Weld Types and Classification

James J. Willis

Odyssey International, LLC, 7190–C Cemetery Hwy., St. Martinville, Louisiana 70582

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EXTENDED ABSTRACT

Welds are structural/stratigraphic elements that record the juxtaposition of formerly separated geologic units and are generally associated with the flowage and/or dissolution of evaporites, especially halite, commonly in association with faulting (e.g., Jackson and Cramez, 1989; Oldham, 1996; Rowan et al., 1999, 2012; Willis et al., 2001a, 2001b; Wagner, 2010; Berry, in press; etc.). Their importance within Gulf of Mexico and other salt-related petroleum systems is well established (e.g., Jackson et al., 1995; Rowan, 1995; Spencer and Sharpe, 1996; Rowan et al., 1999; Mount et al., 2006; Jackson et al., 2014; etc.). However, unit juxtaposition occurs in many additional geologic environments and thus represents a more diverse class of welds (Table 1) (Willis, 2006). Many of these welds are important for respective petroleum systems. In addition to evaporite dissolution, so too can dissolution of carbonates generate welds (e.g., Willis et al., 2001b; Zahm et al., 2015). On a smaller scale, stylolites form by pressure dissolution of carbonates and less commonly quartz sandstones, imparting permeability anisotropy due to impermeable (or less permeable) residue on the stylolite seam or in some cases due to seams serving as flow conduits (e.g., Tada and Sevier, 1989). Intergranular stylolite formation can represent an important aspect of reservoir quality degradation as pore throats and spaces close during grain suturing in both sandstones and carbonate grainstones/packstones (e.g., Houseknecht, 1997; Tada and Sevier, 1989; Willis and Bixler, 2017). As another example, welds may also form from shale flowage during faulting, such as progressive shearing and removal of clay smear, or during folding and resultant transfer of material from flank to core (an important factor in fold genesis during transition from parallel to similar folds) (Willis, 1993, 2006)—formerly separated reservoir rocks can be placed in contact or near contact, resulting in complex reservoir commingling . Additionally, welds may form in sand injectite domains, as autochthonous or allochthonous sand is removed, and in igneous environments, as melt invades and then is removed, often exhibiting remarkable similarity to salt systems (Willis, 2006; Løseth et al., 2013). Weld residuum, representing residual material left behind during the flow and/or dissolution process, which can influence along-weld or cross-weld fluid flow, represents an important consideration for weld influence on petroleum systems, from large-scale welding of former salt sheets to reservoir-scale heterogeneity (e.g., Tada and Se-

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vier, 1989; Heydari, 2000; Willis et al., 2001; Jackson and Lewis, 2012; Jackson et al., 2014; Benison, 2015; Zahm et al., 2015; Willis and Bixler, 2017; Berry, in press; etc.).

…

Weld Types and Classification: Implications toward Petroleum Systems

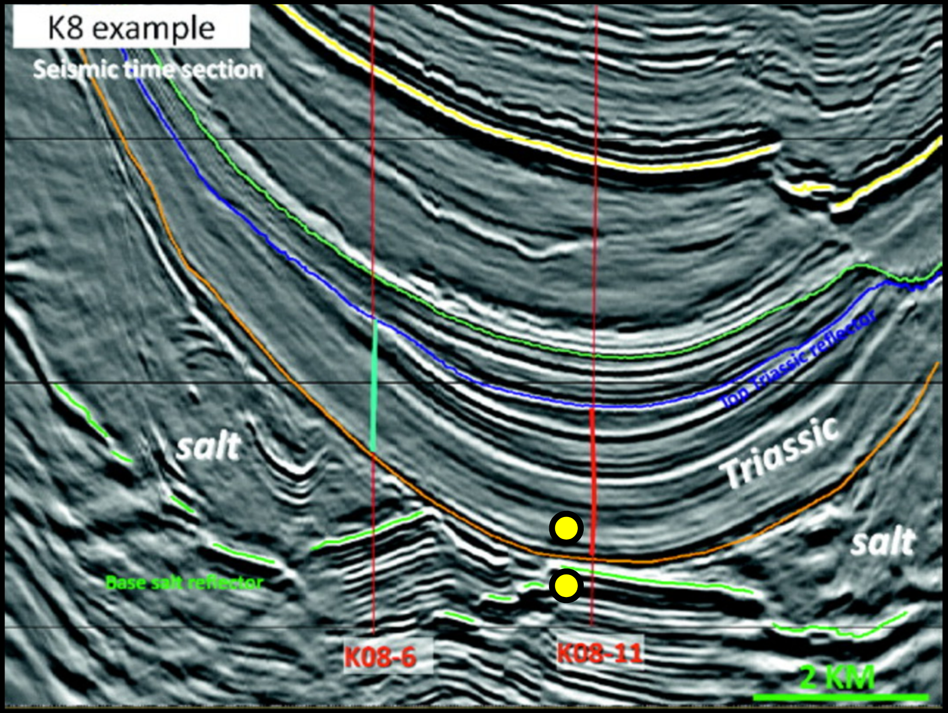
James J. Willis, Ph.D.
Odyssey International, LLC
University of Louisiana at Lafayette
Willis School of Applied Geoscience

Weld Definition

"…the structure joining two rock bodies formerly separated by salt…."

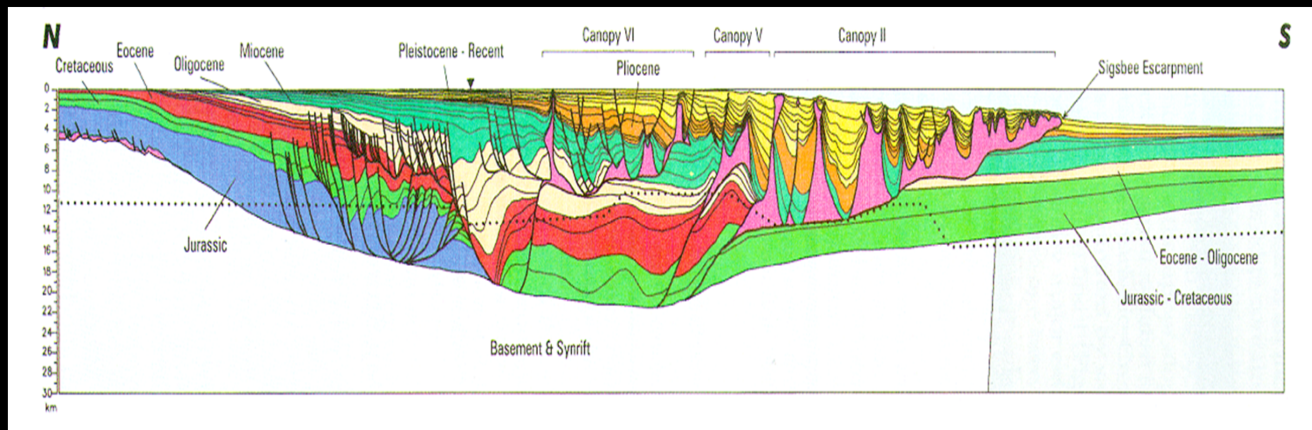
(Jackson and Cramez, 1989,

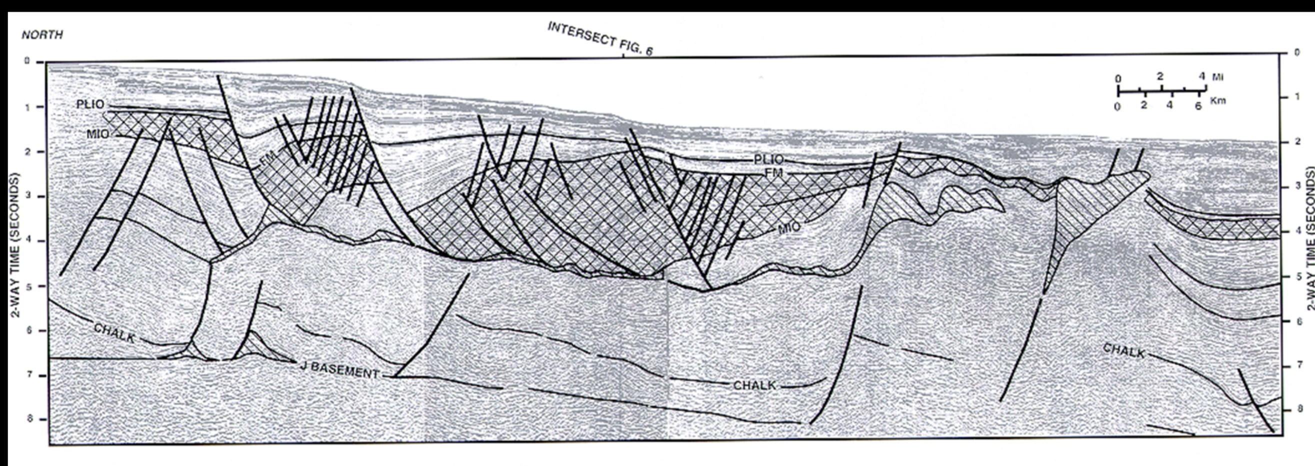
10th GCSSEPM Found. Res. Conf.)



(Hoetz et al., 2011, *Petr. Geosci.*)

Fractal Nature of Deformation





(Peel et al., 1995,
AAPG Mem.)

Weld Definition

- Originally conceptualized as juxtaposition of strata by salt removal due to flow
- Later expanded to include shale flow and dissolution of various rocks and methods

FLOW WELDING

DISSOLUTION WELDING

ADDITIONAL FACTORS

Weld Definition

<u>FLOW WELDING</u>

- Evaporites
- Shale
- Sand
- Tar
- Igneous Melt
- Metamorphic

<u>DISSOLUTION WELDING</u>

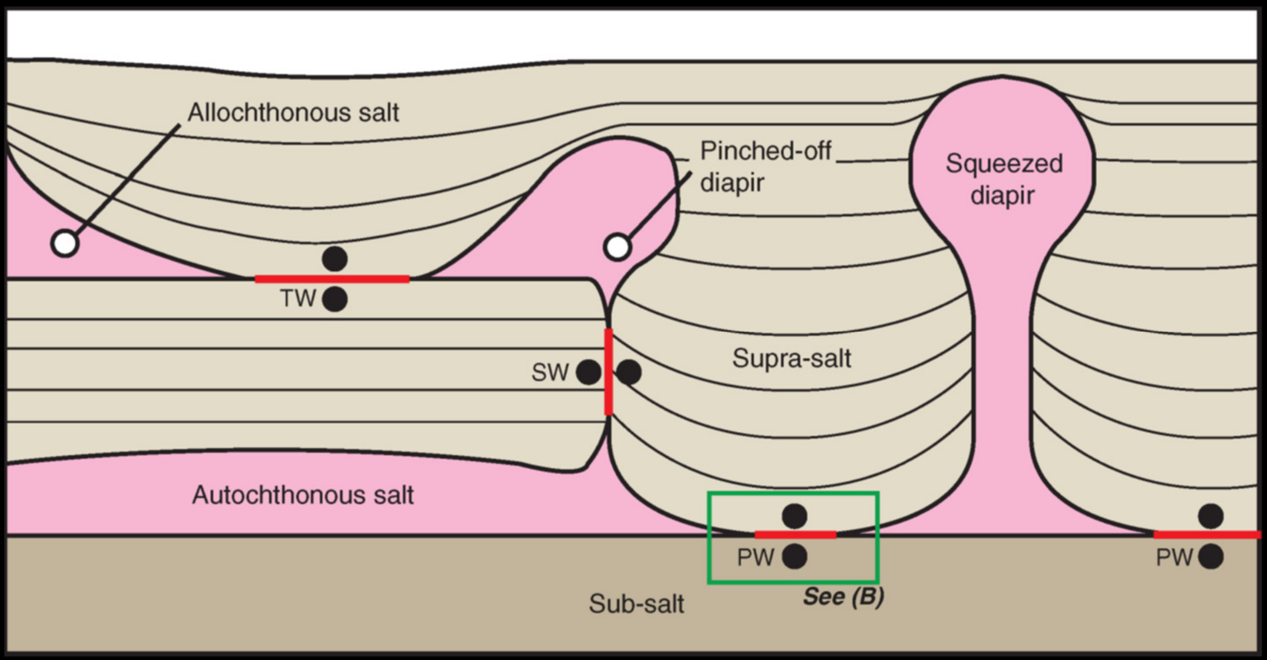
- Evaporites
- Carbonates
- Stylolites (Pressure Dissolution)—bedding, tectonic, and grain-to-grain suture types

<u>ADDITIONAL FACTORS</u>

- Faults
- Shear Zones
- Boudinage (in “pinch” domains)

(modified after Willis, 2006, *GCAGS Trans*.)

Salt Weld Types

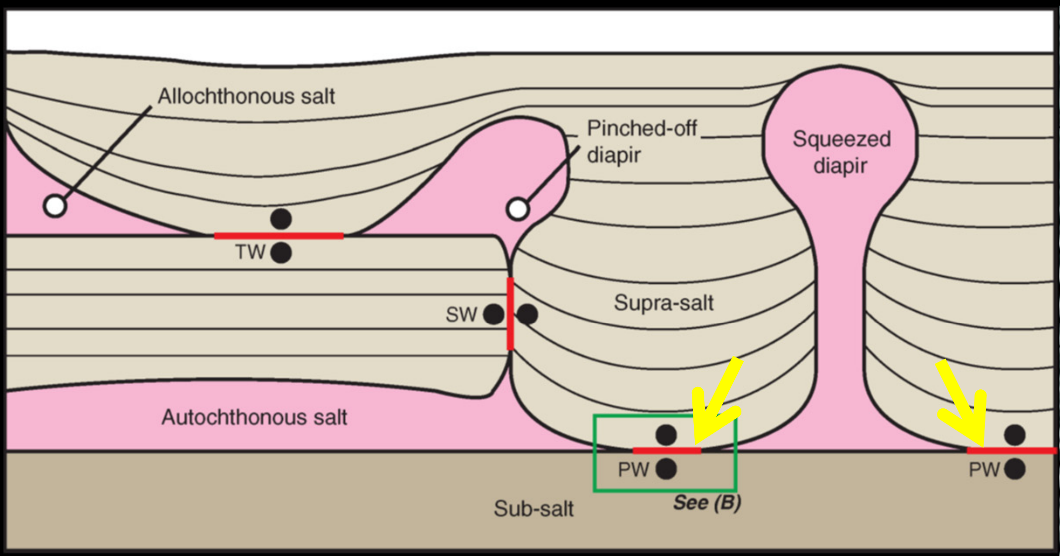


(Jackson et al., 2014, *Interpretation*; after Wagner, 2010, *UT Dissertation*)

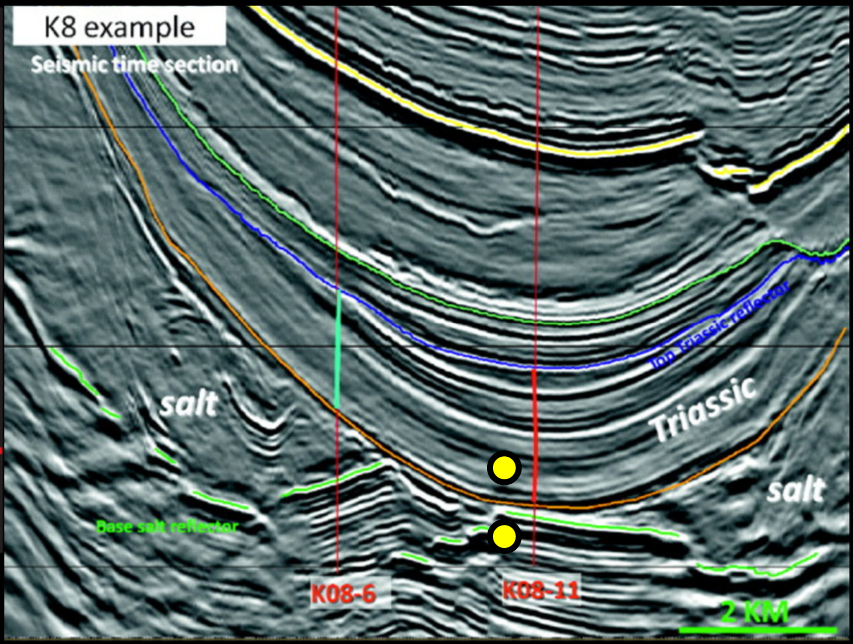
- **Primary Weld** – Removal of Autochthonous Salt
- **Secondary Weld** – Removal of Allochthonous Salt Stock or Ridge
- **Tertiary Weld** – Removal of Allochthonous Salt Sheet

Salt Weld Types

Primary Weld – Removal of Autochthonous Salt



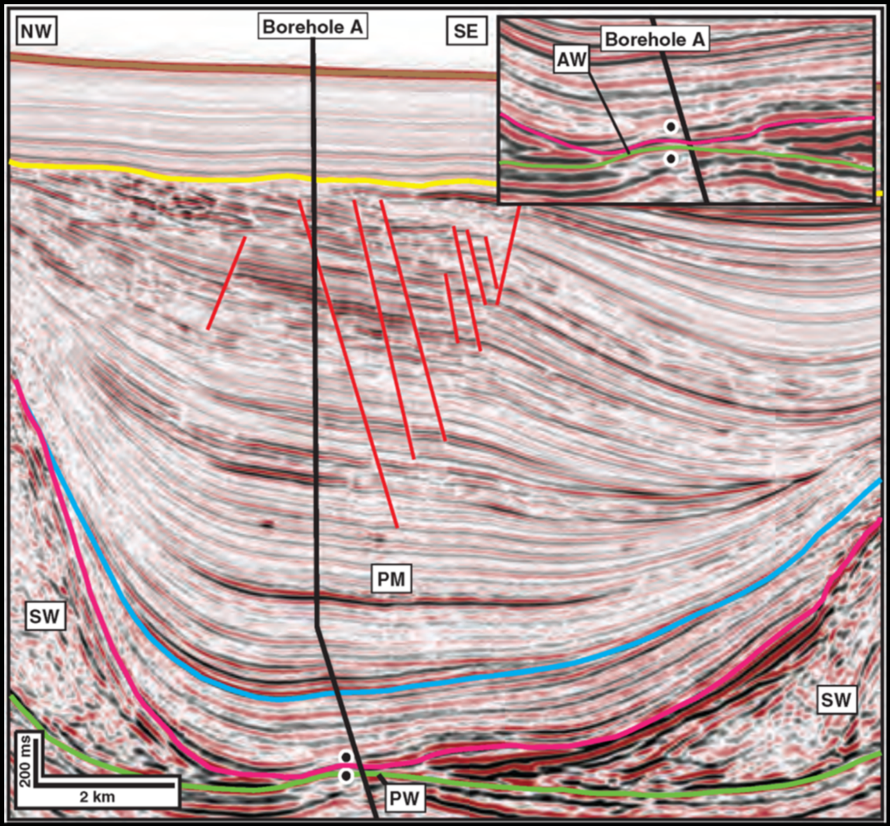
(Jackson et al., 2014, *Interpretation*; after Wagner, 2010, *UT Dissertation*)

