

# **Core Session Guidebook**

# CARBONATE LITHOFACIES WITHIN A SEQUENCE STRATIGRAPHIC FRAMEWORK; THE LATE GIVETIAN TO EARLY FRASNIAN OF THE ALBERTA BASIN

KEN POTMA, IMPERIAL OIL RESOURCES, JOHN WEISSENBERGER, HUSKY ENERGY,

IGCP-580 AND IGCP-596 JOINT MEETING CALGARY, ALBERTA Aug 27 to Sept 1, 2013

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# **CORE SESSION ITINERARY**

August 30, 2013

# Start Time:

8:00 AM

# Location:

Alberta Energy Regulator Core Storage Facility. 3545 Research Way NW, Calgary (in the University of Calgary Research Park)

Aspects of the late Givetian and Frasnian (upper Devonian) Petroleum System within the Alberta Basin.

We will use select core examples to highlight Devonian stratigraphic architecture within a secondorder sequence.

Participants will develop an appreciation for the variability of lithofacies, fauna, reservoir quality, reservoir styles, source rocks and sealing lithofacies.

There will be an emphasis on the expression of carbonate sequences and sequence boundaries in core.

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## **INTRODUCTION**

The presence of Devonian strata in western Canada has been known since the geographical surveys of the mid-19th century. The economic significance of these rocks was first realized after the Imperial Oil discovery of the Leduc field in February, 1947 (Fox and Darling, 1947). This discovery of oil and gas in a Devonian reef complex opened up a major hydrocarbon province in the western Canada basin. Since that time significant exploration and development has taken place resulting in an unsurpassed public dataset of Devonian core and other subsurface data. Particulary well represented are the hydrocarbon-productive reefs of the Givetian Keg River Formation, the early Frasnian Swan Hills Formation, the mid Frasnian Leduc Formation and the Upper Frasnian Nisku Formation. Numerous corporate, academic and government studies have been undertaken on these rocks. The stratigraphy, lithofacies, fauna, diagenesis and resultant reservoir properties are well described (see selected bibliography).

This core workshop will focus on the mostly Frasnian second-order sequence of Potma *et al.* (2001). We will use select core examples to highlight Devonian stratigraphic architecture within a second-order sequence in order that participants develop an appreciation for the variablility of lithofacies, fauna, reservoir styles, sources and seals with an emphasis on the expression of carbonate sequences and sequence boundaries in core.

The selected cores have economic as well as scientific importance. They offer the opportunity to study, over a large basin area reef complexes from the transgressive, early highstand and late highstand of the Frasnian second-order sequence that host  $1,770 \times 10^6 \text{ m}^3$  ( $11.1 \times 10^9 \text{ BBLS}$ ) of recoverable oil reserves and  $565 \times 10^9 \text{ m}^3$  (19.8 TCF) of recoverable gas reserves (AER and BCMEPR estimates). While many of the older pools are in terminal decline, subtle plays in the upper Devonian remain an attractive exploration target in the basin to this day. The Ladyfern discovery in British Columbia in 2000 (450 Bcf) is an example as is the 2004 Shell Canada discovery of a new Leduc reef in the Ricinus West area (190 Bcf). New technology – specifically horizontal drilling have opened up a new play in thin porosity developments within the broader carbonate platforms, notably in the Slave Point and lower part of the Swan Hills Formation. The major source rock of the sequence, the Duvernay Formation, is currently the focus of exploration and early development efforts in unconventional bio-siliceous organic-matter porosity (shale gas and shale oil).

The Alberta Basin is a significant hydrocarbon province with some 59 billion barrels of original conventional oil in place and a current recoverable volume of 16 billion barrels. About 60% of this recoverable volume was hosted by middle and upper Devonian carbonates. The basin also contained about 137 Tcf of gas reserves and a very large volume of oil sands (1.6 Trillion barrels). East of the foothills disturbed belt, which produce from thrusted Mississippian

and Devonian Rocks, the unfaulted sediments dip gently (2-3 degrees) to the west and production is related to stratigraphic traps. Aside from the Devonian reef complexes and platforms, the bulk of the production occurs in Cretaceous marine sandstones, Cretaceous fluvial sandstones and subcropping Mississippian and Triassic carbonates.

