Predictive Modelling for Plume Detection Applied to CCUS Projects

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Summary

This paper outlines the considerations for predictive modelling of CO_2 sequestration in potential subsurface reservoirs. There are a number of considerations and data required to fully understand and enable prediction of the potential plume growth upon injection. These include understanding and modelling of the host rock, modelling the injected fluids, the ability to detect the plume and thresholds as well as anticipated fluid saturations over time. These considerations, as well as workflows and models to achieve future detection, are discussed in the following sections.

Introduction

Case studies of CO_2 sequestration projects, such as the Sleipner CCUS project in Norway, emphasize the need for understanding the plume growth over many years of the project operation (Chadwick et al., 2006). This often includes the directions of plume growth; how much CO_2 can be stored over time and whether the CO_2 will be contained in the injection zone or will migrate into other unintended nearby reservoirs. In other projects, such as the In Salah project located in Algeria, considerations for nearby gas field production, as well as preferential growth along undetected fractures, highlight the need to understand the reservoir and injection growth ahead of project initiation to ensure longtime economic success (Ringrose et al., 2009, 2013).

This paper outlines a method for predictive modelling of CO_2 sequestration in potential subsurface reservoirs in an effort to address some of the challenges of plume imaging in advance of the CO_2 injection and large project sanctions. There are a number of considerations and data required to fully understand and enable prediction of the potential plume growth. These include understanding and modelling of the host rock, modelling the injected fluids, the ability to image the resulting plume as well as saturation thresholds over time. These considerations will be discussed with example workflows and models in order to predict and describe future plume growth.

Methodology

Input data for a predictive model needs to be gathered and analyzed to best characterize the reservoir that is contemplated for CO_2 injection. Discussions with the reservoir specialist are required to understand the anticipated injection depths and reservoir intervals.

This plume modelling can be used to answer these specific questions as outlined below:

1. Will the operator be able to see the CO_2 injection on the current seismic dataset?
2. When would the CO_2 injection be first detected after project initiation?
3. At what CO_2 saturations would the injection be first detected?
4. As saturations continue to increase, would the plume still be detectable until end of the injection period?

Data preparation and analysis revolve around finding suitable well log data as input into the model. This is necessary to consider the required model extent, as well as data frequencies and phase. The frequencies and phase considerations are subject to either existing subsurface seismic control and/or anticipated future acquired seismic.

A baseline seismic model is generated and compared to existing seismic control for validity of the initial model state prior to modelling of the plume. As the current dataset consisted of post-stack seismic, no pre-stack modelling was undertaken at this time, although it may be considered for future modelling and analysis. Considerations for baseline models may also include any existing operations in nearby areas that may complicate the baseline understanding, such as current injection schemes or proximal hydrocarbon bearing zones.

Considerations for CO_2 saturations and their effect on model velocities need to be incorporated into the predictive model to understand the differences from the baseline model. The saturation modelling may feature varying saturations over time or variations of injection volumes.

The baseline model and the saturation model then can be compared and characterized based on changes in the model over time, data frequencies, and so forth, subject to an operator's anticipated plans. From there, important questions of plume detection and threshold detection can be addressed.

Data Input

Figures 1 and 2 point to key well data and information required for the predictive model. Figure 1 shows a sonic well log proximal to an anticipated injection site. It is understood that there is no interference in this zone with nearby production or any previous injection in the area. The reservoir here is interpreted as wet. Note that the average velocity (interval transit time) at top of injection formation is approximately 177 us/m, shown by the blue arrow in the figure. The density data for this log was considered unreliable due to hole conditions and was not used in the modelling. Additional minor editing to the sonic log was required prior to modelling to compensate for the hole conditions as well. Wells in this project area were originally drilled in the 1980's for oil and gas purposes and the technologies to log and maintain hole conditions upon drilling were not as robust as they are today.

