PS The Devonian Grosmont: Unconventional Oil in a Fractured and Karstified Dolostone-Evaporite Platform, Alberta, Canada*

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Abstract

The Upper Devonian Grosmont platform in Alberta, Canada is the world's largest unconventional oil reservoir hosted in carbonates, with at least 400 Bbbl bitumen in place depths of about 250 - 500 m. Since ~ 2006, there has been a flurry of activity to bring this reservoir to production. The reservoir characteristics are due to five major factors and/or processes: sedimentary stratigraphy, dolomitization, fracturing, karstification, and biodegradation. Exploitation of the reservoir must take into account all these aspects.

The sedimentary stratigraphy of the reservoir consists of six stacked carbonate units: LGM, UGM1, UGM2, UGM3 (Grosmont Formation), and the overlying Upper Ireton and Nisku Formations. These units are shallowing-upward cycles, interbedded with marls (called 'shale breaks'). In addition, the reservoir contains an evaporite sub-unit, the Hondo Formation, in parts of the platform. The marls and evaporites acted as aquitards during diagenesis and oil migration but are breached or missing in parts of the area today. Dolomitization by density-driven reflux was the first pervasive diagenetic process. Most dolostones are fine-crystalline and tight, however, and the only notable porosity related to dolomitization is scattered molds and vugs. Subsequent fracturing and karstification combined to generate most of the present porosity and permeability. A dense facture network was created probably by Laramide tectonics to the west accompanied and/or followed by local isostatic adjustment of the basement. The Laramide tectonics formed a foreland bulge near the Grosmont platform, which flexed the carbonates regionally, whereas isostatic adjustment of the basement created subvertical stresses. The resulting fracture network was invaded by corrosive water mostly from the top, as shown by countless sinkholes and other epikarstic features (vugs, solution-enhanced factures, collapse-breccias, wholesale evaporite removal, Cretaceous cave infills) that are widely distributed across the Grosmont platform. In addition, circumstantial evidence suggests that the downdip part of the Grosmont was affected by hypogene dissolution from basinal fluids that probably migrated updip along with the oil, followed by extensive

biodegradation that may have further acidified the formation waters. Present bitumen in-situ viscosities are > 1 million cP, API gravities range from 5-9 dgs.

References

Dembicki, E.A., and H.G. Machel, 1996, Recognition and delineation of paleokarst zones by the use of wireline logs in the bitumen-saturated Upper Devonian Grosmont Formation of northeastern Alberta, Canada: AAPG Bulletin, v. 80/5, p. 695-712.

Dembicki, E.A., 1994, The Upper Devonian Grosmont Formation; well log evaluation and regional mapping of a heavy oil carbonate reservoir in northeastern Alberta: Master Thesis, University of Alberta, Edmonton, 221 p.

Higley, D.K., M.D. Lewan, L.N.R. Roberts, and M. Henry, 2009, Timing and petroleum sources for the Lower Cretaceous Mannville Group oil sands of northern Alberta based on 4-D modeling: AAPG Bulletin, v. 93/2, p. 203-230.

Miall, A.D., O. Catuneanu, B.K. Vakarelov, and R. Post, 2008, The Western Interior Basin *in* A.D. Mall, (ed.), The Sedimentary Basins of the United States and Canada: Sedimentary Basins of the World, v. 5, (K.J. Hsu, series editor): Elsevier Science, Amsterdam, p. 329-362.

Mossop, G.D., and I. Shetsen, (compilers), 1994, Geologic Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, Special Report 4, 510 p. Web accessed 18 April 2012. http://www.ags.gov.ab.ca/publications/wcsb_atlas/atlas.html

Selby, D., and R.A. Creaser, 2005, Direct radiometric dating of hydrocarbon deposits using Rhenium-Osmium isotopes: Science, v. 208, p. 1293-1205.

Switzer, S.D., W.G. Holland, D.S. Christie, G.C. Graf, A.S. Hedinger, R.J. McAuley, R.A. Wierzbicki, and J.J. Packard, 1994, Devonian Woodbend-Winterburn strata of the Western Canada Sedimentary Basin, *in* G.D. Mossop, and I. Shetsen, (compilers), Geologic Atlas of the Western Canada Sedimentary Basin: Calgary, Canadian Society of Petroleum Geologists and Alberta Research Council, p. 165-195.

