Stress, strain, deformation mechanisms, fluid pressure and fluid flow in deforming sedimentary rocks : what we can learn from integrated studies of folded strata

Professor Olivier LACOMBE

How to go farther than the simple geometrical and kinematic description of folds in the upper continental crust ?
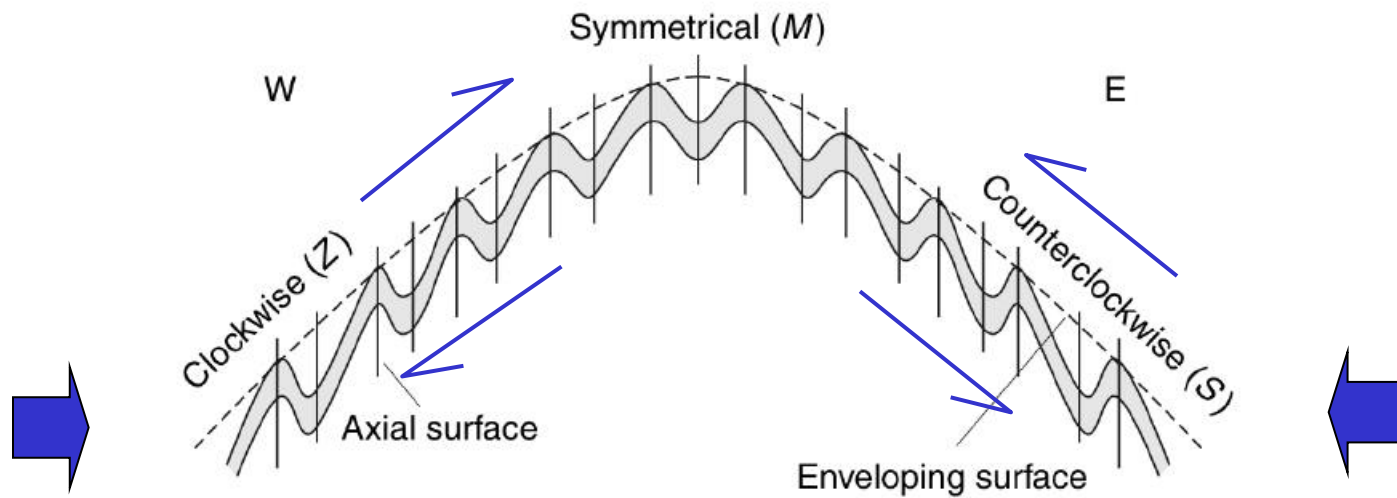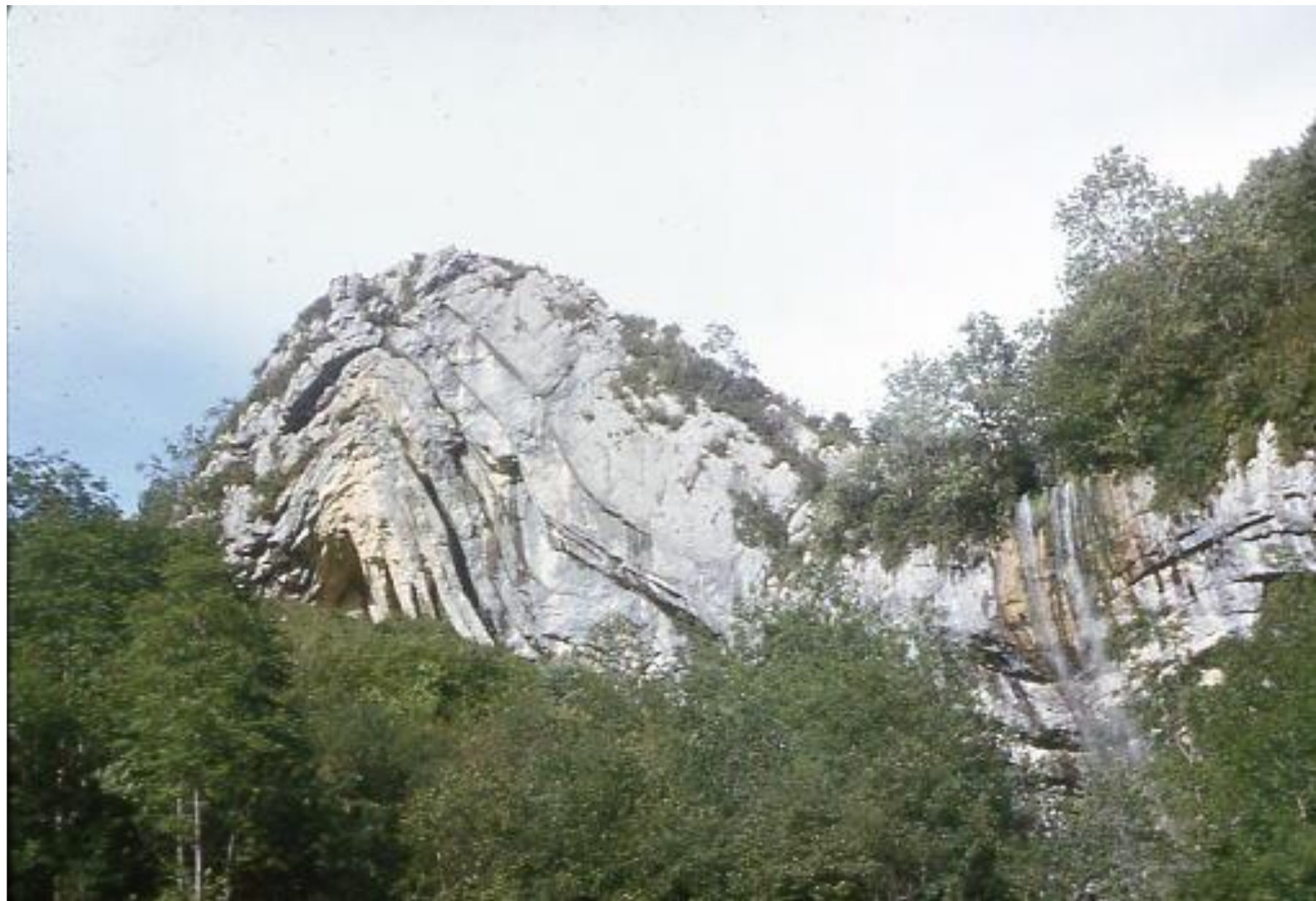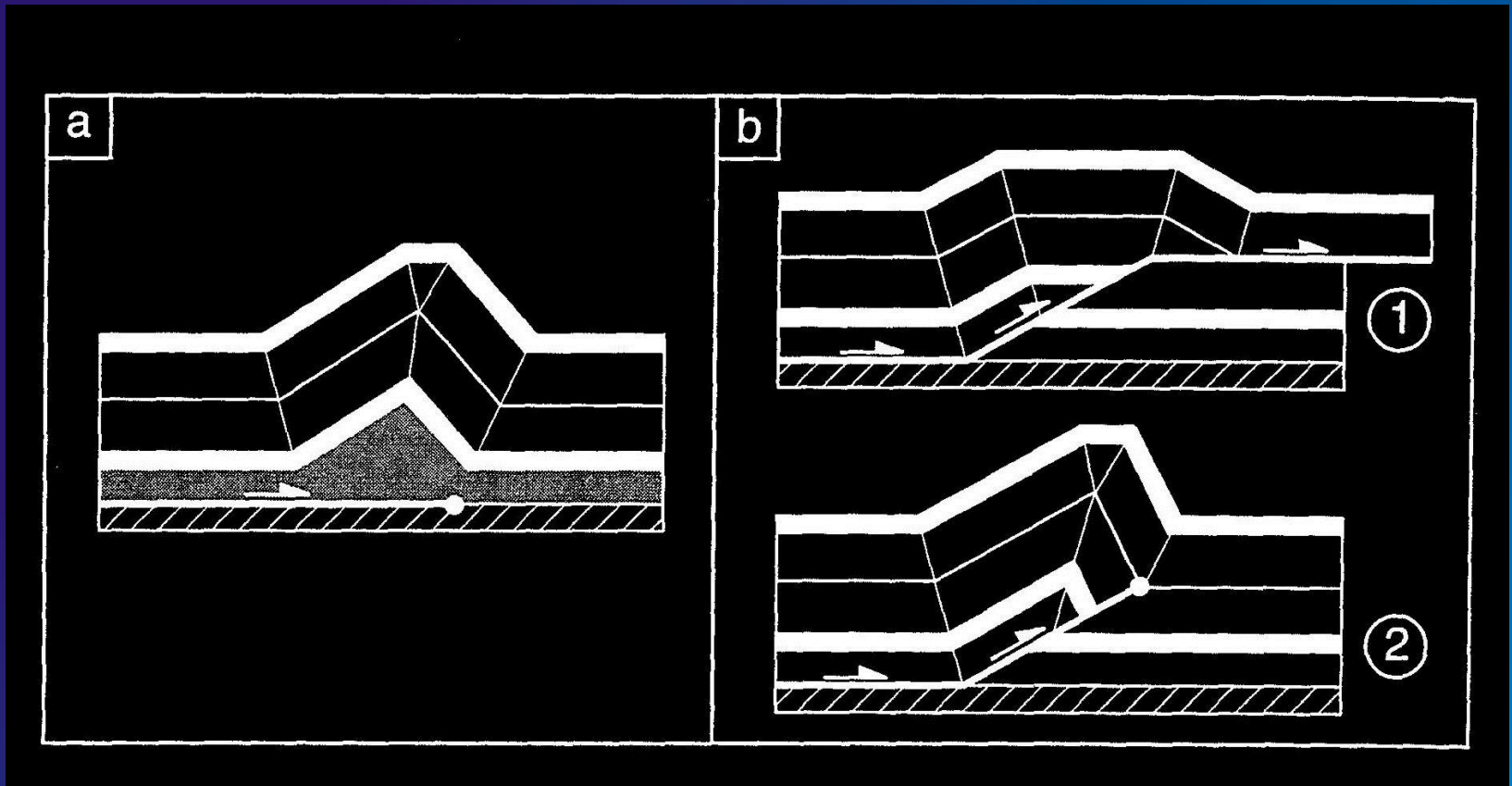
Disharmony

« detachment fold » : strata are folded in order to accommodate sliding along the flat and deformation within the décollement level

« fault-bend fold » : folding above a ramp connecting obliquely two décollement levels

« fault-propagation fold » folding develops contemporaneous with ramp propagation
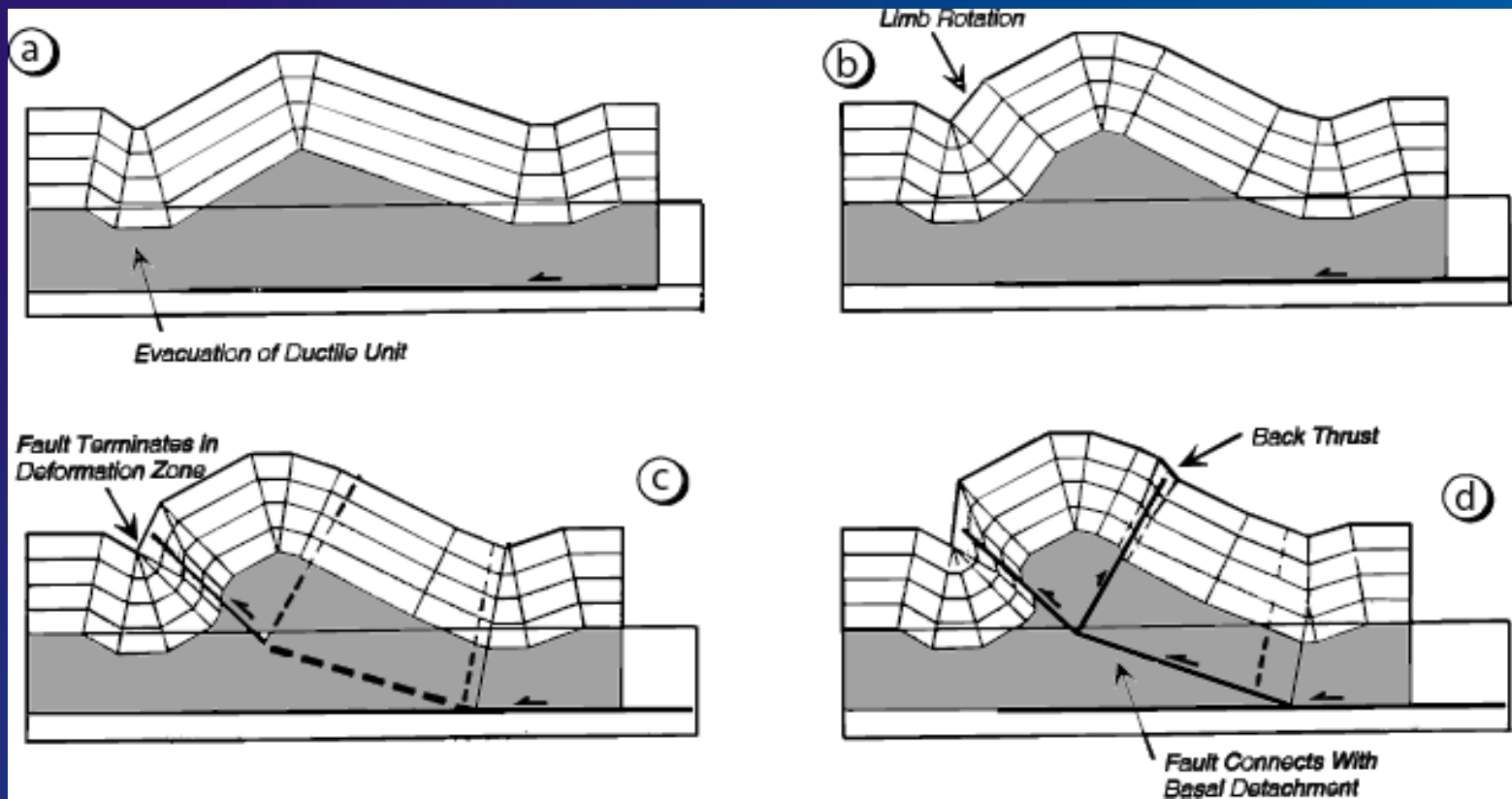
Décollement fold (Tadighoust, Ht Atlas, Maroc)

Courtesy D. Frizon de Lamotte
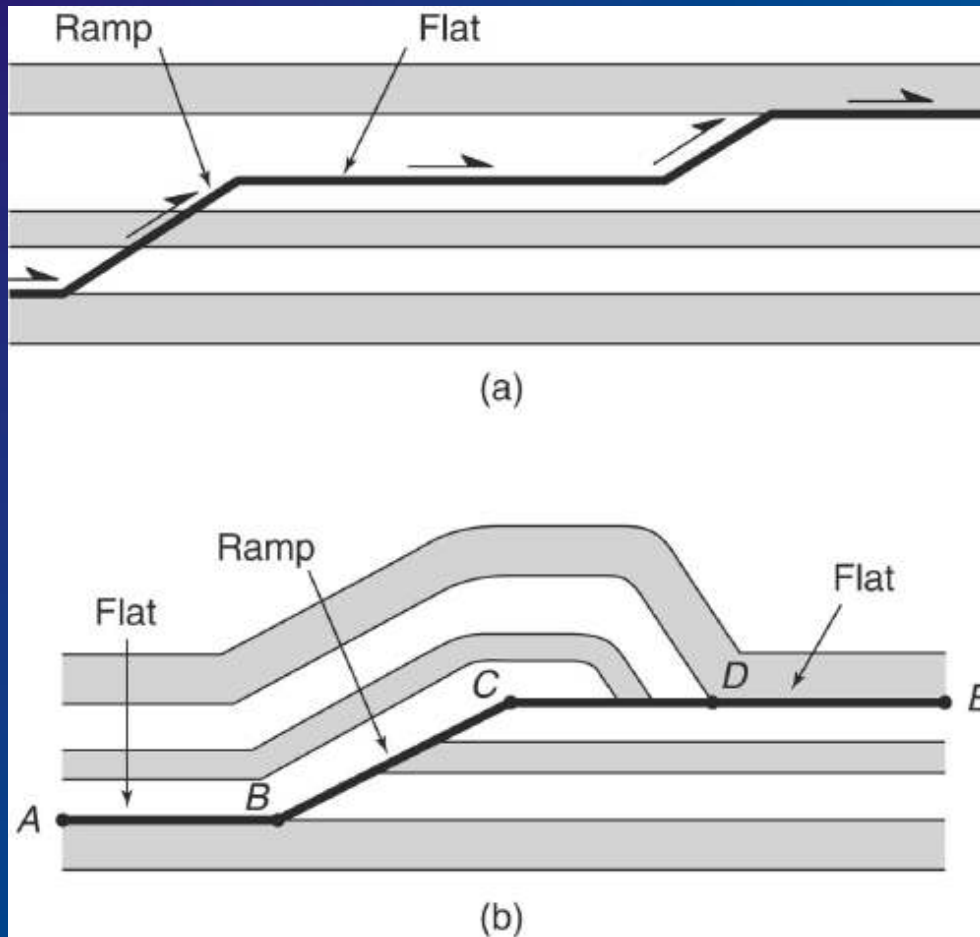
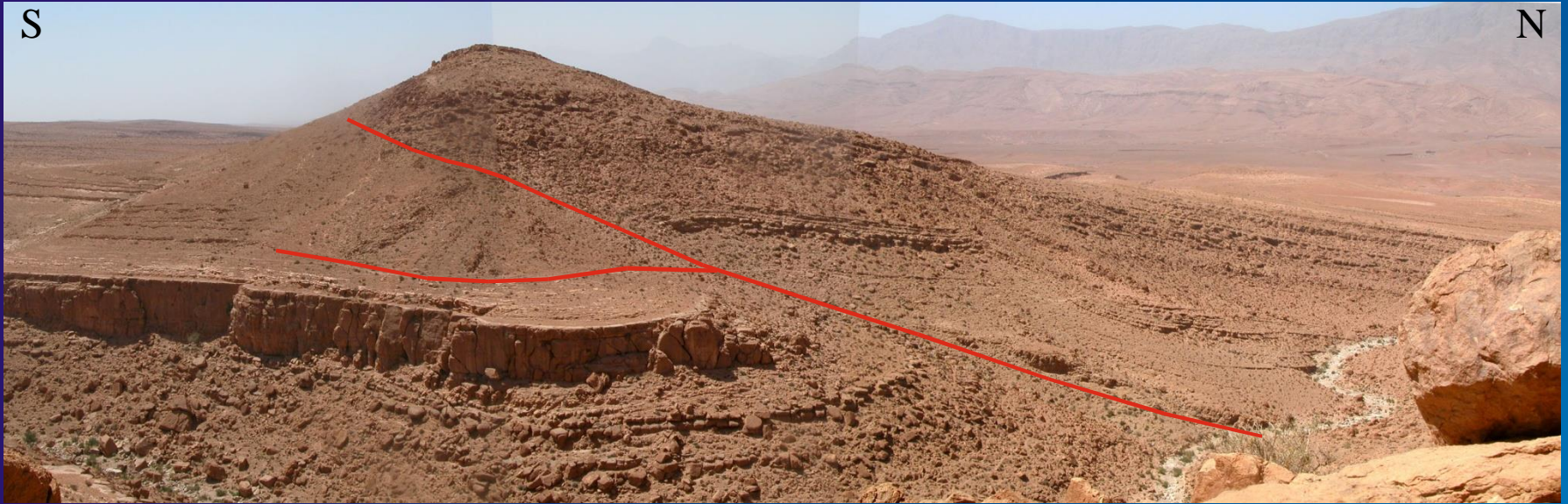Faulted décollement fold (Tadighoust, Ht Atlas, Maroc)

Courtesy D. Frizon de Lamotte

Development of late thrusts (Mitra, 2003)

Fault-bend fold
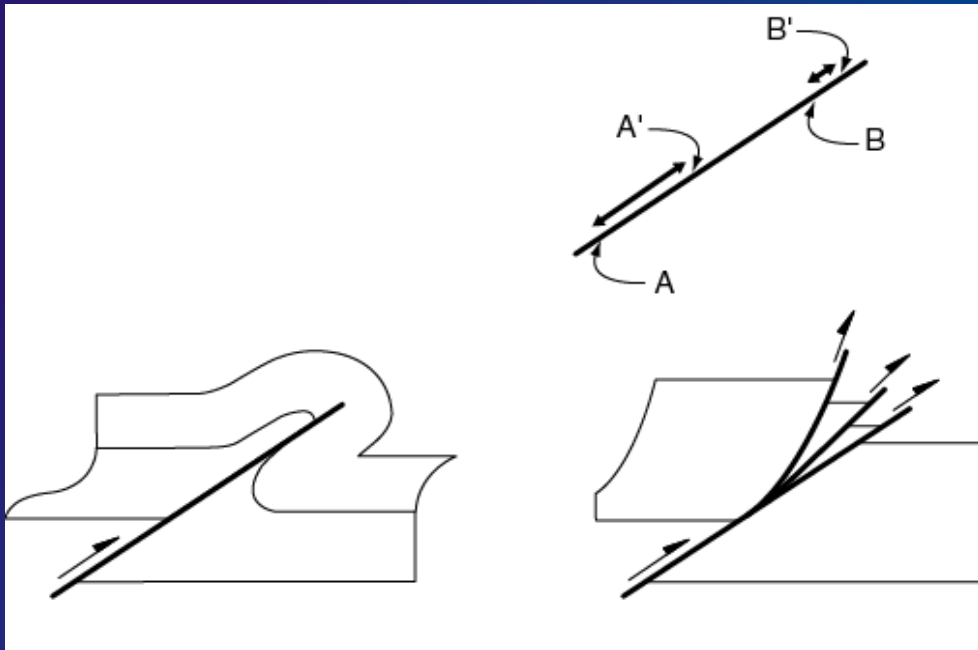
Fault-bend fold, Tadighoust, Ht Atlas, Maroc.
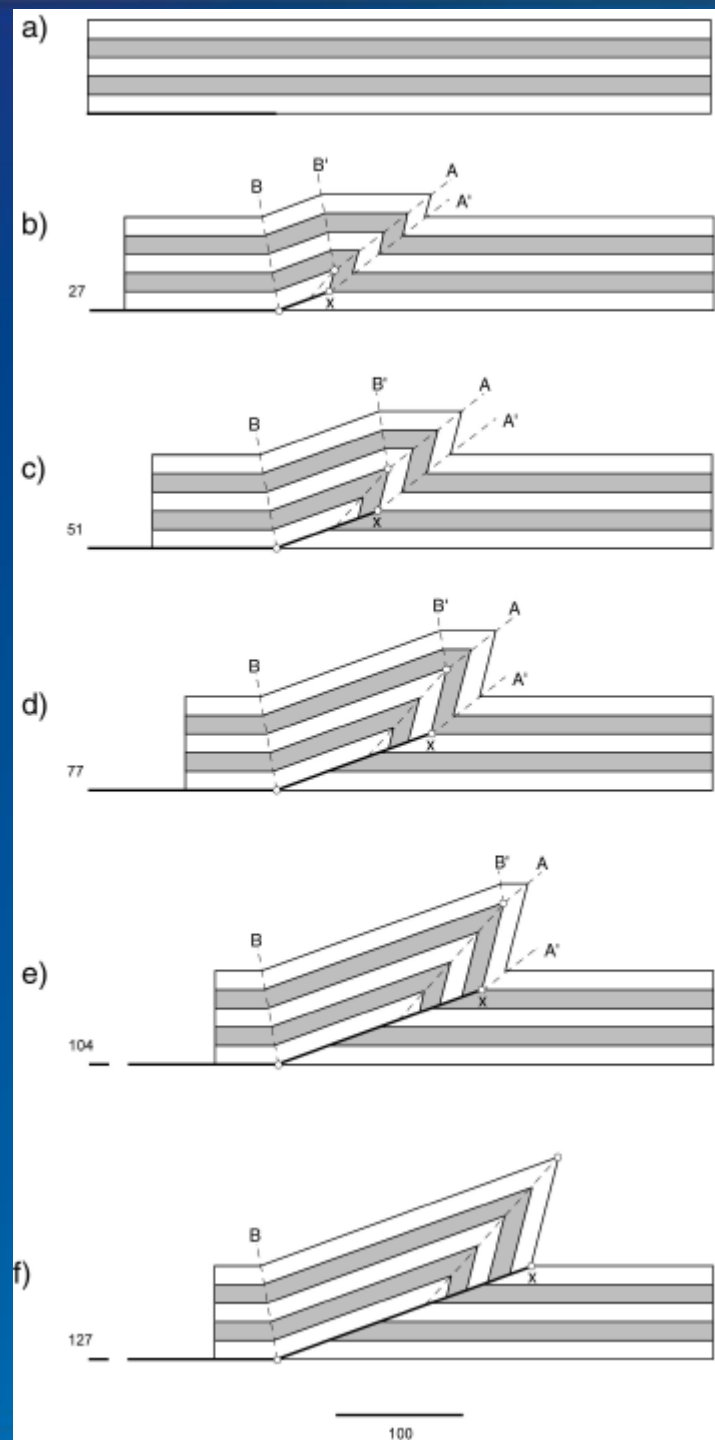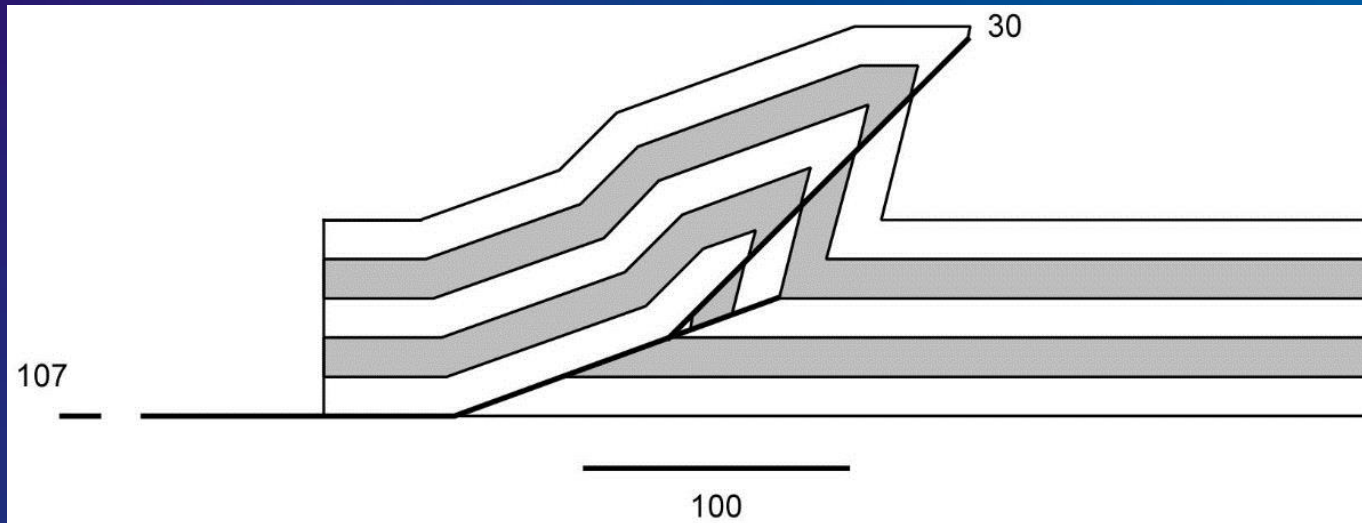
ramp

ramp

flat

flat

flat

Fault-propagation fold
(Suppe, 1985)

How to accommodate a displacement gradient along a fault ?
(modifed after Dahlstrom, 1969)

Possible secondary evolution : rupture of
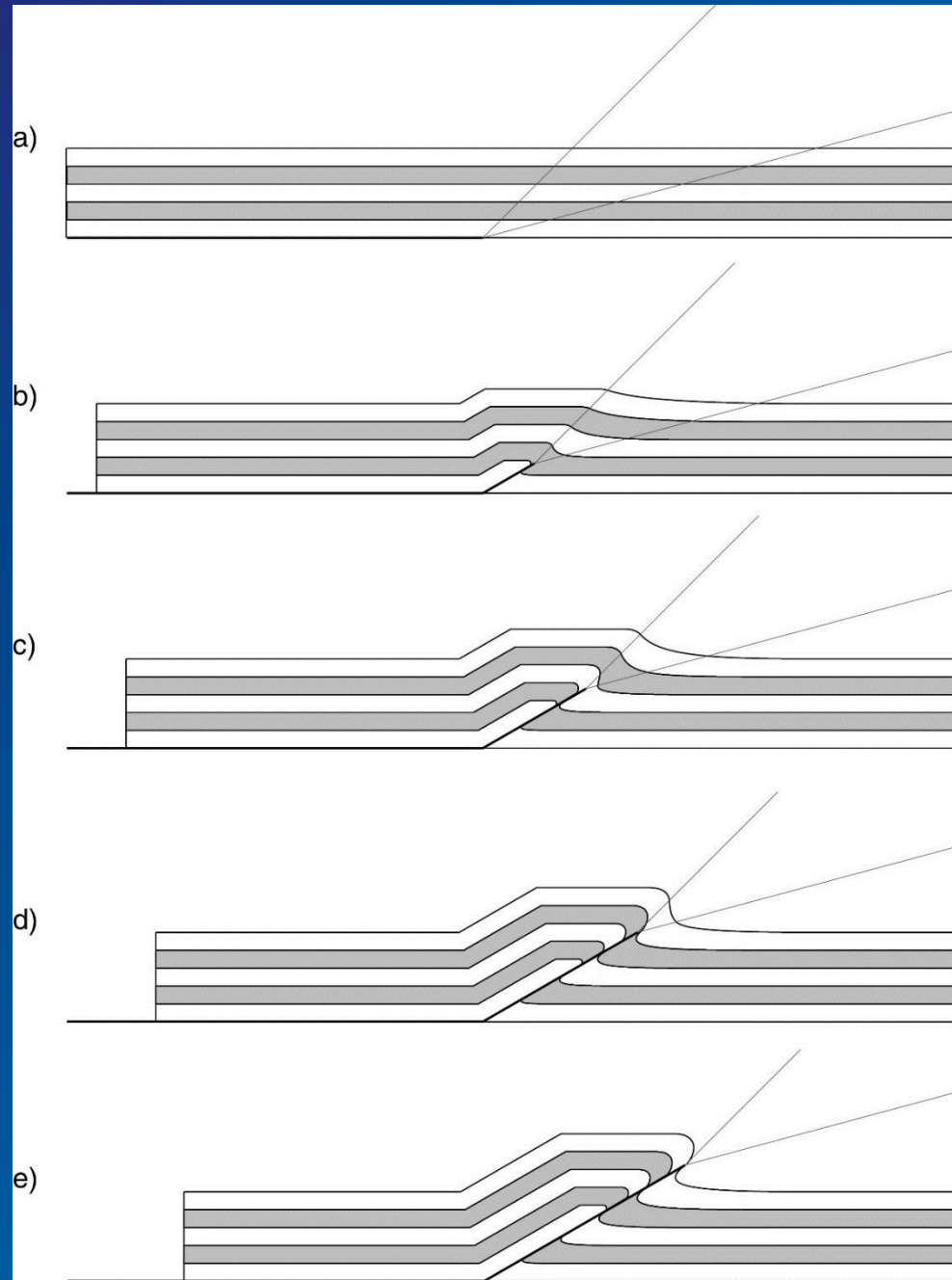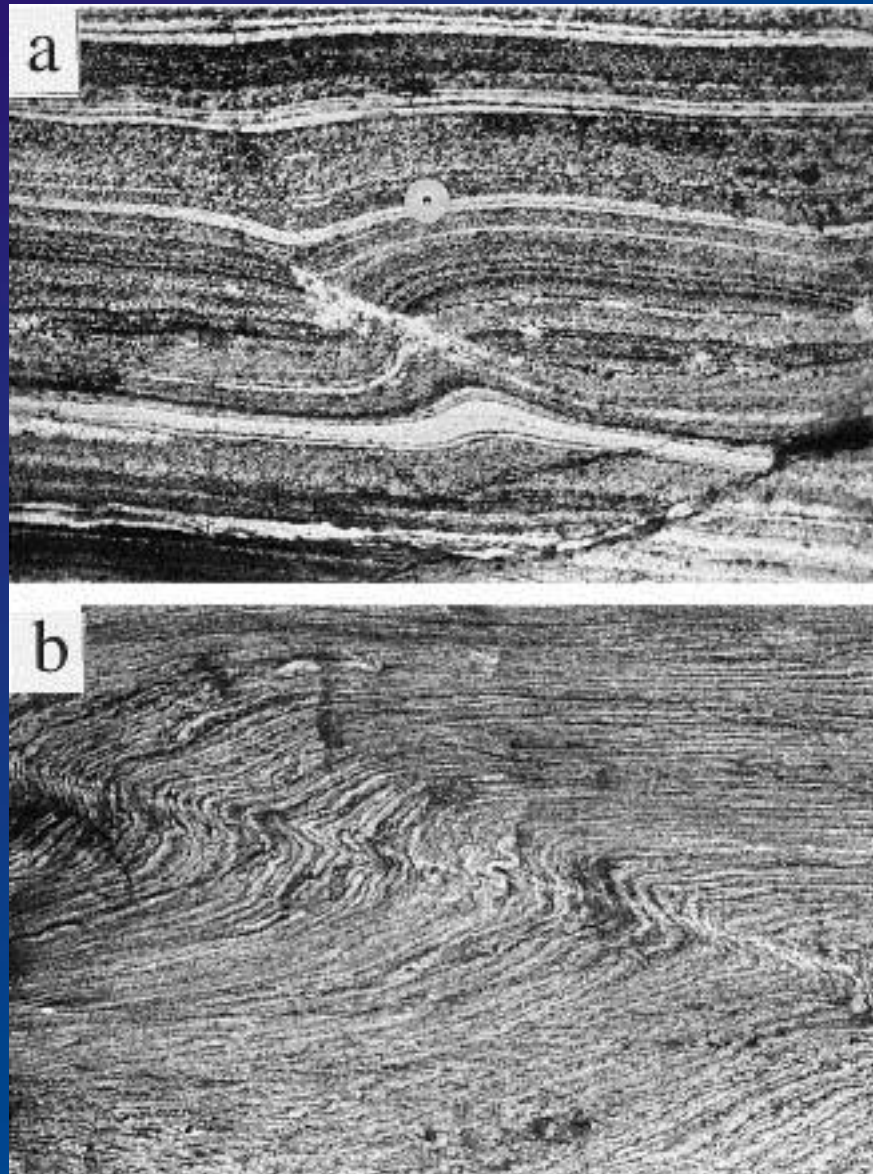the forelimb and development of a footwall
syncline
(Mercier et al., 1997)

Trishear folding :

Formation of a syncline and an anticline at the front of the fault. This fault then cuts across the forelimb of the fault-related fold.

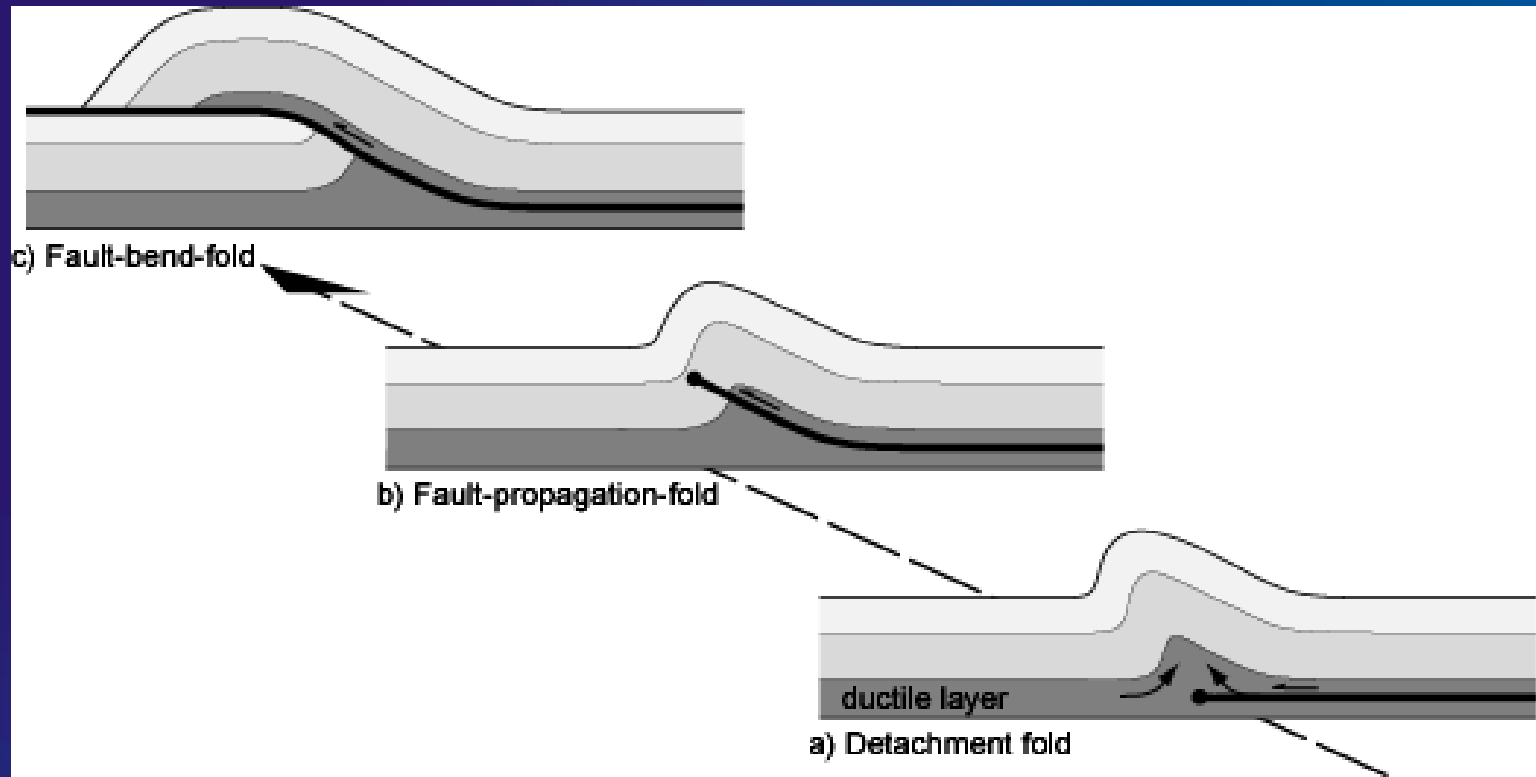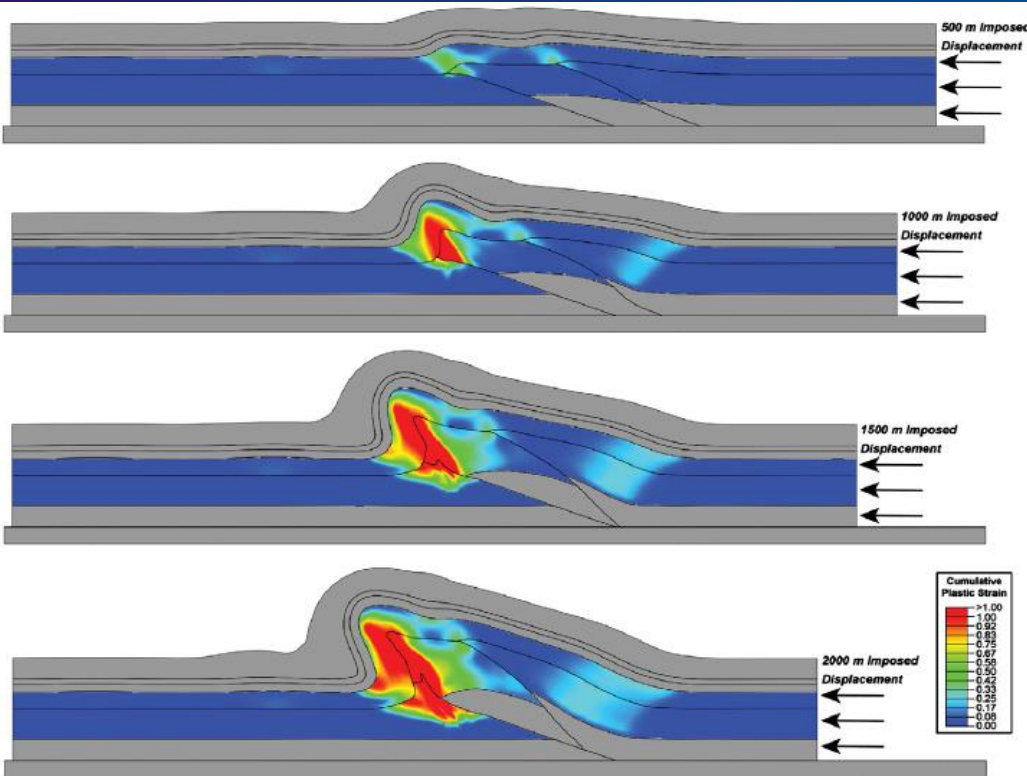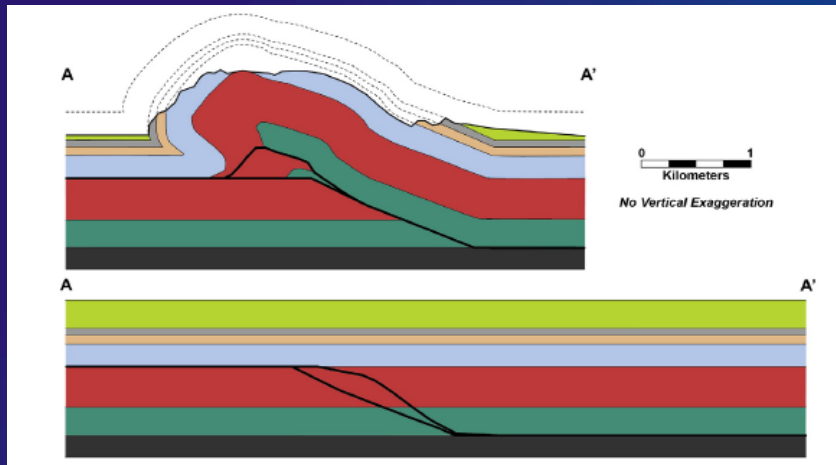Thickening and progressive rotation of the forelimb

The backlimb has a simple « kink » geometry.

