ENHANCE ENERGY INC.
CLIVE LEDUC FIELD
MONITORING, MEASUREMENT & VERIFICATION PLAN

July, 2019

Cover Photo by Isabella Hills

MONITORING, MEASUREMENT & VERIFICATION (MMV) PLAN

MISSION STATEMENT

This document provides the rationale for, and specific details of, Enhance Energy's MMV Plan for its CO_2 EOR and storage project at Clive, Alberta. The MMV Plan's guiding principles are as follows:

- **Protect the public and other lessees by ensuring CO_2 containment;**
- **Provide public assurance CO_2 is confined to the Leduc Formation, and poses no threat to shallow aquifers, biosphere, and atmosphere;**
- **Address the highest-risk events and select monitoring techniques to reduce these risks to as low as reasonably practical;**
- **Tailor monitoring and measurement techniques to the site's specific attributes, including geology and infrastructure;**
- **Ensure early warning, using proven methods, to provide the opportunity to intervene before 'significant leakage' occurs outside of the Leduc reservoir;**
- **Locate and remediate the source should leakage out of the reservoir be detected;**
- **Meet or exceed regulatory requirements and provide assurance for the long-term safety and efficacy of the Clive Project; and**
- **Be adaptive, ensuring Enhance's ability to react to issues appropriately and mitigate them, should they arise.**

Disclaimer

Notice of Redactions

Certain material has been redacted from this version of the document to protect the privacy of members of the public and maintain confidentiality of proprietary technical methods and know-how.

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EXECUTIVE SUMMARY

Enhance Energy ("Enhance" or "the Company") is a privately-owned Alberta-based oil company specializing in **CARBON DIOXIDE** (CO_2) **ENHANCED OIL RECOVERY** (EOR) initiatives. The company's leadership team has extensive experience in the oil and gas industry, particularly with large-scale EOR projects using CO_2 injection.

Throughout this document, full definitions for words appearing in **GREEN ALL CAPS** *can be found in Section 8: References and Glossary.*

The Alberta Carbon Trunk Line will be built to transport CO_2 captured from sources in the Alberta Industrial Heartland and inject it into the Clive Leduc D-3A ("Clive Leduc") pool for EOR and permanent geological storage of CO_2.

CO_2 injection into oil reservoirs is a widely used, proven and safe technique for EOR, and has been used by the oil industry for more than 45 years with no widespread or persistent issues associated with **CONTAINMENT.** As of 2012, it is estimated that CO_2 EOR operations in North America have injected up to 65 million tonnes per year of CO_2 through more than 7,200 injection wells. Cumulative CO_2 injection in the United States is estimated to be 800 to 900 million tonnes.

The project will increment oil recovery of 1 billion barrels, generate $15 billion in royalties for the Province of Alberta and safely store 2 billion tonnes of CO_2 that would otherwise be emitted into the atmosphere.

Enhance has conducted extensive geological studies to evaluate the suitability of the Clive Leduc reservoir for CO_2 EOR and storage. These studies confirm the Clive Leduc reservoir is highly suitable for CO_2 storage, with no possibility of migration to surface through geological pathways. The Ireton Formation, which is the confining seal for the project, has contained a large gas cap within the Leduc reservoir over geological time scale, and will provide the same confining seal for CO_2.

Enhance constructed a geological model of the Leduc reservoir and overlying Ireton cap rock and Nisku reservoir. The model was built from all available core and log data, with petrophysical input from 180 wells. The model confirmed the Leduc and Nisku formations are distinctly separate hydrocarbon accumulations, separated by the Ireton Formation's impermeable tight lime **SHALES**. The Ireton seal's integrity is proven by the existence of a gas cap of up to 11m and an oil column of 18.5m on discovery of the Leduc Formation, overlain by water in the Nisku.

Enhance has built a robust **RESERVOIR SIMULATION** model of the Leduc Formation. The model was history matched to over 50 years of production and injection history with minimal adjustment to geological and fluid property data, thereby validating Enhance's geological characterization of the reservoir.

The same simulation model was run for a period of 475 years following injection to demonstrate CO_2 remained stable and safely stored in the Leduc reservoir. Due to the density difference between CO_2 and the reservoir fluids, the CO_2 will rise to the top of the Leduc reservoir, where it will be structurally trapped against the impermeable Ireton cap rock. Enhance has proved the same conditions that have trapped gas in the reservoir for millions of years will enable storage of CO_2 over similar timeframes.

SECONDARY SEALS above the Nisku reservoir provide assurance there is no quantifiable likelihood of geological containment failure of CO_2 to the surface at Clive. These seals include the Nisku and Wabamun anhydrites, and the Joli Fou, Colorado and McKay shales.

A geomechanical assessment of the host and cap rock at Clive has guided the design and planned operating conditions. Enhance will ensure Ireton cap rock integrity is not compromised by utilizing horizontal injection wells operating safely below virgin reservoir pressure.

Enhance undertook geochemical modelling to evaluate the potential interactions of CO_2 with reservoir **BRINES** and aquifer waters. Results from this study were utilized to design the planned monitoring program, which will provide assurance of containment through independent and complimentary analysis of soil, water well and **COAL BED METHANE** (CBM) gases and analysis of water samples from domestic wells and shallow groundwater monitoring wells.

Enhance will drill all new horizontal injection and production wells for the project to mitigate risk of CO_2 leakage through wellbores. These wells will be drilled and completed to the highest industry standards and will meet or exceed all regulatory requirements set by the Alberta Energy Regulator (AER) for sour fields, thereby mitigating any risk of CO_2 migration.

Existing wellbores present the only possible risk to CO_2 containment at Clive. Enhance has completed a comprehensive study of all existing wells in Clive to evaluate the current status of the existing wellbores, including review of cement bond logs and **SURFACE CASING VENT FLOW (SCVF)** history, both of which confirm hydraulic isolation over the Leduc Formation exists in all existing wellbores.

By meeting or exceeding regulatory compliance governing sour fields, Enhance can demonstrate the highest possible safety standards for CO_2 containment at Clive. Enhance will continue to zonally abandon existing wells to the Level A standards set out in Directive 20, which, in most cases, exceeds the current requirements.

A formal and independent risk assessment of 69 existing wells within the project area has been completed. The study concluded these wells have been managed to high standards, with 65 wells identified as low risk and requiring minimal monitoring. Two wells are medium risk and two wells are characterized as high risk, requiring mitigation prior to CO_2 injection.

Enhance has built an MMV plan that will ensure the Clive Leduc pool is safe for long-term CO_2 storage. This plan is designed to provide public assurance of **HYDROSPHERE**, **BIOSPHERE**, and **ATMOSPHERE** protection, to verify containment in the **GEOSPHERE**, below the Ireton seal, and to monitor existing wellbores for potential leakage pathways.

Enhance has taken a risk-based approach, considering both probability and consequence of occurrence, in selecting monitoring tools and placement of safeguards within the MMV plan.

The Company will gather and analyze data throughout its EOR program to ensure Ireton seal competency and enable simulation modelling as a means of detecting possible CO_2 **CONFORMANCE** or containment issues.

Enhance will monitor the Nisku Formation directly overlying the Ireton seal to provide verification of long-term CO_2 containment within the Leduc Formation.

The probability of geological containment failure to the hydrosphere and biosphere is practically zero, nevertheless, because the consequences of CO_2 reaching these environments have been quantified, Enhance will place safeguards here, too. Monitoring producing CBM wells will provide early detection warning. Likewise, domestic water well monitoring and soil gas sampling will provide public assurance CO_2 is contained to the geosphere.

Wellbore failure presents risks that are somewhat independent of geologically driven factors, as failure here can bypass inherent protection. As existing wellbore leakage has been identified as the only potential risk in the project, Enhance will focus a large part of its monitoring efforts on wellbores. In particular, the Company will monitor for SCVF, which has been identified as the probable outcome in the case of wellbore failure.

Any reservoir-sourced CO_2 leakage will contain hydrogen sulfide (H_2S) in quantities high enough to be detected by H_2S monitors currently employed at Clive. All future injection and production facilities at Clive will incorporate H_2S protection, which will provide a robust method of potential CO_2 leak detection.

Enhance will gather baseline data in all monitoring environments prior to CO_2 injection. One very powerful tool that will be utilized in all environments is **CARBON ISOTOPE SIGNATURE**. Different sources of CO_2 may exhibit different amounts of carbon isotopes ($\delta^{13}C$ & ^{14}C) that effectively allow samples to be fingerprinted. Enhance will establish baseline analysis of $\delta^{13}C$ and ^{14}C contained within the source CO_2 and compare it to baseline $\delta^{13}C$ and ^{14}C in CO_2 in produced gas from existing Leduc, Nisku and CBM wells, in soil gas and in headspace gas and/or dissolved inorganic carbon from domestic water wells.

In addition to the **PASSIVE SAFEGUARDS** provided by the characteristics of the site itself and the **ACTIVE SAFEGUARDS** that Enhance will implement, the regulatory regime in Alberta provides ancillary safeguards that afford significant benefit. Including its predecessors, the AER has been in existence for almost 80 years and is widely recognized for its excellence in regulating industry to promote safe, efficient and effective resource recovery. CO_2 EOR and other injection processes are proven, safe and effective techniques. There are over 17,000 wells licensed for various forms of injection in Alberta with no evidence of widespread or persistent containment issues, speaking to the efficacy of regulations and industry practices in the province. Enhance will meet or exceed all regulatory requirements to ensure CO_2 is safely injected and contained within the Clive Leduc reservoir.

