Sandstone Injectites Record Pre-, Syn-, and Post-folding Deformation at Sheep Mountain Anticline, Wyoming*

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Abstract

Large, up to 1 km long, sandstone injectites first described by Warner (1968) intrude the Cretaceous Mowry Formation in the vicinity of Sheep Mountain Anticline (Bighorn Basin, WY). These injectites were sourced by the Peay sand member of the overlying Cretaceous Frontier Formation, and represent a significant potential fluid pathway through impermeable shales. We present the characterization of the 3D geometry, internal structure, and intrusion mechanics of these injectites using high-precision GPS, traditional field measurements, and structural analysis. Sand injection was aided by pre-existing joints in the Mowry Formation before the folding of Sheep Mountain Anticline. Most of the injectites restore to vertical (dike) and horizontal (sill) orientations when unfolded around bedding. Downward injection of the Peay Sand is evidence of a highly stratified stress field resulting from the deposition, burial, and lithification history of the rock units in the area. The internal structure of the injectites is dominated by two sets of mutually offsetting deformation bands. The deformation bands have shear and compaction components, exhibiting significant porosity loss, as well as minor cataclasis and pressure solution. After formation of the deformation bands, subsequent faulting occurred along planes parallel to the deformation bands, evidenced in the field by slickensided surfaces. A detailed kinematic analysis of slickenline lineations yield shortening and extension axes consistent with deformation band formation associated with the initiation of Laramide–oriented shortening, and continuing through the folding of Sheep Mountain Anticline. While the injectites represent potential fluid pathways for hydrocarbon migration, the deformation bands may act as barriers to fluid flow. Constraining the timing of injectite intrusion and deformation band formation will provide a better understanding of their petrophysical implications and how they are related to the kinematic development of the Sheep Mountain area.

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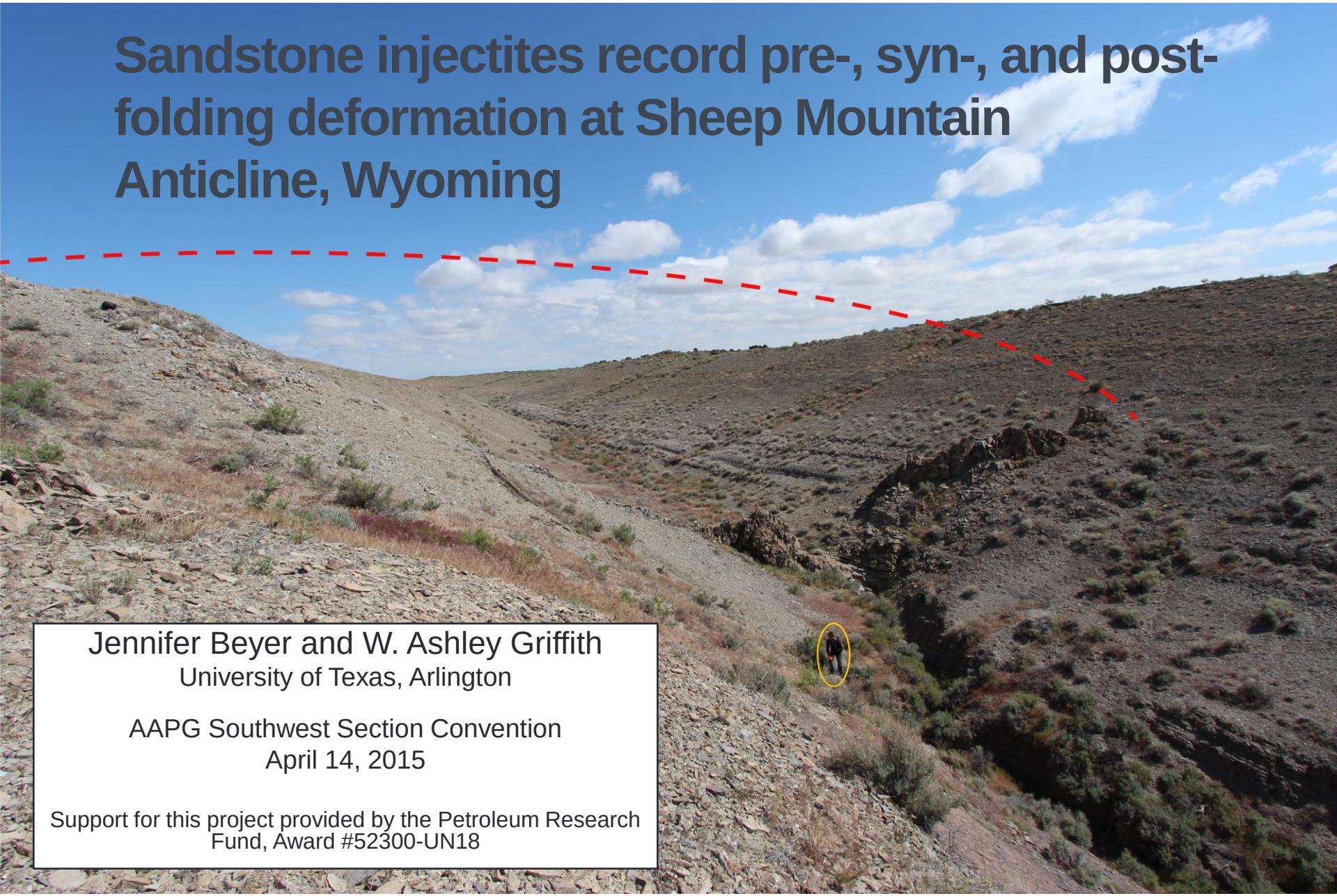
Sandstone injectites record pre-, syn-, and post-folding deformation at Sheep Mountain Anticline, Wyoming



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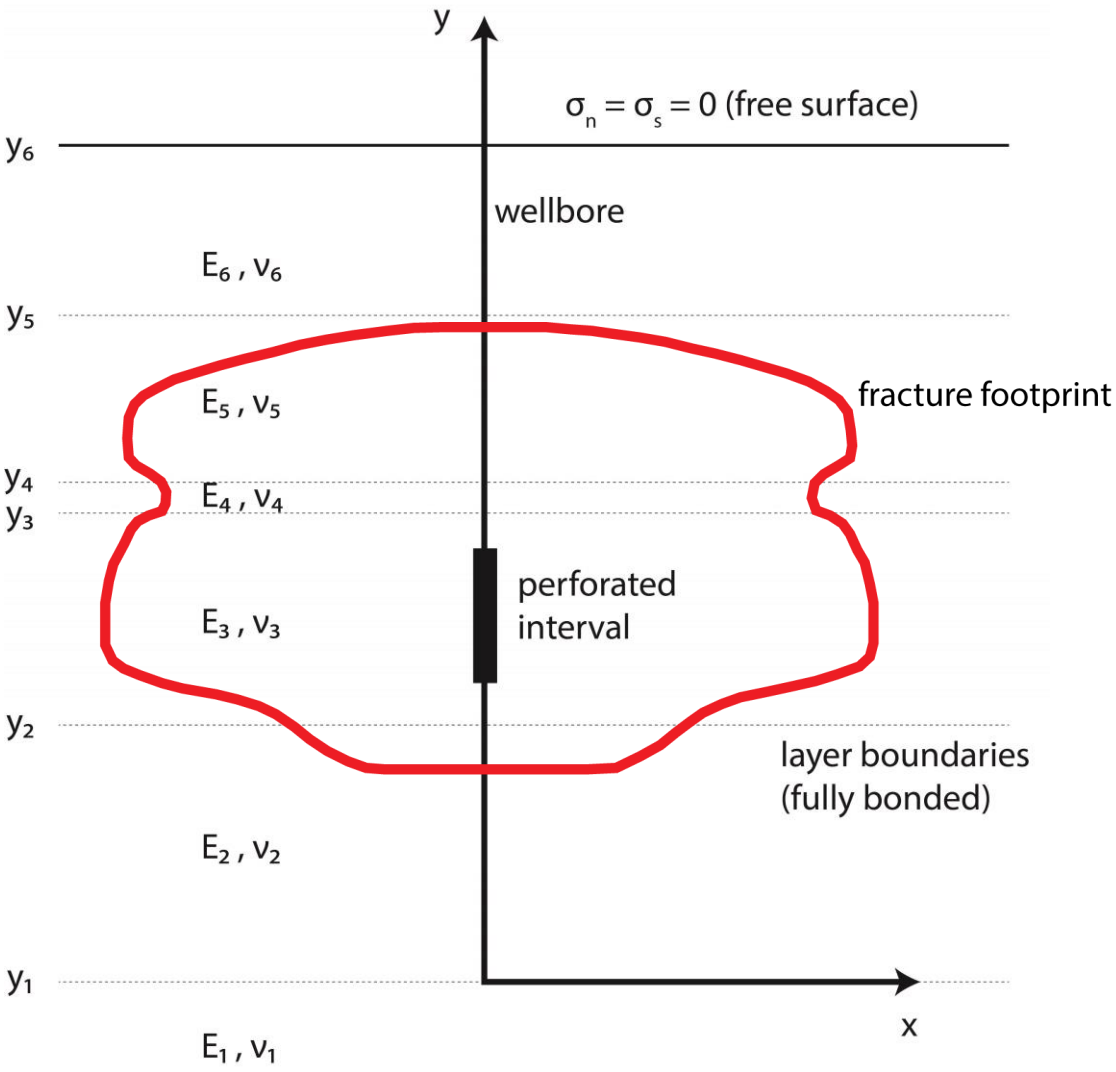
Clastic Injectites

From Braccini et al., 2006

Hydraulic Fractures

- Natural hydraulic fractures
- Fracture propagation significantly influenced by material properties



