The Influence of Small Displacement Faults on Seal Integrity and Lateral Movement of Fluids

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THE INFLUENCE OF SMALL DISPLACEMENT FAULTS ON SEAL INTEGRITY
AND LATERAL MOVEMENT OF FLUIDS

by

Eric A. Rasmusson

A thesis submitted in partial fulfillment of the requirements for the
of
MASTER OF SCIENCE
in
Geology

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Logan, Utah

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ABSTRACT

The Influence of Small Displacement Faults on Seal Integrity and Lateral Movement of Fluids

by

Eric Rasmusson, Master of Science
Utah State University, 2016

Major Professor: James P. Evans
Department: Geology

In the subsurface, faults can act as conduits for seal bypass or as lateral barriers to subsurface fluid flow. Recent reservoir modeling shows that the area where a reservoir-seal interface is in contact with a fault—the fault-interface corner—can be a site of high pore-fluid pressure that may cause seal failure. This can have negative implications for industries dependent on the quality of that seal, for example, petroleum, CO₂ sequestration, waste fluid injection, and nuclear waste storage industries.

In order to better understand the fault-interface corner and improve models, we examined five mesoscale (cm- to m- scale) normal-slip faults that juxtapose medium cross-bedded sandstone (1-2 m thick beds) against red or green siltstone or mudstone (~1 m thick beds) in the San Rafael Swell, Utah. Outcrop observations, X-ray diffraction mineralogy, whole-rock geochemistry, petrography, fractured grain density, and porosity data were used to gain insight into past fluid compositions, cross-cutting relationships,
and fault seal qualities in order to better define the fault-interface corner models and identify new fault elements previously not considered in the models.

Fault elements documented here include shale injection into faults, fault-bounded shale blocks, entrained sand blocks, and reactivated joints. Faults with shale injection have almost double the seal thickness and mineralization along the bottom slip surface of the injected shale bed. Step-over faults on either side of fault-bounded shale blocks replace overly simplified single plane faults in previous models. Geochemical alteration and mineralization includes calcite precipitation and clay development in several faults. These faults have varying spatial relationships with the zone of deformation bands. A fault with reactivated joints represents an endmember example of the fault-interface corner models with a large opening mode fracture allowing seal bypass.
PUBLIC ABSTRACT

The Influence of Small Displacement Faults on Seal Integrity and Lateral Movement of Fluids

Eric Rasmusson

As groundwater, liquid and gas hydrocarbons, or CO₂ fluids move through the subsurface, faults can act as pathways or barriers to flow. Recent studies also show that when a fault juxtaposes high permeability sandstone against a low permeability shale, the corner at the sandstone-shale interface and the fault can become a site of high pressure that may fracture the seal and allow fluids to escape. This can have negative implications for industries dependent on the quality of that seal, for example, petroleum, CO₂ sequestration, waste fluid injection, and nuclear waste storage industries.

We examined five small-scale faults in the San Rafael Swell, Utah, in sandstone, siltstone, and mudstone sequences where permeable sandstones (1-2 m beds) are juxtaposed with low permeable siltstones or mudstones (~1 m thick beds). These faults give us insight into the role small-displacement faults have in reservoir-seal systems when looking at faults with similar displacements, lithologies, and tectonic settings. Outcrop observations, X-ray diffraction mineralogy, whole rock geochemistry, petrography, fractured grain density, and porosity data were used to gain insight into past fluid compositions, cross-cutting relationships, and fault seal qualities.

We described how clay, smeared into a fault, can slow or stop flowing fluids. We also found evidence that calcite in the fault had been dissolved, suggesting that these faults can be a pathway for fluids through a seal. We also found that faulted reservoir
seals may be able to heal themselves and prevent fluids from escaping. We created a fault-outcrop map for each fault and simplified them to create four new models in an effort to make current modeling more robust.
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1. Introduction

1.1 Overview

In an ideal traditional petroleum system, buoyant hydrocarbons migrate upward into a permeable reservoir, capped by an impermeable seal (Magoon and Dow, 1994; Magoon and Schmoker, 2000). Without a structural or stratigraphic trap present, the upward migration may continue allowing hydrocarbons to flow laterally up dip and escape the reservoir (Magoon and Dow, 1994).

Faults can be lateral barriers to this flow, trapping the fluids in the corner between the seal and a low-permeability fault zone (Allan, 1989; Weber et al., 1978; Watts, 1987; Caine et al., 1996; Yielding et al., 1997; Fossen et al., 2007; Dockrill and Shipton, 2010; Bense et al., 2013). Deformation band faults are one class of fault that develop in porous sandstone. The high porosity of sandstone allows grains to be rotated and translated, accommodating shear by either 1) disaggregation of grain bonding cements and grain boundary sliding, with or without the help of phyllosilicates, 2) cataclasis of quartz grains, or 3) dissolution and cementation along grain boundaries (Aydin and Johnson, 1978; Antonellini and Aydin, 1994). These faults may result in a 10-1000x reduction of permeability (Antonellini and Aydin, 1994; Shipton et al., 2002; Fossen et al., 2007; Dockrill and Shipton, 2010). In some cases, faults can also be conduits where open fractures enable seal bypass (Allan, 1989; Antonellini and Aydin, 1994; Caine et al., 1996; Beitler et al., 2005; Parry et al., 2004; Dockrill and Shipton, 2010; Bense et al., 2013).

Such bypass adds uncertainty to the quality of the reservoir-seal systems in a hydrocarbon-bearing environment. A leaky seal or a compartmentalized reservoir can limit
the amount of oil extracted. This risk is not limited to the petroleum industry. Seal bypass may also be important in understanding water flow in groundwater aquifers (Levens et al., 1994; Mayer et al., 2007; Bense et al., 2008; Folch and Mas-Pla, 2008), designing geological carbon sequestration facilities (Shipton et al., 2004; Dockrill and Shipton, 2010; Tueckmantel et al., 2012; Pasala et al., 2013), or for nuclear waste storage (Bredehoeft, 1997; Douglas et al., 2000; Mal’kovskii and Pek, 2001; Ofòegbou et al., 2001).

Recent reservoir modeling shows that the area where a reservoir-seal interface is in contact with a fault can be a site of high pore-fluid pressure that may cause seal failure (Fig 1) (Pasala et al., 2013). This may prove to be enough pressure for the corner to become a site of significant leak-off potential (Pasala et al., 2013; Raduha, 2013; Butler, 2014). Barring an open fracture at the interface, the corner site is especially of concern for industries that depend on maximizing the volume of the reservoir, for example the waste fluid and carbon

![Fig 1. Simplified model of the interface-fault corner. Faults juxtaposing reservoir rock with low permeability caprock are potential fluid pathways leading to seal bypass.](image)
sequestration industries. Faults acting as barriers or conduits to fluids could limit the volume of injectates and make the potential site less than ideal.

1.2 Significance and Motivation

Reservoir and seal modeling has great significance to the carbon sequestration, waste-water injection, nuclear waste, and petroleum industries. Evaluating the seal integrity is vital for these industries in order to determine the storage potential and perform risk analyses of subsurface reservoirs (Benson and Cook, 2005; Pasala et al., 2013; Raduha, 2013; Flores, 2014; Petrie et al., 2014). For example, potential carbon sequestration reservoirs caprocks must be rated to store carbon dioxide for thousands of years (Allis et al., 2003; Benson and Cook, 2005; Lagneau et al., 2005). Structures associated with deformation bands and faults can act as conduits and allow fluid to bypass the seal affecting storage capacity (Shipton et al., 2004; Parry et al., 2004; Pasala et al., 2013; Petrie et al., 2014).

Faults and deformation bands in a sandstone reservoir can also act as a barrier or baffle to fluids, helping to compartmentalize a reservoir and trap fluids (Antonellini and Aydin, 1994; Leveille et al., 1997; Fisher and Knipe, 2001; Dockrill and Shipton, 2010). This can be especially problematic as fluids are injected into potential reservoirs for storage (Pasala et al., 2013; Butler, 2014). Numerical fluid flow modeling shows that the interface-fault corner is a potential location for seal failure (Pasala et al., 2013; Butler, 2014). Slight differences in the rock properties in the models at the corner predict significant changes in the pressure and volume of fluids that might fill the area, pressurizing and increasing the leak-off potential through the fault (Butler, 2014).
We hypothesize that there are five potential fault-interface geometries with which fluids can interact, each with different potential for seal bypass (Fig 2). The least geometry likely to leak would be if the majority of the less permeable deformation band were in the upthrown side of the fault (Fig 2 C). Having a deformation band, a low-permeable barrier, between the reservoir and the potential open mode fracture in the seal, would help keep fluid from escaping. We hypothesize that this compartmentalized geometry would result in little evidence of fluid flow across the fault.

The leakiest geometry would be if more than half of the deformation band were in the downthrown side of the fault and minimal clay smearing occurred. This geometry exposes the reservoir to the potential open mode fracture in the seal, allowing fluids to escape (Fig 2 D). We expect in this case that there would be more evidence of fluid flow through the fault.

