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Thick-skinned tectonics in orogenic forelands : the western US Laramide Province and the external western Alps case studies

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Thick-skinned deformation in orogenic forelands : what we know

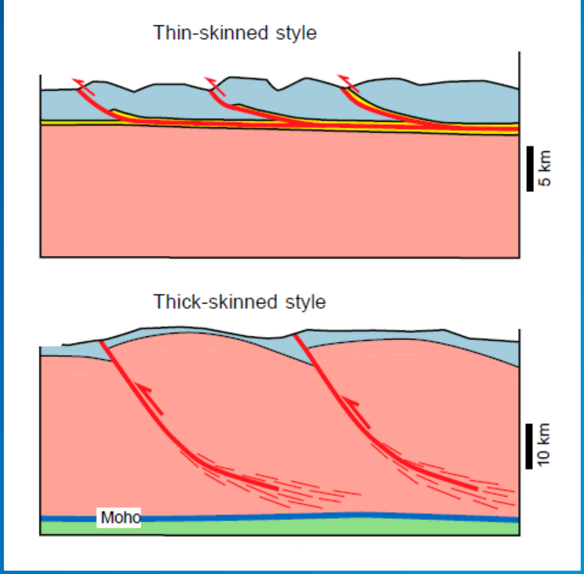
In thick-skinned (i.e., basement-involved) FTBs, shortening involves a significant part of the crust above a deep 'ductile' detachment (≠ thin-skinned)

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

Basement involvement in FTBs requires a significant degree of mechanical coupling between the hinterland and the foreland

Basement involvement in FTBs requires a mechanically weak lithosphere

Orogenic forelands may have a complex, polyphase evolution, with implication of different structural styles in time and space



Pfiffner, 2017

Topics to be addressed today :

* P-T conditions of deformation of cover/basement rocks

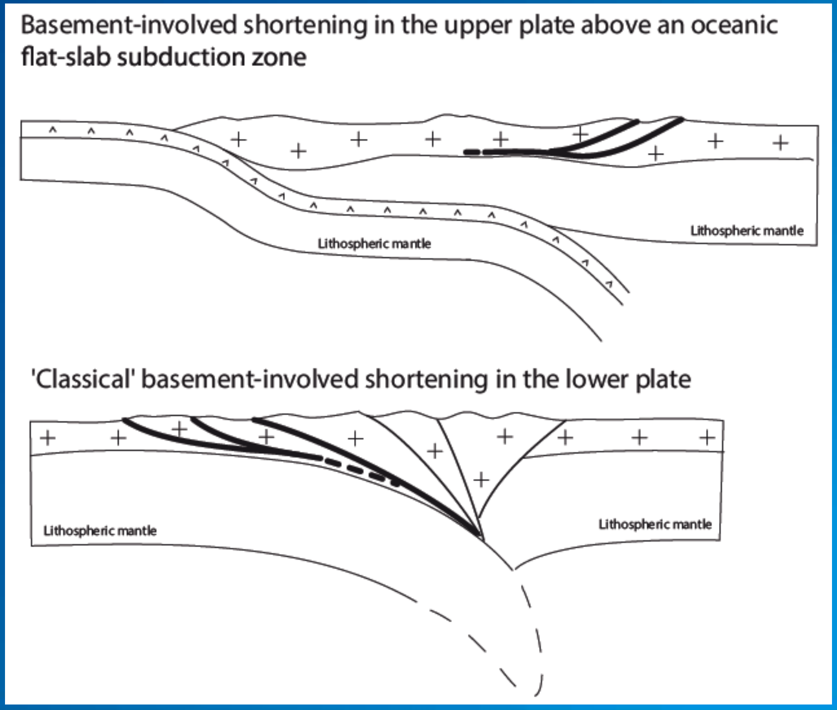
* Deformation mechanisms within basement rocks

* Timing and sequence of deformation /exhumation of basement units

Two different settings / case studies :

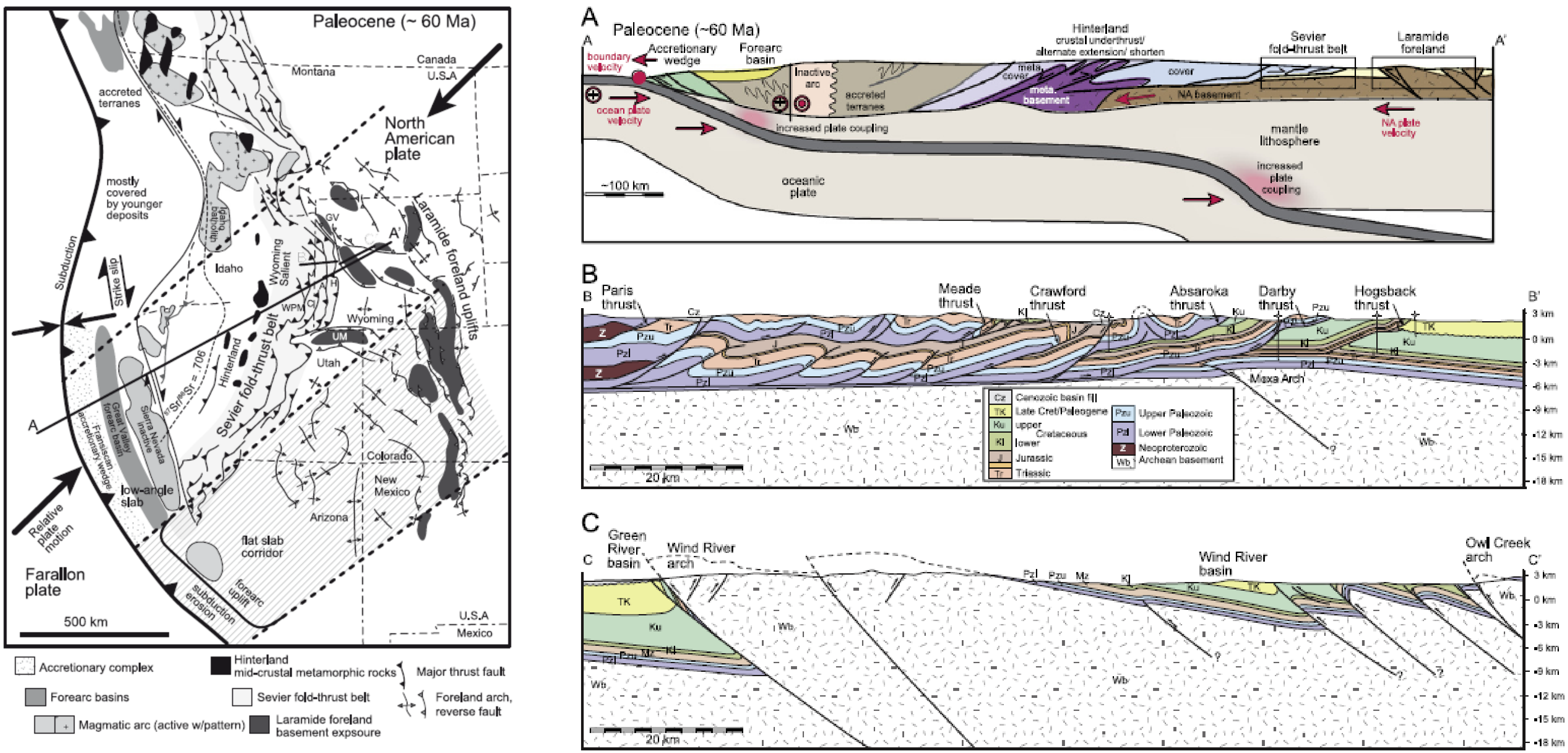
- the Laramide Province developed within the upper plate of a subduction orogen

- the Alpine External Crystalline Massifs formed at the expense of the lower plate in a collision orogen



The Bighorn Basin
and the Laramide orogeny

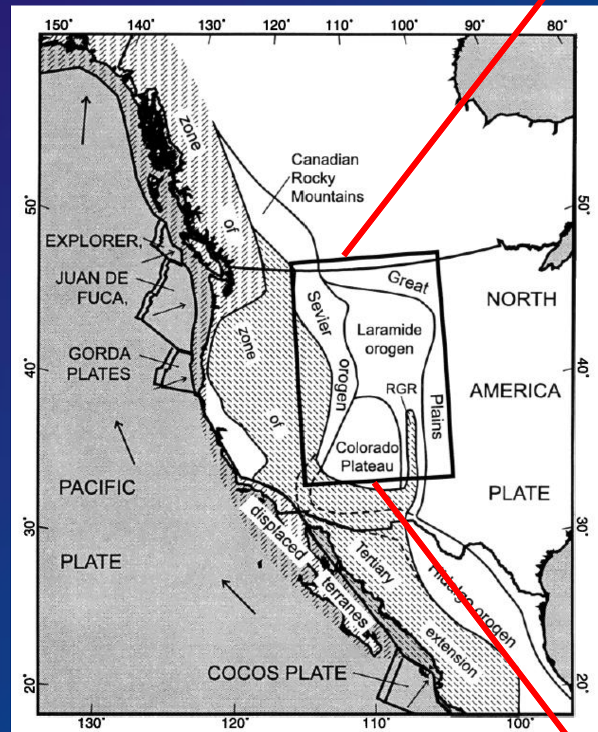
The Laramide belt consists of the deformed and disrupted foreland of the former Sevier orogeny.
It formed in response to the long-lasting subduction of the Farallon plate at the expense of the North American cratonic upper plate during late Cretaceous-Paleogene.

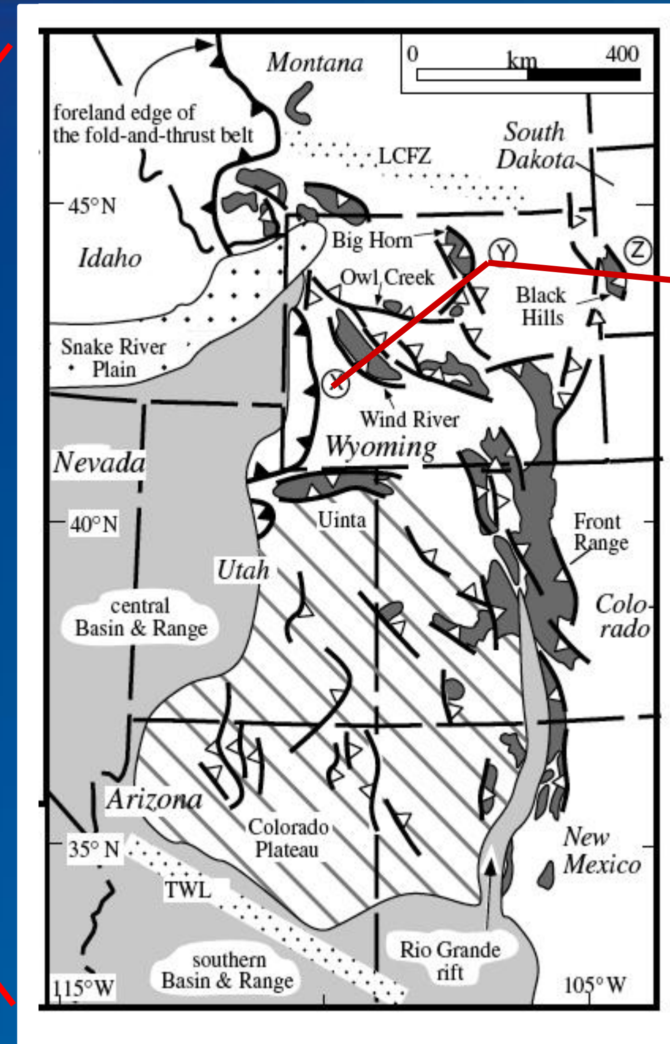


(Weil and Yonkee, 2012)

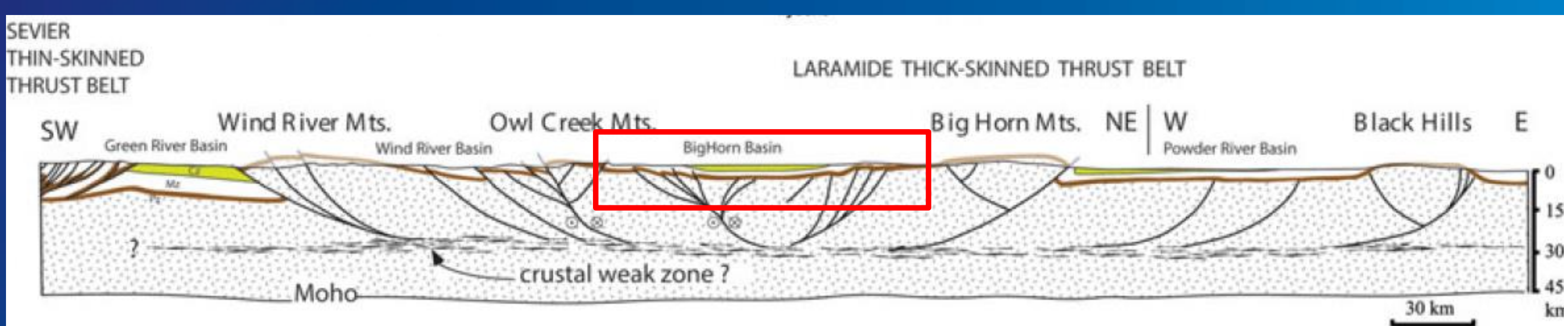
The Laramide belt exhibits a network of anastomosing basement-cored anticlines and uplifts separated by broad basins.

