Spatio-temporal History of Fluid-rock Interaction in the Hurricane Fault Zone

Jace Koger
Utah State University

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SPATIO-TEMPORAL HISTORY OF FLUID-ROCK INTERACTION

IN THE HURRICANE FAULT ZONE

by

Jace Michael Koger

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

in

Geology

Approved:

______________________  ____________________
Dennis L. Newell, Ph.D.  James P. Evans, Ph.D.
Major Professor  Committee Member

______________________  ____________________
Alexis K. Ault, Ph.D.  Mark R. McLellan, Ph.D.
Committee Member  Vice President for Research and
  Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2017
ABSTRACT

Spatio-temporal History of Fluid-rock Interaction in the Hurricane Fault Zone

by

Jace Michael Koger, Master of Science

Utah State University, 2017

Major Professor: Dennis L. Newell, Ph.D.
Department: Geology

The Hurricane Fault is a 250-km long, west dipping, Basin and Range-bounding normal fault in SW Utah and NW Arizona that initiated in the mid-Miocene to Pliocene. It has been primarily active in the Quaternary, with slip rates of 0.2 – 0.6 mm/yr. There are multiple hot springs along its 250-km length and multiple late Tertiary-Quaternary basaltic centers broadly parallel the fault. Possible sources of hot spring fluids include deeply-circulated meteoric water that experienced water-rock exchange at high temperatures (>100 °C) and deep-seated crustal fluids. Aside from the source of modern hot spring fluids and heat, questions about the spatio-temporal history of fluid flow along the Hurricane Fault remain unaddressed. Abundant damage zone veins, cements, and host rock alteration are present, indicative of past fluid flow. Carbonate veining and cementation is a key feature of the Hurricane Fault zone, and is the primary feature exploited to characterize the thermochemical history of fault-related paleofluids. A combination of macroscopic and microscopic carbonate observations, chemical composition, and precipitation temperature of calcite veins was used to determine past water-rock diagenetic interaction and vein evolution in the Hurricane Fault zone. Calcite
in concretions and veins from the damage zone of the fault shows a wide range of carbon and oxygen stable isotope ratios, with δ\(^{13}\)C\(_{\text{PDB}}\) from -4.5 to 3.8 ‰ and δ\(^{18}\)O\(_{\text{PDB}}\) from -17.7 to -1.1‰. Fluid inclusion microthermometry homogenization temperatures range from 45 to 160 °C, with fluid salinities of 0 to 15 wt% NaCl calculated from melting temperatures. Combining the two datasets, two main fluids that interacted with the fault zone are inferred: (1) basin brines with a δ\(^{18}\)O\(_{\text{SMOW}}\) of 9.2 ‰ and (2) altered meteoric fluids with a δ\(^{18}\)O\(_{\text{SMOW}}\) of -11.9 to -8.3 ‰. Calculated dissolved CO\(_2\) δ\(^{13}\)C\(_{\text{PDB}}\) (-8.5 to -1.3 ‰) indicates mixed marine carbonate and organic or magmatic sources. Fault zone diagenesis was caused by meteoric water infiltration and interaction with carbonate-rich rocks, mixed with upwelling basin brines. Fluid-rock interaction is concentrated in the damage zone, where fracture-related permeability was utilized for fluid flow. A distinct mineralization event punctuated this history, associated with basin brines that were chemically influenced by nearby basaltic magmatism. This implies a hydrologic connection between the fault and regional magmatism.

(167 pages)
PUBLIC ABSTRACT

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The Hurricane Fault is a 250-km long, west dipping, active Basin and Range-bounding normal fault in southwest Utah and northwest Arizona. There are multiple known hot springs along its 250-km length and multiple late Tertiary-Quaternary basaltic centers that broadly parallel the fault. Possible sources of hot spring fluids include deeply circulated meteoric water that experienced water-rock exchange at high temperatures (>100 °C) and deep-seated crustal fluids. Abundant damage zone veins, cements, and host rock alteration are present along strike, indicative of past fluid flow. Carbonate veins and cements are key features of the Hurricane Fault zone, and the primary feature utilized to characterize the thermochemical history of fault-related paleofluids. Macroscopic and microscopic observations of veins and cements are combined with analyses of the chemical composition and precipitation temperature of calcite veins to determine past water-rock diagenetic interaction in the Hurricane Fault zone. Fault zone diagenesis is caused by meteoric water infiltration and interaction with carbonate rich rocks, mixed with upwelling basin brines. At least one mineralization event punctuated this history, associated with basin brines that were chemically influenced by basaltic magmatism.
## CONTENTS

Page

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>PUBLIC ABSTRACT</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>CHAPTER</td>
<td></td>
</tr>
<tr>
<td>1 INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Geologic Background</td>
<td>5</td>
</tr>
<tr>
<td>1.2 Fluid Flow in Fault Zones</td>
<td>10</td>
</tr>
<tr>
<td>2 METHODS</td>
<td>13</td>
</tr>
<tr>
<td>2.1 Field Methods</td>
<td>13</td>
</tr>
<tr>
<td>2.2 Microscopy</td>
<td>14</td>
</tr>
<tr>
<td>2.3 C and O Stable Isotope Analysis</td>
<td>14</td>
</tr>
<tr>
<td>2.4 Fluid Inclusion Microthermometry</td>
<td>16</td>
</tr>
<tr>
<td>3 RESULTS</td>
<td>19</td>
</tr>
<tr>
<td>3.1 Fault Zone Diagenesis</td>
<td>19</td>
</tr>
<tr>
<td>3.2 Vein Geochemistry</td>
<td>33</td>
</tr>
<tr>
<td>4 DISCUSSION</td>
<td>41</td>
</tr>
<tr>
<td>4.1 Vein Sets/Fluid Categories – Thermochemical Characterization</td>
<td>41</td>
</tr>
<tr>
<td>4.2 Fluid-Fault Interaction</td>
<td>54</td>
</tr>
<tr>
<td>5 SUMMARY AND CONCLUSIONS</td>
<td>67</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>69</td>
</tr>
<tr>
<td>APPENDICES</td>
<td></td>
</tr>
<tr>
<td>A: Carbon and Oxygen Stable Isotope Data</td>
<td>76</td>
</tr>
<tr>
<td>B: Fluid Inclusion Microthermometry Data</td>
<td>85</td>
</tr>
<tr>
<td>C: Site Descriptions</td>
<td>90</td>
</tr>
<tr>
<td>D: Thin Section Descriptions</td>
<td>101</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>Thermochemical data summary for fluid categories A – D</td>
</tr>
<tr>
<td>A1</td>
<td>Complete calcite carbon and oxygen stable isotope measurements</td>
</tr>
<tr>
<td>A2</td>
<td>Complete list of $T_h$ and $T_m$ measurements, as well as calculated salinities</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>1</td>
<td>Tectonic provinces of the western U.S., modified from (Thompson and Burke, 1974)</td>
</tr>
<tr>
<td>2</td>
<td>Geologic map of the main Hurricane fault study area, modified from (Biek et al., 2010)</td>
</tr>
<tr>
<td>3</td>
<td>Hurricane Fault study area; displaying sample locations, Pliocene and Quaternary basalt flows, and fault strike</td>
</tr>
<tr>
<td>4</td>
<td>Partial stratigraphic column of the Hurricane Fault footwall showing the units sampled, modified from (Dutson, 2005)</td>
</tr>
<tr>
<td>5</td>
<td>Partial cross-section of the Hurricane Fault</td>
</tr>
<tr>
<td>6</td>
<td>Schematic cross-section of fluid flow in a normal fault, showing relative development of the fault core and heavily fractured damage zone in two example rock units of contrasting competency; sandstone and mudstone</td>
</tr>
<tr>
<td>7</td>
<td>Study area location map, showing drainages that are predominantly hosted by limestone vs. sandstone</td>
</tr>
<tr>
<td>8</td>
<td>A typical set of conjugate fractures from field site 1-1</td>
</tr>
<tr>
<td>9</td>
<td>Macroscopic and microscopic examples of damage zone veining</td>
</tr>
<tr>
<td>10</td>
<td>Macroscopic and microscopic examples of fault zone breccias and slip surfaces</td>
</tr>
<tr>
<td>11</td>
<td>Macroscopic and microscopic examples of fault zone host rock alteration</td>
</tr>
<tr>
<td>12</td>
<td>Representative photomicrographs of commonly seen microscopic textures of secondary minerals in the damage zone of the Hurricane Fault</td>
</tr>
<tr>
<td>13</td>
<td>C vs. O stable isotope ratios, broken out by host rock cement and four sets of calcite veins and cement</td>
</tr>
<tr>
<td>14</td>
<td>Study location stereonets, showing a lack of distinct pattern between fracture orientation and vein sets</td>
</tr>
<tr>
<td>15</td>
<td>Drainage transect location 1-2, displaying calcite vein C and O isotope ratios ~ perpendicular to the main fault trace</td>
</tr>
</tbody>
</table>
16  A representative field of 2-phase inclusions from sample 1-2/S-16 ..........38
17  1-phase fluid inclusions from sample 1-2/S-14, showing their relatively sparse nature and 2-3 µm aperture .................................................................38
18  Homogenization (T_h) and melting (T_m) temperatures of fluid inclusions from samples categorized as calcite set 1 and 3 from stable isotope and morphologic characteristics ..........................................................39
19  Theoretical carbonate δ^{13}C and δ^{18}O curves ........................................43
20  A range of fluid compositions and precipitation temperatures calculated or postulated to fit the observed calcite vein set stable isotope data ..........44
21  1-2/S-16 T_h and T_m measurements highlighting their variation from the majority of calcite set 3 measurements and the distinction of fluid X ..........49
22  Generalized fluid flow pathways of fluids X and Y ........................................55
23  Isotope ratio overprinting of host rock cement adjacent to a vein in the Hermit Formation .................................................................................................................58
24  Isotope ratio alteration of limestone adjacent to a fibrous vein in the Brady Canyon member of the Toroweap Formation .............................................59
25  Cross-polarized photomicrograph of one vein within a network of boxwork veins highlighting the indistinct boundary between the vein (left) and the cemented host rock (right) ...............................................................60
26  Spatial distribution of fluid-rock interaction evidence from vein sets corresponding to fluid categories A – D .................................................................63
27  Paragenesis of fluid-fault interaction for fluid categories A, C, and D based on field, stable isotope, and fluid inclusion data from canyon 1-2 ..........64
28  Paragenesis of fluid-fault interaction for fluid categories A – C based on field, stable isotope, and fluid inclusion data from canyon 1-4 ..........65
CHAPTER 1.

INTRODUCTION

Faults in the upper crust affect the volume, distribution, and accessibility of important fluid resources including groundwater, hydrocarbons, and mineralizing fluids related to ore deposit development (Mozley and Goodwin, 1995; Caine and Minor, 2009; Cao et al., 2010). Faults can act as conduits, barriers, or combined conduit/barrier systems with respect to fluid flow, depending on the fault zone structure, host rock properties, and in-situ stress conditions (Caine et al., 1996). Minerals and textures in fault rocks reflect past fluid-rock interaction by recording changes in paleofluid composition and temperature through time (Mozley and Goodwin, 1995; Benedicto et al., 2008; Eichhubl et al., 2009; Caine et al., 2010). Prior work has addressed the paleofluid history of major normal faults by utilizing the mineral record, which exhibit changes in fluid chemistry over the course of fault evolution (Mozley and Goodwin, 1995; Benedicto et al., 2008; Eichhubl et al., 2009). They interpreted changes in fluid chemistry based on the mineral assemblage of veins and stable isotope ratio of precipitated carbonates. Temporal and spatial variability in fluid-fault interaction highlights the necessity for paleohydrology fault investigations in active tectonic settings.

The Hurricane Fault is a major active fault located in the transition zone between the Basin and Range and Colorado Plateau tectonic provinces (Figure 1, Figure 2), and has been regarded as an archetypal example of normal faulting for over 100 years (Anderson and Mehnert, 1979). The fault has a prominent topographic expression juxtaposing Mesozoic and Paleozoic sedimentary rocks along its strike in southern Utah and northern Arizona (Figure 2). This structure offsets Pliocene and Quaternary volcanic
rocks, which are used to estimate slip rates (Sanchez, 1995; Stewart and Taylor, 1996).

Prior work on fluid movement along this fault is restricted to the modern system at Pah Tempe hot spring, issuing from the Hurricane Fault zone near La Verkin, UT, and the warm springs of Travertine Grotto and Pumpkin Springs where the fault intersects the Colorado River in Grand Canyon. At Pah Tempe, meteoric groundwater flow along the fault is causing active diagenesis via dissolution of carbonate rich rocks along deep

Figure 1: Tectonic provinces of the western U.S., modified from (Thompson and Burke, 1974)
Figure 2: Geologic map of the main Hurricane fault study area, modified from (Biek et al., 2010)
flow-paths and subsequent precipitation of carbonate veins in the fault zone near the surface (Nelson et al., 2009). Travertine Grotto and Pumpkin springs are attributed to meteoric water mixing with deep-crustal or “endogenic” fluids convected upwards along the basement-rooted Hurricane Fault (Crossey et al., 2006, 2009).

Periods of basaltic magmatism associated with Basin and Range extension may have created hydrothermal systems in the past that locally influenced groundwater chemistry and circulation in the Hurricane Fault. Analysis of volatiles exsolving from Pah Tempe hot springs identified only minimal modern contributions from mantle or magmatic sources (Nelson et al., 2009). Although magmatic centers that are (or were) contemporaneous with active faulting parallel the Hurricane Fault, the exact relationship between the two is not known (Sanchez, 1995).

Based on these factors, the Hurricane Fault presents an ideal opportunity for a study of fluid-fault interaction in the Basin and Range – Colorado Plateau transition zone. This study investigates the spatio-temporal thermochemical history of paleofluids and fluid-rock interaction in the Hurricane Fault zone. I hypothesize that fault zone diagenesis is mainly caused by meteoric water infiltration that chemically interacts with marine carbonates. Here, I characterize paleofluids with macroscopic fault zone investigations and sampling, conducting microscopic (petrographic) analysis of fault-related rocks, stable isotope analysis of oxygen and carbon in calcite, and fluid inclusion microthermometry measurements. Results reveal that the paleofluid history is dominated by upwelling of basin brines in conjunction and mixed with meteoric water infiltration and fluid-rock interaction. This history is punctuated by at least one episode of fluid flow that was likely chemically influenced by late Tertiary-Quaternary magmatism.
1.1 Geologic Background

The Hurricane Fault is a major N – S striking normal fault that marks the eastern extent of the transition zone between the Colorado Plateau and the Basin and Range tectonic provinces in southwest Utah and northwest Arizona (Figure 1) (Thompson and Burke, 1974; Schramm, 1994). Basin and Range extension began in the late Eocene following the Sevier and Laramide orogenies (Axen et al., 1993). The Sevier orogeny initiated ~125 Ma due to subduction on the western margin of North America, resulting in fold and thrust belts (Heller et al., 1986). Sevier-related deformation progressed eastward due to shallowing of the subduction angle until ~ 75 Ma when the subducted plate encountered the relatively strong lithosphere of the Colorado Plateau (Livaccari, 1991). This caused the initiation of the Laramide orogeny, which was characterized by basement-cored uplifts. Active deformation for the Sevier and Laramide orogenies ceased in the late Eocene.

Normal faults of the Basin and Range broadly follow Proterozoic accretionary and Sevier-Laramide compressional structural fabrics to accommodate late Paleogene normal stress (Armstrong, 1968; Quigley et al., 2002). The Basin and Range province displays ~ 60 – 100 % extension at 37° N latitude, where the Colorado Plateau divides the northern and southern portions of the Basin and Range (Zandt et al., 1995). Extension was associated with widespread volcanism, caused by thermal weakening of subducted oceanic lithosphere and gravitational collapse of thickened crust (Axen et al., 1993). Extension along the eastern margin near St. George, UT did not begin until ~ 15 Ma (Axen et al., 1993). The Colorado Plateau province is largely un-deformed by recent Basin and Range extension, and the transition from the relatively thin crust of the Basin
and Range to the thick, strong crust of the Colorado Plateau occurs over a ~ 100 km wide interval (Zandt et al., 1995). The eastern margin of the transition zone is also coincident with the Intermountain Seismic Belt, with multiple seismically active normal faults (Smith et al., 1989). Late Cenozoic volcanism along the margin between the two tectonic provinces is bimodal, indicative of high heat flow and partial melting from the mantle at 65 – 95 km (Best and Brimhall, 1974).

The Hurricane Fault is a 250-km long, west dipping normal fault in southwestern Utah and northwestern Arizona with poorly constrained origins in the mid-Miocene to Pliocene (Lund et al., 2007; Biek et al., 2010). Fault activity occurred predominantly in the Pleistocene including up to 550 m of its total 600 – 850 m of vertical displacement (Lund et al., 2007). Six segments of the Hurricane Fault are 30 – 40 km long and have been defined based on geometric and structural complexities at segmentation boundaries (Figure 3) (Pearthree et al., 1983; Stewart and Taylor, 1996; Stenner et al., 1999). Delineation of seismogenic segments is difficult due to the lack of demonstrable differences in seismologic histories across geometric boundaries (Stenner et al., 1999). The fault is active, with a magnitude 5.8 earthquake occurring in 1992 east of St. George, Utah with a focus at ~15 km depth along the projected dip of the fault surface (Stewart and Taylor, 1996).

