Duvernay shale lithofacies distribution analysis in the West Canadian Sedimentary Basin

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Abstract. In the West Canadian Sedimentary Basin (WCSB), Duvernay shale is considered to contribute most of the Canadian shale gas reserve and production. According to global shale gas exploration and development practice, reservoir property and well completion quality are the two key factors determining the shale gas economics. The two key factors are strongly depending on shale lithofacies. On the basis of inorganic mineralogy theory, all available thin section, X-ray diffraction, scanning electron microscope (SEM), energy dispersive spectrometer (EDS) data were used to assist lithofacies analysis. Gamma ray (GR), acoustic (AC), bulk density (RHOB), neutron porosity (NPHI) and photoelectric absorption cross-section index (PE) were selected for log response analysis of various minerals. Reservoir representative equation was created constrained by quantitative core analysis results, and matrix mineral percentage of quartz, carbonate, feldspar and pyrite were calculated to classify shale lithofacies. Considering the horizontal continuity of seismic data, rock physics model was built, and acoustic impedance integrated with core data and log data was used to predict the horizontal distribution of different lithofacies. The results indicate that: (1) nine lithofacies can be categorized in Duvernay shale, (2) the horizontal distribution of different lithofacies is quite diversified, siliceous shale mainly occurs in Simonette area, calcareous shale is prone to develop in the vicinity of reef, while calcareous-siliceous shale dominates in Willesdon Green area.

1. Introduction

Over the past 10 years, great progress has been made in the exploration and development of unconventional natural gas in the world and especially in North America, operators have produced a large quantity of unconventional gas and oil from organic-rich shale reservoirs. However, under the current situation of long-term low oil price globally, how to reduce costs and increase economic benefits is the key issue with which global unconventional oil and gas practitioners are confronted. According to the experience in shale oil and gas exploration and development in North America, reservoir property and well completion quality are two key factors determining shale gas economy, which largely depend on lithofacies types (Gamero et al.,2013) [1]. Recognition of the different lithofacies is an important step in the evaluation of gas in place, flow capacity, and mechanical properties of shale (Hickey et al.,2013) [2].

Lithofacies research historically focused on sandstone and carbonate reservoirs, including lithofacies classification and description from core data and outcrops, lithofacies prediction by wireline logs and seismic volumes, lithofacies modeling in two or three dimensions, and the
relationships of lithofacies with reservoir properties. Mudstone lithofacies research is just at the
beginning and primarily focused on the classification and description from core and outcrop
observations. To date, there are few studies on the prediction of shale lithofacies based on
petrophysical and geophysical data and little research concerning the relationships of lithofacies with
TOC, liquid-rich and brittle units, horizontal drilling trajectories, and locations of stimulation(Wang et
al.,2013; Bridge et al., 2000; Berteig et al., 1985; Curtis et al., 2010) [3-6].

Allix et al. (2011) divided shale into 5 types such as calcareous mudstone or dolomitic mudstone,
clay marlite, siliceous marlite, shale and siliceous shale taking calcite, clay minerals, quartz and
feldspar as the three end members of shale lithofacies types according to the percent of each end
member mineral. The above 5 types can be further simplified into 4 types such as calcareous shale,
siliceous shale, clay shale and mixed facies shale [7]. On the basis of the results of Passey et al.,
Gamero et al. (2012) subdivided shale lithofacies types into 16 types [8,1]. Wang and Timothy(2013)
classified Marcellus shale with the clay mineral content over 40% as clay-rich shale and with the clay
mineral content lower than 40% as quartz-rich shale, calcareous shale and calcareous and siliceous
mixed shale [3].

The main purposes of this paper are: (1) divide Duvernay shale lithofacies types; (2) predict the
planar distribution of different lithofacies in the study area with the petrophysical and geophysical data.

2. Geologic setting
The West Canadian Sedimentary Basin (hereinafter abbreviated to WCSB) is a typical wedge-shaped
foreland basin and covers an area of 170×10^4 km^2. WCSB is located between the Canadian Shield and
Cordillera fold mountain system. The Rocky Mountain piedmont thickness is larger than 6000m in
Albert and British Columbia (Jarvie et al., 2010; Shannon et al., 1989) [9-10]. WCSB can also be
divided into two parts such as Albert Basin and Williston Basin. The study area is located in the
central west of Albert and the slope belt of WCSB, where the strata are gentle and their burial depth is
1400~5500m. The paper focuses in Simonette, Pinto, Edson and Willesdon Green area just because of
data limitation (Figure 1).

