A Record of Diagenesis and Sevier Crustal Deformation within Bedding Parallel Fibrous Calcite Veins of the Heath Formation, Central Montana Trough

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Introduction

Bedding parallel fibrous calcite veins (BPFV) form exclusively in organic-rich very fine grained sedimentary rocks (mudstones) commonly acting as primary source rocks in petroleum systems around the world (Cobbold et al., 2013). BPFV genesis has been tied to processes acting in both the deep (> 2 km) and shallow (< 2 km) subsurface that relate to diagenesis, tectonics, and burial that control fracture opening and precipitation of veins. Thus, BPFV hold clues regarding basin history. As basin histories based only on present-day observations are often unable to account for unconformities or other chronostratigraphic uncertainties, BPFV may be utilized to extract snapshots of reservoir conditions in the geologic past.

The purpose of this study is to utilize the age, temperature, and carbon and oxygen isotopic source of BPFV to improve the burial, tectonic, and diagenetic history of the Heath Formation and the Central Montana Trough, an important respective petroleum source rock and basin of Central Montana (Bottjer et al., 2016).To accomplish this purpose, we present:

1. Geologic background of the Central Montana Trough
2. Detailed characterization of veins
3. Host rock mineralogy and organic matter characterization
4. U-Pb geochronology of vein material via LA-ICP-MS
5. Clumped Isotope Thermometry of Heath BPFV
6. Vein and host rock conventional ^{13}C and ^{18}O isotope fractionation analysis
7. A refined burial history based on data obtained
8. Conclusions & Selected References

2 U-Pb Geochronology

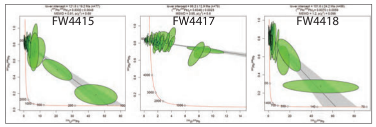


Figure 2 - Samples FW4415, FW4417, and FW4418 were dated by U-Pb geochronology via laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). 80 micron beam size in time-resolved line scans were used to avoid and filter out common lead contamination by mud inclusions (see Figure 5B). Uranium consistently below 1 ppm resulted in large analytical uncertainty. Ages are identical within error; however, temperature of formation via clumped isotopes suggests vein formation occurred at different times. Ages compared to burial history indicate burial depth at time of formation between 500 m to 1.8 km.

3 Clumped Isotope Thermometry

A

Sample	Replicants	Average δ13C	Average δ18O	Temperature of Formation	Standard Error
4415	3	-0.47	-0.83	43.1	2.3
4417 - Vein Median	3	0.32	-0.72	52.1	3.7
4417 - Vein Between	3	-2.27	-0.98	57.7	2.9
4417 - Vein Margin	3	-6.6	-4.9	55.5	2.7
4418	3	-0.08	-0.89	50.2	2.4

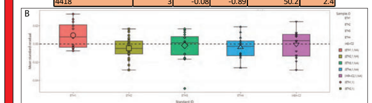


Figure 3 - [A] Results averaged from three replicants for statistical significance. Temperatures coincide with respective age and burial depth (Figure 4). Burial depths range from 500m to 1.4 km assuming a normal geothermal gradient. Sample FW4417 tested for temperature difference from vein median to margin produced same age within error; if a temperature difference is present, it is unresolvable. [B] Standards run alongside samples with expected results.

5 Carbon & Oxygen Isotopes

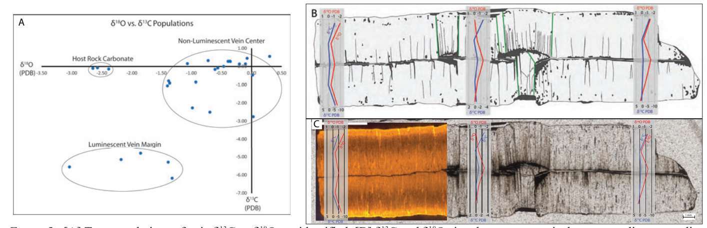


Figure 5 - [A] Two populations of vein $\delta^{13}C$ vs $\delta^{18}O$ are identified. [B] $\delta^{13}C$ and $\delta^{18}O$ signals are symmetrical across median suture lines. Note abundance of host rock inclusions within vein material, particularly along median suture lines and perpendicular fractures. [C] CL imaging compared to stable isotope analyses. Significantly negative isotope fractionation found only along brightly luminescent vein margins. Remaining values represent evolution from original seawater signature ($\delta^{13}C$ of about 4‰ and $\delta^{18}O$ between 0 and -10‰ PDB) to become progressively lighter during sulfate reduction, then heavier during extended methanogenesis.

