Penetrative Strain on the Field Scale: Detrimental to Reservoir Quality?*

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Abstract

Penetrative strain constitutes the proportion of the deformation that is not accommodated by the development of field-scale structures. In compressive settings, PS is reported to be between 2-30% shortening. At a field scale, slip on minor fault arrays and development of minor folds may accommodate significant PS, changing pore space and connectivity of thinly-bedded units. On the grain scale, PS may be accommodated by intragranular (e.g. twinning) or intergranular (e.g. grain impingement) processes. This study considers the PS accommodated by a cover sequence over a basement-thrust-related, Laramide-age fold in the Bighorn Basin, the Rattlesnake Anticline. Field observations, thin-section analysis and structural modeling are used to characterize the amount and mechanisms of PS accommodation in the exposures of the Shoshone Canyon. Faults on the gently-dipping limb are steep, with a reverse sense of movement, and are regularly spaced. They are interpreted as reactivated fractures from an earlier, regional fracturing event. Reactivation occurred during late tightening of the anticline. Other faults on this limb, with generally lower dip angles and without the regular spacing, are likely to have formed during tightening without reactivating fracture sets. An intense zone of deformation is observed in the cover rocks immediately adjacent to the inferred master fault. Thrust faulting in this zone is either sub-parallel to the master fault, or forms low angle, out-of-the-syncline faults. Most faults contain some fault gouge. Rocks in this zone have also deformed by buckling of the thin, competent carbonate layers and thickness variations in the mudrock interlayers. Cross-section restoration indicates that fault structures accommodate over 10% of the strain in the system, with the remaining PS taken up by grain impingement and twinning. Overall, volume loss by PS accommodation is detrimental to the reservoir quality of unconventional fields. Significant grain impingement contributes strongly to the reduction of pore space, reducing the amount of hydrocarbon that can be trapped. Fault gouge in a mudrock-dominated system tends to reduce the permeability of a fault, and in this example, has led to reduced permeability of an otherwise promising fracture set. Thus, understanding the contribution of PS to the deformation of an unconventional reservoir allows for more realistic estimates of hydrocarbon in place, and improved operating decisions.

References Cited

Burberry, C.M., 2015, Spatial and Temporal Variation in Penetrative Strain during Compression: Insights from Analog Models: Lithosphere, v 7, p. 611-624. doi:10.1130/L454.1

Beaudoin, N., R. Leprete, N. Bellahsen, O. Lacombe, K. Amrouch, J-P. Callot, L. Emmanuel, and J-M. Daniel, 2012, Structural and Microstructural Evolution of the Rattlesnake Orogenic Stress Build-up in the Bighorn Basin: Tectonophysics, v. 576-577, p. 20-45.

Mitra, G., 1994, Strain Variation in Thrust Sheets across the Seviers Fold-and-Thrust Belt (Idaho-Utah-Wyoming): Implications for Section Restoration and Wedge Taper Evolution: Journal of Structural Geology, v. 16/4, p. 585-602.

Twiss, R.J., and E.M. Moores, 2007, Structural Geology, 2nd ed., W.H. Freeman & Co., New York. 736 p.

Yonkee, A., and A.B. Weil, 2010, Reconstructing the Kinematic Evolution of Curved Mountain Belts: Internal Strain Patterns in the Wyoming Salient, Sevier Thrust Belt, USA: Geological Society of America Bulletin, v. 122/1-2, p. 24-49.

Penetrative Strain on the Field Scale: Detrimental to Reservoir Quality?

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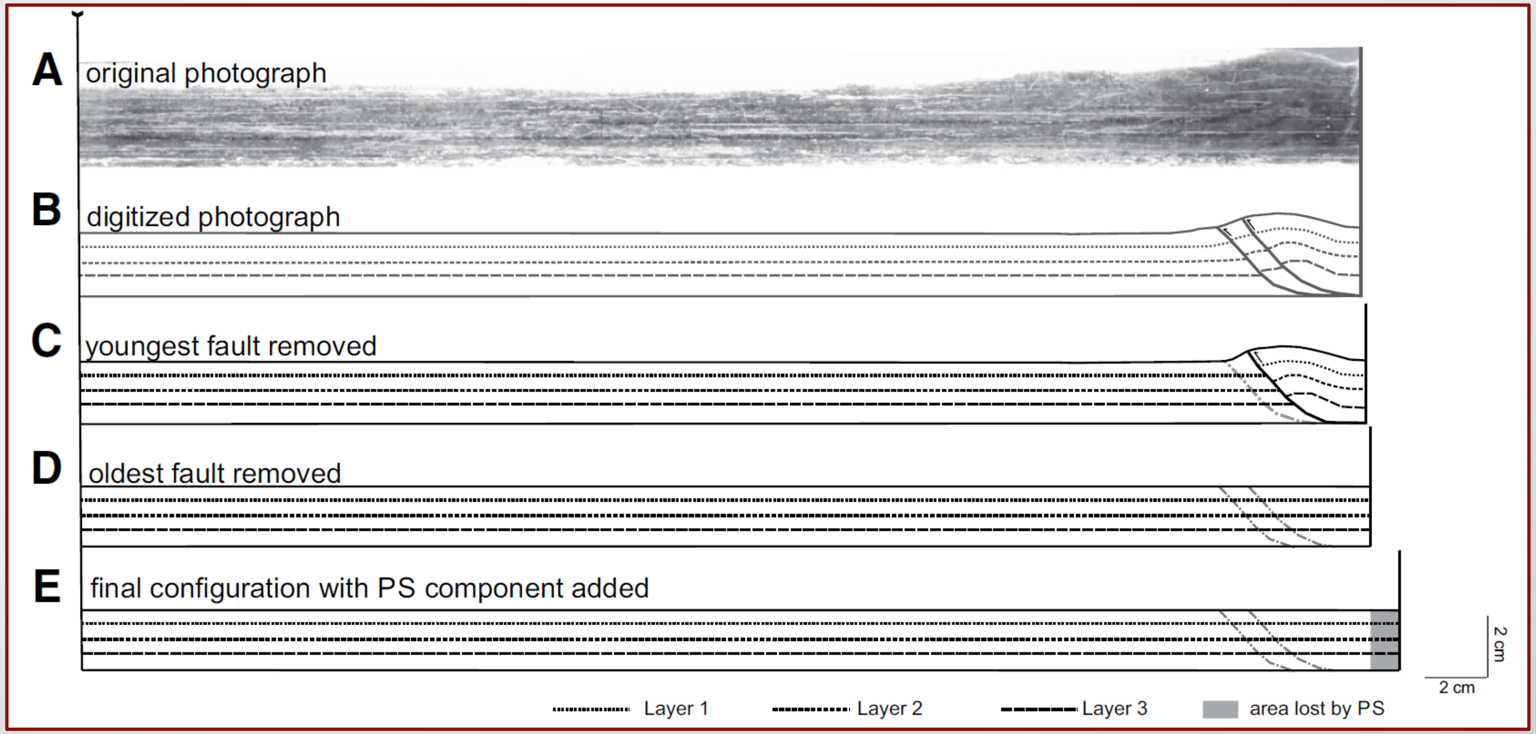
What do we mean by Penetrative Strain?

- That percentage of the total shortening which is not accounted for by the development of macroscale features



Burberry, 2015

CAVEATS

- "macroscale" - subjective! This example considers faults with offsets of mm-cm as evidence of penetrative strain
- If the feature or offset is smaller than can be displayed on the scale of a cross-section, it's probably PS.

How much shortening can be accommodated?

- Field data gives 13.8 km (20%) penetrative strain across this section (Mitra, 1994; Yonkee & Weil 2010)
- Analog model suites suggest approx. 10.7 km (12%) across an equivalent section

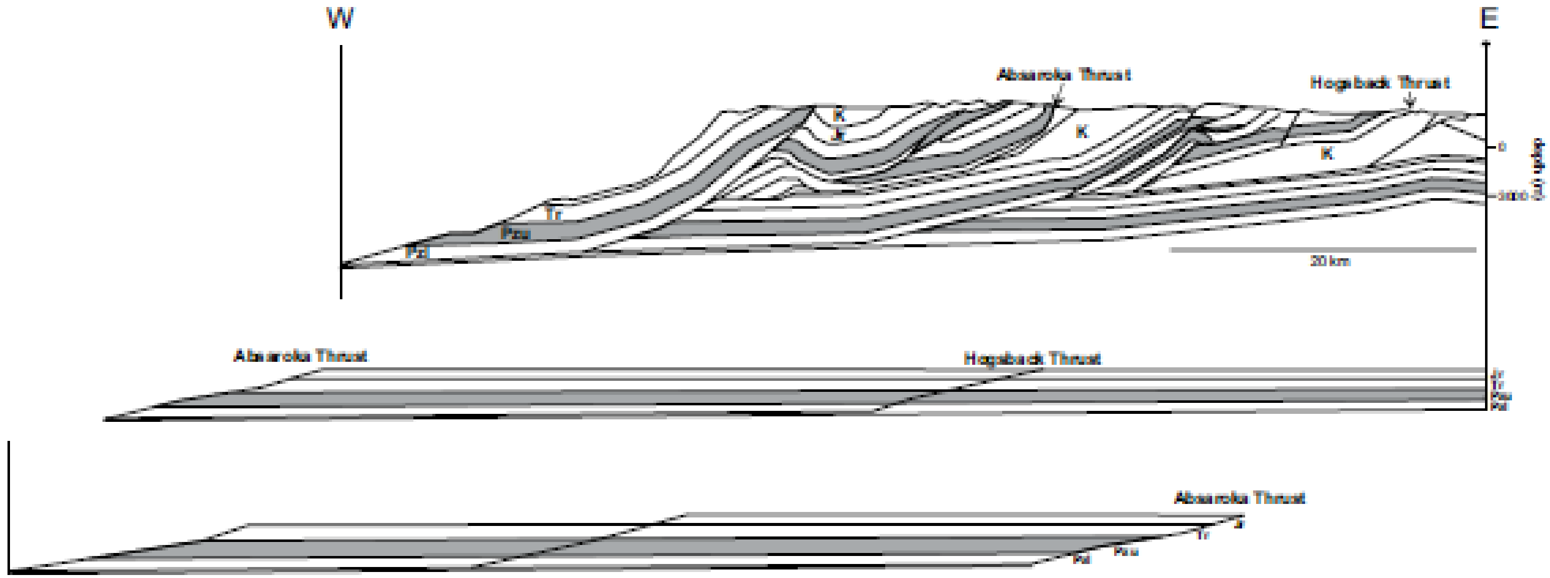
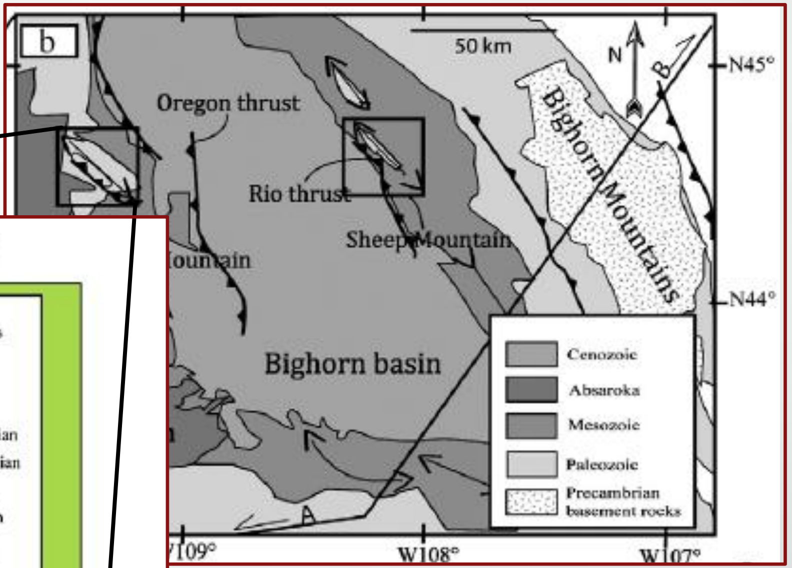


