Bern, 26/11/2018

Folding, fracturing, stress and fluid flow above basement thrusts in the Bighorn basin (Laramide belt, Wyoming, USA)

Olivier LACOMBE

Collaboration with
Nicolas BEAUDOIN, Khalid AMROUCH (former PhD students)
Nicolas BELLAHSEN … and many others

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Thick-skinned deformation in orogenic forelands : what we know

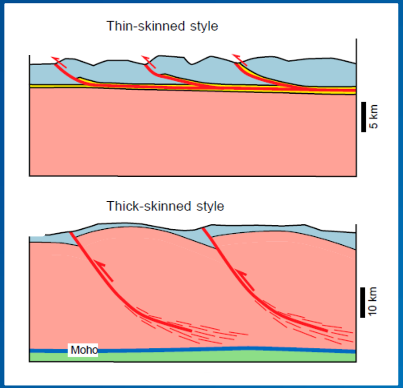
In thick-skinned (i.e., basement-involved) FTBs, shortening involves a significant part of the crust above a deep ductile detachment (≠ thin-skinned)

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

Basement-involvement in FTBs requires mechanical coupling between the orogen and the foreland and far-field orogenic stress transmission through the crust and/or mantle lithosphere

Basement involvement in FTBs requires a generally rather hot, hence mechanically weak lithosphere

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



Pfiffner, 2017

Pending questions to be addressed today :

* How do stress (orientation / magnitude) distribute and evolve during thick-skinned folding ?

* How does deformation propagate and distribute in forelands ?
Is the sequence of thick-skinned deformation similar to that of thin-skinned deformation ?

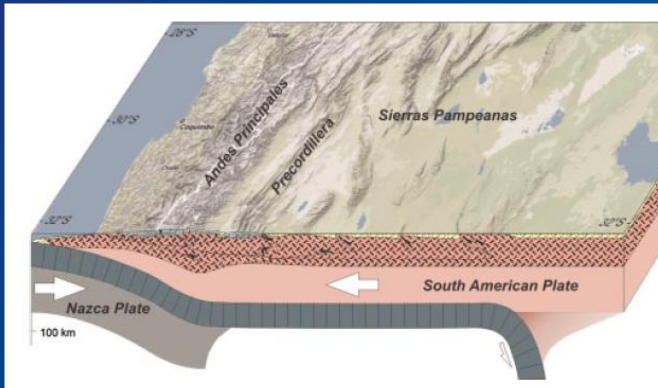
* How do fluids flow (and fluid pressure) evolve during thick-skinned folding ?

The Bighorn Basin
and the Sevier and Laramide orogenies

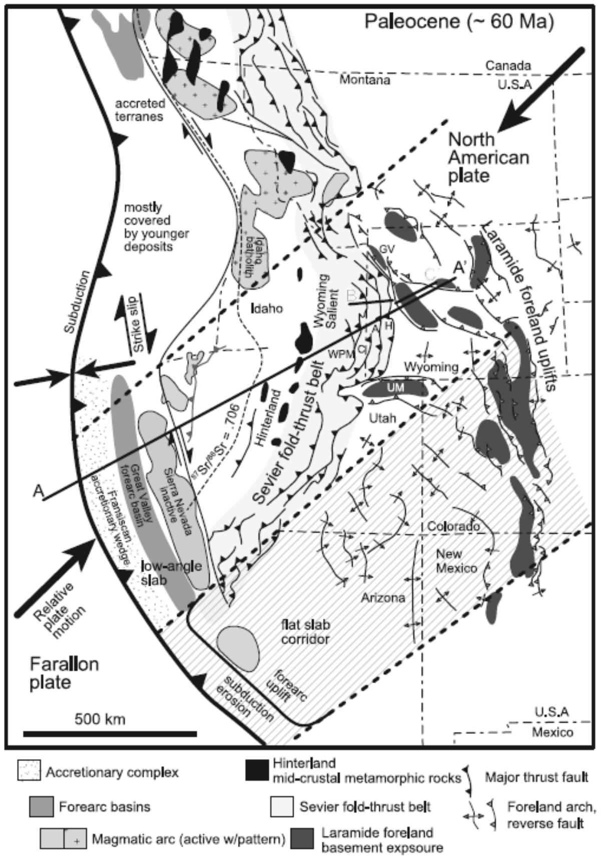

WELCOME TO
WYOMING
FOREVER WEST

Long-lasting subduction of the Farallon plate along the North America margin

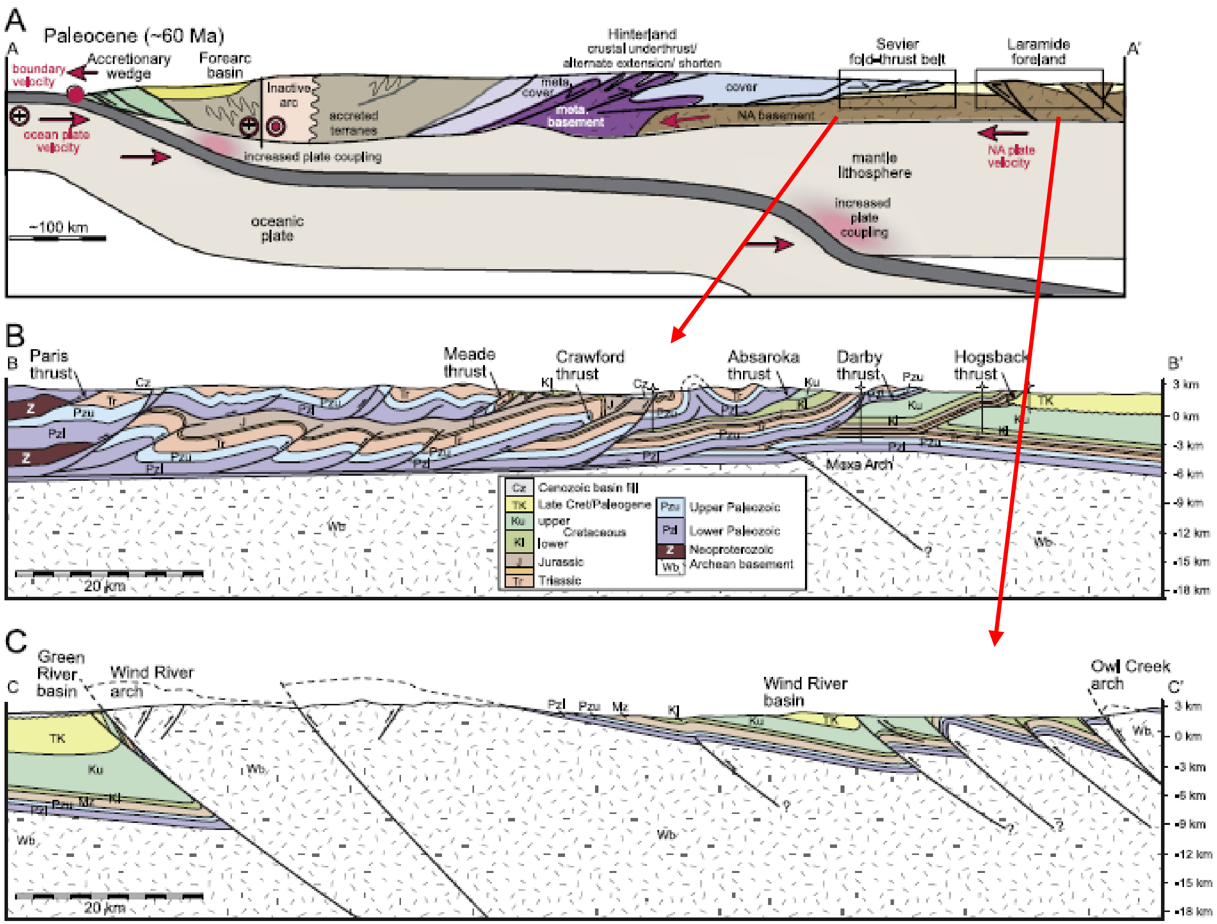
The Sevier belt formed formed and propagated eastward as a thin-skinned wedge during Cretaceous to early Paleocene times.
Thick-skinned Laramide deformation initiated cratonwards by Late Cretaceous until Paleogene times
→ time overlap with final stages of Sevier deformation.



(Ramos, 2010)



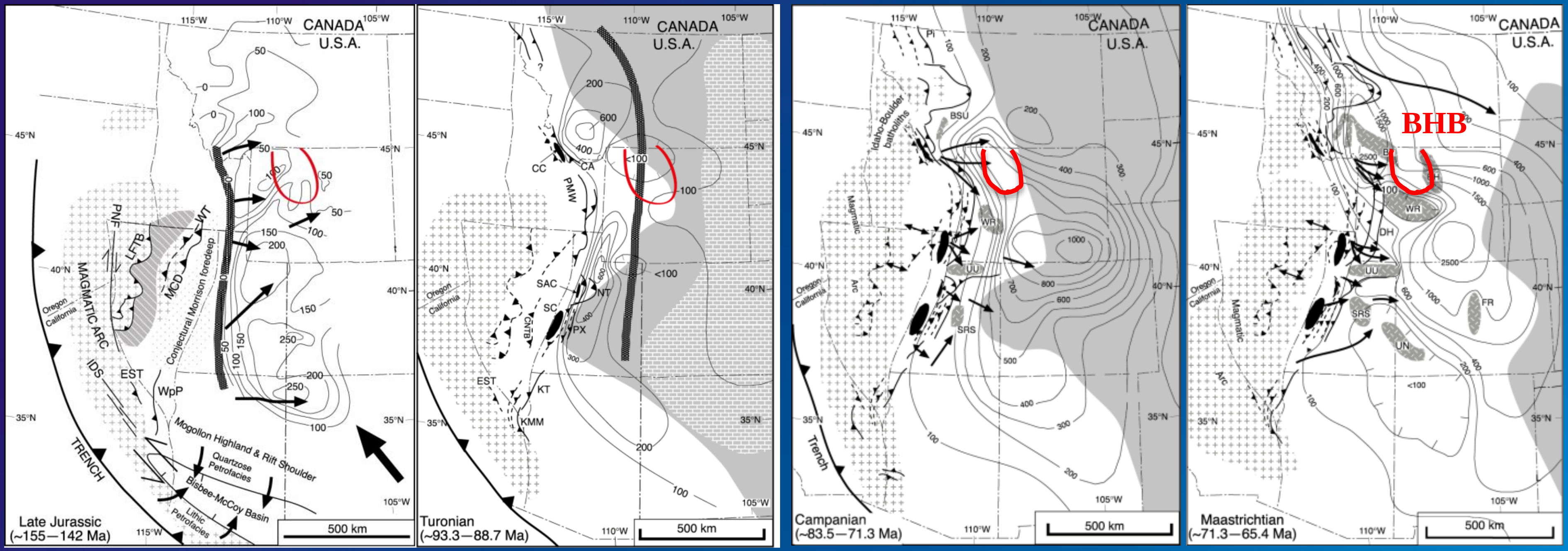
(Weil and Yonkee, 2012)



DeCelles, 2004

Jurassic – Cretaceous: The Western Interior Basin

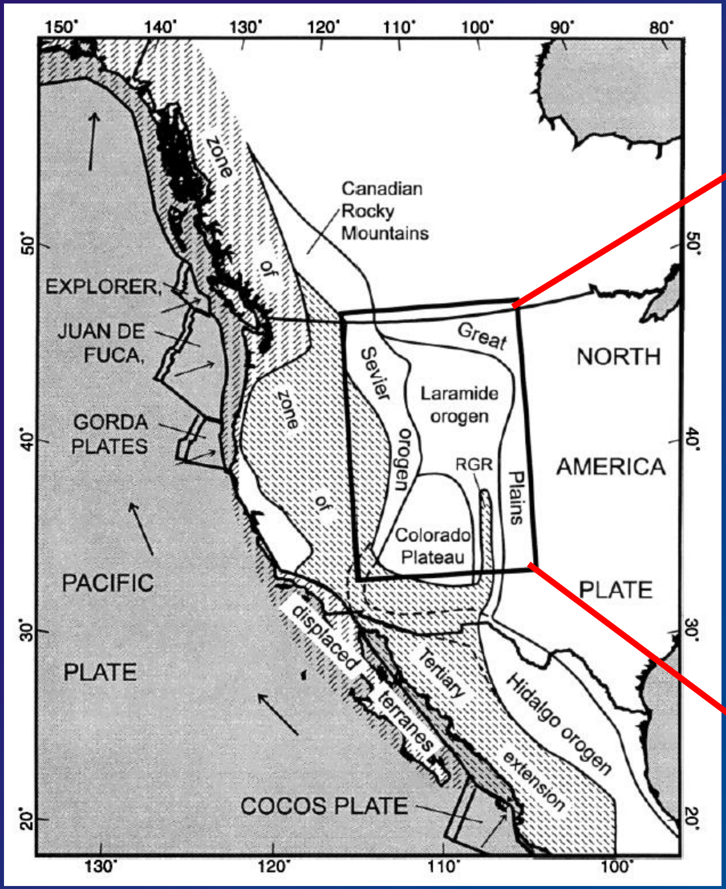
Late Cretaceous – Paleocene: The Bighorn Basin

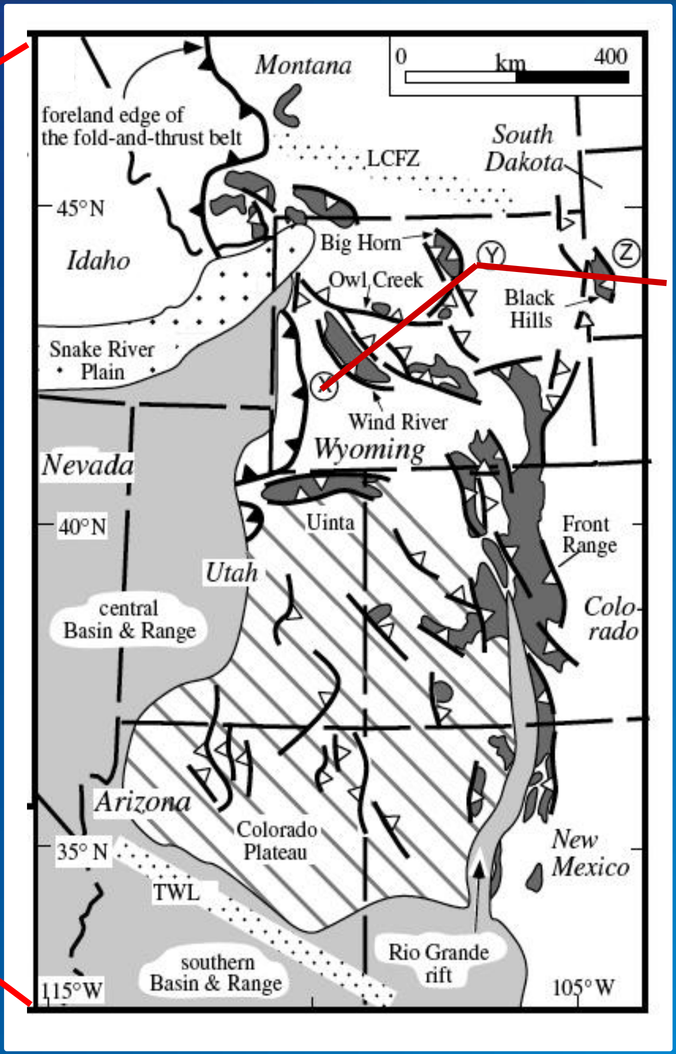


The Laramide belt = network of anastomosing thick-skinned, basement-cored anticlines and uplifts separated by basins

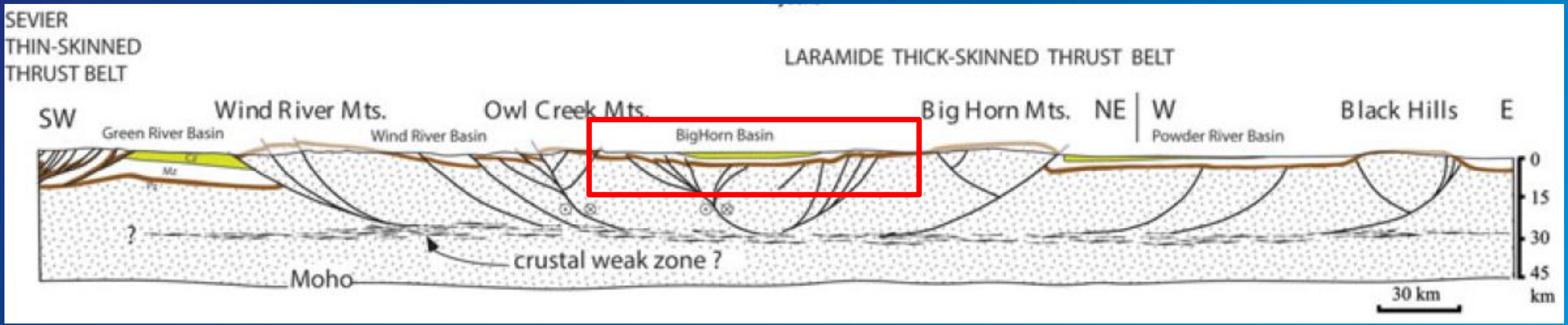
→ topographic compartmentalization of the former marine Sevier foreland basin into continental, endorheic basins since the late Cretaceous

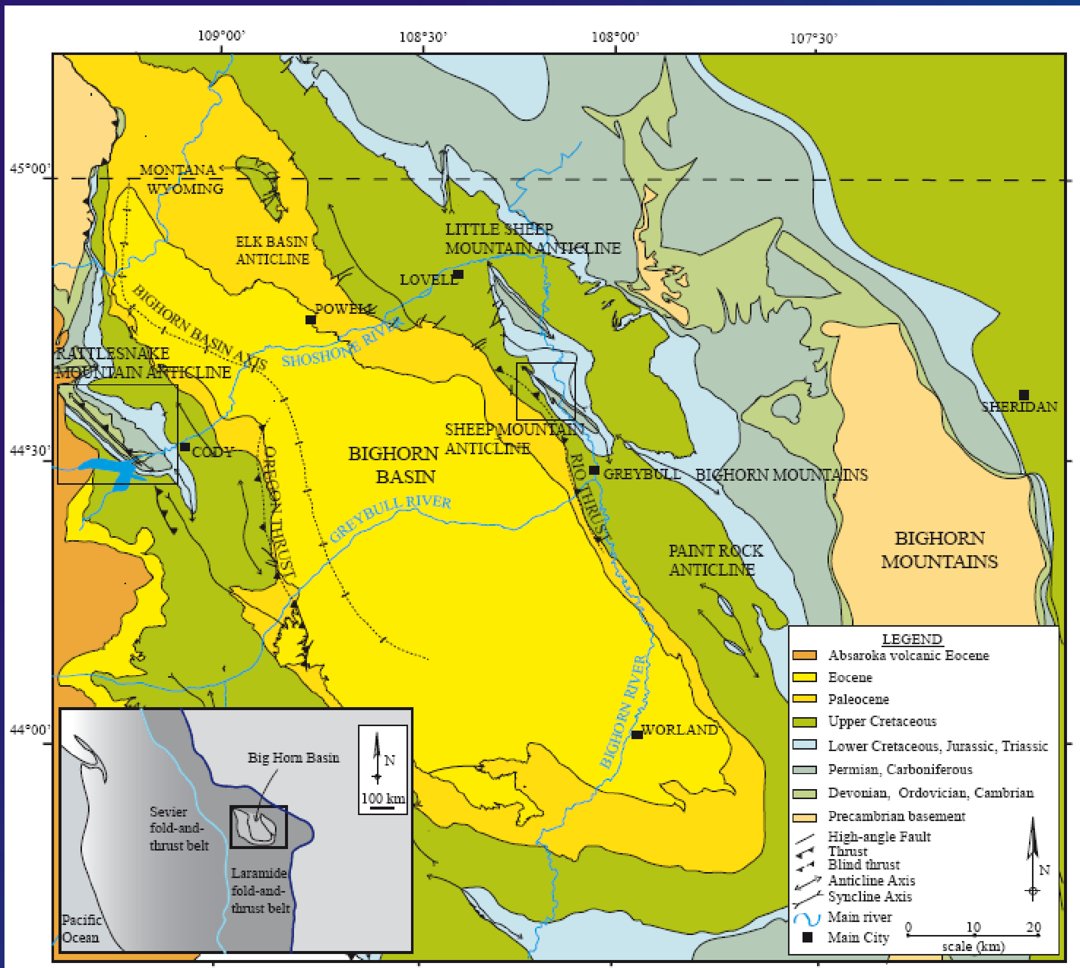
→ the Bighorn Basin

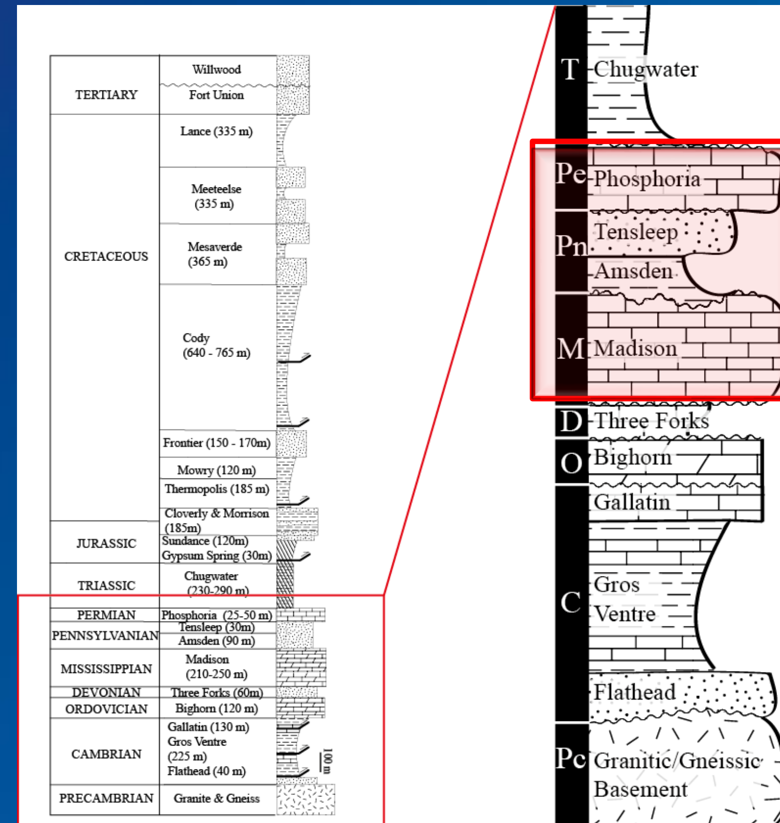


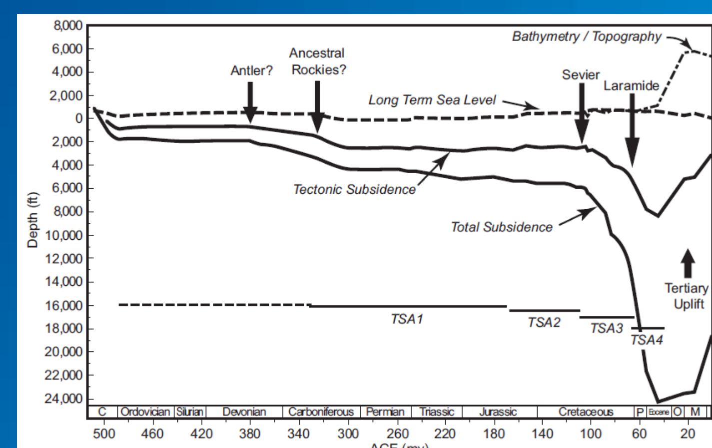


(Marshak et al., 2000;
Lacombe and Bellahsen, Geological Magazine, 2016)



