

**Stress, strain, fracturing, deformation mechanisms,
fluid pressure and fluid flow
in folded-fractured reservoirs :
what can we learn from integrated studies of natural
analogues ?**

*Sheep Mountain and Rattlesnake Mountain Anticlines
(Wyoming, USA) as case studies*

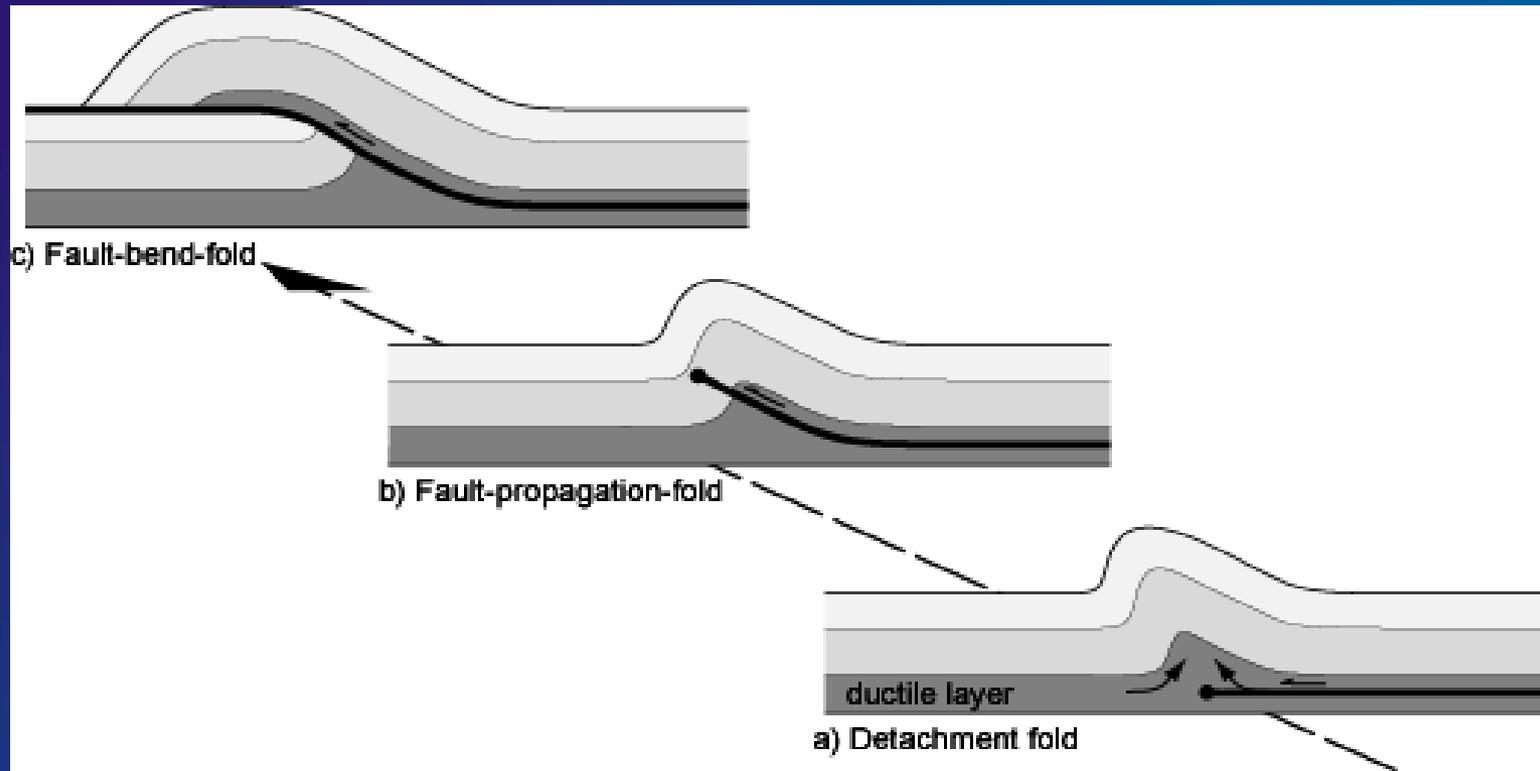
Olivier LACOMBE

Collaboration with :

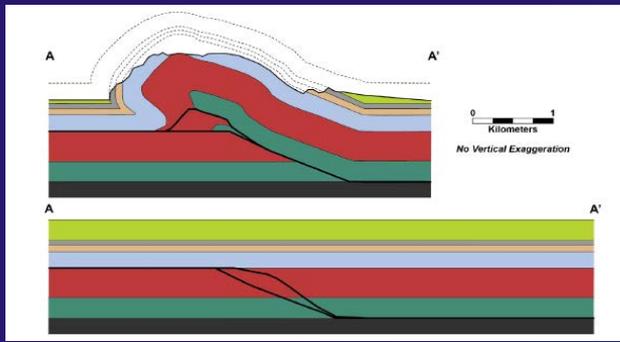
Nicolas BELLAHSEN, Laurent EMMANUEL, Khalid AMROUCH, Nicolas BEAUDOIN (UPMC)
Jean-Marc DANIEL (IFP-EN), Jean-Paul CALLOT (Univ. Pau), P. ROBION (Univ. Cergy)

The study of fold evolution has for long been based on geometrical models.

These models were used to investigate possible kinematic scenarios of folding, based on the present-day geometry of folded strata and geometrical assumptions (thickness and/or length preservation).



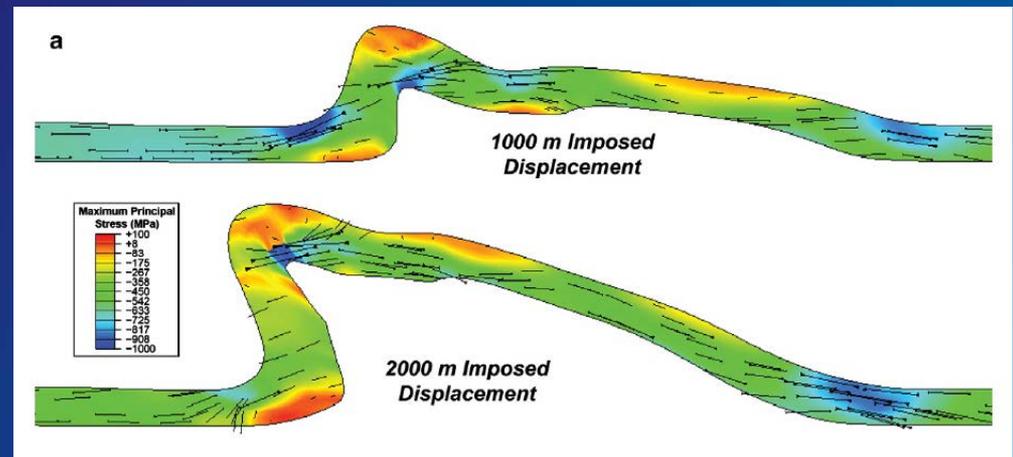
Unified model where folding modes may illustrate different stages of evolution of a single fold (Molinaro, 2004; Sherkati, 2004)



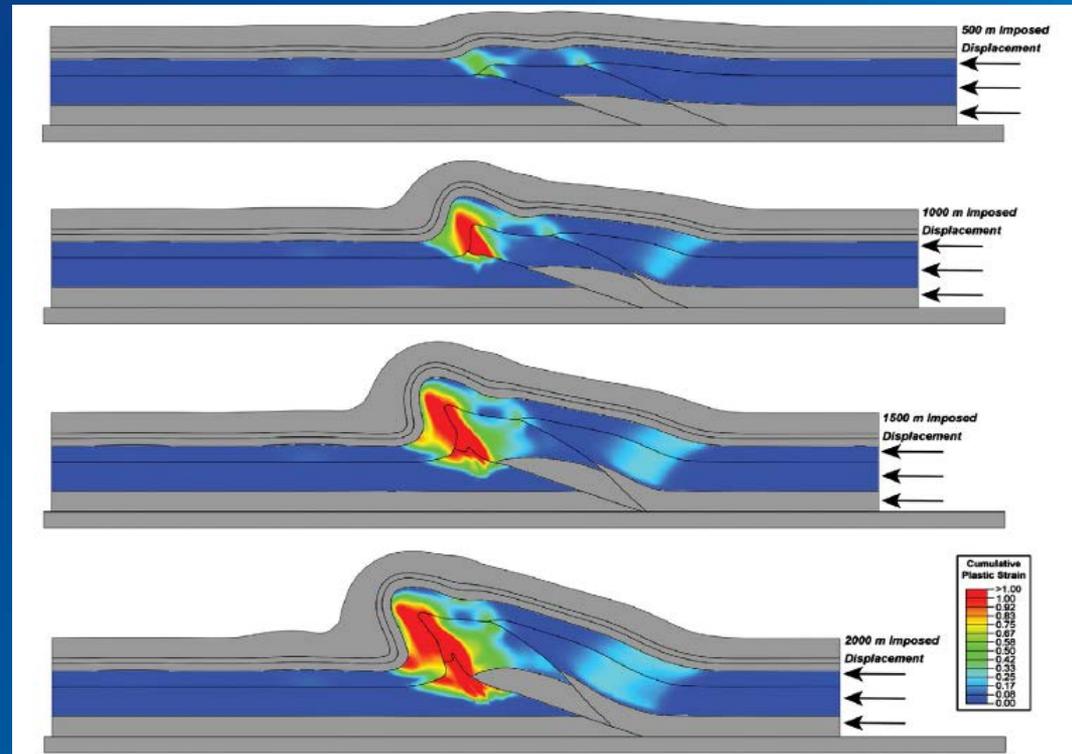
Geomechanical modeling can predict the onset of failure and the type and abundance of deformation features along with the orientations and magnitudes of stresses.

Forward models incorporate realistic mechanical stratigraphy, include faults and bedding-slip surfaces as frictional sliding interfaces, reproduce the overall geometry of the fold structures 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 loading.



(Smart et al., 2012)



Only few works have attempted to bridge the gap between the macroscopic scale and the microscopic scale and to provide quantities like stress or strain to be compared with outputs of geomechanical models.

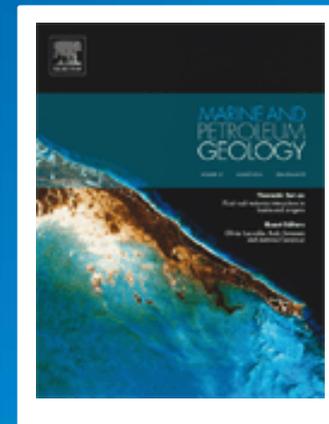
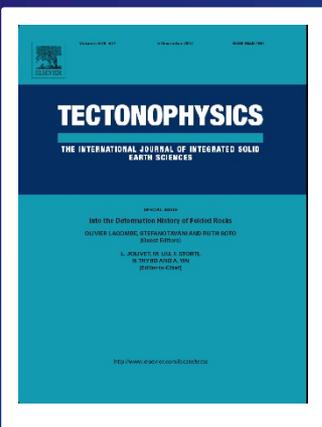
Changes in P-T-X conditions, fluid flow, fracture development as well as stress and strain pattern within folded strata are still to be more properly linked to the geometric/kinematic macroscopic evolution of folds.

Advances in understanding deformation processes and history of folded rocks have important socio-economic implications : accurate description and simulation of geological reservoirs for resources or waste require a good knowledge of the mechanical/hydraulical behavior of rocks when they are folded, faulted and fractured.

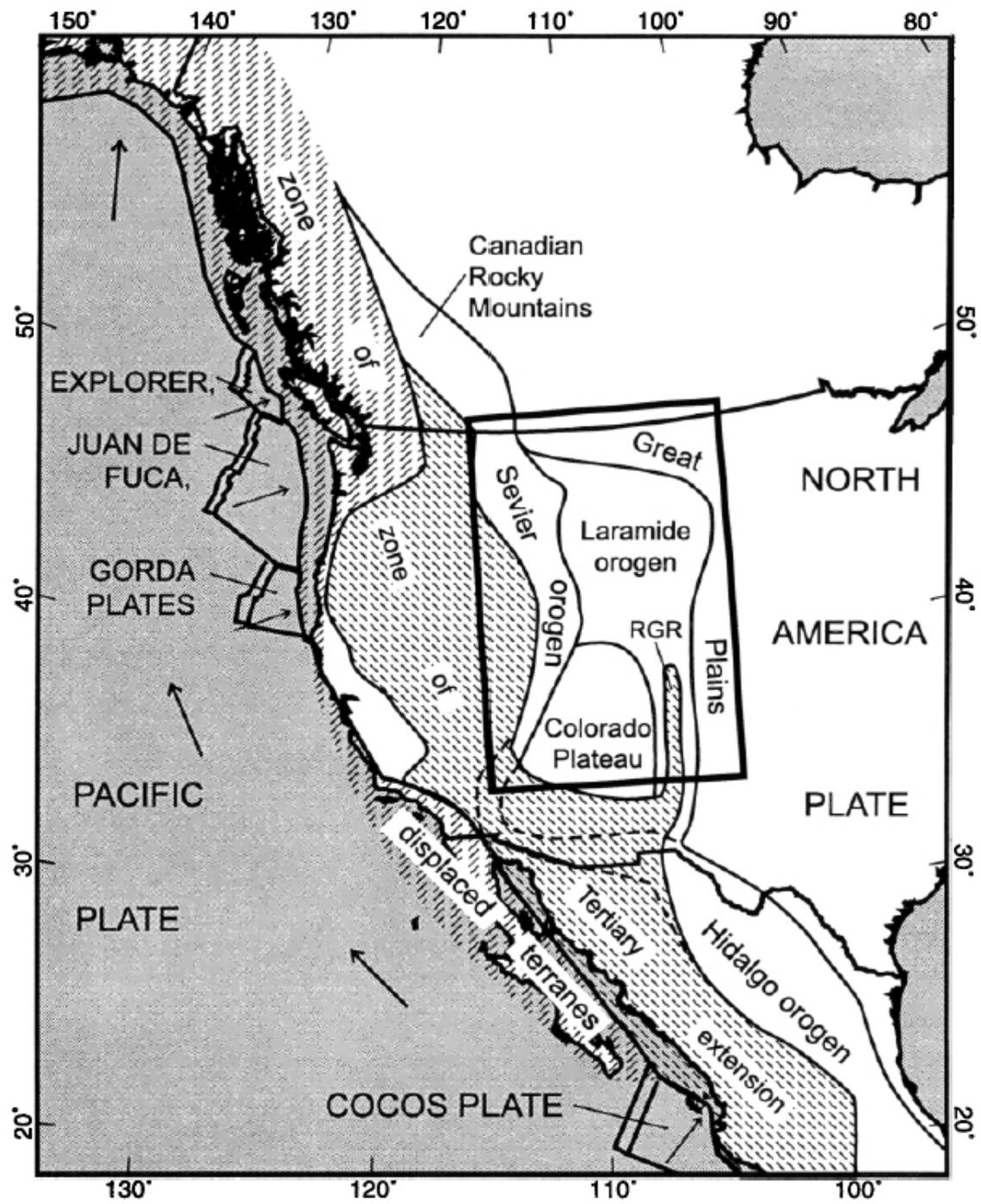
These questions were addressed in 2 recent Thematic Issues

Into the deformation history of folded rocks, 2012
Guest Editors : O. Lacombe, S. Tavani, R. Soto

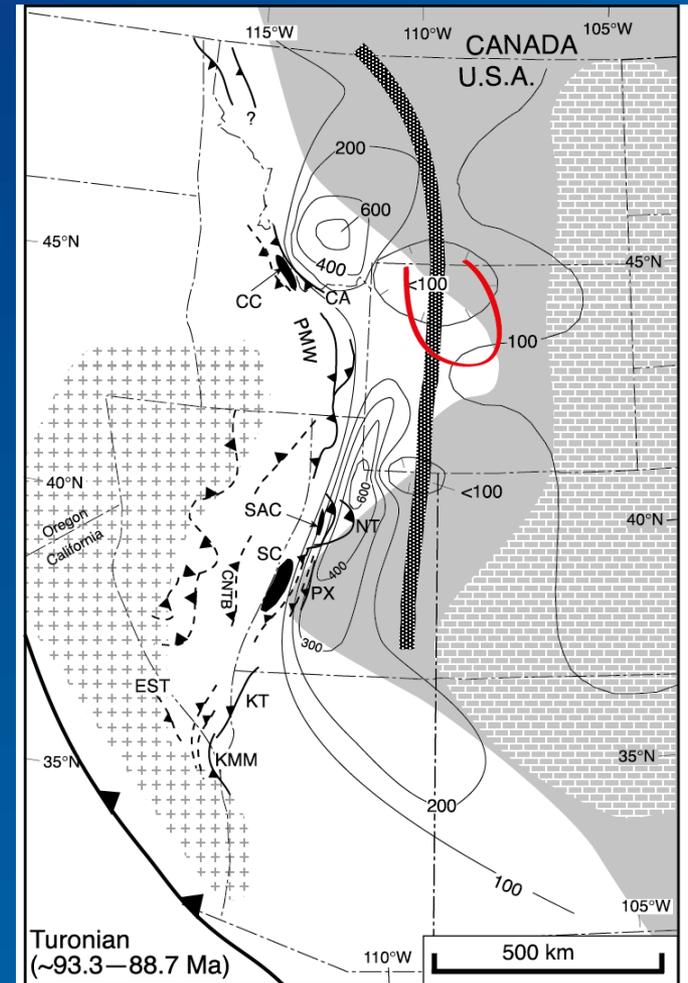
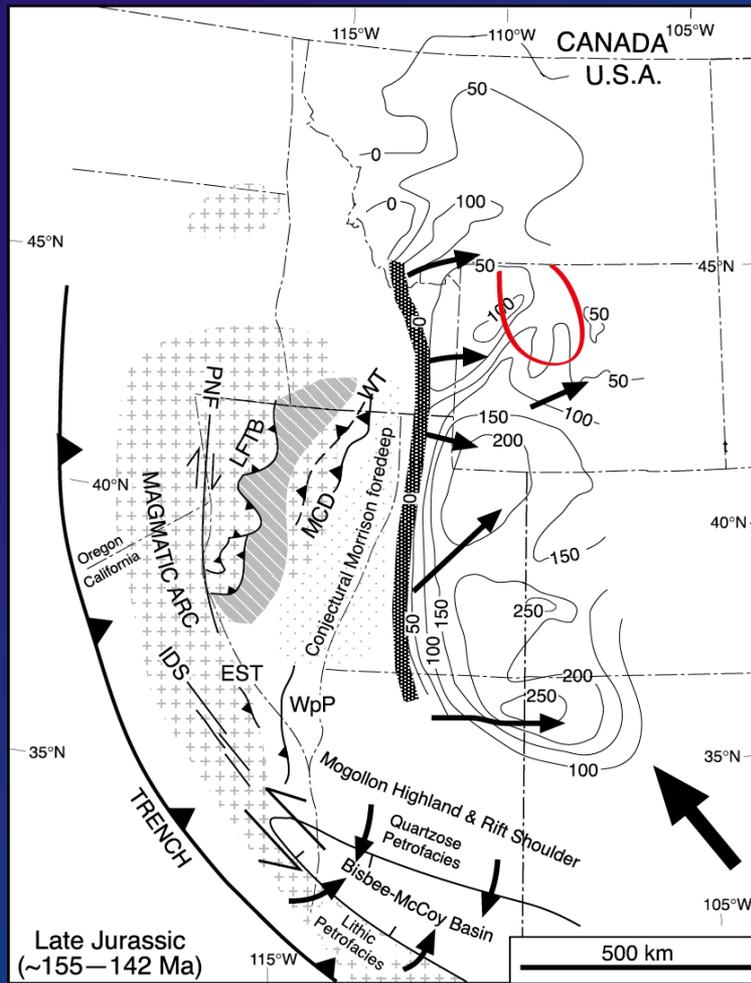
Fluid-rock-tectonics interactions in basins and orogens, 2014
Guest Editors : O. Lacombe, R. Swennen, A. Caracausi



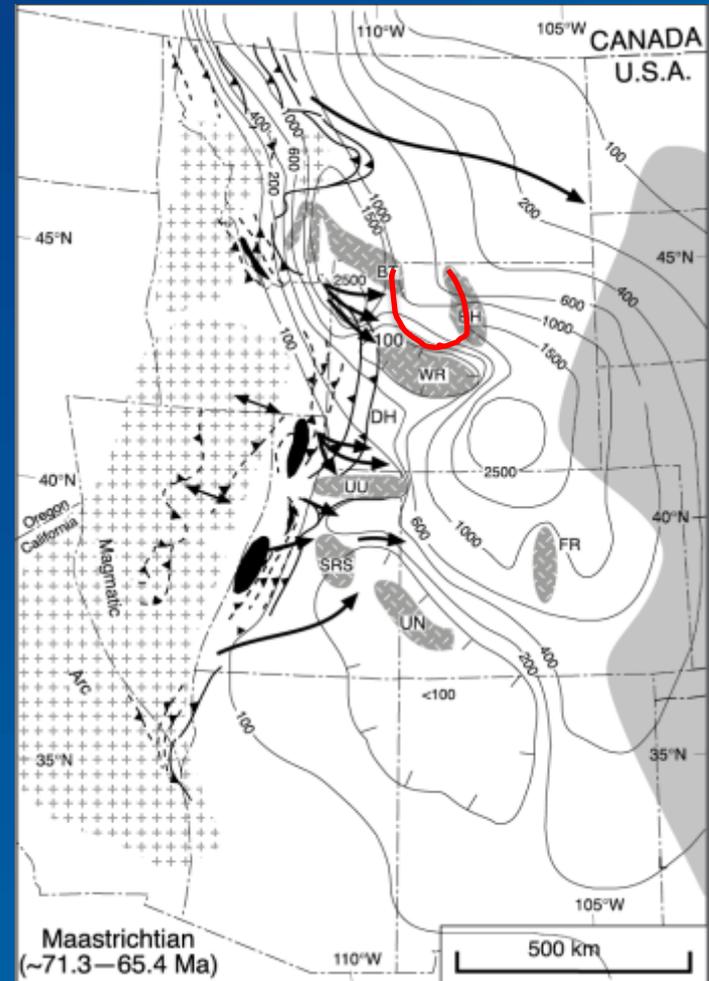
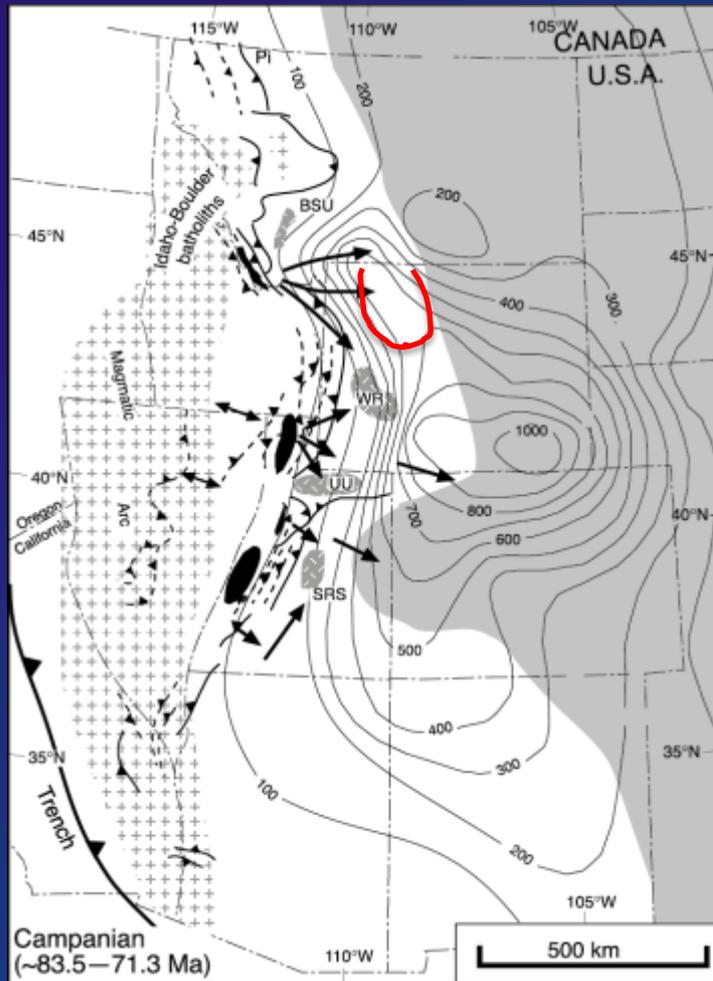
**The Bighorn Basin
and the Sevier and Laramide orogenies**



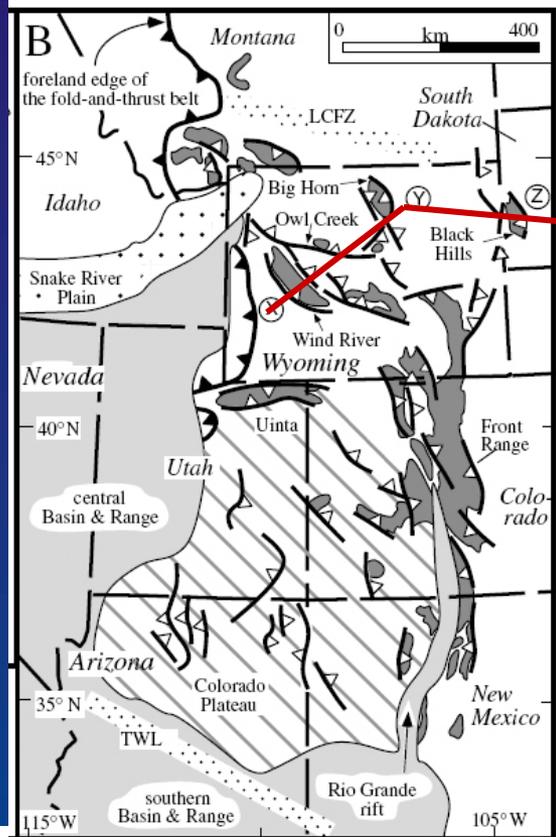
Jurassic - Cretaceous: The Western Interior Basin



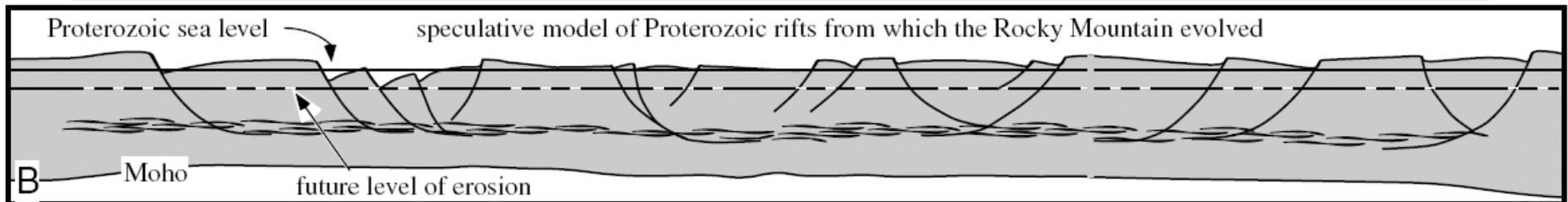
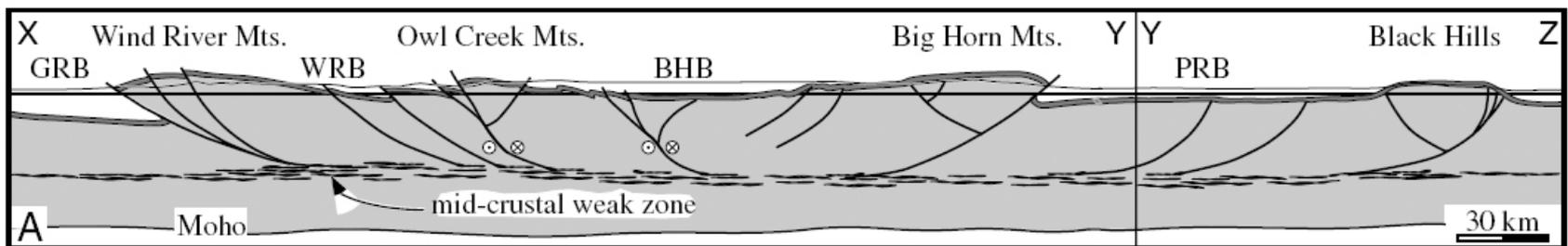
Late Cretaceous - Paleocene: The Bighorn Basin

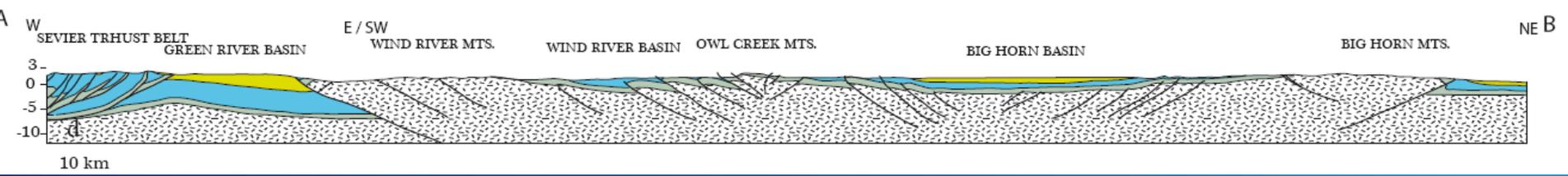
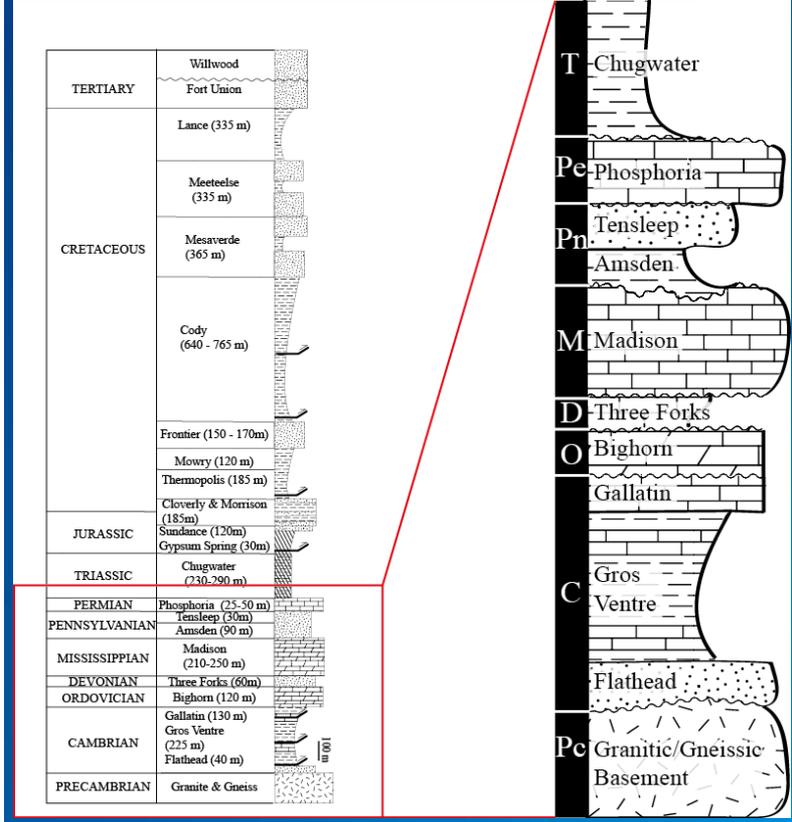
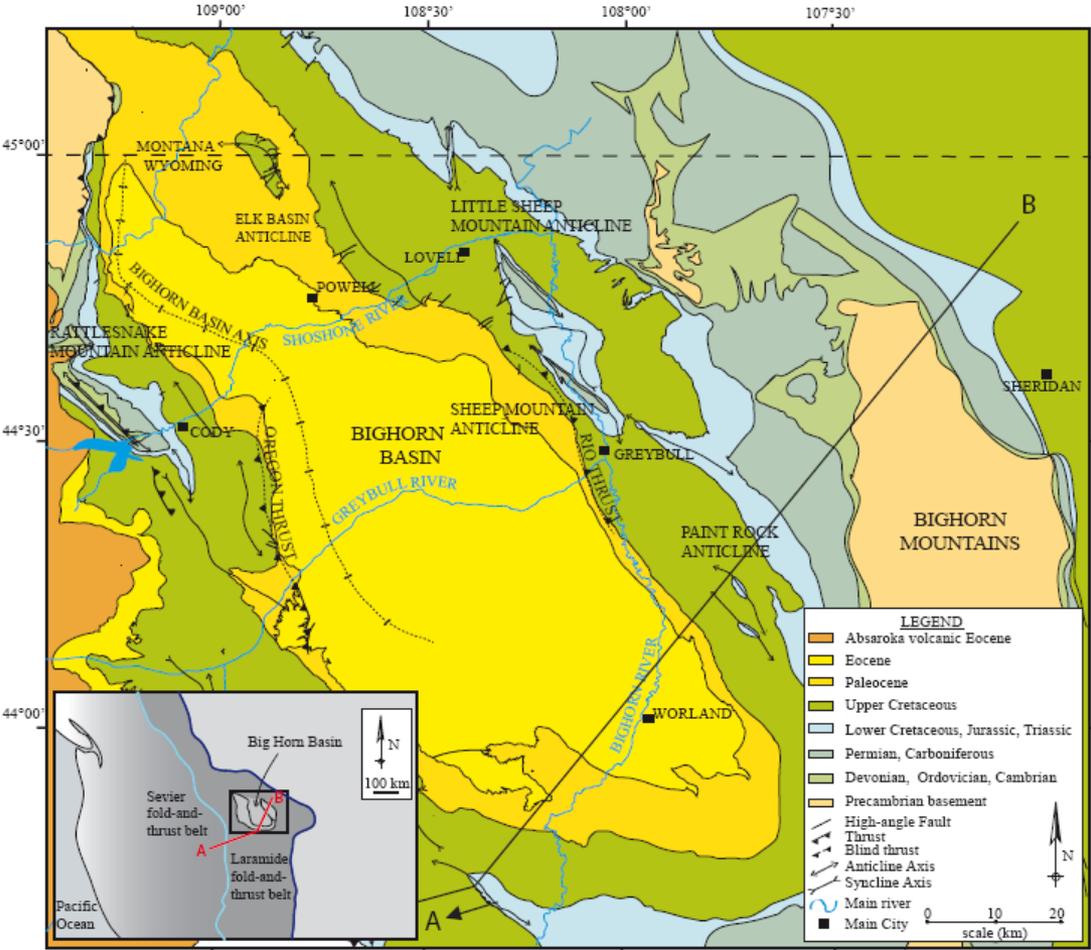