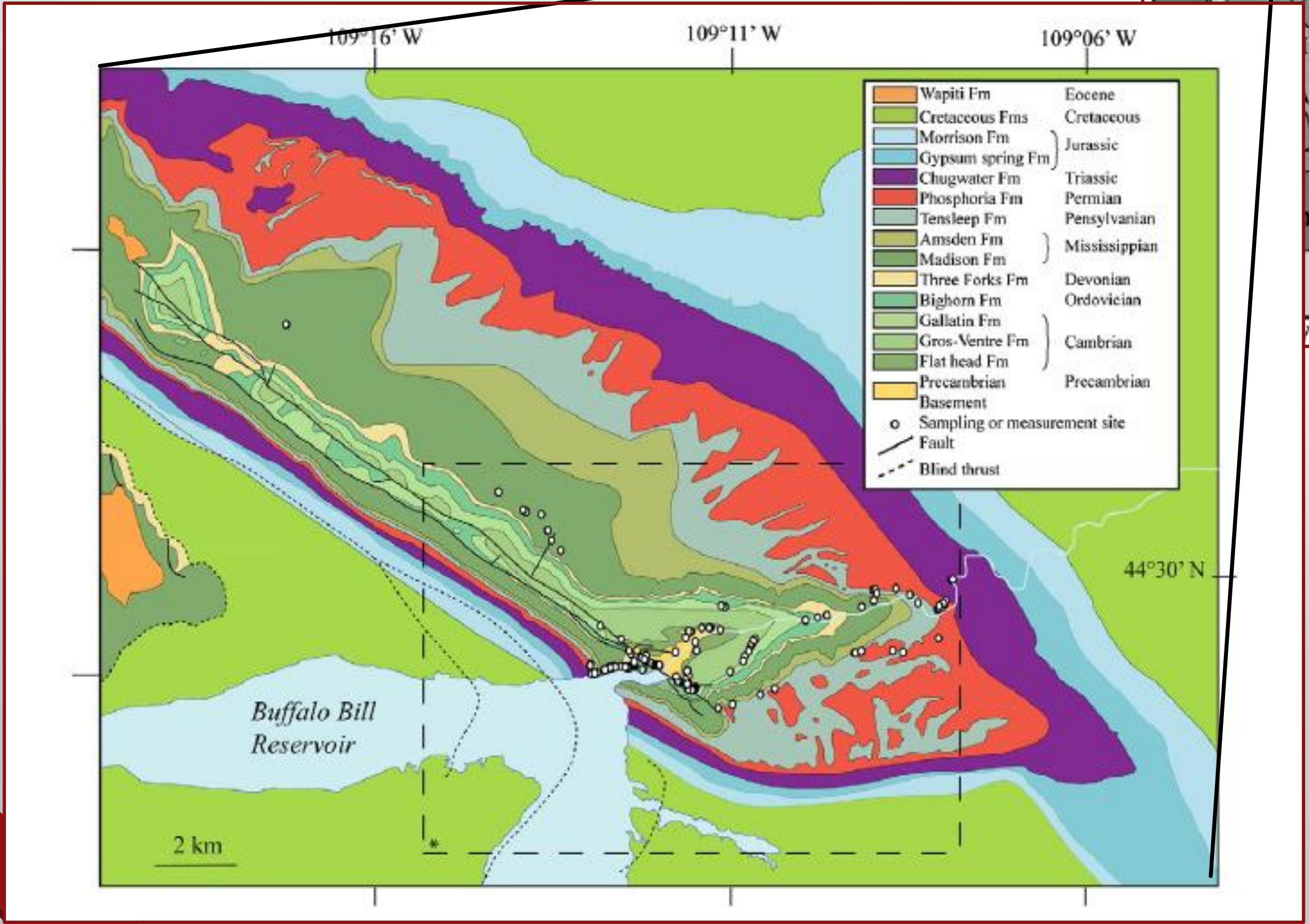
Figure 17. Comparison to an example from the Wyoming salient, after Yonkee and Weil (2010). The upper image shows the segment reproduced from Yonkee and Weil (2010). The lower images show the restored thrust systems. Pzl—Lower Paleozoic units, Pzu—Upper Paleozoic units (shaded gray), Tr—Triassic units, Jr—Jurassic units, and K—Cretaceous units. Important thrust faults are labeled.

Burberry, 2015

This study: less complex system (?) than previous example

- Study area Rattlesnake Anticline, WY

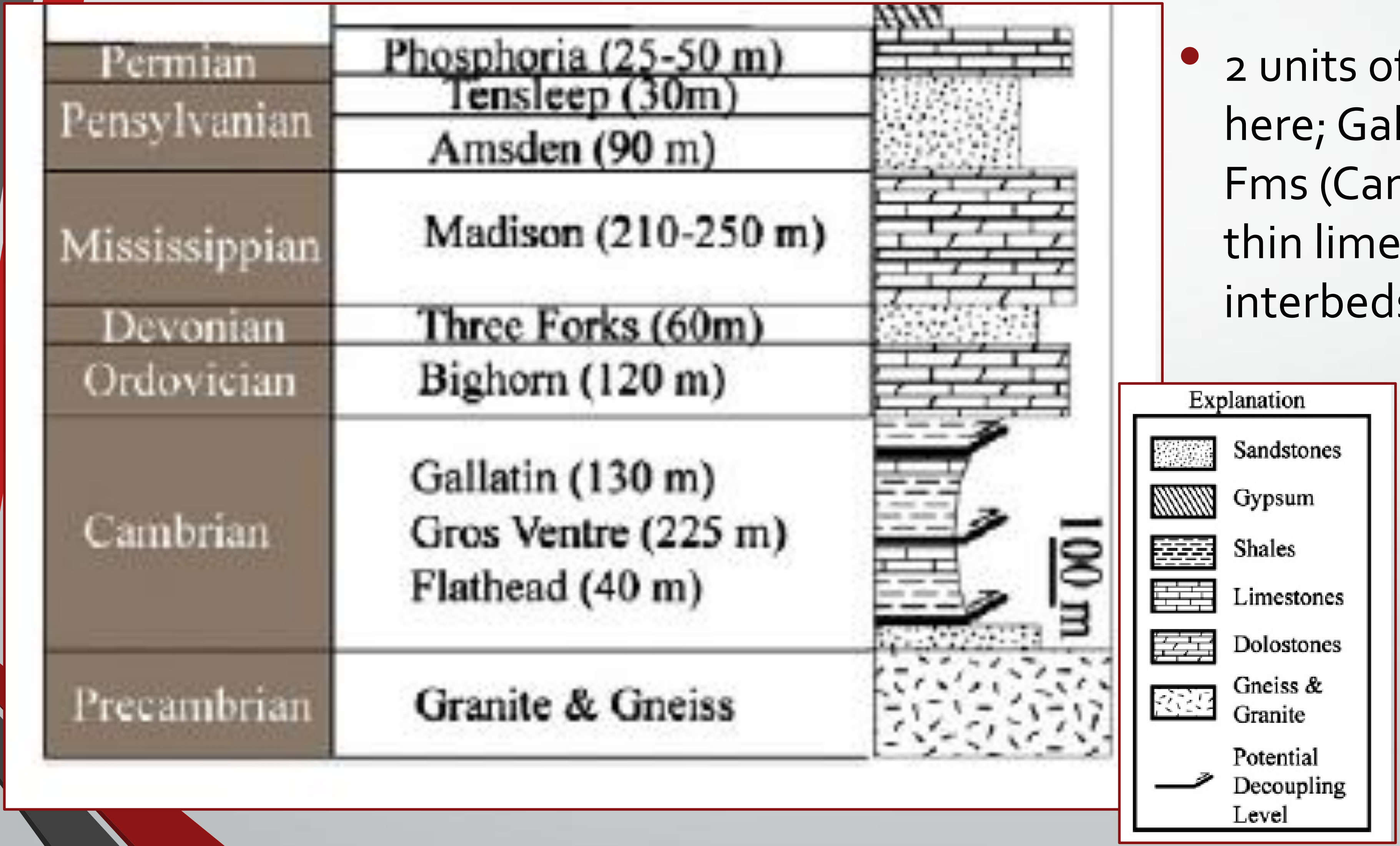




- Laramide-age fault-cored anticline in the western part of the Bighorn Basin, WY

Maps from Beaudoin et al., 2012

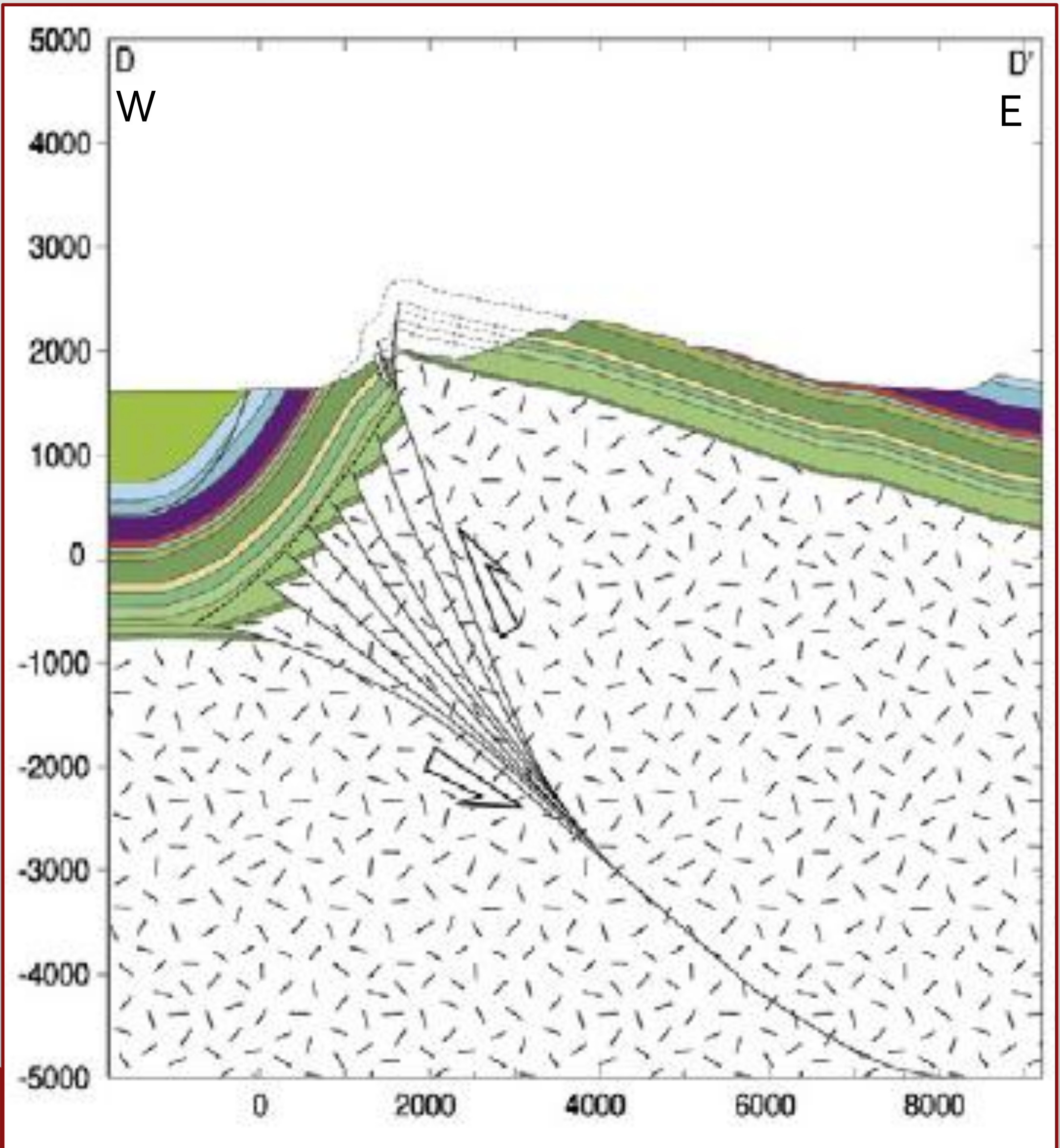
Rattlesnake Anticline: relevant stratigraphy