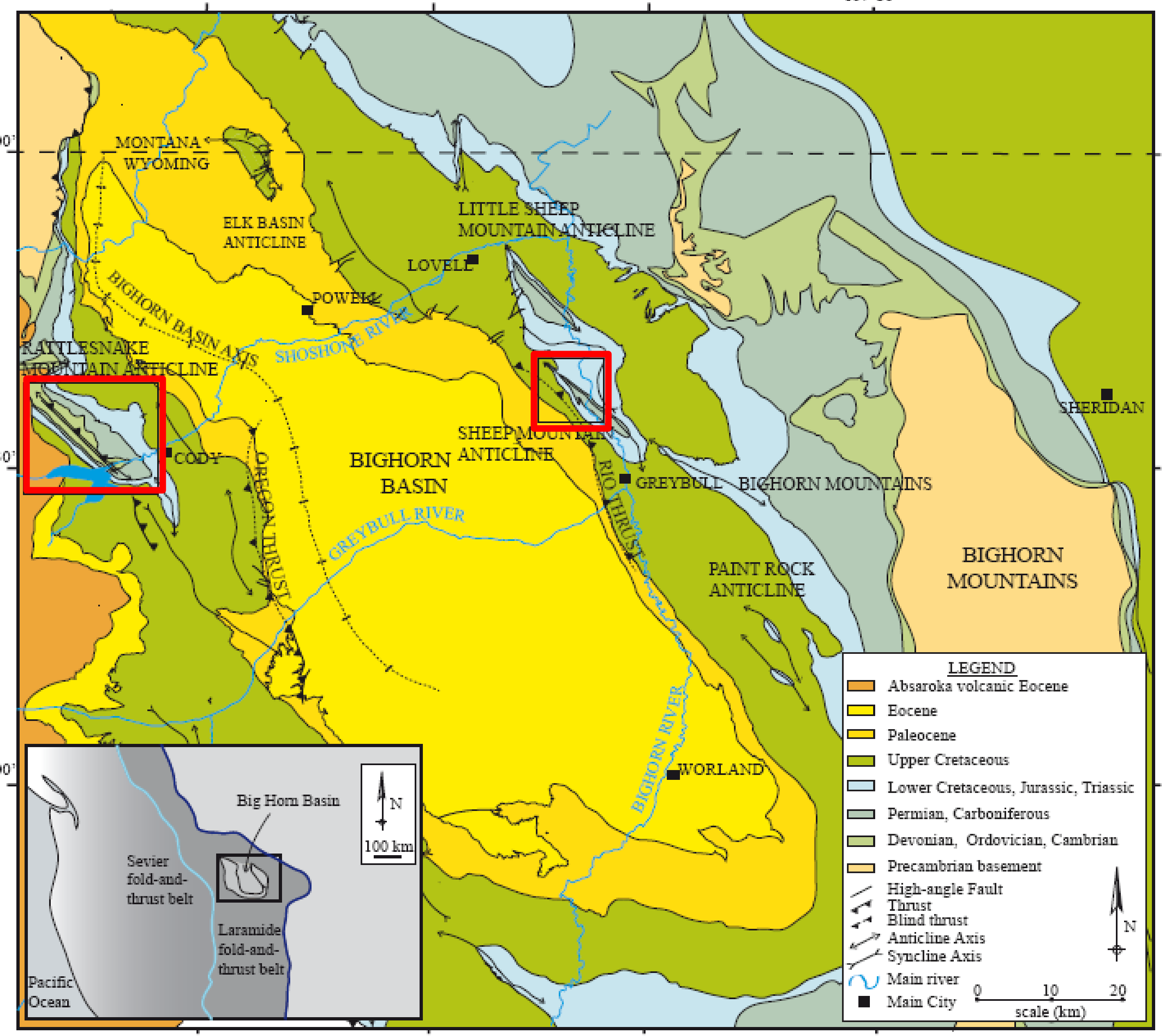




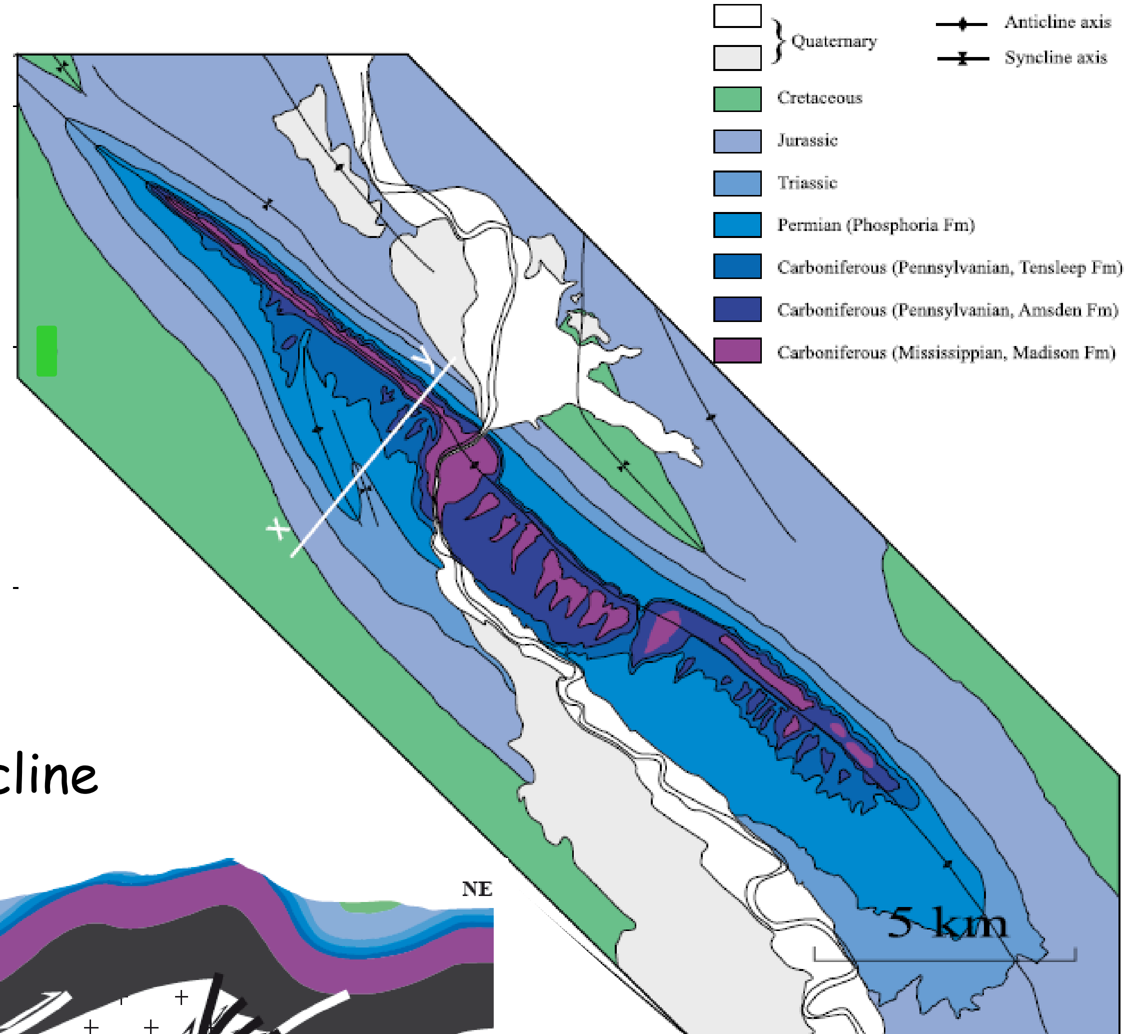


(May et al., GSAB, 2013;
Beaudoin et al., Basin Research, 2014)

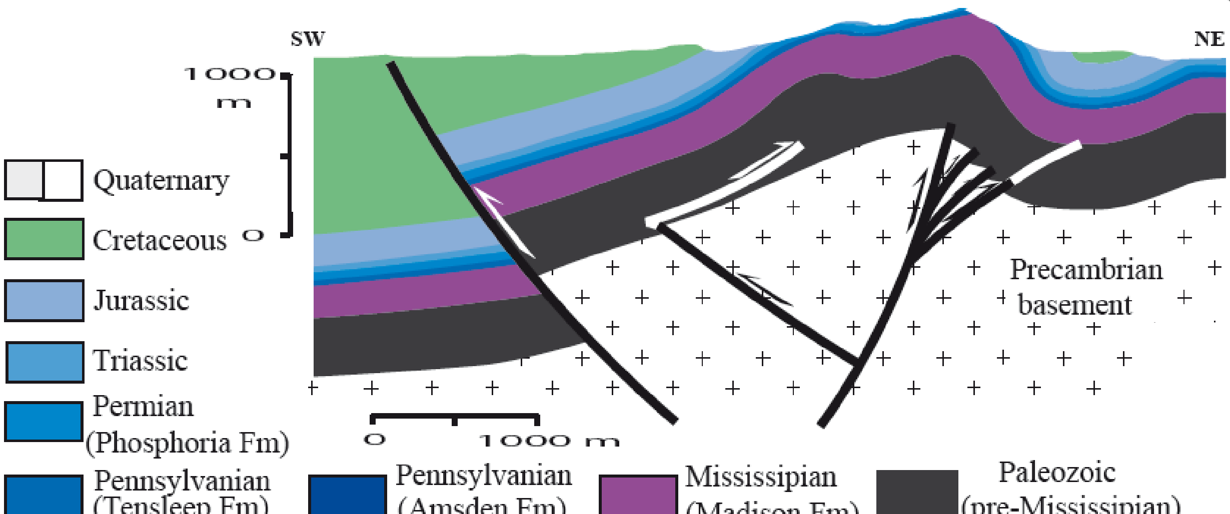
Structure of Sheep Mountain
and Rattlesnake Mountain anticlines


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
BIGHORN BASIN AXIS
SHOSHONE RIVER
RATTLESNAKE
MOUNTAIN ANTICLINE
CODY
OREGON THRUST
BIGHORN
BASIN
SHEEP MOUNTAIN
ANTICLINE
RIO THRUST
GREYBULL
BIGHORN MOUNTAINS
SHERIDAN
GREYBULL RIVER
PAINT ROCK
ANTICLINE
BIGHORN
MOUNTAINS
BIGHORN RIVER
WORLAND
Big Horn Basin
N
100 km
Sevier
fold-and-
thrust belt
Laramide
fold-and-
thrust belt
Pacific
Ocean
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
N
0
10
20
scale (km)


Sheep Mountain anticline



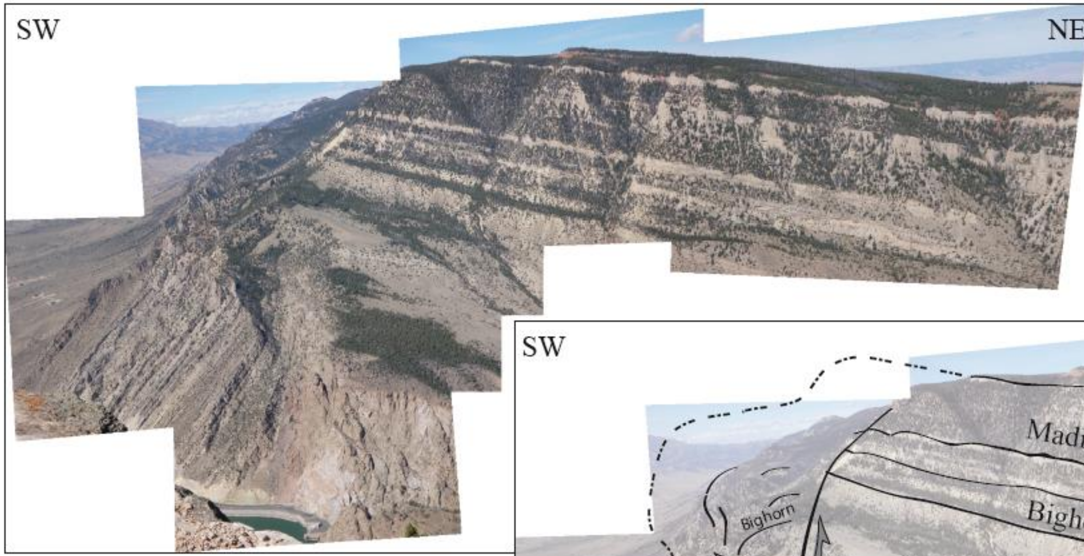
Sheep Mountain anticline

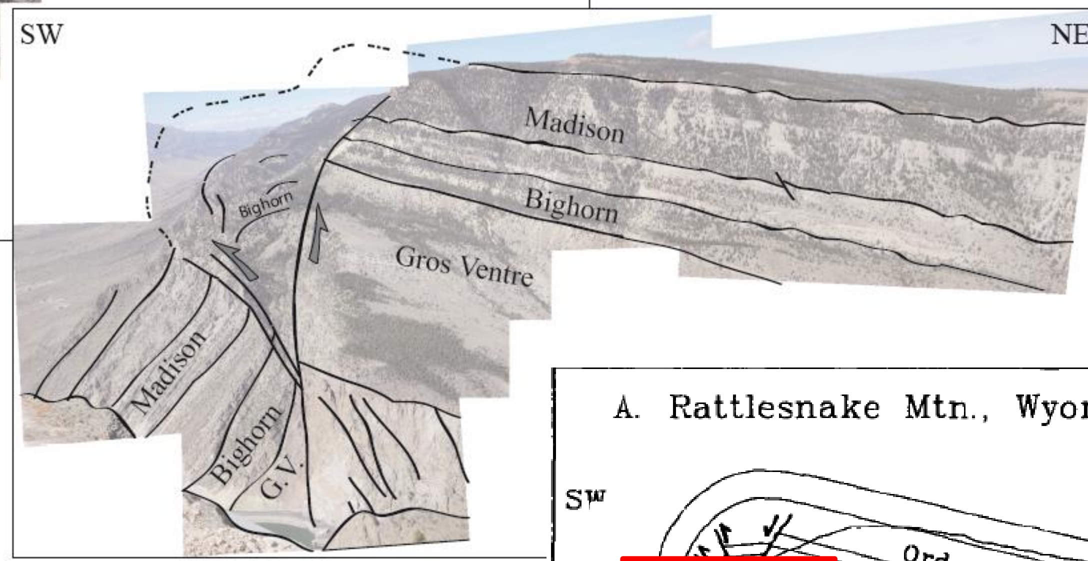


(Amrouch et al.Tectonics, 2010)

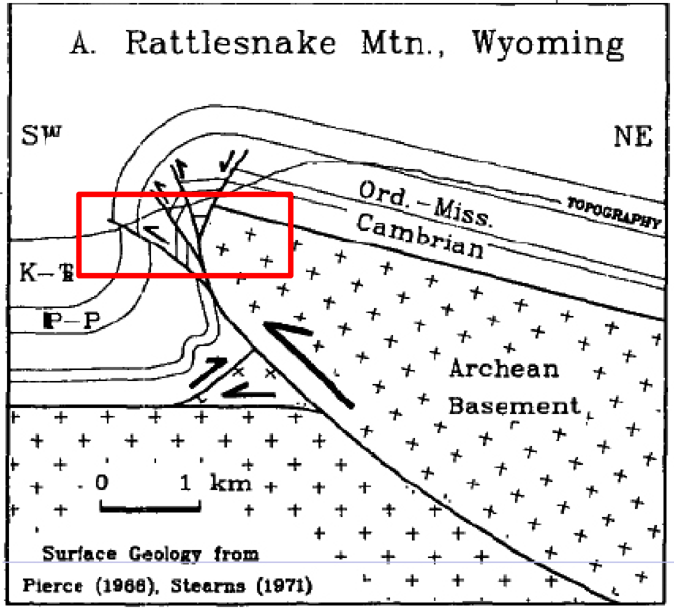

OLD TRAIL TOWN
Museum of the Old West
A Great Family Experience
SUMMER HOURS
8AM to 7PM
OPEN
Cody
Cody
Cowboy Village
Rated #1 Hotel by Tripadvisor.com
#1
Rated Hotel in Cody
FREE INTERNET & Conti
tal Breakfast

(Beaudoin et al., Tectonophysics, 2012)

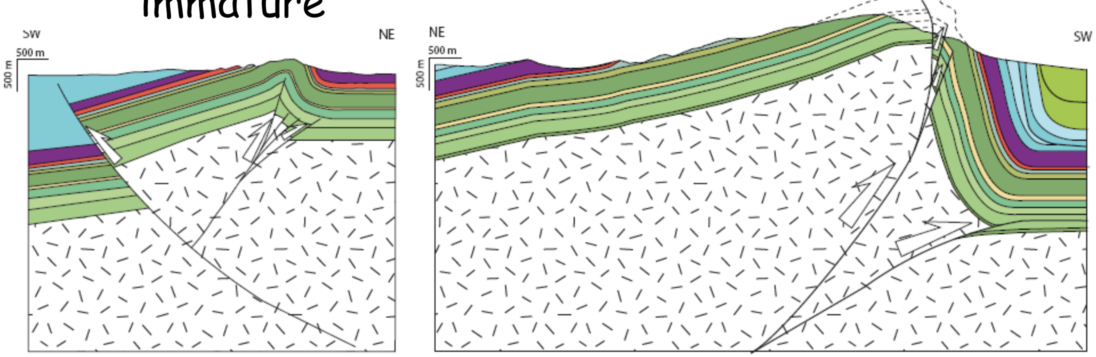




Rattlesnake Mountain anticline

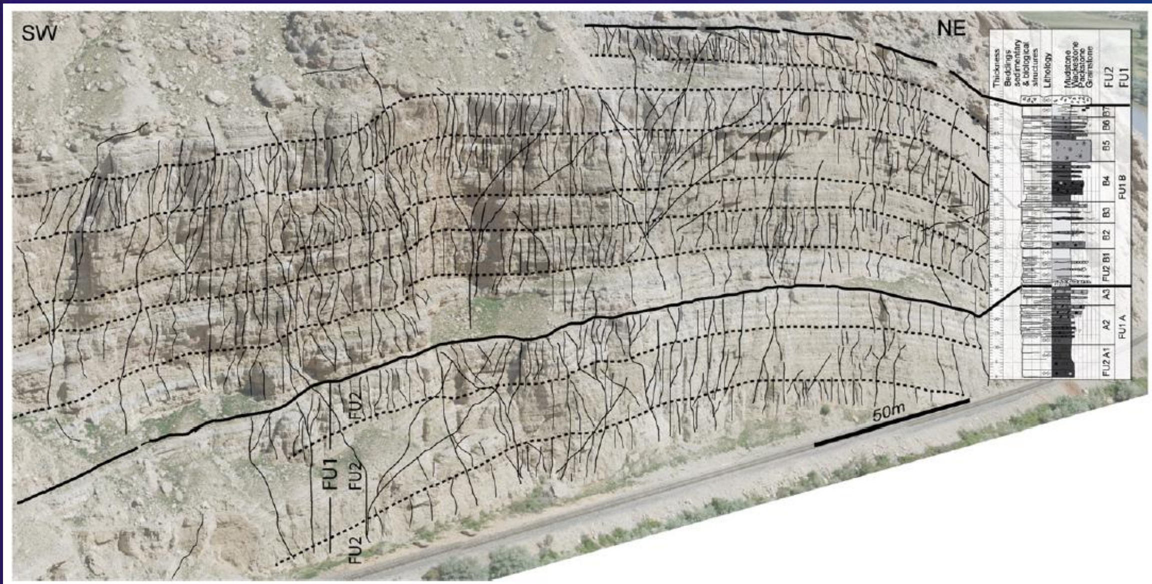


SMA immature → RMA mature



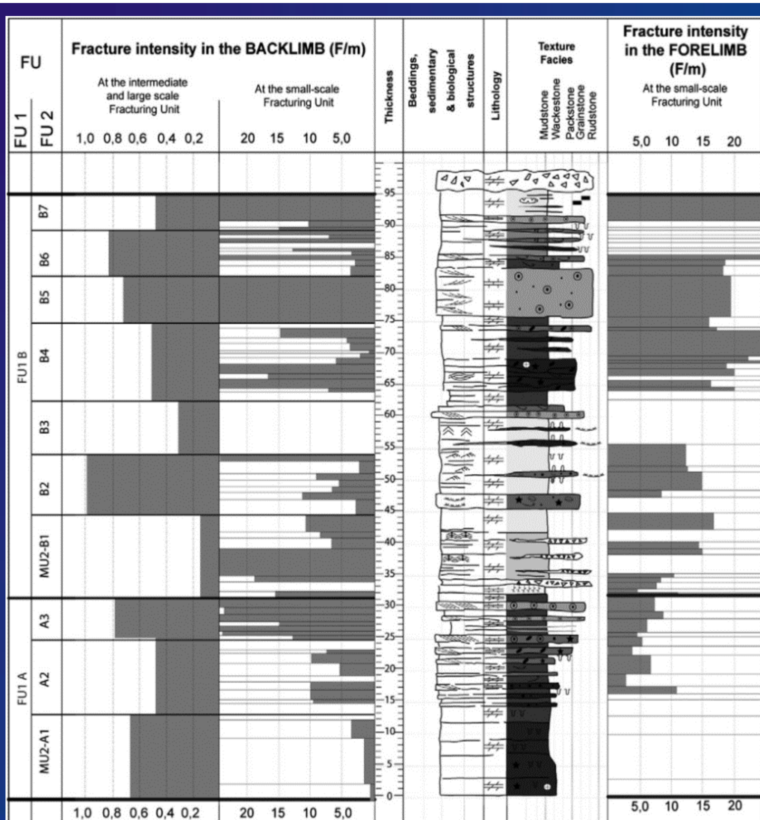
(Erslev, 1986)

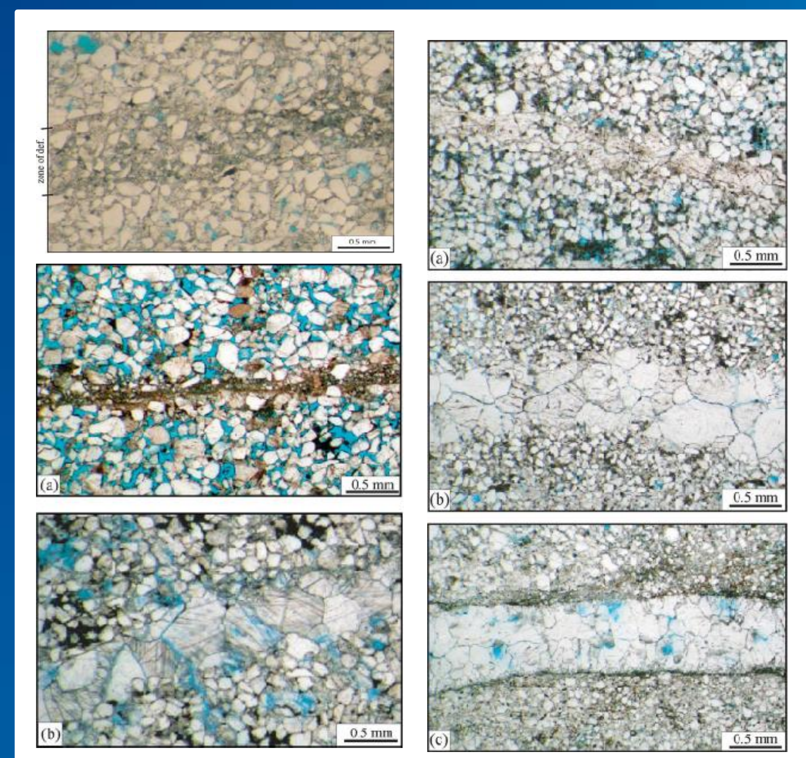
Fracture populations
at Sheep Mountain and Rattlesnake Mountain anticlines



Sheep Mountain anticline

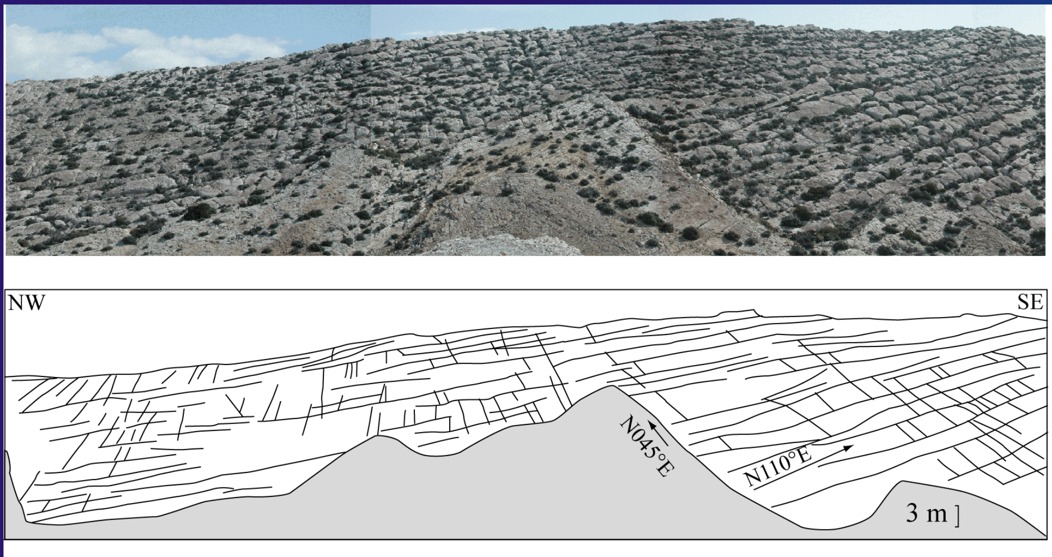
Fracture attributes and mechanical stratigraphy