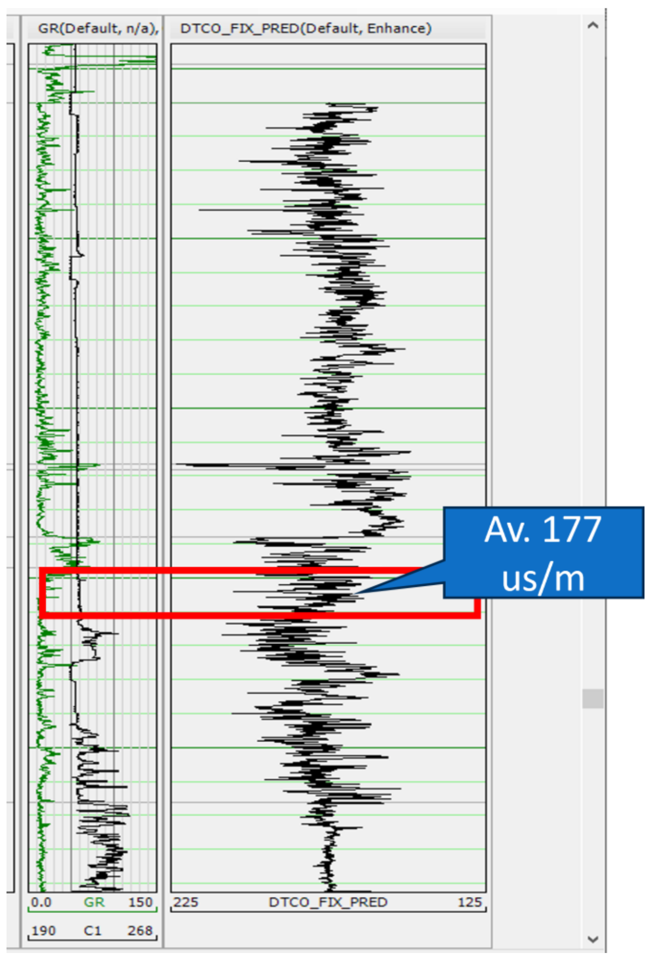

Figure 1. Sonic well log for model input. Arrow points to top of injection zone.

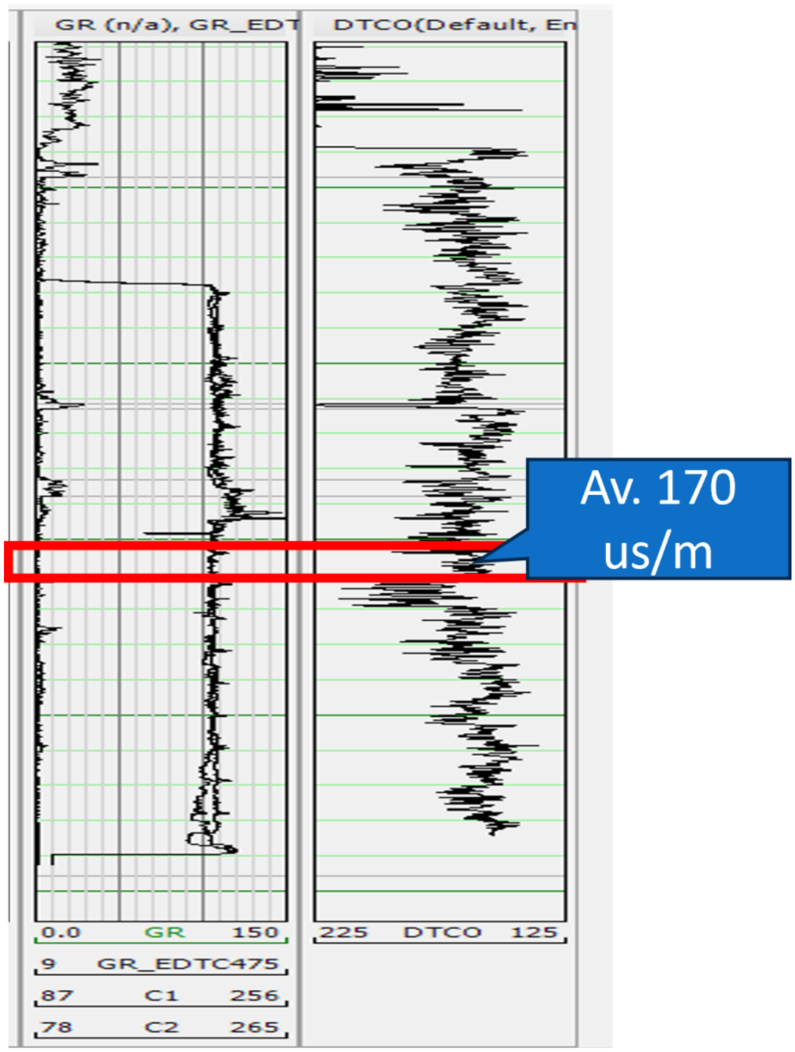

Figure 2. Nearby sonic well log with CO2 injection. Arrow indicates injection zone values of 170 us/m.