Example of forelimb thickening

Unified model suggesting that instead of different processes, folding modes illustrate different stages of evolution of a single fold (Molinaro, 2004; Sherkati, 2004)

(Smart et al., 2012)

Geomechanical modeling can predict the onset of failure and the type and abundance of deformation features along with the orientations and magnitudes of stresses. This approach enables development of forward models that incorporate realistic mechanical stratigraphy, include faults and bedding-slip surfaces as frictional sliding interfaces, reproduce the overall geometry of the fold structures of interest, and allow tracking of stress and strain through the deformation history.
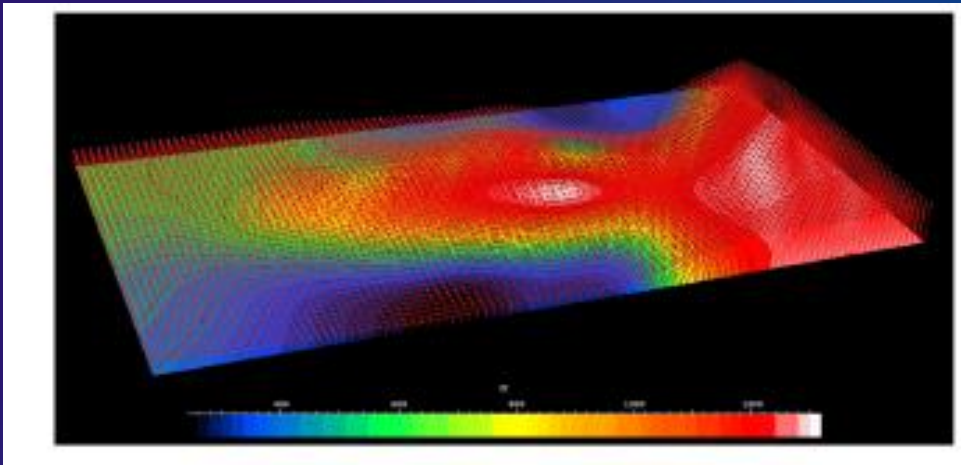
The use of inelastic constitutive relationships (e.g., elastic–plastic behavior) allows permanent strains to develop in response to the applied loads.
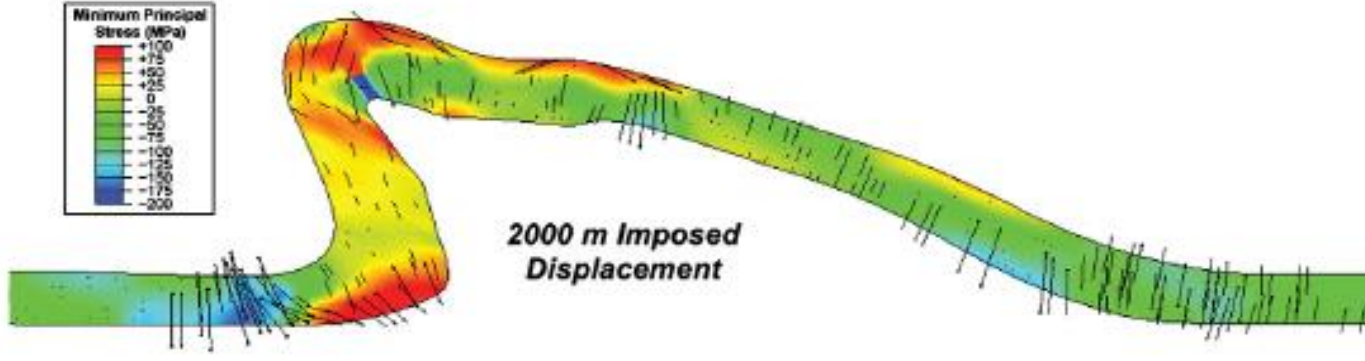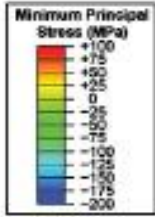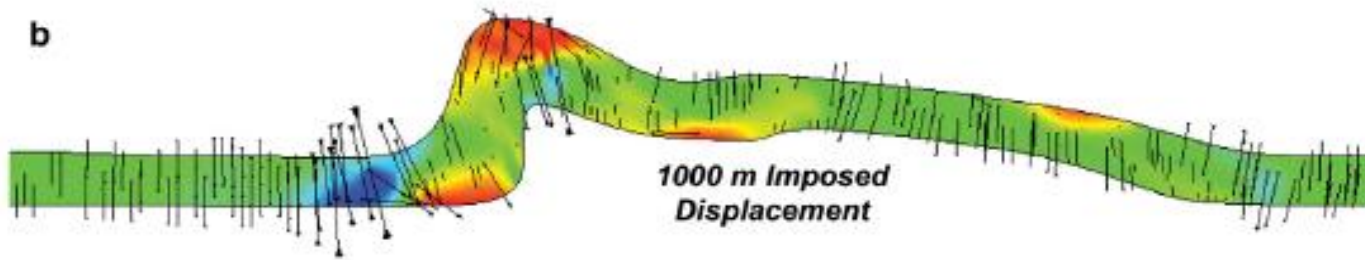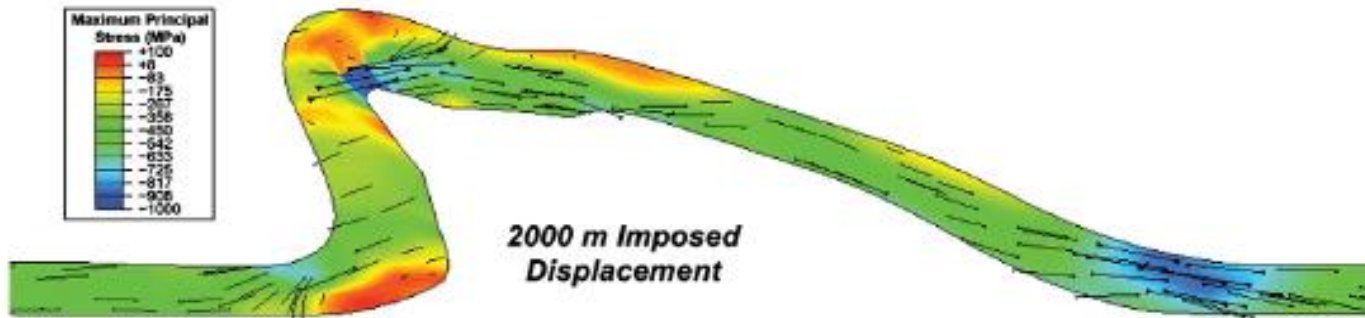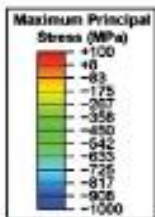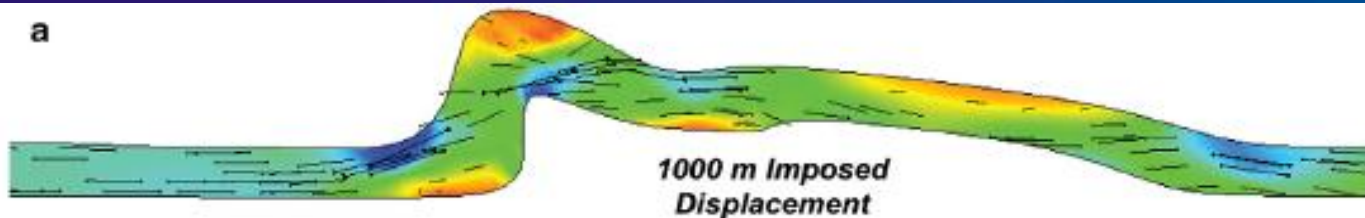
(Smart et al., 2012)

(Sassi et al., 2012)

The 3D restoration of a fold provides the external displacement loading conditions to solve, by the finite element method, the forward mechanical problem of an idealized rock material with a stress-strain relationship based on the activation of pervasive fracture sets.
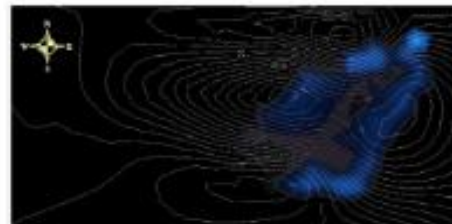
In this elasto-plasticity constitutive law, any activated fracture set contributes to the total plastic strain by either an opening or a sliding mode of rock failure. Inherited versus syn-folding fracture sets development can be studied using this mechanical model.
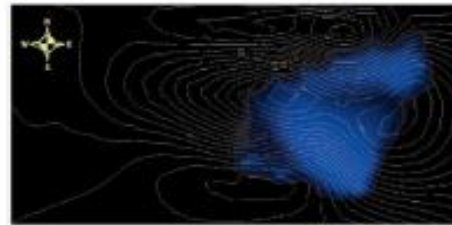

STEP 1

STEP 2

STEP 3
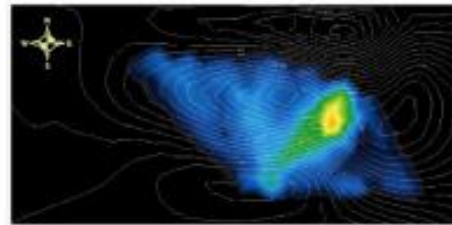
STEP 4
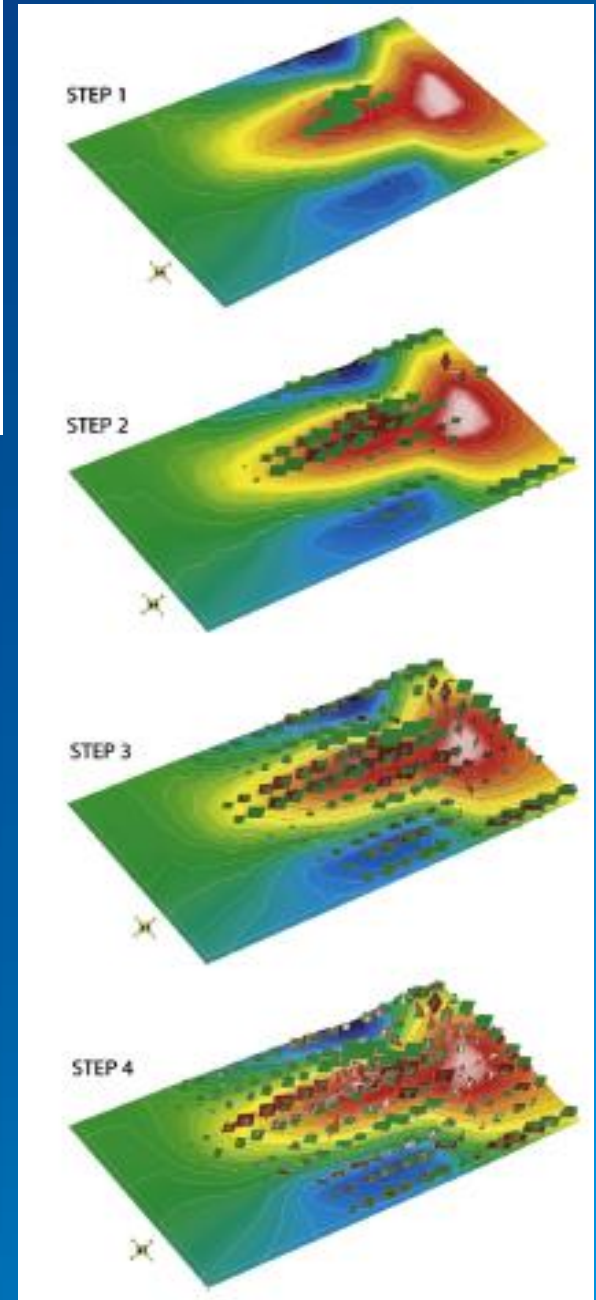
(Sassi
et al., 2012)

SLIDING MODE FRACTURES   OPENING MODE FRACTURES

Fracture class
azimuth

NS

NE-SW

EW

NW-SE

N120

0   0.02   0.04
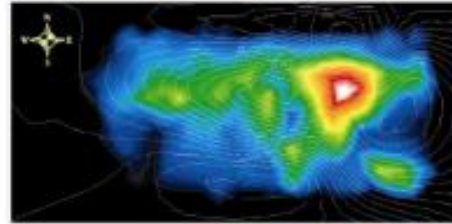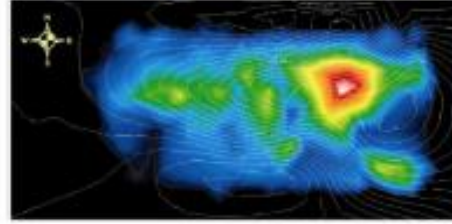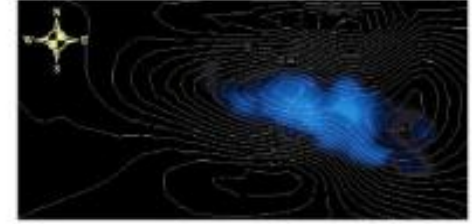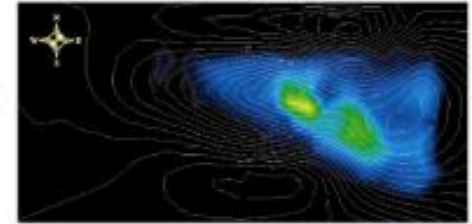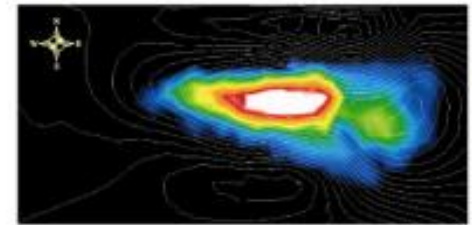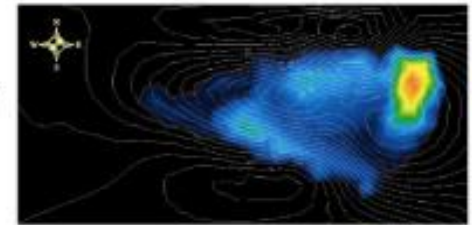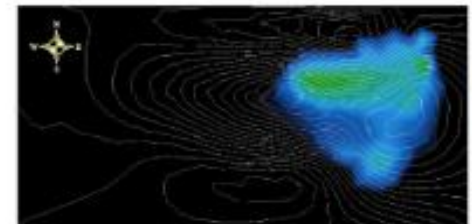
Scale of irreversible deformation

(Yamato et al., 2011)
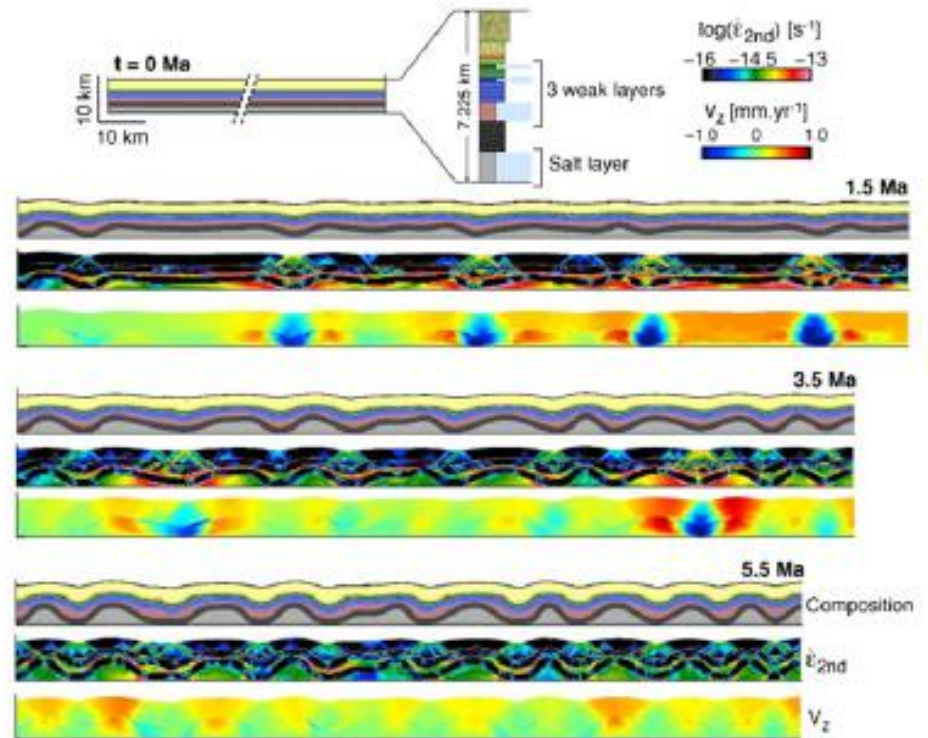
The study of fold evolution is typically based on analytic and numerical models that are used to investigate possible kinematic scenarios of folding, based on the present-day geometry of folded strata and geometrical assumptions such as thickness and length preservation.

Although this approach has proven to be useful to propose consistent geometrical models of folding, it is mainly macroscopic, and the successive deformation mechanisms that accommodate

internal strain within folded strata (fractures and faults at the mesoscale, pressure-solution cleavage and grain-scale deformation (e.g. mechanical compaction, twinning in calcite grains) at the microscopic scale remain to be properly

linked to such geometrical models.

Geomechanical modeling has been a significant improvement
by allowing prediction of the onset of failure
and the type and abundance of deformation features
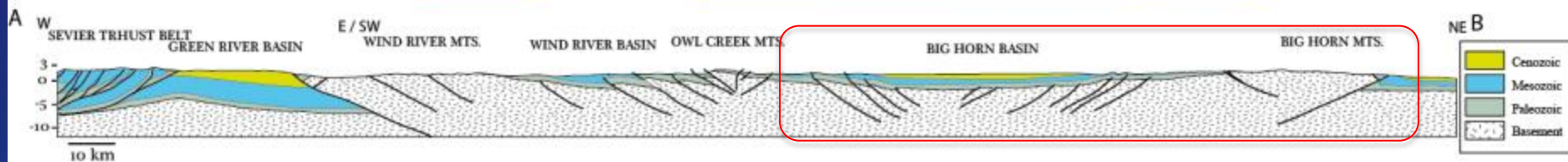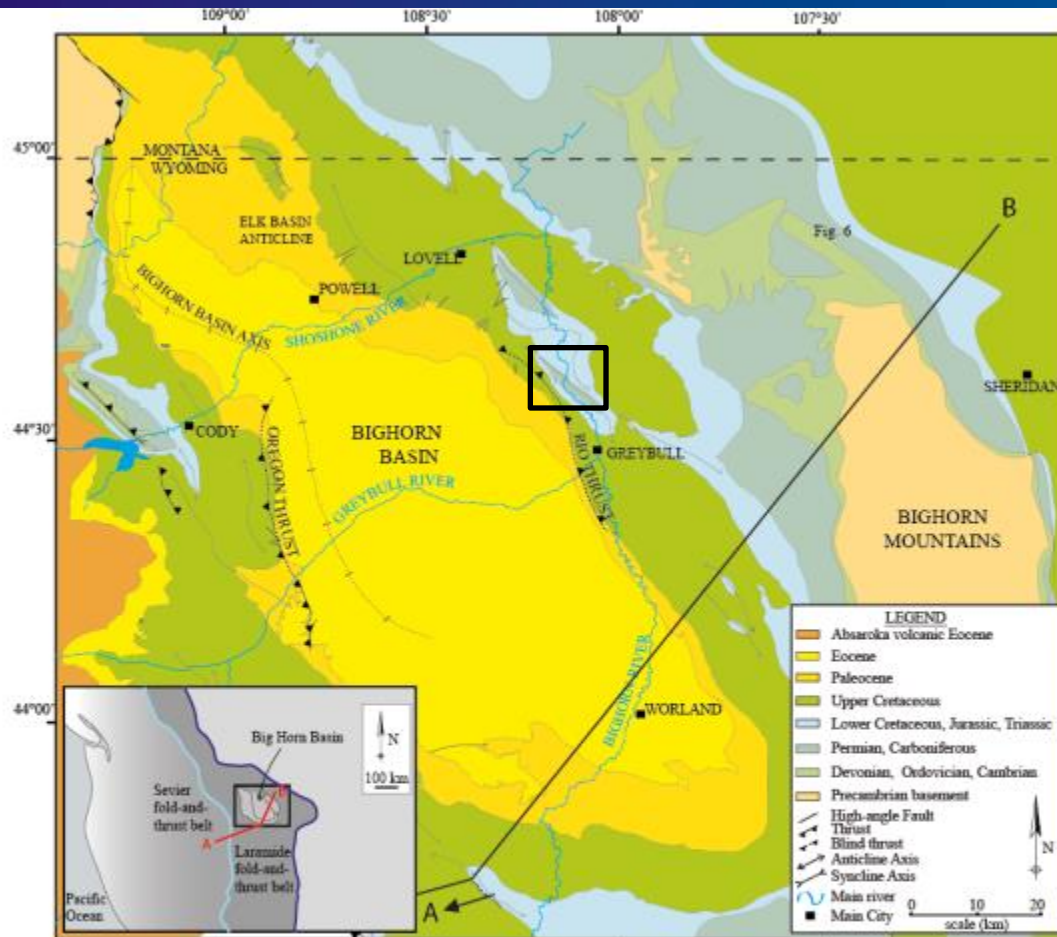along with the orientations and magnitudes of stresses.

While the appraisal of the mechanical behaviour of folded strata is
an essential aspect to understand and simulate the evolution of
folded/faulted formations, only a few attempts have been made to
bridge the gap between the macroscopic scale and the microscopic
scale and to provide quantities like strain or strain to be compared
with outputs of geomechanical models.

Aim at unraveling the history of strain acquisition

and at linking macroscale and microscale mechanisms of
deformation active during folding

Sructural and microstructural evolution
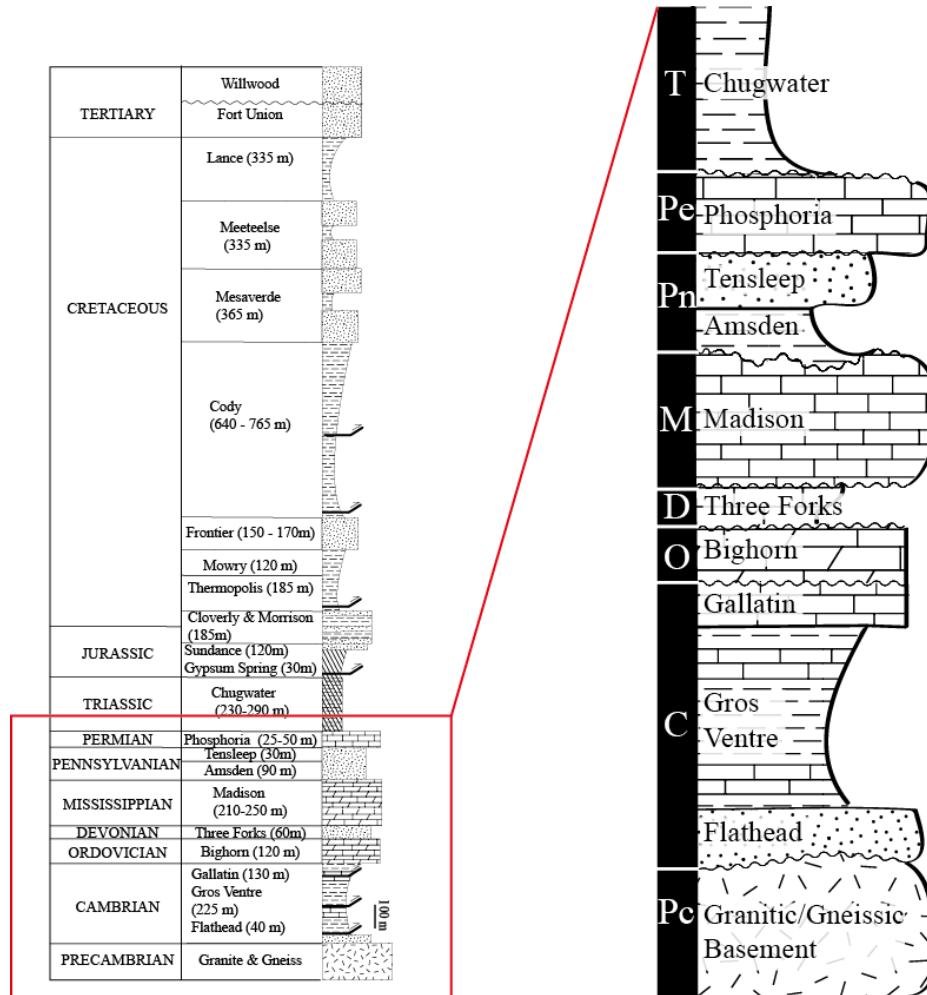## of Sheep Mountain Anticline (Wyoming, USA)

The Bighorn Basin, and the Sevier and Laramide orogenies
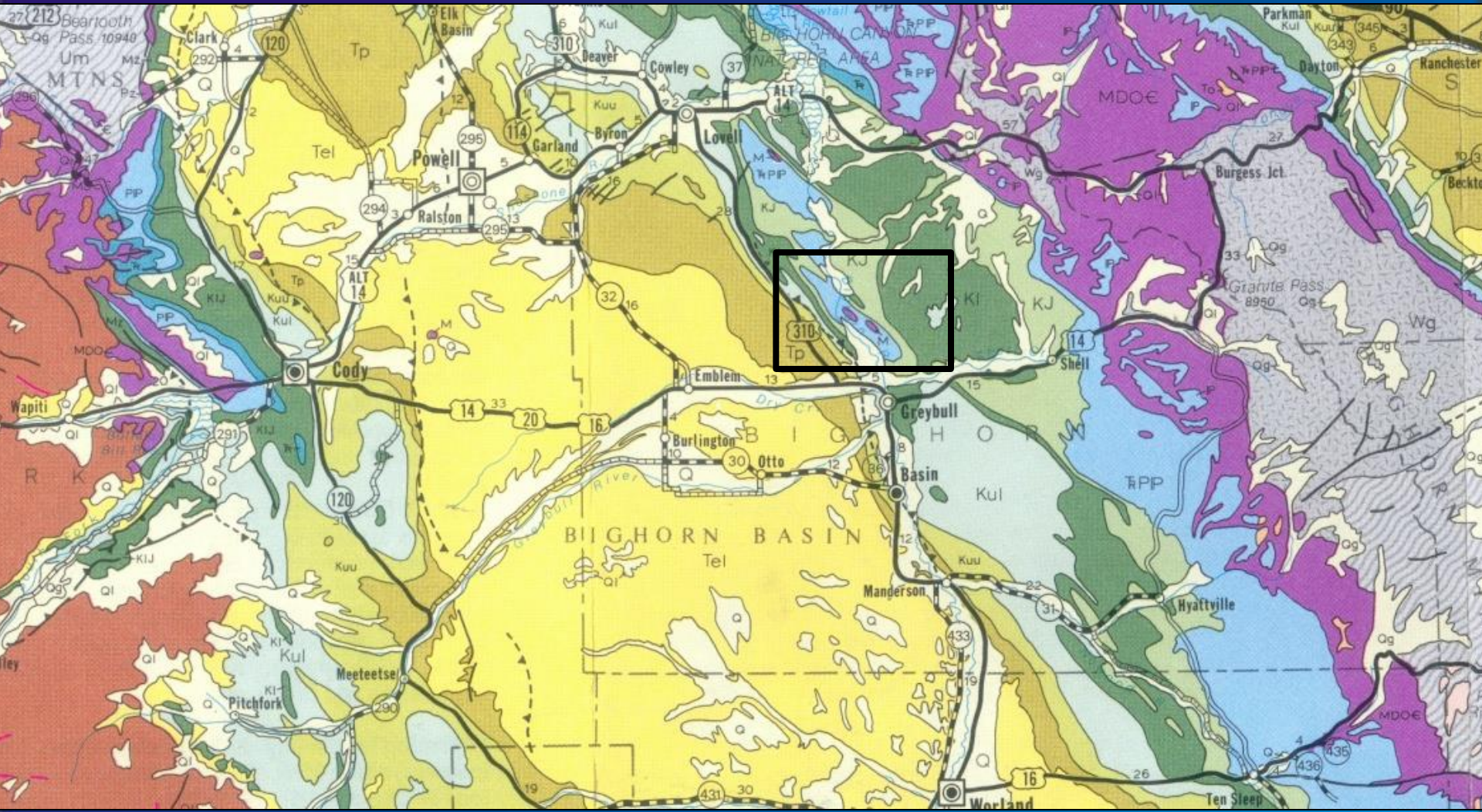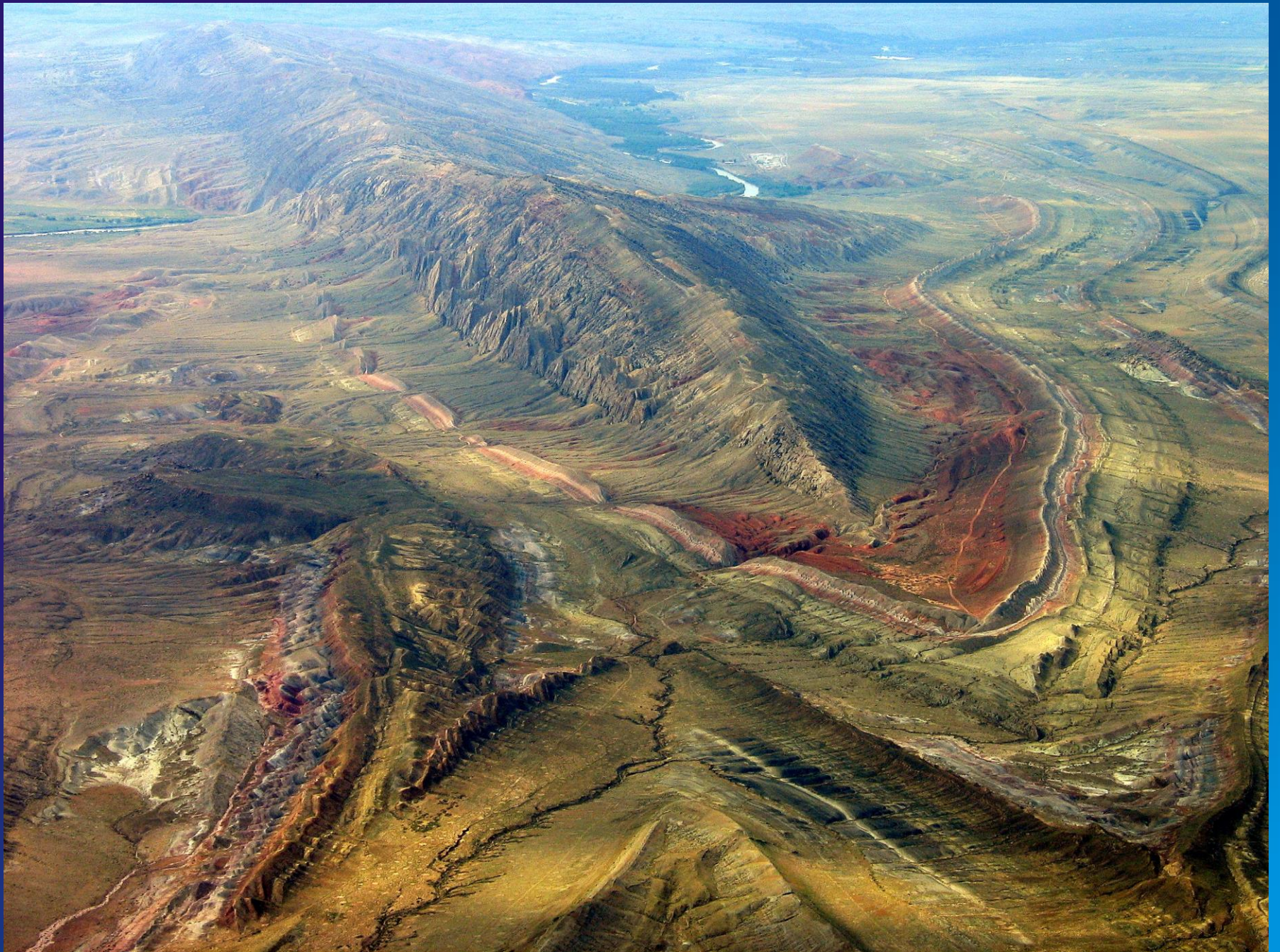
(Weil and Yonkee, 2012)

Stratigraphic units of the Bighorn Basin

10 km

Stratigraphy of Sheep Mountain Anticline

Mesa Verde (365 m)

Cody (670 m)

Frontier (180 m)

Mowry (100 m)

Thermopolis (150 m)
Cloverly (55 m)

Morrison (105 m)

Sundance (105 m)
Gypsun Spring (60 m)

Chugwater (170 m)

Phosphoria (90 m)

Tensleep
Amsden (110 m)

Madison (230 m)

Jefferson-Three Forks (…)
Bighorn (140 m)

Gallatin (150 m)

Gros Ventre (150 m)

Flathead (40 m)
Granite

300 m

K

J

T

P

Ca

D

O

Cam

SW

N E

MADISON

AMSDEN

TENSLEEP

PHOSPHORIA
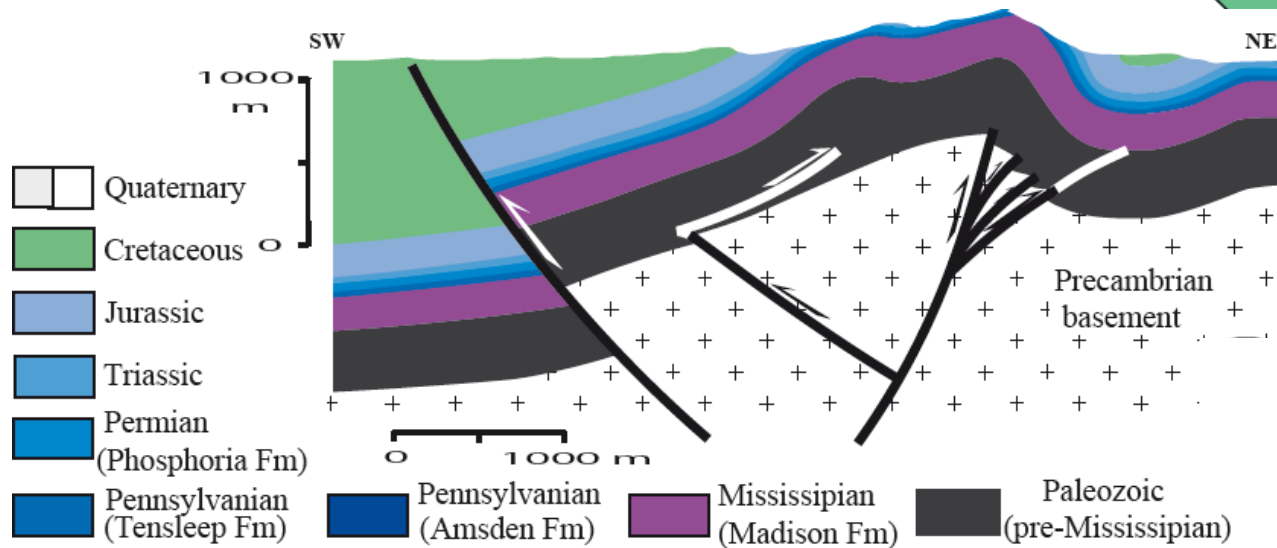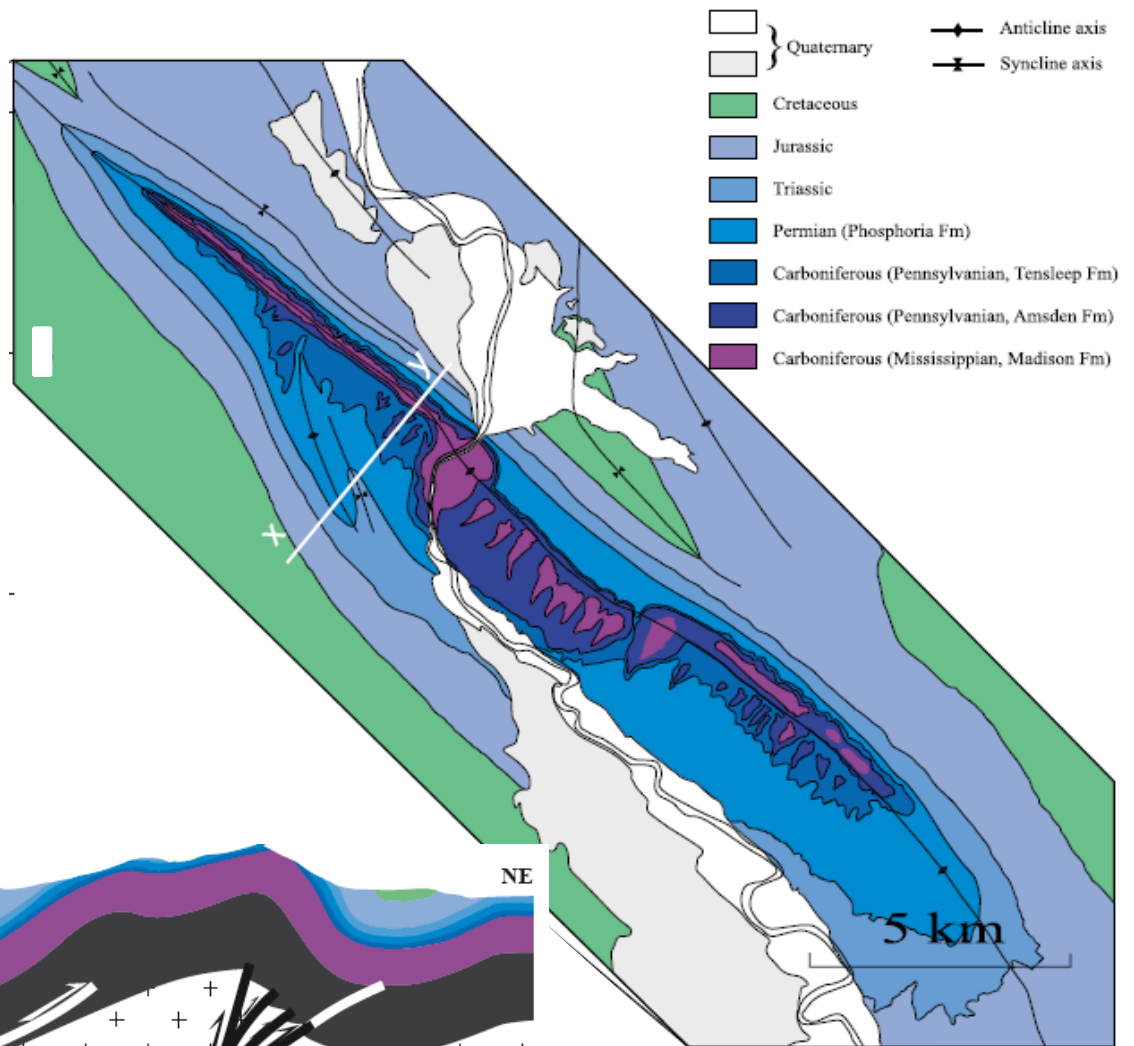
NW

SE

PHOSPHORIA FORMATION

TENSLEEP FORMATION

AMSDEN FORMATION

MADISON FORMATION

BIG HORN RIVER

➢ 300 meters of exposed competent formations (mainly carbonates)

➢ Shaly stratigraphic series (3000m thickness)

(Amrouch et al. Tectonics, 2010)

Legend (map):
Quaternary
Cretaceous
Jurassic
Triassic
Permian (Phosphoria Fm)
Carboniferous (Pennsylvanian, Tensleep Fm)
Carboniferous (Pennsylvanian, Amsden Fm)
Carboniferous (Mississippian, Madison Fm)

Anticline axis
Syncline axis

5 km

Cross-section labels:
SW
NE
1000 m
0
Precambrian basement
0   1000 m

Legend (cross-section):
Quaternary
Cretaceous
Jurassic
Triassic
Permian (Phosphoria Fm)
Pennsylvanian (Tensleep Fm)
Pennsylvanian (Amsden Fm)
Mississipian (Madison Fm)
Paleozoic (pre-Mississipian)

Investigating folding at the microscale : anisotropy of rock physical properties and calcite twinning in folded strata

Anisotropy of sedimentary rocks

The anisotropic behaviour of sedimentary rocks with respect to a particular physical property (elasticity, magnetic susceptibility, electrical conductivity and permeability) is determined by both matrix properties and pore space distributions.

The matrix of a sedimentary rock can be anisotropic because of preferred mineral orientation, water currents during deposition or pressure solution in response to an anisotropic stress field during loading.

The pore space distribution can be anisotropic because of the sedimentation processes controlled by gravity, which often result in transversely isotropic rocks, depositional processes driven by water currents, and the presence of preferentially oriented cracks within or between the minerals

AMS

The measurement of AMS helps characterize penetrative tectonic fabrics in deformed rocks because AMS is sensitive to even slight preferred orientations of magnetic minerals.
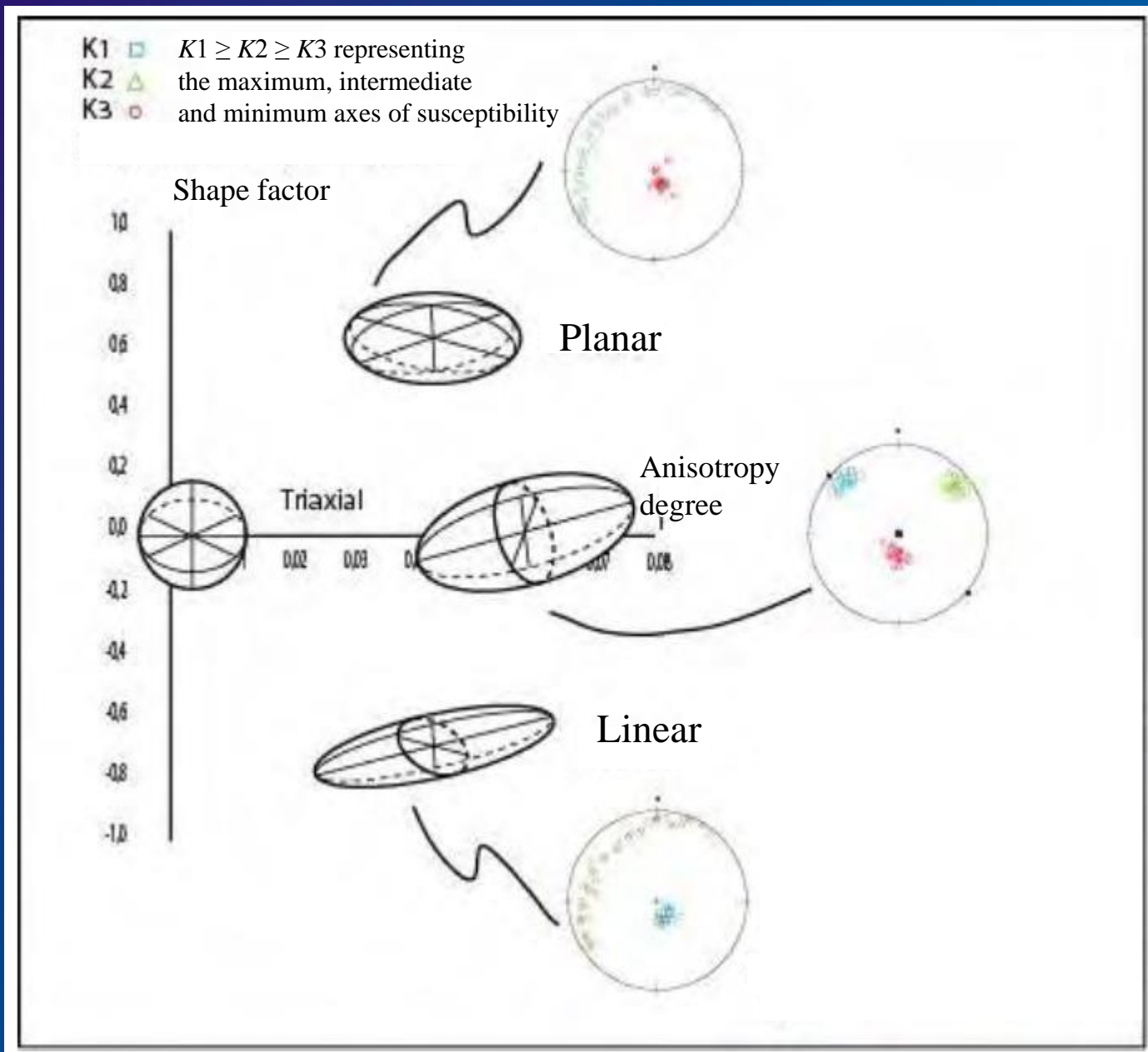
In sedimentary rocks, magnetic susceptibility Km originates primarily from three distinct sources: (1) the dominant diamagnetic minerals (quartz or calcite), (2) the paramagnetic minerals (claysand other Fe-bearing silicates) and (3) diluted ferromagnetic minerals (magnetite, hematite and pyrrhotite), depending on their relative proportion.

