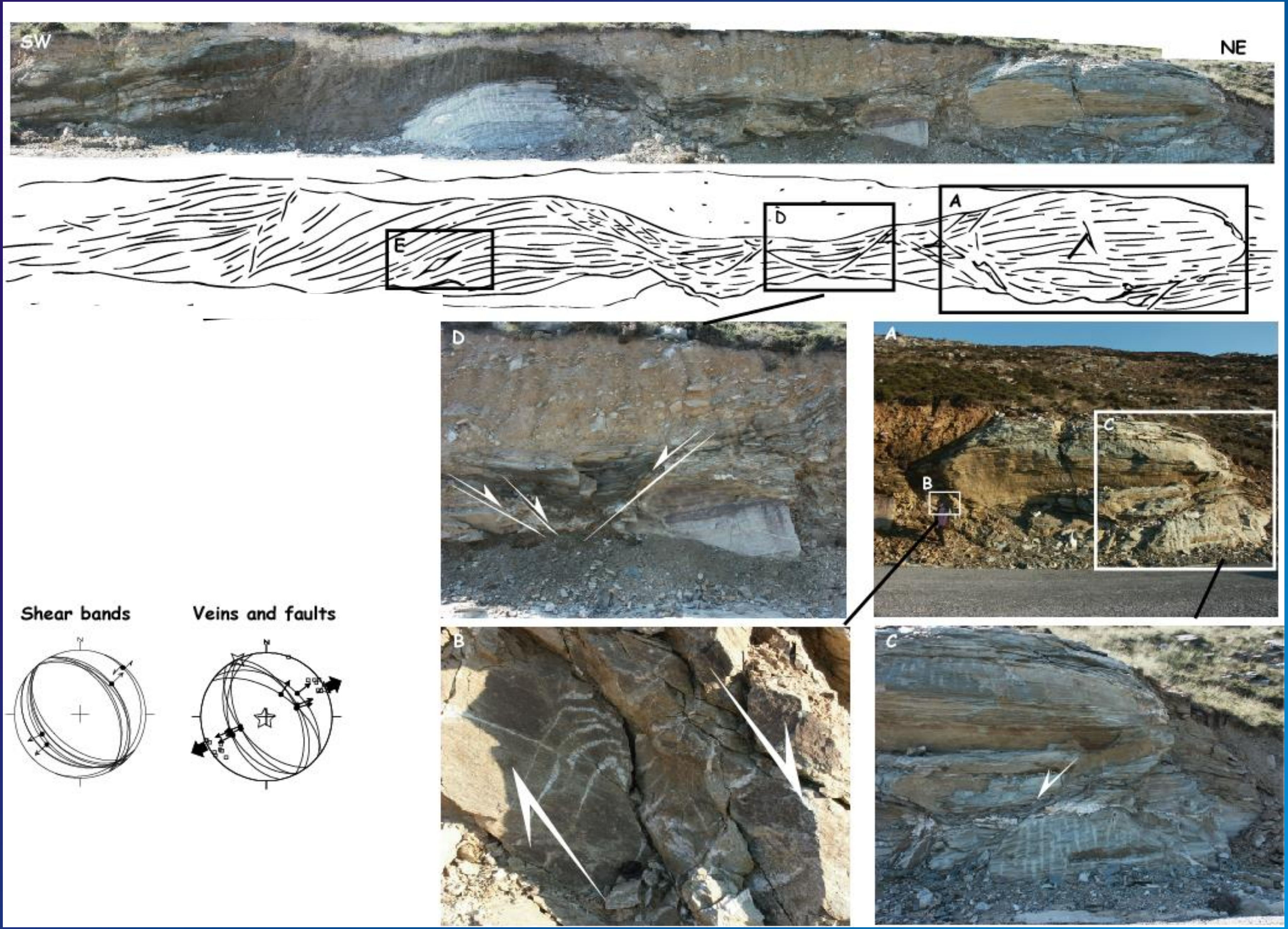
Andros :
Symmetric boudinage
away from the detachment

Andros :
Asymmetric boudinage
closer to the detachment

LOCALIZATION OF SHEAR BANDS at the end or in the neck between boudins

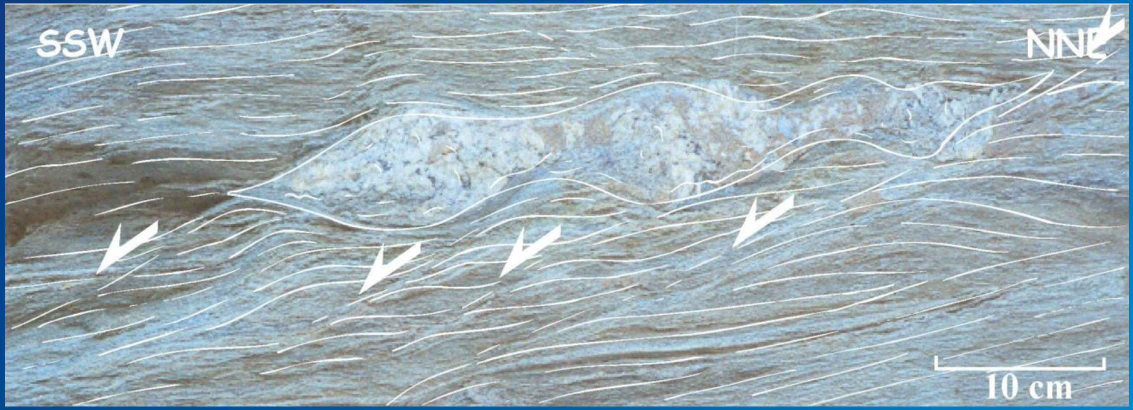


(Mehl et al., 2007)

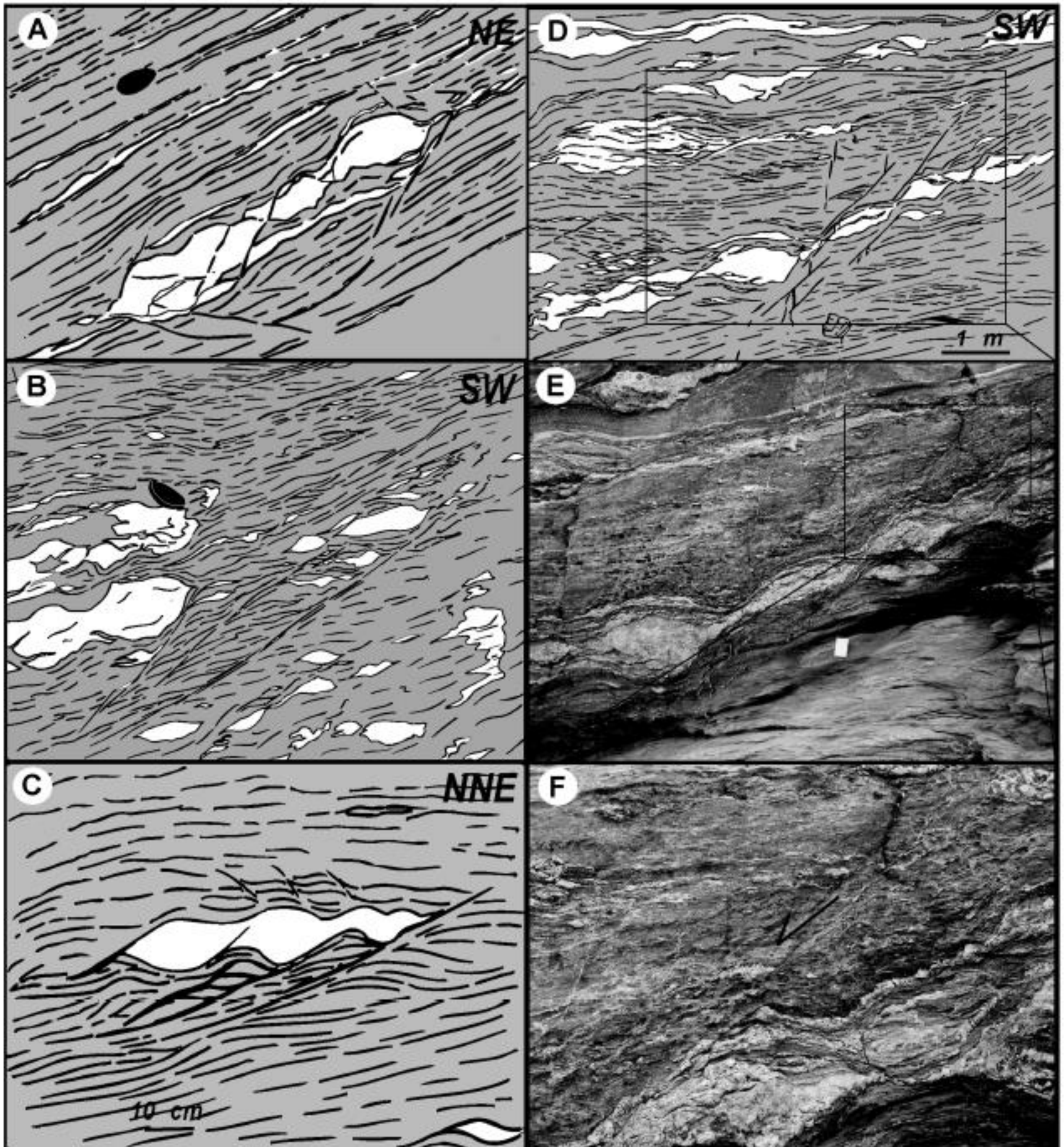


(Mehl et al., 2007)

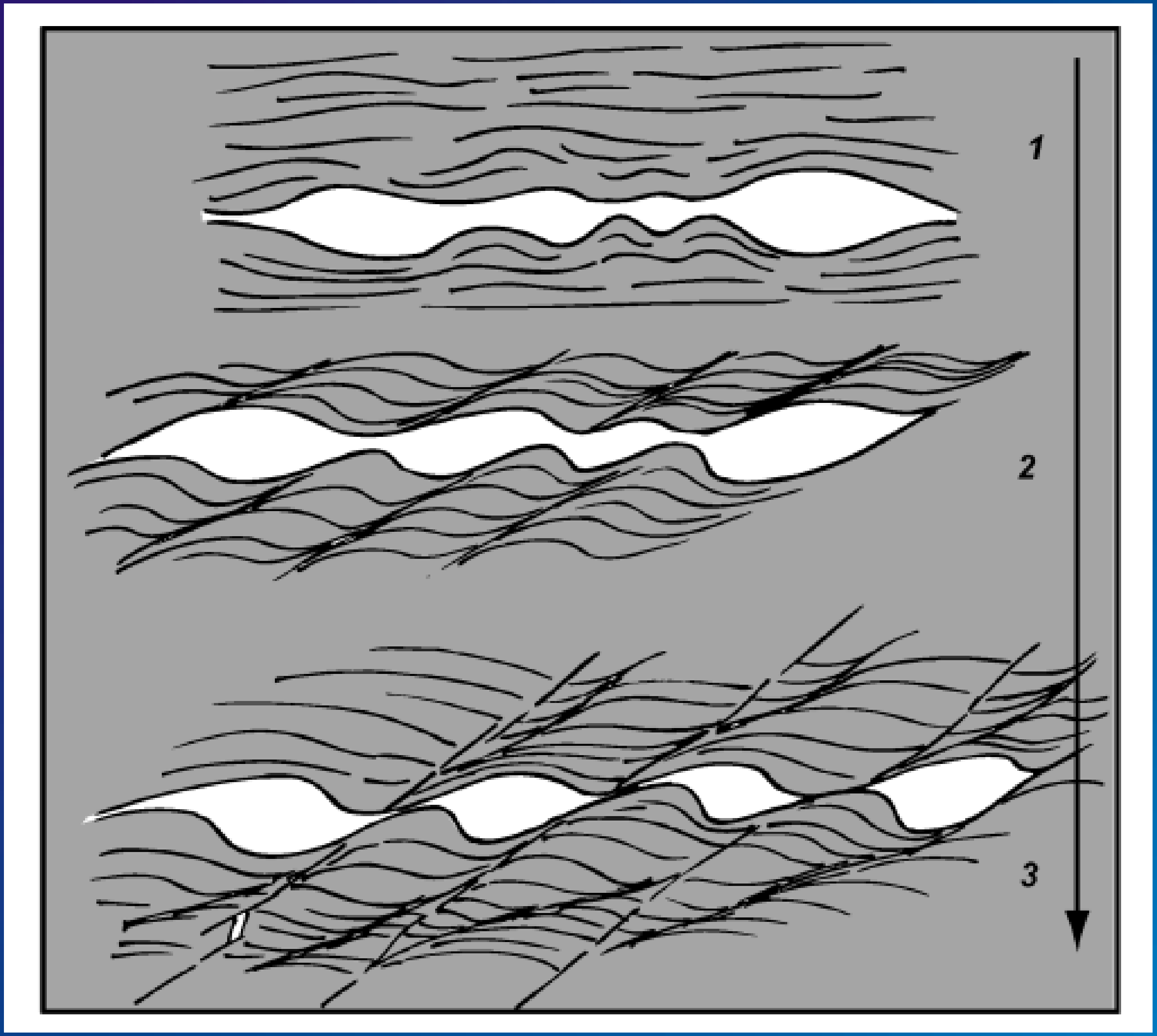
Boudinage: a localization process at all scales...