Other geometries include the development of foliated mud or clay smear, which may help to reduce the permeability of the corner but still give fluids a pathway through the seal (Fig 2 B and E) (Yielding et al. 1997).
Fig 2. Possible interface-fault geometries. A and D provide fluids with a very open pathway past the seal. B, C, and E provide less of a pathway past the seal or may even be a complete barrier to flow.
1.3 Objectives

The purpose of this study is to constrain the geometries of faulted reservoir and seal rock in natural examples of the fault-interface corner areas of small-displacement faults with similar throw and lithologies. We describe the geometries of the fault-interface corner areas in each of the studied faults. We attempt to explain how past fluids have affected the sites and how fluids might migrate through each of these sites if they were still in the subsurface. We conducted mesoscopic structural analyses of several sites, described alteration patterns in the rocks, documented small-scale structures, and performed geochemical analyses and petrographic analyses of deformed and altered rocks. Geochemical analyses included X-ray fluorescence (XRF), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma atomic emission spectroscopy (ICP-AES), and X-ray powder diffraction (XRD). Petrographic analyses included mineralogical descriptions, fractured grain densities, and porosity measurements.

1.4 Study Area Setting

The San Rafael Swell is an excellent location to study exposed deformed sedimentary rocks at a range of scales in a similar tectonic setting (Gilluly, 1929; Aydin and Johnson, 1978; Bump and Davis 2002). Sites within the region are a type section for analogs of reservoir and seal models in the subsurface (Shipton et al., 2002; Beitler et al., 2005; Hansen, 2007; Fossen et al., 2007; Petrie et al., 2013; Ogata et al., 2014). For this study, we identified four sites with five faults on the southeastern side of the San Rafael Swell to examine interface-fault corner areas. Three of the four sites (W1-W2, W3, and ISS) are within the Entrada Formation. The BC fault site is an interdunal lake deposit in the Navajo Sandstone.
Fig 3. Simplified geologic map of the San Rafael Swell. Permian and Triassic rocks are inside the anticline and Jurassic rocks along the outside. The steepest dipping beds of the double plunging anticline are along the southeast side. Modified from Petrie et al. (2013).
1.4.1 Stratigraphic Setting

The Jurassic Navajo Sandstone is one of the largest preserved eolian dune systems in the world (Verlander, 1995) (Fig 4), where the erg once covered approximately 350,000 km$^2$ (Hansen, 2007). The Navajo Sandstone consists of subrounded to subangular, medium-grained, thin- to thick cross-bedded quartz arenite (Peterson and Pipiringos, 1979; Verlander, 1995; Hansen, 2007; Petrie et al., 2013). The primary permeability and porosity in the Navajo Sandstone are high and variable with permeability averages from 4.6 to 5000 md (Hood and Patterson, 1984; Chan et al., 2000; Shipton et al., 2002). The J-2 unconformity is between the top of the Navajo Sandstone and the Carmel Formation. The unconformity marks advance of a marine environment over the eolian Navajo Sandstone and provides a clear stratigraphic marker in the area (Pipiringos and O’Sullivan, 1975; Blakey et al., 1988; Hintze, 1993; Allis et al., 2001).

The depositional environment of the Entrada Formation included tidal flats, fluvial environments, and eolian dunes (Kocurek, 1981; Blakey and Gubitosa, 1983). The Entrada Formation has two members, the Slick Rock Member and the Earthy Member which interfinger in the study area. The Slick Rock Member overlays the Carmel Formation and is comprised of massive, cross-bedded sandstone. The Earthy Member of the Entrada is a silty, very fine-grained, thin-bedded sandstone (Doelling et al., 2015).
Fig 4. Stratigraphic column of the San Rafael Swell. This study focuses on the Jurassic rocks of the San Rafael Swell indicated by the red boxes. Modified from Blakey (2014).
1.4.2 Structural Setting

The San Rafael Swell is an asymmetric, NNE-trending, doubly plunging anticline (Gilluly, 1929; Bump and Davis, 2002) (Fig 3). The San Rafael Swell has a steep east limb and a shallow west limb. Faults and fracture zones are dominated by two strike orientations, ESE-WNW and ENE-WSW (Bump and Davis, 2002). Uplift and folding of the San Rafael Swell happened from ~93 Ma to 58 Ma (Fouch et al., 1983; Lawton, 1986; Guiseppe and Heller, 1998; Shipton and Cowie, 2001). Fault and fracture system events and related fluid flow occurred in the late Cretaceous to early Tertiary (Harkins and Becker, 2013). Faults in this study are normal-slip faults with 1 to 5 meters of slip and varying damage zone widths. Deformation bands are the most common form of strain accommodation in the Navajo Sandstone (Aydin and Johnson, 1978; Mollema and Antonellini, 1996; Davis, 1999; Shipton et al., 2002).

The primary permeability of the deformation bands tends to be up to one thousand times less than the host rock in the Navajo Sandstone (Antonellini and Aydin, 1994; Shipton et al., 2002). Significant permeability anisotropy can exist in the fault zones, allowing fluid to preferentially flow through the fault plane, reducing lateral flow (Shipton et al., 2002; Shipton et al., 2004; Parry et al., 2004; Pasala et al., 2013; Petrie et al., 2014). Subsurface fluid flow has occurred during numerous events since deposition (Chan and Archer, 2000; Davatzes et al., 2003; Gratier et al., 2012; Petrie et al., 2013). A range of fluids with a range of chemistries, including freshwater, saline water, natural gas, hydrocarbons, and CO₂ has migrated through the area (Gilluly, 1929; Hawley et al., 1968; Davatzes et al., 2003; Gratier et al., 2012).
2. Methods

2.1 Sample Collection

To best analyze evidence for fluid-fault interactions, four sites with five faults were identified and examined (Fig 3). Site BC, located in Bell Canyon, was identified during field reconnaissance. Sites W1-W2 and W3 were found in Barton (2011). Jim Evans and Peter Mozley identified the ISS site. Many of the outcrops are nearly vertical rock faces up to 40 m high. Most rocks were accessed with a 4.5 m ladder making the highest sample at about 5 m. Any rocks above 5 m were not accessed. Table 1 summarizes the faults investigated in this study.

Samples of host and fault-related rocks were collected to target possible fluid-rock interaction related to each fault. Most samples were collected for each fault simply using a hammer. In order to sample the finer grain caprocks a sharpened tube was driven into the rock using a hammer (Fig 5). Samples of host rocks and fault-related rocks were collected so we could document changes to the host rock.

Table 1
A list of study sites and their locations.

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<th>Site</th>
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<td>Bell Canyon (BC)</td>
<td>515956.44 4272461.63</td>
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<tr>
<td>West 1, 2, and 3 (W1-W2 and W3)</td>
<td>517140.88 4270420.13</td>
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<tr>
<td>ISS (ISS)</td>
<td>546059.74 4288860.93</td>
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2.2 Sample Preparation

All samples for BC, W1, W2, and W3 faults were cut and prepared for thin sections. Forty-one samples were impregnated with blue dye stained epoxy and made into uncovered thin sections. Any sample that was at risk of falling apart in transit was epoxied in house before being mailed out to Wagner Petrographic.

Twenty grams of each sample for all faults were crushed in a tungsten carbide rock mill in preparation for XRD, XRF, ICP-MS, and ICP-AES analyses. The XRD analysis was done in house at the X-ray diffraction lab with Dr. Kelly Bradbury at USU. Select samples were sent to SGS Inc. in Canada for XRF, ICP-MS, and ICP-AES analyses.

2.3 Sample Analysis

X-ray diffraction analyses were completed in house using a Philips PANalytical X’Pert X-Ray Diffractometer (XRD) in order to determine the bulk mineralogy of the faulted
and unfaulted rocks. Each scan was run using Cu Kα radiation at 45kV and 40mA operating conditions from 0° to 75° 2Θ. The software PANalytical X’Pert Data HighScore, version 2.2.0 was used to analyze and interpret the readings from the XRD. A total of 38 samples were processed in order to constrain rock mineralogy.

Whole-rock X-ray fluorescence analyses (XRF) were performed by an SGS lab in Canada in order to identify the major and trace elements for each sample. The lab performed a borate fusion in preparation for the XRF whole rock analysis to analyze for 14 elements. SGS also performed a sodium peroxide fusion to prepare the samples for a combined ICP-AES and ICP-MS analysis for 55 elements. These analyses identify the major and trace elements for each sample. A total of 15 samples were processed from faults W1, W2, W3, and BC. The results from the XRF for major elements are reported in weight percent of the oxides (wt% oxides).

Mineral identification, observations on secondary mineralization and alteration products, porosity calculations, and fractured grain analyses were done for each thin section. A total of 41 thin sections were analyzed from faults W1, W2, W3, and BC. Each thin section was examined for the nature and distribution of fractured grains in order to relate fractured grain densities to fault proximity. Measurements were made along a scan line in the long axis of the middle of each slide. If there was more than one thin section per sample location, the fracture densities were averaged. Fractured grains were counted if they intersected the microscope’s crosshairs.