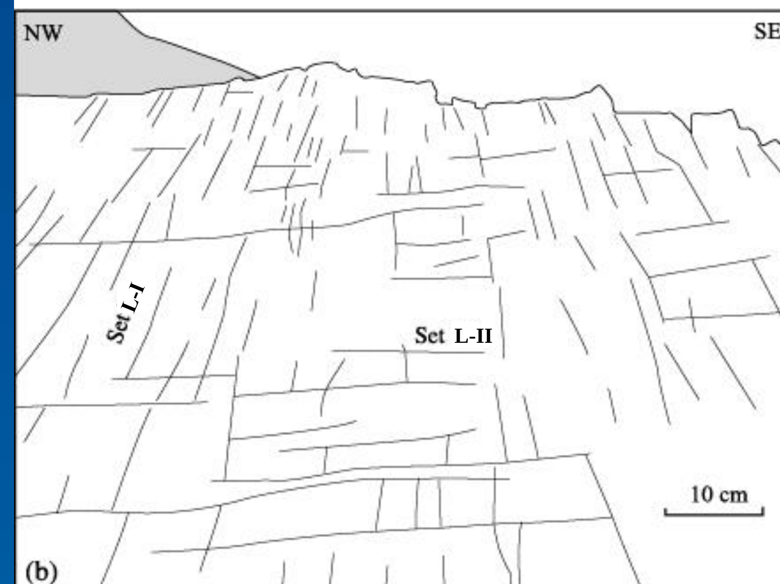


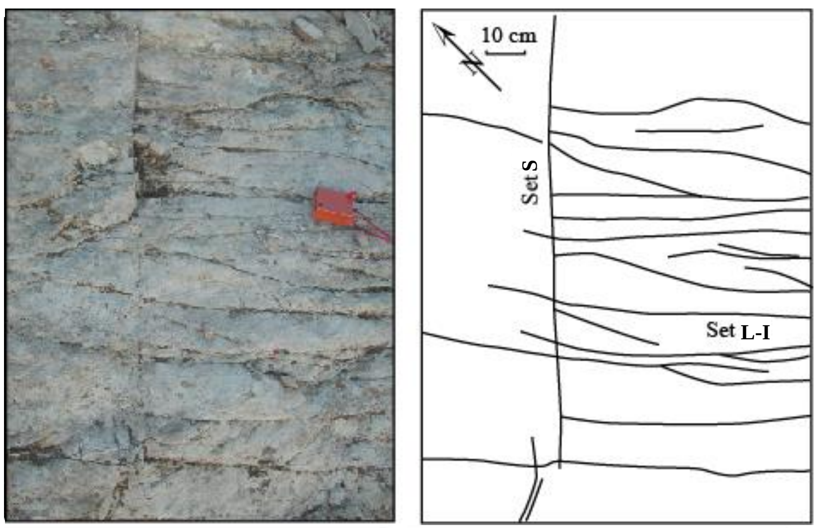


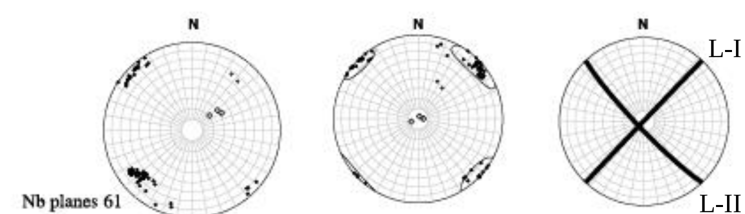
(Bellahsen et al., 2006; Barbier et al.,Tectonophysics, 2012)

Sheep Mountain anticline

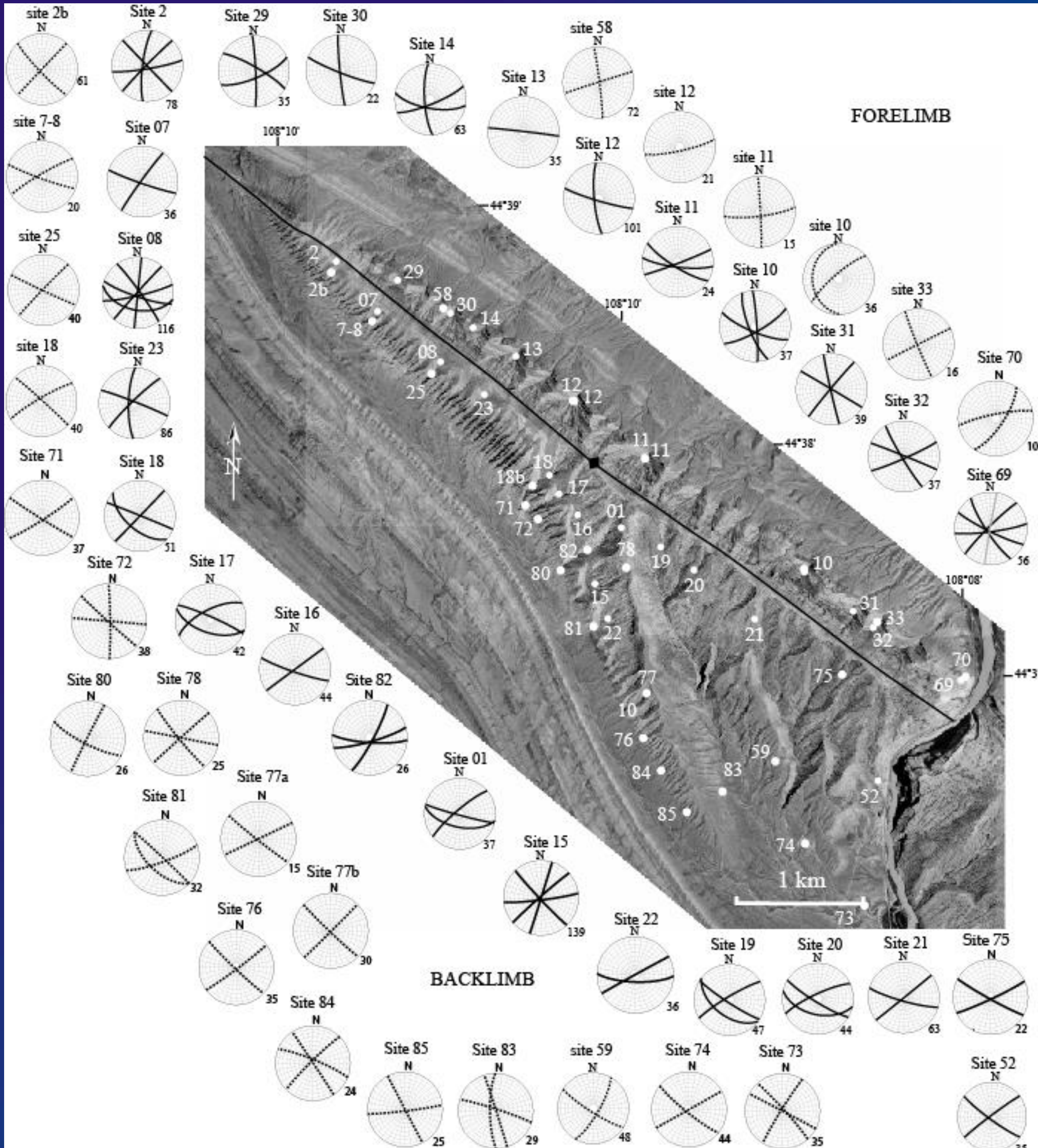








(Bellahsen et al., 2006;
Amrouch et al., Tectonics, 2010)

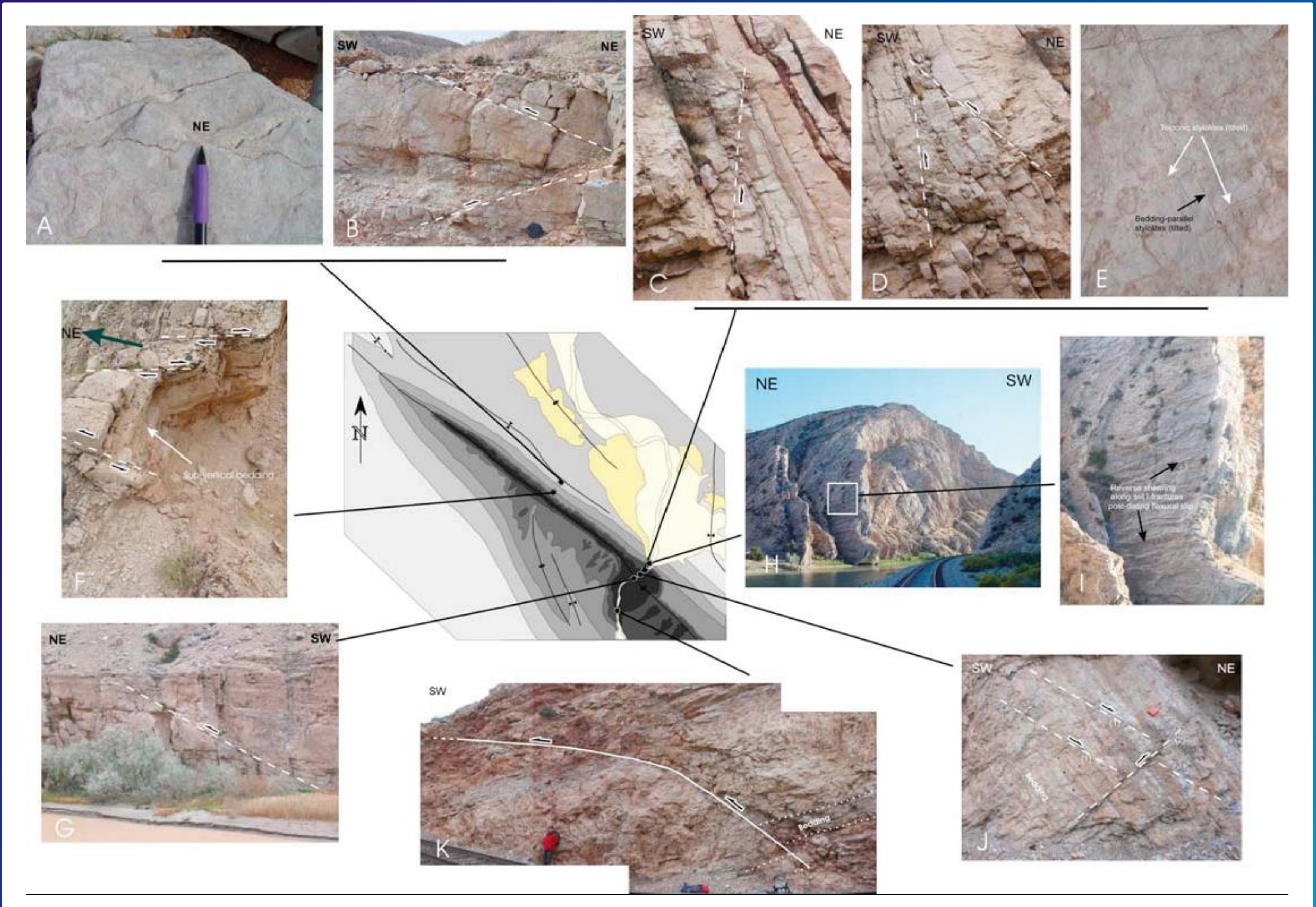


Sheep Mountain anticline

Distribution of joint/vein sets at different structural locations within the fold
(limbs, hinge, pericline)

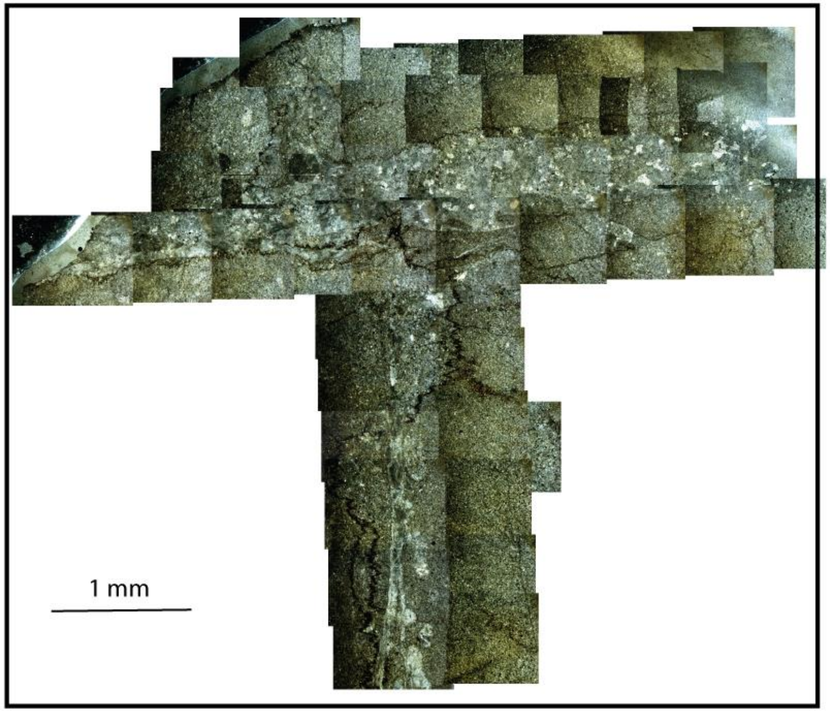
(Bellahsen et al., 2006;
Fiore, 2007;
Amrouch et al., Tectonics, 2010)

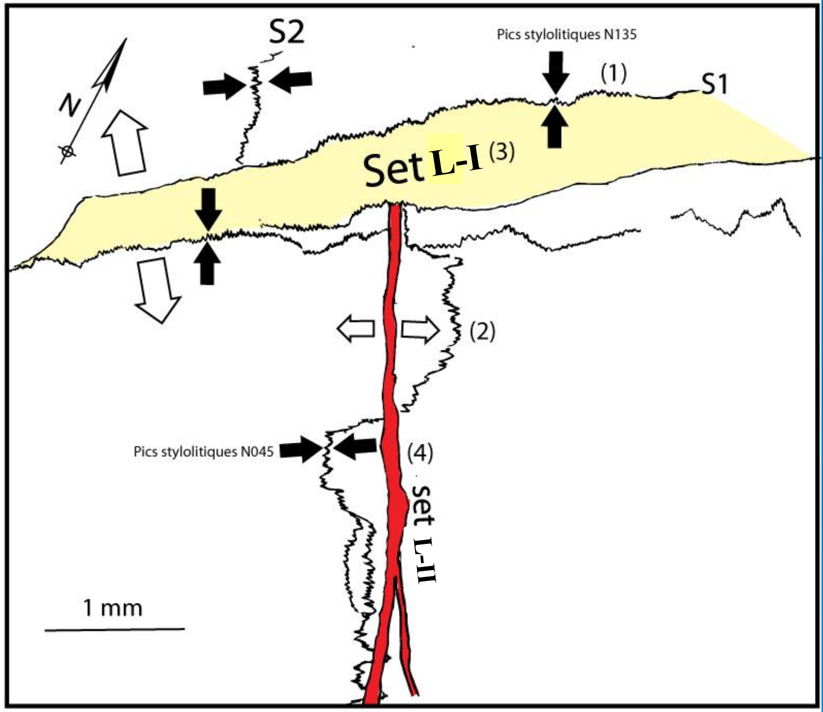
Pressure-solution and meso-scale faulting at Sheep Mountain anticline



(Amrouch et al., Tectonics, 2010)

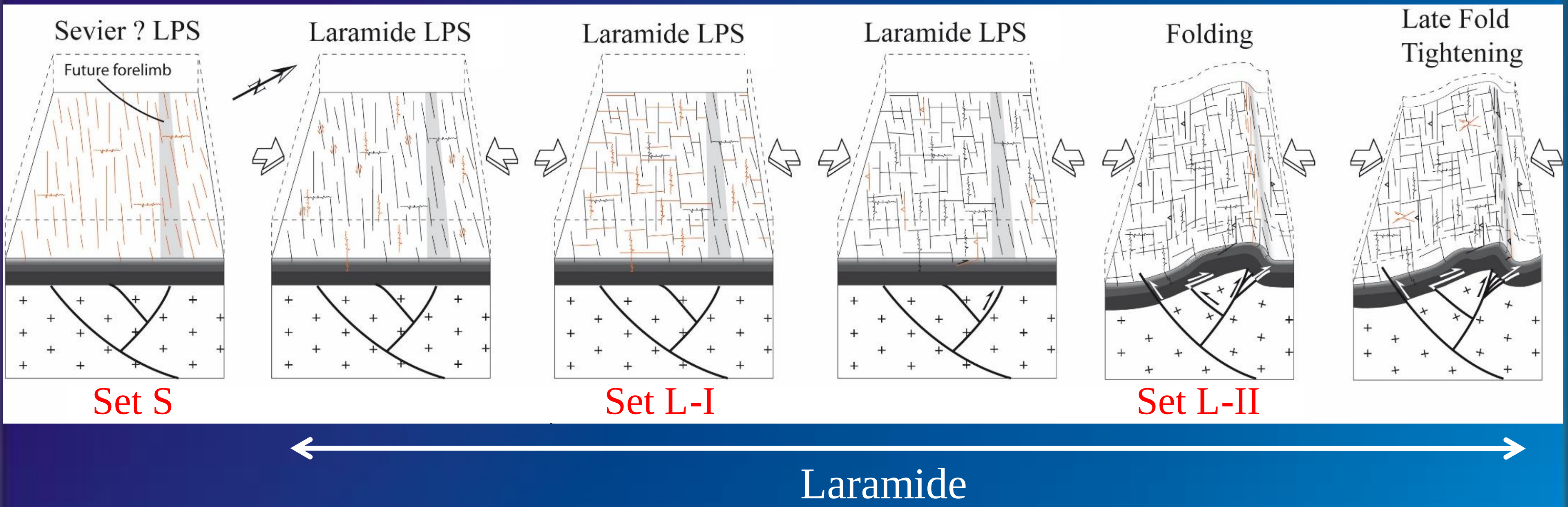
Relationships between pressure solution seams and veins



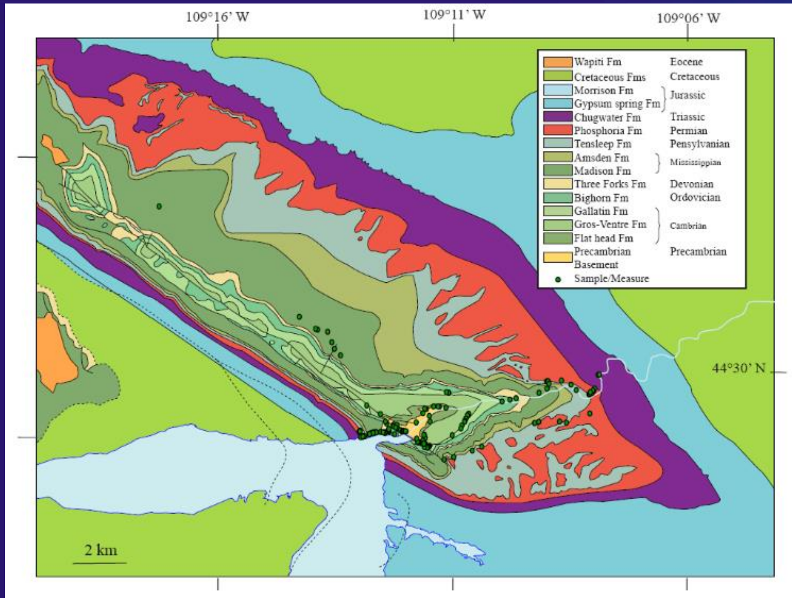


Sequence of fault-vein development at Sheep Mountain anticline

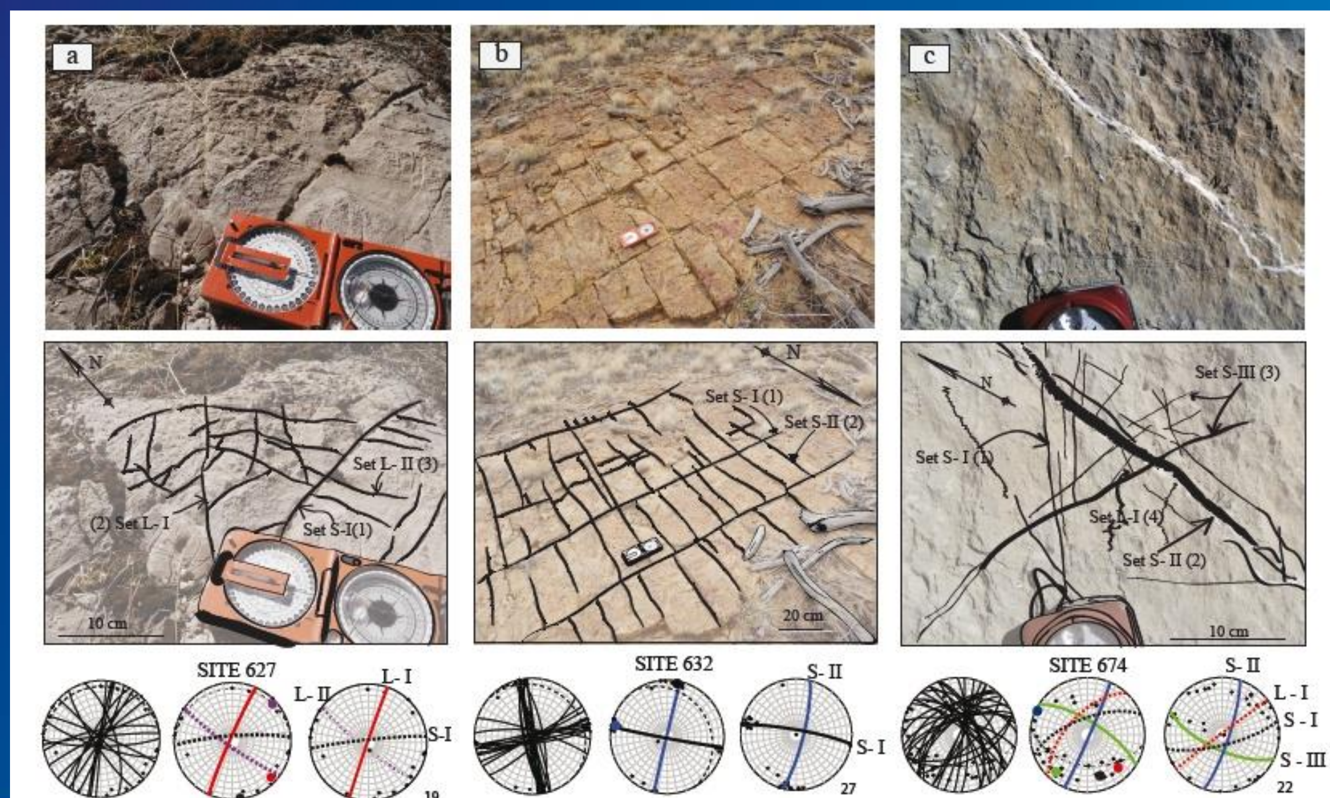
(Amrouch et al., GRL, 2011)



- <u>Mode I opening of pre-Laramide set S joints/veins</u>
- Shear reactivation of pre-Laramide set S veins (LPS).
- <u>Laramide stylolites with NE-trending peaks and mode I opening of set L-I veins (LPS)</u>
- Reverse faulting parallel to the fold axis (LPS).
- <u>Mode I opening of syn-folding, outer-rim extension-related set L-II veins</u>
- Late stage fold tightening (LSFT) marked by strike-slip faults and reactivation of tilted set S joints/veins as small reverse faults in the forelimb

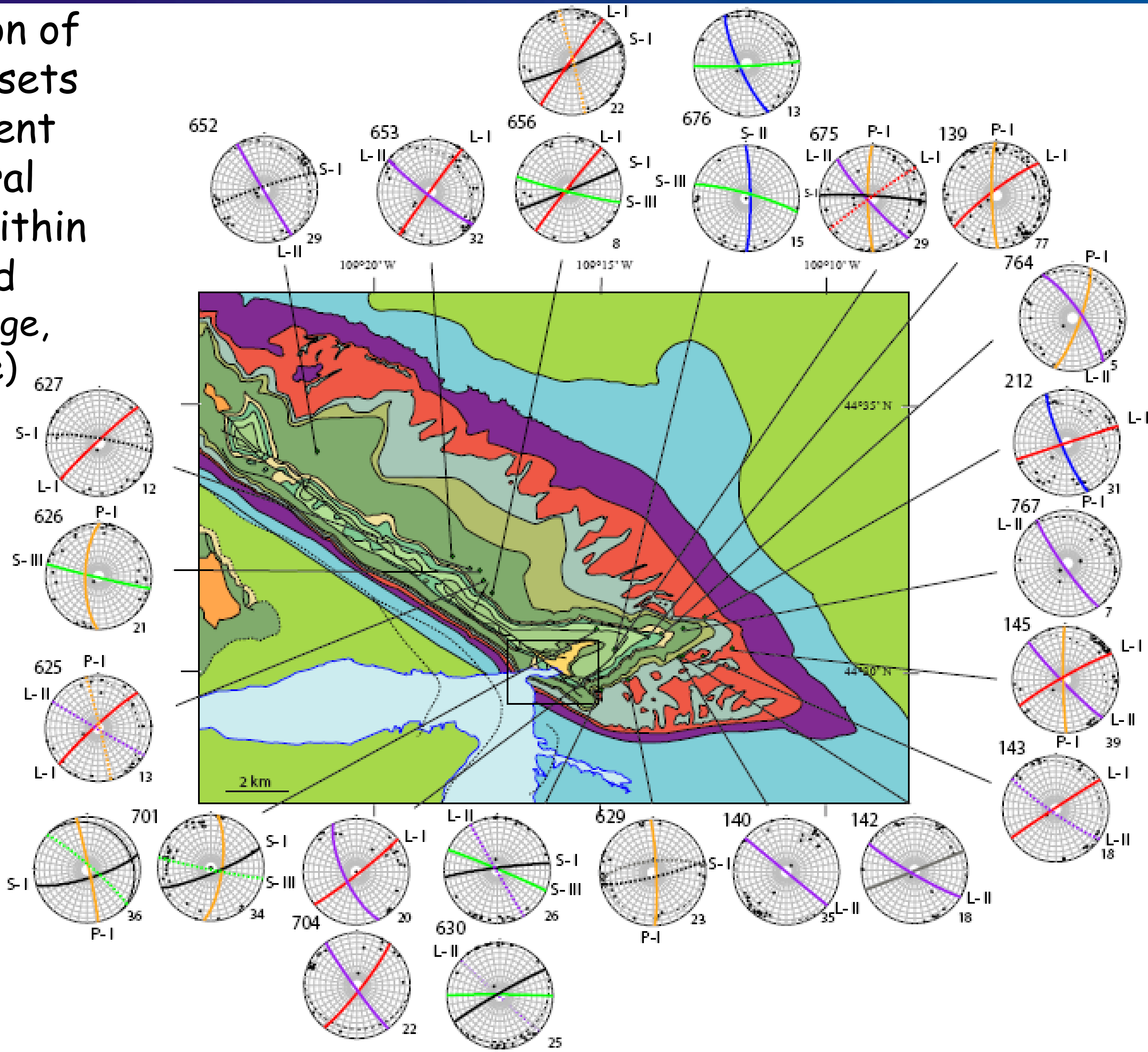


Rattlesnake Mountain anticline



(Beaudoin et al., Tectonophysics, 2012)