Generally, Km ranges between low negative values and low positive values (from -10×10^{-6} SI to 10×10^{-6} SI). In Fe-bearing silicate rocks Km covered susceptibilities up to $500–1000 \times 10^{-6}$ SI whereas ferromagnetically dominated rocks are generally characterized by values higher than 1000×10^{-6} SI. The lack of paramagnetic minerals tends to decrease the limit of influence of ferromagnetic fraction on magnetic susceptibility.

AMS
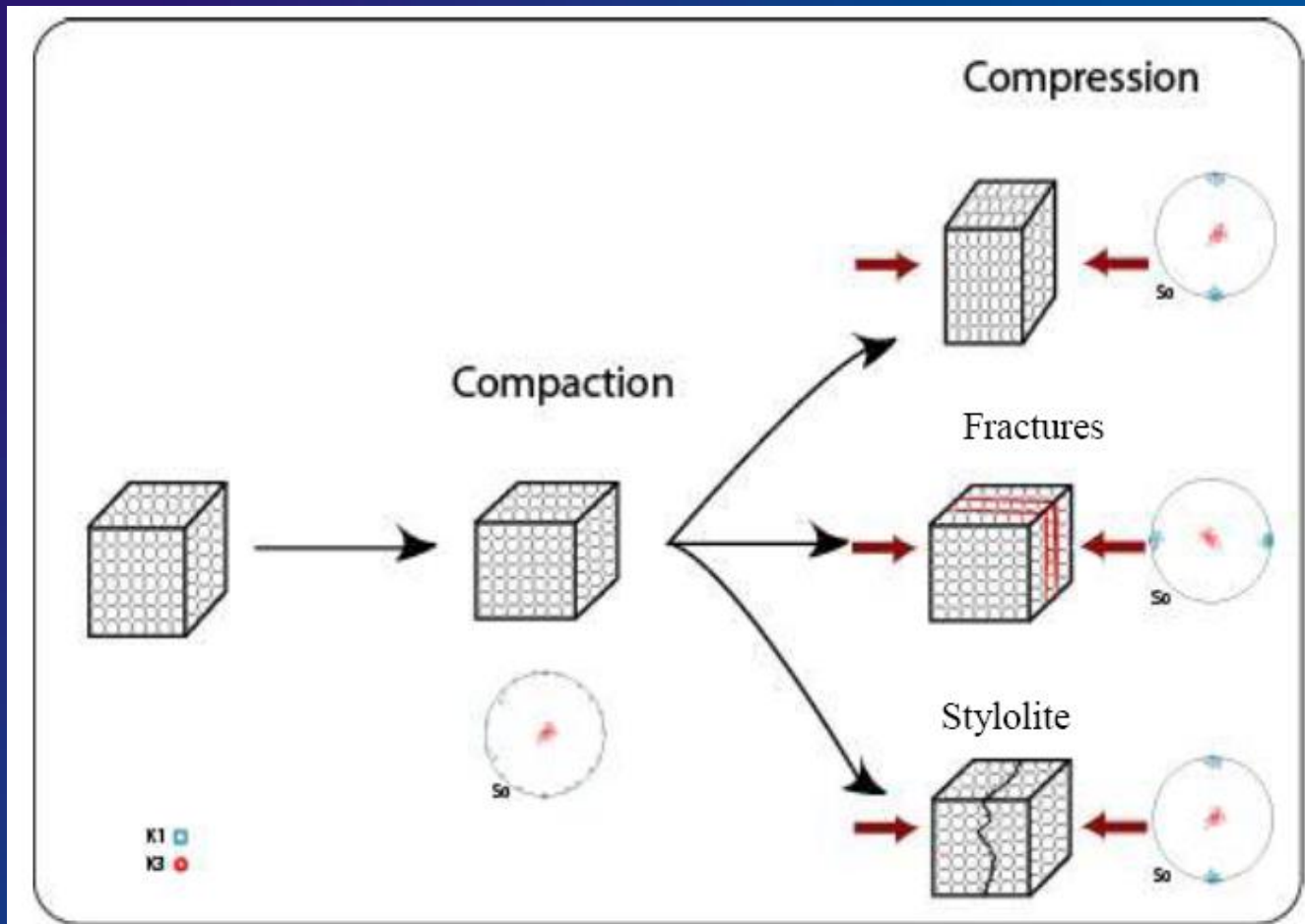
The interpretation of AMS fabrics is strongly dependent on the carrier of the magnetic signal

AMS

The magnetic fabric is typically defined using the orientation of either the magnetic foliation, that is, the plane containing the $K1$ and $K2$ axes when $K1 \approx K2 \gg K3$, or the magnetic lineation, that is, the direction of the $K1$-axis.

Increasing internal strain in pure shear regime
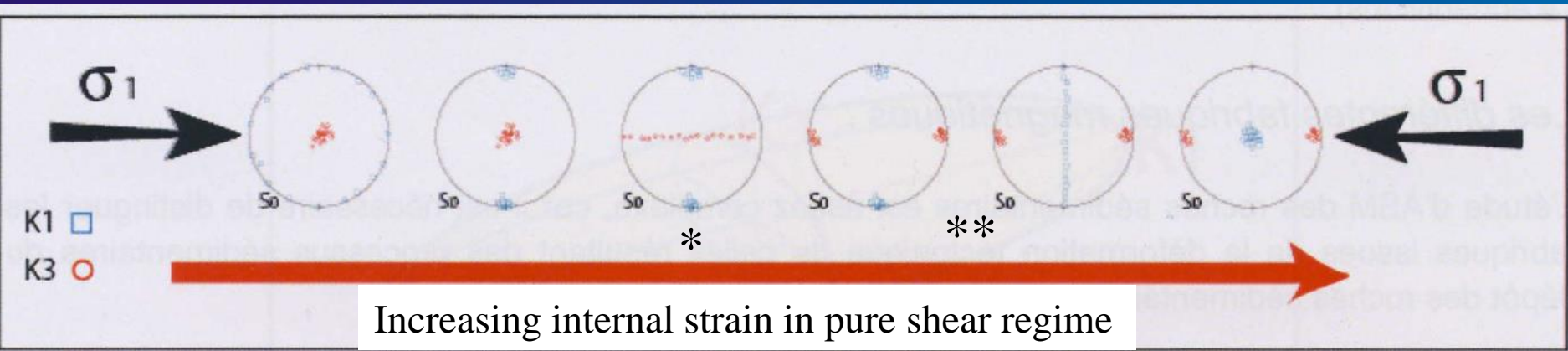
* Intermediate fabric : magnetic lineation K1 still contained within the bedding but clustered at right angle to the shortening direction, whereas the $K3$ is leaving the pole to bedding and exhibits a girdle distribution around $K1$.

** Tectonic fabric characterized by $K3$ parallel to the shortening direction. $K1$ is either parallel to the intersection between the bedding and the incipient cleavage or exhibits a girdle around $K3$

(Frizon de Lamotte et al., 1992)

While the correlation between the orientations of principal AMS axes and principal strain axes tends to be very consistent, the correlation between the magnitudes of principal AMS axes and corresponding principal strain axes is not.

AMS (sandstones)
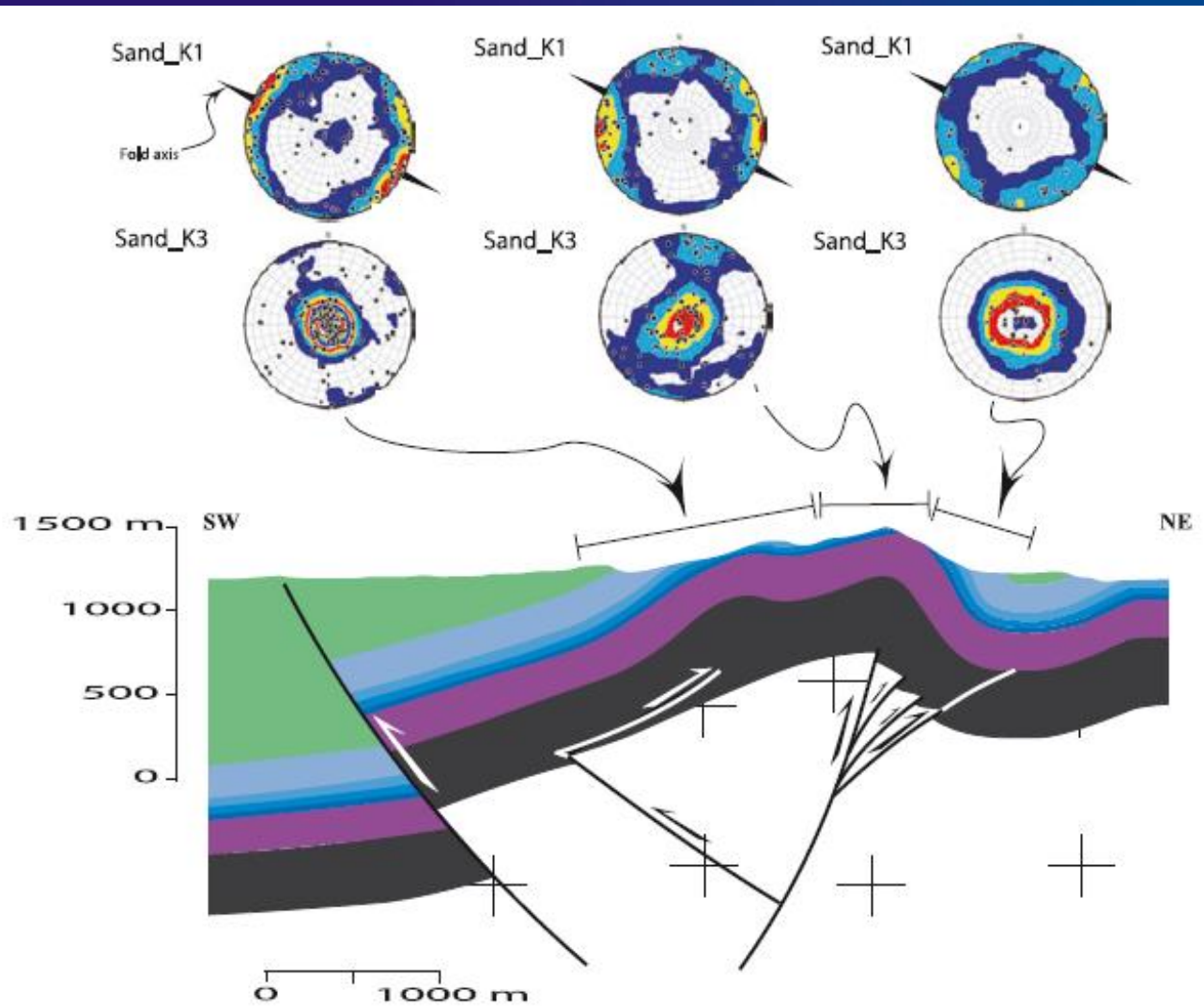
Forelimb : planar oblate fabrics with the maximum axes K1 scattered in the plane of bedding, the minimum axes K3 being on average normal to it. --> sedimentary fabrics.

Backlimb : similar fabric but with significantly more clustering of K1 close to the direction of fold axis in the plane of bedding. Fabrics mixing both shortening direction and pole of bedding → tectonic (sandstones deformed by prefolding LPS).

Hinge : linear fabric with a girdle distribution of K3; competition between intermediate and true tectonic fabrics. Inferred shortening direction, normal to the magnetic lineation and parallel to the K3 girdle

(Amrouch et al., 2010)

AMS (carbonates)
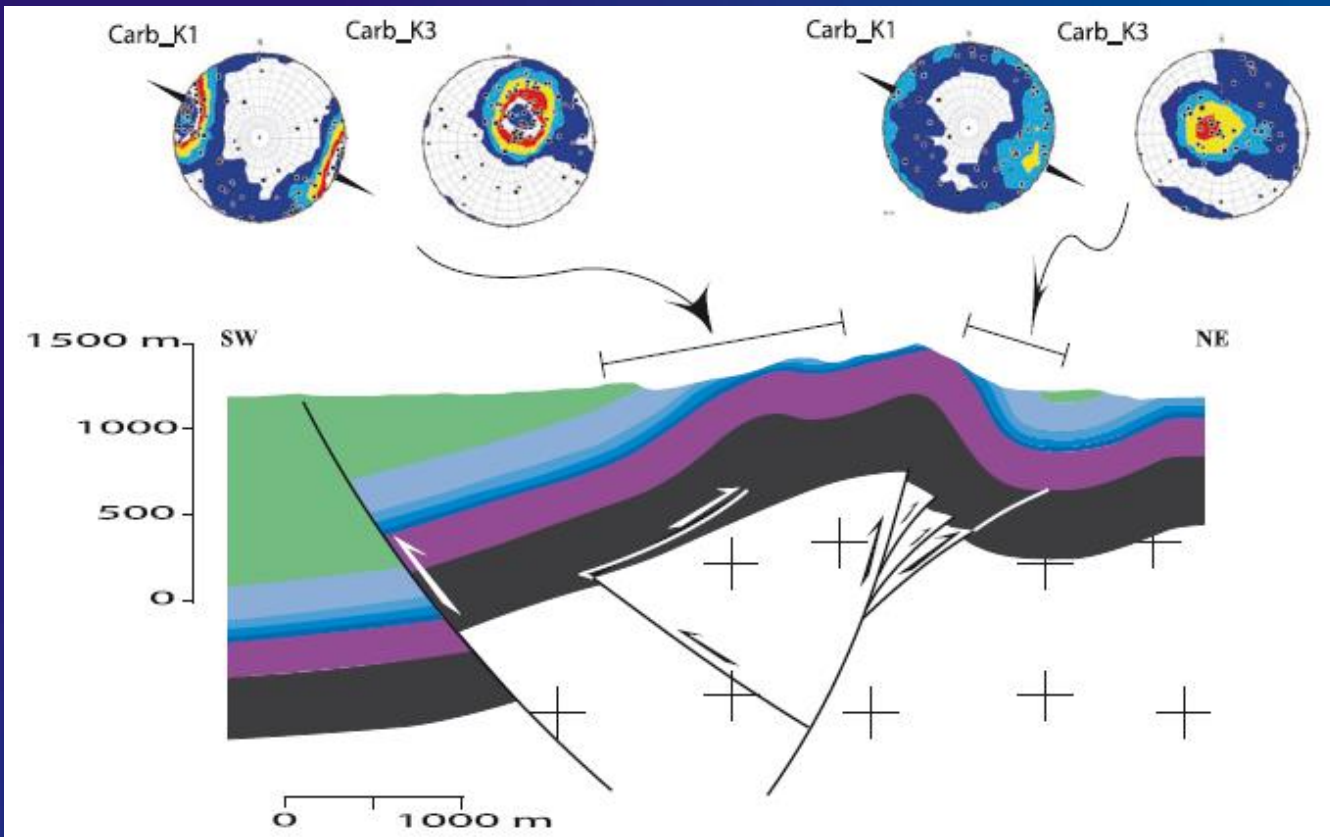
Forelimb : K1 scattered in the plane of bedding with a weak maximum close to the fold axis orientation, and K3 clustered either along the pole of bedding or perpendicular to it. Similarly to sandstones, combination of relict sedimentary fabrics with intermediate and tectonic fabrics locally.

Backlimb : well defined cluster of K3, which significantly deviates from the pole of bedding, and very well clustered K1 axes. Similarly to sandstones, K1 mean axis is trending ~N120°, close to the trend of the fold axis. → fabric associated to the regional shortening direction.
Obliquity of the magnetic foliation with respect to bedding plane → bed-parallel shearing instead standard LPS

(Amrouch et al., 2010)

APWV

At laboratory conditions (no confining pressure) the anisotropic behaviour of rocks with respect to the propagation of P waves is mainly controlled by microstructures (at μm scale) leading to a reduction of the inter- or intragranular cohesion. Such microstructures can be the pore network, the microfractures and the contacts between grains.

Considering the simple case of an elliptic pore space, the maximum velocity will be observed in the direction of long axis of the pore. In the case of a planar distribution of cracks or pressure solution cleavage planes, P-wave velocity is greatly reduced along the direction normal to the plane.

A preferred orientation of intergranular contacts will be characterized by a maximum velocity normal to it.

However, one must keep in mind that the resulting acoustic fabric is a composite of these fabrics.

APWV

There is an overall tendency for the mean velocity to be higher in the carbonates than in the sandstones, and, within the same lithology, to be lower in high porosity samples. These classical trends are generally explained by the fact that velocities range between the velocities of the mineral grains (intrinsically higher in calcite than in quartz) and those of the mineral–pore fluid filled (air or water) assemblage.

A significant decrease of anisotropy after water saturation, with a concomitant increase of velocity can be matched with a model of velocity anisotropy controlled by the porosity and its shape.

A rock made of an anisotropic matrix and an isotropic pore space will be characterized by velocity and anisotropy increase when it is saturated with incompressible material (water).

APWV
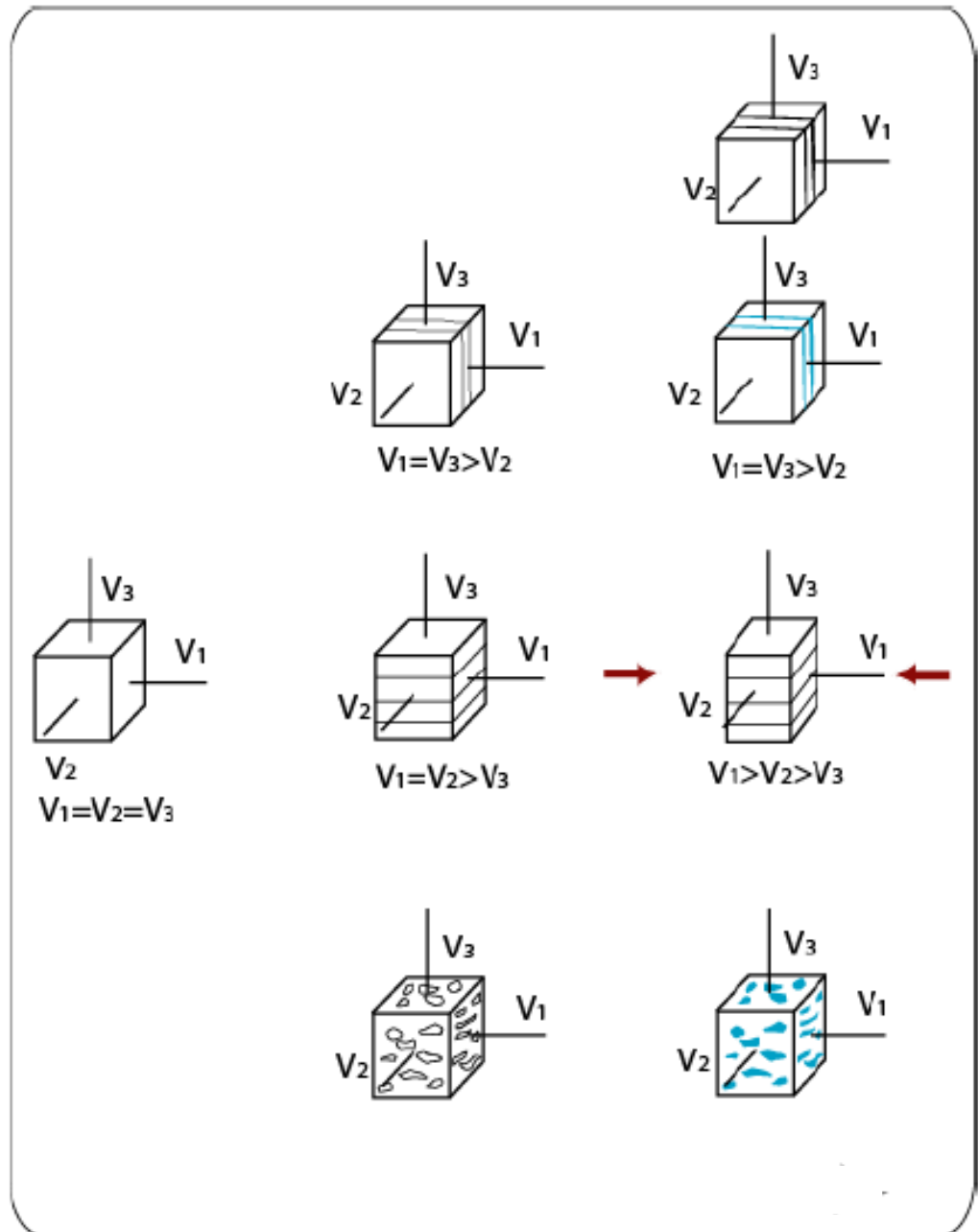
APWV

(Amrouch et al., 2010)
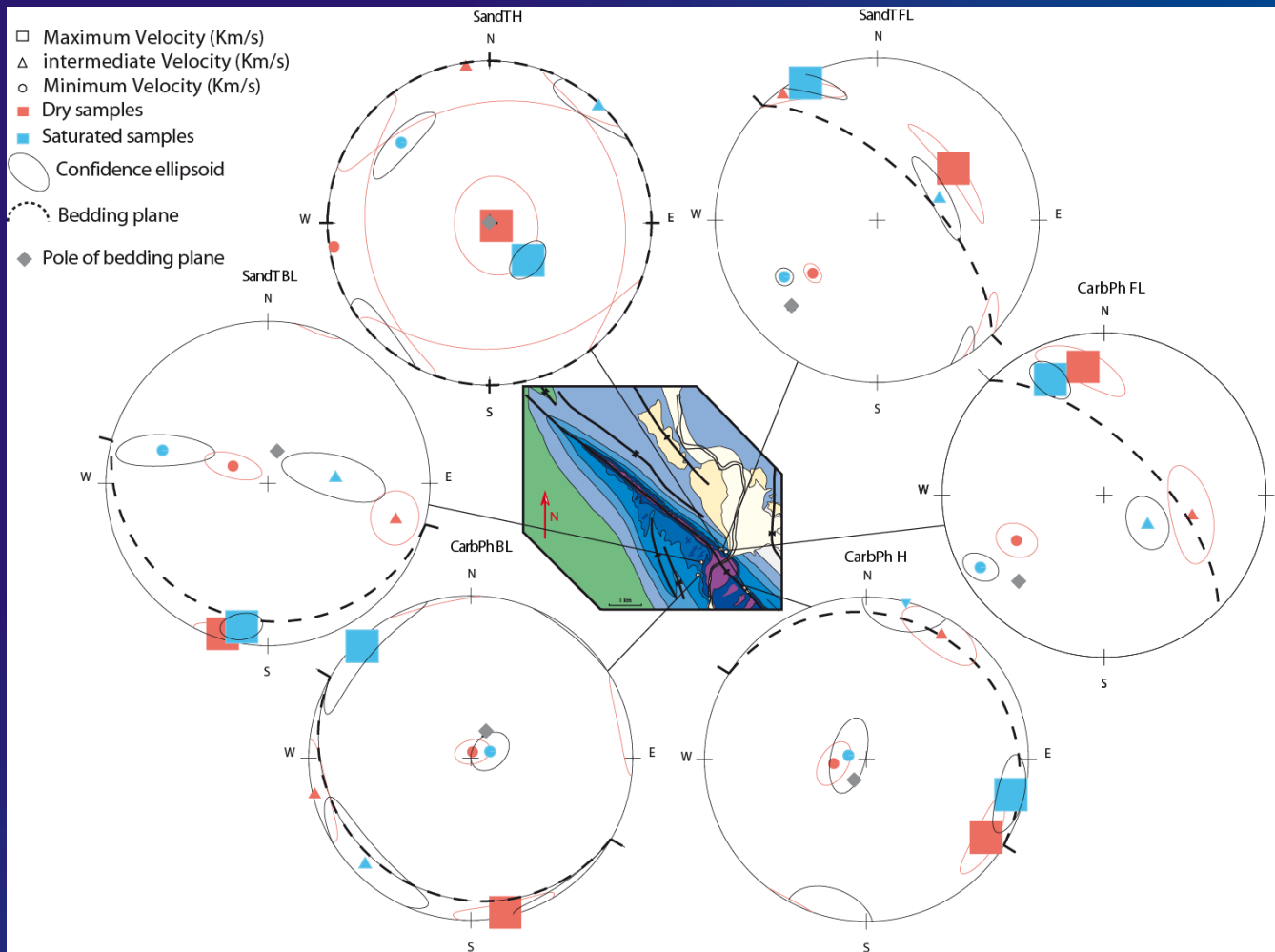
Forelimb : Deformation is preferentially revealed by the porosity, which is systematically oriented with its long axis parallel to the fold axis. APWV indicates that the anisotropy is dominated by an anisotropic pore network embedded into an almost isotropic matrix.

Backlimb : APWV fabrics are grain-supported, showing that the matrix is more anisotropic in the backlimb than in the forelimb. The direction of anisotropy is roughly related to the plane of bedding indicating that APWV fabrics could also be linked to early stage LPS deformation.
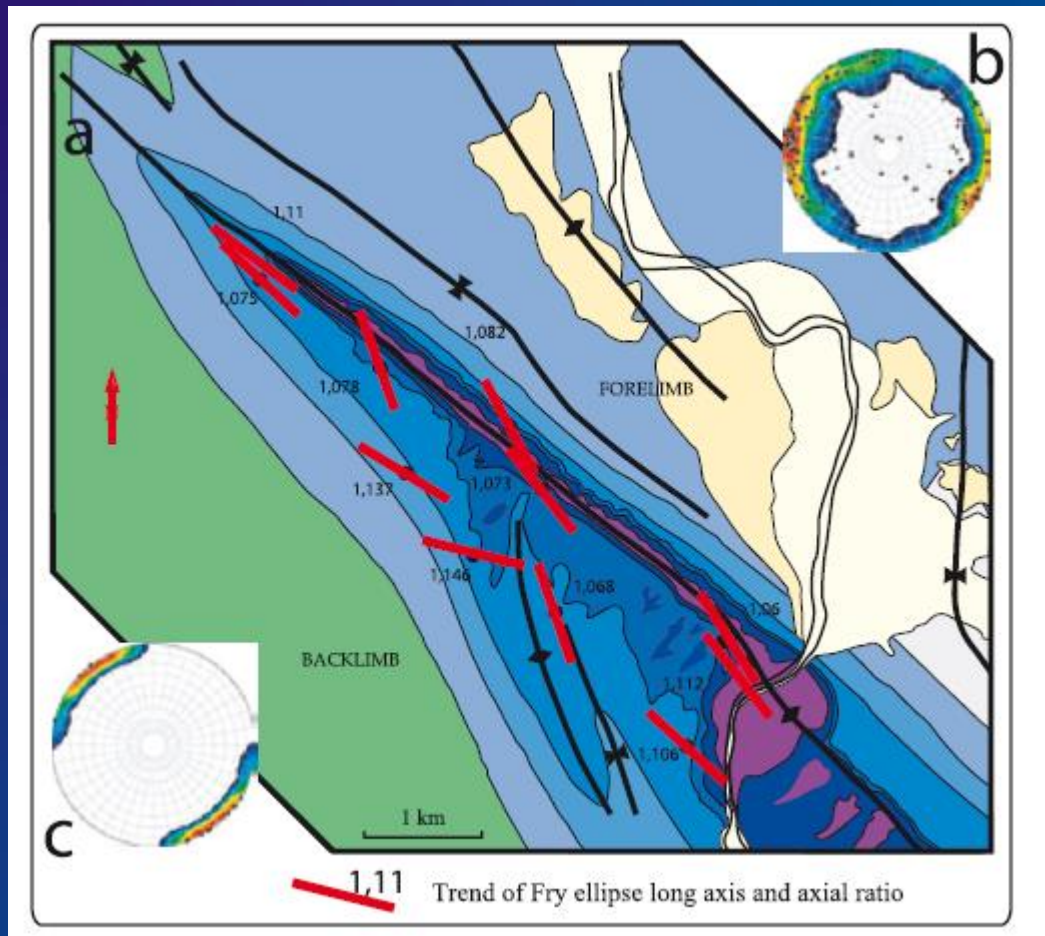
Strain axes deduced from Fry method at Sheep Mountain anticline: (a) Geological map of Sheep Mountain Anticline with long-axis trends and axial ratios of individual bedding-parallel Fry ellipses at sampling locations throughout the study area and (b) trends of all the K_1 axes of AMS fabrics measured from the same samples used for Fry analysis. (c) The lower-hemisphere stereoplot illustrates the long axes of bedding parallel Fry ellipses in the study area

(Amrouch et al., 2010)

Summary

<u>Forelimb</u> :
AMS : Preservation of sedimentary magnetic fabrics, weak anisotropy
APWV : anisotropy dominated by anisotropic pore network embedded into an almost isotropic matrix.

<u>Backlimb</u> :
AMS : true tectonic strain at the matrix scale (sandstones : pre-folding LPS, carbonates : bedding-parallel shear).
APWV : grain-supported fabrics, showing that the matrix is more anisotropic in the backlimb than in the forelimb. Direction of anisotropy roughly related to bedding indicating that APWV fabrics could also be linked to early stage LPS deformation.

→ succession of microscopic deformation mechanisms active before and during folding
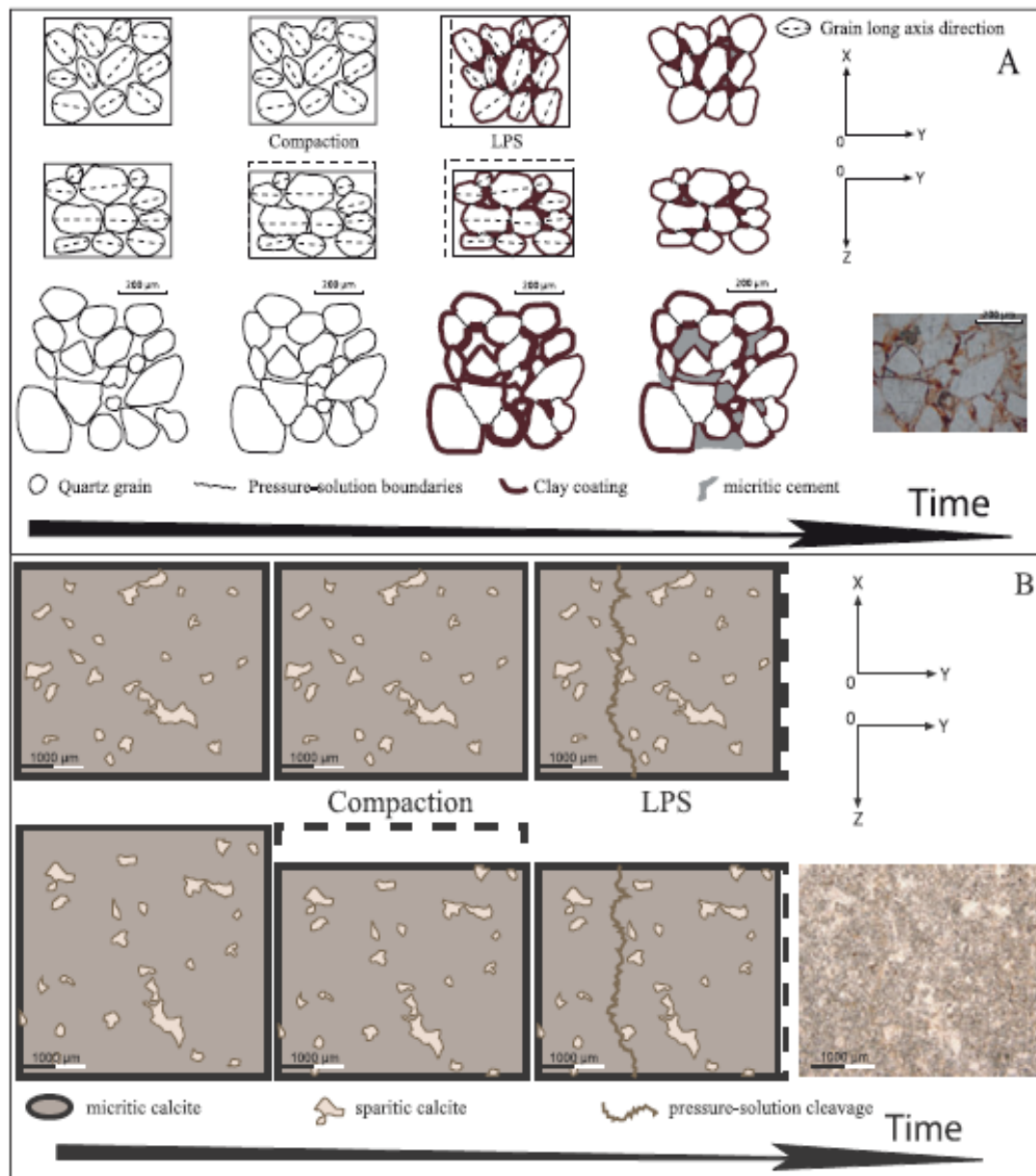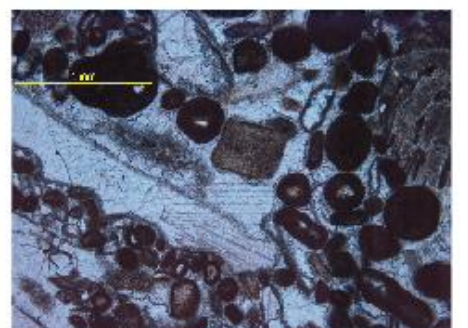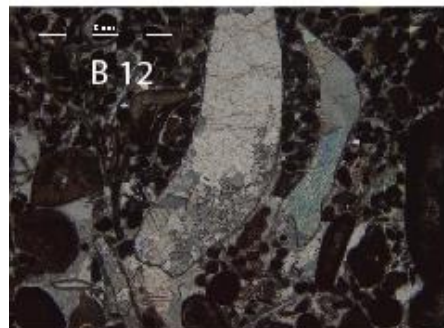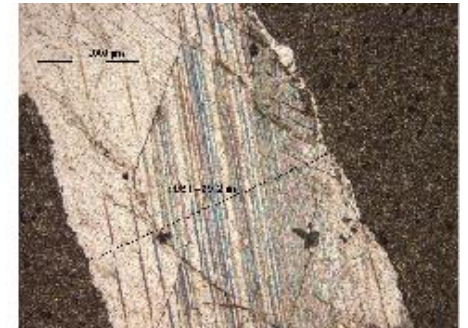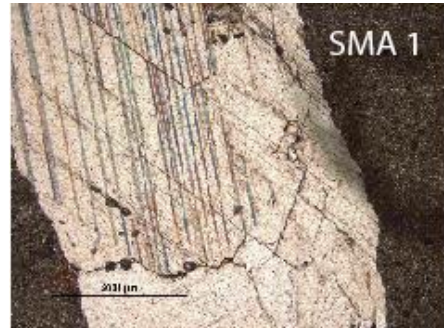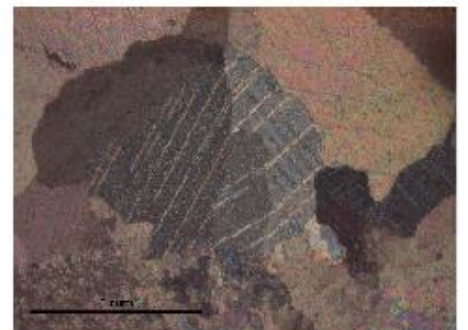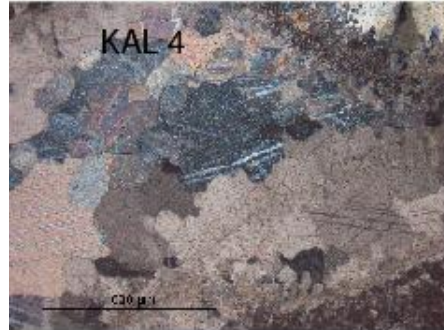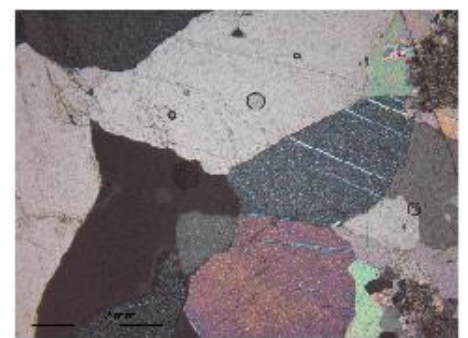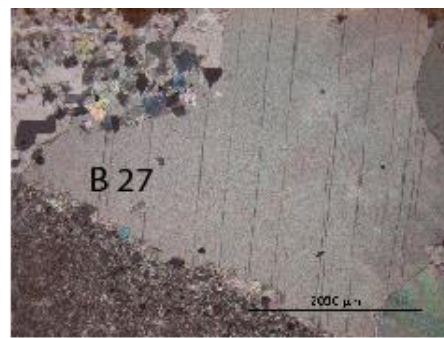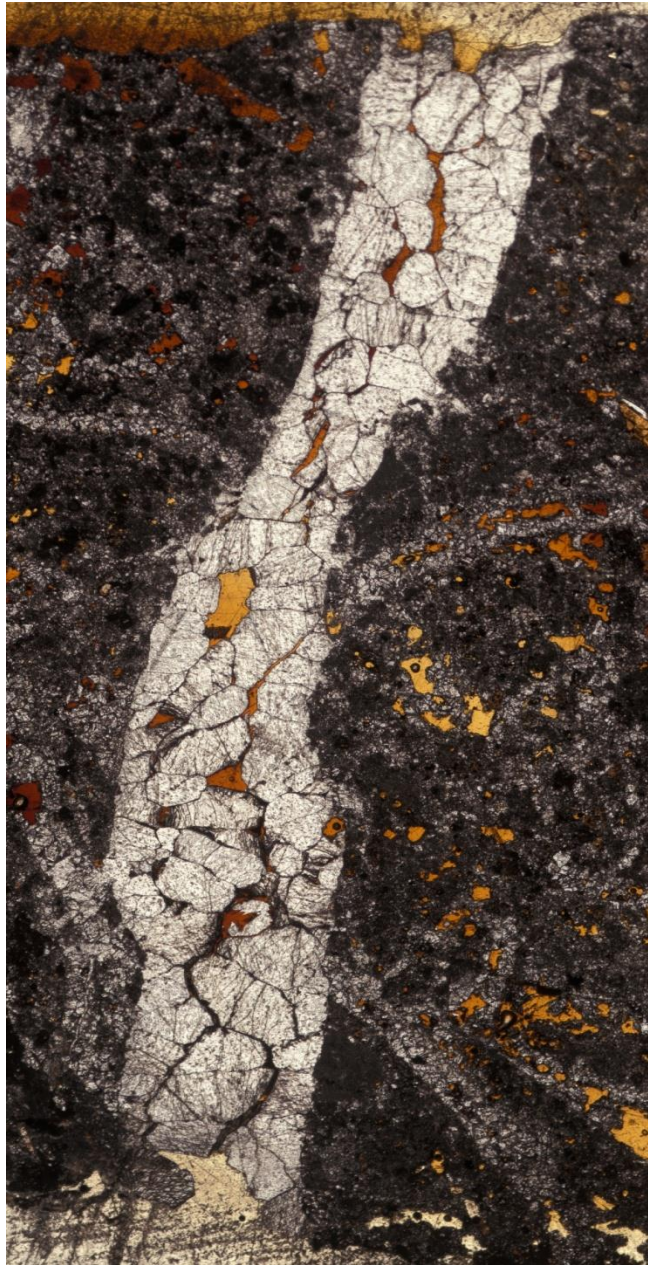
Sketches of different stages of formation/deformation of a sedimentary rock until a final state illustrated by the microphotographs of polished thin sections observed in natural light. (a) Sandstones (Amsden); (b) Carbonates (Phosphoria). *XY* plane is the bedding plane (*X*: Strike; *Y*: dip), *YZ* is the plane perpendicular to the bedding plane.

(Amrouch et al., 2010)

The macroscopic asymmetry of the NE-verging SMA,likely related to underlying basement thrust, is also clearly marked at the mesoscopic and the microscopic scales. Structural observations made at the microscopic scale in part of a fold may therefore be relevant to the fold scale.