(DeCelles, 2004)



(Marshak et al., 2000)





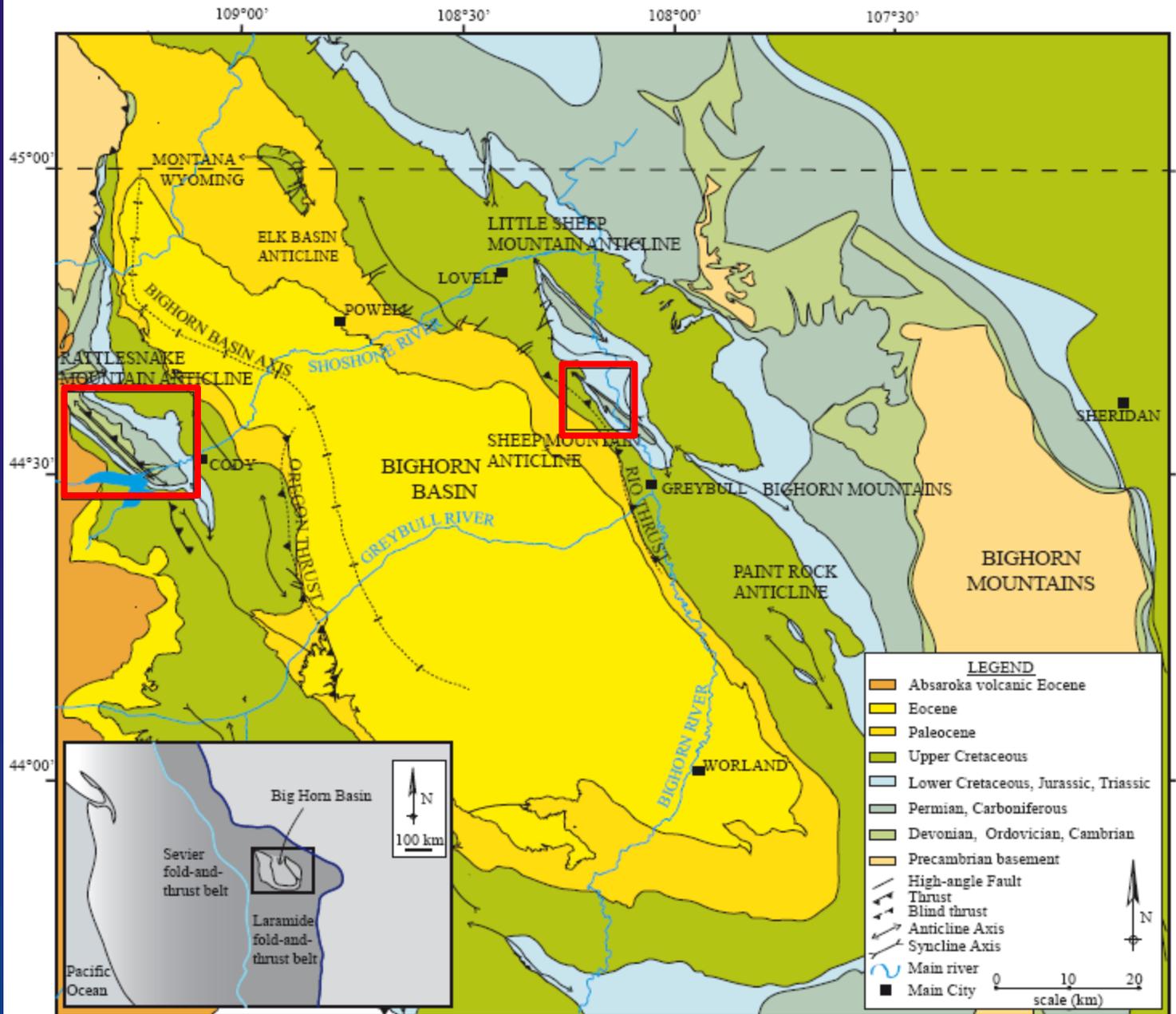
**Structural, microstructural and paleo-hydrological evolution
of Sheep Mountain and Rattlesnake Mountain anticlines**

WELCOME TO

WYOMING



FOREVER WEST



109°00'

108°30'

108°00'

107°30'

45°00'

44°30'

44°00'

MONTANA
WYOMING

ELK BASIN
ANTICLINE

LITTLE SHEEP
MOUNTAIN ANTICLINE

LOVELL

POWELL

RATTLESNAKE
MOUNTAIN ANTICLINE



CODY

BIGHORN ANTICLINE
BASIN



SHEEP MOUNTAIN
ANTICLINE

GREYBULL

BIGHORN MOUNTAINS

SHERIDAN

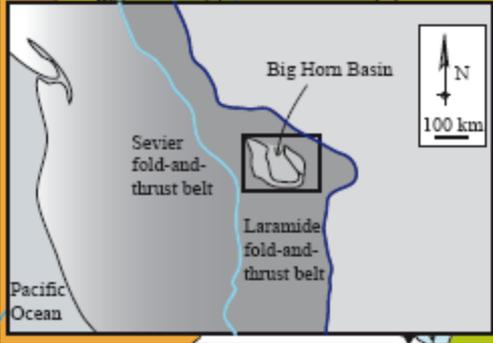
GREYBULL RIVER

PAINT ROCK
ANTICLINE

BIGHORN
MOUNTAINS

BIGHORN RIVER

WORLAND



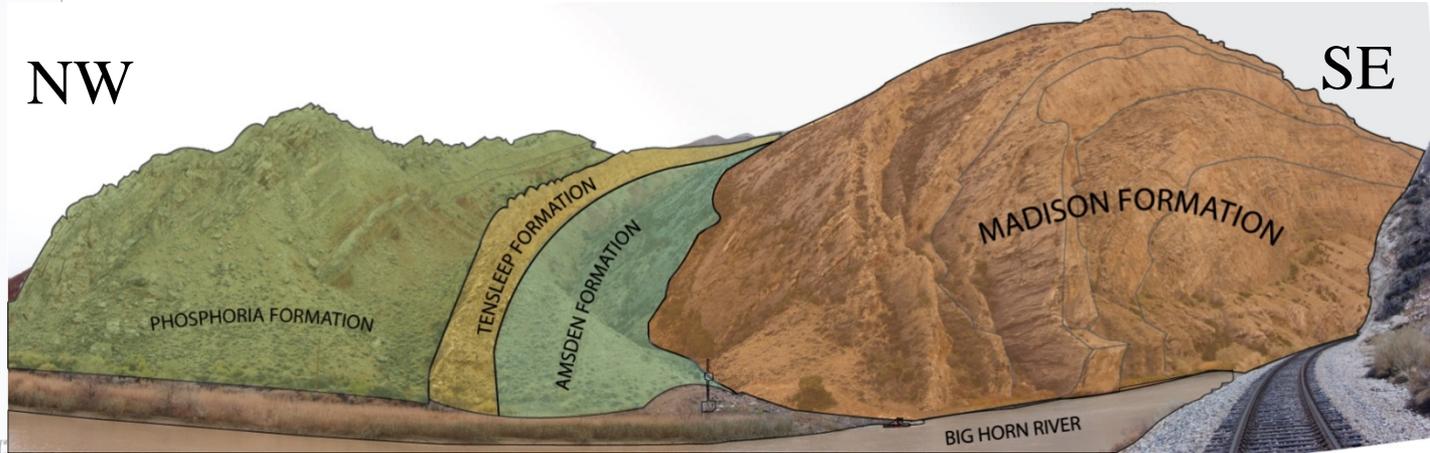
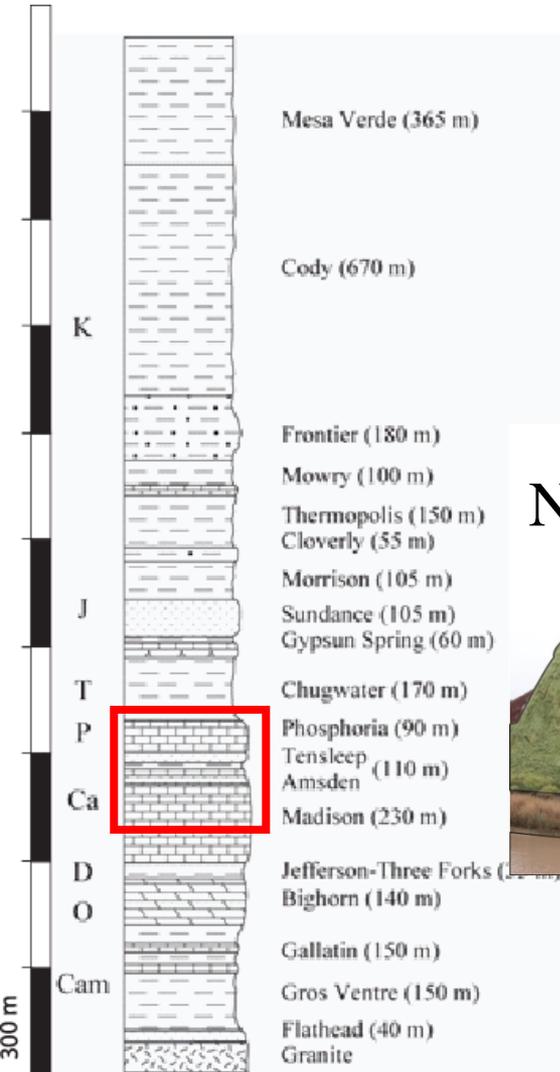
LEGEND

- Absaroka volcanic Eocene
 - Eocene
 - Paleocene
 - Upper Cretaceous
 - Lower Cretaceous, Jurassic, Triassic
 - Permian, Carboniferous
 - Devonian, Ordovician, Cambrian
 - Precambrian basement
 - High-angle Fault
 - Thrust
 - Blind thrust
 - Anticline Axis
 - Syncline Axis
 - Main river
 - Main City
- 0 10 20
scale (km)

Sheep Mountain anticline



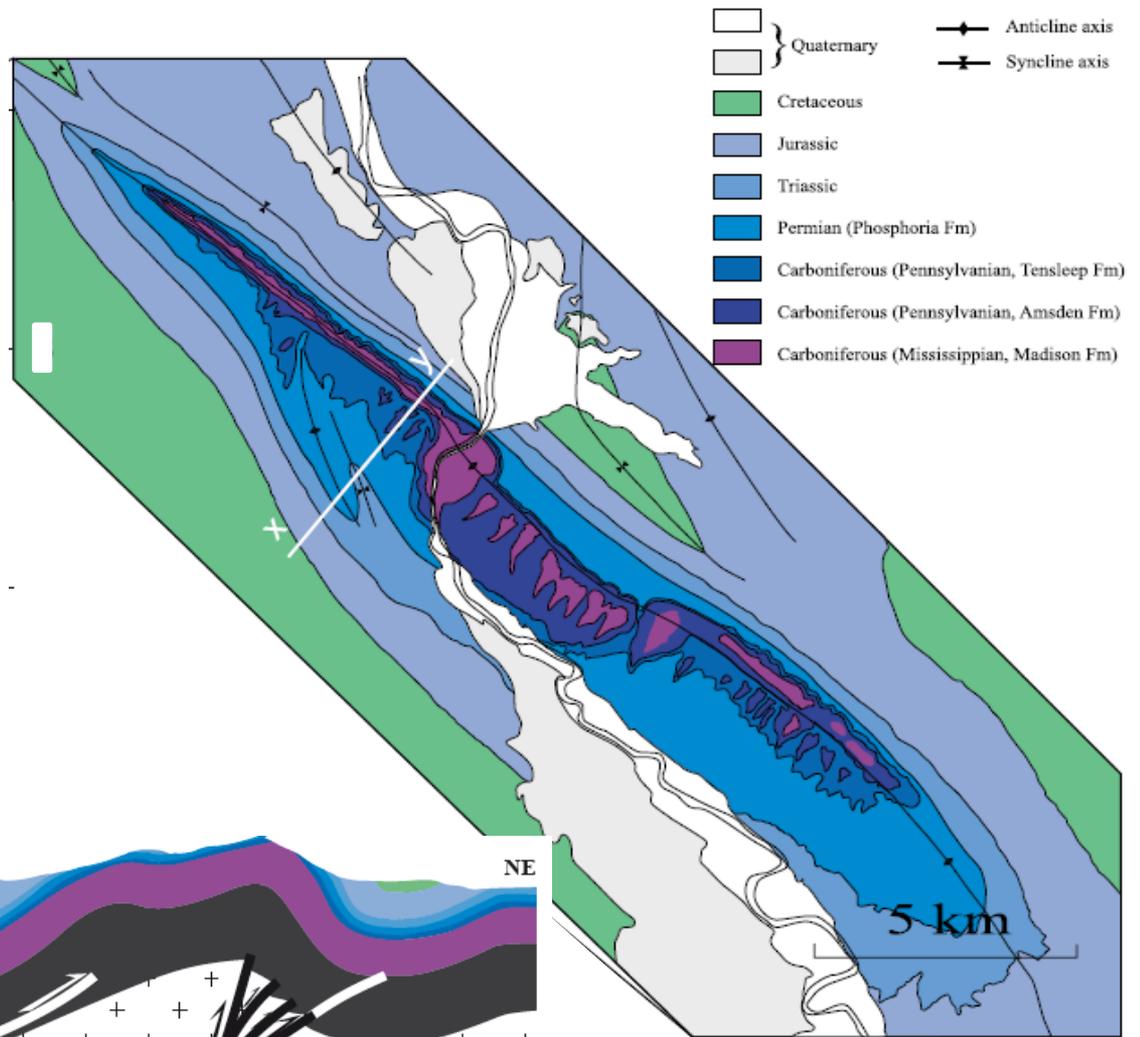
Sheep Mountain anticline



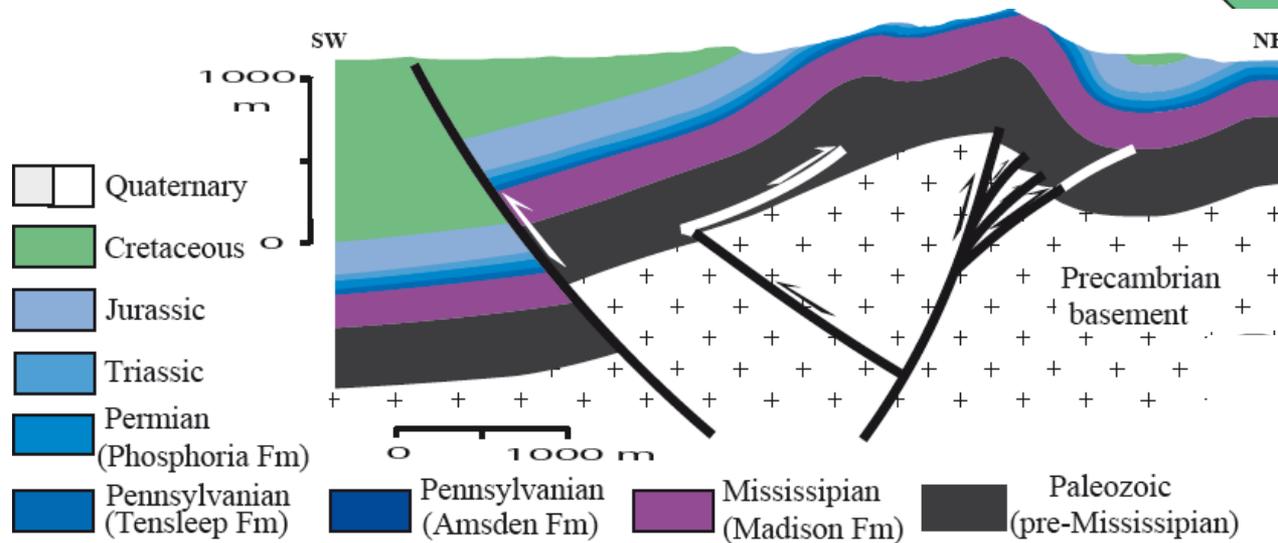
- 300 meters of exposed competent formations (mainly carbonates)
- Argillaceous stratigraphic series (3000m in thickness)

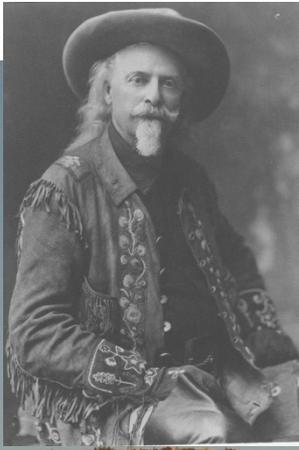


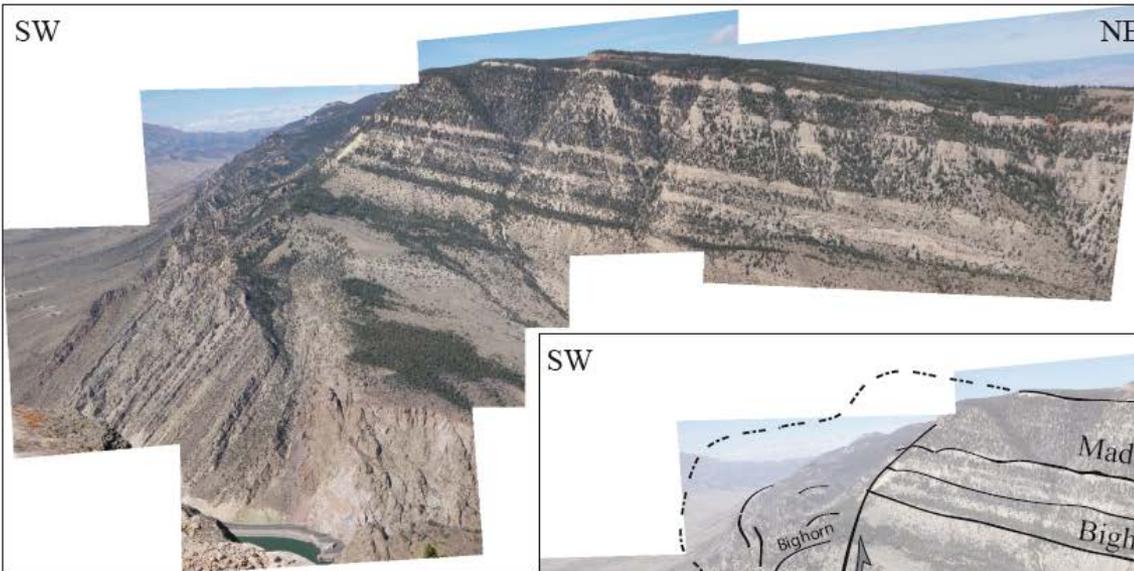
(Amrouch et al. Tectonics, 2010)



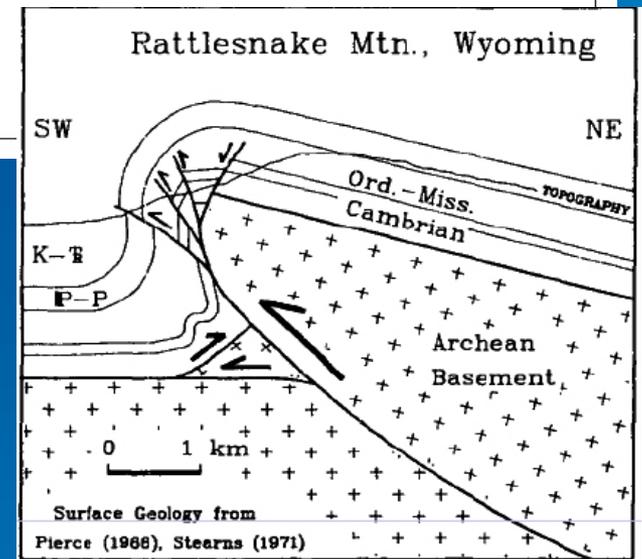
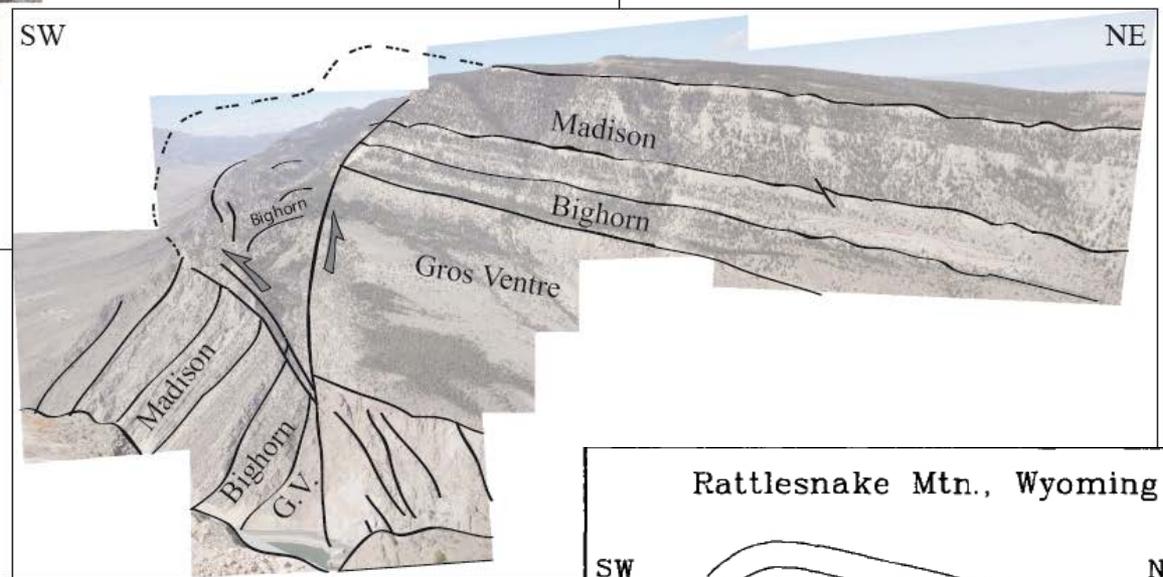
Sheep Mountain anticline





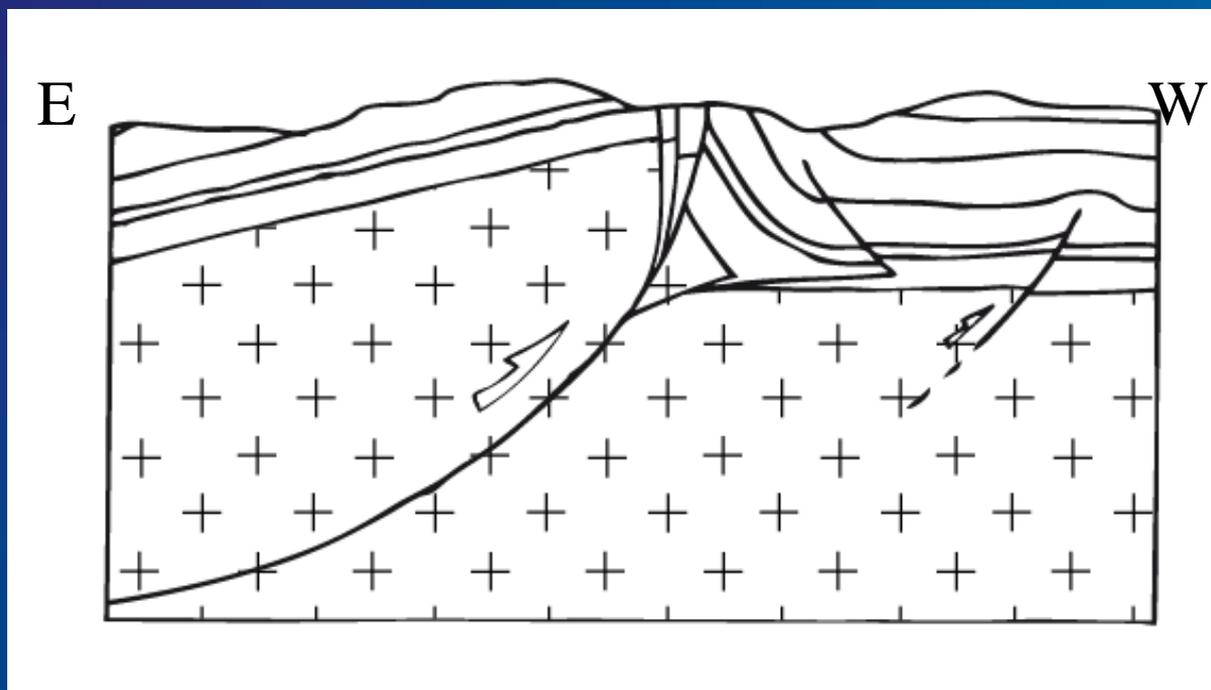


(Beaudoin et al.,
Tectonophysics, 2012)



Rattlesnake Mountain anticline

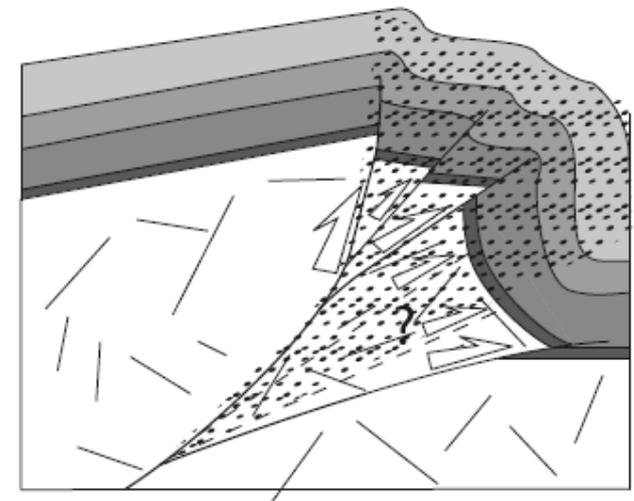
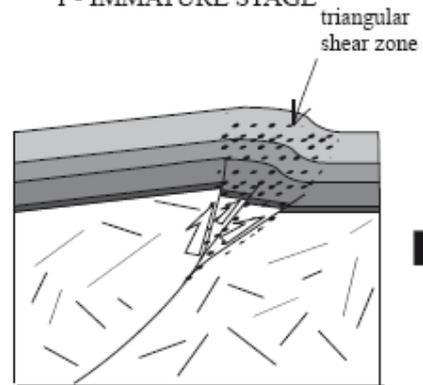
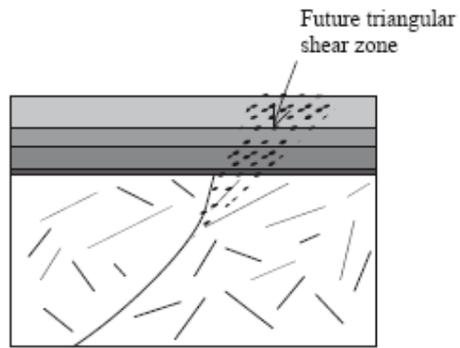
(Erslev, 1986)



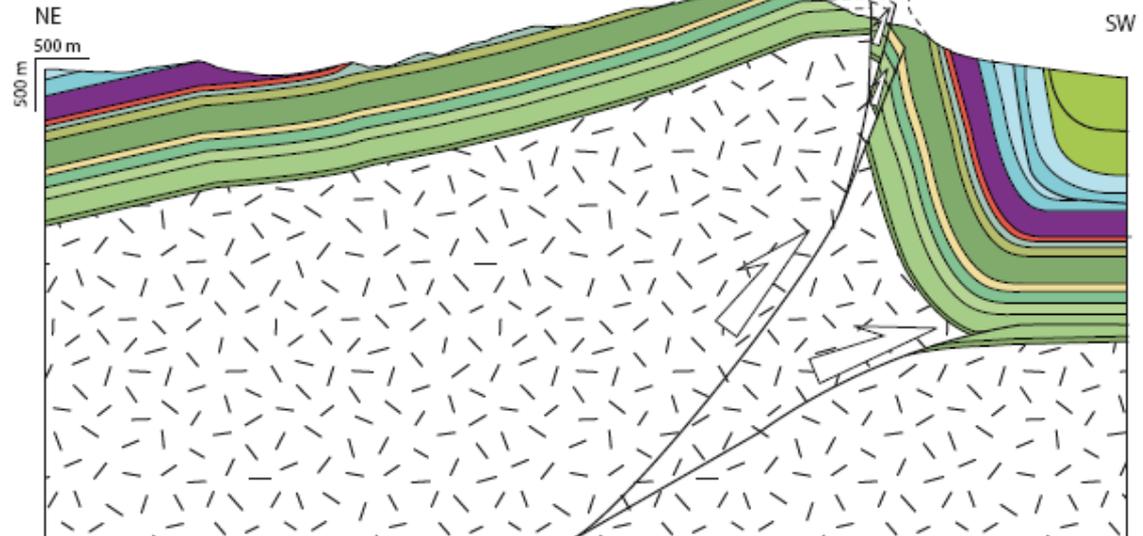
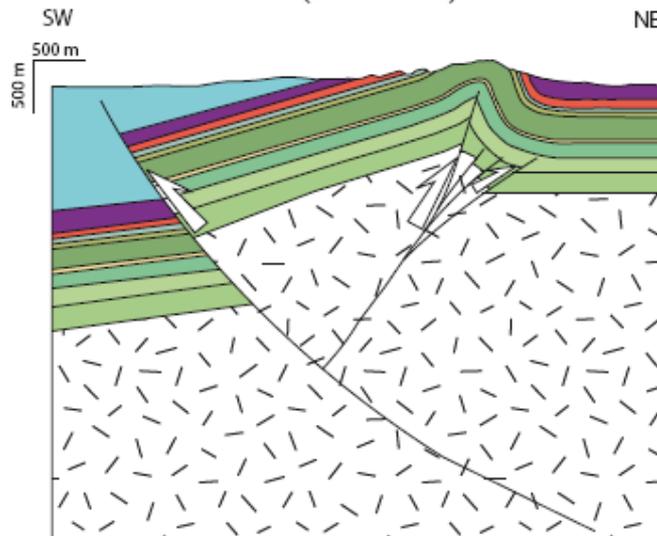
a

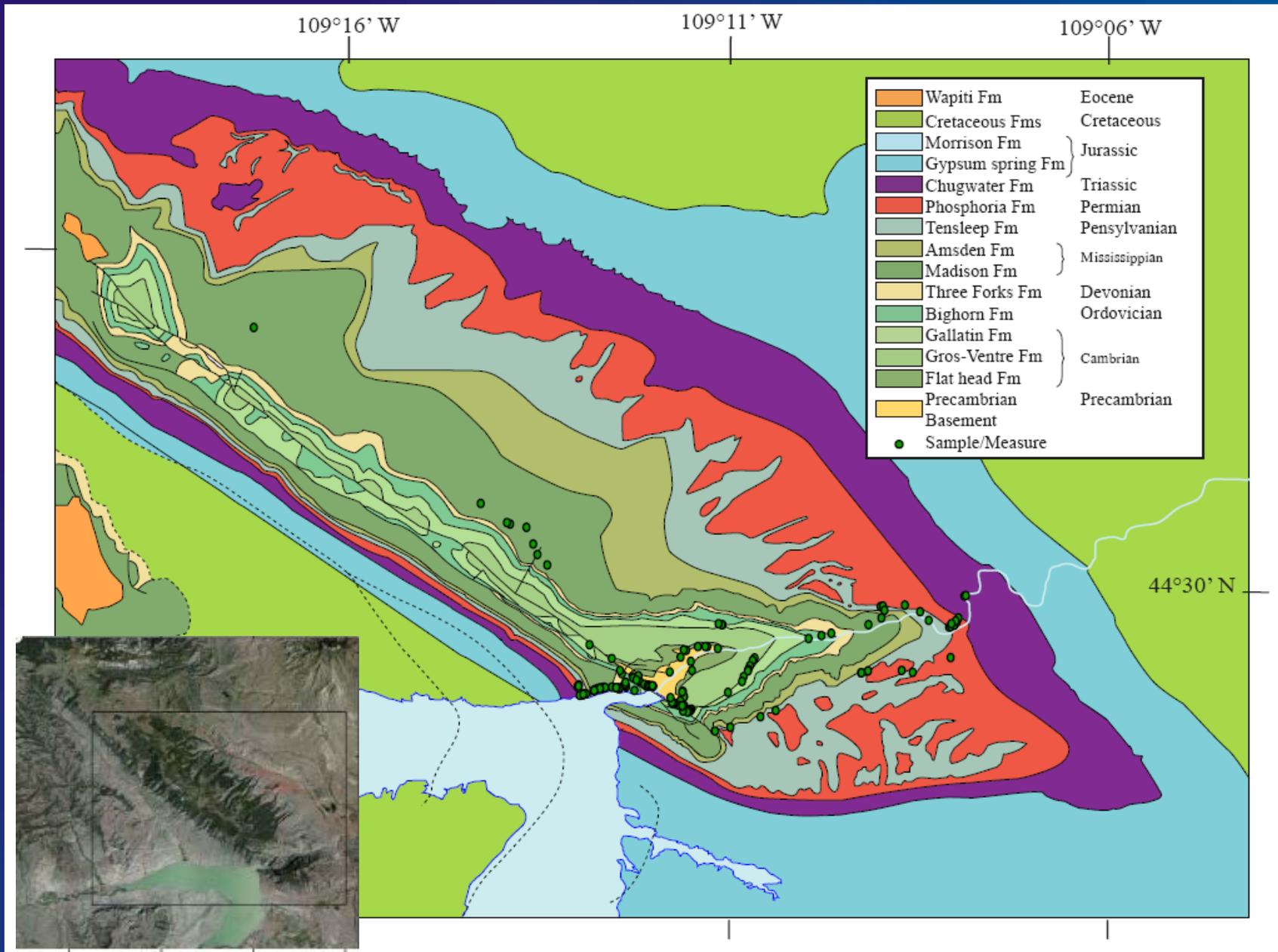
0 - INITIAL STAGE

1 - IMMATURE STAGE



b

SMA
(IMMATURE)RMA
(MATURE)



(Beaudoin et al., Tectonophysics, 2012)

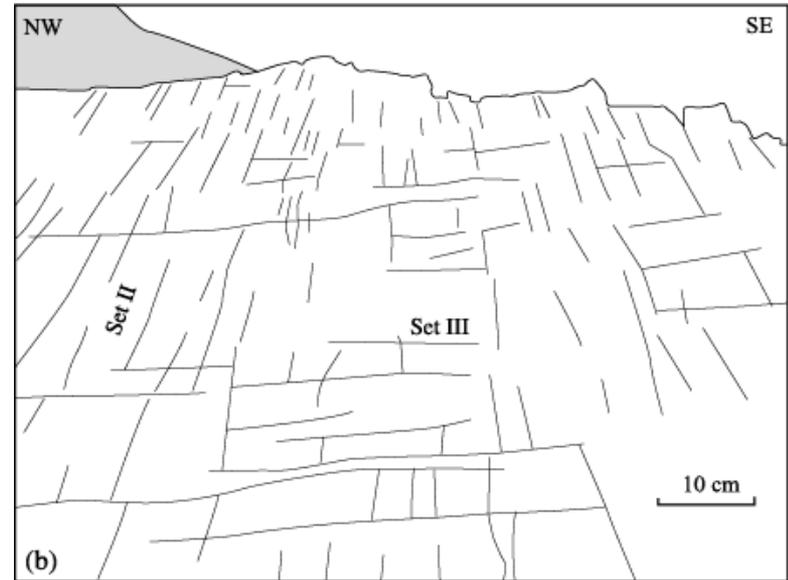
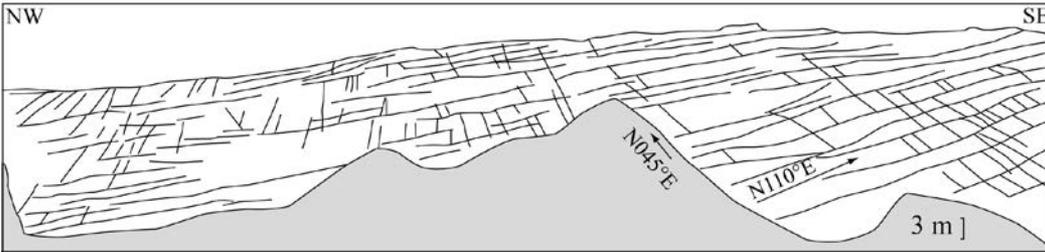


ATTENTION

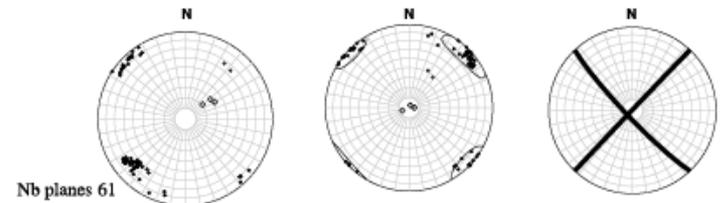
YOU ARE ENTERING GRIZZLY BEAR COUNTRY!
PLEASE TAKE THE NECESSARY PRECAUTIONS.
IF YOU WOULD LIKE TO LEARN MORE ABOUT
THE GRIZZLY BEAR AND YOUR SAFETY, PLEASE
CONTACT THE CODY OFFICES OF THE BLM, U.S.
FOREST SERVICE OR WYOMING GAME AND FISH.

