Hydrothermal Fluid Flow: Structural and Stratigraphic Controls on Thermal Structure, Flow Rate, and Reservoir Properties

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SUBSURFACE APPLICATION: Ghawar Field, North Field, Ladyfern, presalt Brazil/Angola, Mississippian Lincoln County Colorado, Albion-Scipio, Tengiz, Trenton-Black-River, Arbuckle/Ellenberger and Pennsylvanian Permian Basin and Midcontinent, Mississippian Lime in Kansas, Woodford Chert of the southern USA midcontinent, Shale plays of the Permian Basin, and Bakken/Lower Lodgepole play
STATUS: Proposed project
TIMING: Preliminary results available; to be completed if recommended by membership
FUNDING: Partial from DOE

Purpose
This project proposes to improve understanding of the effects of hydrothermal fluid flow in regionally advective systems. This will be accomplished by integrating data from a regional case study from the Midcontinent of North America to be followed by coupled flow and thermal modeling. The workflow for modeling will be tested by using the rock record of a well-studied example that shows density controls on hydrothermal fluid flow leading to predictable alteration with a stratigraphic and structural control. The results will be broadly applicable to improving approaches to modeling thermal history and diagenetic evolution in hydrothermally altered systems in hydrocarbon reservoirs.

Project Description
In many conventional and unconventional carbonate reservoirs, there is strong evidence that hydrothermal fluid flow has had an impact on reservoir quality (Davies and Smith, 2006). Hydrothermal systems require flow of warm fluids into cooler rocks to affect the thermal regime. Hydrothermal porosity enhancement has been incorrectly ascribed to meteoric diagenesis in many cases. For example, in the Midcontinent of North America, it has been suggested that meteoric dissolution associated with unconformities led to much of the reservoir porosity in Midcontinent carbonate reservoirs (e.g. Duren 1960; Ewuer 1965; Thomas 1982; Rogers et al. 1995; Montgomery et al. 1998; Franseen, 2000; Watney et al. 2001; Franseen et al. 2004; Mazzullo et al. 2009). New data show that late hydrothermal fluid flow in Ordovician, Mississippian, and Pennsylvanian reservoir rocks of the Midcontinent have had a major impact on porosity in conventional high-permeability reservoirs as well as low-permeability unconventional reservoirs (Goldstein and King, 2014; Ramaker et al. 2014). These fluids also have had an impact on hydrocarbon migration and local thermal maturation in these systems. Although recent publications have challenged the impact of porosity generation at high-diagenetic temperatures in hydrocarbon reservoirs (Ehrenberg et al. 2012), the small Midcontinent reservoirs have clearly been affected. Moreover, this effect is unequivocal at the other end of the size spectrum, including the largest hydrocarbon reservoir in the world, Ghawar (Cantrell et al, 2004). Thus, understanding the controls and impact on hydrothermal alteration is of broad import for the oil and gas industry.
The Midcontinent USA is ideal to develop the geologic constraints necessary to improve our ability to develop general modeling approaches applicable to other systems. The hydrothermal fluid flow in the USA Midcontinent occurred in three late stages (King, 2013). Fluid flow was controlled by stratigraphic discontinuities, fault and fracture systems, and temperature-controlled density differences, and had an impact on thermal maturation, porosity, and hydrocarbon migration.

Work to date demonstrates how stratigraphic discontinuities associated with unconformities control later hydrothermal fluid flow to create the superficial appearance that porosity originates during low-temperature meteoric diagenesis. It develops a regional data set from reservoirs, shallow cores, and outcrops from the Midcontinent, USA and integrates regional stratigraphic data from the Ordovician through the Pennsylvanian, petrography, fluid inclusions, and stable isotopes to demonstrate the evolution of the hydrothermal system. Petrographic data show that the entire region and stratigraphic succession experienced a similar late time equivalent paragenesis with megaquartz, silica dissolution, carbonate dissolution, baroque dolomite, ore minerals, and calcite. Fluid inclusion data in the megaquartz, baroque dolomite, and calcite confirm a complex record of hydrothermal fluid flow, beginning with migration of low salinity connate fluids and gas, and evolving to migration of concentrated brines and oil (Fig. 1).