Calcite twinning in folded strata

B 27

KAL 4

SMA 1

B 12
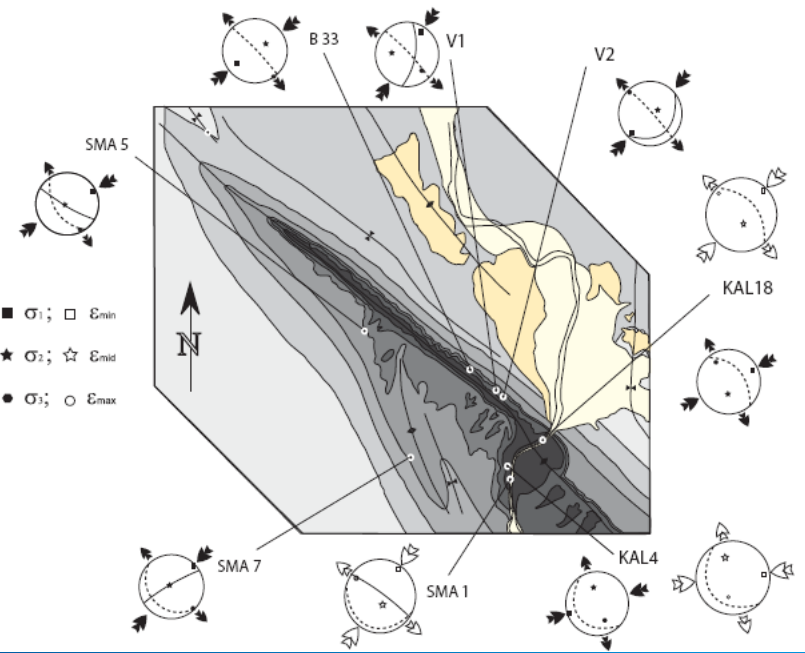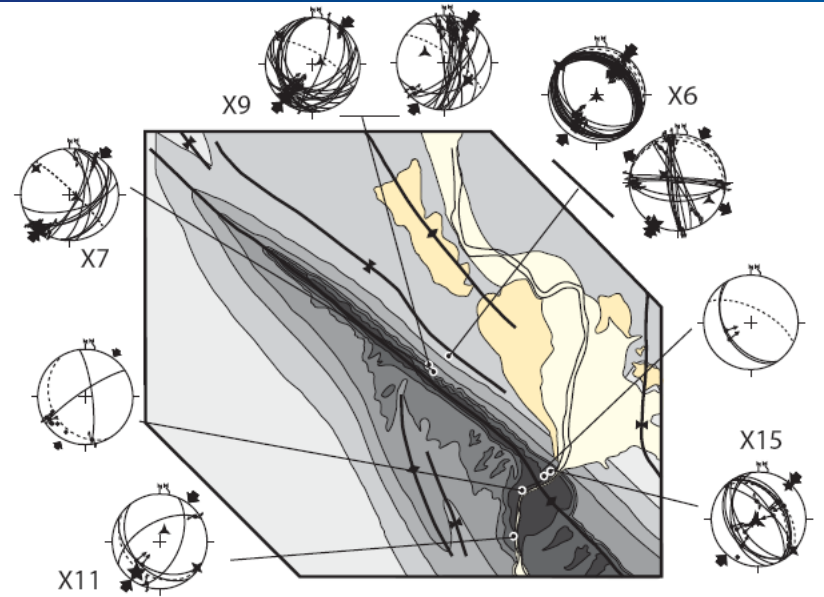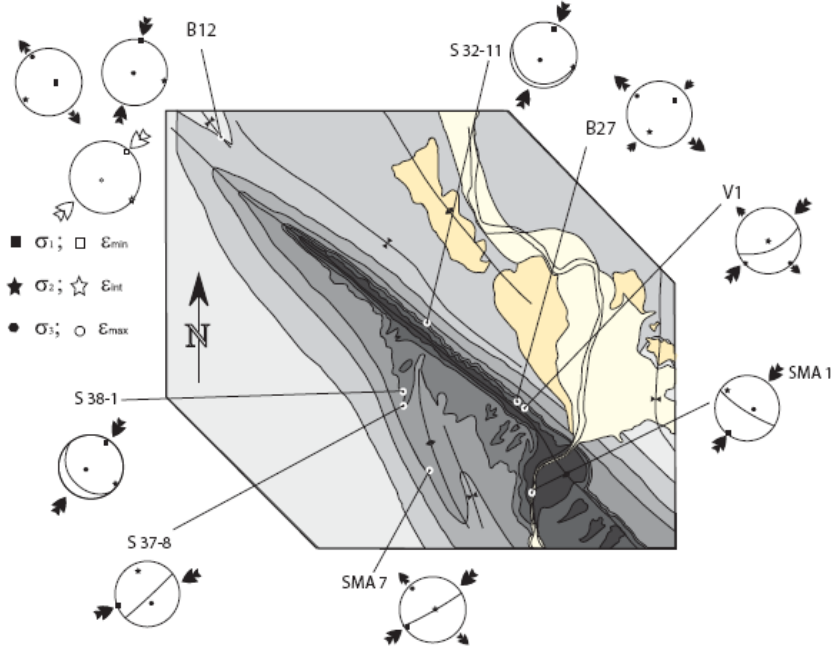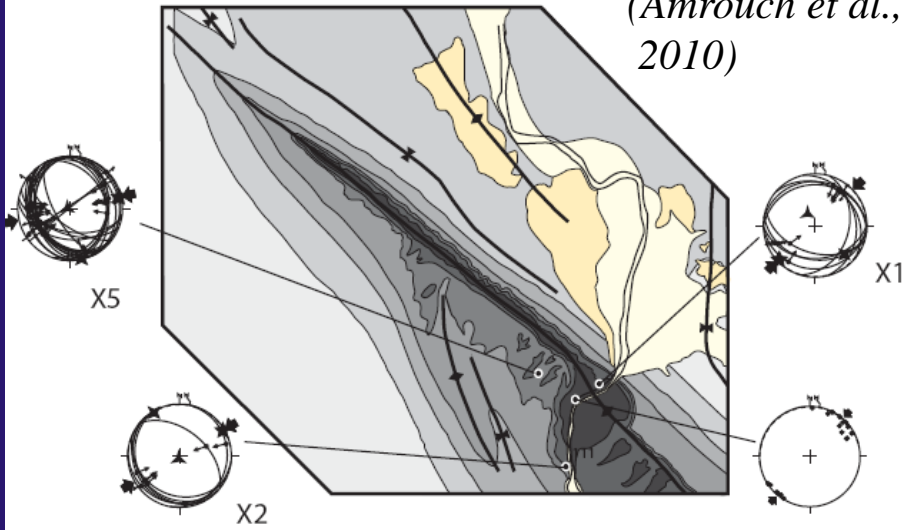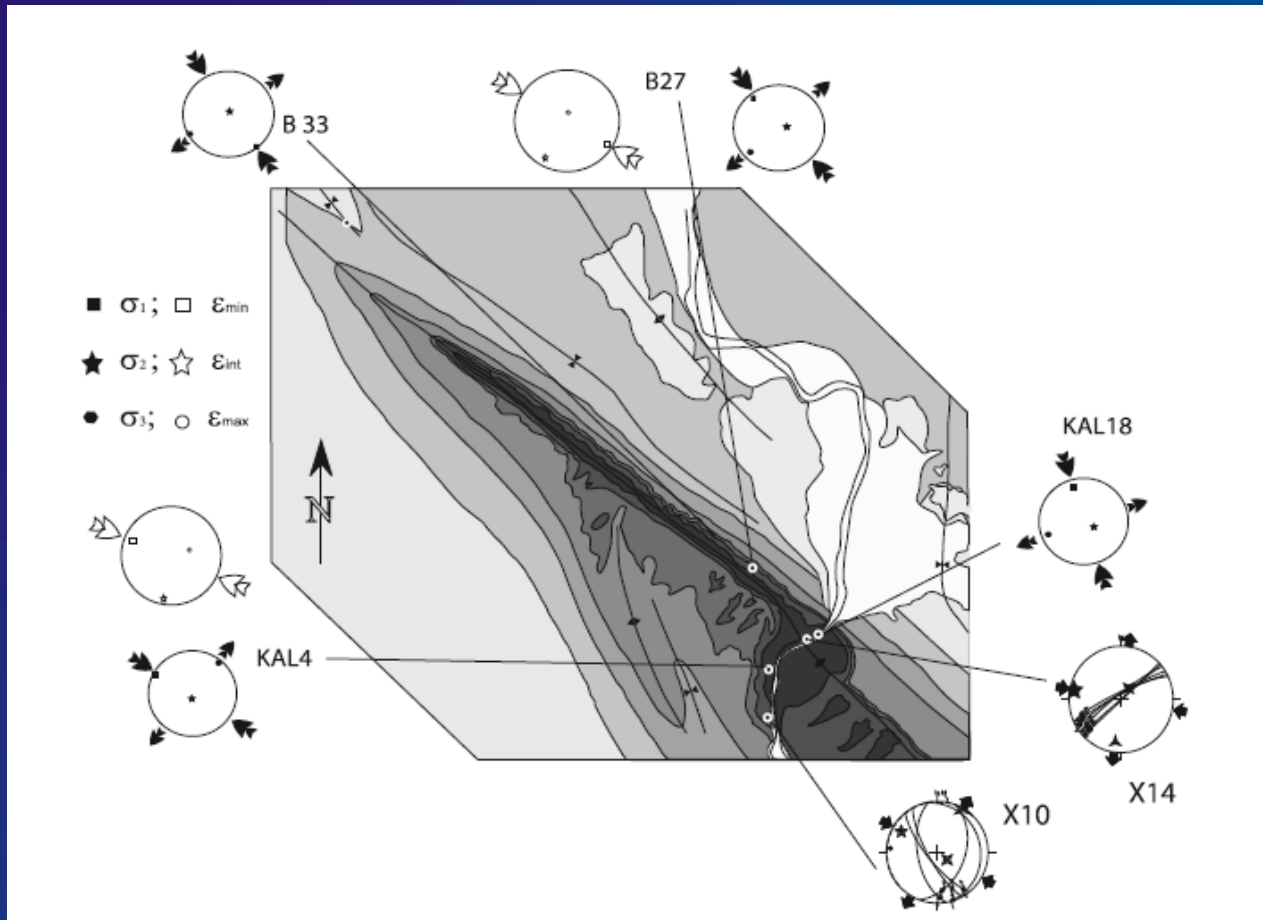
(Amrouch et al., 2010)

Pre-folding stage : strike-slip stress regime under a NW-SE horizontal compression

Early-folding stage:
Paleostress /strain orientations related to Laramide LPS.
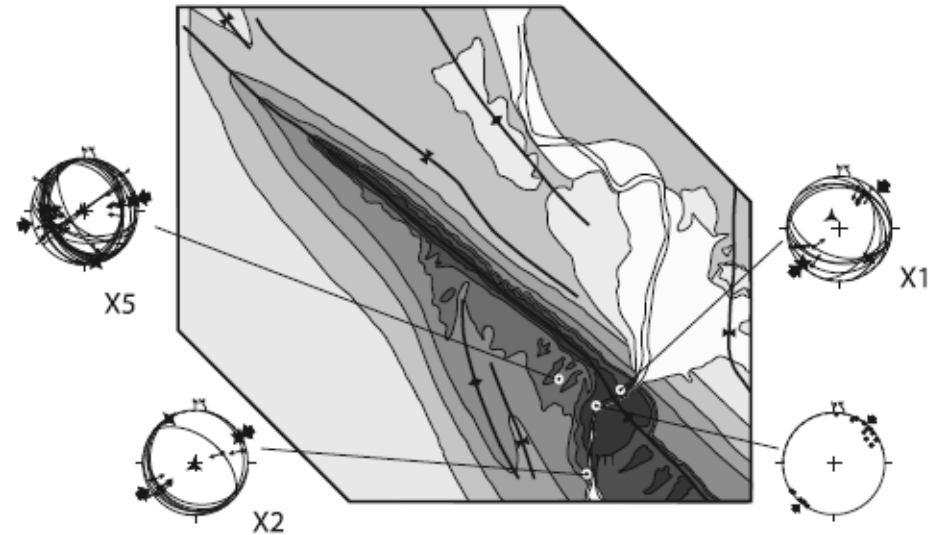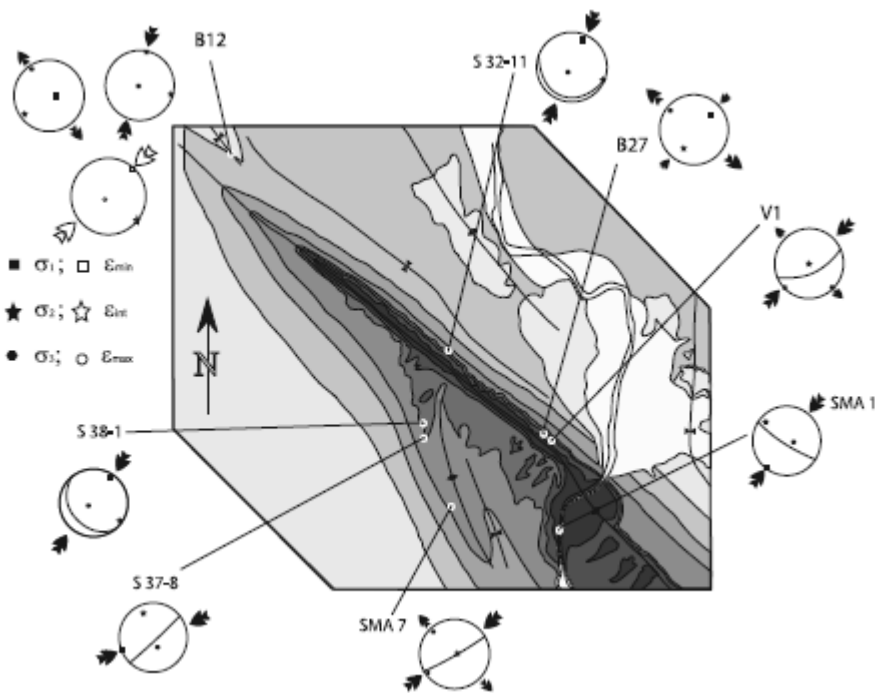
(Amrouch et al., 2010)

Laramide Layer-Parallel Shortening (LPS). The compression was oriented NE to ENE either in a strike-slip or in a compressional regime.

Late-folding stage: paleostress / strain orientations related to Laramide late stage fold tightening.

(Amrouch et al., 2010)
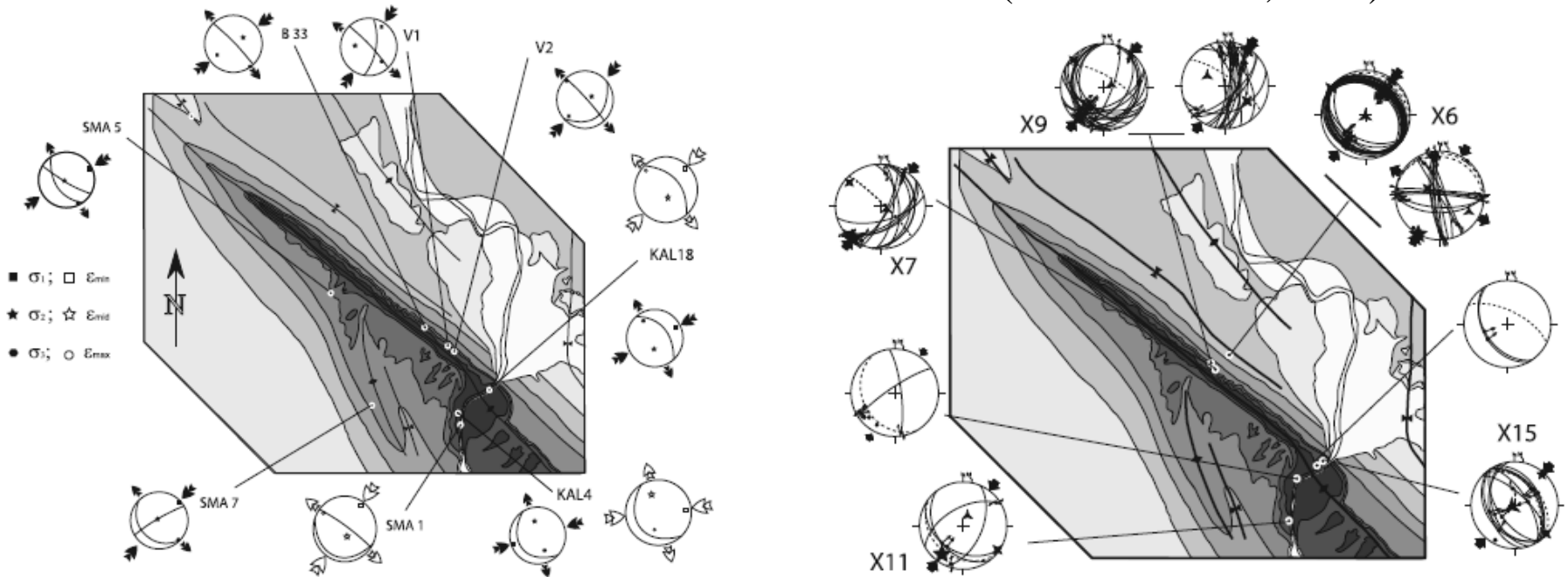
Faults and calcite twins reveal a late fold tightening stage, associated with a strike-slip stress regime and a paleo-$\sigma 1$ axis also oriented NE.

Early-folding and late-folding Laramide paleo-differential stress magnitudes from calcite twinning paleopiezometry
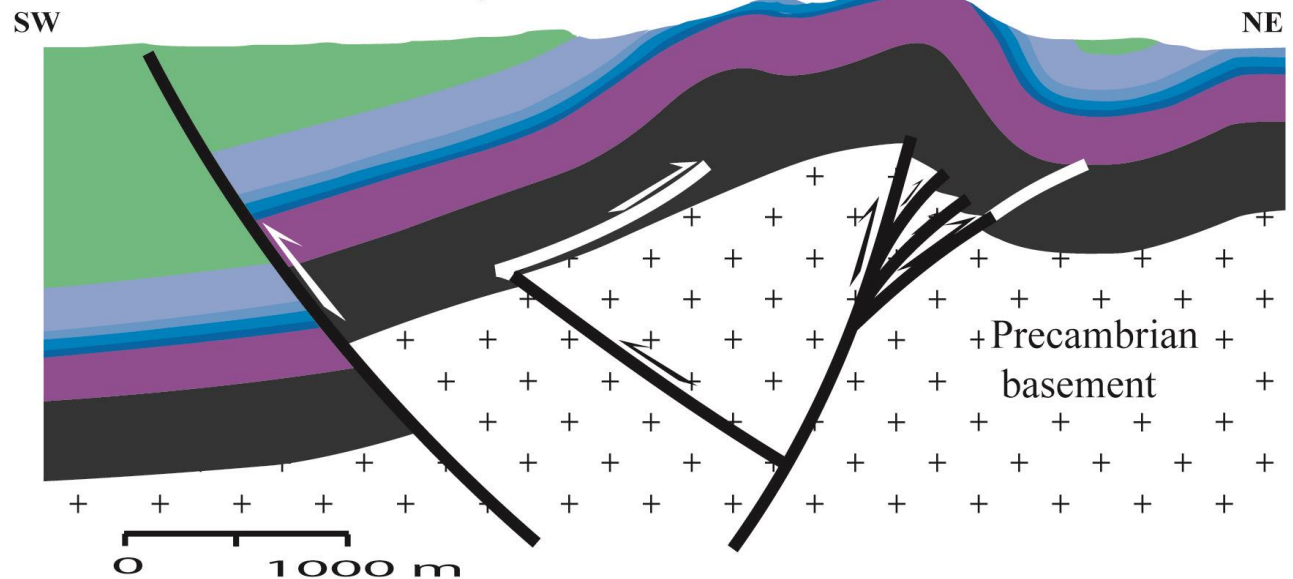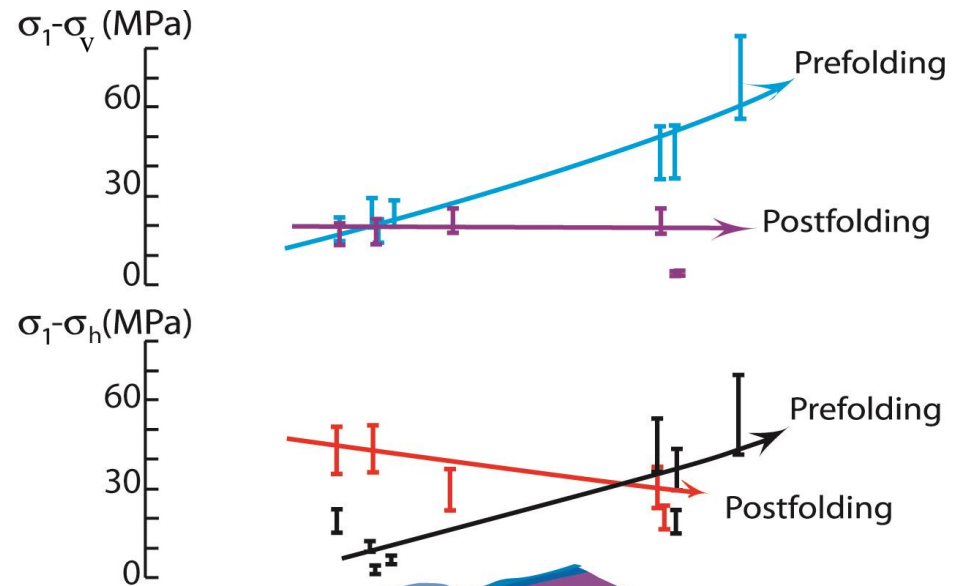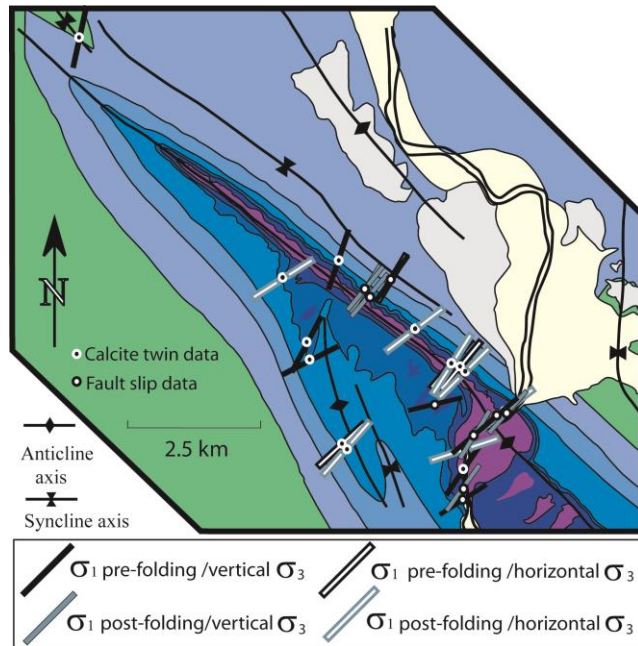
(Amrouch et al., 2010)

Stress perturbations in the sedimentary cover at the tip of the underlying basement fault starting to move during Laramide stress build-up
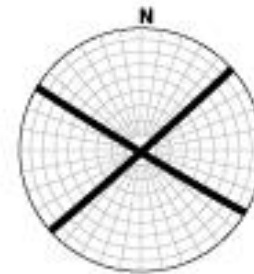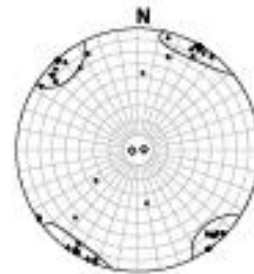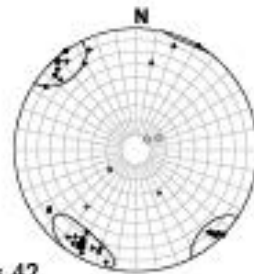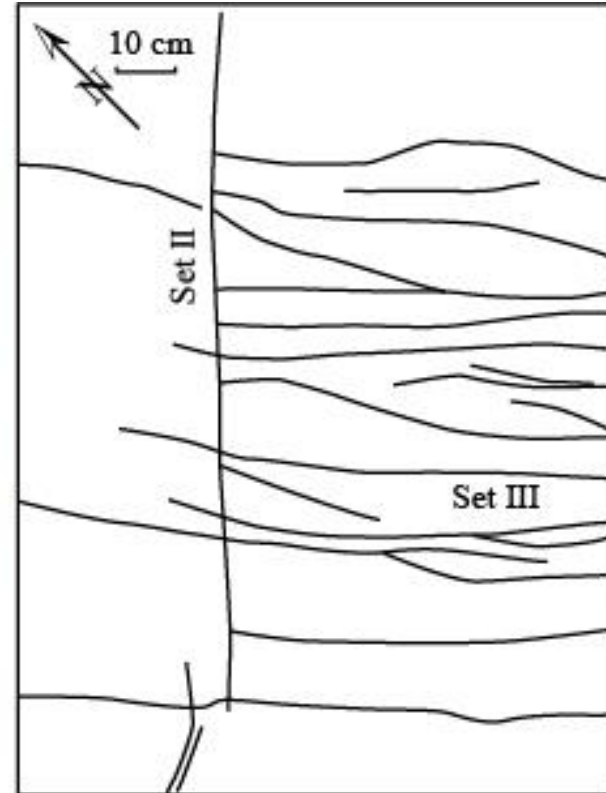
Contrainte principale minimale
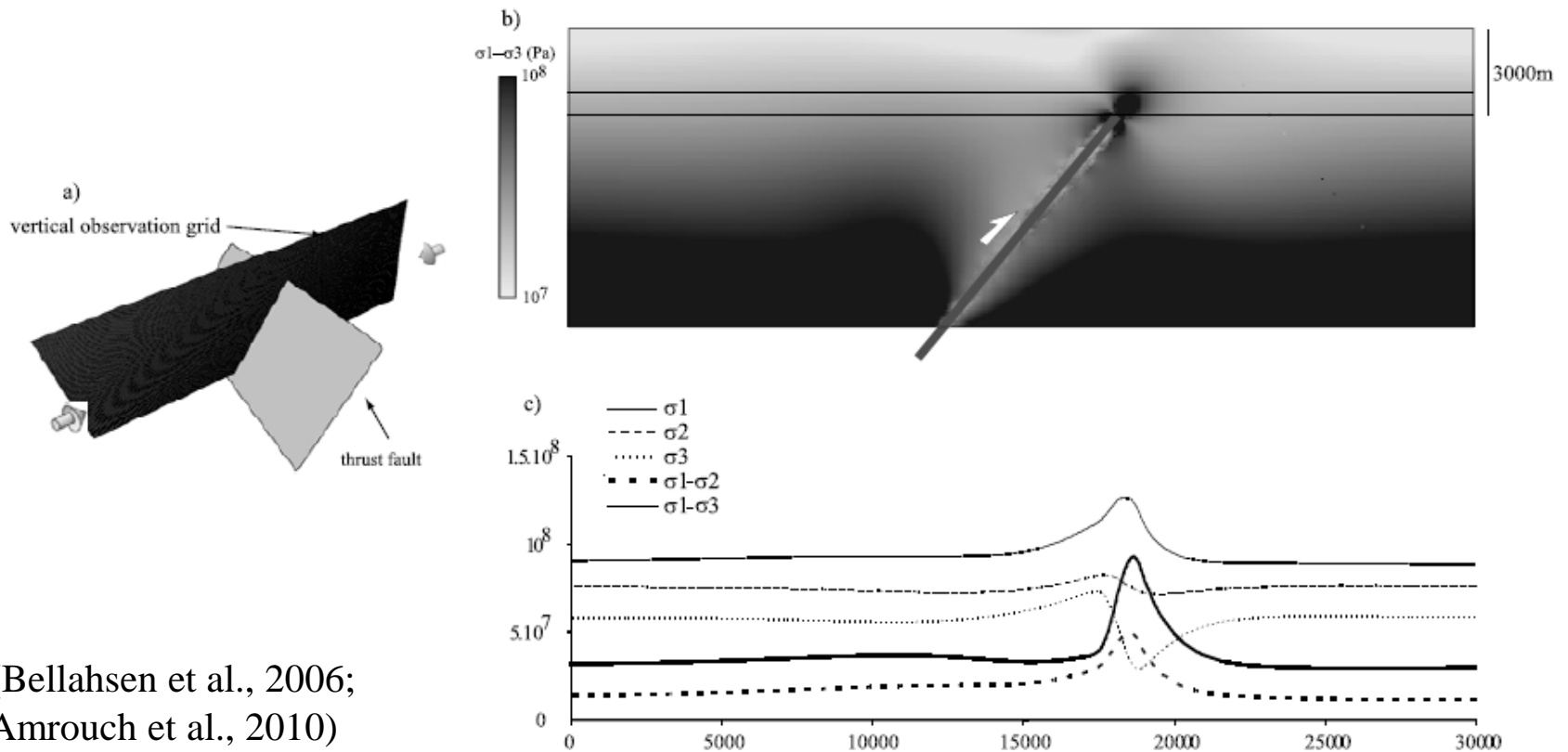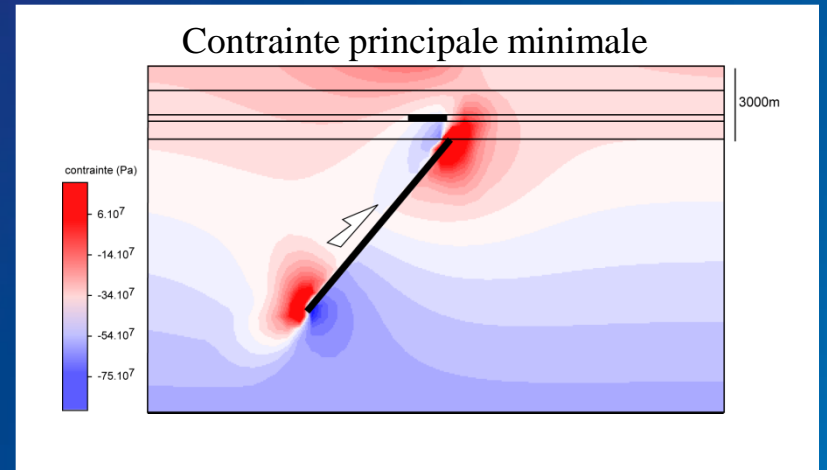
(Bellahsen et al., 2006; Amrouch et al., 2010)

The estimated paleo- principal stress magnitudes are in the range of 20-60 MPa for $\sigma 1$ and -3-10 MPa for $\sigma 3$ in the limestone rocks deformed at 1000-2000m depth.

These estimates of are amongst the very few ones available for upper crustal paleo-stresses at the particular time of tectonic deformation (e.g. Taiwan, Lacombe, 2001).

Being related to ongoing deformation, and averaged over the duration of the Laramide event, they are theoretically hardly compared to modern stresses measured in situ which are rather representative of ambient instantaneous stresses.
They are nevertheless <u>of the same order</u> than the modern principal stress values determined in strike-slip or compressional stress regimes at various places
e.g., at the SAFOD pilot hole (Hickman and Zoback, 2004)

Investigating folding at the mesoscale : fracturing in folded strata

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 mesostructures to either the structural domains of the fold or to quantitatively estimated curvature of strata

A B
C D

SSV

N20FSV

a

b

SSV

N20FSV

a

b

SSV

N20FSV

a

b

(a)

(b)

Systematic joint

Secondary cross joints

Systematic joint
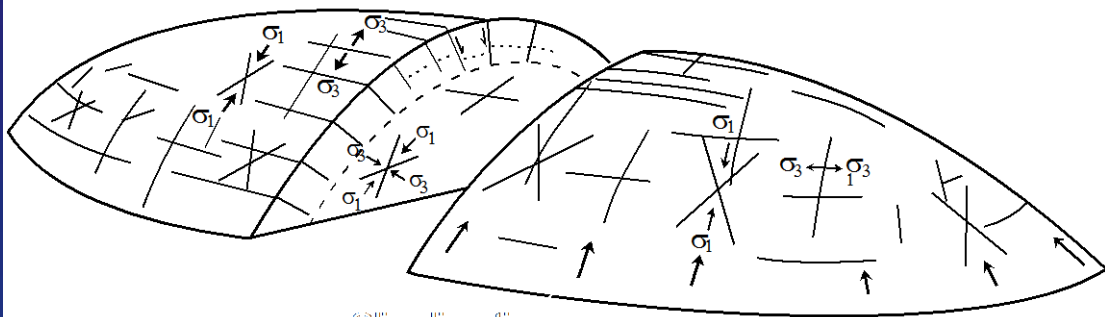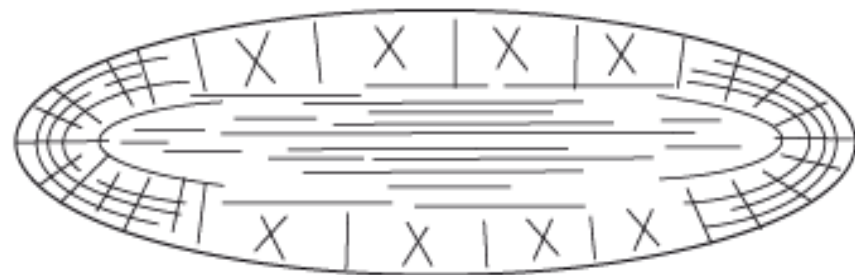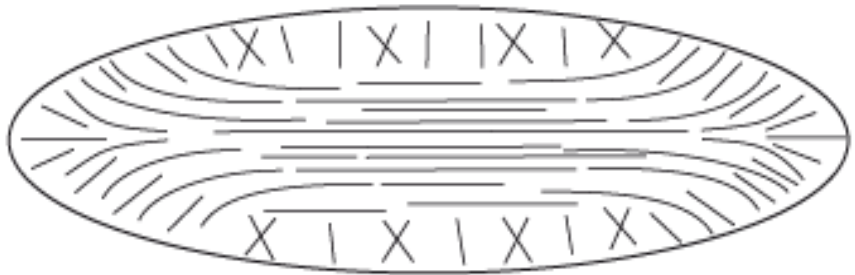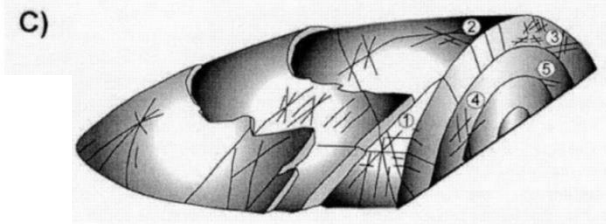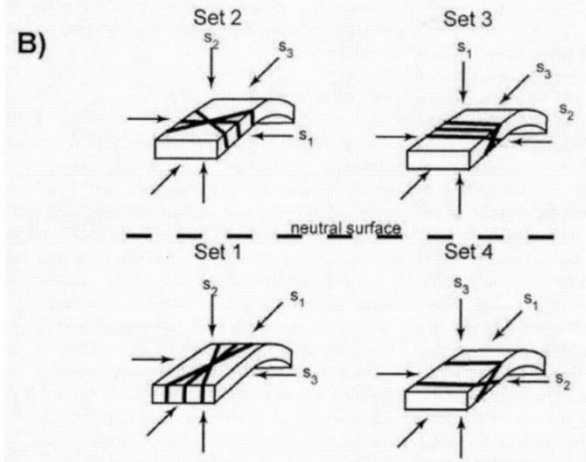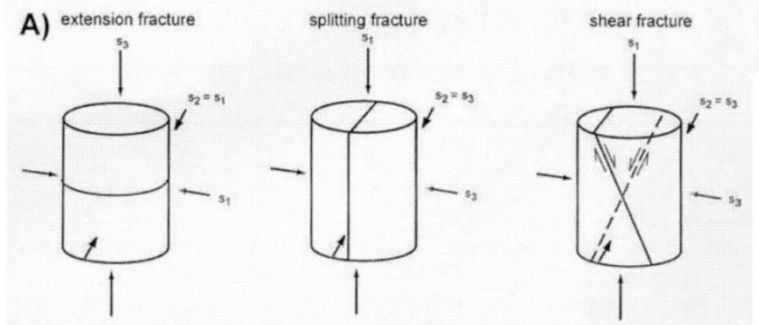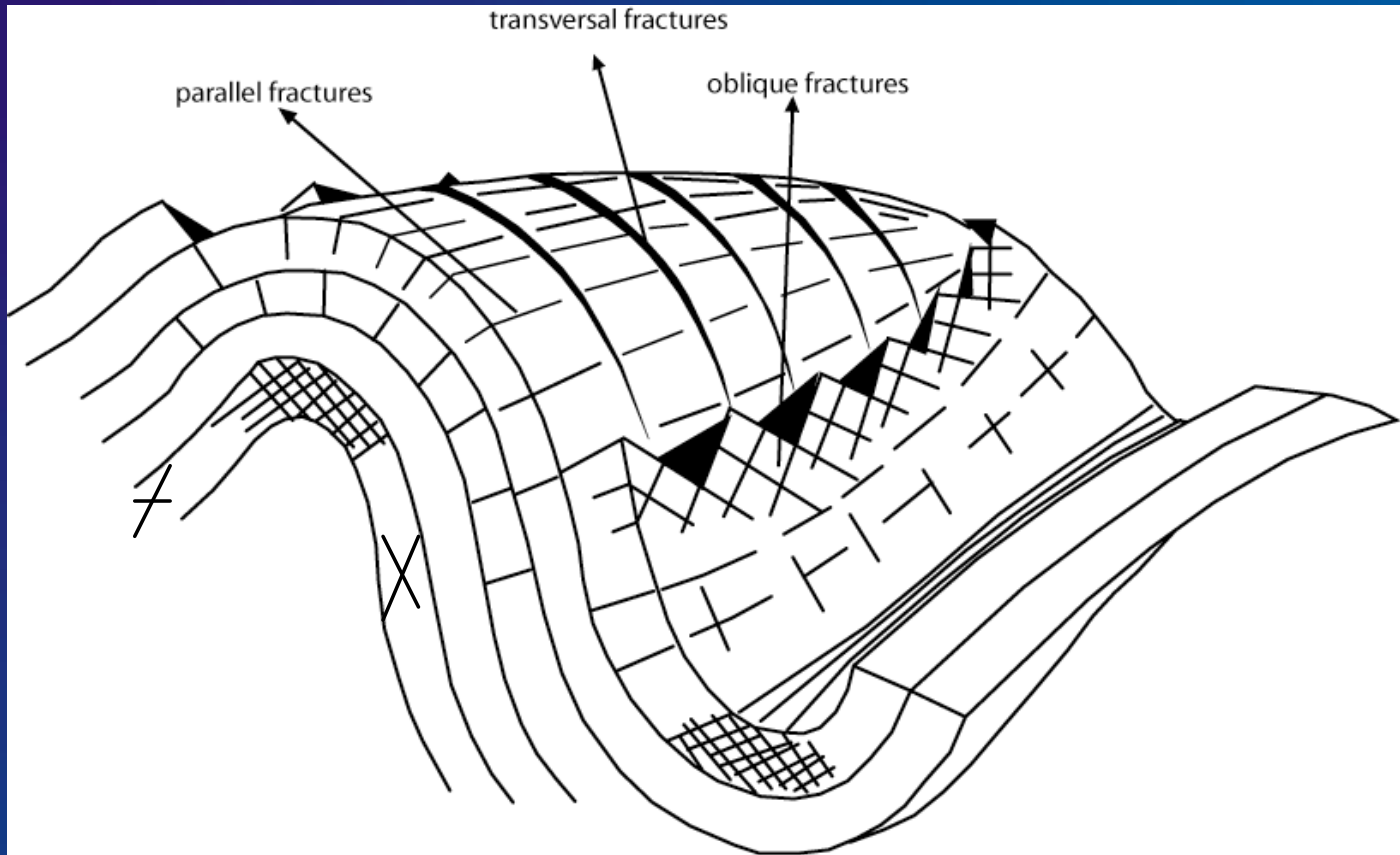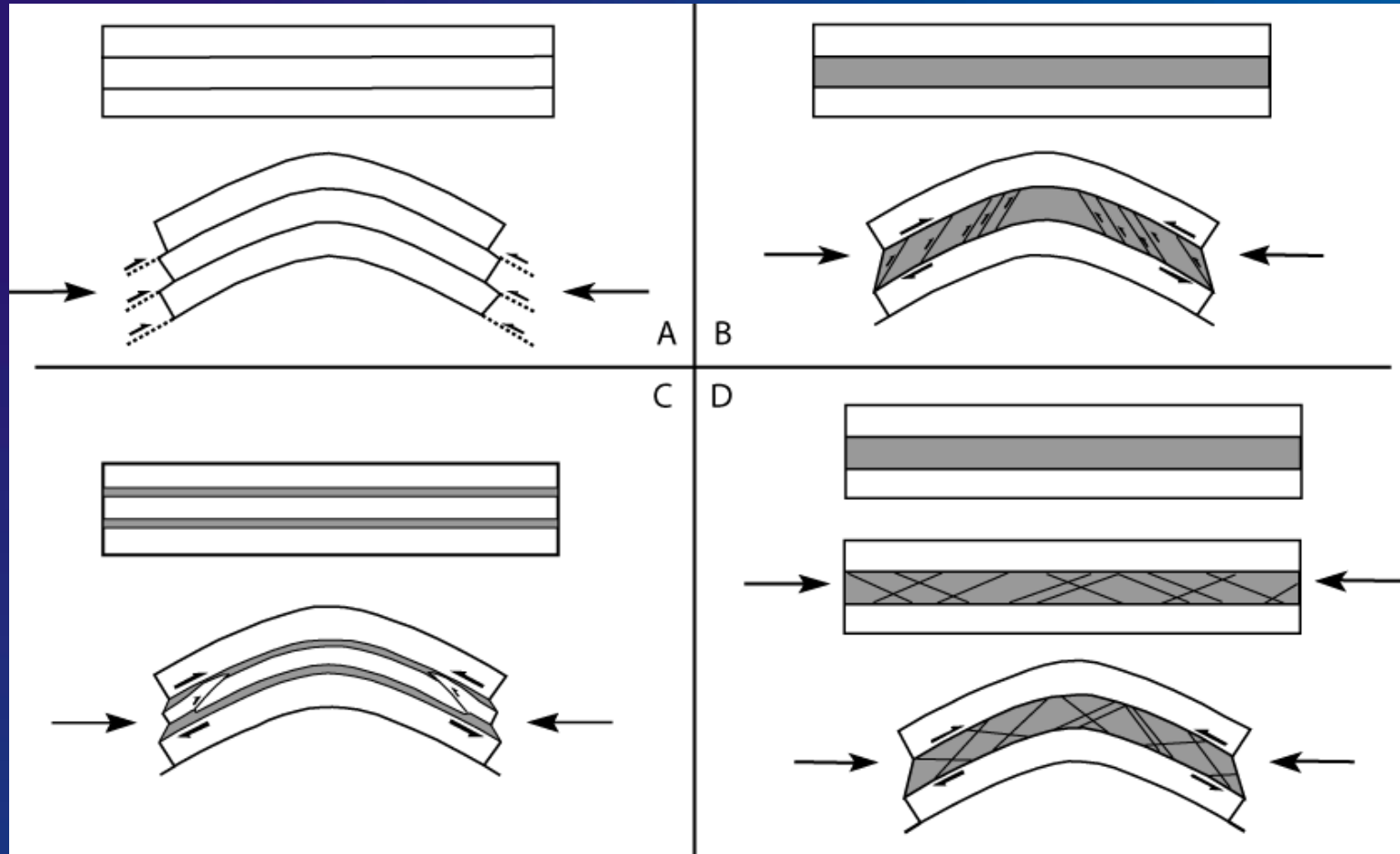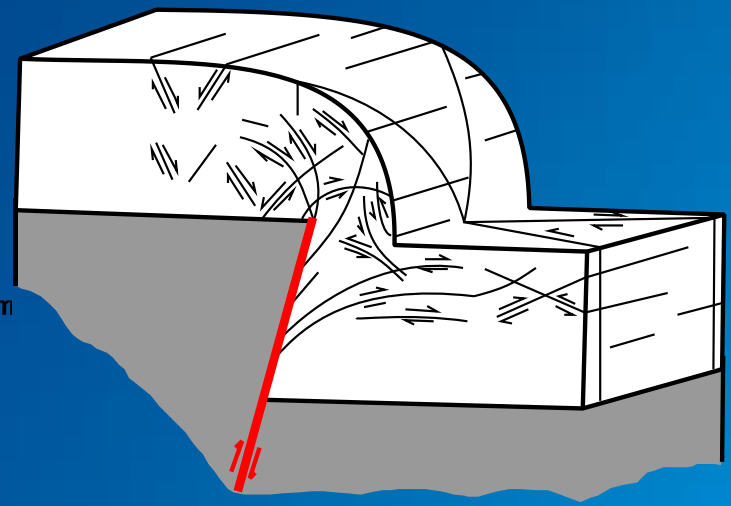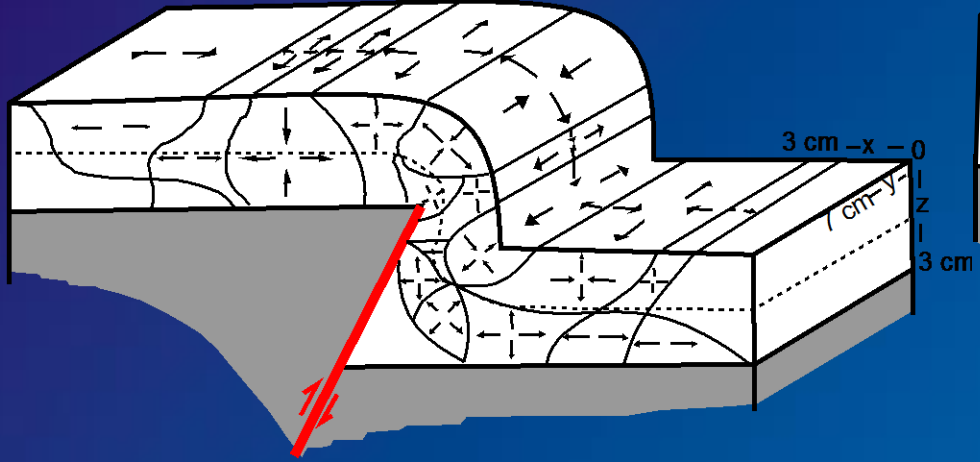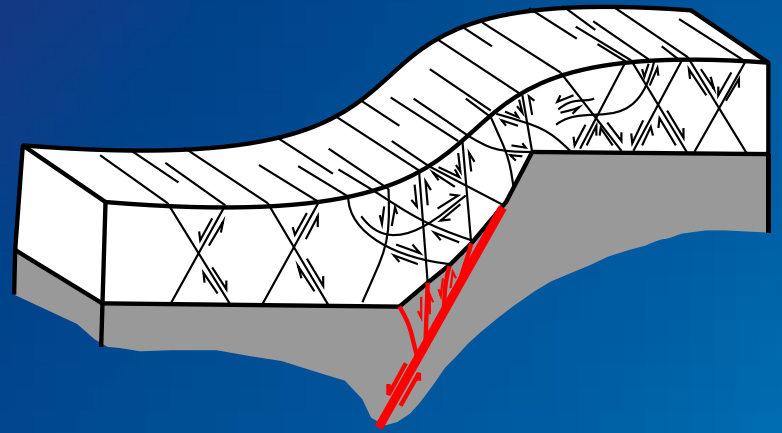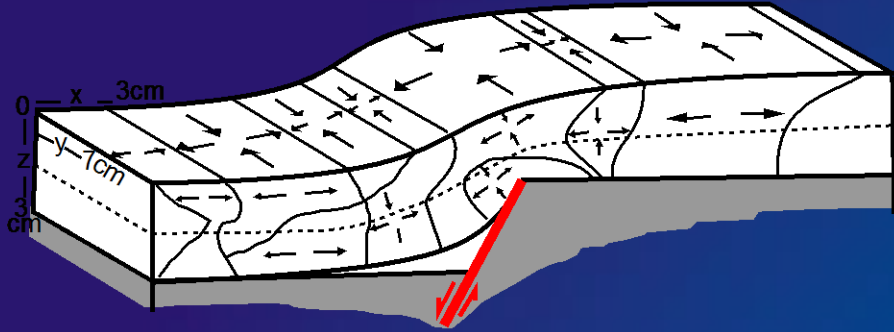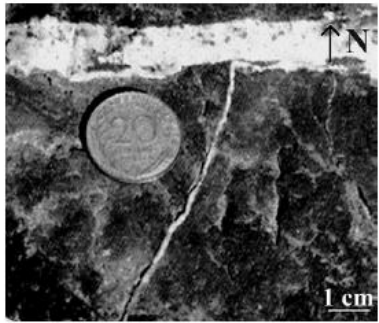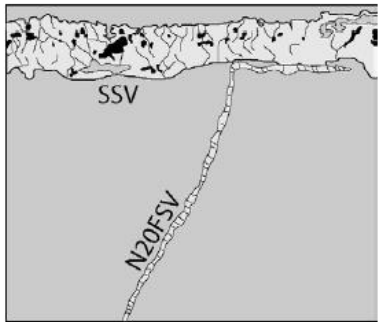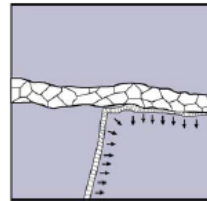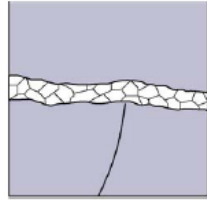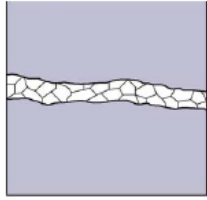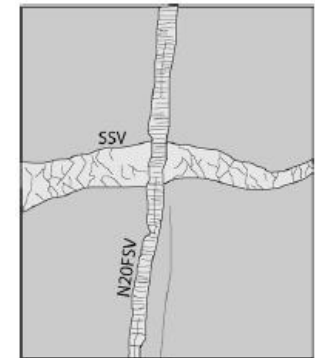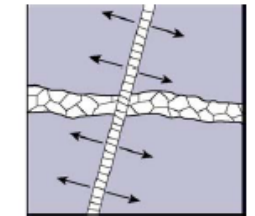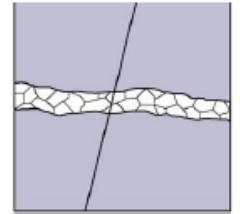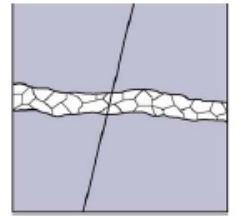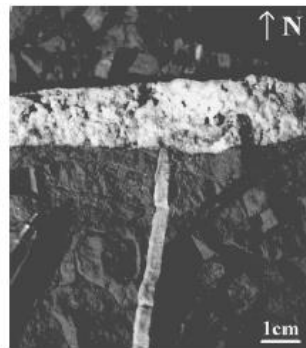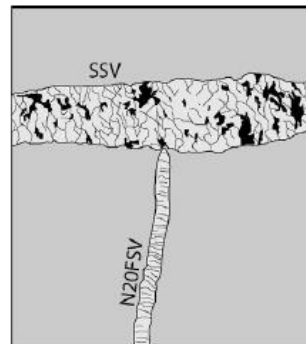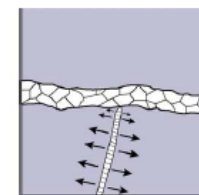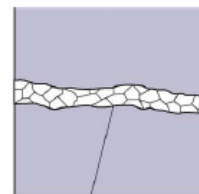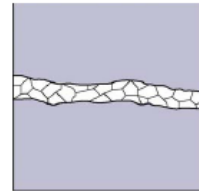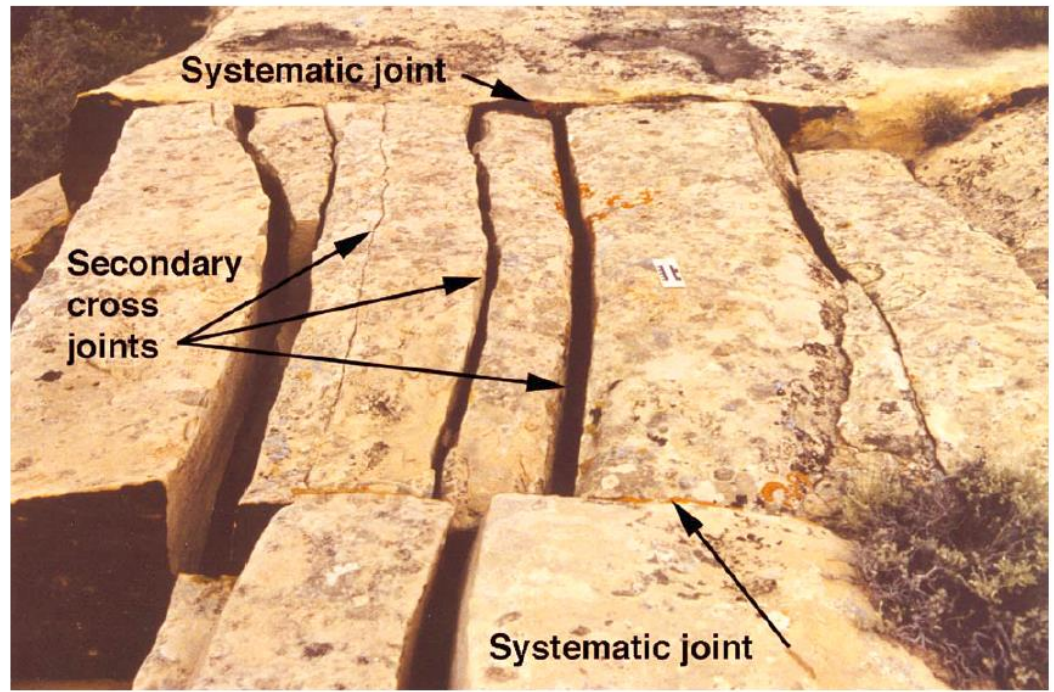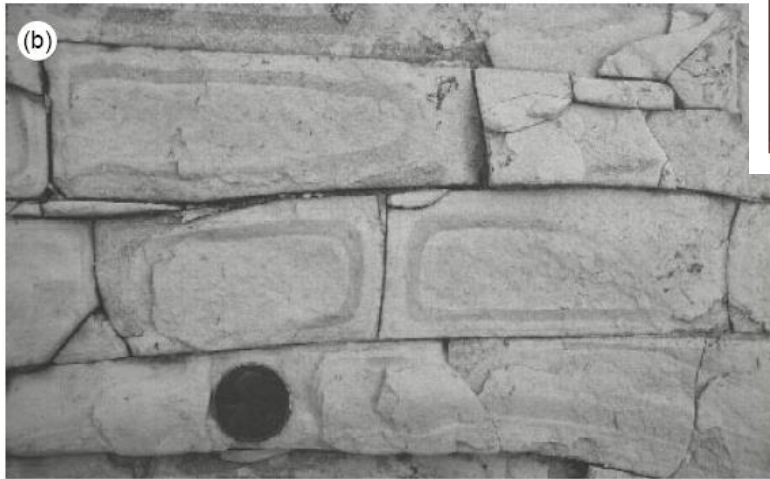
Caution with perpendicular fracture sets

