PS Fluid Histories of Middle Ordovician Fault-Fracture Dolomite Oil Fields of the Southern Michigan Basin*

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Abstract

The Middle Ordovician Trenton and Black River formations of the southern Michigan Basin host the type example of fault-fracture "hydrothermal dolomite" reservoirs, the Albion-Scipio Field. Within the basin, a number of parallel trending smaller structures contain the same type of fault-fracture reservoirs including the Freedom, Reading, Northville, Stoney Point, Napoleon, and several other oil fields. These reservoirs share many characteristics in common with Mississippi Valley-type mineral deposits including dolomitized breccias, coarse crystalline saddle dolomite and calcite cements, and sulfide and sulfate mineralization. The fields appear to be structurally related, trending southeast to northwest. However, it is not known if they also share related fluid histories.

Fluid inclusion data in several of the fields display homogenization temperatures (T_h) ranging from 91° C in saddle dolomites to over 250° C in late calcite cements. Last ice melt temperatures (T_m) generally indicate high salinities and range from -10° C to -37.1° C. Infrequently, included daughter halite crystals are observed in the late calcite cements. Some trends exist in these fluid inclusion data. Cross plotted T_h and T_m temperatures for the Reading Field, near the Indiana border, exist in a cluster distinct from the other fields in the study, containing generally cooler and less saline fluids. However, data from the Albion-Scipio trend and the distant Northville display considerable overlap in values with most T_h measurements between 175° C to 250° C and T_m between -19° C and -31° C.

Stable Carbon and Oxygen isotopes for the same fields have been evaluated. Data overlaps well with previous studies with a mean of $\delta^{18}O$ = -8.07 ‰ (VPDB) and mean $\delta^{13}C$ = +0.47 ‰ (VPDB) for dolomite cement samples. These values are less depleted in both $\delta^{18}O$ and $\delta^{13}C$ than studies from the early 1980s, but they are in agreement with more recent studies.

Cathodoluminescence (CL) microstratigraphy observed in dolomite and calcite crystals may allow correlation of diagenetic events among the fields. Multiple distinct CL zones have been observed and are being evaluated. Carbonate cements collected in close geographic proximity

show more similar CL cement stratigraphies than cements distal from one another. However, carbonate cements from separate fields display similarities in banding that may indicate related fluid flow events.

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Introduction

The Middle Ordovician Trenton and Black River formations of the southern Michigan Basin host the type example of fault-fracture "hydrothermal dolomite" reservoirs, the Albion-Scipio trend. Such petroleum reservoirs share many characteristics with Mississippi Valley-type ore deposits, such as late diagenetic brecciation, open-space filling saddle dolomite and calcite cements, and sulfide and sulfate mineralization (Budai and Wilson, 1991; Jaiswal et al., in press). Within the Michigan Basin, a number of parallel trending smaller structures contain the same type of fault-fracture dolomite reservoirs including the Freedom, Reading, Northville, Stoney Point, Napoleon, and several other oil fields. The fields appear to be structurally related, trending northwest to southeast. However, it is not known if they also share related fluid histories. Three distinct types of dolomite are recognized in the basin: a regional dolomite, the cap dolomite, and fault-fracture hydrothermal dolomites. The regional and cap dolomites were studied extensively by Taylor and Sibley (1986) and Yoo et al. (2000), respectively. The Albion-Scipio trend reservoirs have also been subject to detailed study (Gregg and Sibley, 1984; Hurley and Budros, 1990; Budai and Wilson, 1991; Grammer and Harrison, 2013). However, no systematic regional study exists (petrology, isotope geochemistry, and fluid inclusions) of the hydrothermal dolomites across the southern Michigan Basin. In this study, cathodoluminescence (CL) petrography was conducted on hydrothermal cements to determine if correlatable microstratigraphies exist among the fields. Stable carbon and oxygen isotope data was collected for hydrothermal cements and host rocks. Fluid inclusion microthermometry (homogenization (T_h) and last ice melt (T_m) temperatures) was performed on hydrothermal cements to determine crystallization temperatures and fluid properties. Data from this study show that fluid histories are unique for each field although a common genesis for the hydrothermal fluids is likely.