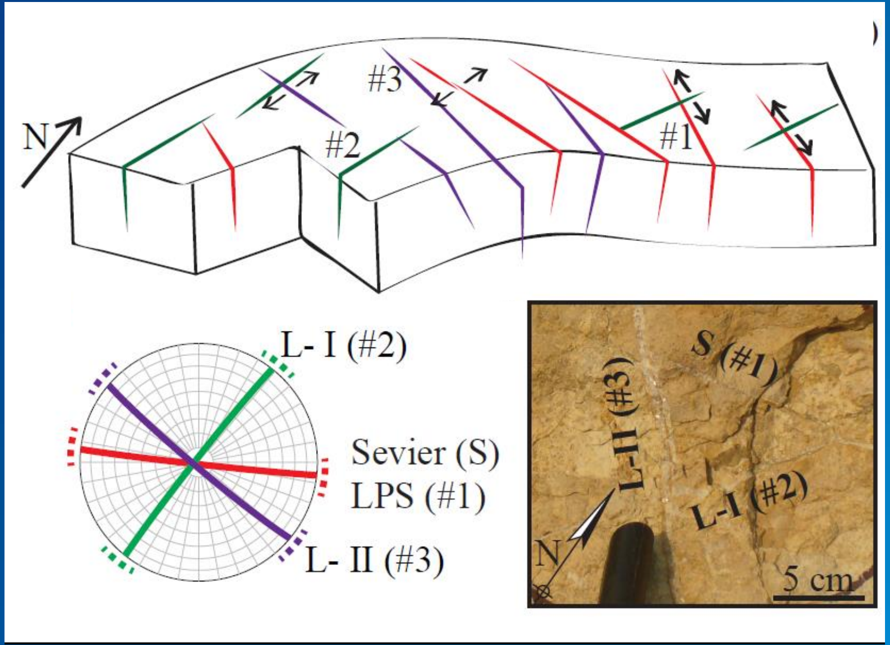
Distribution of joint/vein sets at different structural locations within the fold (limbs, hinge, pericline)



(Beaudoin et al., Tectonophysics, 2012)

Fracture sequence in the Bighorn Basin (SMA, RMA and other folds)

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

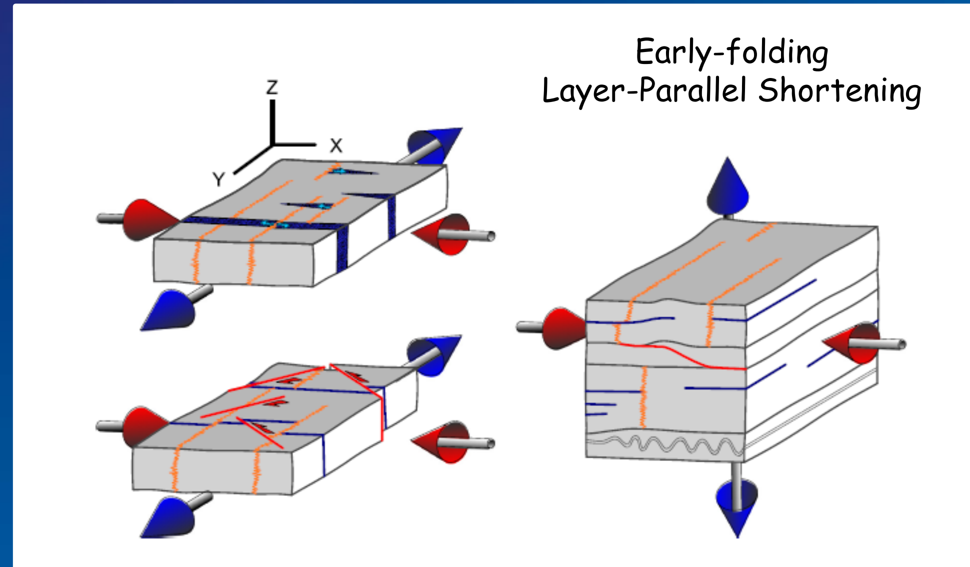


Systematic vein sets

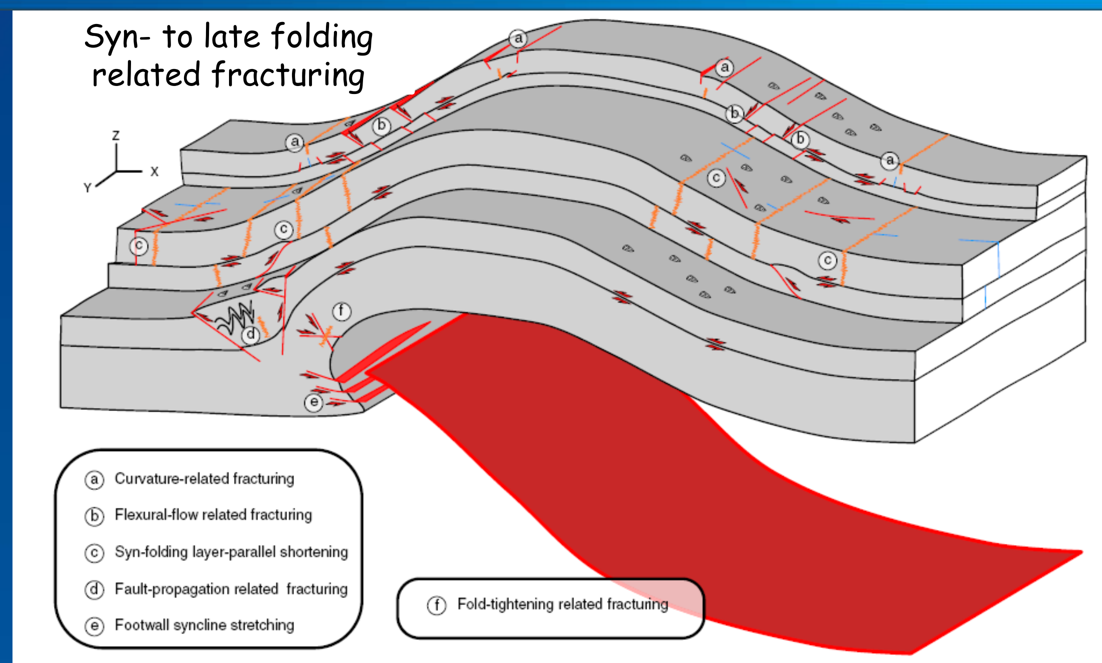
(Beaudoin et al., Tectonophysics, 2012)

*Widespread fold-related fractures
(early-, syn- and late- folding),
especially early-folding, LPS-related

* Pre-folding fractures are unrelated to either fold geometry or kinematics and are often reopened /sheared during folding
possibly inhibiting development of fold-related fractures



→ Complex fracture patterns in folded strata

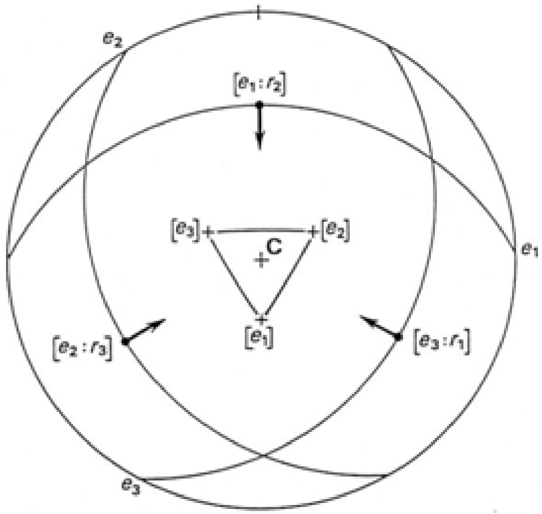


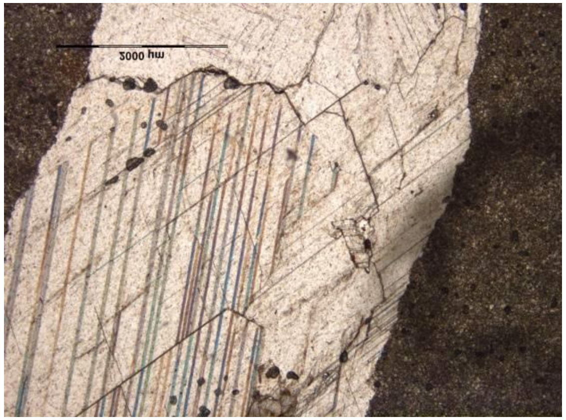
*Variable vertical persistence of fractures
(stratabound vs through-going),
hence potential variable vertical connectivity
and break in stratigraphic compartmentalization
(→ potential impact on fluid flow)

(Tavani et al., Earth Science Reviews, 2015)

Reconstruction of paleostress orientations and regimes
by inversion of calcite twins
(and striated meso-faults)
at Sheep Mountain and Rattlesnake Mountain
anticlines

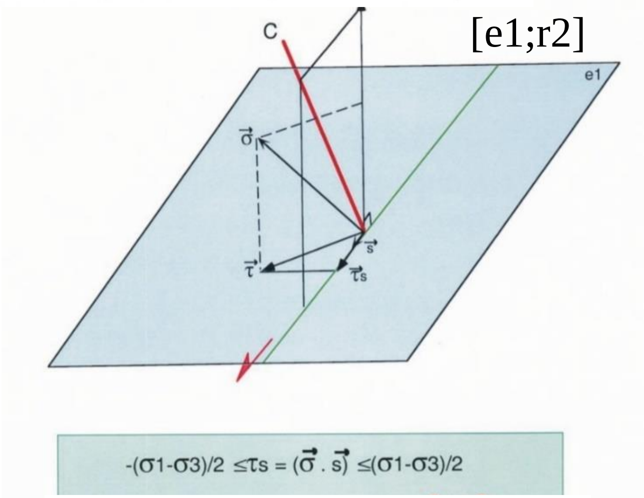
Etchecopar (1984) and Parlangeau et al. (2018) technique of inversion of calcite twin data for stress

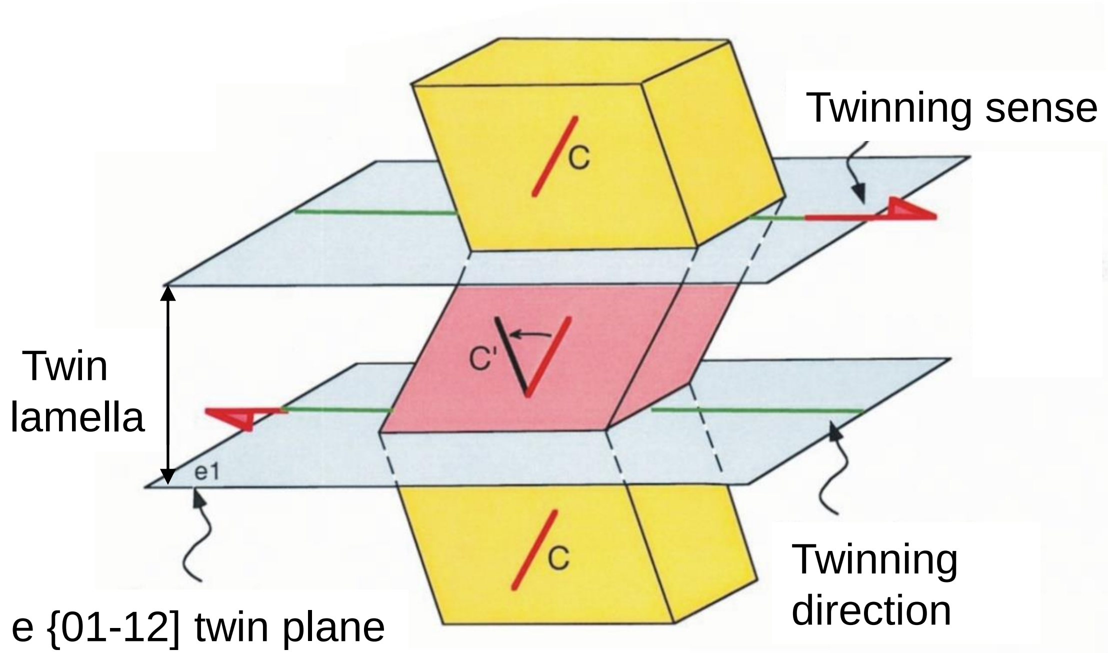




* Orientation of principal stresses
* Differential stress magnitudes

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



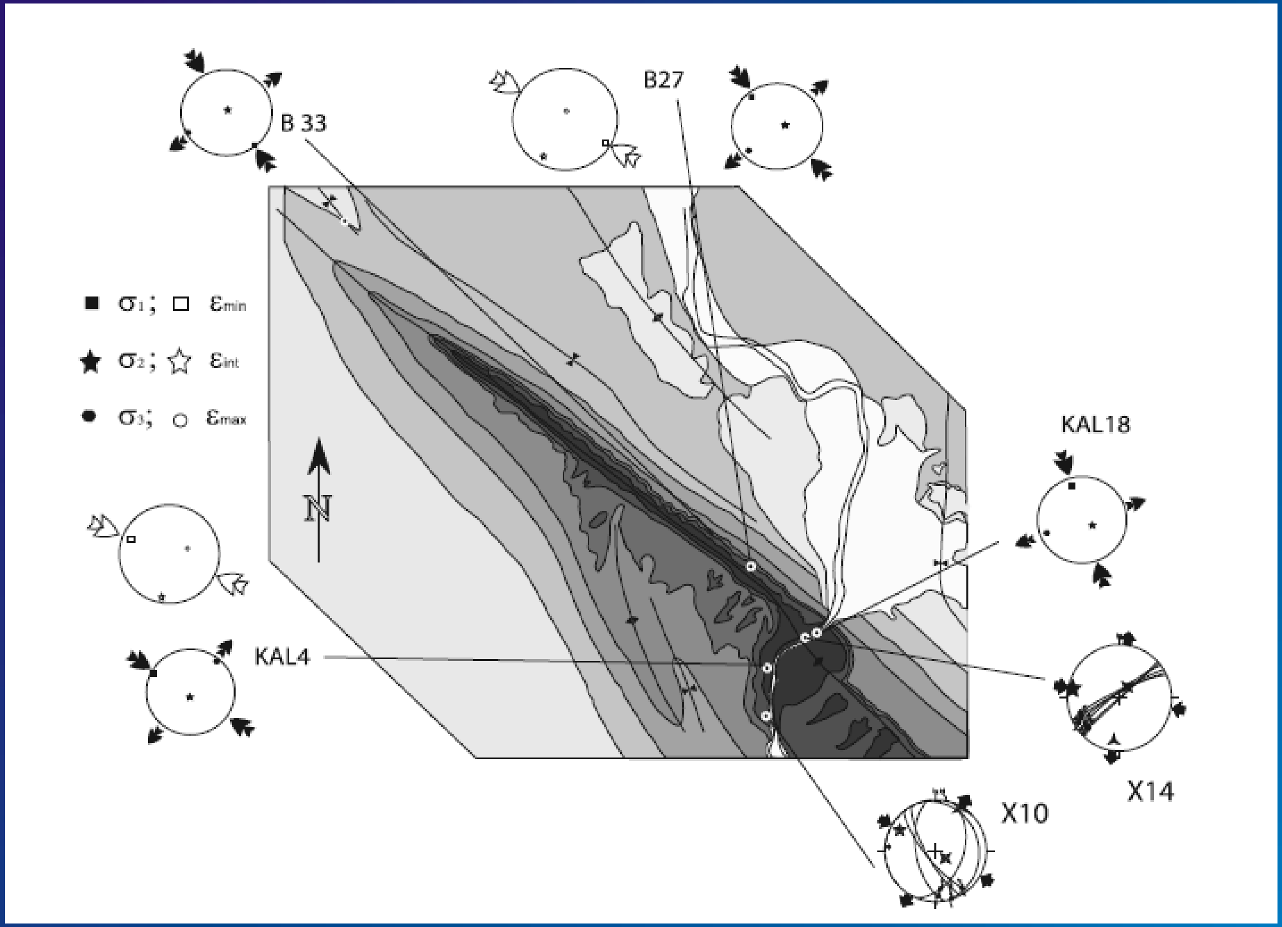


Calcite from S and L-I veins and/or rock matrix

(Amrouch et al., Tectonics, 2010)

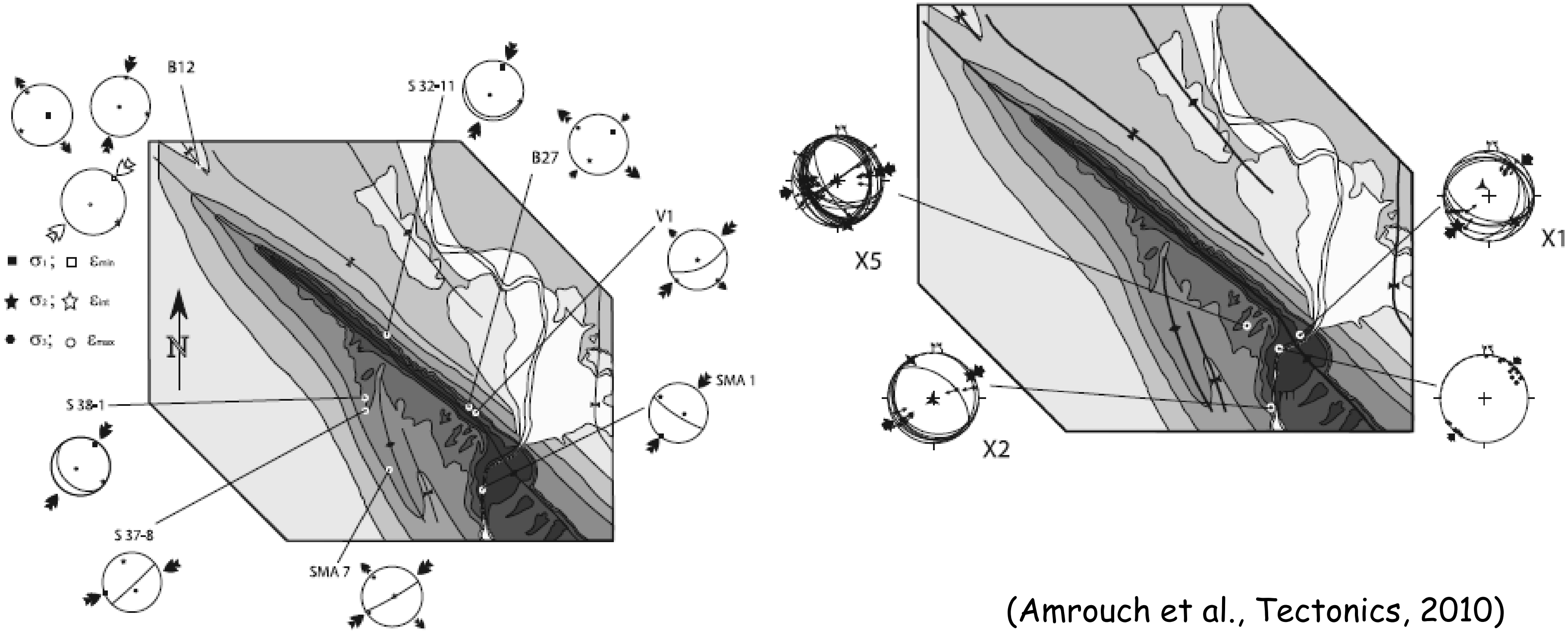
Sheep Mountain anticline

Pre-folding stage:



Set S formed under a WNW horizontal σ1
in a strike-slip stress regime (pre-Laramide : Sevier ?)

Early-folding stage:

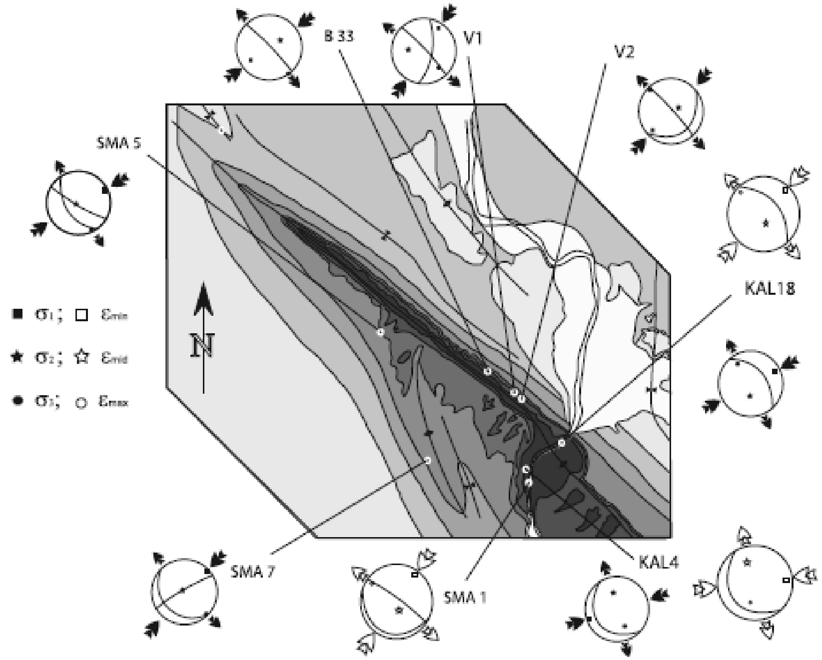


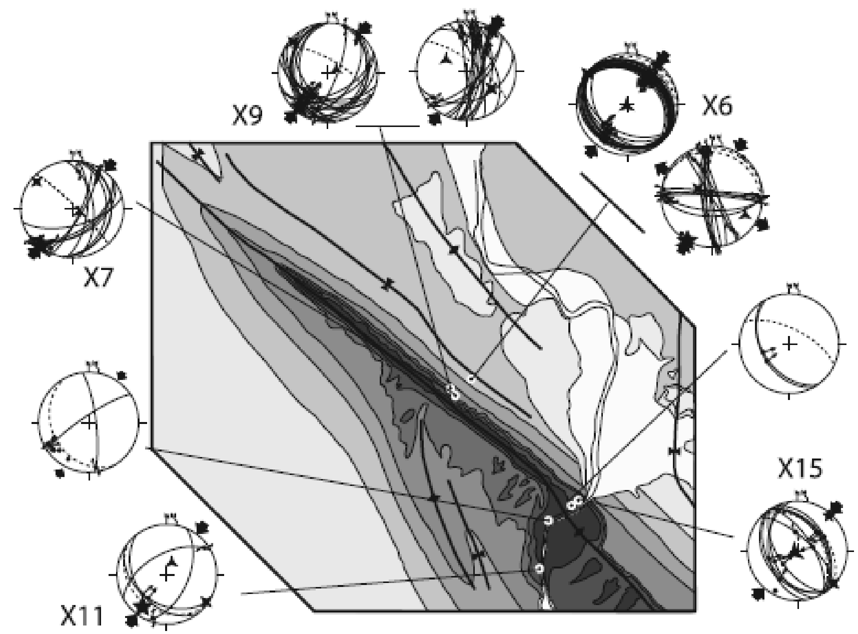
(Amrouch et al., Tectonics, 2010)

Set L-I formed under a NE horizontal σ1
either in strike-slip or compressional stress regime
= Laramide Layer-Parallel Shortening (LPS).