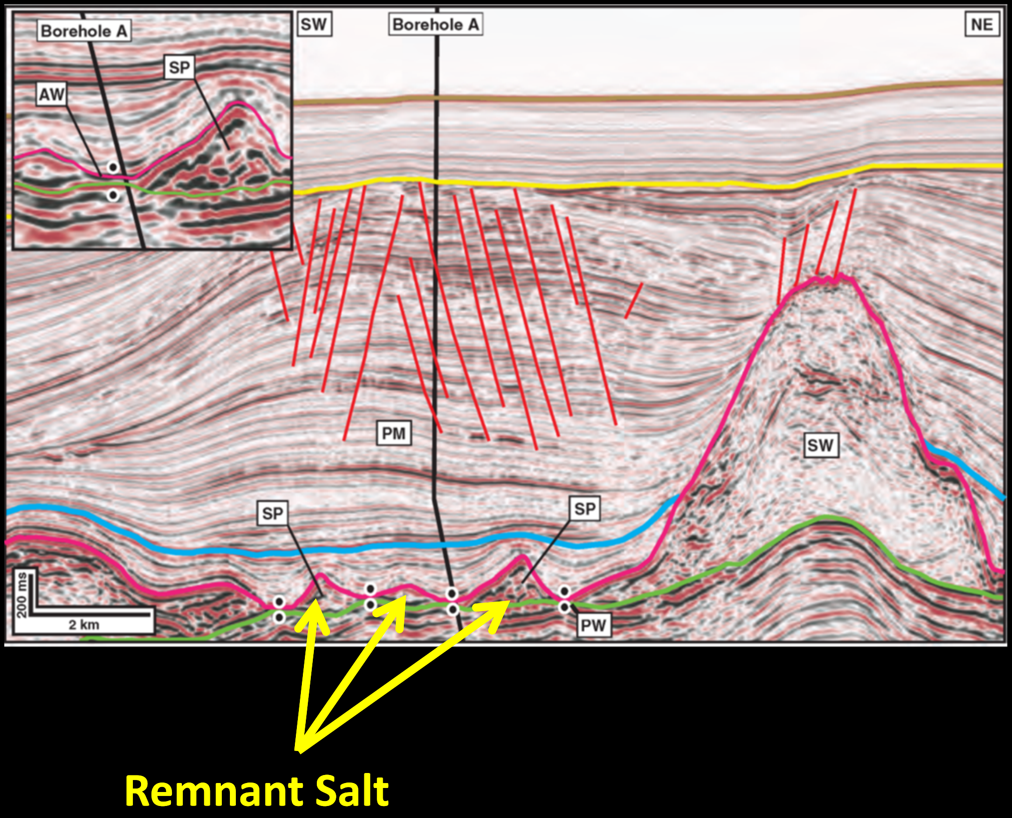


(Hoetz et al., 2011, *Petr. Geosci.*)

Salt Flow Weld

Santos Basin, Offshore Brazil

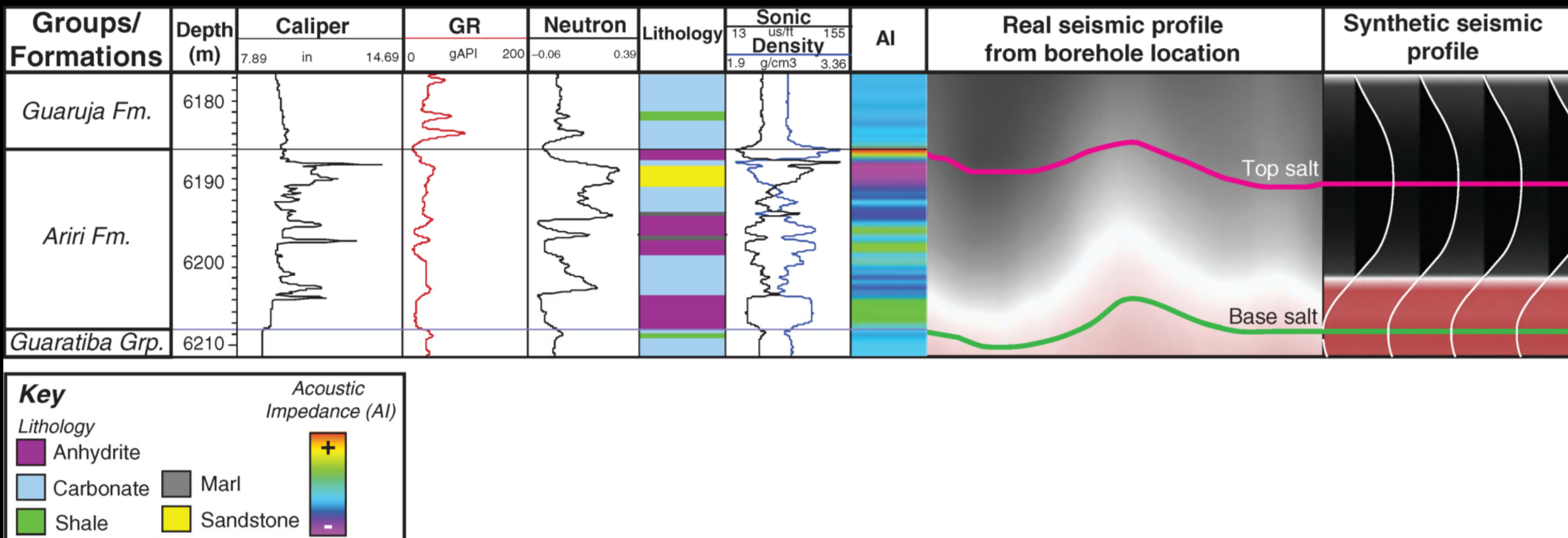




(Jackson et al., 2014, *Interpretation*)

Salt Flow Weld

Santos Basin, Offshore Brazil

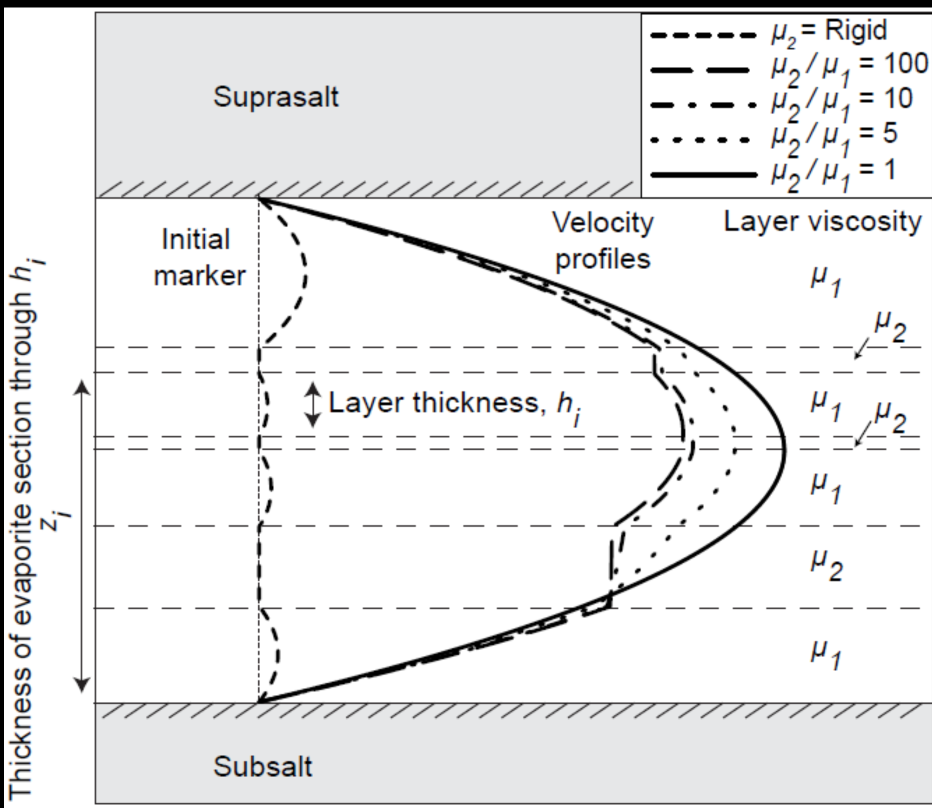


◊ Although seismic data suggests weld, anhydrite and other lithologies remain indicating incomplete weld (and potential weld seal.)

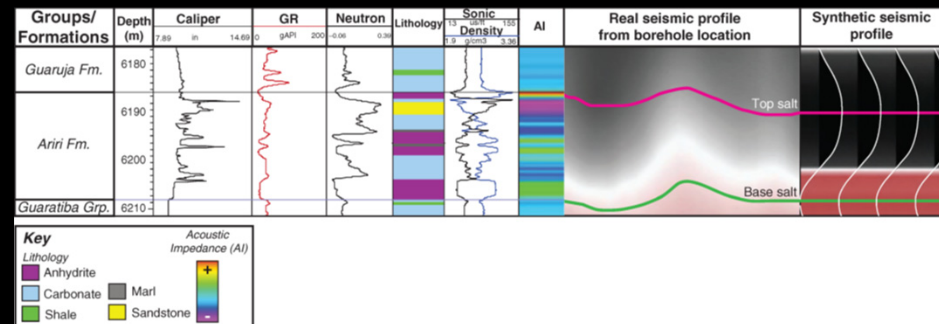
(Jackson et al., 2014, *Interpretation*)

Salt Flow Weld

Santos Basin, Offshore Brazil



(Wagner, 2010, *UT Dissertation*)



(Jackson et al., 2014, *Interpretation*)

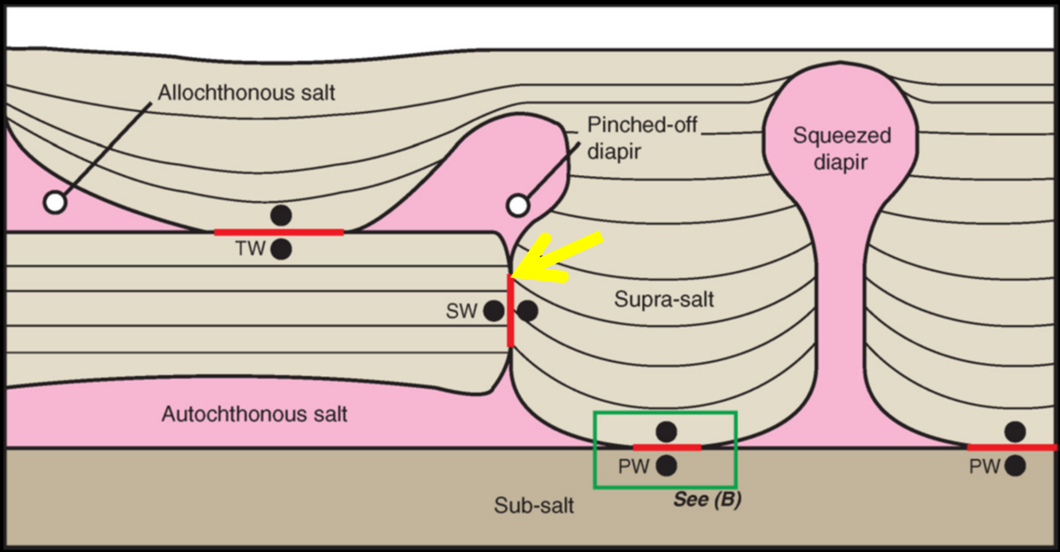
◊ Reduced flow at salt-sediment interface may leave residual salt along weld

◊ Dissolution may be required to complet the weld

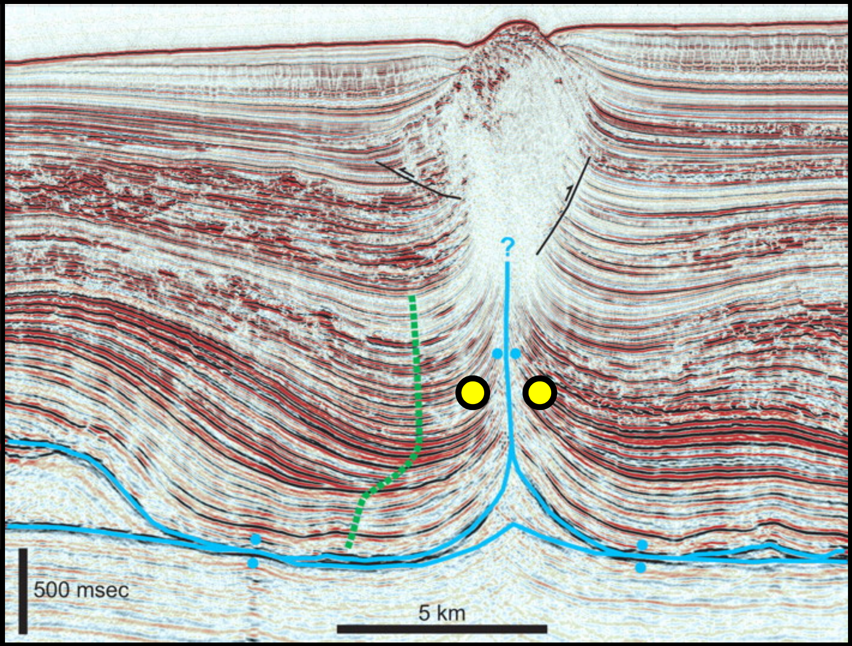
◊ Not-salt lithologies complicate flow and remain behind as “residuum”

Salt Weld Types

Secondary Weld – Removal of Allochthonous Salt Stock or Wall



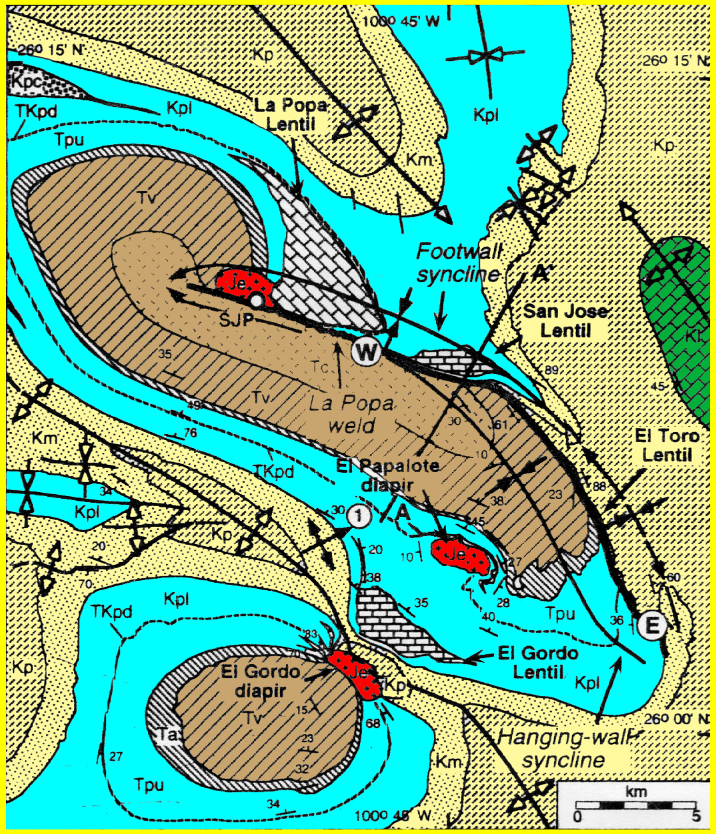
(Jackson et al., 2014, *Interpretation*; after Wagner, 2010, *UT Dissertation*)

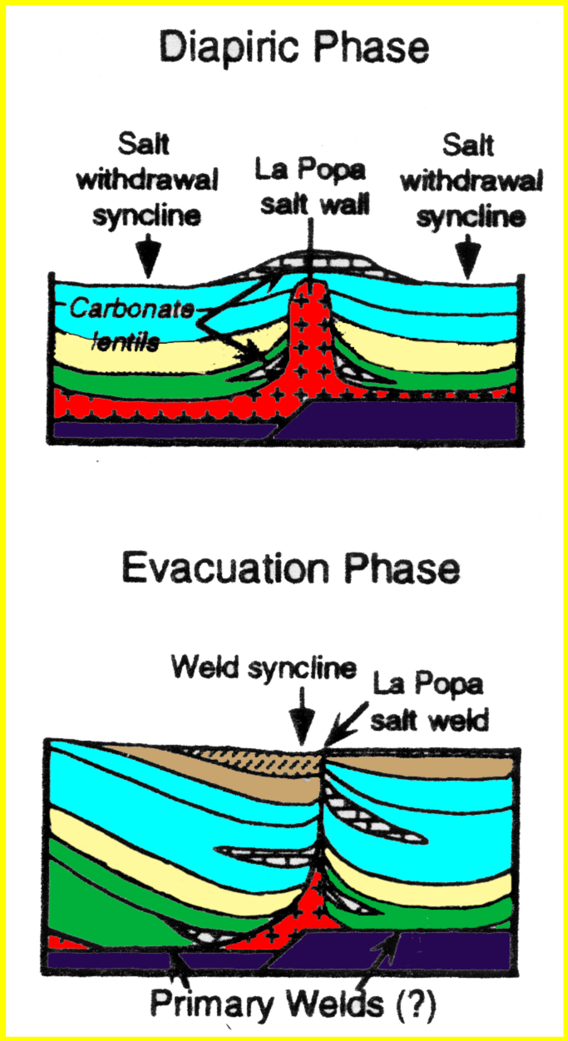


(Rowan et al., 2012, *Geol. Soc. London Spec. Publ. 363*)

La Popa Area, Mexico
Exposed Salt Wall Weld and Diapirs

- Former salt wall (carbonate 'lentils' developed on ridge uplift)
- Peripheral salt-withdrawal basins
- Exposed weld and diapirs

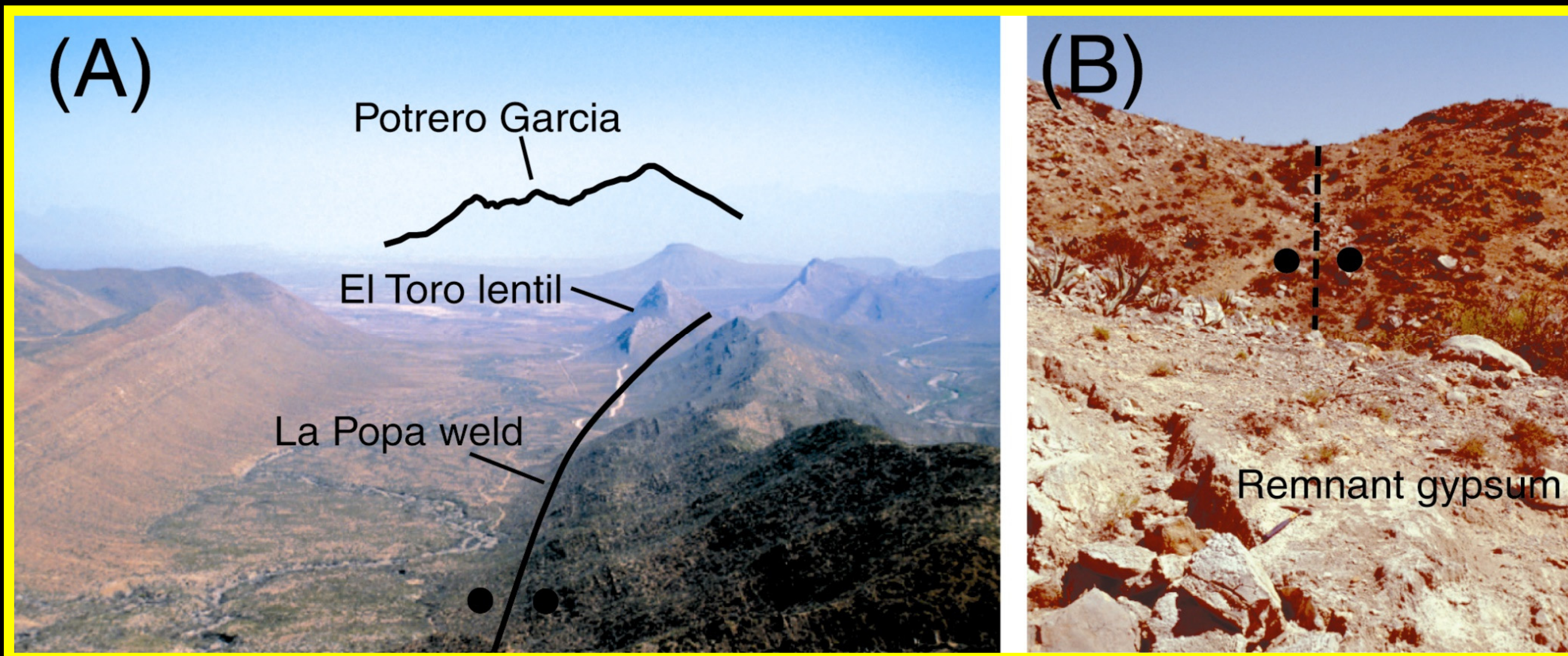




(Giles and Lawton, 1998, *Geology*)