Geologic Background

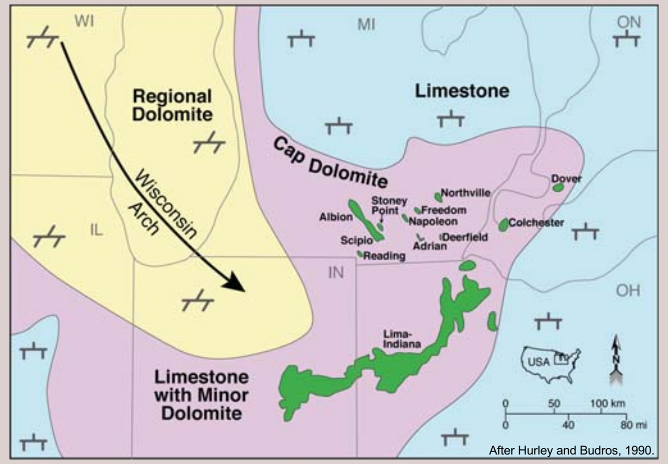


Figure 1. (Left) Distribution of petroleum fields adjacent to and within the southern Michigan Basin. Three isotopically and petrographically distinct dolomite lithological types are recognized in the Middle Ordovician of the region. A regional dolomite is likely related to early diagenetic seawater dolomitization along the Wisconsin Arch (Yoo et al., 2000). The "cap dolomite", which underlies the Utica Shale, is related to dewatering of the overlying shale during burial (Taylor and Sibley, 1986). Fault-fracture dolomite petroleum reservoirs are thought to be related to hydrothermal fluids (Gregg and Sibley, 1984; Hurley and Budros, 1990; Grammer and Harrison, 2013 and many others).

Figure 2. (Right) Stratigraphic column for southern Michigan. The Trenton and Black River Groups underlie the Utica Shale and overlie the Glenwood Shale and St. Peter Sandstone. Note the overlying Silurian Salina Group evaporite units (Adapted from Swezey, 2008).

