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Geophysical characterization of the Devonian Nisku Formation for the Wabamun Area CO₂ Sequestration Project (WASP), Alberta, Canada

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Abstract

Geophysical characterization of the Devonian Nisku Formation in the Wabamun area, Alberta, Canada for large-scale CO₂ sequestration project has been successful in revealing two primary groups of anomalies. The first group is interpreted to be due to contrasts in lithology of the Nisku Formation. This interpretation is supported by constraints provided by well control, seismic modeling and petrophysical data. The second group is interpreted to be footprints of geological discontinuities which are induced by dissolution and karsting in a geologic formation shallower in the stratigraphy. Even though there is no evidence to indicate that the integrity of the Nisku Formation or the overlying caprock has been compromised, such geologic discontinuities should be taken into consideration if supercritical CO₂ were to be injected into the Nisku Formation. The analysis has identified favorable low-impedance high-porosity locations that could be developed for a CO₂ injection site. Those locations exhibit a good correlation with relatively high porosity-permeability zones of the Nisku Formation on maps derived from wireline data and core analysis using petrophysical analysis. Finally, fluid replacement modelling was undertaken to predict the feasibility of time-lapse seismic monitoring for detecting an injected CO₂ plume. The results suggest that changes in seismic response will most likely be subtle and that the plume will probably be at the lower threshold of seismic detectability.

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1. Introduction

The province of Alberta contributes more than 30% to the total Canadian CO₂ emissions according to recent statistics by United Nations Framework Convention on Climate Change [1]. In an effort to offset the carbon emissions, several CO₂ sequestration projects were recently launched in the province. These include the Alberta Saline Aquifer CO₂ Project (ASAP), the Heartland Area CO₂ Sequestration Project (HARP), and the Wabamun Area CO₂ Project (WASP). In the Wabamun area, the Paleozoic carbonate saline aquifer known as the Nisku Formation has been advocated as a sink for large-scale CO₂ sequestration project with injectivity in the order of 1 megatonne/year [2]. Hence, WASP is a study being coordinated by the University of Calgary to undertake regional geological and geophysical characterization of the Nisku Formation over an area of approximately 5000 km² and assess the formation suitability for geological storage of CO₂. This paper reports some of the results of the seismic characterization that was undertaken as part of the first phase of the project with primary objectives to generate

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detailed attribute maps of the Nisku Formation and delineate any potential geologic discontinuities in the area that may compromise the integrity of the CO₂ storage within this formation. Another primary objective was to assess the feasibility of implementing time-lapse seismic monitoring as part of a perspective measurements monitoring and verification (MMV) program [3].

2. Study Area and Geology

The proposed CO₂ sequestration area is located in the central plains of Alberta, approximately 50 km southwest of the capital Edmonton (Figure 1). The injection target is the Devonian brine-bearing Nisku Formation. In the local-scale study area, the Nisku aquifer sits on the edge of a carbonate shelf and consists predominantly of dolomite minerals. The aquifer ranges in thickness from 40 to 80 m and occurs at a depth between 1800-2000 m and its properties, such as temperature (50°C) and pressure (15 MPa), make it a favorable candidate for storage of CO₂ in supercritical phase [2]. Furthermore, the overlying Calmar shale makes a good cap rock, which prevents supercritical CO₂ from migrating upwards into shallow aquifers. The geophysical characterization is focused on a local area, where favorable conditions in terms of seismic coverage and other factors exist (Figure 1).

Figure 1. Study area location and base map showing the distribution of the seismic and borehole data as well as main the geological trends in the area. Violet contours depict the Leduc Reef hydrocarbon trend while the area to the northwest marks hydrocarbon resources associated with Moon Lake reef play. Cyan shapes indicate bodies of water. Alberta map (top-left corner) is courtesy of Natural Resources Canada [4].

3. Geophysical Characterization Approach

The regional geophysical characterization was based on the analysis and interpretation of seismic data consisting of more than two hundred 2-D lines and seven 3-D volumes that were available from previous hydrocarbon
exploration in the WASP area (Figure 1). The 2-D and 3-D seismic datasets have different acquisition and processing specifications and were acquired over many years before this project was undertaken. Therefore, prior to interpretation, inversion and attribute analysis, two primary data processing steps were undertaken: data calibration and amplitude normalization. These steps were necessary to account for the vintage and datum differences within the dataset. The 2-D seismic data were used primarily for identifying long-wavelength structures whereas the high-quality 3-D data were used for detailed mapping, inversion and generation of seismic attributes. These attributes, namely normalized root-mean squares (NRMS) amplitude, acoustic impedance, and coherence were generated to help develop a static geological model, identify trends in Nisku porosity and lithology and to delineate potential geologic risks in the area that may compromise the integrity of the Nisku Formation for CO₂ storage. The seismic attributes were complemented by porosity-permeability maps derived from wireline data and core analysis. In addition, the latter were invoked in the fluid substitution modeling to investigate the magnitude of a predicted seismic anomaly due to CO₂ injection. The workflow adopted in this study is depicted in Figure 2.