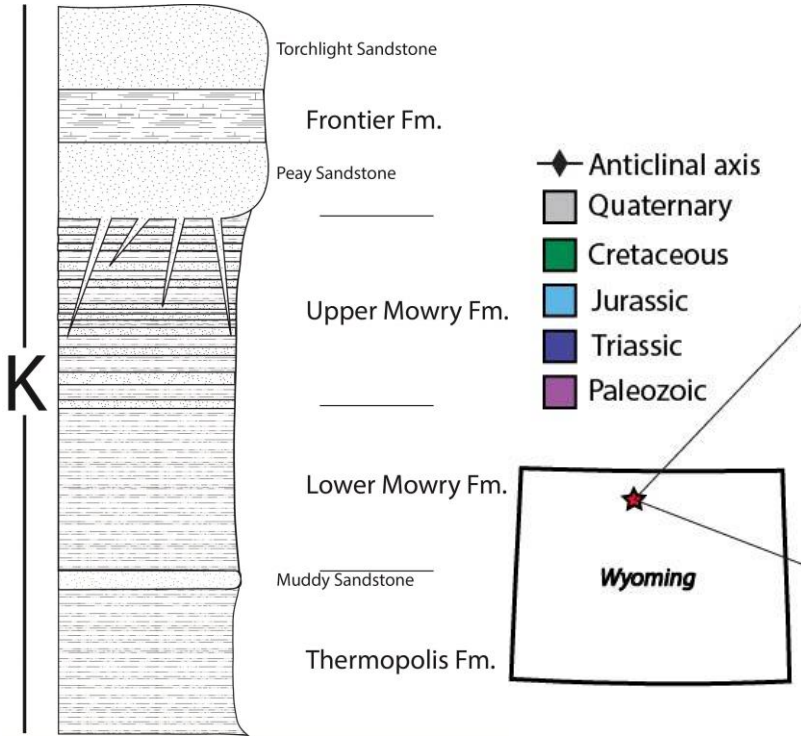
From Adachi et al., 2007

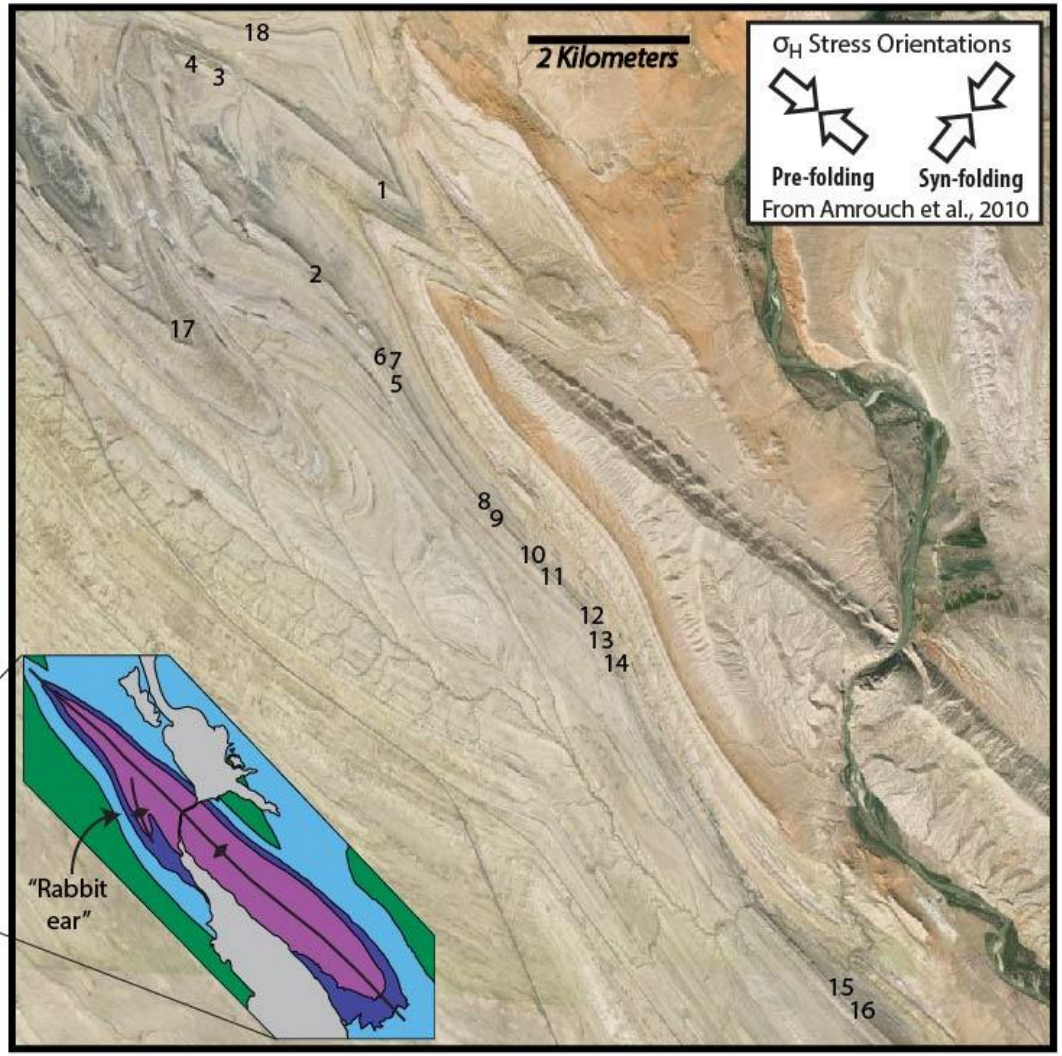
Sheep Mountain Anticline (SMA)

- Doubly plunging, asymmetric anticline
- Trends NW-SE
- Overlies a SW-dipping thrust, later cut by a NE-dipping thrust (Stanton and Erslev, 2003)

SMA and our study area

- Located in the Bighorn Basin, WY
- Formed during the Laramide Compression



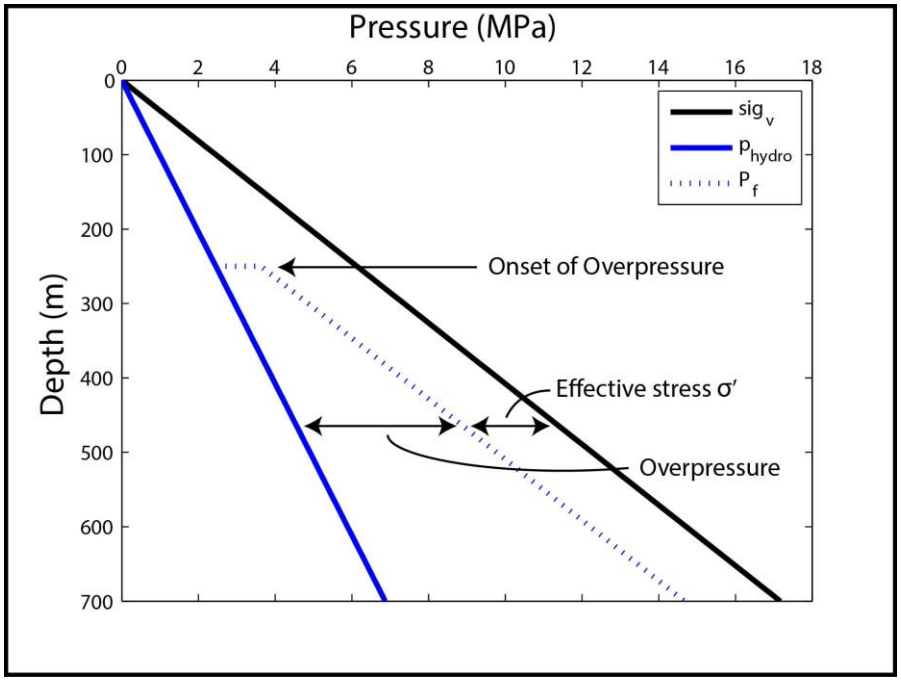


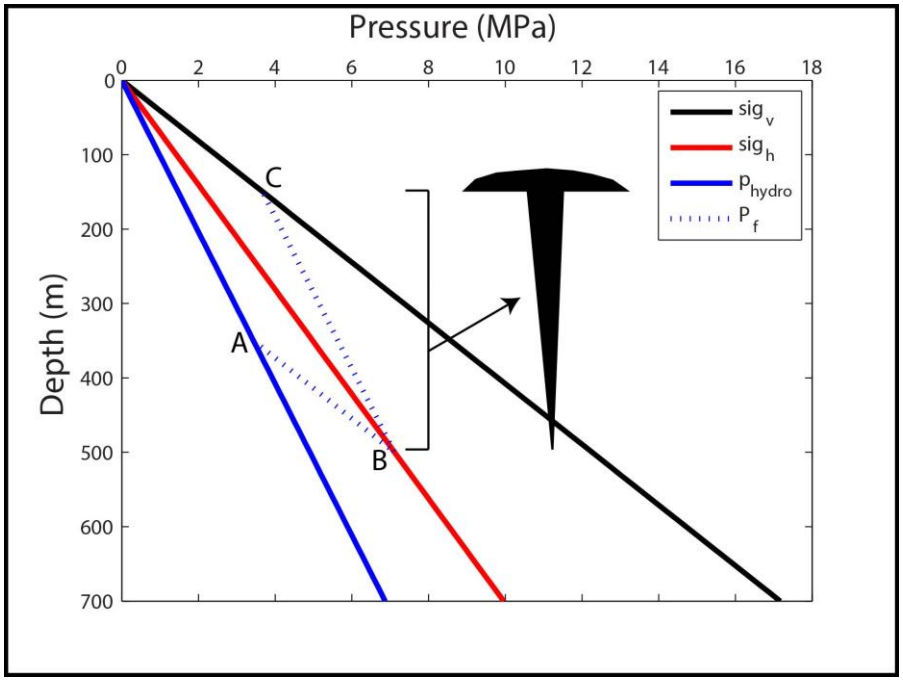
Warner (1968)

- Albert Warner described the injectites at SMA for his Master's thesis in 1968
- Mapped 13 injectites and structural elements (e.g. systematic fractures in surrounding units)
- Conclusions:
  - Injectites were sourced by the Peay Sandstone
  - Injectites were forcefully injected downward at a critical time in folding

General intrusion mechanics

- Pore fluid (P_f) increases along hydrostatic until unit is sealed
- Dike propagates upward when P_f overcomes least compressive stress (σ_h)
- Sill can open when P_f overcomes vertical stress (σ_v)