Website

Blakey, R.C., 2011, Colorado Plateau Geosystems, Inc., Reconstructing the Ancient Earth. Web accessed 18 April 2012. http://cpgeosystems.com/paleomaps.html

The Devonian Grosmont - Unconventional oil in a fractured and karstified dolostone-evaporite platform, Alberta, Canada

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Abstract

Beneath the Cretaceous oil sands deposits of Alberta, The Upper Devonian Grosmont carbonate platform hosts at least 400 billion barrels IOIP as low-gravity (API ~5° to ~9°) bitumen, by some estimates up to ~500 billion barrels. This renders the Grosmont the world's largest unconventional oil reservoir hosted in carbonates.

The Grosmont reservoir is located at an average depth of about 250 400 m. Our study, which aims to aid in thermal recovery of this reservoir, shows that the current reservoir characteristics were created by the succession of five major factors and/or processes: sedimentary stratigraphy, dolomitization, polyphase and polygenetic fracturing, polyphase and polygenetic karstification, and biodegradation. Most of the present porosity and permeability is due to fracturing and karstification.

The sedimentary stratigraphy of the Grosmont reservoir consists of 6 stacked carbonate units interbedded with marls and some evaporites. The latter two originally acted as aquitards during diagenesis but are breached or missing in parts of the area today. Dolomitization by density-driven reflux created fine-crystalline and tight dolostones with scattered molds and vugs.

A dense fracture network was created in three or four phases. Most fractures probably originated from collapse following subsurface salt dissolution and/or from Laramide tectonics far to the west, whereby pulsed crustal loading in the fold-and-thrust belt created a dynamic forebulge in the Grosmont region via multiple pulses of basin-wide crustal flexing, each followed by relaxation. The fracture network probably was reactivated and/or expanded by glacial loading and post-glacial isostatic rebound in the Pleistocene and Holocene, respectively.

The region experienced three or four prolonged periods of epigene (topdown) karstification, although there is tangible evidence for only two of them in the Grosmont platform. The first of these episodes was a 'warm epigene karstification' during the Jurassic - Cretaceous, and the second was/is a 'cold epigene karstification' that started sometime in the Cenozoic and is continuing to this day, as is biodegradation. In addition, there is circumstantial evidence for hypogene (bottom-up) 'karstification' (= dissolution) throughout much of the geologic history of the Grosmont since the Late Devonian, with two possible maxima around the time of hydrocarbon emplacement, i.e., Early-Middle Cretaceous and Early Tertiary, respectively.

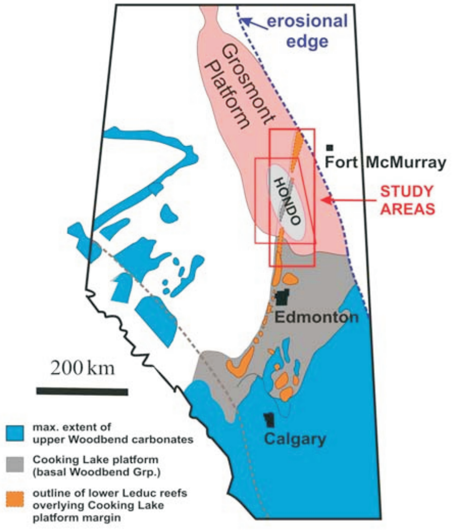

Fig. 1: Simplified subsurface map of the Upper Devonian Woodbend carbonate platforms and reefs in Alberta (modified from Switzer et al. 1994). Most of our studies were concentrated within the rectangle marked as study area. The Hondo study was conducted in the trapezoid study area.

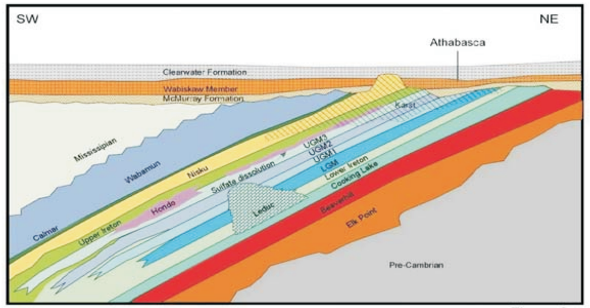

Fig. 2 : Schematic SW-NW stratigraphic section in study areas.