Key known reservoir parameters are that the depth of injection will be at approximately 2000 m subsea, with porosity ranges of 3 -15% in the proposed zone. The variability in porosity is mainly due to the reservoir being a carbonate with variations in permeability (and/or fractures) that track with porosity. This variability does provide some uncertainty as to how this will affect the injection over the longer term and might need further analysis once injection has begun. The full formation thickness is 200 m with the injection to be at the top of the reservoir.

Figure 2 is the sonic log from the only well in the project area that has had CO_2 injection. The sonic reflects the reservoir property changes with injection. Note the velocity decrease compared to previous well near the top of the formation as a result of the CO_2. This represents a 5% decrease in velocity from the well without injection. This appears to be a lower than expected effect on the velocities with saturation and is likely explained by wellbore washouts and well bore integrity issues. None the less, it demonstrates that CO_2 can be detected with a sonic log in the area.

As a result of limited nearby CO_2 saturation well log information, several published papers were reviewed for data inputs to be used for the effects on acoustic logs. From White et al., 2011, a maximum decrease in acoustic impedance of 12% was observed in the immediate vicinity of horizontal CO_2 injection wells after 10 years of injection in the Weyburn field. The 12% drop was measured with a corresponding 100% CO_2 saturation in a nearby wellbore.

Tiwari et al., 2021 reported a decrease of 12% - 14% of the P-wave velocities over a period of 5-15 years on injection. This result was from two Malaysian fields analyzed with depths and reservoir parameters similar to this project but with slightly higher porosity. From this information and other literature results, it was deemed suitable to use a maximum decrease of 10% of the p-wave velocities to model saturations of CO_2 over time for the model input.

As the project has existing seismic data, the imaging capabilities of a potential plume and its detection needed to be assessed and calibrated for the model. Figure 3 shows the comparison between the frequency contents of the synthetic model and the real seismic data – confirming that the model will reflect realistic frequencies near the potential injection site. This figure shows a reasonable match of the potential model frequencies to the frequencies of the existing seismic data. Using a center frequency of about 30 Hz, in this case, to model the plume seems reasonable as a starting point for the analysis. Likewise the phase of the data should also be calculated and applied appropriately in the initial model. In this case, zero phase is assumed for the existing dataset.

The monitoring techniques anticipated post CO_2 injection are worth consideration at this point. Knowledge of data parameters such as frequency/phase/subsurface sampling will be required to effectively model the plume and best match it to anticipated monitoring methods in the future. Some of the techniques that may be considered include traditional 3D/4D seismic schemes, a spotlight type of subsurface imaging, vertical seismic profiles, or a combination of these. The plume modelling can be adjusted according to the types of monitoring anticipated if known prior to injection. We generated only models to match the current seismic dataset, but it would be simple enough to update the model if other frequencies are required for analysis.

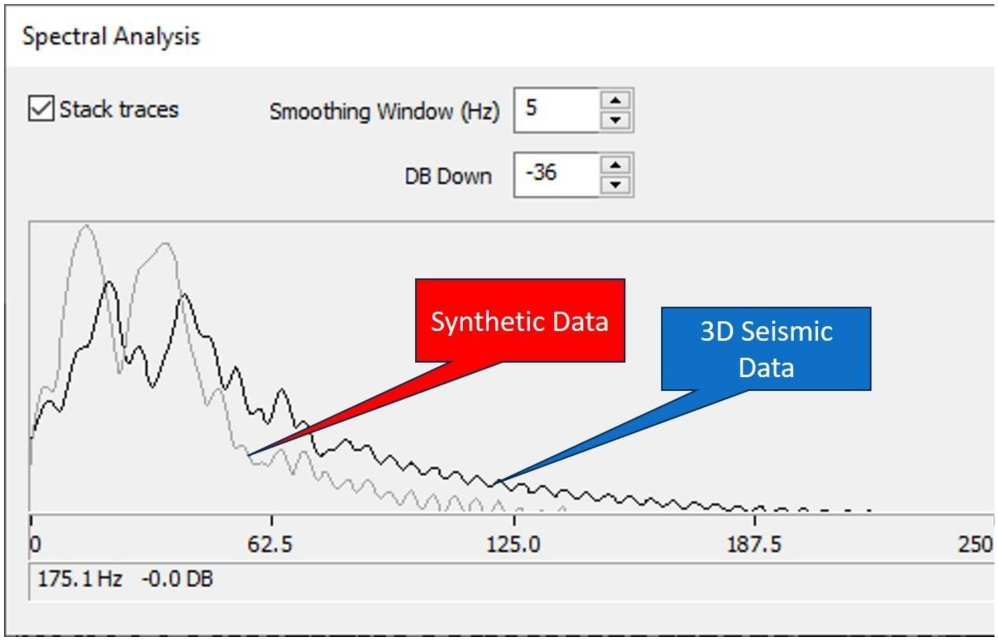

Figure 3. Model imaging capabilities versus seismic data frequencies.

