AAPG Search and Discovery Article #90012©2003 AAPG Hedberg Conference, Vail, Colorado, July 21-26, 2002 (2003).

AAPG HEDBERG CONFERENCE
"*Late Paleozoic Tectonics and Hydrocarbon Systems of Western North America – The Greater Ancestral Rocky Mountains"*
July 21-26, 2002, Vail, Colorado

Precambrian Basement Structure and Crustal Oxidation State of the Ancestral Rocky Mountains – Its Possible Importance to Petroleum Systems as a Physical Control on Fluid Path and Trapping Mechanism and as a Chemical Control of Hydrocarbon Stability and Fractionation

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The structure and oxidation state of the Precambrian basement of the Ancestral Rockies are possible first-order controls on the development of basement-involved petroleum systems. In particular, both the unique structural patterns of the last Precambrian orogeny (1400 Ma) to affect the basement of the region and the relationship of crustal oxidation state to hydrocarbon fluids, provide new insights into late Paleozoic petroleum systems. The migration paths of the hydrocarbon fluids are influenced by the reactivation of basement structures and in some cases these paths may be traced from source to trap. In some cases, these flow paths also help reveal the kinematics of basement fault movement. In addition, crustal oxidation state predicts the hydrocarbon stability in any area.

The 1400 Ma orogenic event that affected the Ancestral Rocky Mountain region extended from Scandinavia to Mexico. Although previously thought to be anorogenic, recent work has shown that it is characterized by extensive intrusion of mantle- and crustally-derived, hydrous, granitoid serial sequence that in places comprise volumetrically up to 75% of the mid- to upper crust. This massive granitoid serial sequences emplacement has resulted in a structurally isotropic crust for much of the Precambrian basement of the U.S. Numerous transcurrent WNW shears developed at the end stages of granite emplacement and exist at least from the Lewis and Clark Zone in Montana to the Texas Zone in Arizona. The Anadarko-Arbuckle Zone is a well known example of this WNW shear zone. Due to the widespread granite intrusion, the shears may constitute the most significant anisotropy of the Precambrian basement of the Ancestral Rockies. When involved in later-generated petroleum systems, these basement faults did not function as merely passive conduits and seals that statically received and trapped hydrocarbon fluid sometime after fluid formation. Rather, the process of fluid formation, movement, and deposition within the fault system is characteristically an active process that co-dynamically conjoins fault kinematics with fluid generation, flow, and deposition.

During the past 25 years, a transcurrent fault-related, fluid flow model developed for the mineral industry has directly contributed to 10 major porphyry Au and/or Cu discoveries. This exploration approach has recently been applied in recent research for the oil and gas industry in New York State. Preliminary results suggest that fluid migration in lateral strain (strike-slip) settings hosting hydrothermal metalliferous systems is analogous to migration of oil and gas into hydrothermal dolomite reservoirs and to migration of methane from coal beds. Work in the auriferous Carlin North Trend of Nevada was one key to identifying the common process that affects all these fluid systems. The Nevada work indicates a synkinematic relationship between strike-slip fault movements, the emplacement of possible pluton gold sources, and the release of gold-bearing fluids into Riedel-tensile splays and/or wedge-like stratigraphic traps. The most economic traps result from the intersection of favorable stratigraphy with the footwall of P-shear conduits. Where a favorable carrier-bed stratigraphy is blocked in its updip portions by other faults that mark changes in dip domain or juxtapositions with unfavorable hanging-wall stratigraphy, a wedge-like 'trap' can be associated with especially high-grade gold accumulations (e.g., Meikle mine). Unlike petroleum accumulations, in mineral systems the fluids (magma and metal-bearing volatiles) are "frozen" in place and are thus more accessible to analysis. The fluid migration path can be clearly identified through direct sampling and geochemistry. As fluids migrate from a high-pressure source to low-pressure deposition sites, they chemically fractionate, resulting in a systematic paragenetic chemical dispersal sequence. Although temperature and pressure affect deposition, changes in oxidation state during the process (typically reduction followed by oxidation) are the first-order control on the actual compositional fractionation of fluid chemistry. Three-dimensional, geographic analysis of these chemical patterns of fractionation are the basis of the Cu and/or Au discoveries. These chemical patterns (especially in CO_2, O_2, and C-1 to C-17 hydrocarbon, gas chemistry, halogen fractionation and low levels of transition metal zonation) can also be applied to hydrocarbon migration, providing a new tool for predicting migration pathways.