Stress perturbations/permutations :

Around a fracture, there is a stress perturbation that creates a stress shadow where development of a new fracture is inhibited.

When 2 joints are close to each other, the formation of a new joint is inhibited. According to local stresses, a stress permutation may occur that may lead to formation of a perpendicular fracture set.

(a) Local stress switch model

Stage 1: $S/T_f > (S/T_f)'_{cr}$

Stage 2: $S/T_f \leq (S/T_f)'$ for some pairs of systematic joints because of the infiling.

Stage 3: Resulting joint patterns due to the local stress switch.

no orthogonal cross joints

Stage 4: Infilling of more systematic joints.

Stage 5: Final joint patterns.
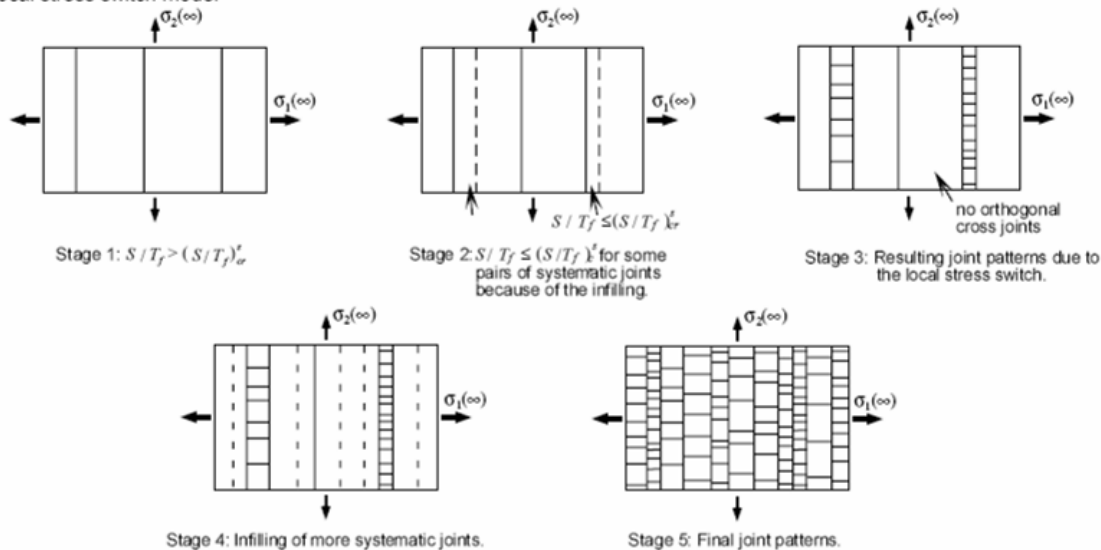
(b) Regional stress rotation model
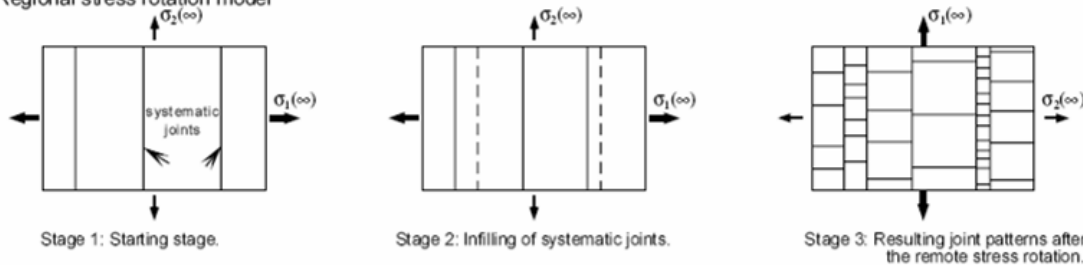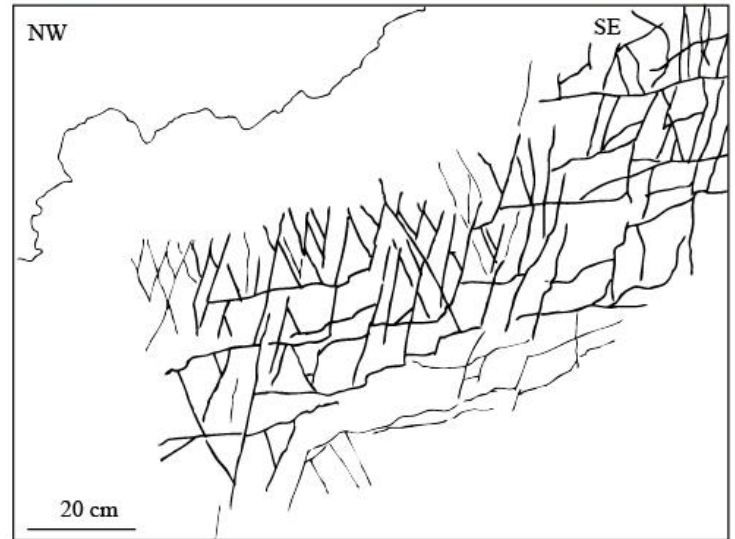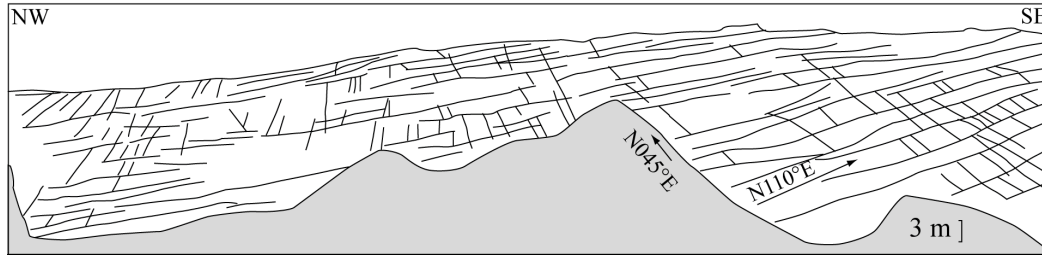
systematic joints

Stage 1: Starting stage.

Stage 2: Infilling of systematic joints.

Stage 3: Resulting joint patterns after the remote stress rotation.

No regional meaning

NW   SE

N045°E   N110°E   3 m]

NW   SE

20 cm

(Bellahsen et al., 2006; Amrouch et al., 2010)

(a)

S / N

Set I

1 m

Nb planes 94

(b)

SE / NW

Set I

1 m

Nb planes 35

Set I

10 cm

NW — SE

N045°E
N110°E
3 m

10 cm
Set II
Set III

Nb planes 42

(Bellahsen et al., 2006;
Amrouch et al., 2010)

S — N
Set I
1 m
Nb planes 94
(a)

SE — NW
Set I
1 m
Nb planes 35
(b)

Set II

Set III

10 cm

Nb planes 42

(Bellahsen et al, 2006)

(a)

NW   SE

Set II   Set III

10 cm

(b)

Set I

Set II

N   N   N
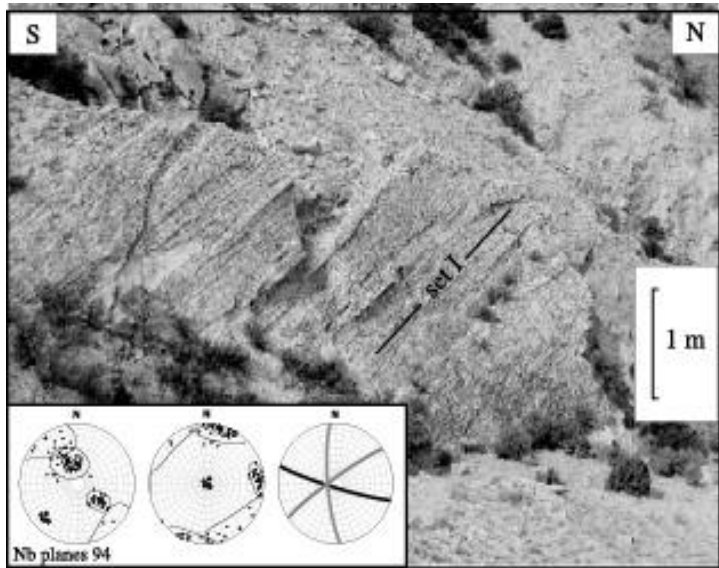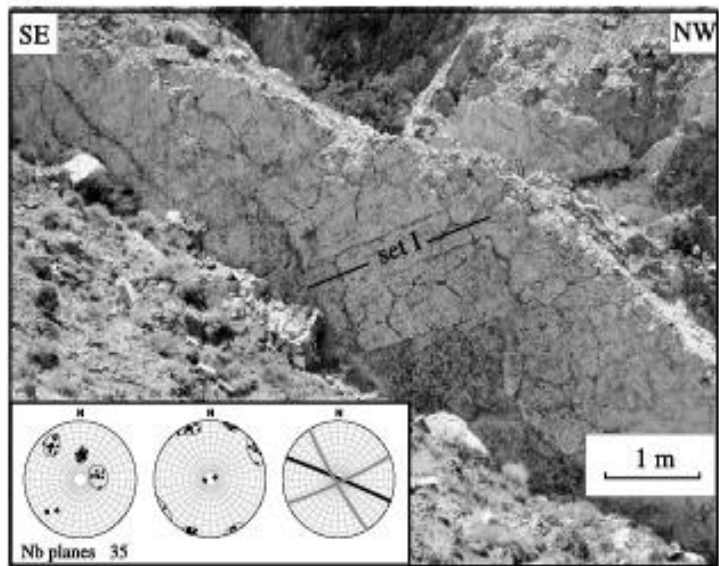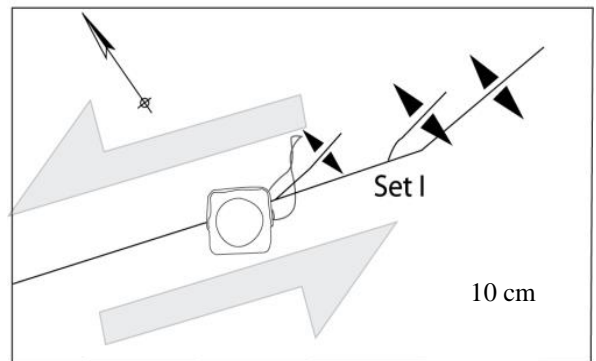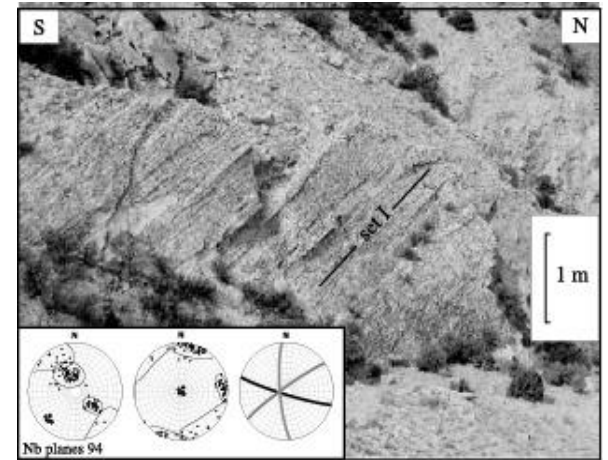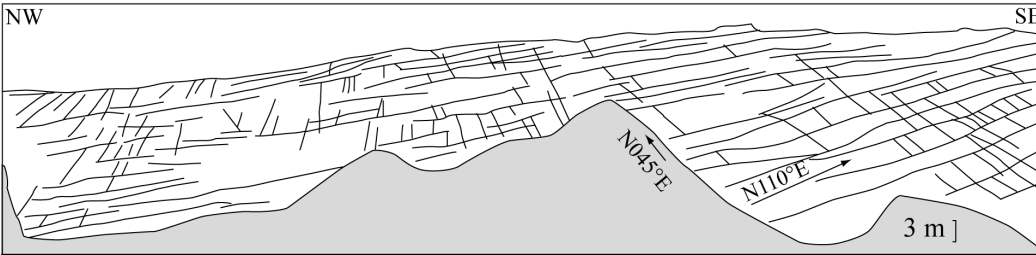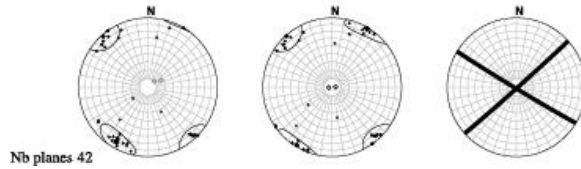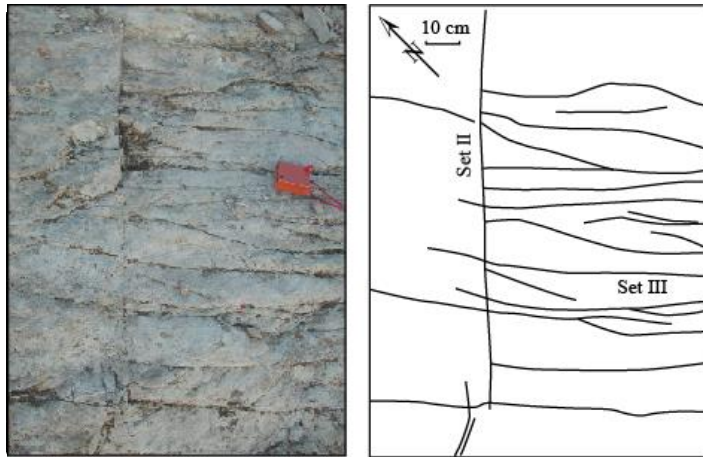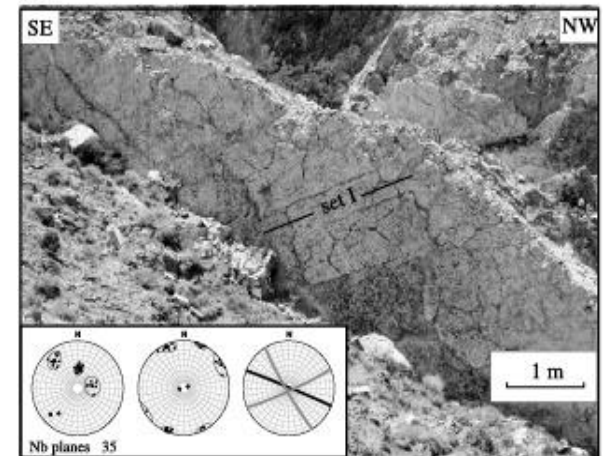
Nb planes 61
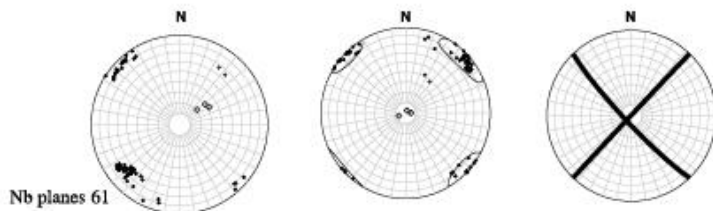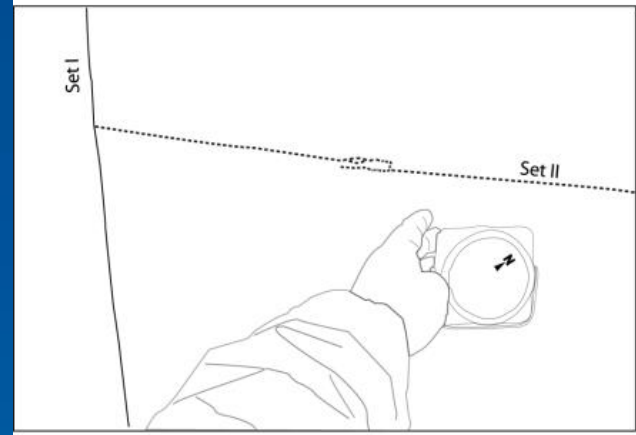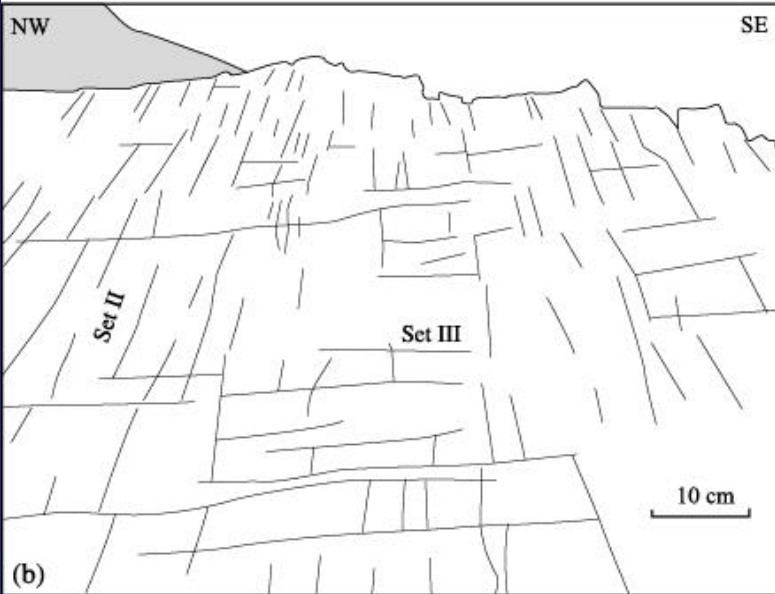
(Bellahsen et al, 2006)

Checking opening mode of joints/veins in thin sections
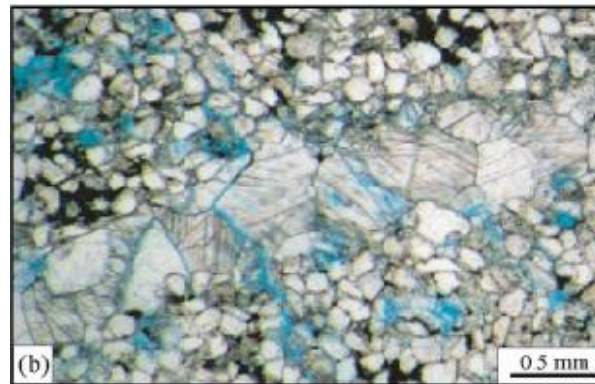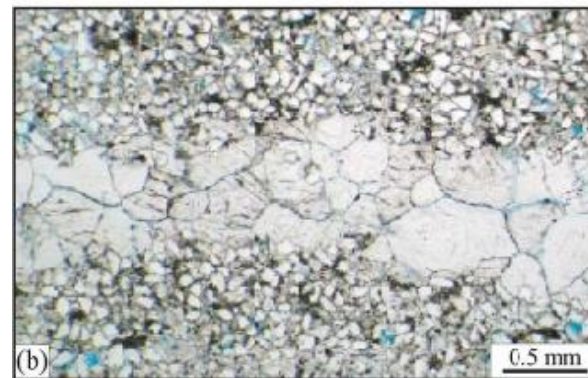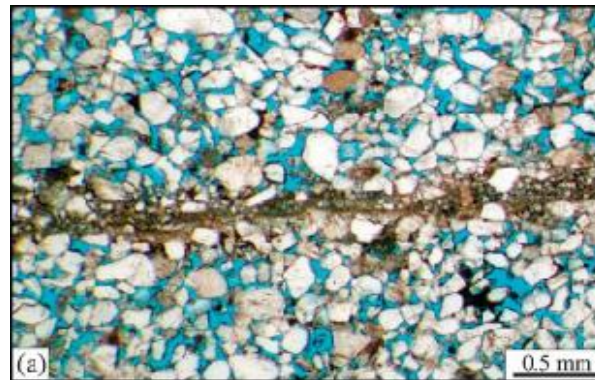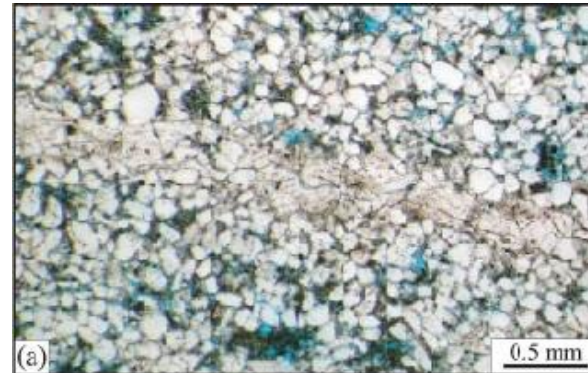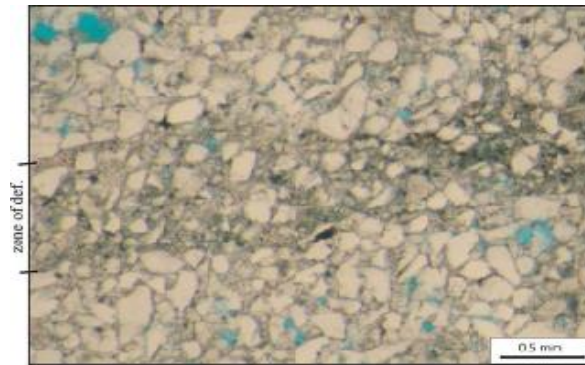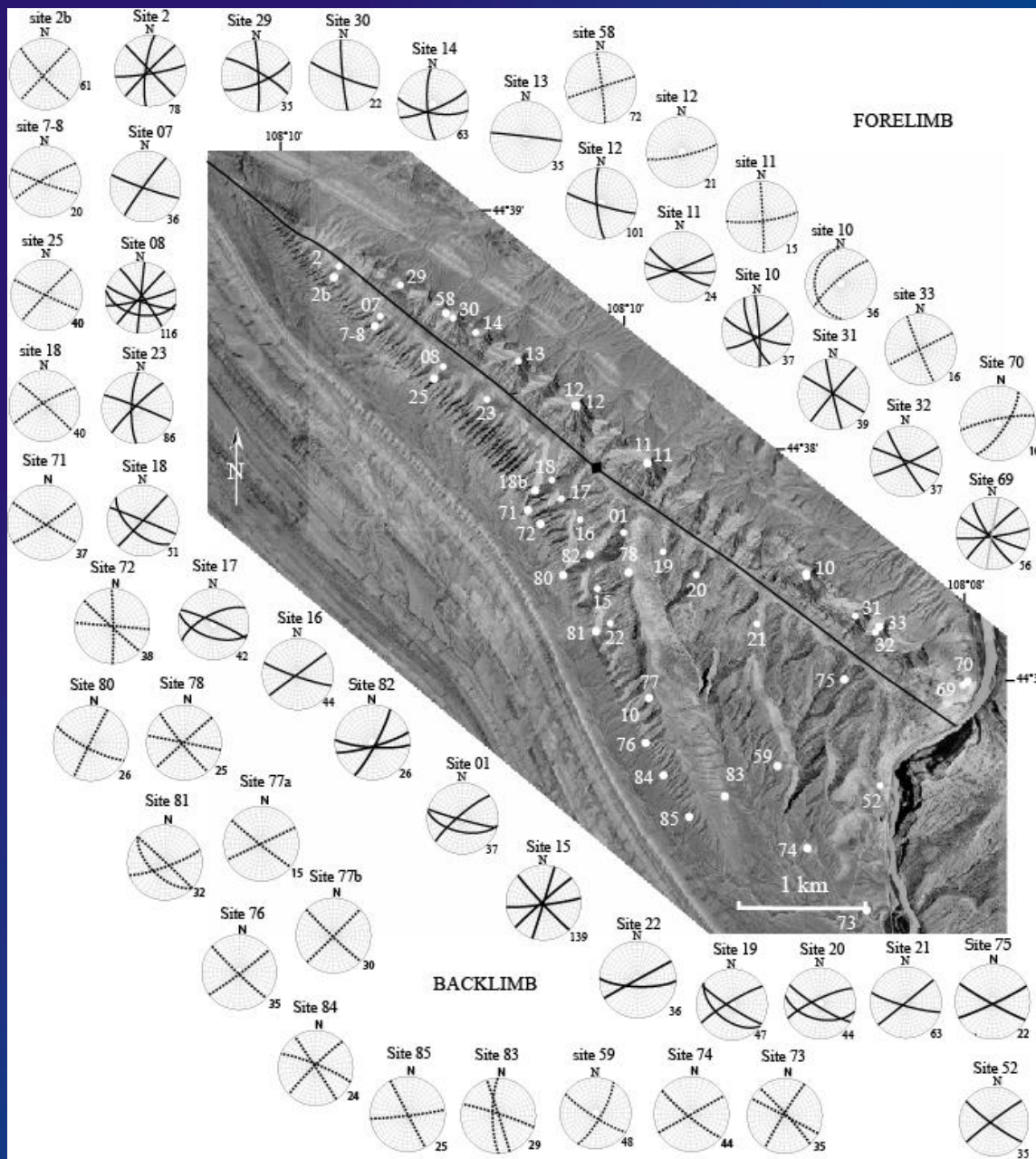
Distribution of joint/vein sets

(Bellahsen et al., 2006; Fiore, 2007; Amrouch et al., 2010)

Relationships between pressure solution seams and fractures
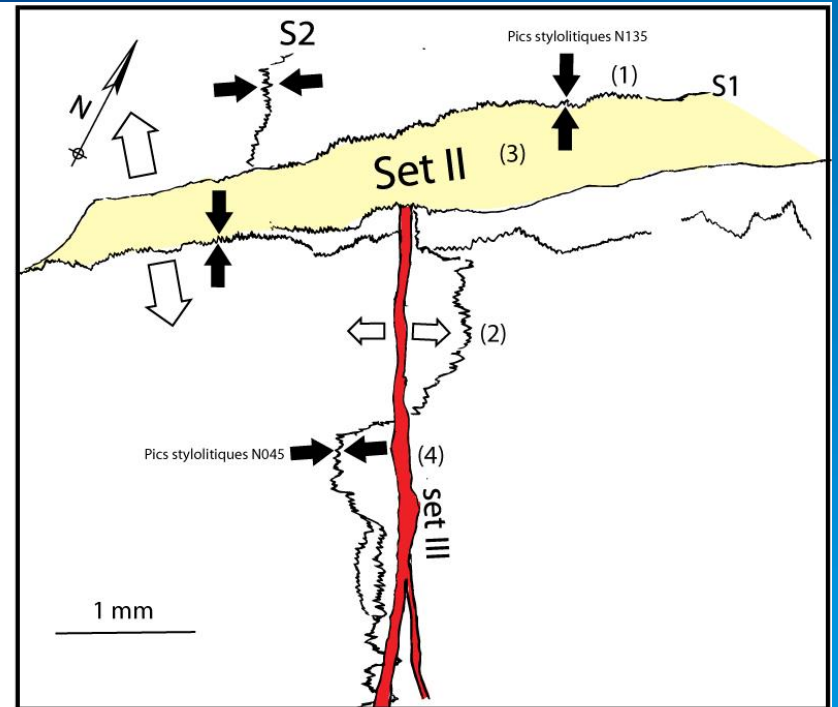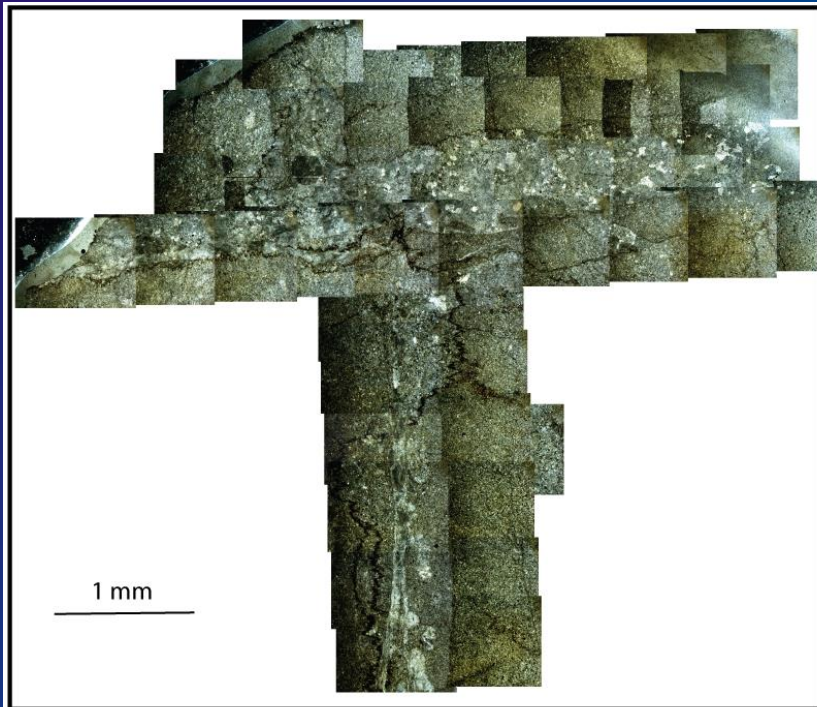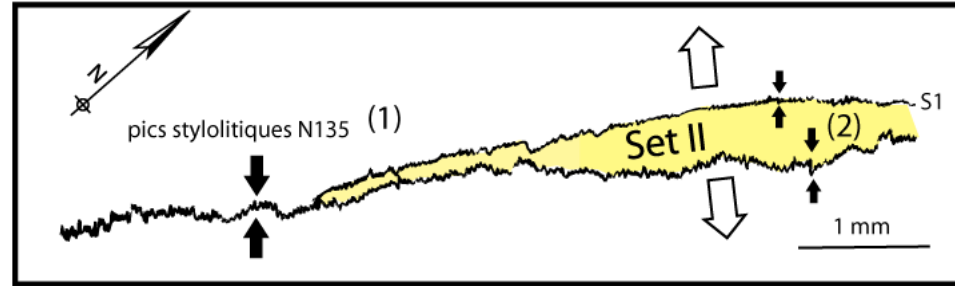
First-order sequence of fracture development

Pre-Laramide
Set I

Laramide
Syn-folding
Set III

Laramide LPS
Set II

Set I

Set III

Set III

Set I

Set IV

a)

b)

c)

d)

(modified after Bellahsen et al. , 2006)
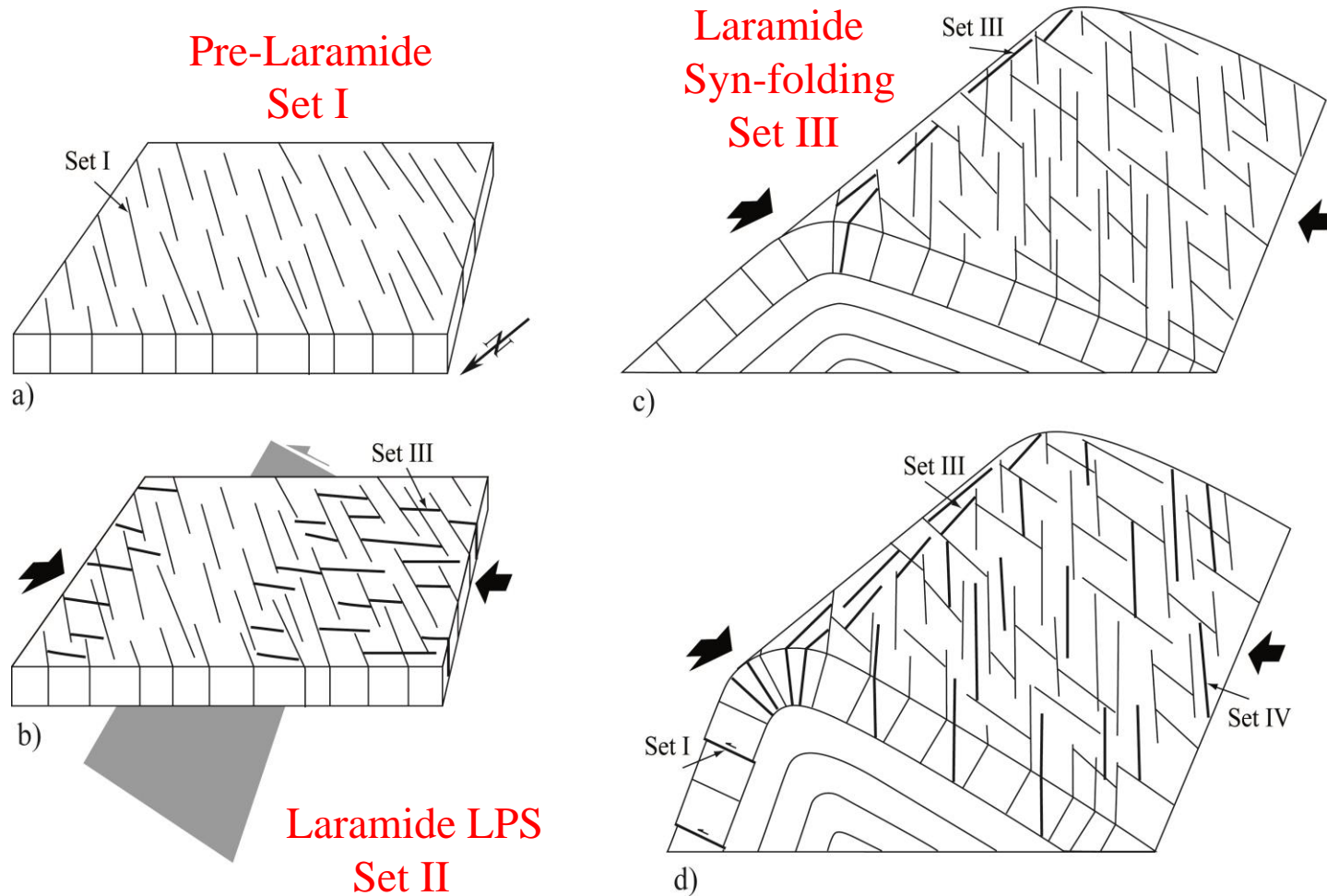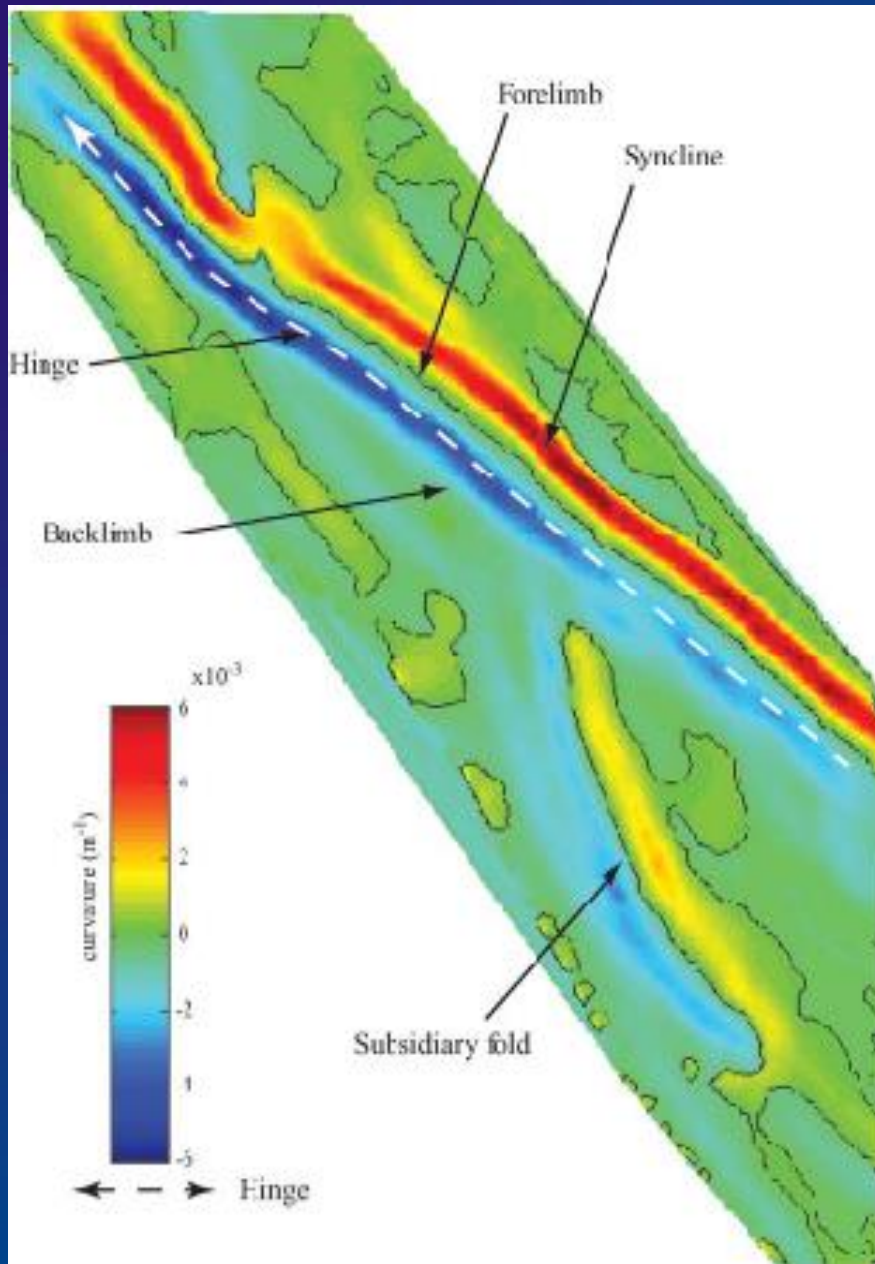
Curvature analysis