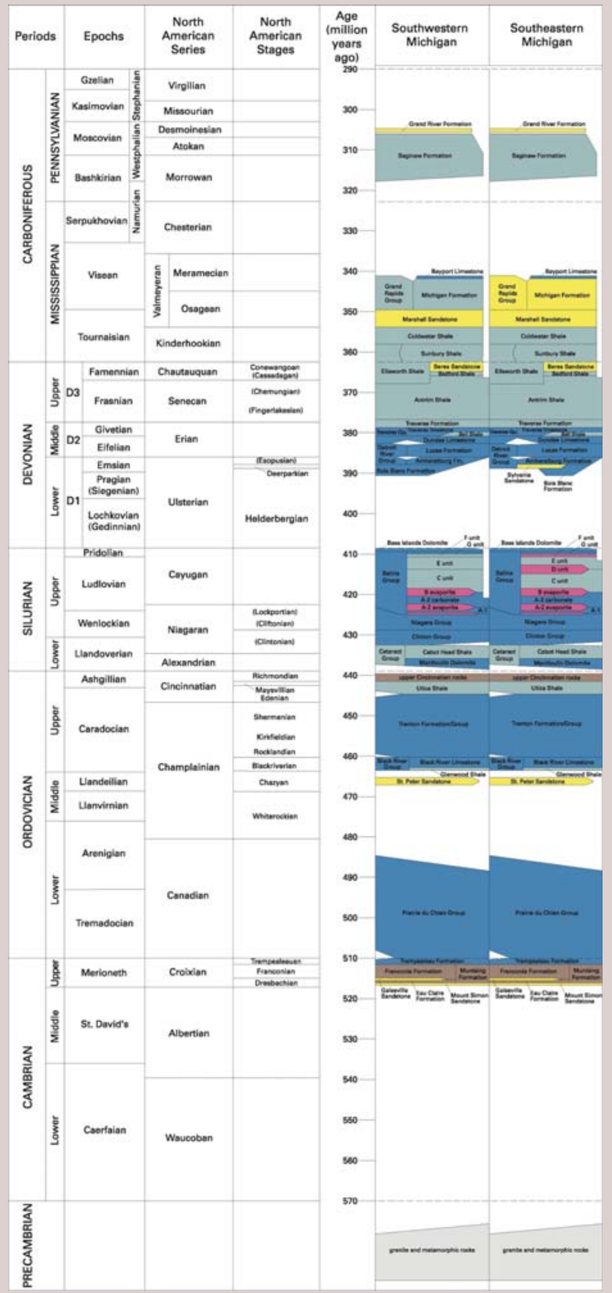


Figure 3. (Above) Fault-fracture dolomite petroleum reservoirs in the Trenton and Black River formations in southeastern Michigan are shown in green. Cores used in this study are yellow circles. Note the elongate NW-SE geometry and narrow width of the productive fields. Reservoir dolomites form along pre-existing brittle failure surfaces and are stratigraphically bound by tight host limestones distal from dolomitized zones. A seal is formed by the overlying cap dolomite and Utica Shale.

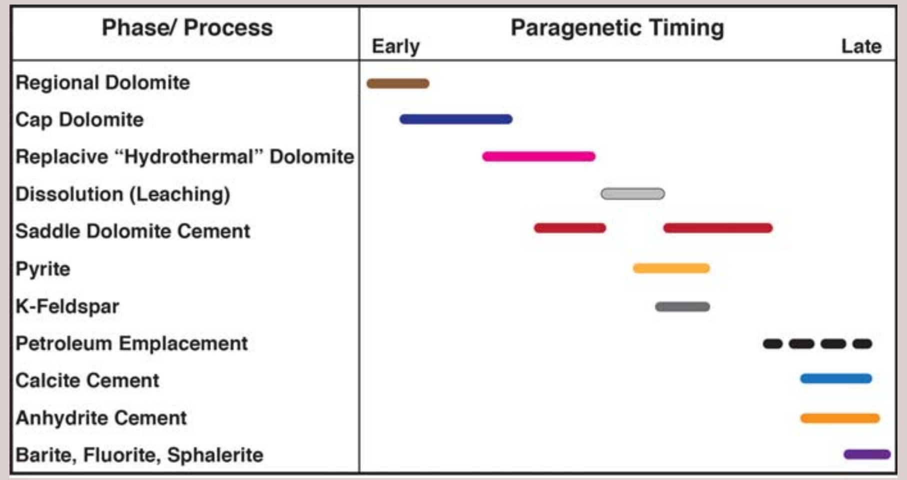
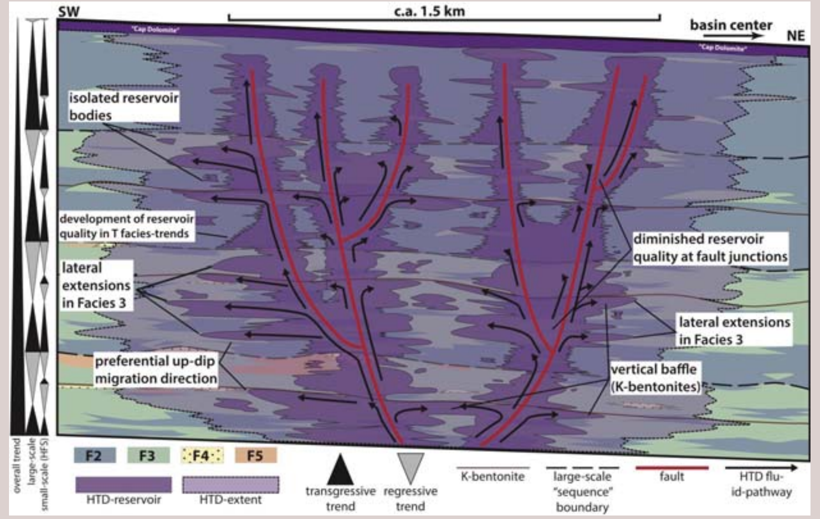


Figure 4. (Left) A generalized mineral paragenesis for fault-fracture oil fields in the southern Michigan Basin (after Budai and Wilson, 1991). This paragenesis displays a strong resemblance to the paragenesis observed in Mississippi Valley-type ore deposits (Gregg and Shelton, 2012).