Fluid migration paths typically display curved migration trajectories as they move from the P-shear carrier conduit to a sealed, stratigraphic-wedge, Riedel-tensile, dilational zone or transpressive, anticlinal structural trap. This fluid history appears to be characteristic of fluid migration in both porphyry metal and petroleum accumulations related to strike-slip fault tectonism. Rotation of stress fields during strain within a transcurrent fault is a secondary influence on fluid movement within the larger context of far-field, regional compression. The geochemistry of carbon-bearing volatiles should display fractionation or zoning laterally along Riedel-tensile conduits.

An example is the hydrothermal dolomite-hosted gas field at Glodes Corner in Steuben County, NY, which is controlled by a transcurrent, basement-rooted fault. A fluid pathway can be clearly identified from the presence of a more H-rich, more reduced assemblage with higher CO_2/O_2 ratios and more C-1 to C-4 gases near the intersection with an inferred carrier structure. The fluid pathway and movement away from the primary carrier structure is indicated by a more oxidized, H-poor environment that is characterized by an assemblage of higher C-number gases (especially C-5 and C-6) and a more oxidized, O-rich assemblage characterized by lower CO_2/O_2 ratios.

The Glodes's Corner case history shows that understanding fluid movement and its fractionation can allow prediction of specific, reservoir-scale, economic targets or 'sweet spots' for gas condensates (especially ethane) with given gas reservoir. Fluid movement and its fractionation are necessary products of interactively coordinated kinematics within lateral strain (strike-slip) fault systems.

In the same way that migrating hydrocarbon fluids systematically fractionate or are buffered towards the oxidation state of enclosing rock, hydrocarbon fluids in basement-involved petroleum systems are subject to buffering toward the oxidation state of the basement rock. The redox stability and fractionation of the hydrocarbons are partly dependent on the oxidation state of the crust along the pathway of the volatiles and at the reservoir site. Thus, if the oxidation state is reduced (where ferric:ferrous ratios of crustal wallrocks are less than 0.6), the hydrocarbons will be stable during transport and will be preserved at reservoir sites. If the oxidation state of the enclosing crust is oxidized, the whole process will be compromised as hydrocarbons oxidize to an ultimate CO_2-water end-product and economic potential decreases.

The above model successfully demonstrates the physical aspects of gas accumulations in Cretaceous sandstone reservoirs that were formed during transpressive tectonics related to the Laramide orogeny in the Rocky Mountains. Specifically, the giant Jonas Field exhibits a large, wedge-shaped trap configuration. Gas entered the wedge from the northeast during a left-slip phase of movement on the Wind River Thrust system. This occurred during early to mid-Laramide orogeny when the region was undergoing far-field, E-W to ENE-WSW, regional compression. In the Cave Gulch Field, gas was gas trapped in transpressive anticlines beneath a seal of crystalline basement in the upper plate of the Owl Creek thrust. The Cave Gulch field may have formed during the late Laramide orogeny in mid-late Eocene when the region was being affected by NNE-SSW, far-field, regional compression. The ultimate tectonic driver for these fluid migration events may have been Laramide flat subduction.

A similar tectonic regime may have affected the Ancestral Rocky orogen in Pennsylvanian time. Although we, as yet, have no specific case histories for Pennsylvanian-age Ancestral Rocky petroleum reservoirs, similar processes may have been present. If so, similar, Laramide-analog, basement-involved, transcurrent, tectonic-driven, fluid migration scenarios may have operated in the Ancestral Rocky orogen. One particular model that may be especially relevant to the above discussion is oil and gas accumulations hosted in hydrothermal dolomite and/or chert reservoirs.

These above scenarios ultimately provide provocative opportunities for applying exploration concepts and fluid migration model analogs from the mineral industry to the petroleum industry.