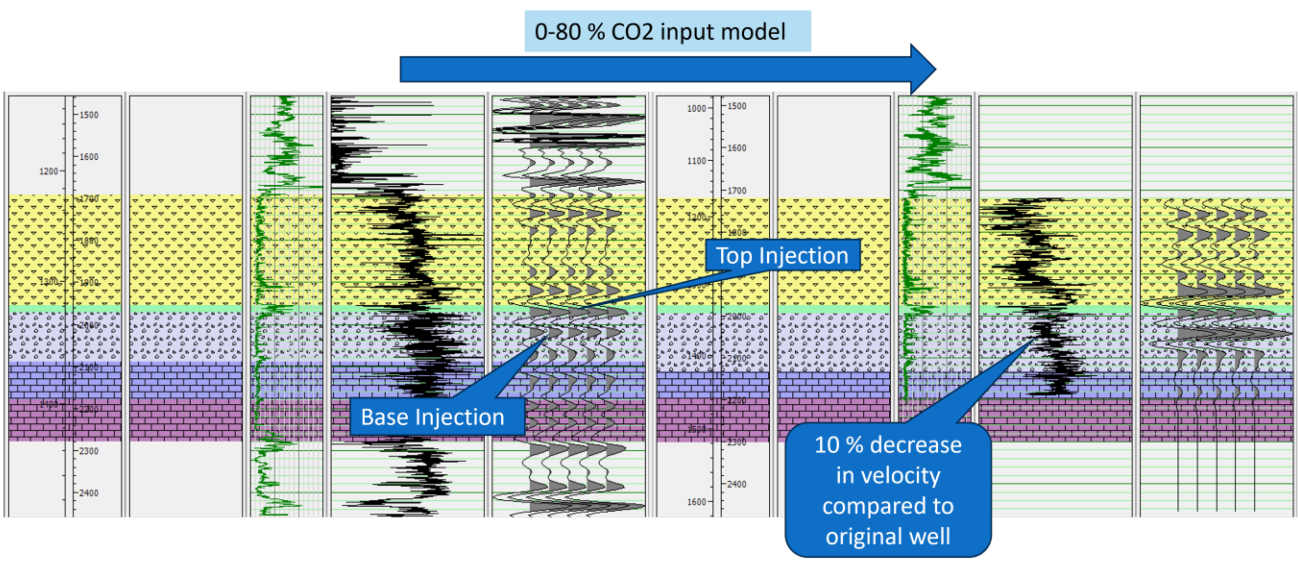

Figure 4. Baseline to injection well cross-section.

Using the well log information, the curves were loaded into a cross-section to initiate the modelling process. This cross-section is shown in Figure 4. The well on left in the figure is the original wet well with no injection in the formation of interest. The well on right, a different nearby control well, has had the velocities modified to represent CO_2 saturation of up to 80% by decreasing the velocities by 10% in the entire interval. Note the injection zone is bounded by peaks at the top and base of the reservoir on the resulting synthetics for both wells. As part of the analysis, there is interest in seeing if there are observational and measurable differences in these peaks in the modelling pre- and post-injection. This can be achieved by generating a full synthetic model over a multitude of traces from one end member of this cross-section to another. The results of this modelling are discussed in the next section.

Modelling Results

Once the input data have been assessed and gathered, the modelling can be constructed to provide the baseline image, prior to injection, as well as the injection image, after a period of injection. The difference between the two models provides important information about the plume and can answer the questions posed.

The results of forward modelling for CO_2 injection in a potential reservoir are shown in Figure 5. Here the seismic response changes from the baseline (no CO_2) to the CO_2-injected side of the model, from left to right. This model shows an increase in saturation from 0 to 80% going from left to right. Eighty percent saturation was used as this was deemed the highest possible saturation expected on injection. From this figure we can see the effect of the CO_2 in the change of amplitudes and would expect to see the plume image and development in the subsurface over time.