Late-folding stage:

(Amrouch et al., Tectonics, 2010)





Faults and calcite twins also reveal Laramide late fold tightening under NE horizontal σ1 in a strike-slip stress regime

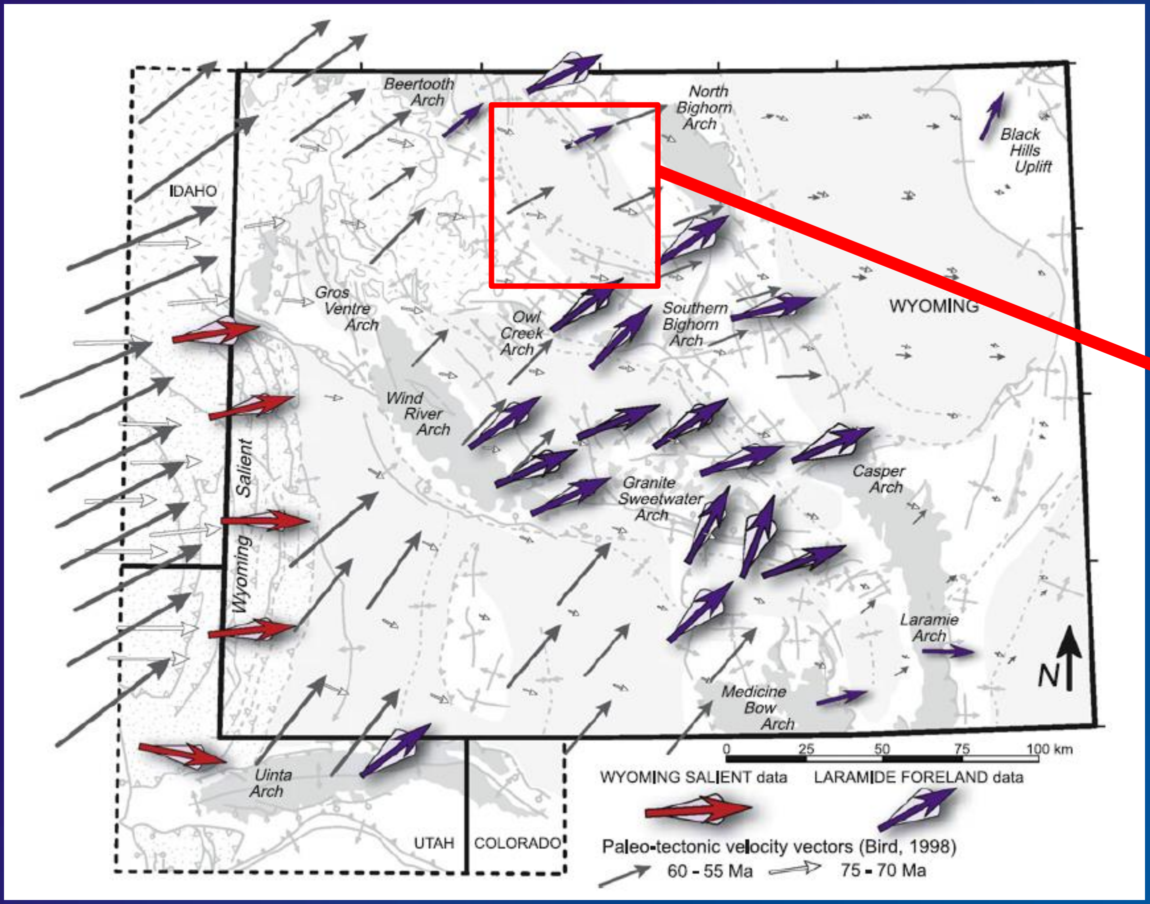
Paleostress orientations and regimes in the Bighorn Basin

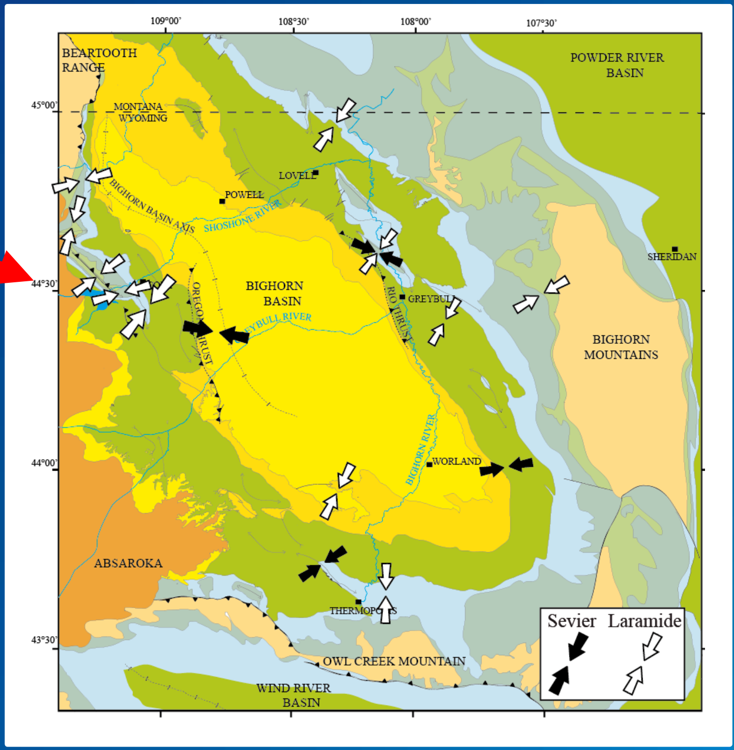
Fracture set	Mean strike of fractures	Paleostress from fractures	Paleostress from striated microfaults	Paleostress from calcite twins	Related Tectonic events
Set S-I	090°E to 060°E	σ_3 σ_1 ?			Sevier layer-parallel shortening ?
Set S-II	180°E to 020°E	σ_3			Formation of the flexural foreland basin
Set S-III	110°E	σ_3 σ_1 ?	σ_1	σ_1	Sevier layer-parallel shortening ?
Set L-I	045°E	σ_3 σ_1 ?	σ_3 σ_1	σ_1 σ_3	Laramide layer-parallel shortening
Set L-II	135°E	σ_3		σ_3	Local curvature-related extension
Set L-III	045°E		σ_1	σ_1 σ_3	Late stage fold tightening
Set P-I	180°E to 160°E	σ_3		σ_3	Basin and Range extension

Pre-Laramide / Laramide / Post Laramide

(Beaudoin et al., Tectonophysics, 2012)

(Weil and Yonkee, 2012)





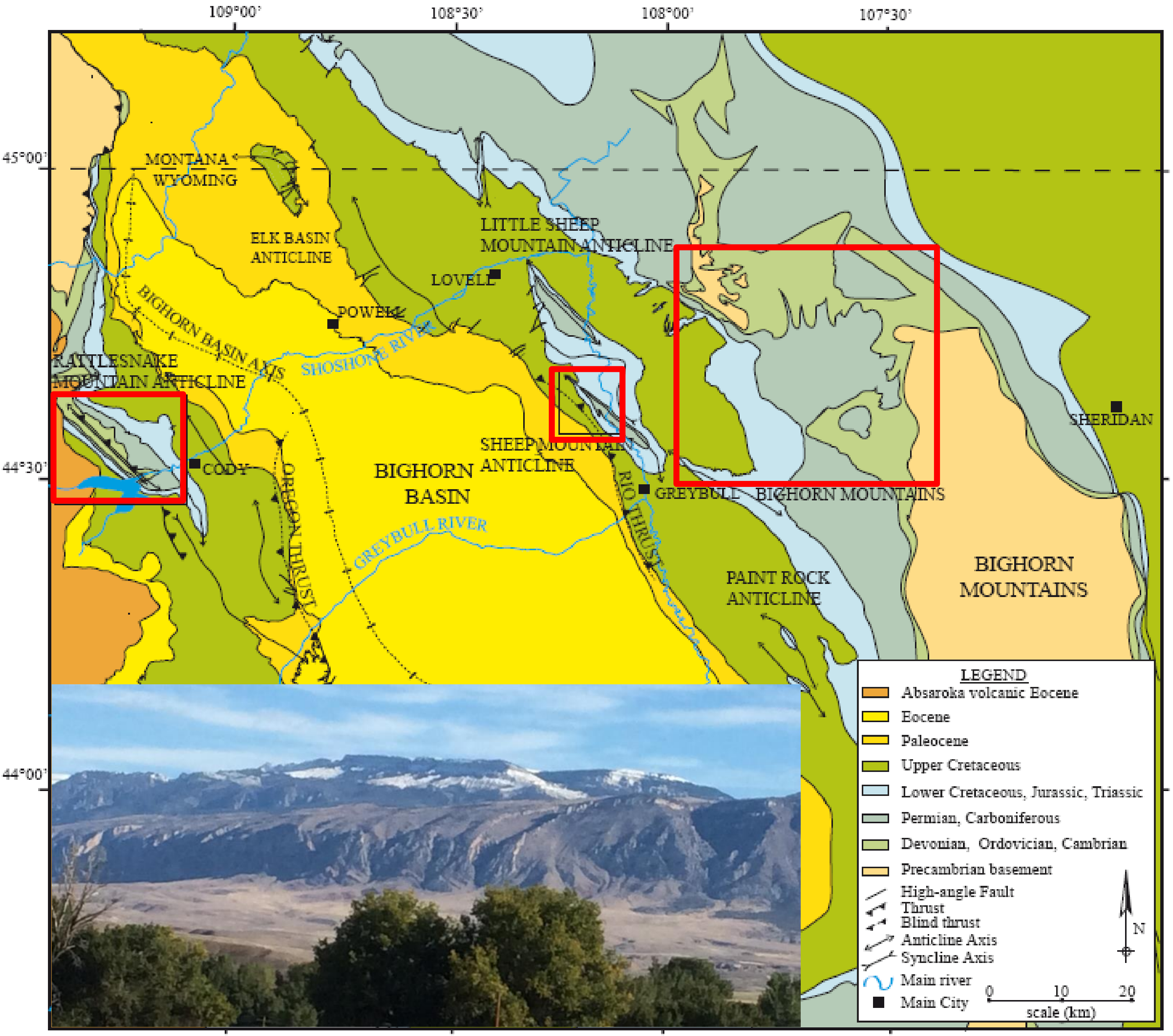
Stress history of the Bighorn Basin = polyphase

Laramide stress + pre-Laramide (Sevier ?) stress
+ …

Based only on (1) orientations of microstructures
and (2) relative chronology between
microstuctures and with respect to folding

Direct time constraints ?

Absolute (U-Pb) dating of calcite veins in the Bighorn basin : constraints on stress build-up and on the sequence of folding and basement thrusting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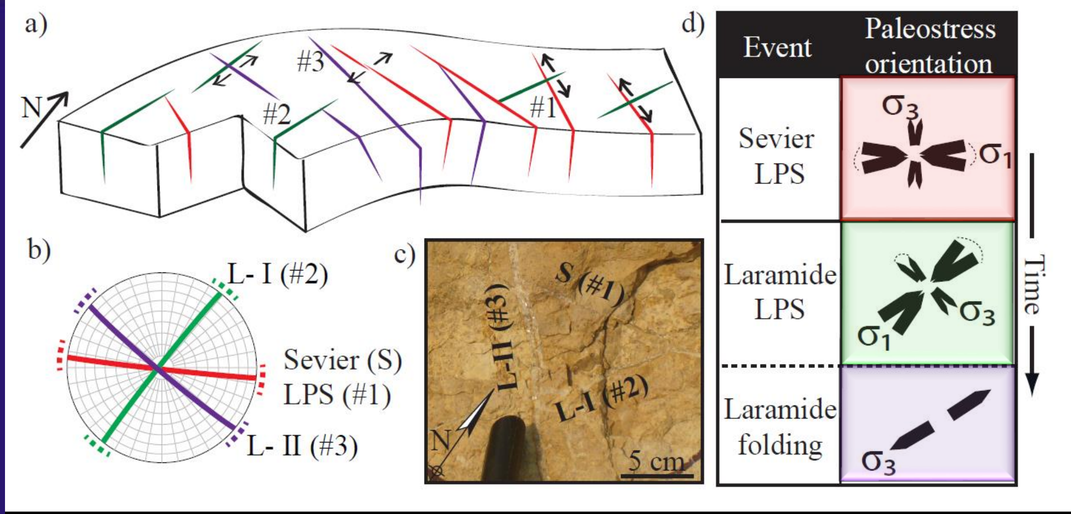
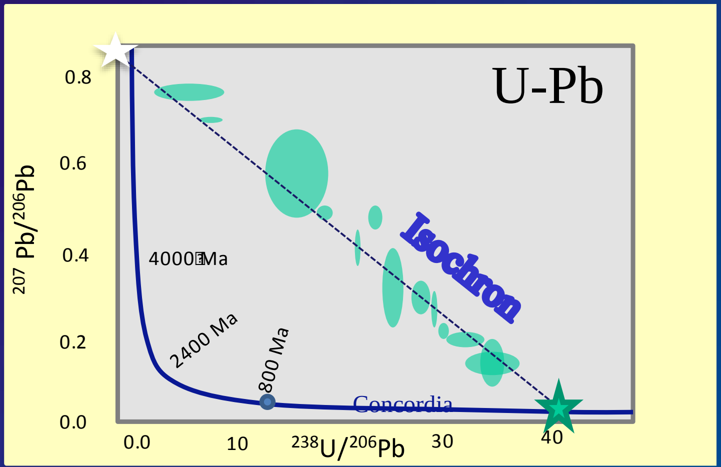
SHEEP MOUNTAIN ANTICLINE
RIO THRUST
GREYBULL
BIGHORN MOUNTAINS
GREYBULL RIVER
PAINT ROCK ANTICLINE
SHERIDAN
BIGHORN MOUNTAINS
LEGEND
Absaroka volcanic Eocene
Eocene
Paleocene
Upper Cretaceous
Lower Cretaceous, Jurassic, Triassic
Permian, Carboniferous
Devonian, Ordovician, Cambrian
Precambrian basement
High-angle Fault
Thrust
Blind thrust
Anticline Axis
Syncline Axis
Main river
Main City
N
0
10
20
scale (km)



TERA-WASSERBURG DIAGRAM



Technically challenging because of low U concentrations (<10 ppm) in calcite → several laser spots are needed

Better if :

- High heterogeneity in U/Pb and Pb/Pb ratios
- High U/Pb
- No mixing among phases (eg. partial dolomitization)

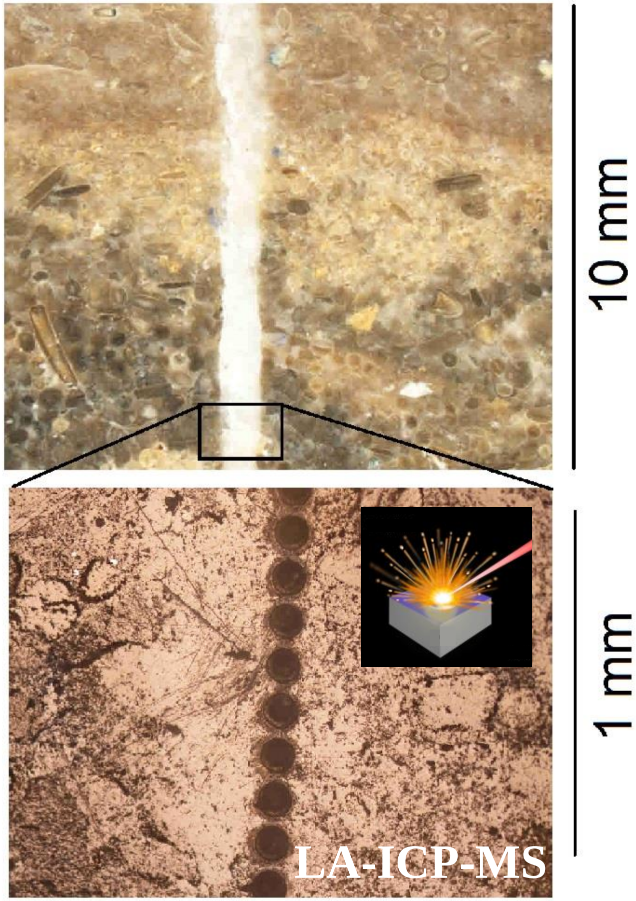
Data acquisition and treatment, Nick Roberts, BGS

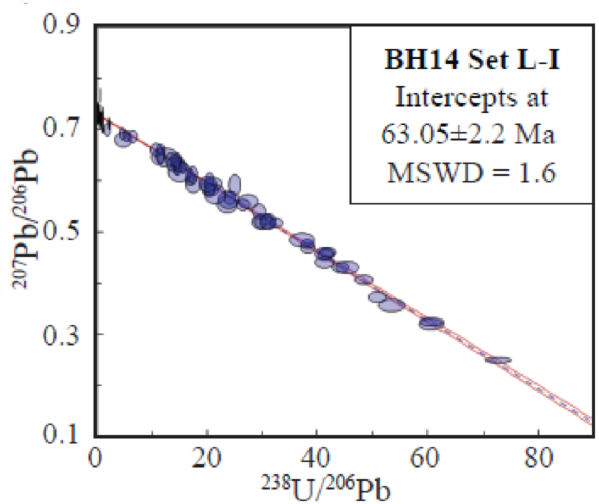
Criteria for reliable/accurate ages

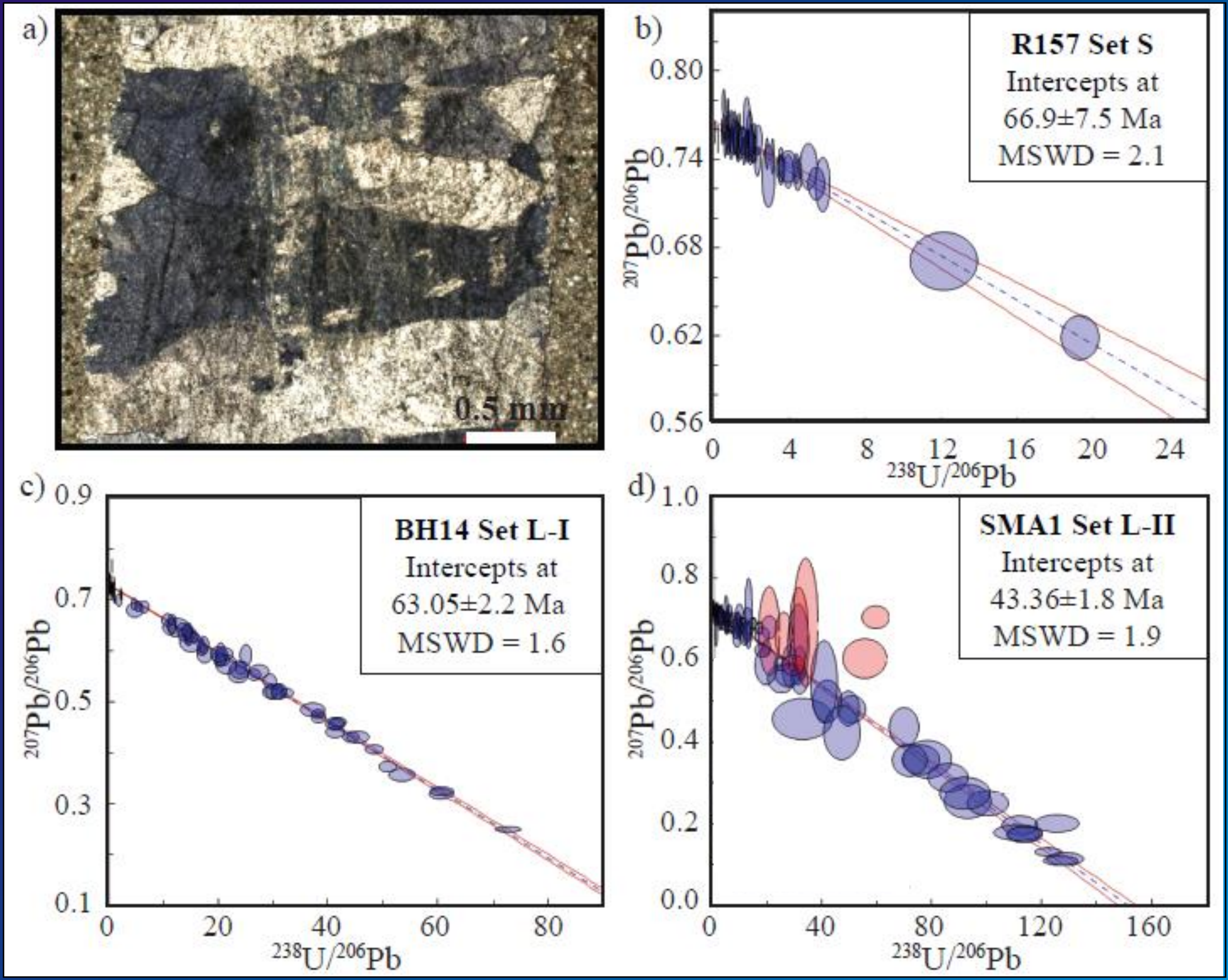
1) **MSWD < 2.5** Mean Squared Weighted Deviates

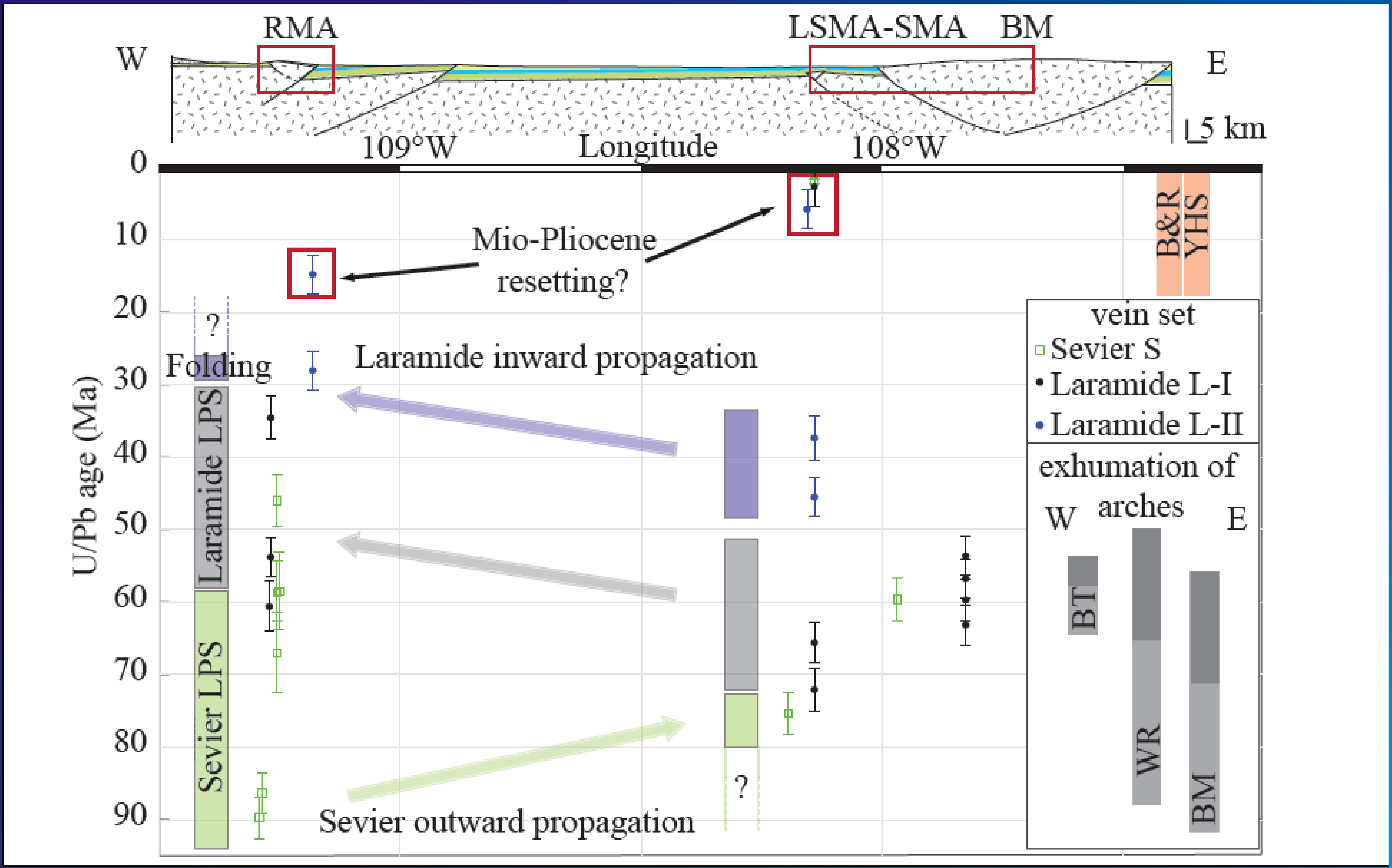
2) **n > 10** Number of ablation spots

3) **Er <5%** Relative error

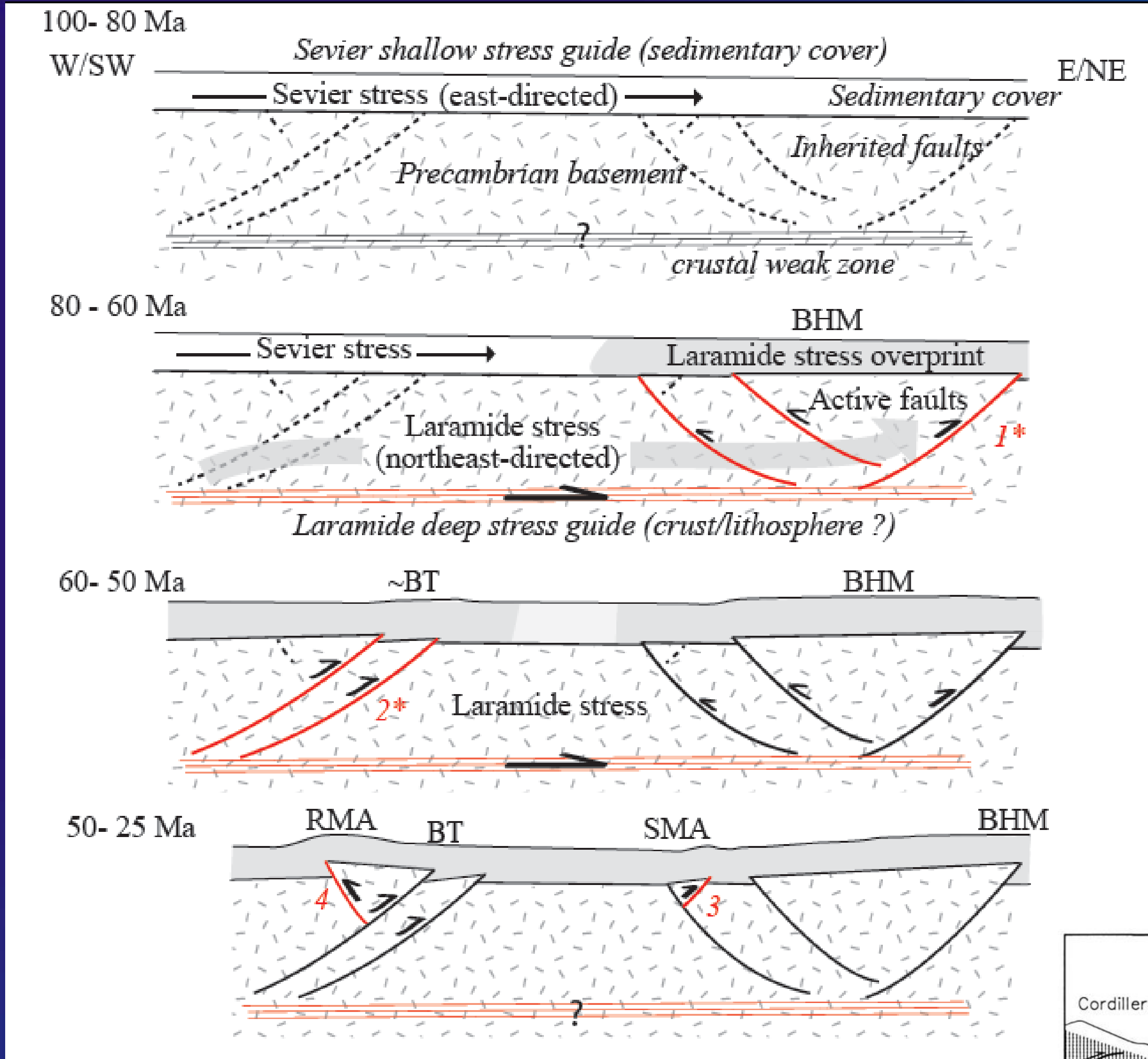





a)
0.5 mm
b)
R157 Set S
Intercepts at
66.9±7.5 Ma
MSWD = 2.1
0.80
0.74
0.68
0.62
0.56
0 4 8 12 16 20 24
207Pb/206Pb
238U/206Pb
c)
BH14 Set L-I
Intercepts at
63.05±2.2 Ma
MSWD = 1.6
0.9
0.7
0.5
0.3
0.1
0 20 40 60 80
207Pb/206Pb
238U/206Pb
d)
SMA1 Set L-II
Intercepts at
43.36±1.8 Ma
MSWD = 1.9
1.0
0.8
0.6
0.4
0.2
0.0
0 40 80 120 160
207Pb/206Pb
238U/206Pb