The thin section image analysis software JMicroVision v1.2.7 was used to extract pore space from the dyed slides using the Object Extraction tool. Pore space was identified
using an intensity, hue, saturation (IHS) color threshold, specifically any pixel that had an intensity over 100, a hue over 100, and any saturation (Fig 6). The porosity is the percent of pixels that held those qualifications, ±0.65%. Porosity was calculated in order to help identify possible rock-fluid interactions.

![Fig 6. Screenshot of JMicroVision calculating porosity from a plain light photomicrograph of sample W3-1. The red polygons are where the pixels representing porosity have been extracted.](image)

3. Results

We examined five faults in four sites as analogs for fault-fluid-caprock interactions. We focused on sites W1, W2, W3, BC, and ISS (Fig 3). For each fault we first discuss the mesoscopic structural geology and present maps of each fault-interface corner area. We then discuss any observations pertaining to the mineralogy and alteration in outcrop. Following that, we discuss the mineral interpretations of the XRD analysis and the whole rock
geochemistry of each sample. Lastly, we discuss the analyses from thin section including petrographic analysis, fractured grain analysis, and porosity analysis.

3.1 Outcrop Observations

Each fault represents an end member for small-displacement faults in siliciclastic rock sequences. Although the throw, lithology, and tectonic setting are controlled for, there is significant difference between each site. In some sites there is clear evidence for fluid alteration, and in others there is not.

3.1.1 Site W1-W2

Faults W1 and W2 are exposed on the south side of Wild Horse Road and form a small graben in the Entrada Formation 400 m from the axis of the Swell (Fig 7 and 9). At the top of the outcrop the graben is 21 m across and narrows to 7.6 m across at the base. Beds dip about 3° to the southeast. The interfingering Earthy and Slick Rock Members of the Entrada Formation act as reservoir-seal analogs.

Fault W1 consists of an east-dipping fault with a branch point at about 5 m from the bottom of the outcrop. Fault W2 is a west-dipping fault. Both faults strike perpendicular to the axis of the Swell at about 310°. Fault W2 has a shallower dip than fault W1 at 66° SW and 75° NE respectively. Fault W1 has a throw of 2.24 m and a heave of 0.61 m. Fault W2 has a throw of 0.87 m and a heave of 0.40 m. Many small-displacement faults parallel W1, W2, and W3 within a 300 m zone. These faults can be traced for 20 to 100 m on the surface. The change in the fault dips at the top of the outcrop in Fig 8 is due to the change in the steepness of the outcrop and is an optical illusion.
Fig 7. Geologic map showing site locations for W1-W2, W3, and BC and the related geology. Modified from Doelling et al. (2015).

There is little evidence of fluid alteration associated with the faults at the mesoscale. Only one vein was found with gypsum near W1 (Fig 9). Both faults have wedge shaped clay gouge 75 cm long and 15 cm at its thickest from the source bed (Fig 10). The geometry of these faults is similar to the modeled geometry where foliated clay from shale layers dominates the fault-interface corner (Fig 2 E).
Fig 8. Overview (A) and line work (B) for site W1-W2. Faults W1 and W2 form a graben in the Entrada Formation. Two marker beds of the Slick Rock Member have been highlighted in yellow. The interfingering of the Slick Rock (marked in yellow) and Earthy (unmarked) Members can be seen. Sample locations are marked with yellow dots. View is to the south.
Fig 9. Close up views of fault W1. A) The only observed example of mineralization is gypsum growing in a fracture between W1 and W2. B and C) Clay smear from the Earthy Member in fault W2. D) Overview of the fault with yellow boxes indicating where photos A, B, and C were taken. View is to the south.
Fig 10. Close up views of fault W2. A and B) Clay smear from the Earthy Member in fault W1. There was no visible mineralization near this fault. C) An overview of the fault with yellow boxes indicating where Figs A and B were taken. View is to the south.

The shale bed in the reachable section of W1 begins to be deformed and smeared into the fault zone at about 40 cm from the main fault plain (Fig 11). The smeared wedge is
continuous from the bed to the fault. Some of the sandstone bed was entrained into the fault in small blocks. It was difficult to distinguish the blocks due to a coating of dried mud eroded from shale beds above. Fractures are present in the stranded sand block area but are often covered up and hard to trace. Deformation bands were found in some fresh surfaces.

Fig 11. Detailed line work of the fault-interface corner geometry of fault W1.

There are two clay smear wedges in fault W2 (Fig 12). The upper wedge thins upward and does not appear to continue into the fault at the mesoscale. The lower wedge continues at least 1 m into the fault zone. It thins to about 1 cm before it is covered. There is
also a small section of entrained sand blocks that have been dragged downward into the fault (Fig 12). Deformation bands were not found, even in fresh surfaces under the mud coating.

Fig 12. Detailed linework of the fault-interface corner geometry of fault W2.
3.1.2 Site W3

Fault W3 lies within the interfingerling Earthy and Slick Rock Members of the Entrada and is about 7 m up section and 70 m to the northeast from W2 along the same 10 m tall cliff face (Fig 13). Beds dip about 3° to the southeast. Fault W3 forms the western flank of a small graben, the eastern side of which is covered and was exploited for the use of a road. Fault W3 strikes the same as faults W1 and W2 (~310°) and dips 76° NE with a throw of 2.7 m. Slickenlines on the main slip surface are almost purely dip-slip (Fig 14).

Fig 13. Overview of fault W3 and sample locations. A) An overview of fault W3 indicating the three main sections of the outcrop, the lower, middle, and upper sections. B) Line drawing of fault W3 with sample locations, marked fault, and two highlighted beds of the Slick Rock Member to show offset. View is to the south.
The stratigraphy in this outcrop is split into three sections, the lower thinly bedded section, the middle massive section, and the upper tabular section (Fig 13). The 5 m upper tabular section was inaccessible and will not be described here. The lower and middle sections were sampled and will be described here.

The lower section contains the Earthy Member of the Entrada Formation. At this location, the Earthy Member is a thinly bedded very fine-grained siltstone. Originally a deep red or purple, some laminations have been altered to white and pale gray, giving it a striped appearance (Fig 13). On the east side of the fault only one bed of the interfingering Earthy Member is exposed. The alteration in this bed is localized to the top and bottom of the bed with about a 0.3 m red zone in the middle. Within the fault zone the whole bed has been altered on both sides of the fault. A second bed of the Earthy Member is exposed on the west side of the fault below and separated from the first by a 1.5 m bed of the Slick Rock Member. The color alteration in this bed is localized to thin laminae 2 to 14 cm in thickness.
The middle section of the outcrop contains the Slick Rock Member, a massive to tabular fine-grained sandstone. The bottom of this section consists of a 1 m bed of altered rock. Like the lower section just below it, it too is has been altered (Fig 15). It contains circular to ellipsoidal nodules confined in this 1 m thick bed (Fig 15 and 17). Based on field observations the nodules are likely hematite concretions; however, this was not confirmed analytically. The nodules can be found tens of meters in either direction from the fault. Each nodule is yellow to light green inside with an orange concentric crust. Fractures often radiate from the nodules, which likely formed due to the concentrated stresses around them due to rheology differences. Closer to the fault, nodules are aligned appearing to have formed in fractures.
Fig 16. Close up view of nodules at site W3. A) The nodules formed along bedding of site W3. A, B, D) Nodules are usually associated with fractures, especially radiating fractures. C) Closer to the fault the nodules concentrate in fractures.

Gypsum veins, up to 1 cm thick, are also common in the middle section of the outcrop (Fig 17). The veins are subparallel to bedding. Crosscutting relationships indicate that the gypsum veins formed after the nodules (Fig 18 A, 17 B, 17 C). Unlike the nodules, the veins are distributed throughout the middle section (Fig 17). Most of the gypsum veins seemed to be unaffected by any deformation found in the outcrop; however, a few veins are offset (Fig 18 E). There was also a 5 mm thick vein of gypsum in the main fault core of W3 (Fig 18 D).
Fig 17. Gypsum veins in the middle section of fault W3. Most gypsum veins are subparallel with bedding. The core of the fault contains a 5 mm thick vein of gypsum.

Fig 18. Close up of crosscutting relationships between gypsum, nodules, and deformation bands at site W3. A, B and C) Nodules are cut by gypsum growth in fractures. E) Deformation bands offset gypsum veins. D) A large gypsum vein formed in the fault core.
A thick package of clay smear is present across fault W3 (Fig 19). The zone of clay smear has been faulted into 4 distinct sections (Fig 19 B). The faulted clay smear zone is unlike those typically documented (van der Zee et al., 2003). Models typically use pure clay, but the Earthy Member is actually a very fine-grained sandstone, and while it may be clay-rich, the Earthy Member is not pure clay. This slight lithological difference explains the slight variation from clay smear laboratory results.