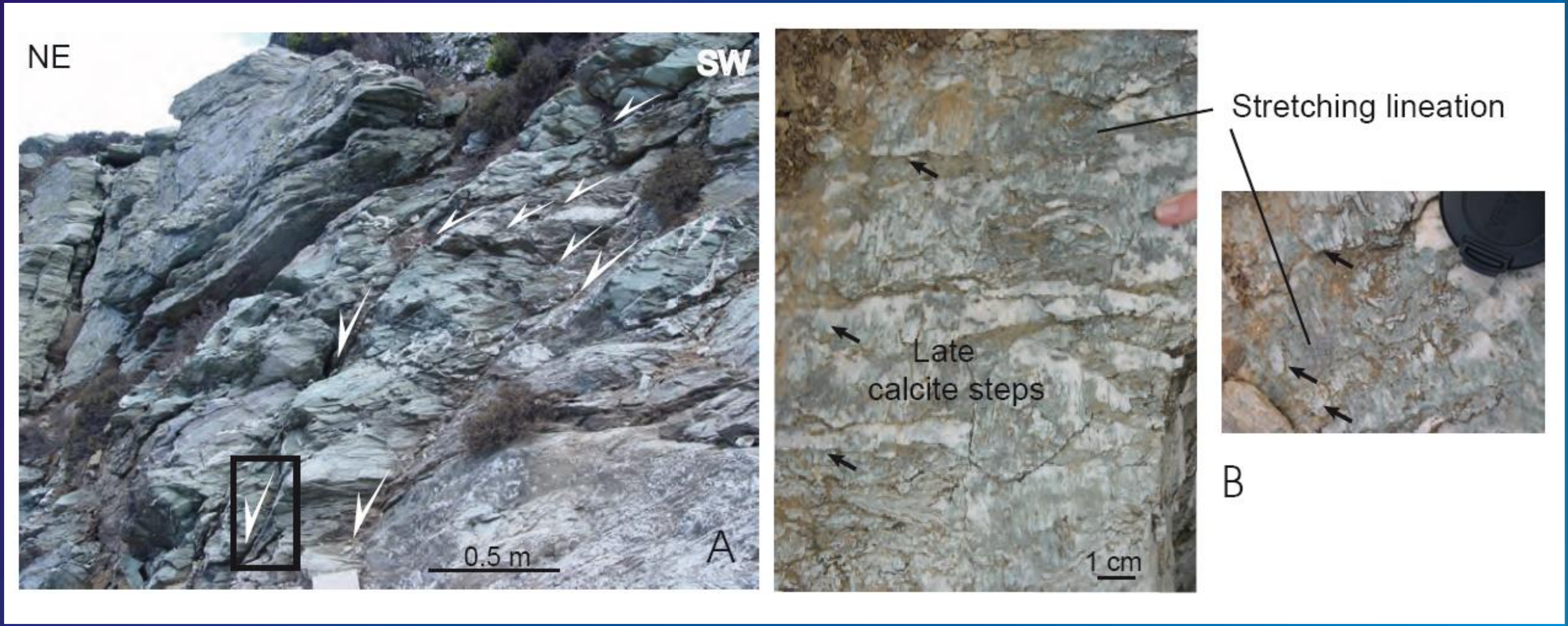
TINOS



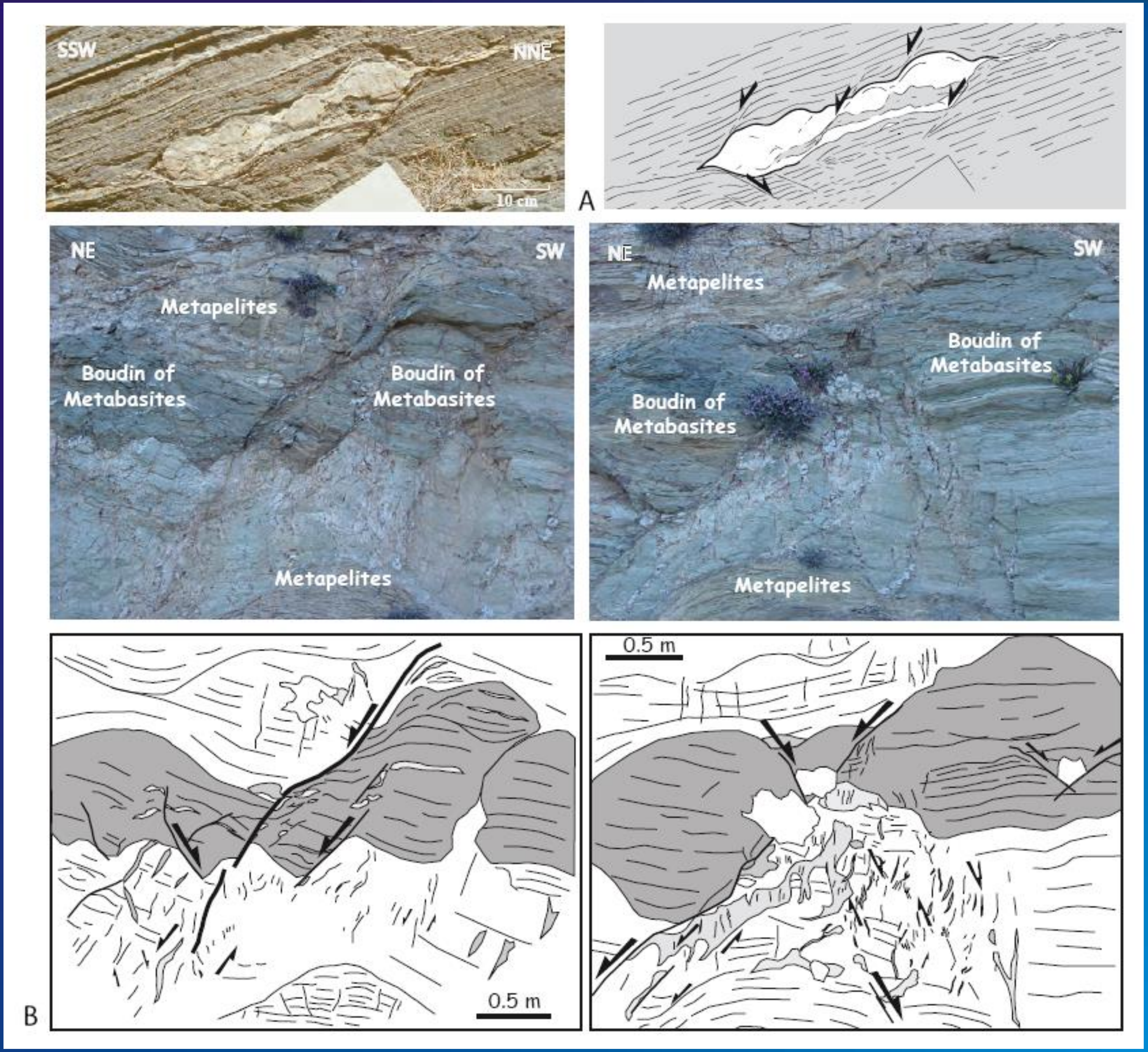
(Jolivet et al., 2004)



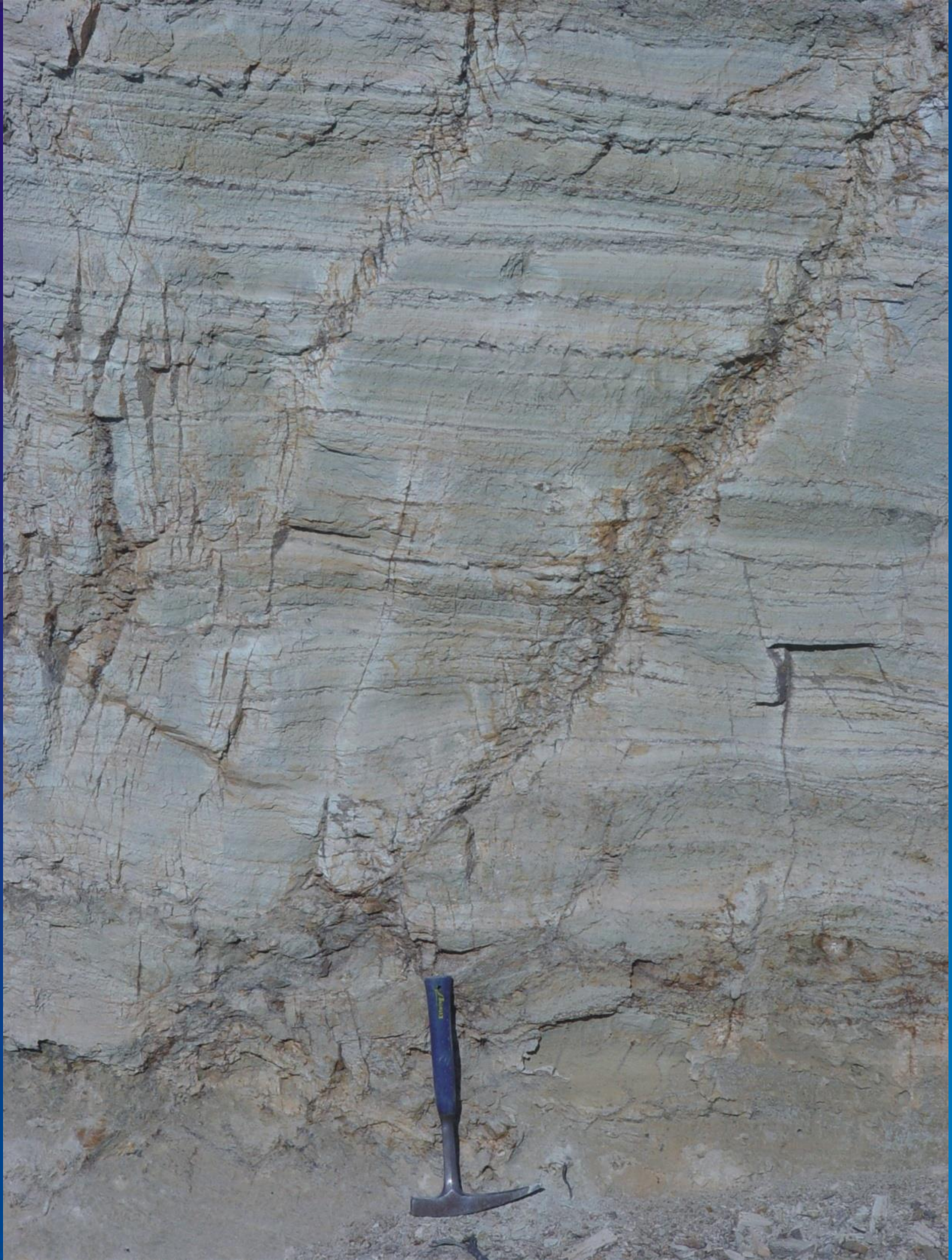
(Jolivet et al., 2004)