Stratigraphy and Deposition

The sedimentary stratigraphy of the Grosmont reservoir consists of six stacked carbonate units interbedded with marls and some evaporites (Fig. 2). Each of these stratigraphic units has shallowing-upward facies characteristics (Fig. 3).Thin, regionally extensive marl layers, commonly referred to as 'shale breaks', mark relatively short-lived flooding events at the beginning of each cycle. Layers of anhydrite are referred to as the Hondo Formation or Member (Figs. 3F, 4A, 4B). There also are isolated occurrences of halite hopper molds (Fig. 3H). Secondary/replacive anhydrite nodules and patches are also present (Fig. 4C) and most probably are diagenetically redistributed from the original depositional gypsum layers.

The platform margin migrated from east to west through time. The first time Hondo evaporites were deposited was during deposition of the UGM1. At that time the Grosmont platform margin was located on top of the underlying Cooking Lake platform margin, and the Leduc reef(s) at the Cooking Lake margin formed a slight paleotopographic high that permitted evaporite deposition in the region to its east (Figs. 5, 6). The second time of recognizable evaporite deposition was during UGM3/Upper Ireton times. Subvertical, syndepositional faulting provided for a slightly raised margin, which enabled evaporation in a lagoon or salina on the platform (Figs. 5, 6).

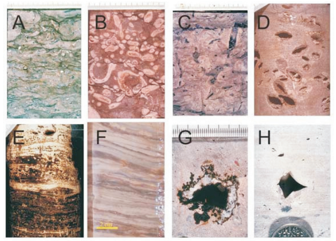

Fig. 3: Facies in an idealized shallowing-upward cycle of the Grosmont platform. A: subtidal skeletal grainstone facies; B,C,D shallower shelf facies; E: intertidal algal mat facies; F: brine pond anhydrite facies; G,H: supratidal muds with dissolved anhydrite nodule (G) and halite hopper mold (H).

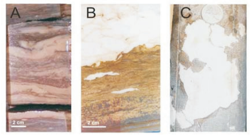

Fig. 4: A, B: 'Primary' subaqueous anhydrite facies; C: secondary/replacive anhydrite.

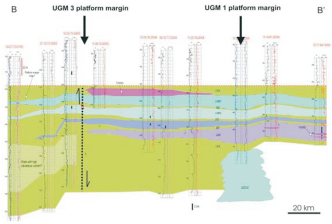

Fig. 5: Stratigraphic W-E section about midway through the Hondo area shown in Fig. 6. Note Hondo deposition at two stratigraphic levels: UGM1 and UGM3 and locations of corresponding platform/ramp margins.

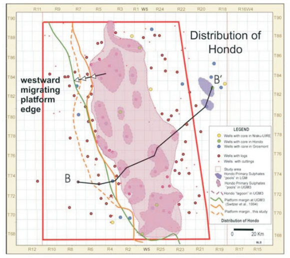

Fig. 6: Map of the Hondo area with well control and positions of platform margin/edge through time.

Burial history

The Grosmont region underwent two relatively rapid periods of subsidence (Fig. 7). Estimated maximum burial depths are about 1700m in the western downdip part and about 800 m in the eastern updip part of the platform, which is now exposed and/or eroded. However, these burial depths are very poorly constrained and the actual maximum burial depths may have been much less. The Grosmont platform was affected by many diagenetic processes that partially overlapped in time and space (Fig. 8). The processes that most affected the current reservoir characteristics on a regional scale are/were dolomitization with partial subsequent recrystallization, fracturing, karstification, and biodegradation.

Dolomitization

There were at least two dolomitization events caused by fluids of differing composition and hydrologic drives (Dolomite-1 and 2, Fig. 8). Dolomite-1 in the UGM2 and 3 is stratiform, mostly fine_crystalline and fabric retentive (Fig. 3D-H). Most of these dolostones are tight except for scattered molds and vugs, and generally do not qualify as 'good' reservoir rocks. In contrast, dolomite-2 is medium to coarse-crystalline with significant intercrystal porosity. Dolomite-1 was formed by mesohaline reflux more or less syndepositionally during deposition of the UGM2 and UGM3. On the other hand, dolomite-2 probably was formed by ascending basinal brines.

Fractures

Fractures are of great interest for any investigation of reservoir characteristics. In the Grosmont reservoir, the fractures will not only provide fluid pathways during thermal recovery, they probably will create increasing permeabilities during bitumen extraction.