Fig 19. Detailed linework highlighting the fault-interface corner geometry of W3.
Deformation bands occur in the sandstone on either side of the fault. The number of deformation bands decreases in the nodule bed. There is a fractured zone at the bottom of the outcrop where antithetic displacement has occurred through a shale bed in a series of step over faults. These geometries are much more complicated than the fault-interface corner models.

3.1.3 Site BC

Site BC is a fault that cuts the base of the Jurassic Navajo Sandstone in the San Rafael Swell. The outcrop is over 15 m tall in a vertical cliff face. The massive to tabular sandstone of the Navajo Sandstone is segmented by 10-35 cm thick green clay-rich interdunal lakebeds dipping 5° SE (Fig 20). The sandstone beds are pink and unaltered. The fault is a sub-vertical normal fault with about 0.5 m of displacement. It strikes 120° and dips 64° S with a throw of 0.32 meters. The fault is a subsidiary of a larger fault/fracture swarm in the area (Fig 7).
Fig 20. Outcrop exposure of the fault in site BC. A) This site is a small outcrop in the Navajo Sandstone. Interdunal lakebeds interfinger the typical erg deposits of the Navajo. B) Line work showing the main fault as well as highlighting the sandstone beds in yellow. Pictures are not along the fault plane. View is to the west.

The main slip surface of fault BC runs down the middle of Fig 21. The downthrown side of the fault has deformation bands and joints in the sandstone beds. The upthrown side of the fault has many small antithetic faults creating small fault blocks. These faults may be reactivated joints. There was some evidence of a small amount of clay smear related to one of the antithetic faults in the upthrown side of the major slip surface.
3.1.4 Site ISS

The fault at site ISS is northeast of W1, W2, and W3 and cuts the Entrada Formation where the Earthy and Slick Rock Members interfinger (Fig 22). The 0.7 m tall outcrop is made up of one 15 cm bed of the Earthy Member between two beds of the Slick Rock Member (Fig 23). The beds dip 2-6° NE. Deformation bands have accommodated most of the strain of the ISS fault which dips at about 85° SE and strikes at 80°. The fault has a total displacement of about 12 cm. The 11 cm bed of Earthy Member exposed at this outcrop is
fissile to tabular-lenticular (Fig 24). It has experienced about 9 cm of thickening in the fault zone, possibly due to a process similar to shale injection.

The mineralization observed in outcrop included hematite and calcite (Fig 25). The hematite was concentrated in the sandstone footwall in the corner area in thin bands parallel to the fault plane. The hematite bands thickened upward toward the interface.
Fig 23. Overview image and line work of the ISS site. A) This site is mostly made up of the Slick Rock Member of the Entrada Formation. B) There is only one thin bed of the Earthy Member exposed in this outcrop highlighted in grey. Faults are marked with red lines. View is to the north.
Fig 24. Close up of the Earthy Member at site ISS. The shale bed has experienced about 9 cm of thickening.
Fig 25. Mineralization at the ISS site. A) Close up view of the interface-fault corner including hematite and calcite veins. B and E) Close up of hematite veins in the fault-related rock. Hematite seems to be localized in the deformation bands. C and D) Close up of calcite precipitation filling fractures.

The top sandstone bed at site ISS contains fractures on the downthrown side (Fig 26). The upthrown side was not sampled or inspected well enough to identify the method of deformation. From Fig 26 A, the upthrown side of this sandstone bed appears to lack fractures and deformation bands; however, deformation bands may exist since the lower sandstone bed has deformation bands on the upthrown side. The downthrown side of the lower bed was also not sampled or inspected well enough but appears to lack any deformation. A stranded 7 cm thick sandstone block split a portion of the injected shale bed (Fig 26 B).
3.2 X-ray Diffraction Analysis

We analyzed thirty-eight whole-rock crushed samples from the fault zones, damage zones, and host rocks using X-ray diffraction to determine the major rock-forming minerals. In general the samples contain different combinations of quartz, carbonate, feldspar, clays,
and gypsum. The most common carbonate is calcite, followed by dolomite, and ankerite. The feldspars include microcline, orthoclase, anorthite, and anorthoclase. Due to uncertainties in the XRD analyses, the polymorphs of potassium feldspar have been grouped and labeled as K-feldspar, and the members of the plagioclase feldspar solid solution series have been grouped and labeled as plagioclase. The clays include illite and kaolinite (Table 3, 4, 5, 6).

Table 2
Overall XRD averages for samples in all the faults. Percentage of samples containing each mineral in the protolith, fault, and damage zone.

<table>
<thead>
<tr>
<th></th>
<th>Illite</th>
<th>Gypsum</th>
<th>Kaolinite</th>
<th>Feldspars</th>
<th>Calcite</th>
<th>Ankerite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protolith</td>
<td>64%</td>
<td>9%</td>
<td>0%</td>
<td>27%</td>
<td>82%</td>
<td>64%</td>
</tr>
<tr>
<td>Fault</td>
<td>50%</td>
<td>0%</td>
<td>17%</td>
<td>33%</td>
<td>67%</td>
<td>67%</td>
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<tr>
<td>Damage Zone</td>
<td>27%</td>
<td>7%</td>
<td>0%</td>
<td>20%</td>
<td>80%</td>
<td>47%</td>
</tr>
</tbody>
</table>

Quartz is in every sample and has the greatest intensities. Calcite is most commonly found in samples from the protolith and least likely to be found in samples from the faults (Appendix A4). Ankerite and feldspars are most likely found in samples from the fault and least likely to be found in samples from the damage zone (Appendix A4). Gypsum is most likely to be found in the protolith but least likely in the faults (Appendix A2). Kaolinite is only found in samples from the fault (Appendix A3). Illite is found in more protolith samples than samples from the damage zone (Table 2 and Appendix A1).
3.2.1 Site W1-W2

Ankerite and calcite are the most common carbonates in samples from W1 and W2 (Table 3). Potassium and plagioclase feldspars are more common in shale samples than sandstone samples. Illite is common in shale samples from the protolith.

Table 3
XRD interpretations for samples from site W1-W2 sorted as protolith or damage zone. Clays are absent from the damage zone.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Major</th>
<th>Carbonate</th>
<th>Feldspars</th>
<th>Clay</th>
<th>Protolith Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Protolith</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Damage Zone</td>
</tr>
<tr>
<td>W1-1</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
<td>K-Feldspar</td>
<td>Illite</td>
<td>Shale</td>
</tr>
<tr>
<td>W1-4</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
<td>K-Feldspar</td>
<td></td>
<td>Sandstone</td>
</tr>
<tr>
<td>W2-2</td>
<td>Quartz</td>
<td>Calcite</td>
<td></td>
<td>Illite</td>
<td>Shale</td>
</tr>
</tbody>
</table>

3.2.2 Site W3

Ankerite and calcite are the most common carbonates in fault W3 (Table 4). Feldspars are common in shales in the protolith, fault, and damage zone. Protolith sandstone sample W3-8 has K-feldspar. Clay minerals are more prevalent in shales, but there is also one faulted sandstone sample, W3-12, where illite was found. Despite many mesoscale observations of gypsum, the mineral was not identified through XRD.
Table 4
XRD interpretations for samples from site W3 sorted as protolith, fault, or damage zones.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Major</th>
<th>Carbonate</th>
<th>Feldspars</th>
<th>Clay</th>
<th>Protolith lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>W3-1</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
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<td>Sandstone</td>
</tr>
<tr>
<td>W3-2</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
<td></td>
<td></td>
<td>Sandstone</td>
</tr>
<tr>
<td>W3-4</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
<td>K-Feldspar</td>
<td>Illite</td>
<td>Shale</td>
</tr>
<tr>
<td>W3-8</td>
<td>Quartz</td>
<td>Ankerite, Calcite</td>
<td>Plagioclase</td>
<td></td>
<td>Sandstone</td>
</tr>
</tbody>
</table>

| W3-5   | Quartz| Ankerite, Calcite| K-Feldspar  | Illite | Shale               |
| W3-6   | Quartz| Ankerite, Calcite|             |        | Sandstone           |
| W3-9   | Quartz| Ankerite, Calcite| K-Feldspar  | Illite | Shale               |
| W3-10  | Quartz| Ankerite, Calcite|             |        | Sandstone           |
| W3-12  | Quartz| Dolomite         | Illite      |        | Sandstone           |
| W3-7   | Quartz| Ankerite, Calcite| K-Feldspar  | Illite | Shale               |
| W3-11  | Quartz| Ankerite         |             |        | Sandstone           |

Table 5
XRD interpretations for samples from site BC sorted as protolith, fault, or damage zone.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Major</th>
<th>Carbonate</th>
<th>Feldspars</th>
<th>Clay</th>
<th>Protolith lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-1</td>
<td>Quartz</td>
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<td>Shale</td>
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<td>BC-3</td>
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<td>BC-2</td>
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<td>Kaolinite</td>
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<td>BC-5</td>
<td>Quartz</td>
<td>Dolomite</td>
<td>K-Feldspar</td>
<td></td>
<td>Sandstone</td>
</tr>
</tbody>
</table>
3.2.3 Fault BC

Dolomite is the most abundant carbonate for site BC (Table 5). Dolomite is common in the damage zone and is present in the protolith but absent in the fault. K-feldspar is the only feldspar detected and is found in every sample except in the only shale sample, BC-1. Illite and kaolinite are found in almost every sandstone sample.