#### **OBJECTIVES**

This core workshop will familiarize you with Devonian carbonate reservoir and nonreservoir lithofacies in the subsurface prior to the field trip to Grassi Lakes to view equivalent strata in outcrop. Lithofacies and depositional cyclicity will be emphasized.

Vertical and lateral facies relationships will be examined within the framework of a second order depositional sequence (*sensu* Vail *et al.*). The vertical facies succession will be broken up into a hierarchy of depositional sequences and shoaling upward cycles or parasequences. Cycle boundaries can be traced laterally, demonstrating how a carbonate reservoir or carbonate play can be mapped in three dimensions, so that lithofacies and reservoir relationships become predictable.

We will examine core from several prolific reservoir units across a spectrum of systems tracts and reservoir types discussing similarities and differences between them. Many of these are from reef complexes which host a giant conventional oil or gas pools. Sandstone reservoirs of the Gilwood Member occur at the base of the sequence. Depositional textures are very well preserved in the limestone Judy Creek reef (Swan Hills Formation) that occur in the transgressive part of the sequence. These cores provide a good grounding in Devonian carbonate facies.

We will also examine cores from the Leduc Formation at Golden Spike (limestone) and Windfall (dolostone) to compare and contrast textures in tall reefs that form at the transgressive heart of the sequence. At the transgressive maximum we will examine core from the Duvernay Formation organic rich mudstones which are the current focus the aforementioned unconventional play. The late highstand is represented by cores from the Nisku Formation at Leduc-Woodbend and in West Pembina (dolomite) to see both platform and pinnacle reef reservoirs. Finally we look at latest highstand carbonates of the Blueridge Member overlain by siltstones of the overlying second-order sequence.

We will investigate some surfaces that are candidates for sequence boundaries and discuss the criteria for recognizing them. We will investigate these interpreted sequence boundaries and other surfaces, in different settings. We will discuss a seepage reflux model tied to the stratigraphic framework for the dolomitization of these units. The excellent reservoir properties of these reefs, varying with lithofacies and position within the second-order sequence,

will also become apparent. The excellent source rocks and seals all combine to form a worldclass petroleum system.

# **GEOLOGICAL SETTING**

During deposition of the late Givetian to Frasnian second-order sequence (upper Devonian), Alberta was located on a relatively passive western margin of North America. As shown in the paleogeographic reconstruction by Ron Blakey (Figure 1), a large epeiric sea, connected to the proto-pacific, covered the province. Numerous shallow water reefs and carbonate platforms flourished within this basin.



# FIGURE 1 - PALEOGEOGRAPHIC RECONSTRUCTION

The schematic cross section below (Figure 2, Wong *et al.*, 1992) illustrates the carbonate-bearing strata, associated shales and the sequence boundaries discussed in this workshop. This, together with the successive paleogeographic maps (Figure 3) illustrate the

evolution of the basin through this time period. The early part of the sequence is probably Givetian in age, the upper part is latest Frasnian. The capping sequence boundary marks the Frasnian-Famennian boundary. The second-order sequence is subdivided into nine third-order sequences.



# FIGURE 2 SCHEMATIC CROSS SECTION



FIGURE 3 - PALEOGEOGRAPHIC RECONCONSTRUCTIONS (upper left Beaverhill Lake, upper right Leduc, lower left Nisku, lower right Blueridge)

The lowstand at the base of the second-order sequence represents a time of significant exposure of the previously deposited Keg River-Muskeg sequence. A widespread arkosic sandstone, the Gilwood Member of the Watt Mountain Formation, was laid down in fluvial and deltaic settings. The sediments were sourced from the granitic Peace River Arch and the exposed Cambrian rocks of the west Alberta Ridge. The early part of the transgressive systems tract resulted in widespread shallow and hypersaline waters across the basin and the the deposition of the laminated anhydrites and dolostones of the Fort Vermillion Member.

