Carbonate reservoirs in Western Canada: An update

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ABSTRACT

Devonian Carbonate Reservoirs types in the Western Canada Sedimentary Basin are presented. A review of the reservoir parameters: geometry, lithology, porosity, fluid content, pressure, stress and their seismic estimation with compressional and shear waves velocities introduce the seismic method as a powerful tool in carbonate reservoir characterization.

INTRODUCTION

In Western Canada the carbonate rock reservoirs of Devonian age host large reserves of hydrocarbons (GSC, 1989; 1993). As these reserves depletes production optimization is an expensive and strategic goal for the oil companies.

The Devonian deposition history in the Western Canada Sedimentary Basin (WCSB) is that of a dominant carbonate-evaporite sedimentation province. The carbonate reservoir types recognized and their seismic characterization are discussed. The sensitivity of compressional $V_p$ and shear $V_s$ wave velocities to structure, lithology, porosity, permeability, fluid content, temperature, stress and anisotropy variations confirm the seismic method as a principal tool in reservoir characterization. As the reservoir rock parameters are independent variables, specific geological constrains at the well control points are necessary to resolve the inverse problem: from wave seismic velocity measurements to the reservoir parameters.

3-D seismic, well-to-well tomography, amplitude, multicomponent, seismic borehole studies enhanced by innovative processing are promising tools to improve the geophysical abilities in imaging the subtle carbonate reservoirs.

THE WESTERN CANADA SEDIMENTARY BASIN

THE DEVONIAN SYSTEM

The Western Canada Sedimentary Basin (Fig. 1) through time is a product of two major tectonic settings:

1). From Late Paleozoic to Middle Jurassic the basin acting as a passive continental margin, was filled eastward in a series of episodic transgressive events,

2). From Late Jurassic to Tertiary, the Colombian and Laramide orogenesis controlled the sedimentation in the Foreland Basin.
The Phanerozoic Time Scale records six major unconformities as a result of sporadic epirogenic and orogenic movements.

During the Devonian, Western Canada was situated in equatorial latitudes. Five major transgressive-regressive sequences separated by unconformities are identified by Moore (1988; 1989) The relatively thick epeiric sea sediment complexes were deposited during eastward pulsatory transgression over the craton. Seven associated depositional cycles are correlated with the eustatic fluctuations of the sea level in North America as is proposed by Johnson et al. (1985) are discussed and shown in Fig 2.

Figure 1. Basin Fill Map, Western Canada Sedimentary Basin.

Lower Elk Point (Cycle C1 and Cycle C2)

From Basal Red Beds to Upper Chinchaga a succession of redbeds, evaporites and carbonates was deposited within a restricted epicontinental sea. These strata have a maximum thickness of 300m and pinchout over the Tathlina, Peace River and Western Alberta arches.

Upper Elk Point (Cycle C3)

A major transgression is marked by ramp-to platform carbonates of Lower Keg River Formation. As the subsidence of the basin continued, the Upper Keg River barrier reef complex developed toward the northern limit of the basin. Isolated pinnacle reefs and reef mounds, (60m to 250m thick) within the central part of the basins.
The Muskeg-Prairie Evaporite Formations deposited in evaporitic conditions cover the entire basin with the exceptions of the north region of the Presquile' Barrier Complex where the normal marine sedimentation continued.

At the end of the Elk Point Cycle during a minor marine incursion peritidal to shallow-marine carbonates of Sulphur Point Formation covered the Northeastern Alberta.

Coastal marine and continental shale and sandstones of the Watt Mountain Formation terminates this cycle as the sea level drops.

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Figure 2. Table of Formations, Devonian, Western Canada Sedimentary Basin

**Beaverhill Lake Group (Cycle 4).**

Peritidal anhydrites and carbonates of Fort Vermilion Formation overlain during a gradual marine transgression the relatively flat surface of the Watt Mountain Formation. The sedimentation continued with the open-marine platform carbonates of the Slave Point Formation ranging from 20 m along the flanks of Alberta Ridge and the Peace River Arch to 150m near the Presquile' Barrier Complex. An extensive reef rimmed carbonate platform and the atoll like reef complex of the Swan Hills Formation developed in west-central Alberta. Basinal shales and argilaceous limestones of
Waterway Formation overlie the Swan Hills reef-complexes. In northern Alberta, the Waterways strata overlap the Slave Point reef complexes and in the southern Alberta interfinger with the shelf complex.