The basement uplifts are bounded by moderate-dipping crustal thrusts, likely resulting from the reactivation of Precambrian normal faults.

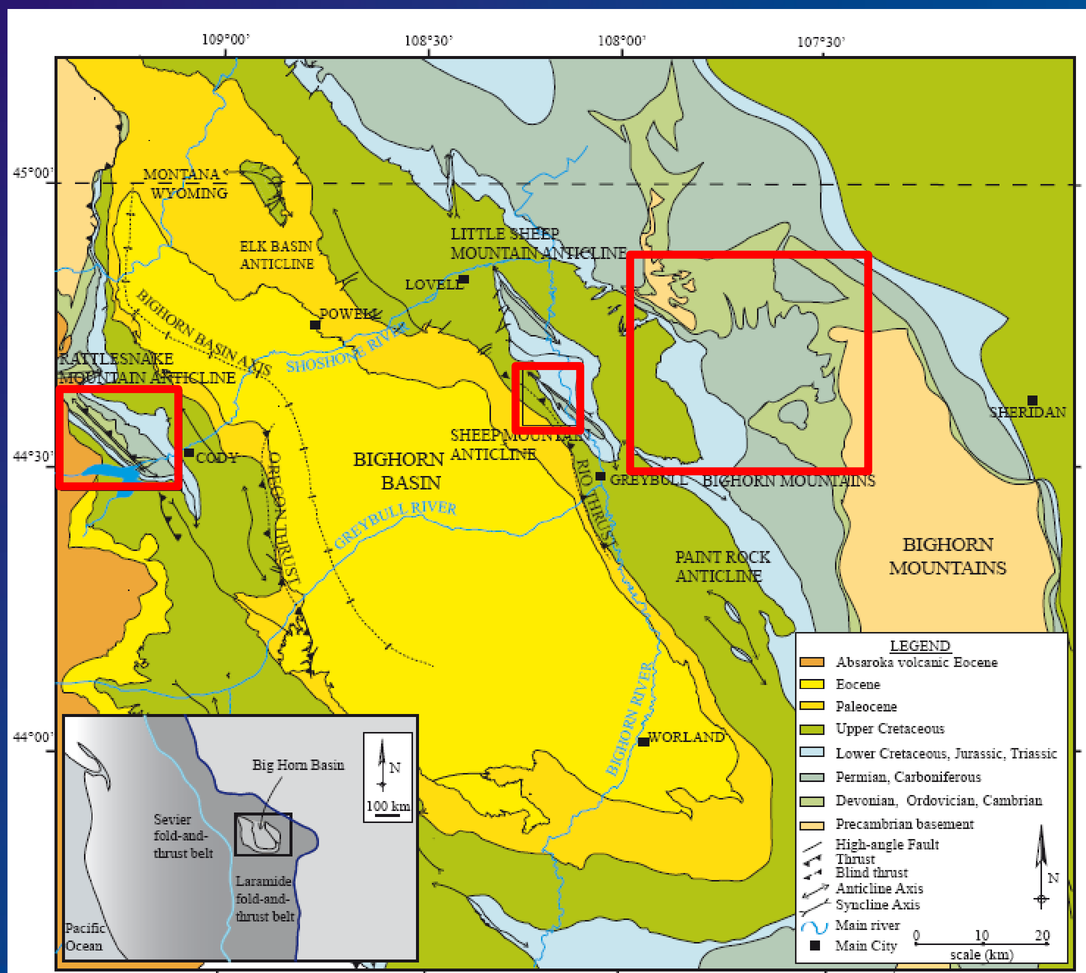


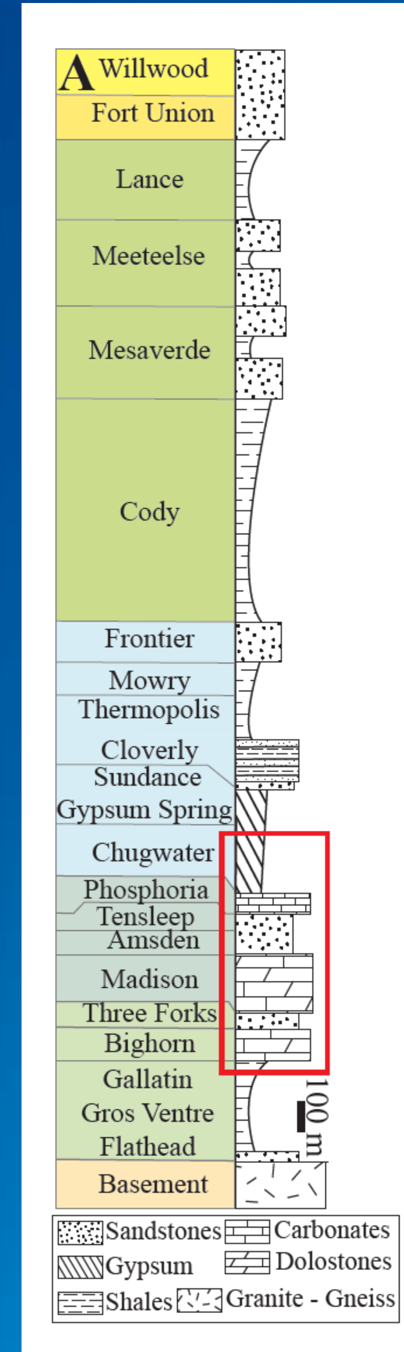


(Marshak et al., 2000; Lacombe and Bellahsen, 2016)

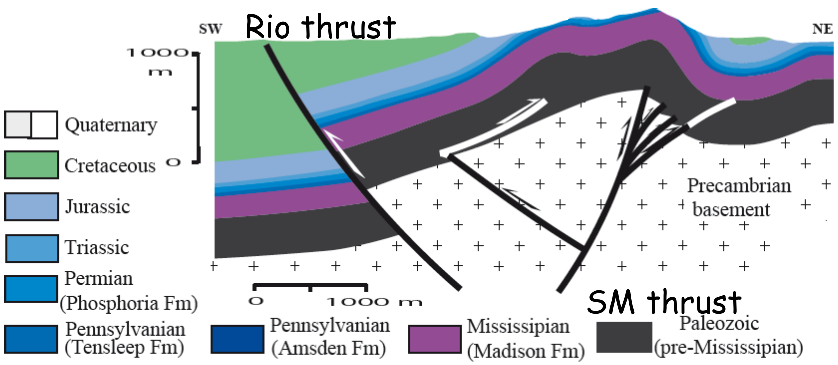


The Bighorn basin and its surrounding basement-cored anticlines and arches

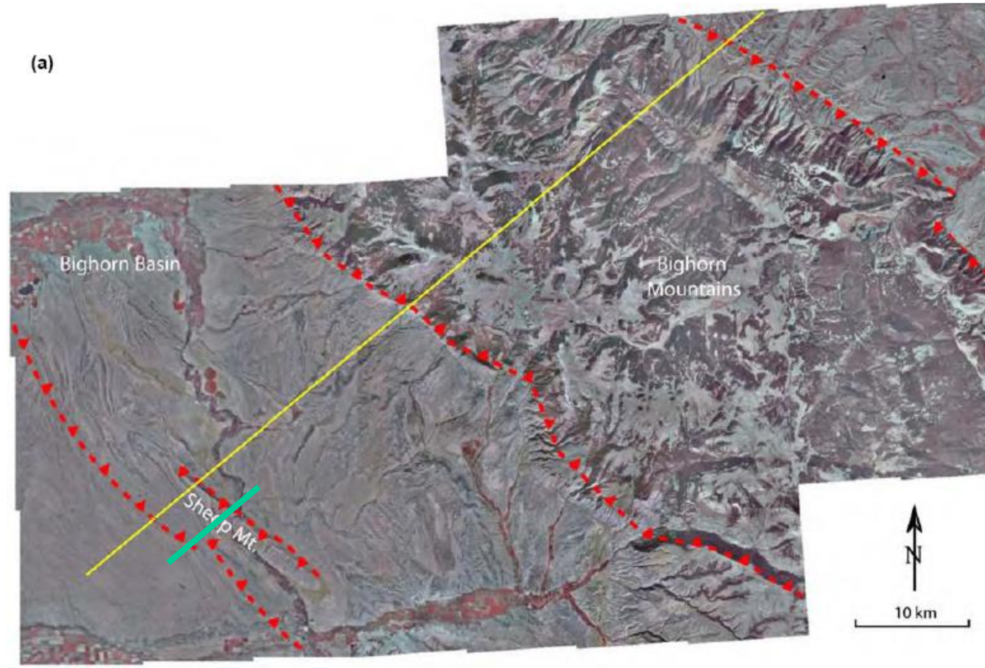


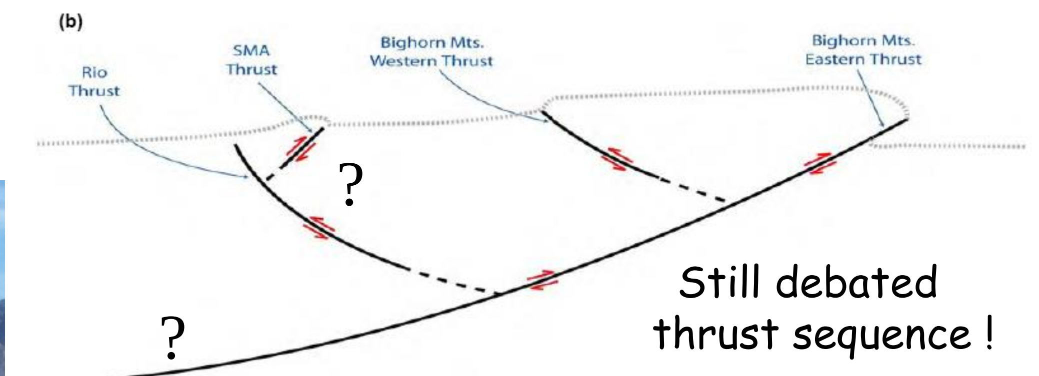


Sheep Mountain basement-cored anticline



(Amrouch et al., 2010)