Dolomitization Model

Figure 5. (Left) Model of dolomitization (from Grammer and Harrison, 2013). Extensional faulting coupled with left-lateral strike-slip movement in the basin resulted in sub-vertical fault and fracture pathways (Hurley and Budros, 1990). These pathways were invaded by basinal fluids that moved upward through the pre-existing voids created by faulting. The fluids alternately leached and preferentially dolomitize specific carbonate facies to develop high-quality reservoirs (Grammer, 2008). Saddle dolomite and calcite cements, as well as sulfate and sulfide minerals were precipitated in voids occluding some porosity. The overlying Utica Shale acted as a barrier to fluid flow at the top of the Trenton, forcing fluid to flow laterally at the bed boundary forming the cap dolomite. K-bentonite beds acted as vertical baffles within the Trenton and Black River formations forcing upward-moving hydrothermal fluids laterally along these boundaries in thin layers away from the primary faulted surfaces (Grammer and Harrison, 2013).

Petrography

Figure 6. (Right) Examples of rock textures observed in Albion-Scipio trend reservoirs. Zebra fabrics are prevalent where very coarse saddle dolomite cements form along bed boundaries. Matrix clasts 'float' in coarse void filling saddle dolomite cements in hydrothermal breccias. Larger voids formed due to leaching with dolomite lining the resulting vugs and fractures. (after Grammer, 2008).

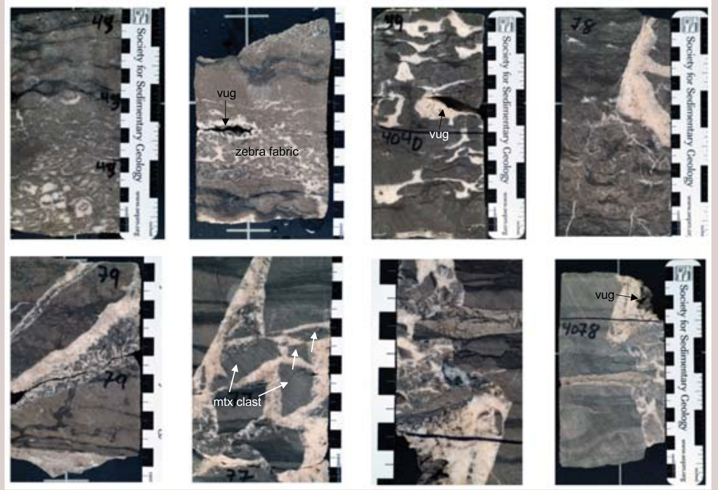


Figure 7. (Below) Petrography

Host limestone: (A) Sample from the Northville Field. Host limestone is largely comprised of packstone to wackestone lithologies containing skeletal fragments. Planar-e dolomite cement lines a void filled by anhydrite cement. Cross polarized light (XPL). (B) CL excitation reveals partial replacement of micritic component with planar-e dolomite.
Branch County Core: (C) Saddle dolomite cement crystals display sweeping extinction. Matrix dolomite is comprised of coarse crystalline planar-s to nonplanar crystals (XPL). (D) CL view of (C). Saddle dolomite cement displays no observable CL stratigraphy.
Reading Field: (E) Cloudy dolomite cement bands are fluid inclusion rich and correspond to bright CL bands in (F). Matrix dolomites display planar-s to nonplanar texture. Plane polarized light (PPL). (F) CL view of (E). Saddle dolomite cement displays moderate CL followed by a wide bright band and outer wide dull CL band. Sharp contacts suggest that a minimum of 3 separate fluids formed these cements.