During the second phase of hydrothermal alteration integrated data indicate advective fluid flow from the basin to the South. A regional dataset shows the Ordovician through Mississippian section was hydrologically connected and that the shale-rich Pennsylvanian section acted as a leaky confining unit (Fig. 2). Temperatures increased upward in the Ordovician-Mississippian section and were lower and decrease upward in the Pennsylvanian section. The data indicate vertical hydrologic connections that allow the warmest, lowest density fluids to float toward the top of the hydrothermal aquifer, concentrating dissolution from hydrothermal solutions below the Mississippian-Pennsylvanian unconformity.

Later, the system evolved from a regionally advective hydrothermal system to a fracture-
controlled system. After or during fracturing, hydrothermal solutions precipitated calcite and showed regional geochemical trends indicating vertical fluid flow along fractures, directly from basement or a basal sandstone aquifer (Fig. 3). This late system shows no stratigraphic control and is likely driven by highly localized fault pumping of the hydrothermal fluids.

For the reservoirs studied, the most important system for porosity modification was the regionally advective hydrothermal aquifer, which had warmer fluids at its top, coincident with a stratigraphic discontinuity/unconformity. Porosity enhancement immediately below the unconformity can be ascribed to hydrothermal fluids, which leads to a significantly different model for exploration for the best reservoir quality. This type of fluid flow differs greatly from the highly localized fluid flow interpreted for Trenton-Black River hydrothermal dolomite reservoirs (Davies and Smith, 2006).

![Figure 2. Oxygen isotopic data from baroque dolomite showing evidence for hydrothermal dolomite temperatures increasing upward in the Ordovician-Mississippian section. Lower temperatures are in the Pennsylvanian confining unit.](image)

This study will focus on developing an improved understanding of predictability of hydrothermal alteration associated with regionally advective hydrothermal flow.

- All Midcontinent reservoir and nonreservoir carbonate diagenetic data (geochemical) and thermal alteration data will be synthesized to develop an improved picture of spatial and stratigraphic impacts of hydrothermal alteration.
- The spatial distribution of these data will be correlated to oil field data (locations of producing wells, water cuts, production history, reservoir quality) and seismic data (provided by consortium members) to improve exploration tools for hydrothermal reservoir enhancement.
- The final phase of the project will use coupled modeling approaches incorporating tools such as BASIN2 and TOUGH. The modeling parameters will be constrained by matching the known results from the Midcontinent system to create a broadly applicable simulation model for predicting alteration by advective hydrothermal systems.

**Deliverables**
The project will explore an important type of hydrothermal alteration in which fluid flow
and porosity enhancement had a stratigraphic control. This differs greatly from a common perception of fault pumping as the only applicable model.

The full data set of Midcontinent diagenetic and thermal alteration will be provided as an integrated report focusing on the Ordovician through Pennsylvanian section. This will provide the basis for testing hypotheses of the parameters controlling hydrothermal alteration.

When these data are compared to oil field data, the project will provide a set of conceptual models for reservoir sweet spots in such a system. When they are compared to seismic data, the results will provide seismic signatures that aid in exploration for hydrothermal alteration and porosity enhancement.

Finally, the simulation model set up and parameters that will most effectively be used to predict this type of hydrothermal alteration will be provided to consortium members for application to their exploration and production problems.

![Figure 3. Sr isotope data from Stage 3 calcite and Stage 2 baroque dolomite. Baroque dolomite shows values similar to host rock, indicating long distance advective fluid transport and extensive rock-water interaction. Calcite data indicate progressive rock-water interaction from base to top and well-to-well variation suggestive of vertical fluid flow along localized faults and fractures.](image)

References
DUREN, J.D., 1960, Some petrophysical aspects of the Mississippian chat, Glick field, Kiowa County, Kansas: Shale Shaker, 11, 2-8.