Quaternary basaltic volcanic centers are spatially associated with this fault. Basalt flows frequently span both the footwall and hanging wall. Offset flows were used as the primary means of dating slip rates (Lund et al., 2007). Basaltic volcanism in the eastern
Figure 3: Hurricane Fault study area; displaying sample locations, Pliocene and Quaternary basalt flows, and fault strike.
Basin and Range and transition zone regions began approximately 15 Ma but has been most active within the last 2.5 My (Nelson and Tingey, 1997). Volcanism shows a north-south trend and volcanic eruptions are predominantly alkali-rich basalts with lesser basaltic andesite. Neodymium isotope ratios of Quaternary basalts reflect primarily lithosphere sources along the northern half of the Hurricane Fault and asthenosphere/mixed source to the south (Crow et al., 2011). The division occurs approximately 25 km south of the Utah-Arizona border.

Figure 4: Partial stratigraphic column of the Hurricane Fault footwall showing the units sampled, modified from (Dutson, 2005).
Figure 5: Partial cross-section of the Hurricane Fault. See Figure 2 for location. The Moenkopi and Chinle formations are projected above the ground surface, since they are encountered and sampled elsewhere along the fault. The Hermit formation is also shown, although it pinches out ~ 15 km south of the cross section. Modified from (Biek, 2003).

Rock types juxtaposed by the fault are predominantly sandstone, marine limestone, mudstone, and evaporites (Figure 4) (Billingsley and Workman, 2000; Billingsley and Wellmeyer, 2003; Rowley et al., 2008; Biek et al., 2010). The hanging wall is broadly covered by Quaternary colluvium and underlain by Jurassic and Triassic rocks, and Triassic and Permian units are exposed in the footwall (Figure 5).
Moenkopi, Kaibab, Toroweap, and Pakoon Dolomite Formations all contain members dominated by gypsum and carbonates. The Hermit Formation is fine-grained quartz rich sandstone with minor feldspar grains and common hematite grain overgrowths, cemented by calcite. The Queantoweap Sandstone is composed of massive to horizontally bedded quartz rich sandstone, cemented by calcite and quartz.

1.2 Fluid Flow in Fault Zones

Fault zone architecture creates a distinct hydrologic system, causing faults to act as conduits and barriers for groundwater flow along strike and dip. Fault zones can be broken up into three basic units: the fault-core, the damage zone, and the protolith (Figure 6) (Caine et al., 1996; Evans et al., 1997). The fault-core and damage zone may act as separate hydrologic units, controlling fluid flow along the fault by the ratio of damage zone to fault-core. This ratio controls whether a fault will act as a barrier, conduit, or combined barrier/conduit to fluid flow. It can vary up and down-dip, along strike, with rock type, and as a function of fluid-rock interaction in and near the fault. Shale-rich and other low-competency layers are fault-core dominated, whereas high competency layers such as sandstone and limestone, like those present along the Hurricane Fault, tend to be damage zone dominated (Figure 6). Grain size reduction and breccia cementation in the fault-core typically result in lower porosity/permeability of fault-cores relative to the host rock and the damage zone. Once the fault-core is established it can disrupt regional fluid flow and communication between aquifers. Dense fracture networks in the damage zone result in high secondary permeability that is 2-3 orders of magnitude higher than the normally fractured protolith and 4-6 orders of magnitude higher than the fault-core (Caine et al., 1996). The result may be fault-parallel fluid flow focused in the damage
Figure 6: Schematic cross-section of fluid flow in a normal fault, showing relative development of the fault core and heavily fractured damage zone in two example rock units of contrasting competency; sandstone and mudstone. Example regional groundwater flow shown in blue, with number and thickness of lines representing relative fluxes.

zone, causing pervasive diagenesis and mineralization. Fluid flow is progressively more focused along fault zones as depth increases, because of the protolith’s high susceptibility to permeability reduction with increasing pressure relative to the damage zone and fault core (Evans et al., 1997).

Fault-related fluid flow is commonly expressed as springs at the Earth’s surface. Localized, meteorically-fed geothermal springs influenced by geothermal gradient-driven convection are a common expression of fluid flow (Kilty et al., 1979). In addition to topographically driven hydraulic head, convection along zones of high permeability is a primary mechanism for fluid flow from depth to the surface (Forster et al., 1997). For meteorically fed convective fluid cells to form there typically must be a confining unit, which is disrupted by the fault zone that the springs issue from, that overlies an aquifer at depth (Forster and Smith, 1989). Geothermally-heated fluids primarily issue from low permeability rocks that are dominated by zones of high fracture density (Forster et al.,
1997). Lateral, fault-strike parallel fluid flow can also be deflected up-dip along a fault at segment boundaries, resulting in springs (Kilty et al., 1979).
CHAPTER 2.

METHODS

2.1 Field Methods

Field investigations along the Hurricane Fault were conducted between 37°30’ and 36°20’ North, from approximately Cedar City to the fault’s intersection with Grand Canyon to identify and sample evidence of paleofluid flow (Figure 3). Studies were restricted to well-exposed areas of the fault zone, typically where drainages cross-cut the fault. Because of Quaternary cover on hanging wall rocks, this study focused on the exposed footwall rocks. Twenty-four sites along the 250-km long Hurricane Fault were investigated. Drainage transects were documented, with particular attention paid to zones 10 – 20 m wide (orthogonal to the fault trace) of relatively high fracture density where there was diagenetic evidence of paleofluid flow. Cross-cutting relationships and diagenetic observations were recorded, and 173 hand samples were collected for laboratory analysis. Representative samples were chosen for vein morphology, direct cross-cutting vein relationships, varying vein/fracture orientations, and a range of apparent diagenetic modification, including unaltered host rocks. Hand samples were collected using a mini-sledge hammer and chisels. Geographic coordinates of samples were recorded in UTM – WGS 1984 using a Garmin Rino110 GPS unit.

Fracture density, spacing, aperture, fracture orientations, and approximate distance from the fault trace were recorded within zones of interest. Fracture density as fractures per meter was recorded in one dimension roughly orthogonal to the fault trace into the hanging wall. Fracture density was measured using a 1 m tape measure, and
small, discontinuous weathering related cracks were omitted from counts. Fracture orientations were measured using a standard Brunton Compass.

2.2 Microscopy

2.2.1 Microscopy Sample Selection and Preparation

Standard thin sections were made from 34 representative hand samples displaying diagenetic alteration. Thin section duplicates were made of each of the 15 thick sections in order for direct relation of fluid inclusion analyses to petrographic observations. Wagner Petrographic® prepared thin sections with the following specifications; 24x46 mm, 30 μm thick, and without cover slips.

2.2.2 Microscopy Sample Analysis

Thin section petrographic observations were made using a Leica Z16 APO microscope and Leica DM 2700P petrographic microscope. An attached Leica MC 170 HD camera was used to take photomicrographs. The Leica Application Suite 4.6 software was used to acquire images and perform basic processing.

2.3 Carbonate C and O Stable Isotope Analysis

2.3.1 Stable Isotope Sample Selection and Preparation

A total of 298 samples from calcite veins, mineralized fracture surfaces, limestone, and calcite-cemented sandstones were collected using a Dremel® tool. Sub-sampling of hand samples targeted distinct veins, individual laminations of veins, morphologically distinct sections of heterogeneous veins, and adjacent host-rock. The
purpose of sub-sampling was to capture C and O stable isotopic variation spatially and temporally along the Hurricane Fault at the vein scale.

2.3.2 Stable Isotope Sample Analysis

Carbon and oxygen stable isotope ratio analysis of calcite veins and cements was performed in the Department of Geology Stable Isotope Laboratory at Utah State University using a Thermo Scientific Delta V Advantage Isotope Ratio Mass Spectrometer (IRMS) and a GasBench II with a GC PAL auto-sampler. ISODAT 3.0 Gas Isotope Ratio MS Software® was used to collect data from the mass spectrometer and perform basic data reduction.

Standards and relatively pure carbonates from veins and slip surfaces were weighed out between 150 – 200 μg. Samples of host rock carbonate cements mixed with oxides and silicates were weighed out from 300 to 8000 μg to target peak amplitudes (mass 44) between 2500 – 15,000 mV. All weighed samples and standards were loaded into 12 mL EXETAINER® vials.

The carbonate-phosphoric acid digestion method was used to liberate CO$_2$ from the carbonate samples for subsequent analysis (Eq. 1) (McCrea, 1950).

$$3\text{CaCO}_3 + 2\text{H}_3\text{PO}_4 \rightarrow 3\text{CO}_2 + \text{Ca}_3(\text{PO}_4)_2.$$  (1)

Vials were placed into a 50°C reaction tray and flushed with ultra-high purity helium for 6 minutes. After flushing, 100 μL of anhydrous phosphoric acid was added to each sample and allowed to react for two hours at 50°C to ensure complete dissolution and CO$_2$ release (McCrea, 1950). The generated CO$_2$ is transferred to the gas-bench via helium carrier gas for separation and purification, then input to the IRMS. Stable isotope
ratios of C and O were determined by measuring CO$_2$ masses 44, 45, and 46 of each sample relative to an in-house CO$_2$ reference gas.

Three international standards, NBS 18, NBS 19, and LSVEC, were measured in duplicate to perform a 3-point calibration to the Pee Dee Belemnite (PDB) scale. Yule marble 120, an in-house calcite standard, was placed once every ~10 samples to correct for drift. Another in-house calcite standard, Yule marble 80, was weighed out at 50 μg increments from 50 – 300 μg for use in linearity correction. Carbon isotope ratios are reported using delta notation ($\delta$) in per mil (‰) on the PDB scale (Eq. 2), and oxygen isotope ratios are reported using the same notation on the PDB (Eq. 3) and standard mean ocean water (SMOW) scales (Eq. 4).

$$\delta^{13}C_{\text{sample PDB}} = \left( \frac{^{13}C_{\text{sample}}}{^{12}C_{\text{standard PDB}}} - 1 \right) \times 1000$$ \hspace{1cm} (2)

$$\delta^{18}O_{\text{sample PDB}} = \left( \frac{^{18}O_{\text{sample}}}{^{16}O_{\text{standard PDB}}} - 1 \right) \times 1000$$ \hspace{1cm} (3)

$$\delta^{18}O_{\text{sample SMOW}} = 1.03091 \times \delta^{18}O_{\text{sample PDB}} + 30.91$$ \hspace{1cm} (4)

Errors were calculated by averaging the standard deviations of all triplicate samples for each run, ranging from 0.03 to 0.27 ‰ for C and 0.08 to 0.35 ‰ for O (Table A1).

### 2.4 Fluid Inclusion Microthermometry

#### 2.4.1 Sample Selection and Preparation

Sparry calcite veins of 15 representative samples were chosen for fluid inclusion microthermometry. Wagner Petrographic® prepared thick sections of submitted samples with the following specifications: 24 x 46 mm, 150 μm thick, doubly polished, and
adhered to a glass slide with super glue for later removal. For placement in the heating and freezing stage, thick sections were removed from the glass slides by soaking in acetone for ~ 10 – 48 hours. Sections were then broken into smaller chips for re-mounting to 1-inch glass rounds with a small dab of super glue.

2.4.2 Sample Analysis

149 homogenization temperatures (T_h) and 49 melting temperatures (T_m) were determined from two-phase fluid inclusions in calcite using a modified USGS gas-flow heating-freezing stage. The stage was calibrated to the critical point of water using a synthetic supercritical H_2O inclusion (374.1 °C), the freezing point of a synthetic 25 mol % CO_2-H_2O inclusion (-56.6 °C), and the freezing point of distilled water using an ice bath (0 °C). State changes in the fluid inclusions were observed using a Zeiss Universal transmitted light microscope with a Zeiss Epiplan 50x long-working distance objective. Photographs of fluid inclusions were taken with a Canon Powershot G7 10MP digital camera.

T_h and T_m were determined using heating and freezing cycling procedures described by Goldstein and Reynolds, (1994). After performing heating measurements, numerous 2-phase fluid inclusions with homogenization temperatures from 45 – 85 °C became metastable 1-phase liquid inclusions. In order to re-nucleate a bubble to determine freezing temperatures, all samples were intentionally stretched by heating them at 110 °C for 18 hours in a laboratory oven (Goldstein and Reynolds, 1994).

No pressure correction was performed to convert T_h measurements to trapping temperatures (T_t). Assuming vein formation at a maximum depth of 800 m (maximum throw on the fault), a maximum pressure using a lithostatic load (2675 kg/m^3 rock
density), and the maximum measured \( T_h \) of 160 °C, the pressure correction is <10 °C and considered insignificant for this study (Table A2) (Fisher, 1976; Anderson and Mehnert, 1979). \( T_h \) measurements in this study are considered representative of \( T_t \).
CHAPTER 3.

RESULTS

3.1 Fault Zone Diagenesis

In this section, I describe the variety of mineralization and alteration products that are observed in the footwall of the Hurricane fault. Examination of the fault zone at 23 field sites reveals that it is composed of a damage zone >10 – 400 m wide (the extent of the damage zone not known, due to limited access in the drainages) and a rarely exposed fault core 0.5 – 2 m wide. The record of paleofluid flow and deformation is primarily preserved in competent units of sandstone and limestone within the damage zone. Observed features are dependent on the host rock type, with differences between the 12 sandstone and 11 limestone hosted sections (Figure 7). Mixed carbonate and siliciclastic strata are found at 4 field sites and are classified as limestone if they are matrix supported. Diagenetic products include host rock alteration, mineralized slip surfaces, and veins. Secondary minerals include calcite, hematite, manganese oxide (pyrolusite?), and gypsum. Reduction and oxidation (redox) features are observed in fine-grained sandstone strata with calcite and iron oxide cements. Manganese and iron oxide vein cements and brecciated veins are also primarily observed in sandstone strata. Sparry calcite veins are the most common diagenetic feature in limestone strata. See Appendix C for a compilation of observed features by field site.

Diagenetic products are most commonly associated with zones of dense fracturing, although sparse veins occur throughout the damage zone. Fracture density
Figure 7: Study area location map, showing drainages that are predominantly hosted by limestone vs. sandstone.

Figure 8: A typical set of conjugate fractures from field site 1-1
varies from ~2 to 20 m\(^{-1}\) within the Hurricane Fault’s damage zone. Densely fractured zones of 10–20 m\(^{-1}\) are 1–2 m wide and were pervasively mineralized (Figure 11A). Fracture orientations typically follow two main sets: one striking 0 ± 10° sub-parallel to the fault, and one 300 ± 15°, both dipping 90 ± 20° (Figure 8, Figure 14).

3.1.1 Veins and Fracture Coating

Veins and fracture coatings (<1 mm thick) are commonly observed features in the damage zone (Figure 9A & C). Cross-cutting veins indicate that multiple episodes of fracturing and mineralization occurred, with evidence for fracture reactivation (Figure 7E). Calcite is the most common fracture and vein precipitate, found at every field site investigated. The majority of veins are filled with sparry calcite, particularly within limestone strata. Interconnected, web-like “boxwork” calcite veins are common in sandstone within ~50 m of the main fault trace and contain entrained quartz grains (Figure 9D).

Other precipitates include manganese oxides, hematite, and gypsum. Intergrown oxide and calcite veins are commonly observed in calcareous sandstone strata that contain minor oxide cement (Figure 9A & C). The Hermit Formation hosts most of these secondary minerals, particularly well-exhibited at sites 1-4 and 5-2 to 5-3. Although the majority of calcite + oxide veins are found within sandstone and sandy limestone strata, one location (site 1-2) hosts intergrown calcite and hematite veins in cherty limestone (Figure 3, Figure 9B). They are located within a ~10 m wide zone of dense fracturing (~5 m\(^{-1}\)) relative to the surrounding damage zone (~2 m\(^{-1}\)). These are syntaxial and fibrous veins with alternating bands of calcite and hematite (Figure 9F). Gypsum veins are rare,
present only within and immediately stratigraphically adjacent to gypsum-rich facies at site 4-11.

3.1.2 Breccias and Slip Surfaces

Mesoscopic structures associated with slip along the Hurricane Fault include fault-core breccias, brecciated veins, and striated slip surfaces. Small-scale displacement along minor subsidiary faults is common within the damage zone. Slip is identified on small faults by striated slip surfaces and comminuted breccia veins, as there is an absence of stratigraphic markers of displacement (Figure 10).

Fault-core breccias along the main trace of the fault are exposed in two locations (1-2 and 4-2) between the footwall damage zone and the buried trace of the fault, both adjacent to cherty limestone units. They are preserved as carbonate cemented and weathering-resistant “fins”. Fault-core breccias exhibit grain size reduction, with fractured clasts of chert being the dominant host-rock clast (Figure 10A & B). Alternating bands of calcite and brecciated host rock within the breccia indicate multiple planes of strain distribution (Figure 10B).

Brecciated veins are observed in the fine-grained sandstone of the Hermit Formation, particularly sites 1-4 and 5-2 to 5-3. They are matrix-supported and cemented by hematite and calcite (Figure 10C & D). They are present within zones of relatively high fracture density (≥5 m⁻¹) and associated with redox alteration of the host rock. Brecciated veins contain angular to sub-rounded clasts of partially dissolved calcite and hematite cement as well as host rock clasts in a matrix supported fabric (Figure 10D). Angular clasts are jigsaw-piece shaped and heterogeneous in size (Figure 10C). There is evidence for multiple generations of brecciation (Figure 10D).
Figure 10: Macroscopic and microscopic examples of fault zone breccias and slip surfaces. A) Calcite-cemented fault core breccia showing alternating bands of well-cemented and poorly cemented clasts. Location: 4-2. Key sample: 4-2/S-1. B) Photomicrograph of (A) showing increased comminution and concentration of host rock clasts in discrete bands (outlined). See thin section description in Appendix D for details. Location: 4-2. Key sample: 4-2/S-1. C) Brecciated vein cemented by calcite. Host rock clasts are lined by hematite and elongated parallel to the vein orientation. Location: 5-2to5-3. Key Sample: 5-2to5-3/S-8 D) Photomicrograph of (C) showing multiple generations of brecciation and cementation. See thin section description in Appendix D for details. Location: 5-2to5-3. Key Sample: 5-2to5-3/S-8 E) Calcite and hematite coated slip surface in the damage zone of the fault. Location: 1-5. Key Sample: 1-5/S-3 F) Photomicrograph of a calcite and hematite coated slip surface, showing two separate polished surfaces on either side of the calcite veneer. Sample: 1-5/S-3
Striated slip surfaces are common throughout the damage zone at each study location. They are commonly coated by slickenfibres of calcite that vary from <1 mm to multiple cm thick or intergrown calcite and hematite ≤2 mm thick. Polished slip surfaces are composed of multiple discrete planes, implying multiple stages of slip (Figure 10F).