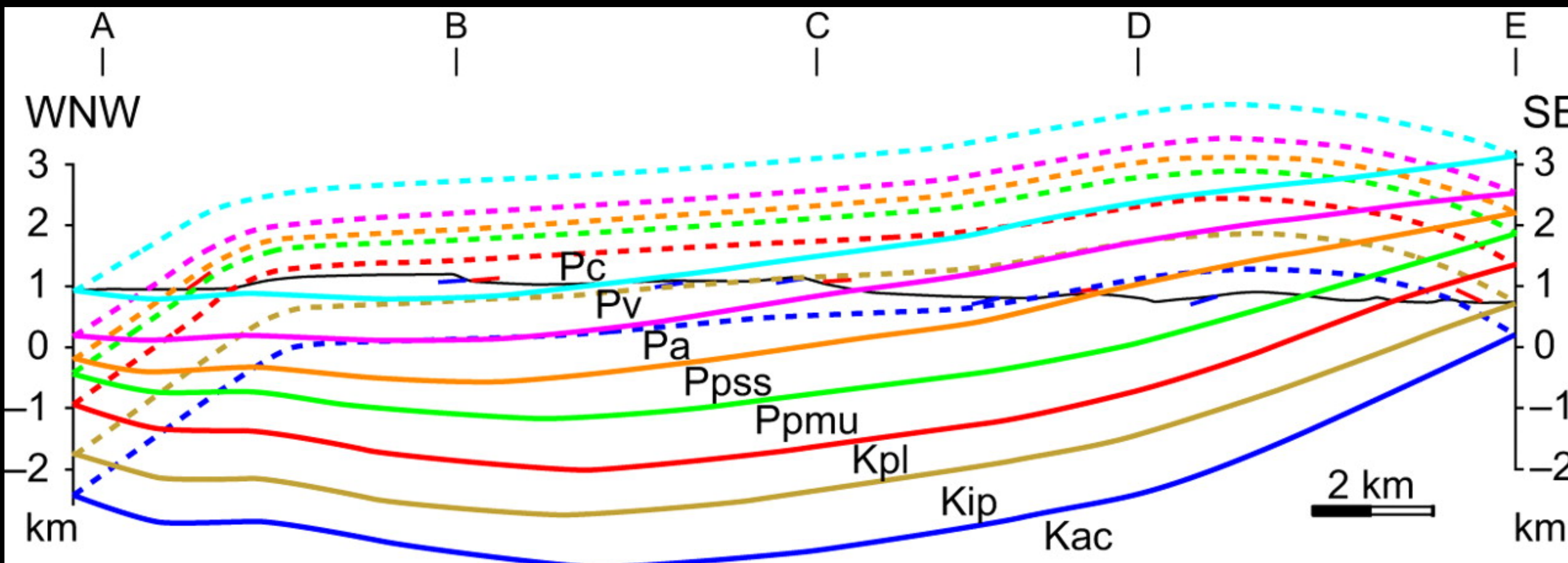
La Popa Area, Mexico

Exposed Salt Wall Weld and Diapirs



(Willis et al., 2001a, *GCAGS Trans.*)

La Popa Area, Mexico
Exposed Salt Wall Weld and Diapirs

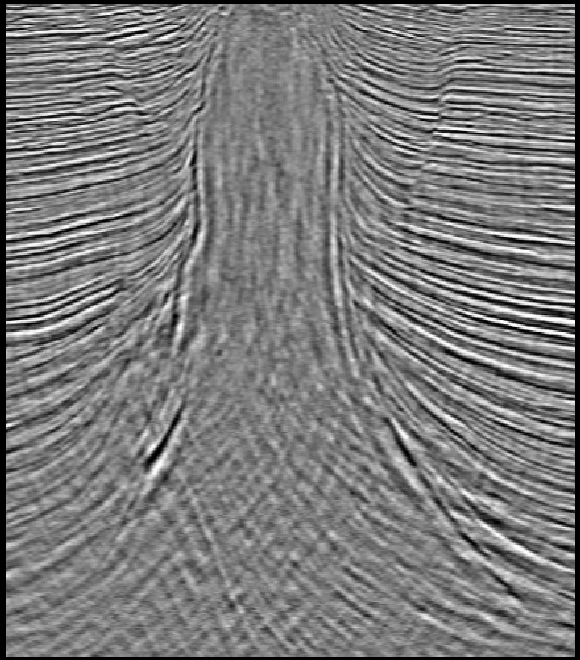


(Rowan et al., 2012, *Geol. Soc. London Spec. Publ. 363*)

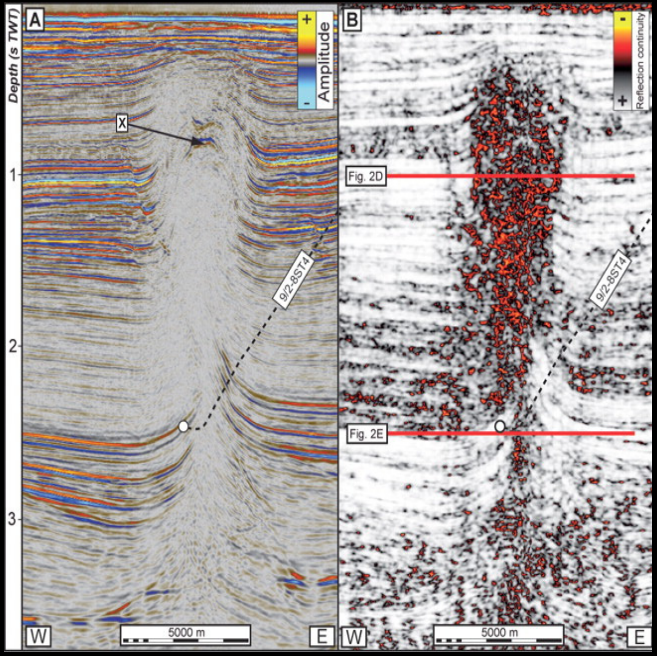
Basin-Centered Contraction

Dome to Ice Cream Cone

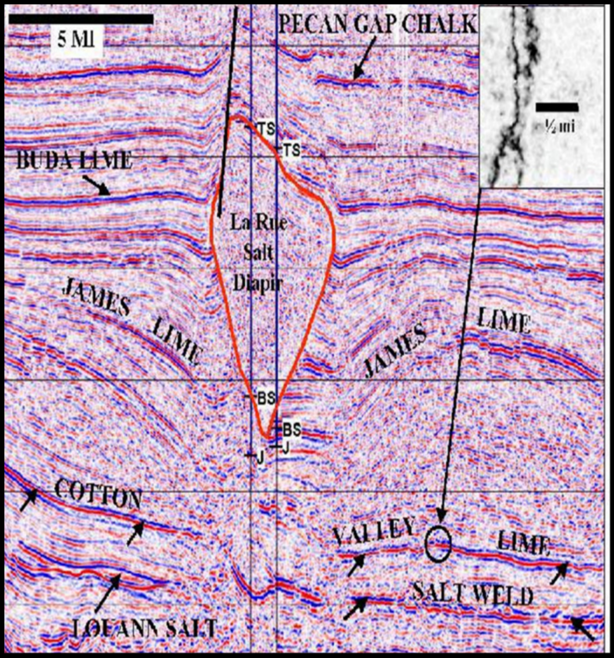
Progressive Removal of Salt Stock



(courtesy of Hill Geophys. Consulting)

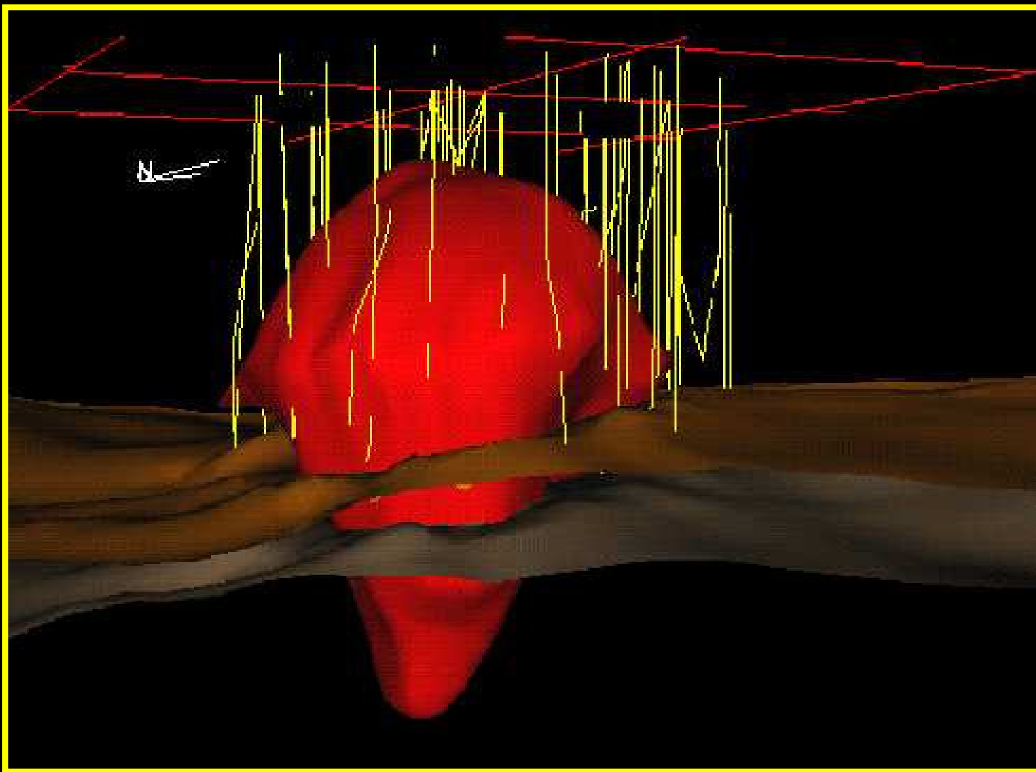


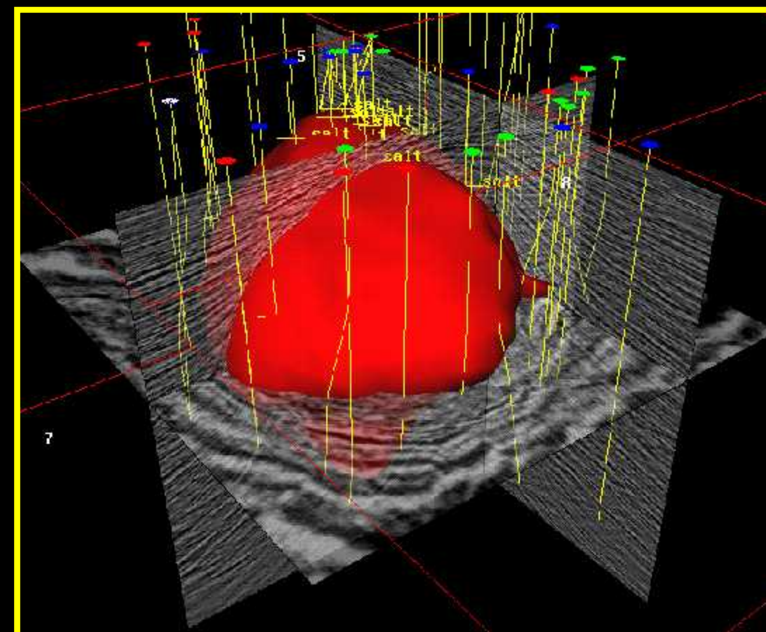
(Jackson and Lewis, 2012, *Jour. Geol. Soc. London*)



(Maione, 2000, *GCAGS Trans.*)

Dome to Ice Cream Cone

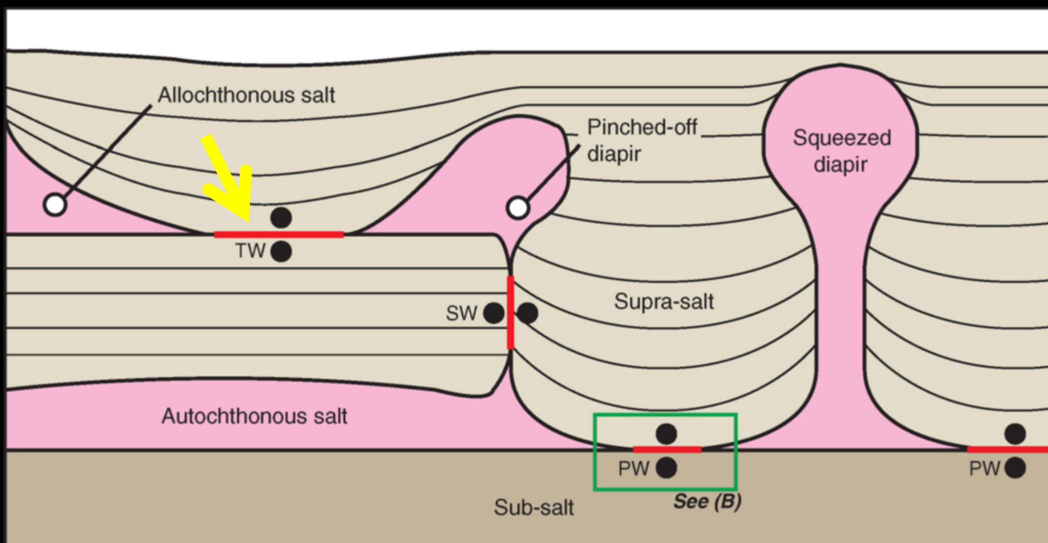




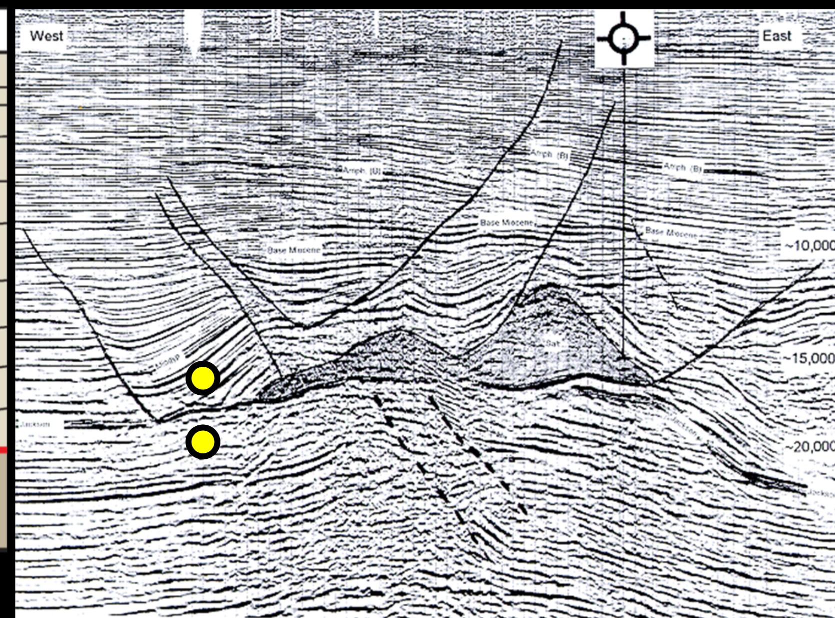
(images courtesy of SEG website and Phillips Petroleum)

Salt Weld Types

Tertiary Weld – Removal of Allochthonous Salt Sheet



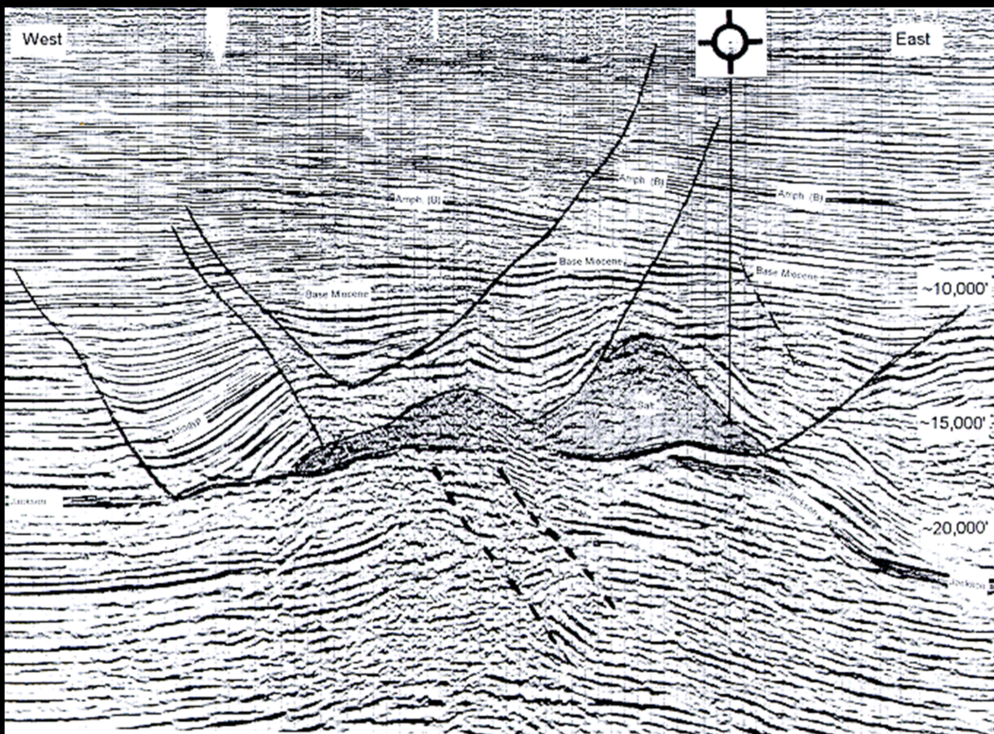
(Jackson et al., 2014, *Interpretation*; after Wagner, 2010, *UT Dissertation*)

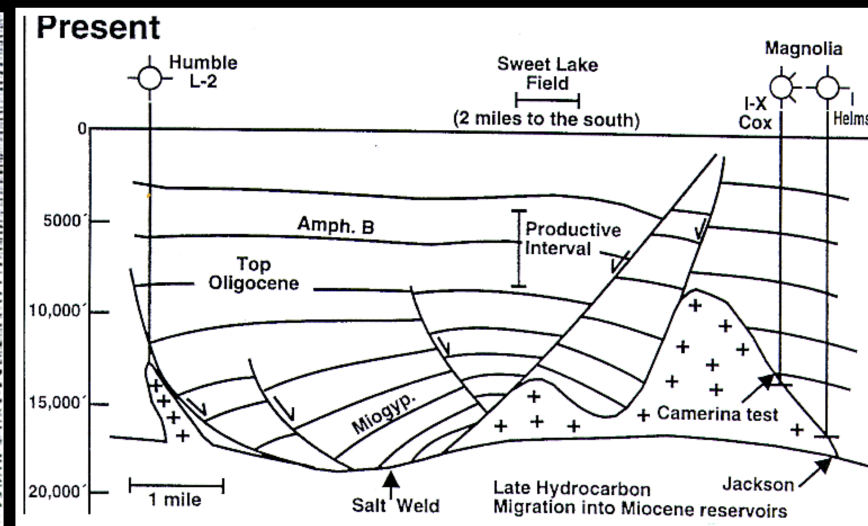


(Spencer and Sharpe, 1996, *GCAGS Trans.*)

Sweet Lake Field, Southwestern LA

Tertiary Weld of Eocene Jackson Salt Mass



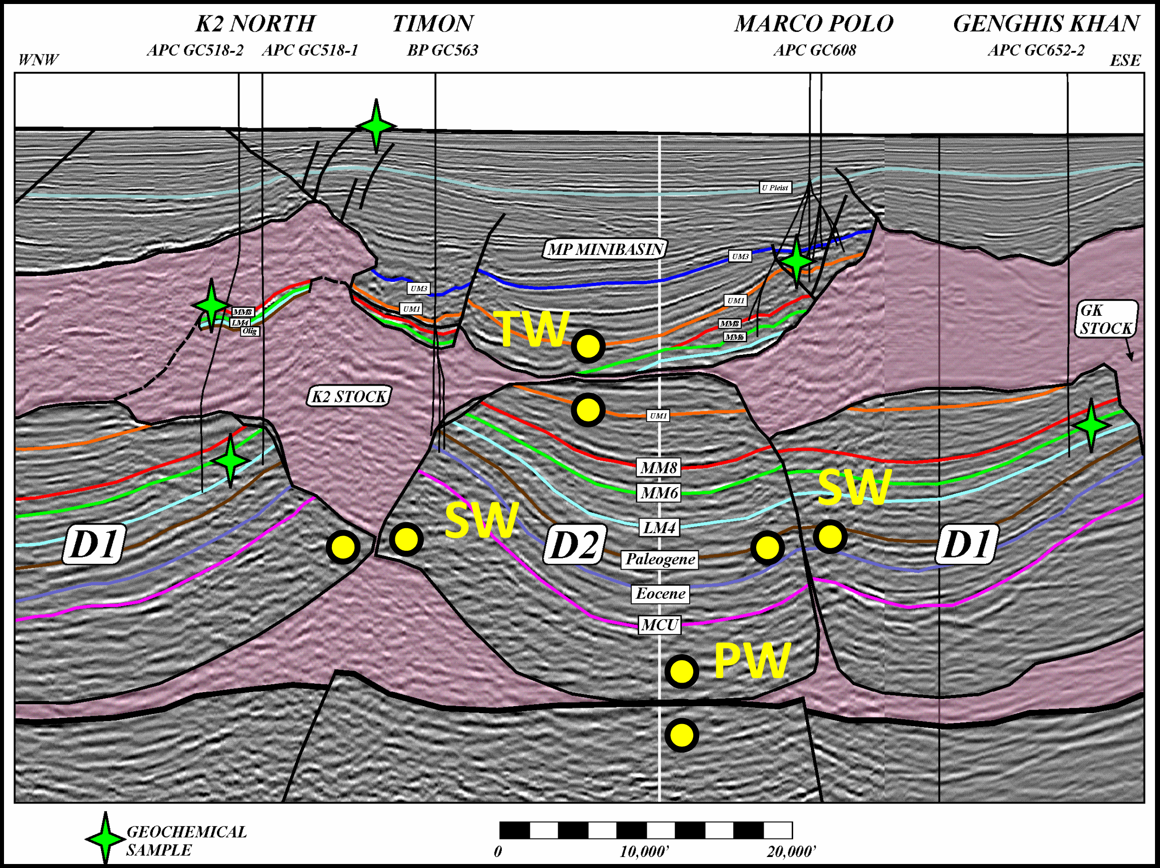


(Spencer and Sharpe, 1996, *GCAGS Trans.*)

Hydrocarbon migration to charge Sweet Lake Field occurred following welding of an Eocene-aged allochthonous salt sheet.