As the transgression continued, normal marine conditions were established and widespread carbonate deposition initiated in the warm, equatorial sea. Extensive carbonate platforms and reefs of the Slave Point and Swan Hills Formations of the Beaverhill Lake Group were laid down during Beaverhill Lake sequences one through three. The expansive atoll reefs and carbonate banks form prolific oil and gas reservoirs, notably in the Swan Hills area where the reefs are about 75 metres thick (250 feet, Fischbuch, 1968). The initial Frasnian transgressive units are absent or thin in most of the mountain belt due to on-lap onto the west Alberta ridge, a positive topographic feature at that time.

The transgressive heart of the sequence, Woodbend sequences one through three, is marked by the tall reef complexes of the Leduc Formation which hosts prolific oil and gas pools, largely in atoll reef complexes located east of the mountain belt. An example is the Rimbey-Meadowbrook reef chain, which formed along the western margin of the Cooking Lake shelf and divided the inland sea into an eastern and western basin. Basin bathymetry was greatest at this time, reefs along the trend are almost 200 m (600 feet) thick and can contain full columns of oil (e.g. Golden Spike, McGillivray and Mountjoy, 1975). The main source rock for the system, the Duvernay Formation was also deposited at this time. It is a world class type II marine algal source rock. Widespread, it displays favourable maturities and can reach thicknesses of about 40 metres (120feet).

The basin began filling with more argillaceous sediments of the Ireton Formation during the early part of the highstand (Woodbend Sequence 3). Shales clinoform into the basin progrogressively from east to west and reduced the basin size substantially after Leduc time (Stoakes, 1980).

Widespread carbonate deposition was re-established during deposition of the Nisku Formation of the Winterburn Group (Winterburn sequence 1). A regional Nisku bank extended from West Pembina, southwest towards the mountain front at Cripple Creek. Downslope pinnacle reefs developed outboard of the bank along the west Pembina Pinnacle Trend. In contrast, the Nisku shoal is dominantly backstepped, relative to the Leduc, in the western part of the basin. There carbonate deposition continued relatively uninterrupted, distant from the Ireton shale input points. The pinnacle reefs and the regional Nisku bank, primarily where draped over underlying Leduc Formation reefs host important oil and gas reservoirs.

The basin was almost completely filled by relatively restricted carbonate platforms and siliciclastics during the last two third-order sequences. These shallow platforms contained briney ponds preserved as anhydrite deposits in these strata. The importance of these in providing potential dolomitizing fluids is discussed later.

## DEVONIAN LITHOFACIES

We recognize 14 major lithofacies, recognizable in the Frasnian sediments of the basin. Progressing from deep to shallow water environments they are: organic mudstone facies, illiticcalcareous mudstone facies, nodular mudstone facies, cylindrical/dendroid coral wackestone and boundstone facies, dark-coloured tabular stromatoporoid boundstone facies, light-coloured tabular stromatoporoid boundstone facies, stromatoporoid rubble facies, cylindrical stromatoporoid grainstone facies, dark-coloured *Amphipora* facies, light coloured *Amphipora* facies, homogenous micrite facies, fenestral mudstone facies, skeletal/peloidal packstone facies and anhydritic mudstone facies.

Each of the facies has unique textures, sedimentary structures and fossil assemblages. Interpretation of the depositional environment of each of these facies is based upon lateral and vertical variation of the facies (Walther's Law) and comparison with modern analogues. Figure 4, based, in part, on Wendte and Stoakes' (1982) work on the Swan Hills Formation Judy Creek reef complex, shows the facies depicted on a paleobathymetric profile.

The major non-algal frame-builders in the upper Devonian were stromatoporoids. Like modern corals, stromatoporoids had varying morphologies based on environmental controls. Growth forms range from platy to bulbous and cylindrical. Associated fauna consisted of rugose corals, algae, brachiopods, crinoids and other organisms. More detailed facies descriptions are Available in Klovan (1964), Fischbuch (1968), or Krebs (1974) etc.