3.1.3 Host Rock Alteration – Redox Features and Concretions

In the siliciclastic strata of the Queantoweap Sandstone and Hermit Formation, evidence for fluid-rock interaction in the fault zone includes fracture-related redox features and intragranular cement. Dissolution of iron and manganese oxide cements is common where the Hurricane Fault exposes these units, from ~ 5 – 60 km south of Hurricane, UT. Zones of white – light tan colored alteration radiate from fault-parallel fractures, from here on referred to as bleaching (Figure 11). Bleaching halos vary in width from fracture to fracture, and along individual fractures (Figure 11D). Fracture parallel bleaching halos up to ~ 1 m wide are found in densely fractured zones (≥5 m⁻¹), and narrower halos between 0.1 and 3 cm wide dominate where fracture densities are lower (Figure 11). Alternating stratigraphic horizons ~ 1 – 2 m thick are also bleached, with finer-grained lenses separating them (Figure 11A).

Evidence of oxidation occurs as fracture-related precipitation of manganese and iron oxides. Manganese oxides radiate from fractures in dendritic patterns, and iron oxides are intergrown with calcite in brecciated veins (Figure 9C, Figure 11D). Fracture parallel secondary oxide cement precipitation is observed in oxide-poor facies, stratigraphically adjacent to red beds within the Hermit Formation (Figure 11C). Recementation and fracture-parallel calcite concretions occur in siliciclastic host rock around bleaching and tanning halos (Figure 11D).
Figure 11: Macroscopic and microscopic examples of fault zone host rock alteration. A) ~1.5 m wide zone of dense fracturing, showing reduction or “bleaching” and dissolution of hematite cement in the host sandstone. Bleaching extends laterally into the host rock in discrete layers, separated by fine-grained, clay-rich boundaries. Bleaching is incomplete, as evidenced by a wedge of unbleached host rock within a discrete layer (outlined). Location: 1-4. Key sample: 1-4/S-24. B) Bleaching halo with variable width, narrower in stratigraphic bands of denser iron oxide cement. Key Sample: 4-12/S-6 C) Fracture-related oxide staining in sandstone. Location: 1-4. Key Sample: 1-4/S-14 D) Calcite and hematite cemented breccia vein with associated parallel band of calcite concretions, and later fracture coating by calcite. This complex vein with a multi-stage history is within a densely fractured and bleached zone. Location: 1-4. Key Sample: 1-4/S-4 E) photomicrograph of a calcite concretion (outlined) See thin section description in Appendix D for details. Location: 1-4 Key Sample: 1-4/S-27
Calcite concretions are prevalent in siliciclastic strata as well. Calcite cement concentration is increased adjacent to fractures, and in association with boxwork veins (Figure 9D, Figure 11D). These features are most clearly observed at locations 1-4 and 1-5. In thin section, areas of increased calcite cement and lower porosity coalesce into matrix-supported concretions. These concretions are crystallographically aligned in some cases (Figure 11E).

3.1.4 Petrographic Characteristics

Microscopic observations confirmed and supported macroscopic observations, providing textural context for the formation of veins and cements. Complete thin section descriptions may be found in Appendix D. Veins, slip surfaces, and cemented breccias displayed textural differences in thin section between sandstone and limestone host rock.

The majority of calcite veins are sparry and show no distinct fabric (Figure 12A). Calcite veins show a shear fabric at the margins and deformed twinning in rare samples within limestone host rock (Figure 12B). Veins hosted in siliciclastic rock lack a distinct boundary between the vein and host rock (Figure 12C). They often form a network of interconnected boxwork veins with a mixture of sparry and microcrystalline calcite (Figure 12C).

Calcite and hematite are commonly intergrown in veins, primarily in siliciclastic units. In the Brady Canyon member of the Toroweap Formation, intergrown calcite and hematite form banded, fibrous veins (Figure 9F). Calcite crystals show undulating extinction and alternate with hematite as the dominant mineral. Bands dominated by hematite terminate at multiple planar breaks throughout the vein. Calcite and hematite cemented breccia veins are common in the siliciclastic Hermit Formation.
Figure 12: Representative photomicrographs of commonly seen microscopic textures of secondary minerals in the damage zone of the Hurricane Fault. A) Sparry calcite veins in a fossiliferous limestone. Sample 4-7/S-1.5 B) Sparry calcite grain showing deformation twinning. Sample 5-4/S-3 C) Boxwork calcite veins showing the indistinct boundary between vein and host rock. Sample 1-5/S-1 D) Brecciated vein cemented by hematite and calcite. Sample 5-2/S-12 E) Brecciated vein cemented by hematite and calcite, showing linear shear fabric. Sample 4-1/S-5 F) Manganese oxide dendrite cementing intergranular pore space in a sandstone. Sample 1-4/S-17
Figure 12 continued
Host rock clasts are rimmed by hematite 10s to 100s of µm thick (Figure 12D). Intergrown, sparry calcite and hematite cement grains are rimmed and cross-cut by microcrystalline calcite cement and boxwork calcite veins (Figure 10D). Sparry calcite grains intergrown with hematite also display partial to whole dissolution in some cases (Figure 10D). Similar to calcite boxwork veins, there is a general sense of shear in the breccia veins and their connected boxwork veins (Figure 12E). Manganese oxide radiates from mineralized fractures within the Hermit Formation as well, filling the pore space between quartz grains and forming dendrites (Figure 12F).

Fault core breccias and mineralized slip surfaces give microscopic evidence of displacement. Fault core breccias show grain size reduction and multiple clast vs. cement dominated bands (Figure 10B). Slickenfibres do not show grain elongation in the direction of slip, although this may be due to the angle at which thin sections were cut (Figure 10F).

3.2 Vein Geochemistry

3.2.1 Carbon and Oxygen Stable Isotope Ratios

Calcite veins and host rock calcite cements from every field site were analyzed for stable isotope ratios of C and O. A complete list of values, errors, and sample classification is provided in Appendix A. Primary carbonate in siliciclastic and limestone host-rock was analyzed directly adjacent to veins and at ~ 1 – 2 m away for comparison. The $\delta^{13}$C_PDB values range from -4.5 to 3.8 ‰ and $\delta^{18}$O_PDB values from -17.7 to -1.1 (Figure 13). Cements are further divided based on the presence of damage zone-related alteration. “Unaltered” cement $\delta^{13}$C_PDB values range from -2.0 to 3.8 ‰ and $\delta^{18}$O_PDB...
values from -8.5 to -1.1 ‰. “Altered” cement $\delta^{13}\text{C}_{\text{PDB}}$ values range from -4.5 to 2.8 ‰ and $\delta^{18}\text{O}_{\text{PDB}}$ values from -17.7 to -8.6 ‰.

Calcite veins, breccia cements, mineralized fractures, and slip surfaces are separated into 4 sets (Figure 13). This is done based on isotopic expression in $\delta^{13}\text{C} - \delta^{18}\text{O}$ space, and common field associations and morphologic features described in the previous section. Calcite sets span multiple locations and, with the exception of set 4, show no pattern in C and O isotope ratios with structural orientation along strike of the fault (Figure 14). Multiple sets are found within individual drainage transects (17 of 24),
Figure 14: Study location stereonets, showing a lack of distinct pattern between fracture orientation and vein sets.

cross-cutting each other at the outcrop to hand sample scale rather than study location-scale (Figure 15).

Set 1 calcite exhibits a strong positive correlation between C and O, and is commonly intergrown with hematite when hosted in siliciclastic strata. $\delta^{13}$C$_{PDB}$ values range from -0.5 to 4.0 ‰ and $\delta^{18}$O$_{PDB}$ values from -22.1 to -13.5 ‰. Calcite in set 2 displays a weaker positive correlation in isotope ratios that are shifted to lower $\delta^{13}$C
of the fault face, although this does not hold true for most drainages. Emphasizing the importance of quarter-scale and hand sample variability, calcite set I is observed only within 75 m of the fault face. A wide spread of isotopic values (~7% to 15% D and ~15% to 10% O) is observed over distances of >10 m from the fault face.

Figure 15: Drainage transect location 1-2, displaying calcite vein C and O isotopic ratios perpendicular to the main approximate distance (m) from fault face.
values compared to vein set 1. $\delta^{13}\text{C}_{\text{PDB}}$ values range from -5.3 to 2.4 ‰ and $\delta^{18}\text{O}_{\text{PDB}}$ values from -20.2 to -13.5 ‰. Calcite from set 3 has a wide range of isotopic values, showing no strong trends or patterns. Set 3 typically shows intergrown MnO when hosted in the Hermit Formation. $\delta^{13}\text{C}_{\text{PDB}}$ values range from -3.0 to 3.2 ‰ and $\delta^{18}\text{O}_{\text{PDB}}$ values from -13.5 to -5.0 ‰. Set 4 calcite is isotopically similar to set 3 in terms of $\delta^{18}\text{O}$, but shows a shift in $\delta^{13}\text{C}$ values to significantly lower values. The majority of these data are from location (1-2), where calcite is intergrown with hematite in fibrous bands (Figure 9F). Additional samples that fall into set 4 isotopically include calcite coated slip surfaces (locations 4-2 & 2-2). Set 4 $\delta^{13}\text{C}_{\text{PDB}}$ values range from -7.0 to -1.4 ‰ and $\delta^{18}\text{O}_{\text{PDB}}$ values from -10.9 to -6.0 ‰.

### 3.2.2 Fluid Inclusion Microthermometry

Samples of 2-phase fluid inclusions in calcite veins were analyzed for homogenization ($T_h$) and melting ($T_m$) temperatures. Homogenization temperatures are used to approximate the trapping temperature and are thus representative of fluid temperatures during mineralization. Melting temperatures depend on the nature and concentration of dissolved species, and are used to estimate the salinity of precipitating fluids (Bodnar, 1992). Metastability was an issue with melting temperature measurements, particularly of fluid inclusions which had been intentionally stretched, resulting in positive melting temperatures. These were not used in salinity calculations. All homogenization and melting temperature data can be found in Table A2, Appendix B.

15 key samples, spanning each of the 4 vein sets, were investigated. Of these, 7 contained 2-phase fluid inclusions. 2-phase fluid inclusions ranged from ~ 5 – 40 µm in
size on the long axis (Figure 16). Most inclusions appear to be primary and there was little evidence available to identify trails of secondary inclusions. Therefore, no fluid inclusion assemblages are assigned to data. The majority of samples containing only 1-phase (Table A2) inclusions measured ≥15 μm long on the long axis. 1-phase inclusions
Figure 18: Homogenization (T_h) and melting (T_m) temperatures of fluid inclusions from samples categorized as calcite set 1 and 3 from stable isotope and morphologic characteristics. A) T_h measurements. B) T_m measurements and associated calculated salinities.
in one outlier sample (1-2/S-14) measuring ~ 2 – 3 \( \mu \)m long, with very rare inclusions up to 10 \( \mu \)m long (Figure 17).

In addition to calcite-hosted fluid inclusions, one boxwork vein sample (1-4/S-27) contained entrained quartz grains with 2-phase fluid inclusions and inclusion trails. Analysis revealed a \( T_h \) range of 60 – 260 °C and \( T_m \) range of -24 to 0 °C. It is concluded that the sources are varied and the data is not used in this study focused on calcite veins.

Fluid inclusion homogenization and melting temperature data is categorized by the calcite vein set (see section 3.2.1). Data for vein sets 2 and 4 are not reported due to a lack of observed 2-phase fluid inclusions. Homogenization temperatures from samples categorized as calcite set 1 range from 45 – 90 °C (Figure 18). Vein set 3 samples have homogenization temperatures from 55 – 160 °C. Their distribution is skewed towards lower temperatures, with a mode at 65 – 70 °C.

Melting temperatures from calcite set 1 range from -3 – 0 °C, equating to a salinity of 0 to 5 wt% NaCl (Figure 18B). Calcite set 3 displays melting temperatures from -11 – 4 °C, equating to 0 to 15 wt% NaCl. Since no initial melting was observed, NaCl dominated salinity is assumed and calculated via Eq. 5 (from Bodnar, 1992).

\[
\text{Salinity} (\text{wt\% NaCl}) = 0.00 + 1.78T_m - 0.0442T_m^2 + 0.000557T_m^3 \quad (5)
\]
CHAPTER 4.
DISCUSSION

4.1 Vein Sets/Fluid Categories – Thermochemical Characterization

Four vein sets were defined using common morphologic features found in the field and carbon and oxygen stable isotope trends (Figure 20, Appendix A). These data are used in conjunction with fluid inclusion microthermometry measurements to calculate paleofluid C and O stable isotope composition and salinity. Four major paleofluid compositions (categories A – D) are defined based on these calculations, corresponding to vein sets 1 – 4. These fluid categories share similarities, and some are postulated to have a similar thermochemical signature and history. Since fluid inclusion data is limited to a suite of 7 total samples from vein sets 1 and 3, fluids calculated for categories A and C were used as a basis to “model” the observed range of calcite stable isotope ratios for each of the four vein sets. Fluids X and Y are mixing end members of category C, and are used as the basis to model fluid composition for categories B, C and D. This required testing a range of precipitation temperatures and processes to fit the observed data. Processes such as water-rock interaction, mixing, progressive precipitation, and degassing are considered in the following discussion.

4.1.1 Paleofluid Compositions

Paleofluid C and O stable isotope compositions are calculated by using the calcite stable isotope and fluid inclusion microthermometry data sets. The salinity of these paleofluids is informed by the available fluid inclusion results. All calculations are made with the assumption that calcite precipitation occurred under isotopic equilibrium.
The $\delta^{13}$C of dissolved CO$_2$ (Eq. 6) and $\delta^{18}$O of water (Eq. 7) are calculated as follows.

$$1000 \ln \alpha_{CO_2-CC} = -2.4612 + \frac{7.6663 \times 10^3}{T} - \frac{2.9880 \times 10^6}{T^2}$$  \quad (6) \quad \text{(Bottinga, 1968)}

$$1000 \ln \alpha_{H_2O-CC} = 2.89 - \frac{2.78 \times 10^6}{T^2}$$  \quad (7) \quad \text{(O'Neil et al., 1969, 1975)}

$$\alpha_{x-y} = \frac{1000 + \delta_x}{1000 + \delta_y}$$  \quad (8) \quad \text{(Sharp, 2007)}

$$\Delta_{x-y} = \delta_x - \delta_y$$  \quad (9) \quad \text{(Sharp, 2007)}

For equations 6, 7, and 8 the variable $\alpha_{x-y}$ is the temperature dependent fractionation factor between x and y (e.g., CO$_2$ and calcite), and T is temperature in Kelvin. The value delta ($\Delta$) is the difference between the delta ($\delta$) values (‰) of phases x and y and considered a good approximation for $1000 \ln \alpha$ in equations 6 and 7 (Sharp, 2007).

Paleofluid values are then used to calculate $\delta^{13}$C and $\delta^{18}$O of calcite that would precipitate in equilibrium at a certain temperature. Since there is a limited suite of samples with combined temperature and stable isotope data, carbonate $\delta^{13}$C and $\delta^{18}$O curves are “modelled” by fixing either the $\delta^{13}$C of CO$_2$ or $\delta^{18}$O of the fluid and varying temperature to fit the observed data. Two examples of the calculation for modelling are illustrated in Figure 15. Figure 15A illustrates the expected $\delta^{13}$C and $\delta^{18}$O of calcite precipitated from a fluid with a dissolved CO$_2$ $\delta^{13}$C$_{PDB}$ of -7 ‰ (median value calculated from calcite samples) and water $\delta^{18}$O$_{SMOW}$ from -15 to 10 ‰. Figure 15B illustrates the expected $\delta^{13}$C and $\delta^{18}$O of calcite precipitated from a fluid with a dissolved CO$_2$ $\delta^{13}$C$_{PDB}$ of -18 to -2 ‰ and water $\delta^{18}$O$_{SMOW}$ of -11.9 ‰ (the lower bound for category A fluid).
Figure 19: Theoretical carbonate $\delta^{13}$C and $\delta^{18}$O curves. A) Calculated calcite compositions using a fixed CO$_2$ $\delta^{13}$C$_{PDB}$ of -7‰ and varying the H$_2$O $\delta^{18}$O$_{SMOW}$ from -15 to 10‰ (diagonal contours), along with varying temperatures (vertical isotherm). B) Calculated calcite compositions using a fixed H$_2$O $\delta^{18}$O$_{SMOW}$ of -12‰ and varying the CO$_2$ $\delta^{13}$C$_{PDB}$ from -18 to -2‰ (PDB) (diagonal contours) and variable temperatures (horizontal isotherms).
Figure 20: A range of fluid compositions and precipitation temperatures calculated or postulated to fit the observed calcite vein set stable isotope data. A) Category A’s bounding lines are calculated as calcite precipitated from two fluids of similar composition, varying temperature. The fluids were calculated with samples 5-2 to 5-3/S-5B (L) (90°C) and 3-1/S-6A (U) (25°C) (starred). B) Category B’s bounding lines are calculated as calcite precipitated from two fluids of equal H2O δ18O composition (-10.1 ‰) calculated using sample 3-1/S-6A (90°C), and postulated CO2 δ13C values of -7.5 ‰ (L) and -11.5 ‰ (U). C) Category C is approximated by calcite precipitated from a mixture of two fluids calculated using samples 1-2/S-16 (140°C) (fluid X) and 1-2/S-3 (25°C) (fluid Y) (yellow stars) from 0 to 100% fluid X. D) Category D is modeled using fluid X’s composition as a starting point. The mixing curve is calculated from CO2 with a δ13C PDB of -1.2 ‰ (0%) to 100% CO2 with a δ13C PDB of -8.5 ‰. Degassing and precipitation show δ18O and δ13C values of calcite precipitated from an open system with up to 40% calcite precipitated or CO2 degassed. The trajectories at 80 and 140°C are given.
Figure 20 continued

Figure 20A: Scatter plot showing the distribution of δ¹³C‰ and δ¹⁸O‰ values for different sets of samples. The plot includes symbols representing different sample types and sets.