Deepwater GOM—K2/Timon/Marco Polo
Multiple Weld Types

- Primary Weld (PW)
- Secondary Weld (SW)
- Tertiary Weld (TW)



(Mount et al., 2006, *GCAGS Trans*.)

Shale Flow Welding

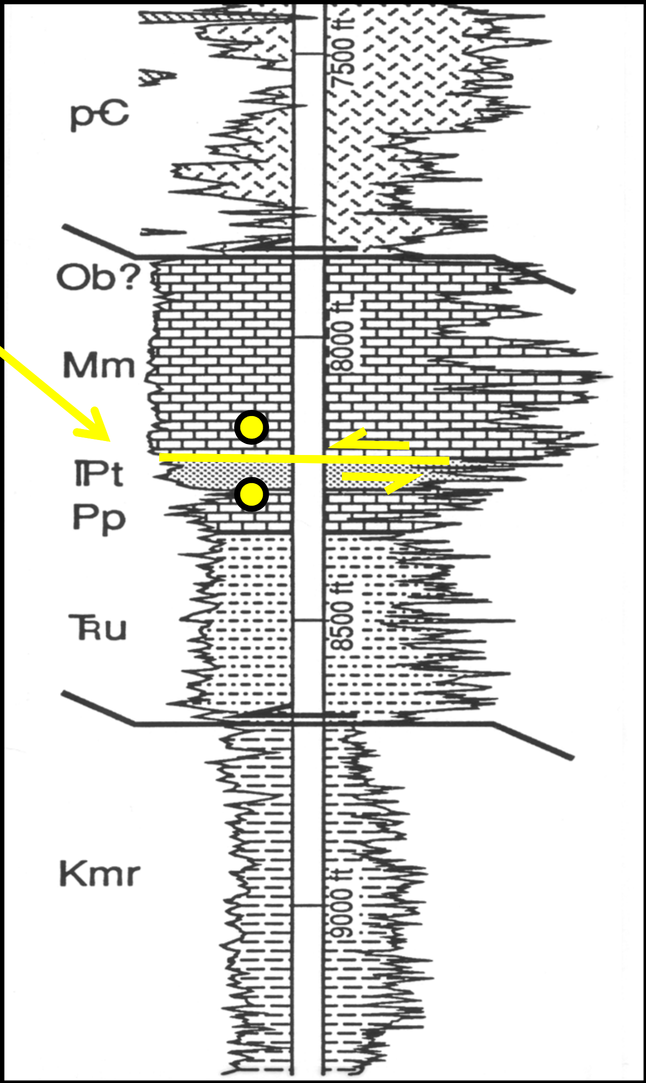
◊ Intense folding / thrusting associated with the EA fold-thrust system has created a fault-bounded overturned limb.

◊ Note that well drilled initially through Precambrian granite!!

◊ In the overturned limb, flank thinning has caused shale flowage which has completely removed the Amsden shales.

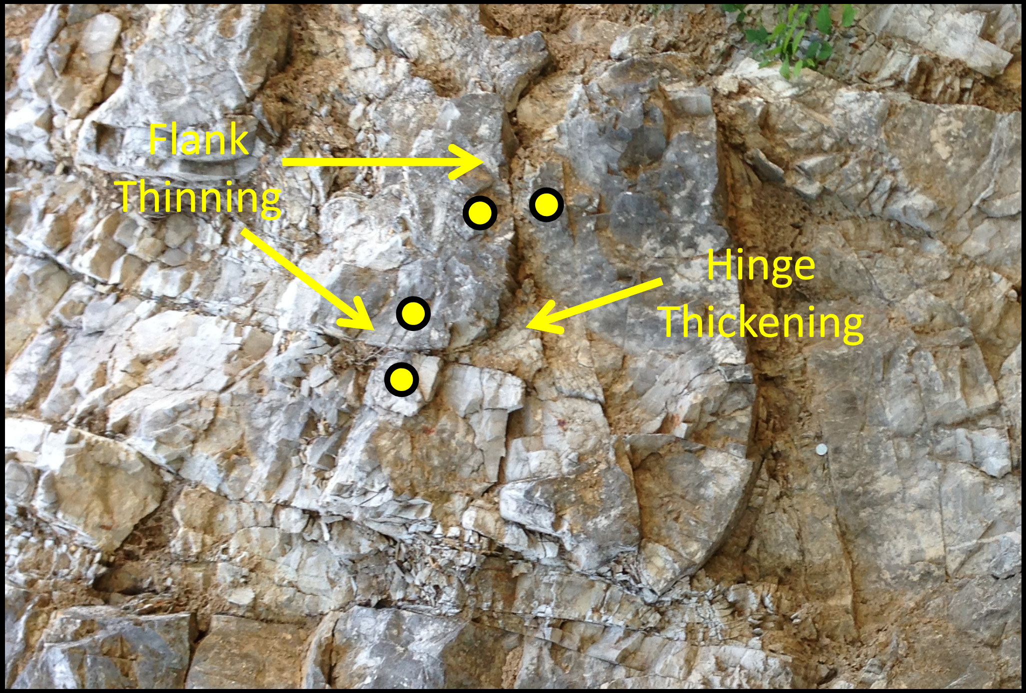
◊ Madison Limestone next to Tensleep Sandstone = Shale Flow Weld

Amsden is Thinned Out



(Willis, 1993, *Ph.D. Diss.*)

Shale Flow Welding



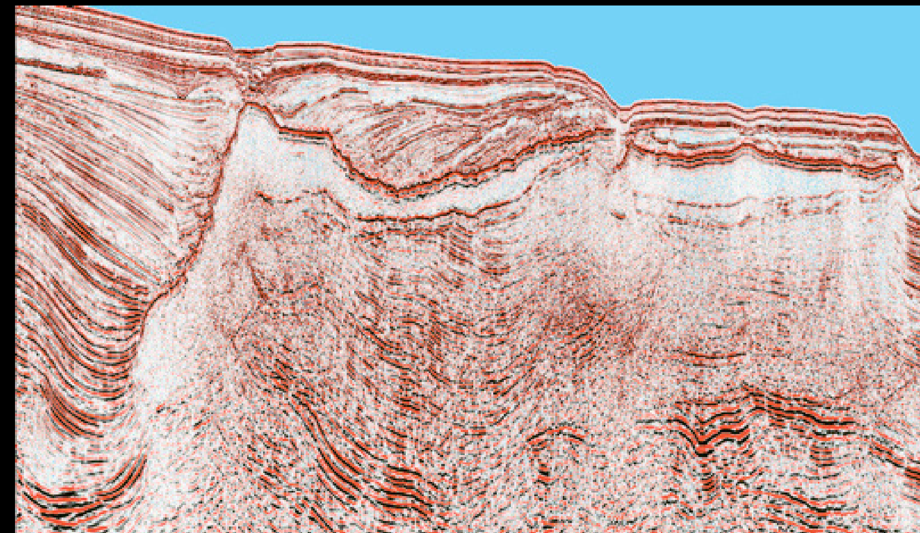
Flank thinning and shale flow creating welds, Viola LS, Arbuckle Mtns., Oklahoma

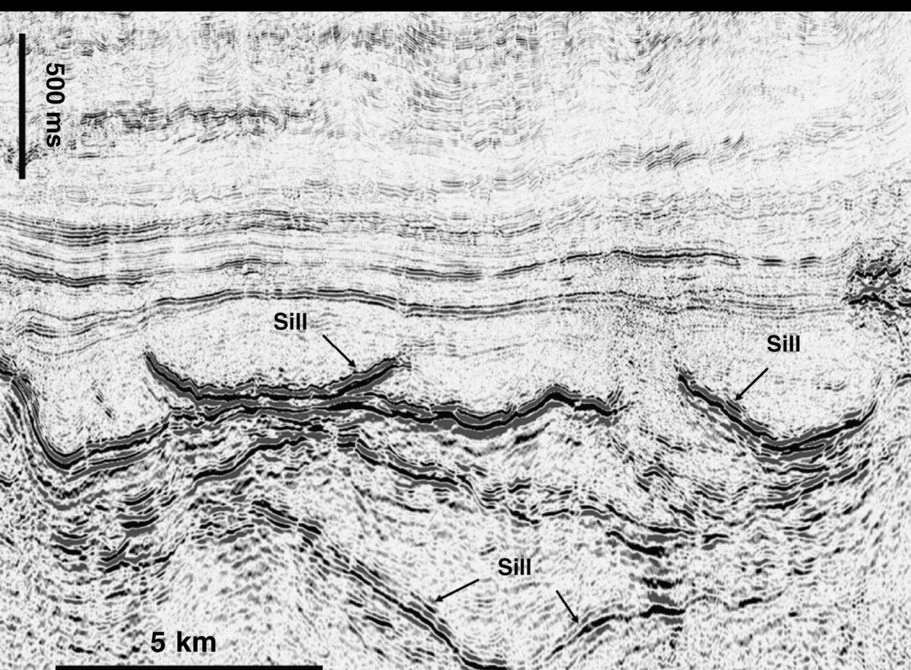
(Willis and Bixler, 1993, *Ph.D. Diss.*)

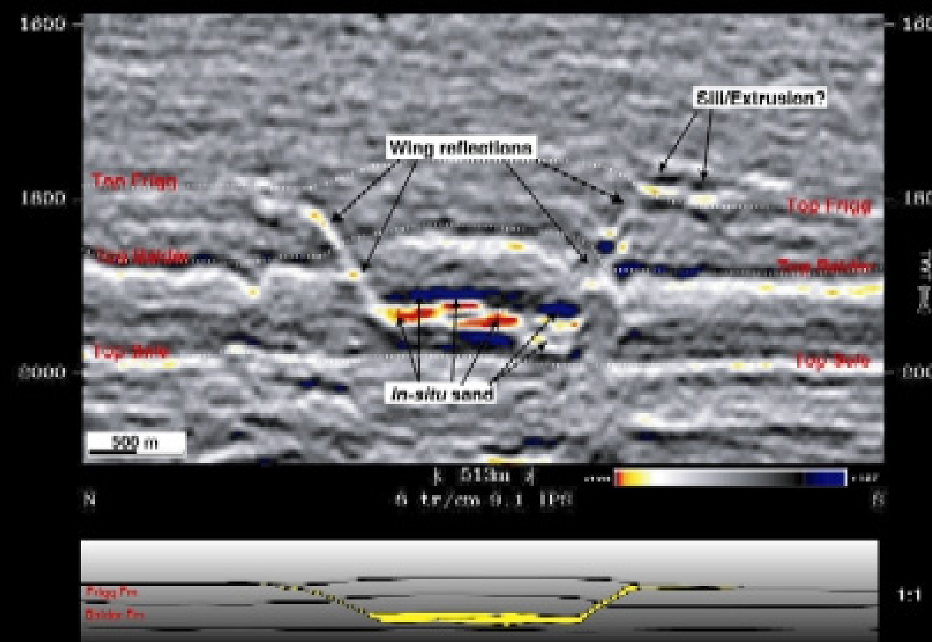
Boudinage

Injectite Processes

- Salt (upper right)
- Sand (lower right)
- Igneous Melt (lower left)
- Tar (not shown)





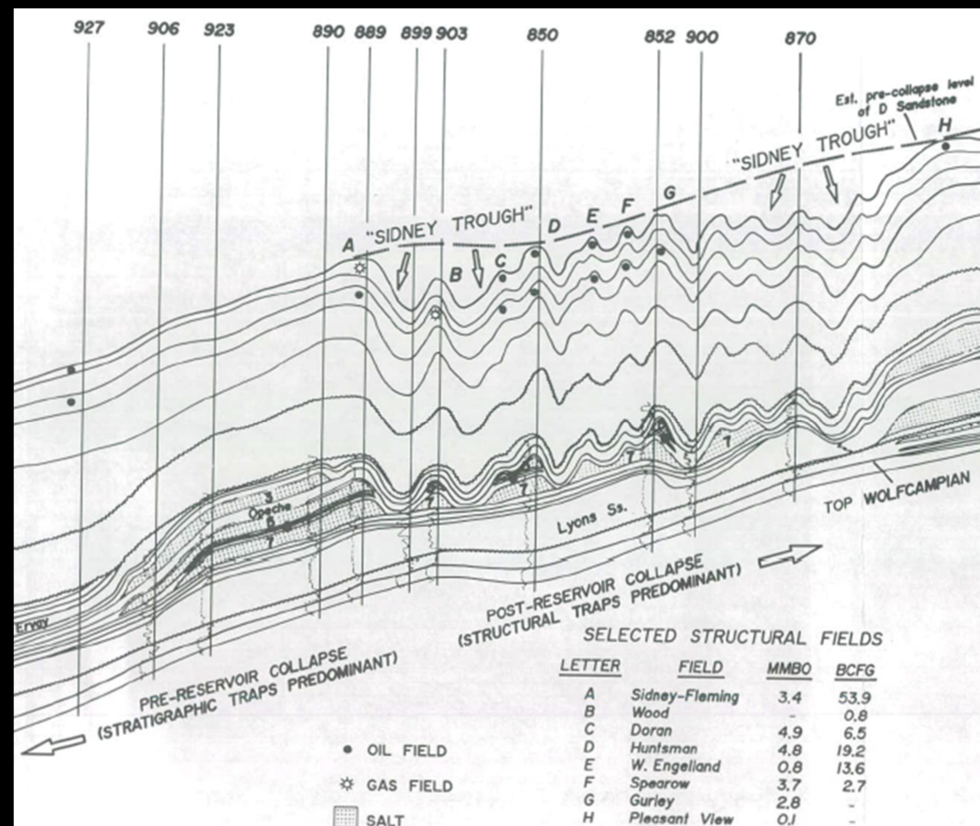


Salt Dissolution Weld

Flank of Cambridge Arch, Nebraska

◊ Structural traps associated with structural highs created by dissolution of salt forming adjacent collapse basins (modified after Oldham, 1996).

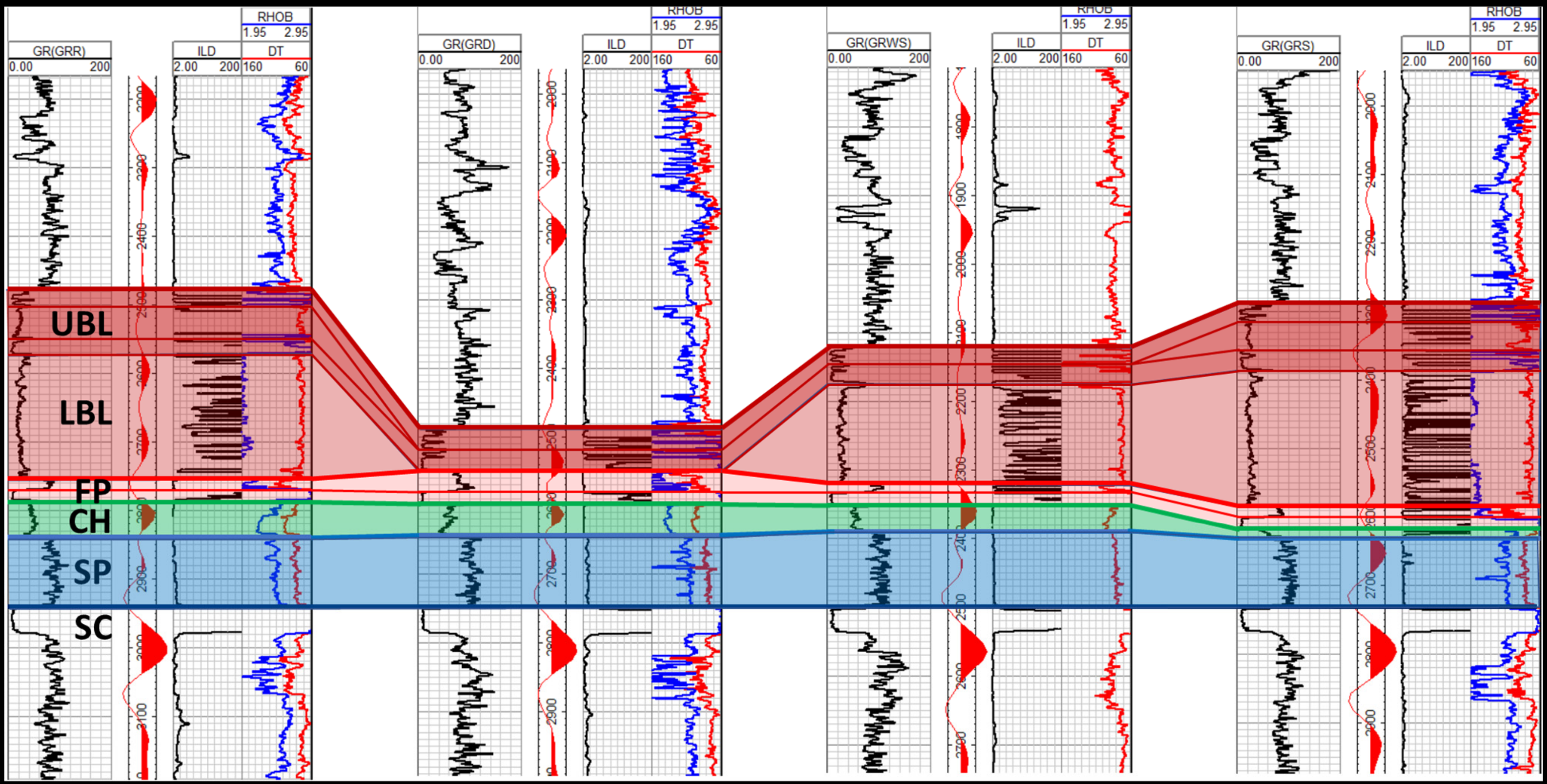
◊ Stratal thickening in collapse basins. Productive examples exist in Powder River Basin intrabasinal stratigraphy.