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Regional location map of the study area
(revised as per reference Jarvie et al.,2010).

Duvernay shale is a set of dark brown or black organic-rich shale deposited in the maximum
transgression period of Upper Devonian Woodbend Group. The shale and Leduc reefs deposited
simultaneously. Large scale transgression occurred in the sedimentary period of Woodbend Group,
apron reefs were mainly developed near the Peace River structural belt, the lithology inside the basin
was deepwater limestone and shale, and Leduc reefs were characterized by patch reefs, and appeared
mainly in the shallow water area on the carbonate platform and the west margin of the basin. At the end of the sedimentary period of Woodbend Group, the approximate 325km long NE-trending Rimby-Meadowbrook reef belt across Edmonton Region divided Albert Basin into east and west shale basins[11]. Simonette is located in the deepwater area of the basin, and the sedimentary shale thickness varies from 40m to 46m. Pure shale predominate in south Simonette and has a maximum thickness up to 46m. A set of relatively stable deepwater carbonate interlayer deposited at the bottom of north Simonette, the interlayer thickness is 8~16m, and the lithology of the upper part is 22~35m thick shale. The shale thickness in Pinto varies from 0 to 88m. The thickness of shale in Edson is relatively stable ranging from 25m to 35m, the lithology of the bottom is around 5m thick marlrite. The thickness of shale in Willesdon Green is 30~49m, due to being affected by multi-phase sea level changed, 3 sets of regional 2~5m thick carbonate rocks are developed in the shale section, and the thickness of the pure shale section is about 7~10m[12].

3. Data and methods

3.1. Data available

The primary available data consists of 91 wells with wireline logs, 9 wells with cores, 9 wells with 306 XRD and thin sections, 63 wells with production data, 6 wells with 50 2D SEM and 17 SEM-EDS and two 3-D seismic volumes about 2000km² covering most Simonette and Willesdon Green area.

3.2. Methods

The integrated methods of shale lithofacies classification and prediction used in this study include: (1) mineral petrology analysis based on core observation, XRD, thin section, 2D SEM and SEM-EDS; (2) establish the logging response equations and simultaneous equations of matrix minerals by the constraints of petrologic analysis of cores, logging interpretation matrix minerals content based on the equation; (3) classify lithofacies using ternary plot of quartz + feldspar, clay minerals and carbonate minerals based on the core analysis and the mineral content from logging interpretation; (4) establish the seismic wave impedance inversion model on the basis of shale lithofacies elastic attribute analysis and rock physics; (5) finely depict the spatial distribution of lithofacies.

3.2.1. Logging interpretation and standardization

Based on the results of whole-rock X-ray diffraction (XRD) analysis, together with shale content of the study area obtained from conventional logging interpretation, the logging responses of quartz, calcite and pyrite, the logging response volume formula of shale gas reservoir in the study area is built, as follows:

\[
\begin{align*}
\text{GR} & \times \text{Por} + \text{GR}_{\text{sh}} \times V_{\text{sh}} + \text{GR}_{\text{orc}} \times V_{\text{orc}} + \text{GR}_{\text{cal}} \times V_{\text{cal}} + \text{GR}_{\text{qz}} \times V_{\text{qz}} + \text{GR}_{\text{py}} \times V_{\text{py}} = GR \\
\text{NPHI} & \times \text{Por} + \text{NPHI}_{\text{sh}} \times V_{\text{sh}} + \text{NPHI}_{\text{cal}} \times V_{\text{cal}} + \text{NPHI}_{\text{qz}} \times V_{\text{qz}} + \text{NPHI}_{\text{py}} \times V_{\text{py}} = \text{NPHI} \\
\text{RHOB} & \times \text{Por} + \text{RHOB}_{\text{sh}} \times V_{\text{sh}} + \text{RHOB}_{\text{cal}} \times V_{\text{cal}} + \text{RHOB}_{\text{qz}} \times V_{\text{qz}} + \text{RHOB}_{\text{py}} \times V_{\text{py}} = \text{RHOB} \\
\text{UC} & \times \text{Por} + \text{AC}_{\text{sh}} \times V_{\text{sh}} + \text{AC}_{\text{cal}} \times V_{\text{cal}} + \text{AC}_{\text{qz}} \times V_{\text{qz}} + \text{AC}_{\text{py}} \times V_{\text{py}} = \text{AC} \\
\text{Por} & + V_{\text{sh}} + V_{\text{cal}} + V_{\text{qz}} + V_{\text{py}} = 1
\end{align*}
\]