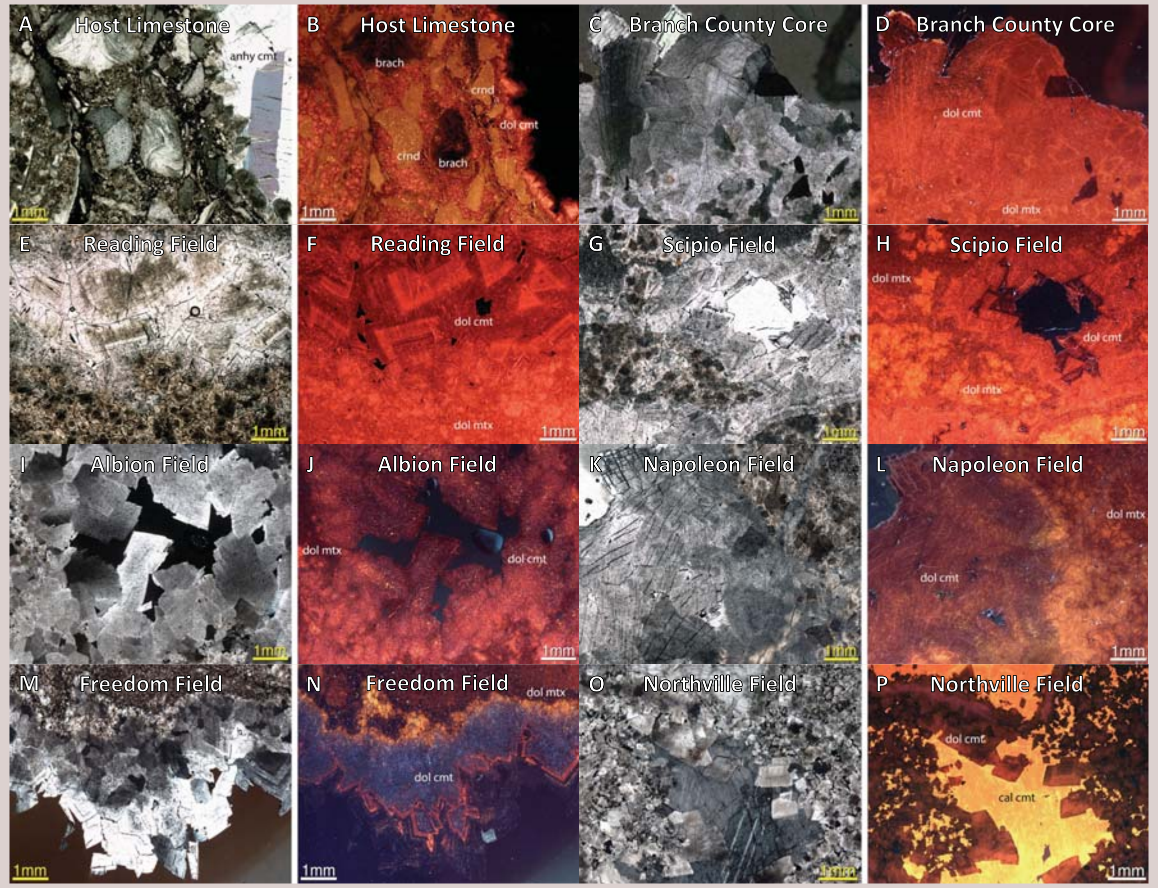
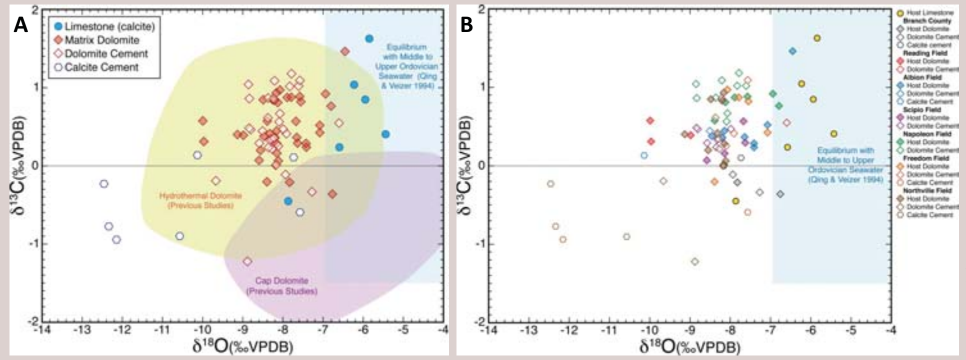