(Oldham, 1996)

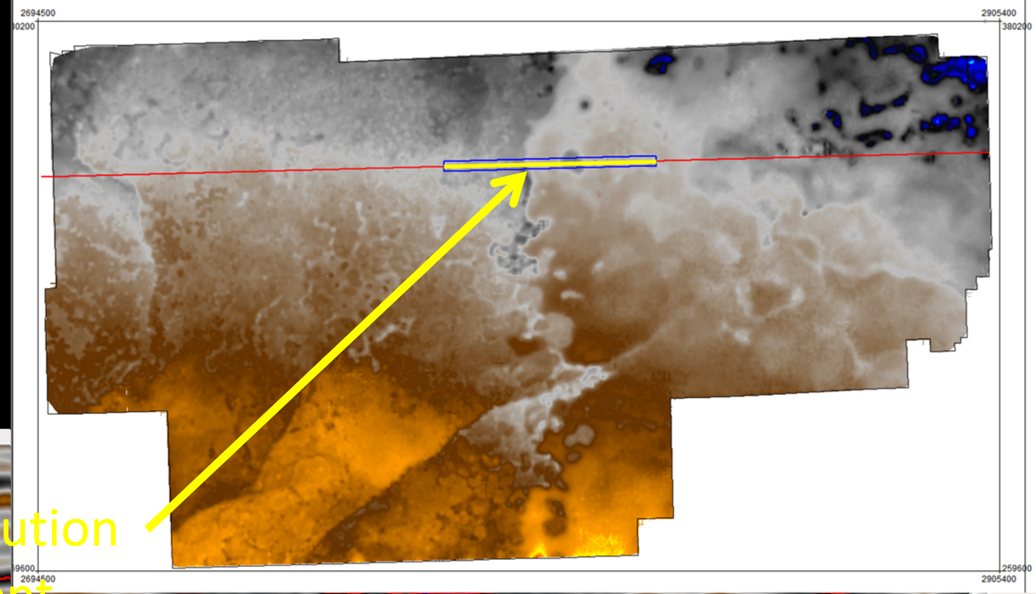
Salt Dissolution Weld

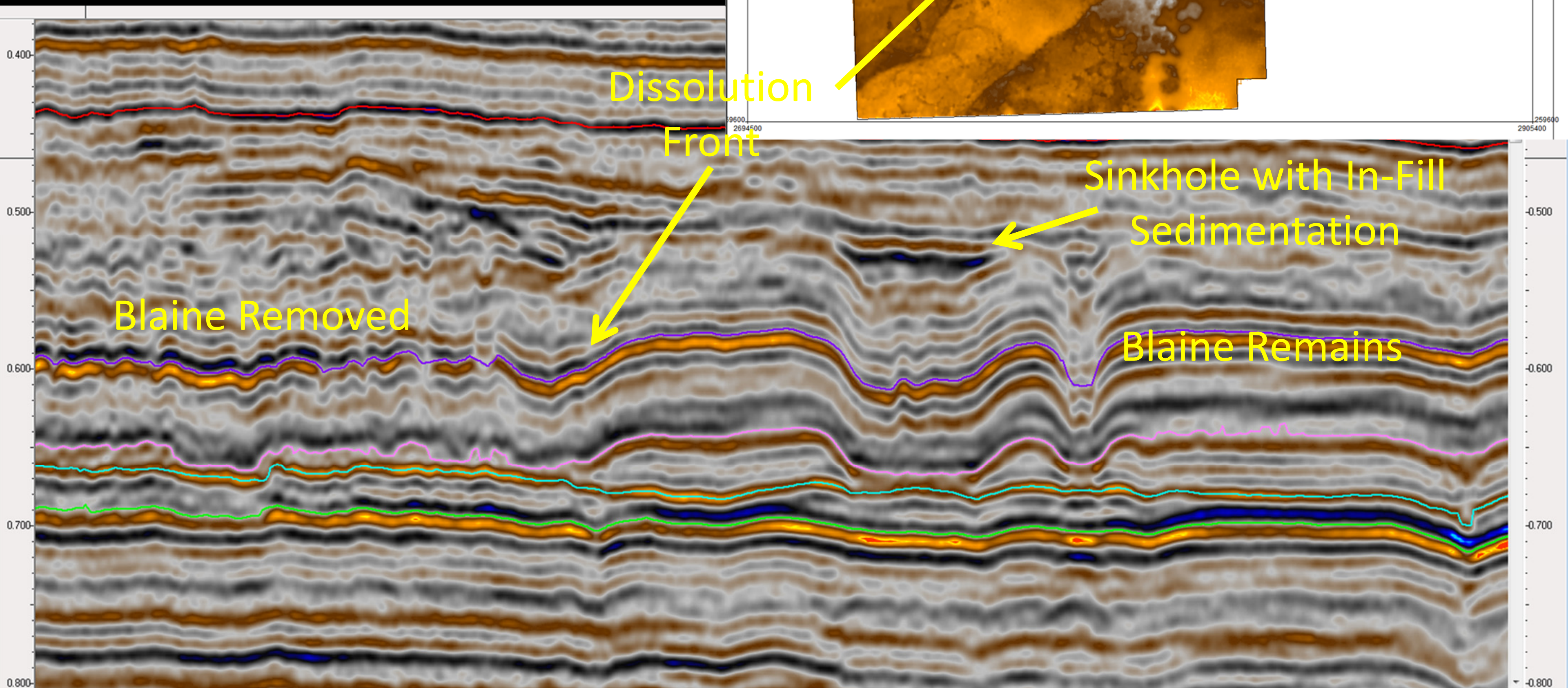
Las Animas Arch, Colorado



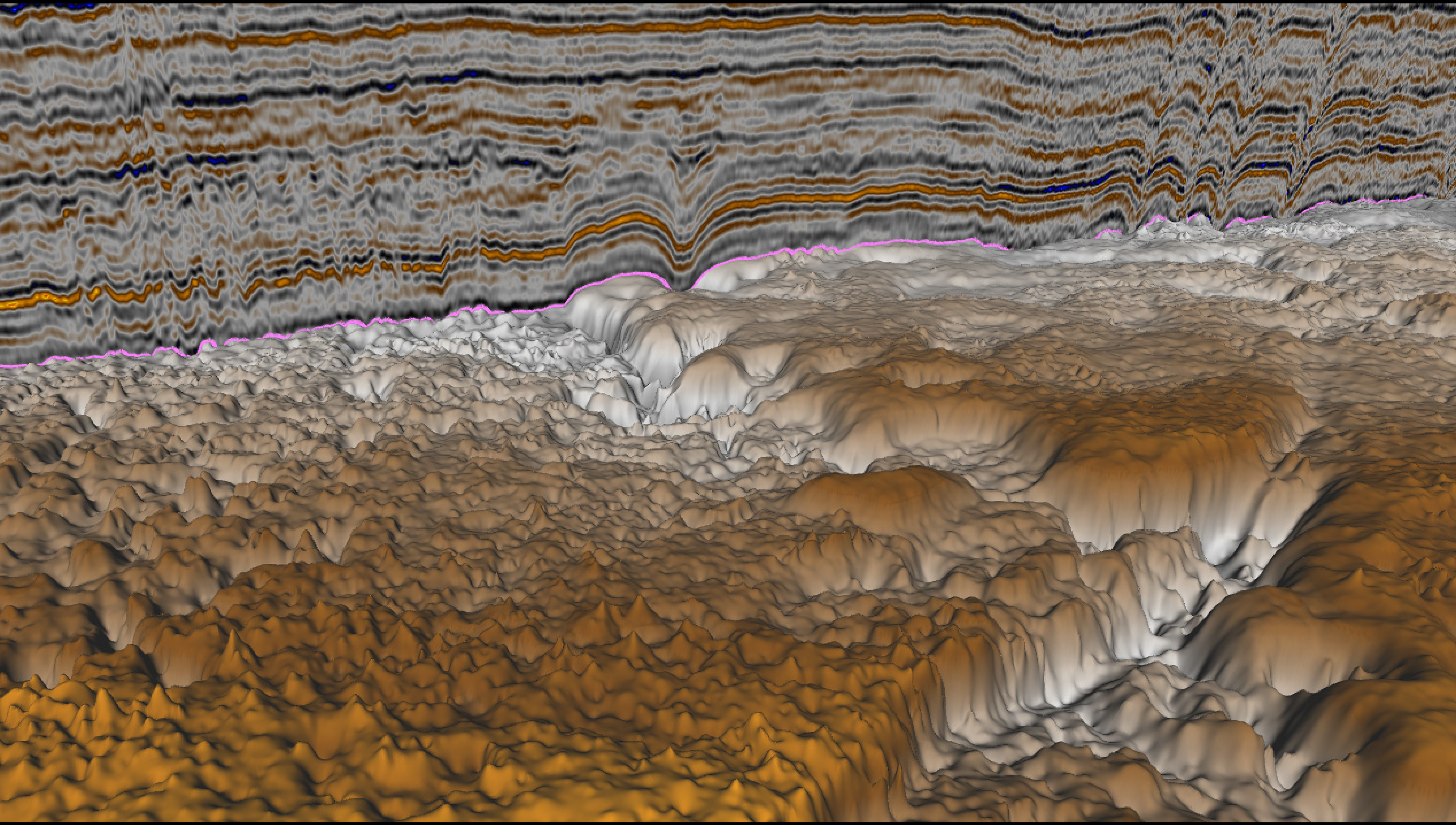
Salt Dissolution Weld

Las Animas Arch, Colorado



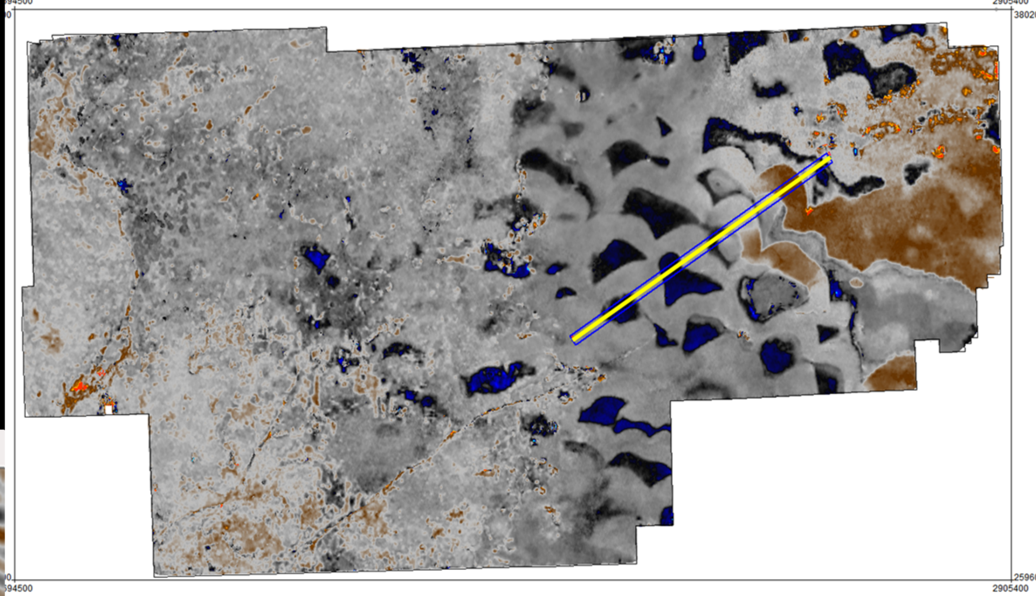


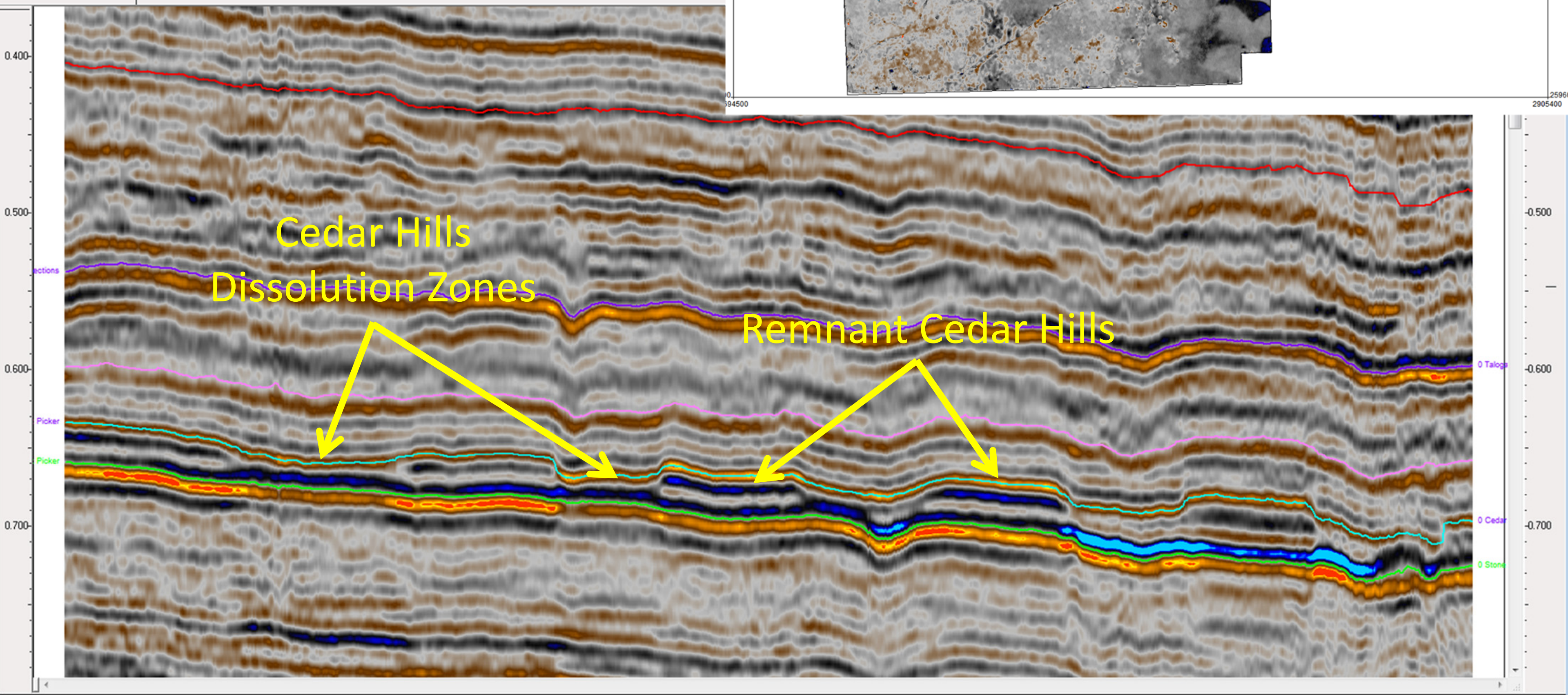
(data courtesy of TGS)



(data courtesy of TGS)

Salt Dissolution Weld
Las Animas Arch, Colorado





(data courtesy of TGS)

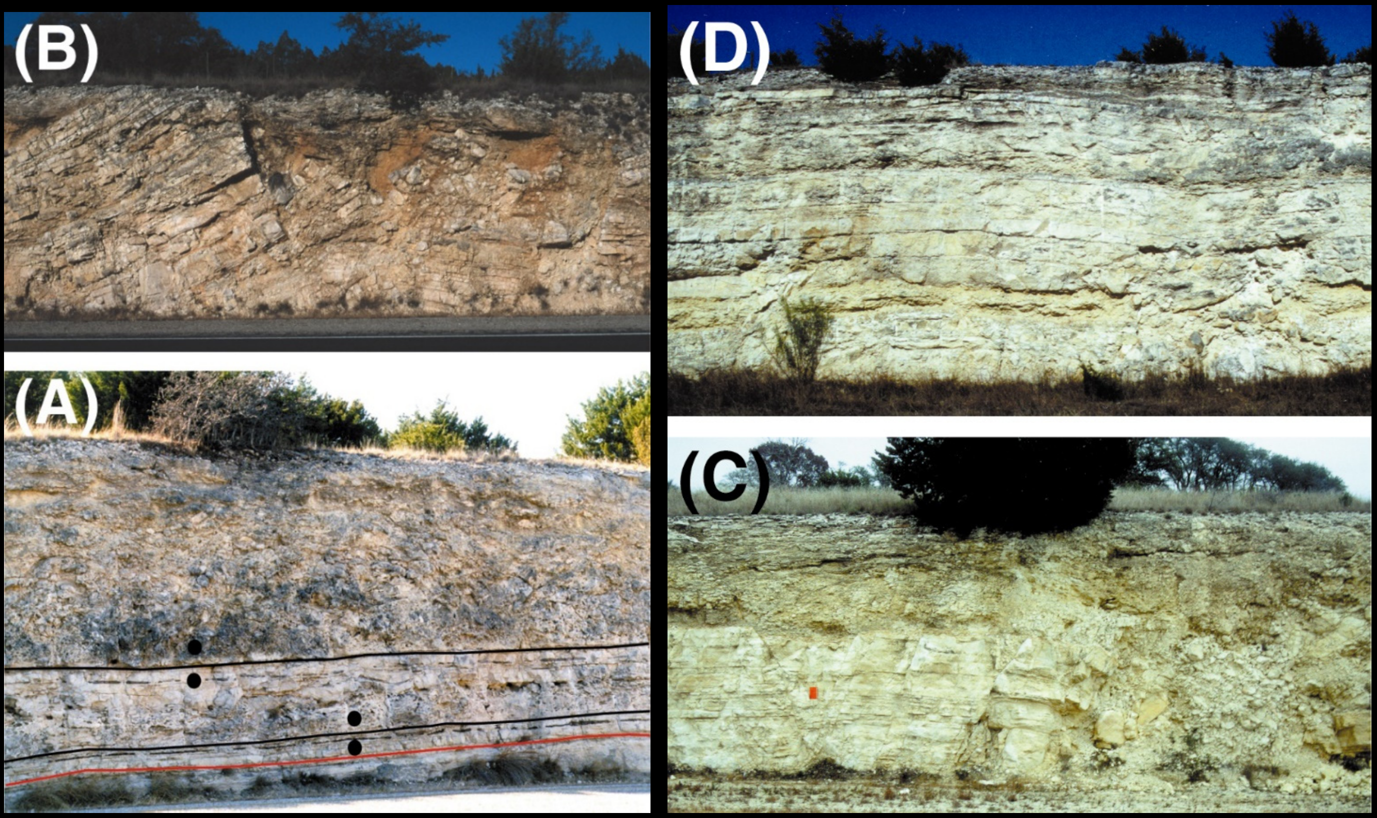
Salt Dissolution Weld

Ft. Terrett Formation, Edwards Plateau, Texas

◊ Ft. Terrett evaporites removed by dissolution

◊ Numerous I-35 roadcuts in Kerrville-Junction-Sonora areas expose different levels of the weld

◊ Allows reconstruction of vertical weld profile.