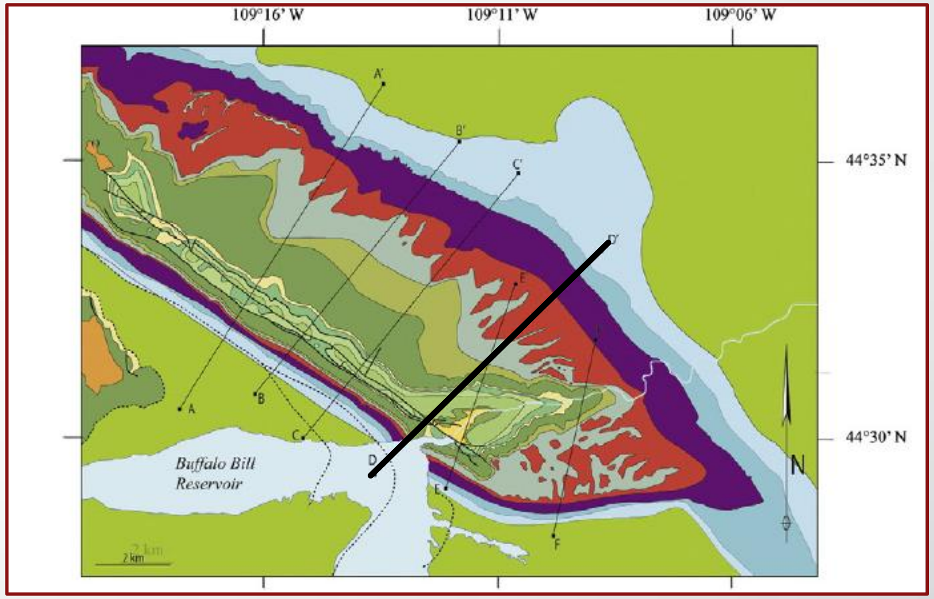


- 2 units of primary interest here; Gallatin/Gros Ventre Fms (Cambrian, shale and thin limestone/dolomite interbeds)

Strat Column from Beaudoin et al., 2012

Rattlesnake Anticline in XS





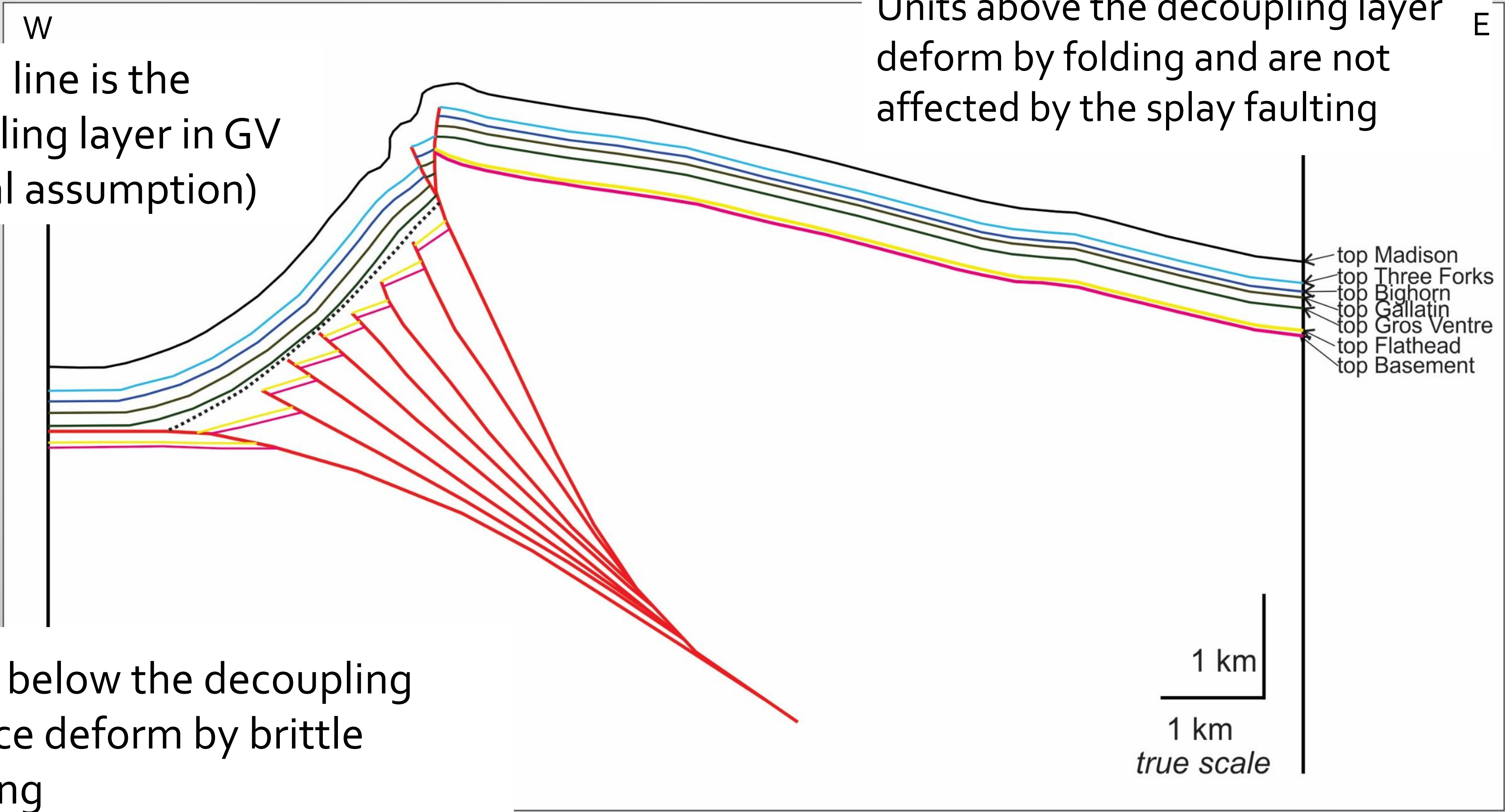
- Triangular zone of shear in forelimb; multiple basement fault strands; decoupling in Gros Ventre Fm.

XS from Beaudoin et al., 2012

Rattlesnake Anticline: balanced XS

Dashed line is the decoupling layer in GV (original assumption)

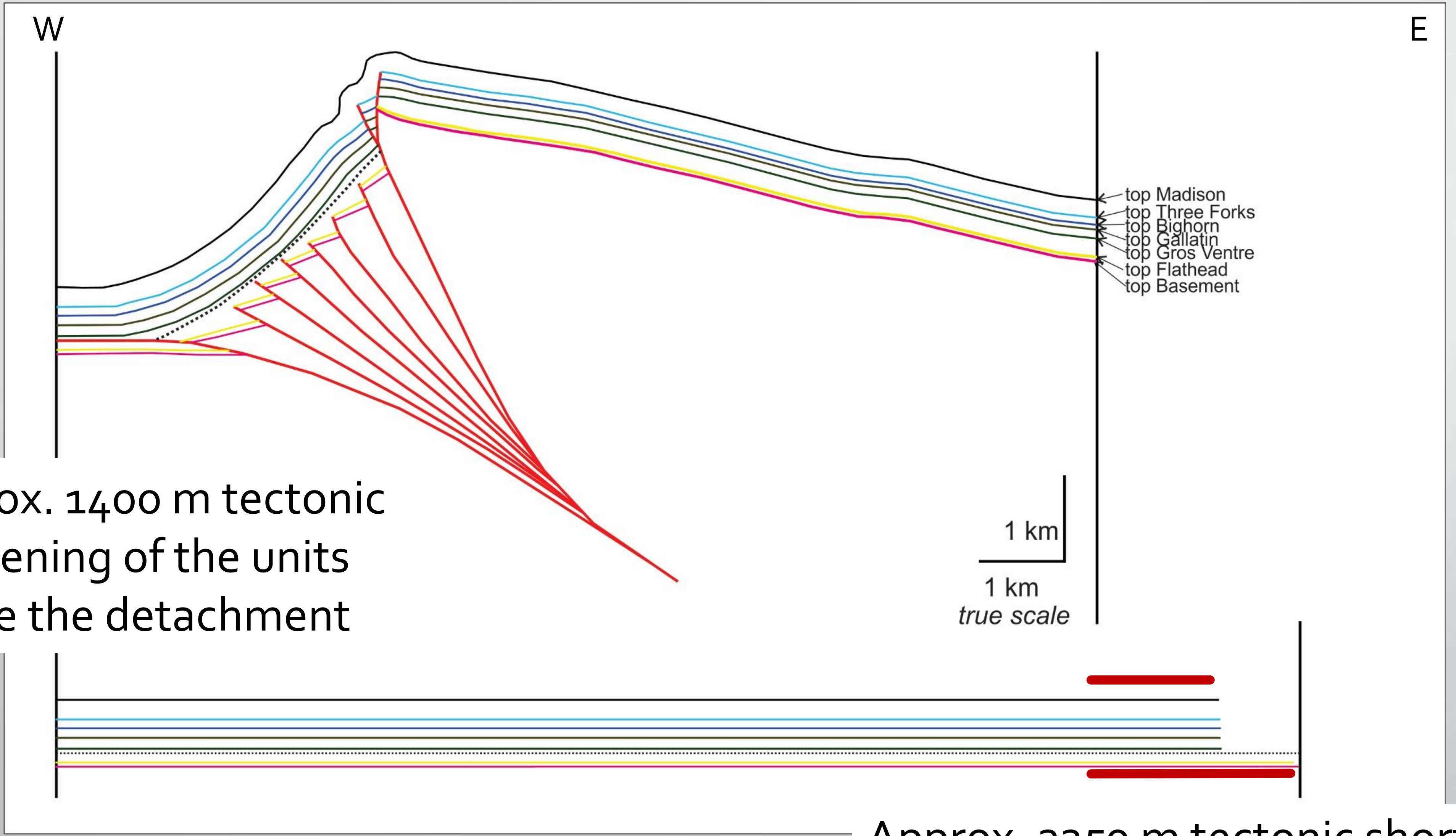
Units above the decoupling layer deform by folding and are not affected by the splay faulting