**Fracture populations
at Sheep Mountain and Rattlesnake Mountain anticlines**

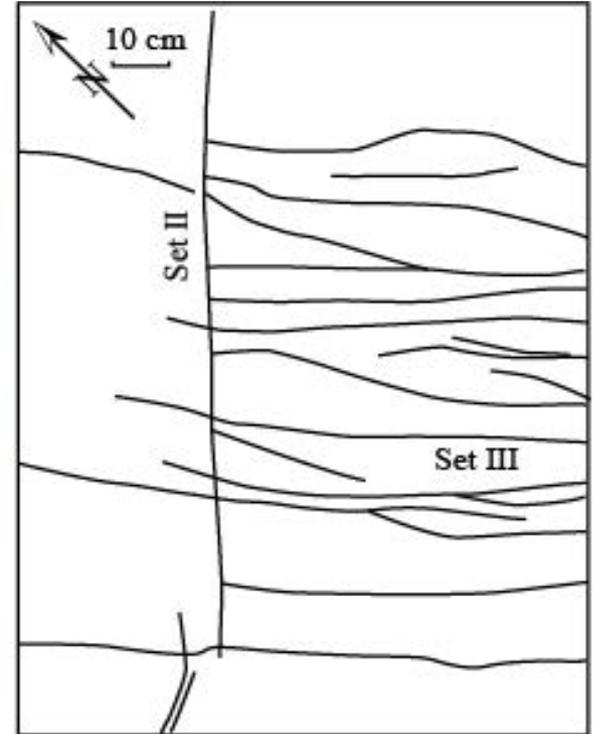
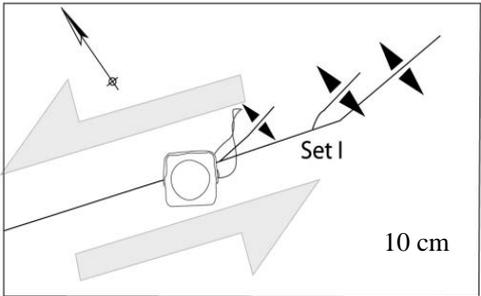
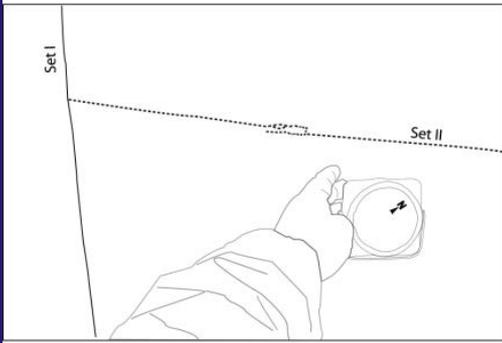
Sheep Mountain anticline



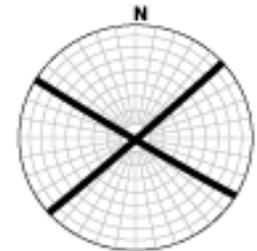
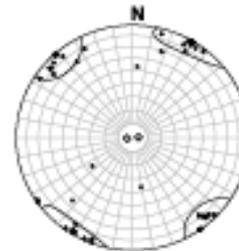
(Bellahsen et al., 2006; Amrouch et al., Tectonics, 2010)



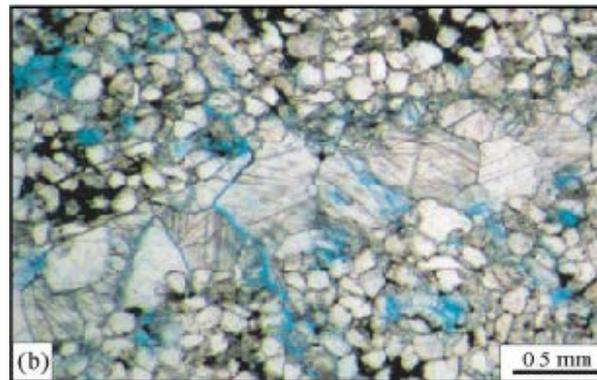
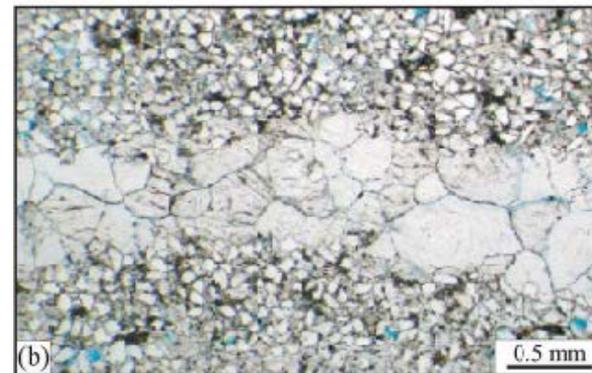
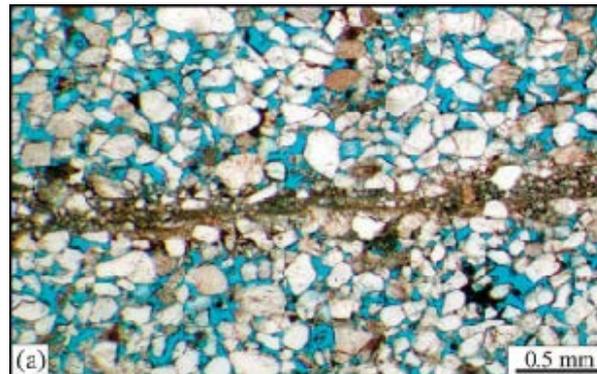
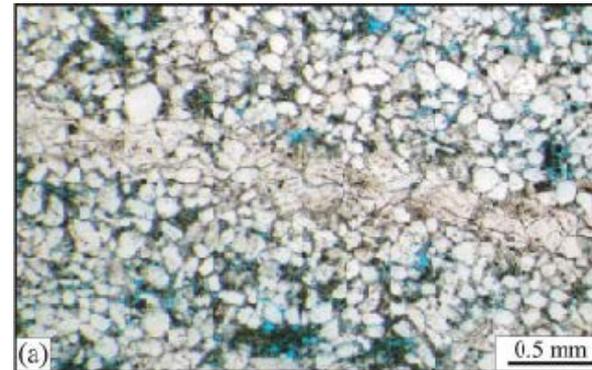
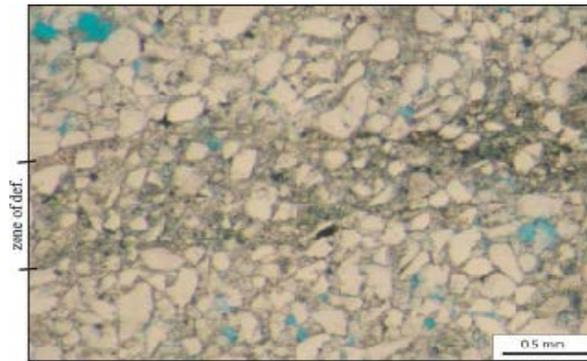
Sheep Mountain anticline



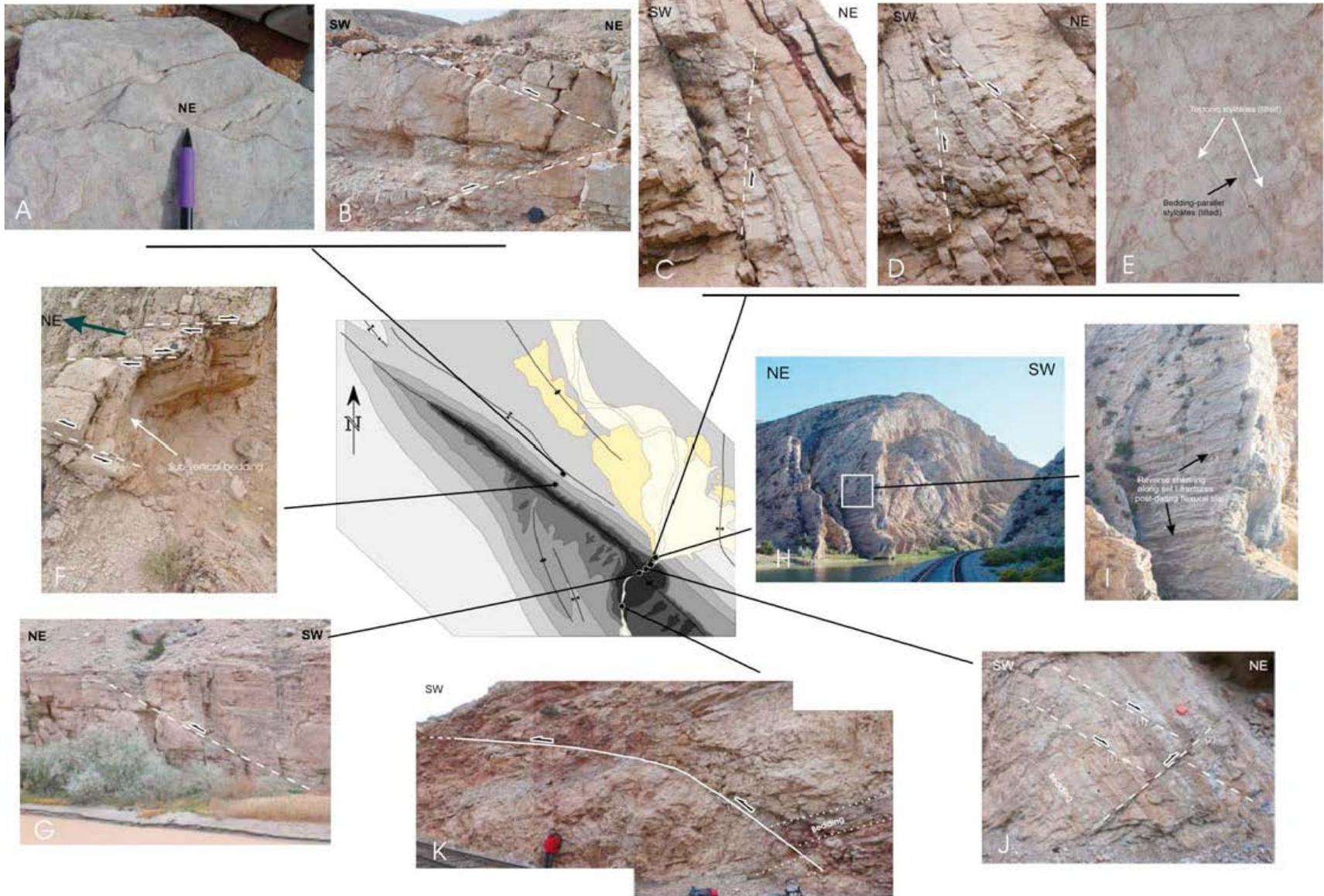
Nb planes 42



Checking opening mode of joints/veins in thin sections

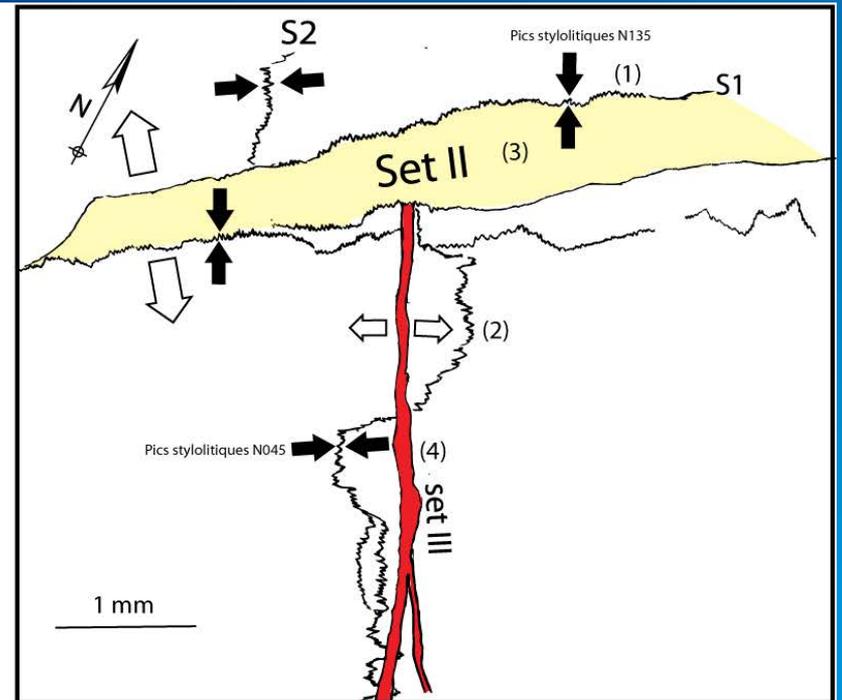
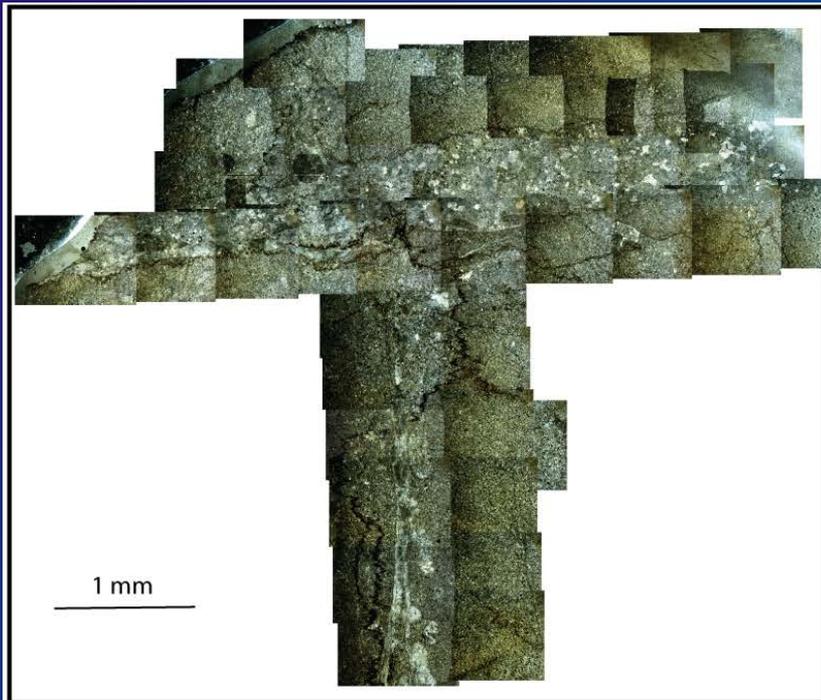
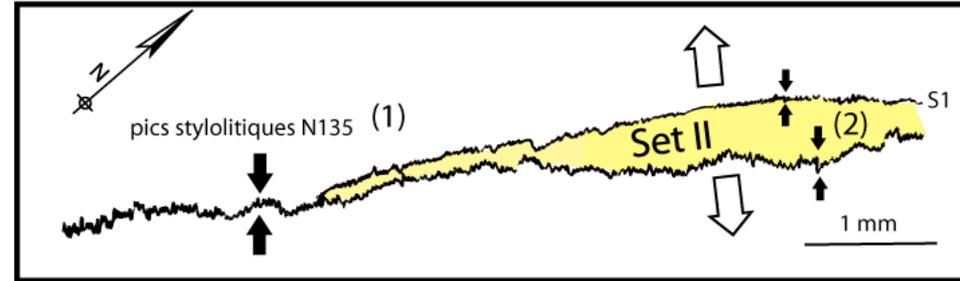


Pressure-solution and meso-scale faulting at Sheep Mountain anticline



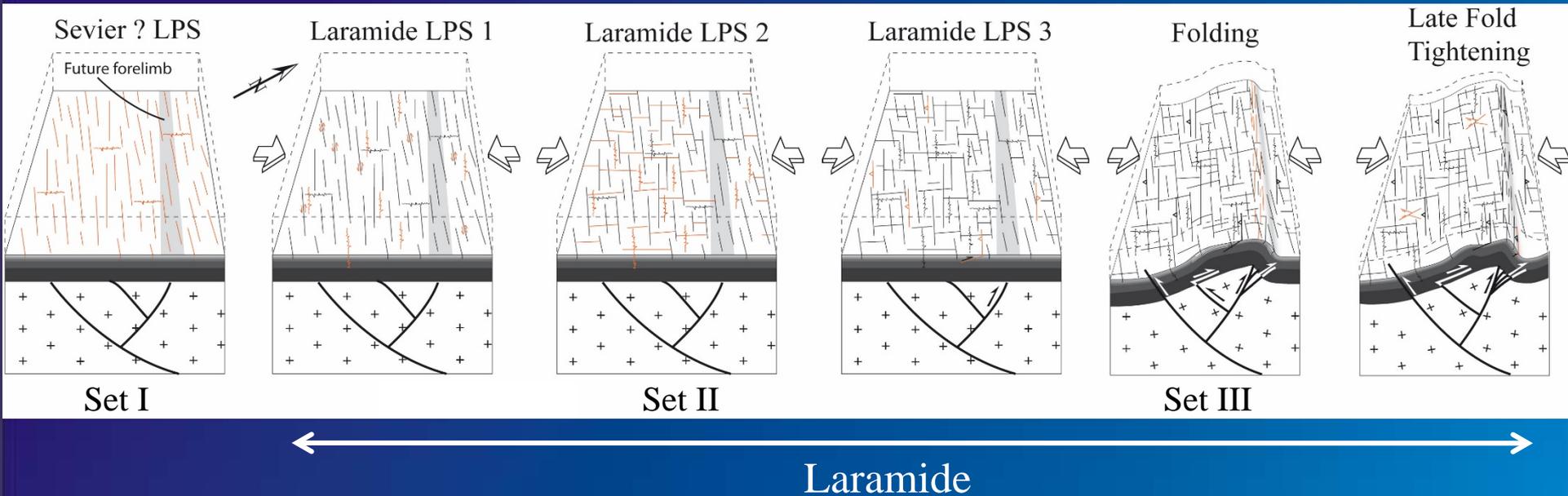
(Amrouch et al., *Tectonics*, 2010)

Relationships between pressure solution seams and fractures



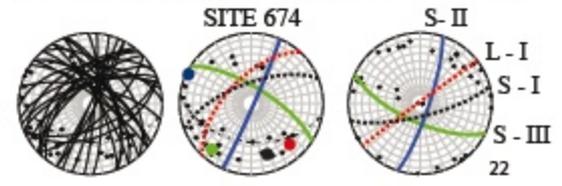
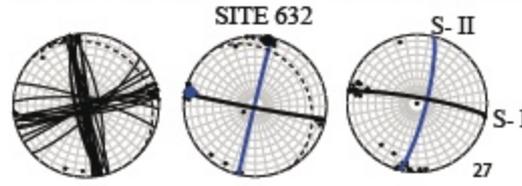
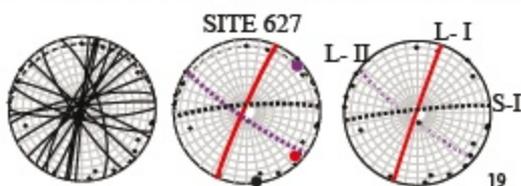
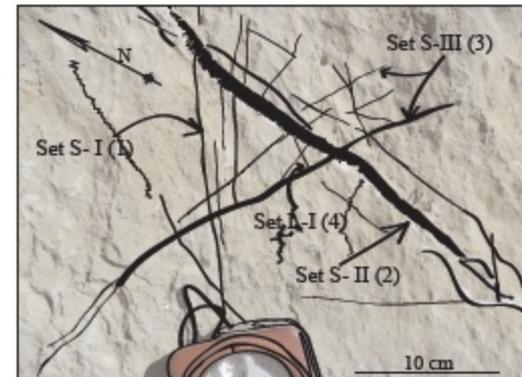
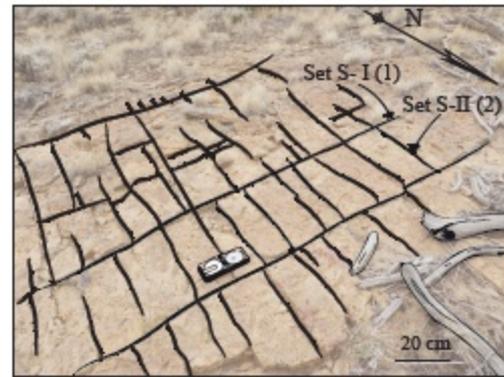
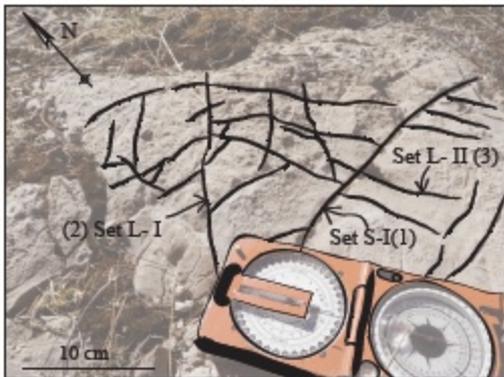
Scenario of fault-fracture development in space and time for Sheep Mountain anticline

(Amrouch et al., GRL, 2011)

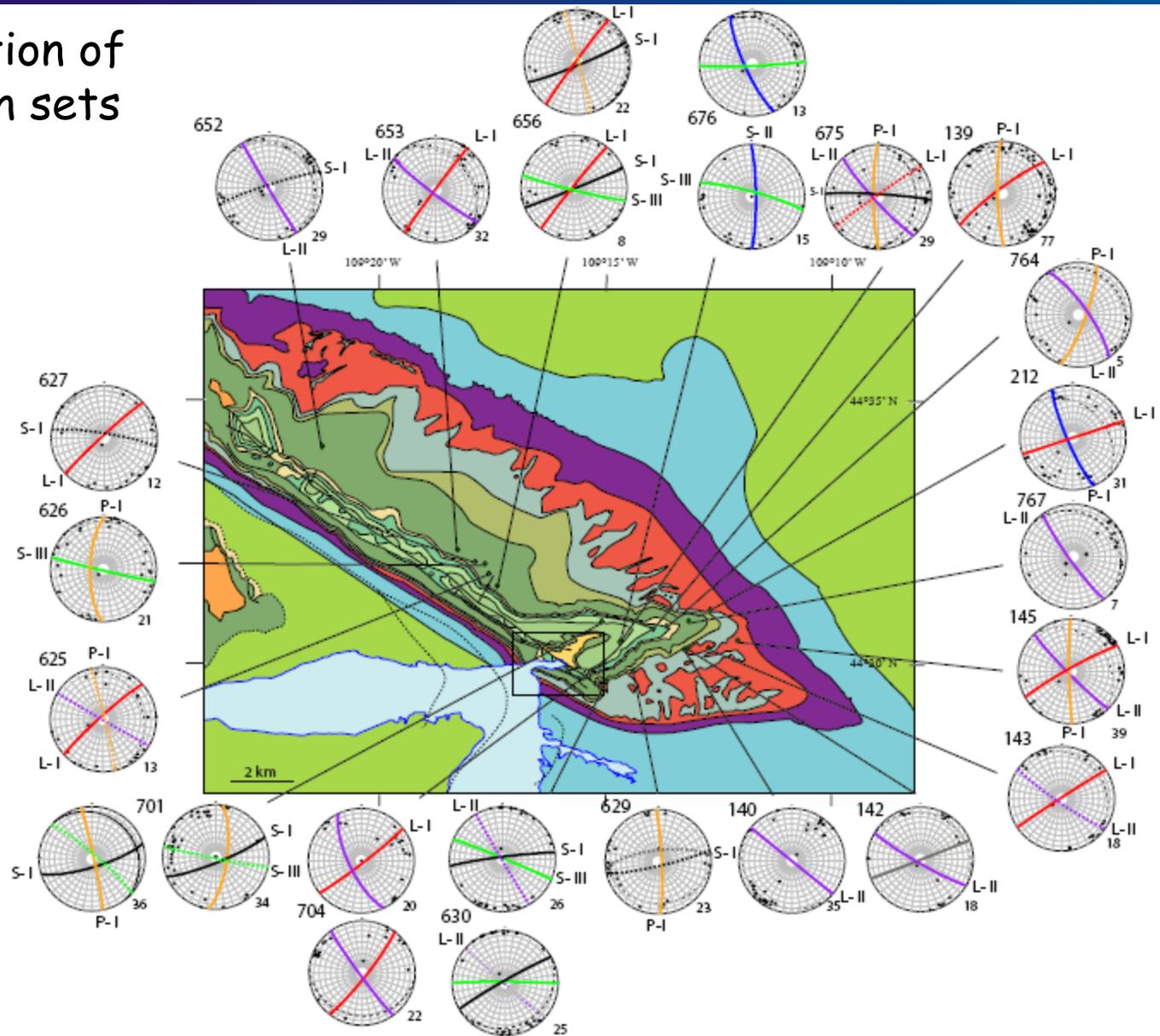


- Mode I opening of pre-Laramide set I fractures
- Shear reactivation of pre-Laramide set I fractures (LPS 1).
- Laramide stylolites with NE-trending peaks and mode I opening of set II fractures (LPS2)
- Reverse faulting parallel to the fold axis (LPS3).
- Mode I opening of syn-folding, outer-rim extension-related 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

Rattlesnake Mountain anticline



Distribution of joint/vein sets



Fracture sequence in the Bighorn Basin

Fracture set	Mean strike of fractures	Related Tectonic events	
Set S-I	090°E to 060°E	Sevier layer-parallel shortening	Pre-Laramide
Set S-II	180°E to 020°E	Formation of the flexural foreland basin	
Set S-III	110°E	Sevier layer-parallel shortening	Laramide
Set L-I	045°E	Laramide layer-parallel shortening	
Set L-II	135°E	Local curvature-related extension	
Set L-III	045°E	Late stage of fold tightening	
Set P-I	180°E to 160°E	Basin and Range extension	Post-Laramide

Summary on fractures at SMA and RMA

Strong occurrence of early-folding, LPS-related fractures, faults and stylolites.

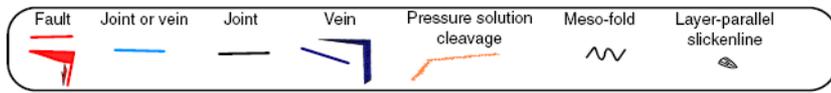
In addition to fold-related fractures (early-, syn- and late- folding), occurrence of fracture sets having originated before folding and being unrelated to either fold geometry or kinematics (i.e., pre- or post-folding).

Fracture systems observed in folded strata may result from the interplay between kinematic boundary conditions (e.g. far-field collisional stresses, foreland flexural stresses) and local deformational events such as fold growth or movements along major faults.

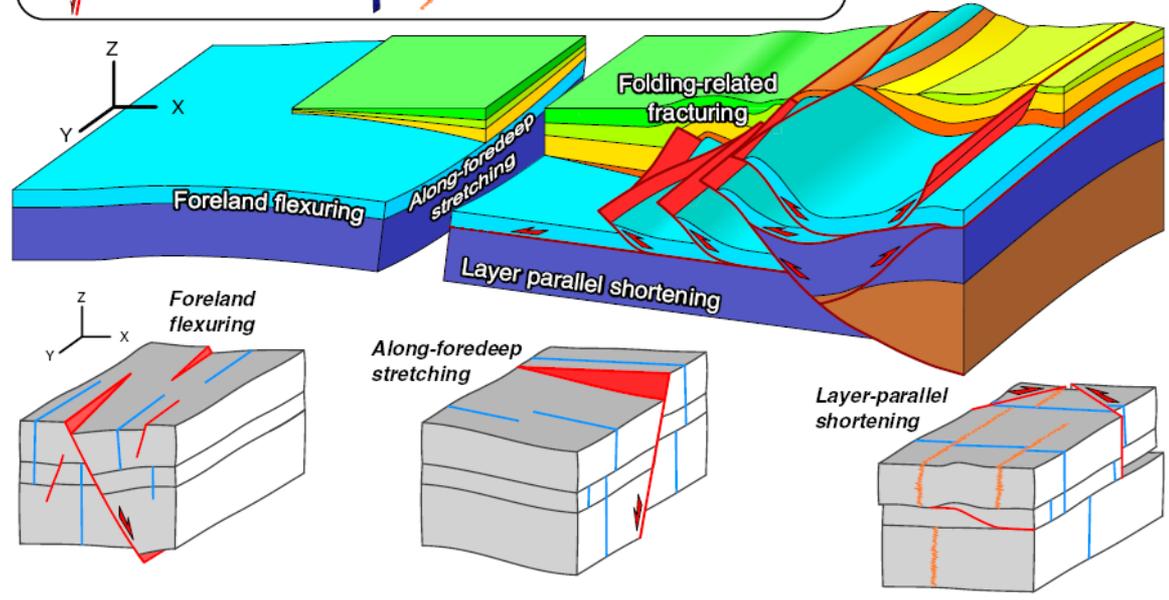
Pre-folding fractures are commonly reopened or sheared or passively tilted during folding. They can also inhibit development of classical sets of fold-related fractures.

Occurrence of such pre-folding (fold-unrelated) fractures has to be carefully considered in order to build realistic conceptual fold-fracture models.

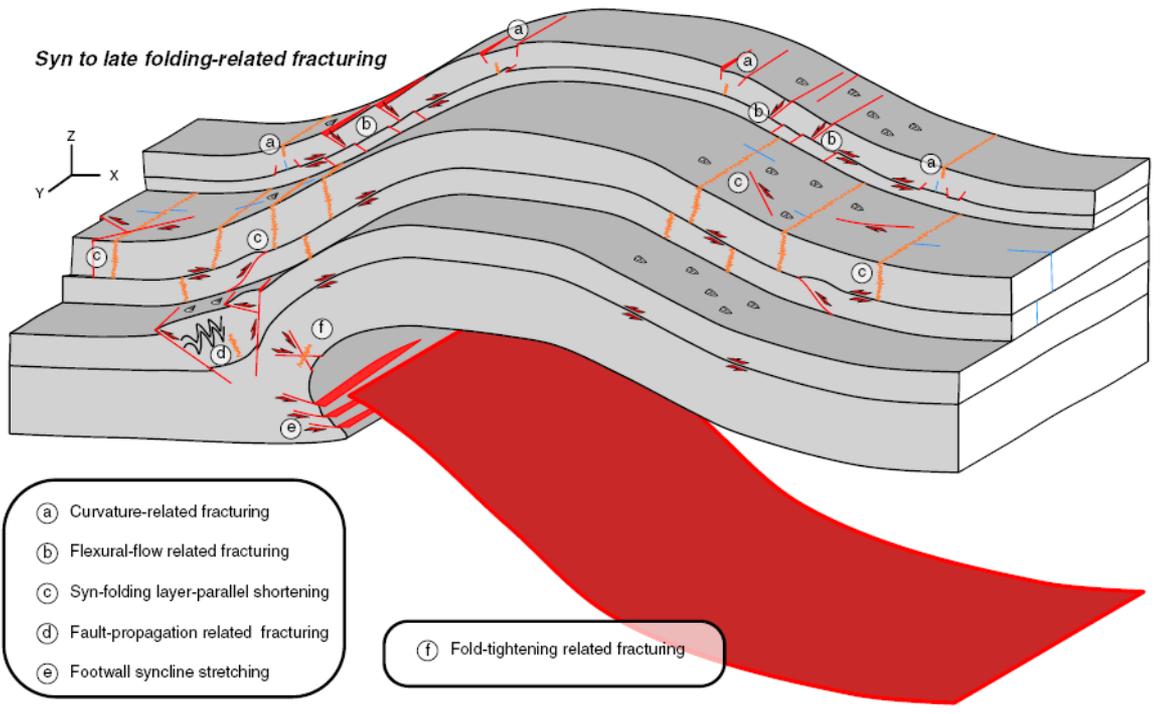
Fractures show variable vertical persistence (stratabound vs through-going), hence potential variable vertical connectivity and break in stratigraphic compartmentalization.