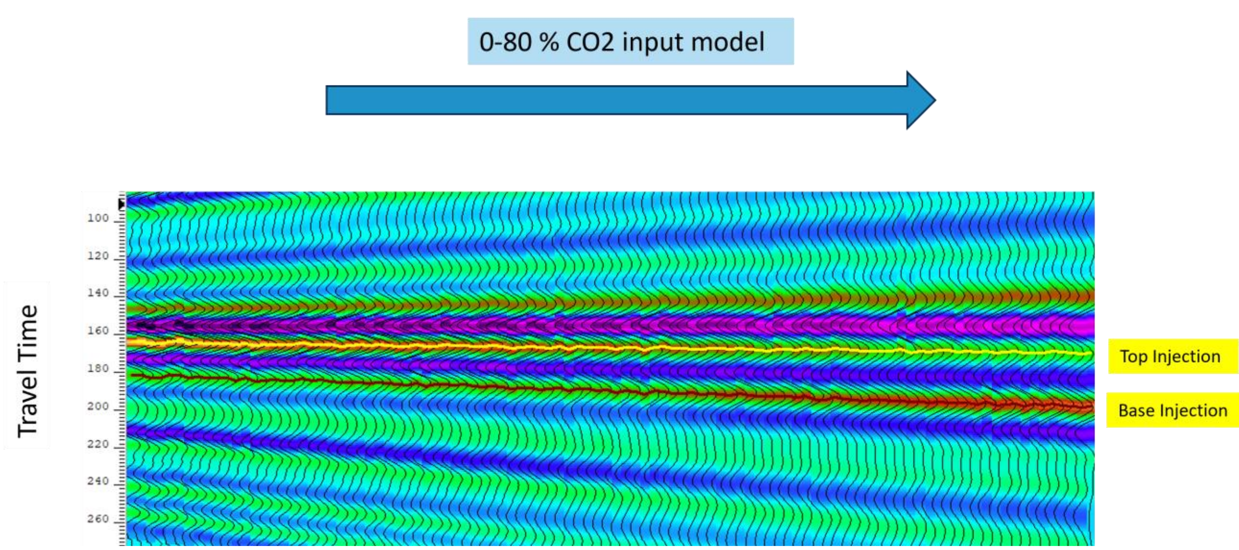

Figure 5. Synthetic seismic model of CO_2 saturation of the reservoir over time.

Figure 6 shows the amplitude graphs versus the CO_2 saturations. The amplitude graph of the peak at the top of the injection zone is compared to the amplitude graph at the base of the injection zone. Both show changes in amplitudes but the top of the injection zone change is more rapid and would be easier to detect on real seismic data. The base of the injection zone marker is much slower to show change (highlighted by blue arrow on figure). This is likely due to a tuning effect coming from stratigraphic markers below the base of the zone.

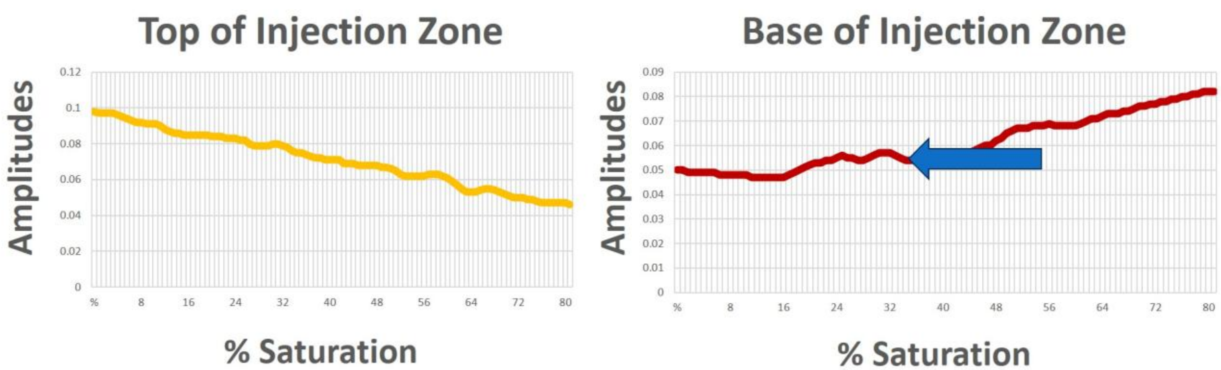

Figure 6. Model amplitudes versus CO_2 saturation.