Units below the decoupling surface deform by brittle faulting

XS digitized after Beaudoin et al., 2012

Rattlesnake Anticline: balanced XS

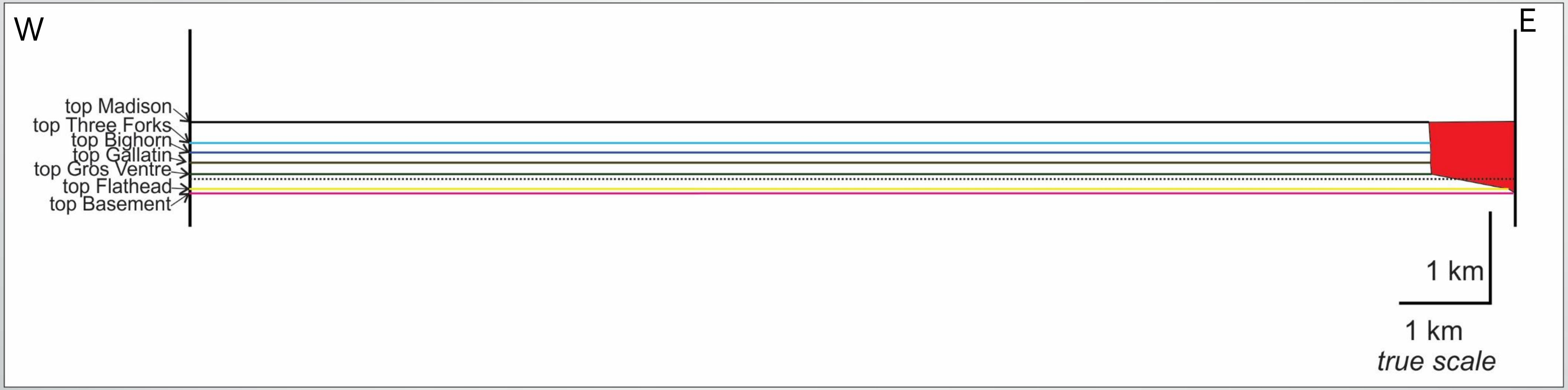


Approx. 1400 m tectonic shortening of the units above the detachment

Approx. 2250 m tectonic shortening of the units below the detachment

Rattlesnake Anticline: balanced XS

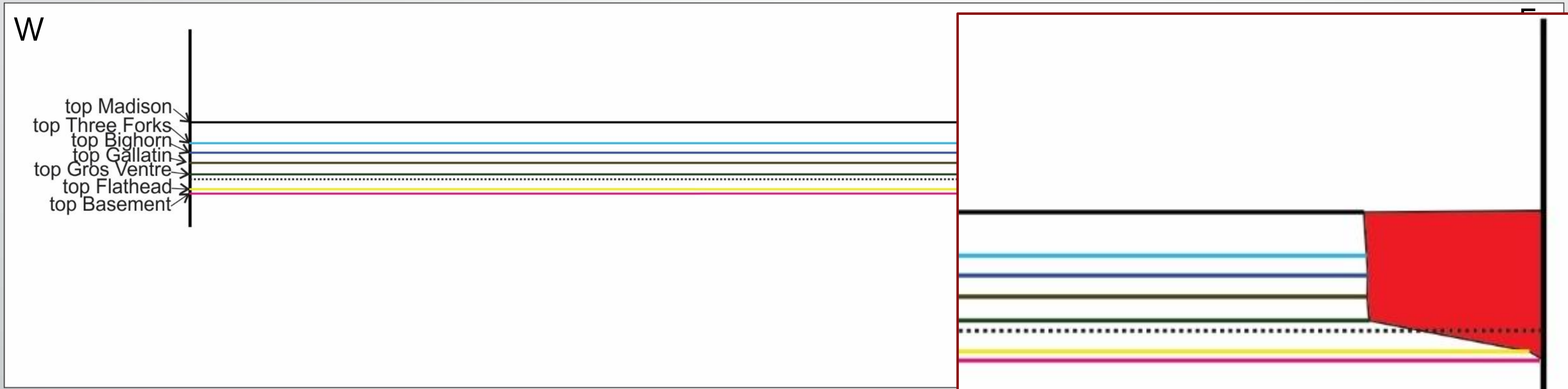
- Assuming rigid basement, approx. 2300 m total shortening; thus, start length of the section = 14.3 km, and total shortening = 16%

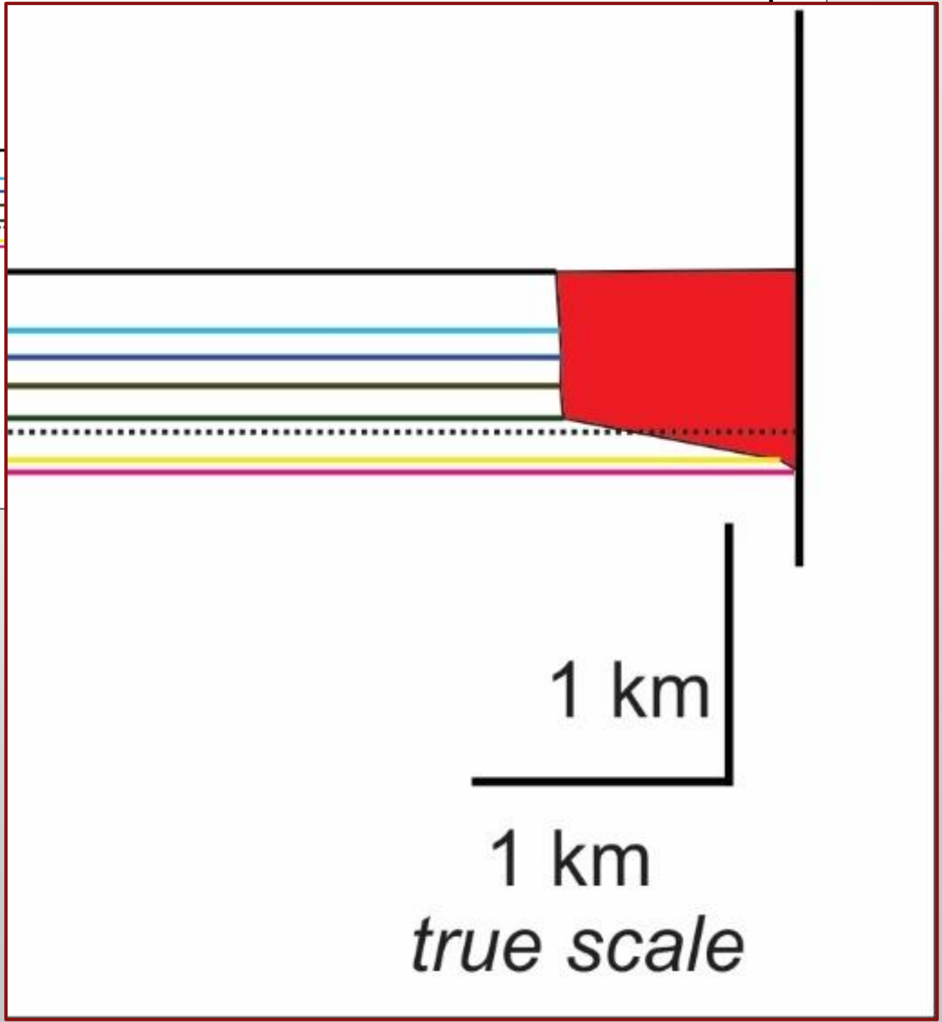


- Above the decoupled layer, we must account for an extra 900 m shortening
- Below the decoupled layer, we must account for an extra 50 m shortening

Rattlesnake Anticline: balanced XS

- Assuming rigid basement, approx. 2300 m total shortening; thus, start length of the section = 14.3 km, and total shortening = 16%

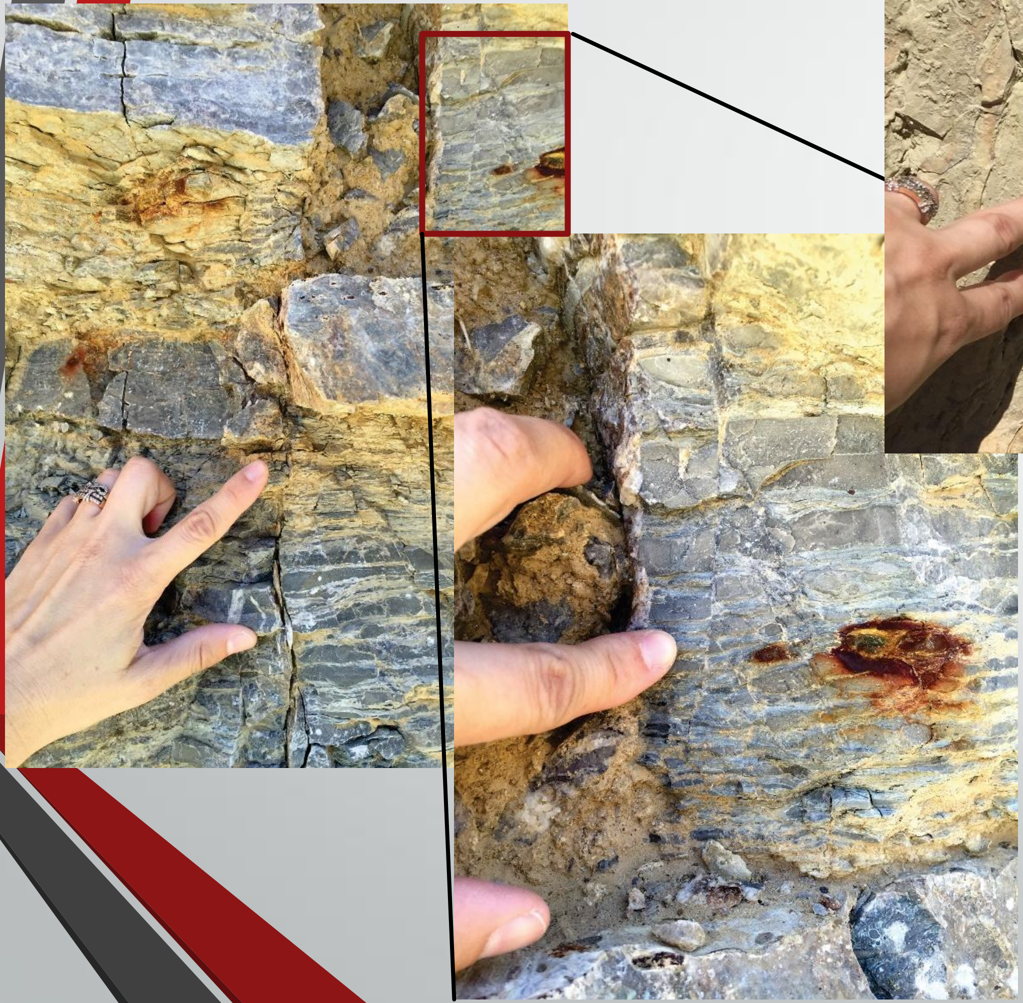


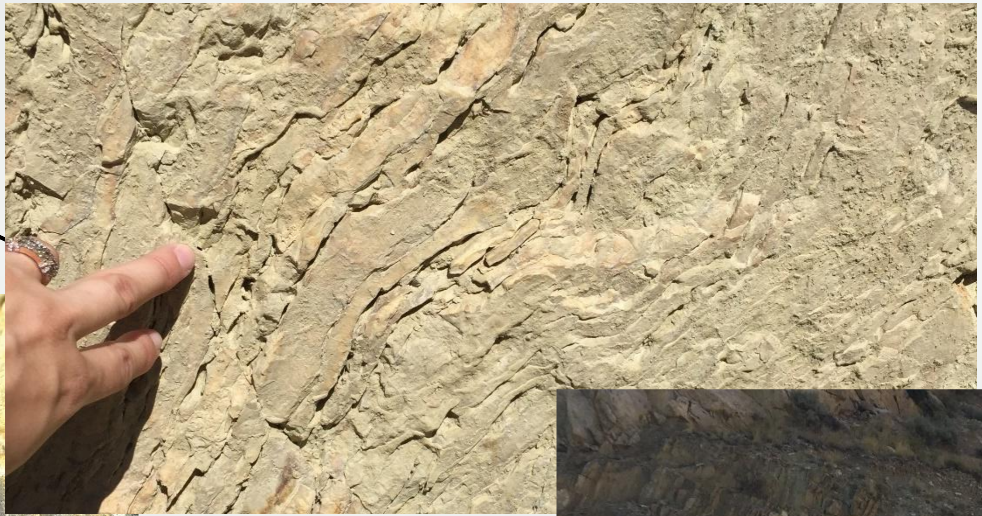


- Above the decoupled layer, we must account for an extra 900 m shortening
- Below the decoupled layer, we must account for an extra 50 m shortening

So how does that upper package deform?