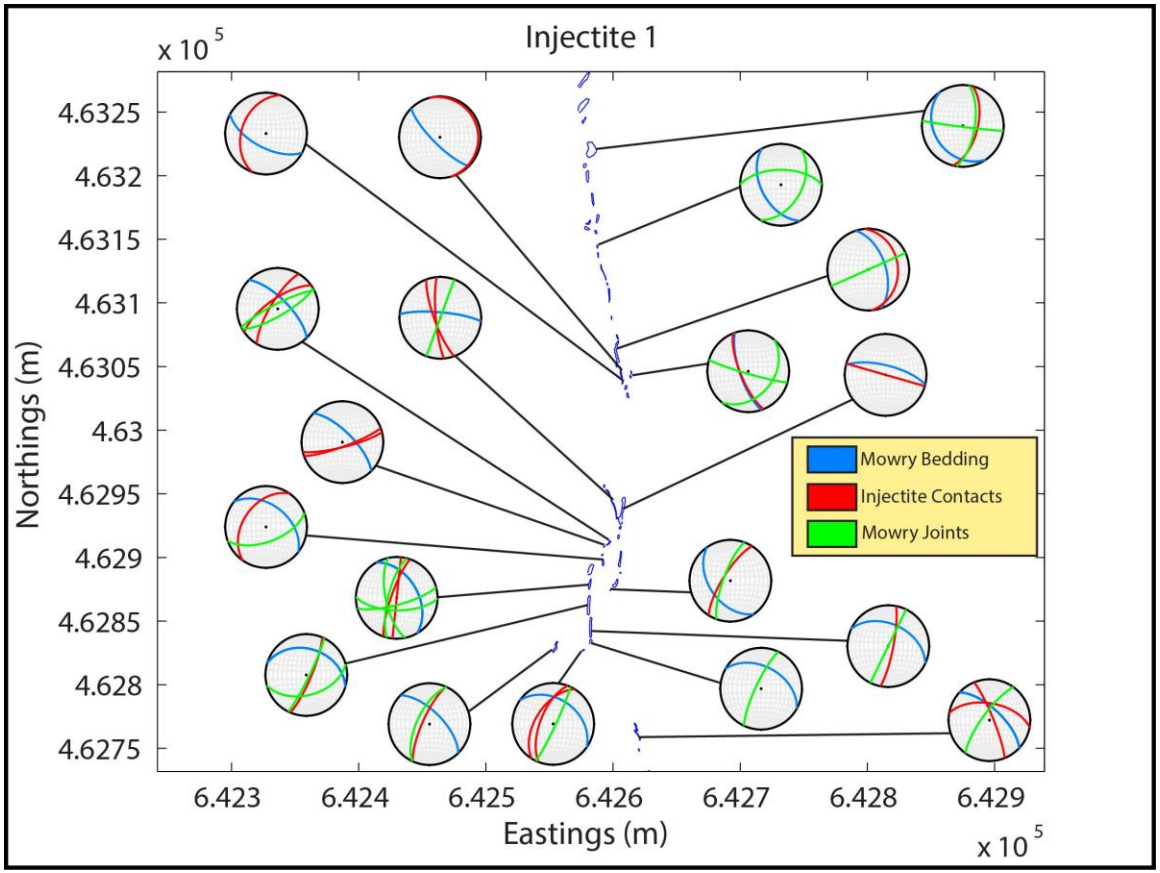




From Jolly and Lonergan, 2002

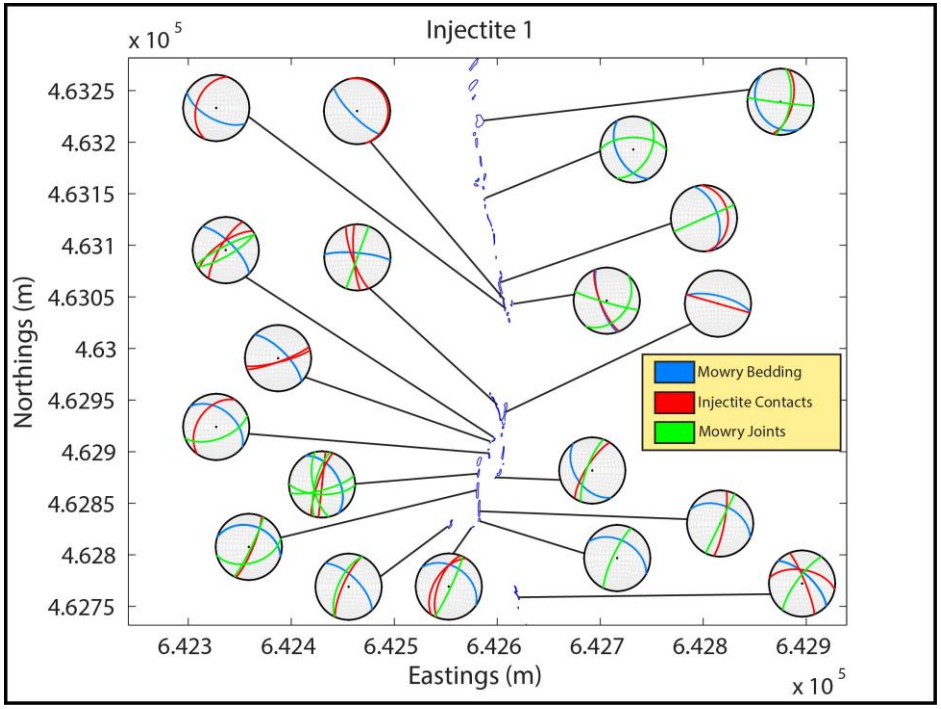
Methodology

- We used traditional mapping techniques to measure the orientation of structural elements

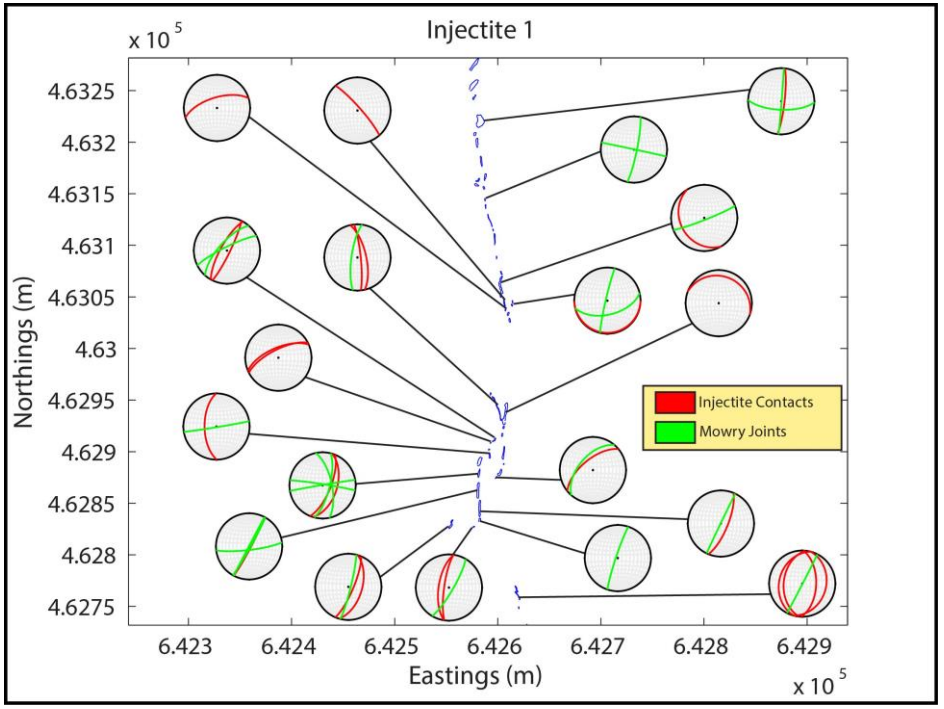


- We used Stereonet and Matlab to manipulate the data to obtain pre-folded orientations of structural elements

Present Day Orientations



Pre-folded Orientations

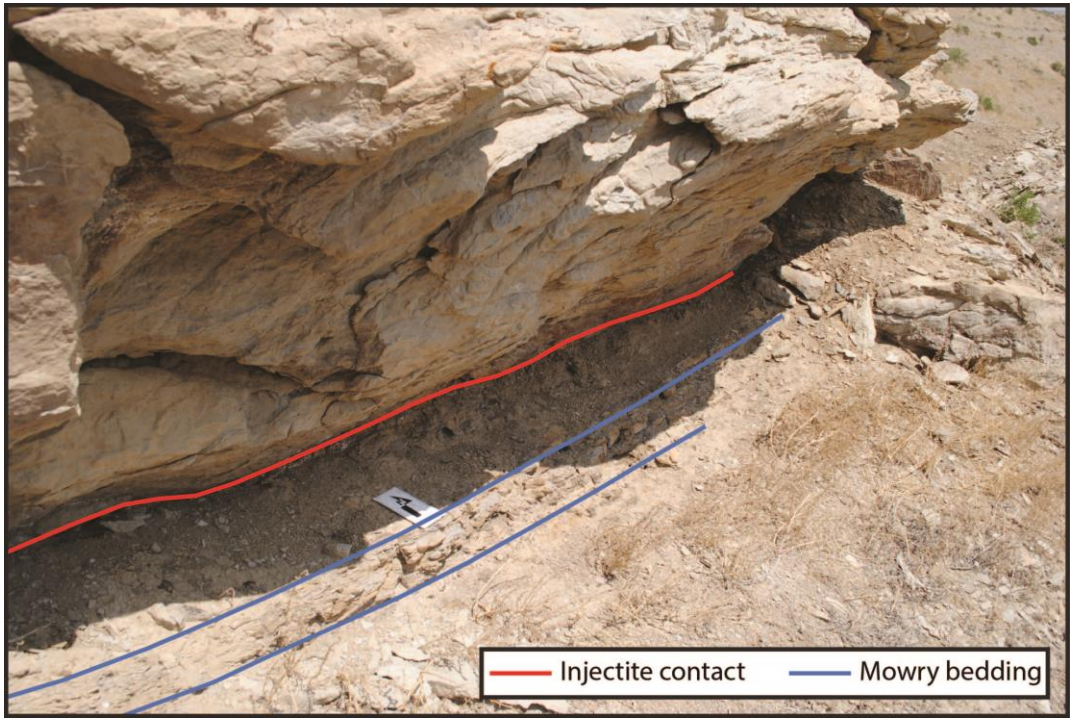


Injectites at SMA

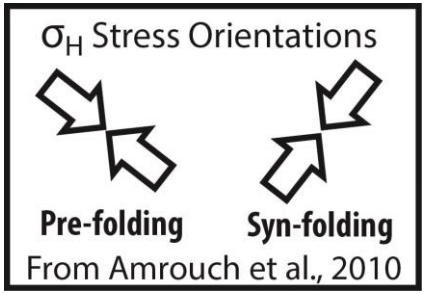
- Large, massive sand intrusions
- Kilometers long
- 1-2 meters wide
- Only found in the Upper Mowry Shale