FIGURE 4 – LITHOFACIES MODEL



Figure 5A Typical Devonian Lithofacies 1. Fenestral Mudstone 2. Dark Amphipora Wacke-Packstone 3. Light Amphipora Wacke-Packstone 4. Cylindrical Stromatoporoid Grainstone



5. Abraded Stromatoporoid Grainstone 6. Nodular Lime Mudstone 7. Cylindrical Stromatoporoid Grainstone 8. Dark Coloured Tabular Stromatoporoid Boundstone Facies ORGANIC MUDSTONE FACIES: This facies consists of dark coloured bio-siliceous carbonate mudstones with alternating laminations of carbonate and organics. Fauna in the laminites is sparse and consists of conodonts, styliolinids and tentaculitids.

The sediments are thought to represent deposition in deeper water, below wave base, under conditions that were sufficiently euxinic to exclude a burrowing in-fauna. These sediments can have sufficiently high organic content to be source rocks and if sufficiently mature, reservoir rocks.

ILLITIC MUDSTONE FACIES: This facies consists of illitic mudstone interbedded with calcareous and illitic mudstone. It displays lamintated to bioturbated textures; with limited fauna, mostly crinoids and brachiopods. It is an important seal lithofacies.

NODULAR LIME MUDSTONE FACIES: This facies is composed of dark coloured nodular to wavy bedded carbonate mudstones with a sparse to locally abundant fauna of crinoids, bryozoans, corals and atrypid brachiopods. The sediment often shows a bimodal grain size having grainier burrows within a more micritic matrix.

The nodular to bedded nature of the sediment, the fossil material and the presence of burrows suggest that this facies was deposited below wave base under conditions that were sufficiently aerobic to allow an in-fauna.

CYLINDRICAL AND DENDROID CORAL WACKESTONE AND PACKSTONE: This facies is composed of dendroid, cylindrical and rugose corals in a muddy to sandy matrix with a sparse to locally abundant fauna of crinoids, bryozoans, megalodonts, atrypid brachiopods and some stromatoporoids.

This facies is also typical of the deeper portions of pinnacle reefs, representing reef initiation in 10 to 30 metres of water.

DARK COLOURED TABULAR STROMATOPOROID BOUNDSTONE FACIES: This facies is composed of dark coloured, organic, micritic boundstones and packstones. The fauna consists of *in situ* thin tabular stromatoporoids associated with common *Thamnopora*, rugose corals, crinoids and brachiopods. The facies may have thin beds of fine grained carbonate sand representing storm deposits.

This facies is thought to be deposited in water depths of greater than 10 metres, where light conditions were reduced and wave energy sufficiently low to preclude the winnowing away of the fine grained material.

LIGHT COLOURED TABULAR STROMATOPOROID BOUNDSTONE FACIES: This facies consists of packstones and boundstones containing a fauna of tabular stromatoporoids, cylindrical stromatoporoids, and rarely, small bulbous stromatoporoids, *Amphipora* and corals. The algae *Renalcis* can also be found in this facies. The shallower part of the facies contains significant amounts of carbonate sand with abundant abraded fossil material.

The light-coloured tabular stromatoporoid boundstone facies was deposited in wellcirculated, moderate wave energy conditions where the water depths are thought to have been one to ten metres.

STROMATOPOROID RUBBLE FACIES: The stromatoporoid rubble facies consists predominately of abraded stromatoporoid rubble and some *in situ* thick tabular stromatoporoids. The matrix consists of medium to coarse-grained carbonate sand.

These rocks were deposited at the reef margin under high-energy conditions in the zone where the waves crashed on the reef front. Under these conditions, most fine-grained material was winnowed away and moved to either deeper water in front of the reef or to the sheltered lagoon behind the reef margin.

CYLINDRICAL STROMATOPOROID GRAINSTONE FACIES: This facies consists of a fauna of cylindrical stromatoporoids, bulbous stromatoporoids and commonly, *Amphipora*. There is also a considerable amount of abraded stromatoporoid debris. The matrix is a medium to coarse carbonate grainstone.

The cylindrical stromatoporoid sand facies is interpreted to have been deposited in the moderately high-energy reef flat zone directly behind the reef margin where sand from the reef margin would be deposited during storms. This facies is also formed in shoals on drowned platforms.

