Maturing DAS VSP as an Onshore CCUS monitoring technology at the Quest CCS Facility

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Summary

Quest is a commercial scale Carbon Capture and Storage (CCS) facility operating at the Shell operated joint venture Scotford Complex near Fort Saskatchewan Alberta. The Scotford Complex includes an upgrader that turns bitumen from the Athabasca Oil Sands Project into synthetic crude that may be further refined into commercial products. The Quest CCS facility captures CO_2 created in the production of Hydrogen at three Hydrogen manufacturing units located at the Scotford Complex. This capture accounts for roughly one third of the CO_2 produced at the Scotford Upgrader. The captured CO_2 is then compressed and transported by a dedicated CO_2 pipeline to three injection wells where it is safely injected and stored as a supercritical fluid within a highly porous, permeable, brine filled sandstone reservoir located at a depth of approximately 2km from surface.

In order to maintain a license to operate with the government and demonstrate that CO_2 is permanently stored within the reservoir, a Measurement Monitoring and Verification (MMV) plan is in place. This is a risk-based plan covering several domains including the Geosphere. Part of the Geosphere portion of the MMV plan includes seismic based technologies for conformance and containment monitoring of the injected CO_2 away from the wellbore where well logs cannot provide sufficient information. Distributed Acoustic Sensing Vertical Seismic Profiling (DAS VSP) was identified during Quest's project planning stages as a cost-effective seismic based technology for early monitoring of the CO_2 plume as it grows away from the wellbore. Optical fibers were installed permanently behind casing in each of the three injection wells for purposes of Distributed Temperature Sensing and DAS VSP. The installation of the fibers behind casing means that surveys may be conducted without well intervention or injection interrupting further improving the feasibility of frequent monitoring. Baseline DAS VSP surveys were acquired prior to first injection in 2015. These surveys were repeated in 2016, 2017 and 2019 to measure the seismic response change due to the injected CO_2.

Early processing efforts provided fit for purpose results that were interpreted by the Quest subsurface team to demonstrate conformance to modeled behavior and containment of the CO_2 plume within the reservoir. Although the processing results provided sufficient quality for interpretation, advancements in time lapse and DAS VSP processing within Shell could be applied to the Quest data to improve the results and further demonstrate DAS VSP as a robust cost-effective technology for onshore CCUS monitoring. In 2019 an integrated approach was taken leveraging the expertise developed within Shell since the early processing efforts to develop an enhanced workflow and improve the results over previous deliverables. Refining steps from the previous processing efforts and introducing rigorous channel calibration and shot dependent wavelet derivation for deconvolution produced results with improved imaging, repeatability and time lapse interpretability.

Theory / Method / Workflow

During the project planning stages of the Quest project the viability of time-lapse seismic based methods was investigated. Petrophysical data from the injection wells were taken and used to calculate the acoustic properties of the injection formation. It was determined that supercritical CO_2 when injected into a brine filled reservoir shares very similar acoustic response characteristics to gas. Therefore, Gassmann substitution was used to forward model the response of injected CO_2 and verify the viability of time-lapse seismic.

A baseline DAS VSP was acquired in 2015 at each injection well prior to the injection of any CO_2. The survey was conducted using three Vibrosies sources with shot point intervals of 100m along four walkaway lines roughly centered around each injection well. This limited shot pattern was chosen in part due to the surface restrictions in the area. The surface rights are privately owned consisting mainly of farmland. This means it is desirable that the surveys have minimal footprint in order to reduce the permitting required and increase the probability of acquiring repeat surveys at the same location each time. Repeat surveys were acquired at intervals of one to two years in the active injection wells. Injection was not stopped during VSP acquisition. These repeat surveys were acquired with the primary goal of tracking the CO_2 plume in the reservoir based on changes in acoustic impedance from the replacement of brine with supercritical CO_2. The observed evolution of the plume can then be correlated back to reservoir models to demonstrate conformance. In addition, time-lapse VSP imaging of the overburden helps demonstrate containment.

Survey shot locations were highly repeated during each repeat survey and acquisition times were consistently chosen in the winter months to attempt to replicate the near surface conditions between surveys. Near surface condition non-repeatability provides the most significant challenge to effective time-lapse seismic onshore. Despite these best efforts, acquisition conditions did vary significantly between some vintages. For example, the 2017 and 2019 monitor surveys had a nearly 40 degrees Celsius difference in environmental temperature. Spatial near surface variations between shot locations are also typical for onshore.