Bellahsen et al, 2006

Meso-scale faulting
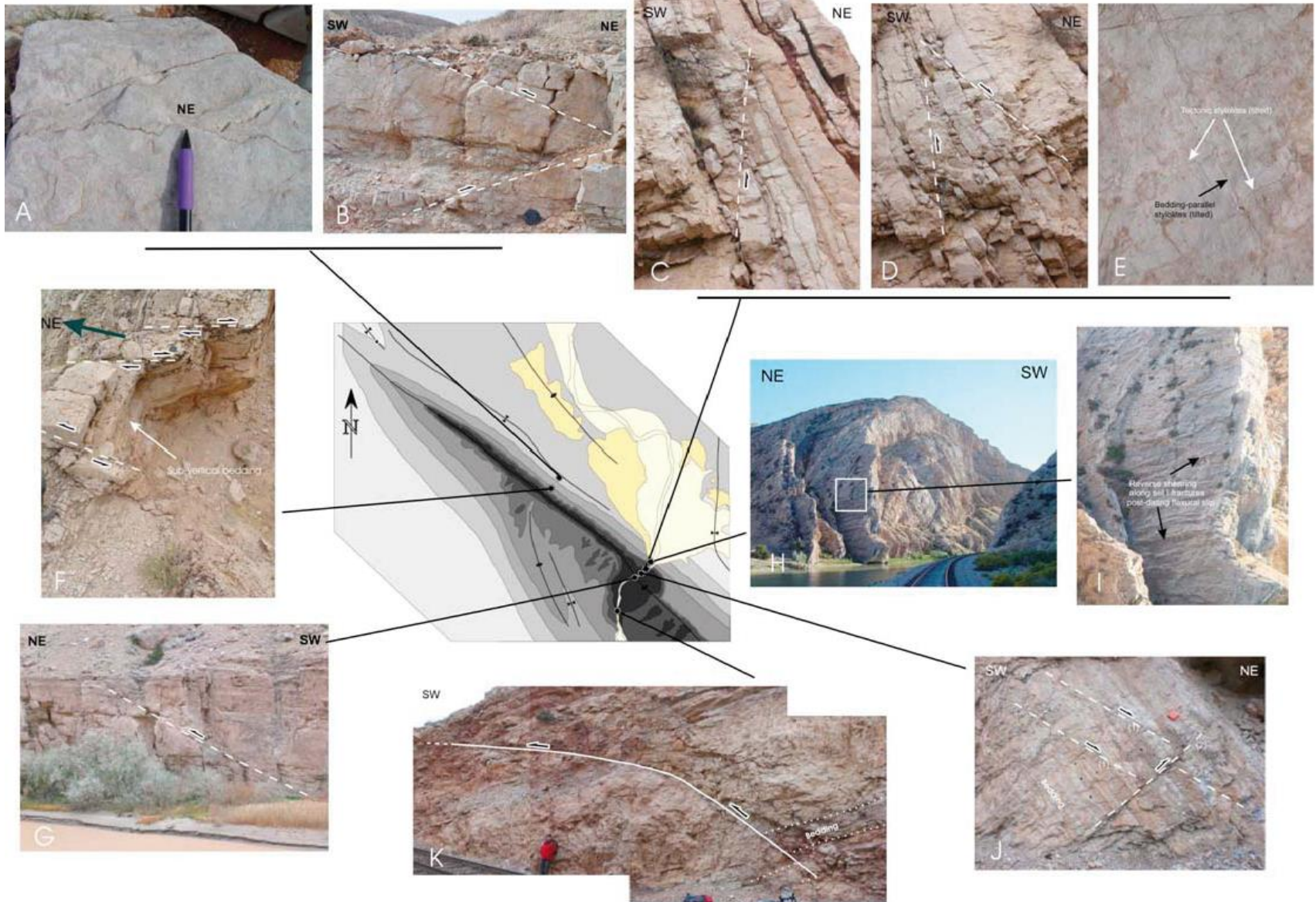
Scenario of fault-fracture development in space and time
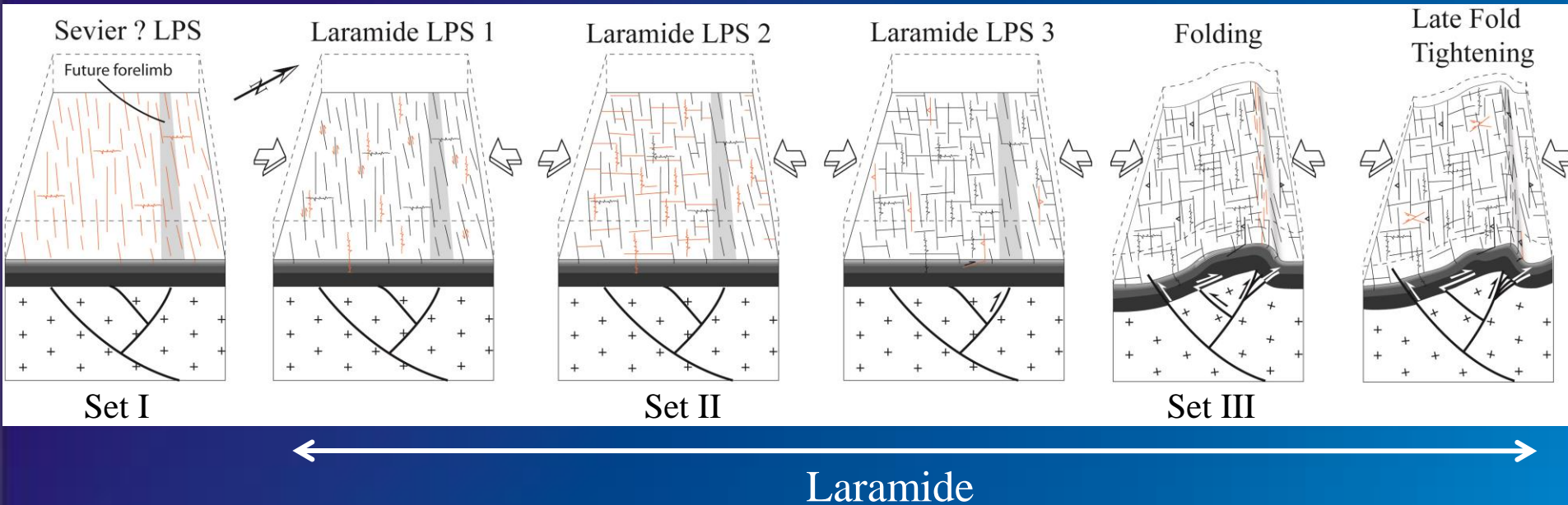
(Amrouch et al.,2011)

Set I — Sevier ? LPS — Future forelimb

Laramide LPS 1

Laramide LPS 2 — Set II

Laramide LPS 3

Folding — Set III

Late Fold Tightening

Laramide

- Mode I opening of pre-Laramide set I fractures
-Shear reactivation of pre-Laramide set I fractures (LPS 1).
-Laramide stylolites with NE-trending peaks and mode I opening
 of set II fractures (LPS2)
- Reverse faulting parallel to the fold axis (LPS3).
-Mode I opening of syn-folding, outer-rim extension-related set III fractures
-Late stage fold tightening (LSFT) marked by strike-slip faults and reactivation of tilted
set I fractures as small reverse faults in the forelimb

Insights into mechanical behaviour of folded strata :

* Early folding stage - LPS :

Forelimb : stress perturbations, that partly prevented development of fractures. In turn limited fracture development + weak internal deformation (AMS and APWV) → poor stress relaxation → differential stress increase.

Backlimb : no stress perturbation + stress relaxation by widespread development of fractures and by internal strata deformation (AMS) → much lower differential stresses

* Late-folding stage – LSFT :

Forelimb : drop of differential stresses while limited internal deformation (poorly evolved AMS fabrics and low anisotropy of the matrix revealed by APVW → strata were tilted during folding without any additional significant internal deformation, LSFT being mainly accommodated by newly formed microfaults and reactivation of earlier fractures → stress relaxation

Backlimb : Strata sustained most of LSFT without developing much fractures,
→ increase of differential stresses and development of more evolved ASM fabrics

Coaxiality of stress and strain and consistency with anisotropy of rock physical properties

(Amrouch et al., 2010)
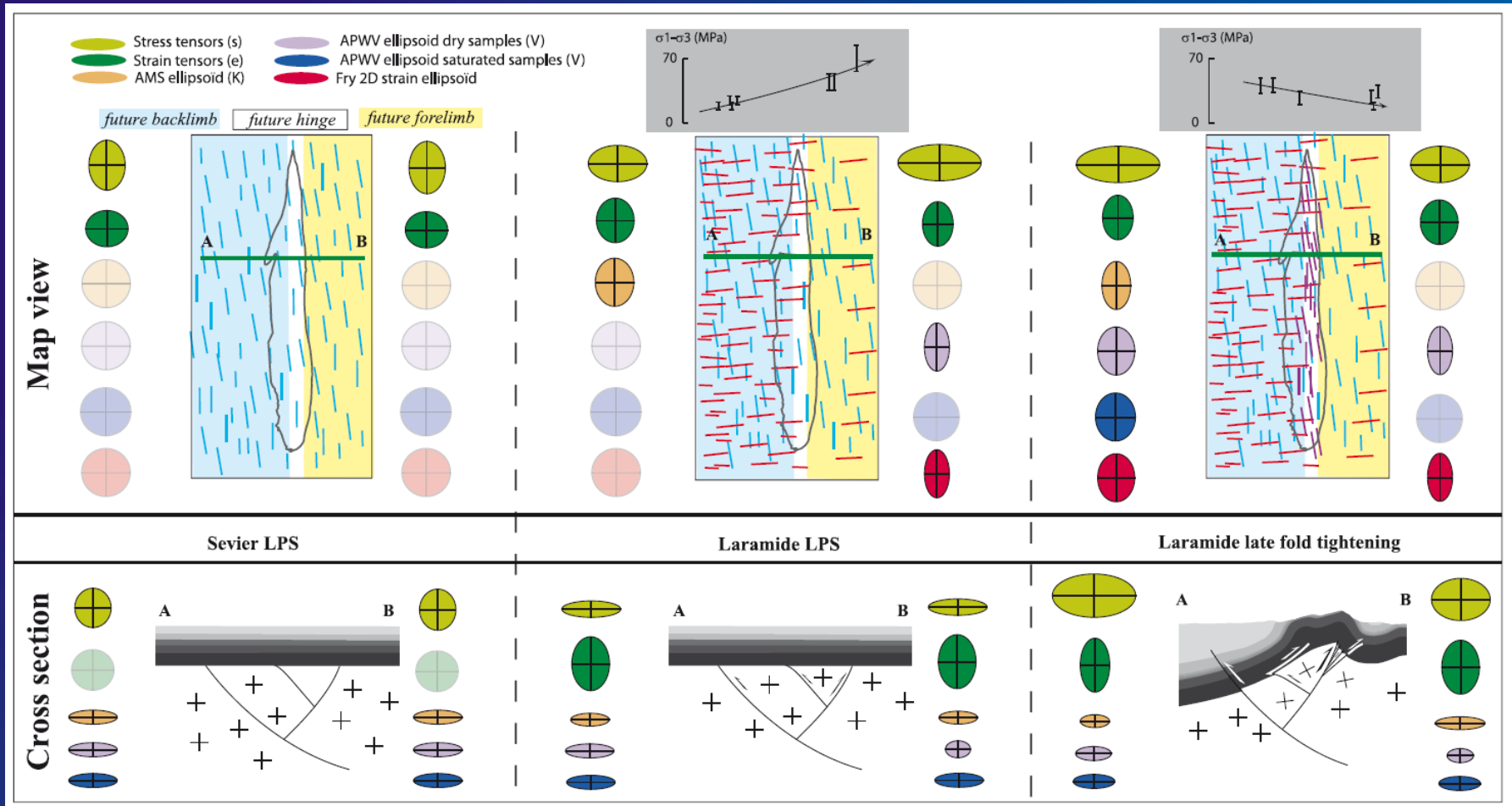
Investigating fluid flow in folds (1) : geochemical and microthermometric analyses of cemented fractures in folded strata

B 27

KAL 4

SMA 1

B 12

Veins : an access to fossil fluids

Calcite veins

O, C stable
  isotopes

Microthermometry
of fluid inclusions

• $^{87/86}$ Sr ratios

5 mm
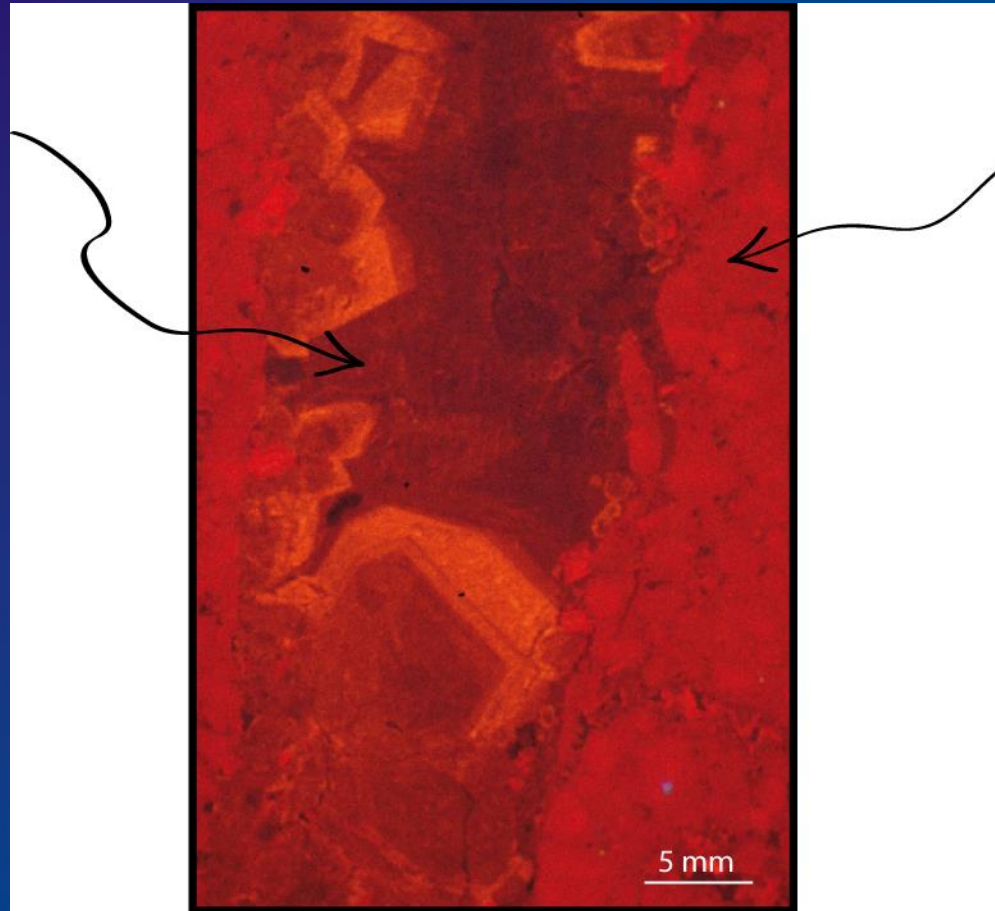
**Limestone
Host-Rock**

O,C stable
isotopes

$^{87/86}$ Sr ratios

Fluid temperature

**Fluid origin and
pathways**

**Fluid-Rock
Interactions**

Textures and vein fillings
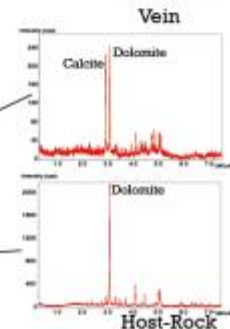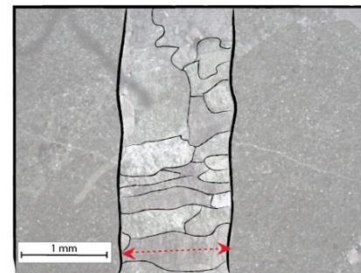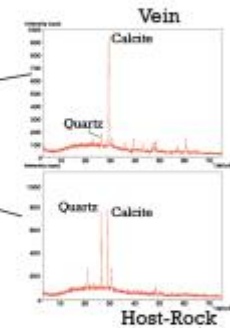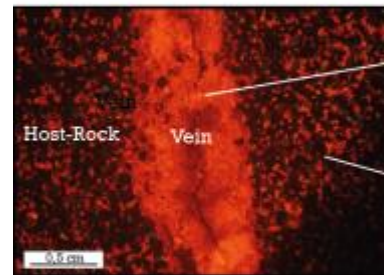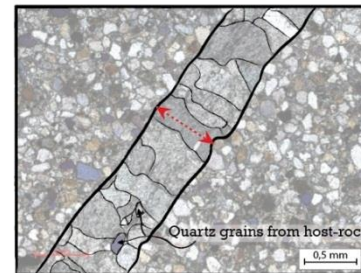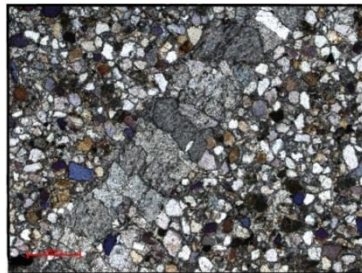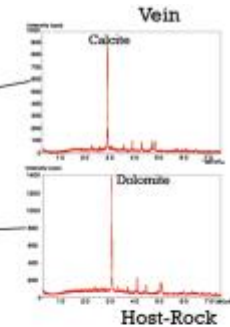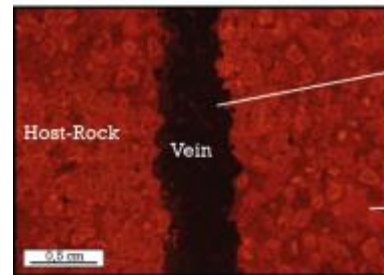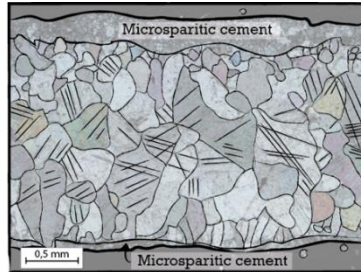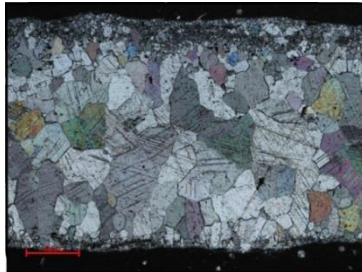
Cathodoluminescence
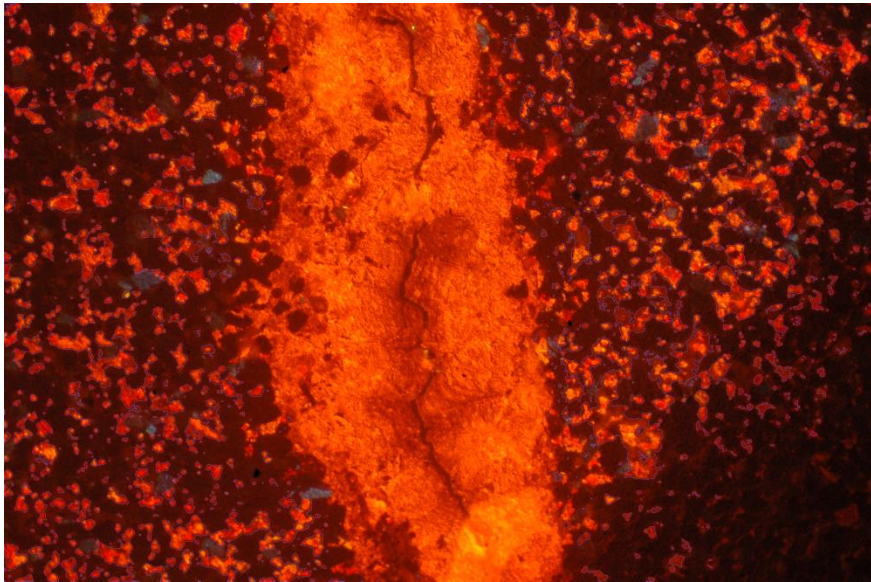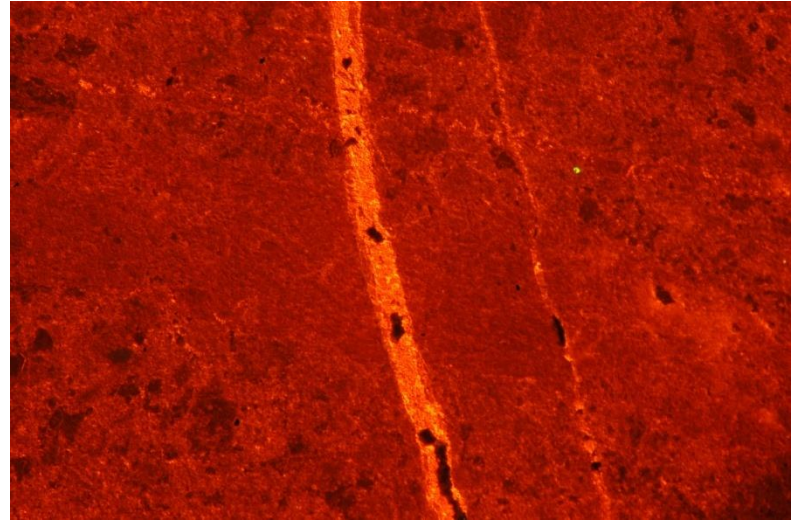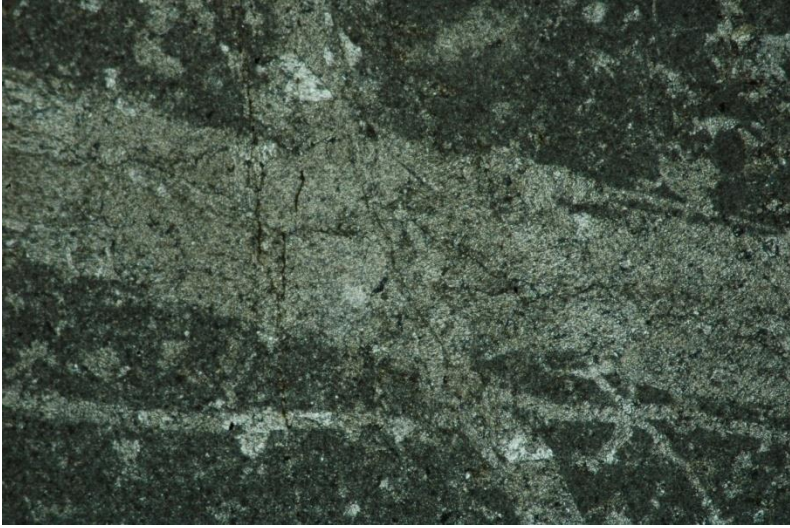
Identifying successive filling phases and parageneses
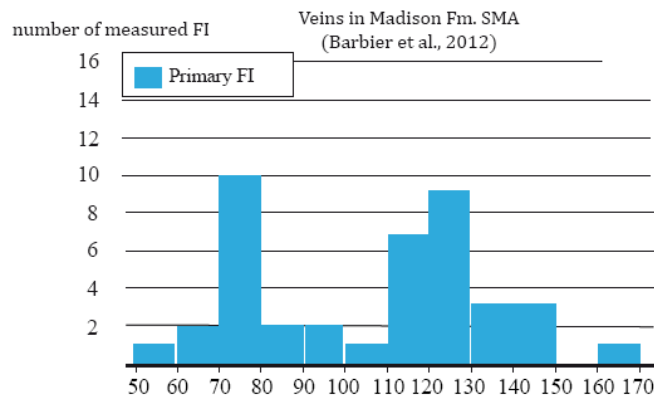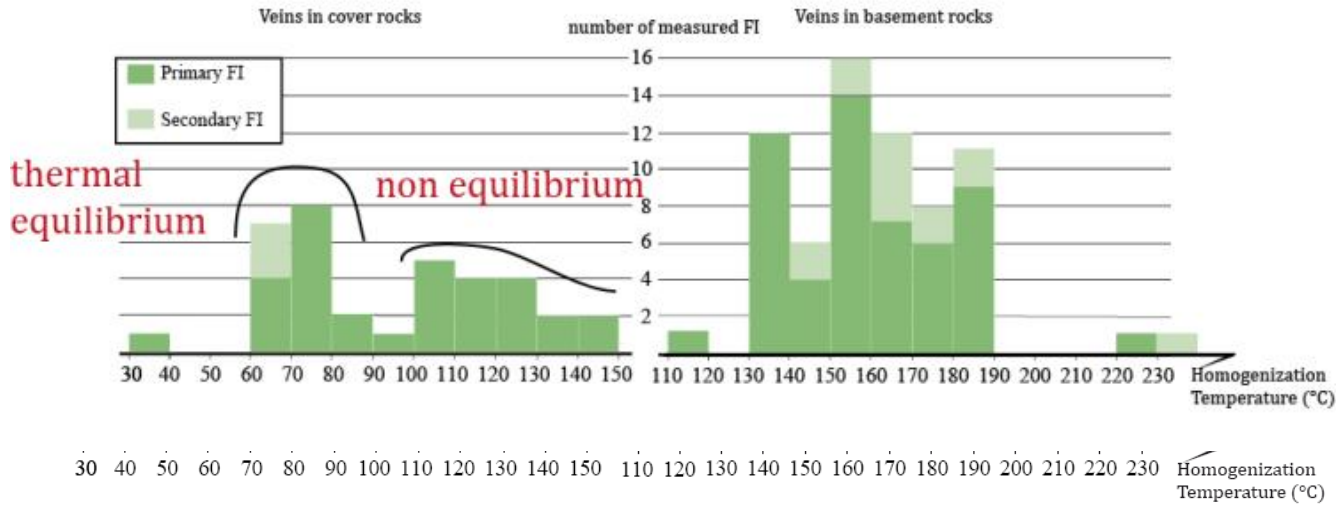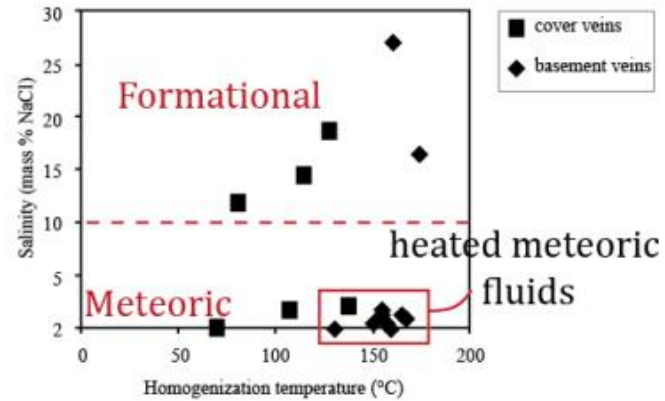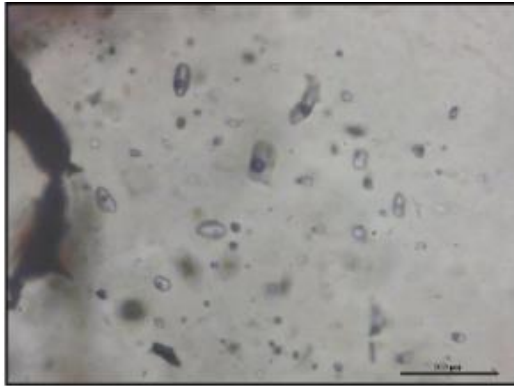
Microthermometry and Raman spectrometry of fluid inclusions

Homogeneization temperatures vs $\delta^{18}O$
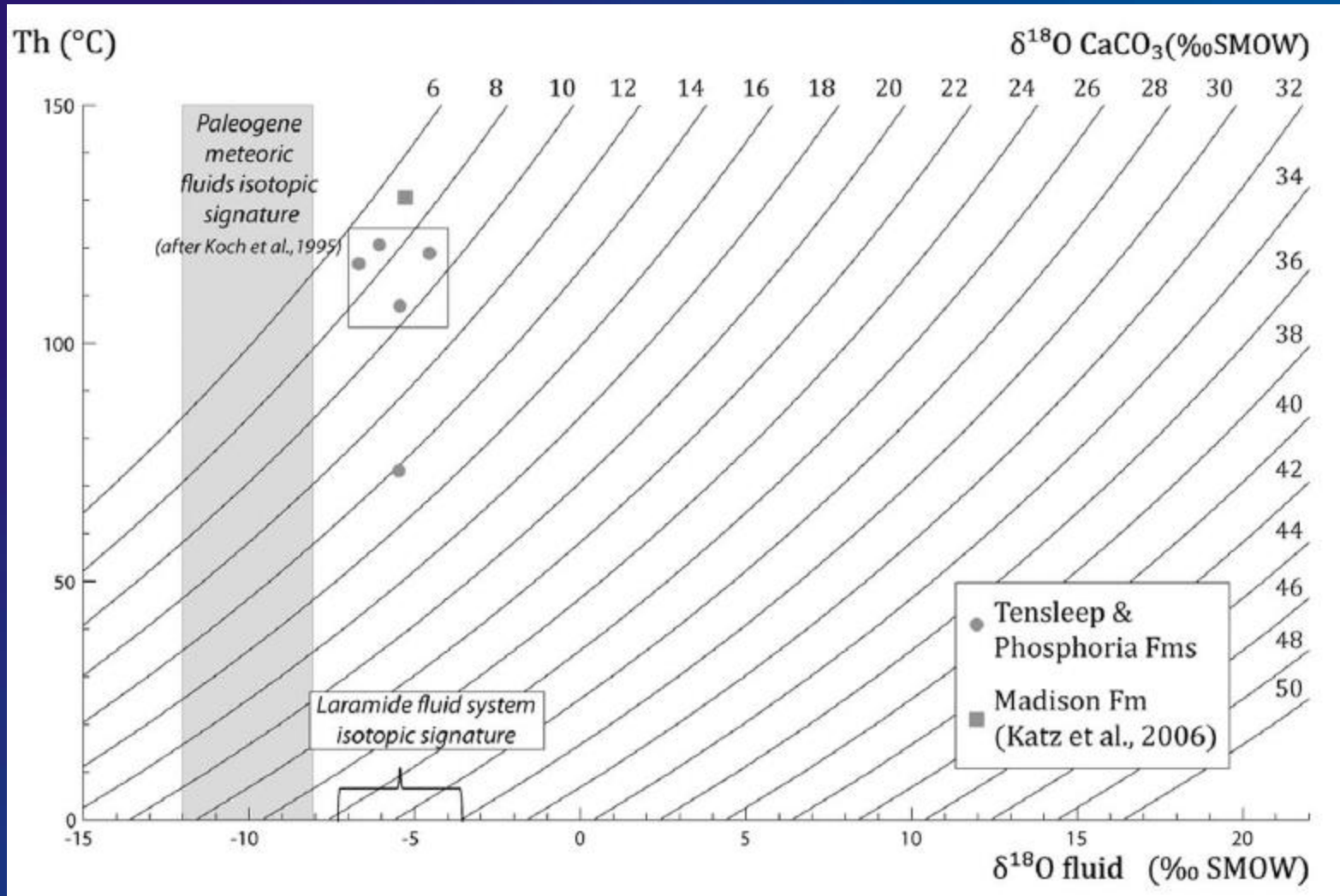
(Beaudoin et al, 2011)

O, C stable isotope geochemistry
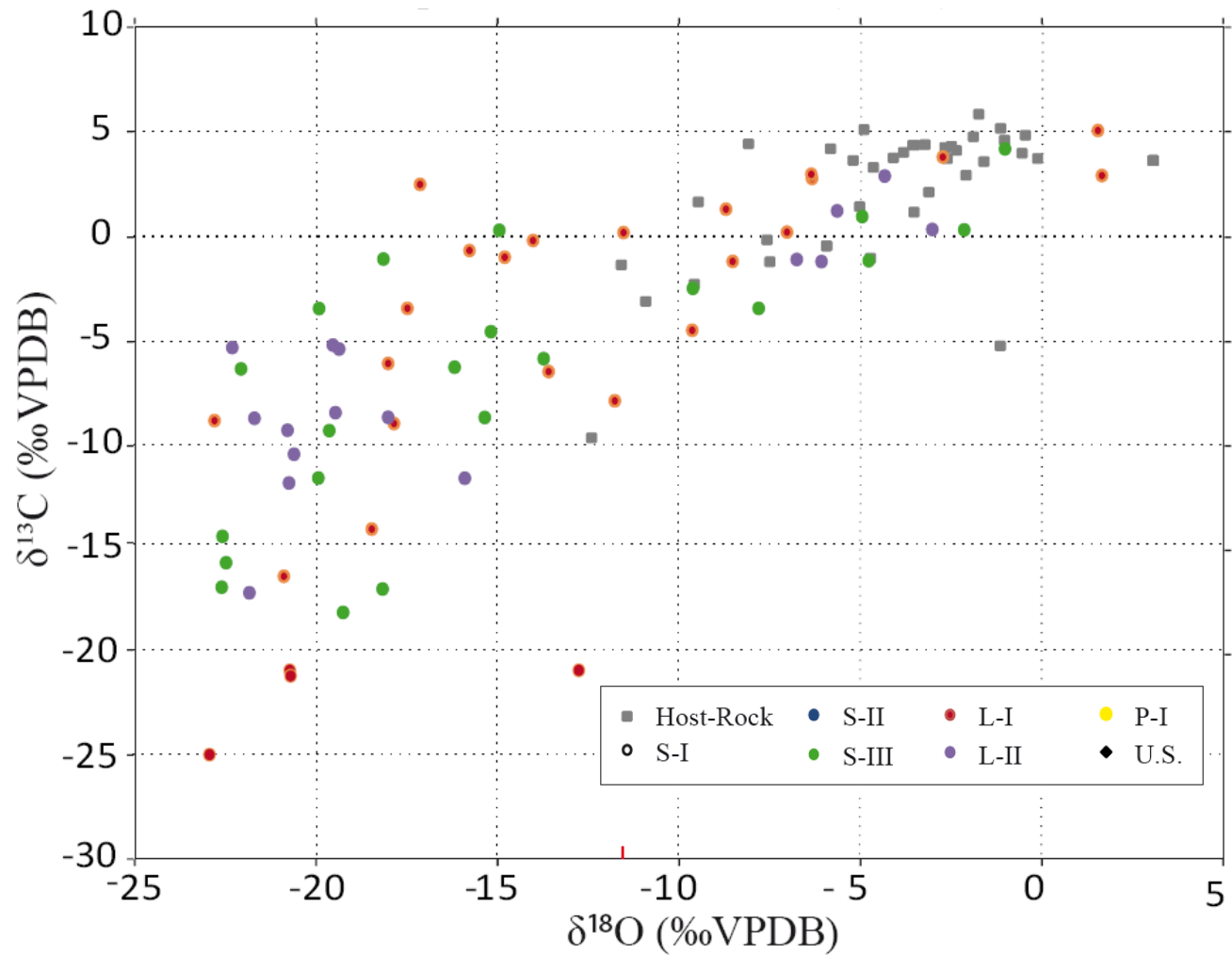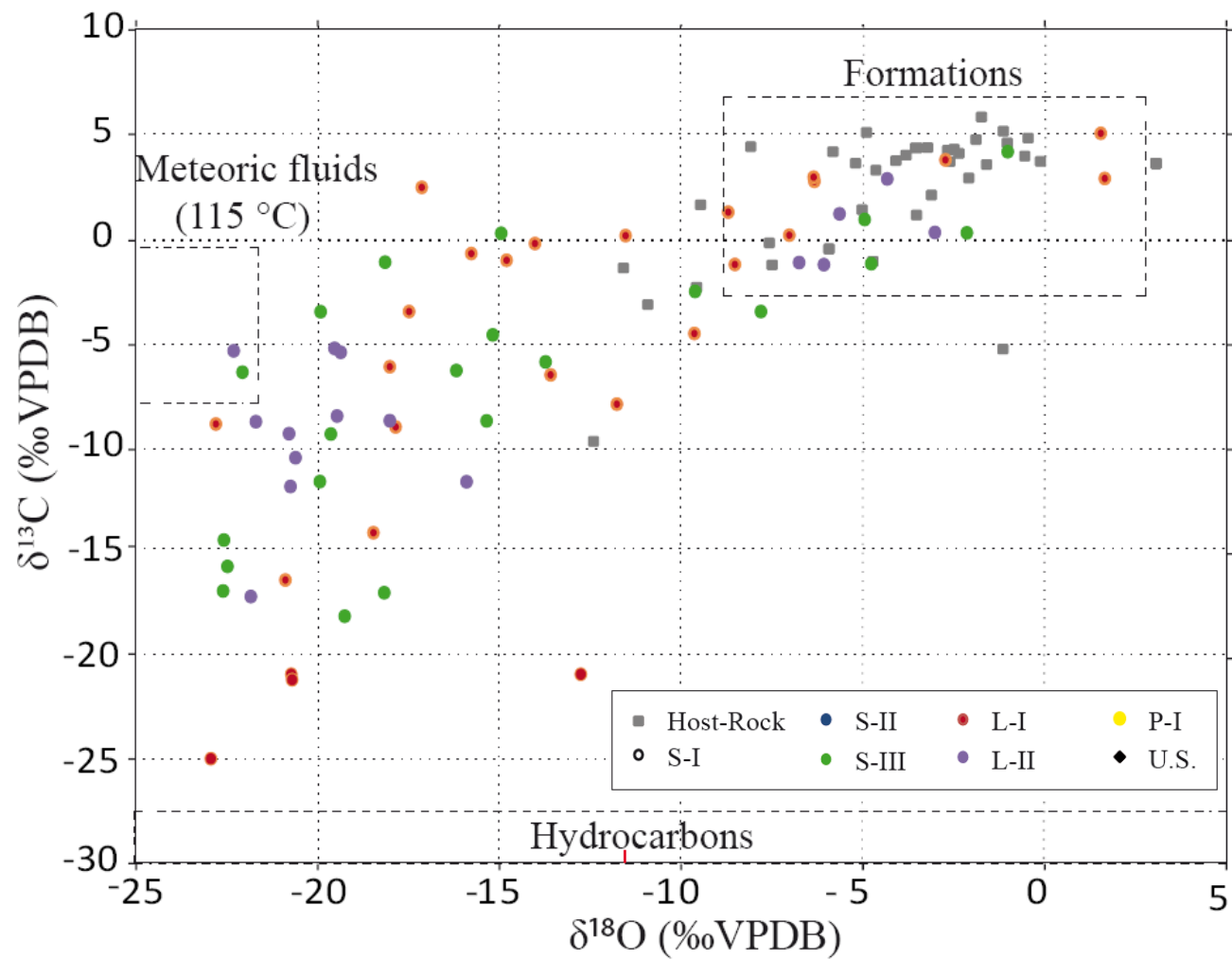
Total isotopic and thermal equilibrium with host-rock
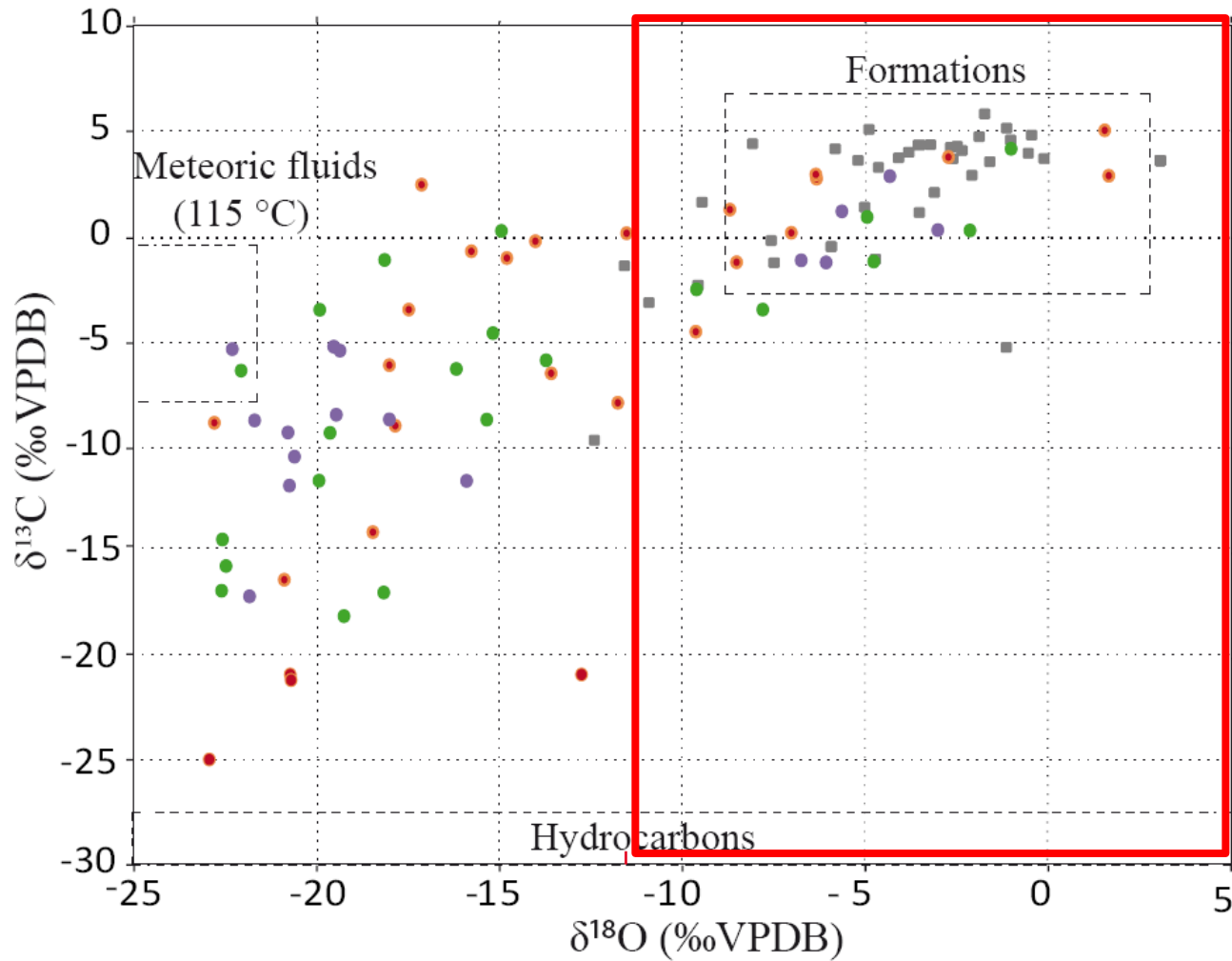
$\delta^{18}O$ depletion but thermal equilibrium with host-rock