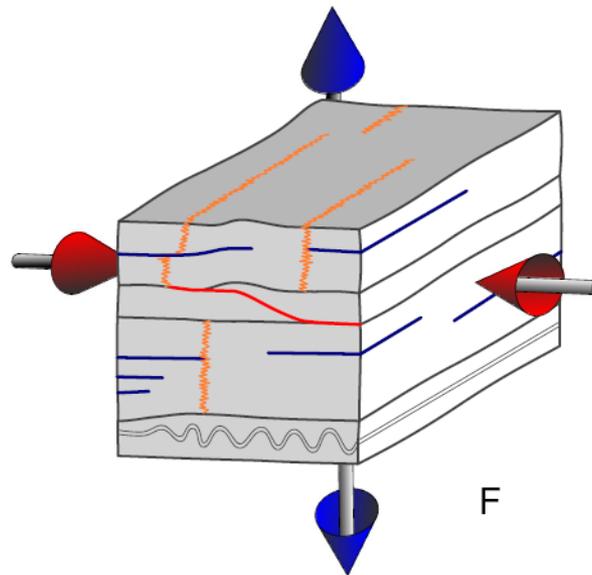
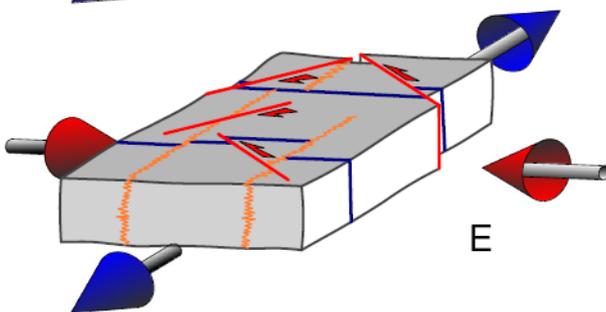
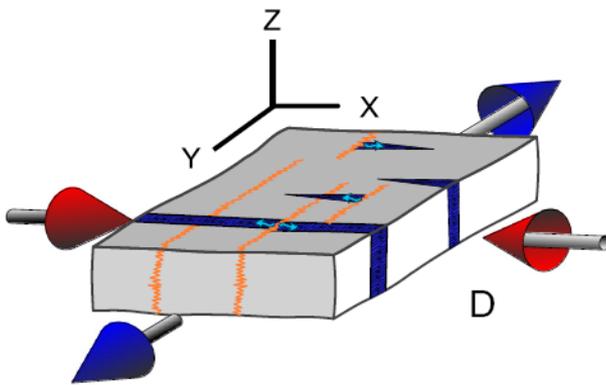
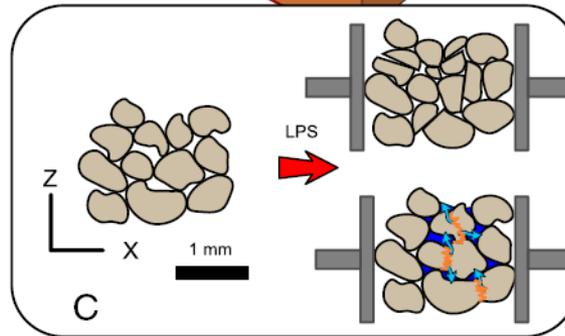
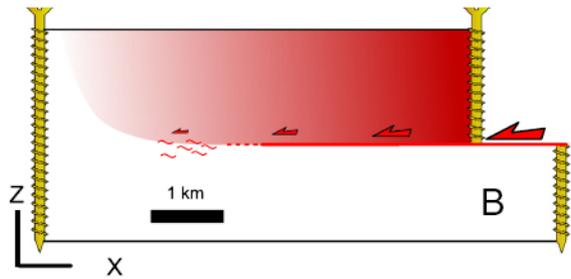
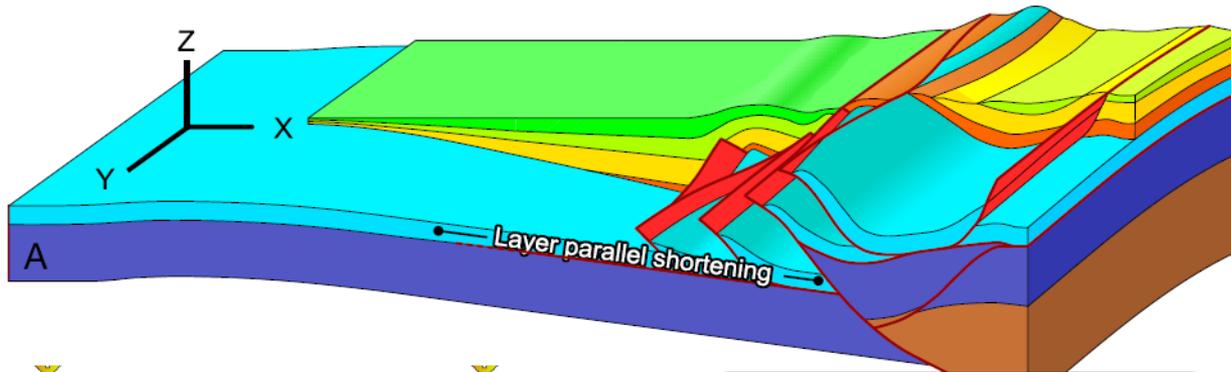
Unloading-related fracturing



Typical (micro) structural assemblages potentially observed in folded strata



(Tavani et al., ESR, 2015)



Layer-parallel shortening

(Tavani et al., ESR, 2015)

**Physical properties of rocks, proxies of internal strain
at Sheep Mountain anticline**

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.

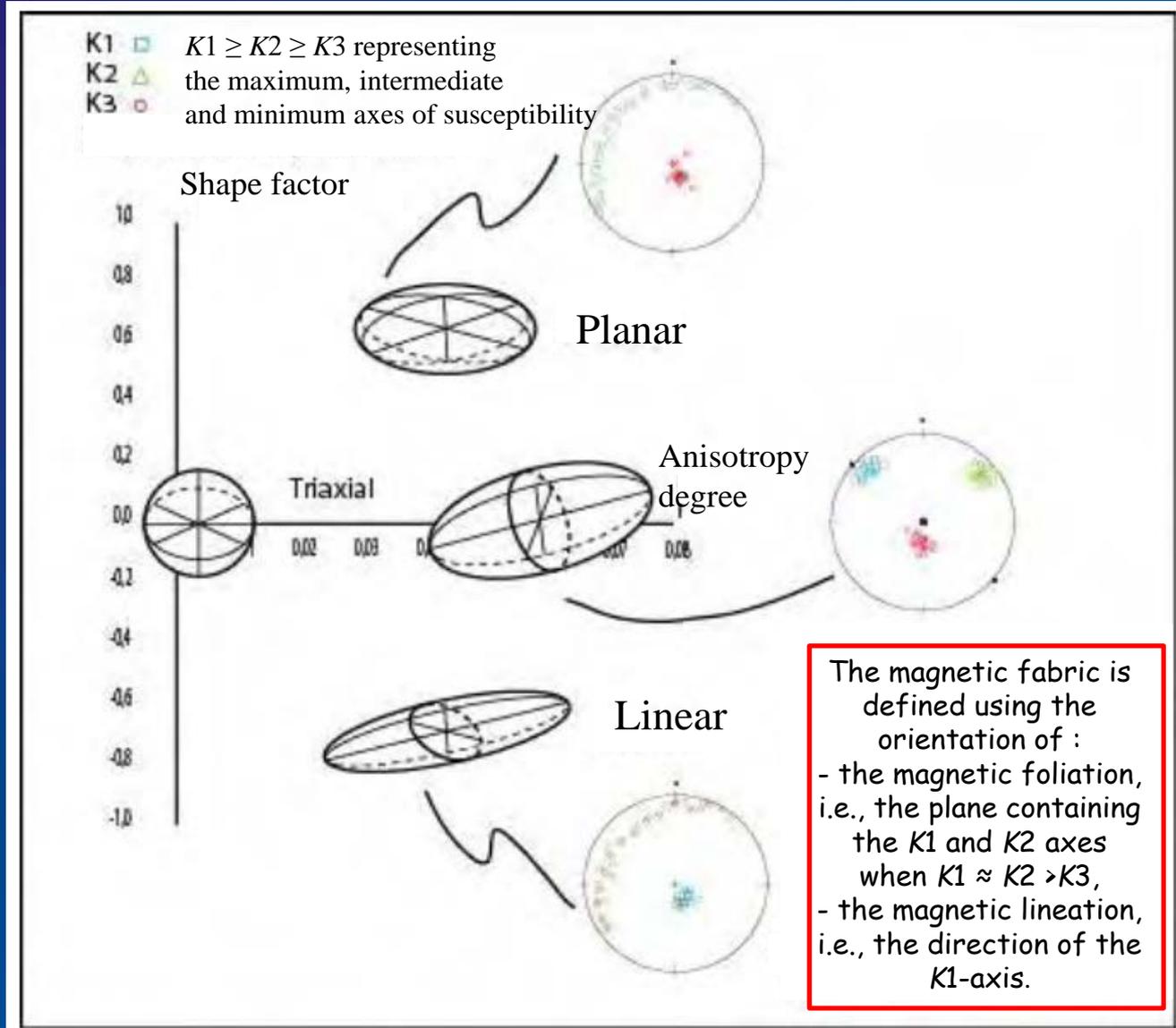
The matrix of a sedimentary rock can be anisotropic because of preferred mineral orientation, water currents during deposition or pressure solution.

The pore space distribution can be anisotropic because of depositional processes driven by gravity or water currents, or presence of preferentially oriented cracks within or between the minerals.

The AMS technique provides an accurate image of the petrofabric structure, which reflects the average preferred orientation of tens of thousands of magnetically susceptible minerals in the rock matrix, called the "magnetic fabric".

Measurement of AMS helps characterize penetrative tectonic fabrics in deformed rocks because AMS is sensitive to even slight preferred orientations of magnetic minerals.

AMS

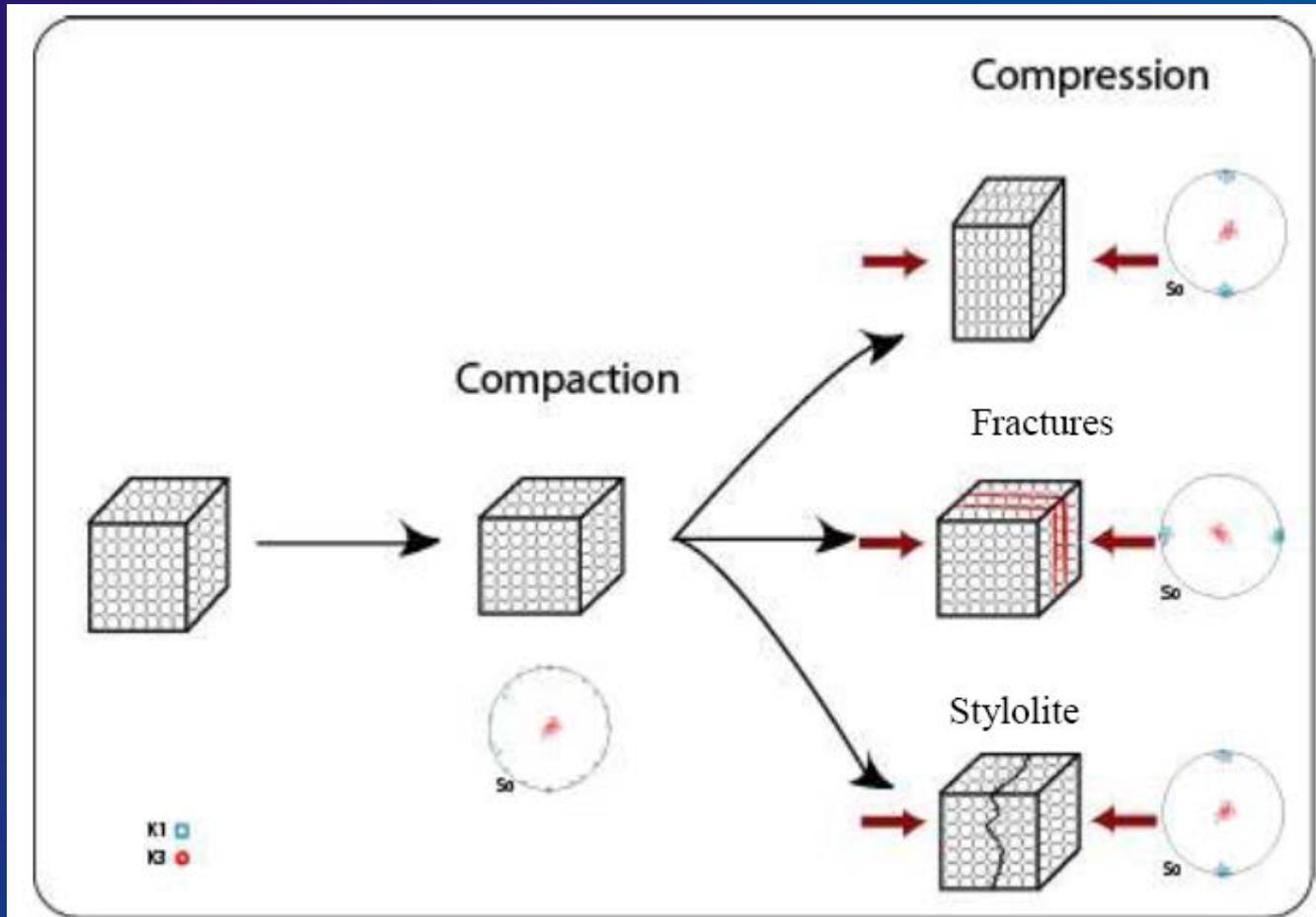


In sedimentary rocks, magnetic susceptibility K_m originates primarily from three distinct sources:

- the dominant diamagnetic minerals (quartz or calcite),
- the paramagnetic minerals (clays and other Fe-bearing silicates)
- diluted ferromagnetic minerals (magnetite, hematite and pyrrhotite), depending on their relative proportion.

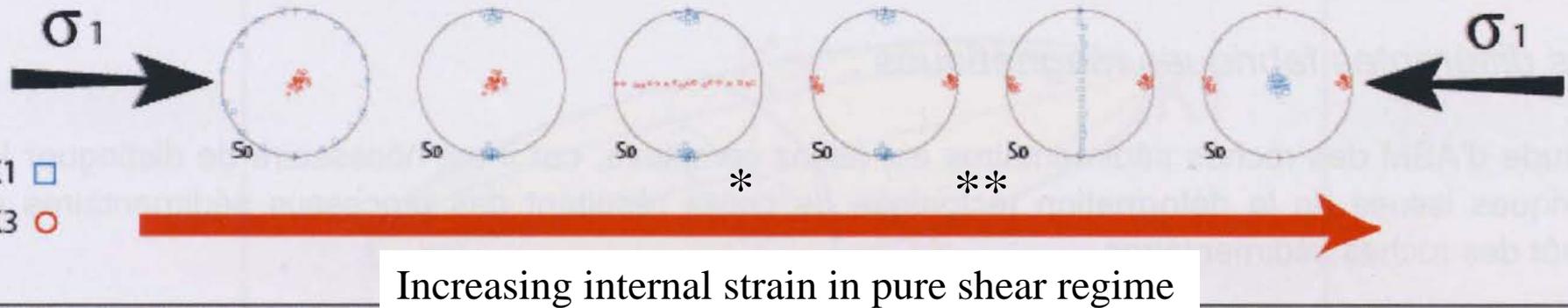
Generally, K_m ranges between low negative values and low positive values (from -10×10^{-6} SI to 10×10^{-6} SI). In Fe-bearing silicate rocks K_m covered susceptibilities up to $500-1000 \times 10^{-6}$ SI whereas ferromagnetically dominated rocks are generally characterized by values higher than 1000×10^{-6} SI.

AMS



The interpretation of AMS fabrics is strongly dependent on the carrier of the magnetic signal and so requires additional careful microstructural and petrographic characterization.

AMS



* Intermediate fabric : magnetic lineation $K1$ still contained within the bedding but clustered at right angle to the shortening direction; $K3$ leaves the pole to bedding and exhibits a girdle distribution around $K1$.

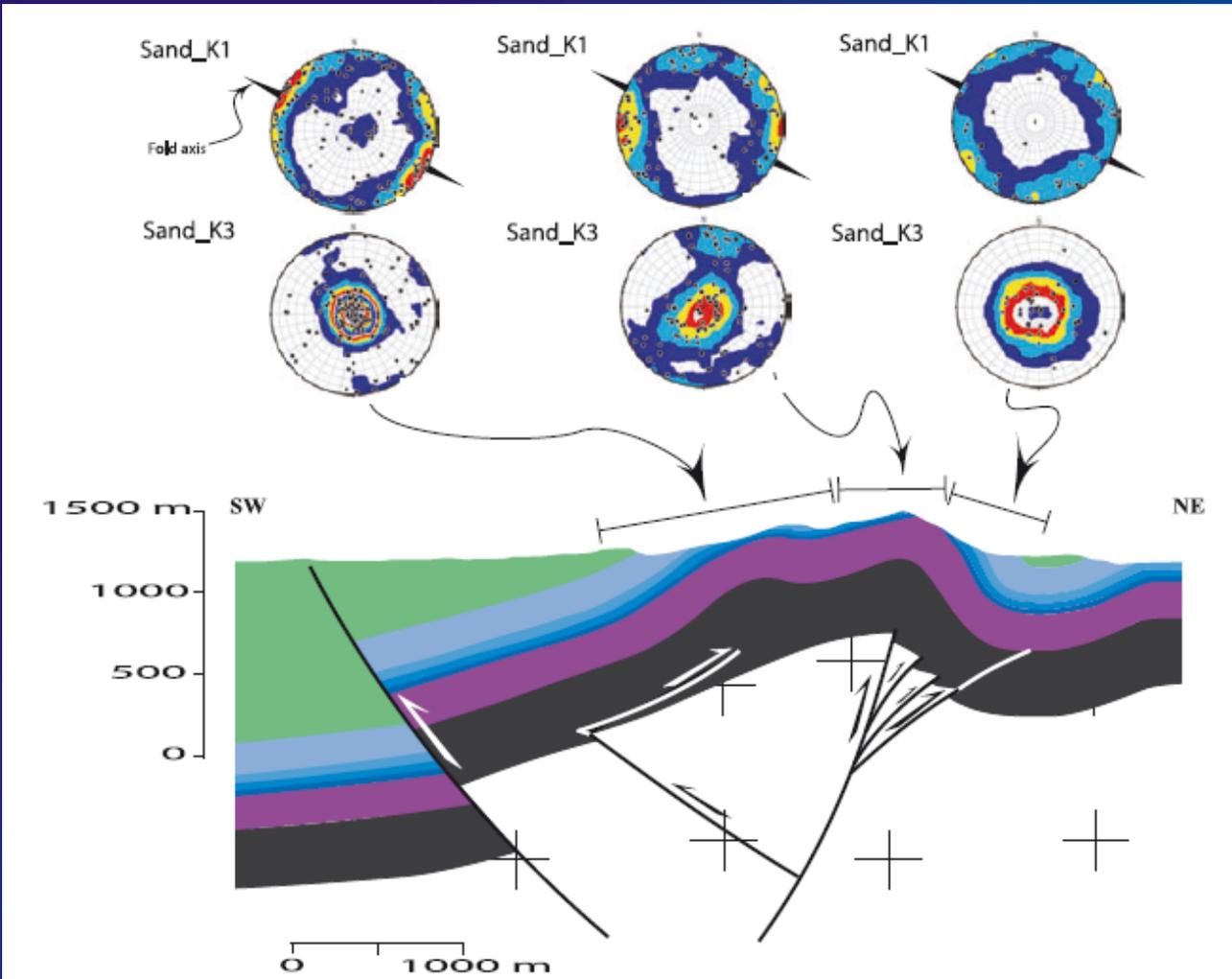
** Tectonic fabric with $K3$ parallel to the shortening direction. $K1$ is either parallel to the intersection between the bedding and the incipient cleavage or exhibits a girdle distribution around $K3$

(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)

Sheep Mountain anticline



Forelimb : planar oblate fabrics with K1 scattered in the plane of bedding, K3 normal to it.
→ Sedimentary fabric.

Backlimb : similar fabric but with clustering of K1 close to the direction of fold axis in the plane of bedding. Fabric mixing both shortening direction and pole of bedding
→ Slight tectonic fabric (early-folding 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., GJI, 2010)

AMS (carbonates)

Sheep Mountain anticline

Forelimb : K1 scattered in the plane of bedding with a weak maximum close to the fold axis trend.

K3 clustered either along the pole of bedding or perpendicular to K1.

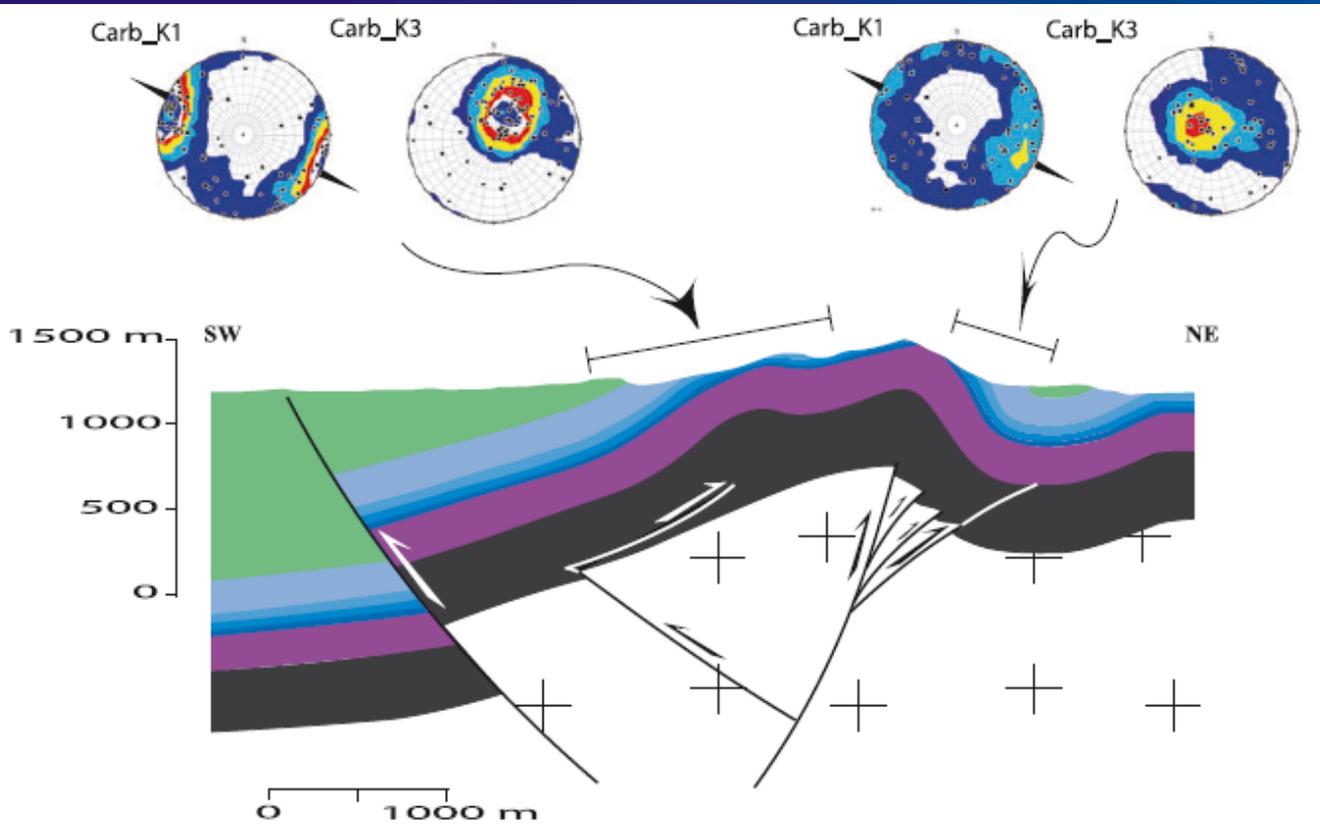
→ combination of relict sedimentary fabrics with intermediate and tectonic fabrics locally.

Backlimb : well defined cluster of K3, which significantly deviates from the pole of bedding, and very well clustered K1 axes $\sim N120^\circ$, close to the fold axis (\sim sandstones).

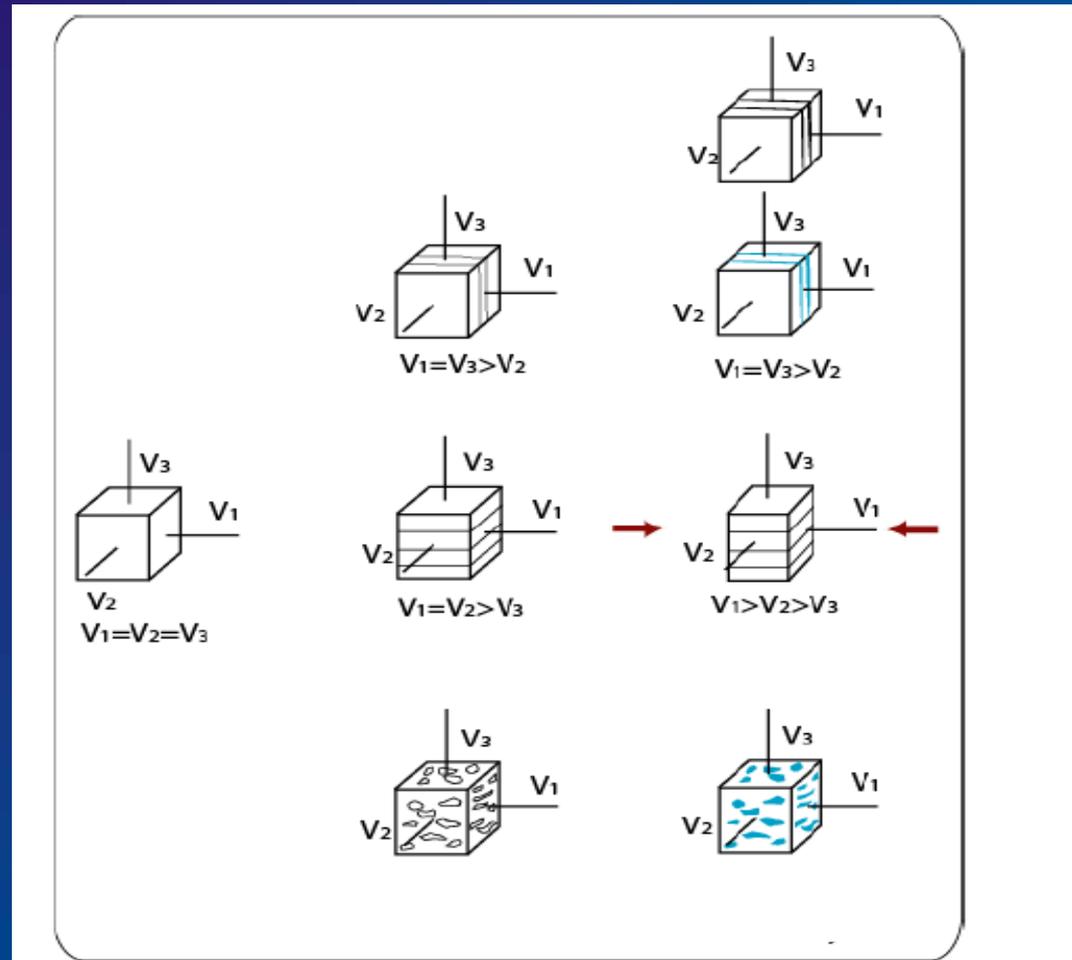
→ fabric associated to the regional shortening direction.

Obliquity of the magnetic foliation with respect to bedding plane

→ bed-parallel shearing instead of standard LPS

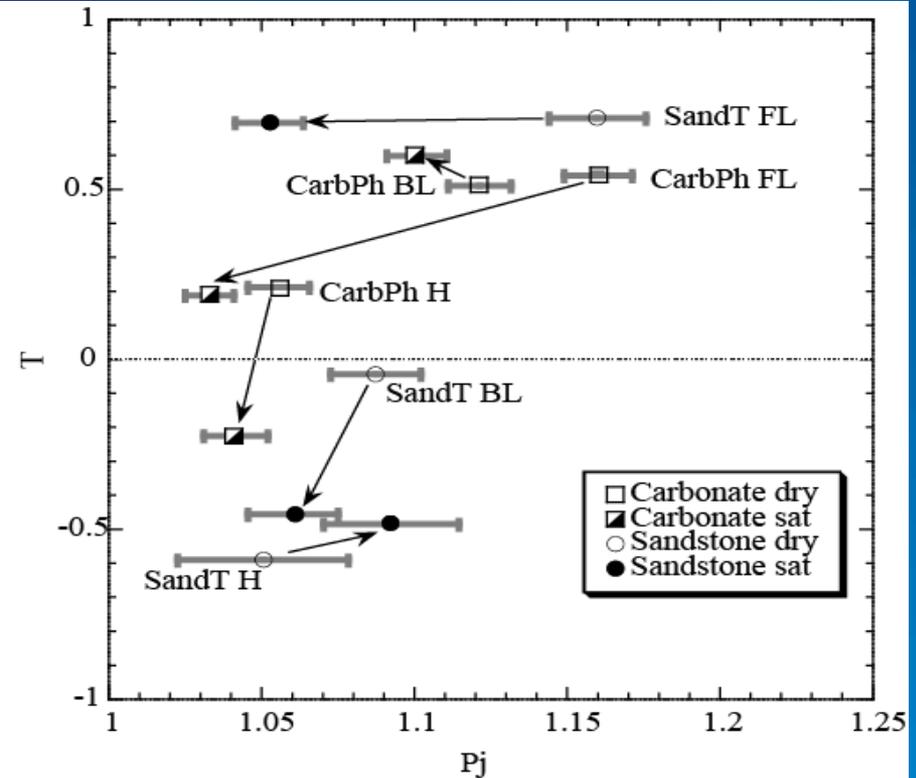
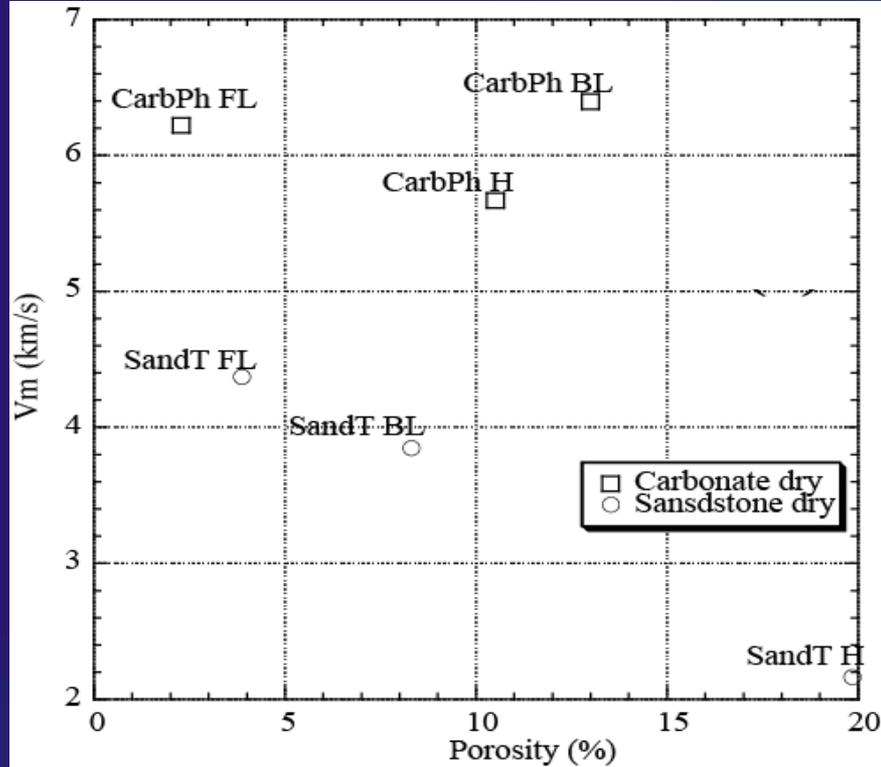


APWV



At laboratory conditions (no confining pressure), APWV 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/or the contacts between grains.



T is the shape parameter, P_j the Jelinek anisotropy parameter (Jelinek 1981).

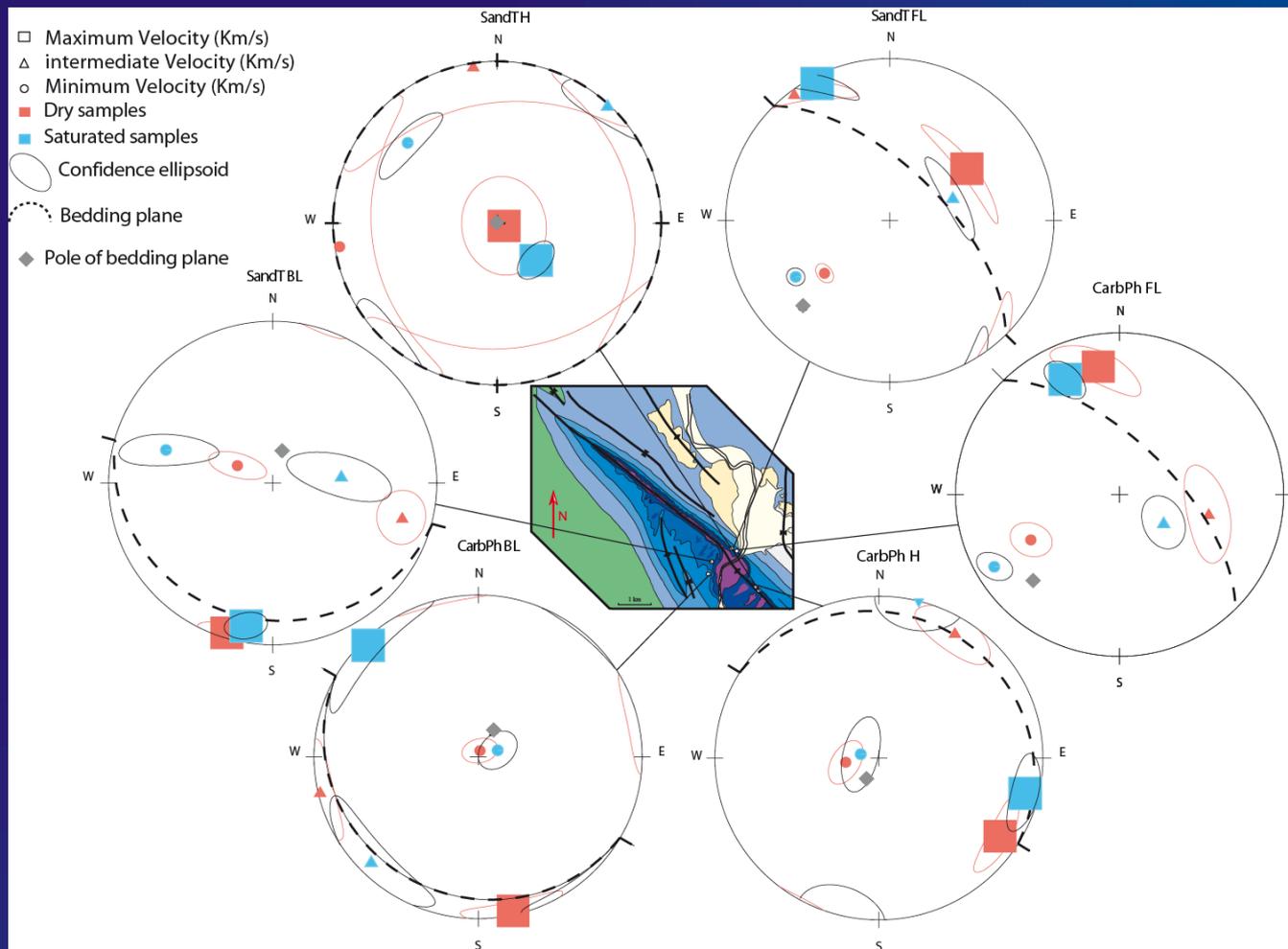
Velocity measurements performed on dry and saturated samples. Velocities range between the velocities of the mineral grains (higher in calcite than in quartz) and those of the mineral-pore fluid filled (air or water) assemblage.