The ability to reduce the impact of such near-surface variations is the key advantage of VSP over surface seismic for time-lapse monitoring. The direct arrivals in a VSP carry information about changes near the source that are used to correct target reflections and thus, reduce time-lapse noise. Additional advantages of the VSP are that reflections travel through the heterogeneous near surface only once and receivers are relatively unaffected by major surface noise sources such as ground roll.

Early processing efforts prior to 2019 were able to provide the Quest subsurface team with a fit for purpose time lapse result that could be used to detect the presence of the injected CO_2 [6]. From these early processing efforts, the subsurface team was able to interpret a time lapse signal and correlate it to estimated plume growth in the subsurface. Although these early efforts produced useable results, they carried a strong imprint of noise on the data and desire for improved results. In 2019 an internal processing project was kicked off integrating the Quest subsurface team with the land processing group and global DAS VSP specialists. The goal of this effort was to provide uplift over previous results in the form of better imaging and higher repeatability and interpretability of the time-lapse results.

The primary steps taken in the legacy processing remained intact. However, important steps were modified, and some additional steps were introduced to reduce noise and increase repeatability between the baseline and monitor surveys as described below.

The main processing steps include importing the full waveform data from the DAS acquisition vendor and applying edits to standardize the datasets. Preliminary noise attenuation was performed on the full wavefield data consisting mainly of random spurious noise attenuation followed by up-going/down-going wavefield separation and additional linear noise suppression to remove optical and environmental noise.The down-going wavefield was processed to isolate the direct arrival and derive an improved deterministic deconvolution to a desired wavelet using shot-consistent filters. This contrasts with the legacy processing which used a single wavelet per survey. Post deconvolution linear and spurious noise suppression removed residual noise. Additional Spectral matching was applied to improve the match of each monitor survey back to the spectrum of the baseline survey.

Data was then migrated using reverse time migration (2D RTM) of common shot gathers. Post migration steps included shot side illumination compensation, shot image domain dip-filtering and matching to align the monitor and baseline datasets.

To compensate for 2D image-posting issues related to shot lines not passing exactly above the vertical wells, raytracing was utilized to determine the approximate location of reflection points at the target level. One quarter of the offset between the injection wellhead and shot line was found to be a good estimate for three of the four shot lines that have a slight offset from the injection well. Data was then posted to a 2D line at this location.

The new workflow included a fast-track method to quickly output time-lapse datasets which could be interpreted early and used to fine tune steps in the full production processing. To investigate processing improvement areas, the baseline survey and one monitor survey were migrated after each processing step and the repeatability was calculated. One of the most significant uplifts to repeatability came from applying deterministic deconvolution of the up-going wavefield with a wavelet estimate derived from a small window around the direct arrival for each shot. This step removed shot variations caused by the source or near-surface conditions.

A known problem with DAS VSP data is depth positioning errors in the channel locations which impact both the migrated image quality and the time-lapse response [3, 4, 5]. The method for DAS VSP depth calibration based on receiver-consistent scalars was followed [1, 2]. As routinely done in land seismic processing, receiver consistent amplitude scalars were derived for each DAS channel and then used to depth-calibrate the baseline survey. The receiver scalars were plotted alongside upscaled well logs as a function of depth, showing a strong correlation with geology and providing a log-type response that could be correlated with sonic and density logs. The product of density*sonic^2 logs was used to tie the DAS receiver channels of the baseline survey to geology. For subsequent monitor surveys, the monitor receiver scalar curves were aligned to the baseline receiver scalar curve as a relative depth calibration [2]. Calibration steps provided significant improvement in the time-lapse response.

Two post migration steps provided significant uplift to the image and repeatability. The first filtered out remnant artifacts like migration swing by using geologic dip information available from surface seismic. As geologic dips are near flat at the Quest storage site, steeply dipping energy coming from shot-point migrations could be filtered without damaging the image. Finally, shot images were aligned to the full stacked images and residual shot dependent statics in the final stacked image were filtered out.

The key steps of depth calibration, shot dependent deconvolution, additional postmigration alignment and dip filtering provided the most significant uplift to the enhanced processing flow, with several other steps providing minor uplift. The combination of processing improvements resulted in a world class onshore NRMS of <10% [7].