Carbon Capture and Storage (CCS) in deep saline **AQUIFERS** and storage in EOR projects both provide for excellent opportunities to remove greenhouse gases from the atmosphere through capture and geological storage. Between CCS and EOR, there are similarities in the injection wells but there are differences in the storage risks and mitigation procedures, meaning different MMV plans are required. This MMV plan is specifically designed to account for the unique setting of the Clive Leduc pool and the characteristics of CO_2 EOR.

Enhance's CO_2 EOR and storage project at Clive will be safe, effective, environmentally responsible and will provide a number of outstanding benefits to Albertans.

The table following provides a summary of the monitoring techniques to be used within Enhance's MMV Plan.

Enhance MMV Plan

GEOSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During ACTIVE EOR**	**Frequency of Testing POST INJECTION**
Most recent AER D-65 EOR Approval	Meet all clauses and requirements specified within Approval No. 12832	As per approval	As per approval	N/A
Monitor physical status of all wells per AER Directives 13, 20, 51 and 65, ID2003-1 or as applicable at the time	All Enhance wells within **MMV Plan Area**.	Verify no SCVF or casing pressure on existing wells prior to CO_2 injection.	Monitor SCVF and casing pressure on existing wells minimum two times per year. Evaluate frequency after two years, if no issues seen.	Per AER requirements at time. SCVF and casing pressure to be checked and remediated (if required) at final abandonment.
Conduct reservoir simulation and day-to-day flood management	Entire EOR operation with focus in specific areas, as required.	History match of Central Leduc Area prior to CO_2 injection and baseline CO_2 EOR performance prediction.	Day-to-day monitoring of EOR performance. Annual (minimum) updates to simulation for two years, then as required. Monitor voidage replacement ratio (not to exceed 1.0 cumulative).	N/A
Seismic	Acquire existing 3D seismic over project area as per AER D65 project approval.	Process and Interpret baseline seismic. Confirm no faults transects the seals.	Evaluate as required based on event trigger.	N/A
Nisku monitoring wells	Isotope & gas analysis, water chemistry and reservoir pressure as per AER D65 project approval.	Once. Gas carbon isotope. Water chemistry (from Nisku pool).	Isotopes annually, and gas analysis bi-annually. Evaluate frequency of isotope and gas analysis after two years. Annual reservoir pressure.	N/A
Leduc monitoring well	Isotope & gas analysis, water chemistry and reservoir pressure as per AER D65 project approval.	Once. Gas carbon isotope. Water chemistry (from Leduc pool).	Isotopes annually, and gas analysis bi-annually. Evaluate frequency of isotope and gas analysis after two years. Annual reservoir pressure.	N/A
Leduc and Nisku Reservoir Pressure	Annual stabilized formation pressure per AER D-40 requirements	Once.	Annual.	N/A

	and D-65 project approval.			
Monitor tubing and annulus pressure on injection wells	All injection wells.	N/A	Continuous tied into SCADA.	N/A
Injection well hydraulic isolation testing	All injection wells.	Pressure test packer, hydraulic isolation log and cement bond log.	Annual pressure test packer, hydraulic isolation log every five years.	N/A
MUD LOG new surface and build drills	Three project new drills within the **MMV Plan Area**	Once C_1-C_5, including isomers and CO_2.	N/A- may be considered if infill or replacement well required.	N/A
Measure injected and produced fluids	All injection and production wells.	N/A	Follow measurement requirements as outlined by AER D-17.	N/A
Analyze produced liquids and gas	All production wells.	N/A	Periodically prior to breakthrough, every three months post breakthrough.	N/A
Analyze injected source gas	Nutrien and Northwest Redwater Partnership (NWR).	Once for chemistry and carbon isotopes.	Annual isotopic and continuous CO_2 concentration.	N/A
Analyze produced and recycled gas	Produced gas at individual wells and recycle streams.	Baseline (including isotope) on existing Leduc producers.	Minimum quarterly gas analysis on production wells and monthly on recycle stream & combined injection stream.	N/A

BIOSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During Active EOR**	**Frequency of Testing Post Injection**
Conduct soil gas surveys	19 locations within **MMV Plan Area**. Planned during unfrozen ground conditions to obtain the most reliable and representative samples	Spring, summer and fall prior to injection. Gas chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set.	Spring, summer and fall. Evaluate frequency after two years. Analyses per baseline.	Evaluate frequency based on results to date.

HYDROSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During Active EOR**	**Frequency of Testing Post Injection**
Monitor CBM wells for CARBON ISOTOPE SIGNATURE	Gas-gathering system encompassing well clusters for the entire **MMV Plan Area** and at main gas plant.	Once	Annual isotope analysis and monthly composition.	Annually
Conduct landowner water well surveys	9 Landowner water wells within **MMV Plan Area**.	Spring, summer and fall prior to injection. Water and headspace gas (if obtainable) chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set. Supplement with Baseline Water Well Testing for Coalbed Methane Development.	Quarterly in 2020. Evaluate frequency at YE 2020. Analyses per baseline.	Evaluate frequency based on results to date.
Dedicated monitoring wells	Three dedicated monitoring wells completed at 20, 40 and 80m BGS for chemistry and pressure monitoring. Low flow sampling and downhole pressure recorder.	Spring, summer and fall. Water and headspace gas (if obtainable) chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set.	Quarterly. Evaluate after two years.	Evaluate frequency based on results to date.

CONTRIBUTORS

The information reported in this document is the culmination of research by numerous individuals and specialist companies that have been involved with the project, in addition to Enhance Energy's work.

In particular, Enhance would like to acknowledge the contributions by **Alberta Innovates Technology Futures (AITF)**, now known as **InnoTech Alberta**, a subsidiary of Alberta Innovates. As part of the early-stage due diligence for the project, Enhance enlisted AITF to conduct a number of studies on the suitability of the Clive Leduc pool for CO_2 storage. **Dr. Stefan Bachu**, a recognized authority in the area of carbon capture and storage and co-winner of a 2007 Nobel Peace Prize for his work with the Intergovernmental Panel on Climate Change, contributed to and/or oversaw much of AITF's work.

Avasthi & Associates Inc. completed a full review of Enhance's simulation model for correctness of inputs, specifically residual oil saturations, **RELATIVE PERMEABILITY** curves and rock fluid interactions.

Enhance has chosen **Golder Associates (Golder)** to conduct program design, sampling and interpretation of soil gas and shallow aquifer monitoring programs based on their technical strength and experience providing similar services to the Shell Quest Aquifer Storage Project.

Other significant data contributors include **Jeff Packard** PhD. (Geology), **Bill May** (Petrophysics), **Core Laboratories**, and **Computer Modelling Group** (CMG).

Finally, Enhance would like to recognize its own technical contributors: **Dave Hassan**, P. Eng. (MMV development); **David Hills**, M Sc., P. Geol. (Geology and Modelling); **Amir Ghadari**, Ph.D., P. Eng. (Simulation); **Chris Markwart**, P. Eng. (Reservoir Specialist); **Brendan McGowan**, P. Eng. (Project Manager); **Kevin Meyer**, P. Eng. (Production and Drilling); and **Sunita Sood**, P. Eng. (Exploitation Engineer).

ABBREVIATIONS

ACTL	Alberta Carbon Trunk Line
AER	Alberta Energy Regulator
AITF	Alberta Innovates Technology Futures
BGWP	Base of Groundwater Protection
CBL	Cement Bond Log
CBM	Coal Bed Methane
CCS	Carbon Capture and Storage
CMG	Computer Modelling Group
CO_2	Carbon dioxide
EOR	Enhanced Oil Recovery
H_2S	Hydrogen sulphide
MMV	Measurement, Monitoring and Verification
SCADA	Supervisory Control And Data Acquisition
SCVF	Surface Casing Vent Flow
WAG	Water-Alternating-Gas

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C: Geochemical Effects on Deep Strata in Case of CO_2 Leakage from the Leduc D3-A and Nisku D2 Oil Reservoirs in the Clive Oil Field in Alberta, March 2012, AITF

D: Geomechanical Analysis of the Effects of CO_2 Injection in the Clive Leduc and Clive Nisku Reservoirs in the Clive Field, Phase 2 Report, March 2012 Phase 2 Report, AITF

E: Characterization of the Wells that Penetrate the Leduc (D-3A) and Nisku (D-2) Oil Reservoirs in the Clive Oil Field in Alberta CO_2

F: Risk Assessment of Clive Existing Wells, VZFox

G: Clive EOR Risk Assessment

H: Monitoring Tool Cost Benefit Analysis and Selection

J: Geophysical Study of Cretaceous Porous Intervals at Clive in Response to CO2 Emplacement

K: Golder Associates Groundwater and Gas Monitoring Program July, 2019

L: Golder Associates Baseline Shallow (non-saline) Groundwater Monitoring

M: Study on Effectiveness of Observation Wells in Detecting Loss of Containment

N: Alberta Energy Regulator D-65 EOR Approval No. 12832

O: Baseline Water Test Reports

1 INTRODUCTION

Enhance Energy Inc. ("Enhance" or "the Company") is a privately owned, Alberta-based oil and natural gas development company founded in 2005. Enhance specializes in Carbon Dioxide Enhanced Oil Recovery initiatives. The Company's leadership team has extensive experience in the oil and gas industry, particularly with large-scale EOR projects using CO_2 injection.

CO_2 injection into oil **RESERVOIRS** is a widely used, proven and safe technique for EOR, and has been used by the oil industry for more than 45 years. The first commercial CO_2 EOR flood was initiated in the Permian Basin of Texas, United States, in 1972. Since then, the number of CO_2 EOR projects in the world has nearly doubled in each of the past three decades, with approximately 40 projects in 1984, 78 projects in 1994 and 142 projects in 2012. To date, over 600 million metric tonnes of CO_2 have been safely shipped by pipeline and injected into oil fields of the Permian Basin alone, producing an incremental 1.4 billion barrels of oil which would not otherwise have been produced.