A rock made of an anisotropic matrix and an isotropic pore space is characterized by velocity and anisotropy increase when it is saturated with incompressible material (water) \rightarrow degree of anisotropy of the matrix

Sheep Mountain anticline

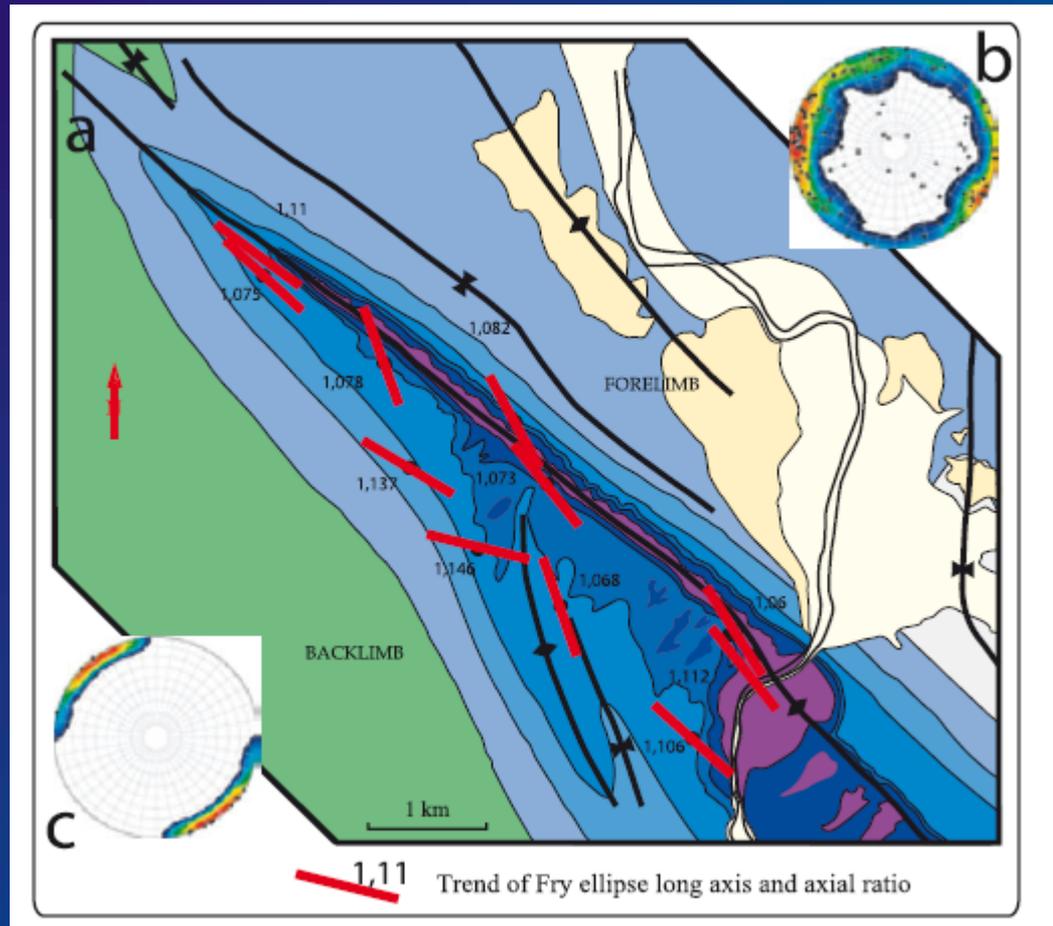
APWV

(Amrouch et al.,
GJI, 2010)

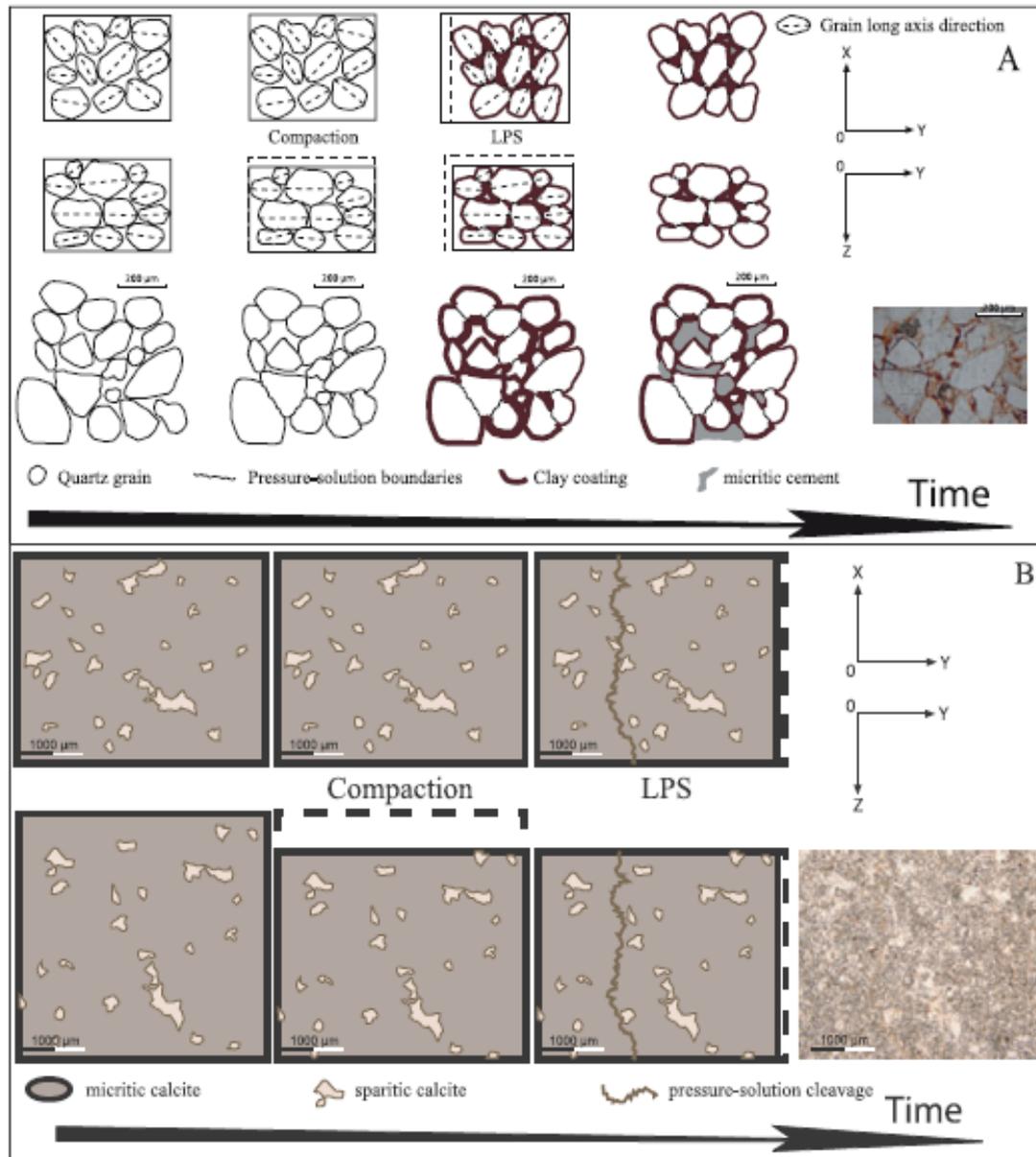


Forelimb : Deformation preferentially revealed by porosity, oriented with its long axis parallel to the fold axis. Anisotropy dominated by anisotropic pore network within an almost isotropic matrix.

Backlimb : Grain-supported APWV fabrics → 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 be linked to early-folding LPS.



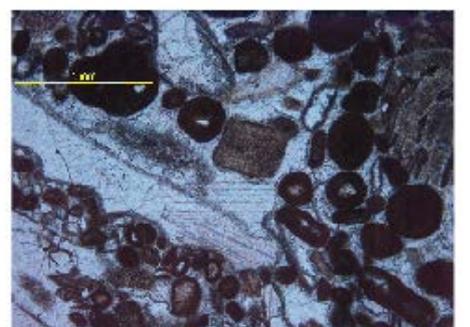
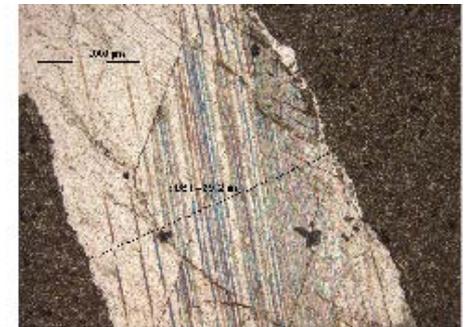
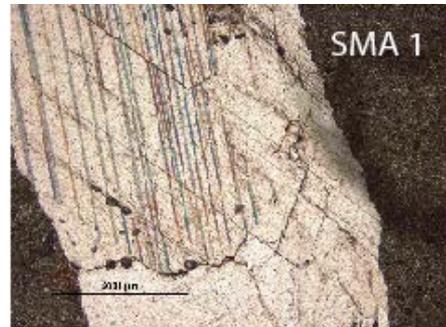
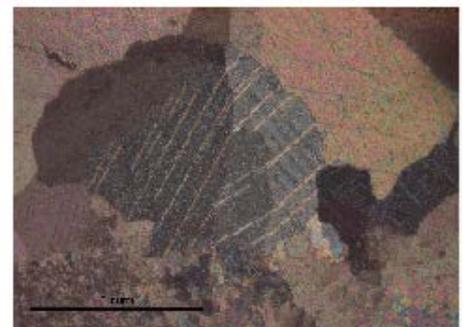
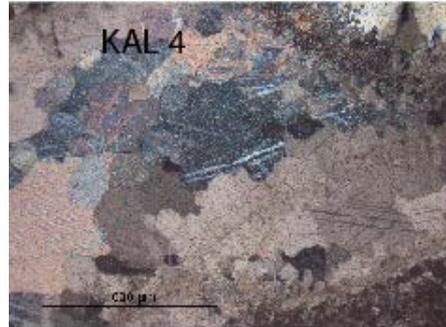
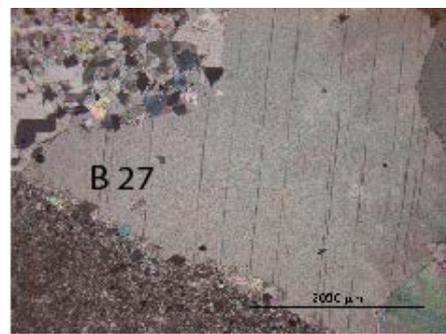
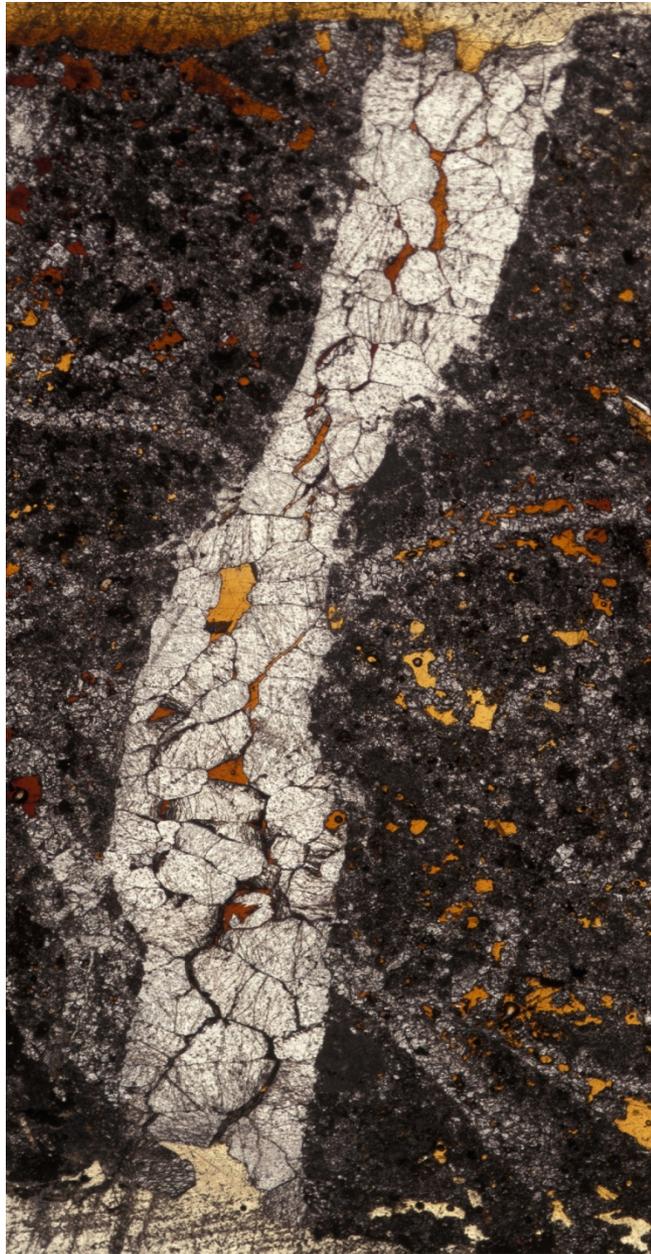
Strain axes in sandstones deduced from Fry method



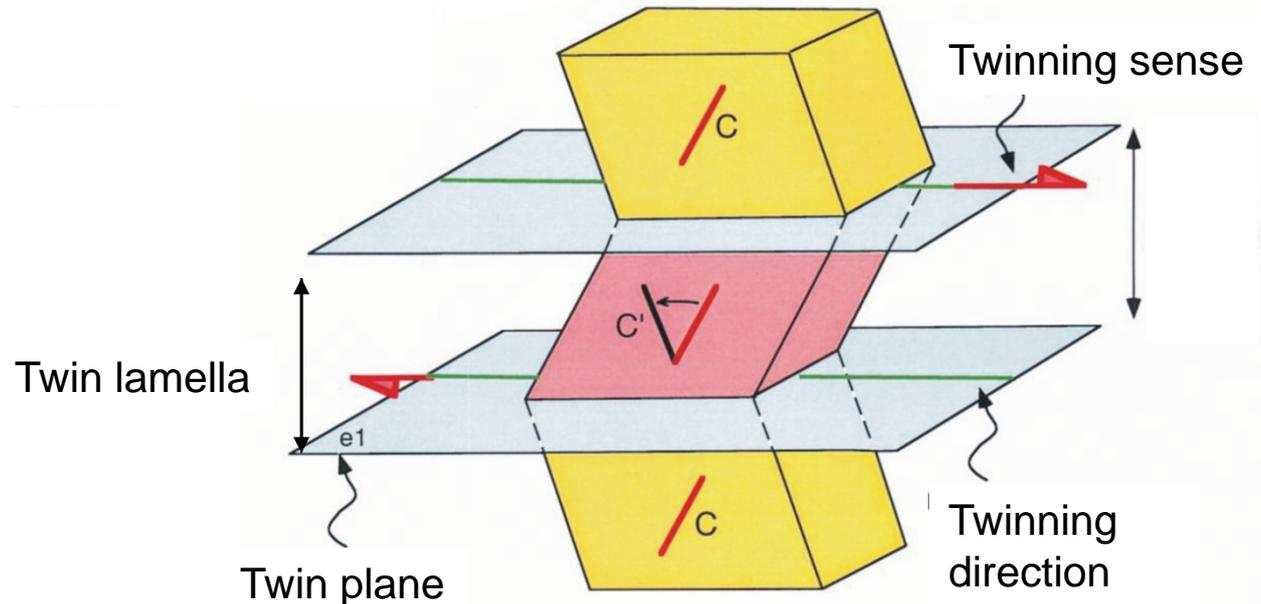
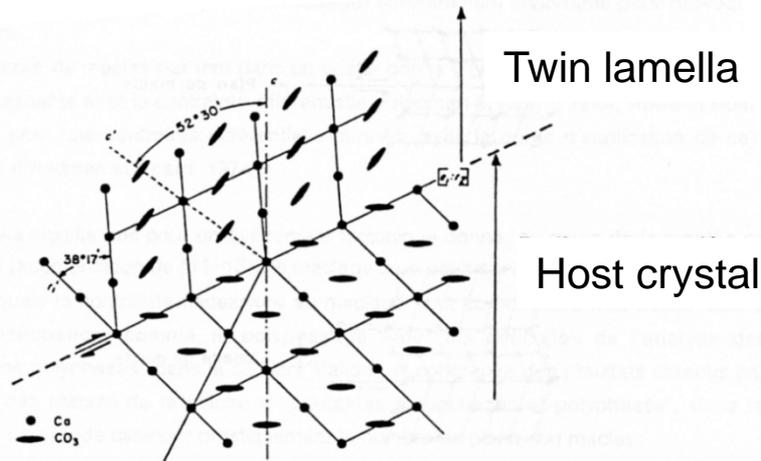
Sketches of different stages of formation/deformation of a sedimentary rock until a final state illustrated by the microphotographs of polished thin sections observed in natural light. (a) Sandstones (Amsden); (b) Carbonates (Phosphoria). XY plane is the bedding plane (X : Strike; Y : dip), YZ is the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

(Amrouch et al., GJI, 2010)

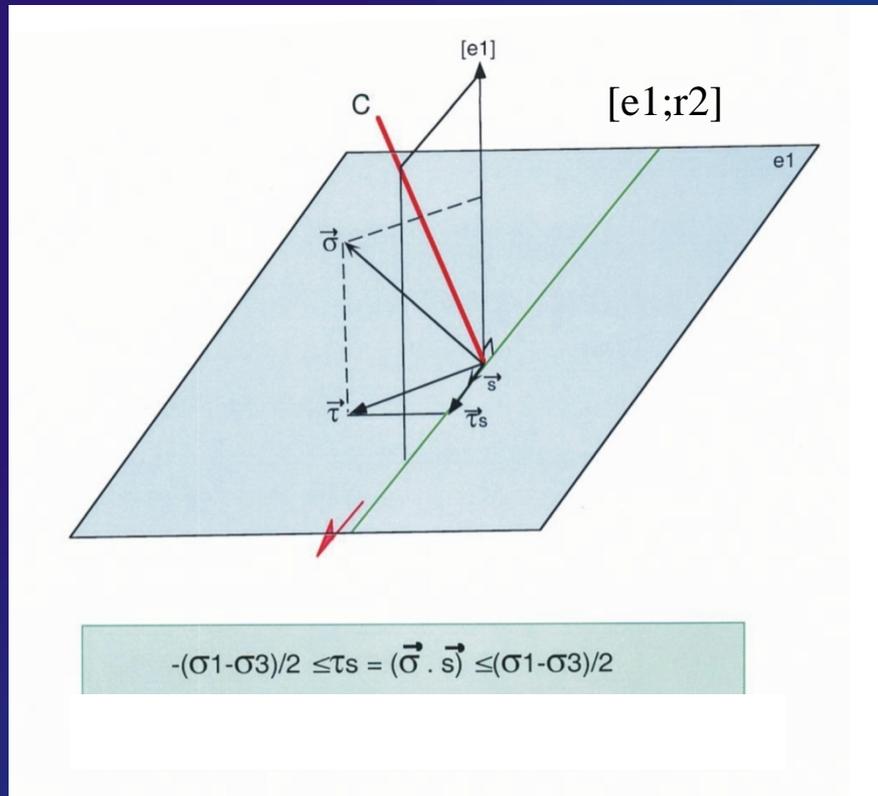
**Paleo-stress/strain orientations
and magnitudes of differential stresses revealed by
calcite twin analysis
at Sheep Mountain and Rattlesnake Mountain
anticlines**



Twinning ~ simple shearing in a particular sense and direction along e-planes {01-12}



« Etchecopar » (1984) technique : determination of the reduced stress tensor



The inversion process is very similar to that used for fault slip data :

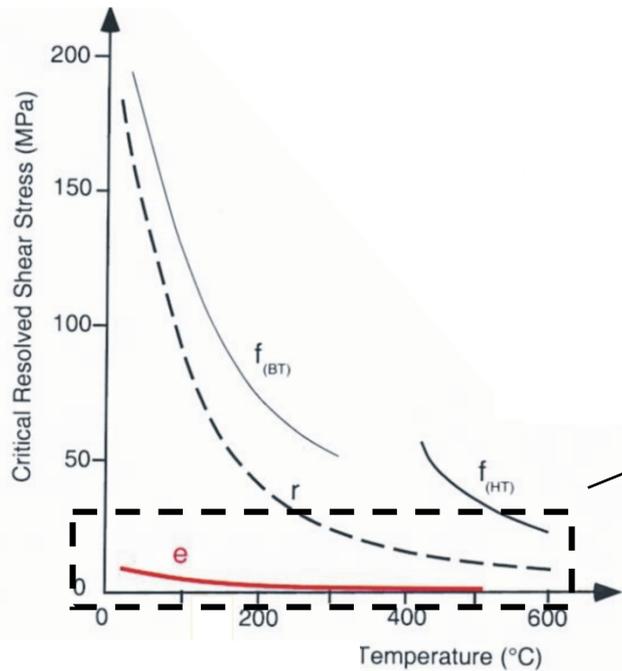
twin gliding along the twinning direction within the twin plane is geometrically comparable to slip along a slickenside lination within a fault plane.

But the inversion process takes into account both twinned planes (resolved shear stress > CRSS)

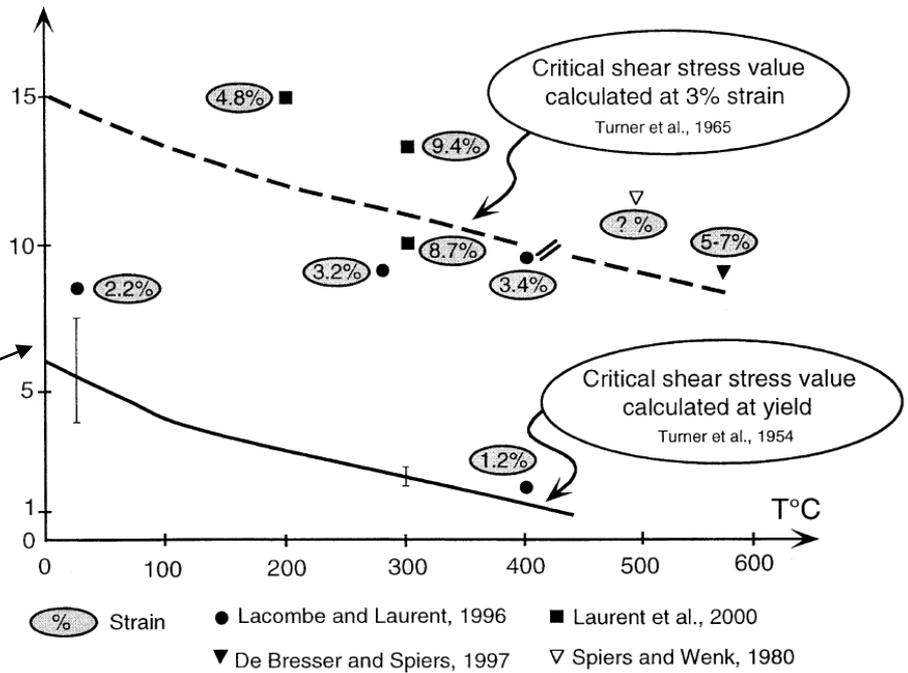
AND

untwinned planes (resolved shear stress < CRSS),

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \Phi \end{bmatrix} \quad \Phi = \frac{(\sigma_2 - \sigma_3)}{(\sigma_1 - \sigma_3)}$$



Critical shear stress value for twinning (MPa)



The Critical Resolved Shear Stress for twinning is ~ independent on T°C but depends on grain size and internal strain (hardening)

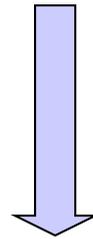
(Lacombe, 2001, 2010)

Inversion of calcite twin data

➔ **Reduced stress tensor : 4 parameters**

Orientation of principal stresses and stress ellipsoid shape ratio

$$\Phi = \frac{(\sigma_2 - \sigma_3)}{(\sigma_1 - \sigma_3)}$$



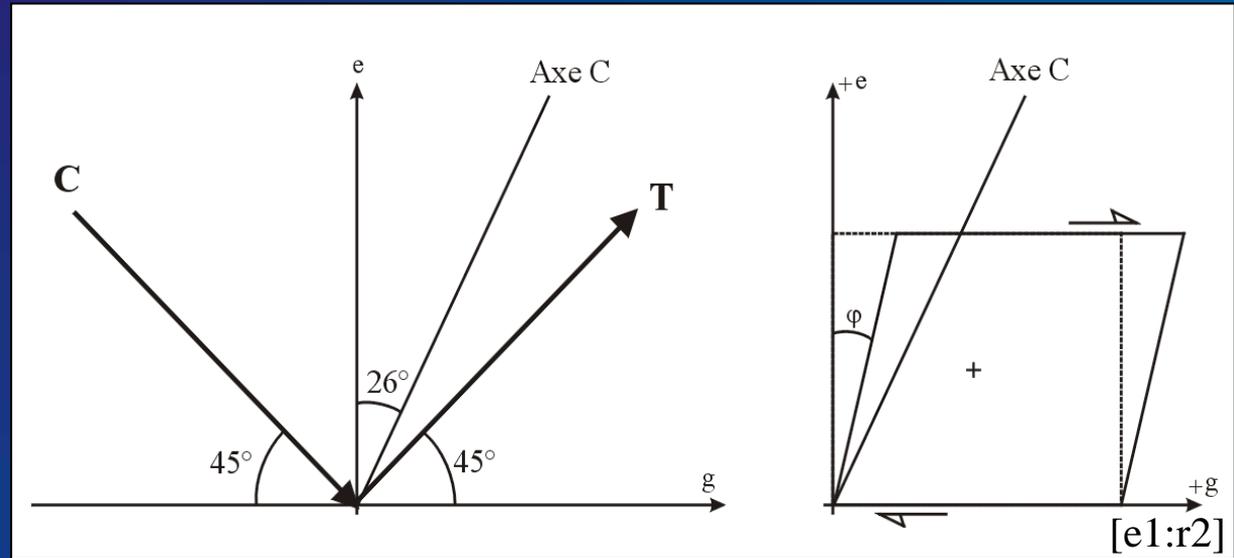
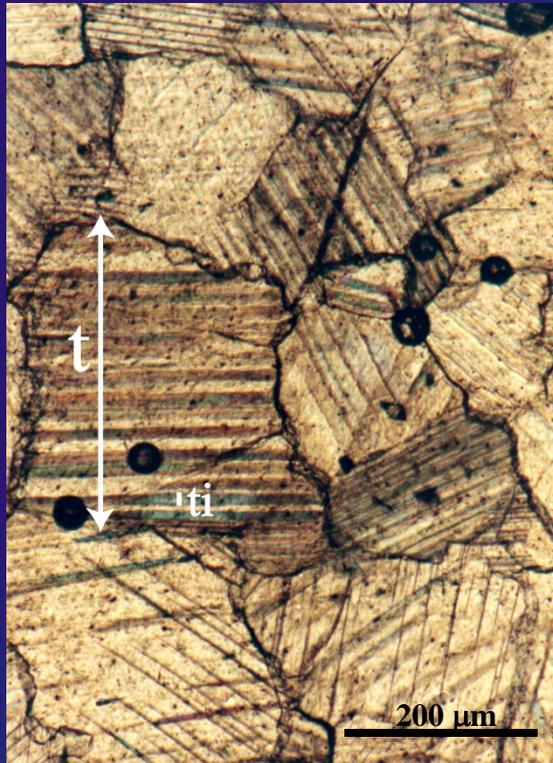
'constant' CRSS
for a set of calcite grains
of homogeneous size

**Deviatoric stress tensor
5 parameters**

Orientation of principal stresses and differential stress magnitudes

$$(\sigma_1 - \sigma_3) \quad (\sigma_2 - \sigma_3)$$

« Groshong » (1974, 1984) technique : determination of the strain tensor



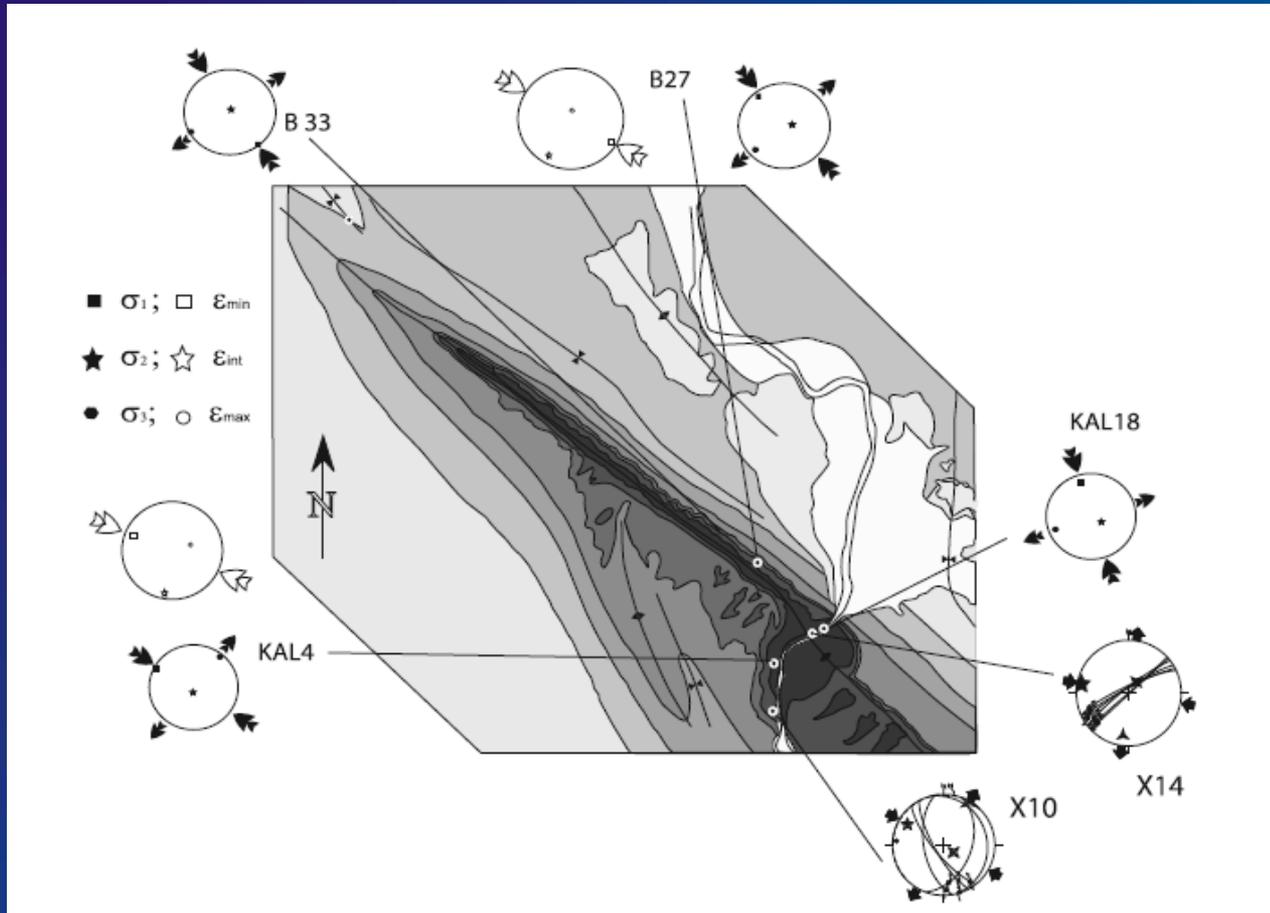
$$\Gamma_{eg} = \frac{1}{2} \cdot \tan \varphi = \frac{0.347}{t} \cdot \sum_{i=1}^n t_i$$

Deformation
by shearing
for a twin set

$$\Gamma_{eg} = (l_e l_g - n_e n_g) \epsilon_x + (m_e m_g - n_e n_g) \epsilon_y + (l_e m_g + m_e l_g) \Gamma_{xy} + (m_e n_g + n_e m_g) \Gamma_{yz} + (n_e l_g + l_e n_g) \Gamma_{zx},$$

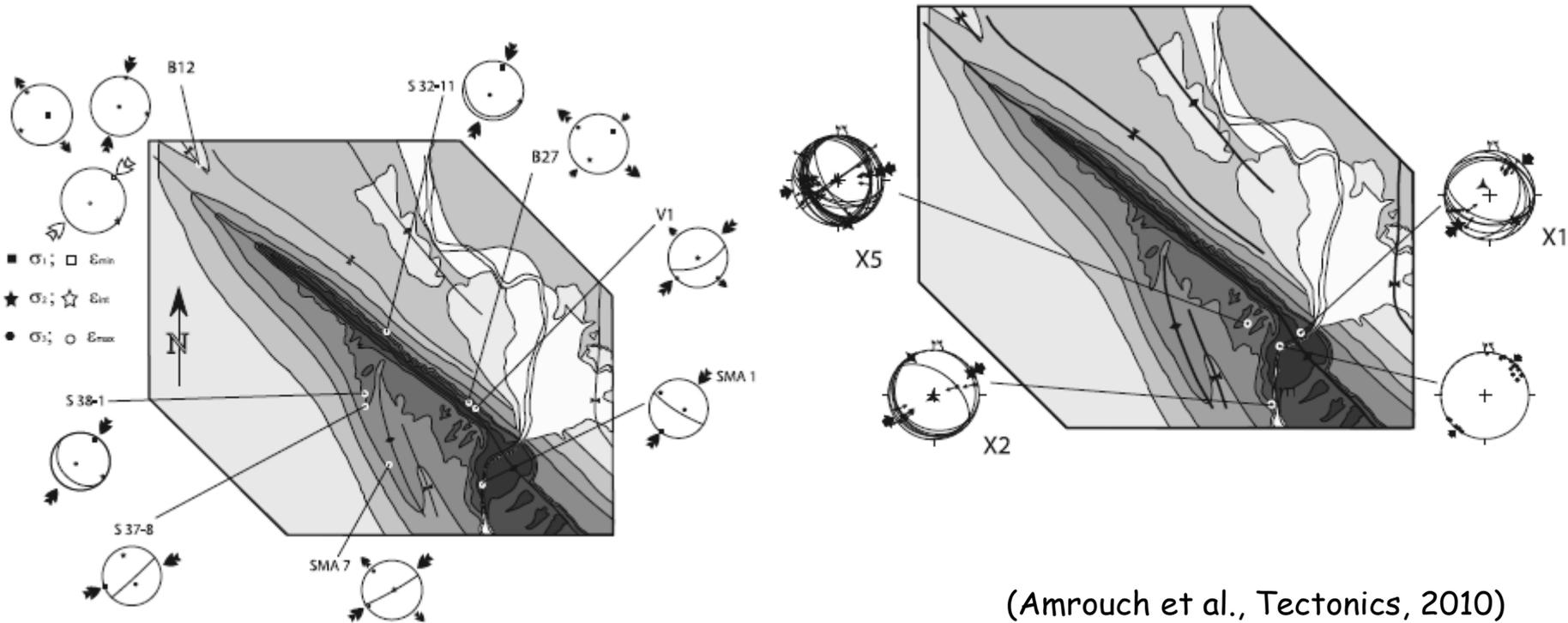
with ϵ_x , ϵ_y , Γ_{yz} , Γ_{xy} and Γ_{zx} being the components of the strain tensor in (x,y,z) and l_e , m_e , n_e and l_g , m_g , n_g the direction cosines of e and g in (x,y,z) . $\epsilon_z = -(\epsilon_x + \epsilon_y)$ assuming $\Delta V = 0$

Pre-folding stage:
Paleostress / strain orientations related to Sevier LPS.