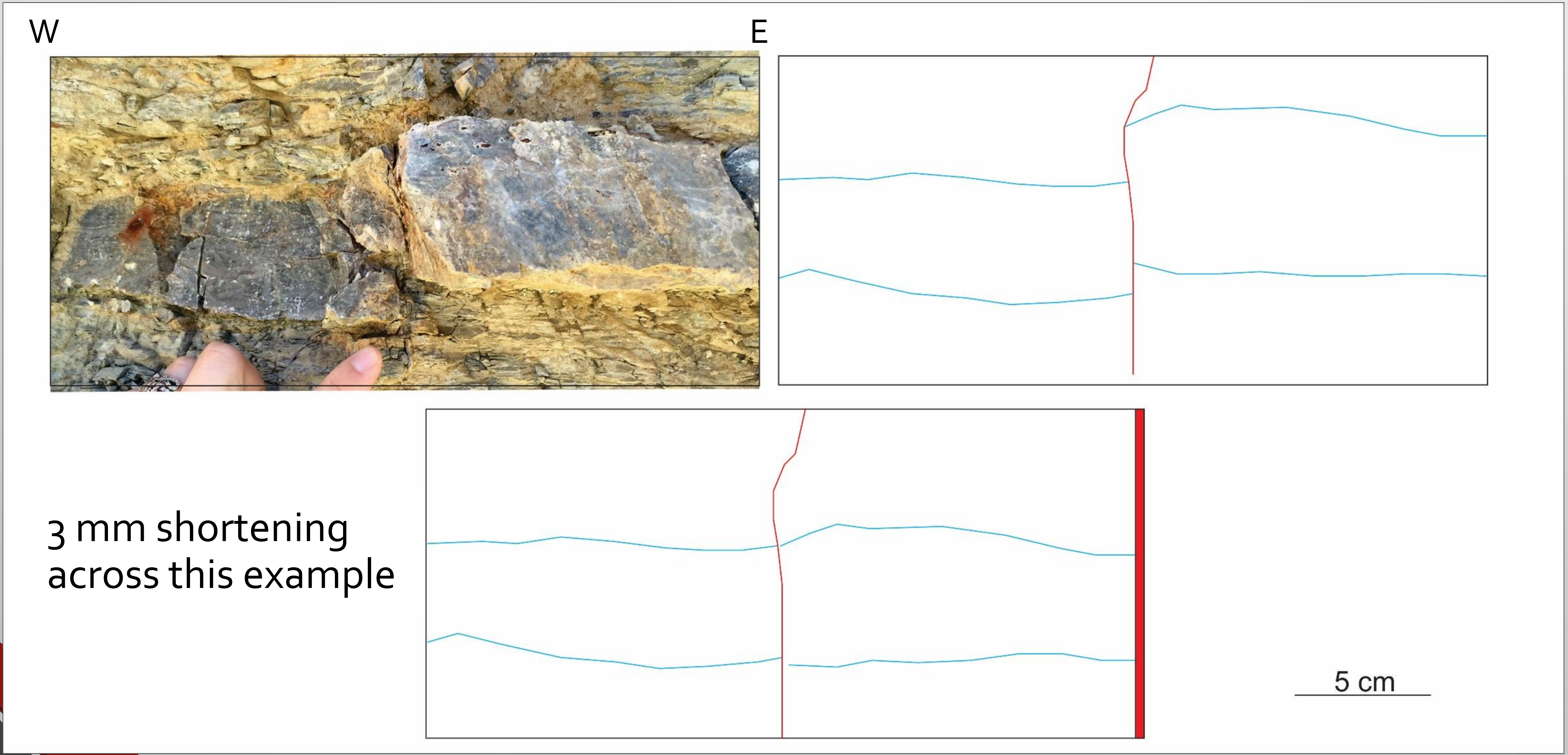
- Small scale offsets along sub-vertical fractures; buckling and out-of-the-syncline thrusting





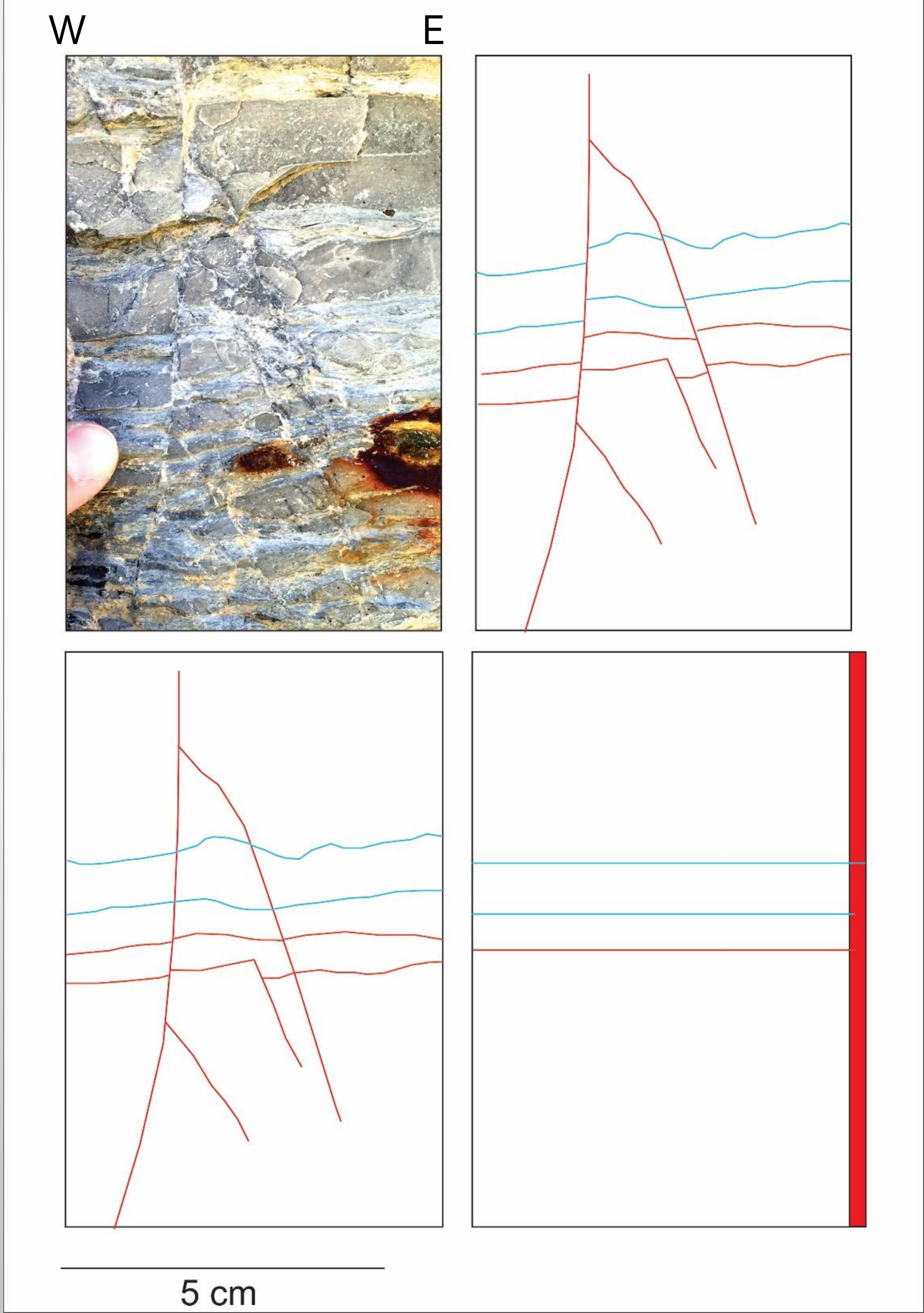
So how does that upper package deform?

- Regularly spaced sub-vertical fractures (8 m spacing, oriented NE) show evidence of minor compression



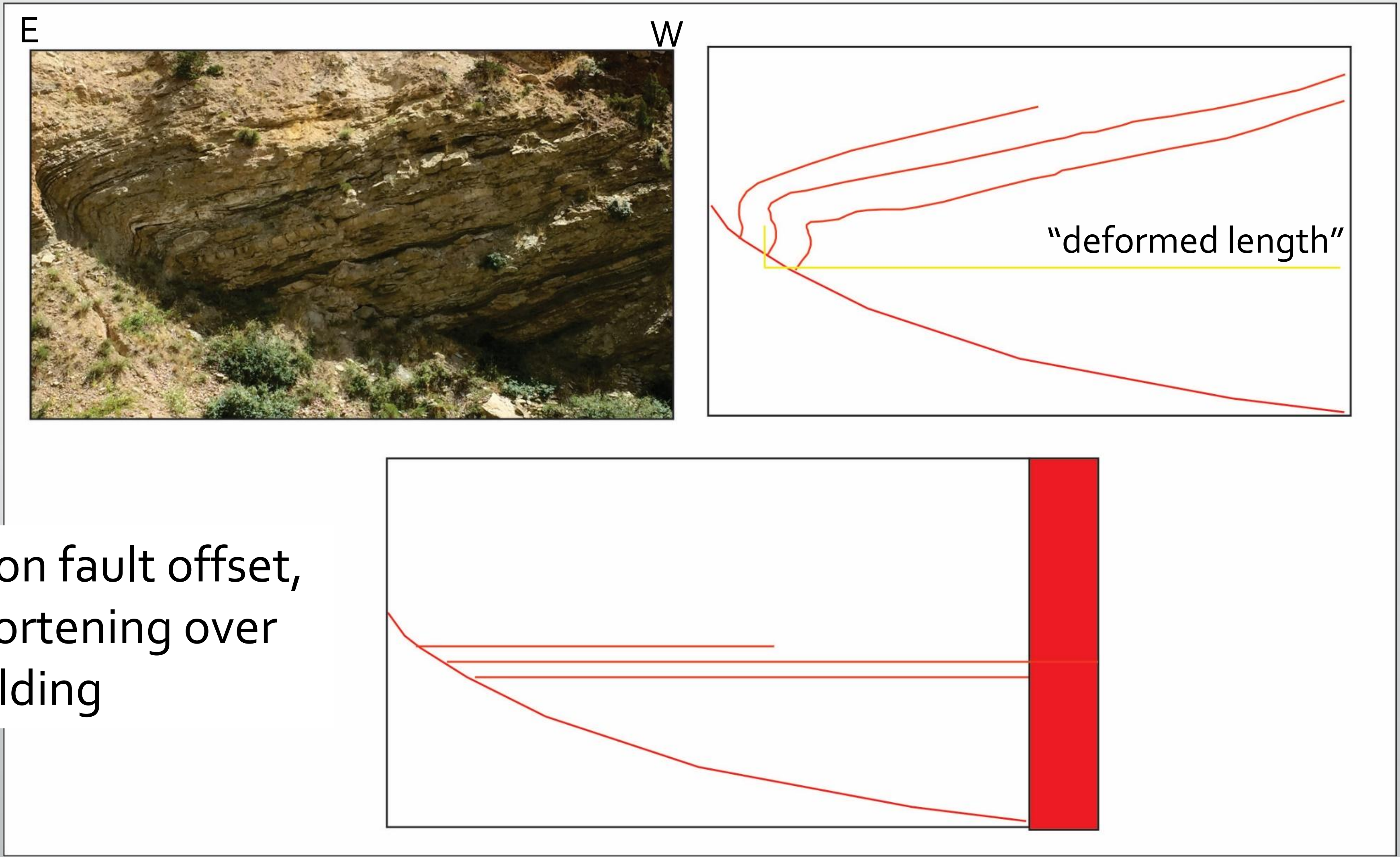
So how does that upper package deform?

- “minor” faults form on several scales.
- This example shows another 1-3 mm of shortening, depending on assumptions made.
- May seem insignificant, but think about the density of smaller faults across a section that is 12 km long.
- Compression reduces the number of open faults/fractures; detrimental to fluid flow.



So how does that upper package deform?

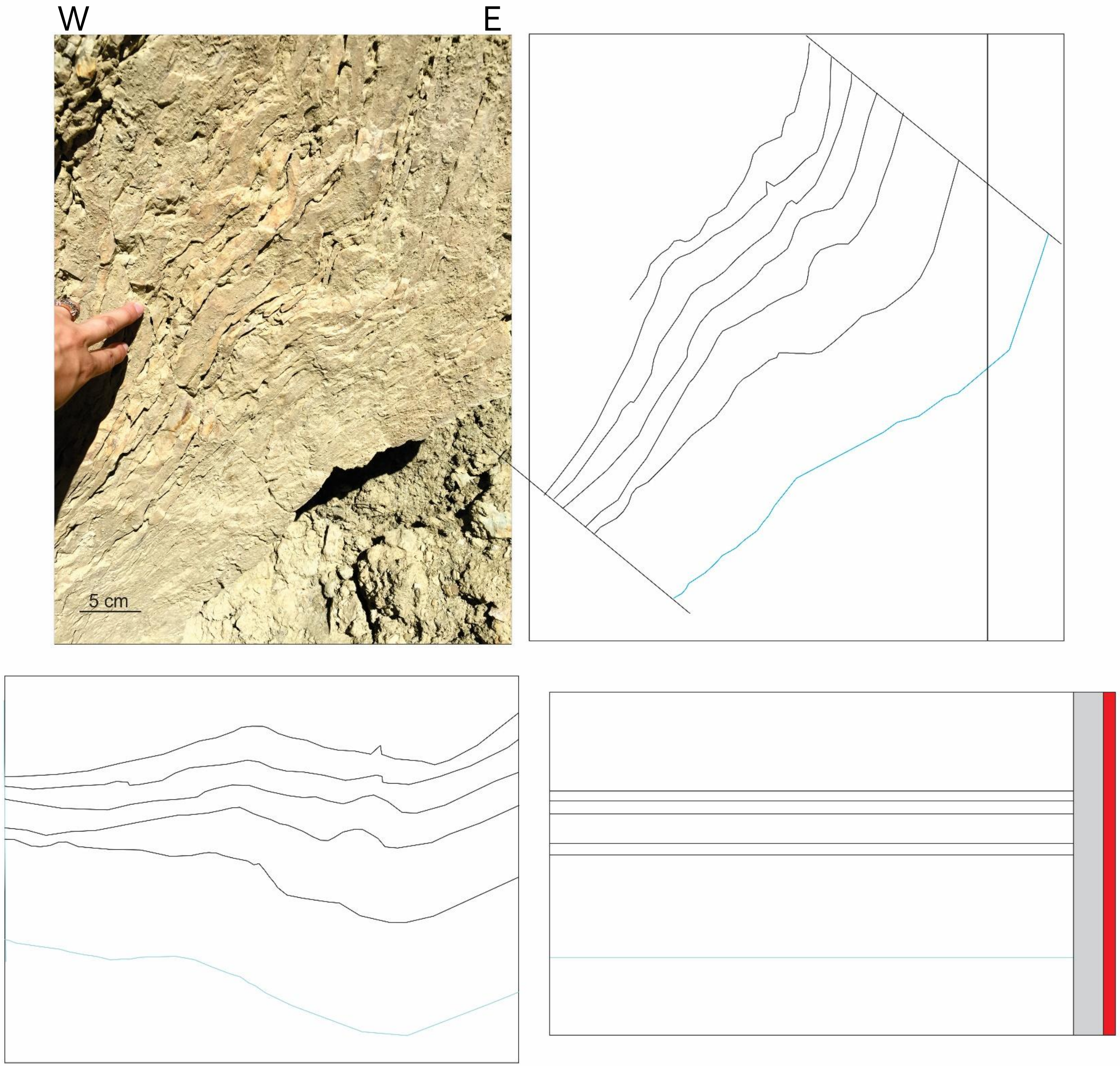
- Antithetic blind (?) thrust faults and folds