In Canada, the Alberta Carbon Trunk Line (ACTL) has been designed with ultimate capacity of 40,000 tonnes per day (14.6 million tonnes per year) of CO_2 delivery from the Alberta Industrial Heartland near Fort Saskatchewan. The ACTL is expected to revitalize the EOR industry in Central Alberta. As an additional benefit, it will significantly reduce the carbon footprint of oil sands production through permanent storage of CO_2 produced from refining and upgrading facilities. The ACTL will ultimately enable the production of one billion barrels of light oil while storing two billion tonnes of CO_2. This will create an impactful economic stimulus for the province, creating thousands of jobs for Albertans and generating a new revenue stream of up to $15 billion in royalties for the Province of Alberta.

Figure 1-1 ACTL Route
The Alberta Carbon Trunk Line will carry CO_2 from the Alberta Industrial Heartland to the Clive oil field for injection and permanent storage, while enhancing oil recovery.

The goal of the project is to reduce Alberta's greenhouse gas footprint by capturing, transporting and permanently storing CO_2 emissions from the North West Redwater Partnership's Sturgeon Refinery and the Nutrien (formerly Agrium) Redwater fertilizer complex. The ACTL will transport CO_2 approximately 220 km from the Redwater area to the Clive oil field, located eight kilometers southeast of Clive, Alberta. The Clive oil field is owned and operated by Enhance and has been in operation since its discovery in 1952.

As well as increasing oil recovery while reducing carbon emissions, there are a number of advantages to CO_2 EOR storage: oil companies possess a long record of know-how to manage, inject and track CO_2; depleted oil fields offer known reservoir capacities and injectivity, and can accept large volumes of CO_2 for tertiary oil production and subsequent storage; oil fields are proven traps, known to

hold oil and gas for millions of years; the process takes place in areas where the public is already accustomed to oil and gas activities; the sale of CO_2 provides value to capturing companies; increased oil recovery, royalties and job creation provide value to the EOR operator and the province; multiple injection and production wells offer the potential to manage the subsurface CO_2 plume; and additional surface disturbance is minimized because existing infrastructure is used, such as leases, roads and facilities.

CO_2 will be utilized for EOR in the Clive Leduc reservoir. Situated approximately 1,900m below the surface, the Clive Leduc reservoir is overlain by the Ireton shale, which provides a strong, contiguous confining seal for the reservoir. The large gas cap of 10 billion cubic feet, securely contained within the reservoir for millions of years, demonstrates the seal's effectiveness. The reservoir has been under production since the early 1960s; the gas cap and 47 MMbbls of oil have since been produced, thereby reducing the reservoir pressure from 17.5 Mpa to the current pressure of 13.5 MPa. Enhance plans to inject 1.6 million tonnes of CO_2 into the Clive field per year in a manner that will not materially increase the current pressure, providing assurance the integrity of the overlying Ireton confining seal will not be compromised during the operation, and confidence that CO_2 will be permanently stored during and post CO_2 injection.

CO_2 EOR starts with injection of compressed CO_2 into the reservoir through dedicated injection wells. The CO_2 advances through the reservoir, contacts the remaining oil and mobilizes it to the production wells. The pore space that was once filled with oil is replaced by the CO_2, which remains permanently stored within the reservoir. The overlying impermeable reservoir cap rock physically traps the CO_2, ensuring it remains contained within the formation. Based on the Clive Leduc reservoir's history of trapping oil and gas for millions of years prior to discovery, the reservoir is proven to be an excellent storage **CONTAINER**.

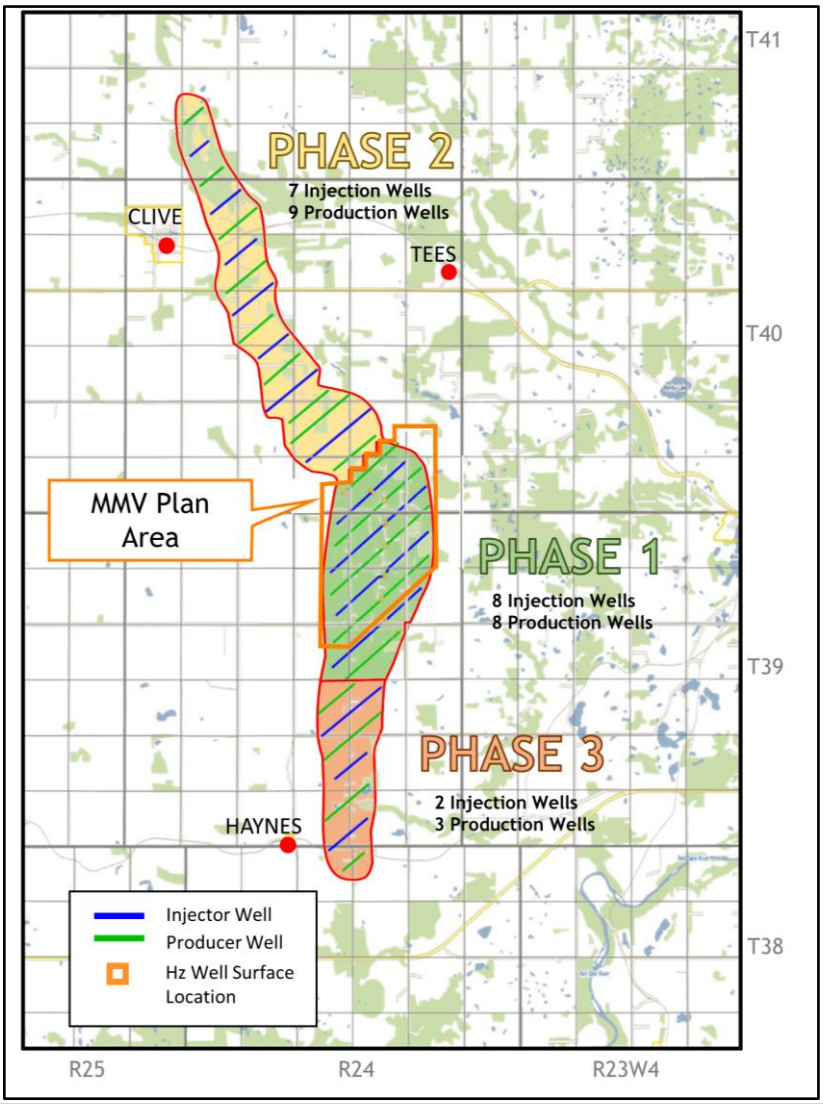


Figure 1-2 Project Phases

The Clive EOR project will take place in three stages, beginning with a 12-well program in the **MMV Plan Area**. Operations in North Clive will begin within two to three years, and development in South Clive will follow.

The extensive geological information and operational history available for the Clive Leduc reservoir provide for minimal uncertainty and risk with regards to CO_2 injection. This MMV plan applies to the initial development with six horizontal injection wells covering a large portion of the Phase 1 Area in the central portion of the Clive Unit. Enhance defines this as the **MMV Plan Area** of the project; the plan will be expanded to include the remainder of the Central Area and subsequent phases as they are developed over a 10-year time frame.

Development of the **MMV Plan Area** will begin with the drilling of 12 new horizontal wells, of which six will be dedicated to CO_2 injection. Later phases in the program will include drilling the remaining 4 wells in the Central Area (2 injectors and 2 producers), expansion into North Clive for Phase 2 and South Clive in Phase 3. Future development of the Clive Field will include expansion into the overlying Nisku Formation.

Injection pressures will conform to regulatory requirements and be maintained at levels that ensure the injection formation and overlying seals remain unaltered, thus maintaining full confidence in long-term CO_2 storage. At the conclusion of the injection phase, a period of continued monitoring will take place, after which the project wells will be plugged and abandoned to establish long-term permanent CO_2 storage.

The MMV plan relies on a thorough understanding of the reservoir, developed through decades of production data and dense well control. Enhance and expert consultants have carefully designed the plan to detect and provide early warning in the unlikely event of CO_2 migration outside of the storage reservoir or EOR project area, and to provide safeguards ensuring CO_2 storage is secure and effective for the entirety of the project and beyond.

2 CLIVE GEOLOGY AND FORECASTS FOR CO_2 EOR AND STORAGE

In preparation for the Clive CO_2 EOR project, Enhance has conducted extensive geological studies to characterize hydrocarbon and CO_2 trapping and **HYDRODYNAMICS**, and to provide a robust **GEO-MODEL** for reservoir simulation.

Regional geological analysis confirms the Clive Leduc pool is an ideal EOR target and storage reservoir for CO_2. The Devonian Leduc Formation injection target is part of the Bashaw Platform, an extensive **CARBONATE** reef complex. Clive is a localized structural high in the Leduc Formation, associated with differential compaction between tidal shoals at Clive, the neighbouring lagoon to the west and the tidal channel to the east. Overlying formations of the Ireton mudstones and the Nisku platform **DOLOMITES** are also affected by the drape, leading to the configuration of the Leduc and Nisku reservoirs, capped by the Ireton and Upper Nisku **ANHYDRITES**, respectively. The Ireton's effectiveness as a seal to the Leduc is demonstrated by the geological containment of up to 11m of gas and 18.5m of Leduc oil. Above the Nisku, extensive sheet anhydrites of the Devonian Wabamun and regionally extensive Cretaceous shales of the Joli Fou, Colorado and McKay Formations form a series of secondary seals, ensuring no quantifiable likelihood of geological containment failure to surface at Clive.