Injectites at SMA

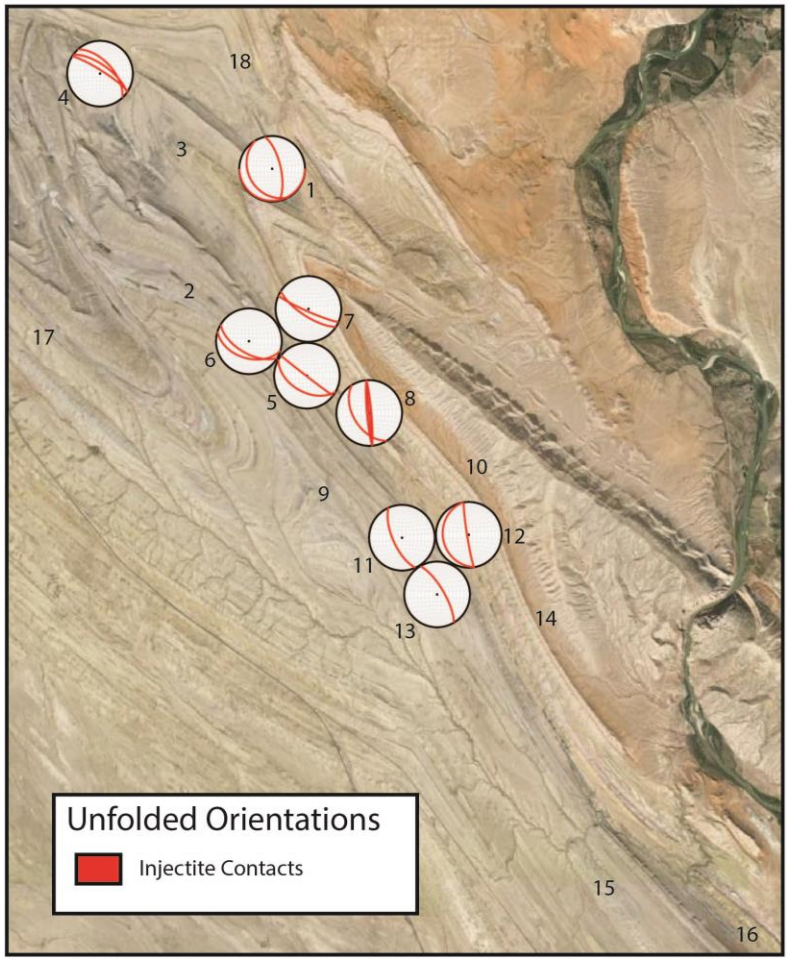
- Some segments are dikes
- Some segments are sills

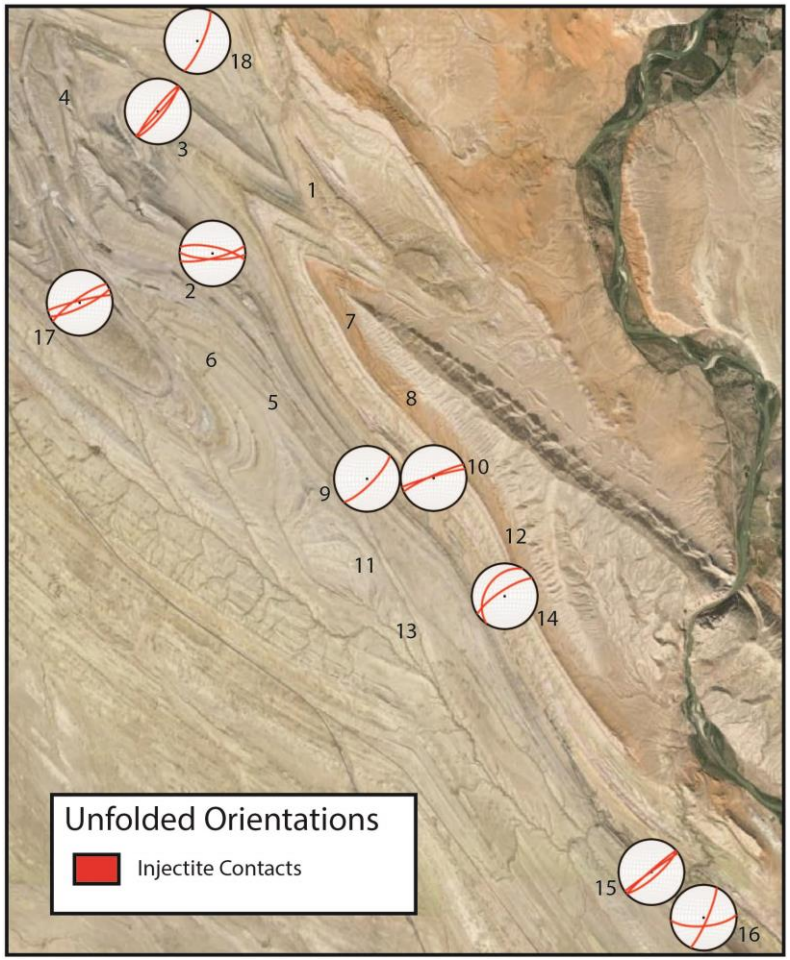


Injectite Orientations

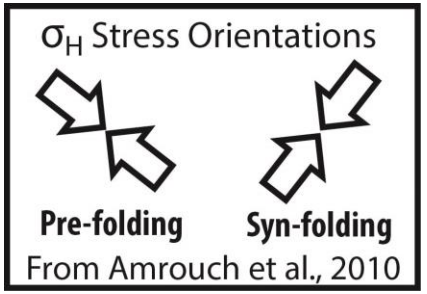


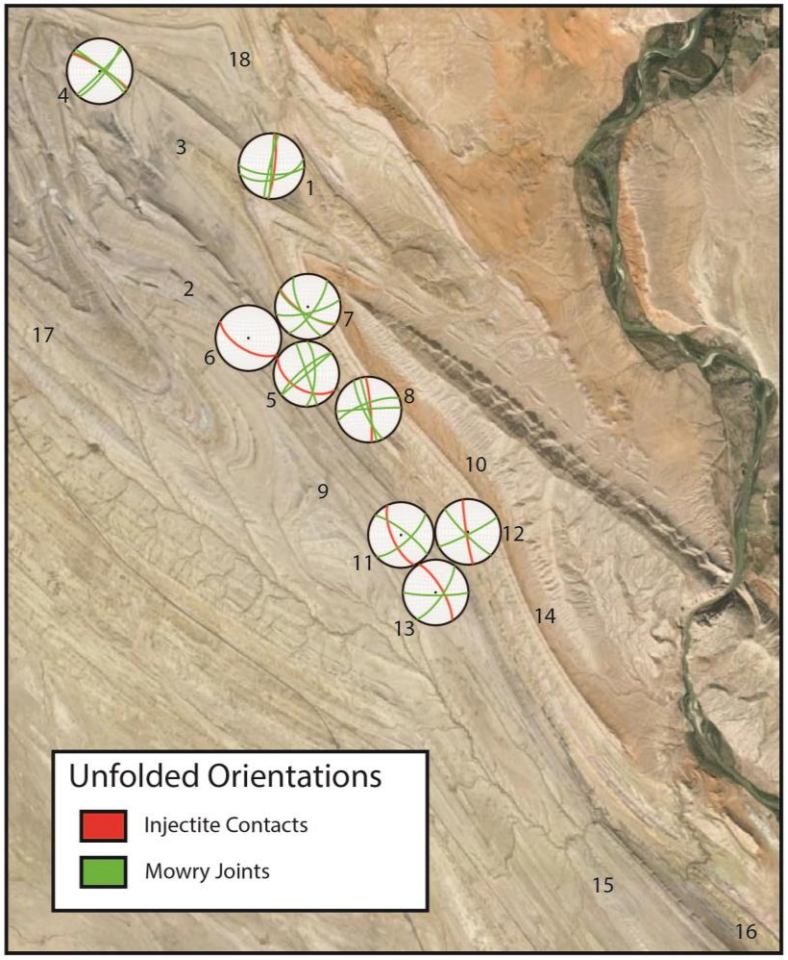
- Injectites can be sub-divided into two groups:

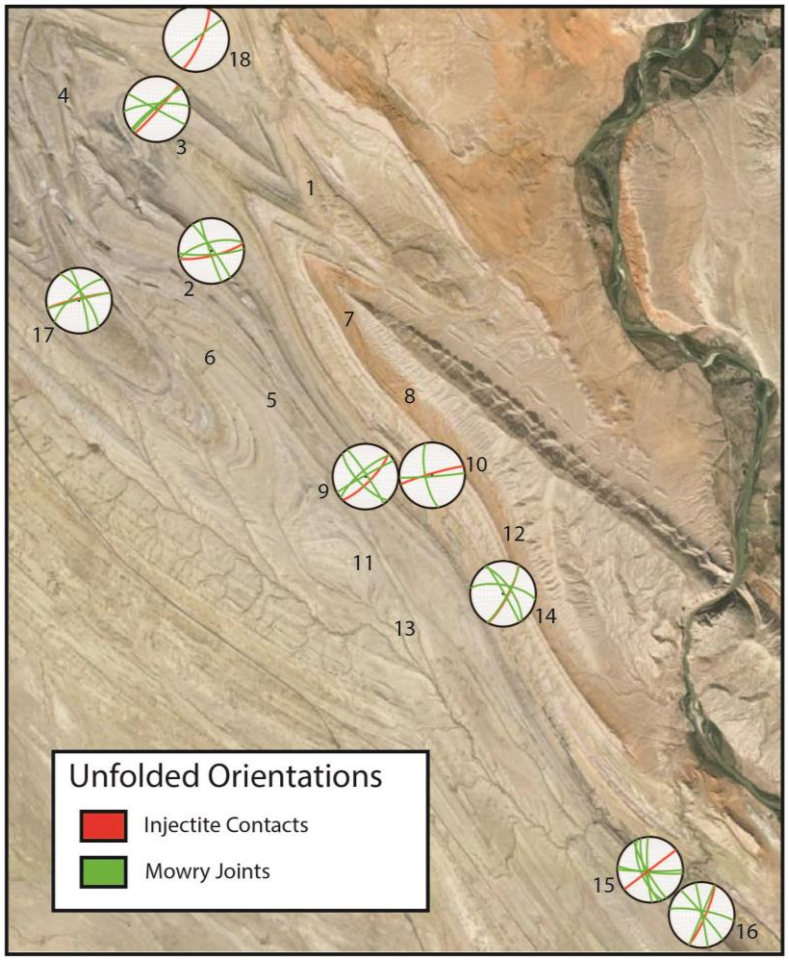




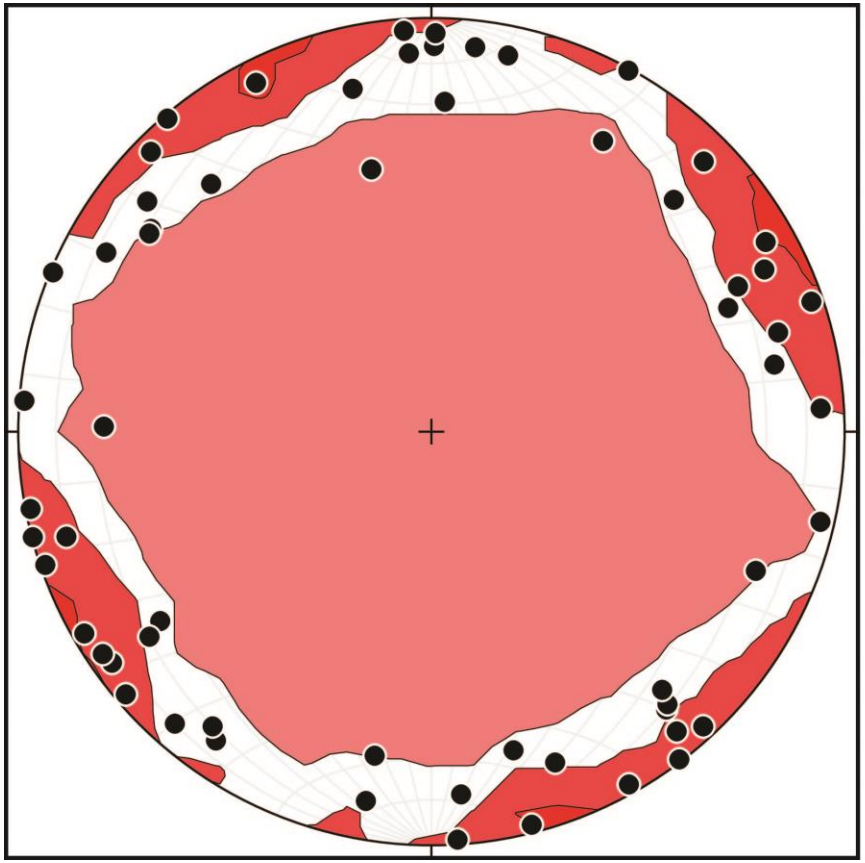
Exploiting Mowry joints?

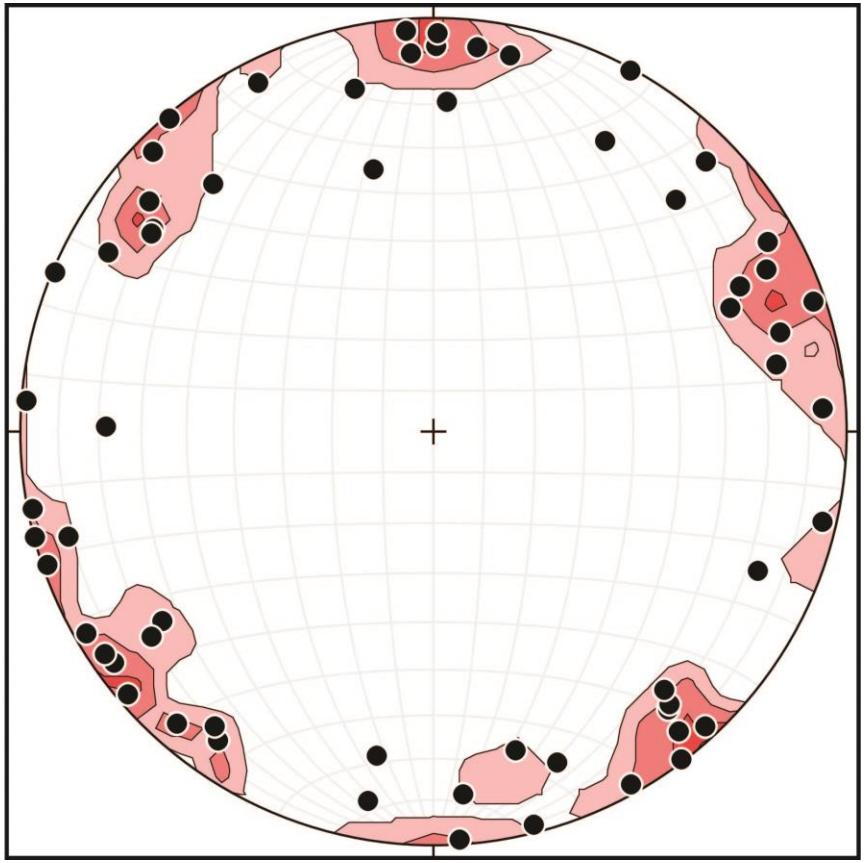




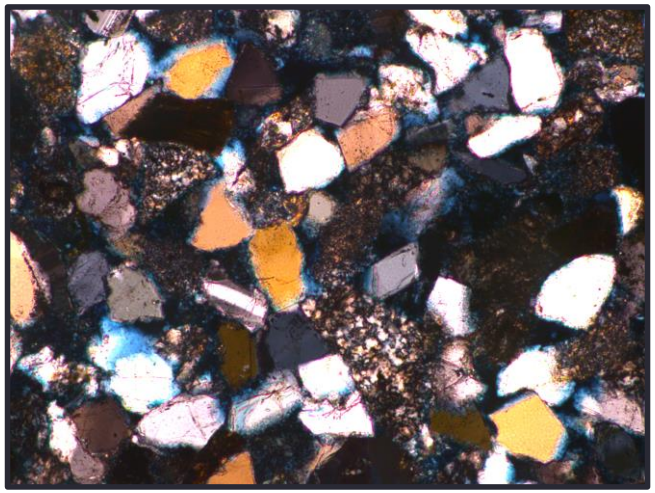
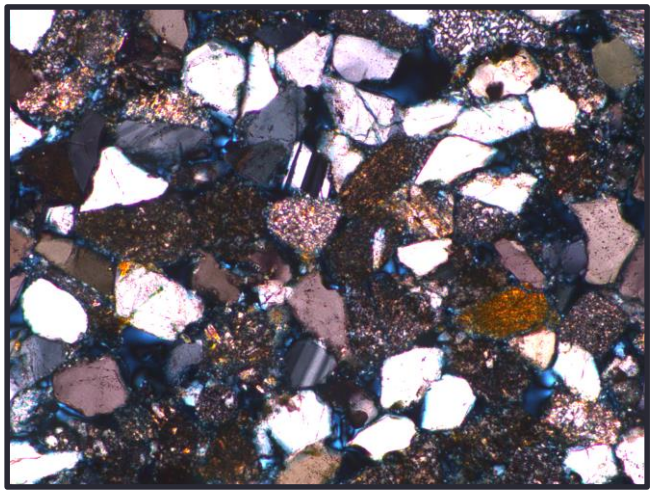
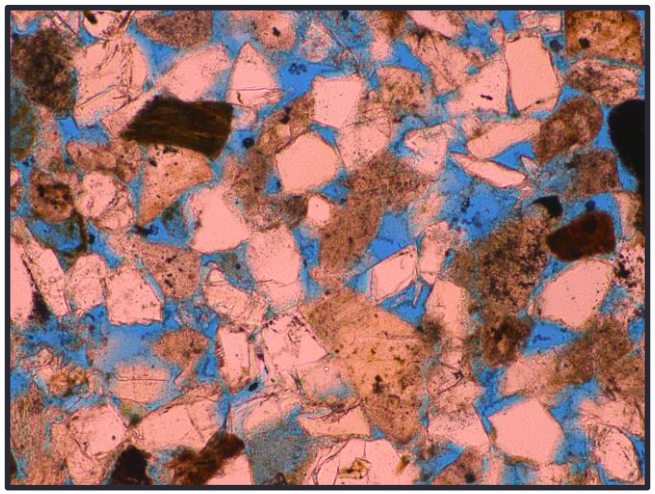
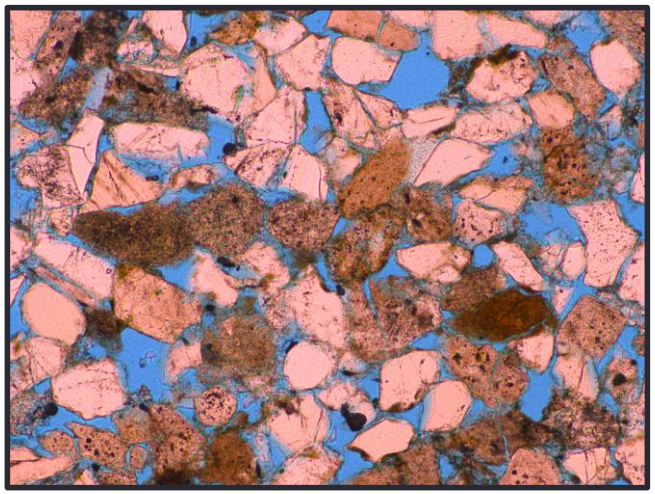