High $\delta^{18}O$ depletion and thermal disequilibrium with host-rock

Sheep Mountain Anticline (SMA)
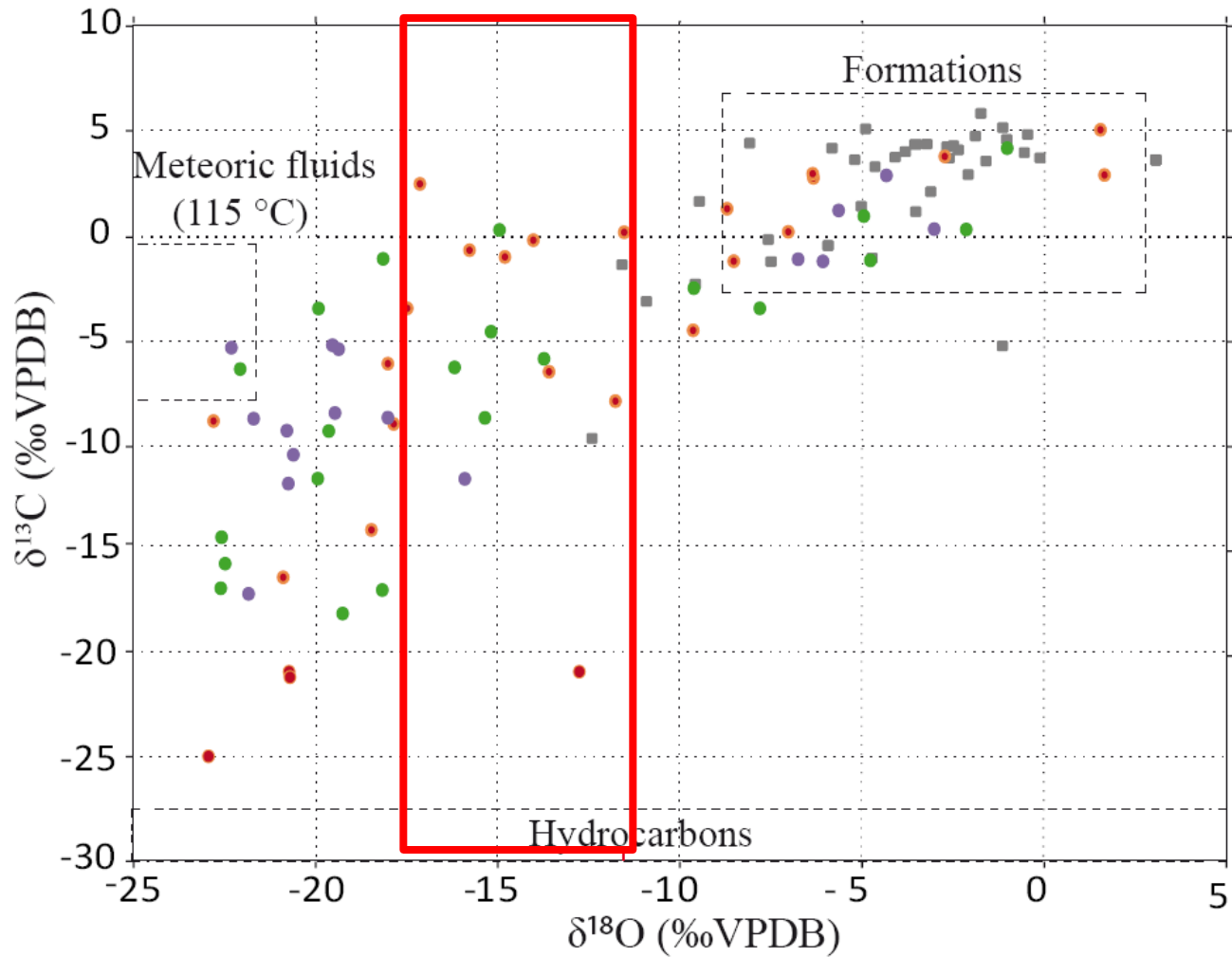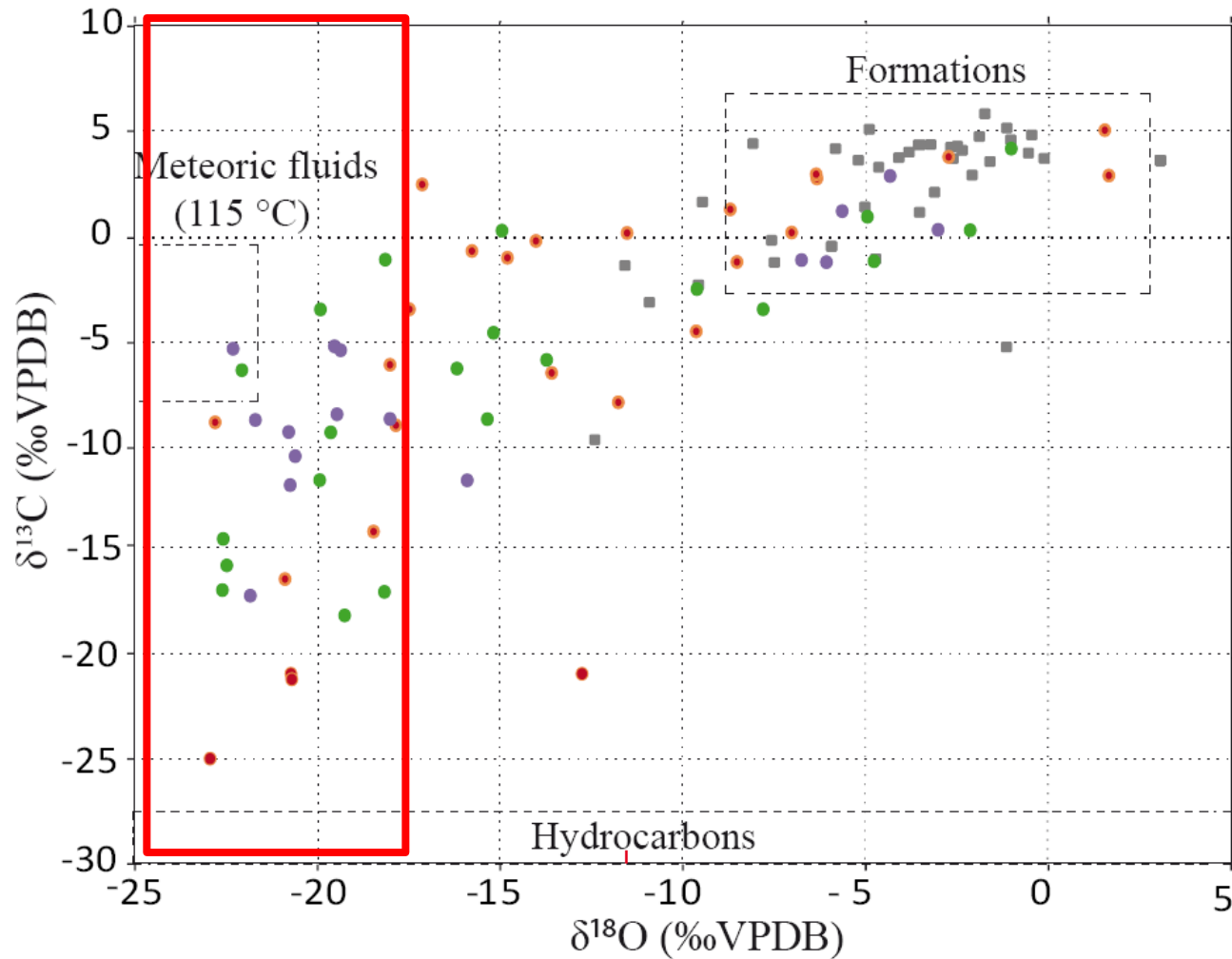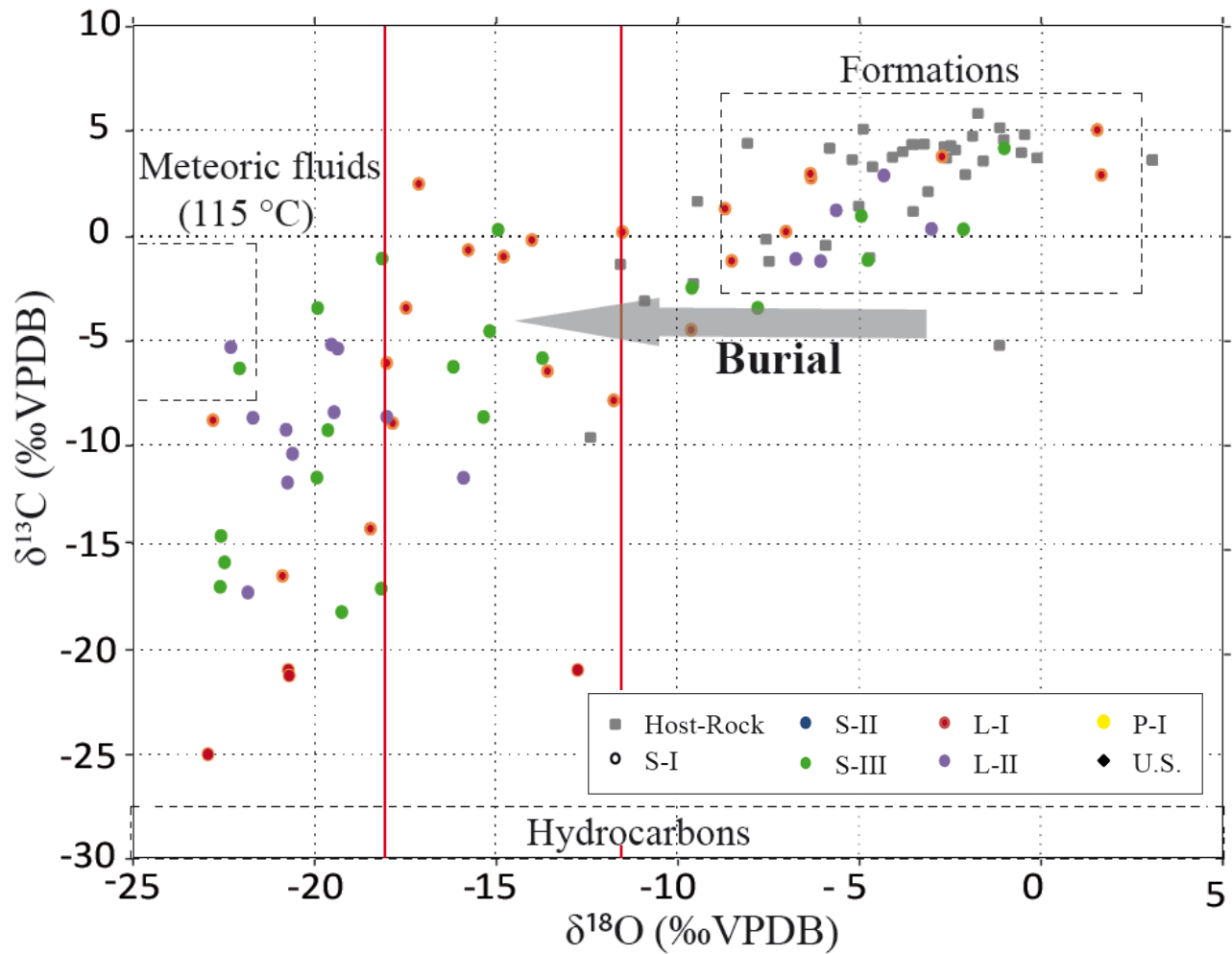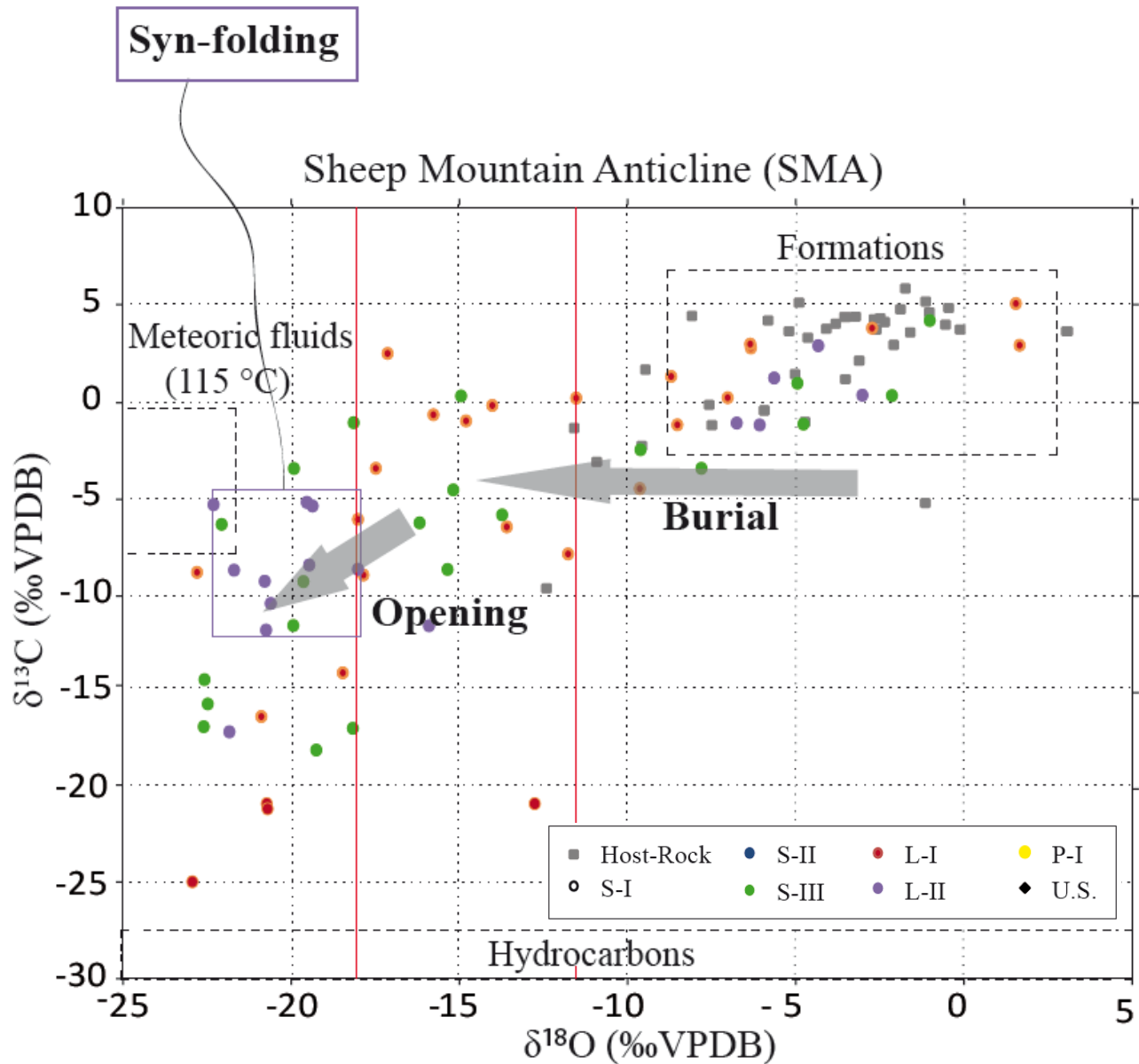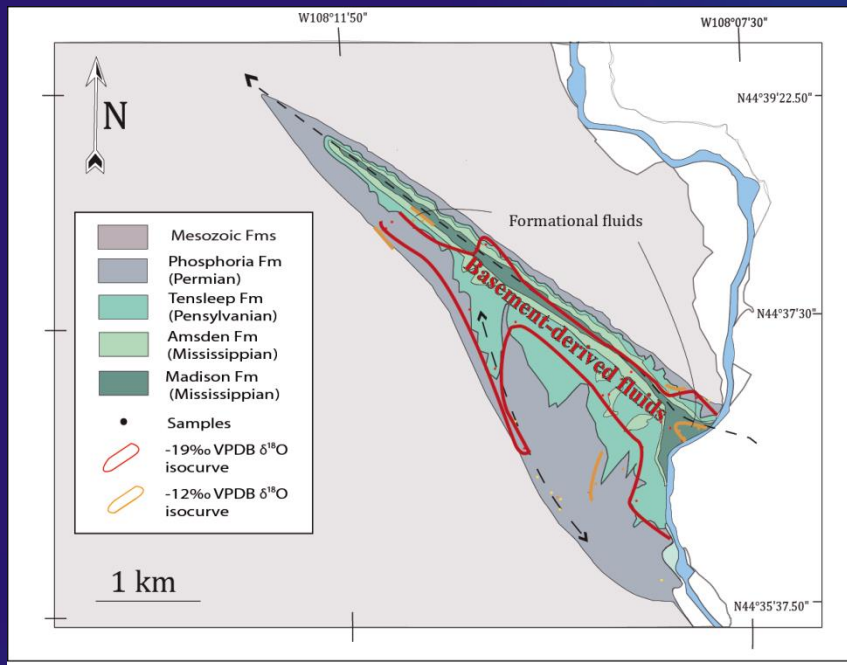
Localization of basement-derived hydrothermal fluid pulse at SMA

(Beaudoin et al, 2011; later redrawn by Evans and Fischer, 2012)
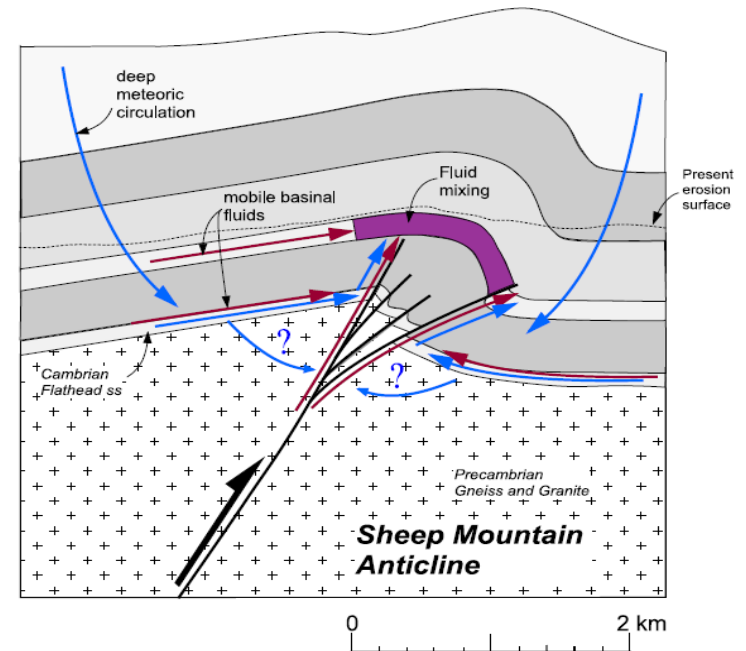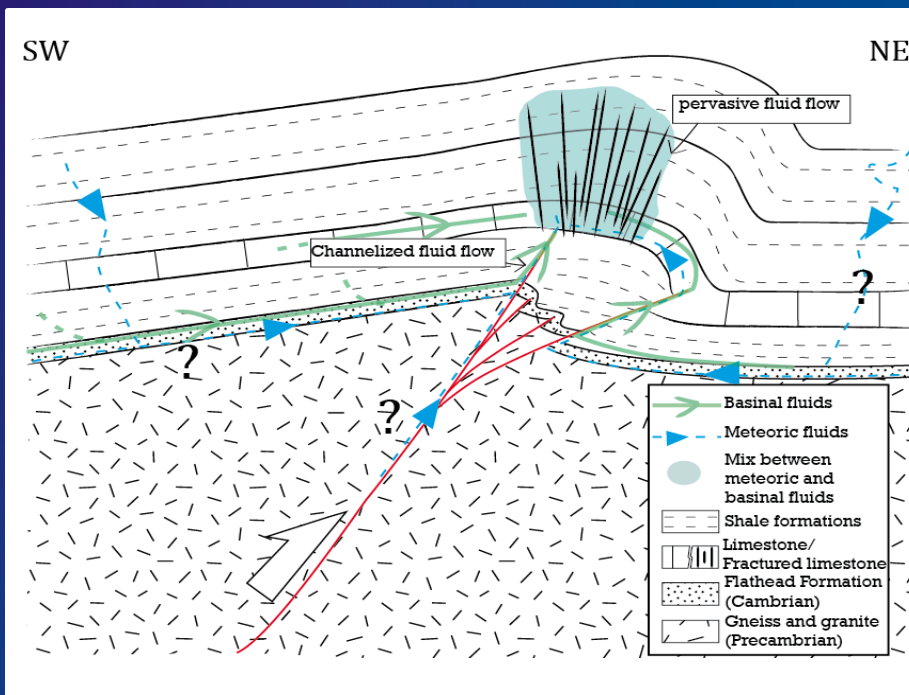
Investigating fluid flow in folds (2) : constraining fluid (over) pressure

Scenario of fault-fracture development in space and time
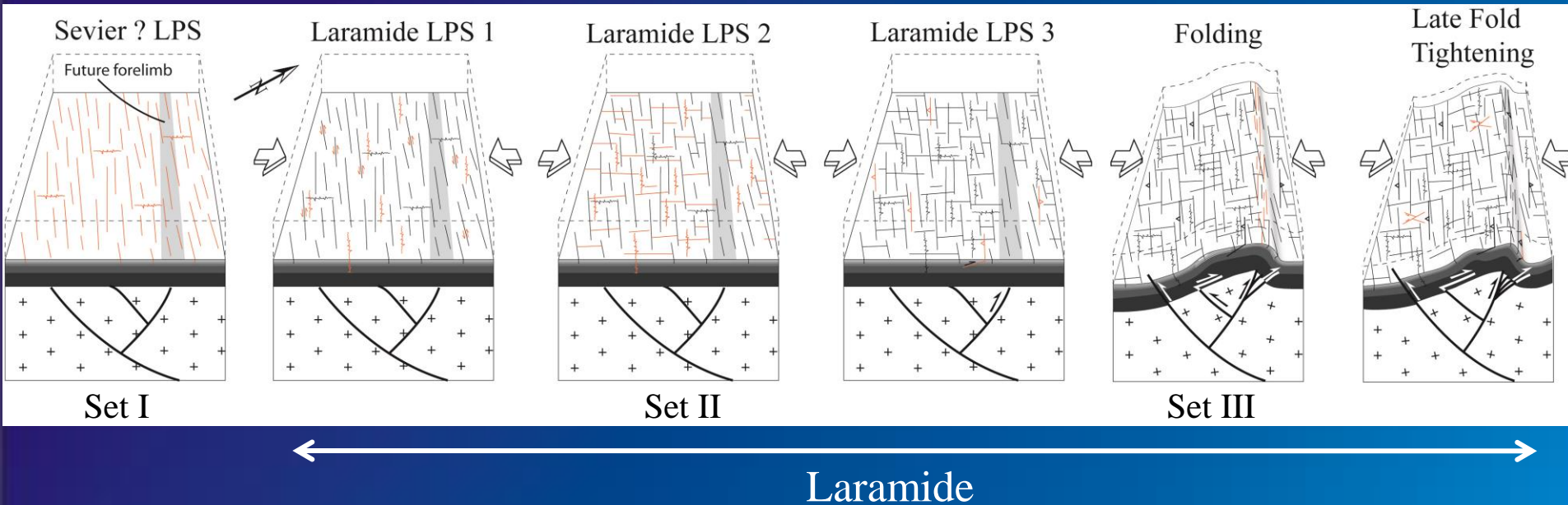
(Amrouch et al., 2011)

- Mode I opening of pre-Laramide set I fractures
- Shear reactivation of pre-Laramide set I fractures (LPS 1).
- Laramide stylolites with NE-trending peaks and mode I opening
  of set II fractures (LPS2)
- Reverse faulting parallel to the fold axis (LPS3).
- Mode I opening of syn-folding, outer-rim extension-related set III fractures
- Late stage fold tightening (LSFT) marked by strike-slip faults and reactivation of tilted
set I fractures as small reverse faults in the forelimb

The method : finding for each deformation step the values of σ1, σ2 and σ3 required for consistency between differential stresses estimated from calcite twinning, frictional sliding along preexisting planes (i.e., Byerlee's law) and newly formed faulting/fracturing.
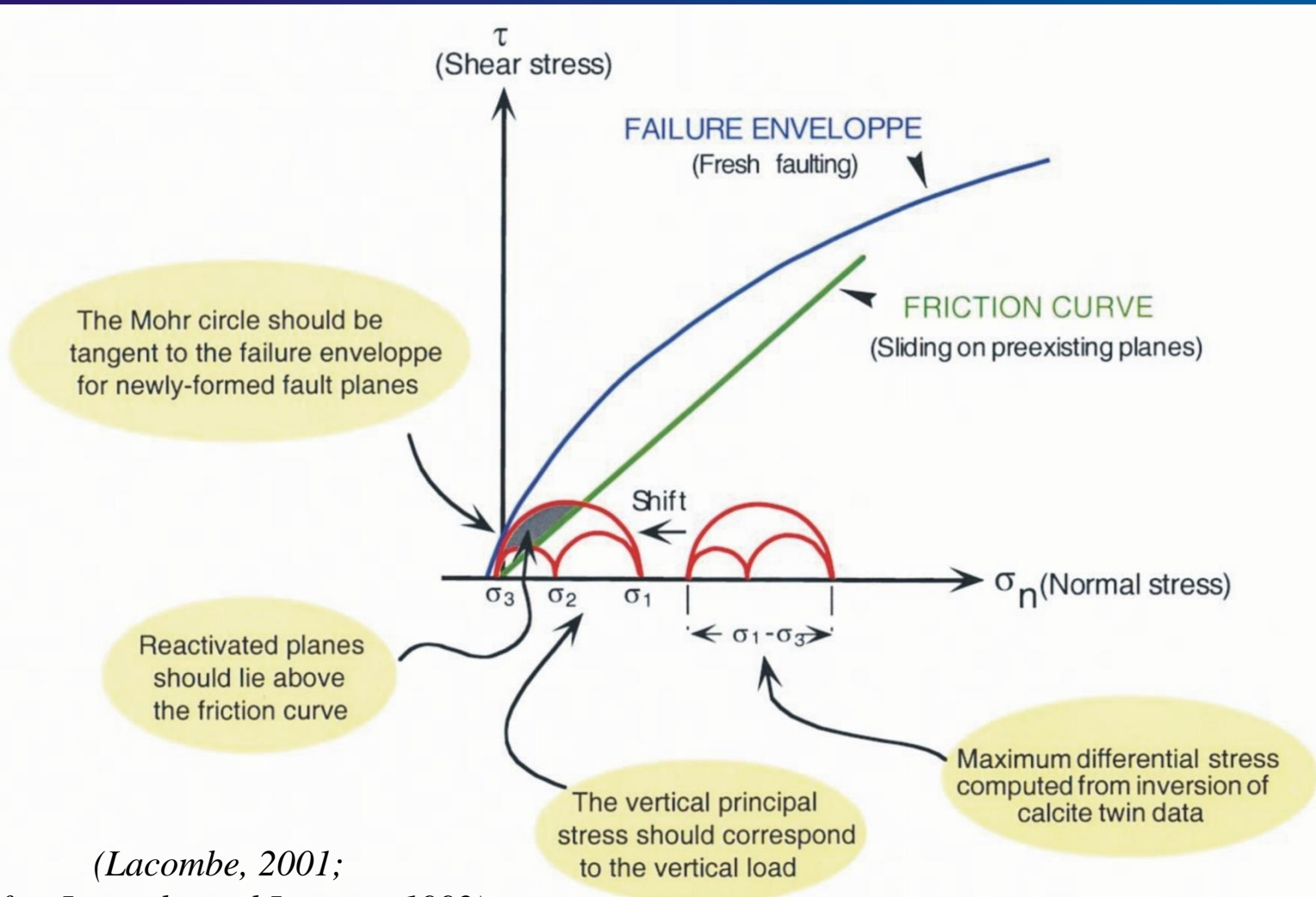
(Lacombe, 2001; after Lacombe and Laurent, 1992)
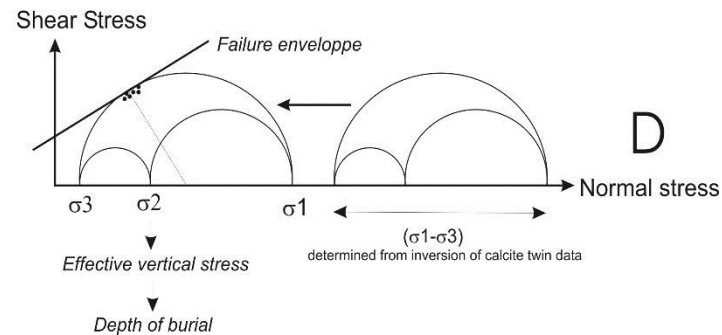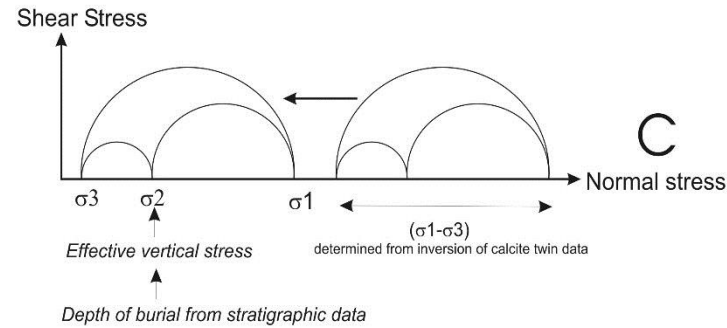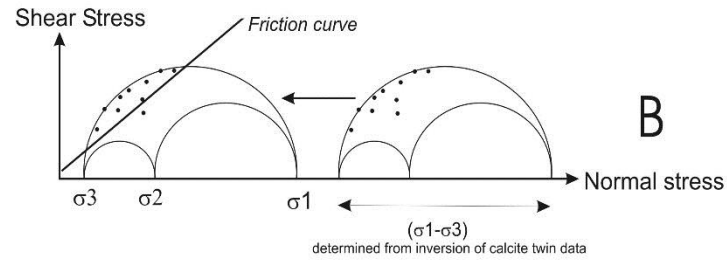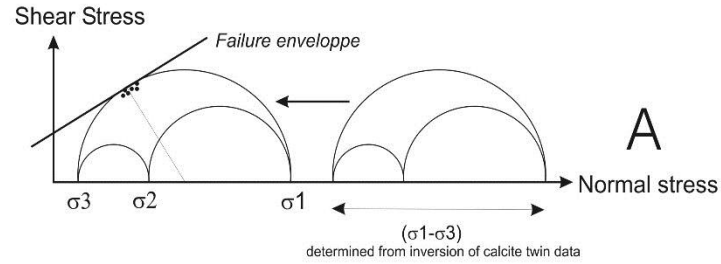
(Lacombe, 2007; Modified after Lacombe et al., 1996)
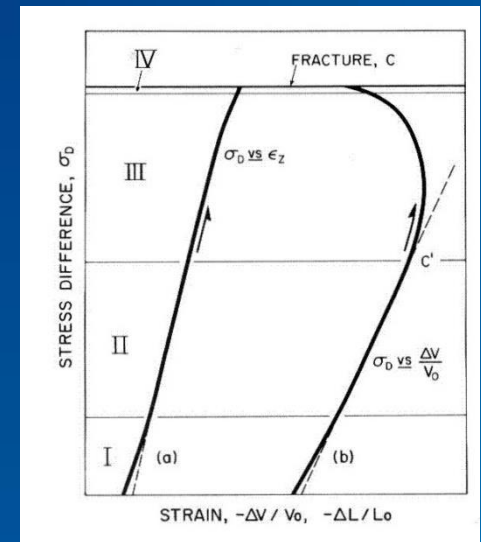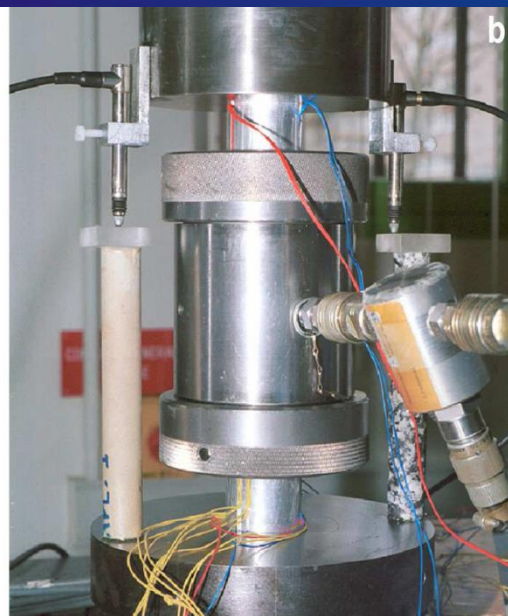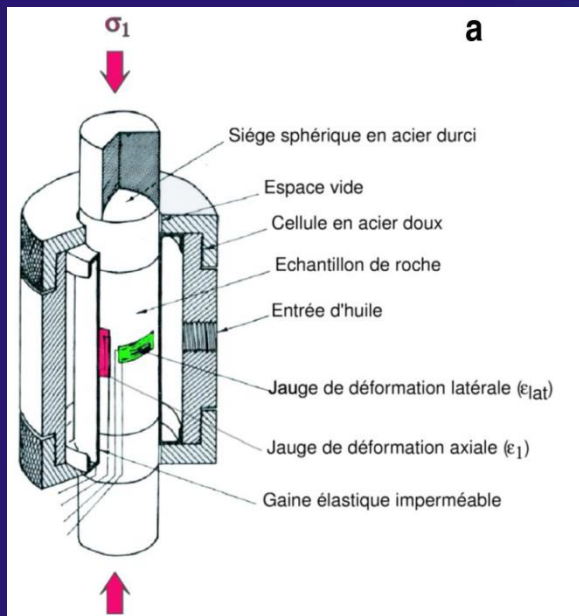
Experimental determination of the intrinsic failure envelopes
of the Phosphoria and Madison formations

(Amrouch et al,
Geophysical Research Letters,
2011)
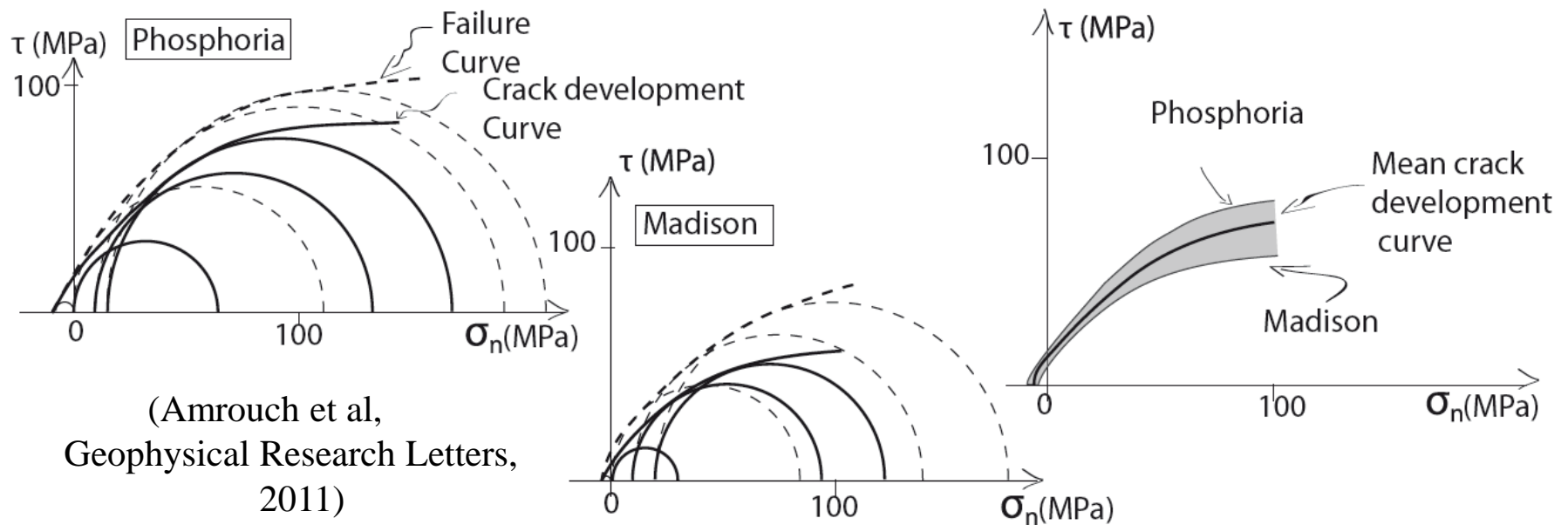
Calculation of the $\Delta\sigma_v$ to infer fluid overpressure
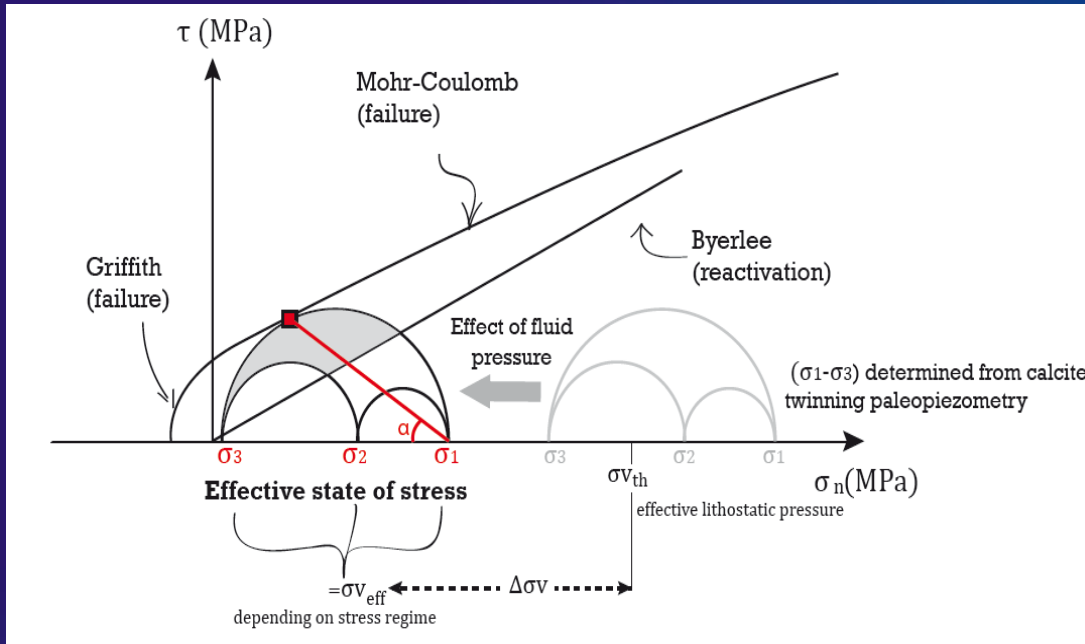
Theoretical effective vertical principal stress calculated considering lithostatic pressure corrected from hydrostatic fluid pressure:

$$\sigma_{vref}=(\rho- \rho_w).g.h$$

Comparison between the theoretical effective vertical principal stress σ_{veff} and the reconstructed effective vertical principal stress σ_{vref} :

$$\Delta\sigma_v=\sigma_{vref} - \sigma_{veff}$$

No erosion or increase of burial before folding
$\rightarrow$ $\Delta\sigma v$ primarily provides an estimate of the fluid overpressure.
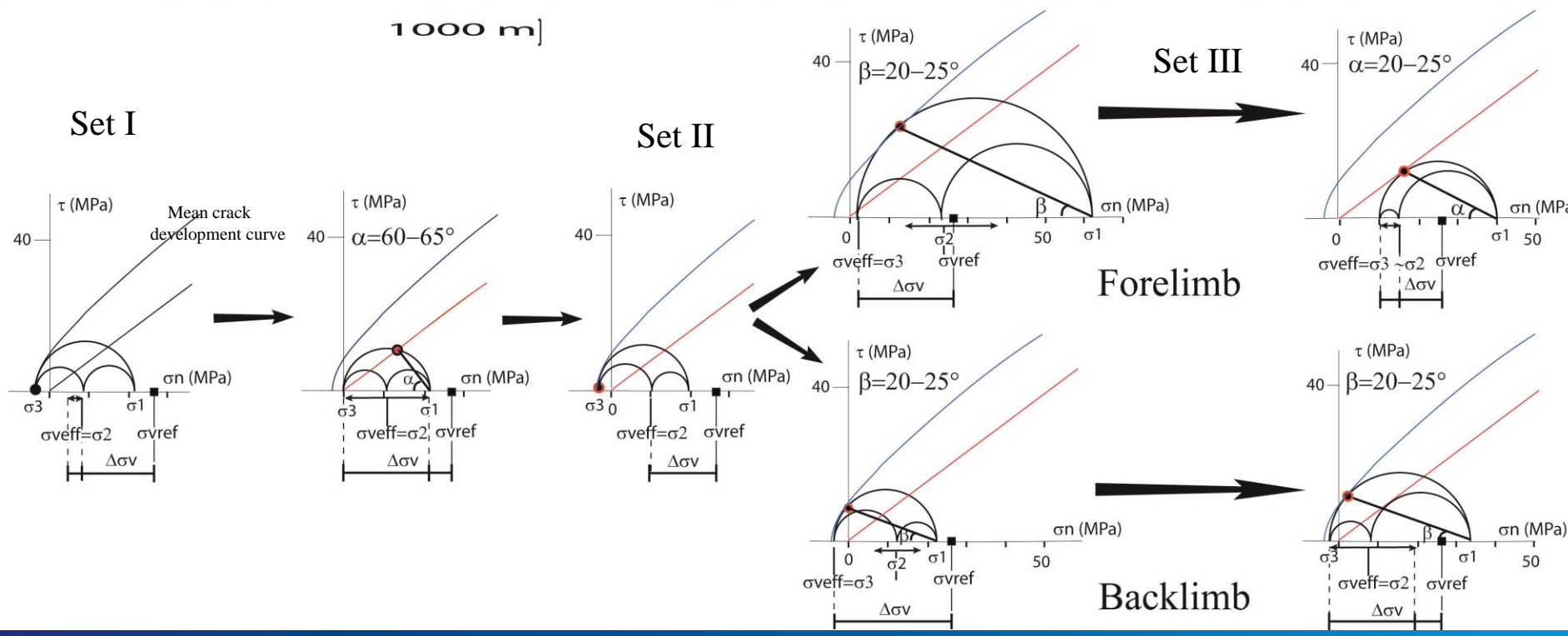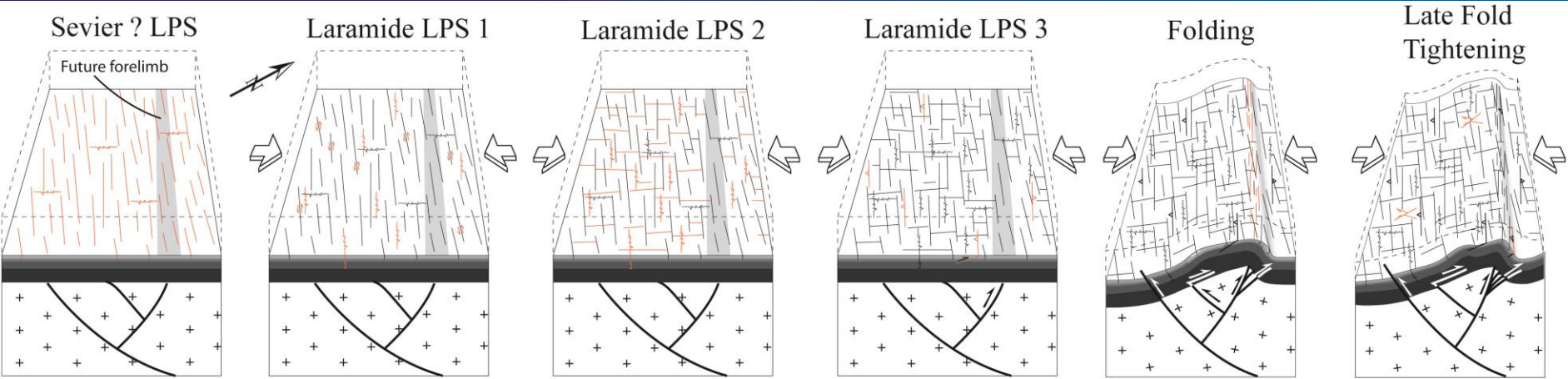
Determination of principal stress magnitudes
using simple Mohr constructions

(Amrouch et al, 2011)

Inference of fluid (over)pressures

(Amrouch et al, Geophysical Research Letters, 2011)
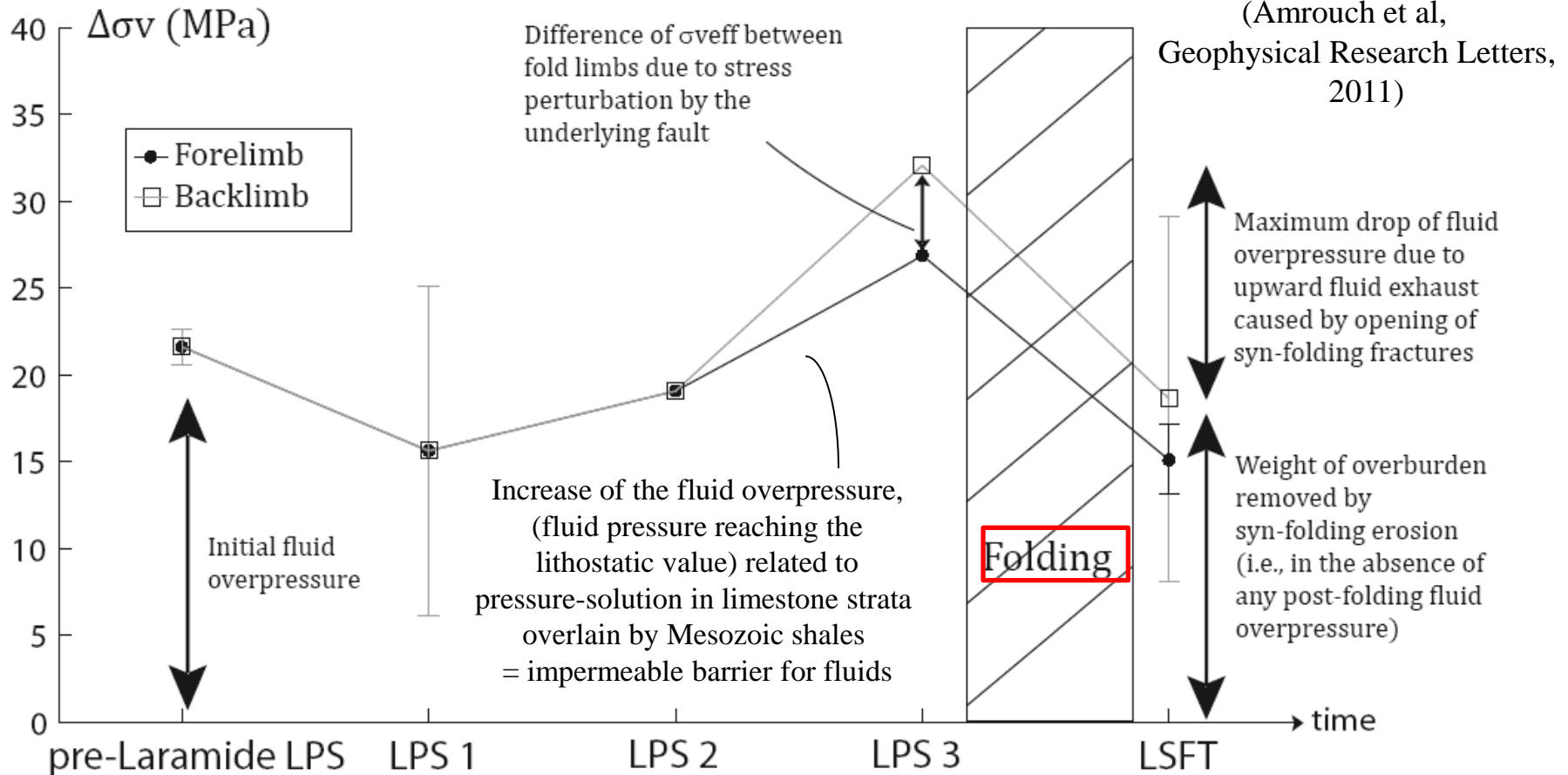
If the entire fluid overpressure was released during folding, it is possible to also derive the maximum value of syn-folding erosion (~1000m)

Comparison with Rattlesnake Mountain Anticline

10 km

SW   NE

SW   NE

Madison
Bighorn
Gros Ventre
Madison
Bighorn
G.V.