**Woodbend Groups (Cycle 5)**

In the deep water condition created by a renewed marine transgression and continuum deepening of the entire basin organic rich limestone and shale were deposited within the Duverney, Majeau Lake and Muskwa Formations. South and Southeast Alberta platform carbonates of Cooking Lake Formation were deposited in shallow waters. Leduc Formation and equivalents developed as reef-rimmed complex (Southern Alberta Shelf Complex).

In the Deep Basin area isolated Leduc reef complexes up to 250 m thick overlay direct Cooking Lake or Beaverhill platforms. Leduc reefs also developed in an arcuate fringe around Peace River Arch. The thick Ireton - Fort Simpson shales close the Woodbend Cycle as the Central Alberta basin was nearly filled.

**Winterburn Group (Cycle 6)**

The regressive sedimentation started in cycle 5 continued with the shelf carbonates of the Nisku Formation. A major regression terminated the Nisku sedimentation. The terigenous Calcar Formation deposits interfinger with shelf carbonates of Blue Ridge Member deposited during a shallow marine incursion.

At the end of the cycle the Gramina Silt was deposited as a second regression occurred.

**Wabamun Group (Cycle 7)**

A transgressive prograding carbonate ramp was initiated over central and northern Alberta and northeastern British Columbia. In southeastern Alberta the Nisku carbonates interfinger with the evaporitic deposits of the Stetller Formation. In northeastern British Columbia, the equivalent deeper water shales belong to the Besa River Formation.

**DEVONIAN CARBONATE RESERVOIRS**

The Carbonate reservoirs in The Devonian System in Western Canada Sedimentary Basin follow standard carbonate depositional models. In the Geological Survey of Canada (GSC) classification the typical Devonian carbonate reservoirs and their associated traps are illustrated in Figures 3, 6, 7 and 8.

**Barrier Reef**

A belt of transgressive phase reefs which separates deep seaward deposition of landward sedimentation. Open marine circulation was restricted behind the barrier reef.

**Reef Complex**

A large transgressive phase reef with complex facies surrounded by deeper-water deposits.
Figure 3. North-south cross section illustrating the major cycles in the Devonian of the Western Canada Sedimentary Basin. (Modified from Moore, 1989.)

Figure 3. East-west cross section illustrating the major cycles in the Devonian of the Western Canada Sedimentary Basin. (Modified from Moore, 1989)
Figure 5. Trap Styles, Devonian transgressive phases (GSC)

**Pinnacle Reef**

A transgressive phase reef with a simple facies distribution and an areal extent less than a half square kilometer. Its thickness is larger than its diameter.

**Patch Reef**

A transgressive phase reef with less than three square kilometer in area with complex internal facies.
Platform Carbonate

Extensive, carbonate strata deposited during the first stages of marine transgression.

Shelf Carbonate

A sequence of thin, cyclic carbonate and evaporite sediments deposited in shallow marine waters.

Shelf Margin Reefs

Thinner barrier reefs with little impact on water circulation.

Shelf Interior Reefs

Regressive phase patch reefs that are surrounded by shelf carbonate and evaporite units.

Figure 6. Trap Styles, Devonian regressive phases (GCS).
Figure 7. Structural and Structural-stratigraphic traps, Devonian (GSC).
SEISMIC VELOCITIES IN SEDIMENTARY ROCKS

In the laboratory and in situ, seismic velocities and densities for typical rock forming minerals (Table 1) and for typical sedimentary rocks (Table 2) have been measured as outlined below:

Table 1. Seismic Velocities and Densities in Typical Rock-Forming Minerals. (After Anderson & all, 1966)

<table>
<thead>
<tr>
<th></th>
<th>Vp (km/s)</th>
<th>Vs (km/s)</th>
<th>Vp/Vs</th>
<th>p (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>6.057</td>
<td>4.153</td>
<td>1.46</td>
<td>2.65</td>
</tr>
<tr>
<td>Calcite</td>
<td>6.259</td>
<td>3.243</td>
<td>1.93</td>
<td>2.71</td>
</tr>
<tr>
<td>Dolomite</td>
<td>4.689</td>
<td>2.720</td>
<td>1.73</td>
<td>2.87</td>
</tr>
<tr>
<td>Halite</td>
<td>4.525</td>
<td>2.616</td>
<td>1.73</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Table 2. Seismic Velocities and Densities in Typical Sedimentary Rocks. (After Domenico, 1984)