The oldest fracture set (I) strikes 110° to 130° and is interpreted as a regional fracture set that predates the Laramide orogeny (Sevier?). This set formed in a strike-slip stress regime under a NW-SE horizontal compression

Early-folding stage:
Paleostress /strain orientations related to Laramide LPS.

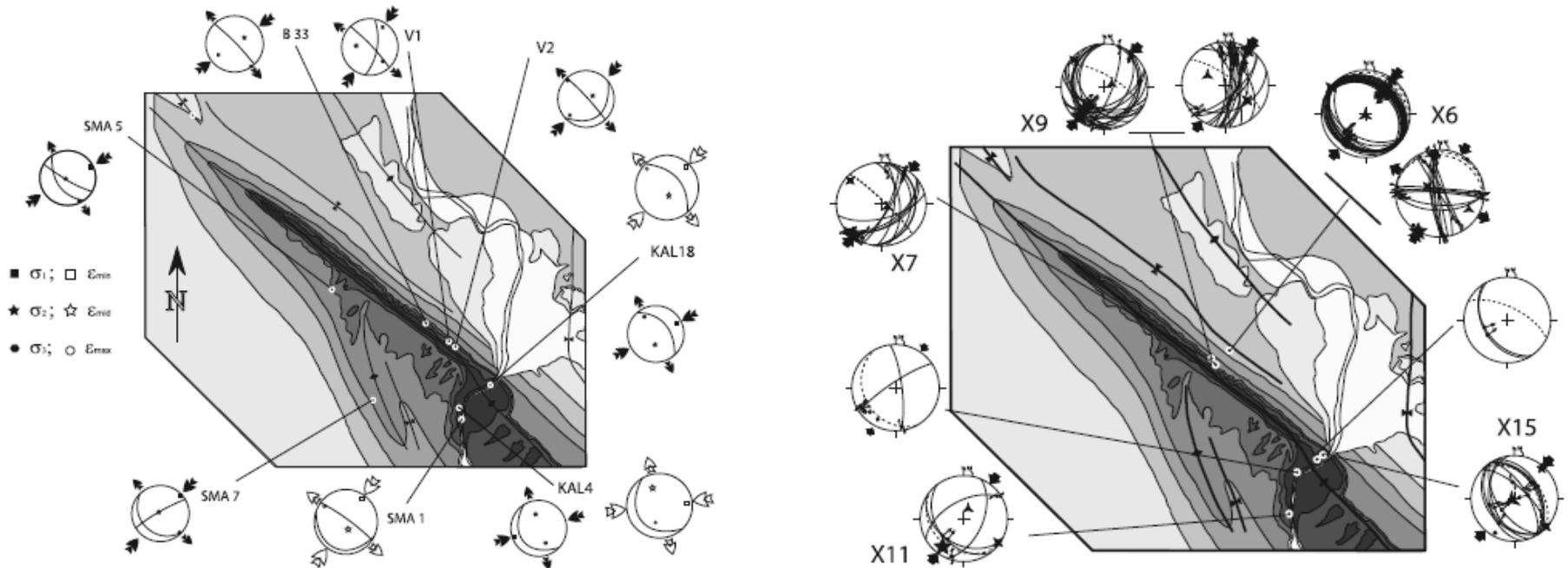


(Amrouch et al., Tectonics, 2010)

Set II joints striking $\sim 045^\circ$ and associated stylolites are related to the 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 (LSFT).

(Amrouch et al., Tectonics, 2010)



Faults and calcite twins reveal a late fold tightening stage, associated with a strike-slip stress regime and a compression axis also oriented NE.

Paleostress orientations and regimes in space and time in the Bighorn Basin

Fracture set	Mean strike of fractures	Paleostress from fractures	Paleostress from striated microfaults	Paleostress from calcite twins	Related Tectonic events
Set S-I	090°E to 060°E				Sevier layer-parallel shortening
Set S-II	180°E to 020°E				Formation of the flexural foreland basin
Set S-III	110°E				Sevier layer-parallel shortening
Set L-I	045°E				Laramide layer-parallel shortening
Set L-II	135°E				Local curvature-related extension
Set L-III	045°E				Late stage fold tightening
Set P-I	180°E to 160°E				Basin and Range extension

Pre-Laramide
Laramide
Post-Laramide

Summary

Mesoscopic fracture networks and anisotropy of rock physical properties reveal a similar Laramide NE-SW shortening direction.

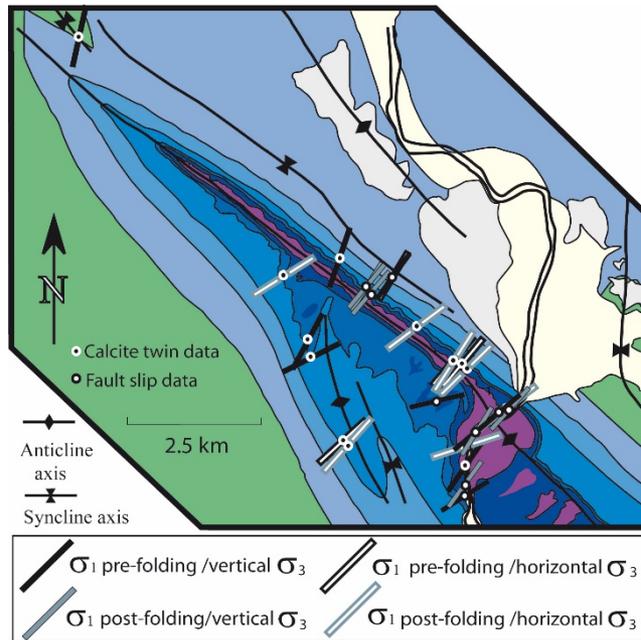
Both techniques are complementary and help unravel the tectonic rock damage at different scales, as well as the fracture-related porosity properties.

The type of deformation (fracture formation vs. matrix damage) recorded in the rock depends on the matrix rheological properties, which result from various processes such as fluid flow, degree of cementation of the matrix or diagenesis.

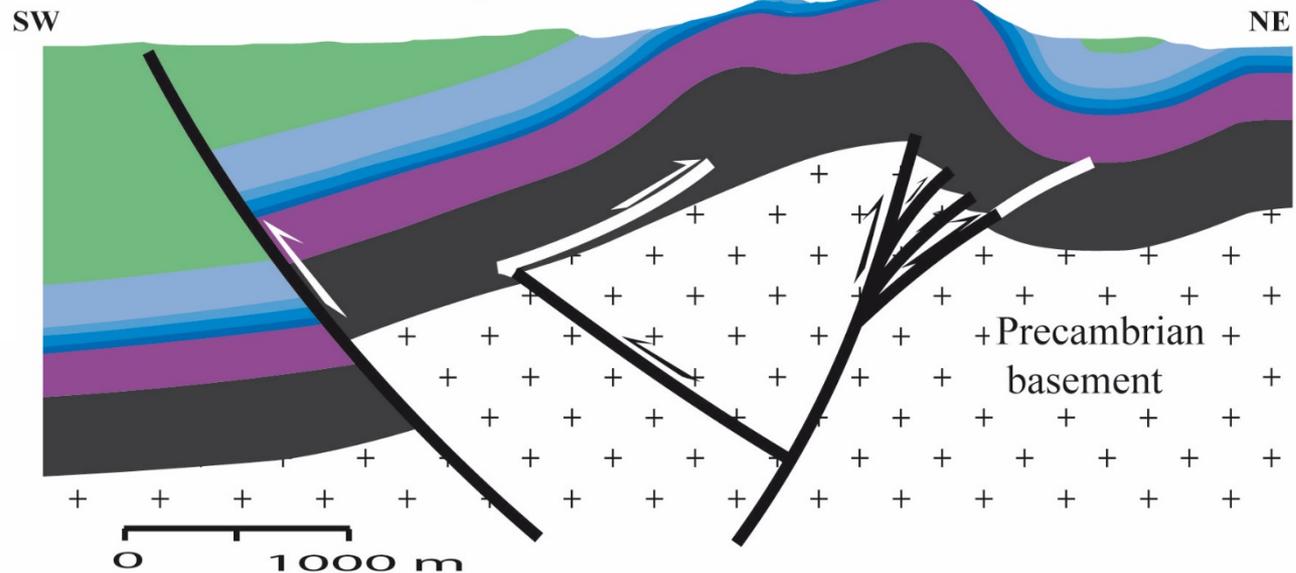
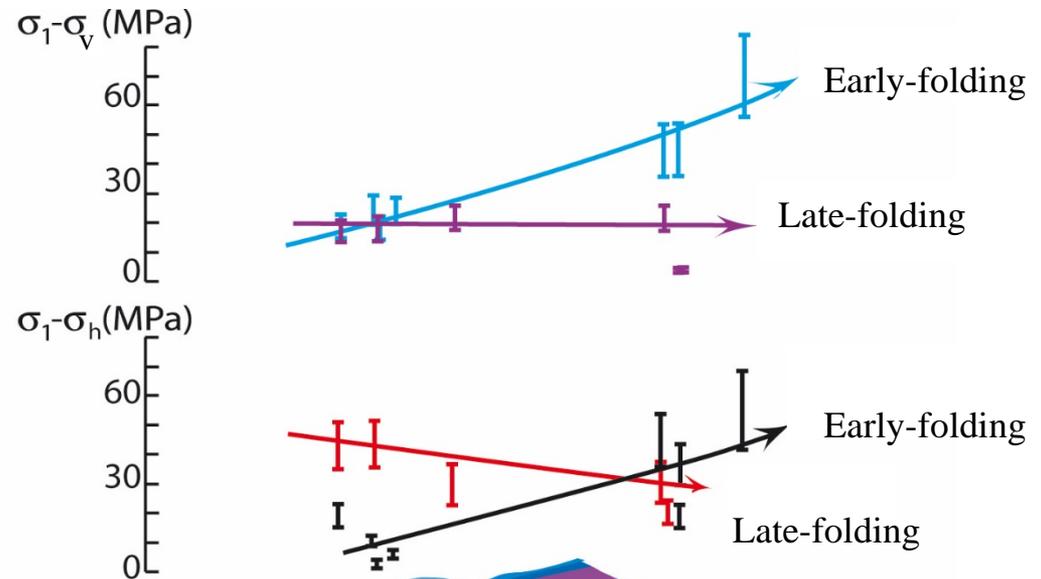
Anisotropy of rock physical properties, differential stresses and fracture distribution outline the strong contrast between forelimb and backlimb, likely related to the way the fold developed asymmetrically above the basement thrust. Structural observations made at the microscopic scale in part of a fold may therefore be relevant to the fold scale.

Micro-mechanisms appear to be more efficient before and at the onset of folding (LPS) and during late stage fold tightening, whereas macro-mechanisms (development of extensional fractures at the hinge or bedding-parallel slip) seem to prevail during folding ss. ('partitioning' through time),

Early-folding and late-folding paleo-differential stress magnitudes from calcite twinning paleopiezometry

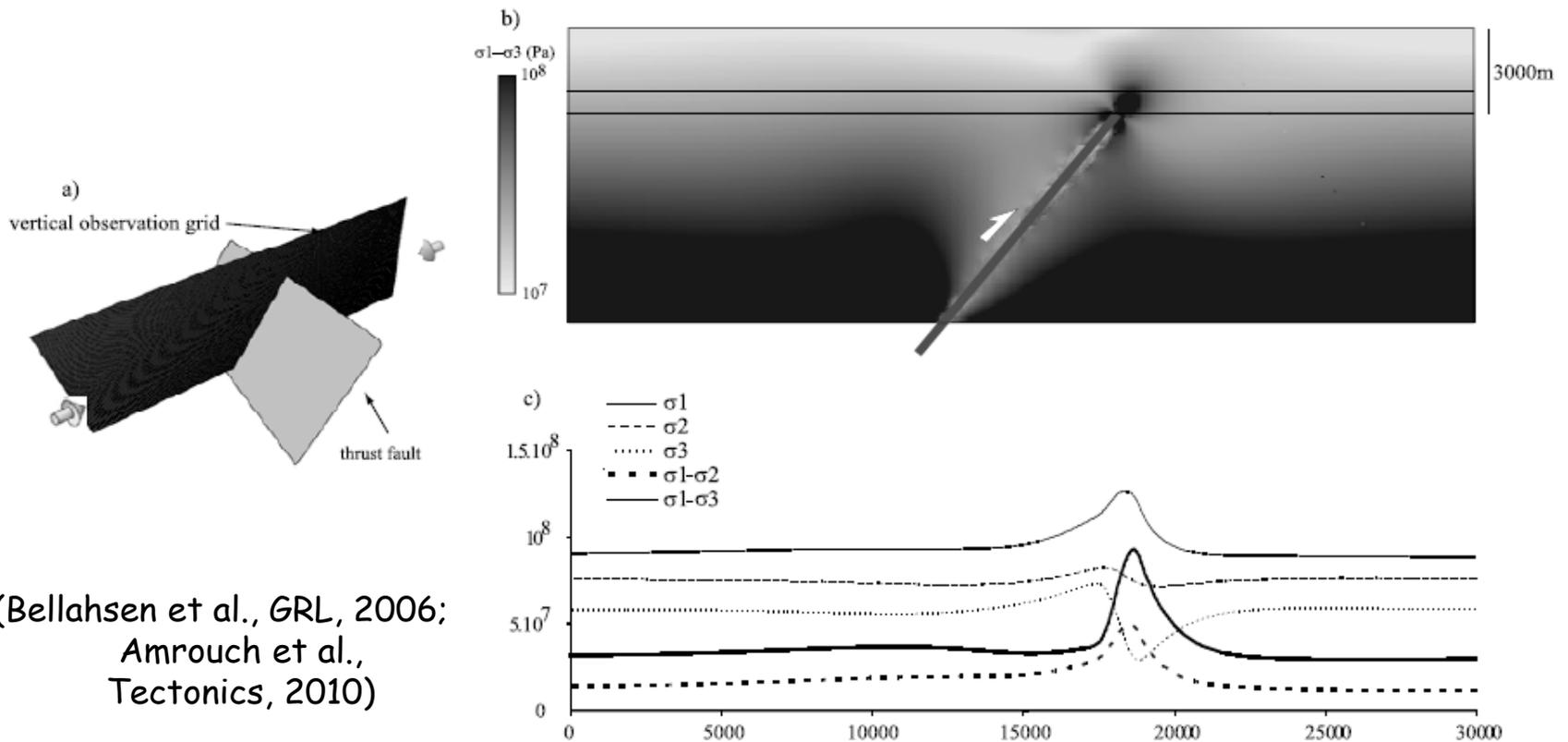
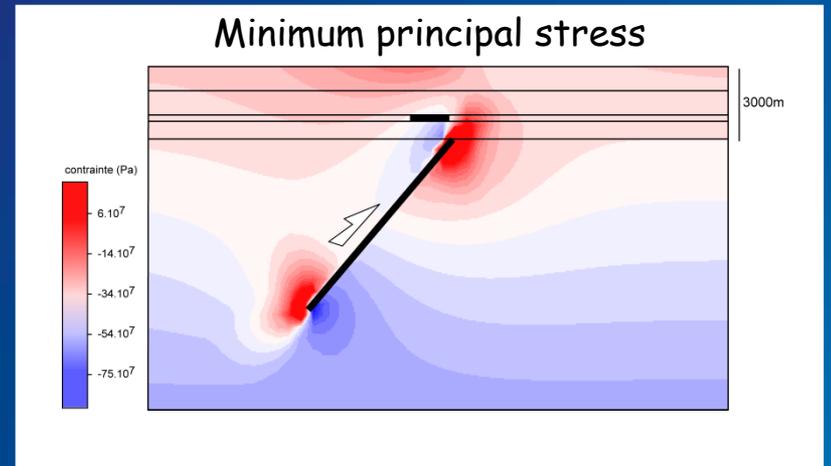


Sheep Mountain anticline



(Amrouch et al.,
Tectonics, 2010)

Stress perturbations in the sedimentary cover at the tip of the underlying basement fault starting to move during Laramide stress build-up



(Bellahsen et al., *GRL*, 2006;
Amrouch et al.,
Tectonics, 2010)

Conclusion on the mechanical behaviour of folded strata at SMA:

* Early folding stage - LPS :

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

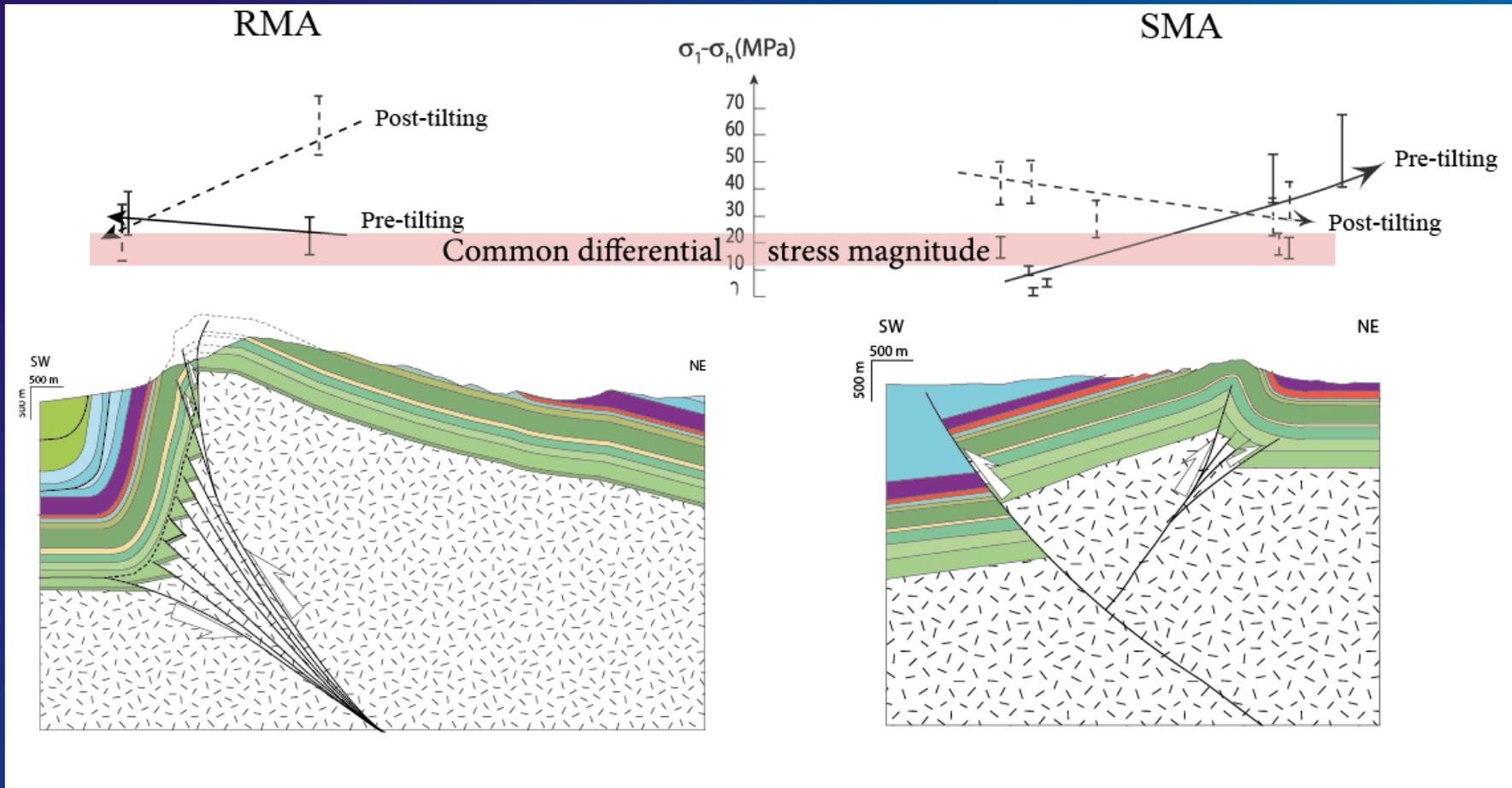
Backlimb : no stress perturbation + stress relaxation by widespread development of fractures and by internal strata deformation (AMS) → much lower differential stresses

* Syn- to 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 APWV)
→ 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 AMS fabrics

Early-folding and late-folding Laramide paleo-differential stress magnitudes from calcite twinning paleopiezometry (normalization of RMA to same depth than SMA for comparison)



Summary

Laramide differential stresses remained at a sub-constant level of about 20 ± 10 MPa, the formation of widespread LPS-related structures preventing stress increase in the sedimentary layers.

Variations from these values are related either to perturbations at the tip of underlying basement thrusts (forelimb of SMA during LPS) and/or to stress increase where strata remain weakly internally deformed. (backlimb of both folds, during LSFT).

Laramide differential stresses were not attenuated between RMA and SMA, in contrast to the eastward attenuation of Sevier stresses.

→ This likely reflects the influence of the structural style : stress magnitudes are seemingly mainly controlled by local (basement) structures during thick-skinned tectonics rather than by the distance to the orogenic front as in thin-skinned tectonics.

**Paleo-hydrology
at Sheep Mountain and Rattlesnake Mountain anticlines**

Veins : an access to fossil fluids

Calcite veins :

O, C stable isotopes

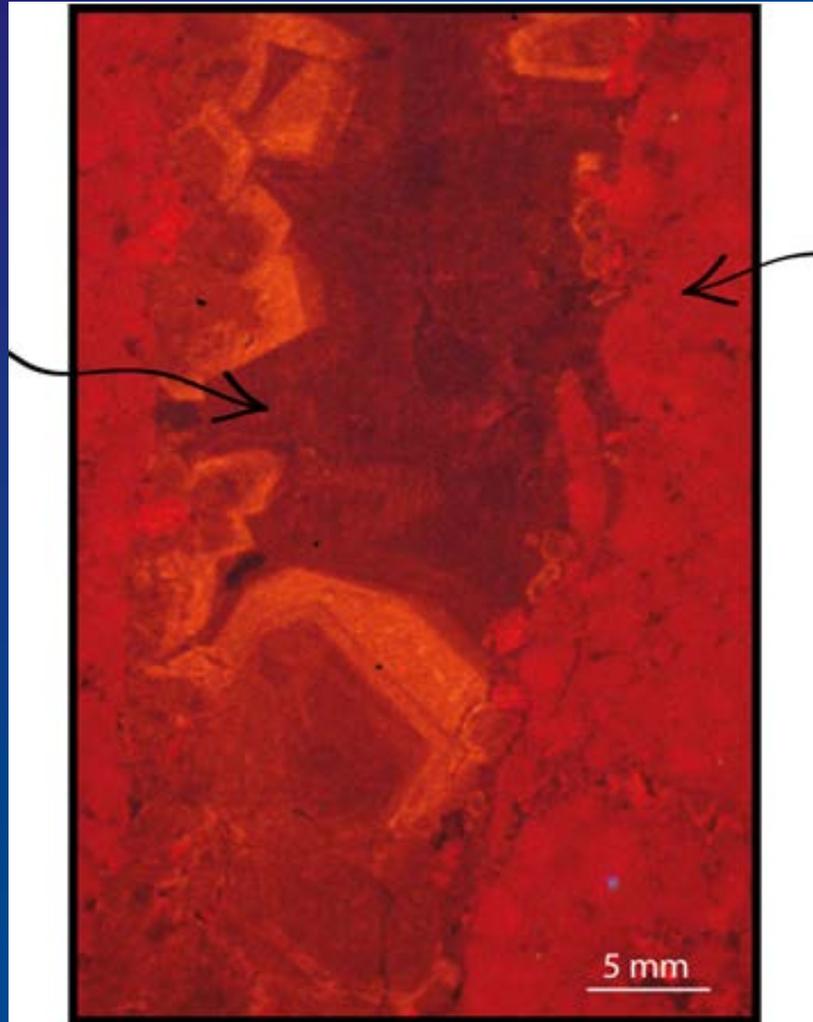
Microthermometry
of fluid inclusions

Sr ratios



Fluid temperature

Fluid origin and
pathways



Host rocks :

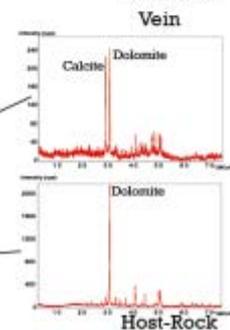
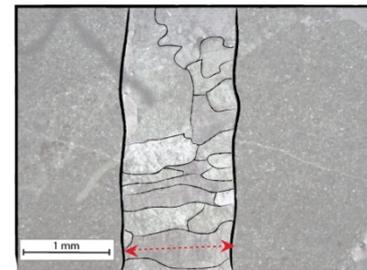
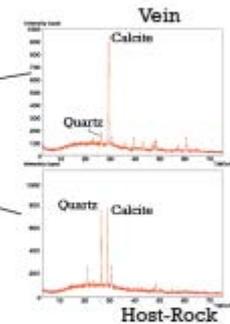
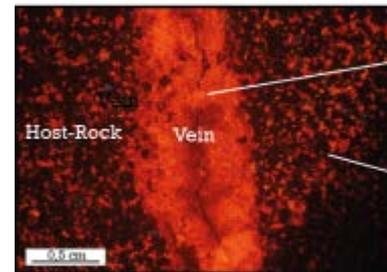
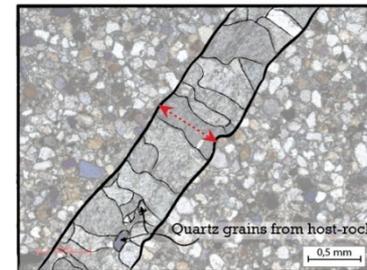
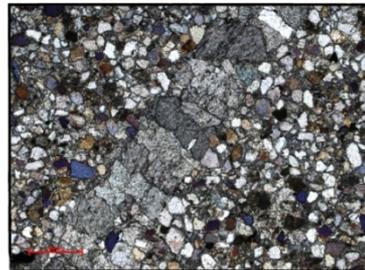
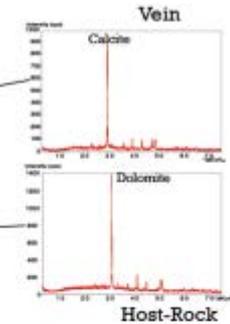
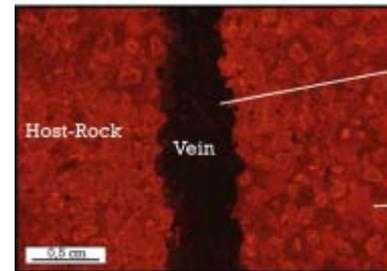
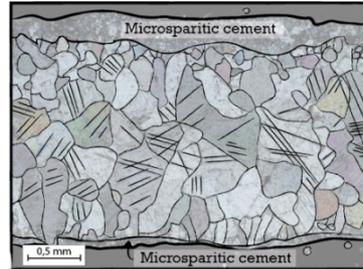
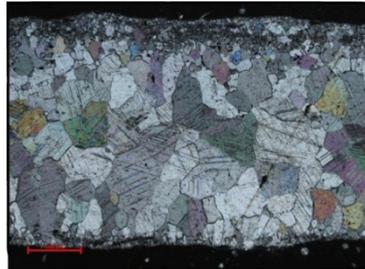
O, C stable isotopes

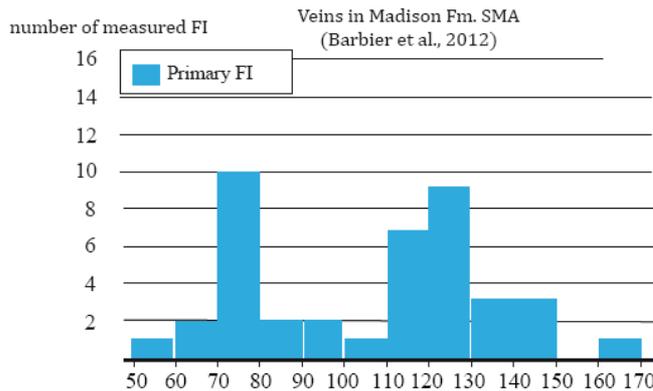
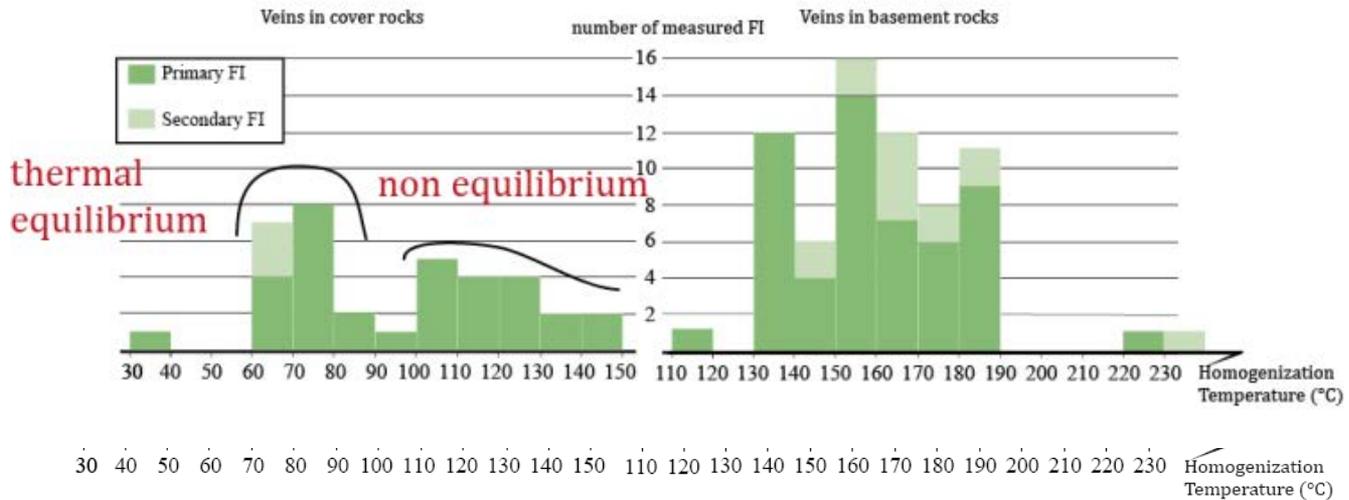
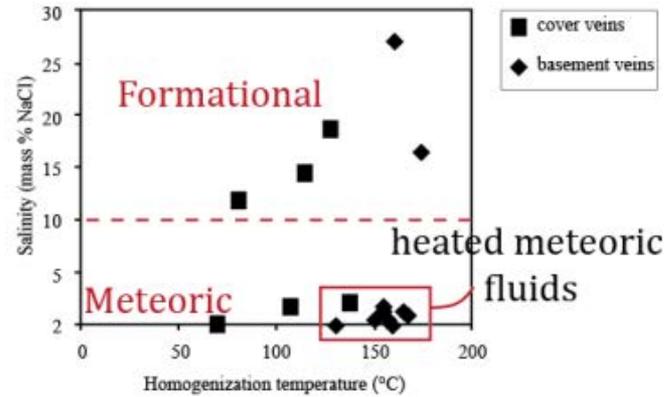
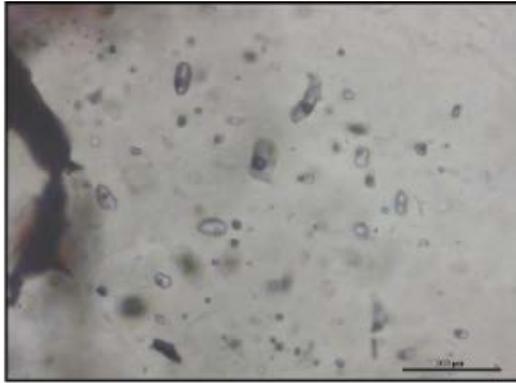
Sr ratios