Figure 7. Petrography (cont.)
Scipio Field: (G) Cloudy inner cores in saddle dolomite are fluid inclusion rich and correspond to brighter CL bands and inclusion poor clear rims correspond to low CL in (H) (XPL). (H) CL view of (G). Moderate CL in saddle dolomite centers are followed by a dull to non-CL band.
Albion Field: (I) Sweeping extinction is visible in saddle dolomite. Matrix dolomite displays medium to coarse crystalline planar-s to nonplanar texture (XPL). (J) CL view of (I). Moderately bright CL centers of crystals transition to moderately dull CL outer zones in saddle dolomite cements.
Napoleon Field: (K) Saddle dolomite lining a vug. Matrix dolomite crystals display medium crystalline nonplanar texture (XPL). (L) CL view of (K). Dolomite cement displays a relatively uniform dull to non-CL response with no CL zonation.
Freedom Field: (M) Open-space filling saddle dolomite. Matrix dolomites display fine to medium crystalline planar-s to nonplanar texture (XPL). (N) CL image of (M). Saddle dolomite cements display very dull to non-CL response except for two thin bright bands separated by a thin dark band near the outer edge of crystals, followed by a non-CL zone.
Northville Field: (O) Saddle dolomite lining open space filled by blocky calcite cement. Note twinning in calcite cement (XPL). (P) CL view of (O). Coarse crystalline saddle dolomites display two zones, an inner zone that is dull to non-CL followed by a thick moderate CL zone. Bright yellow CL calcite cement fills void space.



Isotope and Fluid Inclusion Data

Figure 8. (Left) Carbon and oxygen isotope values obtained for matrix dolomite and void filling dolomite and calcite cements in this study overlap with previous isotope work (Taylor and Sibley, 1986; Haefner et al., 1988; Budai and Wilson, 1991; Coniglio et al., 1994; Yoo et al., 2000; Grammer and Harrison, 2013). Host limestones are in equilibrium with Middle to Upper Ordovician seawater (Qing and Veizer, 1994). There is some variation in values for void filling cements among the reservoirs studied.

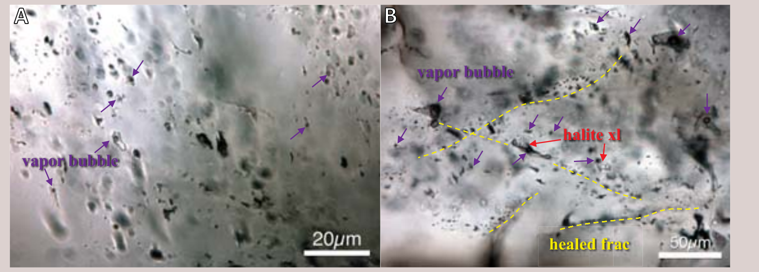


Figure 9. (Above) (A) Aqueous fluid inclusions in void filling saddle dolomite cement from the Albion Field. Fluid inclusions in dolomite typically are less than 10 μm in diameter. Nearly all inclusions observed in dolomite crystals in this study are primary. (B) Assemblages of calcite inclusions from the Northville field. A mix of primary and secondary inclusions are visible. The secondary inclusions occur in healed fractures. Halite daughter crystals are present in two primary inclusions (red arrows).

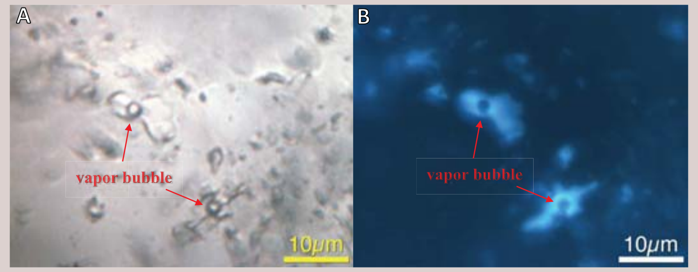


Figure 10. (Above) (A) Primary hydrocarbon fluid inclusions in void filling saddle dolomite crystals in the Northville field. (B) Ultraviolet epifluorescence of hydrocarbon inclusions ranges from a pale yellow-white to bright pale blue. Hydrocarbon inclusions were observed in all of the reservoirs studied, except for the non-productive Branch County core, and occurred as both primary and secondary inclusions. All appear to have formed paragenetically late.