3.2.4 Fault ISS

Calcite is the only carbonate found in samples from ISS (Table 6). K-feldspars are rare at this site, only being identified in samples from the fault. With the exception of sample ISS-6 in the fault, illite is mostly associated with the samples of shale.

Table 6
XRD interpretations for each sample from site ISS sorted as protolith, fault, or damage zone.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Major Carbonate</th>
<th>Feldspars</th>
<th>Clay</th>
<th>Other</th>
<th>Protolith Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS-5</td>
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<td>Illite</td>
<td>Gypsum</td>
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<td>ISS-6</td>
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<td>Illite</td>
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<td>ISS-2</td>
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<td>ISS-3</td>
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</table>
3.3 Whole Rock Geochemistry

Whole rock XRF analyses were performed on 15 samples from faults W1, W2, W3, and BC. The data are summarized in Table 7 and Figs 28-32.

Table 7
Raw XRF data for major element oxides. These measurements are in weight percent of the oxide grouped by protolith, fault, and damage zone.

<table>
<thead>
<tr>
<th>Protolith</th>
<th>W1-1</th>
<th>W1-4</th>
<th>W2-2</th>
<th>W3-1</th>
<th>W3-4</th>
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<th>BC-1</th>
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<tr>
<td>SiO₂</td>
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<td>66.2</td>
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<td>63.5</td>
<td>75.7</td>
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<td>49.4</td>
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<tr>
<td>Al₂O₃</td>
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<td>7.66</td>
<td>1.41</td>
<td>10.70</td>
<td>6.66</td>
<td>20.20</td>
<td>7.61</td>
</tr>
<tr>
<td>Fe₂O₃</td>
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<td>6.11</td>
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<td>99.3</td>
<td>98.6</td>
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<table>
<thead>
<tr>
<th>Fault</th>
<th>W3-5</th>
<th>W3-10</th>
<th>BC-2</th>
<th>W3-6</th>
<th>W3-11</th>
<th>BC-3</th>
<th>W3-7</th>
<th>BC-4</th>
</tr>
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<tbody>
<tr>
<td>SiO₂</td>
<td>70.4</td>
<td>87.1</td>
<td>88.3</td>
<td>55.2</td>
<td>54.9</td>
<td>64.8</td>
<td>63.8</td>
<td>8.42</td>
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<tr>
<td>Al₂O₃</td>
<td>8.85</td>
<td>1.02</td>
<td>6.05</td>
<td>7.00</td>
<td>1.52</td>
<td>9.11</td>
<td>8.42</td>
<td>4.40</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.82</td>
<td>0.63</td>
<td>0.34</td>
<td>2.77</td>
<td>0.24</td>
<td>2.10</td>
<td>2.46</td>
<td>5.59</td>
</tr>
<tr>
<td>MgO</td>
<td>2.64</td>
<td>0.92</td>
<td>0.26</td>
<td>5.25</td>
<td>0.62</td>
<td>2.73</td>
<td>4.40</td>
<td>2.93</td>
</tr>
<tr>
<td>CaO</td>
<td>4.09</td>
<td>4.28</td>
<td>0.12</td>
<td>11.10</td>
<td>23.40</td>
<td>7.18</td>
<td>5.59</td>
<td>0.12</td>
</tr>
<tr>
<td>K₂O</td>
<td>2.57</td>
<td>0.46</td>
<td>2.43</td>
<td>2.21</td>
<td>0.65</td>
<td>2.73</td>
<td>2.93</td>
<td>0.12</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.73</td>
<td>0.11</td>
<td>0.06</td>
<td>0.78</td>
<td>0.13</td>
<td>0.69</td>
<td>0.12</td>
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<tr>
<td>TiO₂</td>
<td>0.39</td>
<td>0.03</td>
<td>0.22</td>
<td>0.28</td>
<td>0.05</td>
<td>0.39</td>
<td>0.51</td>
<td>0.04</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.02</td>
<td>0.00</td>
<td>0.07</td>
<td>0.09</td>
<td>0.04</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.10</td>
<td>0.00</td>
<td>0.07</td>
<td>0.10</td>
<td>0.04</td>
<td>0.14</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>LOI</td>
<td>8.16</td>
<td>4.92</td>
<td>2.31</td>
<td>15.9</td>
<td>18.6</td>
<td>10.1</td>
<td>10.5</td>
<td>98.9</td>
</tr>
<tr>
<td>Sum</td>
<td>99.8</td>
<td>99.5</td>
<td>100.2</td>
<td>100.7</td>
<td>100.2</td>
<td>100.0</td>
<td>98.9</td>
<td></td>
</tr>
</tbody>
</table>
The major element data can be broken down into three groups: silicon (Si), carbonate-related cations (Mn, Fe, Mg, and Ca), and feldspar and clay-related cations (Al, K, and Na). Some of these major elements fit both groups, but we show trends in shale- and sandstone-normalized data that suggest this crossover is minimal.

Major and trace element concentrations are normalized with respect to protolith sandstone and protolith shale samples from each outcrop in order to test for changes due to fluid-rock interaction associated with the fault zones (Figs 28-32). This is built on the assumption that that protolith sampled has been uninfluenced by fault related fluids. Samples that were outside the observable damage zone and from unaltered rock were chosen as protolith samples.

Fault-related rocks from site W1 and W2 were grouped together because of their proximity and because they cut the same beds. Shale-normalized data show that the fault-related shales have changed little compared to shale protolith (Fig 27). Sandstone-normalized data show a large variation between fault-related sandstone and the sandstone protolith (Fig 28). The fault-related sandstone, W2-3, is depleted in Fe, Mg, and all of the feldspar-related cations. It is enriched in Mn and Ca. However, this sample is compared to the protolith from a different bed. The stratigraphic differences between the two samples, not alteration, may explain differences in Fig 28.

Shale-normalized major element compositions for fault W3 show that, like W1 and W2, fault-related shale samples exhibit little elemental variation and have not been significantly altered by any fault-related fluids (Fig 29). Sandstone-normalized data show a
depletion of carbonate-related cations, Na, Ti, and P. Al and K remain consistent with the protolith (Fig 30).

Because there was only one shale sample from site BC, the shale-normalized data is not shown here. Two sandstone samples, BC-2 and BC-4, are compared with the protolith sample BC-3 in the sandstone-normalized data (Fig 31). Sample BC-4, from the damage zone, is relatively unaltered with only some slight depletion of carbonate-related cations. Sample BC-2, from the fault zone, is depleted in carbonate-related cations by one or two orders of magnitude, much more than the protolith and damage zone.

Fig 27. Shale-normalized XRF oxide percentages for sites W1 and W2. The y-axis represents the ratio of each major element of the sample to the major element of the shale protolith sample W2-2. Protolith samples are blue and damage zone samples are grey. Sandstone samples are marked with a solid line and shale samples with a dashed line.
Fig 28. Sandstone-normalized oxide percentages for sites W1 and W2. The y-axis represents the ratio of each major element of the sample to the major element of the sandstone protolith sample W1-4. Protolith samples are blue and damage zone samples are grey. Sandstone samples are marked with a solid line and shale samples with a dashed line.

Fig 29. Shale-normalized XRF oxide percentages for site W3. The y-axis represents the ratio of each major element of the sample to the major element of the shale protolith sample W3-4. Protolith samples are blue, fault samples are orange, and damage zone samples are grey. Sandstone samples are marked with a solid line and shale samples with a dashed line.
Fig 30. Sandstone-normalized oxide percentages for site W3. The y-axis represents the ratio of each major element of the sample to the major element of the sandstone protolith sample W3-1. Protolith samples are blue, fault samples are orange, and damage zone samples are grey. Sandstone samples are marked with a solid line and shale samples with a dashed line.

Fig 31. Sandstone-normalized oxide percentages for site BC. The y-axis represents the ratio of each major element of the sample to the major element of the sandstone protolith sample BC-3. Protolith samples are blue, fault samples are orange, and damage zone samples are grey. Sandstone samples are marked with a solid line and shale samples with a dashed line.
3.6 Thin Section Petrography

Petrographic analyses were done on faults W1, W2, W3, and BC to document crosscutting relationships and identify primary and secondary mineralogy.