(Willis et al., 2001a,b, *GCAGS Trans.*)

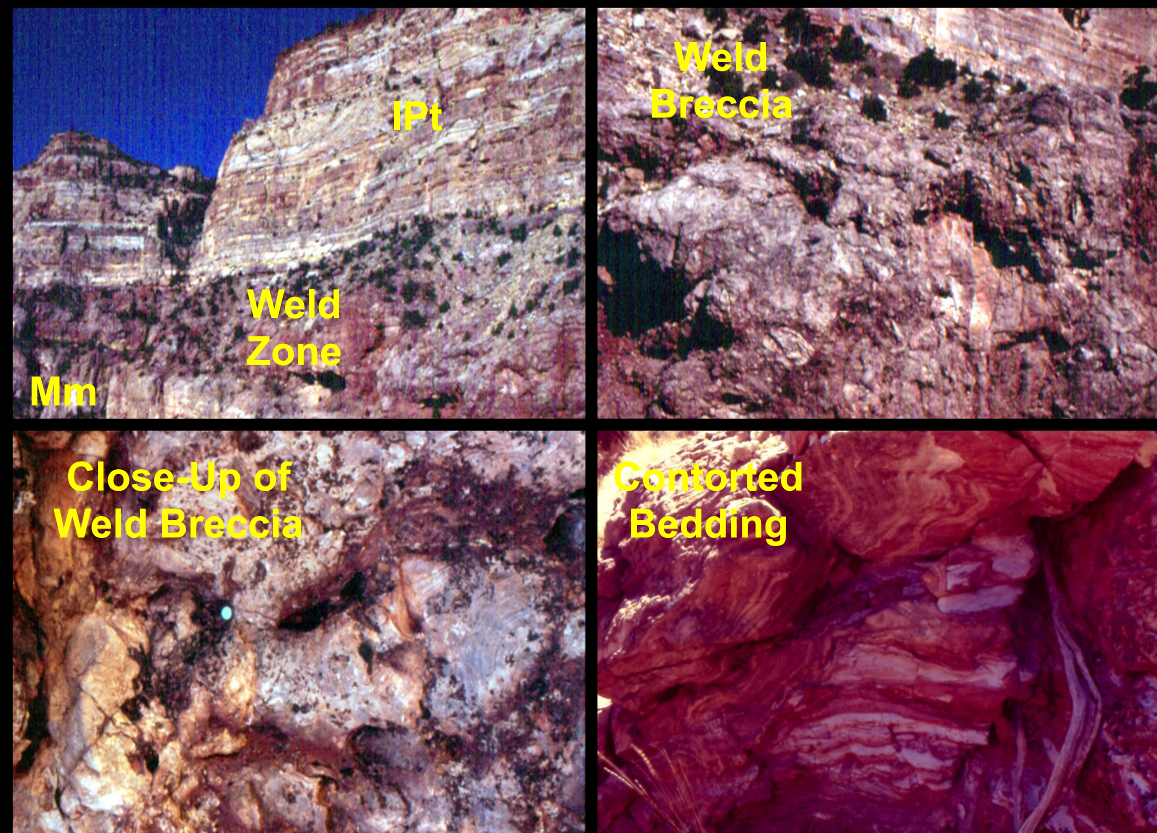
Carbonate Dissolution Weld

Alcova area, Wyoming

◊ Karsting in upper Madison Group carbonates resulted in collapse of overlying strata.

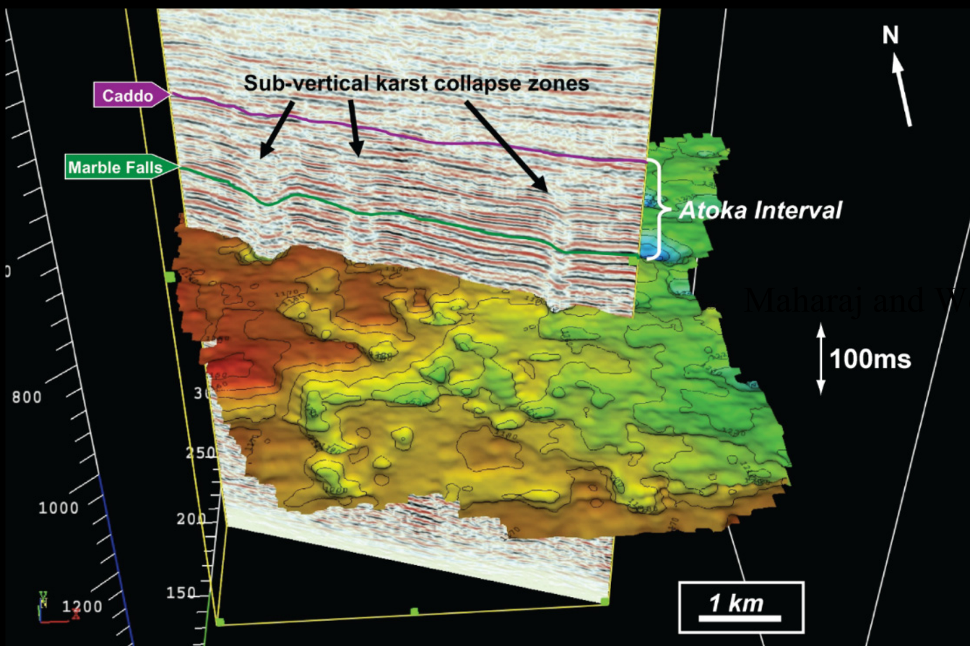
◊ Amsden Formation integrated into weld breccia.

◊ Tensleep Sandstone now in contact with Madison strata.

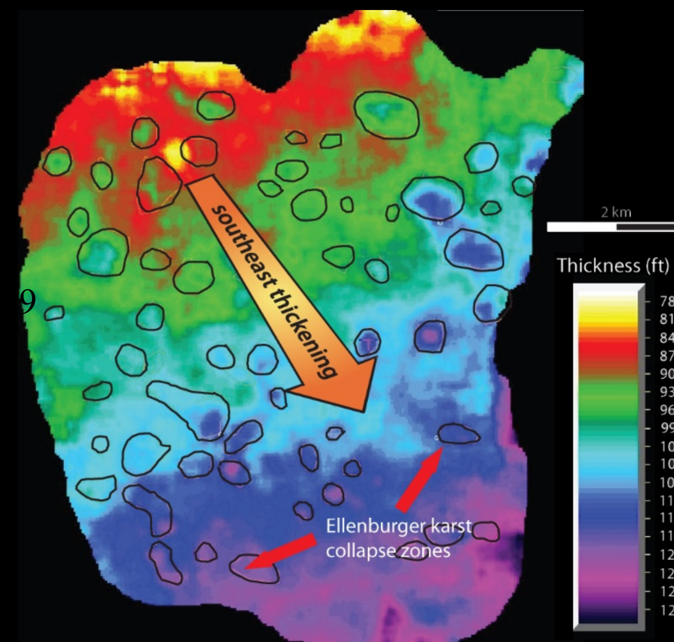


Carbonate Dissolution Weld

Ellenburger Group, Fort Worth Basin, Texas



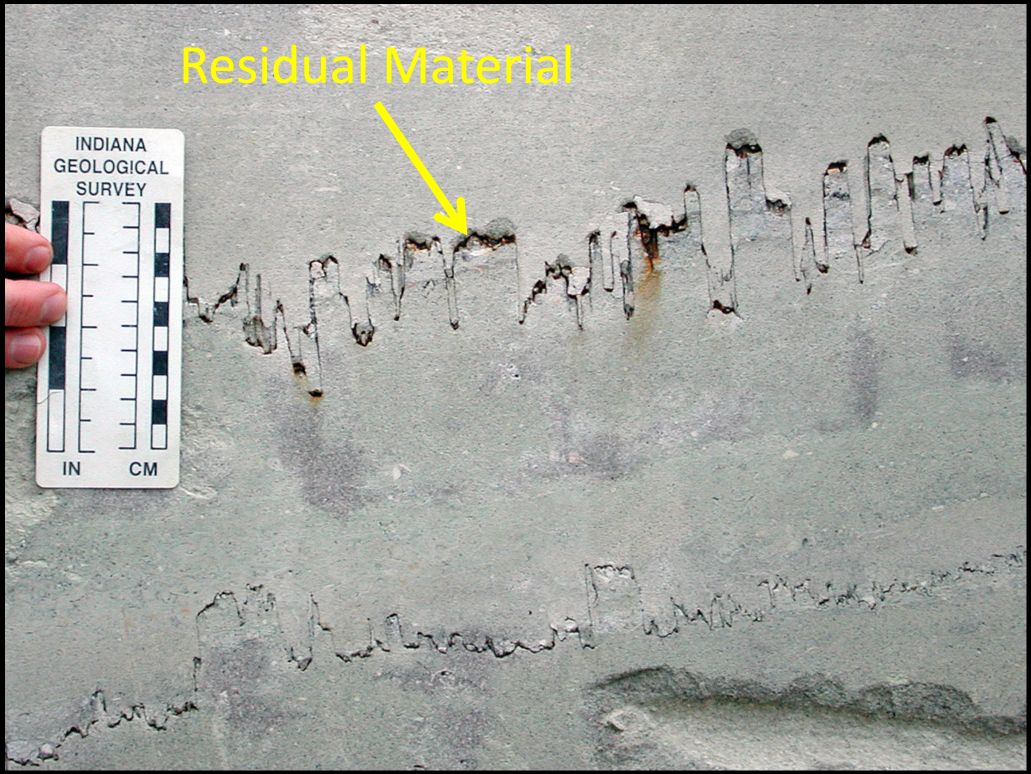
Ellenburger Karst Zone

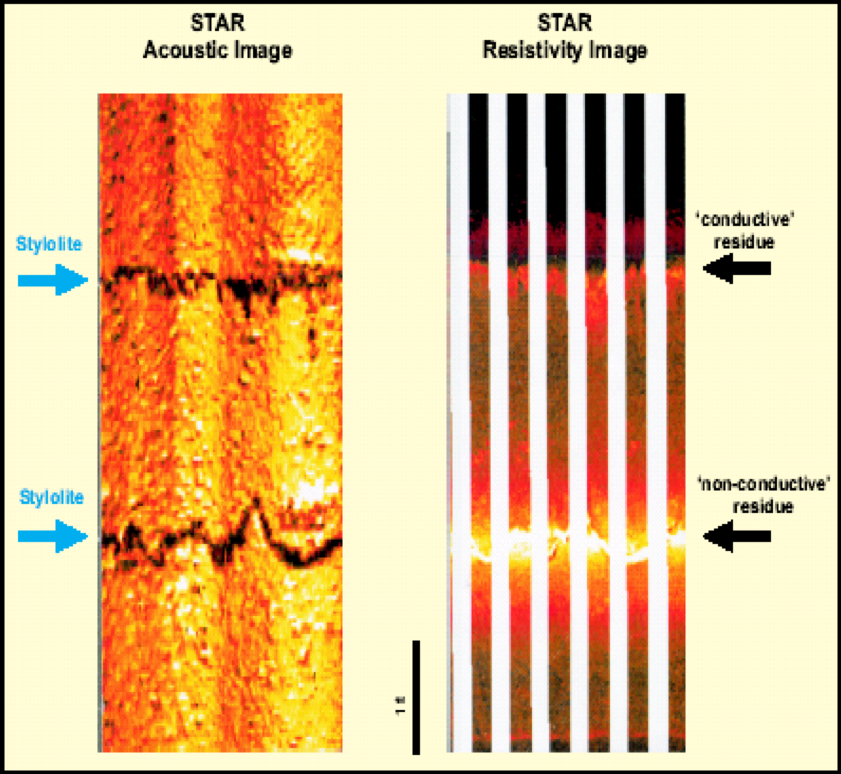


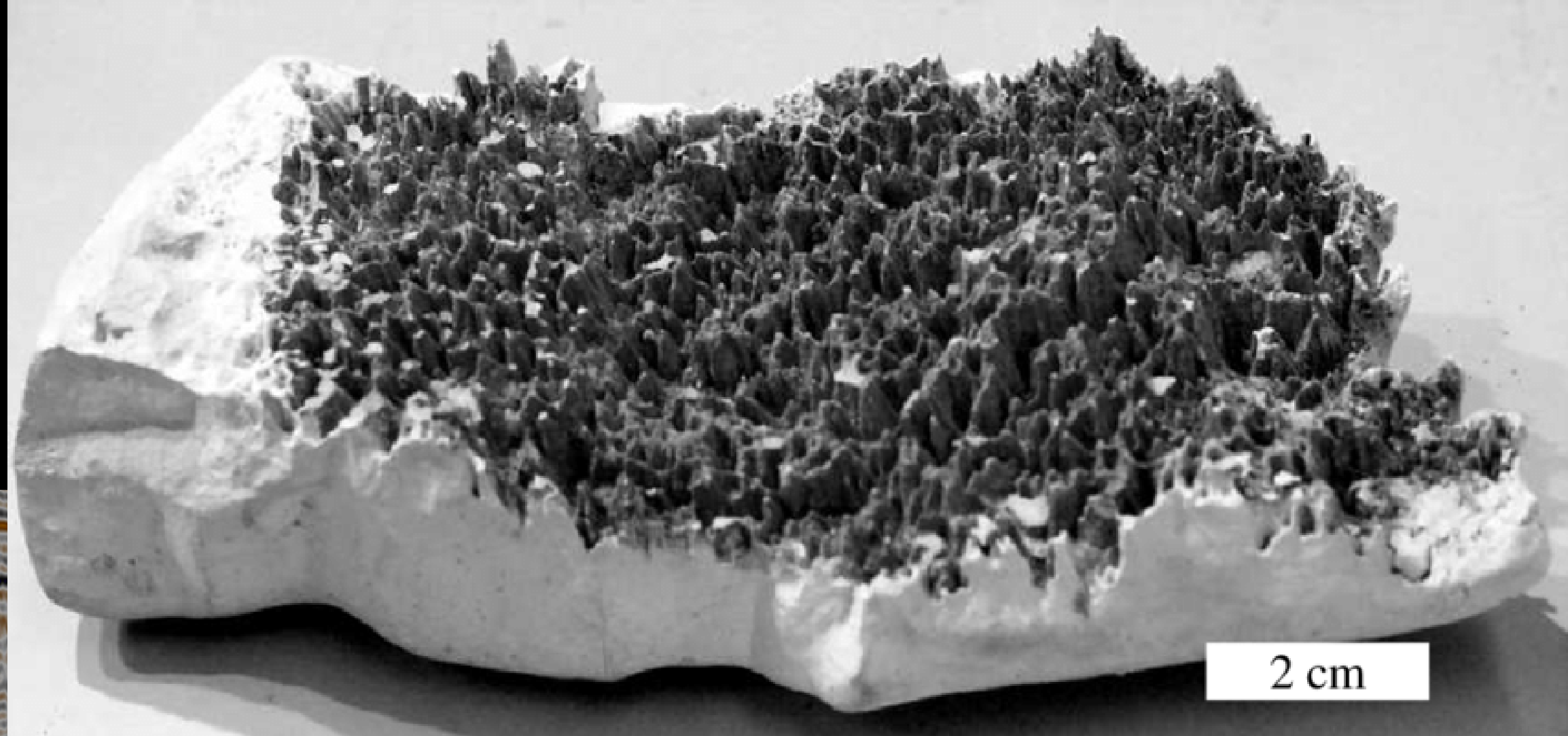
Atoka Collapse Basin Thicks

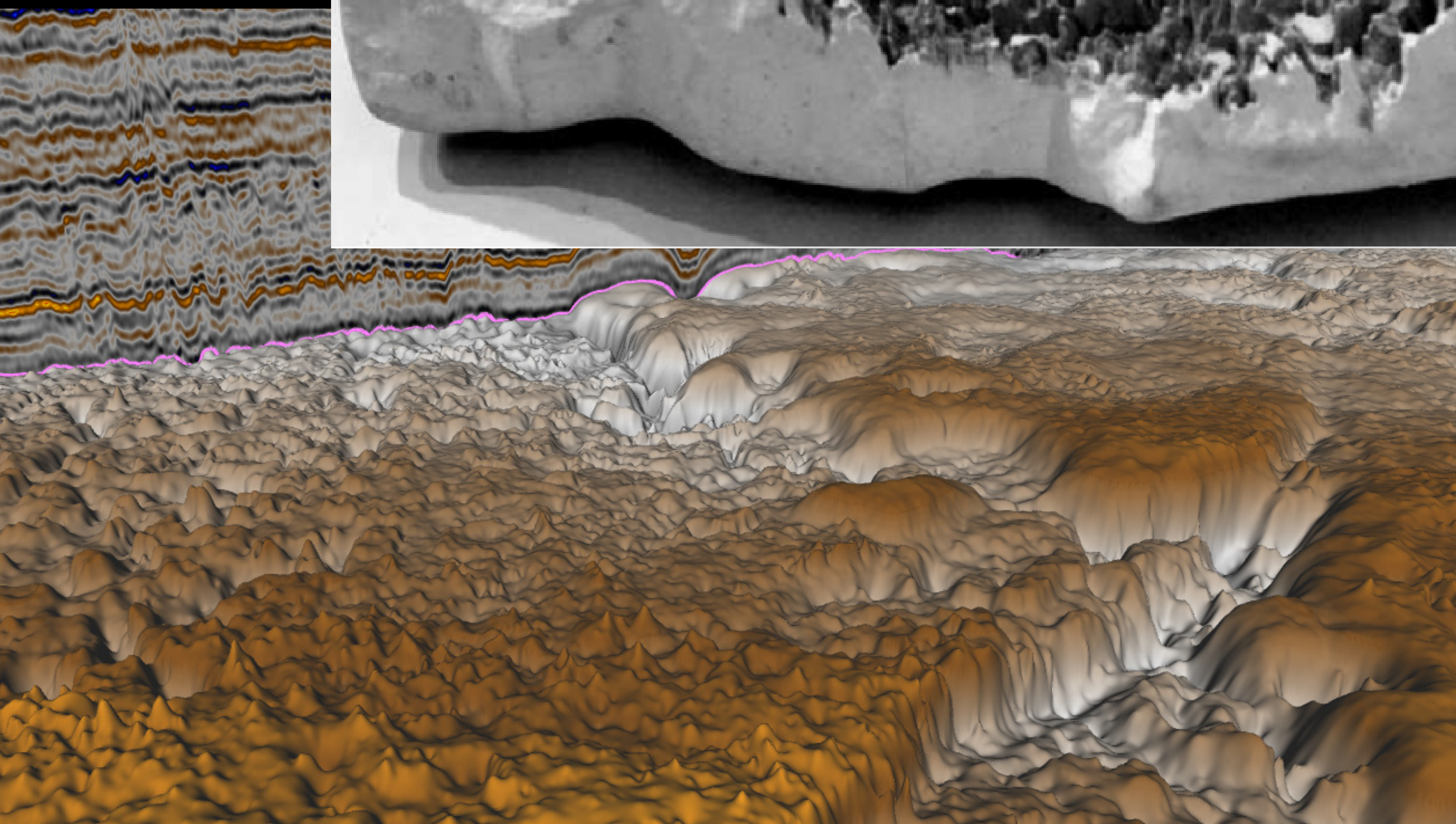
(Maharaj and Wood, 2009 GCAGS Trans.)

