# TSR-HTD Ten Years Later: An Exploration Update, With Examples from Western and Eastern Canada.

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## BACKGROUND

A decade has passed since Reimer and Teare first presented their TSR-HTD model for reservoir diagenesis and hydrocarbon exploration in regionally tight carbonate platforms. TSR-HTD is the mnemonic for a linked organic-inorganic reaction involving thermochemical sulfate reduction (TSR) and hydrothermal dolomitization (HTD). Reimer & Teare proposed that TSR-HTD was the principal diagenetic mechanism that created widespread hydrothermal dolostone reservoirs within the Middle Devonian Slave Point and Keg River Formations of northeastern British Columbia. This dolostone lithofacies, which is locally referred to as the Presqu'ille Dolomite, hosts massive natural gas reserves.

Three key exploration concepts were introduced in the TSR-HTD model:

(1) Process Chemistry: TSR is coupled with, initiates and sustains the dolomitization reaction;
(2) Process Model: Reaction mechanics and product rock fabrics may be categorized using an intensity-of-reaction analogy referred to as the "furnace model" (figure 1); and
(3) Exploration Model: The rock volume conversion associated with total dissolution and replacement at the "furnace core" results in caving and collapse of the host carbonate unit. The collapse features should be readily visible on conventional seismic data, providing an excellent, indirect HTD prospecting tool.

These concepts have been applied to exploration programs across several Paleozoic carbonate platforms in western and eastern Canada. In particular, the Authors have been involved with drilling HTD-targeted wells at Peggo, Parkland and Ladyfern, British Columbia and on Anticosti Island Quebec. The ensuing discussion presents a condensed summary of each of these projects.

## PEGGO

During 1993, Home Oil and partners drilled the Peggo b-100-B/94-P-08 location, targeting Slave Point gas approximately 25 kilometers east of the Helmet gas field. The prospect was identified on 2-dimensional seismic data specifically acquired to hunt for diagenetic collapse features along the Helmet – Pesh carbonate bank edge. Situated on a well-defined collapse at the top Middle Devonian time horizon, the b-100-B well encountered 23 meters of tight limestone overlying 47 meters of porous hydrothermal dolostone within the upper Slave Point. The HTD interval averages 5% porosity, spiking to 15%. Despite testing wet, this well was considered a technical success from a reservoir viewpoint and represented our first deliberate drill on the collapse model.

PARKLAND

In 2000, Encal Energy drilled a development well testing the downdip limits of the Parkland Wabamun gas field, which is projected to produce more than 350 Bcf of raw gas. A suite of 3-dimensional seismic data sets were depth-converted and integrated to create a coherent structural model for this field, which is trapped in a major fault block forming the southern edge of the Fort St. John graben. The mapping exercise identified a prominent collapse feature located within section 18-81-15W6M. This feature covers approximately 350 acres, exhibits 30 to 50 meters of collapse relief and is situated against the downthrown side of a major east-west trending normal fault. The 08-18 location was drilled into the heart of this collapse and encountered a completely dolomitized Wabamun section, including 23 meters of continuous reservoir exceeding 12% average porosity.

LADYFERN

In early 2001, industry released the seismic and drilling results of a major natural gas discovery within Slave Point hydrothermal dolostones at Ladyfern, British Columbia. The Ladyfern discovery is situated along the eastern splay of the Hay River shear system approximately 30 kilometers southwest of the Hamburg Slave Point gas field. Four successful gas producers have been drilled at Ladyfern including the very prolific a-97-H/94-H-01 well, which is reportedly capable of flowing at 100 MMcfpd from the dolomitized interval. Available 3-dimensional seismic trade data clearly indicates that the a-97-H well was drilled into a subcircular collapse feature within a local bank complex. This collapse covers approximately 25 acres and exhibits up to 10 milliseconds of two-way time relief relative to adjacent bank areas.

ANTICOSTI ISLAND

During 1998 and 1999, Encal Energy, Shell Canada, and Corridor Resources, drilled five wildcat wells into the Ordovician platform carbonates of Anticosti Island, Quebec. These wells targeted a mix of trapping styles, including collapse features. Hydrothermal dolostones were expected to form the principal reservoir facies, as evidenced from outcrop studies conducted along the eastern edge of the Anticosti Basin in western Newfoundland. The Riviere De La Chaloupe location was drilled into a major collapse trend approximately 4 kilometers long as mapped from a loose grid of 2-dimensional seismic data. The core of this collapse trend exhibits up to 20 milliseconds of local two-way time relief plus a “scrambling” of intra-carbonate reflectors. The Chaloupe well encountered more than 65 meters of variably porous dolostones within the Romaine Formation, plus extensive fracturing and lost circulation zones in the overlying Trenton limestones.