(Beaudoin et al., Geology, 2018)



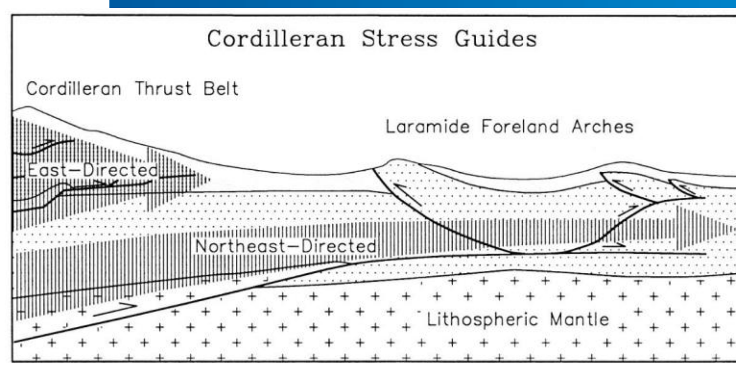
(Beaudoin et al., Geology, 2018)

*Occurrence of Sevier and Laramide related veins

*Time overlap between Sevier and Laramide stress reflects spatial stress compartmentalization within the basin

*Sequential thrust reactivation of inherited basement faults. Vertical transmission of Laramide stress from the basement to the overlying (attached) cover
→ progressive Laramide stress imprint

*Shallow Sevier stress guide (cover) vs deep Laramide stress guide (crust)



Schematic cartoon showing multiple stress guides and multilevel detachment during Cordilleran-Laramide lateral compression.

(Erslev, 1993)

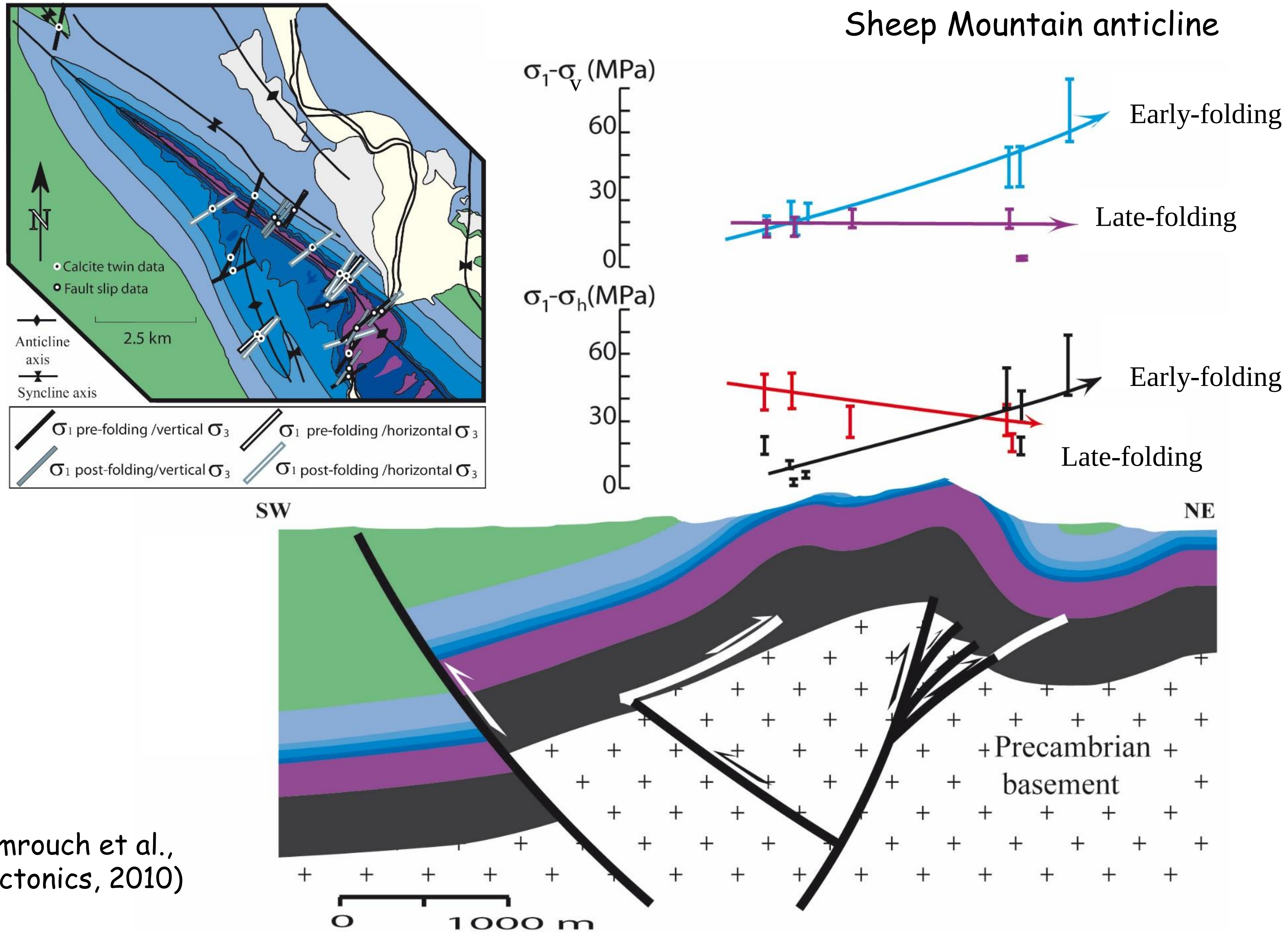
LA-ICP-MS U-Pb direct dating of calcite veins in the Bighorn Basin :

-provides absolute time constraints on formation/cementation of systematic vein sets
-confirms the relevance of vein sets to large-scale tectonics
-confirms existing models for propagation of Sevier deformation and for exhumation of Laramide basement-cored structures;
-helps refine age and sequence of activation of individual basement thrusts;
-improves our understanding of stress transmission and build-up throughout the basin.

→ Thin-skinned orogenic wedges develop through a progressive outward (forelandward) stress loading and propagation of deformation through time;
→ Thick-skinned systems show a more erratic sequence owing to the reactivation of basement heterogeneities that govern the stress field in the overlying sedimentary cover.

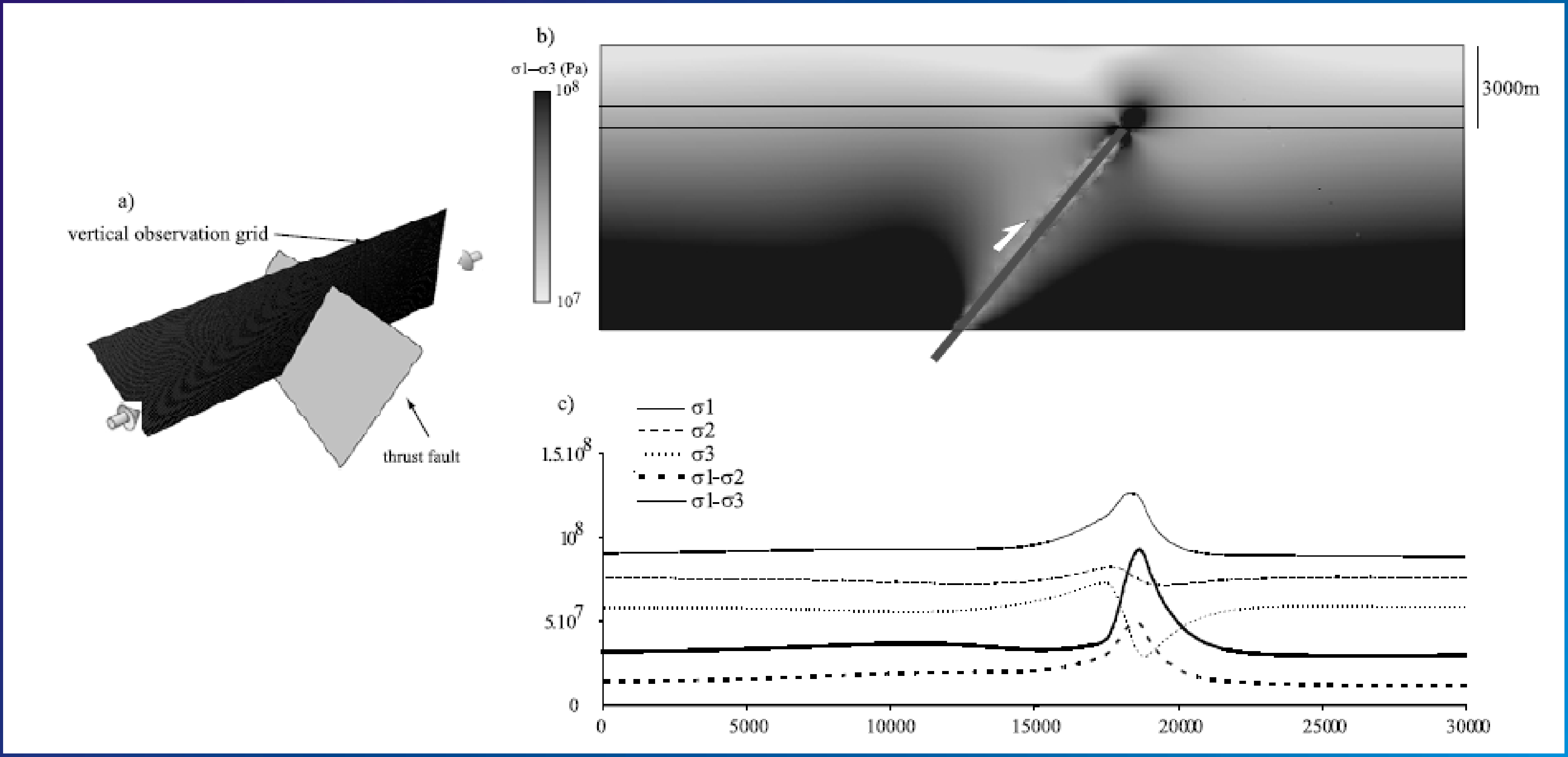
Magnitudes of differential stresses revealed by calcite twin analysis at Sheep Mountain and Rattlesnake Mountain anticlines

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



(Amrouch et al., Tectonics, 2010)

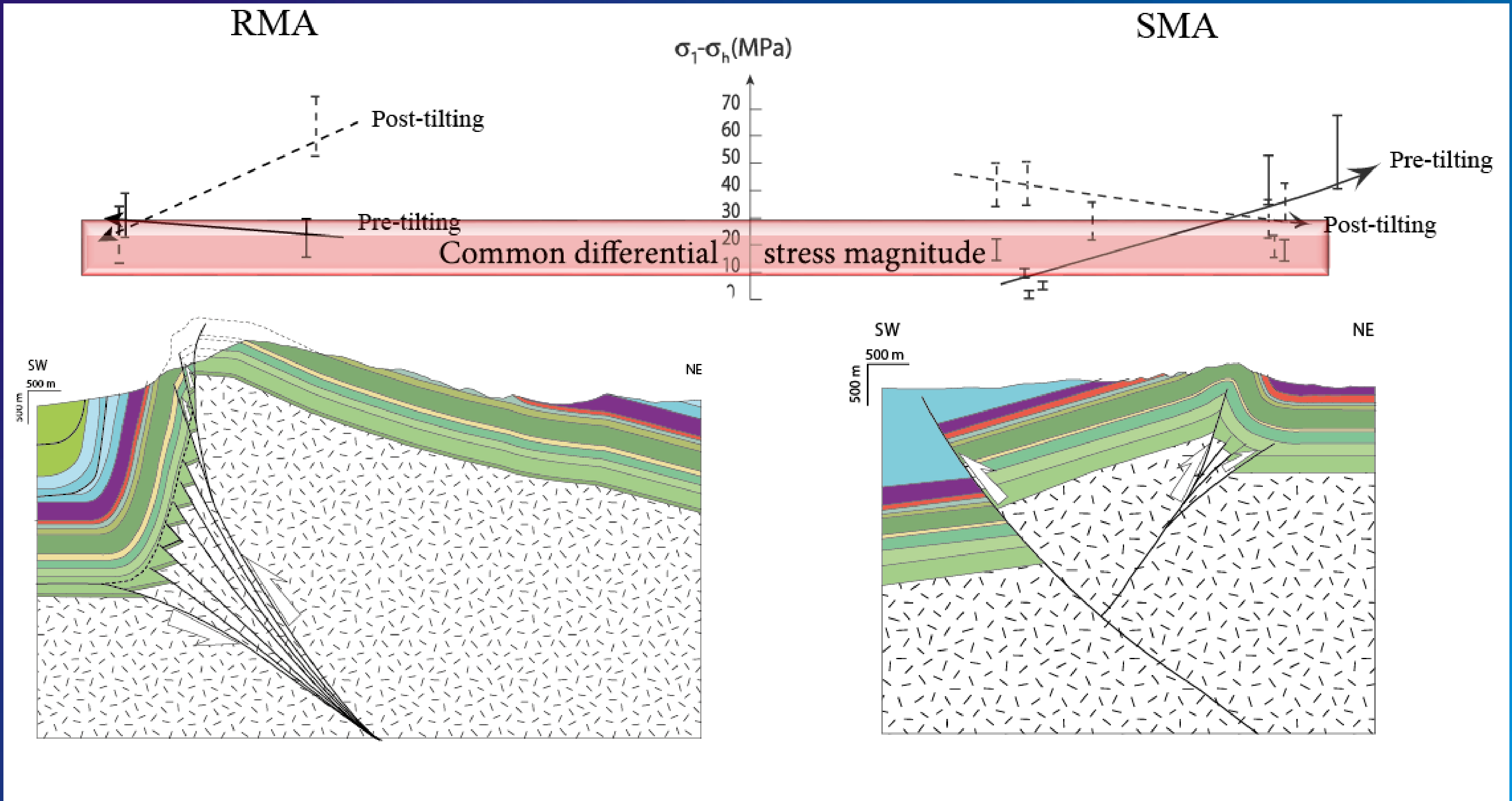
Stress perturbations in the cover at the tip of the underlying basement fault starting to move during Laramide stress build-up



(Amrouch et al. Tectonics, 2010)

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

(normalization of RMA to same depth than SMA for comparison)



(Beaudoin et al., Tectonophysics, 2012)

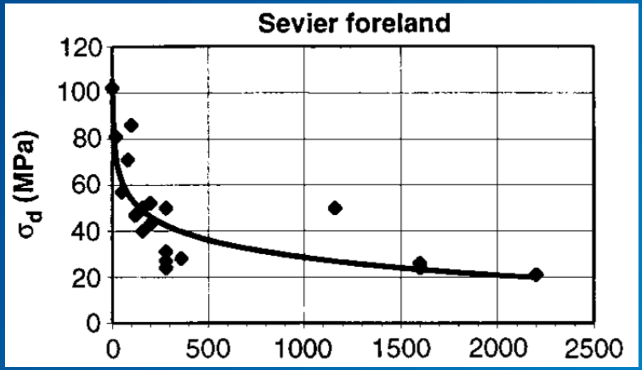
Sub-constant low background of Laramide differential stresses
in the cover of about 20±10 MPa

Local variations

related either to perturbations at the tip of underlying basement thrusts and/or to stress increase where strata remain weakly internally deformed.

Asymmetrical stress distribution between fold limbs
echoing asymmetry of folding above a basement thrust

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



(Van der Pluijm et al., 1997)

→ <u>influence of the structural style</u> :
stress magnitudes in the cover 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

Vein-filling calcite : an access to fossil fluids

Calcite veins :

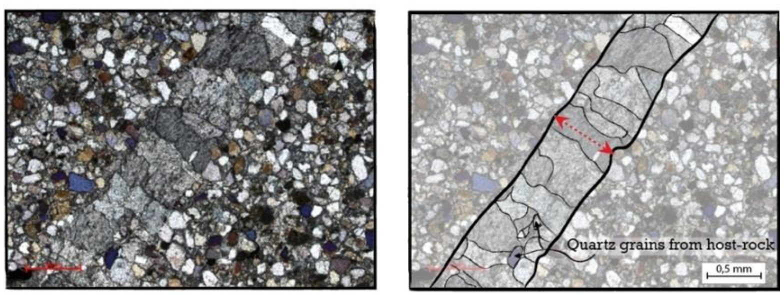
- O, C stable isotopes
- Microthermometry of fluid inclusions
- Sr ratios

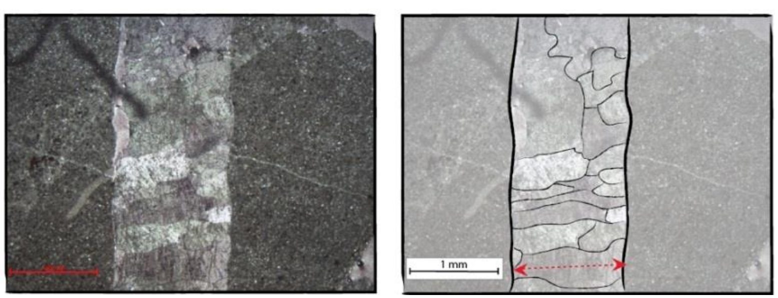
→ Fluid temperature, origin and pathway

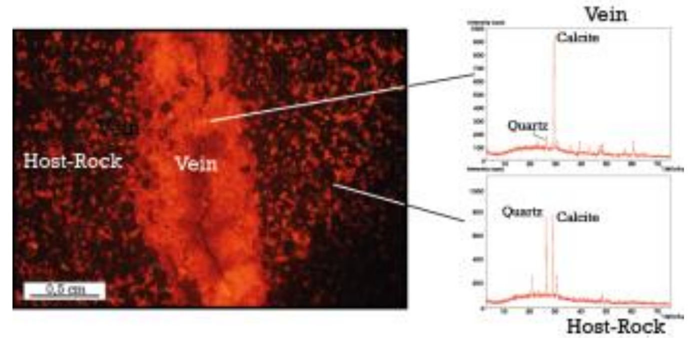
Host rocks :