- Three joint sets:
  - E/W striking set — Formed prior to Laramide
  - NW/SE striking set — Formed prior to Laramide
  - NE/SW striking set — Formed during Laramide



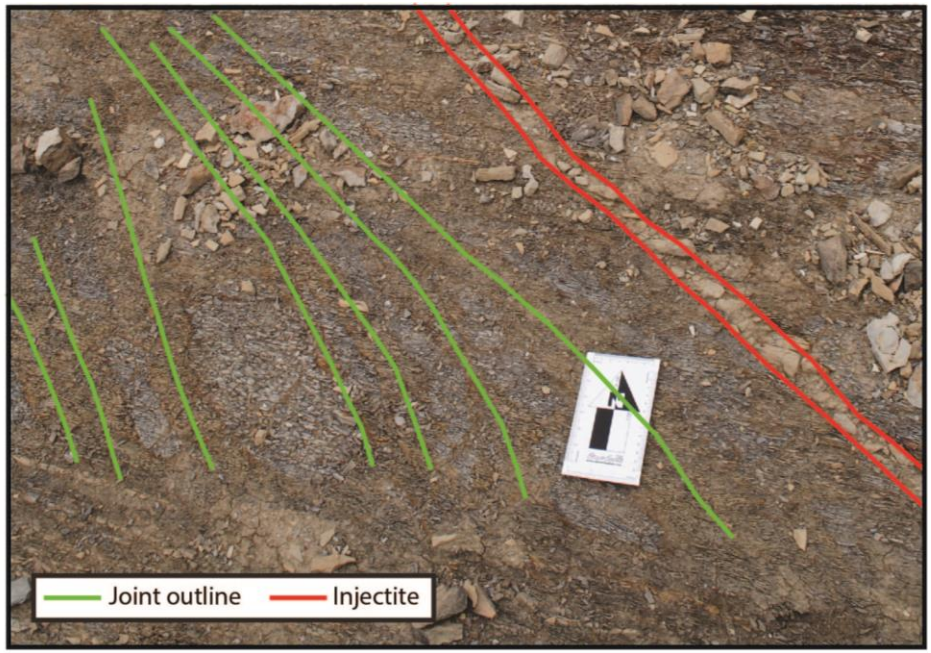


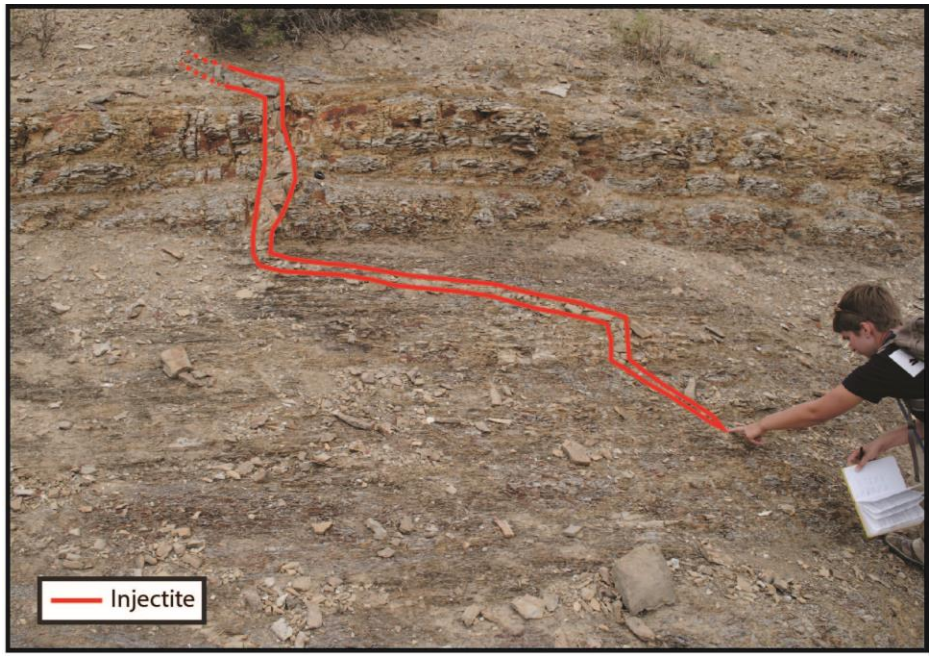
Source of the injectites

	Injectite Material	Peay Sandstone
Cross-polarized light		
Plain light		

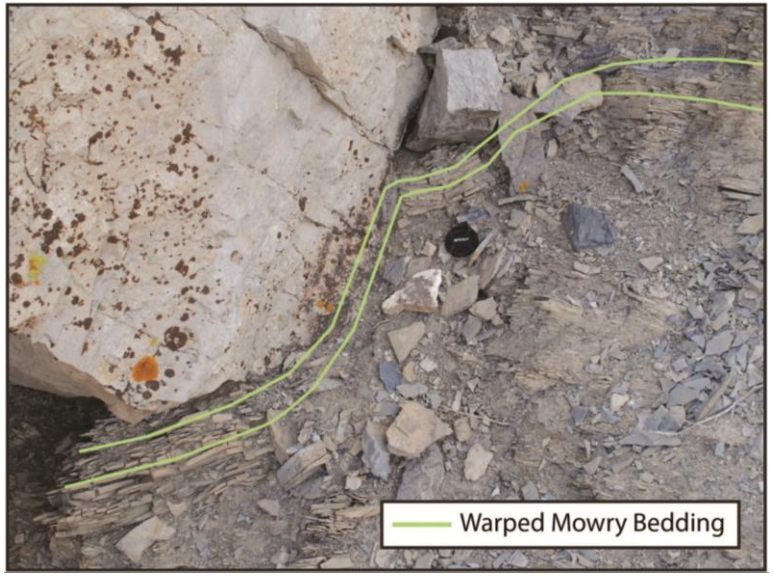
Field evidence for downward intrusion

- Injectites exploit systematic joint sets in the Mowry Shale
- Mini injectites (<10cm) seen to pinch out at their lower extent

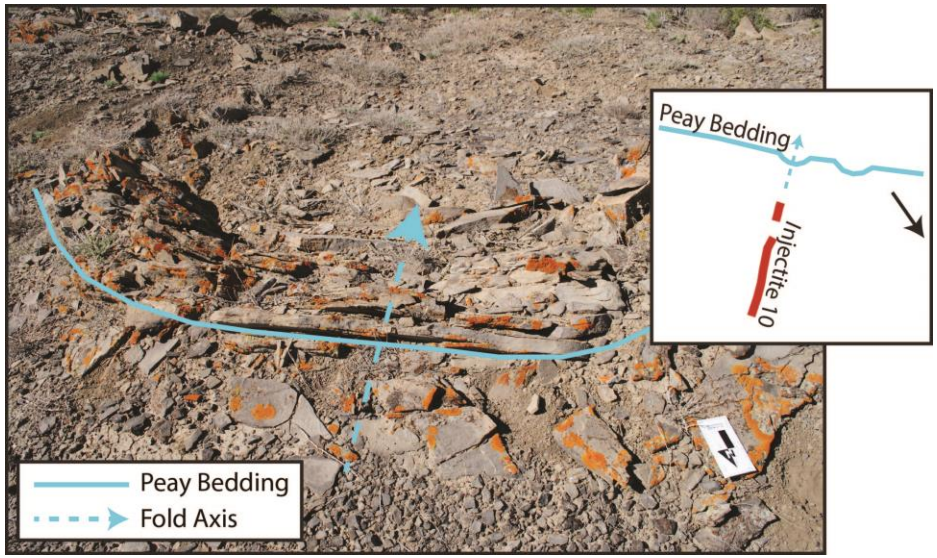


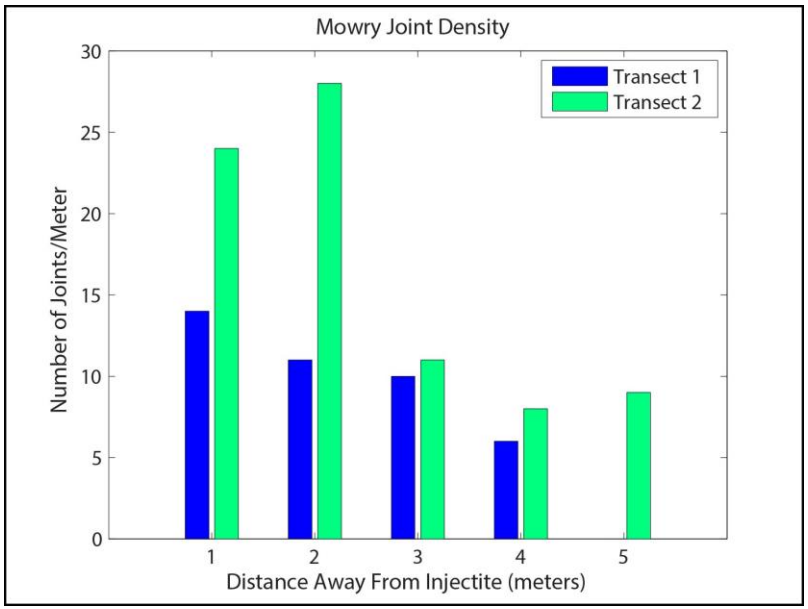


Field evidence for downward intrusion



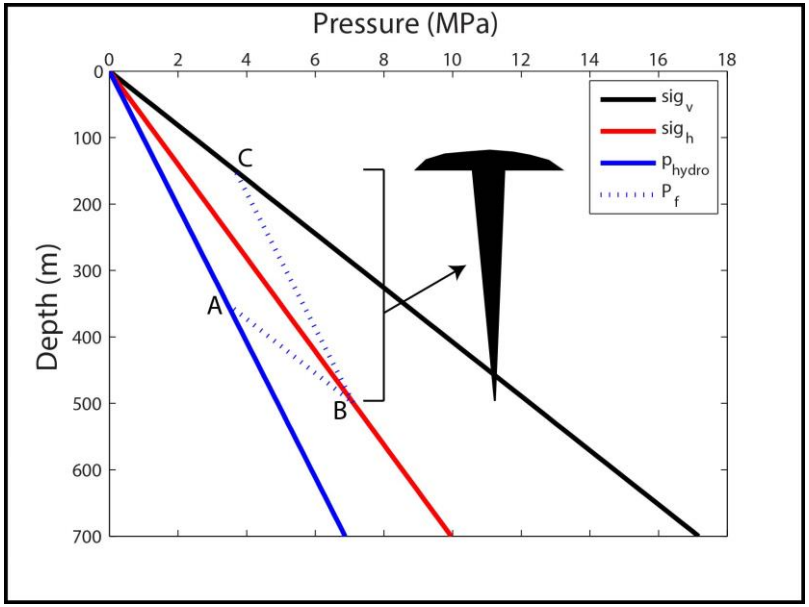
- Downward warping of Mowry bedding
- Slump folding of Peay bedding above injectites
- Increase in joint density near injectites