No scale, no detail on fault offset, but at least 10% shortening over this image, from folding

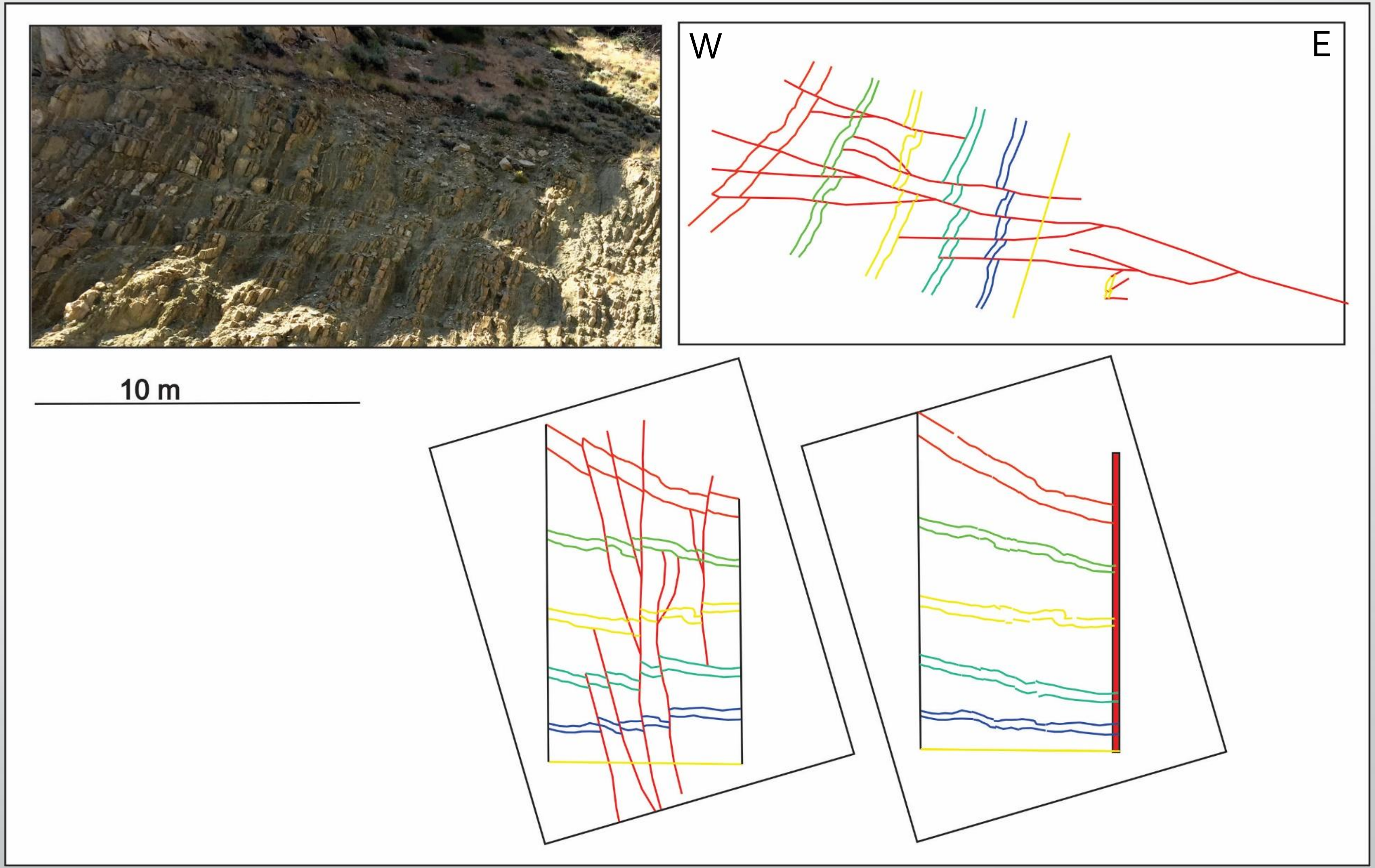
So how does that upper package deform?

- Buckling of thin layers in the over-steepened limb
- Some shortening due to overturning (grey box)
- 10 mm of shortening due to buckling in this image



So how does that upper package deform?

- Additional “out of the syncline” faulting in steep forelimb
- Buckling not removed (already in approximation)
- 20.5 cm of shortening across this image



Scaling up…

BACKLIMB

- NE trending fractures 8 m spacing; backlimb 8320 m long, thus approx. 1040 fractures in this set, in backlimb
- Field observations indicate 2/3 have small offsets, thus 3 mm shortening across 694 fractures is 2080 mm shortening = **2.08 m**
- Field observations indicate a further third have 1-3 mm of shortening across related small scale fractures, this totals 346 fractures * 3 mm = 1040 mm = **1.04 m**
- *Plus 10% shortening (no scale) across the observed fold/thrust feature*

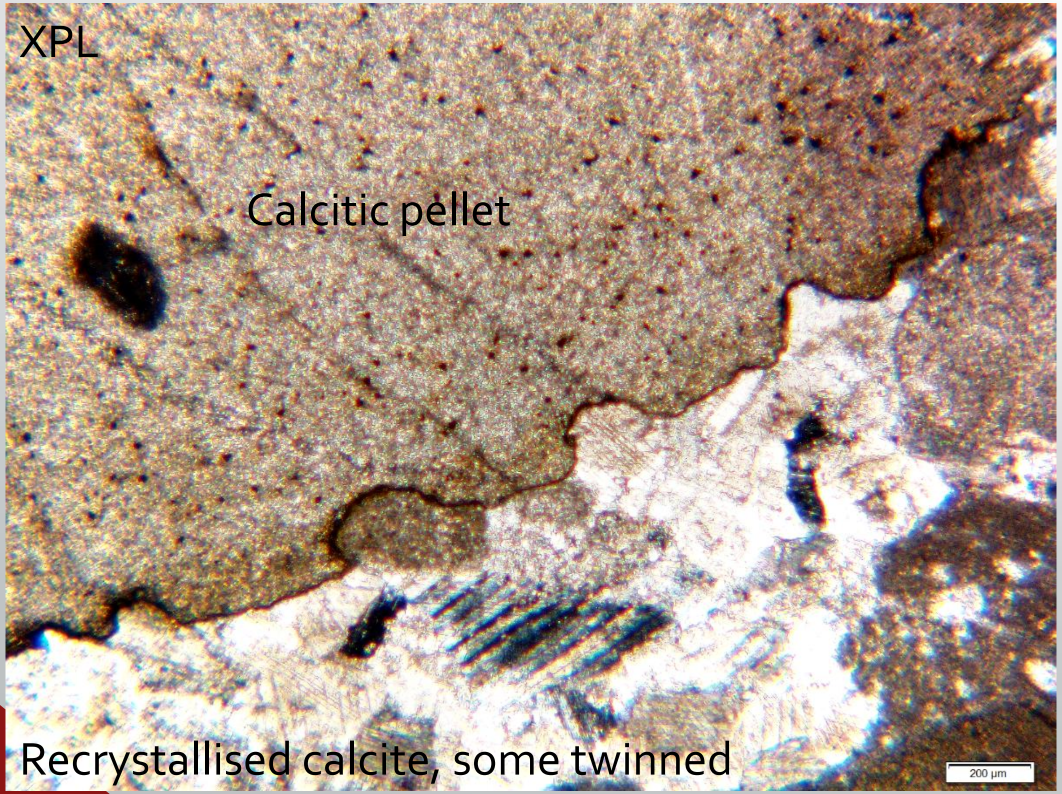
FORELIMB

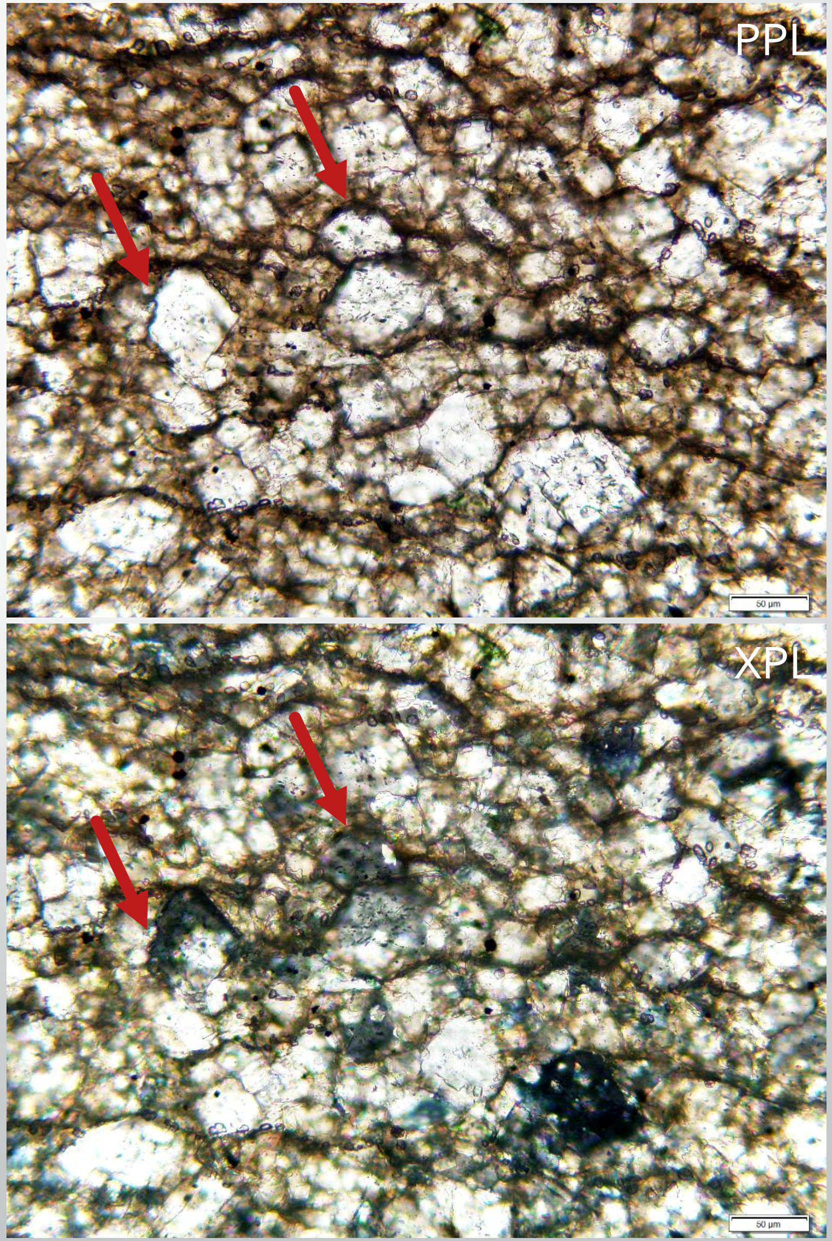
- Buckling accounts for 10 mm shortening over 42 cm of outcrop; steep limb is 3513 m long, so buckling could account for **83.6 m** shortening in this limb
- Out of the syncline faulting accounts for 20.5 cm of shortening over 5.8 m of outcrop, so faulting could account for **124.2** m of shortening in this limb