Where: GR, NPHI, RHOB, AC and U are respectively gamma ray, neutron porosity, compensated density, acoustic, and photoelectric absorption coefficient; Vqz, Vcal, Vsh, and Vtoc are respectively the volume percent of quartz, calcite, feldspar, pyrite, pore, clay minerals and organic matters.

The standardization of log curves of shale gas reservoir is similar to that of conventional reservoir. The main standardization methods include two kinds, trend surface method and marker bed method. In light of the application conditions of the two methods and the log curves of the study area, the standardization of the log curves in the study area adopted marker bed method. Standard layer and standard well are crucial for marker bed method. Through analysis of wells, wells with
good quality log curves, wellbore conditions and complete log curve series were taken as standard wells. According to the lithology development feature and the selection principle of marker bed, the limestone widespread at the bottom of the shale was taken as the standard bed. According to the standard well and standard layer selected, the difference between the limestone section in the well needed standardization and that in the standard well was taken as the standardization value to implement the standardization of the log curves in the study area.

3.2.2. Seismic acoustic impedance inversion. The original intention of lithologic inversion is to address the issue of optimizing the design of shale gas horizontal well trajectories and hydraulic fracture simulation strategies. However, conventional impedance inversion has higher horizontal resolution, but its vertical resolution is not high enough for shale horizontal well trajectories design. Therefore, the post-stack geo-statistics inversion module of the Jason software is used to enhance the vertical resolution.

In order to accomplish such goal, well to seismic tie was done when the logging and seismic data meet the requirements of inversion. Then, synthetic seismograms were made, and the seismic wavelets were extracted. After that, low frequency model and stratigraphic framework were established. Finally, the wave impedance distributions of different lithologic facies were obtained by inversion based on the statistic characteristics of the elastic parameters of different lithology under the constraints of seismic and wavelets.

4. Results and discussions

4.1. Shale lithofacies classification

From figure 2, it can be seen that matrix mineral contents obtained from logging interpretation are in high agreement with those from cores and XRD analysis, revealing the accuracy and prospect of the proposed logging interpretation model. So the logging interpretation results can be used to classify the lithofacies.

Figure 2. Comparison of logging interpretation with experimental analysis of cores.

According to the analysis of totally 306 core minerals from 9 wells and logging interpretations from 91 wells in the study area, the mineral components in Duvernay shale are mainly quartz, feldspar, calcite and clay minerals. The quartz content is generally 5.6~70% and averaging 32%. The feldspar content is generally 0~19.6% and averaging 8.22%. The clay mineral content is generally 2.6~61.2% and averaging 31.73%. The calcite content is generally 4.2~90% and averaging 24.11%. The pyrite content is generally 0~8.9% and averaging 3.33%. As a whole, Duvernay shale has high content of
brittle minerals, similar to those of Barnett shale minerals. In addition, part samples from the study area mainly contain carbonate minerals such as calcite etc. Such minerals also have very good brittleness and their composition features are similar to those of Eagle Ford shale minerals.

There is a very big difference in the mineral contents in the study area, Simonette is rich in quartz minerals, while the content of clay minerals and calcite is low. In Pinto, there is a small difference in the contents of quartz, clay minerals and calcite. In Edson, the content of clay minerals increases somewhat. The contents of clay and calcite minerals increase in Willesdon Green.