<table>
<thead>
<tr>
<th></th>
<th>Vp/Vs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone</td>
<td>1.46 - 1.76</td>
</tr>
<tr>
<td>Calc Sandstone</td>
<td>1.67 - 1.76</td>
</tr>
<tr>
<td>Dolomite</td>
<td>1.78 - 1.84</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.84 - 1.99</td>
</tr>
<tr>
<td>Shale</td>
<td>1.70 - 3.00</td>
</tr>
</tbody>
</table>

It is evident that each mineral or rock has a set of values (Vp, Vs, Vp/Vs) which in particular conditions could identify with accuracy that material. Ideal these conditions will be determined by the medium in which the measurements are made, only. Based on these facts researchers over the last fifty years were trying to establish equations which will increase the probability of a realistic identification of these rocks.

RESERVOIR PARAMETERS

Gassman (1951) calculated the bulk modulus K of a fluid-saturated porous medium from the known bulk moduli of the solid matrix K_m, the frame dry K_d, and the pore fluid K_f. The shear modulus of the rock is not affected by fluid saturation.

$$K = K_d + \frac{(1 - \frac{K_d}{K_m})^2}{\frac{1 - \frac{K_f}{K_m}}{K_f}} \frac{1 - \frac{K_f}{K_m}}{K_f}$$  \hspace{2cm} (1)

In Figure 8 and 9, from Wang and Nur (1992), Gassman calculated compressional and shear velocities versus measured velocities for typical carbonates are displayed. The deviation between observed and calculated velocities recommends caution in any use of Gassman equation when predicting saturating fluids.
VELOCITIES IN CARBONATE ROCKS

(a)

Figure 8. Comparison of laboratory measured compressional (a) and shear (b) wave velocities with those calculated using the Gassman equation at lower pressure (6.9 MPa). (after Wang and Nur. 1992).

(b)
Figure 9. Comparison of laboratory measured compressional (a) and shear (b) wave velocities with those calculated using the Gassman equation at lower pressure (34.5 MPa). (after Wang and Nur. 1992).
Figure 10. Maximum Biot dispersions of compressional (a) and shear (b) wave velocities in sandstone and samples saturated with water. (After Wang and al., 1992)
Figure 11. Maximum Biot dispersions of compressional (a) and shear (b) wave velocities in carbonate samples saturated with oil. (After Wang and al., 1992)
Wyllie et al. (1956) from experimental data discovered that in a rock of porosity \( \varphi \) the compression wave velocity \( V_p \), the velocity in the matrix \( V_m \), and the velocity in the saturating fluid \( V_f \) fit the equation

\[
\frac{1}{V_p} = \frac{\varphi}{V_f} + \frac{1 - \varphi}{V_m}
\]  

(2)

Since its beginning this formula has been used to derive porosity from the sonic log. It has to be mentioned that this equation should not be used for carbonates as stated in Wyllie et al (1958).

Biot (1956; 1962) developed a theory for elastic wave propagation in porous media. The equations derived interrelates the compressional and shear velocities with the elastic constants of the rock and saturating fluid. In Figure 10 and Figure 11 from Wang et al. (1992) compressional and shear wave velocities calculated by the Gassman \( V_G \) and Biot \( V_B \) equations are compared for sandstones and carbonates.

\[
\text{Biot Dispersion} = \frac{V_B - V_G}{V_B}
\]

(3)

Lithology

Picket (1966) from laboratory measurements stated that \( V_p/V_s \) discriminates between clean sandstone, carbonates and limestones (fig. 12). Later other researchers confirmed this result with new measurements: Hamilton (1979), Domenico (1984), Robertson (1987).

\[
\sigma = \frac{0.5\left(\frac{V_F}{V_s}\right)^2}{\frac{V_F^2}{V_s} - 1}
\]

(4)

The possibility of mapping lithologies throughout elastic wave velocities measurements has very important value for reservoir evaluation. Recording S- and P-wave seismic data on the surface in optimum conditions of S/N information from the subsurface can be derived accurately.