Figure 20B: Another scatter plot with a similar layout as Figure 20A, highlighting variations in δ¹³C‰ and δ¹⁸O‰ for various sets of samples.
Neither end member calculation perfectly captures the observed $\delta^{13}$C and $\delta^{18}$O of calcite in the Hurricane Fault zone. Thus, a combination of the two is used for modeling composition for most of the fluid categories as described below.

**Fluid Category A.** Vein set 1 calcite data can be explained by a fluid (A) with a narrow range in $\delta^{13}$C$_{\text{PDB}}$ (-7 to -4 ‰) and $\delta^{18}$O$_{\text{SMOW}}$ (-11.9 to -10.1 ‰) over a range in $T$ (25 – 90 °C) based on 2-phase fluid inclusion homogenization temperatures (45 – 90 °C) (Figure 20A). Seven samples from vein sets 1, 2, and 3 contain 1-phase fluid inclusions measuring ≥15 μm, indicating likely precipitation temperatures of $\leq$ ~50 °C (Goldstein and Reynolds, 1994), falling within the observed 2-phase measurements. The salinity of category A fluids ranges from 0 – 5 wt% NaCl.

**Fluid Category B.** Vein set 2 shows a weaker $\delta^{13}$C and $\delta^{18}$O covariation than vein set 1, but can still be approximated by a fluid with a narrow range in dissolved CO$_2$ $\delta^{13}$C$_{\text{PDB}}$ (-11.5 to -7.5 ‰) and fixed $\delta^{18}$O$_{\text{SMOW}}$ (-10.1 ‰) over a range in T (25 – 80 °C) (Figure 20B). In the absence of temperature constraints from 2-phase fluid inclusion homogenization data, a range of temperatures and a fixed $\delta^{18}$O$_{\text{SMOW}}$ from category A fluids are used. The salinity of these fluids is likely similar to category B, despite the lack of fluid inclusion data for this vein set.

**Fluid Category C.** Vein set 3 can be described using a mixture of two end-member fluid compositions (X and Y) in conjunction with varying temperature (Figure 20C). Scatter beyond the modeled isotopic bounds is likely due to limitations in fluid inclusion microthermometry data, not allowing for full characterization of the end member fluids. The binary mixing model (Eq. 10) uses two fluids with a dissolved CO$_2$
\[ \delta_{\text{fluid mix}} = F \cdot \delta_{\text{fluid X}} + (1 - F) \cdot \delta_{\text{fluid Y}} \]  

(10)

Although there is overlap in microthermometry measurements between categories A and C, the range of observed temperatures is larger for category C veins (55 – 160 °C). Fluid X is calculated using sample 1-4/S-26 at 140 °C, the highest repeatable temperature. Fluid Y is calculated based on sample 1-2/S-3 with an assumed lower bound temperature of 25 °C; this lower bound is based on the presence of only single phase fluid inclusions. Calculated salinity ranges from 0 – 15 wt% NaCl, with an approximate bimodal distribution (Figure 18). The lower end of the salinity measurements (0 – 7.8 wt% NaCl) correspond to lower temperatures and fluid Y, whereas higher salinity measurements (9.2 – 15 wt% NaCl) correspond to higher temperatures and fluid X.

**Fluid Category D.** Vein set 4 is modeled using fluid X’s (one end member of the category C mixing curve) composition as a starting point (Figure 16D). Due to the lack of fluid inclusion data constraints, temperatures (65 – 160 °C) and salinities (9.2 – 15 wt% NaCl) are both assumed to be identical to fluid X of category C (Figure 21). This is due to fluid category D’s isotopic similarity to fluid X of category C with respect to oxygen and carbon at the base of category D veins (Figure 20C, Figure 24). Three processes are evaluated to explain the observed calcite data including fluid mixing, CO₂ degassing, and progressive calcite precipitation from a fluid. Binary mixing is explored (Eq. 10), using fluids with dissolved CO₂ \( \delta^{13}\text{C}_{\text{PDB}} \) of -1.25 and -8.5 ‰ and a fixed \( \delta^{18}\text{O}_{\text{SMOW}} \) of 9.2 ‰. Progressive degassing and precipitation curves were created assuming Rayleigh distillation (Eq. 11), treating the dissolved CO₂ as a finite reservoir (F) for both.
Figure 21: 1-2/S-16 $T_h$ and $T_m$ measurements, highlighting their variation from the majority of calcite set 3 measurements and the distinction of fluid X (Figure 14).
\[ \delta_f - \delta_i = (1000 + \delta_i)(F^{(\alpha^{-1})} - 1) \]  
(Sharp, 2007)

The variables \( \delta_f \) and \( \delta_i \) are the final and initial \( \delta \) values of the reservoir, \( F \) is the fraction of reservoir remaining, and \( \alpha \) is the fractionation factor between the reservoir and the consuming phase. The \( \delta^{13}C \) of dissolved inorganic carbon (DIC) (Eqs. 12 & 13) and \( \delta^{18}O \) of dissolved CO\(_2\) (Eq. 14) in the fluid were used to calculate the degassing curve assuming the modern DIC speciation of Pah Tempe hot springs (58% HCO\(_3\)- and 42% H\(_2\)CO\(_3\)) (Nelson et al., 2009).

\[
1000 \ln \alpha_{H2CO3-CO2} = -0.91 + \frac{0.0063 \times 10^6}{T^2} \]  
(Deines et al., 1974)

\[
1000 \ln \alpha_{HCO3-CO2} = -4.54 + \frac{1.099 \times 10^6}{T^2} \]  
(Deines et al., 1974)

\[
1000 \ln \alpha_{CO2-CC} = -3.2798 + \frac{1.0611 \times 10^4}{T} - \frac{1.8034 \times 10^6}{T^2} \]  
(Bottinga, 1968)

The \( \delta^{18}O \) and \( \delta^{13}C \) of dissolved CO\(_2\) were used to calculate the progressive calcite precipitation curve (Figure 20D). Two trajectories for degassing and precipitation are shown, using the two end-member mode temperatures from fluid X of category C (80 and 140 °C) (Figure 21). Neither progressive degassing nor precipitation can explain the observed \( \delta^{13}C \) trend in vein set 4. Binary mixing between two isotopically distinct dissolved CO\(_2\) sources (\( \delta^{13}C \) of -1.25 and -8.5 ‰) best fits the observed data.

4.1.2 Origins of Paleofluid Categories A - D

Combining stable isotope and fluid inclusion microthermometry data reveals viable water and CO\(_2\) sources of the interpreted fluid categories. Thermochemical signatures of the fluid categories are summarized in Table 1. Oxygen isotope composition
provides important information on the origin and water-rock interaction history of paleofluids, and δ\textsuperscript{13}C values of CO\textsubscript{2} inform on sources of dissolved volatiles. Potential sources of dissolved CO\textsubscript{2} for the study site include dissolved marine carbonate, organically produced CO\textsubscript{2}, and magmatic CO\textsubscript{2}. Unaltered marine carbonate host rock δ\textsuperscript{13}C\textsubscript{PDB} values from this study range from -2.0 to 3.8 ‰, mantle-derived CO\textsubscript{2} has values of -6±3 ‰, and organically derived CO\textsubscript{2} values range from -33 to -9 ‰ (Craig, 1953).

The δ\textsuperscript{13}C\textsubscript{PDB} of dissolved CO\textsubscript{2} and δ\textsuperscript{18}O\textsubscript{SMOW} of water calculated for paleofluids range from -8.1 to -1.3 ‰ and -11.9 to 9.2 ‰, respectively. For reference, the δ\textsuperscript{13}C\textsubscript{PDB} of modern CO\textsubscript{2}(g) exsolving from Pah Tempe hot spring is -5.9 to -5.3 ‰, and δ\textsuperscript{18}O\textsubscript{SMOW} of modern meteoric water measured in southern Utah wells and rivers is -14 to -12.5 ‰ (Nelson et al., 2009).

Category A fluid characteristics closely reflect evolved meteoric discharge at Pah Tempe hot springs (Table 1) (Dutson, 2005; Nelson et al., 2009). They are CO\textsubscript{2}-charged meteoric waters which have been isotopically altered by exchange with country rock. Modified meteoric water δ\textsuperscript{18}O values suggest water-rock isotopic exchange at temperatures >100 °C, and perhaps as high as 150 – 350 °C (Criss, 1999; Nelson et al., 2009). Temperature is also important in determining the source of dissolved CO\textsubscript{2}, which is interpreted to be dissolved marine carbonate. If marine carbonate (δ\textsuperscript{13}C = -2.0 to

<table>
<thead>
<tr>
<th>Fluid Category</th>
<th>CO\textsubscript{2} δ\textsuperscript{13}C\textsubscript{PDB} (%o)</th>
<th>H\textsubscript{2}O δ\textsuperscript{18}O\textsubscript{SMOW} (%o)</th>
<th>T (°C)</th>
<th>Salinity (wt % NaCl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-7.0 – -4.0</td>
<td>-11.9 – -10.1</td>
<td>25 – 90</td>
<td>0 – 5</td>
</tr>
<tr>
<td>B</td>
<td>-11.5 – -7.5</td>
<td>-10.1</td>
<td>25 – 80</td>
<td>0 – 5</td>
</tr>
<tr>
<td>C (fluid X/Y)</td>
<td>-1.3 / -8.1</td>
<td>9.2 / -8.3</td>
<td>25 / 140</td>
<td>0 – 8 / 9 – 15</td>
</tr>
<tr>
<td>D</td>
<td>-1.3 – -8.5</td>
<td>9.2</td>
<td>140</td>
<td>9 – 15</td>
</tr>
</tbody>
</table>
was dissolved and incorporated at temperatures from 25 – 150 °C, the resulting dissolved CO$_2$ δ$^{13}$C would range from -13.4 to 2.0 ‰ respectively (Eq. 6). This encompasses the δ$^{13}$C range of CO$_2$ calculated for fluid category A.

Category B fluids have two proposed thermochemical signatures that can explain the isotope ratios observed for vein set 2. Assuming a similar δ$^{18}$O as category A fluids and distinctly lower δ$^{13}$C values of CO$_2$ requires limestone dissolution at <45 °C to be a valid source of CO$_2$ (Table 1). A different source of CO$_2$ such as mantle derived or organically derived CO$_2$ could also explain the more negative δ$^{13}$C signature. An alternate explanation for category B fluids and dissolved CO$_2$ is that they are an extension of category C, at temperatures >40 °C and with ≤60 % fluid X (Figure 20C). This is the preferred explanation, for reasons discussed in sections 4.2.1 and 4.2.4 below. Fluid category B is henceforth grouped with category C, both defined by mixing of end members X and Y.

Calcite stable isotope ratios belonging to category vein set 3 are roughly bounded by two fluids of different composition and characteristics that compose fluid category C. Fluid Y appears to be dominated by category A type fluids, which are relatively low temperature fluids that are dominated by meteoric recharge and subsequent water-rock interaction (Table 1). Postulated marine carbonate dissolution at temperatures <80 °C fits the calculated δ$^{13}$C$_{PDB}$ (-8.1 ‰), similar to category A. Fluid X is hotter and saltier than fluids from other categories, and has a relatively high δ$^{18}$O, close to oil-field and saline basin brines, which can reach δ$^{18}$O$_{SMOW}$ up to ~10 ‰ and >15 wt % NaCl (Table 1) (Bein and Dutton, 1993; Sharp, 2007; Labotka et al., 2015). Thus fluid “X” may be a
basin brine that has mixed with deeply-circulated meteoric recharge along the fault, resulting in the observed calcite veins in sets 2 and 3.

Category D fluids require a much lower δ^{13}C source than that associated with category A or C fluids (Table 1). Binary mixing of the fluid X end member dissolved CO₂ (δ^{13}C_PDB = -1.3 ‰) with a CO₂ source with a δ^{13}C_PDB ≤ -8.5 ‰ best approximates the observed δ^{13}C values. The δ^{13}C signature of the distinct CO₂ source resembles that calculated for fluid Y of category C. However, with no positive correlation between δ^{13}C and δ^{18}O, an alternate CO₂ source is more likely. Organically-derived and mantle-derived CO₂ are considered. CO₂ with an organic component (δ^{13}C_PDB of -33 to -9 ‰) overlaps with the calculated CO₂ (Craig, 1953). It is likely that the full mixing system was not sampled, and -8.5 ‰ does not represent the lower end-member of the system. For example, calcite cement from the Moab Fault zone, Utah exhibits δ^{13}C_PDB of -15 to 0 ‰, which is attributed to methane oxidation mixed with dissolved marine carbonate species (Baedecker et al., 1993; Tuccillo et al., 1999; Boles et al., 2004; Eichhubl et al., 2009). Mantle-derived CO₂ (δ^{13}C_PDB of -6±3 ‰) also overlaps with the calculated CO₂ source (-8.5 ‰) (Craig, 1953). Mantle-derived CO₂ can be used as an indicator of volatiles sourced from immature basaltic magmas, like those that produced Quaternary basalt flows in the Hurricane Fault region (Nelson and Tingey, 1997; Hilton et al., 2010).

Modern Pah Tempe hot spring CO₂ δ^{13}C_PDB values (-5.9 to -5.3 ‰) are interpreted to be caused by a mixture of crustal CO₂ and dissolved marine limestone (Nelson et al., 2009). The springs are <1 km from the source of the 280 Ka Gould Wash basalt flow (Biek et al., 2010). A mixture of mantle-sourced and crustal-sourced volatiles is also called upon to explain δ^{3}He/δ^{4}He ratios, and CO₂ δ^{13}C at Pumpkin Springs and Travertine Grotto
4.2 Fluid-Fault Interaction

4.2.1 Fluid Sources and Pathways

Ample mineralization is evidence that the damage zone provides a preferential pathway for paleofluids to move up and down the fault, as well as along strike. This is consistent with proposed models of fault zone hydrology, and particularly important in interpreting the thermochemical signatures of the fluid categories identified in this study (Caine et al., 1996; Evans et al., 1997; Eichhubl et al., 2009). Two main sources of fluids were determined based on δ¹⁸O signature: 1) basin brines that had experienced prolonged water-rock isotopic exchange (categories B/C and D), and 2) deeply-circulated meteoric fluids that experienced variable water-rock isotopic exchange during infiltration and flow to the fault system (categories A and B/C). Fluids were circulated upwards along the fault, driven against the topographic gradient by convection as is commonly observed among normal faults (Kilty et al., 1979; Forster et al., 1997). Basin brines rose from depth, likely under pressure after the damage zone of the Hurricane Fault had propagated through their host formations to provide a suitable hydrologic pathway (Figure 18). Basin brines utilize basement-penetrating faults, including the Hurricane Fault, to rise to the surface and impact the chemistry of springs along the Colorado River (Crossey et al., 2006, 2009). Meteoric fluids infiltrated up-gradient of the Hurricane Fault, reached sufficient depths to achieve isotopic exchange with bedrock at temperatures > 100°C, and then rose to precipitate calcite at a lower temperature. Evolved meteoric fluids are analogous with modern Pah Tempe hot spring fluids (Nelson et al., 2009).
Hurricane Fault zone fluids have multiple possible sources for their dissolved inorganic carbon, including marine limestone, biologically processed carbon, and magmatic volatiles. A major source of dissolved carbon is the dissolution of marine carbonates by fluid-rock interaction. Marine carbonate dissolution may occur at depth as a result of acidic or under-saturated fluids (Dietrich et al., 1983; Eichhubl et al., 2009). Deeply circulated meteoric waters in the Hurricane Fault zone have acquired DIC.
through this process. Basin brines reside for a length of time necessary to approach equilibration with the host reservoir, dissolving marine carbonate and resulting in a relatively high concentration of DIC (Bein and Dutton, 1993; Labotka et al., 2015). Additional processes may contribute dissolved carbon into basin brines, including oxidation of hydrocarbons and mantle-sourced CO$_2$. Hydrocarbons are often associated with basin brines, and their oxidation in anoxic environments can occur due to microbial activity (Baedecker et al., 1993; Tuccillo et al., 1999; Eichhubl et al., 2009). Residual oil is present in the Timpoweap member of the Moenkopi Formation along the Hurricane Cliffs, indicating regional hydrocarbon migration in the past (Blakey, 1978). Mantle-sourced CO$_2$ associated with the regional Quaternary basalts is also possible. Quaternary basalt flows in the region roughly parallel the Hurricane Fault, and a deep-crust structural connection was proposed (Delaney et al., 1986; Sanchez, 1995). We propose that the structural connection between basalt conduits and the Hurricane Fault could provide an avenue for magmatic volatiles and fluid circulation to mix with basin brines moving along the Hurricane Fault (Valentine and Krogh, 2006). Of the two proposed CO$_2$ sources for fluid category D, magmatic volatiles are considered more likely than hydrocarbon oxidation due to the lack of hydrocarbon residue in hand samples and thin sections associated with fluid categories B/C and D (Eichhubl et al., 2009).