Enhance has built a robust geo-model to simulate the Clive Leduc pool. The geo-model was constructed by combining knowledge from geological studies with the **PETROPHYSICAL** and **CORE** data from 180 wells. Next, laboratory testing of fluids under reservoir conditions created a fluid property model governing the dynamics of CO_2, oil and water in the geo-model. These tests also demonstrated that CO_2 is less than half the **DENSITY** of Devonian Formation waters, thus ensuring the inherent buoyancy of CO_2 will prevent its migration out of the pool. The simulation model was history matched to over 50 years of production and injection history with minimal adjustment to geo-model and fluid properties, thereby validating the accuracy of the geo-model.

Finally, the simulator was used to help select the most efficient and cost-effective EOR development scenario. The simulator was also used to forecast long-term distribution of CO_2 at Clive. In one model run 475 years after injection, CO_2 was maintained buoyantly capped within the Clive Leduc pool.

The geological studies confirm the Clive Leduc reservoir is highly suitable for CO_2 storage. The Ireton Formation contained a large gas cap within the Leduc over a geologic time scale and will do the same for CO_2. Simulation confirms the Leduc reservoir will safely store injected CO_2, which will rise to the top of the reservoir due to buoyancy effects and be contained by the Ireton cap rock.

REGIONAL GEOLOGY

The Clive Leduc A Pool is located on the Leduc Bashaw Platform, an isolated but extensive reef complex of more than 3,500 km^2 and up to 285m thick, which includes Bashaw, Chigwell, Haynes, Innisfail, Nevis and Wimborne fields (Figure 2-1). Most of the hydrocarbon reservoirs on the Bashaw Platform are located along raised margins generated by differential compaction (Mossup, 1972). One of the Bashaw Reef Complex's prominent features is the north-south extending Clive channel, a localized trough that opens to the north and tapers and shallows to the south. The combination of the Clive channel's orientation, which is near-perpendicular to the direction of **DIP**, and the accompanying raised edge along its southern margin has created

a significant hydrocarbon trap at Clive. The overlying Ireton and Nisku mimic Leduc entrapment geometry (Mossop and Shetsen, 1994).

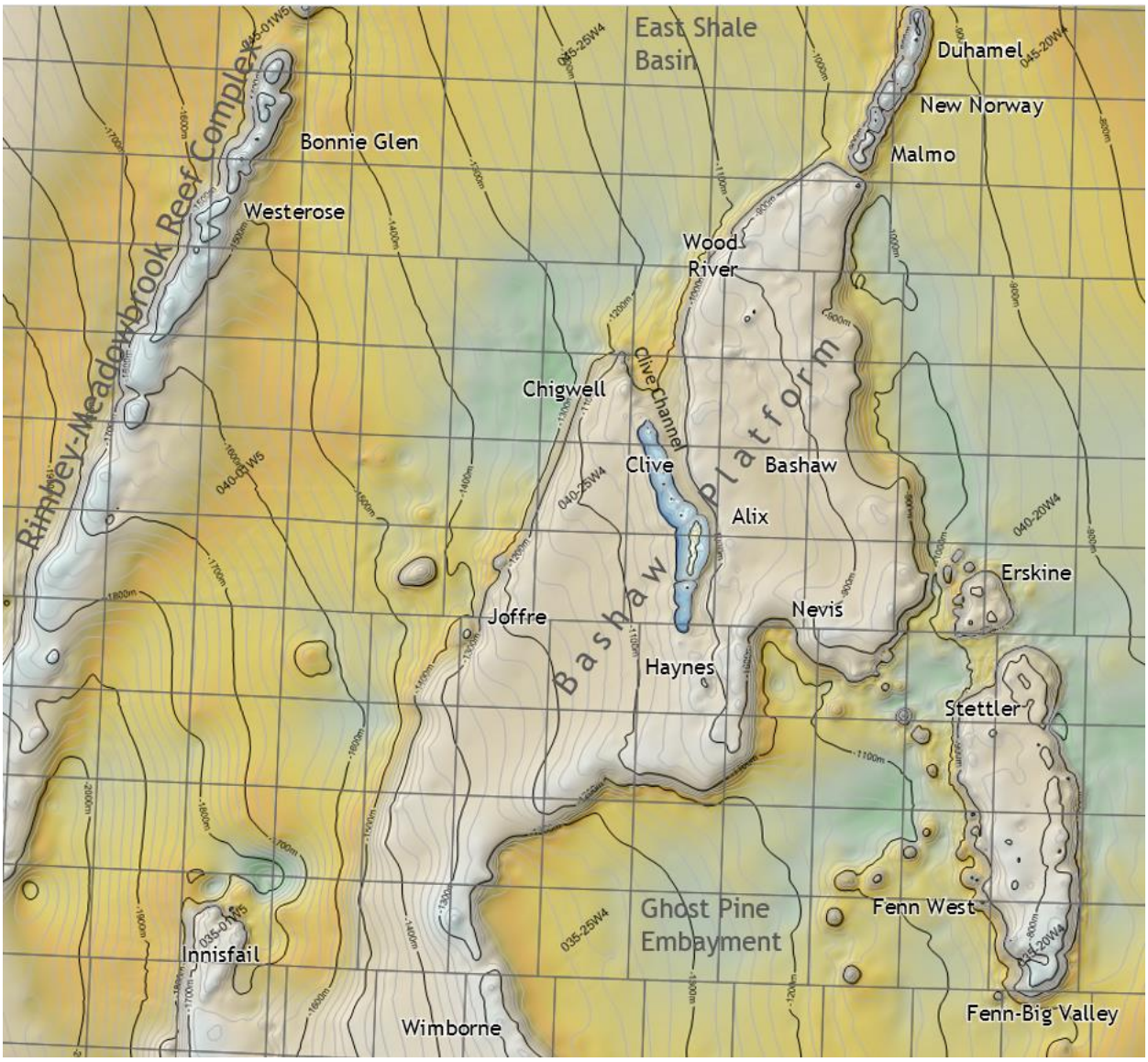


Figure 2-1 Sub-Sea Structure of the Leduc Bashaw Platform

Clive is located on the Bashaw Platform, a large Devonian carbonate reefal system that was surrounded by the Duvernay's deep-water basins. Major Leduc and Nisku fields are located around the raised margins of this and neighbouring banks. Colour fill is a residual of the Leduc Structure. Dip is to the southwest.

The Frasnian-aged Woodbend Group is a stratigraphic sequence consisting of a widespread, shallow marine platform of the Cooking Lake Formation, which is overlain by the Leduc's localized carbonate buildups (Figure 2-2). The Duvernay Formation's shales and deep-water basin-filling limestones are laterally equivalent to the Leduc, which are succeeded by the Ireton Formation's argillaceous (clay-rich, resulting in low **PERMEABILITY**) limestones and shales. The Ireton Formation represents the majority of the basin-filling sediment, which eventually encroached onto, and capped, the Leduc platform. Following Woodbend Group/Ireton deposition, the Winterburn Group deposition was initiated with a return to clean carbonate deposition of the Nisku

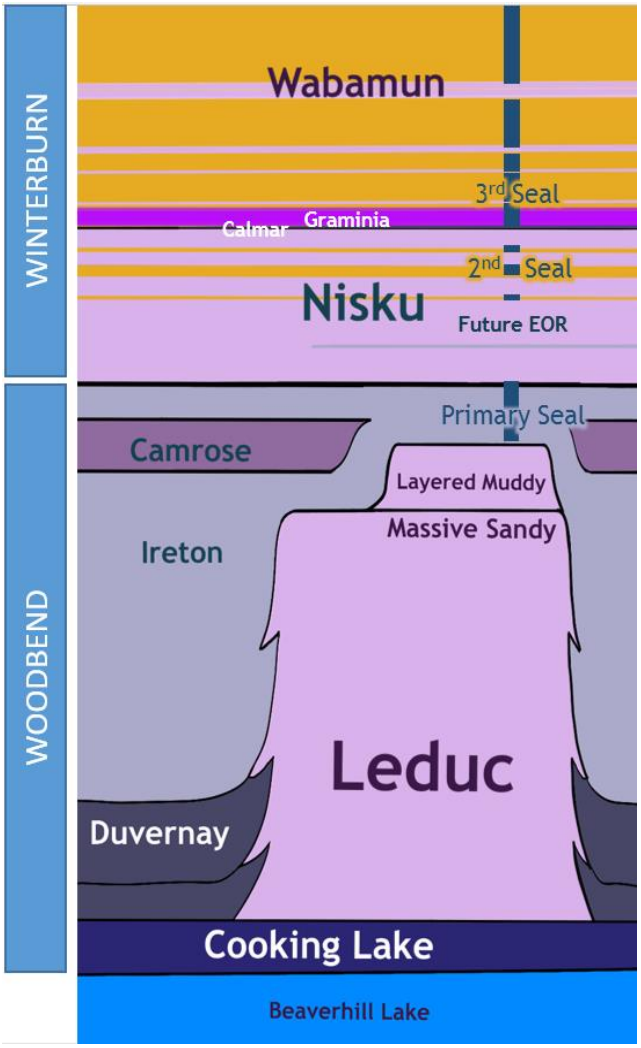


Figure 2-2 Devonian Woodbend Group and Winterburn Group Stratigraphic Sequence at Clive

Duvernay shales sourced oil to the Leduc, which is capped by the Ireton's carbonate shales (grey) that comprise the primary seal encasing the platform. As the Nisku grew, extensive sheets of anhydrites (orange) blanketed the area, adding further vertical seals.