![Flowchart outlining the major steps followed in the geophysical characterization of the Nisku Formation for WASP.](image)

4. Results

4.1. Seismic Attributes

Figure 3 shows a composite display of the Nisku time structure and normalized root-mean squares (NRMS) amplitude maps as well as two other seismic attributes, namely acoustic impedance and coherency maps. The time structure of the Nisku (Figure 3 (a)) is rather smooth and does not exhibit any significant variations within the WASP study area except for following the regional dip in the northeast-southwest direction. The NRMS amplitude map (Figure 3 (b)), on the other hand, exhibits strong variations compared to the time structure map. In addition to time and amplitude maps, the acoustic impedance of the Nisku Formation was estimated using a deterministic post-stack inversion scheme, namely recursive inversion (Figure 3 (c)). Clearly there is a good correlation between the amplitude and acoustic impedance anomalies. However, it is insufficient to separate lithology-driven variations from discontinuity-induced anomalies based on those attributes alone. Furthermore, since the seismic volumes exhibit signs of discontinuities, it was deemed appropriate to invoke a coherency-sensitive attribute (Figure 3 (d)) to discriminate impedance contrasts associated with lithology variations from those caused by footprints from
overlying geologic discontinuities. As demonstrated in Figure 3 (d), the coherency attribute has proven robust in achieving this objective.

Figure 3. Mosaic display of various seismic attributes of the Nisku Formation: (a) time structure map, (b) NRMS amplitude map, (c) acoustic impedance map, and (d) coherency map. The time structure show change in the two-way traveltime to the Nisku Formation whereas NRMS amplitude and acoustic impedance maps delineate change in lithology. The coherence map, on the other hand, is sensitive to discontinuities, such as those caused by karsting in the overlying Wabamun Formation.

4.2. Numerical Modelling

With the discontinuity-driven anomalies identified, the next step was to gain a better understanding of the amplitude and acoustic impedance variations due to changes in lithology versus aquifer thickness. This is important since substantial emphasis was placed on the amplitude to provide one approach for favorable site selection due, in part, to the lack of well control to constrain the inversion. Moreover, since the Nisku reflection is a tuned event,
insight was needed into the principle factors affecting its reflection amplitude. Hence, the Nisku event two-way time and seismic amplitude was modeled using a convolutional model as a function of thickness and P-wave velocity (Figure 4 (a) and (b)) as these were found from well control to be the principle entities affecting the Nisku amplitude. In addition, the acoustic impedance of the synthetic model was reconstructed (Figure 4 (c)) as a function of these parameters using the same inversion scheme employed in estimating the acoustic impedance of the real data (Figure 3 (c)).

Figure 4. Nisku Formation modelling results shown in terms of: (a) two-way traveltime, (b) NRMS amplitude, and (c) acoustic impedance as a function of the formation thickness and average P-wave velocity. The maps are extracted from synthetic seismograms, which were generated by convolving a zero-phase Ricker wavelet with a reflectivity series from a control well log. The black dashed rectangle outlines the likely Nisku thickness and velocity within the study area based on well control. Sensitivity is higher along the vertical axis, which indicates that the thickness (tuning) effect is small compared to the variations in P-wave velocity (lithology).

4.3. Rock Physics and Fluid Replacement Modelling

Understanding the seismic response to fluid changes within the Nisku Formation is crucial to the success of any time-lapse seismic monitoring that may be implemented as part of a measurement monitoring and verification (MMV) program associated with carbon capture and storage in the study area. Therefore, fluid replacement modelling (FRM) was undertaken to predict changes in the rock elastic moduli that would result if the original pore-filling fluid in the rock (i.e. brine) is replaced with another fluid (i.e. supercritical CO₂). In the FRM, the Gassmann approach [5] was invoked in predicting changes in the elastic moduli, where the necessary parameters were supplied from wireline data and core analysis [7] combined with equation of state [8] and petrophysical relations [9]. The maximum change in the fluid indices, i.e. P-wave velocity and acoustic impedance was found to be -3% and -3.9%,
respectively, whereas the lithology indices, namely S-wave velocity and shear impedance, were found to change by 0.77% and -0.76%, respectively. Density was found to vary by -1.5%. Following the prediction of the changes to the elastic moduli through the fluid replacement modeling, the Zoeppritz’s equations [10] were used in simulating the seismic wavefield before and after the CO₂ replacement. Figure 5 depicts the modeling results in terms of predicted time shift and amplitude change of the Nisku and the underlying Ireton formations.