Pressure Dissolution Weld
Stylolites









(data courtesy of TGS)

Granular Deformation
Sandstones and Grainstone/Packstones

Understanding intergranular deformation

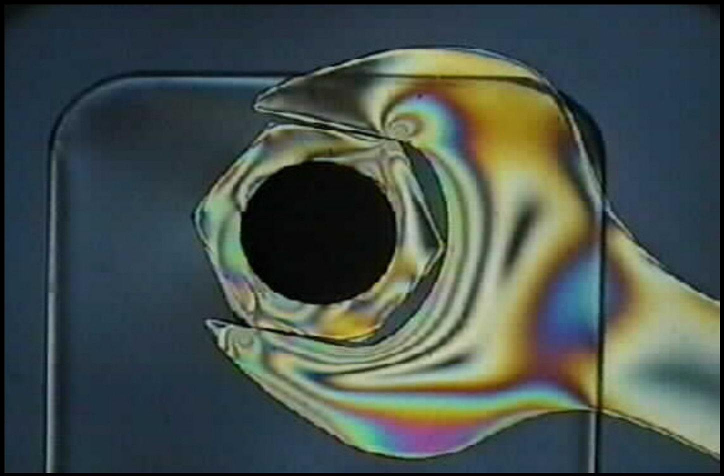
- Modification of original packing arrangement of both sandstones and carbonate grainstones and packstones,
- Subsequent reduction (or destruction!) in porosity and permeability, and
- Resultant diminishment of reservoir quality

Typical manifestations

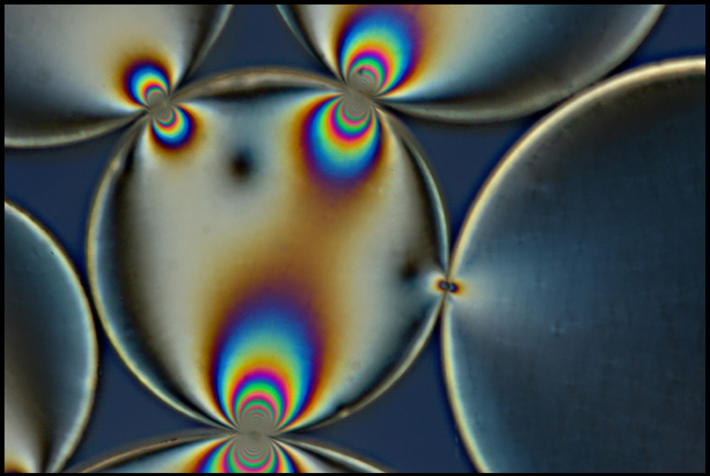
- Repacking and reorientation of grains,
- Intragranular brittle deformation,
- Ductile grain deformation, and
- **Intergranular suturing.**

Granular Deformation

Photoelastic Modeling of Sandstones



(courtesy of E. Gutierrez-Miravete)



(courtesy of K. Ramesh)

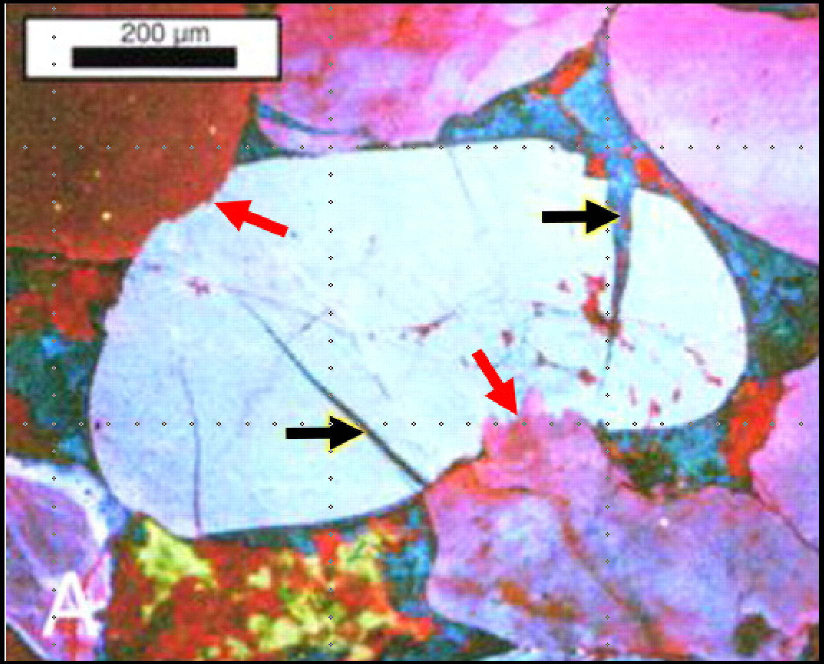
- Photoelasticity provides a means to analyze stresses, including grain-to-grain contact deformation of sandstones

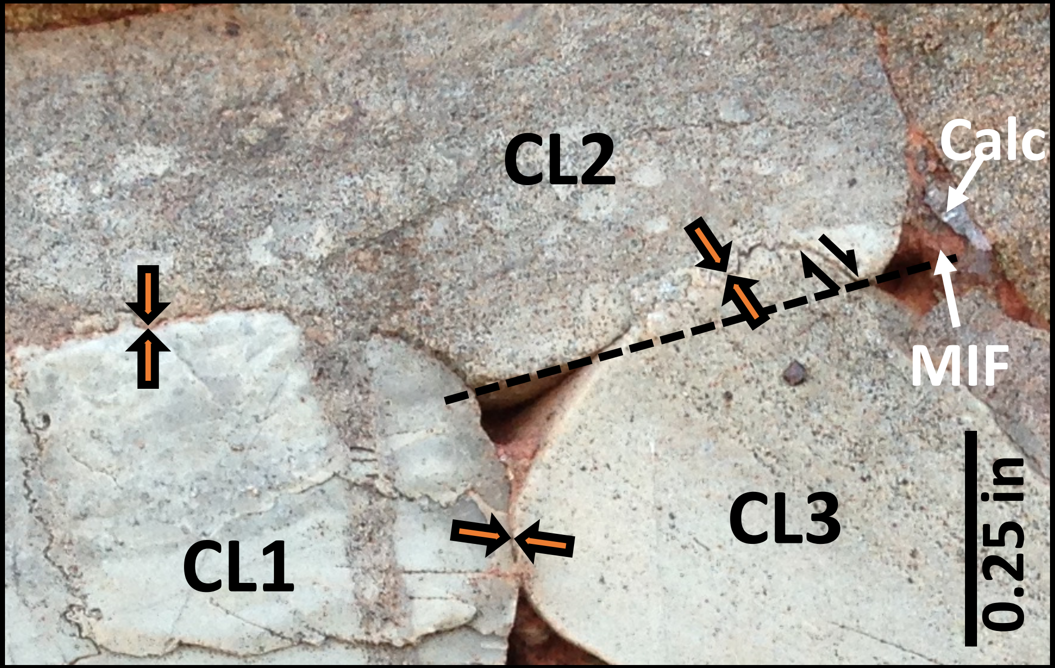
Granular Deformation
Photoelastic Modeling of Sandstones

- Dominant Controls on Granular Deformation
  - Effective Stress (Grain-to-Grain Contact Stress)
  - Mineralogy / Lithology

Pressure Dissolution Weld

Grain-to-Grain Contact Deformation

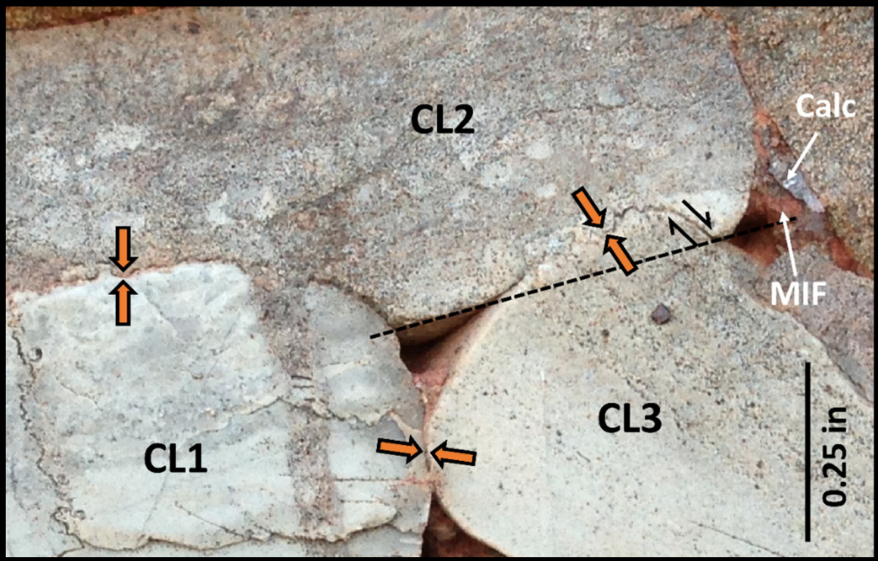


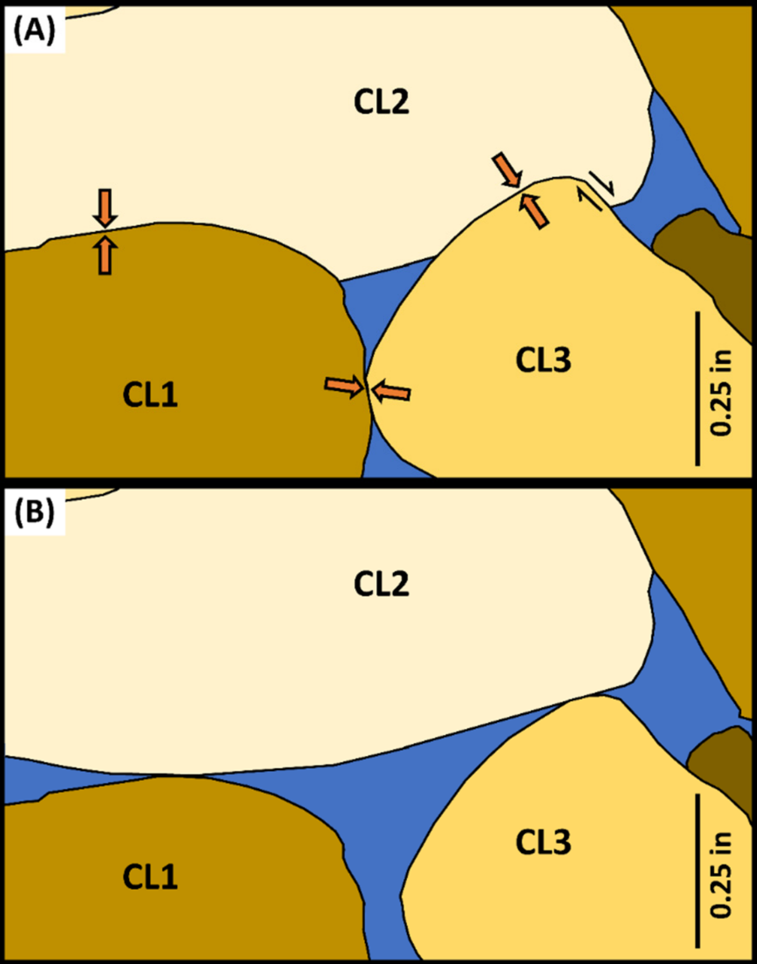


(Willis and Bixler, 2017, *GCAGS Trans*., with A modified after Makowitz and Milliken, 2003)

Collings Ranch Granular Deformation

Interclastic Suturing

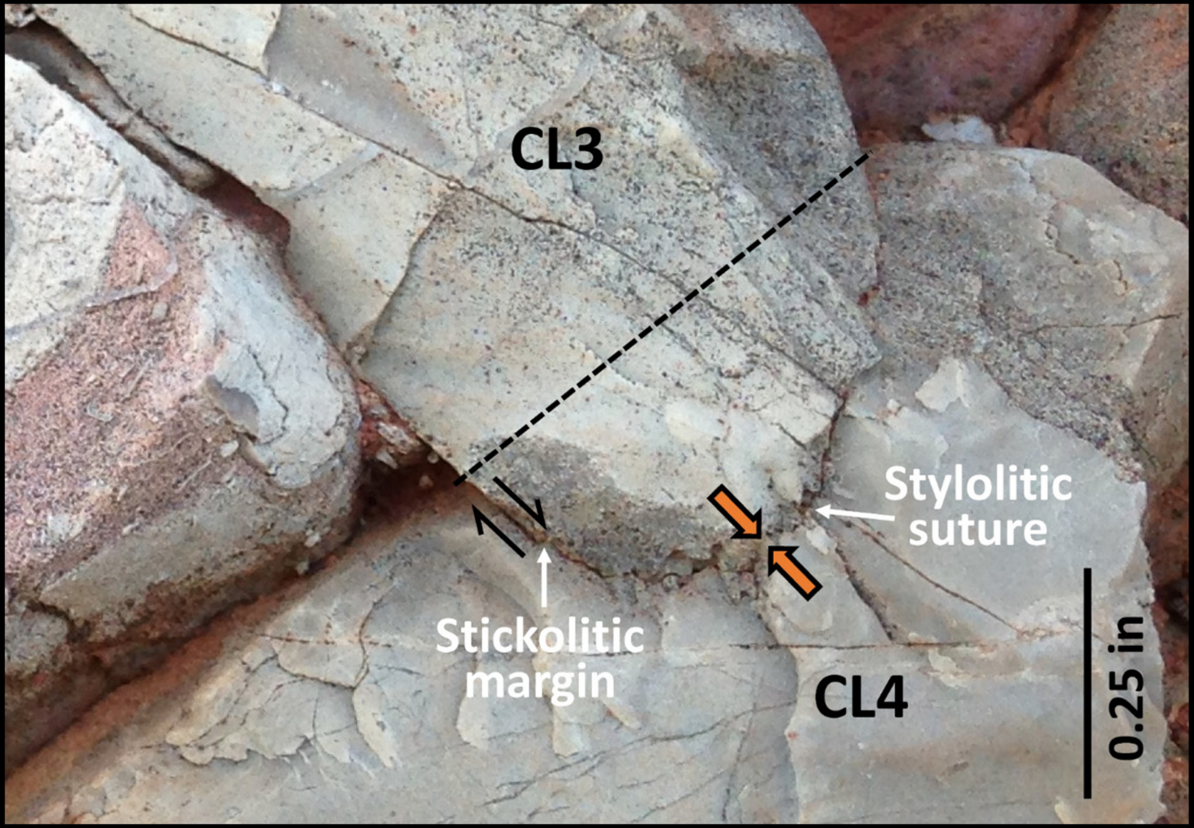




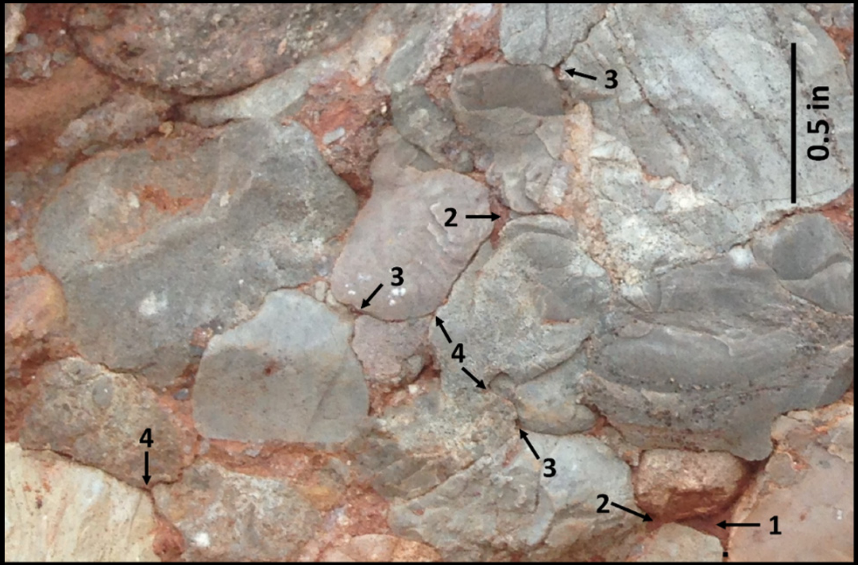
Triple Grain Interaction Showing Pressure Dissolution Suture Boundaries (above) and Restoration (right)

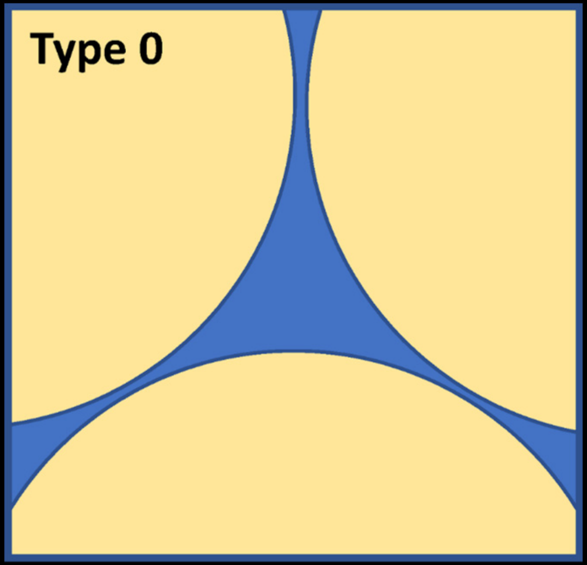
Collings Ranch Granular Deformation

Interclastic Suturing



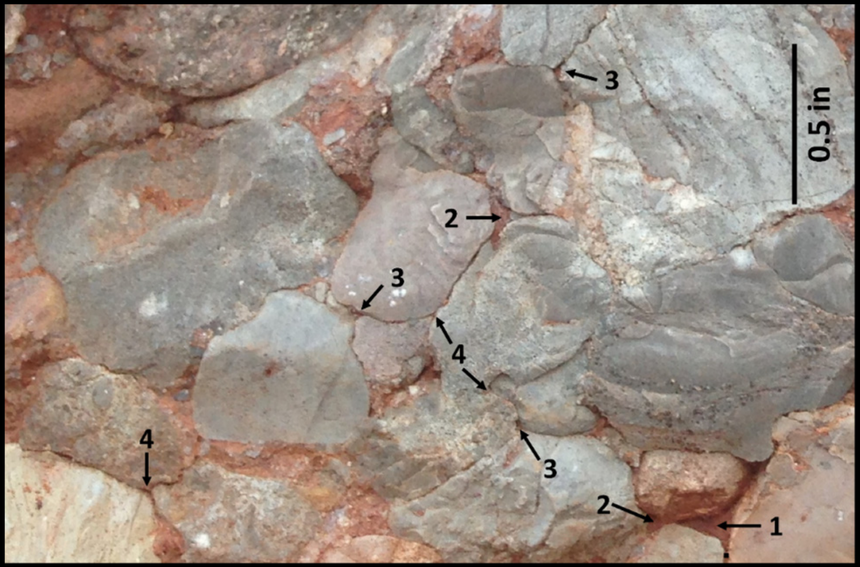
Granular Deformation
Type 0 Suturing (Unsutured)

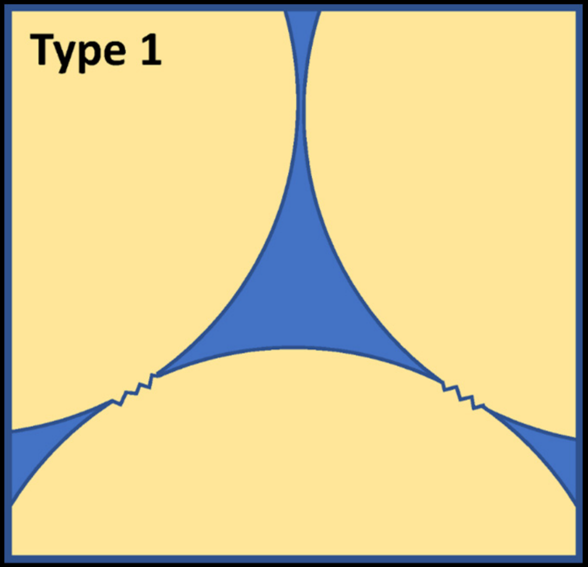




- Type 0 represents no suturing.
- Primarily floating grains and tangential contacts.
- Intergranular volume (IGV) remains high with high connectivity.