### 4.2.2 Fluid-rock interaction

Fluid – fault rock interaction is integral to understanding the thermochemical history of paleofluids along the Hurricane fault, and precipitated minerals and host rock alteration provide evidence for the redox and chemical conditions of the past fluids. There is evidence for fluid-rock interaction associated with the Hurricane Fault in
carbonate and siliciclastic strata exposed in the footwall. This evidence includes
dissolution and precipitation of minerals, including gypsum, carbonate, and oxides,
within host rock focused near fracture zones. Gypsum veins are present within and
adjacent to gypsum-rich facies, suggesting that they are locally derived. Carbonate and
oxide minerals provide clear evidence for CO₂, iron, and manganese bearing fluids.

Evidence of fracture-related mineral-oxide mobilization is abundant in the Hermit
Formation and is used to infer the redox conditions of fault zone paleofluids. Oxide
cements adjacent to fractures are dissolved and re-precipitated in lower concentrations
close to fractures. Bleaching is the result of iron oxide dissolution and mobility due to
reducing and/or acidic fluids (Eichhubl et al., 2009). Calcite cements in bleached halos
are isotopically similar to vein set 1 calcite and hematite cemented breccia veins. I
postulate that calcite and hematite veins may be the result of fluids mobilizing iron and
manganese during bleaching, followed by re-precipitating in voids or along mixing
fronts, similar to proposed mechanisms for iron oxide mineralization in the Navajo
Sandstone (Chan et al., 2000). There is evidence for stratigraphic bed-controlled
bleaching, un-related to fractures. The C and O stable isotope ratios of the calcite cement
in bleached beds appears to be unaltered (δ¹³C_PDB = -1.0 ‰; δ¹⁸O_PDB = -2.2 ‰), implying
that these features record alteration that is unrelated to and possibly older than damage
zone fluid-fault redox interaction.

Fracture-related alteration by paleofluids that are isotopically distinct is also
evident, suggesting cement overprinting and relatively high water/rock ratios. Stable
isotope ratios from definitively un-altered limestone and primary calcite cement in
siliciclastic strata sampled >0.5 m from fractures (δ¹³C_PDB = -1.0 to 3.8 ‰; δ¹⁸O_PDB = -3.2
to -2.2 ‰) largely overlap with the stable isotope range expected for marine carbonates
(δ¹³C/¹⁸O PDB = 0±3 ‰) (Craig, 1953). Host-rock limestone and early sandstone calcite
cements appear altered by water – rock interaction (Figure 11). The host rock is identified
as being diagenetically altered based on clear isotopic or morphologic evidence of cement
replacement or isotopic exchange (i.e. isotope ratios matching adjacent veins and/or
bleaching halos/concretions). Siliciclastic strata are more susceptible than carbonate beds
to overprinting of primary diagenetic cements by secondary calcite cementation related to
fluid flow in fractures. This is commonly associated with concretions (Figure 11D). This
is due to intergranular pore space. Samples drilled from siliciclastic host rock <10 cm
away from fractures closely reflect the isotopic signature of adjacent veins (Figure 23).
Limestone near the fault in some locations is shifted towards lower C and O isotope
ratios as well, consistent with meteoric water-rock interaction (Figure 24). Relatively
high water/rock ratios are required to alter both oxygen and carbon isotope ratios,
implying an open system with fluids flushing through rather than small volumes of pore
water residing for long periods of time (Sharp, 2007).

Figure 23: Isotope ratio overprinting of host rock cement adjacent to a vein in the Hermit
Formation.
Figure 24: Isotope ratio alteration of limestone adjacent to a fibrous vein in the Brady Canyon member of the Toroweap Formation.

4.2.3 Mechanisms for Vein Formation

The minerals present in the damage zone of the Hurricane Fault exist due to the combination of mechanical creation of accommodation space and fluid movement. The majority of calcite veins are simple, sparry veins up to 3 cm in width that fill planar fractures, suggesting that the fracture opening rate was greater than the calcite precipitation rate (Wiltschko et al., 1998). This suggests that the majority of veins were the result of post-fracturing fluid movement, similar to the fluid flow system of the modern Pah Tempe hot spring which is limited by fluid flow rather than fracture permeability (Nelson et al., 2009).
Boxwork veins and calcite/manganese oxide veins contain host rock inclusions, which may indicate multiple episodes of fracture opening (Figure 9A) (Jebrak, 1997). Boxwork veining can be indicative of fault-parallel fluid flow in sandy and porous strata, but not necessarily syn-deformation precipitation (Mozley and Goodwin, 1995).

Individual veins within boxwork structures are cored by sparry calcite, with indistinct boundaries between them and adjacent cement/concretions (Figure 9D, Figure 25). This suggests that discrete fractures provided accommodation space for initial vein formation that expanded, perhaps by crystallization pressure, into the surrounding sandstone (Wiltschko et al., 1998).

Figure 25: Cross-polarized photomicrograph of one vein within a network of boxwork veins, highlighting the indistinct boundary between the vein (left) and the cemented host rock (right)
Brecciated veins in the Hurricane Fault zone contain rounded and partially dissolved clasts of host rock, indicating mechanical wear abrasion and chemical dissolution (Jebrak, 1997). Clasts are heterogeneous in size, sometimes jigsaw-piece in form, and matrix supported which implies fluid-assisted brecciation and volume expansion (Jebrak, 1997). These features are interpreted to indicate high fluid pressure and clast entrainment by fluids (Jebrak, 1997; Benedicto et al., 2008). In rare cases, breccia veins are only partially re-cemented and clast supported, indicating mechanical brecciation and slip (Jebrak, 1997). There are typically multiple generations of brecciation and un-deformed cross-cutting veins, indicating multiple episodes of fluid-assisted and mechanical fracture opening (Figure 10D).

Fibrous veins observed in the study area consist of intergrown calcite and hematite (Figure 9B). Three distinct morphologies within the fibrous veins indicate changes in mineralization rates with time. The base is comprised of lath-like calcite crystals, showing competitive grain growth and indicating rapid initial fracture opening (Figure 9F) (Wiltschko et al., 1998). The middle stage is composed of fibrous calcite and hematite, indicating that increments of fracture opening and vein growth were so small that competitive grain growth did not take place. This is typically viewed as a “crack-seal” texture (Ramsay, 1980; Wiltschko and Morse, 2001). Two mechanisms have been proposed to produce this texture including minute increments of cracking followed by sealing, or crystallization pressure (Wiltschko and Morse, 2001). Increments of cracking and sealing are attributed to oscillations in fluid pressure (Ramsay, 1980). Fluid inclusions are rare and <4 µm in diameter within the observed fibrous veins so this is not likely the case. Crystallization pressure is an alternate explanation (Wiltschko and Morse,
The latest stage of fibrous vein growth consists of intergrown calcite and hematite in a feathery, radiating texture that indicates open-void fill.

### 4.2.4 Fluid Flow – Spatio-temporal History

The four fluid categories show distinct spatial patterns along strike within the Hurricane Fault zone. Each of the categories cuts through both limestone and sandstone strata, except category D which cuts only limestone, indicating independence of stratigraphic horizon (Figure 7, Figure 26). Fluid category A is mostly constrained to the northern half of the fault zone (Figure 26A). It is thermochemically similar to the modern day Pah Tempe hot springs (blue square), which is in the center of fluid A’s distribution. Fluid categories B and C are distributed equally throughout the fault zone (Figure 26B & C). Their similarity in distribution supports the interpretation that fluid category B is an extension of category C. Samples that fall into fluid category D are only found at location 1-2, excluding outliers at locations 4-2 and 2-2.

Cross-cutting relationships between veins along the fault are used in concert with the defined fluid categories to interpret an overall paragenesis of fluid-rock interaction in the Hurricane Fault zone. Absolute age constraints are not available, so the spatiotemporal reconstructions are relative. Although absolute ages are not available for comparison with estimates of initiation/slip rates of faulting, it is assumed that fluid flow and mineralization occurred throughout the history of the Hurricane Fault. This is due to the abundance of secondary minerals and distinct cross-cutting relationships in the damage zone. Terms like “early” and “late” refer to timing relative to the establishment of the Hurricane Fault’s damage zone. Cross-cutting relationships indicate relative timing of vein formation and fluid-flow paths, but do not necessarily imply depth of formation.
Figure 26: Spatial distribution of fluid-rock interaction evidence from vein sets, corresponding to fluid categories A – D. Yellow stars indicate type-section canyons used as basis for paragenetic histories presented in Figure 23 and 24.
(i.e. early = deep, late = shallow). These relationships between vein sets are consistent within each field site, but vary from site to site. This is divided into two separate histories based on cross-cutting relationships at two key locations (Figure 27, Figure 28). Canyon 1-2 within the Toroweap Formation shows key relationships of between set 1, 3 and 4 veins (Figure 27). Set 3 veins are interpreted as the earliest generation, and are cross-cut by set 1 and set 4 veins (Figure 27, Figure 28). There is no direct field evidence for discerning the relative timing between set 1 and set 4 veins. Although they cross-cut vein set 3 to the north, set 1 veins at location 1-4 in the Hermit Formation are the earliest generation documented (Figure 28). They are cross-cut by set 3 veins (Figure 28).

<table>
<thead>
<tr>
<th>Events and Mineralization</th>
<th>Early Fluid Category 3</th>
<th>F.C. 4</th>
<th>?</th>
<th>Late Fluid Category 1</th>
</tr>
</thead>
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<tr>
<td>Hydrothermal brecciation</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Mechanical brecciation</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Calcite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hematite</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Chemical Variations       |                        |        |   |                      |
| CO$_2$ $\delta^{13}$C$_{PDB}$: | -8.1 to -1.3 % | -8.5 to -1.3 % | -7.0 to -4.0 % |
| Fluid $\delta^{18}$O$_{SMOW}$: | -8.3 to 9.2 % | 9.2 $\pm$ 3.0 % | -11.9 to -10.1 % |
| Temperature (°C): | 25 to 160 °C | - | 25 to 90 °C |
| Salinity (wt% NaCl): | 0 to 15 % | - | 0 to 5 % |
Figure 28: Paragenesis of fluid-fault interaction for fluid categories A – C based on field, stable isotope, and fluid inclusion data from canyon 1-4. Representative textures and isotope data from canyon 1-4 provided in panels A - D, displaying the evolution of paleofluids from category A to category C fluids. The vertical gray bar represents the temporal transition between fluid categories.

This shows that fluids interpreted to be basin brines both preceded and followed cooler altered meteoric fluids, depending on the location along the Hurricane Fault. Fluid categories A, B, and C appear present throughout the fault’s history due to variable cross-cutting relationships of veins and prevalence at many locations. Fluids from category D are isolated spatially and temporally.

Fluid flow evolution along the Hurricane fault shows similarities to other faults with a protracted history of fluid movement. Within ~10 km of Pah Tempe hot spring fluids temporally transition from isotopically evolved basin brines to meteoric recharge, consistent with confined fluid flow transitioning to exotic fluid flushing in the evolution
of other faults (Dietrich et al., 1983; Benedicto et al., 2008). Similar observations are made approximately 20 km south of Pah Tempe hot springs. Hydrothermal breccias are documented as the earliest stage of mineralization, indicating high fluid pressure consistent with pressure release following initiation of a fault (Benedicto et al., 2008; Verhaert et al., 2009). However, the origin of high-pressured fluids is altered meteoric recharge, different from those to the north. Confined aquifers hosted in siliciclastic strata are present in the region, and may be responsible for over pressurization of meteoric fluids (Clyde, 1987).
CHAPTER 5.

SUMMARY AND CONCLUSIONS

The history of fluid-rock interaction associated with the Hurricane Fault zone in southwest Utah and northwest Arizona deduced from combined field and geochemical observations of calcite veins varies spatially and temporally and includes multiple sources of fluids and dissolved carbon. Minerals and host rock alteration in the fault zone indicate varying degrees of mixing between two main sources of paleofluids: meteoric recharge and basin brines. Meteoric recharge along deep flow paths through sedimentary strata migrated through the damage zone within ~ 20 km of Pah Tempe hot springs. Meteoric fluids are thermochemically similar to CO₂ charged Pah Tempe hot springs, with precipitation temperatures of 25 – 90 °C and δ¹⁸O signatures suggesting isotopic exchange with bedrock silicates at >100 °C (Nelson et al., 2009). Meteoric fluid flow initiated relatively early in southern reaches of the Hurricane Fault, as compared to northern segments. Mixtures of evolved meteoric fluids with hot and saline basin brines have flowed through the damage zone along the length of the fault. Their relative timing is unknown, and may be a continuum throughout most of the fault’s history. Calcite δ¹⁸O indicates basin brines were in isotopic equilibrium with marine carbonate. Fluid inclusion homogenization temperatures indicate they reached 160 °C. Solutes responsible for mineralization were derived from the host-rock by these two types of fluids, which utilized fracture permeability in the damage zone of the fault. The dominant carbon source for calcite, as indicated by δ¹³C, was dissolved marine carbonate. There was one occurrence of dissolved marine carbonate mixing with a more isotopically-negative carbon source. The chemistry of the mineralizing fluid fluctuates, including a
progressively more negative $\delta^{13}$C, indicating mixing with an organic or likely magmatic CO$_2$ source (Craig, 1953; Baedecker et al., 1993; Tuccillo et al., 1999; Eichhubl et al., 2009; Hilton et al., 2010). Fluid flow in the Hurricane fault zone has resembled modern day Pah Tempe hot springs throughout its history, interjected by periods of upwelling basin brine flow and an occurrence of volatile input from a magmatic source.

The nature of fluid flow in the Hurricane Fault zone has evolved in conjunction with damage zone structure, primarily during the Quaternary while the fault is tectonically active. The initiation of faulting provided an avenue for the release of fluids as the damage zone propagated through confined reservoirs, expelling basin brines and over pressured meteoric fluids. Fractures in mechanically favorable orientations were activated multiple times by continuing deformation in the fault zone, keeping damage zone permeability relatively high once established. This implies that fluid-assisted deformation is important during initial stages of faulting, mechanical deformational features are then utilized by fluids in an open system once the damage zone is established.


Wiltschko, D.V., and Morse, J.W., 2001, Crystallization pressure versus “crack seal” as the mechanism for banded veins: Geology, v. 29, p. 79–82.


APPENDICES
# Appendix A. Stable Isotope Data

Table A1: Complete calcite carbon and oxygen stable isotope measurements.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>δ¹³C ‰ vs. PDB</th>
<th>δ¹⁸O ‰ vs. PDB</th>
<th>δ¹⁸O ‰ vs. SMOW</th>
<th>Sample type</th>
<th>Set #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I/S-1 A</td>
<td>1.42 ± 0.09</td>
<td>-12 ± 0.15</td>
<td>18.54 ± 0.15</td>
<td>Cal w/ slickenlines</td>
<td>3</td>
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<tr>
<td>1-I/S-1 B</td>
<td>2.73 ± 0.16</td>
<td>-8.5 ± 0.16</td>
<td>22.15 ± 0.16</td>
<td>Cal vein</td>
<td>3</td>
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<tr>
<td>1-I/S-2</td>
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<td>-9.81 ± 0.16</td>
<td>20.8 ± 0.16</td>
<td>Cal vein</td>
<td>3</td>
</tr>
<tr>
<td>1-I/S-3</td>
<td>1.07 ± 0.16</td>
<td>-10.82 ± 0.16</td>
<td>19.76 ± 0.16</td>
<td>Cal vein</td>
<td>3</td>
</tr>
<tr>
<td>1-I/S-4 A</td>
<td>0.36 ± 0.16</td>
<td>-11.95 ± 0.16</td>
<td>18.59 ± 0.16</td>
<td>Cal vein</td>
<td>3</td>
</tr>
<tr>
<td>1-I/S-4 B</td>
<td>0.78 ± 0.14</td>
<td>-17.66 ± 0.13</td>
<td>12.71 ± 0.13</td>
<td>Cal vug fill</td>
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</tr>
<tr>
<td>1-I/S-5 A</td>
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<td>-14.84 ± 0.22</td>
<td>15.61 ± 0.22</td>
<td>Cal vein</td>
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</tr>
<tr>
<td>1-I/S-5 B</td>
<td>2.17 ± 0.16</td>
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<td>22.11 ± 0.16</td>
<td>limestone</td>
<td>-</td>
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<td>0.07 ± 0.16</td>
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<td>21.11 ± 0.16</td>
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<td>-9.17 ± 0.16</td>
<td>21.46 ± 0.16</td>
<td>Cal w/ slickenlines</td>
<td>3</td>
</tr>
<tr>
<td>1-I/S-8 A</td>
<td>0.97 ± 0.16</td>
<td>-13.96 ± 0.16</td>
<td>16.52 ± 0.16</td>
<td>Cal vein</td>
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<tr>
<td>1-I/S-8 B</td>
<td>3.17 ± 0.16</td>
<td>-13.49 ± 0.16</td>
<td>17 ± 0.16</td>
<td>Cal vein</td>
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### Table A1 continued

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Appendix B: Fluid Inclusion Microthermometry Data

Table A2: Complete list of $T_h$ and $T_m$ measurements, as well as calculated salinities.