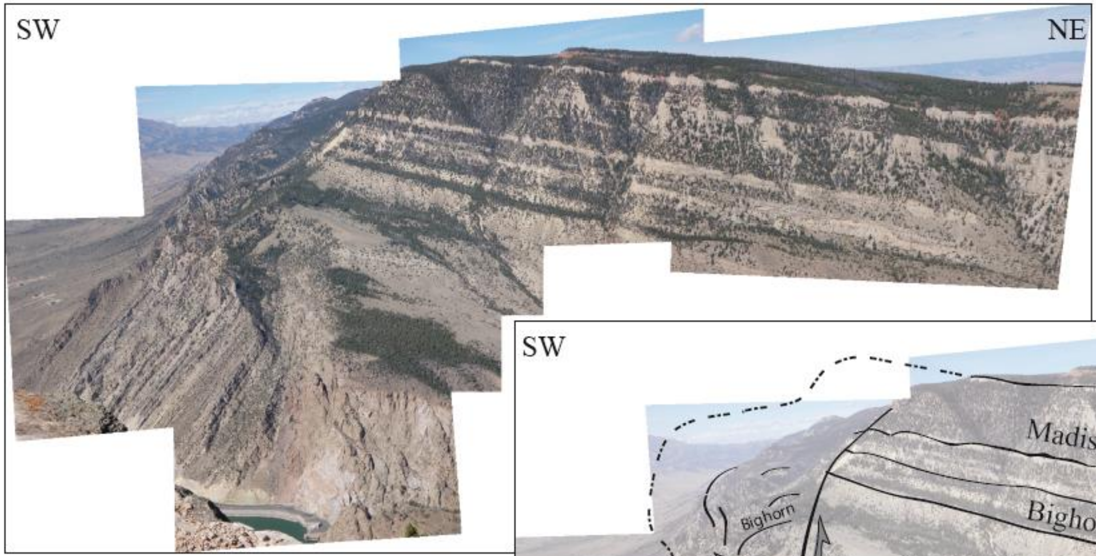


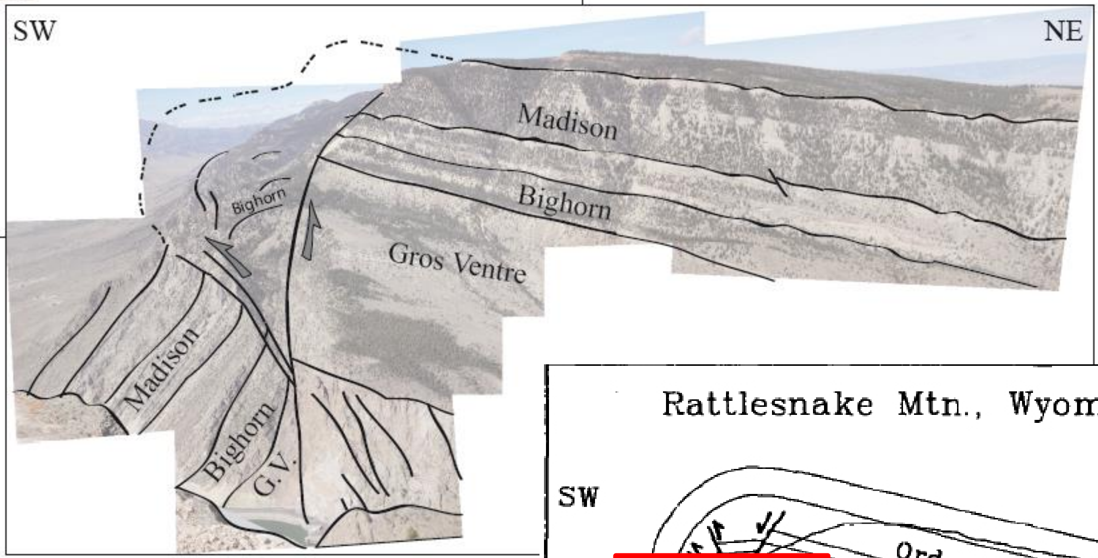


Still debated thrust sequence !

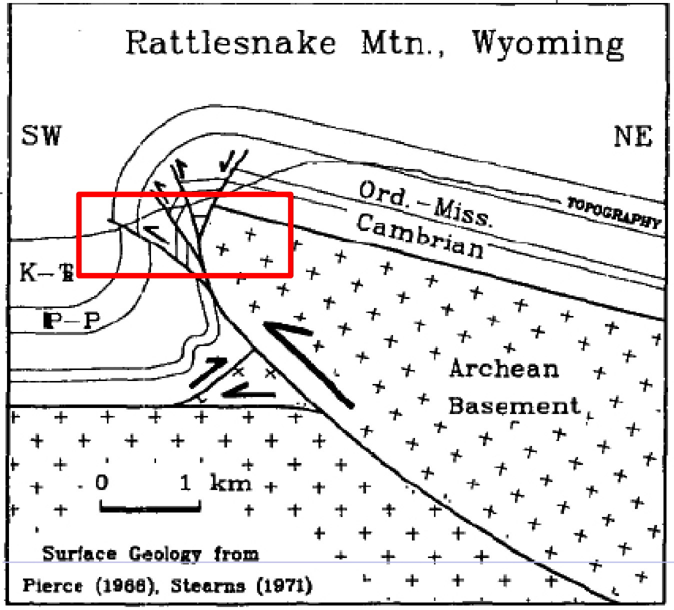
Western BigHorn basement arch

(Beaudoin et al., 2012)

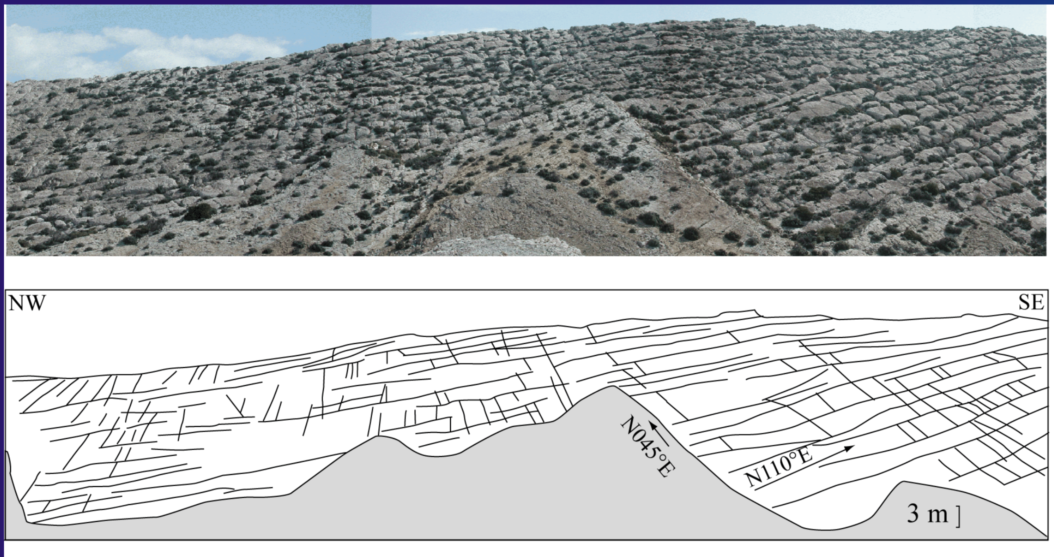




Rattlesnake Mountain
basement-cored anticline



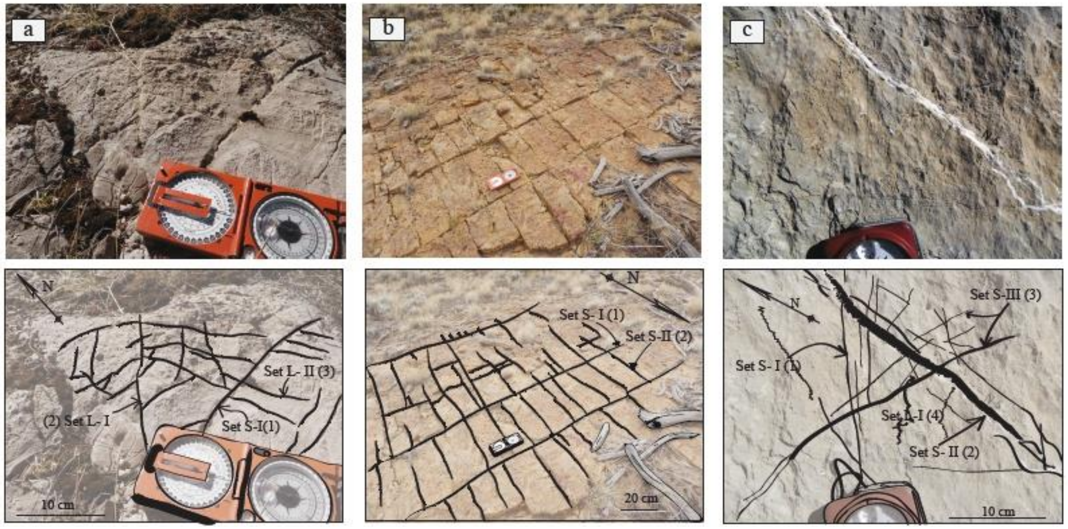
(Erslev, 1986)



Sheep Mountain anticline

Rattlesnake Mountain anticline

Deformation is brittle
in the cover and
in the basement



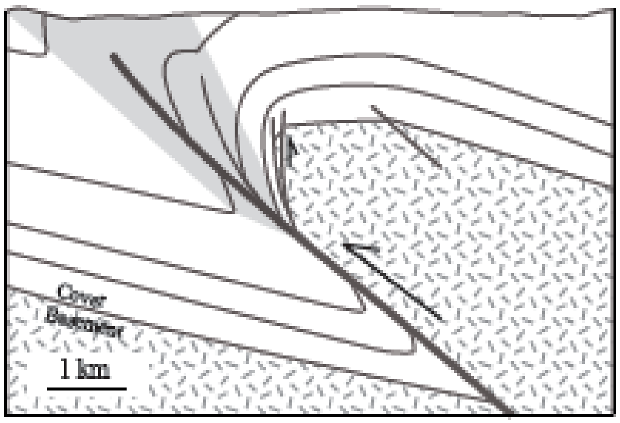
(Bellahsen et al., 2006; Amrouch et al.,2010;
Beaudoin et al., 2012)

The mechanical response of the basement rocks / the overall fold geometry depend on :
P-T conditions during deformation; nature and orientation of pre-deformation basement fabrics; competence of cover rocks; degree of coupling of folded strata with basement blocks.

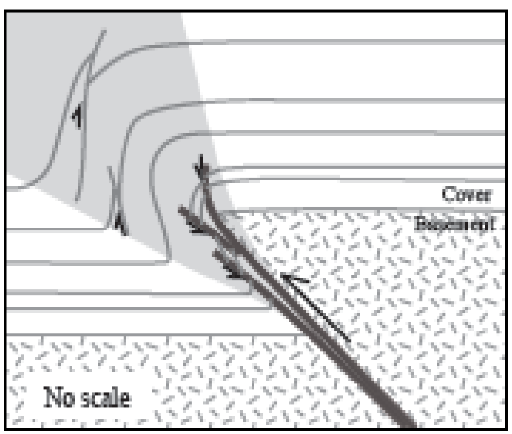
Basement can be deformed through : slip on closely spaced fractures; flexural slip on pre-existing foliation oriented sub-parallel to bedding; slip on foliation favorably oriented for simple shearing parallel to the fault.

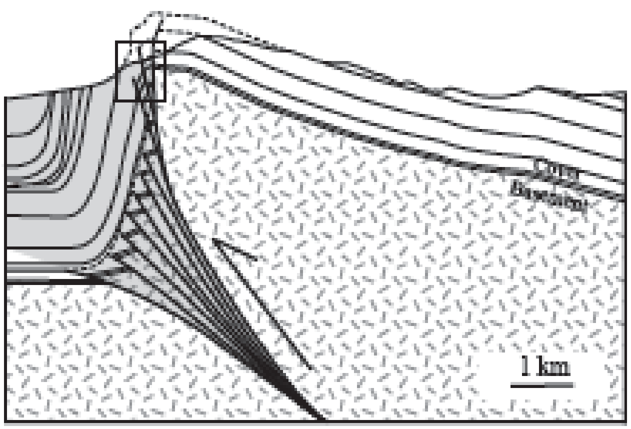
Most outcropping basement rocks are mainly brittlely deformed at shallow depth (about 2.5 to 5 km) and at a temperature of about 70–120°C)

Laramide cover folding is not related to true basement « folding » but is instead associated with distributed damaging of basement rocks by pervasive fluid-assisted faulting/fracturing and/or cataclasis ahead of the propagating thrust.