3.6.1 Site W1-W2

Site W1-W2 has four samples from sandstone beds, W1-2, W1-4, W2-3, and W2-4. Sample W1-4 was sampled as the protolith. Thin section analysis showed that this sample is not the protolith for the other fault-related samples. Samples W1-2, W2-3, and W2-4 are all from the same sandstone bed and consist of two types of grains, rounded to subrounded quartz grains 50-500 µm long and detrital sparry calcite grains ~50-100 µm in diameter surrounded by a ring of micritic calcite 10-75 µm thick (Fig 32 A, B, C). These grains lie in a sparry calcite cement. Sample W1-4, from another bed and further from the fault, contains subangular to subrounded quartz grains about 10-150 µm in diameter. These quartz grains lie in a cement of sparry calcite (Fig 32 D).
Fig 32. Cross-polarized light photomicrographs of sandstone samples from site W1-W2. A, B, and C) Detrital sparry calcite grains (sc) surrounded by a micritic calcite border (mc) with authigenic sparry calcite cement filling in pore space in samples W1-2, W2-3, and W2-4. D) Sample W1-4, although also a sandstone and assumed to be the protolith, is much different than the other three samples. For example, authigenic calcite cement (cc) fills pore space, and grains are much finer.
Fig 33. Photomicrographs of thin sections W3-1 and W3-10. A) Cross-polarized light photomicrograph of sample W3-1 representing protolith. Quartz (qtz) and calcite cement (cc) are the main minerals in this sample. B) Cross-polarized light photomicrograph of fractured grains in fault-related rock sample W3-10. C) Cross-polarized light photomicrograph of a deformation band in sample W3-10 with decreased grain size. D) Cross-polarized light photomicrograph of fine-grained calcite incorporated in a deformation band (db). E) Cross-polarized light photomicrograph of a deformation band (db). F) Plain light photomicrograph of a deformation band used to calculate porosity of both the deformation band and nondeformed rock.
Samples W1-2, W2-3, and W2-4 exhibit evidence of multiple calcite precipitation episodes (Fig 32 A, B, and C). Evidence for the earliest phase of calcite is the presence of micritic calcite coating, possibly due to precipitation in the vadose zone, on detrital sparry calcite grains (James and Choquette, 1984). The evidence for the second phase is the sparry calcite cement, which has been precipitated in the pore space around the micritic calcite and quartz grains. Sample W1-4 is much different than the other sandstone samples (Fig 32 D). Grain size is much finer than the other three. The only calcite in the sample exists as sparry calcite cement.

3.6.2 Site W3

Petrographic analyses of samples from site W3 show insight into the timing of calcite cement and deformation. Samples W3-1, protolith, and W3-10, a fault-related rock, were sampled from the same bed and are calcite-cemented quartz arenites (Fig 33 A and B). Sample W3-1 has rounded to subrounded quartz grains about 50-500 µm diameter in sparry calcite cement. Sample W3-10 has rounded to subrounded fractured quartz grains about 10-500 µm long in sparry calcite cement. Deformation bands are common in W3-10 where porosity was decreased by as much as 140 times due to crushed grains (1.43% for calcite filled non-deformation band rock and 0.01% for calcite-free deformation band in Fig 33 F) (Fig 33 C, E, and F). There was evidence of fine-grained calcite in the center of a few of the deformation bands indicating that precipitation occurred during deformation (Fig 33 D).
Fig 34. Photomicrograph of thin sections from sandstone beds from site BC. Cross-polarized light (A) and plain light (B) photomicrographs of sample BC-3 showing a fine-grained subarkose sandstone with dolomite cement and little porosity. Cross-polarized light (C) and plain light (D) photomicrographs of sample BC-5 also show fine-grained subarkose sandstones with dolomite cement and little porosity. E) Cross-polarized light photomicrograph of sample BC-2, which is a coarse-grained subarkose sandstone with little carbonate cement. F) Plain light photomicrograph of E to show porosity and dissolution of carbonate cement.
3.6.3 Site BC

Sandstone samples from the damage zone and the protolith consist of angular quartz and microcline grains about 10-150 µm long with a dolomite cement and have little porosity (Fig 34 A, B, C, D). Sample BC-2, from the fault, is a much coarser grained sandstone consisting of angular quartz and microcline grains about 100 to 300 µm long with little cement filled porosity. While it is from a different bed, it has evidence of dissolution of carbonate cement indicating fluid movement through the fault but not through the sandstone beds further from the fault (Fig 34 E and F).

3.4 Fractured Grain Analysis

The density of microfractures in grains was measured in forty-one thin sections from faults W1, W2, W3, and BC. Some grains are completely fractured and almost unrecognizable as individual grains (Fig 35). For some samples, fractured grains are common, but most grains contain only one or two fractures (Fig 36). Other samples are so fine-grained that any fractures were unrecognized (Fig 37).

In general, the intergranular fracture density increases with proximity to the faults (Figs 39, 40, 41 and Table 8). At fault W1 there is a 3100% increase in fractures when comparing samples from the fault and protolith. There is a 3500% increase in fractures in fault W2 compared to the protolith. At site W3 there is a 720% increase in the fracture density in the fault compared to the protolith. The only sample from site BC that has fractured grains in it is the sample from the fault.
Fig 35. Photomicrograph of sample W3-10 over plain light with blue dye epoxy highlighting pore space. Most grains are fractured producing very angular grains.

Fig 36. Photomicrograph of sample W2-3 over polarized light. Most grains are not fractured. Any fractured grains remain mostly intact.
Fig 37. Plain light photomicrograph of sample BC-1. Fractured grains are difficult to find because of grain size.
Fig 38. Fractured grain density across site W1-W2. The number of fractured grains increases with proximity to the faults.
Fig 39. Fractured grain density across site W3. The number of fractured grains increases with proximity to the faults. The more ductile samples tend to be shale samples, like W3-9 and W3-5. Although close to the fault, they have much lower instances of fractured grains.
Fig 40. Fractured grain density across site BC. Only one sample, BC-2, had any instances of fractured grains.
Table 8
Results from the fracture analysis. The table shows the number of fractured grains per photomicrograph as well as the distance from the sample to the fault in meters.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Number of Fractured Grains</th>
<th>Distance from Fault (m)</th>
<th>Sample</th>
<th>Number of Fractured Grains</th>
<th>Distance from Fault (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-1</td>
<td>0</td>
<td>0.2</td>
<td>W3-1</td>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td>BC-2</td>
<td>23</td>
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<td>W3-10a</td>
<td>4</td>
<td>0.4</td>
</tr>
<tr>
<td>BC-3pp</td>
<td>0</td>
<td>0.6</td>
<td>W3-10ppa</td>
<td>51</td>
<td>0.4</td>
</tr>
<tr>
<td>BC-3rl</td>
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<td>0.6</td>
<td>W3-10ppb</td>
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<td>0.4</td>
</tr>
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<td>BC-4a</td>
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<td>W3-10rl</td>
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<td>0.4</td>
</tr>
<tr>
<td>BC-4b</td>
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<td>0.03</td>
<td>W3-11pp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>BC-5</td>
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<td>0.2</td>
<td>W3-11rl</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>W1-1pp</td>
<td>0</td>
<td>1.2</td>
<td>W3-12pp</td>
<td>22</td>
<td>0</td>
</tr>
<tr>
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<td>1.2</td>
<td>W3-12rl</td>
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<td>0</td>
</tr>
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<td>W3-2</td>
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</tr>
<tr>
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<td>0</td>
<td>W3-4pp</td>
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<td>0.9</td>
</tr>
<tr>
<td>W1-3rl</td>
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<td>0</td>
<td>W3-4rl</td>
<td>0</td>
<td>0.9</td>
</tr>
<tr>
<td>W1-4pp</td>
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<td>0.4</td>
<td>W3-5</td>
<td>0</td>
<td>0.3</td>
</tr>
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<td>W1-4rl</td>
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<td>W3-6ppa</td>
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<td>W2-1rl</td>
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<td>W3-6rl</td>
<td>17</td>
<td>0.2</td>
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<tr>
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<td>W3-7</td>
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<tr>
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<td>W3-8pp</td>
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<td>W3-8rl</td>
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<td>W3-9</td>
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<td>0.2</td>
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<tr>
<td>W2-4rl</td>
<td>17</td>
<td>0</td>
<td></td>
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</tbody>
</table>