LIGHT-COLOURED AMPHIPORA FACIES: This facies consists of Amphipora wackestones to packstones in a peloidal grainstone matrix. Occasionally bulbous or cylindrical stromatoporoids or gastropods may be present but the facies is typified by a high abundance of Amphipora, with a low diversity of other fauna.

This facies is thought to have been deposited in the shallow, moderate energy conditions present in the lagoon behind the reef margin. Salinity in this environment seems to have been somewhat elevated so that most of the normal marine organisms of the reef margin and foreslope are excluded, and *Amphipora*, which was apparently able to tolerate higher salinities, is the dominant form.

DARK-COLOURED AMPHIPORA FACIES: The dark-coloured Amphipora facies consists of Amphipora packstones and wackestones in a dark-coloured, micritic carbonate matrix. Occasionally, bulbous stromatoporoids are present.

This facies was probably deposited under quiet water conditions in deeper parts of the lagoon behind the reef margin. In the smaller reef complexes such as the Golden Spike reef complex circulation was very good throughout, and this facies less common. It is very common in the larger reef complexes such as Judy Creek.

SKELETAL/PELOIDAL PACKSTONE FACIES: This facies is composed of coarse, matrix- free rudstones consisting of *Amphipora* or cylindrical stromatoporoids. The facies often occurs interbedded with the fenestral facies and the light coloured *Amphipora* facies. In some cases, pendant cements are observed, indicating subaerial deposition.

The facies is interpreted to have been deposited on a beach where wave energy was sufficient to winnow away most of the sand-size carbonate and leave behind only the larger size fossil fragments.

HOMOGENOUS MICRITE FACIES: This facies, as the name suggests, is composed of a homogenous medium brown, ranging to white micrite. The facies is generally unfossiliferous but can contain *Amphipora* and gastropods. Its texture may have derived from extensive bioturbation, and burrows are sometimes preserved in this facies. The micrite may be interbedded with green shales.

This facies is thought to have been deposited on tidal mud flats within the lagoon. Where it is white, it may be bleached and represent near-sabkha conditions. The green shales are thought to represent storm deposits (Wendte and Stoakes, 1982) enhanced during exposure.

FENESTRAL MUDSTONE FACIES: The fenestral facies consists of pelleted, laminated micrite often with a fenestral fabric. *Amphipora,* gastropods and tabular lithoclasts are common additional constituents.

The facies is interpreted to have been deposited in a tidal flat environment along islands or mud flats within the lagoon. The fenestral fabrics are thought to result from trapped bubbles and by the decomposition of algal laminae.

LAMINATED ANHYDRITE FACIES: This facies consists of interbedded laminated anhydrite and shale or micritic dolostone. It is sometimes nodular, displacive or replacive.

The facies is interpreted to be deposited in evaporative brine pools on a shallow shelf.

#### **DIAGENESIS AND POROSITY EVOLUTION**

#### PRIMARY POROSITY DISTRIBUTION

In most limestone Devonian reef complexes primary porosity distribution shows an excellent correlation with primary depositional facies. The well studied Golden Spike (McGillivray and Mountjoy, 1975) and Judy Creek reefs (Wendte and Stoakes, 1982) illustrate this.

Most pores are primary interparticle, intraparticle and growth framework types. Degree of porosity is dependent on the amount of micrite. In general, the higher the amount of micrite the lower the porosity. Higher energy facies found in environments such as reef margins, reef flats and well-circulated lagoons generally have the best primary porosity development, unless it is degraded by early marine cements. Low energy facies such as sheltered lagoons and basinal areas have poor to no porosity and permeability development. Overall reservoir quality can be very good to excellent in the limestone oil pools. However, as discussed below, limestone reservoirs can be negatively impacted by burial related diagenesis.

#### DIAGENESIS

Diagenetic overprint varies from minor in some limestone Leduc Formation reef complexes to reefs that have seen massive replacement dolomitization.