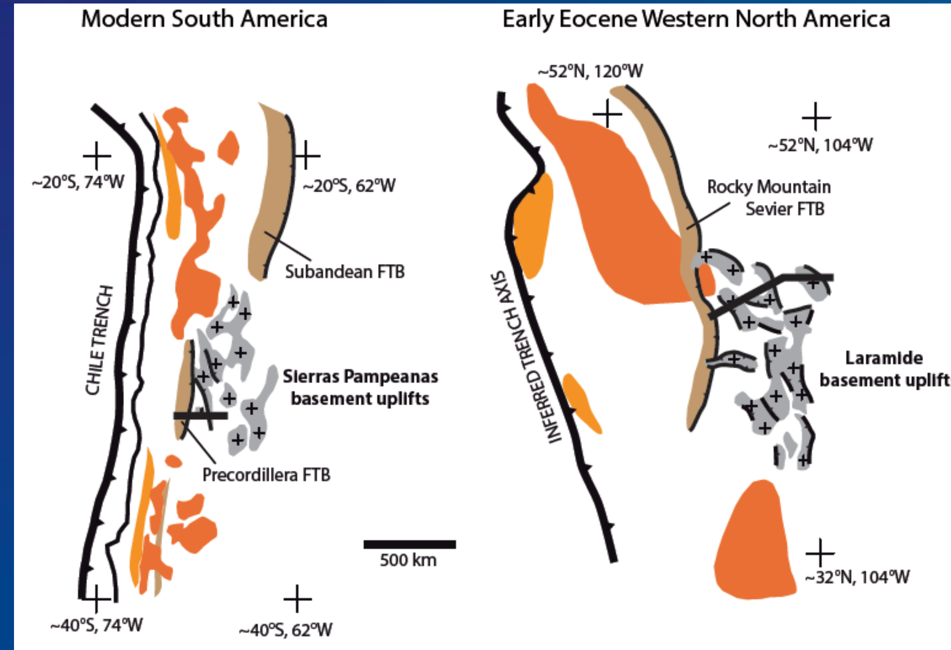
Tri-shear model





(Lacombe and Bellahsen, 2016)

(Modified after Jordan and Almendinger, 1986)



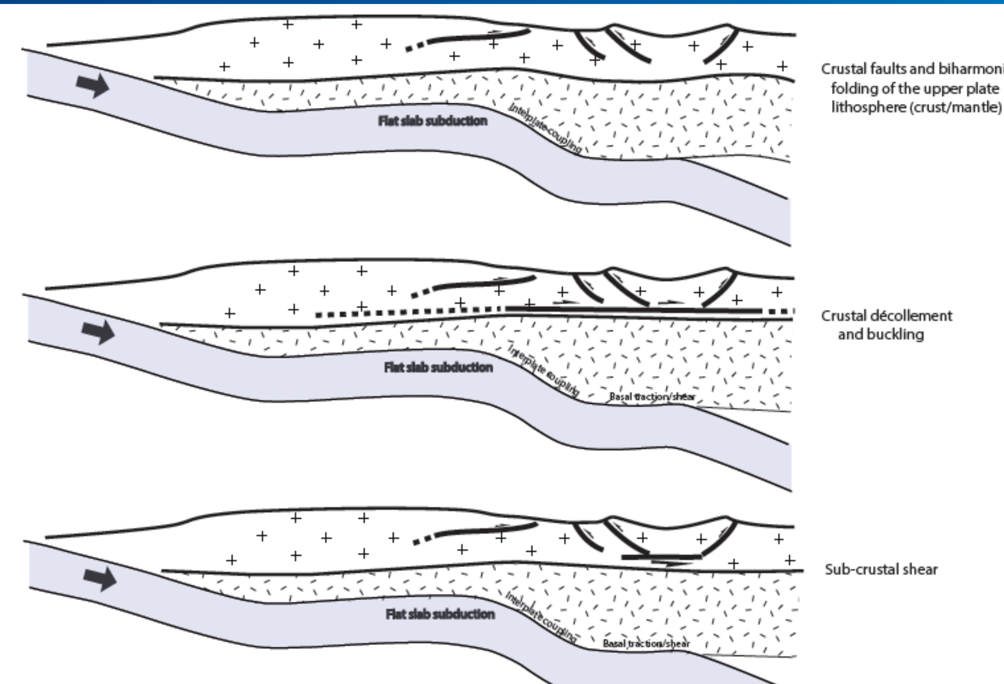
In the Laramide Province, crustal deformation occurred in relatively cold conditions as encountered in a flat-slab subduction setting.

A similar setting can be found in the actively deforming Sierras Pampeanas of Argentina.

How to explain stress transfer and diffuse shortening in the upper plate far from the plate boundary ?

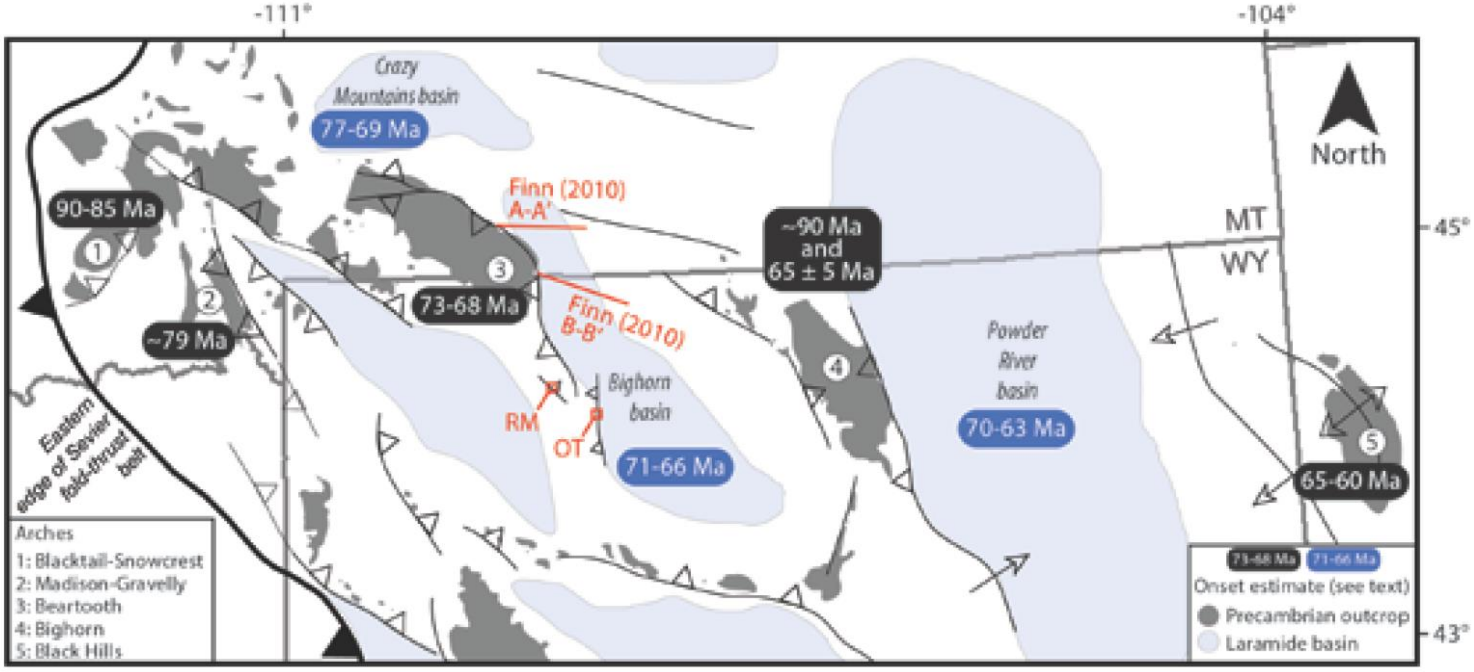
- lithospheric buckling
- fault-propagation folding of the upper crust driven by mid-crustal décollement,

in addition to local structural and/or possible physical /compositional weakening.



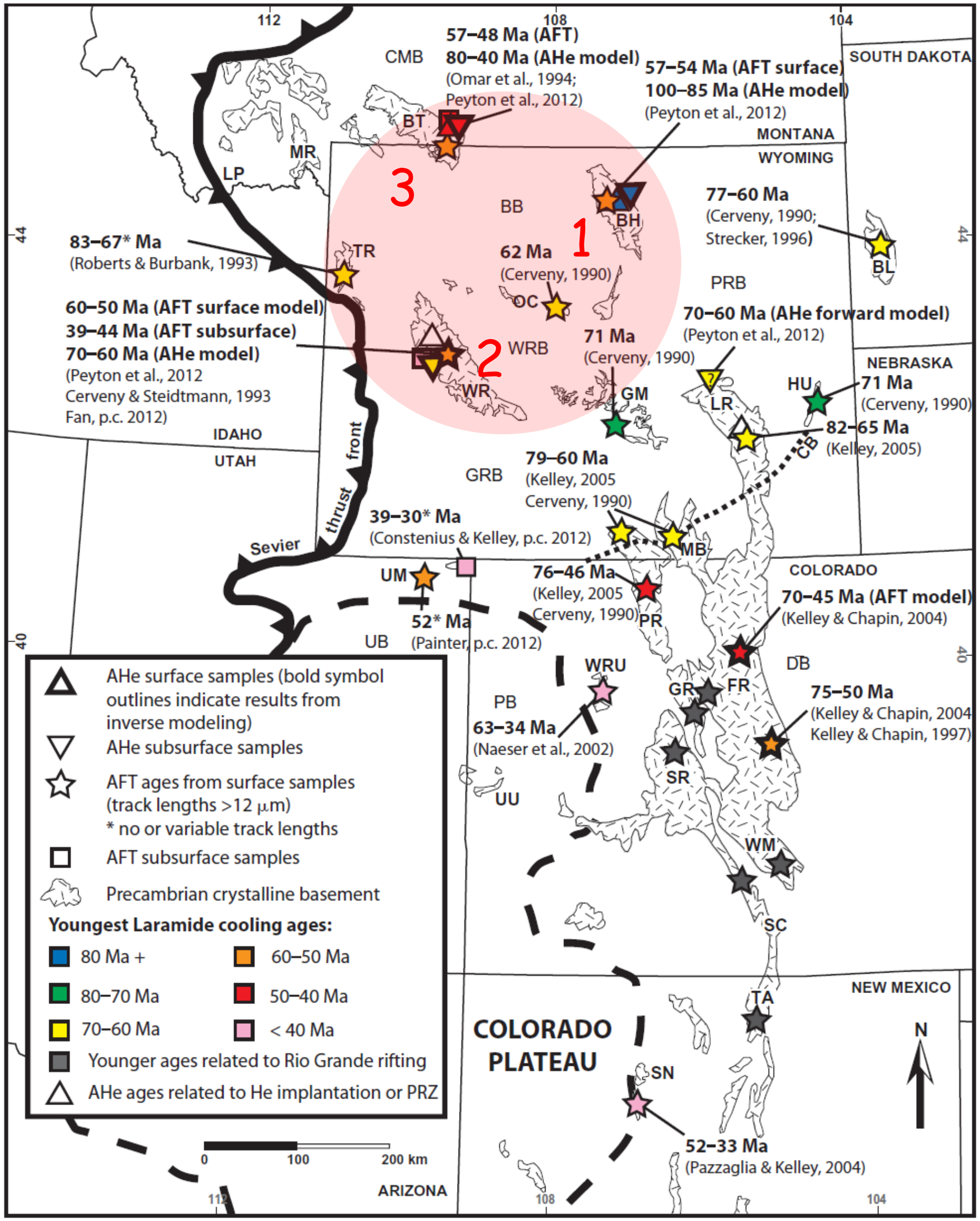
(Lacombe and Bellahsen, 2016)

In northern Wyoming – Montana, thermochronology and stratigraphy seemingly support an eastward sequence of thick-skinned Laramide deformation



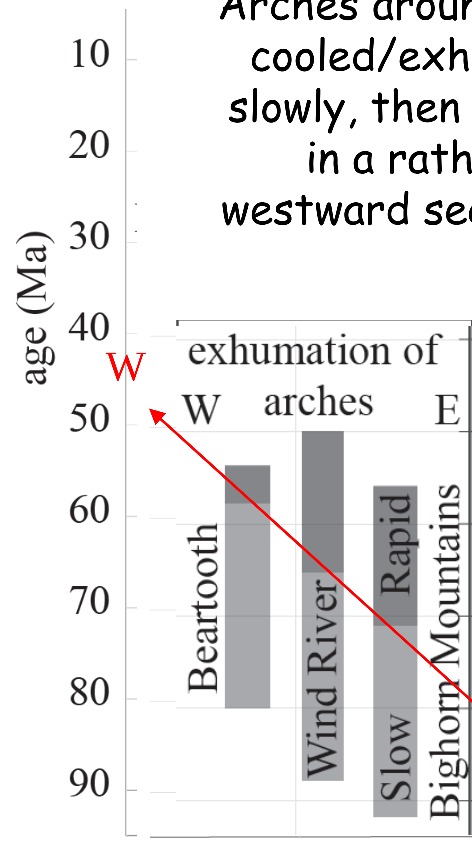
Map showing structural arches and basins RM—Rattlesnake Mountain anticline; OT—Oregon thrust.