Porosity

Gregory (1976) studied the variation of elastic wave velocities with porosity in dry and saturated sedimentary rocks at low and high pressure as illustrated in Figure 13 and 14. A remarkable conclusion is that for a given lithology and porosity \( V_p/V_s \) can discriminate between liquid and gas pore.

Fluid Content

Pore fluids consist of oil, water mixtures and gases. Identification of pore fluids cannot be made with confidence based on \( V_p/V_s \) alone. To reduce the ambiguity detailed lithological information is critical.
Figure 12. Separation of lithology types (after Pickett, 1963).

Pore Shape

Kuster and Toksoz (1974) and Toksoz et al. (1976) developed a model for the propagation of elastic waves in porous media that considers the effect of pore shape on $V_p$ and $V_s$.

Pressure, Depth of Burial.

The variations of $V_p$ and $V_s$ in carbonate rocks with pressure/depth is larger for the first 1000 m and is mainly due to the closure of the elongated pores.
Figure 13. The ranges of Vp/Vs for dry and saturated rocks versus porosity.  
(After Gregory, 1976)
Temperature

The relation between elastic wave velocities and the temperature are less studied but from the reported studies, Timur (1977), the nature of the pore fluids is driving the bulk of the variations. For a brine-oil mixture a decrease in both V- and S- wave velocities are recorded.
Anisotropy

The anisotropy of carbonate rocks is controlled by factors as pore shape, pore and crack orientation, pressure, stress. The Devonian carbonates in Western Canada had a history of intense mechanical deformations. It is very likely that in the field, accurate anisotropy measurements will add to the techniques of reservoir description.

SEISMIC IMAGING THE CARBONATE RESERVOIR

The reflection seismic method for reef identification is well established for transgressive reef complexes, patch, and pinnacle reefs. These reefs present lateral velocities contrasts as well as differential compaction. Their seismic identification as structure anomalies appears easy but in many cases such structure tested dry. Criteria for reservoir characterization do not follow standards and is the geophysicist's challenge to predict reservoir properties.

We have seen that compressional and shear wave velocities together carry pertinent data to predict reservoir parameters. Theoretical and field studies recommend multicomponent seismic as the method for detailed reservoir characterization.

The daily problem the geophysicist is facing is that only seismic compressional reflection is available for interpretation. Through innovative modeling with geological and well information it is possible to calibrate the seismic data to extract from the seismic amplitude the missing Vs value. AVO measurements and amplitude calibration might be adequate to properly assess the reservoir.

Seismic inversion plays an important role in assessing the carbonate reservoir. Theoretical models and direct application to real data fit the best case histories but care is recommended in drawing general conclusions.

Meckel and al (1977) have modeled two carbonate reservoirs: a Carbonate Shelf Margin (Figure 15) and a Carbonate Platform (Figure 16). For the first case the morphological appearance of the reservoir makes possible its identification. In favorable situation amplitudes can be calibrated for reservoir characterization ( ). In the second case due to the low acoustic impedance contrast the reservoir is seismically transparent (Fig. 13). These are the extreme cases for the vast field of the carbonate settings as they are encountered in all the geological times.
Figure 15. Seismic model of carbonate shelf margin (after Meckel and al., 1976)
Figure 16. Seismic model of tidal-flat margin reservoir (after Meckel et al., 1976).
CONCLUSIONS

The reflection seismic method, the most used geophysical method in geoscience studies, is finding applications in reservoir characterization. The Devonian carbonate reservoirs in WCSB represented by a multitude of structural and stratigraphic types are the target of intense exploration and development effort. To make this effort more efficient, the quality of these reservoirs have to be well known prior to new investments.

Today, the 3-D seismic method, sophisticated computer technologies and in depth knowledge of the petrophysical properties of the reservoir rocks open new domains in hydrocarbon reservoir studies.

Lithological calibration of the 3-D seismic amplitudes, acquisition of VSP and multicomponent (V, SV, SH) surveys, seismic anisotropy measurements, AVO studies, etc. expand the geophysicist potential to describe the subsurface, to make critical contributions in reservoir evaluation. Reservoir characterization is today an multidisciplinary effort of significant economic importance in the oil industry.

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