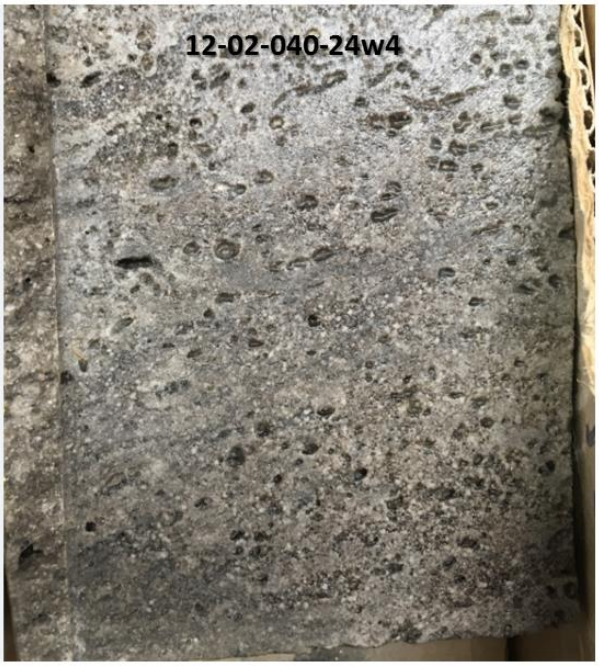
Formation. Continued basin-filling throughout the Nisku led to widespread **EVAPORITE** (anhydrite) deposition in the top part of the Nisku. Calmar shales and Graminia Formations cap the sequence. Ireton shales are the **PRIMARY SEAL** for the Leduc storage reservoir, while evaporites and shales in overlying formations are secondary seals.

Cooking Lake Formation

The Cooking Lake Formation is a widespread, sheet-like, locally dolomitized carbonate that reaches a maximum of 100m in east-central Alberta. No wells reach the Cooking Lake at Clive, but regional extrapolation suggests a thickness of between 55m and 75m. The nearest cored section of Cooking Lake at Bashaw, 16-36-041-23W4, reveals the formation to be a relatively tight limestone with an average **POROSITY** of only 3% (9% max) and permeability of 0.24 mD (1.3 mD max). Gentle topographic highs formed by localized shoals in the Cooking Lake platform gave rise to the Leduc Formation's isolated reef complexes (Wendte, 1994).

Leduc Formation

A handful of deep wells around Clive indicate the Leduc Formation is comprised of approximately 250m of pervasively dolomitized platform carbonates. By contrast, the topmost 35m of Leduc is very well represented at Clive, with 83 cored wells totalling 1,100m of recovery.



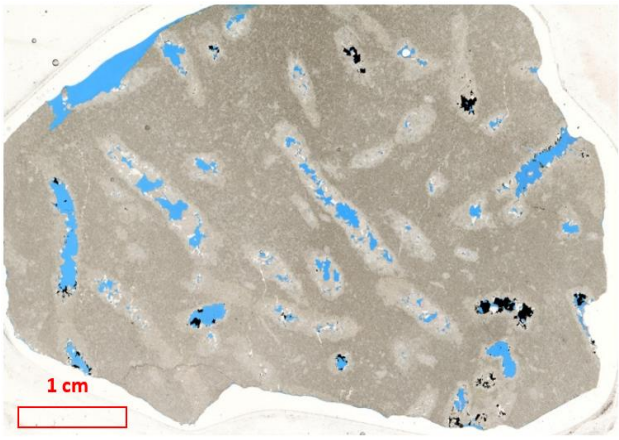


Figure 2-3 Typical Leduc Reservoir Rock

At left, an example of leached *amphipora* fossil-moldic grainstone from the Leduc Formation's Layered Muddy zone. FD 122 at 1,884m. 3.5" diameter core.

Pictured above, a low mag photomicrograph of typical fossil-moldic porosity found in Leduc at Clive (5-14-39-24W4).

DOLOMITIZATION and leaching have obscured original depositional fabric to such a degree that reliable and consistent assignment of depositional **FACIES** is not possible at Clive.

Despite this, one aspect of the original fabric that has survived is the presence of leached **AMPHIPORA** fossil-**MOLDIC POROSITY** in a significant proportion of the core. By analogy with innumerable prior studies of Devonian-age carbonate platform complexes, the near ubiquitous presence of *amphipora* suggests the uppermost Leduc at Clive was lagoon or near lagoon in provenance (Figure 2-3). Enhance's own detailed study of these cores (Packard, internal docs) reveals the majority of Clive reservoir rock to be of shoal, lagoon and tidal sequences. This is atypical of Alberta's Leduc reservoirs, including those on the periphery of the Bashaw Bank, which usually consist of rigid framework fossils associated with reefal zones on the platform edge.

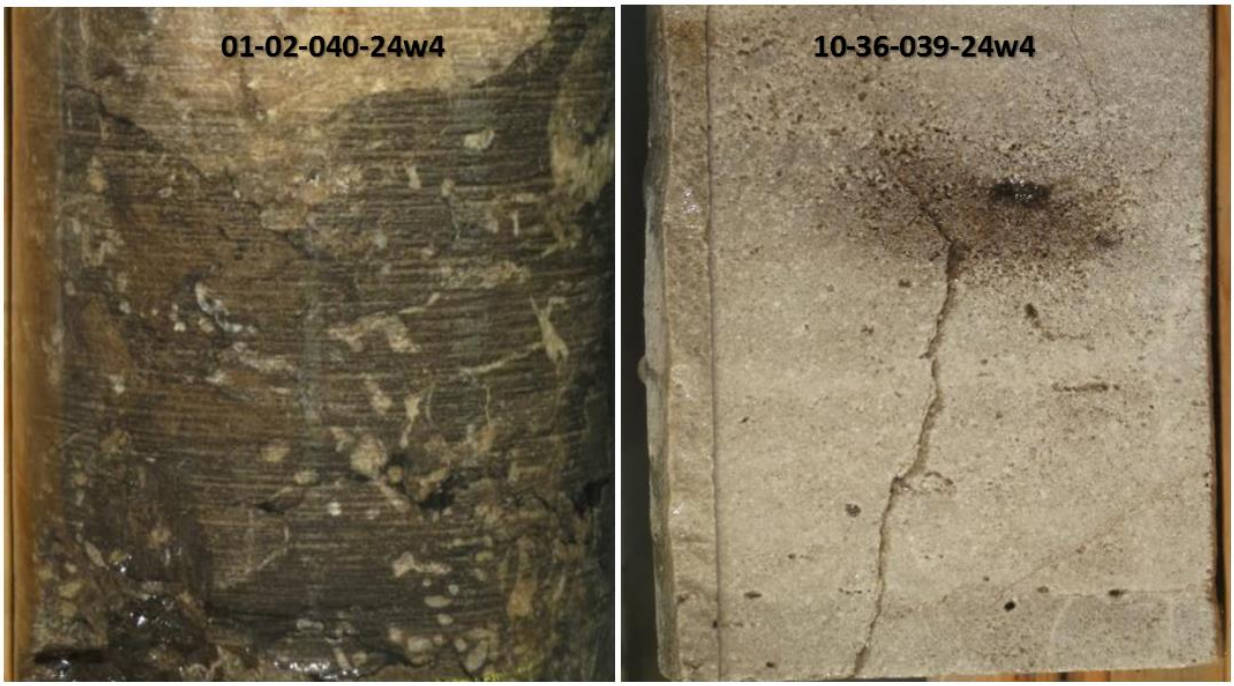


Figure 2-4 Two Representative Examples of Clive Core

At left, the Layered Muddy Zone includes common muddy *amphipora*-dominated lagoon sediments. Pictured at right, a carbonate sand typical of the Massive Sandy Zone showing light-coloured grain-stone with relatively well-distributed leached fossil porosity. Both cores are 3.5 inches in diameter.

The uppermost Leduc can be divided into two zones: a lower, Massive Sandy Zone of granular and variably leached carbonate shoal sands; and an upper Layered Muddy Zone, which exhibits multiple, discontinuous and thinly bedded carbonate mud layers (Figure 2-4). The best reservoir rock is found in the Massive Sandy, which is generally the more homogenous of the two, with relatively well-distributed granular porosity and high vertical permeability. The Massive Sandy Zone extends well below the oil/water contact at Clive's structural peak, and the true thickness is not known. Above this, the Layered Muddy Zone is approximately 10m thick throughout Central and South Clive but thins to the north of the field. This zone incorporates rock similar to the Massive Sandy but is commonly interrupted by thin, discontinuous muddy layers. The transition between the Massive Sandy and Layered Muddy often incorporates a 2m to 3m heavily cemented layer characterized by reduced porosity.

From detailed examination of core data throughout Clive, Enhance has been able to build on the geological history of this part of the Bashaw Platform. Clive owes its current prominence to its association with the Clive Channel. Ebbing, fast-flowing tidal water from the platform interior maintained long-lived shoals on the bank of the channel throughout deposition of the Massive Sandy Zone. Later on, possibly even as the Ireton was filling surrounding basins, the Layered Muddy recorded a period of alternating energy environments and reduced accommodation. Finally, the Leduc carbonate factory was shut down, as it was smothered by the Ireton's silts. Using Ireton thickness as a proxy for depositional environment, a maximum water depth for the top of the platform is estimated of up to 25m, typically around the platform margin (Hearn *et al*., 2011).

Ireton Formation

The Ireton Formation's **CALCAREOUS** shales represent westwardly regressive infilling of basinal areas between the Leduc Reef sequence, conformably overlying the Duvernay at up to 130m thick (north of Clive). Three Ireton stages have been recognized, with the first two stages concurrent with Leduc deposition and a third stage post-dating the Leduc (Oliver and Cowper, 1963, Stoakes, 1980). On the platform, the Ireton filled to a near planar surface that covered all but the highest points of the platform (Haynes and Nevis areas). While the Ireton is mostly considered to be a largely **TERRIGENOUS** unit, the portion that covers the Bashaw Bank has a high carbonate content of approximately 75% (Hearn, 1996) and is commonly observed to be dark brown **BIOTURBATED** mudstones that are interpreted as bank slope to more basinal environments towards the north. The Camrose Member of the Ireton Formation represents a depositional switch to clean carbonate deposition, before switching back again. The Camrose is typically tight and does not form a reservoir at Clive. The package of impermeable rocks that make up the Ireton has created an effective seal for hydrocarbon accumulation in the Leduc; as such, it will provide a similarly effective seal for CO_2 injection.