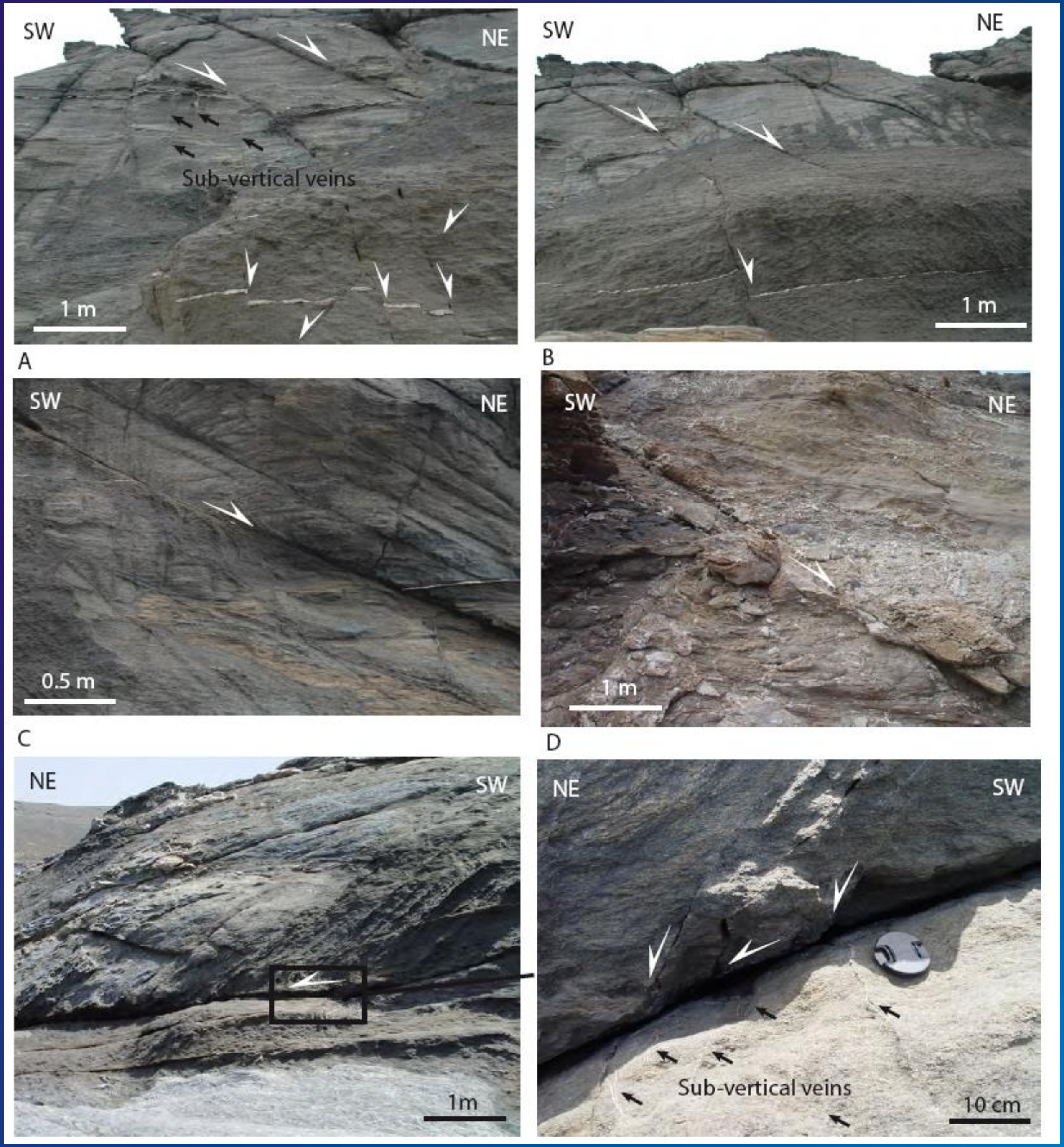


(Lacombe et al., 2013)

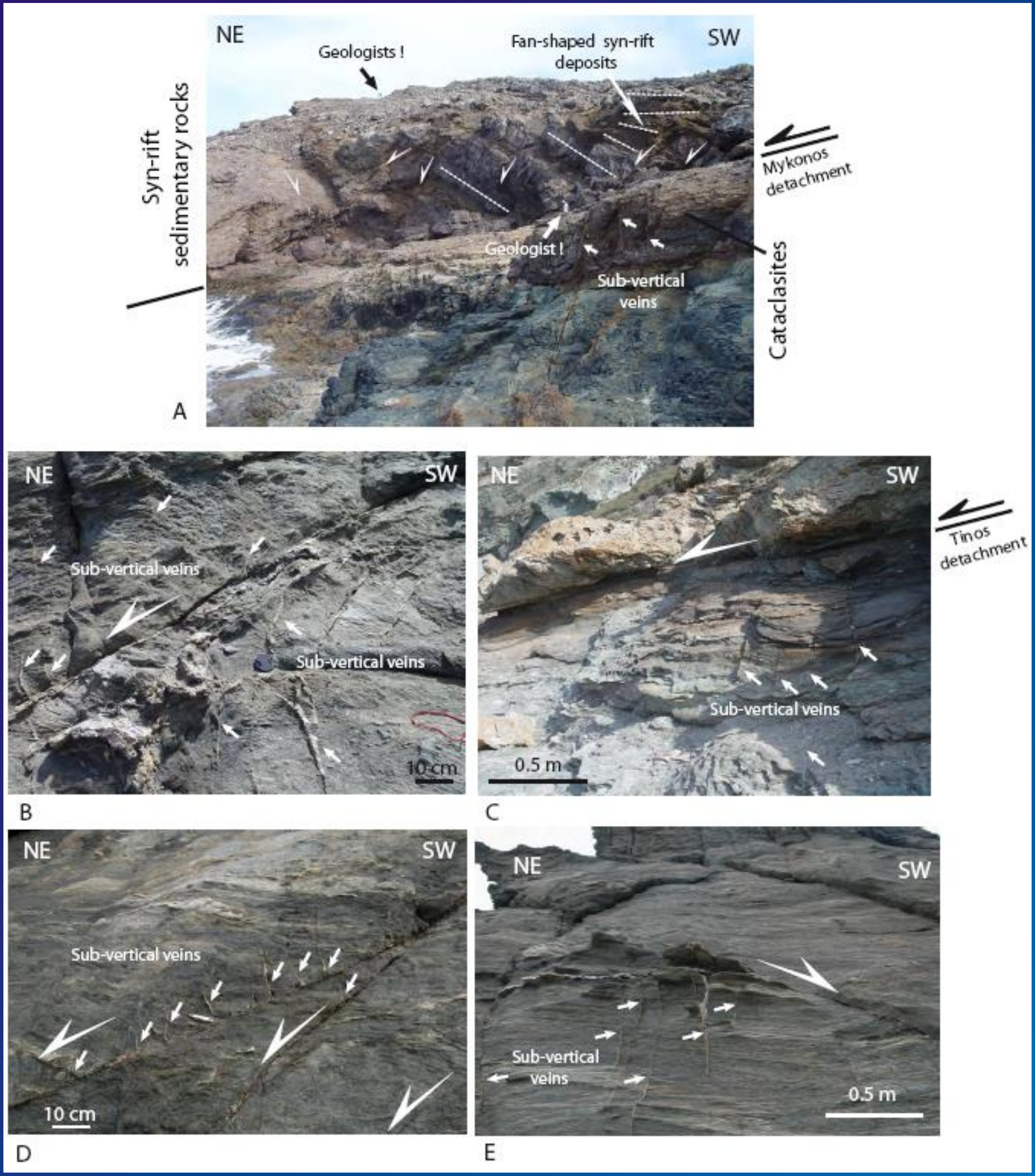


(Lacombe et al., 2013)





(Lacombe et al., 2013)

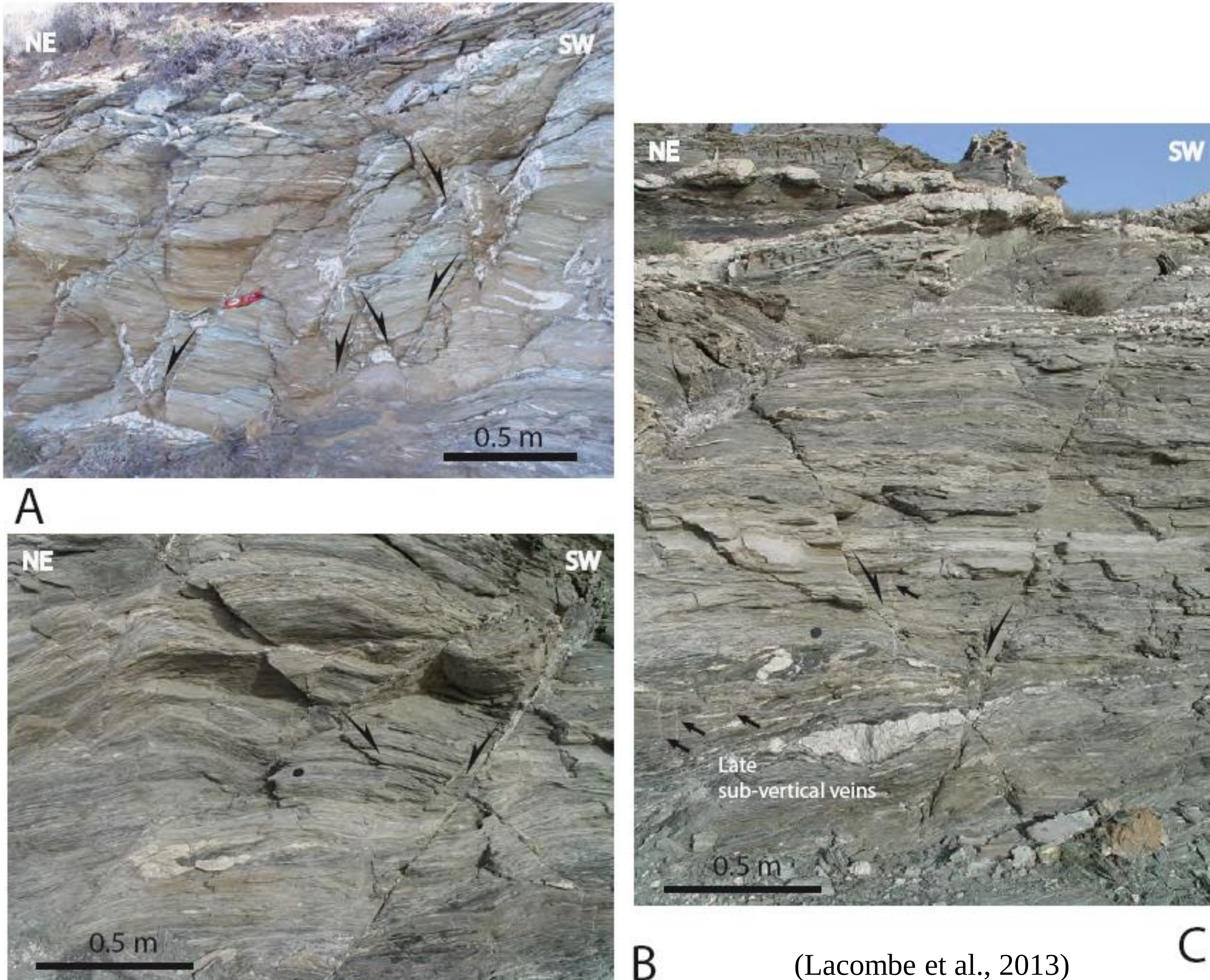


(Lacombe et al., 2013)