## LIMESTONE REEFS

Marine cementation can occlude porosity in the margin of some limestone reefs. These are notable in the Leduc Formation at Golden Spike and in the west Pembina Nisku pinnacle reefs where they render some portions of the reef margin non-reservoir.

Subaerial cements may occur in proximity to exposure surfaces and consist of microstalactitic cements and porosity occluding sparry calcite cements.

In limestone pools pressure solution, associated with increasing burial compaction, result in stylolitization and contemporaneous calcite cementation. It is a common porosity-destroying event, especially in more micritic, argillaceous sediments which are more susceptible to dissolution. Minor dolomite cement is sometimes present.

Compaction, and porosity destruction, increase with depth. In this basin, limestone reefs generally have sub-economic porosity below about 3500 metres.

More information on limestone diagenesis is available in Walls and Burrowes (1985) or McGillivray and Mountjoy (1975) etc.

#### DOLOMITIZED REEFS

With the exception of the atoll reef complexes of the Swan Hills Formation, such as Judy Creek, a few large Leduc Formation reef complexes, notably Golden Spike and some of the West Pembina Nisku Formation pinnacles, the bulk of the reservoirs are dolostone.

Our recent work (Potma *et al.*, 2001) suggests that the bulk of the dolomitization occurred during early burial, prior to the end of the second order sequence. The dolomitizing fluids are not precisely understood but, based on the stratigraphic distribution of the dolomite, it is suggested that dense brines that formed during the Calmar and Graminia lowstands of sea level and that these brines seeped downwards through the connected carbonate complexes and dolomitized them. Considerable recrystallization and later hydrothermal influences have tended to mask this early phase of dolomitization. Dolomitization is the subject of ongoing debate and research (Machel et al, 2002).



FIGURE 6 – REFLUX DOLOMITE MODEL

Dolomites vary from rocks that have spotty matrix dolomitization with limestone allochems to rocks where the matrix is 100% dolomitized and the allochems have either been dolomitized themselves or leached to form the very common vuggy dolomite reservoirs.

Porosity is generally bi-modal with fossil moldic porosity occurring in a fine grained dolomite matrix. Intercrystalline porosity is in the 5-15% range and permeabilities can range to several darcies in favourable facies. In general, facies which do not have porosity to begin with do not develop porosity during dolomitization. In fact, dolomitization may be restricted to the reef margins and higher energy facies with muddier reef interior sediments remaining as tight limestone. Dolomitization homogenizes the porosity and permeability somewhat and reduces the lithofacies control on reservoir quality.

Porosity-occluding diagenesis consists of calcite, dolomite and anhydrite pore-filling cements. Porosity can be significantly reduced in reefs were cementation is extensive. Bitumen occurs as a pore-blocking cement in some Leduc reef complexes. Most dolomite textures have been re-crystallized which reduces the utility of isotopes in diagenetic analysis (Potma *et al.*, 2002).

Fracturing is common in these brittle reservoirs and vertical permeability is enhanced in this manner. This can be both a help and a hindrance as, while flow rates are enhanced, water coning can occur.

The rigidity of the dolomite matrix and the chemical stability of dolomite results in the preservation of porosity with depth. An important result of this is that dolomitized reefs buried to 5000 metres or more in the "Deep Basin" remain viable exploration targets while all primary porosity in limestone buildups at this depth would normally be destroyed. Exceptions to this are some small pinnacles that received gas charge and preserved some of their porosity.

As discussed, dolomitization is generally favourable to conventional carbonate reservoirs, particularly those that have been subjected to deep burial, because reservoir quality is better preserved at depth. However, the same brines that facilitate dolomitization can also favour deposition of anhydrite cements and cause sour (H<sub>2</sub>S-bearing) reservoir fluids.

#### ACKNOWLEDGEMENTS

The authors wish to thank our many colleagues who contributed to this work over these many years, particularly Pak Wong and Murray Gilhooly. We also acknowledge the management of Imperial Oil and Husky Energy for their ongoing support and (previously) PanCanadian (now Cenovus/EnCana) who also supported our work. Many thanks also to Phil Argatoff and Imperial Oil staff for their excellent and conscientious work in preparing the diagrams for this guidebook.

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