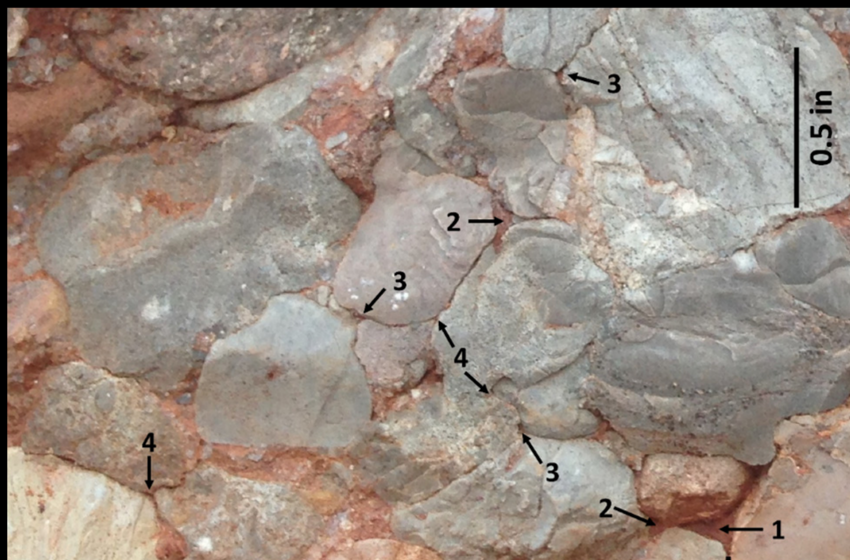
Granular Deformation
Type 1 Suturing

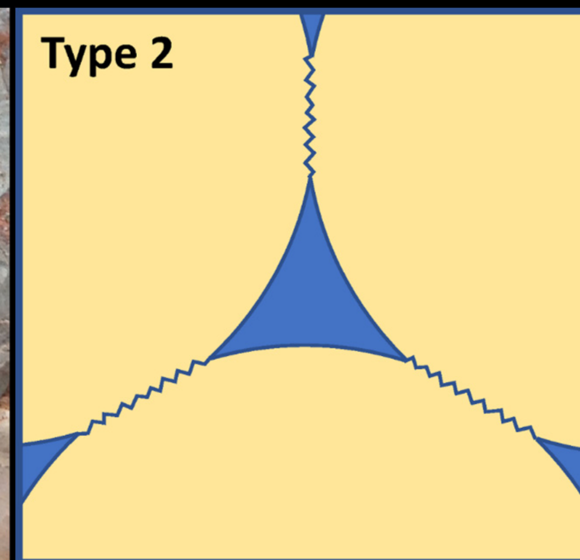




- Type 1 represents minor suturing at tangential contacts.
- Intergranular volume (IGV) still remains high with high connectivity.

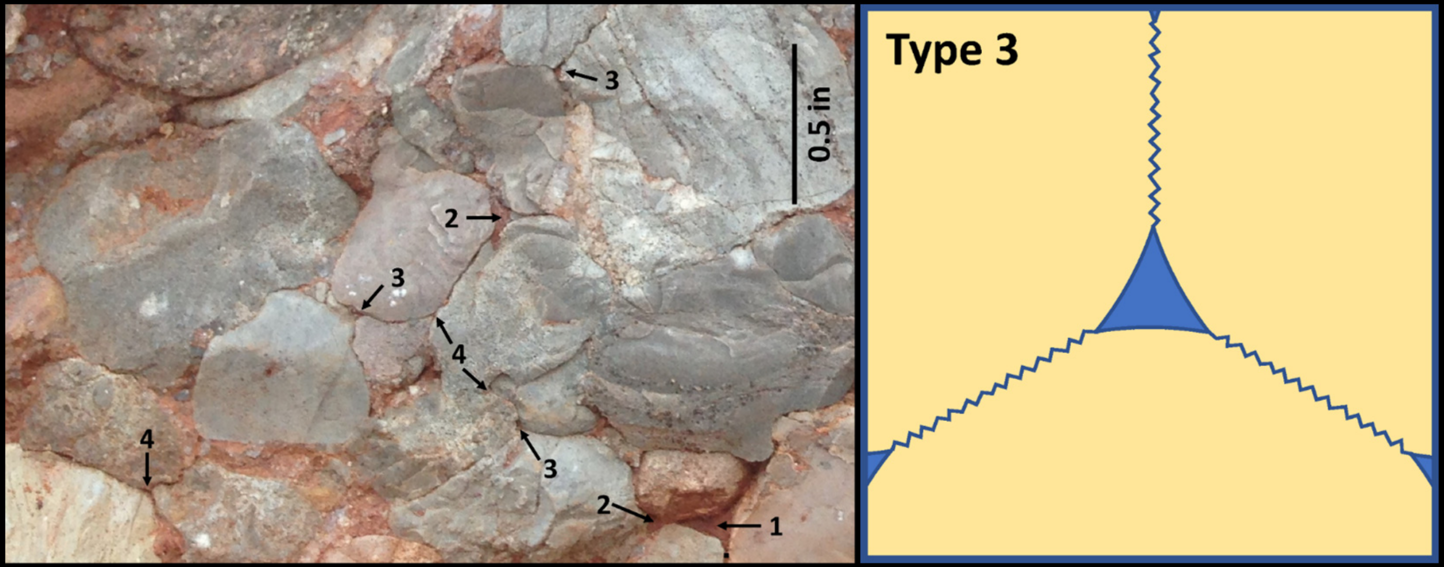
Granular Deformation
Type 2 Suturing





- Type 2 represents moderate suturing at grain contacts.
- Intergranular volume (IGV) and connectivity become reduced.

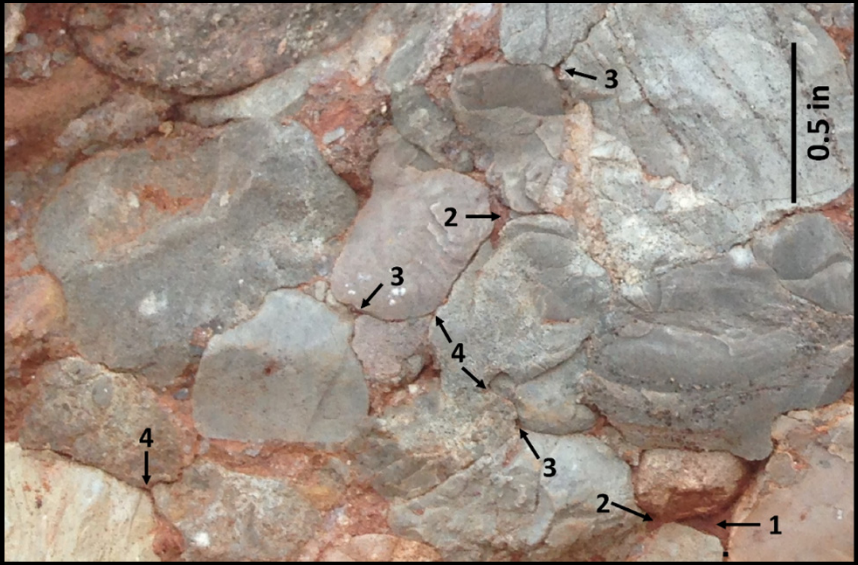
Granular Deformation
Type 3 Suturing

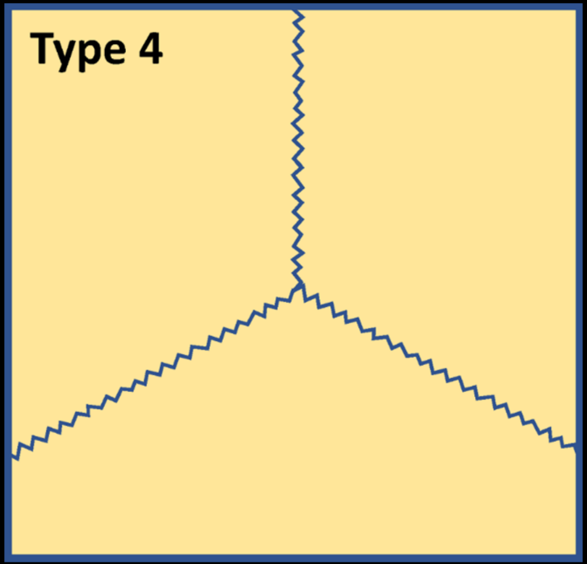


- Type 3 represents major suturing at grain contacts.
- Intergranular volume (IGV) and connectivity become substantially reduced → Isolated intergranular spaces.

Granular Deformation

Type 4 Suturing (Complete Suturing)





- Type 4 represents complete suturing at grain contacts to form triple-grain junctions.
- Near zero intergranular volume and connectivity.

Granular Deformation
Sandstone Examples

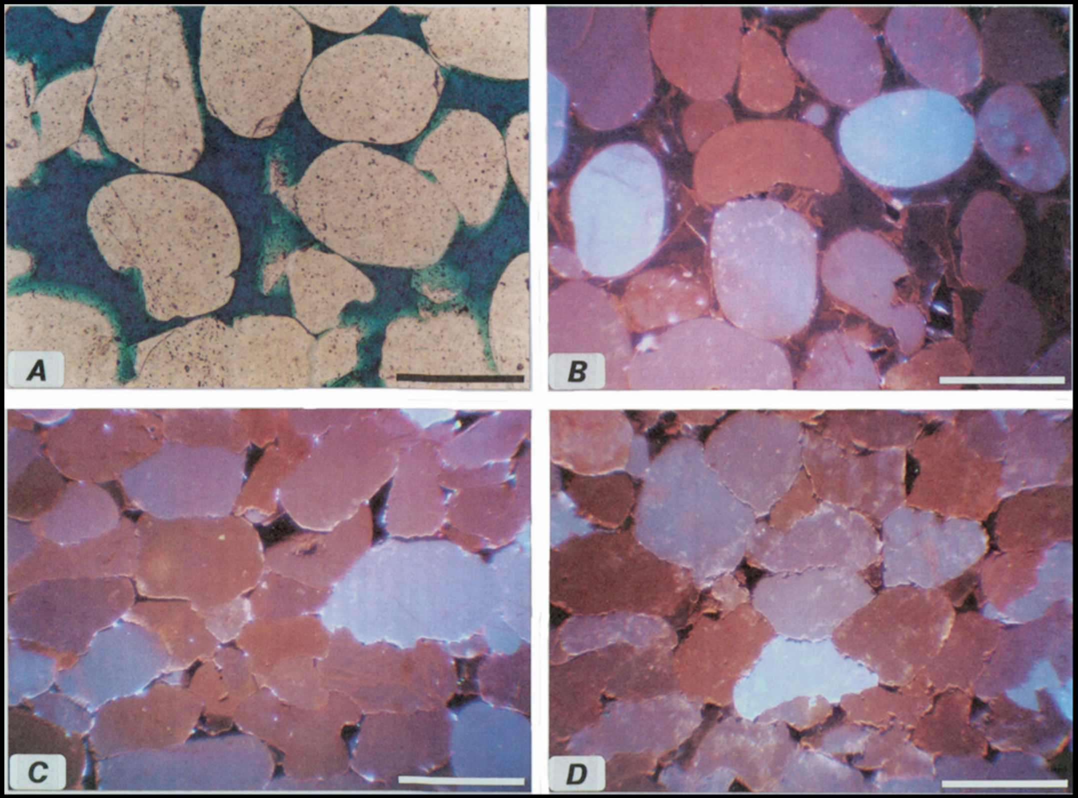
(A) Type 0 Suturing. 30% Inter-granular volume (IGV).

(B) Type 0 and 1. 29% IGV.

(C) Types 2 & 3 with some 4. 5% IGV.

(D) Types 3 & 4. 6% IGV.

(E) Type 4. Near 0% IGV.



(Houseknecht, 1987)

Granular Deformation
Sandstone Examples

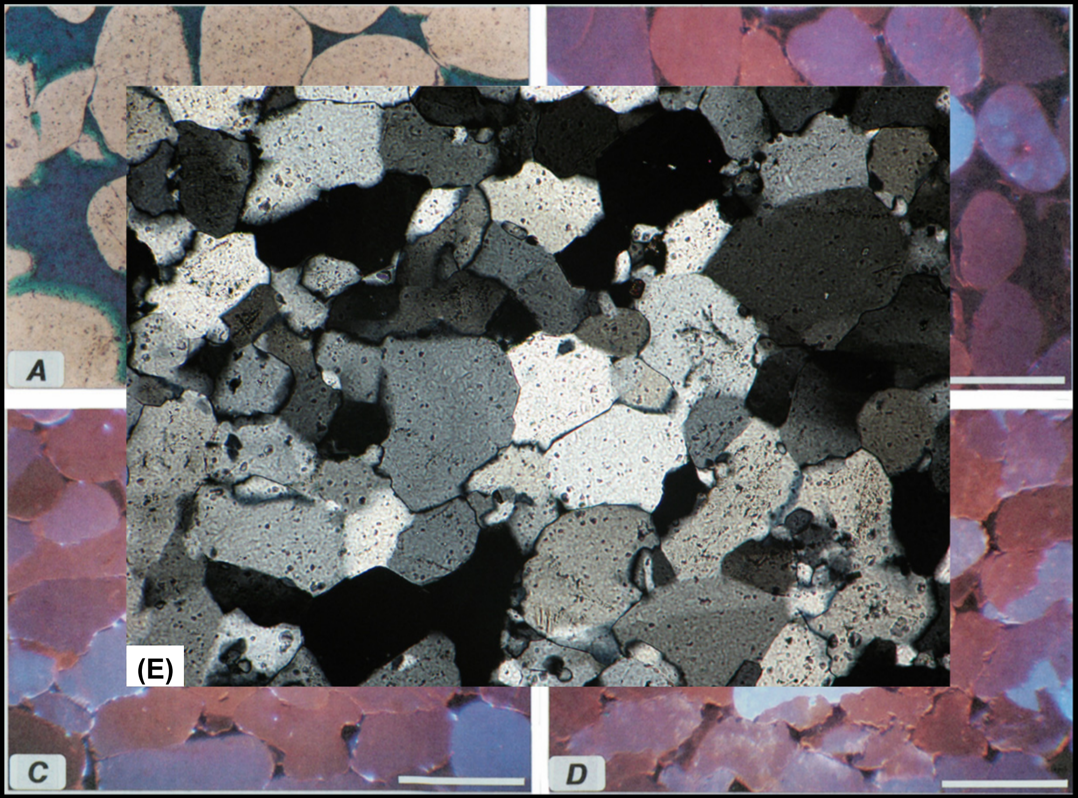
(A) Type 0 Suturing. 30% Inter-granular volume (IGV).

(B) Type 0 and 1. 29% IGV.

(C) Types 2 & 3 with some 4. 5% IGV.

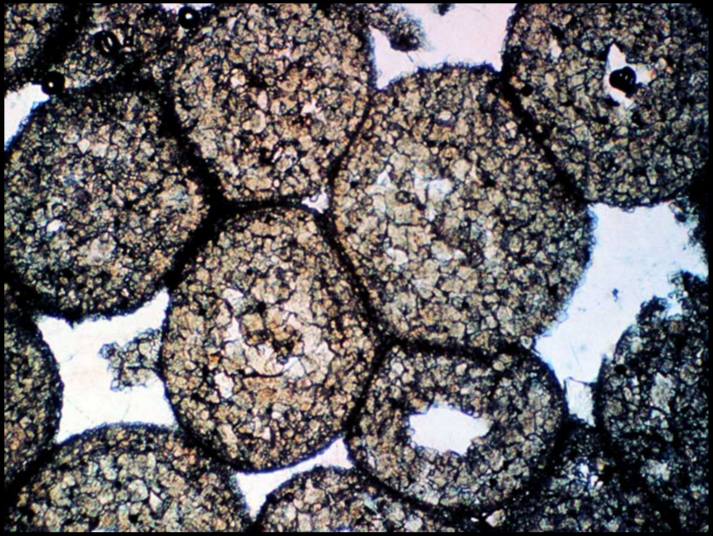
(D) Types 3 & 4. 6% IGV.

(E) Type 4. Near 0% IGV.

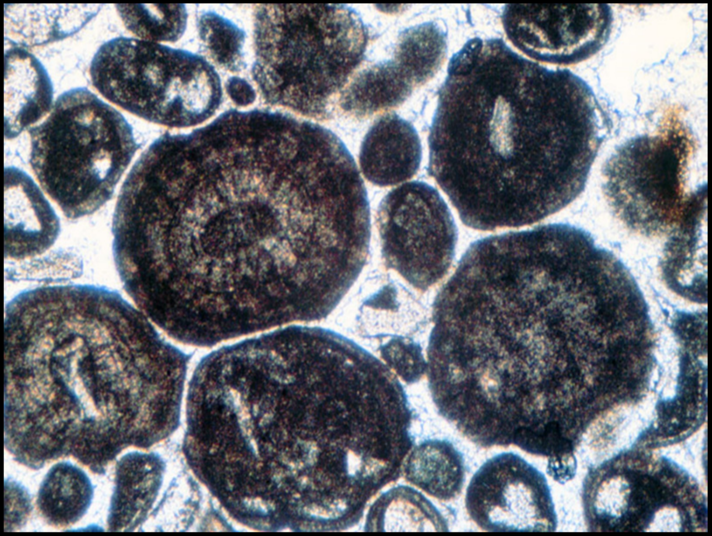


(Houseknecht, 1987)

Granular Deformation
Carbonate Grainstones/Packstones



**Smackover Formation,
Gulf of Mexico Basin**



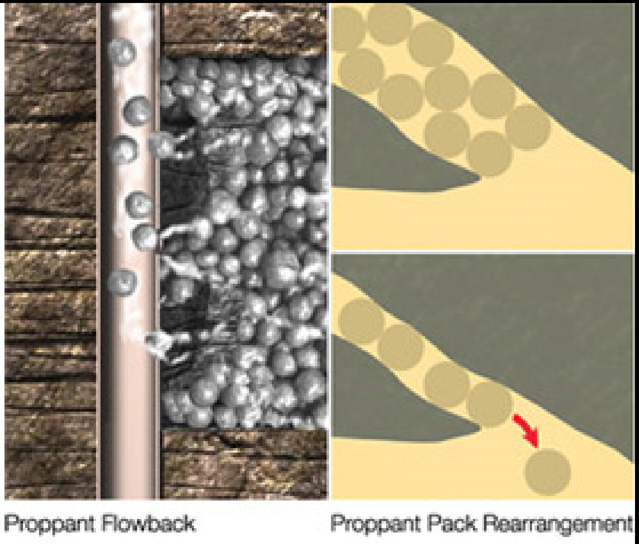
**Oolithe Blanche Formation,
Paris Basin**

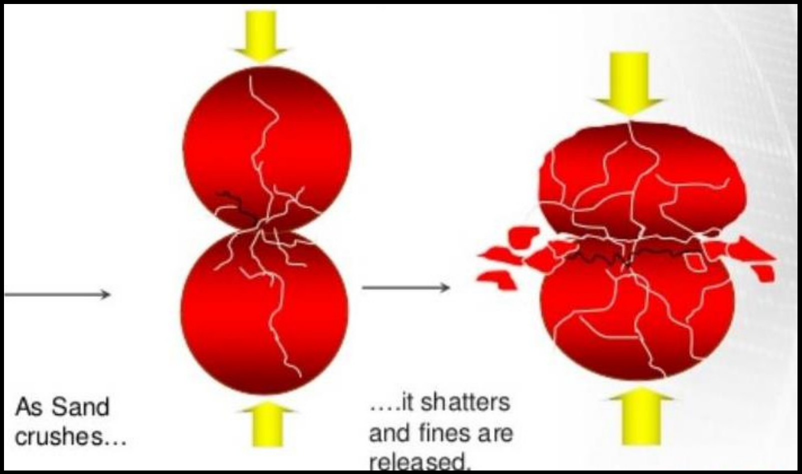
(courtesy of C. G. St. C. Kendall, 2016)

Granular Deformation

Proppant Deformation

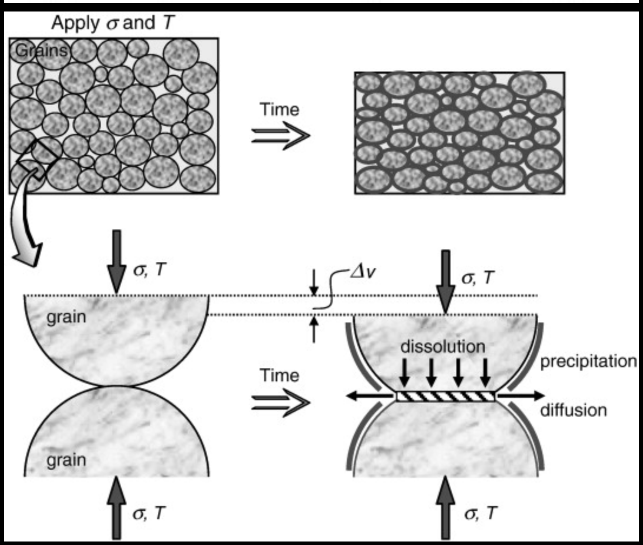
Grain Rearrangement
& Flowback →





↑ Grain Crushing

Pressure Dissolution
Suturing →



Summary