3.5 Porosity

We estimated porosity data for three faults using the petrographic techniques described in section 2.3. Faults W3 and BC exhibit an increase of porosity in the fault (Figs 43 and 44 and Table 9). Even some shale samples, for example W3-7 and BC-1, increase in porosity with proximity to the fault (Figs 43 and 44). At site W1-W2, porosity is much higher near fault W1 than fault W2. For example, sample W1-2 has a porosity of 2.87%, while sample W2-4, taken from the same bed, has a much lower porosity of 0.16% (Fig 41).
Fig 41. Porosity estimates across site W1-W2. Samples from fault W1, in general, have a much higher porosity than samples from fault W2. Samples W2-4 and W1-1 were taken from the same sandstone bed. Porosity changes increase from sample W2-4 toward W1-1.
Fig 42. Porosity estimates across site W3. Porosity increases closer to the fault and with lithology. Shale samples tend to have lower porosity than sandstone samples.
Fig 43. Porosity estimates across site BC. Pore space in samples BC-3, BC-4, and BC-5 is mostly filled with dolomite (Table 5).
### Table 9
Porosity values for each photomicrograph. Porosity was calculated using photomicrographs of whole thin sections.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Porosity</th>
<th>Sample</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC-1</td>
<td>4.91%</td>
<td>W3-1</td>
<td>4.14%</td>
</tr>
<tr>
<td>BC-2</td>
<td>8.12%</td>
<td>W3-2</td>
<td>2.20%</td>
</tr>
<tr>
<td>BC-3pp</td>
<td>0.29%</td>
<td>W3-4pp</td>
<td>0.05%</td>
</tr>
<tr>
<td>BC-3rl</td>
<td>0.67%</td>
<td>W3-4rl</td>
<td>0.15%</td>
</tr>
<tr>
<td>BC-4a</td>
<td>0.05%</td>
<td>W3-5</td>
<td>0.01%</td>
</tr>
<tr>
<td>BC-4b</td>
<td>0.63%</td>
<td>W3-6ppa</td>
<td>0.10%</td>
</tr>
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<td>BC-5</td>
<td>0.76%</td>
<td>W3-6ppb</td>
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<td>W3-6rl</td>
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</tr>
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<td>W3-7</td>
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<tr>
<td>W1-2</td>
<td>2.87%</td>
<td>W3-8pp</td>
<td>4.62%</td>
</tr>
<tr>
<td>W1-3pp</td>
<td>2.26%</td>
<td>W3-8rl</td>
<td>2.85%</td>
</tr>
<tr>
<td>W1-3rl</td>
<td>1.64%</td>
<td>W3-9</td>
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</tr>
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</tr>
<tr>
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<td>4.99%</td>
</tr>
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<td>W3-10ppb</td>
<td>5.95%</td>
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<td>10.47%</td>
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<td>1.73%</td>
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<td>20.81%</td>
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<tr>
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<td>W3-12rl</td>
<td>14.89%</td>
</tr>
<tr>
<td>W2-4rl</td>
<td>0.14%</td>
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</table>

### 4. Discussion

We interpret the data presented above to show that each fault represents an end member of small-displacement faults in siliciclastic rock sequences (Fig 2). Faults W1 and W2 offer insight into fault-fluid interaction where the fault was mechanically sealed through clay smear and there was little fluid-assisted alteration along or near the fault. Fault W3 offers insight into the complexity of fault-fluid histories in a small-displacement fault. Fault
BC offers insight into a possible failed seal indicated by cement dissolution. Fault ISS is an example of a fault with a healing seal despite the deformation that has occurred.

4.1 Site W1-W2

There is little geochemical or mineralogical evidence of fluid flow in either fault. The XRD and petrographic observations show that very little change in mineralogy exists between fault-related rock and protolith. The XRF data indicate some chemical variation exists in the sandstone fault-related rock (Fig 27 and 29). However, stratigraphic differences between the protolith sample and fault-related rock samples may easily explain the chemical differences. For example, sample W1-4, the protolith, is from a different sandstone bed than sample W2-3 (Fig 32). The lithological differences between the presumed protolith and fault-related rock are clear in photomicrographs of thin sections. Sample W1-4 is an angular, very fine-grained, subarkose with sparry calcite and ankerite cements (Fig 32 D). Samples W1-2, W2-3, W2-4 (all from the same bed) are rounded, fine-grained, sublitharenites in sparry calcite cement (Fig 32 A, B, and C). The majority of the lithics are detrital sparry calcite grains coated in micritic calcite (Fig 32 A, B, and C).

With little evidence of geochemical alteration in the fault zones, faults W1 and W2 offer good examples of mechanically sealed faults and of the model proposed in Fig 2 E. We calculate the sealing potential of these two faults according to models developed for faults (Yielding et al., 1997). As a sand-shale sequence of rocks is faulted, clay from the shale beds can be drawn or smeared into the fault core and the clay in the fault can act as a lateral barrier as well as plug potential vertical fracture pathways (Yielding et al., 1997). These clay smears tend to decrease in thickness as offset and distance from the source clay bed increase.
Fig 44. Shale gouge ratio algorithm from Yielding et al. (1997). The SGR quantifies the amount of clay that may have been smeared into the fault zone from shale beds.

Fig 45. Highlighted areas of faults W1 and W2 used in shale gouge ratio. The highlighted areas in green were used to calculate the shale gouge ratio for each fault. The area was based on the amount of throw of each fault.
The shale gouge ratio (SGR) proposed by Yielding et al. (1997) is one method to quantify the quality of the clay smear and its sealing capabilities. This method takes into account the thickness of every shale bed in a package of rock equal in thickness to the throw of the fault (Fig 44 and 46):

\[
SGR = \frac{\sum \text{Shale bed thickness}}{\text{Fault throw}} \times 100\% \quad (1)
\]

Where SGR = shale gouge ratio, with a value > 15-20% being the lower bound for and effective seal. Shale bed thicknesses add up to 1.14 m giving the fault an SGR of 51% (Fig 39). This SGR predicts that the shale smear along this section could provide a seal between the two juxtaposed sandstone beds. Fault W2 has a throw and rock package thickness of 0.87 m (Fig 45). The sum of shale bed thicknesses for this package is 0.54 m and gives W2 an SGR of 62%. Both of these values are well above the sealing threshold of a high barrier fault (Yielding et al., 1997).

A simplified model of the geometry of faults W1 and W2 shows the faults to be most related to the fault-interface geometry illustrated in Fig 2 E, where the corner is filled with clay smear (Fig 46). The clay smear in faults W1 and W2 is not a continuous smear of material into the fault zone but plastically deformed blocks of the shale, which have been entrained into the fault zone (Figs 12, 13, and 46). Our findings suggest that the model proposed in Fig 2 E is much too simplified and that despite the amount of low permeable material in the fault, the small fractures and deformation features between the shale blocks may still enable seal bypass. Faults similar to W1 and W2 will be baffles to flow as the low permeability of the clay smear limits the flow through the rock. However, they will only
serve as temporary seals, ultimately allowing seal bypass between the fractures and deformed areas between the blocks of shale.

Fig. 46. Idealized fault-interface corner geometry based on faults W1 and W2.
There is evidence for geochemical alteration and the likelihood of past fluid flow in and around the fault-related rocks at site W3. The presence of altered gray laminae, nodules, and gypsum veins paired with interpretations of elemental geochemistry point to past active subsurface flow of precipitating and reducing fluids. We interpret the fluids to have been reducing as they altered the originally red beds in the lower section of site W3, especially near the fault (Fig 13). Samples W3-1 and W3-10 were taken from the same bed, and yet the fault-related sample, W3-10 is depleted in carbonates (Fig 30). In thin section, the two samples look compositionally similar with quartz and calcite (Fig 33 A and B). However, sample W3-10 shows more signs of deformation. Fractured grains occur 7.2% more often than in the protolith sample in thin sections and 1-2 mm wide deformation bands are common (Fig 33 B and 36). Most of the deformation bands are free of calcite cement, which is most likely why major element analysis of W3-10 suggests it is depleted in carbonate-related cations (Fig 30).

There is evidence that the calcite-bearing fluid was in the fault zone early in its history as the deformation bands were formed. Petrographic analyses showed small amounts of very fine-grained calcite, possibly crushed, are incorporated within a few of the deformation bands (Fig 33 C and D). Due to the low porosity and permeability of deformation band faults (Antonellini and Aydin, 1994; Shipton et al., 2002; Fossen et al., 2007; Dockrill and Shipton, 2010), it is unlikely that calcite precipitated in the deformation band post-deformation. Even though the fractured grain zone has calcite cement filling the porosity, the porosity in the deformation band is more than 140 times less than in the fractured grain zone (0.01% and 1.43%, respectively) (Fig 33 E and F).
Deformation bands are typically found in highly porous rocks that allow space for grains to be crushed, rotated, or translated (Aydin and Johnson, 1978; Antonellini and Aydin, 1994; Shipton et al., 2002; Fossen et al., 2007; Dockrill and Shipton, 2010). Pore filling calcite cement lowers the porosity of the rock and could make deformation bands an unlikely way to accommodate strain. There are few documented examples, besides our own evidence, for calcite in a deformation band. Main et al. (2000) showed in lab experiments that there is a slight increase in permeability during initial deformation that may help explain how fluids can enter a deformation band (Fossen et al., 2007). This fault is an example of fluid and deformation lowering porosity and most likely permeability.

The simplified model of fault W3’s geometry shows it to be most similar to the fault-interface geometry present in Fig 2 B, where the majority of slip has split the deformation band areas in half and has incorporated some clay smear into the corner area (Fig 47). Deformation bands are in the sandstone beds on both sides of fault W3. Just like with faults W1 and W2, the clay smear in the fault is a small block of shale bounded on either side by a step over fault or releasing fault which later connected together into one continuous slip surface.