(Tacker and Karlstrom, 2019)



(Peyton et al., 2012)

Arches around BHB cooled/exhumed slowly, then rapidly in a rather westward sequence



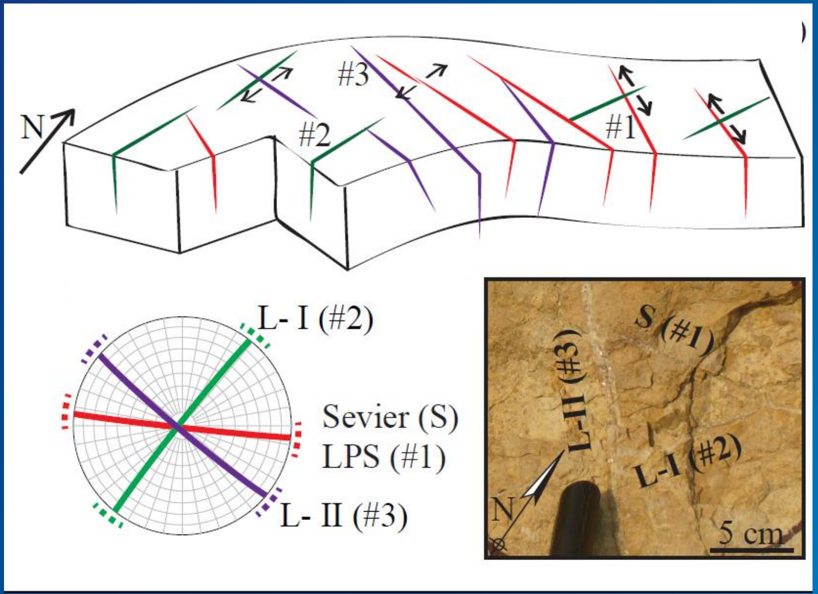
U-Pb dating of systematic calcite vein sets related to Laramide layer-parallel shortening and folding

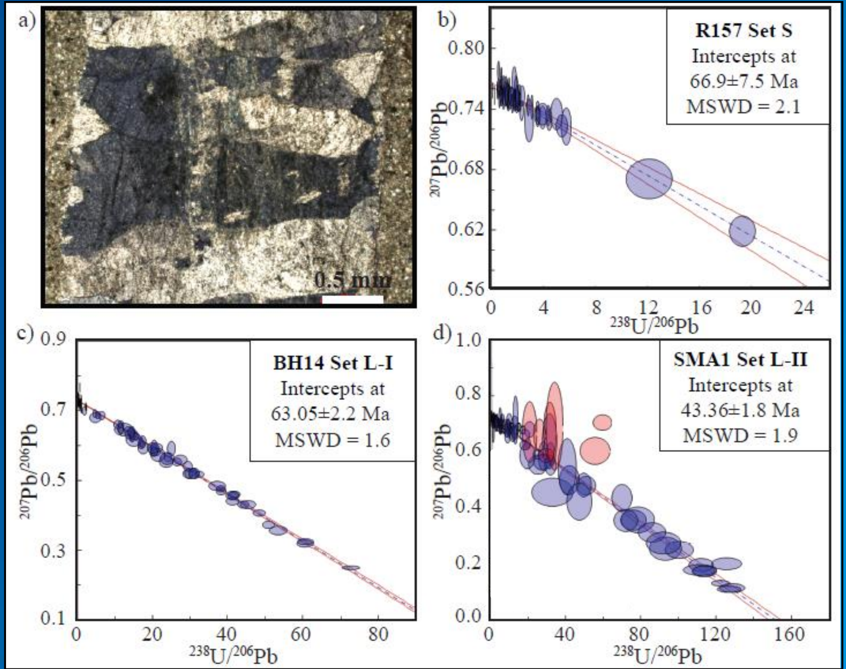
Fracture set	Mean strike of fractures	Related Tectonic events
Set S-I	090°E	Sevier layer-parallel shortening ?
Set S-II	180°E to 020°E	Formation of the flexural foreland basin
Set S-III	110°E	Sevier layer-parallel shortening ?
Set L-I	045°E	Laramide layer-parallel shortening
Set L-II	135°E	Local curvature-related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

Pre-Laramide

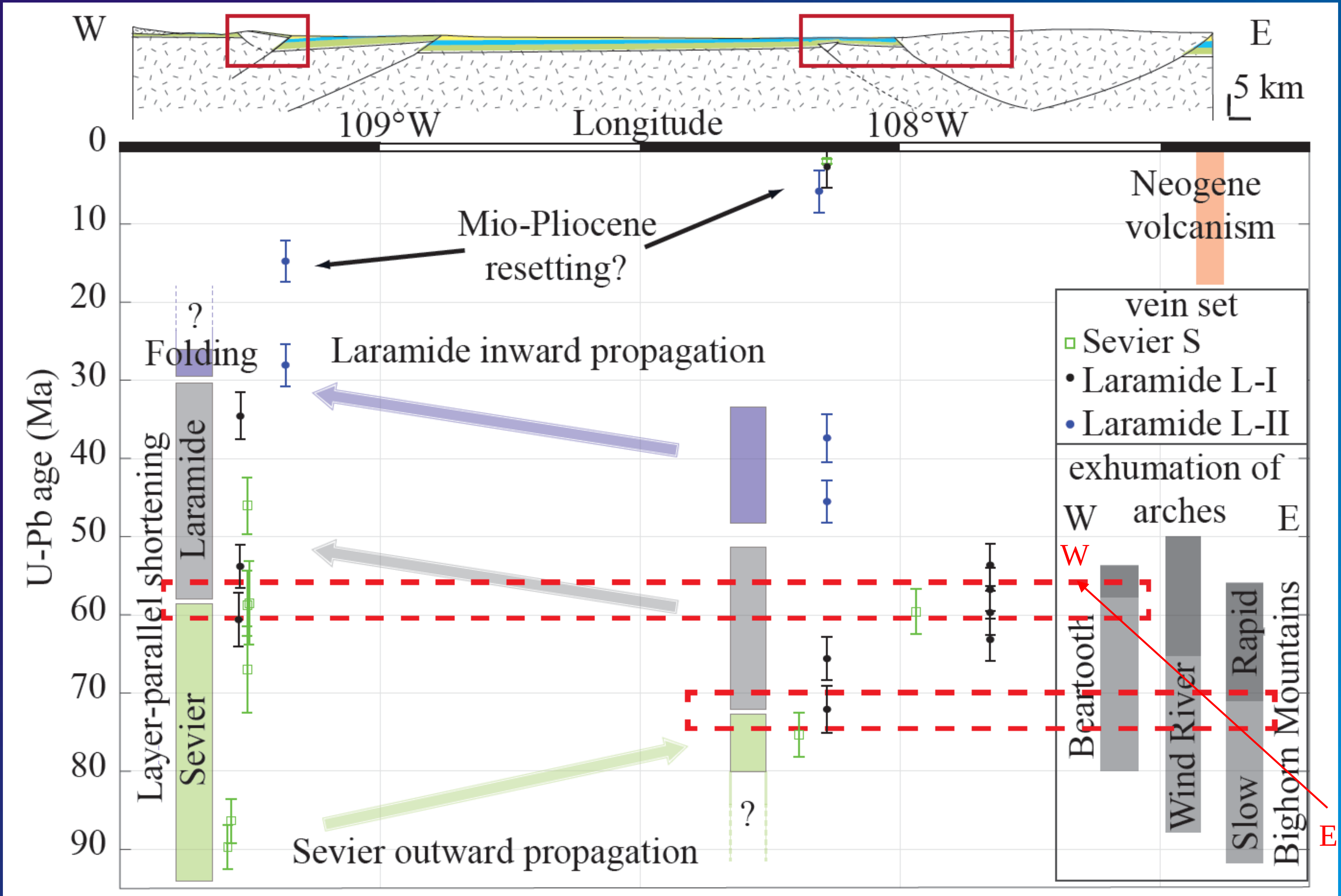
Laramide

Post Laramide





(Beaudoin et al., 2012, 2018)

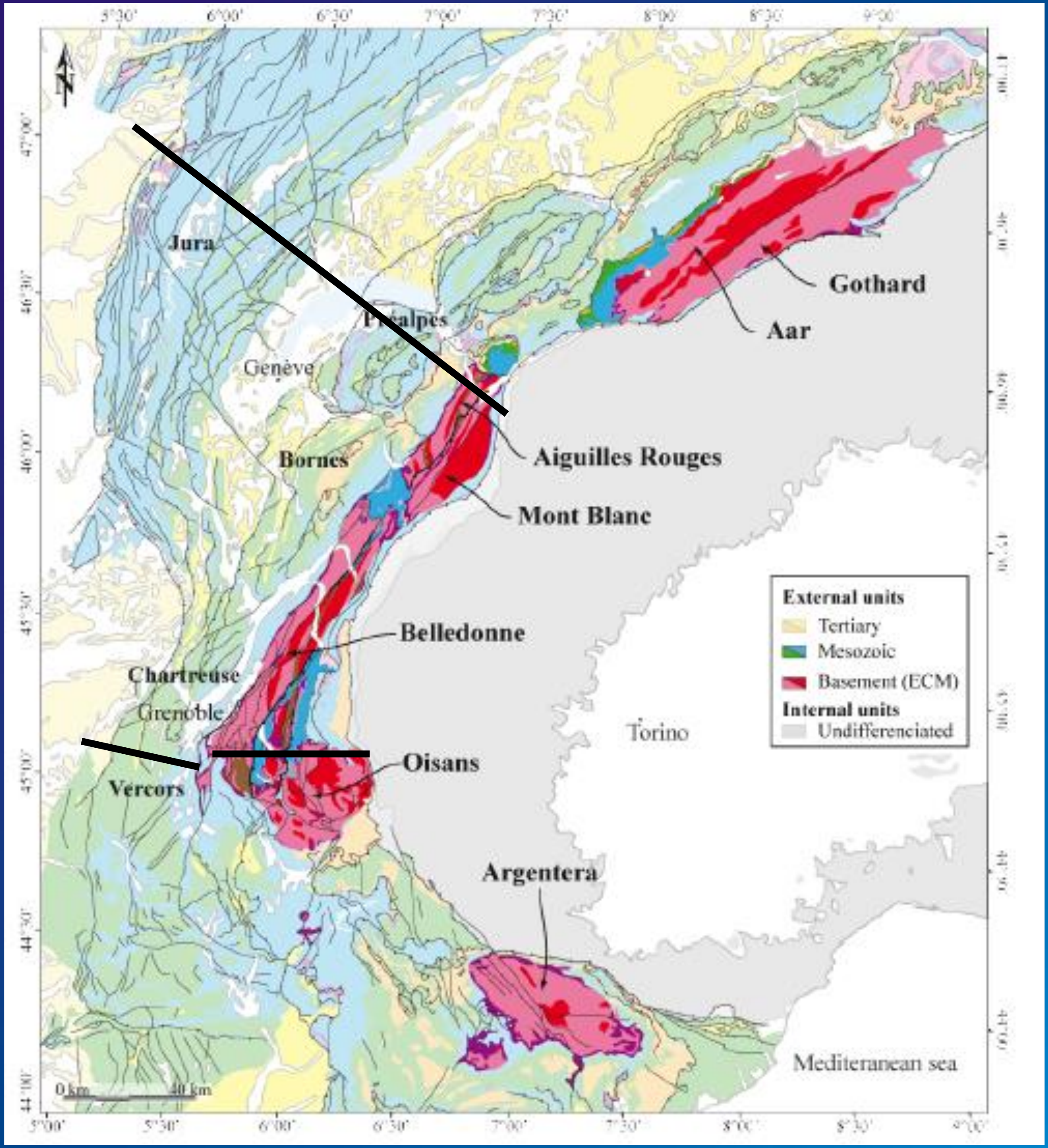


(Beaudoin et al., 2018, 2019)