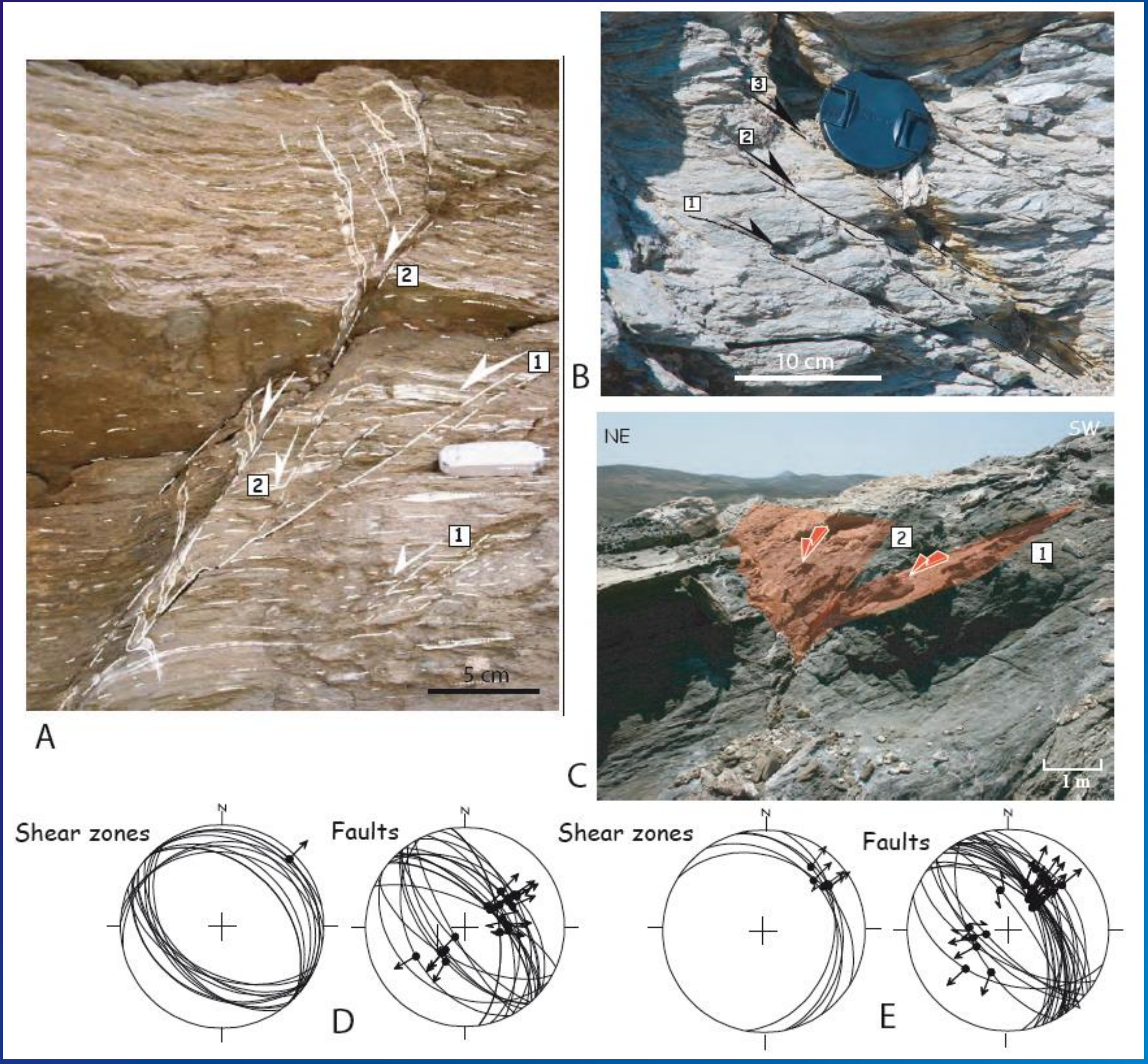
In many cases, even if slickensides are not always observable, the shallow dip of the fault planes synthetic of the main detachment and their geometrical association with boudins indicate that they correspond to reactivated ductile shear zones. When brittle slip occurs along previous ductile shear planes in a direction parallel to the stretching lineation, this superimposition can be viewed as a kind of reactivation of a precursory ductile structure.

Shallow-dipping faults are clearly more numerous in poorly competent metapelites than in metabasites, i.e. in weak lithologies. In contrast, faults often steepen in more competent formations such as marbles and metabasites. A possible explanation for the higher density of low-angle normal faults in metapelites is first related to the development of many of them from precursory shear zones. Precursory ductile and semi-brittle shear zones are more numerous in poorly competent material because in such material the strain rate is higher, the deformation is more penetrative and therefore the spacing of the precursory shear zones, which may be re-used as normal faults, is smaller than in more competent rocks. Furthermore, the feasibility of subsequent brittle reactivation of these precursory shear zones is made possible by the high mica and chlorite content of metapelitic rocks that accounts for a low friction angle that favoured brittle slip at shallow dip.

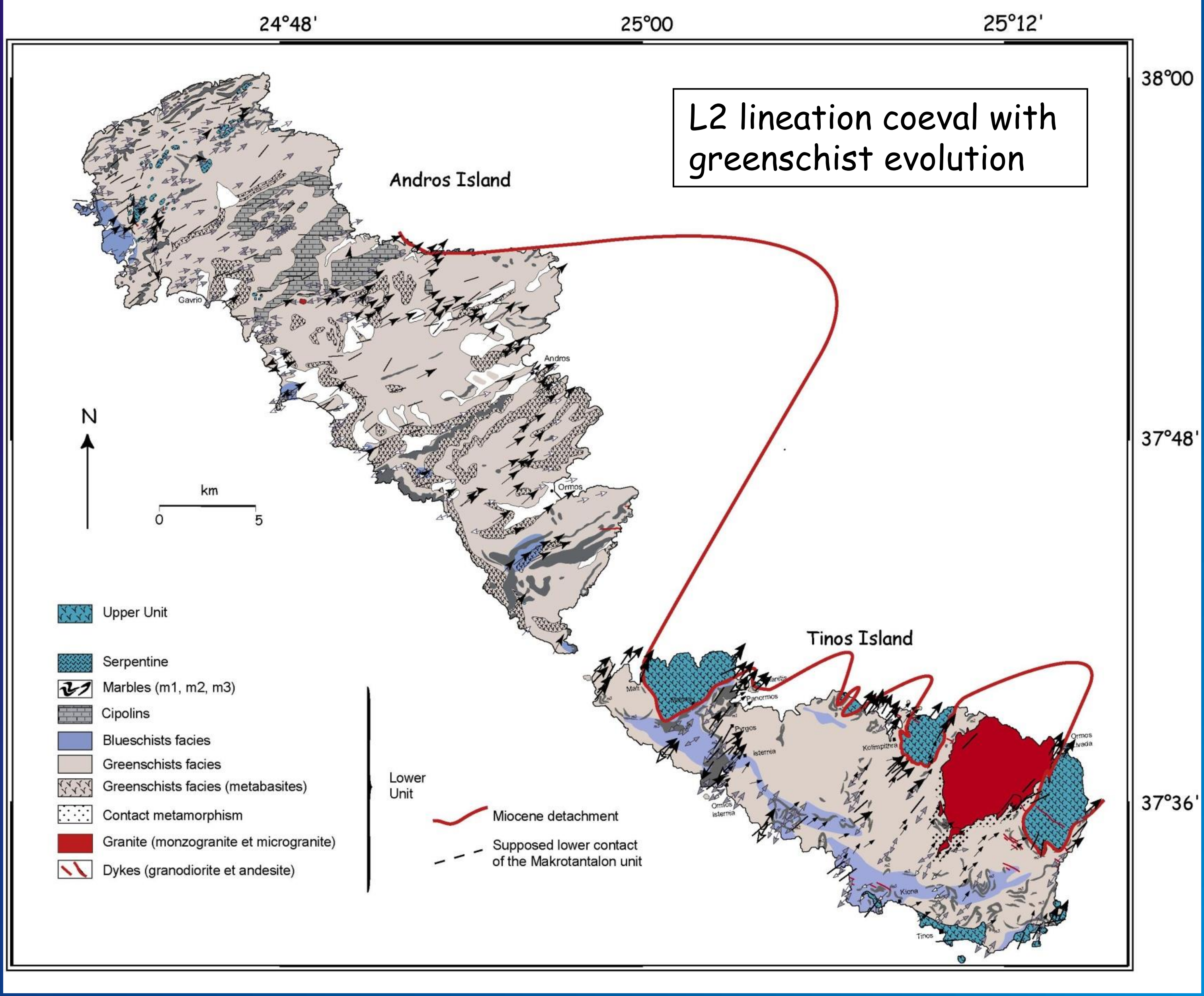
Some shallow-dipping faults can thus be considered as having developed with precursory structures such as ductile shear zones. However, shear zones do not consist of surfaces of displacement discontinuity; they are not themselves, strictly speaking, faults. So the term reactivation, commonly understood as sliding along a pre-existing discontinuity, should be used with care. Reactivation corresponds here to a continuum of shear from ductile to brittle with an increasing localization within a precursory shear zone, that locally modified either the mechanical properties of the rocks, the local strain rate or the local stress field to enhance shallow-dipping brittle faulting during decrease of P and T. Noticeably, only the more steeply dipping shear zones show reactivation as brittle faults.



(Lacombe et al., 2013)



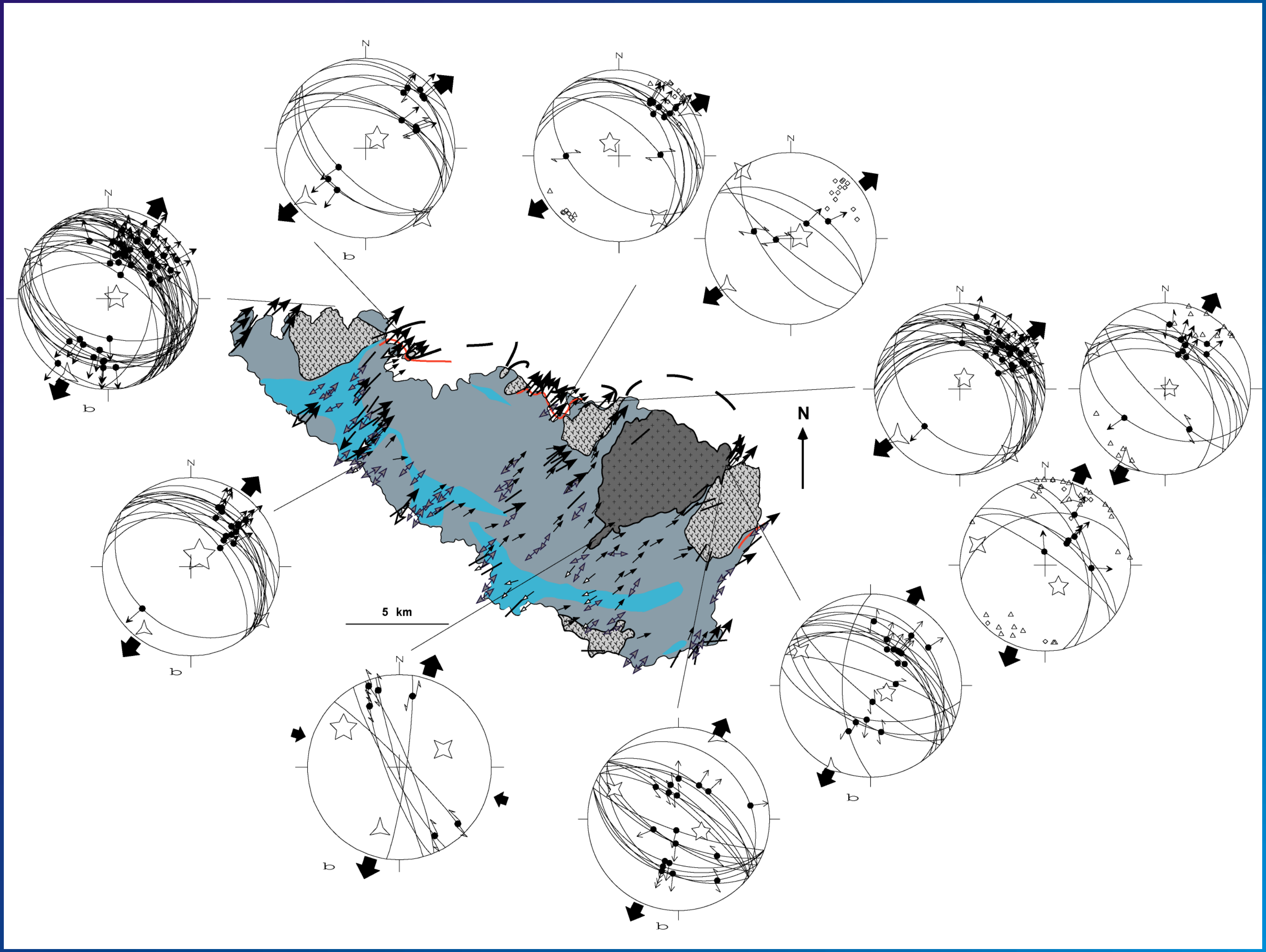
(Lacombe et al., 2013)