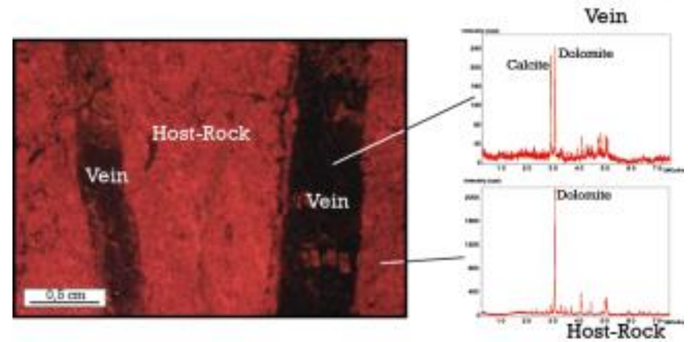
- O, C stable isotopes
- Sr ratios

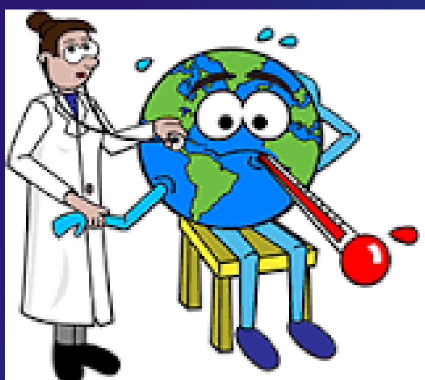
→ Fluid-rock interactions

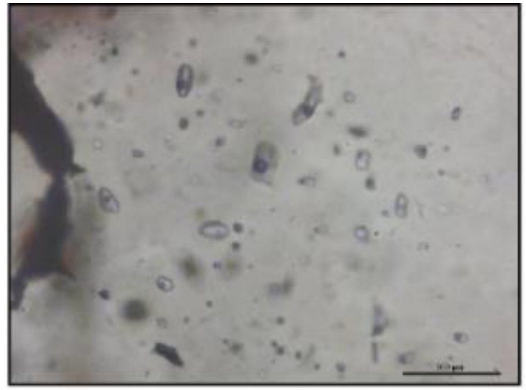


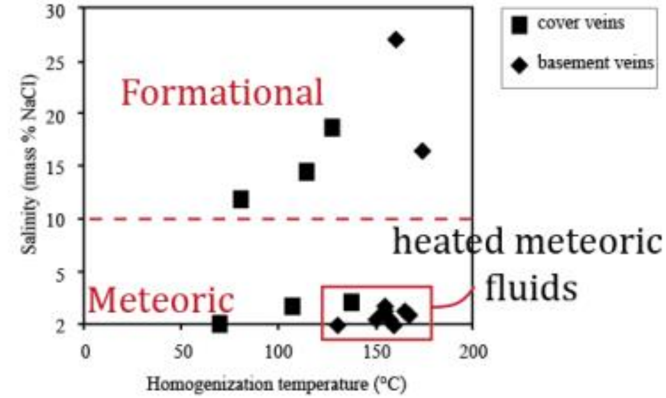


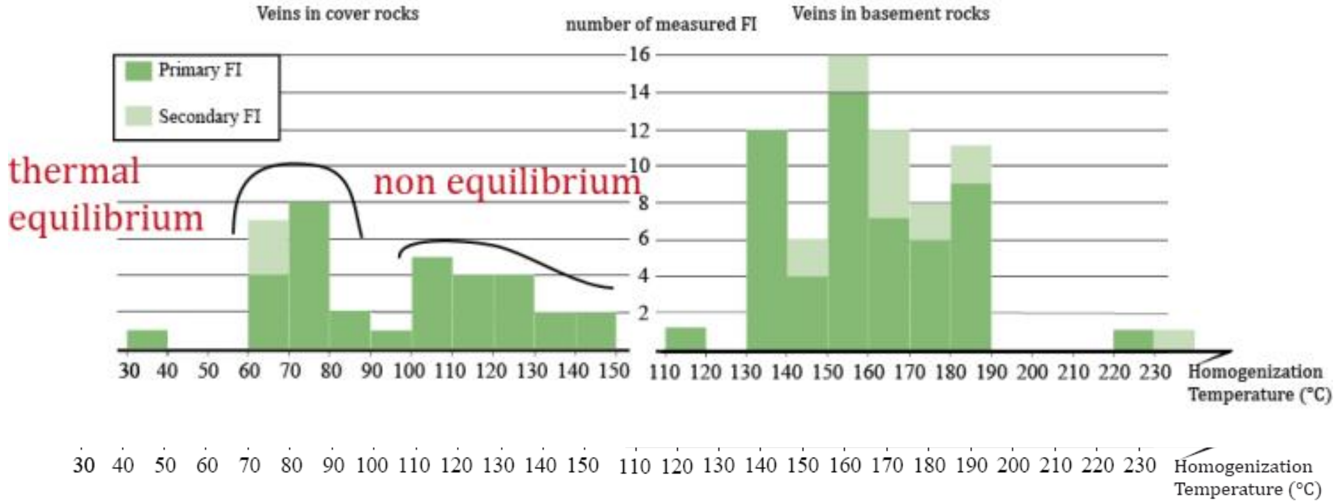


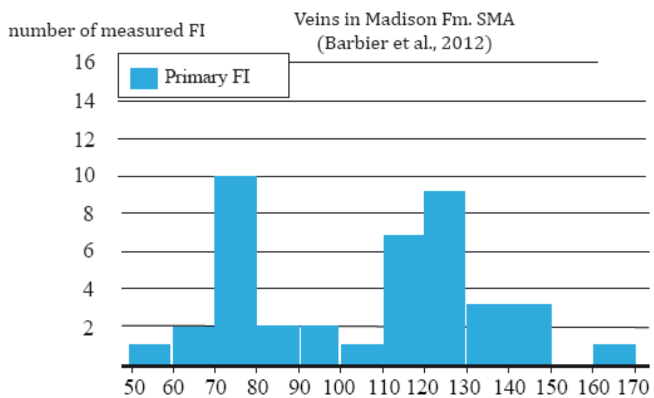






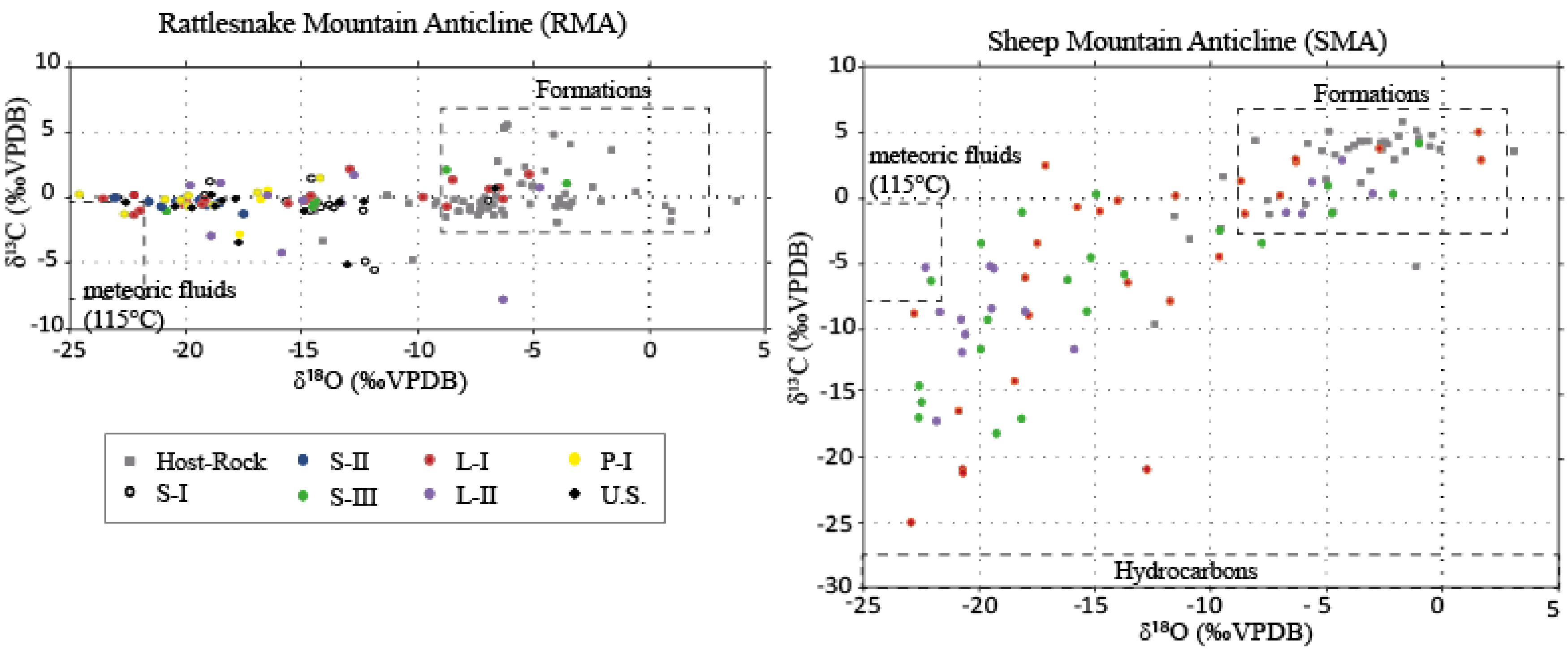






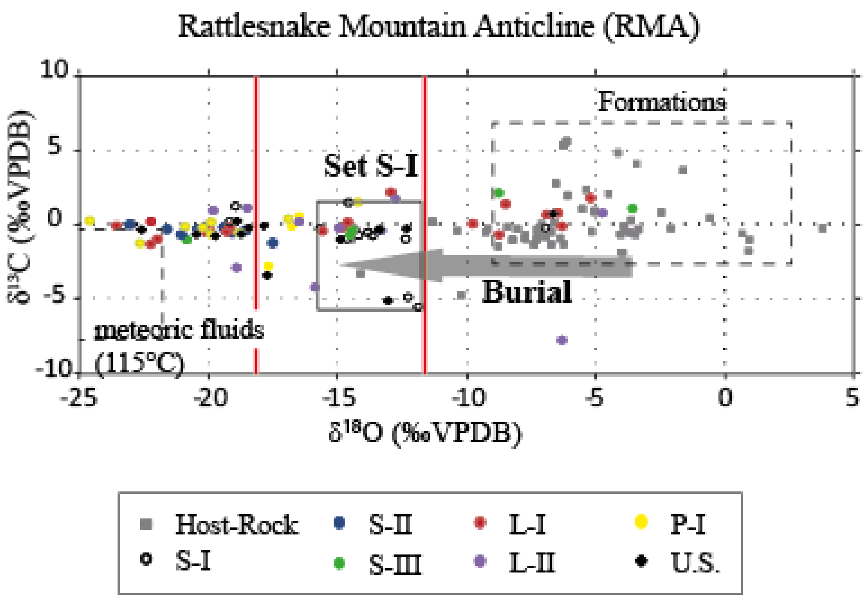
Microthermometry and
Raman spectroscopy
of fluid inclusions

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

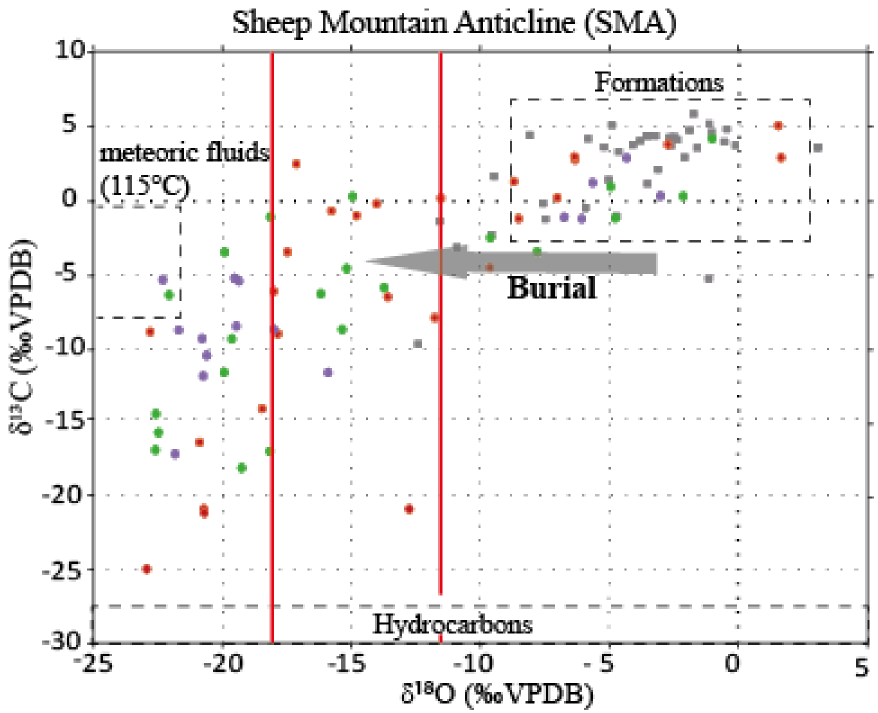


Evolution of fluid system in SMA and RMA

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

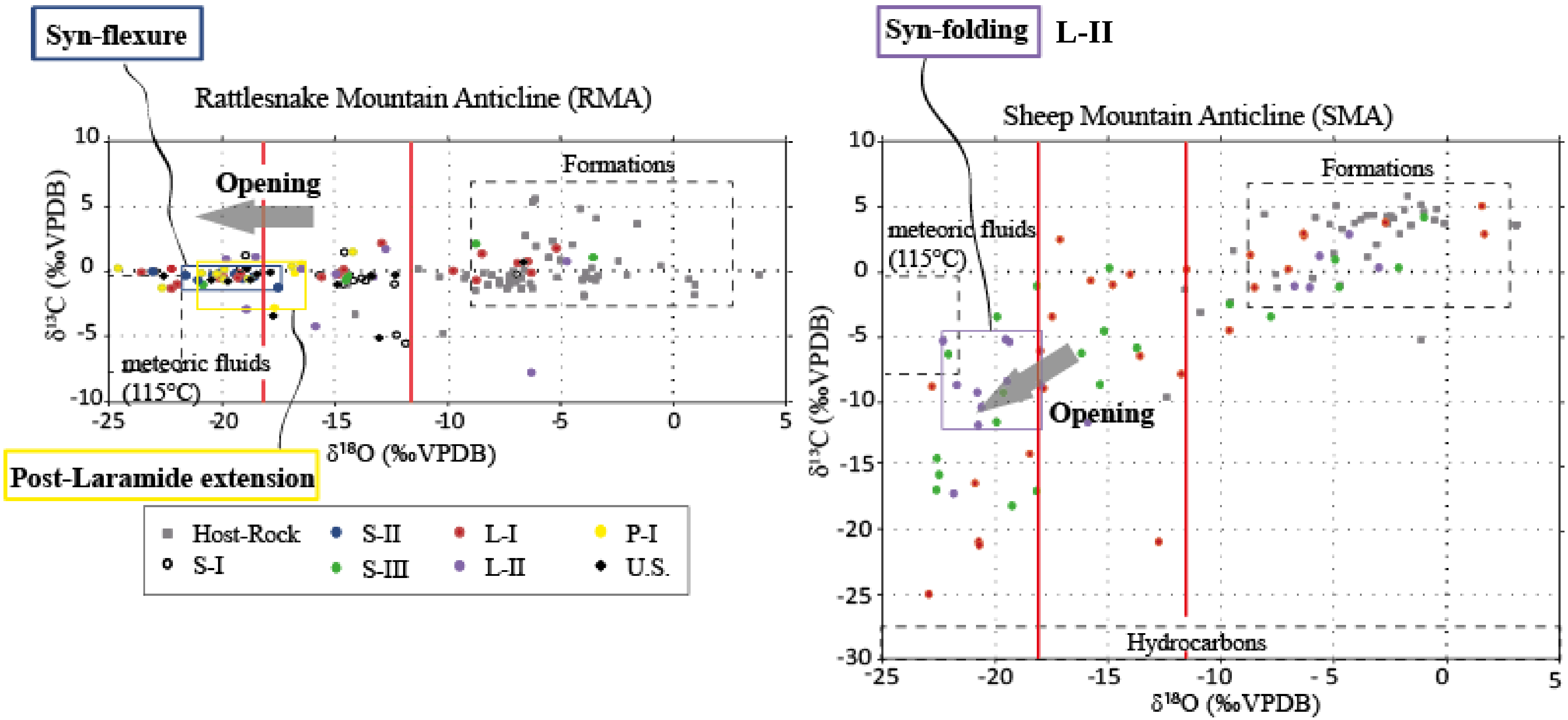


High $\delta^{18}O$ depletion and thermal disequilibrium with host-rock | $\delta^{18}O$ depletion but thermal equilibrium with host rock | Total isotopic and thermal equilibrium with host-rock



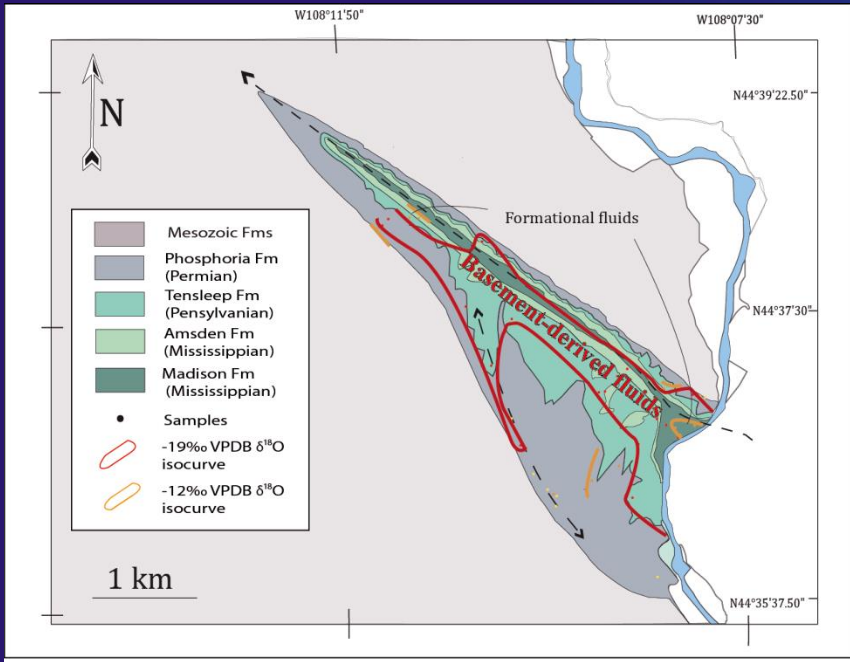
Evolution of fluid system in SMA and RMA

(Beaudoin et al, G3, 2011; Basin Research, 2014)



3 stages of fluid system opening :
Sevier flexure, Laramide folding, post-Laramide extension

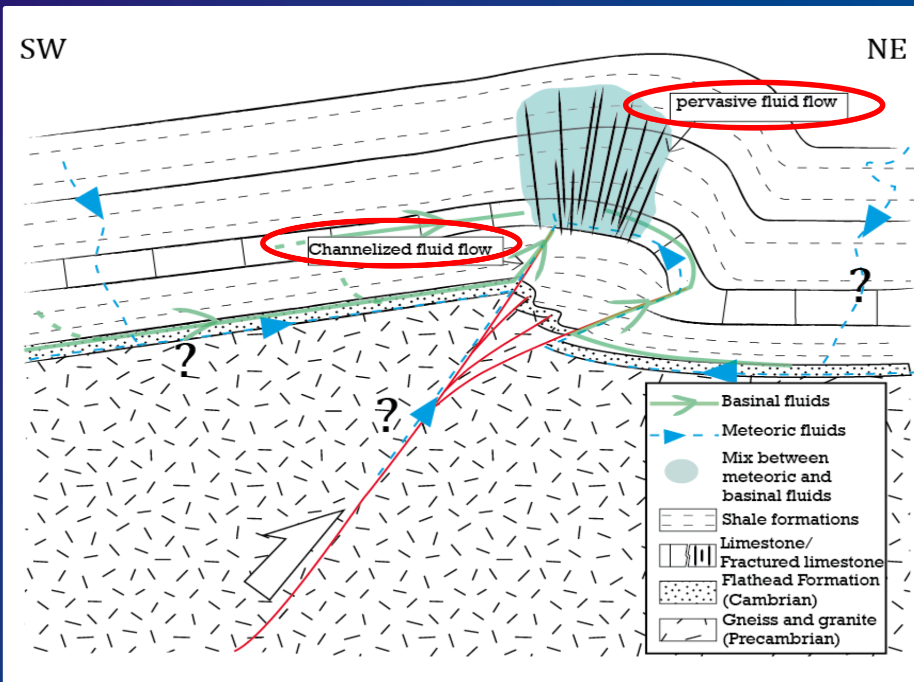
Localization of basement-derived hydrothermal fluid pulse at SMA

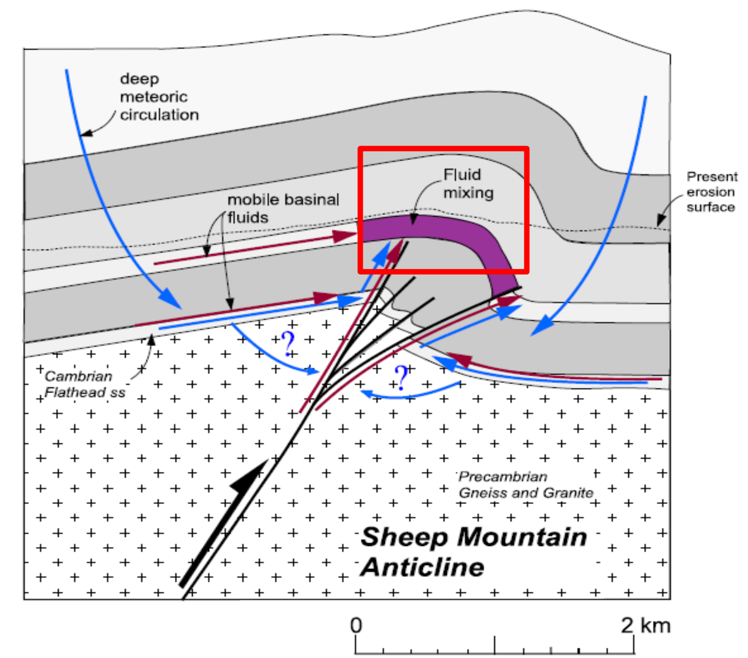


Vertical migration of deeper radiogenic hot fluids within the sedimentary cover explained by the development of Laramide curvature-related veins (L-II) that enhance the hydraulic permeability of the reservoir and break fluid compartmentalization by stratigraphy.

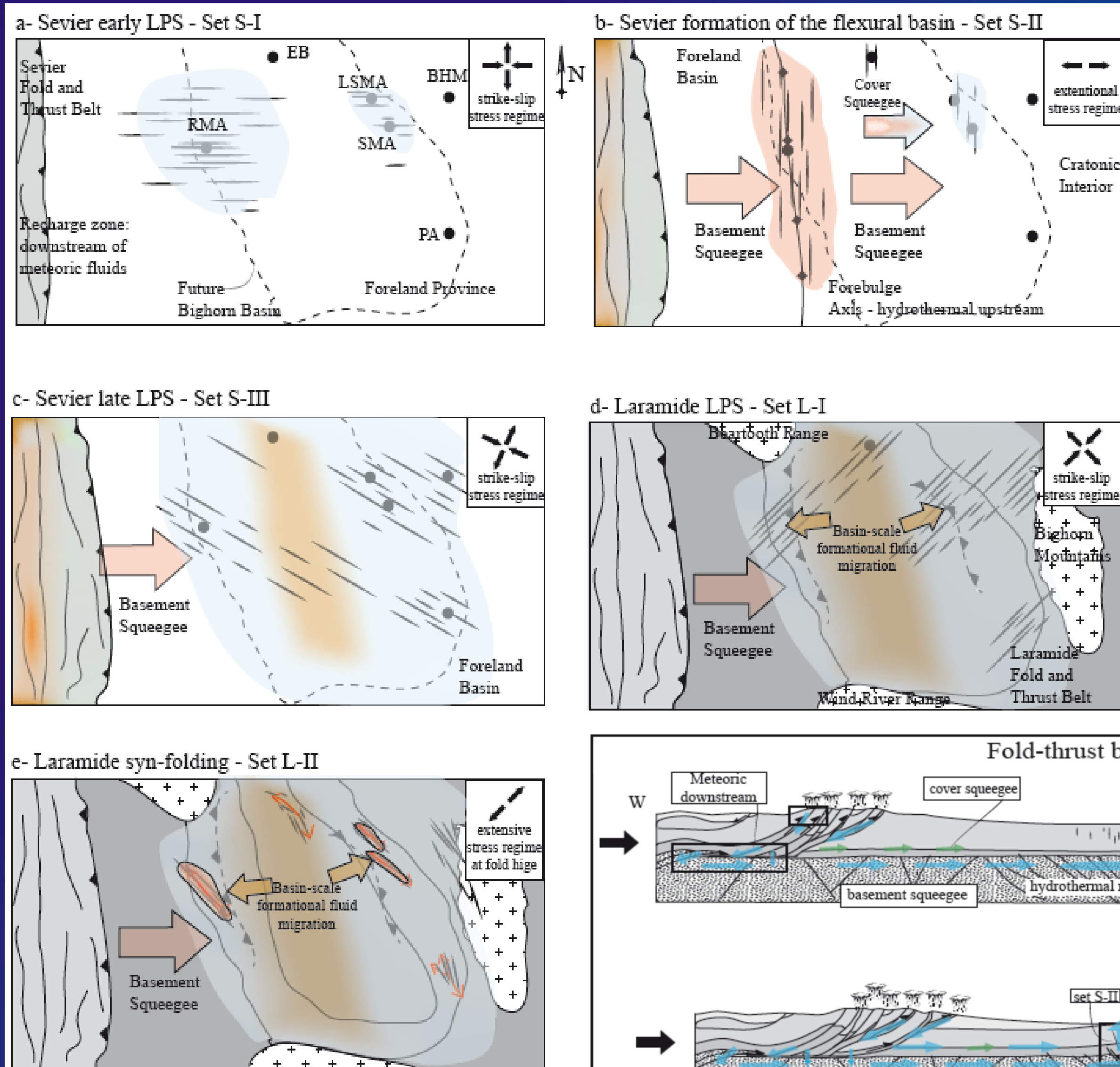
Link with structural style

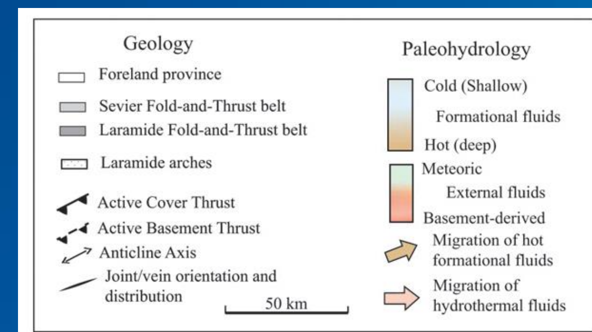
(Beaudoin et al, G3, 2011; Evans and Fischer, 2012)