4.3 Site BC

Site BC also has evidence for fluid flow in and around the fault zone. The XRF analyses show concentrations of feldspar-related cations, Mg, Ca, Mn, and Fe, to be relatively unchanged in the fault zone. However, carbonate-related cations are depleted in the fault zone by two orders of magnitude. Samples further from the fault are less depleted.
Petrographic data confirms the XRF data interpretations. Sample BC-2 from the fault is very porous with evidence of dolomite cement dissolution (Fig 34 E and F). Almost all of the porosity in samples BC-3 and BC-4, further from the fault, has been filled with dolomite (Fig 34 A, B, C, and D). The fluids mostly traveled through the fault yet only slightly through the sandstone beds.
The simplified model of fault BC demonstrates how complex even a small-displacement fault can be (Fig 48). Deformation bands formed in the upper sandstone bed but not in the middle sandstone bed. The jointed sandstone allowed antithetic faults to accommodate strain through reactivation of the preexisting joints. The jointing adds a layer of complication to the interface-fault geometry that is not included in the models proposed in Fig 2. Due to the jointed nature of the sandstone bed, the site fits the model in Fig 2 D most accurately, where an opening mode fracture allows fluids to collect and have direct contact with the faulted seal allowing for greater chances of seal bypass. The XRF and petrographic data suggests this fault was a conduit to flow.
4.4 Site ISS

The best evidence for fluid flow from ISS is the outcrop observations. Fault-parallel hematite veins indicate that an oxidizing fluid passed through the fault zone (Fig 25). The vertical and fault-parallel geometry of the veins suggests that the fluid came from lower in the fault and was not introduced by the sandstone beds in the outcrop.

The shale layer is thickened in the fault zone. This is most likely due to clay injection (van der Zee et al., 2003). In a typical clay injection system, a releasing step in the fault forms in the shale bed (Fig 49 A). A second fault forms in the upthrown block creating a squeeze block. The shale bed beneath the squeeze block is thinned and injected into the space created by the releasing step in the original fault. The fault and shale bed geometries at site ISS are very similar to this model (Fig 49 B). A step over fault has formed in the shale bed and the shale bed is thickened in the fault zone. There is evidence for lateral slip of the clay. For example, the shale bed is split by a section of sandstone acting like a wedge (Fig 49 C). Also, the horizontal texture of the shale is continuous across the thickened section and there is a white band of mineralization along the slip surface (Fig 49 D). The only structures missing from the site were the secondary fault in the upthrown side of the fault, which may have been buried, and thinning in the shale bed under the squeeze block. There may have been some thinning, but it was difficult to measure due to the erosional nature of the interface.
Fig 49. Lateral injection of clay in a fault zone. A) An idealized model of clay injection into a fault zone. B) Line drawing showing the injection of the shale bed into the fault zone. C) Close up view of the sandstone wedge splitting the injected shale bed. D) Close up view of the shale bed texture in the thickened section and the white mineralization along the slip surface.
The simplified model of fault ISS shows that its geometry is most similar to the fault-interface geometry model proposed in Fig 2 C, where the majority of the deformation bands is on the upthrown side of the majority of the slip (Fig 50). This model suggests a strong seal due to low permeability of the deformation bands creating a fault seal. The shale bed injection was not modeled and could add a sealing element to the fault zone. The step over fault was also not included in the original model.

Fig 50. Idealized fault-interface corner geometry based on fault ISS
4.5 Suggested Model Revisions

In order to model these findings more effectively we propose four revised models based on the five studied faults (Fig 51). Faults W1 and W2 mirror each other and have been combined into one model. The W1-W2 and W3 models add a block of shale to the original models shown in Fig 2 B and E to better simulate the fracture-bounded blocky nature of the clay smear. The W1-W2 model differs from the W3 model in the placement of the deformation band zone. In fault W3, the majority of slip goes through the middle of the deformation band zone. In faults W1 and W2, it was only found on one side of the faults. We also added a step over fault to the W1-W2, W3, and ISS models, which was found at each site. The fault ISS model also has a thickened seal between the two faults caused by the injection of the shale bed into the fault zone. The model for site BC includes an opening mode fracture through the sandstone reservoir indicating the reactivation of a joint. These models will better reflect the real world observations of the fault-interface corner.

4.6 Summary and Implications

The data and interpretations here demonstrate the nature and variability of small fault architecture and test their capability to be lateral and vertical seals to fluid movement.

The interpretations of these data of analog sites indicate that small faults may have significant impact on the extraction or injection of fluids. Faults of this size in the subsurface cannot be detected with seismic reflection methods, yet still need to be accounted for as an increase in risk for a new well, either for extraction or injection of fluids.
Fig 51. Suggested model revisions for the fault-interface corner area based on each fault.
The risk for extraction wells is in compartmentalizing the reservoir. If these small-displacement faults are sealed, for example W1 and W2, they will act as barriers, lowering the effective draining area of the well. If hydraulic fracturing is involved in the extraction process, then leaky faults may also act as preferred pathways for fractures or even the frac fluid. This would potentially create a much smaller stimulated rock volume, limiting returns.

A risk for injection wells is in creating pockets of high pressure between the interface and the sealing fault, which may fracture the seal (Butler, 2014). Another risk during injection is encountering a leaky fault, like BC. This would potentially allow the waste fluid to escape through the seal. Encountering faults like W3 have a geochemical risk during an injection. The high-pressured waste fluid could potentially geochemically change the rheology of the already altered rock, causing brittle failure and more potential open fractures through the seal.

Drilling the horizontal section of a well perpendicular to the fault and parallel to the maximum stress will help mitigate the risk of compartmentalization of the reservoir and the risk of faults hindering the hydraulic fracturing’s effectiveness. During creation of a hydraulic fracture, fractures are induced perpendicular to the borehole mostly along the horizontal plane. Drilling perpendicular to the faults would allow those fractures to grow laterally further without intercepting a sealed fault. A risk still exits that the hydraulic fracturing could reactivate fault related fractures limiting the number of new fractures and the volume of stimulated rock. Drilling perpendicular to the fault would also draw fluids parallel with the fault during extraction, avoiding the need to go through the faults to get to the borehole.
Fault elements in the fault-interface corners differ as a function of displacement. Fault ISS, which has the smallest displacement at 0.12 m, contains shale injection, a new fault-interface corner element that was not in the original models. It is only found in at site ISS and is an area for fluid pathways (Fig 50). Faults W1, W2, and W3 may have also experienced some shale injection, but due to their much larger displacements (625-2150% more throw than ISS) any effects of the injection would be small and unnoticeable. In fact, at larger scale displacement, like W1, W2, and W3, the shale in the fault zone should become a fault-bounded block. Shale in a fault zone may follow a natural progression from shale injection to fault-bounded shale block as displacement of the fault increases. The fault in this study represent end members of this progression. Continued study of this progression or evolution of shale in a fault zone may bring more insight and more fault elements to the fault-interface corner models.

5. Conclusions

We described five examples of small-displacement faults in sandstone-shale sequences. We described the faults’ past interactions with fluids and hypothesized about future fluid interactions for analogous systems in the subsurface. We also proposed models for the fault-interface corner based on the observations of each of the studied faults.

We showed that faults W1 and W2 contain blocks of shale along with clay smear within the fault zone. We showed that the clay smear is enough to mechanically seal the fault, creating a baffle for fluids. We also showed in faults W1, W2, and W3, that shale blocks are common in the thicker areas of the clay smear and that the deformed area between the blocks requires more studying and modeling to see if seal bypass through the area is
possible. We showed that fault W3 has been geochemically altered and that cementation and
deformation happened simultaneously. In fault BC we showed evidence that reactivation of
joints in a reservoir can allow seal bypass and showed evidence of such bypass in the
dissolution of calcite cement only in the fault zone indicating fluid movement through the
fault. We showed that fault ISS has injected the shale bed into the fault, apparently healing
the seal in the fault zone. We summarized the results and develop a set of models that
incorporate the fault and fault-related rock geometries and attributes and suggest that these
elements could be quantified. These data indicate that small-displacement faults might have
significant effects on seal integrity and lateral movement of fluids during extraction or
injection.
References


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APPENDICES
Appendix A: Selected X-ray Diffraction Patterns and Data
Fig A1. X-ray diffraction pattern from sample BC-1. The largest peaks are associated with quartz. The peak at 8.8 and 19.8 2θ suggests the presence of the mineral illite.
Fig A2. X-ray diffraction pattern from sample ISS-2. The largest peaks are associated with quartz. The peak at 11.6 °2θ suggests the presence of the mineral gypsum.
Fig A3. X-ray diffraction pattern from sample BC-2. The largest peaks are associated with quartz. The peak at 12.3° suggests the presence of the mineral kaolinite.
Fig A4. X-ray diffraction pattern from sample W1-4. The largest peaks are associated with quartz. The small peaks at 21.9, 24.1, 25.5, 27.3 and 27.8 2θ suggest the presence of a feldspar mineral, microcline in this case. The peak at 29.4 2θ indicates the presence of calcite. The peak at 30.8 2θ suggests the mineral ankerite.