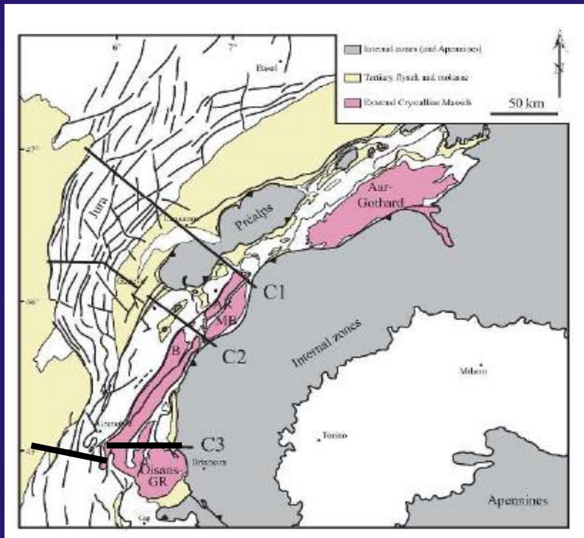
The Laramide arches were exhumed first at slow rate then at higher rate in an overall eastward (cratonward) sequence of deformation, but a westward sequence of uplift is documented in/around the Bighorn basin.

This somewhat erratic sequence is probably linked to the heterogeneous and complex stress transmission and accommodation of shortening through the crystalline basement that displays inherited weaknesses and anisotropies.

The external western Alps and the Alpine orogeny



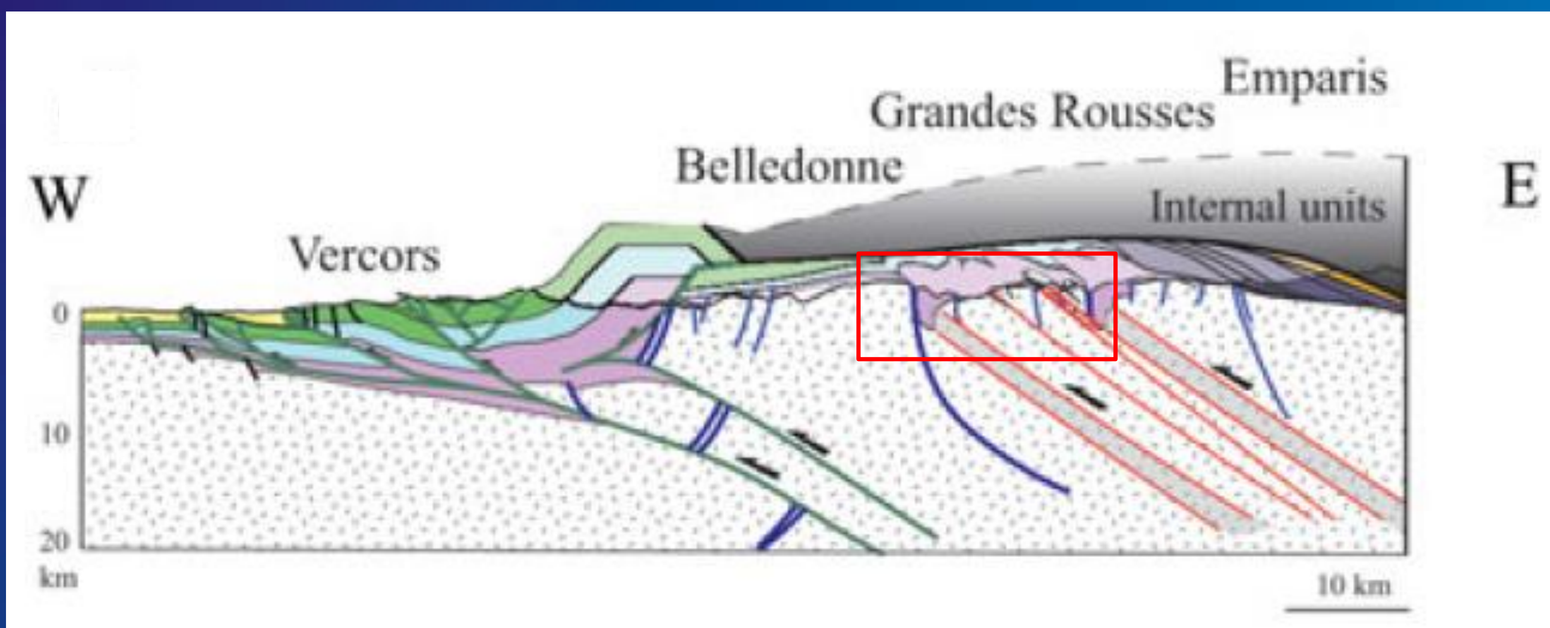
Jura
Préalpes
Genève
Bornes
Aiguilles Rouges
Mont Blanc
Gothard
Aar
Belledonne
Chartreuse
Grenoble
Vercors
Oisans
Torino
Argentera
Mediteranean sea
External units
Tertiary
Mesozoic
Basement (ECM)
Internal units
Undifferenciated
0 km
40 km



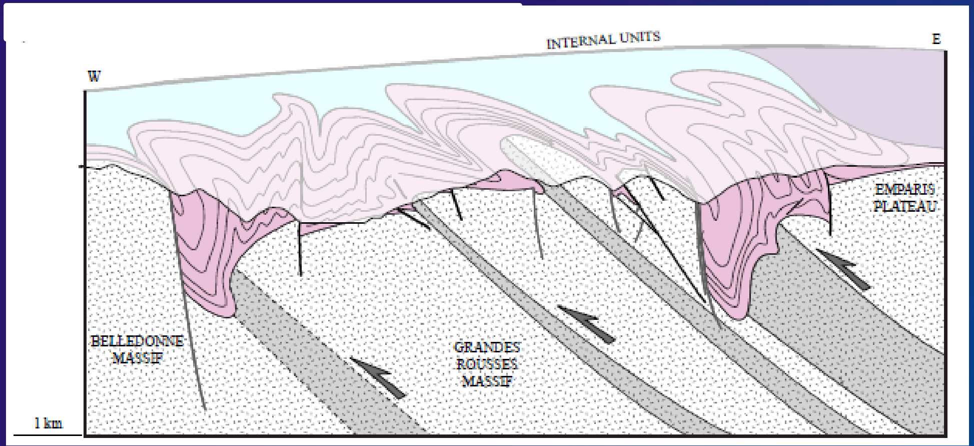
Oisans section

Basement shortened by distributed underplating.

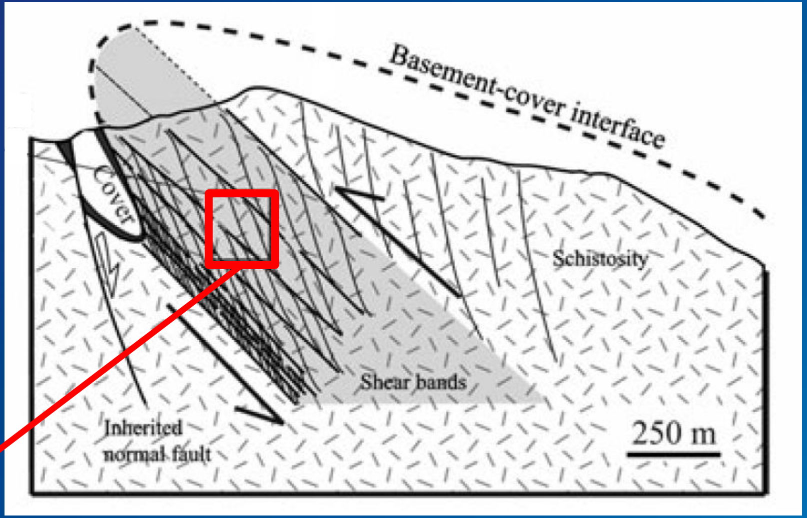
Deformation localization on the frontal ramp that activated the Vercors shallow decollement.

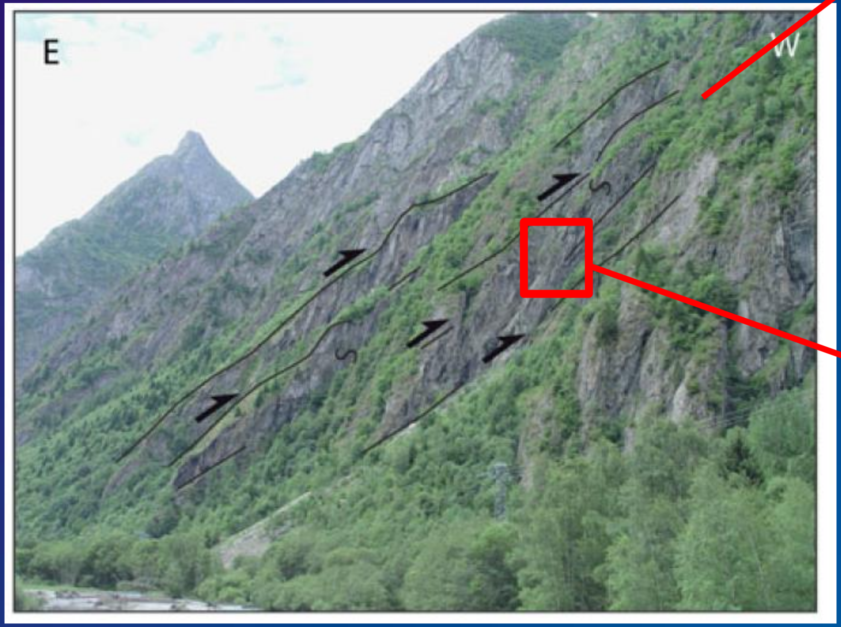


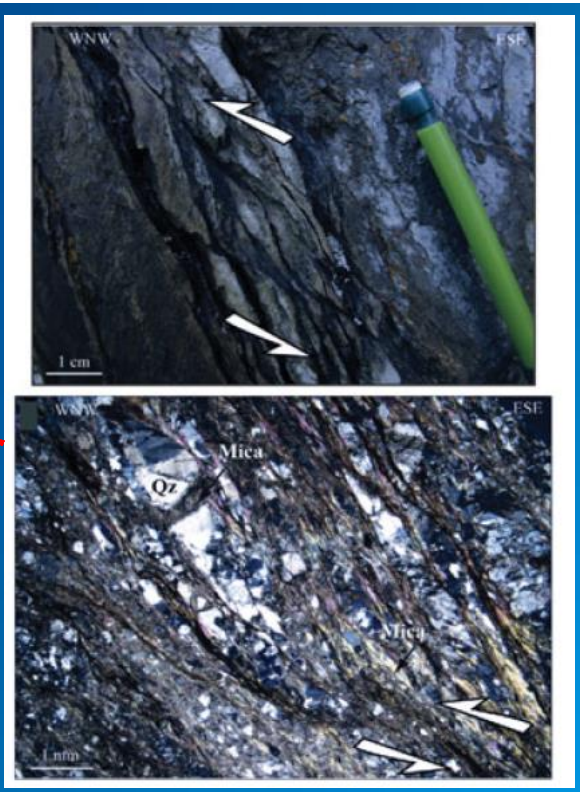
(Bellahsen et al., 2014)