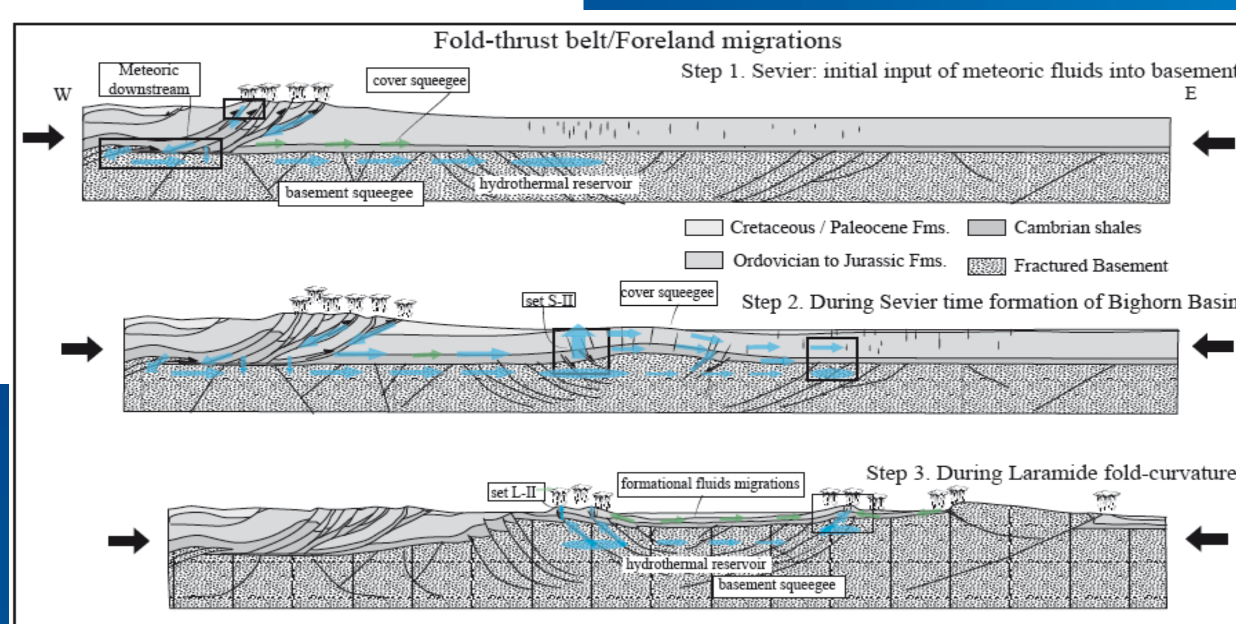




Paleo-hydrogeology of the Bighorn basin





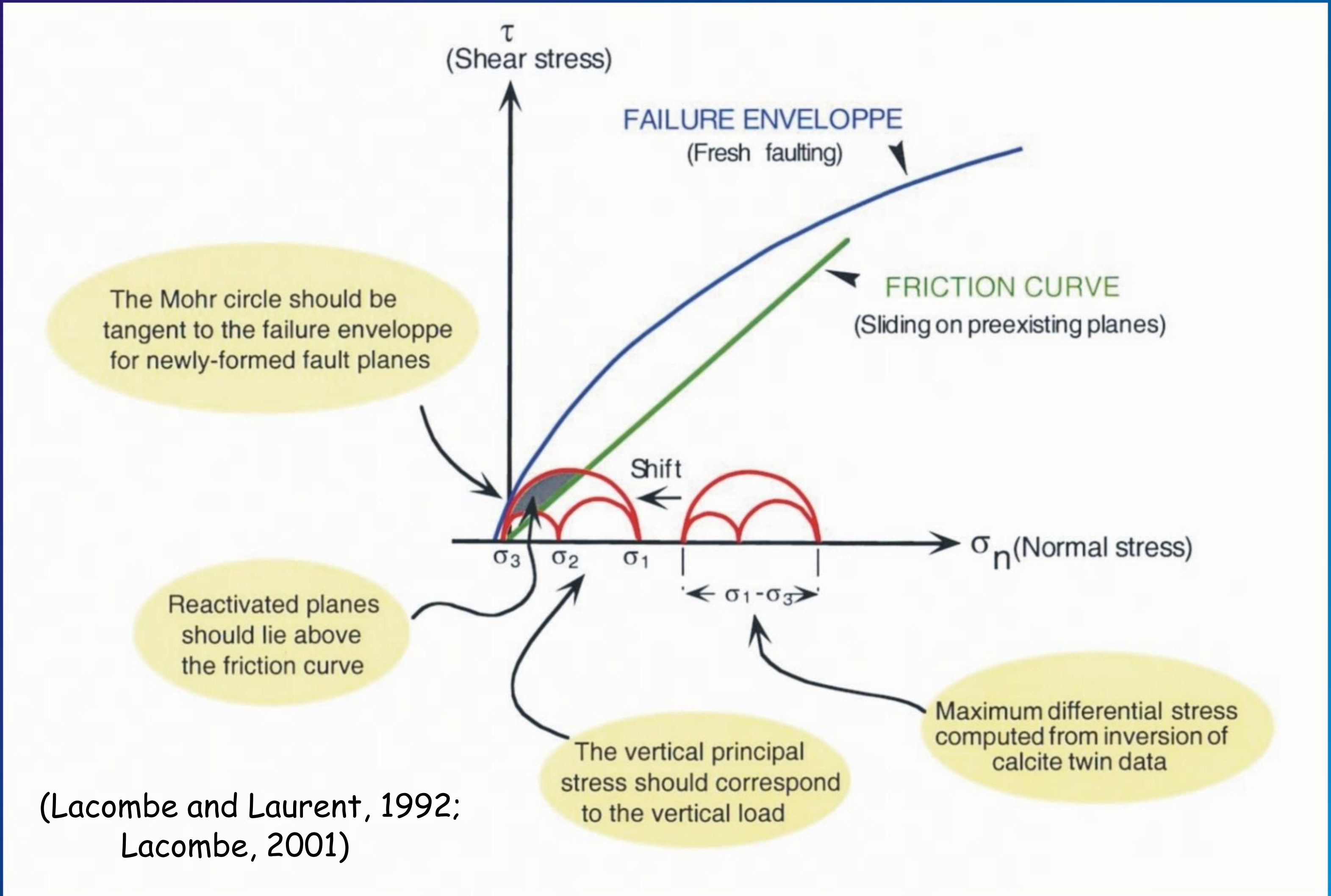


(Beaudoin et al., Basin Research, 2014)

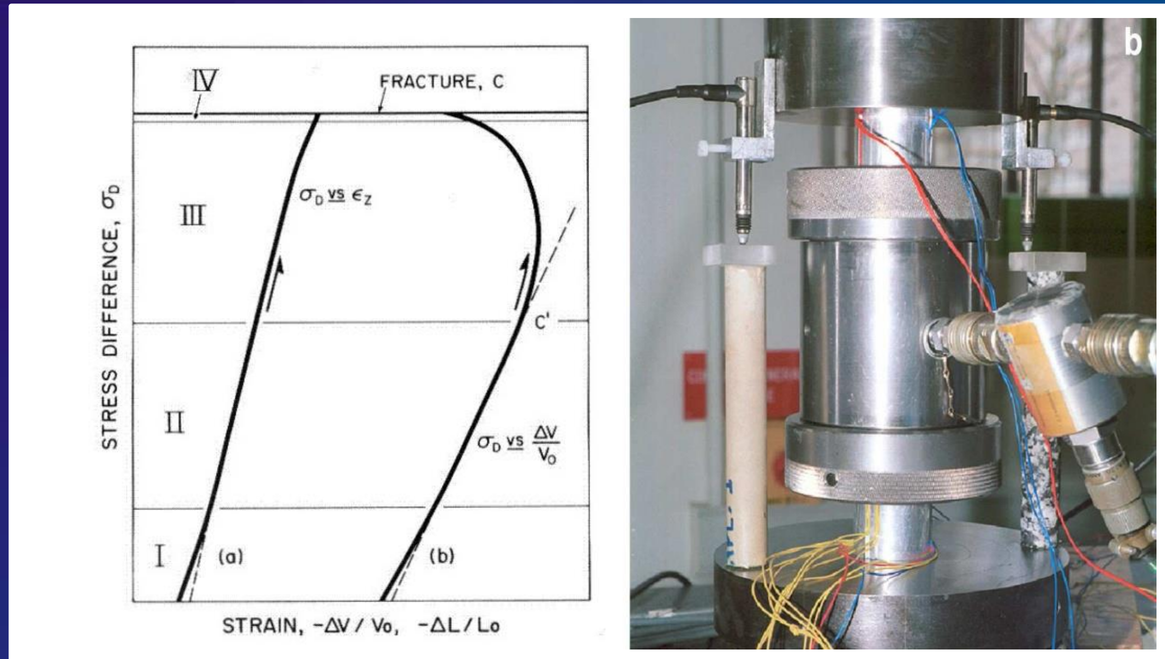
Quantification of principal stress magnitudes and fluid (over)pressures at Sheep Mountain and Rattlesnake Mountain anticlines

Quantifying principal stress magnitudes

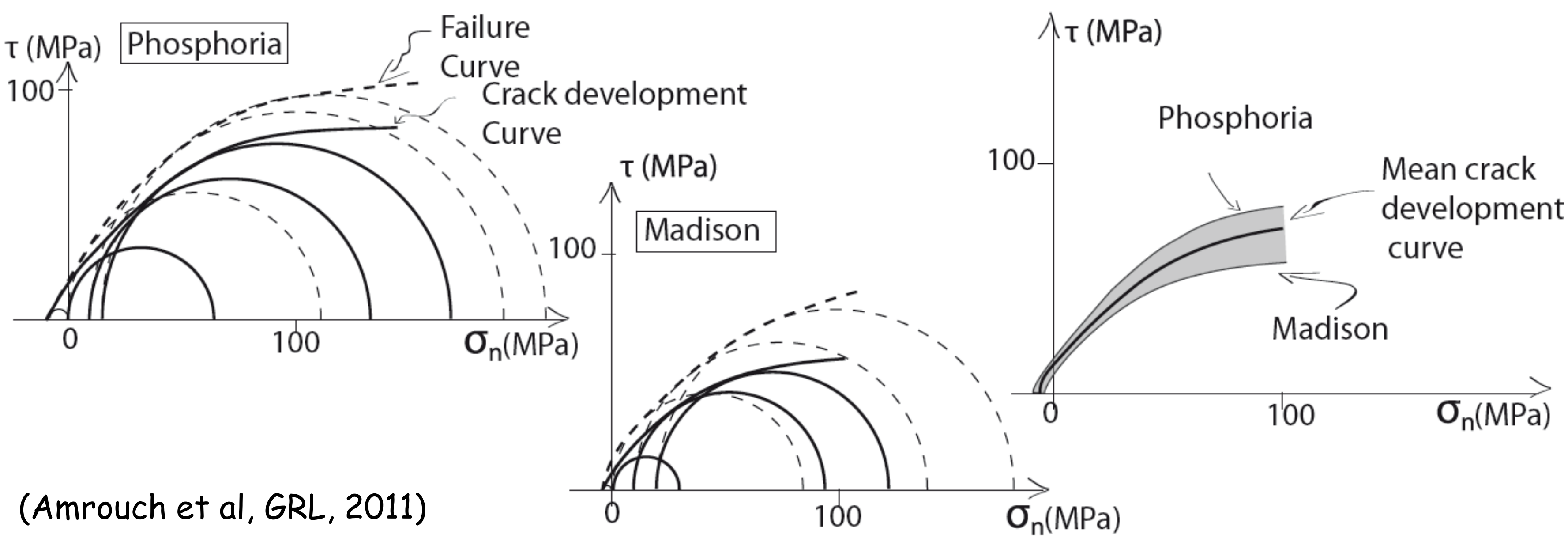
Finding for each deformation step, using a simple Mohr construction, the values of σ1, σ2 and σ3 required for consistency between differential stresses estimated from calcite twinning, frictional sliding along preexisting planes (i.e., Byerlee's law) and newly formed faulting/fracturing.



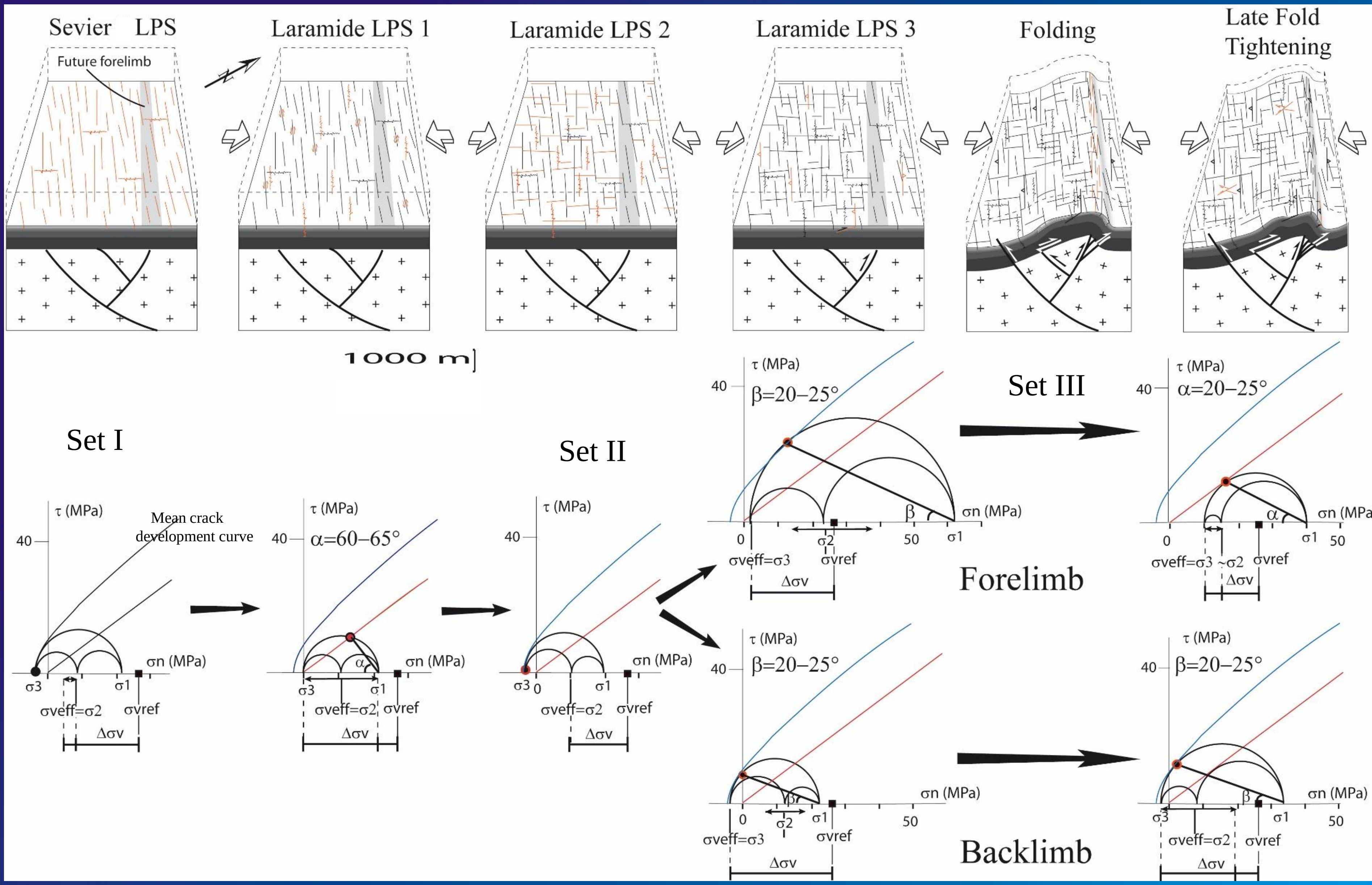
(Lacombe and Laurent, 1992; Lacombe, 2001)



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



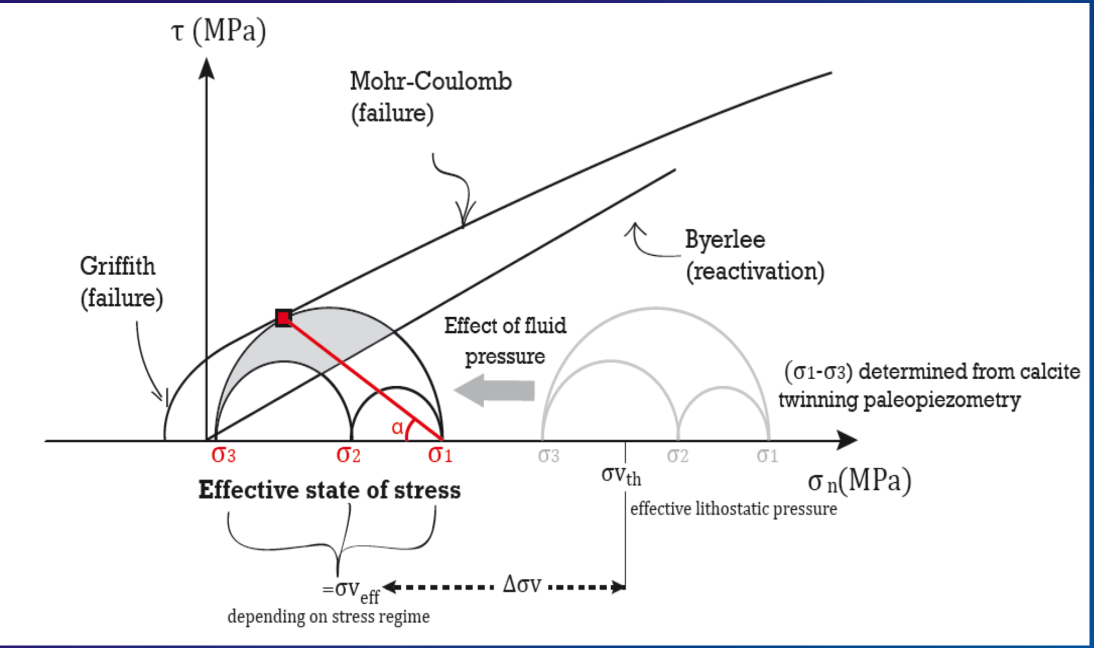
(Amrouch et al, GRL, 2011)



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

(Amrouch et al, GRL, 2011)

Quantifying paleo fluid (over)pressure



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

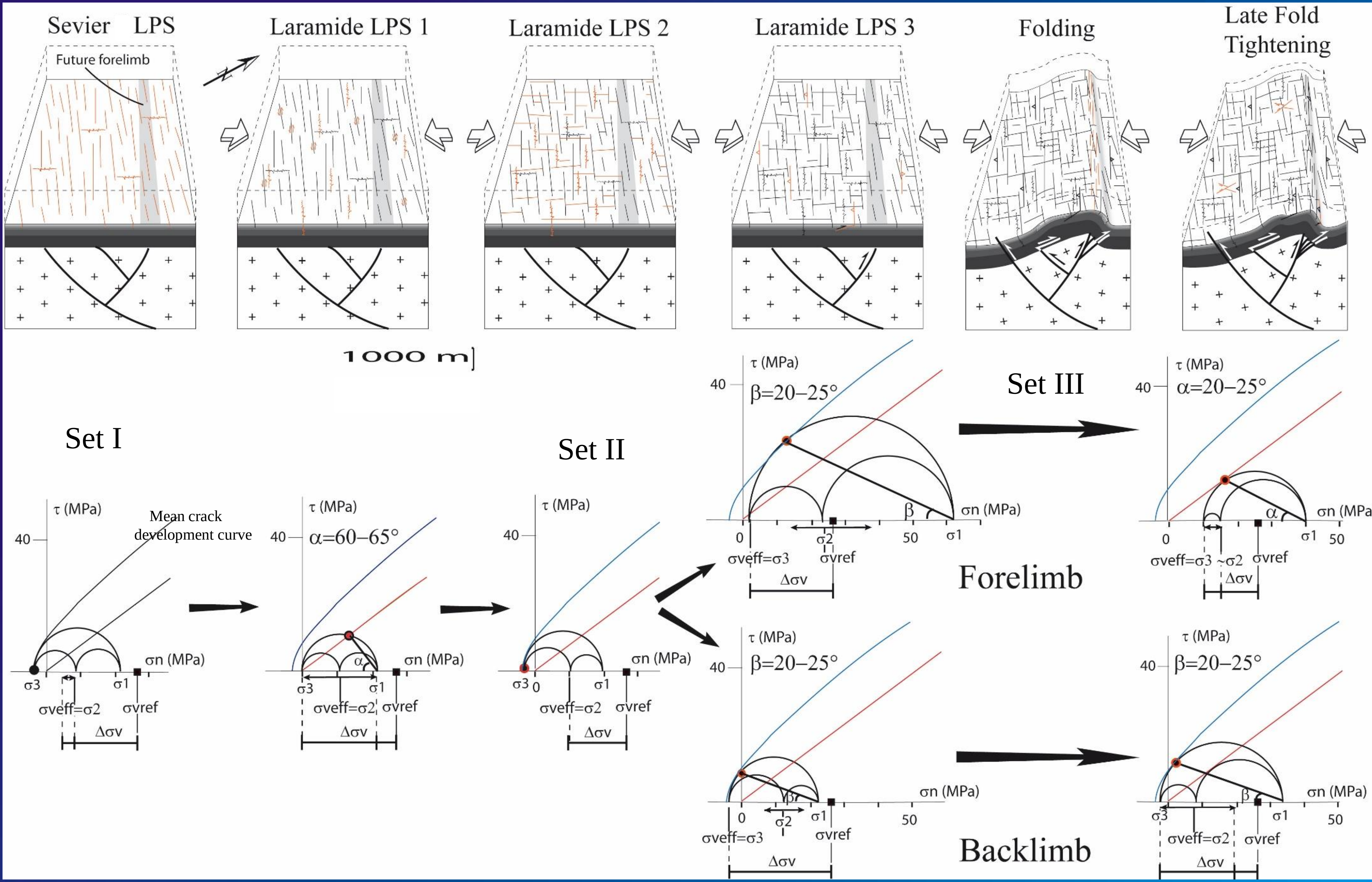
Theoretical effective vertical principal stress calculated considering lithostatic pressure corrected from hydrostatic fluid pressure:

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

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

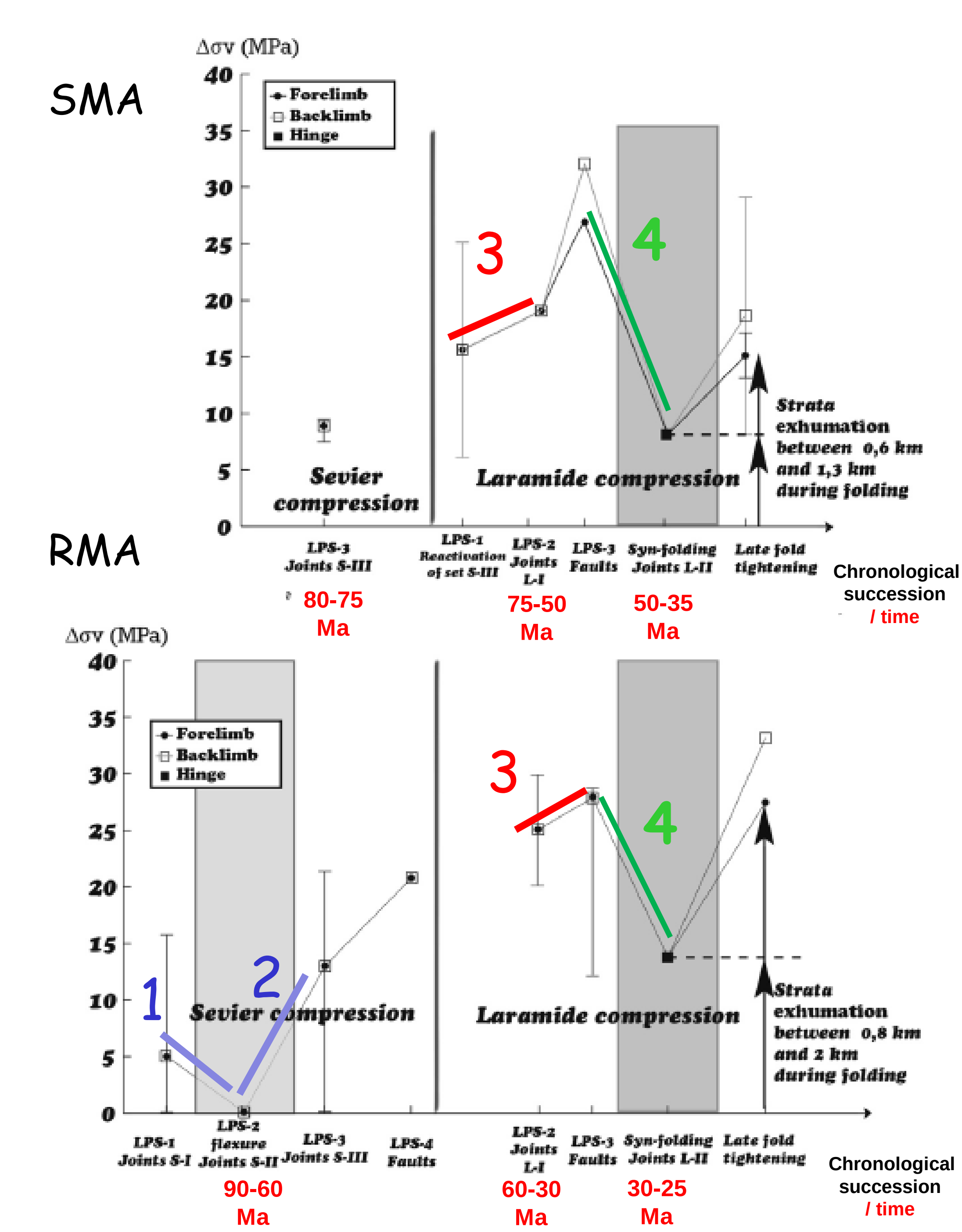
$$\Delta\sigma_v=\sigma_{vref} - \sigma_{veff}$$

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.



Determination of $\Delta\sigma_v$

(Amrouch et al, GRL, 2011)



$\Delta\sigma_v$ / fluid overpressure evolution

1.Decrease from early Sevier LPS to Sevier foreland flexure
due to enhanced permeability by flexure-related extensional fractures.

2. Increase during late Sevier-LPS
due to 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 (low vertical persistence or 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 during folding
due to curvature-related fracturing 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

(Beaudoin et al., MPG, 2014)

Conclusions :

Take-home message

Integrated picture of stress (before and) during (thick-skinned) folding

Evolution of stress magnitudes and pore fluid (over) pressure through time during thick-skinned folding

Changes in P-T-X conditions, fluid flow, fluid (over)pressure and fracture development as well as stress and strain pattern within folded strata consistently linked to the geometric/kinematic macroscopic evolution of folds

→ to be compared to mechanical models

Feedback between tectonic style and paleo-hydrology

Direct age dating → improved understanding of the sequence of deformation and stress distribution in polyphase orogenic forelands
→ access to fluid flow rate and deformation propagation rate

Interest of multi-techniques/scales approach

Many thanks for inviting me