GETS US TO 210.9 m… STILL NEED TO ACCOUNT FOR *689.1* m

Deformation on the grain scale

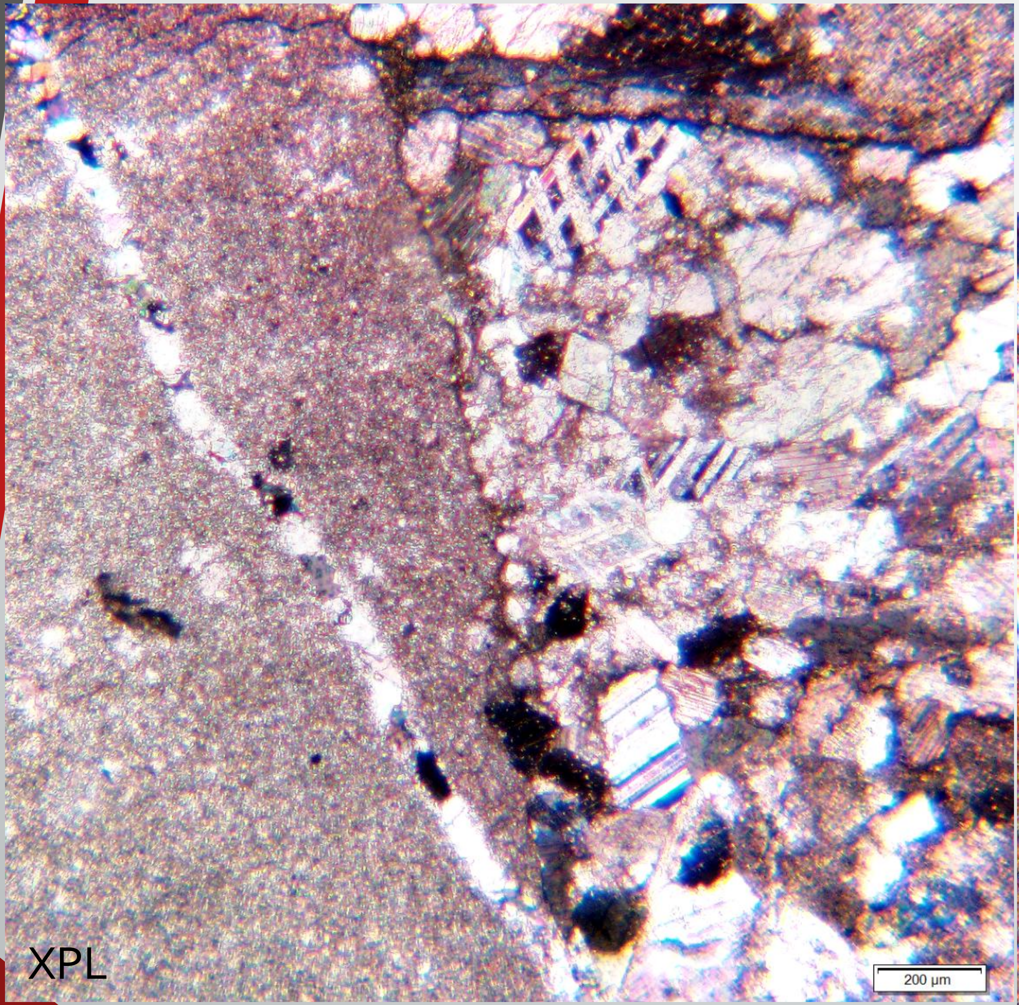
- Primary deformation mechanism in these units is calcite twinning, limited twinning in calcite on backlimb (relatively low shear strain)
- Also dissolution/grain impingement of dolomite, plus undulatory extinction indicating strain



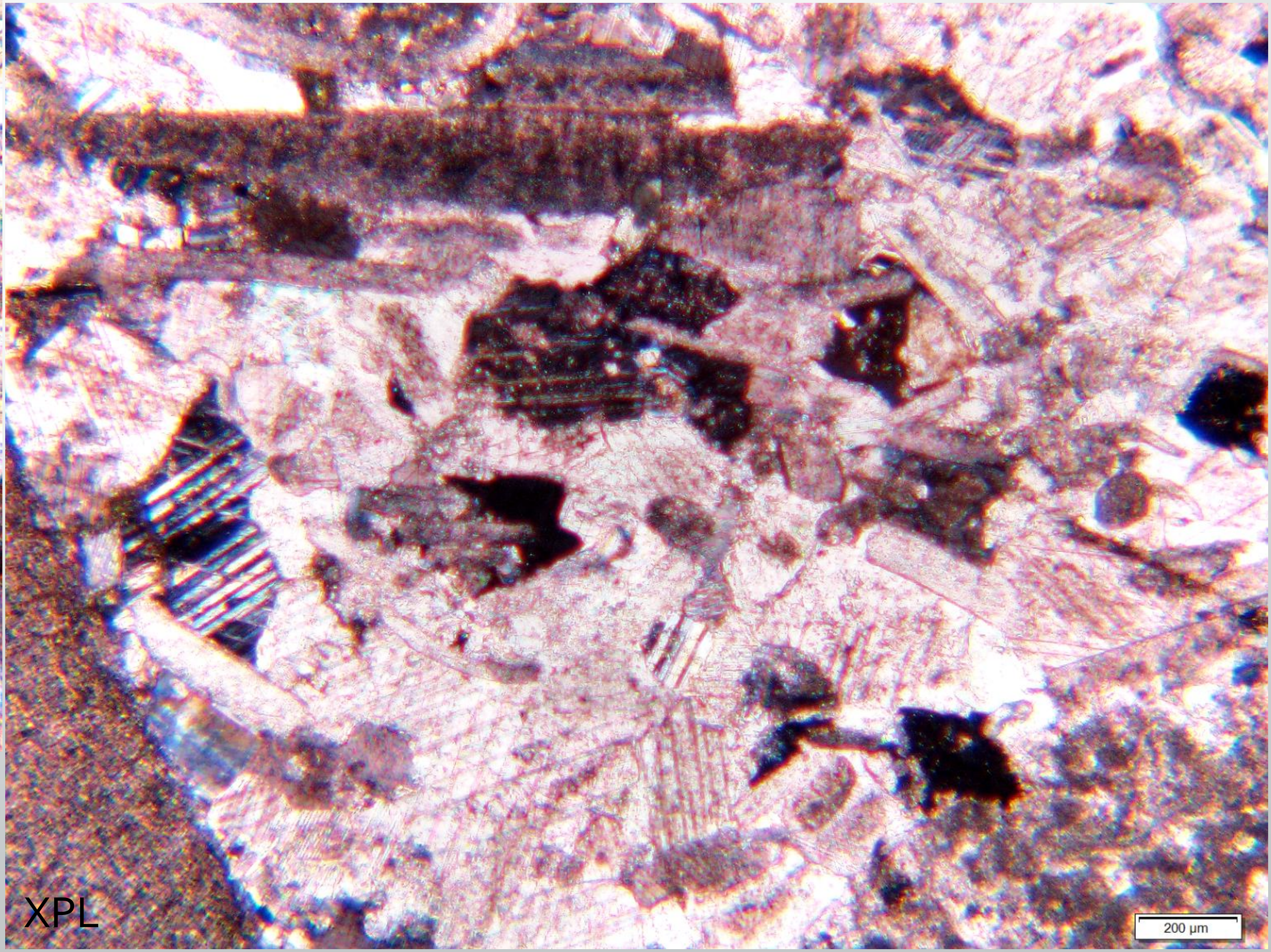


Deformation on the grain scale

- Twinning MUCH more intense in steep limb, greater shear strain

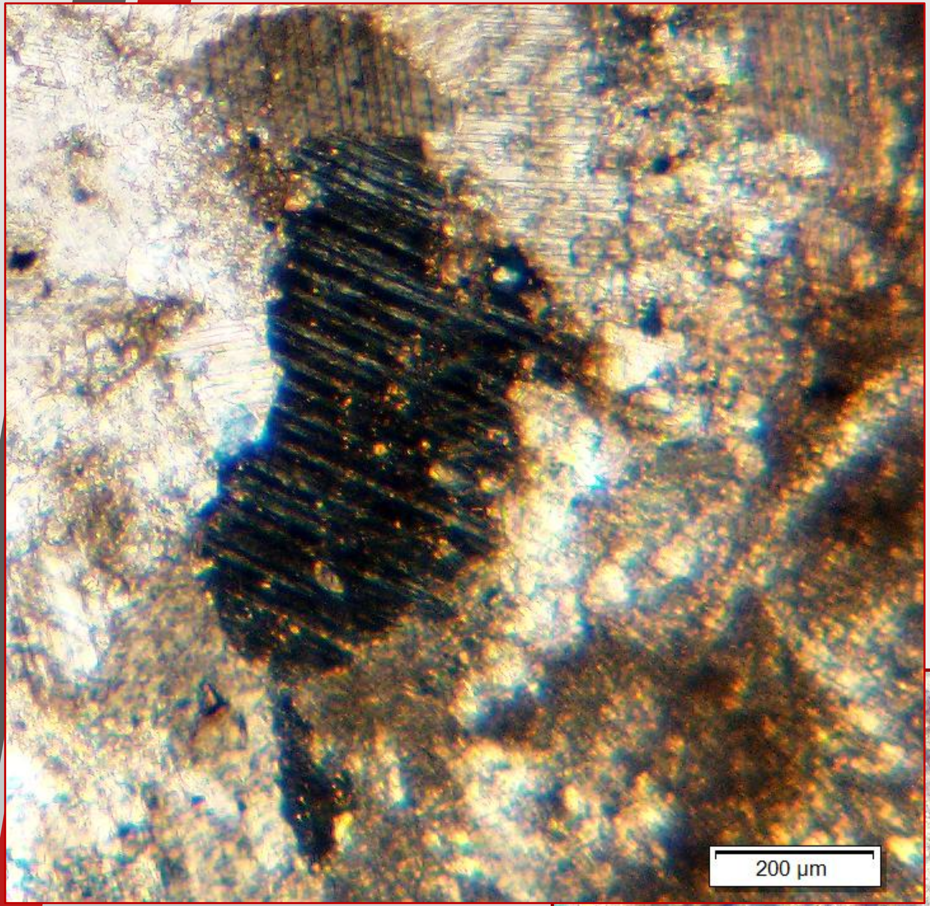


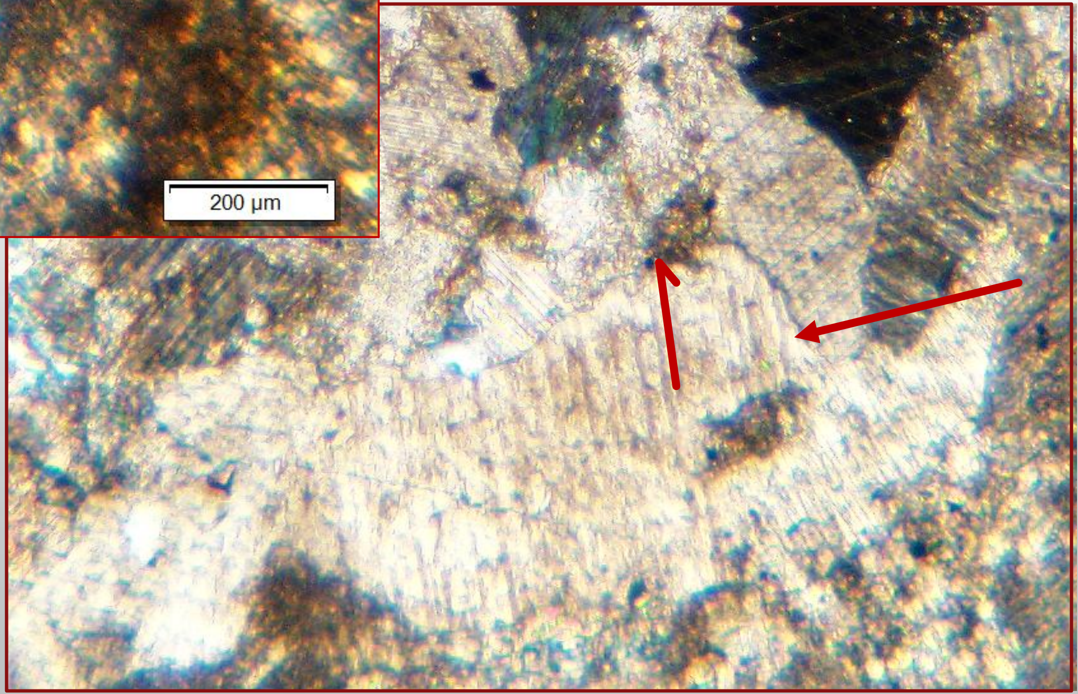
(note pinkish color is due to Alizarin red/Potassium ferricyanide stain)



Deformation on the grain scale

- Calcite twins form by shear stress parallel to the twin axis, but there is an accompanying shortening of the crystal perpendicular to the twin plane.