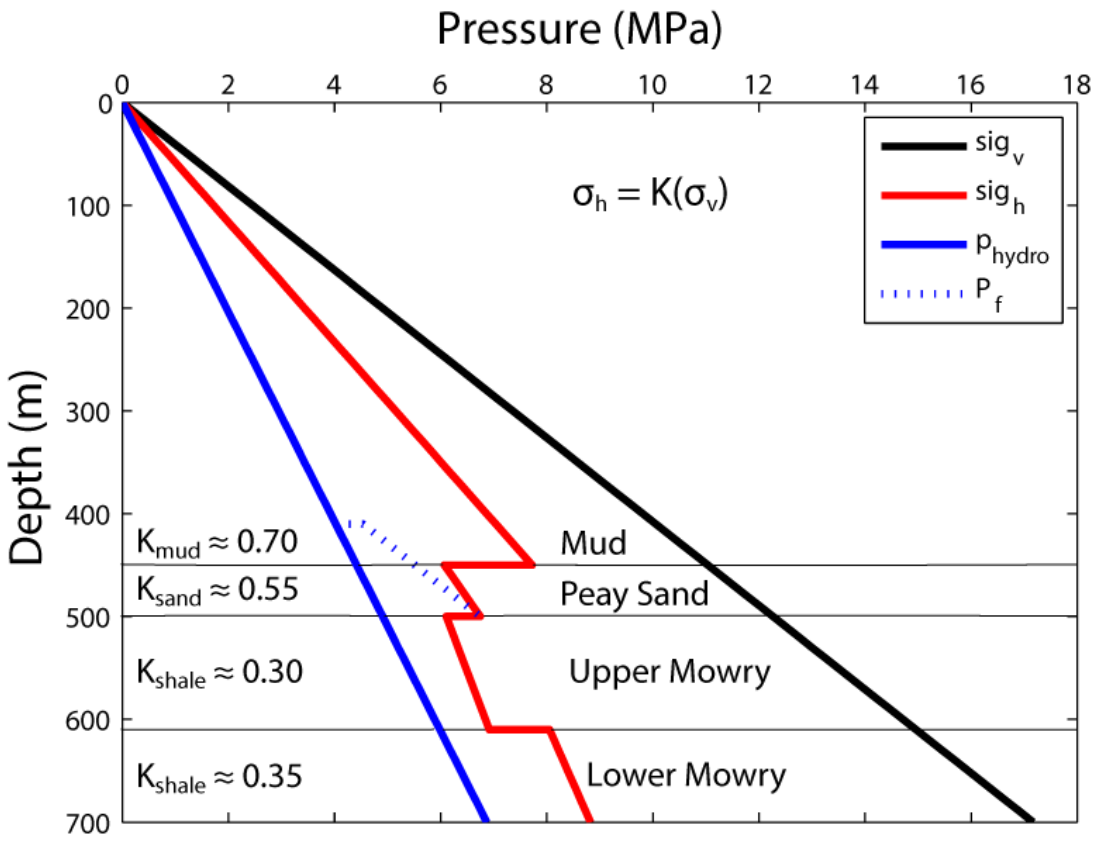
Modeling downward intrusion

- General intrusion model does not include effects of stratigraphy
- Modifying model to incorporate burial and lithification history
- At time of sand intrusion,
  - underlying Mowry Shale was lithified and pre-fractured
  - overlying middle member of the Frontier Formation was still mud



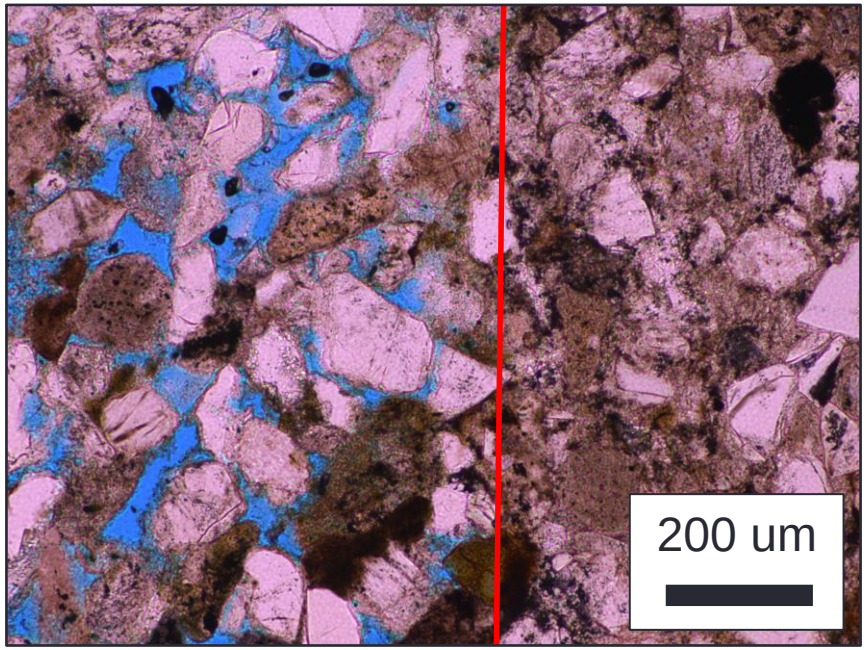
Modeling downward intrusion

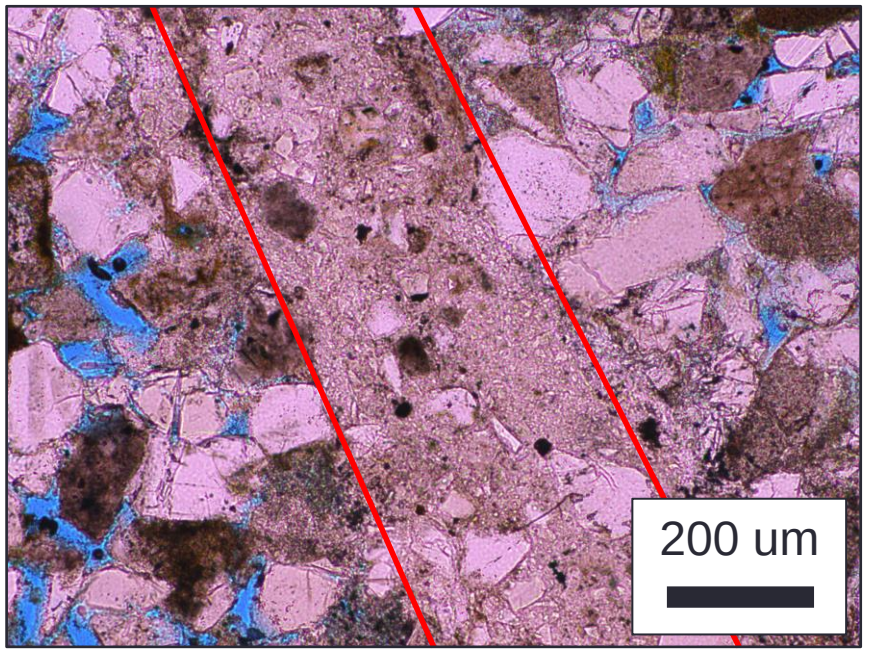
- Assumptions:
  - Tectonically inactive basin
    - $\varepsilon_{xx} = \varepsilon_{yy} = 0$
    - $\sigma_{xx} = \sigma_{yy} = \sigma_h$
    - $\sigma_{zz} = \sigma_v$
  - $\sigma_h = K\sigma_v$
    - For rocks, $K = \frac{\nu}{1-\nu}$
    - For sediments, *K* is determined using triaxial compression experiments (Maltman, 1994)
  - *K* values for rock units determined using a lithification depth of 350m



Deformation bands

- Two mutually cross-cutting sets
- Single bands and compound bands
- Subsequently faulted along edges of compound bands (slickensides)