EXPLORATION SUMMARY

The Authors have mapped several HTD-related collapse prospects using 3-D seismic data. Based on the analyses completed to date, we observe that prospective collapses typically cover 40 to 400 acres, exhibit a subcircular shape, tend to occur in irregular clusters, and demonstrate a vertical relief of up to 50 meters on a depth-converted basis. In certain examples, the internal reflectors become dimmed or scrambled due to brecciation and caving, or the presence of irregular porosity lenses within the dolomitized interval. Notwithstanding these observations, the occurrence of base-porosity reflectors may constitute an important additional indicator of prospective reservoir, particularly when located proximal to collapses. When exploring for collapse plays, it is essential to distinguish burial diagenetic features from unrelated sags and depressions that may be caused by simple horst and graben faulting, tidal channels, meteoric karst, meteor-impact structures, or other processes. Furthermore, it is critical to establish the local timing of prospective features on a region-by-region basis, as collapses of substantially different ages may not offer the same discovery potential. Finally, drilling in lows always carries additional exploration risk due to the possible presence of water. Therefore, it is useful to combine the seismic search for collapse features with detailed hydrogeological studies to identify regions with long hydrocarbon columns.

ROLE of TSR

Academics and co-workers have challenged the role and degree of involvement of TSR within the HTD reaction, citing the often-apparent absence of sulfur species (principally anhydrite and H2S) as precluding evidence. While this observation is valid on a local scale in many areas, the conclusion remains flawed because it confuses oxidized sulfur with reduced sulfur species, while failing to recognize the multiple pathways for sulfur scrubbing. In our opinion, the repeated microscopic textural and regional association of HTD with i) sulfide mineralization including MVT lead-zinc deposits, ii) hydrogen sulfide gas, iii) sulfurized and bitumenized organics and hydrocarbons, or iv) occasional native sulfur, argues for a genetic linkage. On a broader basis, we must identify the appropriate geochemical mechanisms which, as suggested by the rock textures, simultaneously promote the dissolution of limestone and the precipitation of dolostone. A reduction-oxidation (redox) coupled reaction elegantly solves this problem. TSR, TCR (thermochemical carbonate reduction to methane), or perhaps TNR (thermochemical nitrate reduction to nitrogen gas) may be involved, either individually or on a combined basis.