4.4. Petrophysics

Complimentary to the seismic interpretation, wireline data and core samples were analyzed to help predict flow capacity (permeability) and storage capacity (porosity) [11]. The analysis, also, provides a quasi-independent mean of porosity estimation that could assist in reestablishing injection “sweet spots” that were derived from seismic attributes. The WASP area has 27 sonic logs and 50 resistivity logs. Hence, two porosity maps were constructed using these two log types. Porosity estimation from sonic logs (Figure 6 (a)) was made possible through the time-average equation [12] whereas Archie’s law [13] was invoked in estimating the porosity map from resistivity logs (Figure 6 (b)), once the range of cementation factor (m) values was established for the Nisku Formation [11]. The petrophysical analysis has identified a viable relationship between the electrical resistivity and the flow capacity by using core permeability and well test data [11]. Furthermore, the porosity (Figure 6 (a) and (b)) and permeability (Figure 6 (c)) maps were compared with seismic attributes (Figure 3) and porosity derived from inversion of seismic data (Figure 6 (d)). For the limited area of seismic coverage, high porosity-permeability zones as recognized on wireline logs and core samples (Figure 6 (a), (b) and (c)) correspond in many cases with areas of low acoustic impedance (Figure 3 (c)) and high porosity (Figure 6 (d)) as observed in the interpreted 3-D volumes.
5. Discussion and Conclusions

The geophysical approach (Figure 2) implemented for aquifer characterization for CO₂ sequestration was successful in delineating the Nisku Formation character in the WASP study area (Figure 1). Seismic attributes derived from the calibrated and normalized seismic data were grouped into two categories: lithology-induced and discontinuity-induced. The former is best identified on conventional amplitude map (Figure 3 (b)) as well as through maps derived from deterministic acoustic impedance inversion (Figure 3 (c)). The anomalies associated with this category are interpreted to be due to variations in lithology or porosity of the Nisku Formation. This interpretation is constrained by sparse well control and is further supported by the results from seismic amplitude modelling, which suggest that variations in seismic response of the Nisku event are driven primarily by variations in the lithology or porosity rather than by changes due to variable thin-bed tuning. The anomalies corresponding to the
second category are interpreted to be due to footprints of geological discontinuities induced by dissolution in the overlying Wabamun Formation (Figure 3 (d)). Nonetheless, there is no evidence to indicate that the integrity of the Nisku Formation or the cap rock has actually been compromised.

In general, there is a level of uncertainty involved in differentiating between low-impedance changes caused by enhanced porosity and those associated with a possible increase in shale content. However, the interpretation that enhanced porosity, rather than variations in lithology, is responsible for the amplitude and acoustic impedance variations is supported by data from the Nisku Formation water-source well in the study area (Figure 1). Seismic data around this well show significant variations in amplitude and acoustic impedance (Figure 4), with a decrease in P-wave velocity indicating enhanced porosity in the Nisku Formation. In addition, core samples from the water-source well are predominantly dolomite which indicates that change in lithology, in particular shale content, is not an issue. Moreover, the Nisku “sweet spots” derived from the seismic attributes correlate fairly well with those independently constructed from wireline data and core analysis using petrophysical relations (Figure 6), which alleviates some of the uncertainties inherited in seismic interpretation. Hence, it is recommended that site selection for possible CO₂ injection wells should be based on low-impedance anomalies interpreted in the northern part of the study area (Figure 6), coupled with favourable porosity-permeability trends outlined from log and well data. Finally, pertaining to seismic monitoring, the fluid replacement modelling results suggest that changes in seismic response will be subtle and that direct detection of the plume migration in the reservoir through time-lapse surface seismic data will be difficult, but at the threshold of detectability using vertical seismic profiling (VSP). However, seismic sensitivity to CO₂ leakage, although unlikely, is expected to be more robust as the plume migrates toward the surface.

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