(Mehl, PhD thesis, 2006)

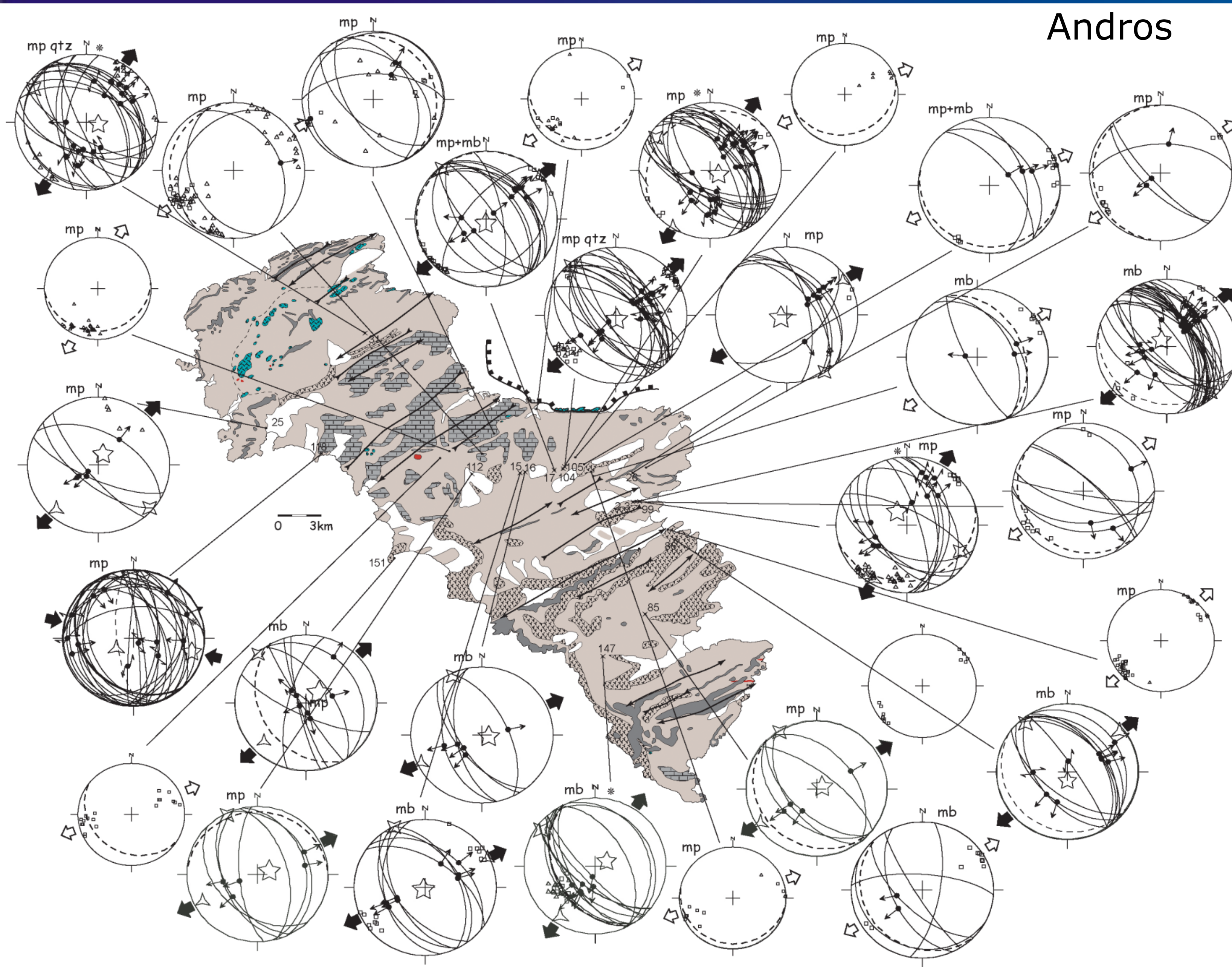
Ductile to brittle continuous evolution

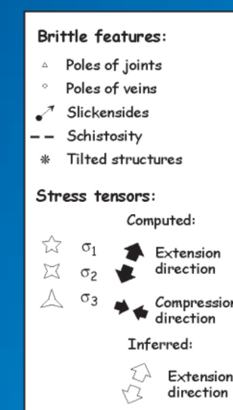
Tinos



(Mehl et al., 2005)

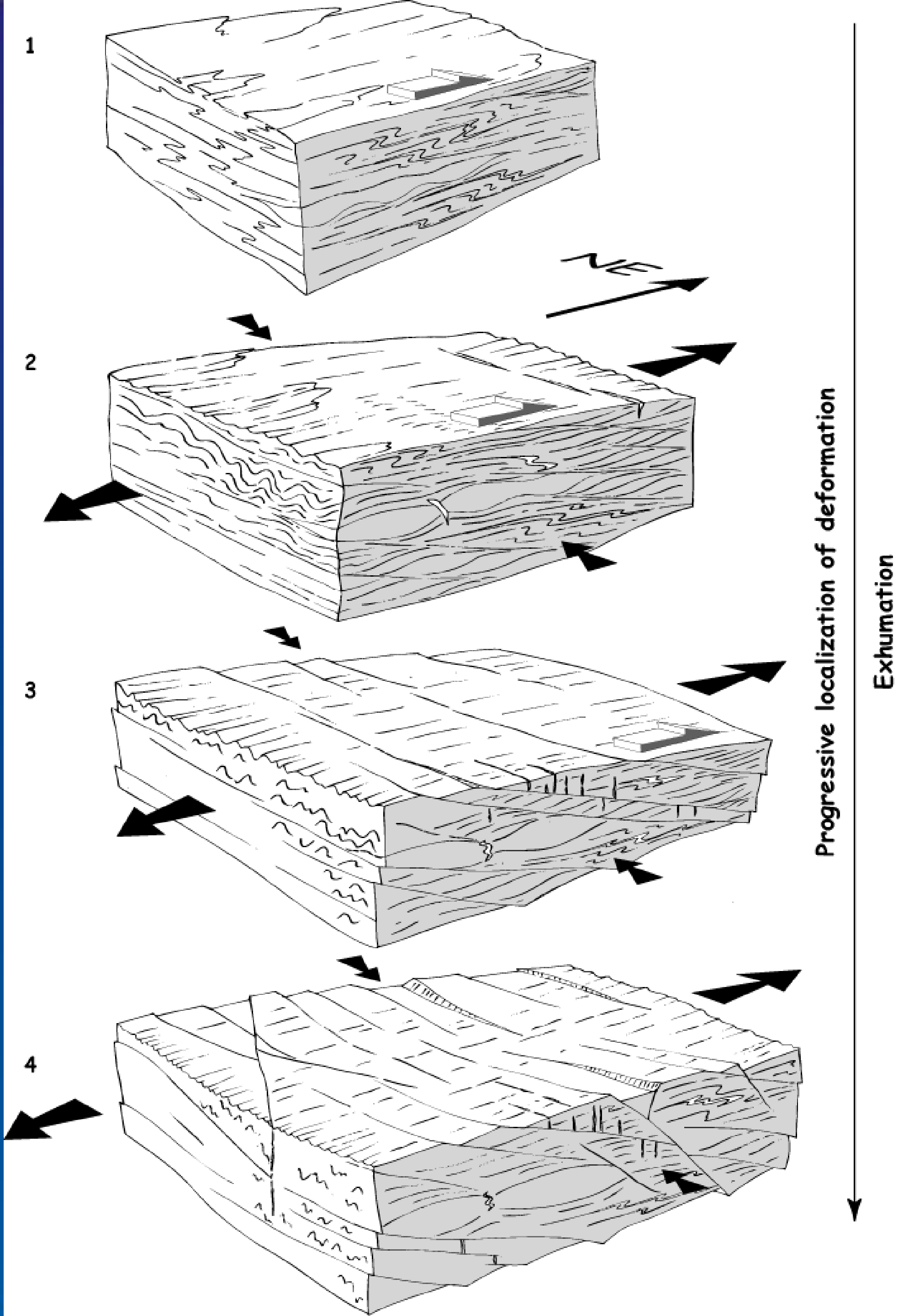
Ductile to brittle continuous evolution



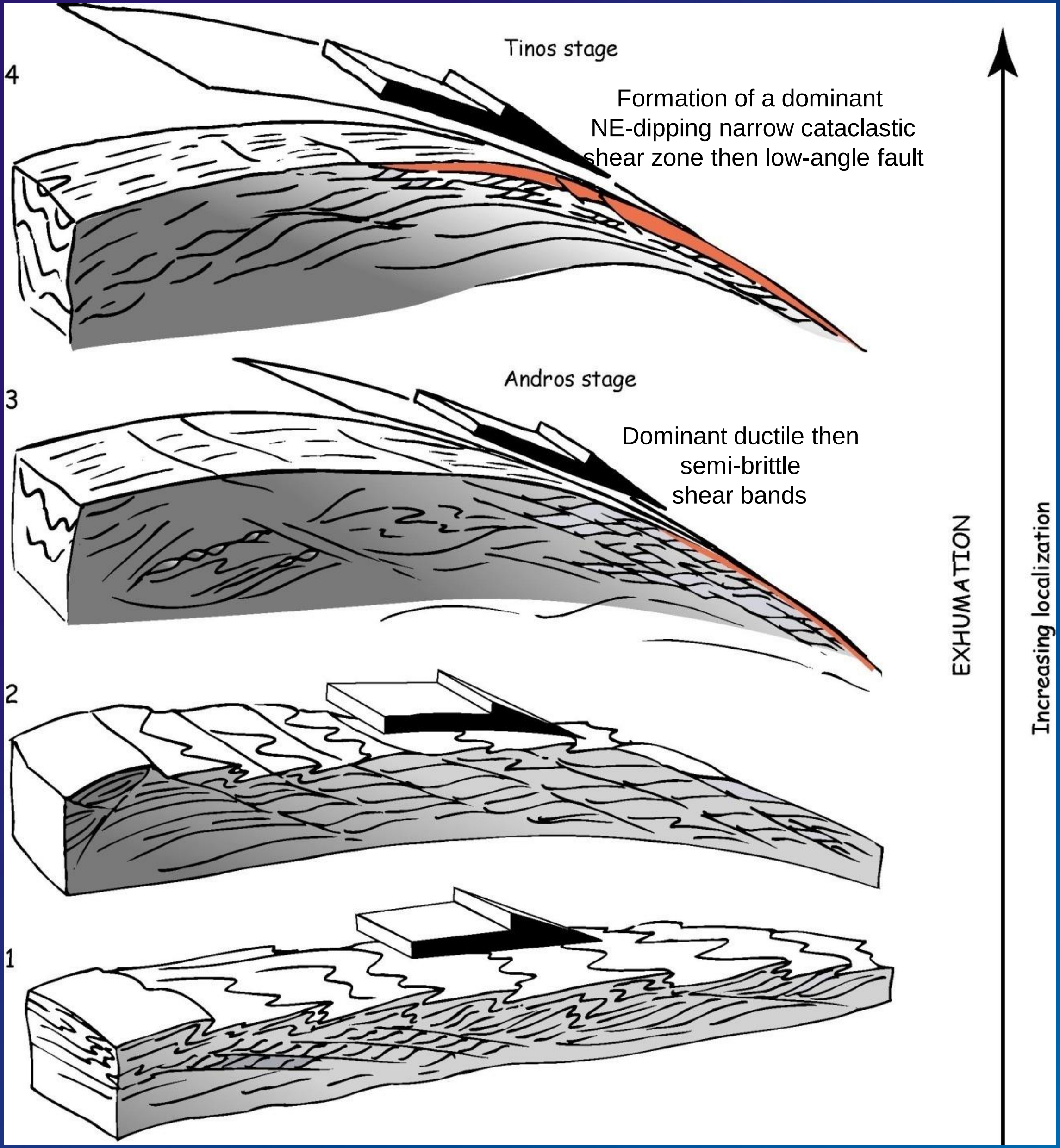


(Mehl et al., 2007)