(Bellahsen et al., 2012; Lacombe and Bellahsen, 2016)



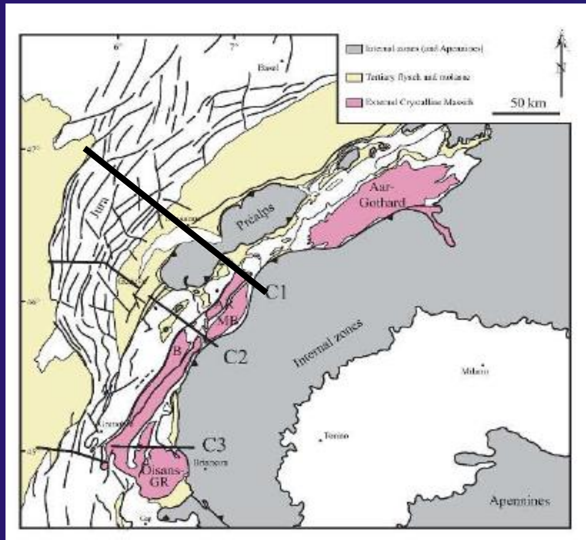




*Non reactivation of normal faults
*Basement « folding » closely associated with top-to-the-W distributed low-angle brittle-ductile Alpine shear zones
(GS facies : 3-4 kb, 330-350°C)
→ Efficient crustal thermal weakening during collisional burial

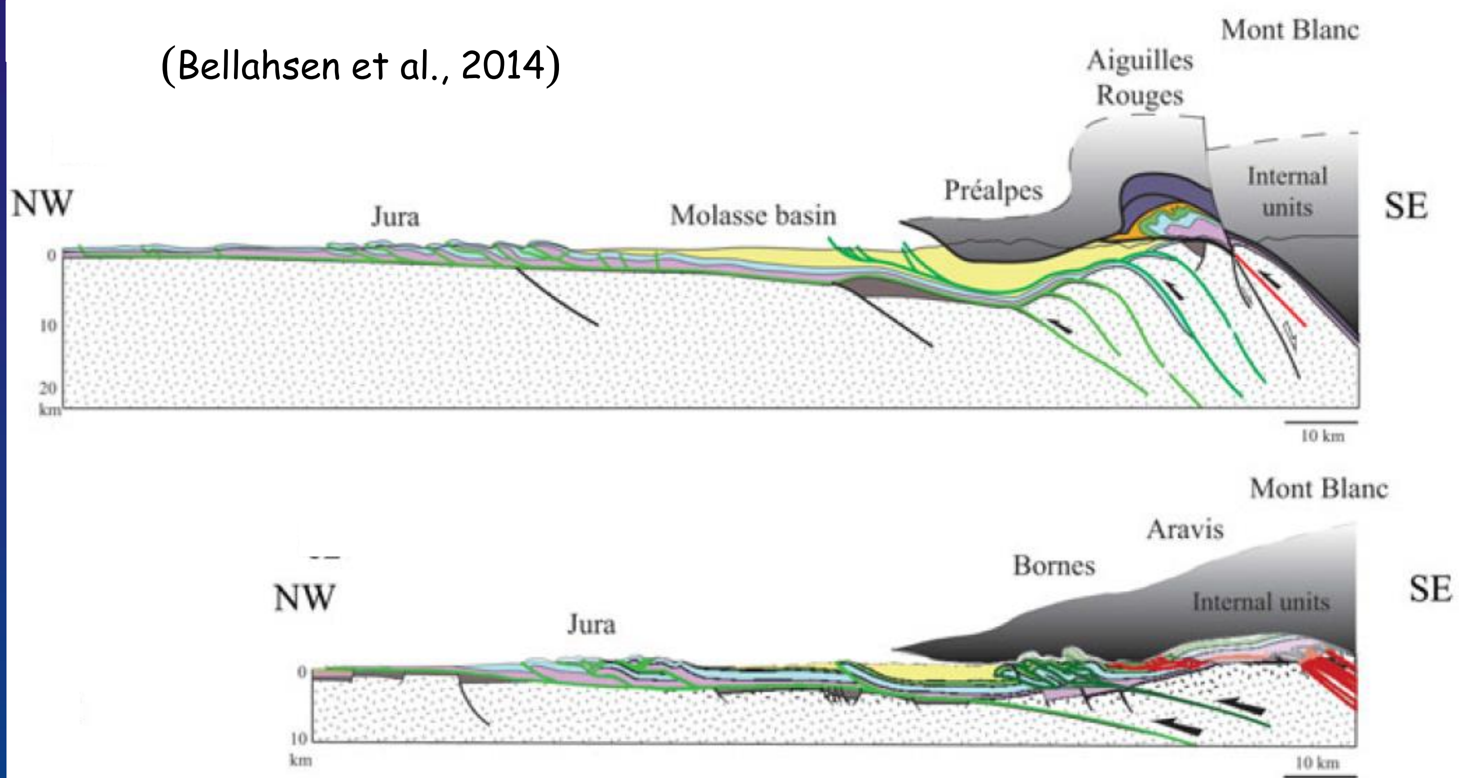
Fractured Qz clasts
Mylonitic deformation related to high white micas content

Mont Blanc-Aiguilles Rouges section

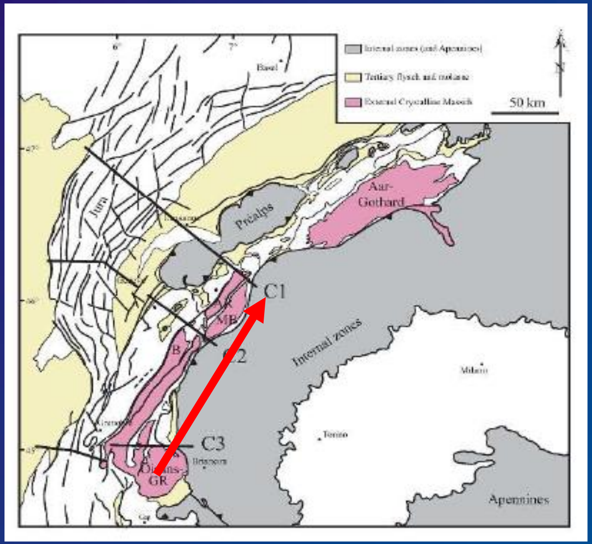


Basement shortened by localized thrust stacking and underplating below the internal units

Accretion of a wide cover domain in frontal parts (Jura and Molasse Basin) with activation of large basement thrusts.



(Bellahsen et al., 2014)



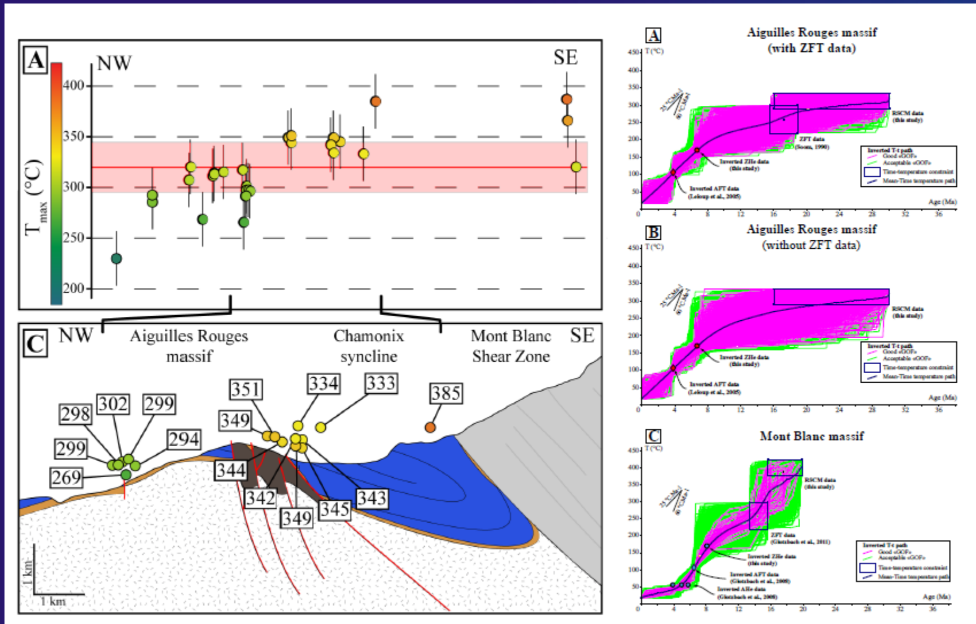
Localization, style of basement-involved deformation and shortening (%) vary along the strike of the western Alpine arc. Shortening increases across the external zone from the Oisans section (ECM : 16%) to the Mont Blanc section (ECM : 30-38%).

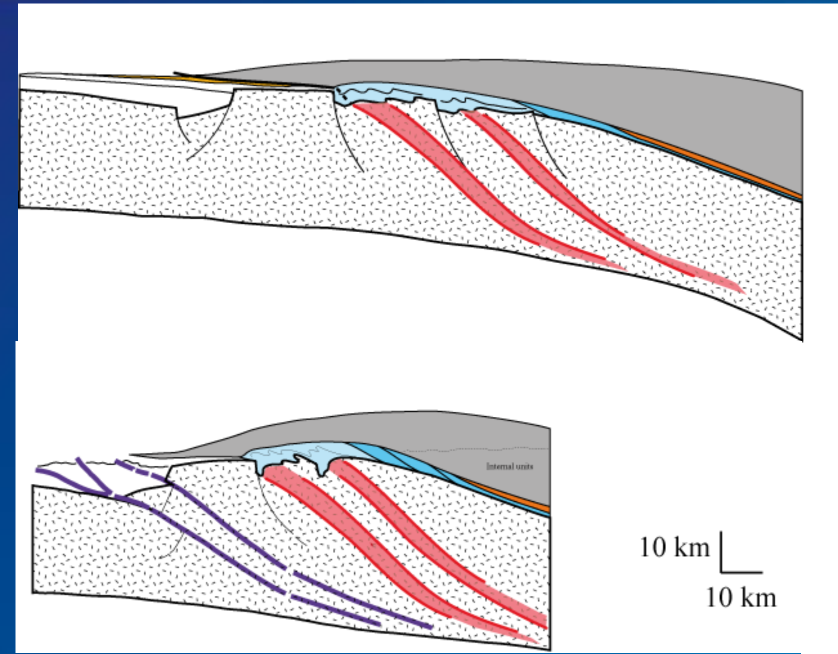
Significance in terms of crustal rheology :

Along the Mont Blanc section, basement shortening remains localized, leading to stacking of basement slices, while it is more distributed along the Oisans section.