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Table A2 continued

Appendix C: Site Descriptions

Canyon: 1-1
Canyon mouth coordinates: 12N 0296965mE 4115492mN

Sampled Units
- Toroweap Formation – Brady Canyon and Seligman Members

Observed Features
- Boxwork calcite veins
- Calcite + hematite cemented bowork veins
- Calcite veins
- Calcite cemented slip surfaces

Isotopic Fluid Categories Present
- 1, 2, 3

General Notes
- Both calcite cemented and calcite + hematite cemented boxwork veins are seen cross-cutting and offsetting each other, with no distinct genetic relationship

Canyon: 1-2
Canyon mouth coordinates: 12N 0295871mE 4112937mN

Sampled Units
- Toroweap Formation – Brady Canyon and Woods Ranch Members

Observed Features
- Boxwork calcite veins
- Calcite veins
- Intergrown calcite and hematite veins
- Calcite cemented slip surfaces
- Calcite cemented breccias

Isotopic Fluid Categories Present
- 1, 3, 4

General Notes
- Repeatedly brecciated limestone with calcite veins – possibly not 100% in-situ on the side of the Hurricane Cliffs
- Intergrown calcite and hematite veins are banded with an alternating greater and lesser hematite/calcite ratio
Canyon 1-2 continued
- Intergrown calcite and hematite veins interconnect and appear to cement the host rock in a pseudo-breccia. They also take on a botryoidal form on the canyon floor, indicating open fracture fill during the last stage of vein growth

Canyon: 1-3
Canyon mouth coordinates: 12N 0295107mE 410790mN

Sampled Units
- Queantoweap Sandstone

Observed Features
- Calcite veins
- Calcite + MnO veins
- Calcite + MnO cemented boxwork veins

Isotopic Fluid Categories Present
- 1, 3

General Notes
- Thin veins relative to other locations, typically < 1 mm wide

Canyon: 1-4
Canyon mouth coordinates: 12N 0296327mE 4099274mN

Sampled Units
- Toroweap Formation – Seligman Member
- Hermit Formation – Upper and Middle Members

Observed Features
- Calcite + hematite coated slip surfaces
- Calcite + hematite cemented breccia veins
- Boxwork calcite veins
- Calcite concretions
- Calcite veins
- Calcite + MnO veins

Isotopic Fluid Categories Present
- 1, 3

General Notes
- Host rock “bleaching” around fractures in red, fine-grained sandstone layers of the Hermit Formation
Canyon 1-4 continued
- Oxide deposition around fractures in tan, fine-grained sandstone layers of the Hermit Formation
- Oxidation of round pyrite concretions ~ 1-5 cm in diameter, concretions are likely diagenetic
- Complete calcification of Seligman Member Sandstone in spider web-like veins, likely diagenetic
- Two main fracture set orientations, orthogonal and ~ parallel to the Hurricane Fault

Canyon: 1-5
Canyon mouth coordinates: 12N 0295018mE 4106323mN

Sampled Units
- Toroweap Formation – Seligman Member
- Queantoweap Sandstone

Observed Features
- Calcite + hematite coated slip surfaces
- Boxwork calcite veins
- Calcite concretions
- Calcite veins

Isotopic Fluid Categories Present
- 1, 2, 3

General Notes
- Secondary main slip zone exposed, stepped back from the Hurricane Cliff face
- Two main fracture set orientations, orthogonal and ~ parallel to the Hurricane Fault

Canyon: 2-1
Canyon coordinates: 12N 0294082mE 4034816mN

Sampled Units
- Kaibab Formation – Fossil Mountain Member

Observed Features
- Calcite veins

Isotopic Fluid Categories Present
- 2
Canyon 2-1 continued

**General Notes**
- Samples collected from the top of the cliff in the drainage ~ 100 m from the fault trace

**Canyon: 2-2**
**Canyon coordinates:** 12N 0295201mE 4033400mN

**Sampled Units**
- Kaibab Formation – Fossil Mountain and Harrisburg Members
- Toroweap Formation – Woods Ranch Member

**Observed Features**
- Calcite veins
- Calcite cemented breccia vein
- Calcite coated slip surface

**Isotopic Fluid Categories Present**
- 2, 4

**General Notes**
- Calcite coated slip surface is a tinted pink and is a thin veneer – collected from a roadcut ~1 km southeast of the other samples; coordinates: 12N 0295728mE 4031506mN

**Canyon: 2-3**
**Canyon coordinates:** 12N 0300564mE 4024121mN

**Sampled Units**
- Kaibab Formation – Harrisburg and Fossil Mountain Members

**Observed Features**
- Calcite veins
- Gypsum veins

**Isotopic Fluid Categories Present**
- N/A

**General Notes**
- ~ 2 m wide densely fractured fault core inaccessible
- One calcite vein sampled – error in isotopic data measurement
Canyon: 3-1  
Canyon coordinates: 12N 0304102mE 4150031mN

Sampled Units  
- Moenkopi Formation – Timpoweap Member

Observed Features  
- Calcite veins  
- Calcite + hematite cemented breccia veins  
- Calcite coated slip surface

Isotopic Fluid Categories Present  
- 1, 2

General Notes  
- Calcite + hematite breccia veins in sandy limestone show repeated brecciation and shear, similar to samples in the Hermit Formation

Canyon: 3-4  
Canyon coordinates: 12N 0297866mE 4129482mN

Sampled Units  
- Queantoweap Sandstone  
- Toroweap Formation – Brady Canyon Member

Observed Features  
- Calcite veins  
- Calcite + hematite coated slip surface

Isotopic Fluid Categories Present  
- 1, 3

General Notes  
- Sample one is taken from a different drainage at coordinates: 12N 0297931mE 4128768mN

Canyon: 3-5 to PT-1  
Canyon coordinates: 12N 0299163mE 4122037mN (multiple ~ parallel drainages)

Sampled Units  
- Moenkopi Formation – Timpoweap, Rock Canyon Conglomerate, and Virgin Limestone Members
Observed Features
- Boxwork calcite veins
- Calcite veins
- Calcite + hematite veins

Isotopic Fluid Categories Present
- 1, 2, 3

General Notes
- Oxide infiltration and deposition in sandy limestone facies
- Multiple, spread out zones of relatively denser fracturing in the damage zone

Canyon: 3-5
Canyon mouth coordinates: 12N 0298470mE 4123676mN

Sampled Units
- Chinle Formation – Shinarump Conglomerate Member

Observed Features
- Boxwork calcite veins
- Calcite concretions
- Calcite veins

Isotopic Fluid Categories Present
- 2

General Notes
- Host rock is calcite cemented coarse-grained sandstone with small hematite concretions, but no hematite present in veins

Canyon: 4-2/4-3
Canyon coordinates: 12N 0298027mE 4066296mN / 0298238mE 4065904mN

Sampled Units
- Kaibab Formation – Fossil Mountain Member

Observed Features
- Calcite filled fractures
- Calcite cemented fault core breccia
- Pink calcite coated slip surface
Canyon 4-2/4-3 continued

**Isotopic Fluid Categories Present**
- 3, 4

**General Notes**
- Brecciated fault core with multiple slip surfaces within cherty limestone present

**Canyon:** 4-7  
**Canyon coordinates:** 12N 0297510mE 4062417mN

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**Sampled Units**
- Kaibab Formation – Fossil Mountain Member

**Observed Features**
- Calcite filled fractures  
- Gypsum filled fractures  
- Calcite coated slip surfaces

**Isotopic Fluid Categories Present**
- 2, 3

**General Notes**
- Multiple low-offset subsidiary faults in ~20 m wide damage zone exposure

**Canyon:** 4-11  
**Canyon coordinates:** 12N 0296773mE 4051500mN

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**Sampled Units**
- Hermit Formation

**Observed Features**
- Calcite filled fractures  
- Calcite + MnO filled fractures  
- Gypsum filled fractures

**Isotopic Fluid Categories Present**
- 3

**General Notes**
- Bleaching and extensive gypsum veining (no detected calcite) in gypsiferous sandstone stratigraphically above the red beds of the Hermit FM
Sampled Units
- Hermit Formation

Observed Features
- Calcite filled fractures
- Calcite + MnO filled fractures

Isotopic Fluid Categories Present
- 2, 3

General Notes
- Fracture-related bleaching and calcite, calcite + MnO veining in fractures and small-offset subsidiary faults within the red beds of the Hermit FM

Sampled Units
- Kaibab Formation – Fossil Mountain Member
- Hermit Formation

Observed Features
- Calcite veins
- Calcite + MnO + hematite veins
- Calcite + MnO veins

Isotopic Fluid Categories Present
- 2, 3

General Notes
- Fracture-associated reduction of the host rock is thin compared to other locations with the same feature (~ 1 – 2 mm on either side of fractures) except for one zone of relatively high fracture density (19 frac/m)

Sampled Units
- Hermit Formation
Observed Features
- Calcite veins
- Calcite + hematite veins

Isotopic Fluid Categories Present
- 3

General Notes
- Large-scale reduction of entire 1 – 2 m thick red, fine-grained sandstone beds of the Hermit Formation
- Beds appear to be predominantly red further up the canyon ~1-2 miles from the fault trace

Canyon: 5-2 to 5-3
Canyon mouth coordinates: 12N 0290184mE 4089282mN

Sampled Units
- Toroweap Formation – Brady Canyon and Seligman Members
- Hermit Formation

Observed Features
- Calcite veins
- Boxwork calcite veins
- Calcite + hematite veins
- Calcite coated slip surfaces
- Calcite + hematite cemented breccia veins

Isotopic Fluid Categories Present
- 1, 3

General Notes
- Reduction of host sandstone associated with calcite + hematite veins
- 3 – 4 cm thick calcite + hematite brecciated veins show shear component in associated boxwork veins

Canyon: 5-2
Canyon mouth coordinates: 12N 0291679mE 4091101mN

Sampled Units
- Toroweap Formation – Brady Canyon and Seligman Members
- Hermit Formation
Canyon 5-2 continued

**Observed Features**
- Calcite veins
- Calcite + hematite veins
- Calcite + MnO veins
- Calcite coated slip surfaces
- Calcite + hematite cemented breccia veins

**Isotopic Fluid Categories Present**
- 1, 3

**General Notes**
- Reduction of host sandstone associated with calcite + hematite veins

**Canyon:** 5-4  
**Canyon mouth coordinates:** 12N 0294854mE 4097009mN

**Sampled Units**
- Toroweap Formation – Seligman Member

**Observed Features**
- Calcite veins
- Calcite cemented breccia veins

**Isotopic Fluid Categories Present**
- 1

**General Notes**
- N/A

**Canyon:** PT-1  
**Canyon mouth coordinates:** 12N 0299170mE 4120763mN

**Sampled Units**
- Moenkopi Formation – Timpoweap, Rock Canyon Conglomerate, and Virgin Limestone Members

**Observed Features**
- Boxwork calcite veins
- Calcite veins
- Calcite cemented breccia – zebra stripe calcite veins
Canyon PT-1 continued

Isotopic Fluid Categories Present
- 2, 3

General Notes
- Fracturing and brecciation of calcite cemented sandstone with complete re-cementation by calcite ~ 10 – 20 m from the buried fault trace

Canyon: PT-2
Canyon mouth coordinates: 12N 0298379mE 4118332mN

Sampled Units
- Toroweap Formation – Brady Canyon Member

Observed Features
- Calcite veins

Isotopic Fluid Categories Present
- 1, 2, 3

General Notes
- Location of modern hot spring
- Common calcite-veins in the damage zone
Appendix D: Thin Section Descriptions

Sample: 5-2/S-12

**TS Billet Description**

**Vein:** 2 – 3 cm wide, hematite + calcite cemented brecciated vein w/ sandstone clasts

**Host rock:** well-cemented, calcareous, tan sandstone

Orientation: 52/84

**MINERALOGY**

**Vein constituents:**

- **calcite:** - two end-member forms are present; sparry, double and single twinned crystals, and microcrystalline cement

- **hematite:** - intergrown with microcrystalline calcite cement, and surrounding/infiltrating sandstone clasts

- **chalcedony:** - grown at the margin of one sandstone clast with an indistinct boundary between the two (photo 1_CP)
  - 20-30 µm microcrystalline quartz (photo 2 and 2_CP)
  - intergrown with sparry calcite grains (photo 2 and 2_CP) at contact with vein matrix

- **quartz:** - multi-crystalline clasts present cemented in the calcite matrix of the vein
  - distinct from sandstone clasts due to a lack of clay grunge (photo 3_CP)

**Host rock constituents:**

- **quartz:** ~60% rounded detrital grains
- **calcite:** ~20% microcrystalline cement
- **clays:** ~20% clay grunge

**TEXTURES**

- dissolution pits in vein calcite (photo 4_CP), range from ~10 µm up to ~1 mm, are not lined with hematite, and can be differentiated from mechanical grain plucking due to sample preparation by the lack of concentric fractures around the void

**Paragenesis:** sandstone brecciation → hematite precipitation (continual until calcite dissolution) → chalcedony and quartz precipitation → sparry calcite precipitation → rebrecciation and microcrystalline calcite precipitation → partial dissolution of sparry calcite crystals
Sample 5-2/S-12 continued
Sample: 5-2 to 5-3/S-8

**TS Billet Description**

Vein: ~1 cm wide hematite cemented brecciated vein with calcite clasts, ≤ 1 mm ladder-work calcite veins parallel and orthogonal to the main vein

Host rock: well-cemented tan sandstone

Orientation: 330/80

**MINERALOGY**

Vein constituents:

- **calcite**: two generations: 1) sparry calcite with crystal sizes ranging from ~ 100 μm to > 1 cm, with both rounded grains and intergrown bands  
  2) microcrystalline calcite cement

- **hematite**: pervasively cementing rounded sparry calcite clasts and cementing host sandstone in patches (photo 1)

- **quartz**: rounded detrital grains cemented by both hematite and microcrystalline calcite, not included within sparry calcite crystals

Host rock constituents:

- **quartz**: ~95% moderately sorted rounded-subrounded detrital quartz grains

- **hematite**: ~5% cement

**TEXTURES**

- pervasive dissolution of rounded sparry calcite crystals in main vein (photos 2 and 2_CP)

- dissolution pits not lined with hematite (photo 2)

**Paragenesis**: primary ~1 cm wide sparry calcite vein formation → shear deformation of sparry vein and rounding of sparry calcite crystals → hematite vein cementation → partial sparry calcite dissolution → precipitation of cross-cutting microcrystalline calcite veins
Sample 5-2 to 5-3/S-8 continued
Sample: 5-2/S-5

TS Billet Description
Vein: ~1 mm wide hematite vein with a < 100 µm patchy calcite veneer (not in thin section)
Host rock: well-cemented, calcareous, tan sandstone
Orientation: 349/85

MINERALOGY
Vein constituents:
calcite: - not sampled in thin section
hematite: - replacing calcite cement in the sandstone, progressing from matrix supported at the fracture surface to grain supported at the vein margin (photo 1)

Host rock constituents:
quartz: ~70% sub-rounded detrital grains
lithics: ~7% sub-angular detrital grains
muscovite: ~3% needle-like detrital laths, mildly deformed
calcite: ~20% microcrystalline cement

TEXTURES
- hematite matrix supported sandstone is indicative of expansion during precipitation and high pore fluid pressure

Paragenesis: hematite precipitation/calcite replacement \(\rightarrow\) calcite veneer precipitation
**Sample:** 1-2/S-14

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**TS Billet Description**

**Vein:** 1 – 5 cm wide, alternating hematite + calcite bands

**Host rock:** micritic limestone

Orientation: 358/73

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**MINERALOGY**

**Vein constituents:**

- **calcite:** microcrystalline in a ~ 50 – 400 µm band closest to the vein wall, with both fibrous and lath-like (up to ~ µm) crystals with undulatory extinction and low birefringence occurring in the rest of the vein (photo 1_CP)
- **hematite:** trellis-like structures (photo 2) and semi-irregular patches elongated in the fibrous calcite growth direction, with varying modal frequency in laterally continuous to discontinuous bands orthogonal to the growth direction (photo 3)
  - absent in the interval from the vein wall to ~ 0.7 mm away

**Host rock constituents:**

- **calcite:** microcrystalline/uniform

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**TEXTURES**

- patchy host rock recrystallization (photo 4_CP)
- infiltration of clays/iron oxides parallel to host rock/vein contact (photo 4)
- fibrous and lath calcite intergrown with trellis-like and fibrous hematite, and ____ laths
- 4 of the laterally continuous hematite bands with > 50% hematite show an erosional surface with hematite growth/smearing perpendicular to the fibrous growth direction (photo 5)
- feathery/fibrous growth of calcite + hematite at the margin of the vein furthest from the host rock/vein contact, indicating precipitation in an open void (photo 6)

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**Paragenesis (Figure 2):** hematite precipitation/host rock infiltration and detrital clay deposition → erosion → microcrystalline calcite precipitation → majority of lath calcite precipitation → fibrous calcite + hematite co-precipitation (continuous for remainder of vein growth) → multiple episodes of hematite saturation dominated fluid chemistry, followed by a precipitation hiatus and erosion in ~ ½ of the cases → feathery calcite + hematite co-precipitation
Sample 1-2/S-14 continued
Sample: 4-12/S-6

TS Billet Description
Vein: N/A
Host rock: calcareous red and tan sandstone
    Orientation: N/A

MINERALOGY
Vein constituents: - N/A

Host rock constituents:
quartz: ~69% sub-angular detrital grains
muscovite: ~1% detrital laths
calcite: ~20% microcrystalline cement
hematite: ~10% cement (~2% cement in unaltered zone)