Strain localization sequence at the outcrop scale



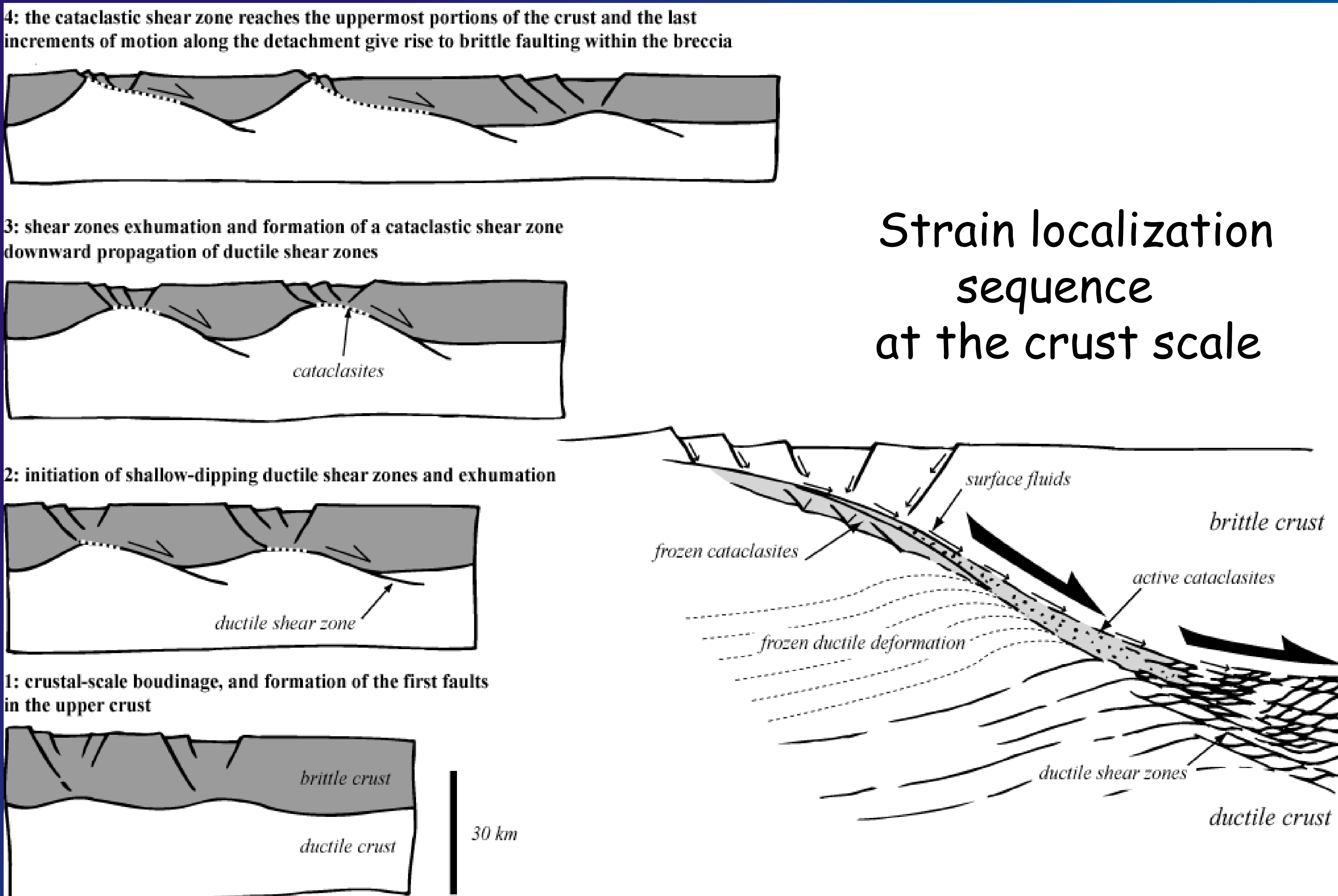
(Mehl et al., 2005)



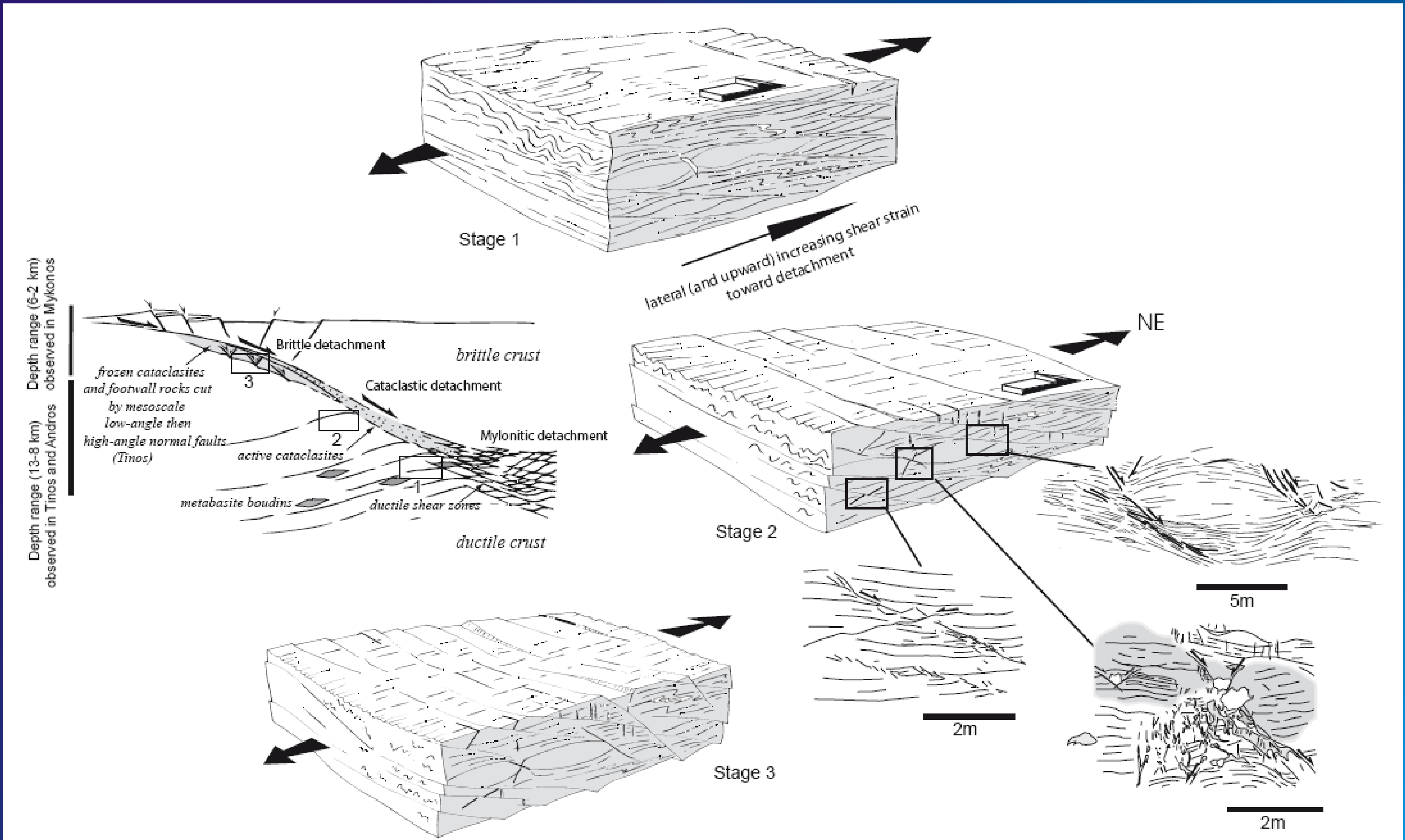
Strain localization
at
the island scale

(Mehl et al., 2007)

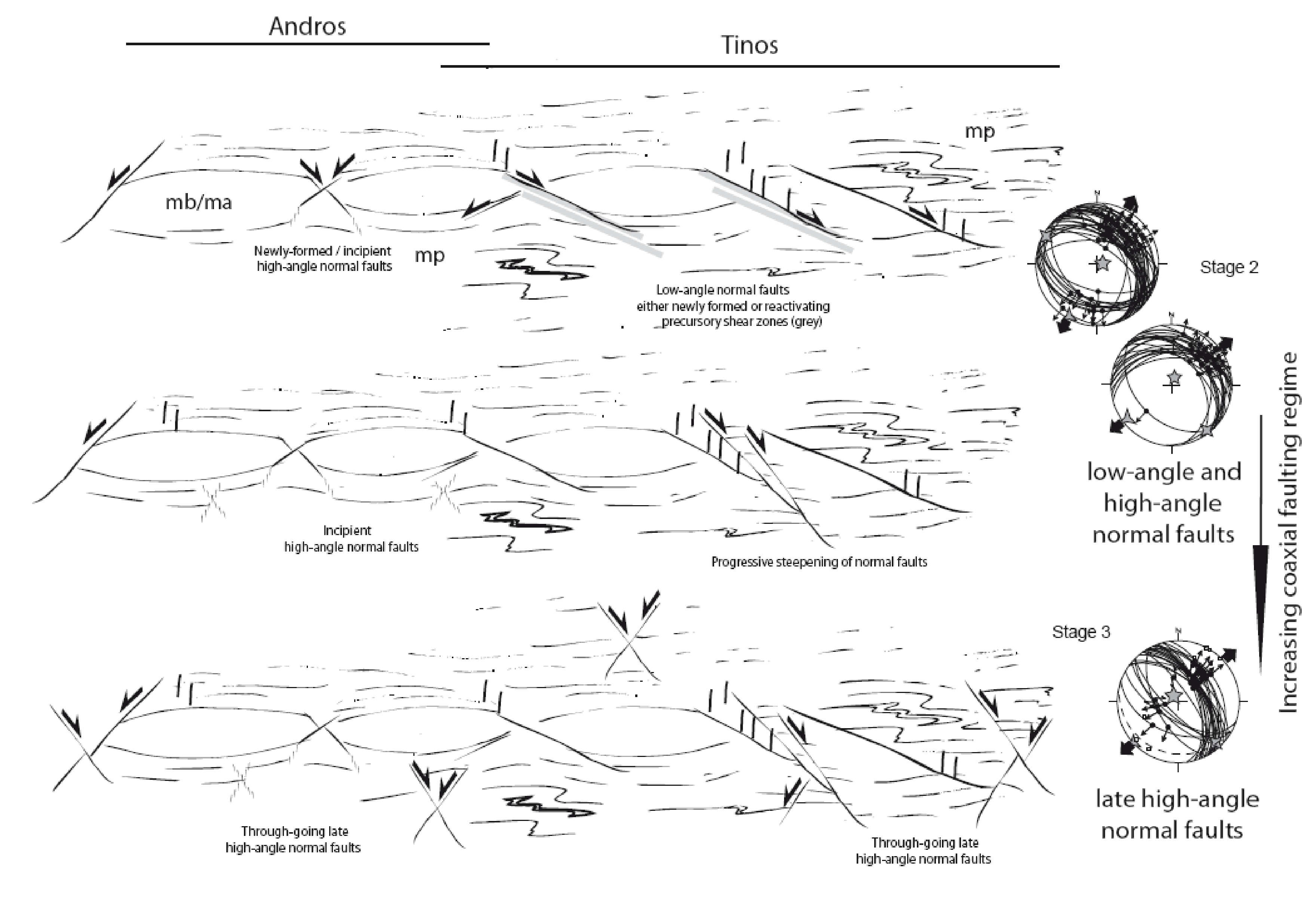
Strain localization sequence at the crust scale



