**Weld Types and Classification**

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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-
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

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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**

**FLOW WELDING**
- Evaporites
- Shale
- Sand
- Tar
- Igneous Melt
- Metamorphic

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

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

(modified after Willis, 2006, *GCAGS Trans.*)
Salt Weld Types

• **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


(Hoetz et al., 2011, *Petr. Geosci.*)
Salt Flow Weld
Santos Basin, Offshore Brazil

Remnant Salt

(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

Reduced flow at salt-sediment interface may leave residual salt along weld.
Dissolution may be required to complete the weld.
Not-salt lithologies complicate flow and remain behind as “residuum.”

(Wagner, 2010, UT Dissertation)
Salt Weld Types

**Secondary Weld** – Removal of Allochthonous Salt Stock or Wall


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)


(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


(Spencer and Sharpe, 1996, *GCAGS Trans.*)
Sweet Lake Field, Southwestern LA
Tertiary Weld of Eocene Jackson Salt Mass

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

(Spencer and Sharpe, 1996, GCAGS Trans.)
Deepwater GOM—K2/Timon/Marco Polo

Multiple Weld Types

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

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

(Willis, 1993, Ph.D. Diss.)
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)
Salt Dissolution Weld
Las Animas Arch, Colorado

Cedar Hills Dissolution Zones
Remnant Cedar Hills

(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.)
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*

(Maharaj and Wood, 2009 GCAGS Trans.)

Ellenburger Karst Zone

Atoka Collapse Basin Thicks

(Maharaj and Wood, 2009 GCAGS Trans.)
Pressure Dissolution Weld

Stylolites

Residual Material
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

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

(courtesy of E. Gutierrez-Miravete)

(courtesy of K. Ramesh)
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*

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% Intergranular 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% Intergranular 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 →

Apply $\sigma$ and $T$

Grains

Time

Dissolution
Precipitation
Diffusion

As Sand crushes...
...it shatters and fines are released.
Summary

Remnant Ign. along Weld

Weld

Ign.