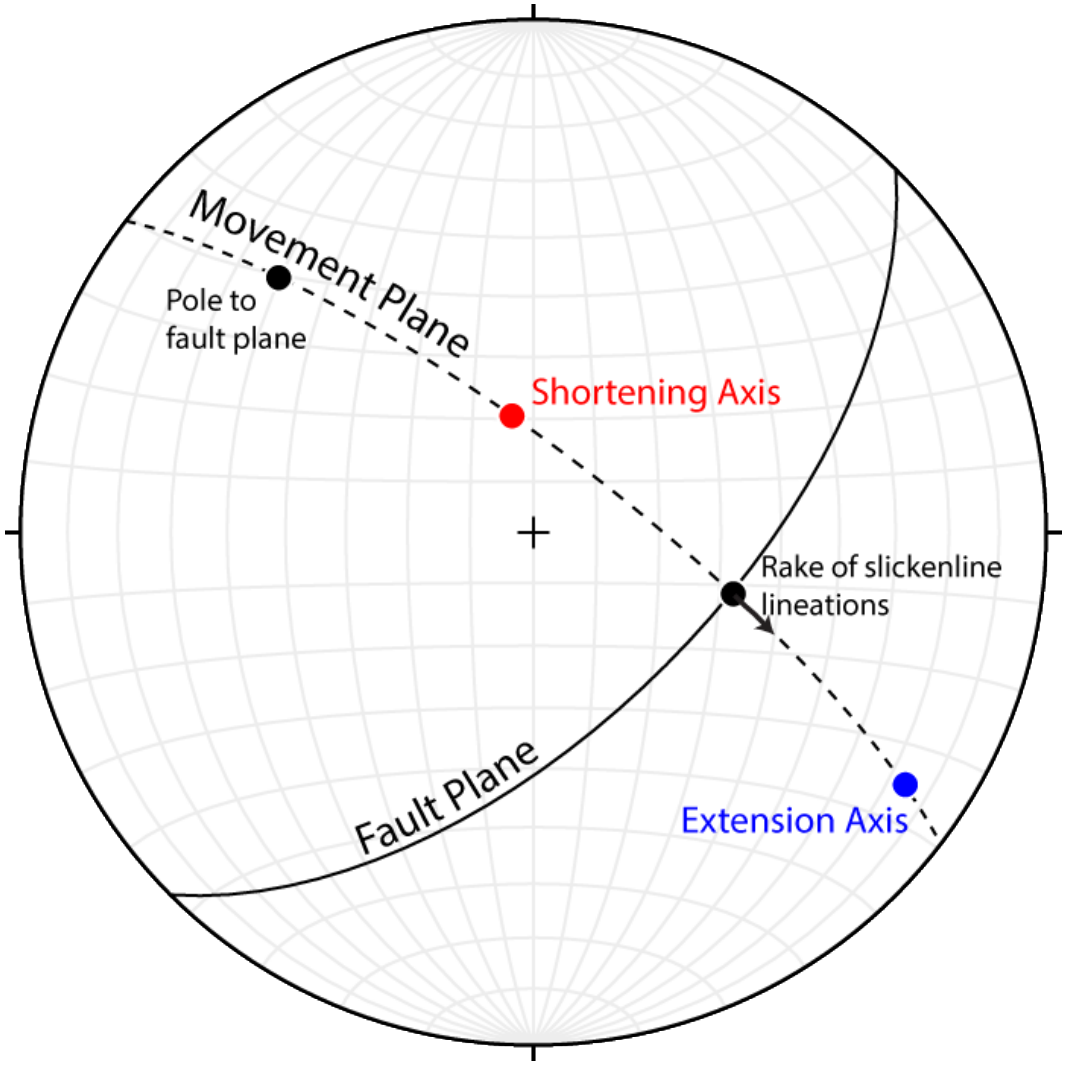




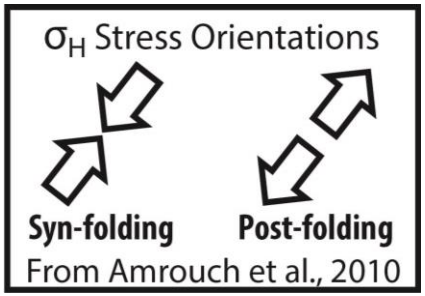
- Significant decrease in porosity
- Deformation bands exhibit different amounts of deformation
  - Minor pressure solution
  - Minor cataclasis
  - Extreme comminution

Bingham Analysis

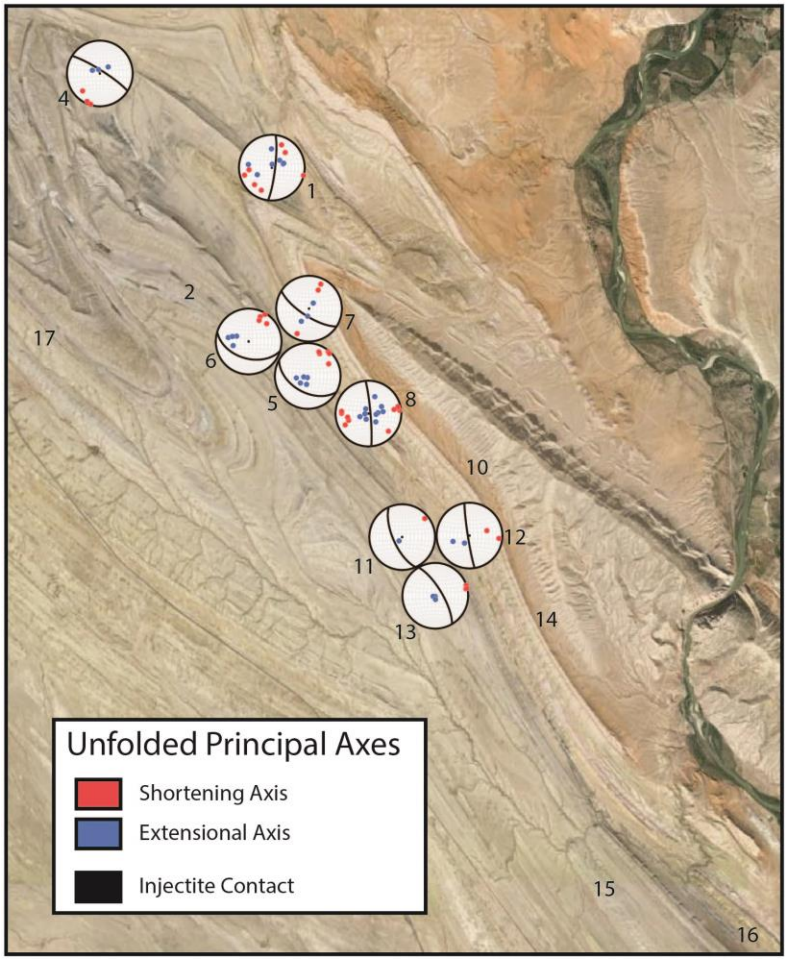
- Movement plane contains the pole to the fault plane and the rake of the slickenline lineations
- Principal axes are each located 45° from the pole to the plane
- The direction of slip always points toward the extension axis

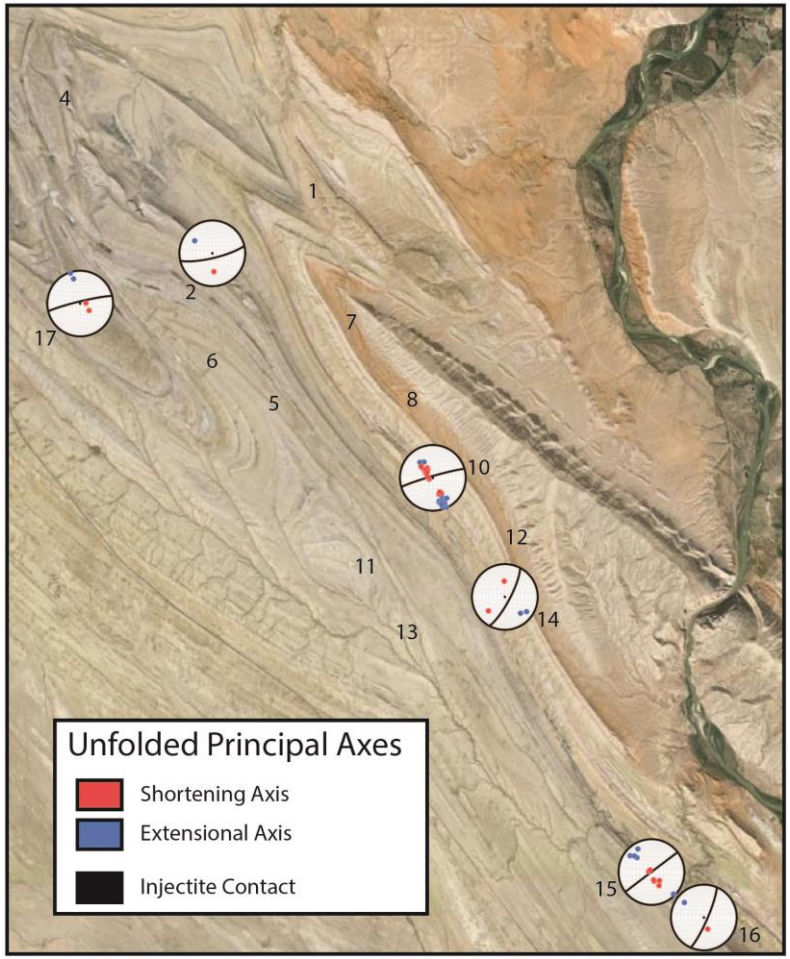


Principal Deformation Axes

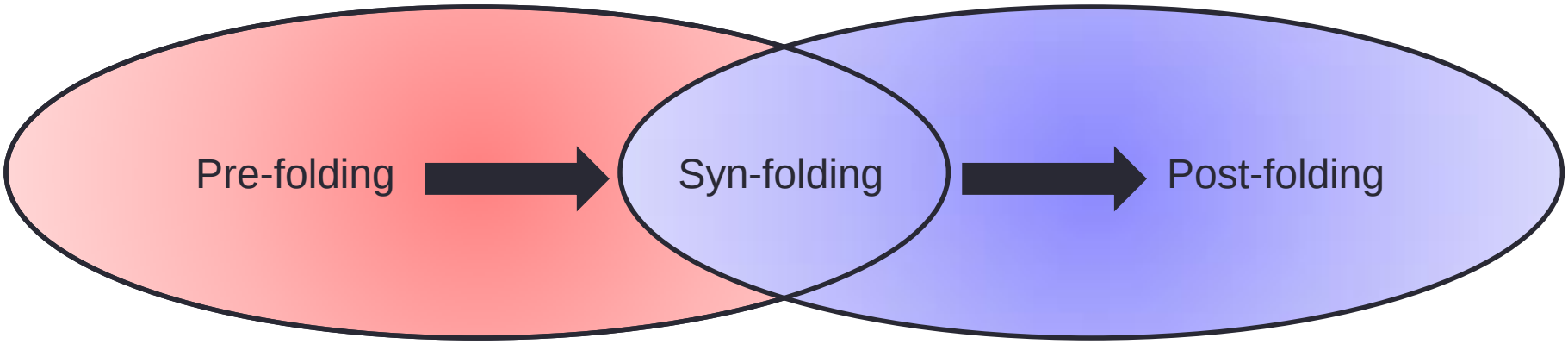


- Injectites sub-divided into two groups:





Timing of Events



Injectite Intrusion → **Deformation Band Formation**

Conclusions

- Injectites were sourced by the Peay Sandstone of the Frontier Formation
- Intrusion occurred prior to, and during early stages of folding
- Injectites were injected downward into underlying Mowry Shale due to a stratified horizontal stress field, and pre-existing joints
- Injectites underwent deformation during late stages of folding and post-folding

Thank you!

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