1 Geologic Background

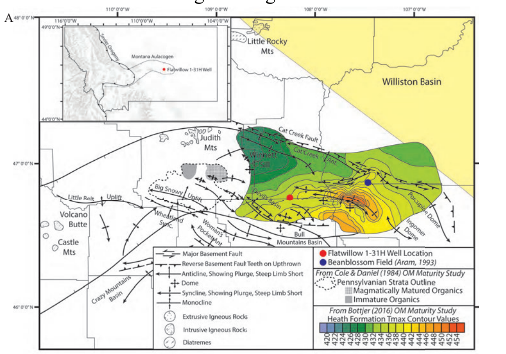
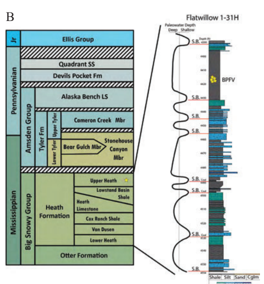


Figure 1 - [A] The Central Montana Trough initial subsidence took place during the Antler Orogeny due to reactivation of proterozoic aulocagen faults. BPFV of this study were taken from the Flatwillow 1-31H well. Organic matter maturity studies within this area suggest normal geothermal gradients around 25 °C/km (Bottjer 2016; Aram, 1993). Anomalous organic maturity noted in well with intrusive igneous body (Cole & Daniel, 1984). Magmatic intrusions noted within and around trough have been dated to 69-29 Ma (Chadwick, 1981; Marvin et al., 1980). [B] Stratigraphic column and core description of the Flatwillow 1-31H well, modified from Ahern & Fielding (2019). Six veins of BPFV were taken from depths ranging between 1345 to 1348 meters (4414 to 4424 feet).



4 Tectonics & Burial History

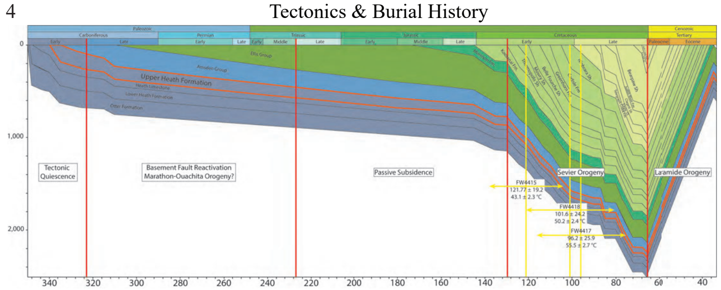


Figure 4 - Burial history diagram produced using BasinMod and using stratigraphy from Lawlor (1956), Maughan (1993), and Singer et al (2019), and tectonic history from Norwood (1965), Nelson (1995), and Heller et al (1986). Vein ages are coincident with the first major burial event of the Central Montana Trough. Overpressure developed as a result of rapid burial combined with stress field orientation by Sevier Orogeny tectonics such that normal (lithostatic) stress is least principal stress allowed BPFV fracturing and precipitation.