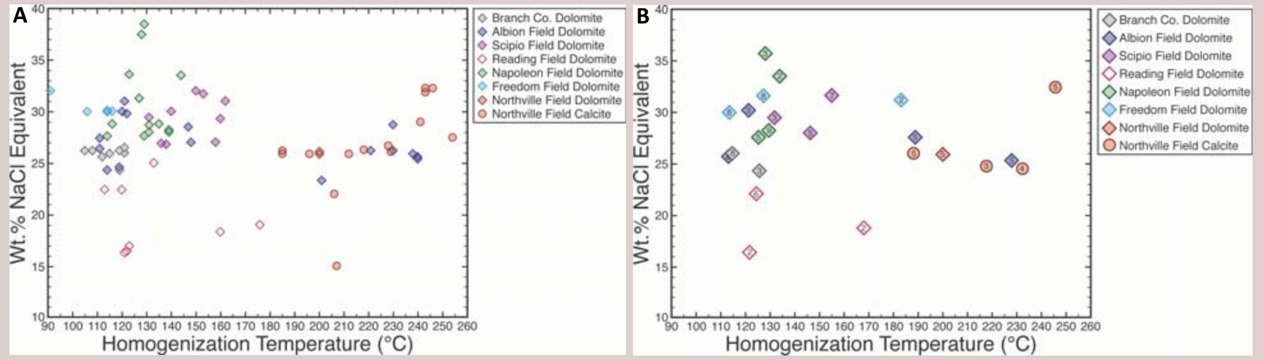


Figure 11. (Right) (A) Plots of fluid inclusion salinities versus T_h values. (B) Fluid inclusion salinities and T_h values grouped as assemblages. The number of individual fluid inclusions for which valid T_h and T_m values were measured are shown on each data point. Dolomite fluid inclusions measured for this study are largely primary. Inclusions measured in calcite cements in the Northville field are interpreted as secondary when observed in healed fracture planes. Calcite values from aqueous inclusions observed in the Branch County core are single phase and only T_m temperatures were obtained (not shown here). Fluids observed in this study fall into two distinct clusters. A cooler fluid with T_h from 110°-155° C, and a hotter fluid from 165°-250° C. Salinities in the cooler fluid range from 16-39 weight % NaCl equivalent, while the hotter fluid has a tighter salinity range from 22-33 weight % NaCl equivalent. Hydrocarbon inclusions appear to be secondary in most assemblages observed although a few primary petroleum inclusions were observed in saddle dolomite cements. Only T_h measurements were obtained for hydrocarbon inclusions. Hydrocarbons were observed as late stage fluids in all petroleum reservoirs in the study. However, hydrocarbon inclusions were not observed in the non-productive Branch County well. Fluids are composed of more complex salts than a simple NaCl brine mixture. The eutectic temperature for NaCl brines is -32° C, but first ice melts were observed for many dolomite and calcite cements as low as -89° and most commonly about -64° C. Last ice melt temperatures for inclusions are often below the eutectic temperature for a pure NaCl system. Hydrohalite also formed rarely upon cooling and melted below 0° C. This behavior is common in CaCl-NaCl brine mixtures (Petts et al., 2017). No pressure corrections were made on fluid inclusions measured in this study.

Conclusions

- The data appear to indicate that each field acted as an independent hydrothermal convection cell with its own unique fluid history. This conclusion is supported by the distinctly different patterns of CL compositional zoning observed in dolomite cements between the oil fields studied. The clustering of carbon and oxygen isotope data and fluid inclusion data between the oil fields supports this conclusion. However, the overall similarity in salinities, temperatures, and isotopic compositions among the oil fields suggest that the hydrothermal fluids may have had a common origin.
- Isotope data support the conclusion of a uniqueness between the oil fields studied. Data for fields generally overlap, but slight clustering of data, by field, appears to exist. Northville values in particular are more depleted in $\delta^{18}O$ and slightly depleted in $\delta^{13}C$ compared to other fields.
- Fluid inclusion microthermometry indicates two fluids: a cooler fluid present in all of the localities studied and a distinctly hot fluid present in the Northville and Albion fields. Both of these fluids are typically hotter and more saline than Middle Ordovician hydrothermal fluids observed in studies adjacent to the Michigan Basin (Haefner et al., 1988; Yoo et al., 2000; Petts et al., 2017). This indicates that hydrothermal fluids involved in southern Michigan oil fields are different than those that affected other oil fields in the region. We suggest that the high salinity is derived from overlying Silurian Salina Group evaporites within the Michigan Basin. Higher temperatures likely resulted from higher heat flow affecting fluids circulating deeper in the basin, or into basement, than those adjacent to the basin.

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