Fluid-Rock
Interactions

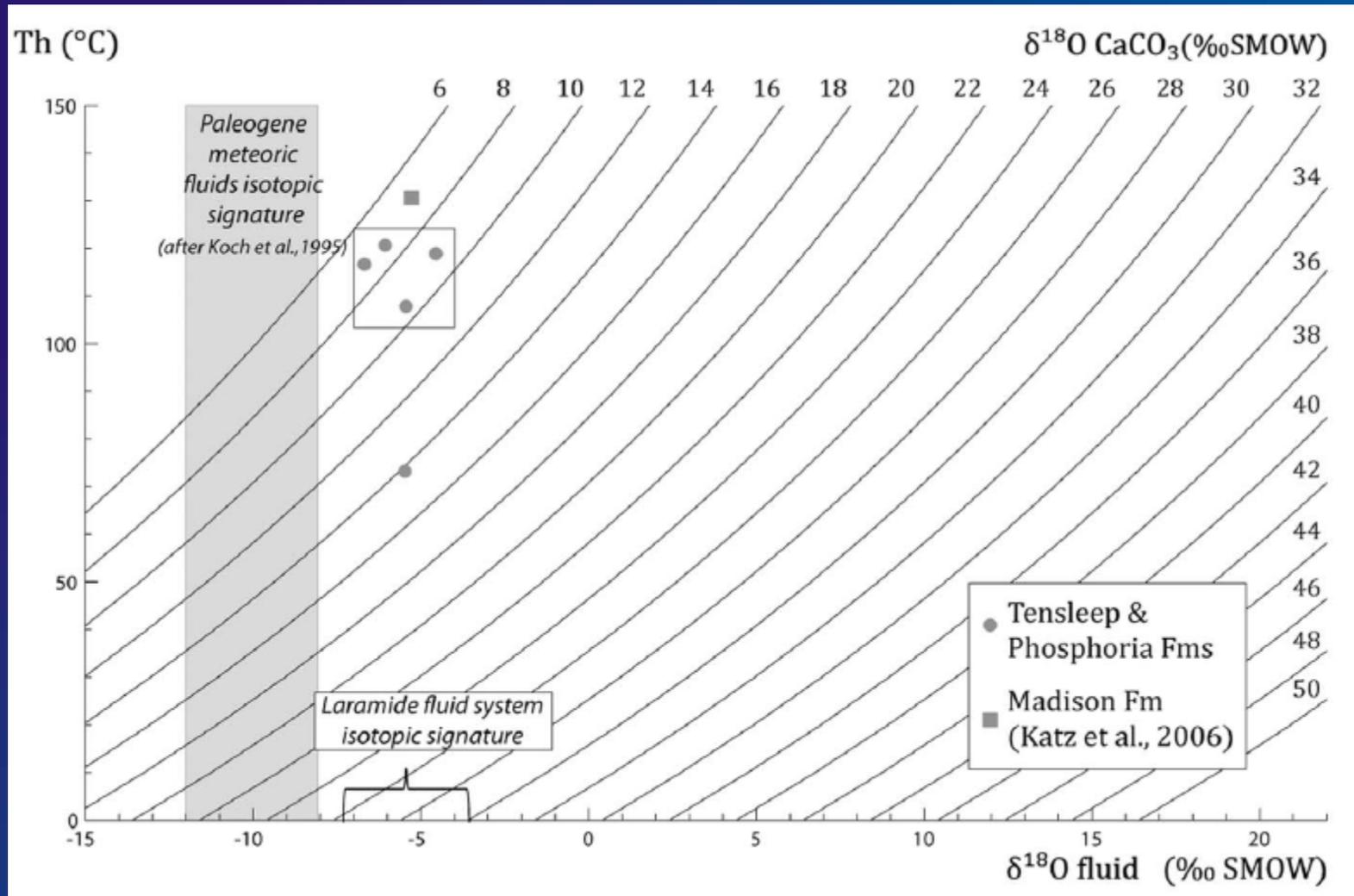
Textures and vein fillings





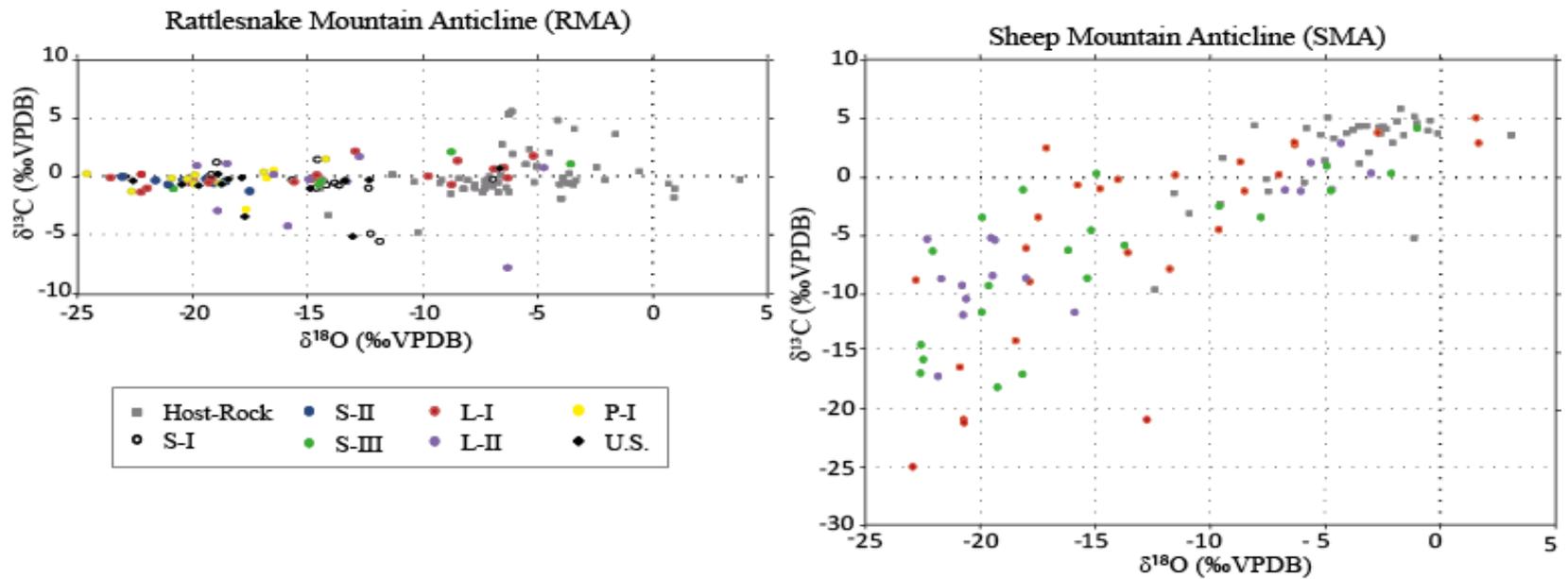
Microthermometry
and Raman
spectrometry
of fluid inclusions

Homogenization temperatures vs $\delta^{18}\text{O}$

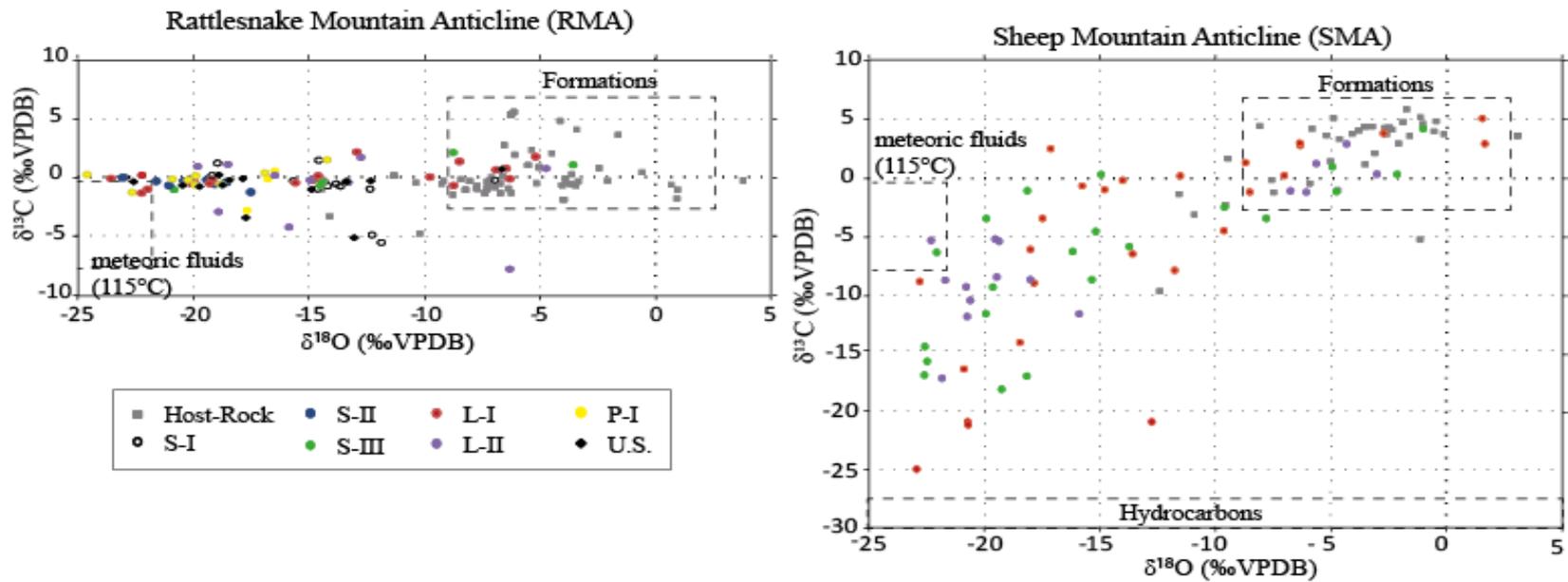


(Beaudoin et al, G3, 2011)

O, C stable isotopic signatures of fluids at SMA and RMA



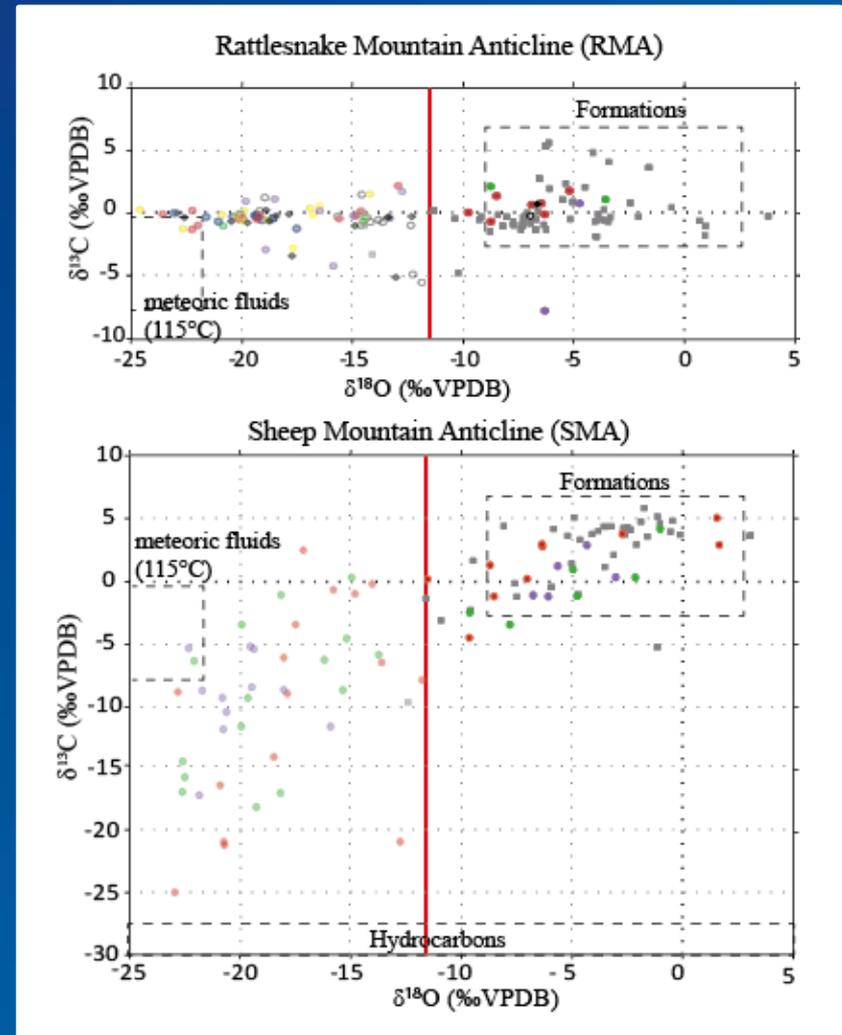
O, C stable isotopic signatures of fluids at SMA and RMA



Defining the fluid system

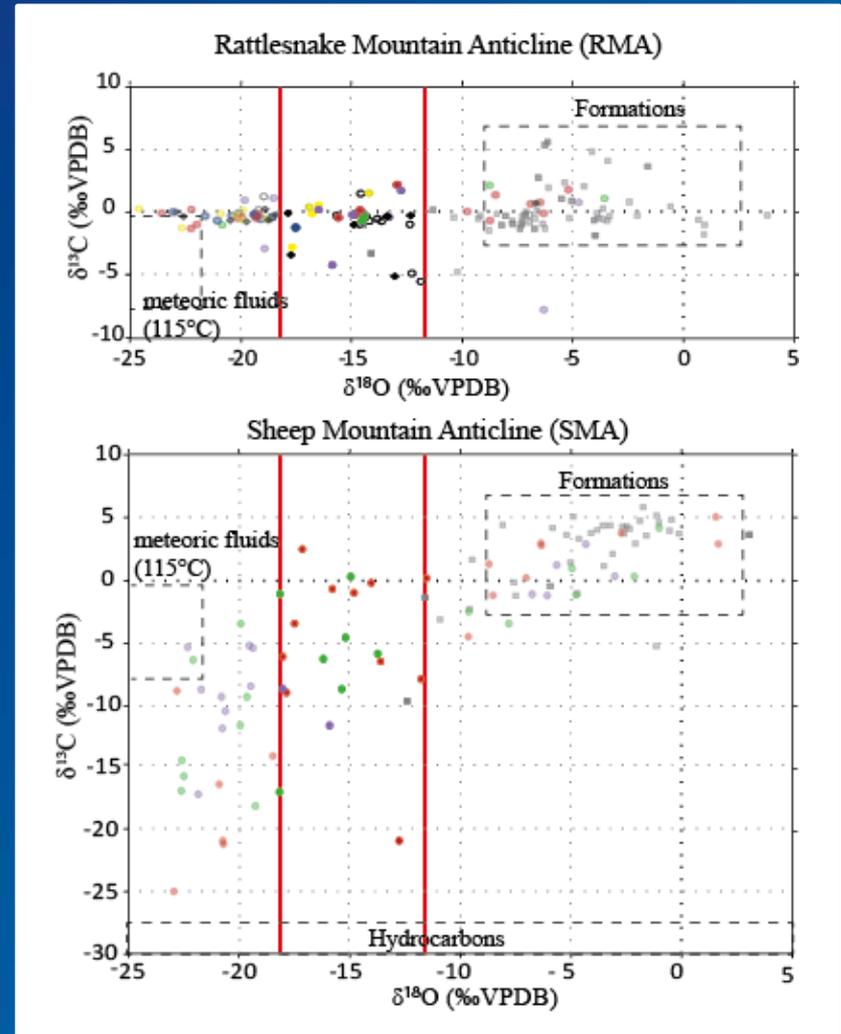
Three types of precipitating fluids:

- Total isotopic and thermal equilibrium with host-rock



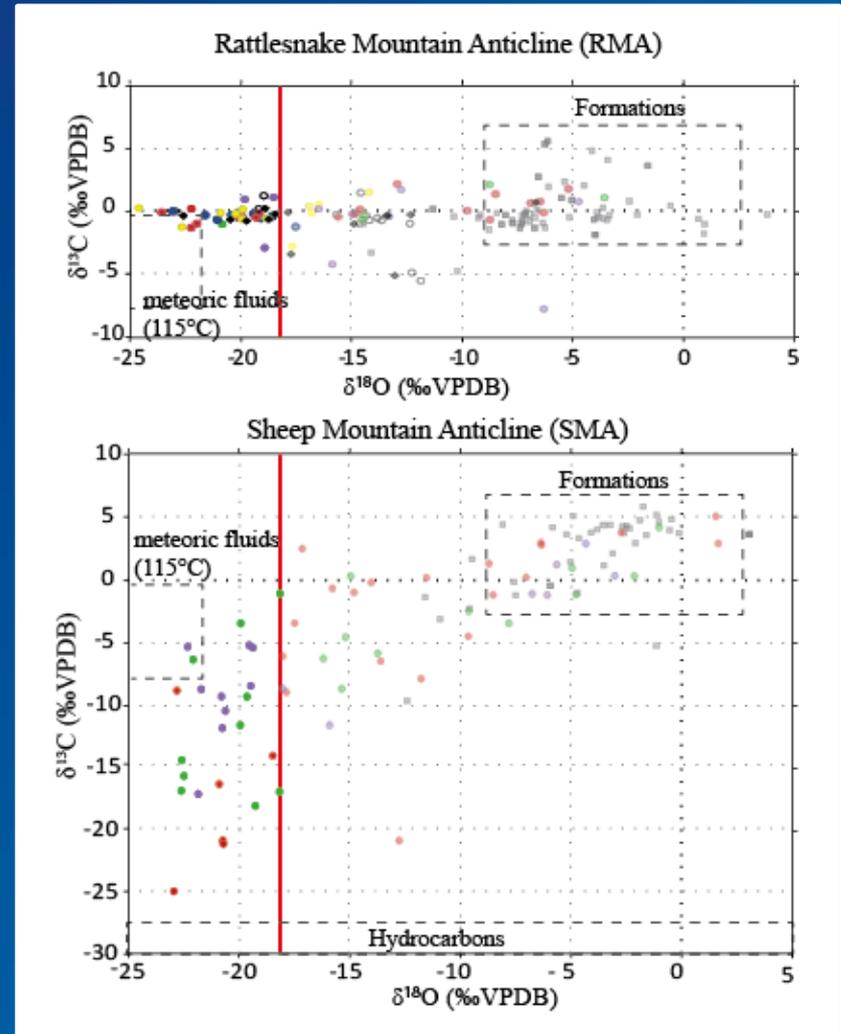
Defining the fluid system

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

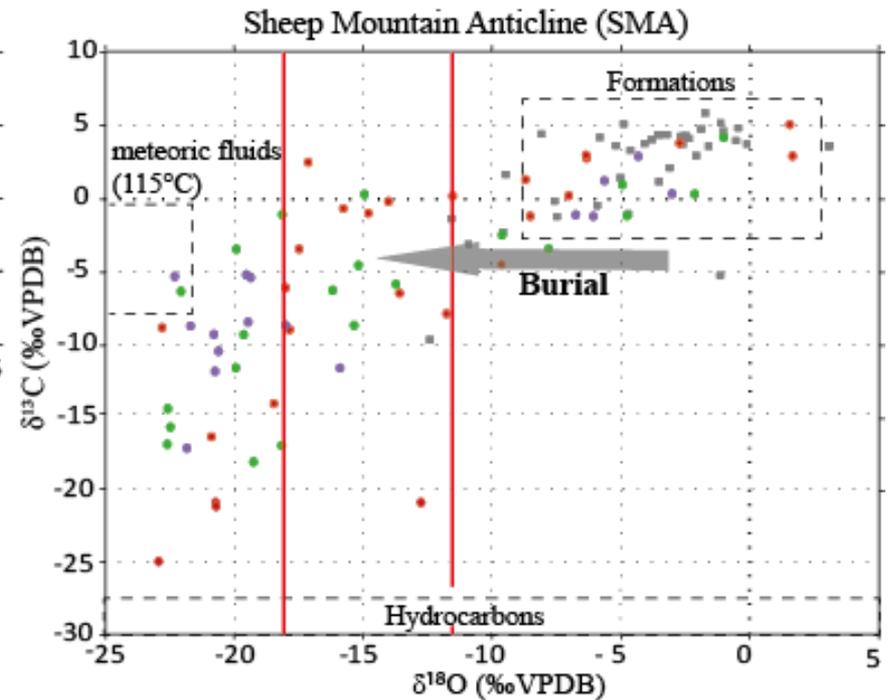
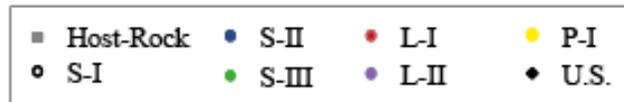
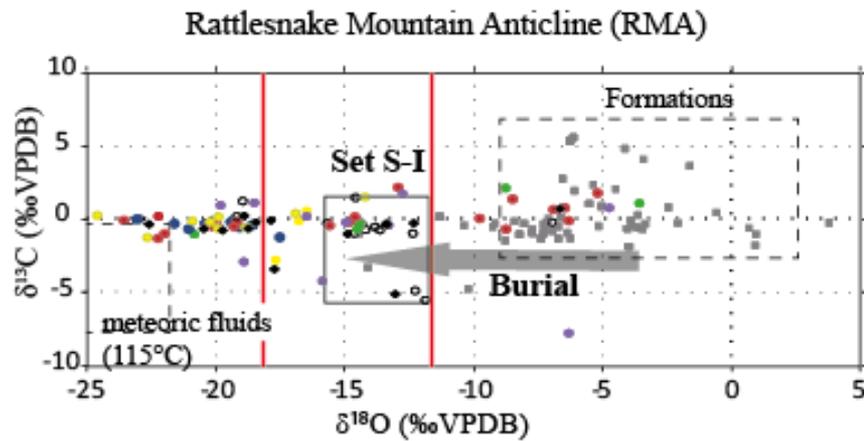


Defining the fluid system

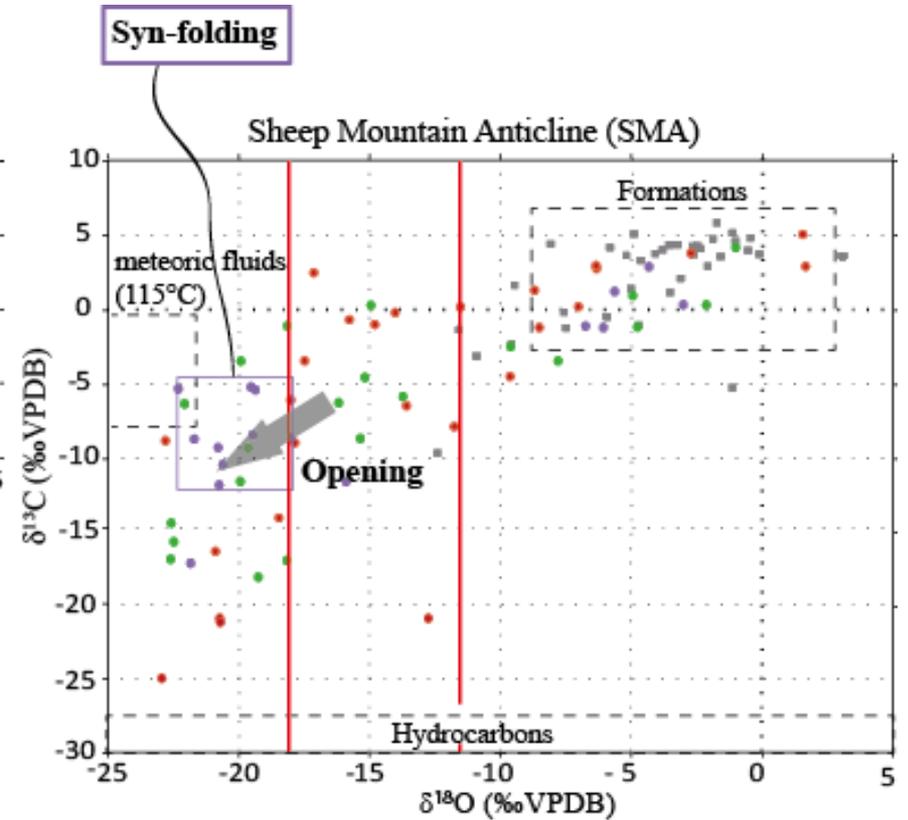
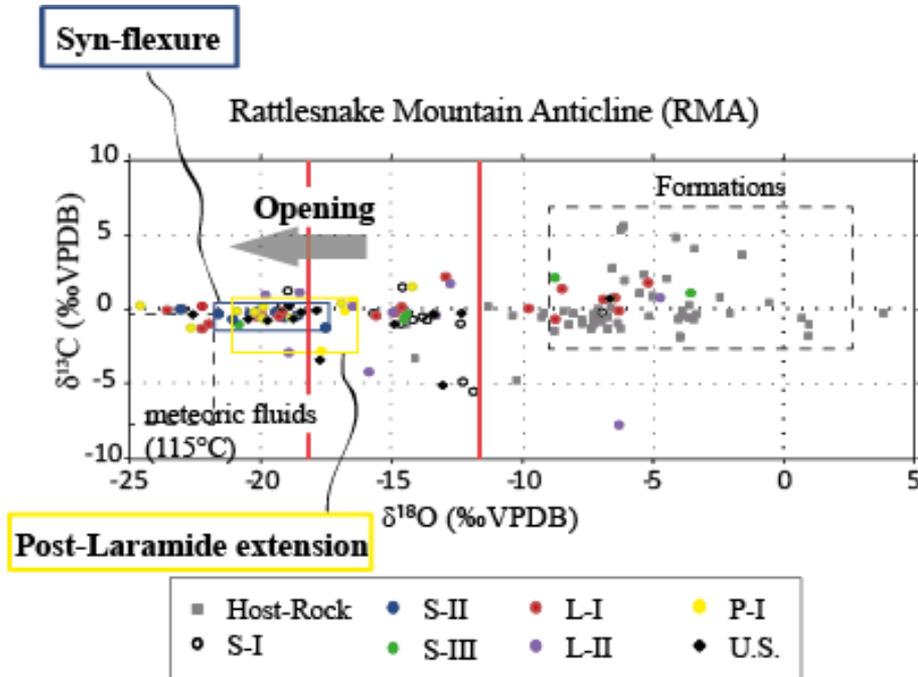
- * Total isotopic and thermal equilibrium with host-rock
- * $\delta^{18}\text{O}$ depletion but thermal equilibrium with host-rock
- * High $\delta^{18}\text{O}$ depletion and thermal disequilibrium with host-rock

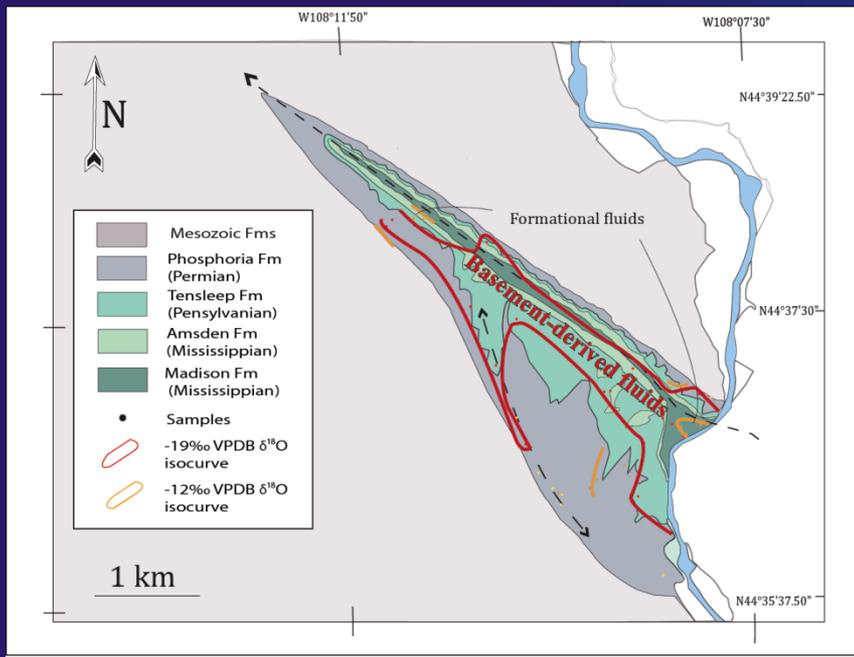


Evolution of fluid system in SMA and RMA



Evolution of fluid system in SMA and RMA



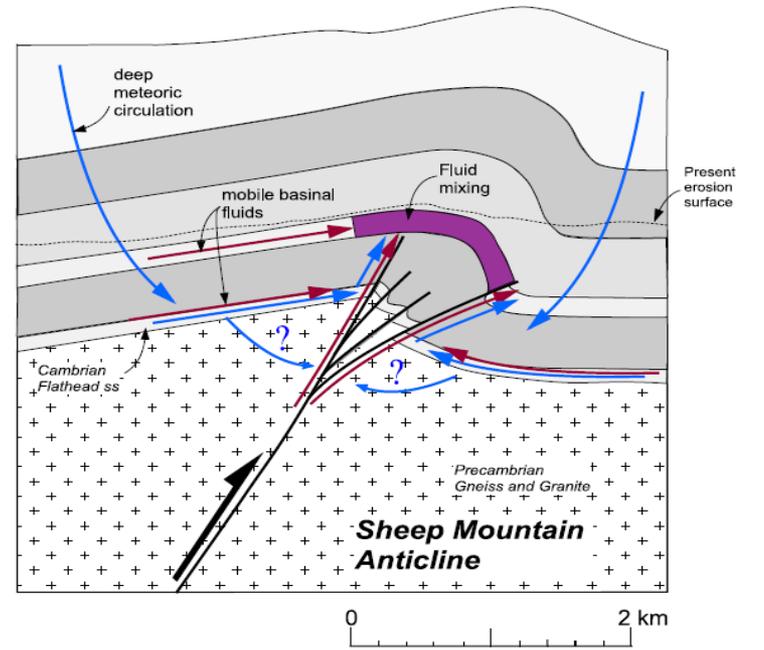
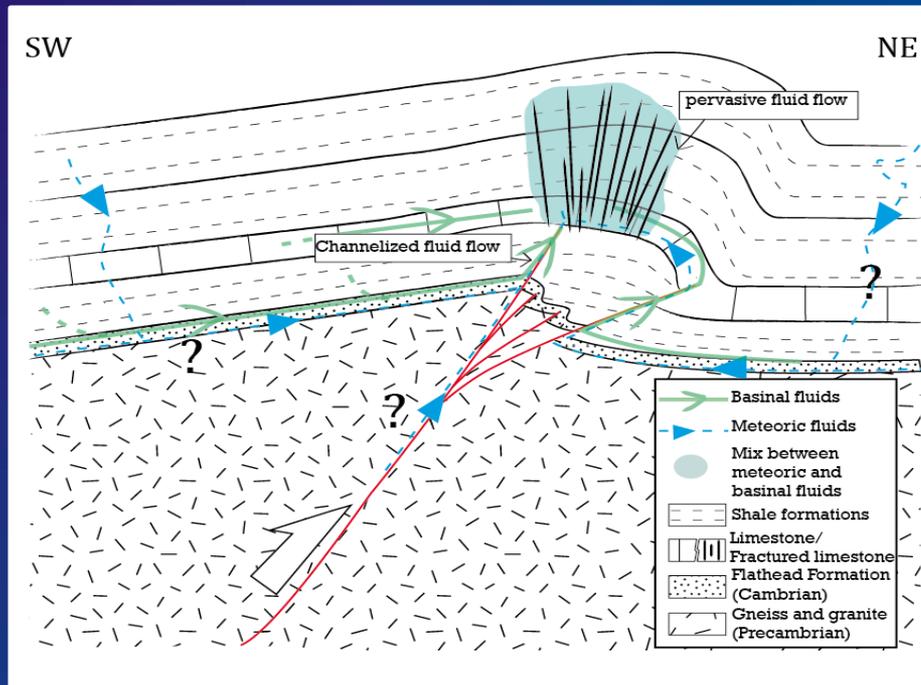


Localization of basement-derived hydrothermal fluid pulse at SMA

Vertical migration of deeper radiogenic hot fluids within the sedimentary cover explained by the development of curvature-related fractures that enhance the hydraulic permeability of the reservoir and break fluid compartmentalization by stratigraphy.