Nisku Formation

The Nisku Formation is characterized by porous, dolomitic open marine platform carbonates, which are capped by layered dolomites and anhydrites. The lower part of the Nisku is a clean dolomite with typically low porosity, followed by 20m of the porous Middle Nisku reservoir zone. At the top is approximately 16m of predominantly layered anhydrites with lesser intervening dolomites. These anhydrites layers are consistent across the Clive Field and act as secondary containment for the Leduc reservoir.

GEOLOGICAL CONTAINMENT

Due to the relatively low density of CO_2 in the reservoir, buoyancy effects will cause it to migrate towards the top seal. The following description of geological containment investigates the possibility of CO_2 leakage as a buoyant fluid.

Enhance has identified the Ireton as the primary seal for the **MMV Plan Area** and for the entire Leduc injection program. Numerous **AQUITARDS** have been identified as secondary seals, which are considered redundant barriers in the unlikely event of a primary seal breach.

Primary Seal: Ireton Aquitard

The Ireton aquitard is the primary seal for Enhance's Phase 1 injection program into the Leduc. The Ireton's effectiveness as a seal is demonstrated by the pool configuration upon discovery, having held down as much as 11m of gas and 18.5m of oil below that from moving up into the Nisku (Figure 2-5). As the EOR program will not exceed original discovery pressures, the Ireton can be expected to provide an excellent barrier for CO_2 containment.

A series of maps based on petrophysical log analysis and a representative cross-section of the Ireton at Clive is included in Appendix A. Mapping includes Ireton structure, **ISOPACH,** net shale thickness and net cap thickness.

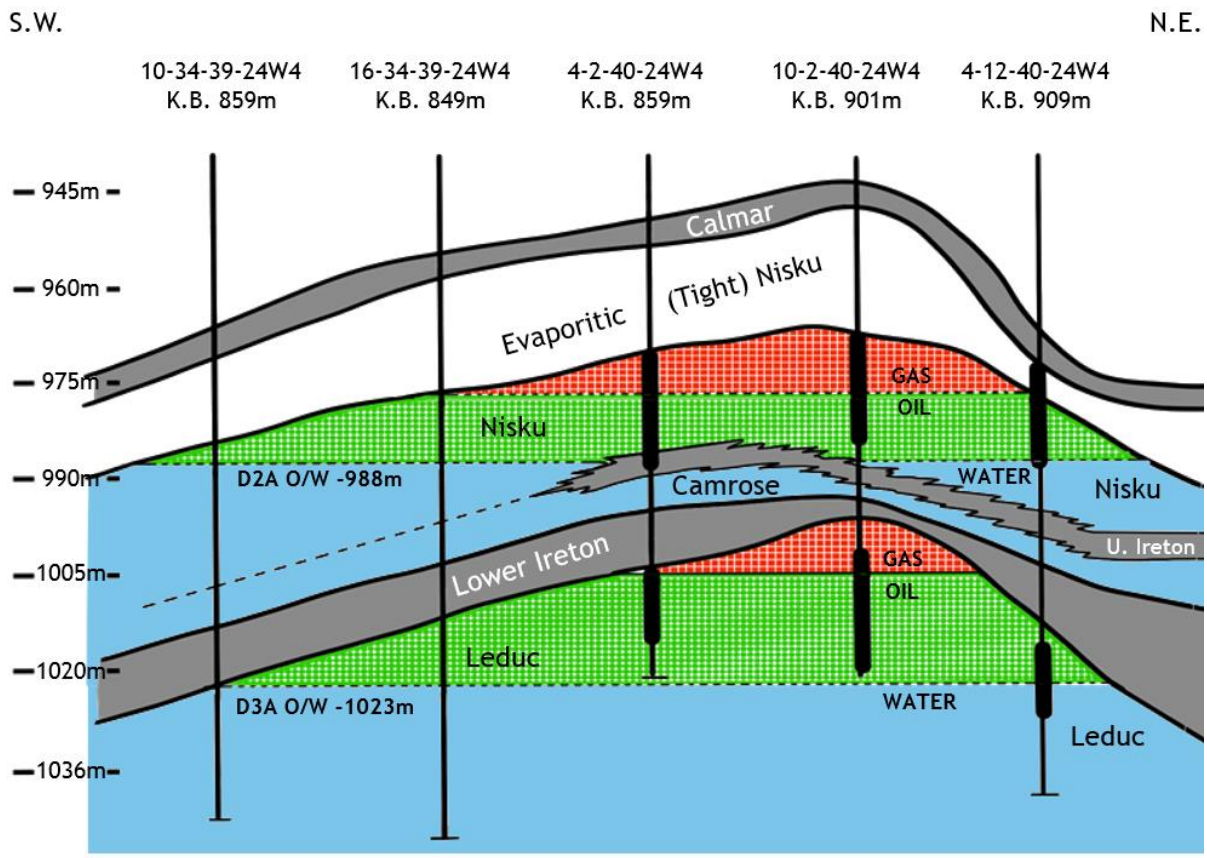


Figure 2-5 Schematic Structural Cross-Section through Clive Central

The Nisku oil/water contact is 35m higher than the Leduc oil/water contact, suggesting the Ireton is an effective and geologically long-term barrier.

Total Ireton thickness across the field is approximately 10m in Central and South Clive, thickening to approximately 17m in the north in response to the presence of the Camrose and Upper Ireton. To better understand the capping mechanism throughout Clive, clean and porous carbonate layers are discounted (i.e. excluding thickness of Ireton with V_{shale} less than 25% and porosity greater than 2%) from the Isopach Map to show a Net Cap Map (see excerpt in Figure 2-6). The thinnest Ireton Cap across Clive is located on the boundary of sections 2, 3 and 11 of Township 40-24W4, where total cap is 4.3m at its minimum (04-11 location). The Ireton held down a 13m column of oil and gas at this location.

Within a 3.2-kilometer radius of the proposed injection well, 102/15-35-039-24W4, neutron-density cross-plot log interpretation (Moradi *et al*., 2016) was supplemented by the review of 22 core analyses where all, or most, of the Ireton Formation was cored. Selected cores were physically examined for evidence of a breach in Ireton

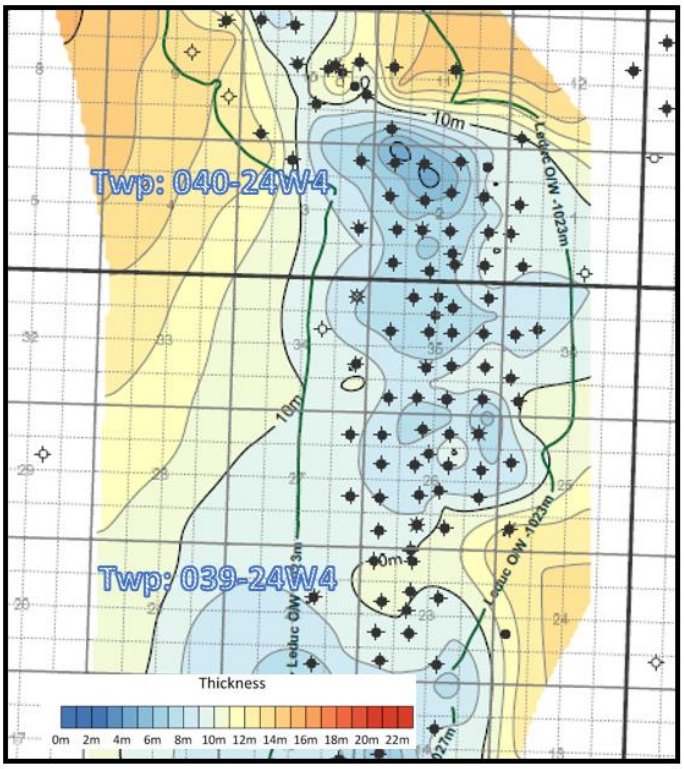


Figure 2-6 Ireton Cap Thickness

Cap is thinnest over the top of Central Clive but has not been breached since oil and gas emplacement. See **Appendix A** for full version.

rocks between the Leduc and the Nisku; no evidence of breaching was found. Enhance has examined select cores where core reports indicated porosity existed in the Ireton Formation and determined the cores were off-depth and that significant Ireton aquitard exists in all cases.

Enhance's detailed examination of Ireton seal integrity was undertaken to evaluate the Ireton aquitard's effectiveness, following review of a paper by Hearn, Machel and Rostron (2011). Enhance's more refined core evaluation and geological mapping confirmed no breach in the Ireton cap rock exists at Clive. Elsewhere on the Bashaw Bank, Hearn *et al*. demonstrate that breaches are indeed present by observed absence of Ireton in the Haynes and Nevis areas, thus explaining pressure communication across the Ireton.

The presence of a competent barrier to the Clive Leduc pool is demonstrated by gas and oil entrapment of the pool on discovery; without the barrier, gas and oil would have leaked away over the tens of millions of years since hydrocarbon emplacement.

While there is evidence of pressure communication between the Leduc and Nisku at Clive, this communication is via documented Ireton cap rock breaches elsewhere on the Bashaw Platform. A detailed investigation of cap rock properties confirmed no hydrocarbons breached the Ireton at Clive. The Ireton cap rock will retain CO_2 injection at Clive.