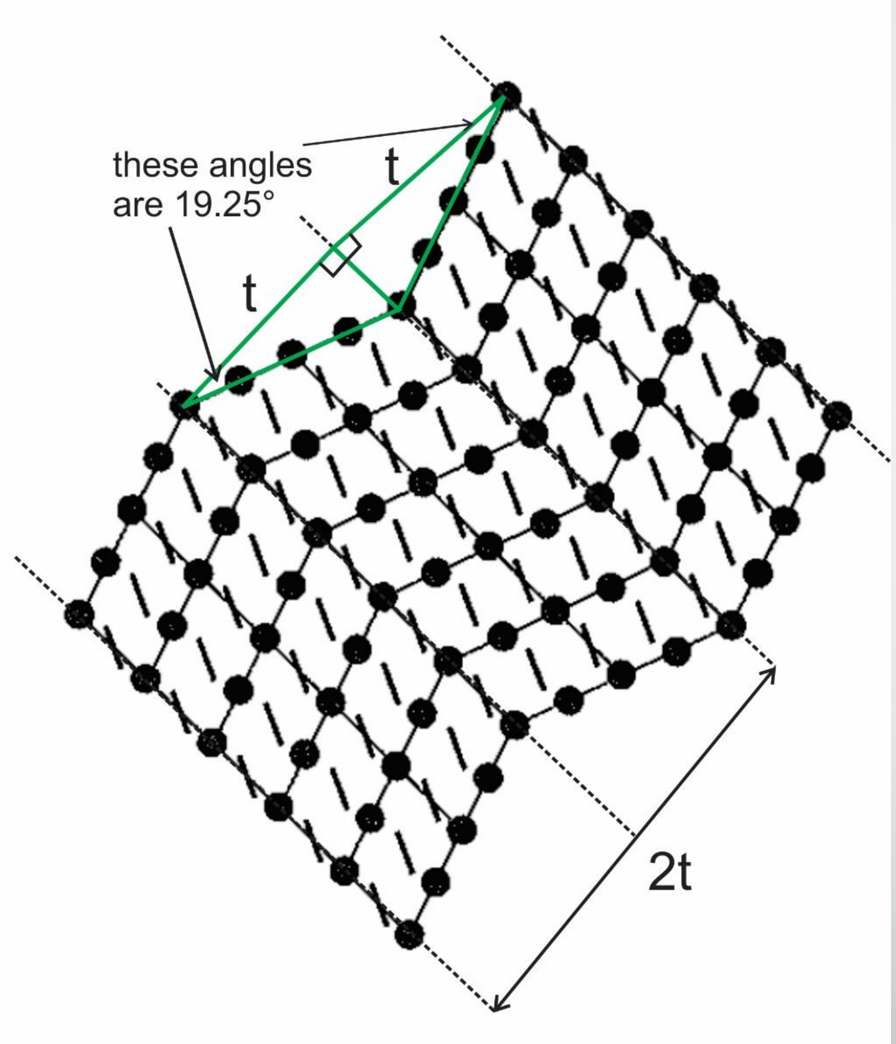




Upper image, XPL, oriented to show twins

Lower image, XPL, slide rotated so long edge parallels shortening direction (black arrow). Red arrows show effective shortening direction and shear direction

Calcite twins: how much shortening?



Lattice and angles from Twiss & Moores, 2007

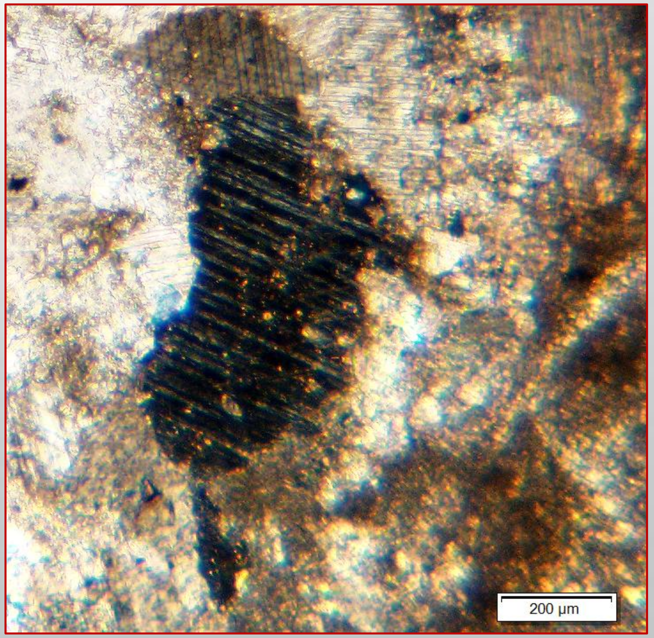
Original length =2 $(t/\cos 19.5)$ and deformed length = $2t$
Where t = average twin width

Then $e = (\frac{2t}{\cos 19.5} - 2t)/(\frac{2t}{\cos 19.5})$ which reduces to

$$e = (t - t\cos 19.5)/t$$

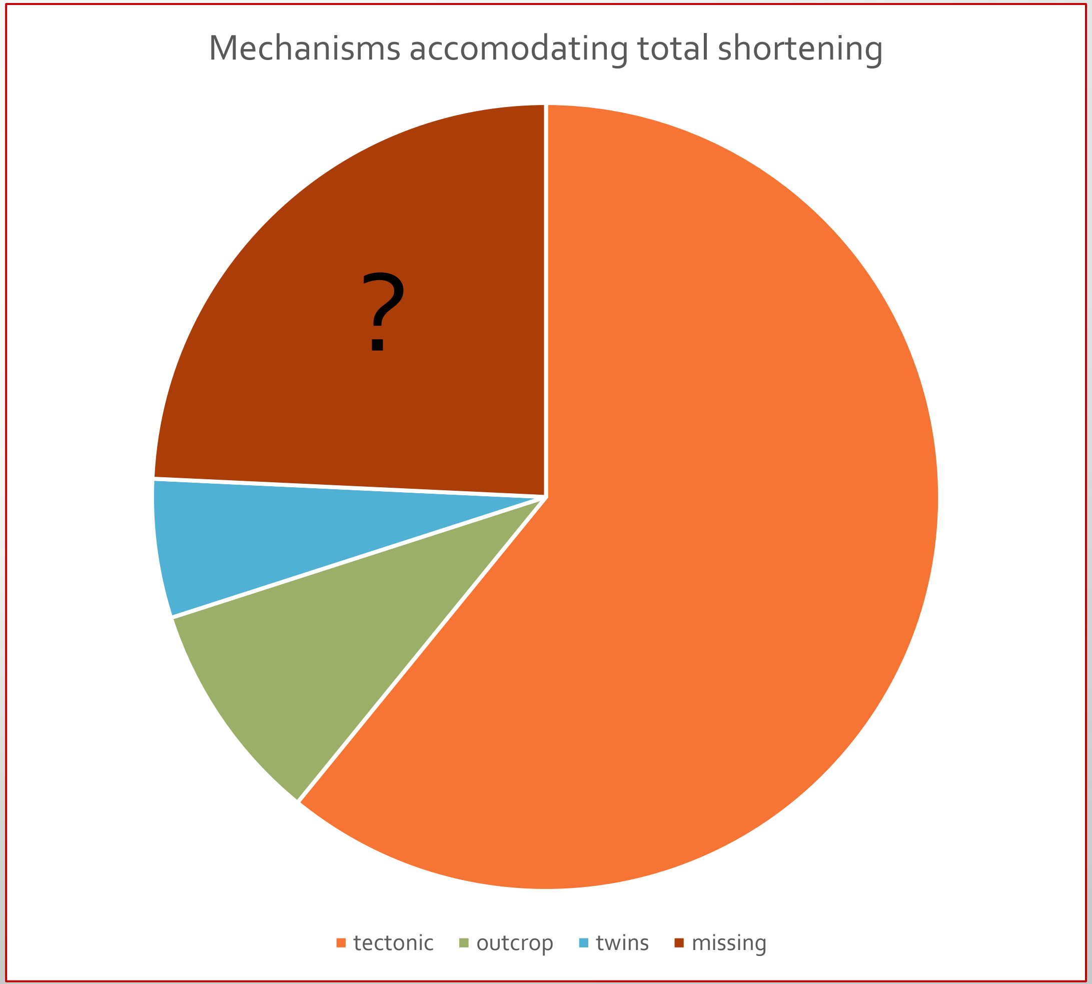
In this example from the previous slide, $t = 30\ \mu m$

$$e = (30 - 30\cos 19.5)/30$$
$$e = 5.7\%$$



Shortening at Rattlesnake Anticline: In summary

- Needed to account for 900 m shortening in the upper cover relative to the basement (40% of total shortening)
- Outcrop-scale folds and faults can account for min. 210.9 m (that is, 9.2 % of total, in green)
- Calcite twinning can account for ~5.7 % total shortening, which would equate to 131.1 m (blue)
- *Still need up to 558 m of shortening! (24%)*
- Other mechanisms? Reduction of porosity prior to calcite cementation? Pressure solution and stylolitization?



What are the implications for exploration?

- Compression and minor movement on fractures has the effect of closing those fractures/adding fault gouge → barrier to fluid flow, reduction of fracture porosity in tight reservoirs
- Small scale fault networks are probably additional barriers to fluid flow
- Other likely mechanisms – reduction in pore space also decreases volume available for hydrocarbon storage
- Penetrative strain processes act to reduce the quality/volume of a reservoir

THANK YOU!

- Burberry, C.M., 2015. Spatial and temporal variation in penetrative strain during compression: insights from analog models. Lithosphere. v 7, p611-624, Doi: 10.1130/L454.1
- Beaudoin, N., Leprete, R., Bellahsen, N., Lacombe, O., Amrouch, K., Callot, J-P., Emmanuel, L. & Daniel, J-M. 2012. Structural and microstructural evolution of the Rattlesnake orogenic stress build-up in the Bighorn Basin. Tectonophysics 576-577, p20-45
- Mitra, G., 1994. Strain variation in thrust sheets across the Seviers fold-and-thrust belt (Idaho-utah-Wyoming): implications for section restoration and wedge taper evolution. Journal of Structural Geology, 16 (4) p585-602
- Twiss, R.J. & Moores, E.M., 2007. Structural Geology, 2nd Ed. W H Freeman & Co., New York. 736pp
- Yonkee, A. & Weil, A.B., 2010. Reconstructing the kinematic evolution of curved mountain belts: Internal strain patterns in the Wyoming salient, Sevier thrust belt, USA. GSA Bulletin, 122 (1-2) p 24-49

- Thanks also to Shashank Khatri for assistance in the field

Rattlesnake Anticline, looking to the E