A. Rattlesnake Mtn., Wyoming

SW   NE

Ord.–Miss.
Cambrian
K–T
P–P
Archean
Basement
0   1 km

Surface Geology from
Pierce (1966), Stearns (1971)

Beaudoin et al., 2012   Erslev (1986)

E   W
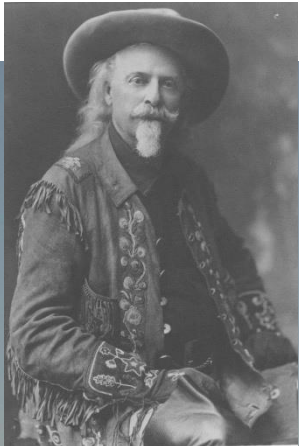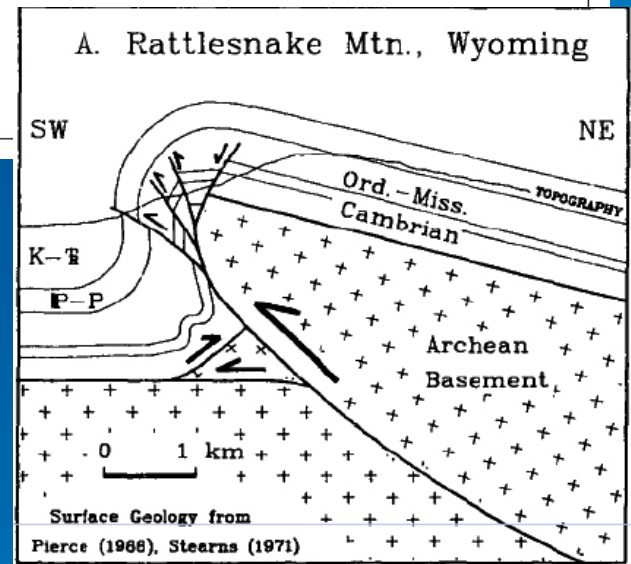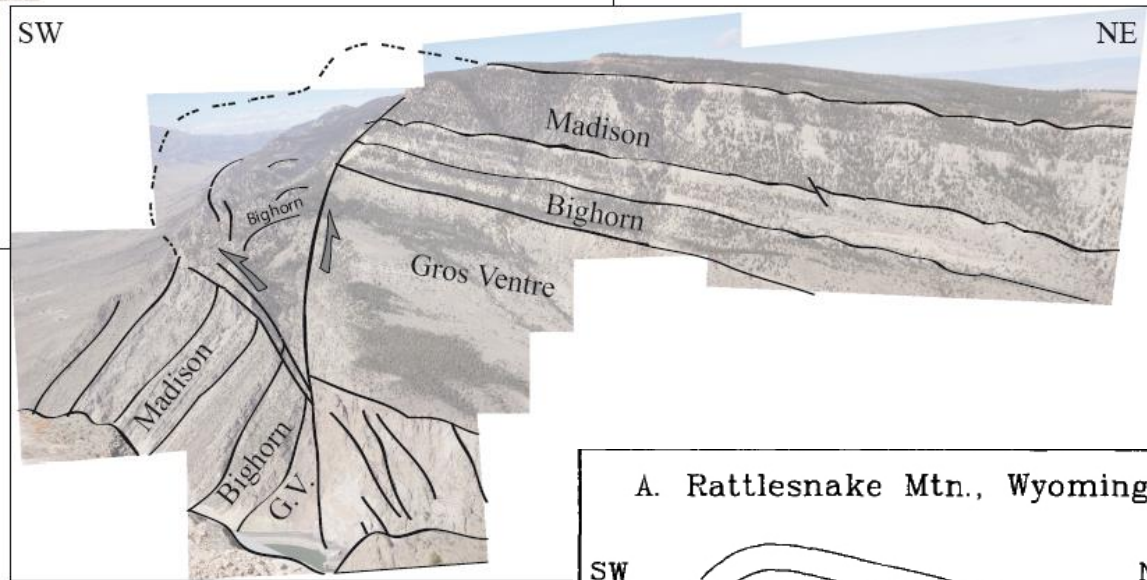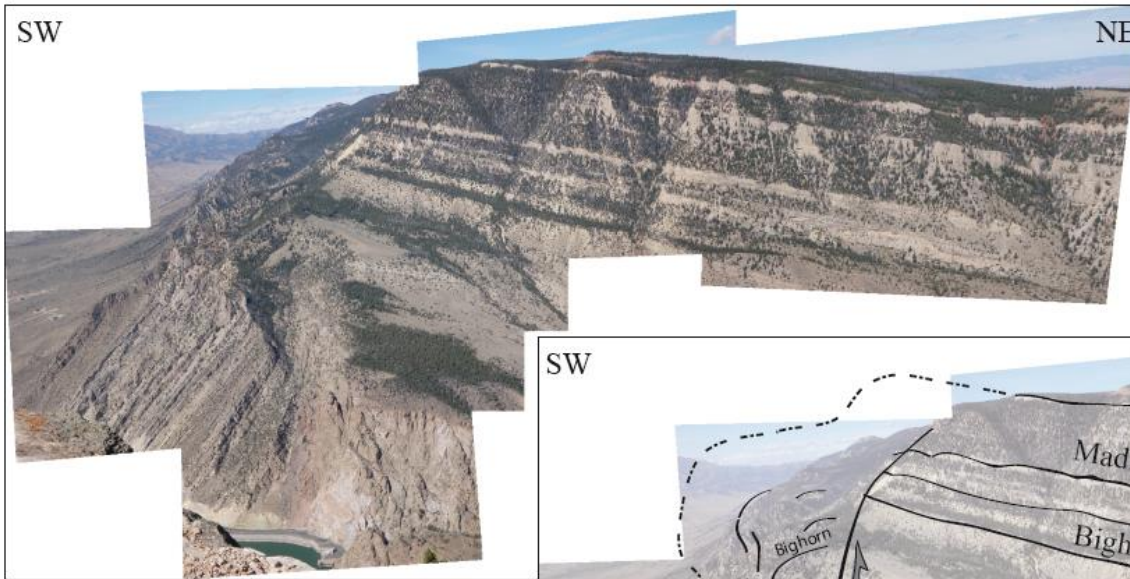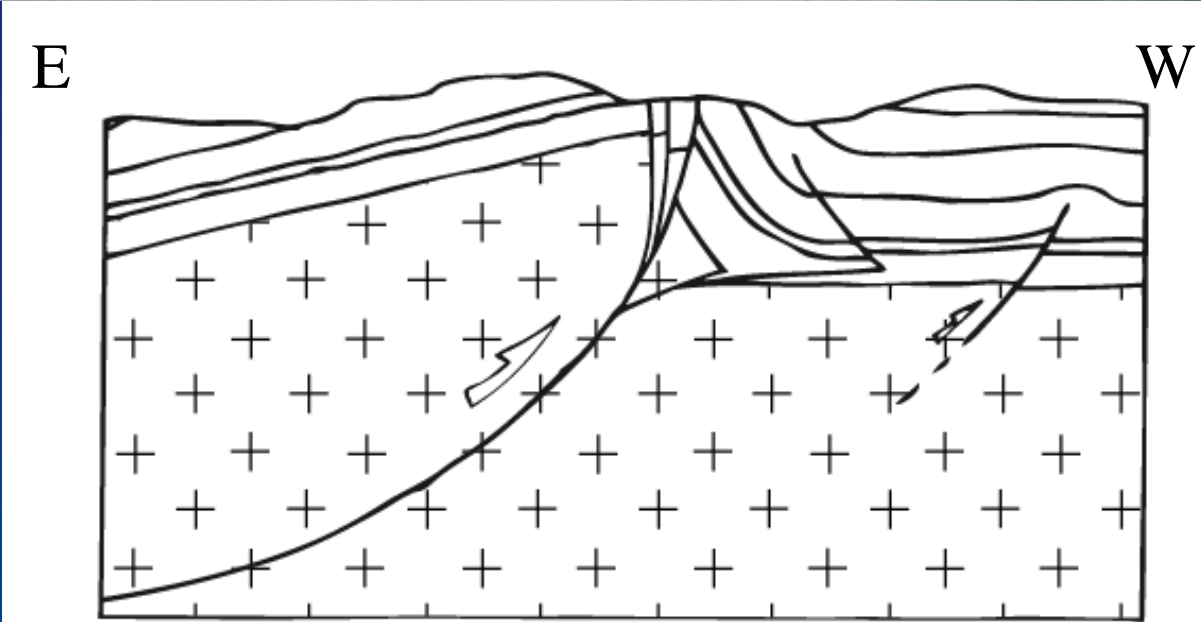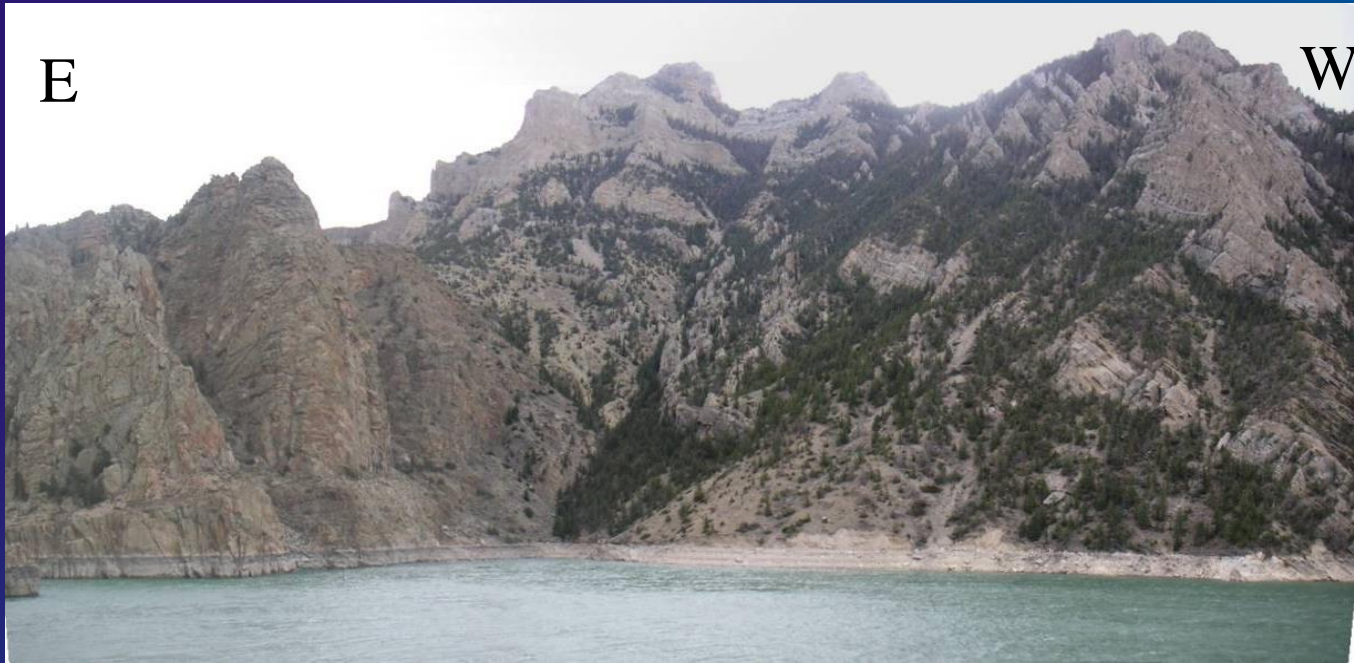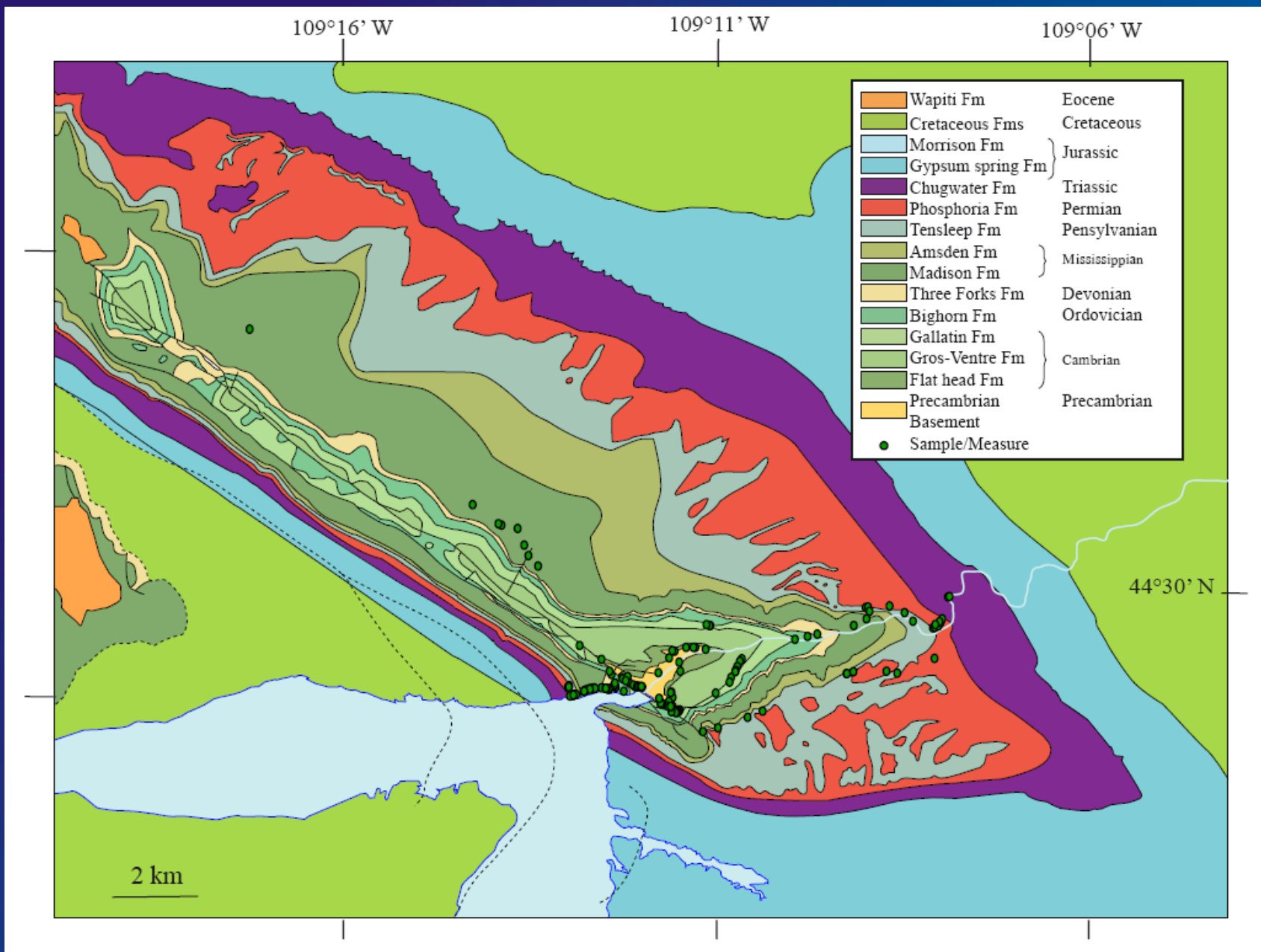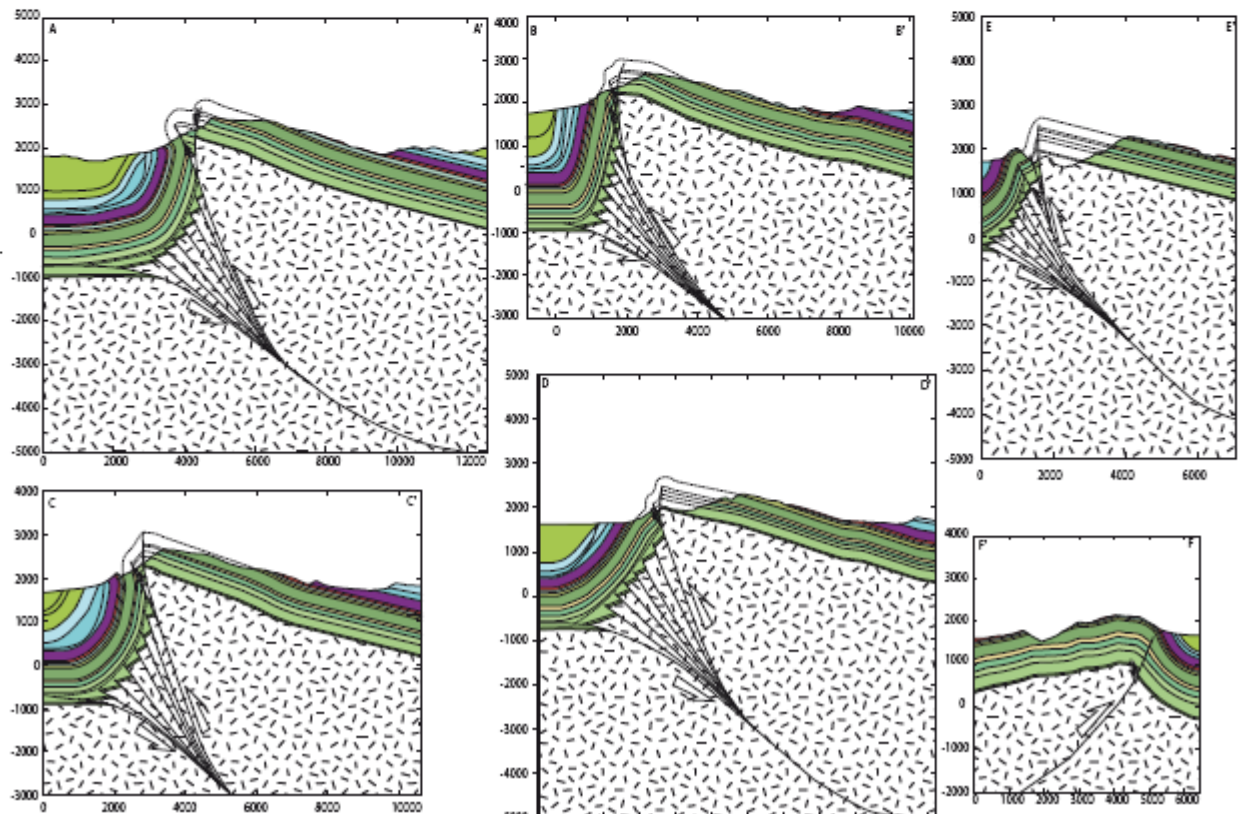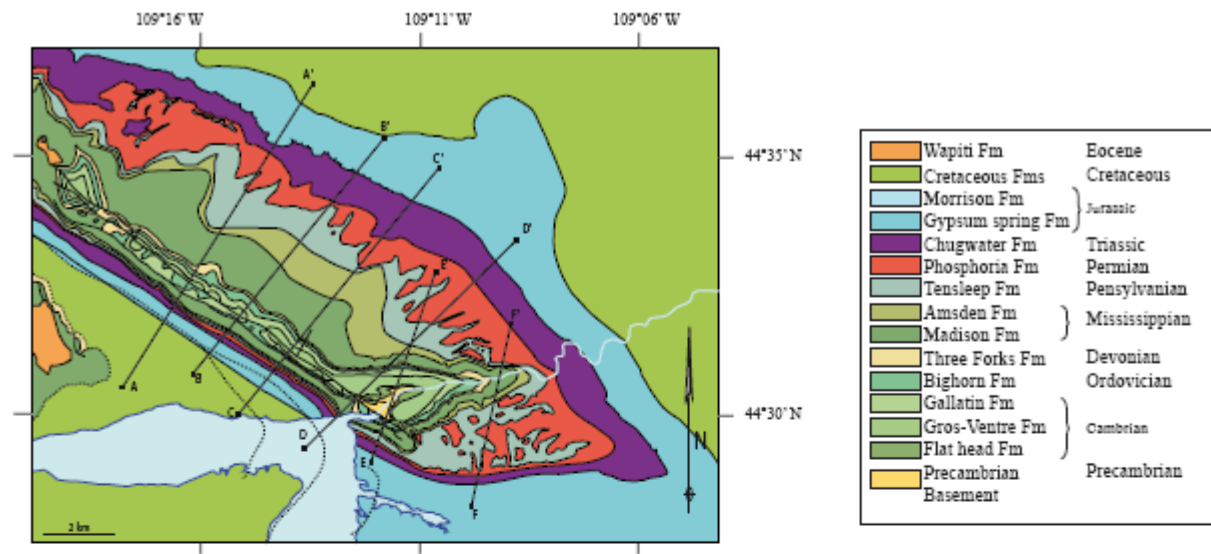
Beaudoin et al., 2012

Beaudoin et al, 2012

a

0- INITIAL STAGE

Future triangular shear zone

1 - IMMATURE STAGE

triangular shear zone

2 - MATURE STAGE

b

SMA (IMMATURE)

SW   NE

500 m

RMA (MATURE)

NE   SW

500 m

Beaudoin et al., 2012
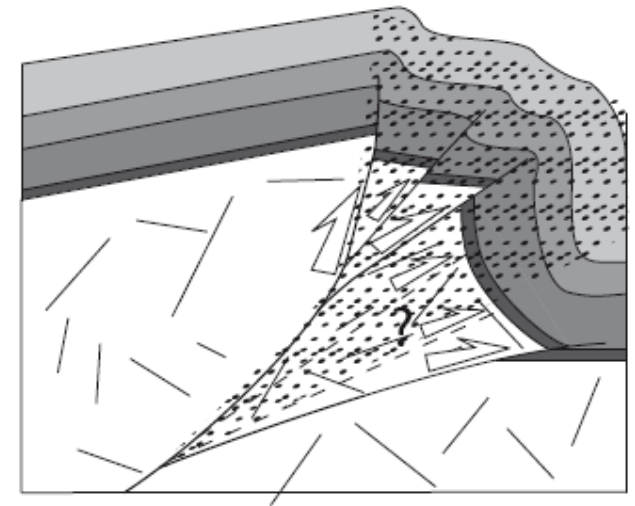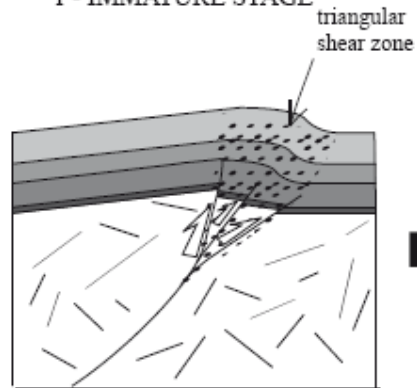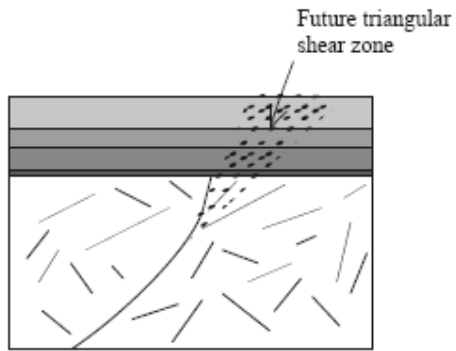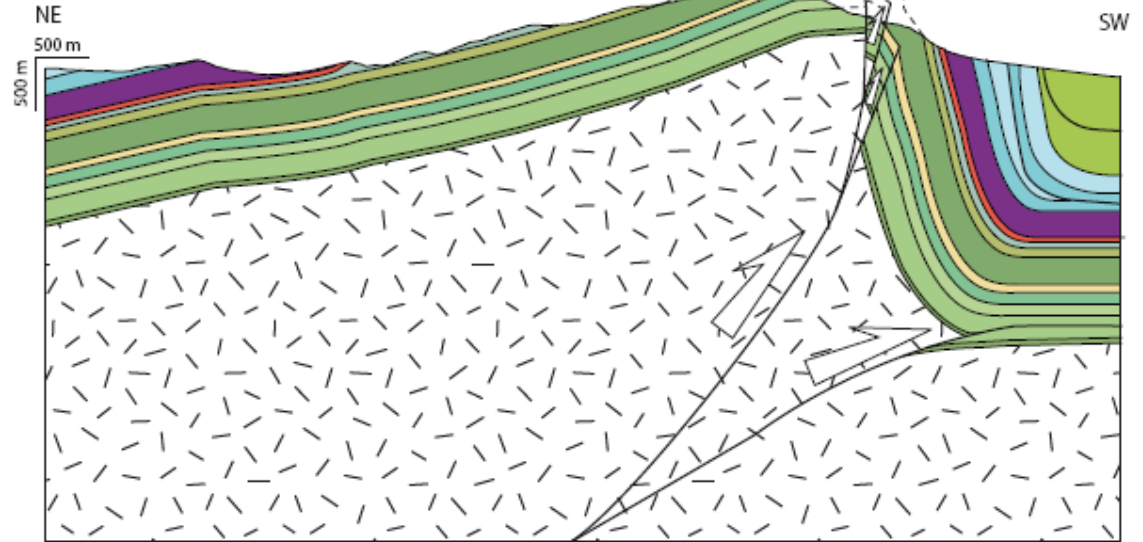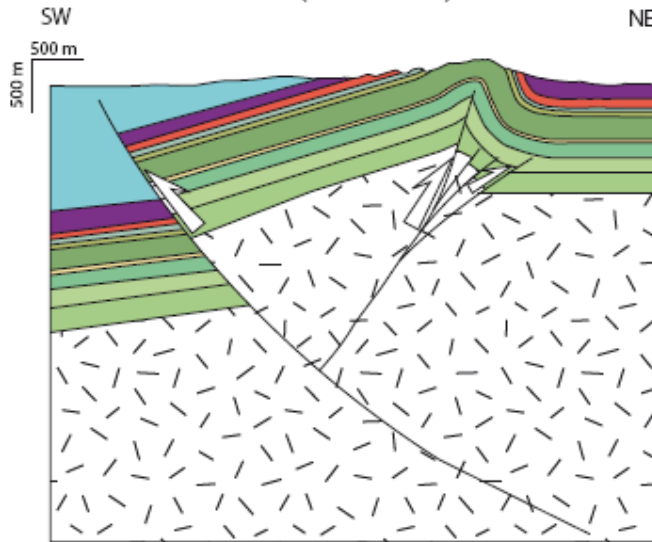
ATTENTION

YOU ARE ENTERING GRIZZLY BEAR COUNTRY!
PLEASE TAKE THE NECESSARY PRECAUTIONS.
IF YOU WOULD LIKE TO LEARN MORE ABOUT
THE GRIZZLY BEAR AND YOUR SAFETY, PLEASE
CONTACT THE CODY OFFICES OF THE BLM, U.S.
FOREST SERVICE OR WYOMING GAME AND FISH.
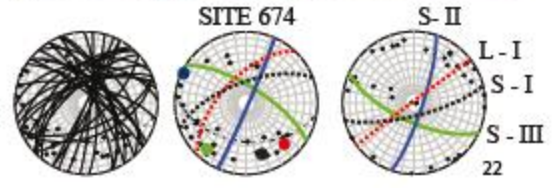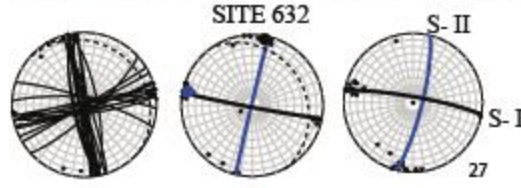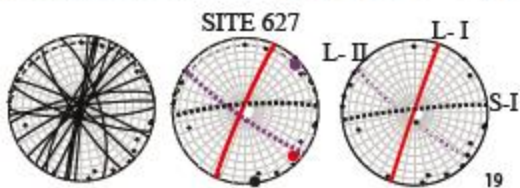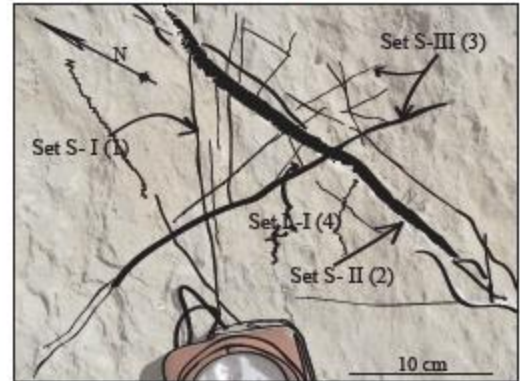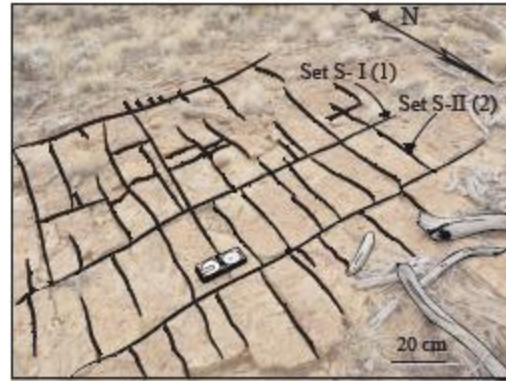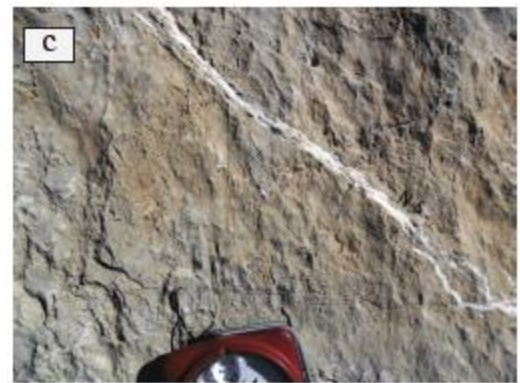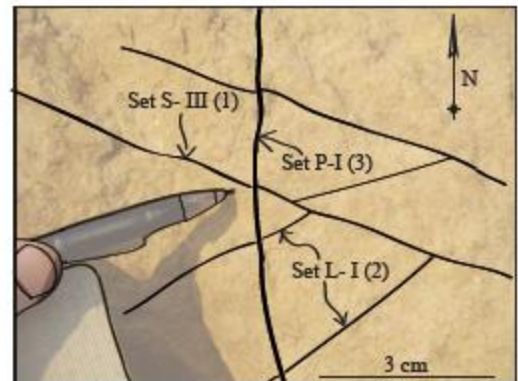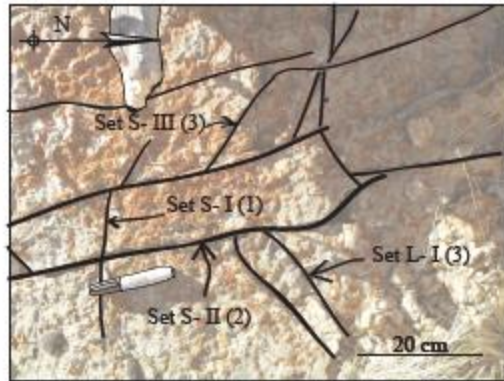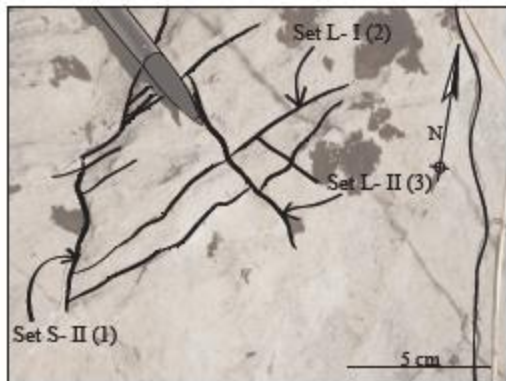
SITE 652

SITE 656

SITE 114

Set L- I (2)
Set L- II (3)
Set S- II (1)
5 cm

Set S- III (3)
Set S- I (1)
Set S- II (2)
Set L- I (3)
20 cm

Set S- III (1)
Set P-I (3)
Set L- I (2)
3 cm

L- I
S- I
L- II
33

S- II
L- I
S- I
S- III
22

L- I
S - III
P - I
41

Beaudoin et al, 2012

Fold-scale fractures

Beaudoin et al., 2012

Beaudoin et al., 2012

Beaudoin et al., 2012

Beaudoin et al., 2012

O, C stable isotopic signatures of fluids

O, C stable isotopic signatures of fluids
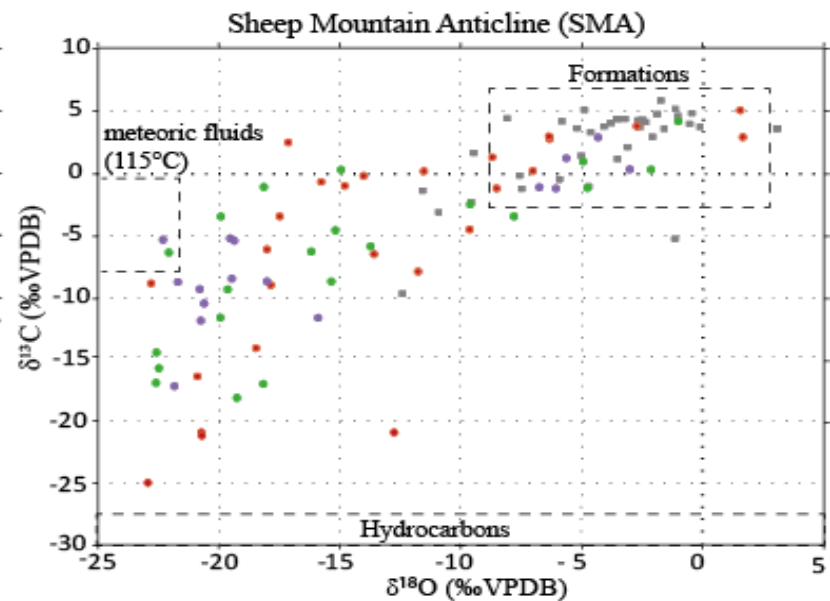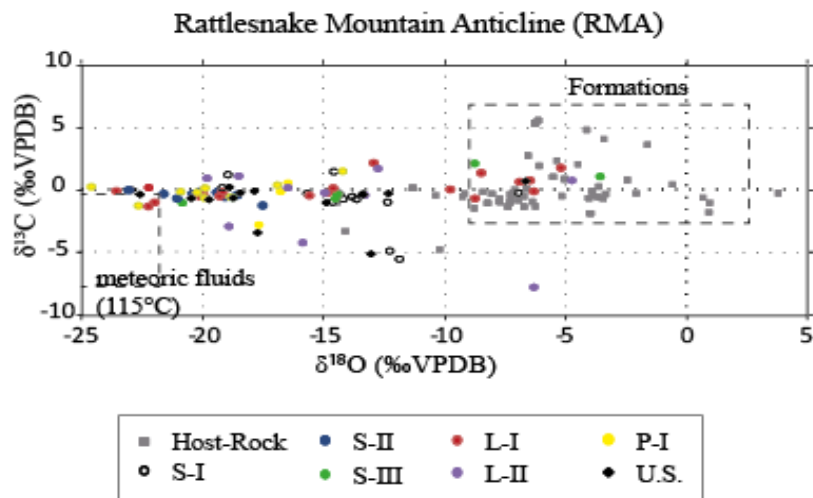
Defining the fluid system

Three types of precipitating fluids:

- Total isotopic and thermal equilibrium with host-rock

Defining the fluid system

* Total isotopic and thermal
  equilibrium with host-rock

* $\delta^{18}O$ depletion but thermal
  equilibrium with host-rock

Defining the fluid system

* Total isotopic and thermal equilibrium with host-rock

* $\delta^{18}O$ depletion but thermal equilibrium with host-rock

* High $\delta^{18}O$ depletion and thermal disequilibrium with host-rock

Comparison of $\Delta\sigma_v$ evolution in SMA and RMA

- Coeval release of fluid overpressure during folding

- Same level of overpressure once normalized to depth

Some brief conclusions …

1. General

Interest/requirement of a <u>multi-source</u> approach

Interest/requirement of a <u>multi-scale</u> approach
(from micro-scale to fold scale, then to basin scale)

Some brief conclusions …

2. More specific

First integrated picture of the evolution of stress, strain
and pore fluid (over) pressure
during folding

Reliability and power of studies of sub-seismic fracture
populations for paleo-hydrological reconstructions
→ Complement fault zone paleo-hydrological studies

Feedbacks between deformation and paleo-hydrology,
role of tectonic style (thick-skinned vs thin-skinned)

→ Next step : fluid flow modelling

Thank you for your attention...

Suggested readings :

Amrouch K., Lacombe O., Bellahsen N., Daniel J.-M. & Callot J.P., 2010, Stress/strain patterns, kinematics and deformation mechanisms in a basement-cored anticline : Sheep Mountain anticline (Wyoming, USA). **Tectonics,** 29, TC1005

Amrouch K., Robion P., Callot J.-P., Lacombe O., Daniel J.-M., Bellahsen N. & Faure J.-L., 2010, Constraints on deformation mechanisms during folding provided by rock physical properties: a case study at Sheep Mountain anticline (Wyoming, USA). **Geophys. J. Int.**, 182, 1105-1123

Amrouch K., Beaudoin N., Lacombe O., Bellahsen N. & Daniel J.M., 2011, Paleostress magnitudes in folded sedimentary rocks. **Geophys. Res. Lett.**, 38, L17301

Beaudoin N., Bellahsen N., Lacombe O. & Emmanuel L., 2011, Fracture-controlled paleohydrogeology in a basement-cored, fault-related fold: Sheep Mountain anticline (Wyoming, USA). **Geochem. Geophys. Geosyst.**, 12, Q06011

Beaudoin N., Lacombe O., Bellahsen N., Amrouch K. & Daniel J.M., 2014. Evolution of fluid pressure during folding and basin contraction in overpressured reservoirs : insights from the Madison-Phosphoria carbonate formations in the Bighorn basin (Wyoming, USA). **Marine and Petroleum Geology**, 10.1016/j.marpetgeo.2013.12.009

Beaudoin N., Bellahsen N., Lacombe O., Emmanuel L. & Pironon J., 2014. Crustal-scale fluid flow during the tectonic evolution of the Bighorn Basin (Wyoming, USA). **Basin Research**, doi: 10.1111/bre.12032