The Grosmont reservoir is pervasively fractured. Fractures were created in three or four phases (F1-F4: Figs. 7,8). Most fractures probably formed in the second and third phases (F2 and F3) and many were reactivated in the last phase (F4). Diagenetic cements are generally absent in all types of fractures, while many appear enlarged by dissolution and/or are filled with bitumen.

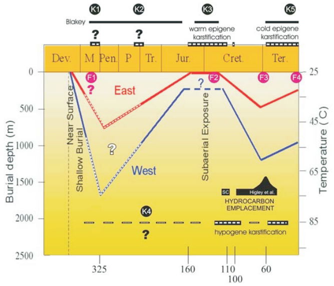

Fig. 7: Burial curve with interpreted periods of karstification (K1-K5) and fracturing (F1-F4). The red burial 'curve' is for the updip portion of the platform in the east, the blue 'curve' is for the downdip limit of the platform in the west. Black bars along the top labeled 'Blakey' designate periods of subaerial exposure according to Blakey's (2011) paleogeographic maps, while the black-and-white bars along the top mark periods of subaerial exposure of the updip portion of the Grosmont platform based on sedimentologic data in Mossop and Shetsen (1994) and Miall et al. (2008). Black-and-white bars along the bottom designate possible (narrow, ?) and likely (bold) periods of hypogene dissolution of the downdip part of the platform Hydrocarbon emplacement probably began about 118-108 m.y. (Selby and Creaser 2005) or between 95-40 m.y., with peak emplacement by volume between 70-50 m.y. (Higley et al. 2009).

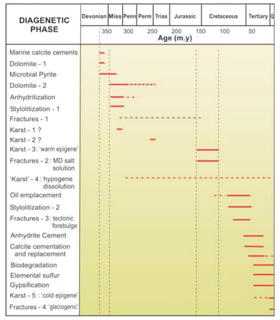

Fig. 8: Simplified paragenetic sequence for the Grosmont region.

In situ subvertical fractures can be recognized in almost all Grosmont cores (Fig. 9A,B). In addition, many core intervals appear irregularly fractured into crackle breccias (Figs. 9C,D) or rubble (Fig. 10A). Other types of breccias fall into several sub-types and include solution-collapse breccias from postdepositional removal of evaporites (Figs. 10B,C), as well as infills of karst (Fig. 9A?, Fig. 11).

Karstification

The Grosmont reservoir is pervasively karstified. The karst is fractal, polyphase and polygenetic (K1-K5: Figs. 7,8). On the largest scale karst features can be properly recognized only in seismic. The most prominent karst features at this scale are circular to oval sinkholes, between 30 and 150 m in diameter, below the regional sub-Cretaceous (Fig. 12). Caves can be recognized by a combination of neutron density and caliper log characteristics. In core, karst can be identified as solution-collapse breccias and intraformational breccia infills (Figs. 9, 10). Paleocaves contain extraformational infills, most notably Cretaceous coal and rare, whitish microcrystalline mixtures of kaolinite and quartz as the dominant minerals (Fig. 11).

The earliest karstification phase of the Grosmont may have happened during the Middle-Late Mississippian when karstification affected the United States and at least the southern perimeter of western Canada nearly continent-wide (Fig. 7: K1).

A second phase may have happened during the Permian-Triassic (Fig. 7: K2). However, there is no tangible evidence in the Grosmont for karstification during either time intervals.

A third, prolonged and definitely pervasive karstification phase that affected east-central Alberta was during the Late Jurassic - Early Cretaceous (Fig. 7: K3). Proof of this timing of karstification in the Grosmont region is provided by incised valleys and the numerous sinkholes. We refer to this karstification as the 'warm epigene karstification' because the climate in what is now Alberta was relatively warm during those times as a result of a relatively warm global climate.

The Grosmont platform was subjected to at least some dissolution from ascending waters that did not have a local meteoric origin, also referred to as 'hypogene karstification' (Fig. 7: K4; Fig. 8). A fourth period of prolonged and pervasive epigene karstification began during the Tertiary and is continuing to this day at least in the updip part of the platform (Fig. 7: K5 = 'cold epigene karstification').

Fracturing from salt solution

Fracturing from dissolution of the underlying Middle Devonian evaporites and of parts of the Hondo affected the platform (Fig. 7: F2; Fig. 8). The largest caves should be located where present or former Hondo evaporites are crossed by one or both levels of non-stratiform enhanced karstification (Fig. 13).