(Mehl et al., 2005)



(Lacombe et al., 2013)



(Lacombe et al., 2013)

Primary localization of ductile deformation is closely linked to boudinage. Extensional shear zones often localize in the less competent matrix at the tips or in the necks between boudins of early veins or competent lithologies (metabasites, marbles), that is, in zones of stress concentration. The initiation of shear zones therefore postdated boudinage, in good agreement with the increasing degree of localization from boudins to shear zones.

Rheological heterogeneities and boudinage have to be considered as an efficient factor to initiate localization. First, boudinage localizes deformation at intervals depending on the contrast of viscosity between strong and weak layers and of the thickness of the competent layers. Once initiated, this process is facilitated because the resistant layers are thinner and thus easier to deform at the tips or in the neck between boudins. There, the local increase of strain rate and/or stress concentrations allow development of extensional shear zones.

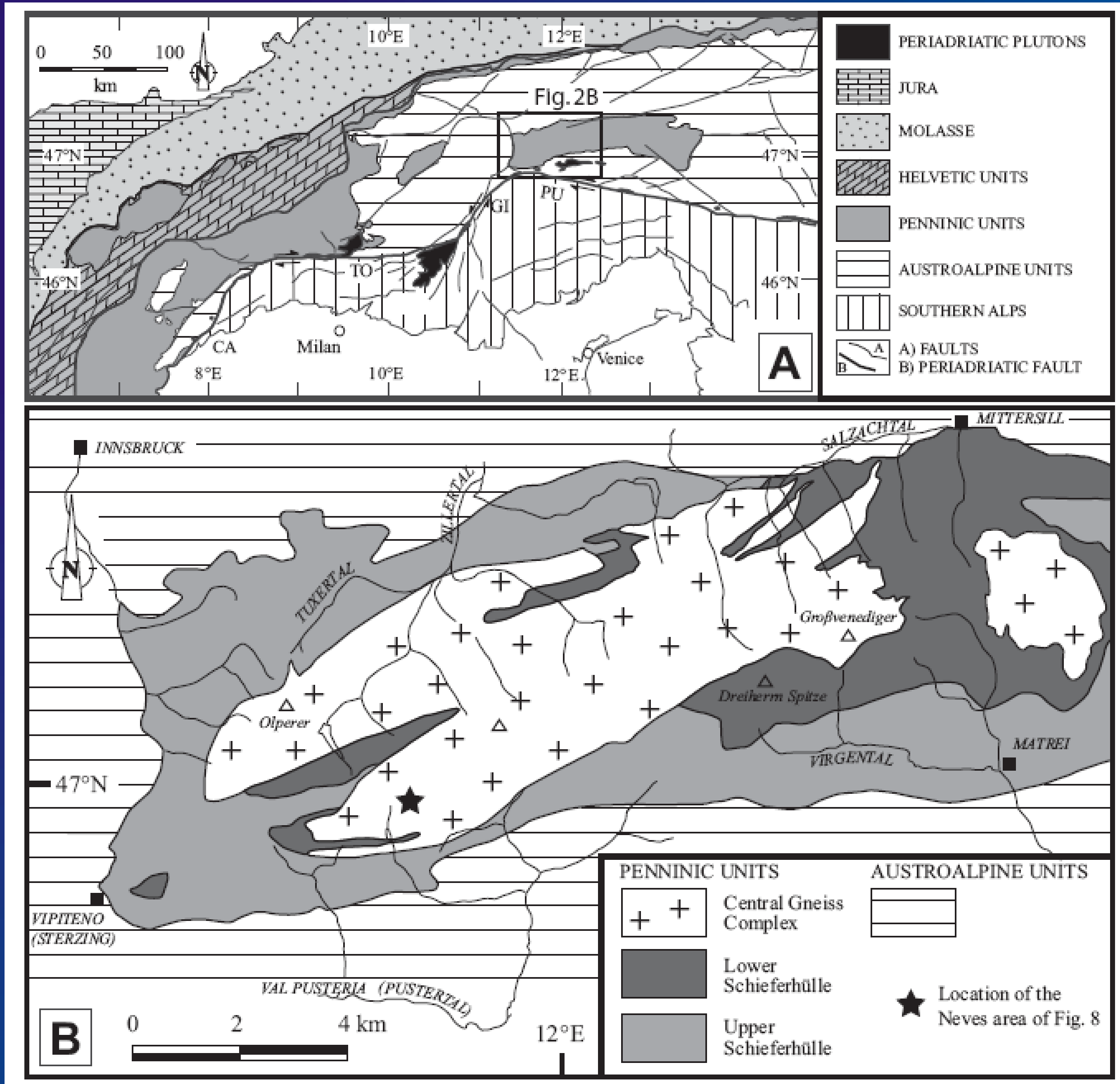
The evolution toward brittle behavior is marked by the reactivation of the extensional shear zones as low-angle normal faults, by the progressive straightening of extensional structures and the development of en echelon arrays of veins or joints (mode I opening.

The ultimate step of localization consists in sliding across the *en echelon* patterns and the formation of steeply-dipping normal faults generally displaying conjugate patterns. The lithological control is also very important during the last brittle increments of deformation : brittle behavior is preferentially observed (and presumably appeared earlier) in more competent layers (metabasites and quartzitic layers). Although the first-order scenario we propose is in good agreement with the sequential evolution of structures from ductile to brittle, the rheological behavior of materials appears as a key point in the localization process : rheological heterogeneities probably had a dominant effect on the depth where the structures initially localized during their way back to the surface.

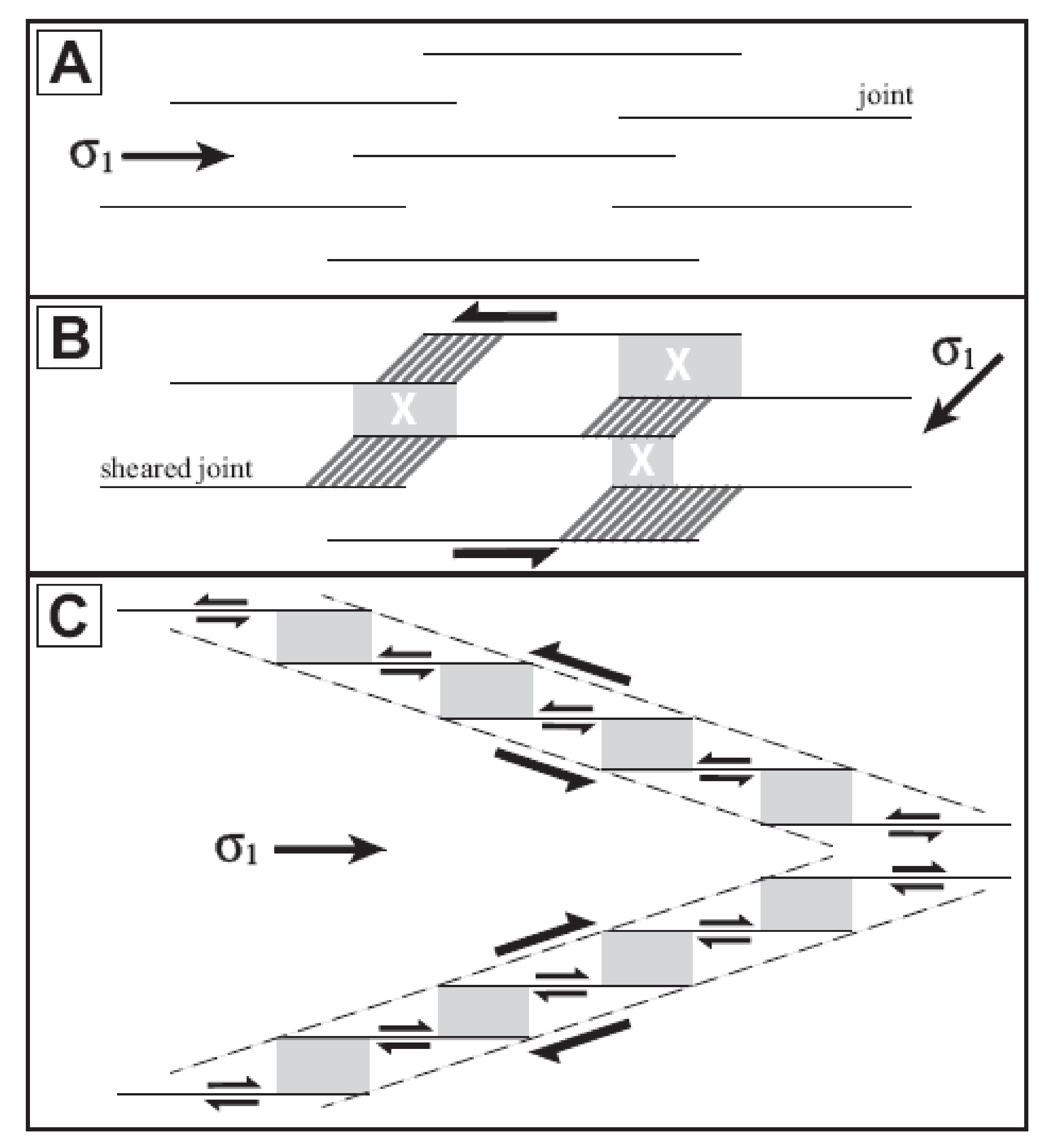
The study of exhuming metamorphic rocks is complementary to that of Crider and Peacock [2004] who reviewed the styles of initiation of faults in the upper crust within previously unfaulted (sedimentary) rocks. The various styles they recognized are partially also encountered, such as initiation as mode I fractures or as precursory shear zones.

The study documents the influence of preexisting rheological and structural anisotropy and the likely control of strain rate variations, local change of rock properties and or local stress perturbations by or within ductile or semi-brittle precursory shear zones on the initiation and the geometry of brittle faults.