TEXTURES
- relatively high concentration of hematite cement in fingertip-shaped body, with progressively decreasing concentrations radiating outwards from the center until host rock concentrations of hematite cement are reached (photo 1)
- calcite cement is not significantly altered or replaced

Paragenesis: infiltration and precipitation of hematite cement
**Sample:** 5-2 to 5-3/S-7

**TS Billet Description**

**Vein:** ~3 cm thick (minimum) brecciated cherty limestone with calcite and hematite cement – slip surface with slickenlines

**Host rock:** fossiliferous, cherty limestone (not sampled in thin section)

Orientation: 344/63

**MINERALOGY**

**Vein constituents:**
- **calcite:** predominantly microcrystalline cement intergrown with hematite cement, with occasional sparry crystals crystallographically aligned with crystals in host rock clasts
- **hematite:** intergrown with microcrystalline calcite cement – not present in brecciated host rock clasts

**Host rock constituents (in the form of breccia clasts):**
- **calcite:** ~60% sparry crystals and microcrystalline
- **chert:** ~40% microcrystalline cement

**TEXTURES**
- minimal evidence of episodic brecciation and recementation, with one clast of re-brecciated cement present (photo 1)
- incomplete cementation with common void spaces lined by microcrystalline calcite and hematite cement (photo 2_CP)

**Paragenesis:** fossiliferous, cherty limestone brecciation coincident with calcite + hematite cementation → slip event creating slickenlines
Sample: PT-1/S-3

TS Billet Description
Vein: ~ 0.5 – 1 cm wide boxwork calcite veins cementing sandstone
Host rock: matrix-supported, calcareous white sandstone
  Orientation: 170/82

MINERALOGY
Vein constituents:
calcite: - sparry calcite cement in addition to host rock cement forms boxwork veins with quartz inclusions that are up to ~90% calcite (photo 1_CP)
- permeates host rock to varying degrees/no distinct boundaries
hematite: - isolated patches of cement

Host rock constituents:
quartz: ~60% single crystal and ~5% multi-crystalline rounded detrital grains
calcite: ~8% microcrystalline and ~25% sparry cement
hematite: ~2% detrital grains

TEXTURES
- fractured quartz grains and grain size reduction common (increasing intensity with proximity to veins, photo 2_CP), with fractures filled by calcite and hematite cement (photo 3_CP)

Paragenesis: quartz grain size reduction coincident with sparry calcite and hematite cementation and vein formation
Sample PT-1/S-3 continued
Sample: 1-2/S-6

TS Billet Description
Vein: sparry calcite veins within micritic limestone clasts
Host rock: matrix-supported calcareous sandstone with micritic limestone clasts
Orientation: N/A

MINERALOGY
Vein constituents:
calcite: - sparry calcite with cross-cutting veins observed in one limestone clast (photo 1_CP)

Host rock constituents:
quartz: ~55% rounded detrital grains
calcite: ~35% microcrystalline cement
clays: ~10% cement and fragments
Limestone clasts:
calcite: - 100% micritic calcite

TEXTURES
- limestone clasts show moderate to heavy dissolution (photo 2_CP)
- minor dissolution of sparry calcite veins and sandstone cement is observed as well (photo 3_CP)

Paragenesis: sparry calcite formation in micritic limestone with at least 2 generations → brecciation → re-cementation in poorly indurated, clay-rich calcareous sandstone → partial dissolution of whole rock
Sample: 3-5 to PT-1/S-5

TS Billet Description
Vein: ~0.1 – 1 cm wide sparry boxwork calcite veins
Host rock: micritic limestone
    Orientation: ~ N-S

MINERALOGY
Vein constituents:
calcite: - sparry, homogenous intergrown crystals, no apparent cross-cutting relationships

Host rock constituents:
calcite: ~96% microcrystalline cement
chert: <1% authigenic grains
clays: ~2% clay staining spots
oxides: ~1% unidentified oxide grains

TEXTURES
N/A

Paragenesis: no relative timing of vein formation is discernible, likely because they are all penecontemporaneous
Sample: 3-5 to PT-1/S-7

TS Billet Description
Vein: ~ 1 – 1.5 cm wide sparry calcite vein
Host rock: matrix-supported calcareous sandstone
  Orientation: ~ N-S

MINERALOGY
Vein constituents:
calcite: - large crystal (up to ~6 mm diameter) sparry calcite fracture fill
  - microcrystalline to ~ 100 μm diameter calcite intergrown with hematite, cementing
    rounded detrital quartz grains (photo 1 and 1_CP)
hematite: intergrown with microcrystalline calcite, cementing rounded detrital quartz
  grains

Host rock constituents:
quartz: ~50% rounded detrital grains
calcite: ~45% microcrystalline cement ~5% large, sparry, non-matrix grains (possibly
detrital)
oxides: ~1% sub-rounded detrital grains

TEXTURES
- both sparry and microcrystalline vein calcite show frequent minor dissolution pits
  (photo 2)
- sharp boundary between microcrystalline and sparry calcite domains within the vein
  (photo 1 and 1_CP)

Paragenesis: sparry calcite vein precipitation → erosion (not brecciation) of surrounding
sandstone and re-cementation by microcrystalline calcite and hematite cement
Sample 3-5 to PT-1/S-7 continued
Sample: 1-5/S-1

TS Billet Description
Vein: ≤ 1 mm wide boxwork calcite veins
Host rock: calcareous tan sandstone
  Orientation: 155/70 (main orientation)

MINERALOGY
Vein constituents:
calcite: - two forms/generations of cement (photos 1 and 1_CP); 1) sparry calcite cemented veins that are cross cut by and mixed with 2) micritic calcite cemented veins intergrown with indistinct clays/oxides
clays/oxides: - indistinct grunge intergrown with gen. 2 microcrystalline calcite cement

Host rock constituents:
quartz: ~70% sub-angular detrital grains
calcite: ~25% microcrystalline cement
hematite: ~3% grains ~2% isolated patches of cement

TEXTURES
- moderately sharp transition from host rock to veins with >90% calcite cement with <10% detrital quartz grain inclusions
- varying degrees of vein calcite cement infiltration into the host rock (photo 2_CP)

Paragenesis: precipitation of sparry calcite in mm scale fractures → co-precipitation of micritic calcite and clays/oxides in reactivated fractures
Sample 1-5/S-1 continued
Sample: 3-1/S-5

TS Billet Description
Vein: ~2 cm wide complex of 4 separate sparry calcite veins
Host rock: dirty carbonate
Orientation: N-S

MINERALOGY
Vein constituents:
calcite: - two forms/generations of cement (photos 1 and 1_CP); 1) sparry calcite cemented veins with large host rock inclusions that do not appear brecciated 2) mixture of smaller crystal size sparry and microcrystalline calcite cemented veins
hematite: - lining open fractures and the margins of #2 calcite cemented veins
- partially cementing clasts of host rock

Host rock constituents:
calcite: ~30% microcrystalline cement ~35% sparry cement
quartz: ~30% sub-rounded detrital grains
oxides: ~5% non-detrital grains and cement patches

TEXTURES
- hematite fracture fill cross-cuts sparry calcite veins (photos 1 and 1_CP)
- #2 calcite veins cross-cut hematite fracture fill (photos 1 and 1_CP)

Paragenesis: host rock fragmentation and multiple sparry calcite veins precipitate → fracturing along planes of weakness between host rock and sparry veins and hematite precipitates to line the fractures as well as infiltrate the more permeable host rock fragments → intergrown microcrystalline and sparry calcite veins precipitate
Sample 3-1/S-5 continued
Sample: 3-5 to PT-1/S-9

**TS Billet Description**
Vein: open fracture coating with ~ 0.1 mm wide hematite layer and ~ 0.5 – 1.5 mm wide sparry calcite layer  
Host rock: tanned fossiliferous limestone  
Orientation: N-S

**MINERALOGY**
Vein constituents:  
calcite: - sparry calcite “caps” fracture coating (photos 1 and 1_CP)  
gypsum: - one symmetric syntaxial vein parallel to cracking/hematite leaching direction, with host rock inclusions elongated in the vein direction (photos 2 and 2_CP)  
- intergrown with hematite at the base of the fracture surface  
hematite: - irregular main fracture coating, intergrown with gypsum (photos 1 and 1_CP)

Host rock constituents:  
calcite: ~30% microcrystalline cement ~35% sparry cement  
quartz: ~5% sub-angular detrital grains  
hematite: ~20% cement and pseudomorph grains  
gypsum: ~10% pseudomorph grains

**TEXTURES**
- gypsum that is intergrown with hematite in the fracture coating is heavily dissolved (photos 1 and 1_CP)  
- hematite in host rock appears to be “leached” from hematite fracture coating, fills micro-fractures and replaces calcite crystals in the host rock matrix, often in fossil pseudof orm (photos 3 and 3_CP)  
- gypsum also appears as a replacement of calcite crystals, although a similar leaching process is unclear

**Paragenesis:** main fracture formation → hematite and gypsum co-precipitate → micro-fractures orthogonal to the main fracture form → hematite and gypsum are dissolved and leached from the main fracture surface and re-precipitated in fractures, and replacing calcite crystals/cement → sparry calcite “cap” precipitates in main fracture
Sample 3-5 to PT-1 continued
Sample: 1-2/S-3

TS Billet Description
Vein: 3 sparry calcite veins from ~ 1 mm to ~ 1 cm thick
Host rock: fossiliferous limestone
   Orientation: 315/53 (only for 1 mm thick vein)

MINERALOGY
Vein constituents:
calcite: - discontinuous and sinuous sparry veins with host rock inclusions elongated in the vein direction (photos 1 and 1_CP)
- ~1 mm thick straight sparry vein orthogonal to and crystallographically intergrown with the sinuous veins

Host rock constituents:
calcite: ~97% mixed sparry and microcrystalline
chert: ~1% grains
oxides: ~2% cement and stylolite boundaries

TEXTURES
- discontinuous and sinuous sparry veins show shearing fabric, indicative of a fracture opening rate < fracture sealing rate (photos 1 and 1_CP)
- sparry calcite veins orthogonal to 1 mm thick vein are cross-cut and minorly offset (~20µm) by the 1 mm thick vein (photos 2 and 2_CP)
- host rock displays rare hematite filled stylolites parallel to sinuous, discontinuous calcite veins (photos 3 and 3_CP)

Paragenesis: discontinuous and interconnected fractures open orthogonal to the principle stress direction, in approximate equilibrium with sparry calcite fracture sealing → principle stress direction changes and 1 mm wide fracture forms orthogonal to previous veins, while being simultaneously filled with sparry calcite
Sample 1-2/S-3 continued
Sample: 5-2 to 5-3/S-5

TS Billet Description
Vein: ~3 cm wide calcite + hematite cemented brecciated vein, with subsidiary boxwork calcite veins
Host rock: calcareous sandstone
  Orientation: 33/69

MINERALOGY
Vein constituents:
calcite: - 2 generations:
  1) sparry calcite grown around and intergrown with hematite veins (photos 1 and 1_CP);
     microcrystalline calcite intergrown with hematite cement as “boxwork” veins with ~5%
     entrained quartz grains (photos 2 and 2_CP)
  2) sparry and microcrystalline calcite veins cross-cut and cement clasts of calcite +
     hematite veins, as well as up to ~10% entrained quartz grains (photos 1, 1_CP, 2, and
     2_CP)
 hematite: - forms coherent veins with ~2% entrained quartz grains surrounded by gen. 1
     sparry calcite, as well as intergrown with gen. 1 microcrystalline cement
     - lines clasts of gen. 1 veins (photos 1 and 1_CP)

Host rock constituents:
quartz: ~80% sutured sub-angular detrital grains
calcite: ~13% sparry cement
hematite: ~7% cement intergrown with the calcite

TEXTURES
- sparry calcite and hematite veins, as well as cogenetic microcrystalline calcite and
  hematite are often broken and floating as clasts in the later pure calcite cemented veins
  (photos 1, 1_CP, 2, and 2_CP)
- whole thin section shows a sinuous fabric with semi-discontinuous and interfingering
  veins

Paragenesis: hematite and calcite co-precipitate, with main sparry veins and separated
hematite/calcite as well as subsidiary boxwork veins with hematite and calcite intergrown
→ brecciation re-cementation by pure calcite in a similar morphology as before, with
sparry veins as well as microcrystalline boxwork veins
Sample 5-2 to 5-3 continued
**Sample:** 1-5/S-3

**TS Billet Description**
*Vein:* ~ 1 mm thick calcite + hematite coated slip surface – patchy
*Host rock:* calcareous sandstone
  Orientation: 167/84

**MINERALOGY**
*Vein constituents:*
  *calcite:* - microcrystalline calcite cement intergrown with hematite
  - sparry calcite cement with 5 – 30 % quartz grain inclusions and ~ 5% hematite grains
    (photos 1 and 1_CP)
  *hematite:* - intergrown with microcrystalline calcite, associated with open fractures and
  comminuted slip surfaces (photos 2 and 2_CP)

*Host rock constituents:*
  *quartz:* ~ 85% sutured sub-angular detrital grains
  *calcite:* ~ 8% microcrystalline cement intergrown with oxides
  *oxides:* ~ 7% cement intergrown with the calcite

**TEXTURES**
- patches of fractured and comminuted host rock present within and at the base of the
  calcite cemented slip surface, with increased cementation by hematite (photos 2 and 2_CP)

*Paragenesis:* repeated fracturing and slip along a plane of weakness and co-precipitation
  ⇔ precipitation of sparry calcite along the slip surface and subsidiary fractures during
  periods of acquiescence
Sample: 1-1/S-9

TS Billet Description
Vein: ~1 mm thick calcite + hematite coated slip surface – patchy
Host rock: dirty limestone
  Orientation: 356/82

MINERALOGY
Vein constituents:
calcite: - two clean, sparry veins, one main vein with clasts of host rock included (photos 1 and 1_CP)
hematite: - replacing dissolution pits left by calcite and chert grains in clasts of host rock and adjacent host rock (photo 2 and 2_CP)

Host rock constituents:
quartz: ~10% sub-rounded detrital grains
calcite: ~85% microcrystalline cement and sparry grains
hematite: ~4% cement in void spaces
chert: ~1% cement

TEXTURES
- hematite fills dissolution voids radiating outward from the main vein, gradually transitioning from ~30% of whole rock at the vein wall to the background level of ~4% of whole rock (overall photo)

Paragenesis: main fracture formation → dissolution and replacement of calcite and chert grains surrounding the main fracture by hematite → second fracture formation → precipitation of sparry calcite veins in both fractures
TS Billet Description
Vein: dense undulatory calcite boxwork veining
Host rock: sandstone
  Orientation: N-S

MINERALOGY
Vein constituents:
calcite: - mixed sparry and microcrystalline interconnected veins with host rock and quartz grain inclusions

Host rock constituents:
quartz: ~ 90% poorly sorted angular detrital grains – sutured
hematite: ~ 5% grains and cement
calcite: ~ 5 % sparry grains

TEXTURES
- multiple reactivation events of the same fractures evidenced by internal divisions in within veins (photos 1 and 1_CP)
- large dissolution voids in sandstone clasts (photo 2_CP)

Paragenesis: multiple episodes of interconnected fracturing and vein precipitation with simultaneous dissolution/brecciation of sandstone clasts
Sample: 3-4/S-4

TS Billet Description
Vein: ~ 1 – 1.5 cm thick sparry calcite vein
Host rock: calcareous sandstone
Orientation: 33/44

MINERALOGY
Vein constituents:
calcite: - discontinuous clean sparry calcite and microcrystalline calcite with ~ 25% detrital quartz grain inclusions at the margin of the main vein with no distinct boundary between them and the host rock (photos 1 and 1_CP)
  - sparry calcite grains in the main vein
hematite: - 2 thin vein boundary between calcite microcrystalline/sparry calcite with quartz inclusions and main vein (photos 1 and 1_CP)

Host rock constituents:
quartz: ~ 90% angular detrital grains – sutured
hematite: ~ 5% cement intergrown with calcite
calcite: ~ 5% microcrystalline cement

TEXTURES
  - sparry calcite grains are etched (photos 2 and 2_CP)
  - void spaces in main vein due to incomplete fracture fill (photo 3)

Paragenesis: slow fracture initiation with calcite precipitation and minor infiltration into the host rock → precipitation of hematite at center of the fracture → another cycle of slow fracture opening and calcite precipitation followed by hematite precipitation → rapid final opening of the fracture → main sparry calcite vein precipitation
Sample 3-4/S-4 continued
Sample: 5-2/S-4

TS Billet Description
Vein: 2 sparry calcite veins rimmed with hematite ~ 1 mm thick each, with a milky calcite vein in-between them
Host rock: calcareous sandstone
  Orientation: 175/79

MинERALOGY
Vein constituents:
calcite: - sparry calcite grains intergrown with microcrystalline calcite and hematite within hematite bounded vein (photos 1 and 1_CP)
  - sparry calcite grains cemented within breccia matrix
  - microcrystalline calcite intergrown with hematite forming main breccia cement
hematite: - intergrown with microcrystalline/sparry cement at the margins of the main sparry vein, with ~ 20% detrital quartz grain inclusions and no clear boundary with host rock (photos 1 and 1_CP)
  - occurs as broken grain inclusions within sparry calcite at opposite end of thin section (photo 2)
  - minor cement and broken grains within microcrystalline calcite breccia cement

Host rock constituents:
quartz: ~ 85% angular detrital grains – sutured
hematite: ~ 5% cement intergrown with calcite
calcite: ~ 9% microcrystalline cement
muscovite: ~ 1% detrital laths

TEXTURES
- sparry calcite grains are etched (photos 1 and 2)
- quartz grains and host rock clasts are suspended in brecciated vein
- hematite cement in brecciated vein appears to be partially leached cement originating from host rock cement and is not primary (photo 3)