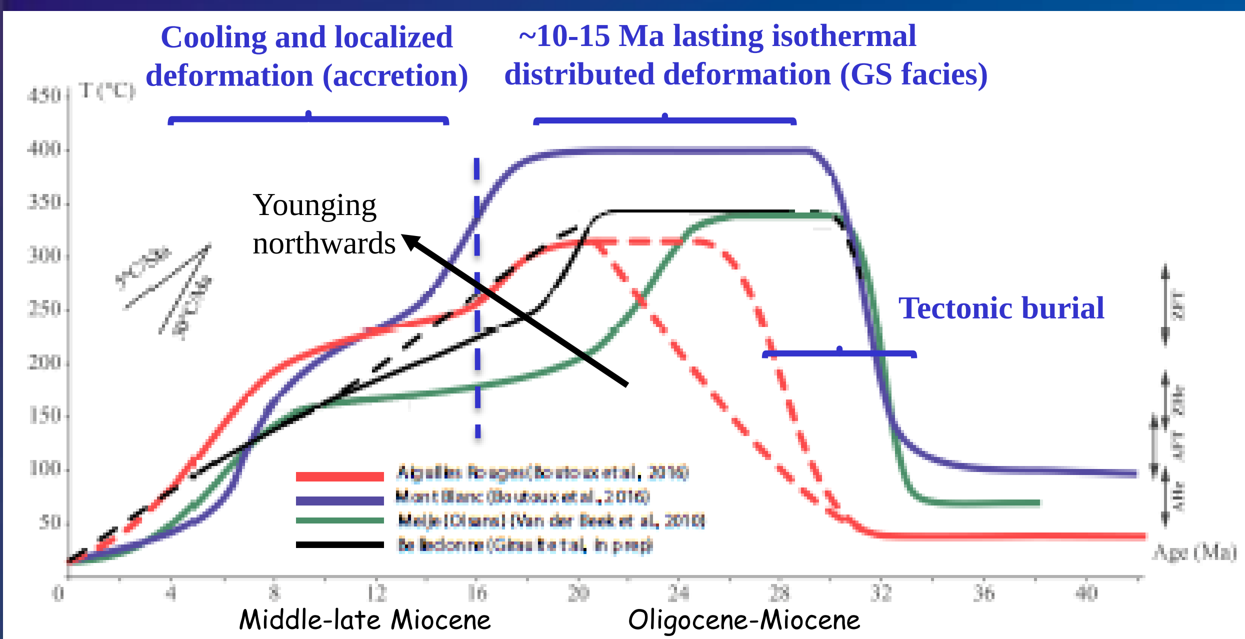
→ the more buried and thermally weakened crust at the latitude of the Mont Blanc (400°C, 5kb) is more prone to localized shortening at the orogen-scale.

(Bellahsen et al., 2014;
Boutoux et al., 2016; Girault et al., in prep)





RSCM, metamorphism and low-T thermochronology



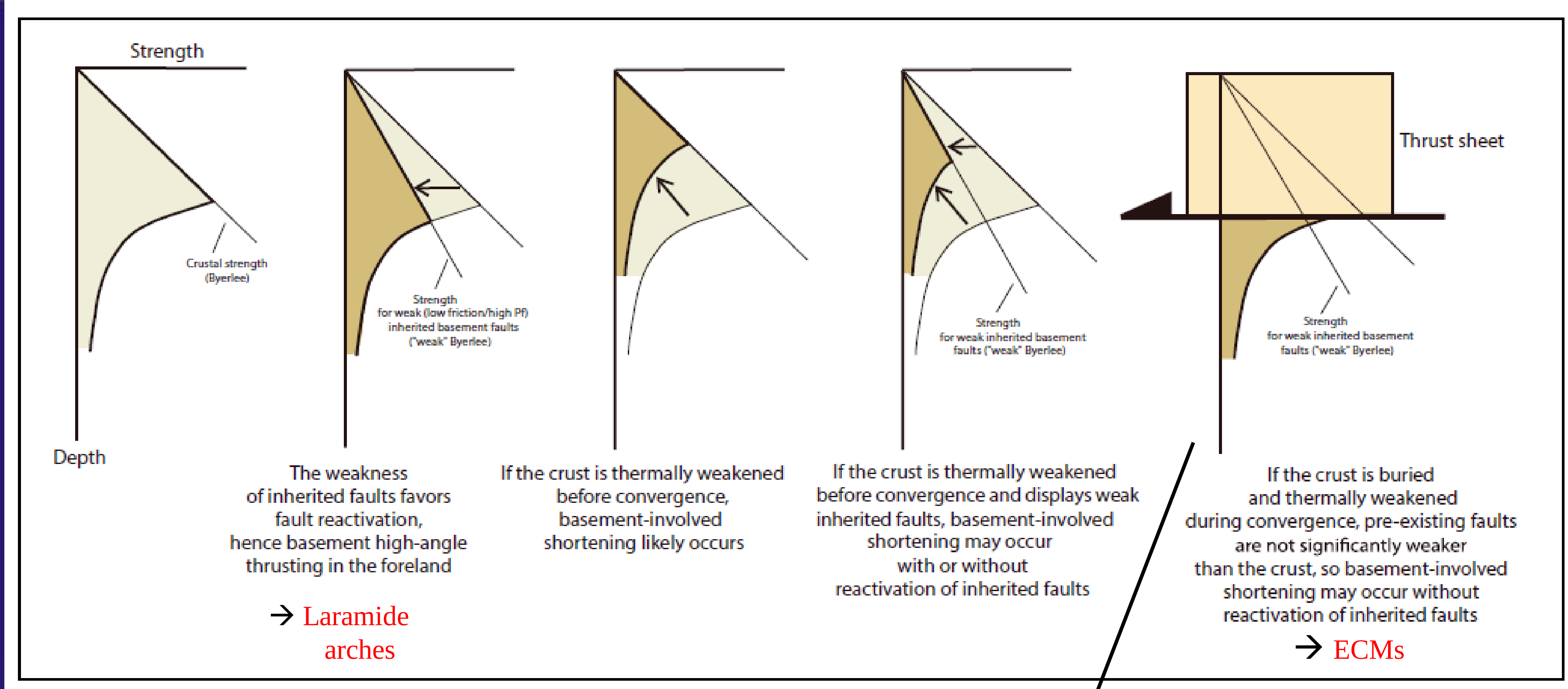
Basement shortening :

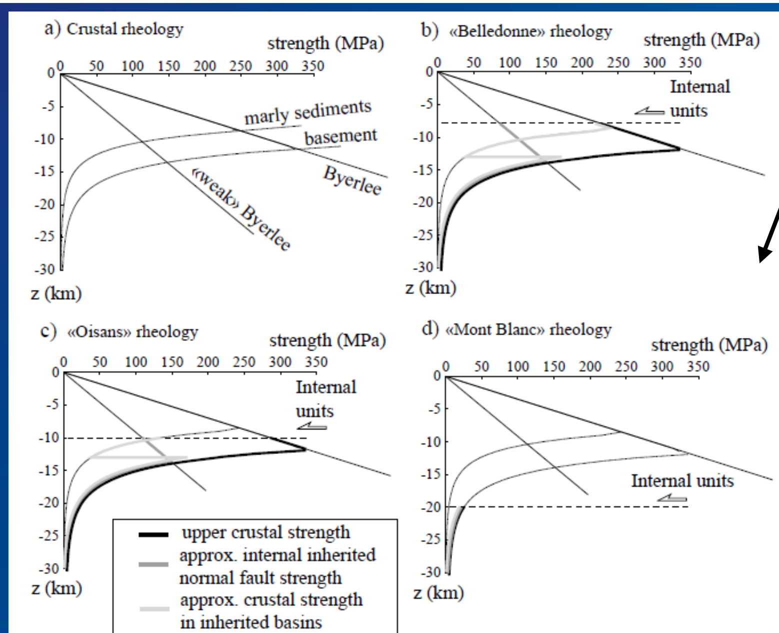
-distributed shearing or stacking of crustal slices during a long-lasting (~10-15 Ma) T°C peak (330-400°C) related to burial (10-20 km) under the Penninic nappes = underplating without orogenic wedge widening

-frontal accretion/exhumation thanks to localized crustal thrust ramps = later stage of orogenic wedge widening

Consistent westward sequence of basement shortening and exhumation

Exhumation younging northwards.

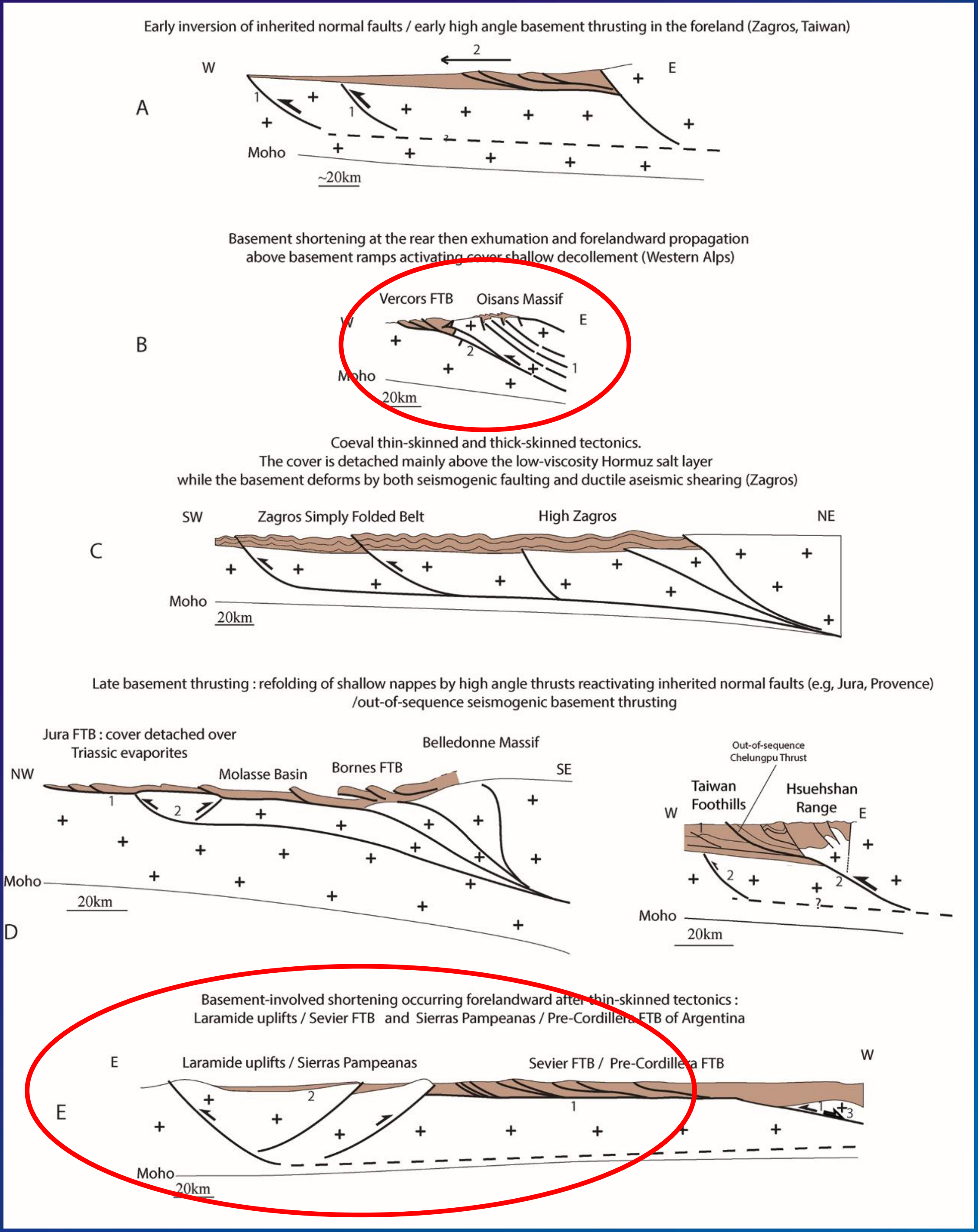




Weakening

+ possible compositional weakening

(Bellahsen et al, 2014; Lacombe and Bellahsen, 2016)



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

(Lacombe and Bellahsen, 2016)

Take-home message

In basement-involved FTBs, shortening is distributed throughout the whole crust and is usually lower than in their thin-skinned counterparts.
This reflects weakness of the underlying lithosphere.

In FTBs resulting from inversion of former proximal passive margins, basement thrusting occurs in a rather localized way in their inner parts. This requires structural inheritance and/or hot crustal temperature either inherited from a recent (pre- orogenic) rifting event or resulting from syn-orogenic underthrusting and heating.

Development of thick-skinned belts within cratons (eg, Laramide, Sierras Pampeanas) remains somewhat enigmatic : it occurs in colder conditions and likely requires specific boundary conditions (strong interplate coupling, such as provided by flat-slab subduction) ensuring efficient transmission of stresses (crustal/lithospheric stress guide) and far propagation of deformation in the foreland by crustal/lithospheric buckling or deep crustal decollement, in addition to local structural and/or possible physical/compositional weakening.

Basement-involvement in FTBs raises the question of the way the orogen is mechanically coupled to the foreland and how orogenic stresses are transmitted through the heterogeneous basement of the foreland/plate interior.

Many thanks for your attention