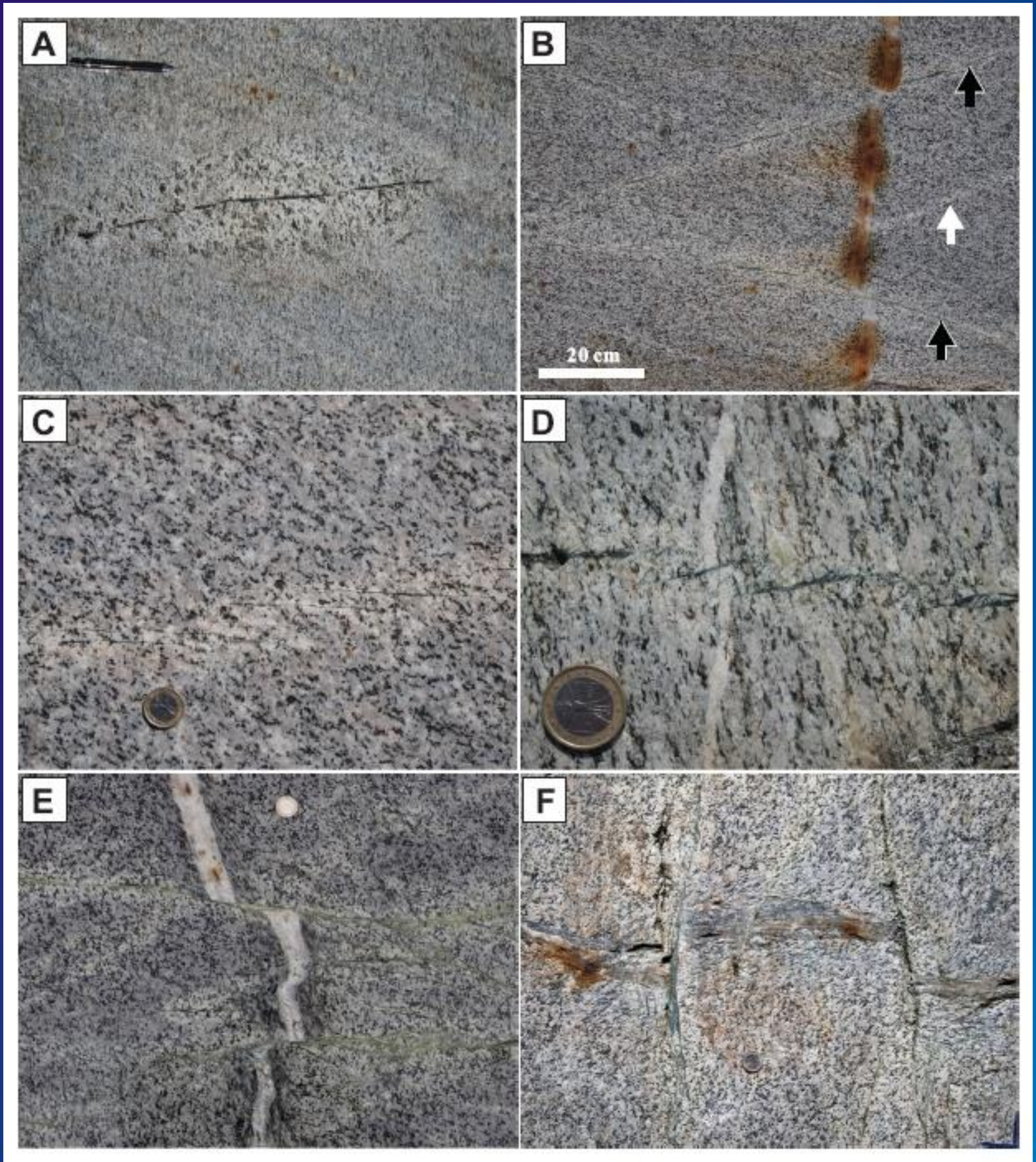
Initiation and geometry of faulting in granitic rocks



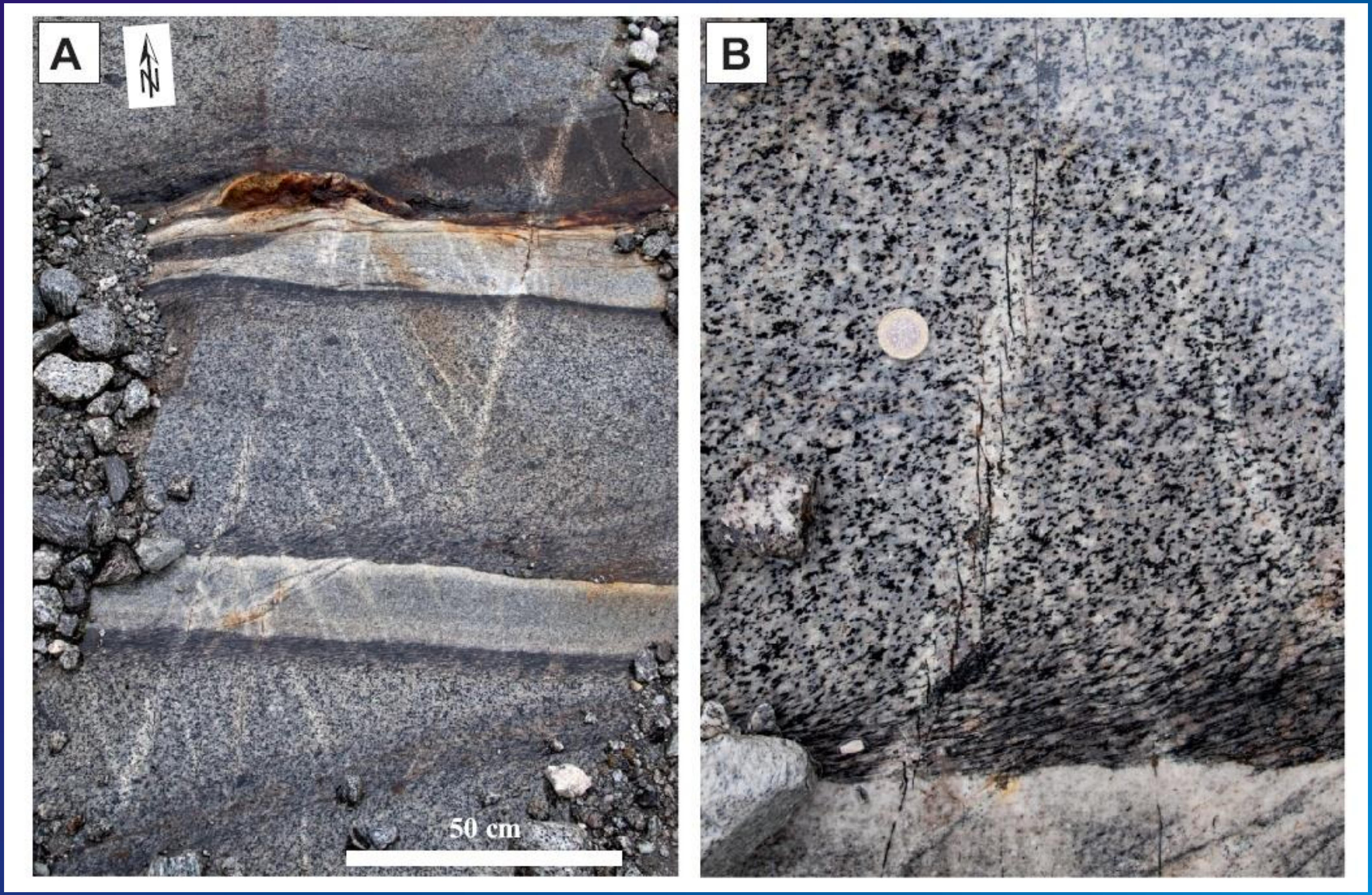
Pennacchioni and Mancktelow, 2013



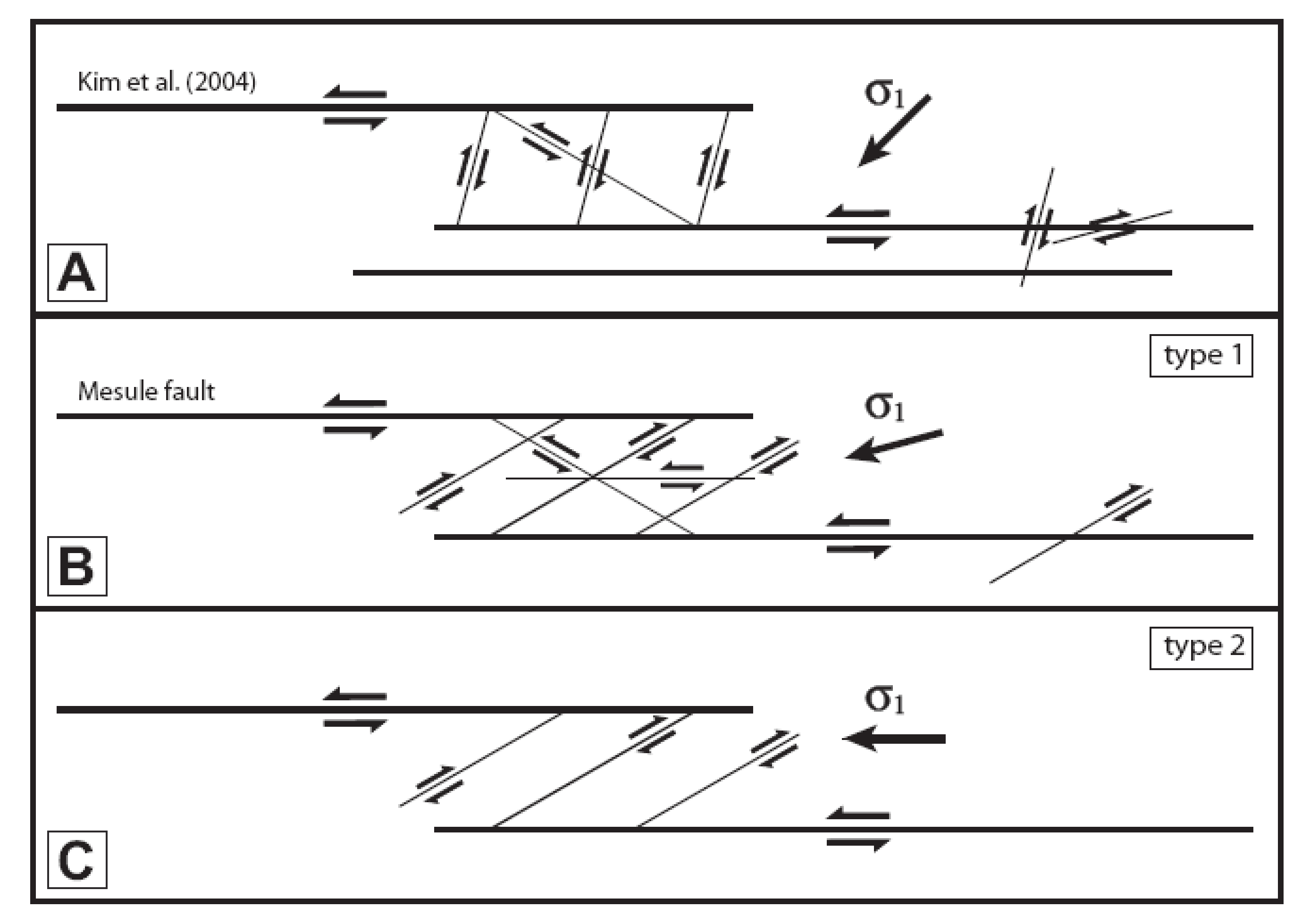
Pennacchioni and Mancktelow, 2013



Pennacchioni and Mancktelow, 2013



Pennacchioni and Mancktelow, 2013



Pennacchioni and Mancktelow, 2013

The Neves area provides unusually detailed field constraints on fault initiation, linkage, and displacement accumulation within non bedded and relatively isotropic granitoid rocks at the base of the brittle crust, where neither a free upper surface nor substantial volume change (e.g., by veining and pressure solution) was a controlling factor in accommodating fault linkage and displacement transfer.

Relatively isotropic and unfractured metagranitoid rocks are widespread in the middle to lower crust, and the development and linkage of new faults in such rocks during synorogenic exhumation into the upper brittle crust must be a common occurrence.

The Neves area provides a model of fault development in host rocks free of exploitable discontinuities at deeper crustal levels near the base of the brittle seismogenic crust, where many large seismic events occur.

Pennacchioni and Mancktelow, 2013

Thank you for your attention...

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