On the basis of predecessors’ research findings, Duvernay shale lithofacies has been divided into 9 types of mineral lithofacies defined by a ternary diagram, with three apexes representing the percentage of quartz+feldspar, clay and carbonate (figure3). The shale lithofacies with the end member content over 50% has been divided into siliceous shale lithofacies, calcareous shale lithofacies and Argillaceous shale lithofacies; the shale lithofacies with the end member content less than 50% has been subdivided into 6 types such as mixed shale lithofacies, siliceous clay shale lithofacies, calcareous siliceous shale lithofacies, etc.. Just because the gas production is mainly related to brittle and clay minerals, the paper focuses on the first three types and groups the other 6 types into one type named others.

In the siliceous shale lithofacies, quartz content is more than 45%, silty sandy quartz grains is filled by clay minerals or quartz grains are wrapped by clay minerals (Figure 4a). In the argillaceous shale lithofacies, quartz grains are distributed in suspension state, quartz and calcite grains are wrapped wholly by clay minerals (Figure 4b). In the mixture lithofacies, there is a small difference between the content of quartz, carbonate and clay minerals, and main minerals are distributed uniformly (Figure 4c). In the calcareous shale lithofacies, the shale is composed mainly of calcite minerals (calcite content >75%), calcite grains are large, and their margin and inside are filled by clay fragments or quartz grains (Figure 4d).

Figure 3. Classification scheme for Duvernay shale lithofacies.

4.2. Planar distribution of mineral lithofacies
According to the analysis and evaluation results of 3D seismic volumes, the data quality of Simonette is obviously better than that of Willesdon Green.

The siliceous shale has distribution features such as high GR and low impedance, the impedance value is 8~11×10^6 kg/m^3·m/s, the main peak is 10×10^6 kg/m^3·m/s, and GR is more than 80API. The calcareous shale or marlite has features such as low GR and high acoustic impedance, GR is less than 80API, the impedance value is 11~17×10^6 kg/m^3·m/s, and the main peak is 14×10^6 kg/m^3·m/s. The
GR and impedance value of argillaceous shale and others are between the above two kinds of values (Figure 5). Establish the seismic wave impedance inversion model according to the impedance difference between various lithofacies in reservoirs; study the planar distribution of various lithofacies based on wave impedance data volumes.

Figure 4. Duvernay shale mineral distribution features.

Figure 5. Rock physical model.

The figure 6 shows that the results from the acoustic impedance inversion are consistent with those from the wells, so the method can be used to predict the distribution of different shale lithofacies. Integrated cores data, logging data with the seismic volumes, the spatial distribution of various lithofacies is mapped(figure7). Due to deep sedimentary water bodies and high contents of quartz
minerals, siliceous shale predominates in Simonette. Pinto is located in the circular reef belt, and siliceous clay shale, mixed facies shale and calcareous shale develop in this area. Mixed facies shale predominates and siliceous shale develops partially in Edson. Willesdon Green is located in front of Rimbev-Meadowbrook reef belt, in the area far away from the reef-beach bodies and water bodies, siliceous shale predominates, followed by mixed facies shale and siliceous clay shale, while adjacent to the reef-beach bodies, calcareous shale develops.

**Figure 6.** Comparison of seismic acoustic impedance inversion with well analysis.

**Figure 7.** Distribution features of various lithofacies.
4.3. Discussions
On the one hand, the data including cores, well logs and seismic volumes mainly concentrate at Simonette, Pinto, Edson and Willesdon Green regions, the lithofacies distribution in other regions may be not very accurate. On the other hand, log data come from different operators used in different tools with large age span, it is hard to standardize them though we do our best to do. It maybe affects the accuracy of lithofacies classification. Although there are some defects, the accuracy is enough to optimize the design of shale gas horizontal well trajectories and hydraulic fracture simulation strategies.

5. Conclusions
Integrated methods (cores, thin section, XRD, SEM-EDS, logging interpretation and seismic acoustic impedance inversion) have been adopted to classify lithofacies and predict their distribution. The following can be concluded from this study.

(1) Duvernay Shale can be divided into 9 types of lithofacies such as siliceous shale lithofacies, calcareous shale lithofacies, argillaceous shale lithofacies, etc.

(2) There is a big difference in planar distribution of different lithofacies. Siliceous shale lithofacies distributes mainly in Simonette region, calcareous shale lithofacies develops mainly near reefs in Willesdon Green region.

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