Results

The enhanced processing provided a much higher repeatability than legacy processing with a repeatability measured in terms of normalized rms below 10% as compared to the legacy's repeatability measurement of 14% NRMS. Significant improvement in 2D imaging was achieved and the high repeatability between the baseline and monitor surveys resulted in a much more interpretable time-lapse signature as shown in figure 1.

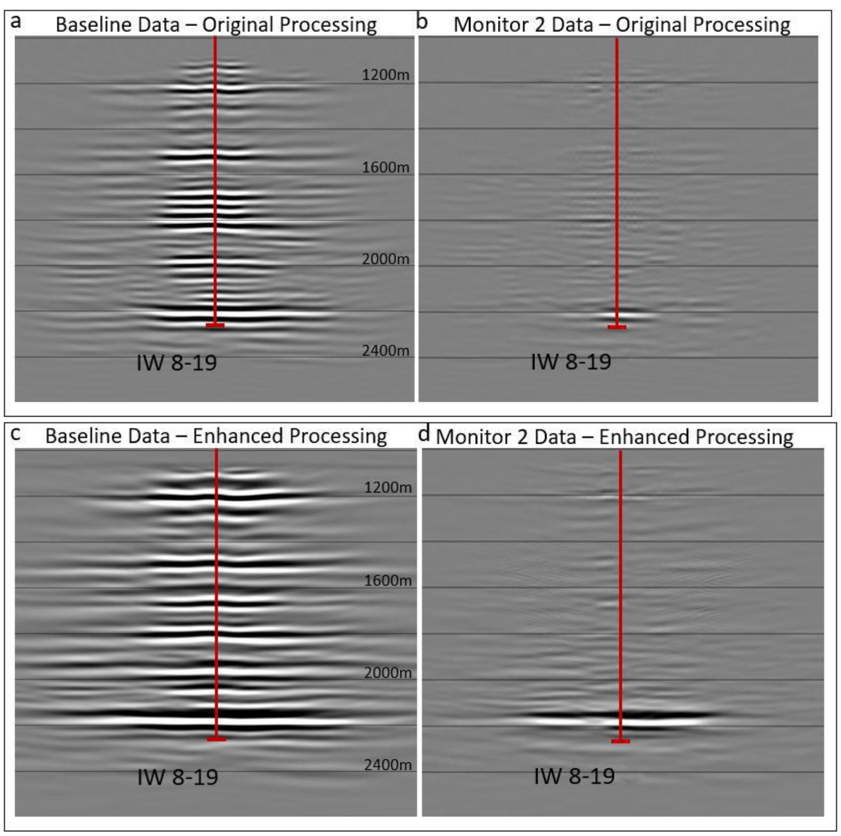

Figure 1: The vertical red line represents Injection Well (IW) 8-19 in depth. a) Baseline 2D DAS VSP image, output from original processing workflow. b) Second monitor 2D DAS VSP difference image, output from original processing workflow. c) Baseline 2D DAS VSP image, output from enhanced processing workflow. (Note: the amplitude scaling in d) is different than in b) for improved display, in view of the reduced 4D noise in d))

Preliminary assessments of the time lapse signal show we can qualitatively see plume growth between monitor surveys. Interpretation of the data is currently underway utilizing measurements of the repeatability to understand the extent of reliable imaging and time-lapse signature. The interpretation will then be integrated with model-based predictions to close the loop between modeled predictions and seismic response measurements.

Conclusions

The Quest CCS project has safely stored over 5 Million tonnes of CO2 since first injection in 2015. DAS VSP was identified early on as a key technology for monitoring containment and conformance as part of the MMV plan. Early processing efforts provided fit for purpose results that could be interpreted by the asset. An integrated processing project starting in 2019 allowed for significant improvement in the repeatability and subsequent interpretability of the time-lapse response dropping the repeatability from 14% down to a level below 10%. Through these efforts DAS VSP has proven itself as a cost effective and robust technology for CCS monitoring in the early stages of injection. This allows for further updating of the dynamic reservoir models to improve their predictive power and further demonstrate our understanding of the plume evolution.

Acknowledgements

The authors of this paper would like to acknowledge the Government of Alberta, the Government of Canada, Natural Resources Canada (NRCan), Shell staff in Calgary, Houston, EU and in the field, 3rd Party Contractors and our joint venture partners Canadian Natural Upgrading Ltd, Chevron Canada, and 1745844 Alberta Ltd.

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