Paragenesis: initial fracturing and associated hematite/calcite precipitation → rapid re-fracturing of weak planes at the center of hematite/calcite veins with relatively slow re-sealing by sparry calcite and microcrystalline calcite/hematite → brecciation of host rock between well-cemented sparry calcite + hematite veins with cementation by sparry calcite → re-brecciation and cementation by microcrystalline calcite → breccia vein cross-cut by a late-stage fracture filled with sparry calcite
Sample 5-2/S-4 continued
Sample: 1-4/S-27

TS Billet Description
Vein: 3 – 4 mm wide sparry gray calcite + hematite fracture coating, with an adjacent ~ 2 cm wide band of boxwork/breccia veins and calcite concretions
Host rock: calcareous sandstone
 Orientation: 340/70

MINERALOGY
Vein constituents:
calcite: - relatively small grained sparry calcite mixed with microcrystalline calcite and up to ~ 10% quartz grain inclusions in fracture coating (photos 1 and 1_CP)
 - microcrystalline calcite cement intergrown with hematite and ~ 40% quartz grain inclusions (photos 1 and 1_CP)
 - clean, large-grained sparry calcite (photos 1 and 1_CP)
 - patchy microcrystalline boxwork cement ranging from grain-supported host rock to matrix supported boxwork
 - calcite concretions in host rock forming matrix-supported patches up to ~ 50% calcite (photo 2_CP)
 hematite: - intergrown with microcrystalline calcite cement with ~ 40% quartz grain inclusions

Host rock constituents:
quartz: ~ 92% sub-angular detrital grains – sutured
hematite: ~ 3% cement intergrown with calcite
calcite: ~ 5% microcrystalline cement

TEXTURES
- multiple layers of small grained/microcrystalline calcite, microcrystalline calcite + hematite + ~40 % quartz grain inclusions, and pure large grained sparry calcite in a sinuous fabric comprise the primary fracture coating (photos 1 and 1_CP)
 - large pits associated with weak vein layer boundaries

Paragenesis: boxwork calcite cement forms via shearing of host rock and crystallization pressure ↔ calcite concretions form by nucleation on host rock calcite cement and crystallization pressure → main fracture forms, with multiple cycles of calcite precipitation and entainment of boxwork vein clasts/hematite precipitation → late-stage shearing unaccompanied by calcite precipitation results in “pull-apart” pits in veins
Sample: 4-7/S-1.5

TS Billet Description
Vein: 2 sub-parallel sparry calcite veins ~ 1 mm wide
Host rock: fossiliferous limestone
  Orientation: 5/60

MINERALOGY
Vein constituents:
calcite: - 2 clean, sparry, undulatory calcite veins
  - one vein is uniform thickness and continuous
  - one vein is discontinuous and branches into microcracks

Host rock constituents:
calcite: ~ 90% microcrystalline cement and ~ 10% sparry grains

TEXTURES
N/A

Paragenesis: minor fracture formation → sparry calcite precipitation
Sample: 1-2/S-9

TS Billet Description
Vein: fault core breccia
Host rock: cherty, fossiliferous limestone
   Orientation: ~ 234/75

MINERALOGY
Vein constituents:
calcite: - comminuted microcrystalline breccia cement
oxide: - very minor occasional patches of cement

Host rock constituents (from host rock clasts):
Fossiliferous, cherty limestone:
calcite: ~ 30% microcrystalline cement ~ 20% microcrystalline and sparry grains
chert: ~ 45% microcrystalline cement ~ 5% grains
Fossiliferous limestone:
calcite: ~ 5% microcrystalline cement ~ 95% sparry grains

TEXTURES
- intense brecciation with a wide variety of clast sizes suspended in microcrystalline matrix cement
- two morphologies of breccia clasts indicate entrainment of host rock from multiple stratigraphic horizons

Paragenesis: repeated brecciation and cementation
**Sample:** 1-2/S-16

**TS Billet Description**

**Vein:** ~ 1.5 cm thick sparry calcite  
**Host rock:** micritic limestone  
**Orientation:** ~ 353/83

**MINERALOGY**

**Vein constituents:**
- calcite: - sparry vug fill with low interference colors and undulatory extinction (photo 1_CP)  
- 2 bands of small crystalline sparry and microcrystalline vein fill (photos 2 and 2_CP)  
- 2 bands of large crystalline sparry vein fill, with occasional inclusions of small crystalline sparry clasts (photos 2, 2_CP, and 3_CP)

**Host rock constituents:**
- calcite: ~ 96% microcrystalline cement  
- oxides: ~ 2% grains  
- quartz: ~ 2% detrital grains

**TEXTURES**
- sparry calcite grains are etched (photos 2 and 2_CP)

**Paragenesis:**  vugs form by isolated dissolution $\rightarrow$ vugs partially fill by calcite precipitation $\rightarrow$ rapid primary fracture opening $\rightarrow$ large crystalline sparry calcite precipitation $\rightarrow$ relatively slow fracture opening $\rightarrow$ small crystalline/microcrystalline calcite precipitation $\rightarrow$ repeat of rapid fracture opening + large crystalline sparry calcite precipitation $\rightarrow$ slow opening + microcrystalline calcite $\rightarrow$ rapid fracture opening + large crystalline sparry calcite precipitation
Sample 1-2/S-16 continued
Sample: 5-4/S-2

**TS Billet Description**
- **Vein:** brecciated limestone with sparry calcite cement – sheared appearance
- **Host rock:** dirty limestone
  - Orientation: 35/85

**MINERALOGY**
- **Vein constituents:**
  - calcite: - intergrown sparry and microcrystalline calcite for intertwining veins and cement host rock clasts and individual quartz grains

- **Host rock constituents:**
  - calcite: ~ 85% microcrystalline cement
  - oxides: ~ 3% grains
  - quartz: ~ 12% rounded detrital grains

**TEXTURES**
- sparry calcite grains are etched
- comminution/shearing planes intertwine (photo 1 and 1_CP)

**Paragenesis:** repeated brecciation, calcite precipitation, and shearing events
Sample: 1-4/S-4

**TS Billet Description**
**Vein:** ~ 2.5 cm thick radial, sparry calcite layers in open void fill cross-cutting hematite + calcite cemented breccia
**Host rock:** calcareous sandstone
  Orientation: 170/82

**MINERALOGY**
**Vein constituents:**
**calcite:** - four generations:
  1) sparry breccia cement intergrown with hematite, with host rock clasts and ~ 10% detrital quartz grain inclusions (photos 1 and 1_CP)
  2) clean, sparry calcite with radial, undulatory extinction
  3) intergrown sparry/microcrystalline calcite with radial, undulatory extinction (photos 2 and 2_CP)
  4) sparry calcite open void fill, cementing clasts of gen 2 and gen 3 (photo 3_CP)
**hematite:** - surrounding host rock clasts in a thin “shell” of cement with shallow infiltration into each clast
  - intergrown with and lining sparry calcite grain boundaries, as well as the boundary between calcite gen 1 and gen 2 (photos 1 and 1_CP)

**Host rock constituents (from host rock clasts):**
**quartz:** ~ 85% sub-rounded to angular detrital grains – sutured
**hematite:** ~ 5% cement
**calcite:** ~ 10% microcrystalline cement

**TEXTURES**
- calcite gen 1 and hematite clast suspended in gen 2 calcite vein
- comminuted microcrystalline calcite boundaries between calcite gen 2, gen 3, and gen 4
- void spaces at center of growth for calcite gen 2 and gen 4 show incomplete vein fill
- sparry calcite grains are etched

**Paragenesis:** host rock brecciation and cementation by calcite + hematite → main fracture opens ≤ 1 mm and is filled by a hematite vein → main fracture opens rapidly, fracturing off and breaking apart part of the hematite vein, and is cemented by calcite gen 2 → slip and grinding occurs along one margin of the vein → fracture opens slowly, with calcite gen 3 precipitating → slip and grinding occurs along the same margin of the vein → brecciation of calcite gen 2 and 3 occurs → calcite gen 4 precipitates, cementing the brecciated main vein
Sample: 1-4/S-17

**TS Billet Description**

**Vein:** ~1 mm thick patchy calcite + hematite coated slip surface with disconnected MnO dendrites radiating from the fracture surface  
**Host rock:** calcareous sandstone  
Orientation: 205/14

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**MINERALOGY**

**Vein constituents:**
- **calcite:** - sparry crystals intergrown with hematite at the fracture surface, with ≤ 5% quartz grain inclusions (photos 1 and 1_CP)  
  - rough, but distinct boundary between calcite coating and the host rock (photos 1 and 1_CP)  
- **hematite:** - intergrown with sparry calcite fracture coating  
  - heavily cementing host rock adjacent to the fracture coating intergrown with calcite cement, with a gradual transition from ~30% hematite cement to background host rock oxide level of ~10%  
  - forms distinct vein boundary between calcite + hematite fracture coating and the host rock (photos 1 and 1_CP)  
- **MnO:** - dendrites in host rock replace almost all other cement (photo 2)

**Host rock constituents:**
- **quartz:** ~80% angular detrital grains – sutured  
- **muscovite:** ~1% detrital grains  
- **oxides:** ~10% cement  
- **calcite:** ~9% microcrystalline cement

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**TEXTURES**

- MnO dendrites are elongated in the direction of fluid flow along micro fractures, with detrital quartz grains elongated parallel to dendrite growth direction (hand sample photo and photo 2)  
- calcite/hematite fracture coating shows fractured grains but no polished surface (photo 3)

**Paragenesis:** main fracture and oblique micro fracture formation → mobilization and recrystallization of oxide cement in host rock into MnO dendrites → hematite and calcite cement precipitation increasing intra-granular pore space, radiating from the fracture surface → calcite and hematite co-precipitation at the fracture surface
Sample: 4-11/DN-15/HR-01

TS Billet Description
Vein: ~2 mm thick sparry calcite intergrown with MnO
Host rock: calcareous, fine-grained, red sandstone
  Orientation: 12/75

MINERALOGY
Vein constituents:
calcite: - sparry grains, composed of many individual crystallographic domains cement the main vein
  - sparry main vein calcite cement is intergrown with MnO dendrites and includes ~15% detrital quartz grains (photos 1 and 1_CP)
  - ~150 µm thick clean sparry calcite veins oblique to, and roughly parallel to/lining one side of the main vein (photos 2 and 2_CP)
MnO: - dendrites intergrown with and displacing main vein calcite cement, and radiating out from the vein with no clear boundary (hand sample photo, and photos 1 and 1_CP)

Host rock constituents:
quartz: ~55% angular detrital grains
muscovite: ~1% detrital grains
oxides: ~4% grains and ~10% cement
calcite: ~10% grains and ~15% microcrystalline cement

TEXTURES
N/A

Paragenesis: small ~100 – 150 µm wide fractures open rapidly a dominant orientation → sparry calcite precipitates to fill the fractures → one primary fracture opens slowly, with calcite and MnO precipitating and infiltrating the host rock
Sample: 4-2/S-1

**TS Billet Description**

**Vein:** fault core breccia - cherty limestone with a ≤ 1 mm thick smooth, calcite coated slip surface

**Host rock:** cherty limestone
- Orientation: 152/82

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**MINERALOGY**

**Vein constituents:**
- **calcite:** - intergrown sparry and microcrystalline cement
  - rounded clasts of sparry calcite grains intergrown with microcrystalline cement and oxides in comminuted breccia bands (photos 1 and 1_CP)
- **oxides:** - intergrown with comminuted calcite cement (photo 1)
  - rimming and intergrown with sparry calcite clasts (photo 1)

**Host rock constituents (from host rock clasts):**
- **chert:** ~ 65% microcrystalline cement
- **calcite:** ~ 34% microcrystalline cement
- **oxides:** ~ 1% grains

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**TEXTURES**
- sparry calcite crystals within clasts show dissolution and subsequent overgrowths (photo 2_CP)
- large void spaces – indicative of brecciation without complete re-cementation
- host rock and sparry calcite clasts/grains are fractured (photo 3)

**Paragenesis:** initial brecciation with sparry calcite cementation → partial dissolution of cement → sparry overgrowth and microcrystalline cement precipitation → comminution and re-brecciation → multiple cycles of fracture opening and re-brecciation with microcrystalline calcite cement precipitation and minimal comminution
Sample 4-2/S-1 continued
Sample: 1-4/S-25

TS Billet Description
Vein: N/A
Host rock: calcareous sandstone
  Orientation: N/A

MINERALOGY
Vein constituents:
N/A

Host rock constituents (from host rock clasts):
quartz: ~ 80% angular detrital grains
calcite: ~ 10% microcrystalline cement intergrown with oxides
oxides: ~ 10% cement intergrown with calcite

TEXTURES
- MnO concretions form ~100% of the cement in up to ~ 150 µm wide patches
- calcite concretions form ~100% of the cement in up to ~ 150 µm wide patches

Paragenesis: N/A
Sample: 1-4/S-5

**TS Billet Description**

Vein: ~ 2 – 5 mm thick sparry calcite + hematite veins and adjacent calcite concretions
- same vein fracture as 1-4/S-4

**Host rock:** calcareous sandstone
  Orientation: 170/82

**MINERALOGY**

**Vein constituents:**

**calcite:** - large sparry crystals in one bifurcating vein with ~ 20% quartz grain inclusions, intergrown with hematite (photos 1 and 1_CP)
  - sparry calcite veins with clasts of host rock and ~ 0 – 30% quartz grain inclusions
  - microcrystalline calcite intergrown with discontinuous hematite band (photos 2 and 2_CP)
  - sparry, radial, calcite with undulatory extinction at the edge of the fracture (photos 2 and 2_CP)
  - ≤ 1 mm diameter concretions in host rock form ~ 95% of cement and ~ 35% of whole rock

**hematite:** - intergrown with sparry crystalline veins disconnected from vein wall, up to ~ 35% cement (photos 1 and 1_CP)
  - forms one discontinuous band intergrown with microcrystalline calcite and one continuous band intergrown with sparry calcite near the fracture surface (photos 2 and 2_CP)

**Host rock constituents:**

**quartz:** ~ 85% angular detrital grains - sutured
**calcite:** ~ 8% microcrystalline cement
**oxides:** ~ 7% cement intergrown with calcite

**TEXTURES**

- overall sinuous, interconnected, sheared texture
- sparry calcite grains are etched
- no clear boundary between intergrown hematite + sparry calcite band and the radial calcite, as in sample 1-4/S-4

**Paragenesis:** slow intitial inter-connected fracture formation → sparry calcite and hematite co-precipitate as fracture fill → brecciation and cementation by sparry calcite → two events of fracturing along primary fracture surface and precipitation of hematite + calcite in ~ 0.5 mm wide fracture → rapid opening of primary fracture → precipitation of radial calcite
Sample 1-4/S-5 continued
**TS Billet Description**

**Vein:** ~ 0.5 cm wide N-S striking sparry calcite vein intersecting a ~ 2 mm wide E-W striking sparry calcite vein

**Host rock:** dirty limestone

Orientation: 280/75 and 30/80

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**MINERALOGY**

**Vein constituents:**
- calcite: - 3 large-grained, clean, sparry calcite veins

**Host rock constituents:**
- calcite: ~ 85% microcrystalline cement
- oxides: ~ 3% grains
- quartz: ~ 11% sub-rounded detrital grains
- muscovite: ~ 1% detrital grains

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**TEXTURES**
- broken, comminuted grains with void spaces in isolated zones indicate vein fracturing and incomplete annealing (photos 1 and 1_CP)
- calcite twinning is mildly deformed in some sparry grains in the main vein (photo 2_CP)
- both smaller, discontinuous veins are crystallographically intergrown, show offset, and are disconnected by broken, microcrystalline calcite (overall thin section photo and photo 3_CP)
- sparry calcite grains are etched

**Paragenesis:** small, discontinuous fractures and main ~ 0.5 cm wide fracture form rapidly → sparry calcite precipitates in all fractures → minor shearing in two orthogonal directions offsets smaller fractures and deforms sparry calcite in main fracture
Sample 5-4/S-3 continued
Sample: 1-4/S-2

TS Billet Description
Vein: < 1 mm thick calcite + hematite fracture coating (not captured in thin section)
Host rock: tanned and red calcareous sandstone
  Orientation: 188/76

MINERALOGY
Vein constituents:
  N/A

Host rock constituents:
  quartz: ~ 60% angular detrital grains
  muscovite: ~ 1% detrital grains
  oxides: ~ 3% grains and ~ 10% cement intergrown with calcite cement
  calcite: ~ 26% microcrystalline cement

TEXTURES
  - oxide cement transitions from ~ 7% near the fracture surface, to ~ 0%, to ~ 10% in the host rock

Paragenesis: reducing fluids flow along fracture and infiltrate ~ 2-3 cm into host rock, mobilizing oxides → change in oxidation state re-deposits oxides in cement near the fracture surface
**Sample:** 1-4/S-14

**TS Billet Description**
**Vein:** N/A  
**Host rock:** calcareous sandstone  
Orientation: 277/88

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**MINERALOGY**

**Vein constituents:**
N/A

**Host rock constituents:**
quilz: ~ 60% angular detrital grains  
oxides: ~ 3% cement intergrown with calcite cement  
calcite: ~ 35% microcrystalline cement  
muscovite: ~ 2% detrital grains

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**TEXTURES**
- oxide cement transitions from ~ 7% near the fracture surface, to ~ 0%, to ~ 3% in the host rock

**Paragenesis:** reducing fluids flow along fracture and infiltrate ~ 2-3 cm into host rock, mobilizing oxides \( \rightarrow \) change in oxidation state re-deposits oxides in cement near the fracture surface