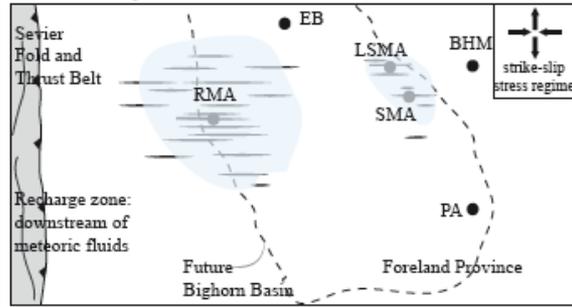
Link with structural style

(Beaudoin et al, G3, 2011; Evans and Fischer, 2012)

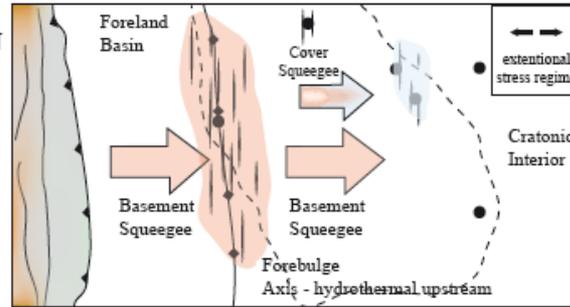


Paleo-hydrogeology of the Bighorn basin

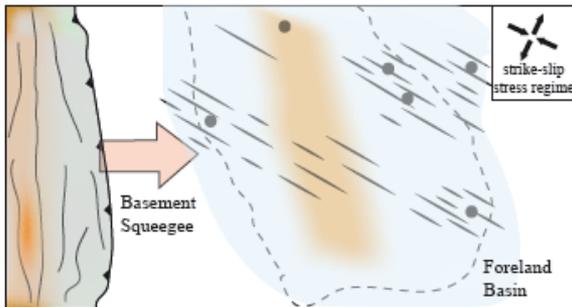
a- Sevier early LPS - Set S-I



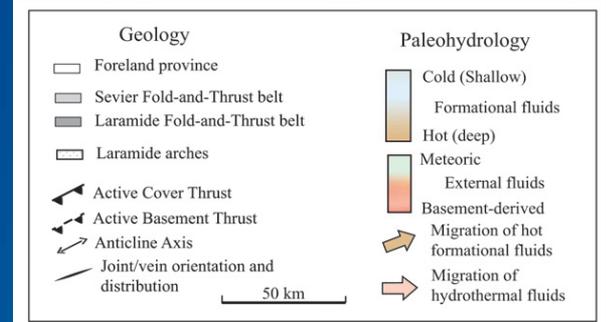
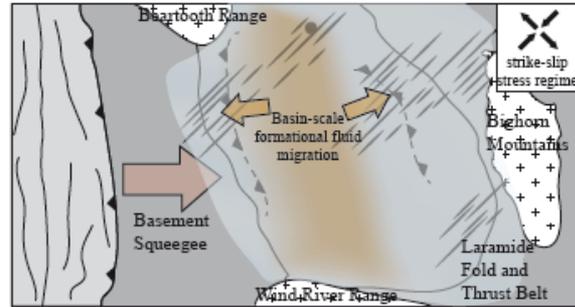
b- Sevier formation of the flexural basin - Set S-II



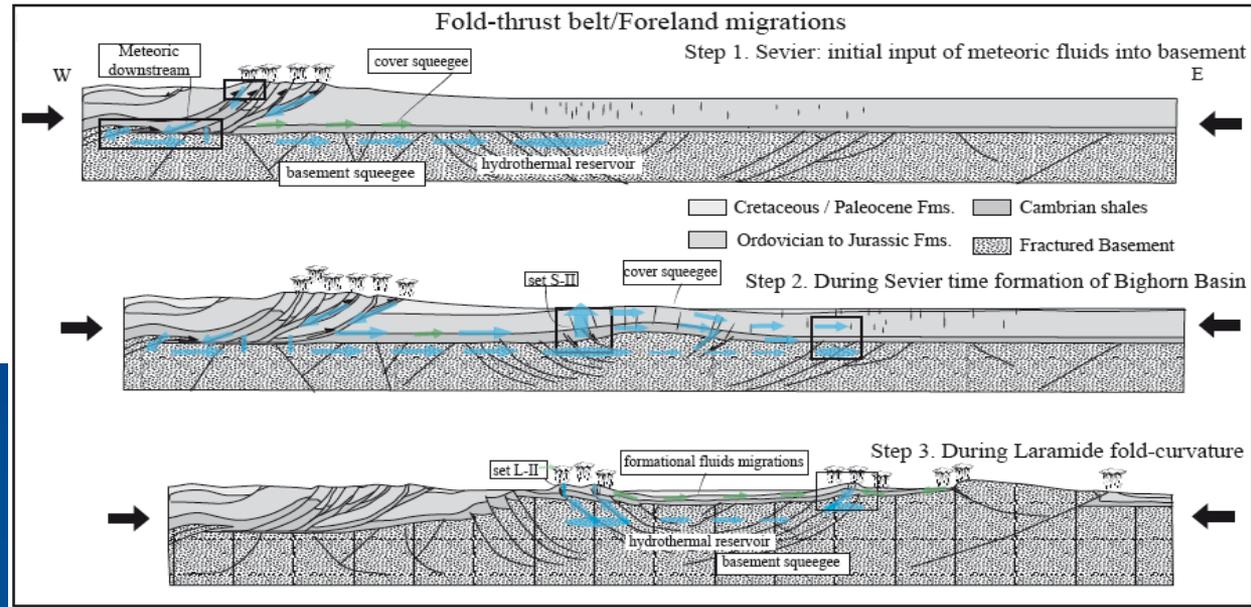
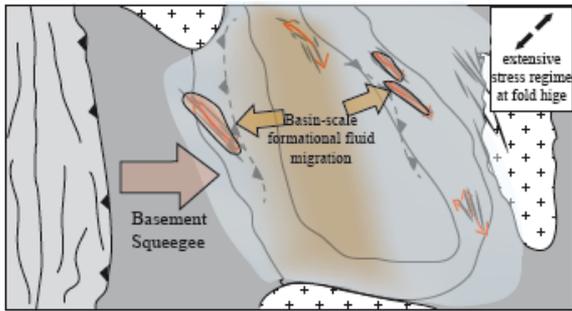
c- Sevier late LPS - Set S-III



d- Laramide LPS - Set L-I

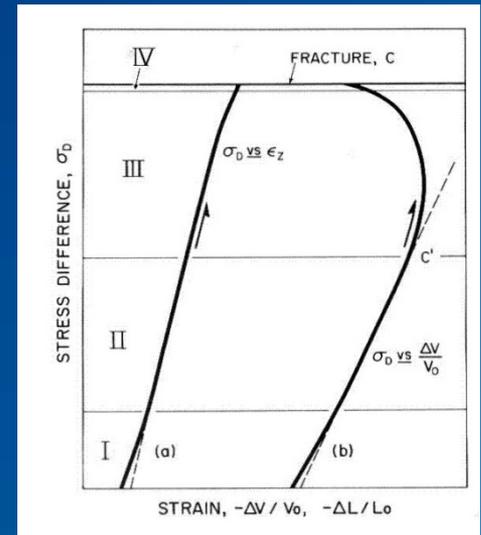
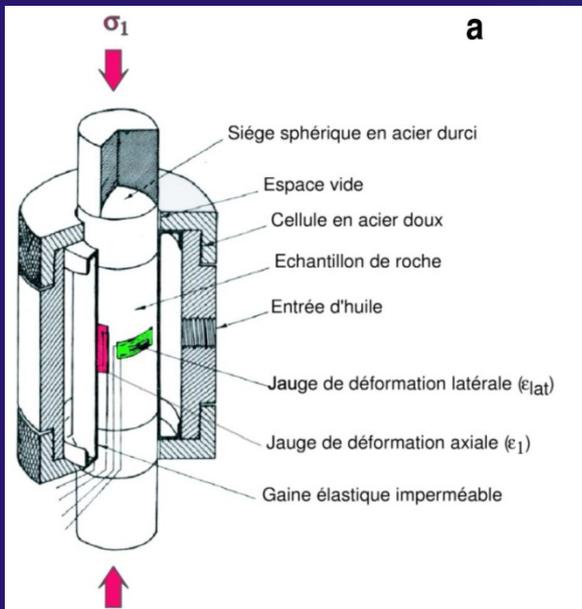


e- Laramide syn-folding - Set L-II

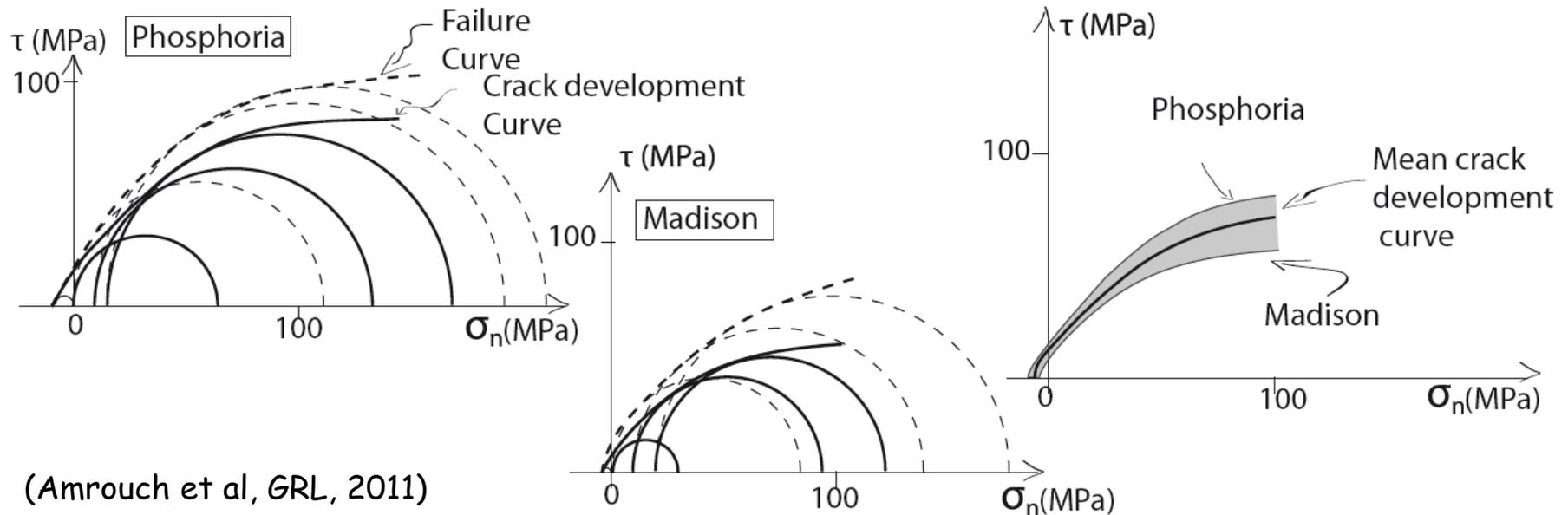


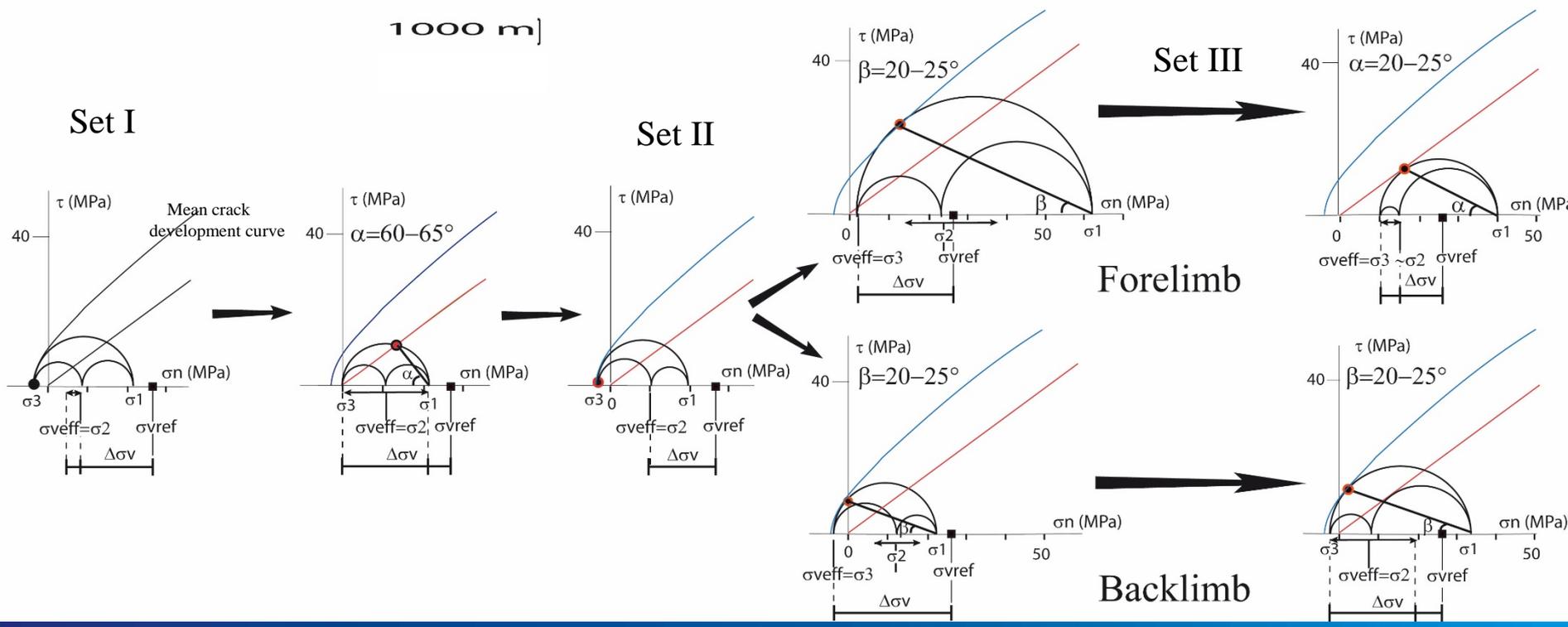
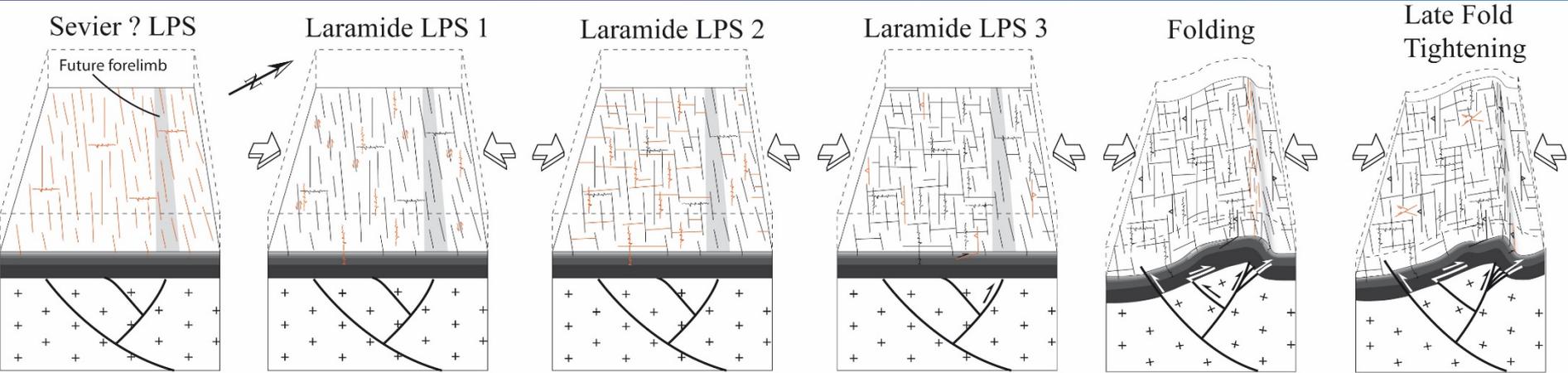
(Beaudoin et al., Basin Research, 2014)

**Quantification of principal stress magnitudes and
fluid (over)pressures
at Sheep Mountain and Rattlesnake Mountain anticlines**



Experimental determination of the intrinsic failure envelopes of the Phosphoria and Madison formations





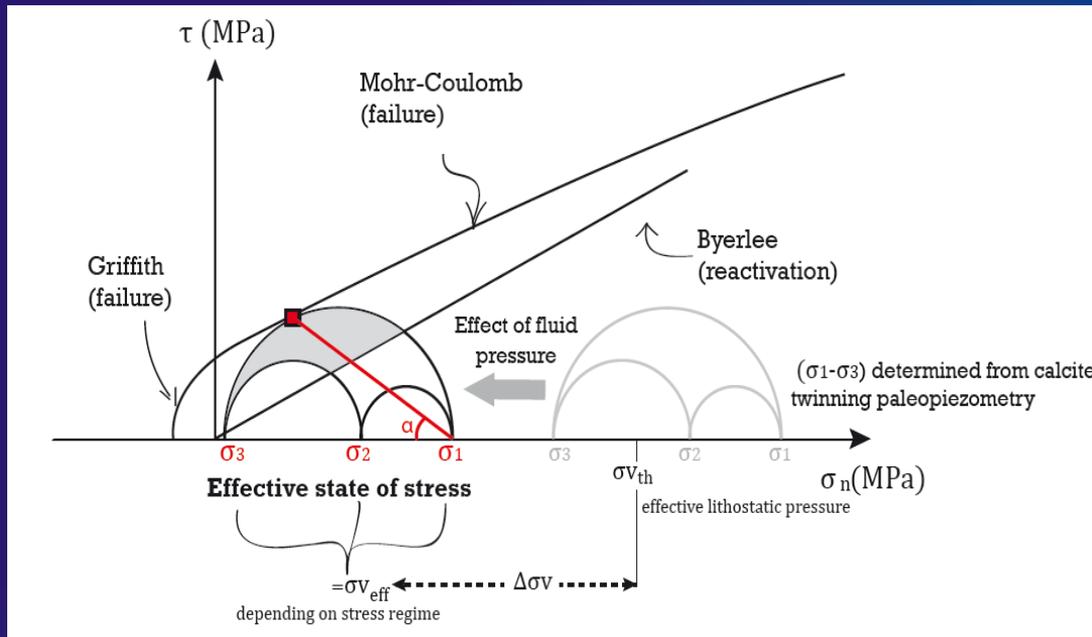
Determination of principal stress magnitudes using simple Mohr constructions (SMA)

(Amrouch et al, GRL, 2011)

The estimated paleo- principal stress magnitudes are in the range of 20-60 MPa for σ_1 and -3-10 MPa for σ_3 in the limestone rocks deformed at 1000-2000m depth.

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

Quantifying paleo fluid (over)pressure



Assumption of a vertical principal stress equal to the effective weight of overburden

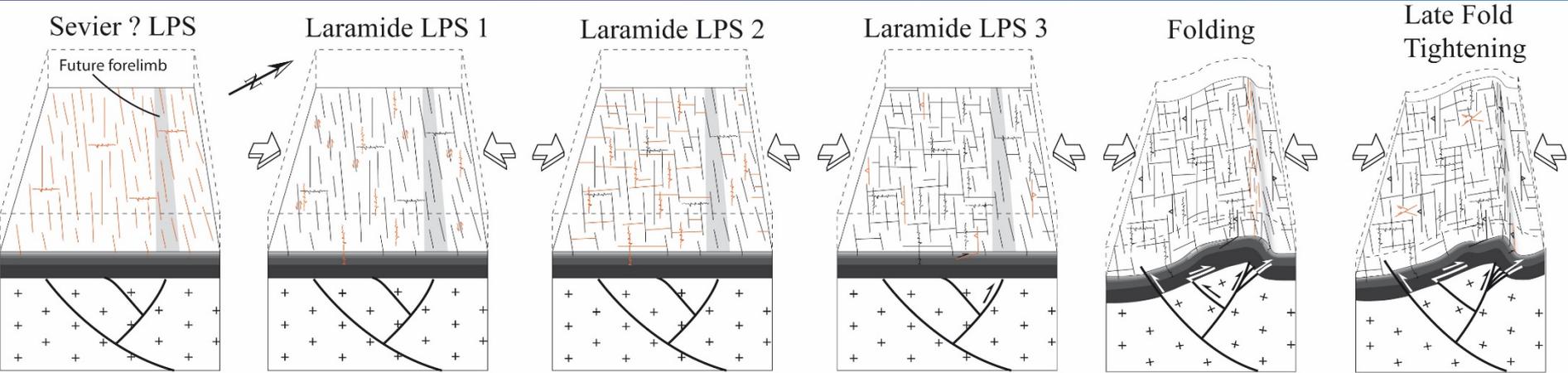
Theoretical effective vertical principal stress calculated considering lithostatic pressure corrected from hydrostatic fluid pressure:

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

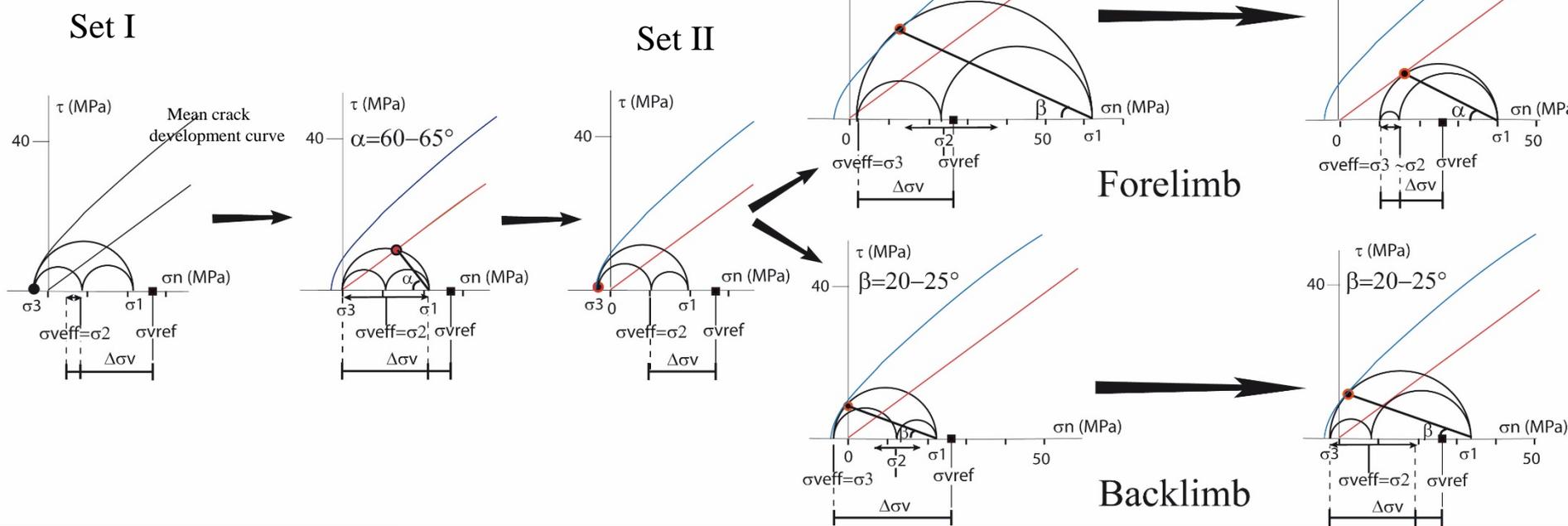
Comparison between σ_{vref} and the reconstructed effective vertical principal stress σ_{veff} :

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

A non-zero $\Delta\sigma_v$ reflects either fluid over- or under-pressure or burial changes (sedimentation or erosion): when $\Delta\sigma_v$ is positive, either the burial depth was less than the value considered for the calculation of σ_{vref} , or the system was overpressured.



1000 m]

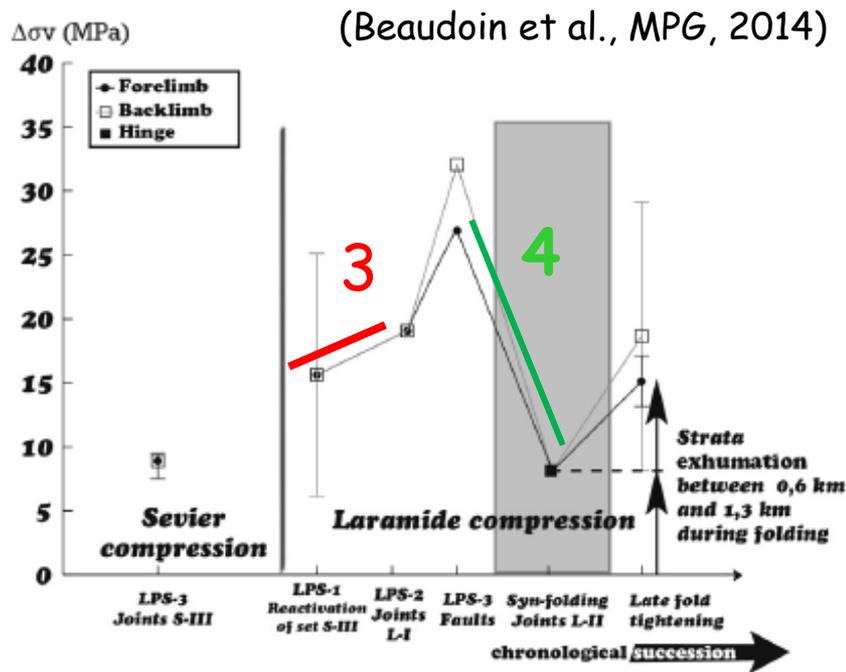


Determination of $\Delta\sigma_v$

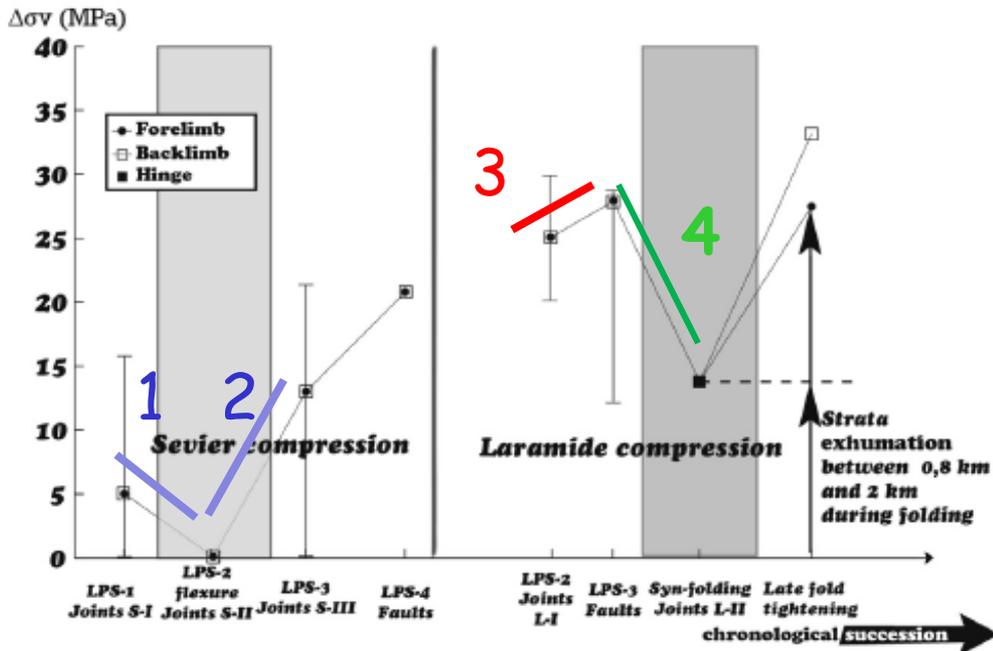
(Amrouch et al, GRL, 2011)

Comparison of $\Delta\sigma_v$ evolution

SMA



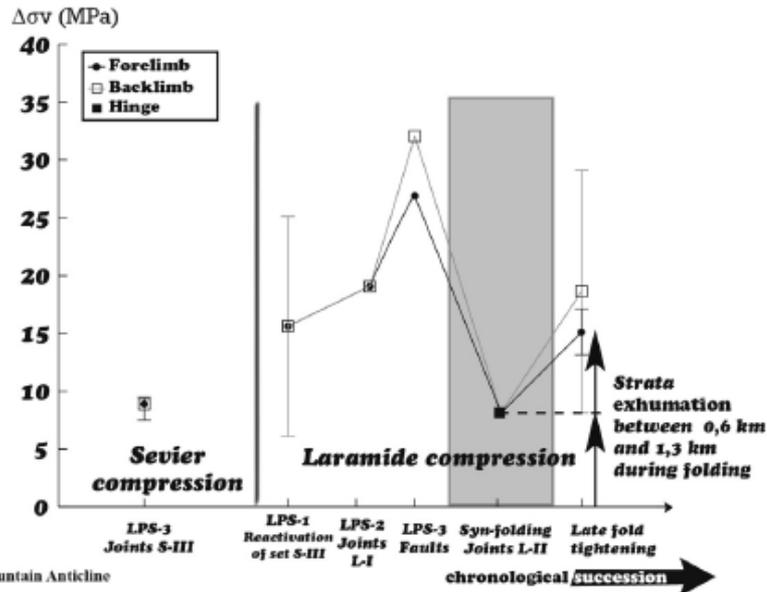
RMA



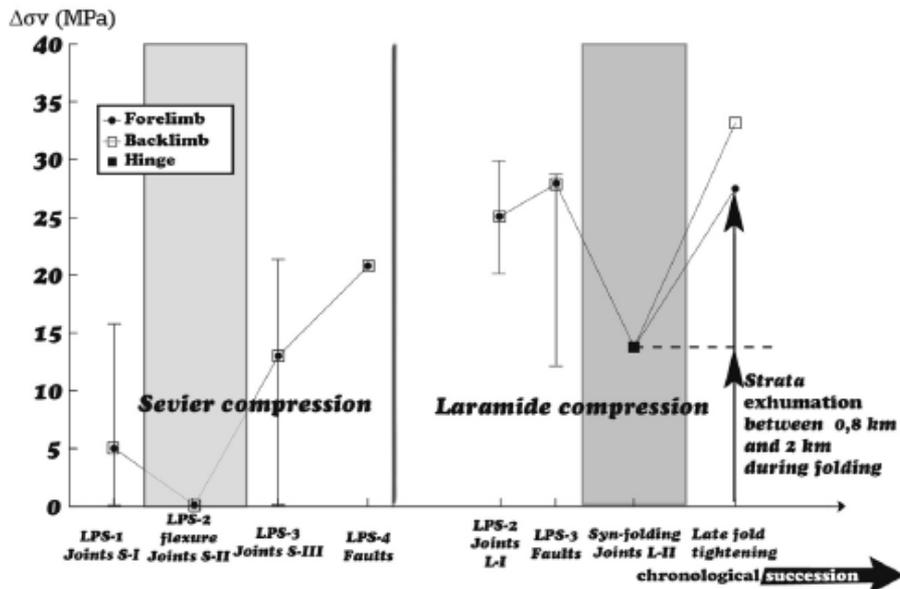
1. Decrease in fluid overpressure from early Sevier LPS to Sevier foreland flexure due to enhanced permeability by flexure-related extensional fractures.
2. Increase during late Sevier-LPS by input of exotic fluids as supported by geochemistry of vein cements.
3. Increase during Laramide LPS due to porosity reduction by pressure-solution/poor hydraulic permeability of fracture sets due to low vertical persistence or to their fast healing/strong increase in horizontal stress magnitude / input of exotic fluids into the reservoir in response to a large-scale fluid migration.
4. Drop due to development of curvature-related fractures that enhanced the hydraulic permeability of the reservoir. Break of fluid compartmentalization within the Madison-Phosphoria core consistent with geochemistry of syn-folding vein cements that suggests a vertical migration of deeper radiogenic hot fluids within the sedimentary cover.

Estimates of syn-folding erosion

a) Sheep Mountain Anticline



b) Rattlesnake Mountain Anticline



The post-folding Δ_{sv} value can be used to calculate the eroded/ burial thickness E as well as the post-folding overburden thickness H

$$E = \Delta_{sv} / [(\rho_{rock} - \rho_{water})g]$$

$$H = [\sigma_{vth} - \Delta_{sv}] / [(\rho_{rock} - \rho_{water})g]$$

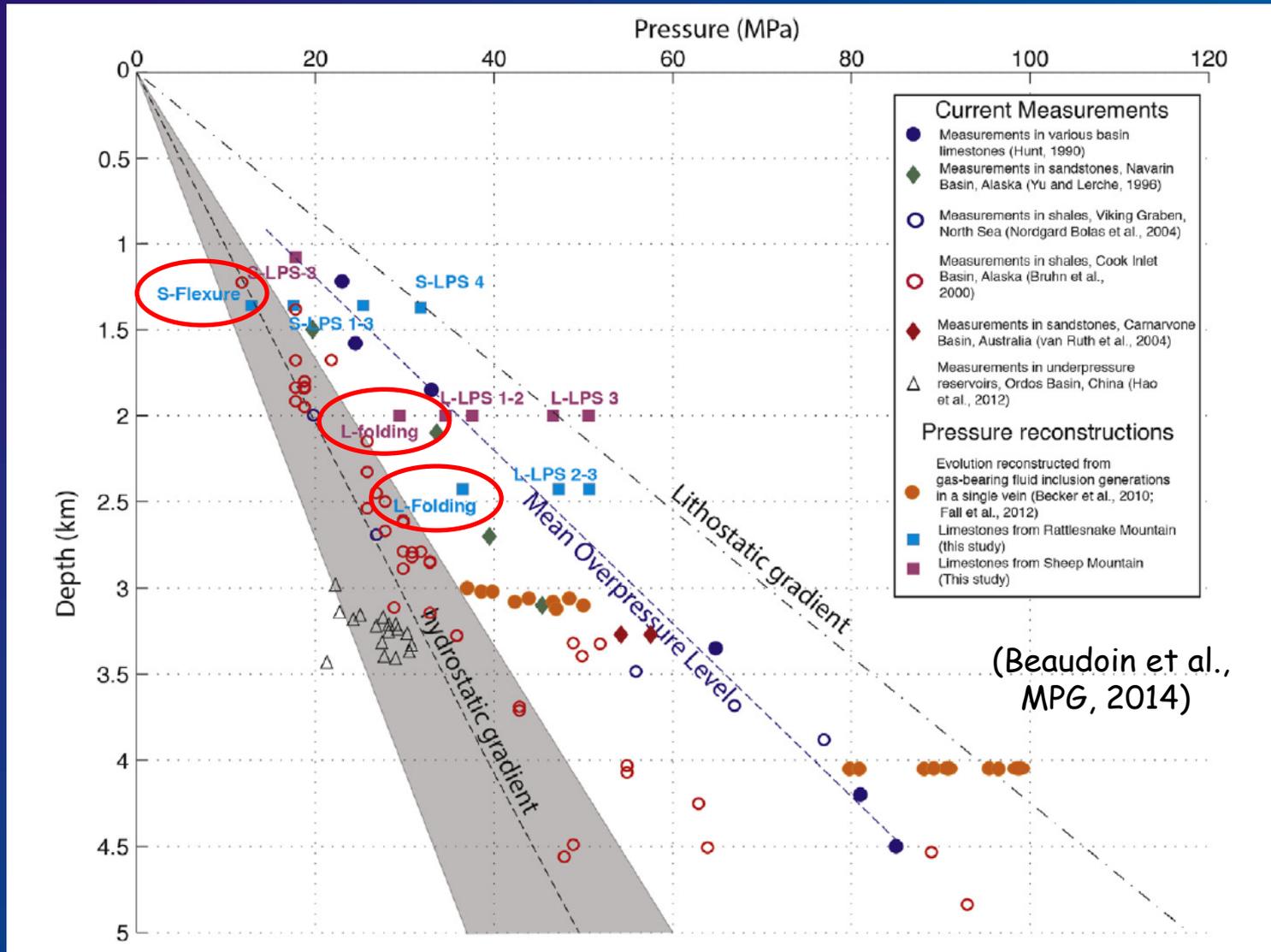
The high Δ_{sv} value recorded during the LSFT suggests exhumation of the strata, consistent with the development of topography during folding.

Drastic drop in fluid pressure during folding :
 -either a hydrostatic fluid pressure prevailed in the reservoir \rightarrow exhumation : 1.3/ 2km at SMA/RMA
 -or a supra-hydrostatic fluid pressure still persisted after folding (overpressure not totally released) \rightarrow syn-folding value of Δ_{sv} reflects the remaining fluid overpressure

\rightarrow exhumation : 0.6/0.8 km at SMA/RMA

Assuming a syn-folding erosion of 0.6-2.0 km and a duration of folding of 5-20 Ma \rightarrow exhumation rate by folding of 0.03-0.40 mm/yr, consistent with exhumation/rock uplift rates in other Laramide arches derived from LT thermochronology and paleoelevation/basin analyses.

Comparison with values of fluid overpressures in sedimentary basins derived from paleo-pressure reconstructions based on gas composition in hydrocarbon fluid inclusions or from direct measurements in limestone or shale/sandstone reservoirs.



Overall conclusions

First integrated picture of stress and strain in folded strata at different scales, and operating mechanisms of deformation

First picture of the evolution of stress magnitudes and pore fluid (over) pressure through time.

Development of fluid overpressure in carbonate strata largely controlled by vertical hydraulic permeability of fractures;
Fractures formed under an extensional stress regime more efficiently trigger fluid exhaust.

Changes in P-T-X conditions, fluid flow, fluid (over)pressure and fracture development as well as stress and strain pattern within folded strata linked to the geometric/kinematic macroscopic evolution of folds
→ key to a better characterisation of folded-fractured reservoir behaviour

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

Feedbacks between deformation, tectonic style and paleo-hydrology



Many thanks for inviting me