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Structurally-Controlled Carbonate Diagenesis: Hydrothermal Dolomite and Leached Limestone Reservoirs

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ABSTRACT:
Structurally controlled hydrothermal dolomite (HTD) reservoir facies and associated productive leached limestones are major hydrocarbon producers in North America and are receiving increased exploration attention globally. They include multiple trends in the Ordovician Trenton-Black River and equivalents (locally, Silurian and Devonian) of the Michigan, Appalachian, and other basins of eastern Canada and the United States, and in the Devonian and Mississippian of the Western Canada Sedimentary Basin. They also occur in the Devonian of Australia, in Jurassic hosts along rifted North and South Atlantic margins, and in the Jurassic-Cretaceous of the Arabian Gulf region and elsewhere.

Hydrothermal dolomitization is defined as dolomitization occurring under burial conditions, commonly at shallow depths, by fluids (typically very saline) with temperature and pressure higher than the ambient temperature and pressure of the host formation. The latter commonly is limestone. Proof of a hydrothermal origin for HTD reservoir facies requires integration of burial-thermal history plots, fluid-inclusion temperature data, and constraints on timing of emplacement.

Hydrothermal dolomite reservoir facies are part of a spectrum of hydrothermal mineral deposits that include sedimentary-exhalative (SEDEX) lead-zinc ore bodies and HTD-hosted Mississippi Valley-type (MVT) sulfide deposits. All three hydrothermal deposits show a strong structural control by extensional and/or strike-slip (wrench) faults, with fluid flow typically focused at transtensional and dilational structural sites and in the hanging wall or down-thrown block. Structural sags interpreted most commonly as transtensional pull-aparts above negative flower structures on wrench faults are favored drilling sites for HTD exploration.

Saddle dolomite in both replacive and void-filling modes is characteristic but not necessarily diagnostic of HTD facies. For many reservoirs, matrix-replacive dolomite and saddle dolomite appear to have formed near-contemporaneously and from the same fluid and temperature conditions. Original host facies exerts a major influence on the lateral extent of dolomitization, resultant textures, pore types, and pore volume. Dilational breccias, zebra fabrics, shear microfractures, and other rock fabrics record short-term shear stress and pore-fluid-pressure transients, particularly proximal to active faults. Internal dolomite sediments within faults and fractures, variably cross-bedded and scoured, add to the record of episodic fluid-flow dynamics. High-temperature hydrothermal pulses may leave a record of thermal transients in altered kerogens and bitumen in the dolomite. Basement highs, underlying sandstone (and/or carbonate?) aquifers (probably overpressured), and overlying and internal shale seals and aquitards also may constrain or influence HTD emplacement.

Carbonate (particularly calcite) solubility is affected by variations in composition, temperature, partial pressure of CO_2, pH, salinity and other parameters of circulating fluids. Leached limestones, often with a high micropore component, typically are developed stratigraphically above and/or lateral to zones of hydrothermal dolomite (although the latter association may be obscure). Leaching may show a close control by original facies and/or structural conduits. Saddle dolomite crystals often are dispersed within the leached limestone. Implications are that cooler, Mg-depleted fluids have leached the limestones, but mechanisms remain debatable. Leached limestones with HTD associations in the WCSB occur in the Slave Point, Jean Marie and Wabamun formations.

Although post-evaporite brines are considered to be a major source for Mg-enriched fluids contributing to dolomitization in many basins, particularly for the Devonian of the WCSB, there are some basins where there are no preserved evaporites or where the age of evaporite formation is incompatible with timing of dolomitization. Further, with the increasing recognition that major dolomite trends (for example, the Ordovician Lima-Indiana trend of the northeastern US) are hydrothermal in origin, huge volumes of fluid (or large volumes of recirculating fluids) must be involved to account for the volume of dolomite and source of Mg. Although these mass-balance problems are the same for large volumes of dolomite regardless of type, the connection between sags, basement-rooted wrench faults, and thermal anomalies for hydrothermal dolomite (and other hydrothermal mineral deposits) suggests a possible linkage to other "non-seawater derived" sources of Mg. Further, there are questions still to be resolved concerning the pressure dynamics of fluid flow up faults. Published data for San Andres wrench faults in California indicate extremely high but episodic fluid flow rates, with implications for advective heat (and solute) transfer and non-equilibrium diagenetic conditions.

As exploration for structurally-controlled HTD and leached limestones continues and/or as this type of diagenetic control on carbonate reservoir development is more widely recognized, it is clear this is a high-risk play. This is inherent in the variability of reservoir characteristics in a fault-driven fluid-flow system. Original coarser-textured, shallower-water limestones in high-energy shelf and shelf-margin settings are preferred hosts for more porous and permeable HTD and leached limestone reservoirs. "A holistic approach involving field relationships, structural geology, seismic interpretation, stratigraphy, geochemistry, fluid inclusion analysis, petrography, hydrology, rock mechanics and more" (L. Smith, NYSM, pers. comm., 2006) is necessary. Regional and high-resolution aeromag (and gravity) mapping, structural mapping (with residuals), and 2D but particularly 3D seismic imaging with seismic anomaly mapping, are incremental steps in defining targets. Horizontal drilling, ideally directed oblique to linear (wrench) fault trends, may help to reduce risk of reservoir variability.

BIOGRAPHY

Graham Davies received his B.Sc. honours and Ph.D degrees from the University of Western Australia in Perth, W.A. His doctoral thesis was on modern carbonates of Shark Bay, W.A., published in AAPG Memoir 13. After a postdoctoral fellowship with James Lee Wilson at Rice University in Houston, he joined the Geological Survey of Canada (GSC) in Calgary. After seven years with the GSC, Graham co-founded and became principal owner (and named the company!) of AGAT (Applied Geoscience *and Technology) Consultants, later Laboratories, in Calgary, for a time with offices in Denver. Since 1983, he has operated through GDGC Ltd.*

Graham has published about 75 papers on the geology of Australia and Canada, and has authored or co-authored more than 650 consulting reports for the petroleum industry in Canada and internationally. He has received many awards and recognition for both published papers and oral presentations from the AAPG, the CSPG and the GSA. In 2002, Graham received the R.J. Douglas Medal of the CSPG for 'outstanding and continuing' contributions to Canadian sedimentary and petroleum geology, mainly for his work on Arctic Paleozoic carbonates and evaporites, and on the Triassic of western Canada. He is co-editor of a special issue of the AAPG Bulletin (November, 2006) on hydrothermally-altered carbonate reservoirs, and is principal author of a major review paper on hydrothermal dolomite reservoirs in that volume. Graham's research in this field is supported by a grant from the Quest Foundation.