Tectonic Fracturing

Tectonic fracturing is herewith recognized as F3 (Figs. 7, 8). Pulses of uplift and relaxation of the Laramide forebulge probably created much of the fracture pattern in the Grosmont.

Biodegradation and bitumen properties

The bitumens in the Cretaceous oil sands and in the Grosmont reservoir are similar in composition and are strongly to severely degraded. Biodegradation was most intense around stratigraphic boundaries and generally increases from SE to NW. The viscosity distribution is also regionally variable, commonly by one order of magnitude.

Glaciogenic Fracturing

Glaciogenic fracturing was the last of four fracturing events (Fig. 7: F4; Fig. 8). Joints and fractures formed by F2_F3 were rejuvenated during glacial loading and post_glacial rebound in the Pleistocene/Holocene. The amounts of glaciogenic depression and isostatic rebound may range between 150 and 200m.

Sweet Spots

In 1994 two of us (Dembicki and Machel) endeavored to identify 'sweet spots' for thermal recovery, i.e., locations within the Grosmont reservoir that would be most profitable. The results of two sets of maps are shown in Figure 14. Both 'sweet spots' are located within the area leased by Shell in 2006 for $465million. Had we only known this was coming !

References

References are available from the author upon request.

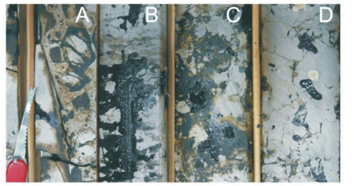

Fig. 9: A: Fracture/fault (or cave) with wall rock on left side and intraformational breccia (or cave infill) on the right, with differential oil stain. Some clasts were fractured and bitumen-saturated while the matrix is not. B: Bitumen oozing out of vertical hairline fracture, which is common in 'legacy cores' (drilled more than ~10 years ago) after a few years of storage. C,D:irreguar fracture network creating a 'crackle breccia' network.

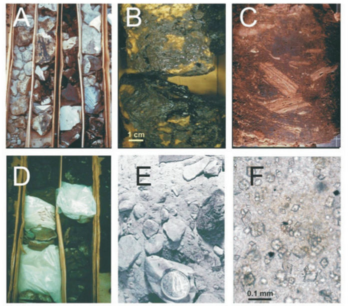

Fig. 10: A - C: Fractured and brecciated core intervals. D: Core interval with 'dolo gunk' = dolomite powder held together by bitumen. Bags contain white dolomite powder after bitumen extraction with organic solvent. E: Dolomite powder. F: Thin section, transmitted light: dolomite crystals floating in bedded anhydrite (Nisku Fm., township 14W4). This kind of rock is the most likely precursor of dolomite powder in the Grosmont.

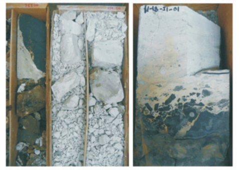
Fig. 11: Core interval with cave infill consisting almost entirely of microcystalline kaolinite and quartz, washed in from an overlying playa in relatively recent times.

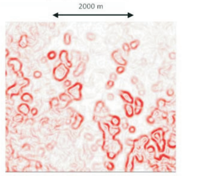

Fig. 12: Seismic image of sinkholes in a part of the Grosmont platform, showing their generally irregular distribution and variable sizes. Image obtained from Shell International and reproduced with permission.

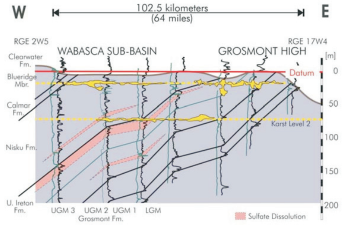

Fig. 13: Schematic W-E cross section though the central part of the study area, showing two levels of enhanced karst (cave?) formation and stratiform intervals of sulfate dissolution.

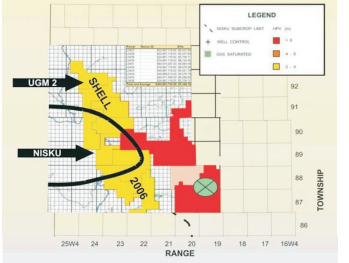

Fig. 14: Map of the northern part of our study area, showing the 'sweet spots' identified by Dembicki (1994) and Dembicki and Machel (1996), as well as the areas leased by Husky (red) and by Shell (yellow) in 2006.