Lateral Seals

The primary updip lateral seal on the eastern side of the Clive Field is the Clive Channel (Figure 2-7). The channel creates a gentle roll off the raised margin into a structural low along Clive's updip edge. The Clive Channel's dimensions are difficult to quantify because well control is lacking, but it is at least 25km long and approximately 1.5 km wide in the Central Clive area. Only one vertical well penetrates close to the axis of the channel, at 10-4-41-24W4, which shows the Leduc at a depth of -1040m sub-sea, 17m below the oil/water contact of the Clive A Pool. Further south, the central axis of the channel shallows but remains well below the Clive Leduc's **SPILL POINT**.

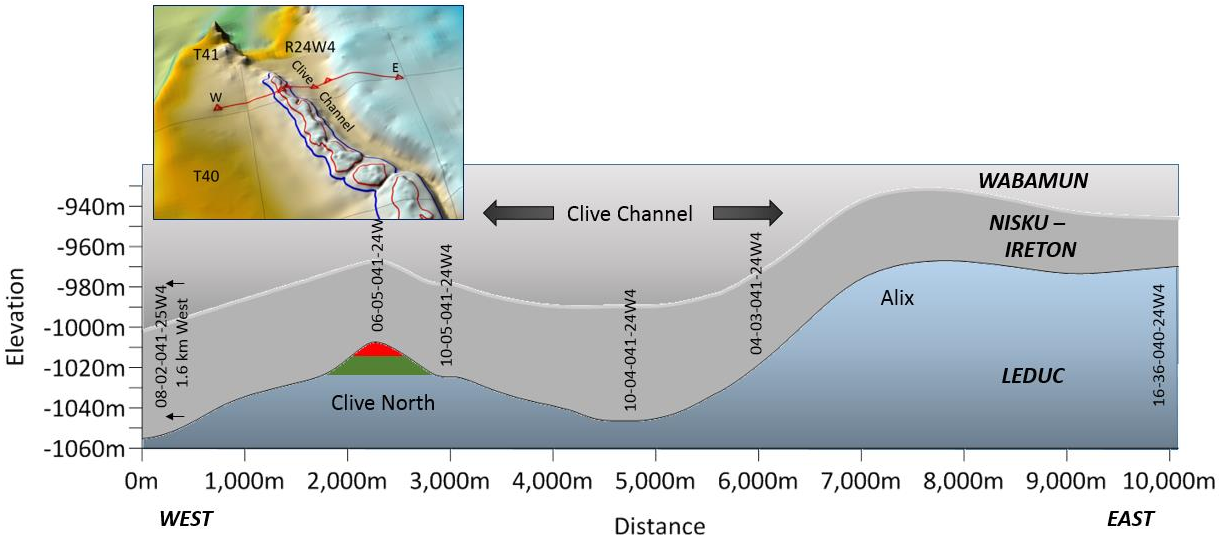


Figure 2-7 East to west slice-through of the Devonian at Clive

The Clive Channel creates the updip barrier for hydrocarbon accumulation at Clive.

As described above, Clive's location is the product of a raised rim associated with the Clive Channel. As such, Clive, Chigwell and Haynes pools are all part of the same linear ridge of the Leduc but have hydrocarbon reservoirs that are separated by saddles along the ridge (Figure 2-8). These lows provide likely spill points between these fields. The saddles have been identified by well penetration and/or inferred by a change in original contacts on either side. The saddles' shape indicates they were small tributary tidal channels that directed ebbing waters from the platform interior eastwards across the shoals and into the Clive Channel. The northern tip of the Clive Leduc pool is defined by an apparently significant low (**S1**, possibly 17m below contact at 10-7-41-24W4) bridging it from the Chigwell Field. The southern tip is a less pronounced saddle (**S4**), possibly only deeper by a few metres below the -1,027m SS Clive South Oil Water contact. This (**S4**) is the Leduc spill point for Clive. Between these saddles that bound the Clive Field, smaller saddles compartmentalise the Clive Central from Clive North (**S2** - at least to -1,014m deep, separating gas contact) and Clive South (**S3** to at least -1,027m deep, separating oil contact). Separation between Central and South Clive (via **S3**) provides another layer of containment during the first phase of CO_2 development between the injection wells and the field spill point. By the time Enhance moves into South Clive, gas dynamics observation will have had the chance to corroborate modelled, or expected, behaviour.

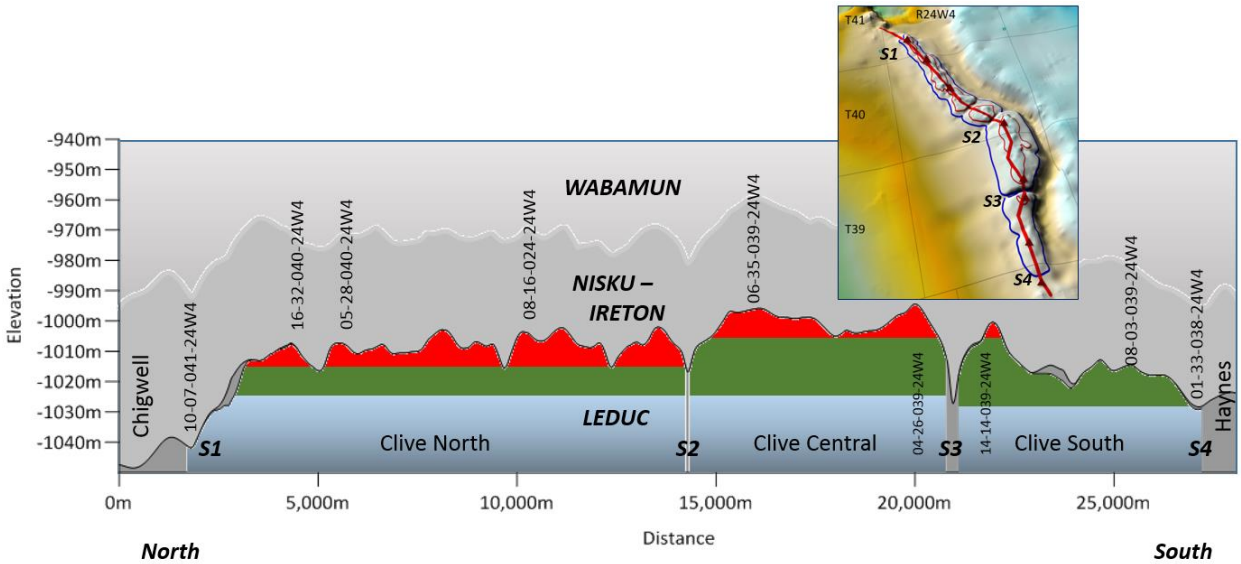


Figure 2-8 North to south slice-through of the Leduc to Wabamun layers at Clive

Saddles bisecting the reservoir give rise to differences in oil/water contacts along the length of the field.

The trapping mechanism that held oil and gas at Clive for tens of millions of years is evident from Leduc surface mapping. A combination of the raised porous Leduc abutted against the Clive Channel's tight Ireton forms the updip seal. Ireton-filled saddles cut across the Leduc pool, segregating it from the Chigwell and Haynes fields. The saddle at Clive's southern point is the field's spill point.

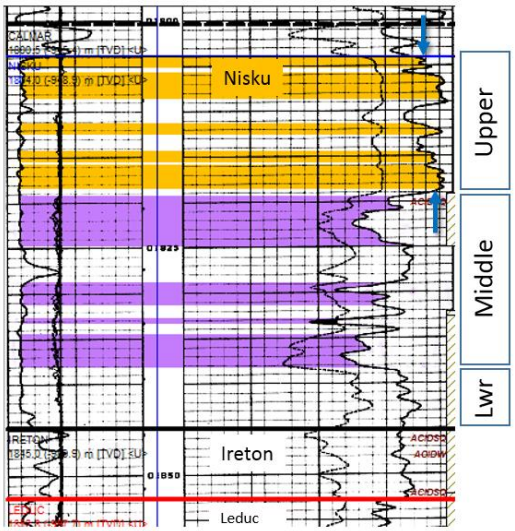


Figure 2-9 Density Log

Density log reveals dense layers of anhydrite (yellow) in the Upper Nisku that blanket the Middle Nisku reservoir (purple).

Full understanding of the reservoir geometry and seal as a container allows Enhance to confidently predict viability and CO_2 storage risk. As such, the geology of the Clive Leduc A Pool can be demonstrated as a safe location for long-term CO_2 storage.

Secondary Seals

As the Ireton shales provide the primary seal for the Leduc reservoir, there are a number of geological formations above the shales that play a role as secondary seals – formations that, in the unlikely event of CO_2 entering the Nisku, would prevent any losses from reaching shallow aquifers. An evaluation of the main barriers' (aquitards) competence to cross-formational flow has been the subject of a detailed hydrogeological characterization by AITF, which used formation waters analysis, **DRILLSTEM** tests and core analyses. The full results are presented in **Appendix B**.