6 Vein Diagenetic Characterization

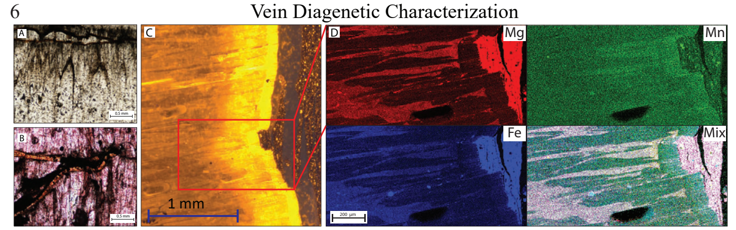


Figure 6 - [A] Cone-in-cone morphology observed with apices pointed towards median suture lines indicating growth away from median (Gallois, 2008; Marshall, 1982; Meinhold et al., 2020) [B] Bivalve shell trapped along median suture line, likely a site of calcite nucleation also indicating growth initiating at medians (Hendry, 2002; Maher et al., 2017; Meng et al., 2017; Milliken et al., 2012; Rodrigues et al., 2009). [C] CL activation along margin of the vein. [D] EPMA element maps coorelating CL activation with compositional changes in calcite. Orange activation has Fe/Mn ratios ranging between 2.9 to 7.2; red range from 7 to 16; and yellow ranges from 0.3 to 2.4. Interfingered transitions between orange and red indicate fluid evolution during precipitation. Sharp transition from yellow to bright yellow represents later precipitation of calcite from further in-situ diagenetically evolved fluid too thin to resolve via clumped isotope thermometry. Lighter yellow represents reaction zone with new precipitating fluid. Fluid invasion into preexisting magin-perpendicular microfractures visible on Figure 5C.

8 Conlcusions

1. Age of veins coincident with first major burial event that likely caused reservoir overpressure to develop
2. Trough burial likely resulted from Sevier Orogeny tectonics producing flexural subsidence and/or sedimentation into the trough
3. Periodic vein precipitation resulting from ongoing overpressure development and contractional tectonic strain
4. Temperature of precipitating fluids between 40.8 to 60.6 °C resulting from burial depth between 500 m to 1.4 km
5. Temperature variations between veins positively correlate with vein U-Pb ages, increasing confidence in age differences between veins
6. Normal geothermal gradient indicated by temperatures, age of magmatic activity, and organic maturity thermal studies
7. Gradual fluid composition evolution due to crystallization within orange and red luminescent zones
8. Vein yellow luminescent margin resulted from second generation of growth occurring after in-situ fluid evolution due to initiation of new diagenetic processes and higher temperature that resulted in lightening of $\delta^{13}C$ and $\delta^{18}O$, respectively

Selected References

Ahern, J. P., and Fielding, C. R., 2019, Onset of the Late Paleozoic glacioeustatic signal: a stratigraphic record from the paleotropical, oil-shale-bearing Big Snowy Trough of Central Montana, USA: Journal of Sedimentary Research, v. 89, no. 8, p. 761-783.

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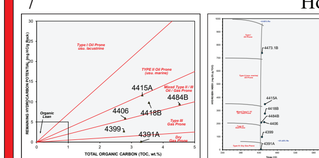
7 Host Rock Characterization



Sample Whole Rock	Quartz	Calcite	Dolomite	10 Å clay (i.e. Illite)	Kaolinite	Illite-smectite	K-feldspar	Pyrite	Gypsum
Diagnostic peak (°2θ)	26.64	29.45	30.82	8.84	12.33	6 - 8.6	27.24	33.04	11.67
FW-4416	17.5	46.9	2.2	16.1	2.7	20.2	2.5	1.2	3.5
FW-4417	16.5	22.4		10	12.3	16.6	9.5	11.3	1.4
FW-4418	19.5	21.6		14.3	17.1	11.3	11.7	2.8	1.7

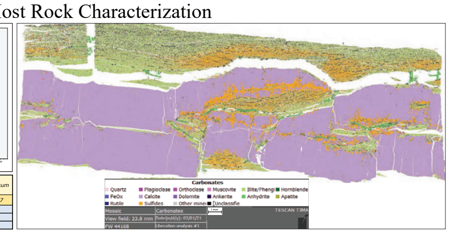


Figure 7 - [A] Wildcat Pyrolysis produced total organic carbon (TOC) between 2.8 to 8.2 wt. %. Organic matter is primarily type II (Bottjer, 2016). [B] Organic matter thermal maturity is within the oil window, consistent with maximum burial depth as discussed in Aram (1993) and Norwood (1965). [C] XRD indicates bulk mineralogy with clay content around 40%. Calcite vs. dolomite important as dolomitic contamination in clumped isotope analyses can produce anomalous temperatures. Clay separation analysis revealed ~50% mixed-layer illite-smectite (Reichweit = 0). [D] TIMA mineral mapping reveals abundance of sulfide phases and clay minerals along medians and vein margins. Abundant inclusions throughout veins to be avoided during LA-ICP-MS U-Pb geochronology.