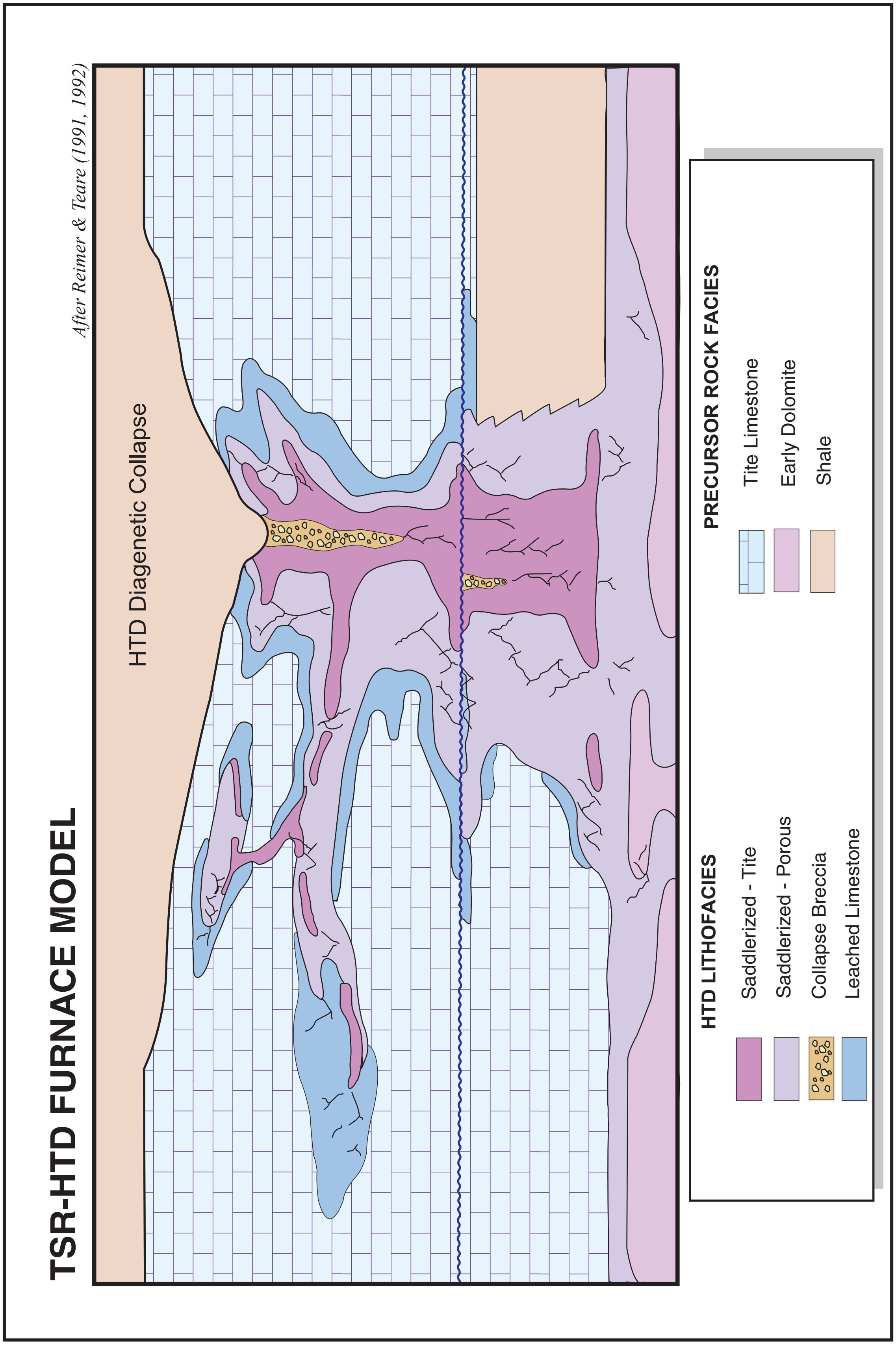
Despite our preference for a redox association, we also recognize that the HTD process may be triggered by other mechanisms, including for example, isothermal boiling (burial effervescence). Therefore, we propose that a process continuum exists between non-redox and fully redox-involved dolomitization, depending on the availability and quantity of a suitable pre-existing reductant, normally hydrocarbons. As a result, our reaction “furnaces” are now interpreted to represent local pockets of redox-intensified dolomitization. Beyond the “furnace core”, the HTD process is less vigorous and not necessarily coupled to a redox reaction.

CONCLUSION

Within the Devonian of northeastern British Columbia, and in many other carbonate platforms worldwide, the principal exploration challenge boils down to finding effective reservoirs, commonly hydrothermal dolostone. In the Authors’ opinion, there remains little doubt that diagenetic collapse features represent strong indirect indicators of HTD. Specifically, we believe that the best chance of proving an HTD play lies in testing the heart of a collapse. Additionally, the most prospective collapses appear to be closely linked to (seismically visible) faults or fault networks.

The common association of reduced sulfur species with HTD on both a microscopic and regional level compels explorationists to consider the potentially important role of sulfate reduction to the dolomitization process. As a refinement to our original model, we now advocate TSR (or an alternate redox mechanism) as a local, intensifying component of the HTD reaction. The furnace model remains valid, with collapse features representing the sites of redox-coupled reactions that occurred when dolomitizing fluids swept through pre-existing light oil or natural gas pools.

Exploratory drilling results in the Devonian and Ordovician of western and eastern Canada over the past ten years have validated the basic tenets of the TSR-HTD model. Since many platform interiors remain under-explored, we believe that continued application of this model should result in new commercial discoveries in areas previously considered non-prospective or high risk for hydrocarbon exploration.


TSR-HTD FURNACE MODEL
After Reimer & Teare (1991, 1992)
HTD Diagenetic Collapse
PRECURSOR ROCK FACIES
Tite Limestone
Early Dolomite
Shale
HTD LITHOFACIES
Saddlerized - Tite
Saddlerized - Porous
Collapse Breccia
Leached Limestone