Assuming we will be able to initially detect 20% amplitude changes in real subsurface seismic data (10% noise is assumed), the corresponding saturation is about 24% at the top of injection zone. Alternatively at 20% amplitude change for the base of injection zone, the saturation is about 45% (Figure 7). The conclusion is that the top of the injection zone is likely better to map the plume growth over the lifetime of the project and plume detection should begin to be detected at about 24% CO_2 saturation. This would apply to the current seismic dataset in the project area.

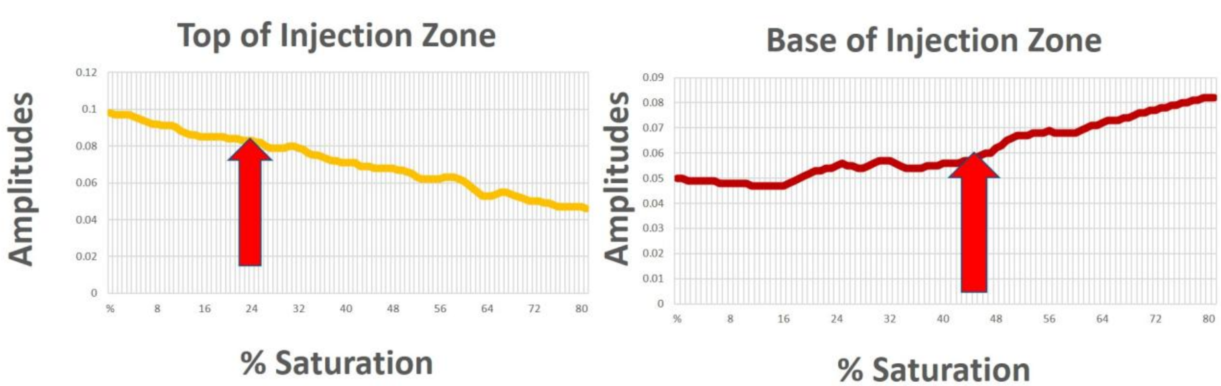

Figure 7. Plume detection: when and at what saturation.

Conclusions

By constructing and generating a forward model for a given subsurface formation, CO_2 plume detection and mapping can be assessed for viability in a given project area.

Plume modelling can be helpful to determine if CO_2 can be detected within a given area/formation. Timing of the plume's first detection after injection and throughout its history can be assessed using expected formation saturations.

There is a need to understand the reservoir parameters and variability for a successful model. Modelling can also help guide what methods of CO_2 monitoring will work in the future based on model parameters and frequency content.

Models like these are an important part of the approval process in given jurisdictions. They can serve as valuable information for project pilot planning, budget estimates for MMV, consideration of likely MMV technologies to apply as well as provide useful information for stakeholders, operators and government regulators.

References

Chadwick, A., et al, 2006. Geophysical monitoring of the CO_2 plume at Sleipner, North Sea: an outline review. Advances in the Geological Storage of Carbon Dioxide (pp. 303-314).

Fawad, M., Mondol, N.H., 2022. Monitoring geological storage of CO_2 using a new rock physics model. Scientific Reports Volume 12, article 297.

Maurya, S. P., et al., 2019. Seismic modelling of CO_2 fluid substitution in a sandstone reservoir: A case study from Alberta, Canada. Journal of Earth System Science. Volume 128, article 236.

Preston, C., et al. 2009. IEA GHG Weyburn-Midale CO_2 monitoring and storage project – moving forward with the Final Phase. Energy Procedia 1 (pp.1743–1750).

Ringrose, P., et al., 2009. Plume development around well KB-502 at the In Salah CO_2 storage site. EAGE First Break Volume 27.

Ringrose, P., et al., 2013. The In Salah CO_2 storage project: lessons learned and knowledge transfer. Energy Procedia 37 (pp. 6226– 6236).

Tiwari, P.K., et al, 2021. Monitoring, Measurement and Verification MMV: A Critical Component in Making the CO_2 Sequestration Success. International Petroleum Technology Conference Proceedings, March 23-April 1 2021 Texas, U.S.A.

White, D.J., et al., 2011. Geophysical monitoring of the Weyburn CO_2 flood: Results during 10 years of injection. Energy Procedia 4 (pp.3628 – 3635).

About the Author

*As a managing partner of Petrel Robertson Consulting in Calgary, Canada, **Ms Dorey** leads a team of geoscience professionals at the forefront of petroleum geoscience skills as well as new resource applications and CO_2 sequestration. **Kathleen** has an Honours Bachelor of Science degree from Western University in Canada and has worked as a geoscientist in both major and junior energy companies.*