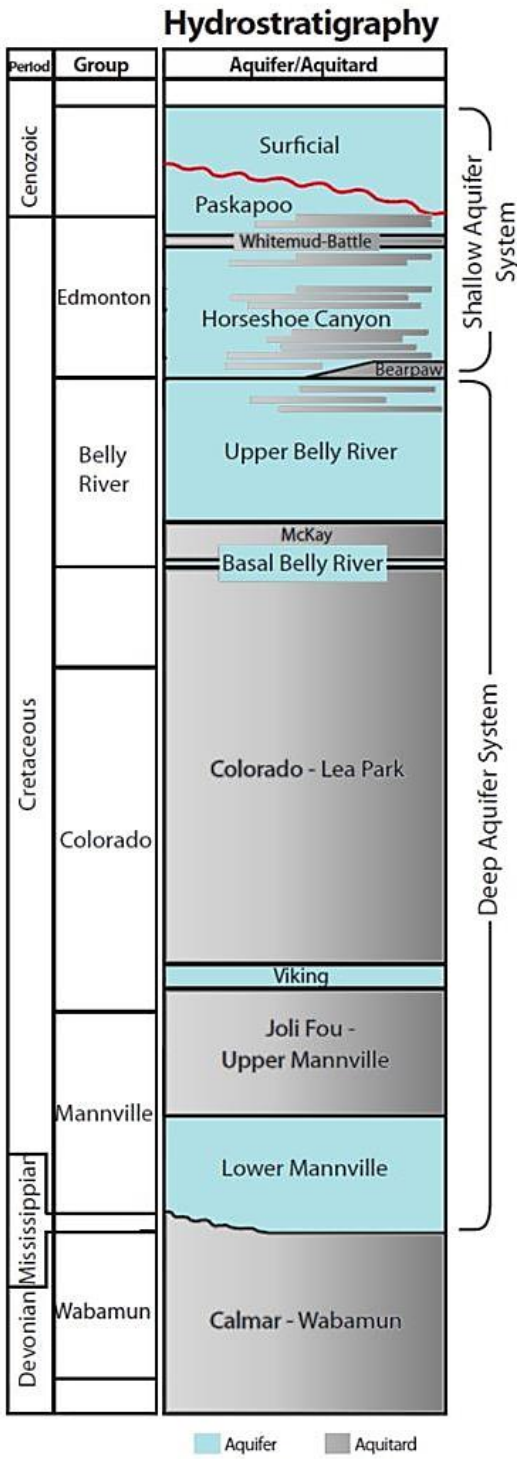


Figure 2-10 Geology overlying Clive Field

Aquifers and aquitards are represented by the blue and grey layers, respectively, in the column at right. From AITF as found in **Appendix B**.

Immediately above the Ireton is the Nisku Formation, a zone very similar to the Leduc and, indeed, as a porous dolomite represents the return to similar carbonate-producing conditions. Like the Leduc, the Nisku has acted as a hydrocarbon reservoir – with a gas column up to 28m thick and an oil column of 8m thick – thereby proving it has a strong confining cap rock. The cap for the Nisku Reservoir is self-contained in the widespread anhydrite sheets that cap the upper third of the formation (Figure 2-9).

A very thick package of Paleozoic, Mesozoic and Cenozoic sediments (approximately 2,000 m thick) overlies the Nisku pool in the study area (Figure 2-10). All the geological, hydrogeological and mineralogical evidence collected and interpreted in this study indicates the Clive Leduc and Nisku reservoirs are capped by strong and thick seals of the Calmar-Wabamun aquitard (which includes, in places, remnants of the Carboniferous shales of the Exshaw and Lower Banff formations). This is overlain in turn by a succession of aquifers, listed in ascending order: Lower Mannville, Viking, Basal Belly River and Upper Belly River. These aquifers are separated by strong intervening aquitards – Joli Fou, Colorado, McKay and Bearpaw – which constitute secondary traps and secondary barriers. The deep aquifers and aquitards in the study area are overlain by a succession of shallow aquifers which are within the depth of protected groundwater in the area: Horseshoe Canyon, Scollard-Paskapoo and Surficial.

In the unlikely event of CO_2 leakage, the formation water will become acidic locally, resulting in reactions with the rock minerals and potential formation of new minerals. The Leduc, Nisku, Calmar and Wabamun strata are primarily carbonate- and/or sulphate-mineral-containing formations. The overlying strata are all siliciclastics (sandstones and shales) and can only be distinguished by the amount of other phases present. Some of the carbonate minerals present in the overlying formations (calcite, dolomite and/or siderite) will likely dissolve. Illite and potassium feldspar would likely react to form kaolinite and slightly change the formation water composition. The presence of plagioclase suggests that, as it dissolves into the more acidic formation water, the increased levels of calcium in the formation will result in calcite precipitation (AITF, **Appendix B**).

The aquitards' strength in the sedimentary succession indicates there is no quantifiable likelihood of leakage through the natural geological and hydrogeological system in the Clive study area.

HYDROGEOLOGY

The Clive Leduc field is located within the Lacombe County in south-central Alberta. The County lies within the Red Deer River watershed, which encompasses 11 sub-basins. Most of the Project area falls within the "Red Deer River Near Nevis" basin, as illustrated in Figure 2-11.

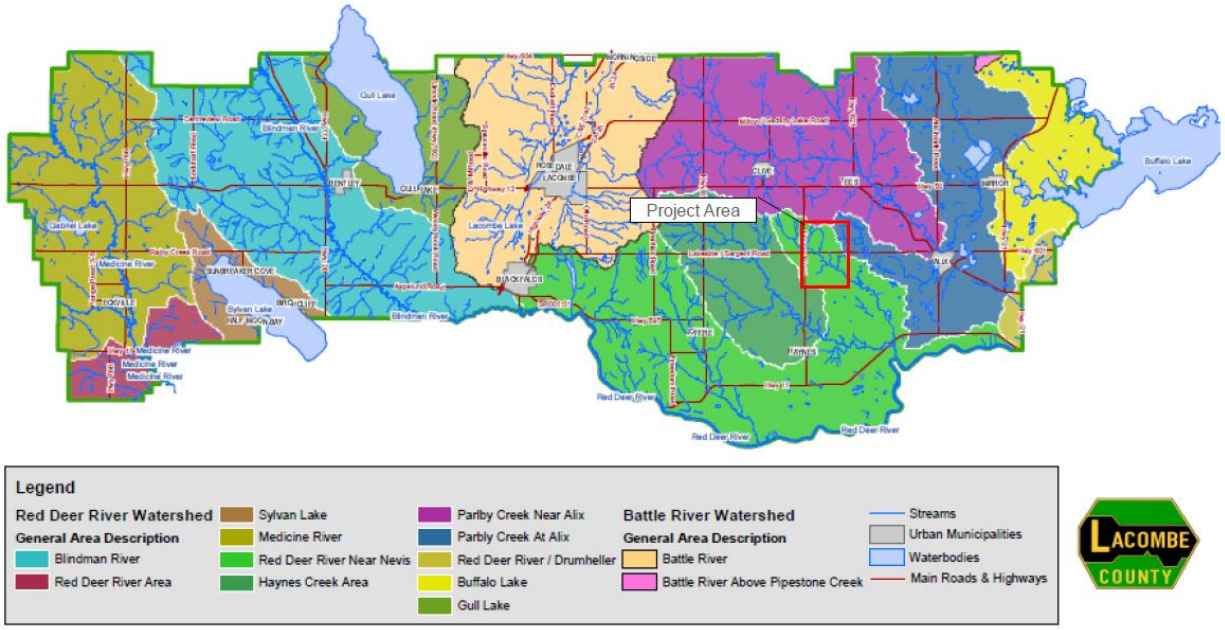


Figure 2-11 Lacombe County Drainage Basins (Lacombe County 2019, internet site)

Surficial Deposits

According to the Regional Groundwater Assessment completed for the Lacombe County (HCL 2001), surficial deposits in the County are typically less than 20 to 30 metres thick and include pre-glacial materials and pre-glacial fluvial and lacustrine deposits. Within the **MMV Plan Area**, the main aquifers are shallow bedrock as the surficial sediments are either absent or relatively thin, i.e., up to 5 m in thickness (Figure 2-12).

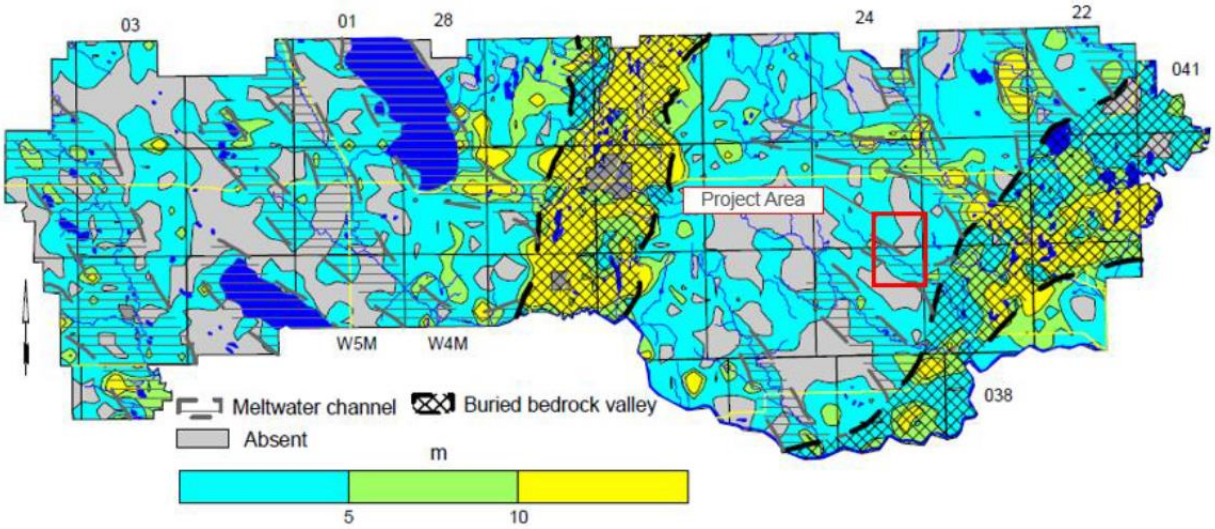


Figure 2-12: Thickness of Sand and Gravel Deposits (HCL 2001)

Water wells completed in surficial deposits are found primarily along the Buried Red Deer and Buffalo Lake valleys (eastern and central side of the County, respectively) and the Gilby Meltwater Channel (western side of the County). Within the **MMV Plan Area**, however, there appears to be few (if any) water wells completed in surficial deposits (Figure 2-13), which may be explained by the absence or low thickness (<5 m) of sand and gravel deposits observed in the Project Area (refer to the previous Figure 2-12).

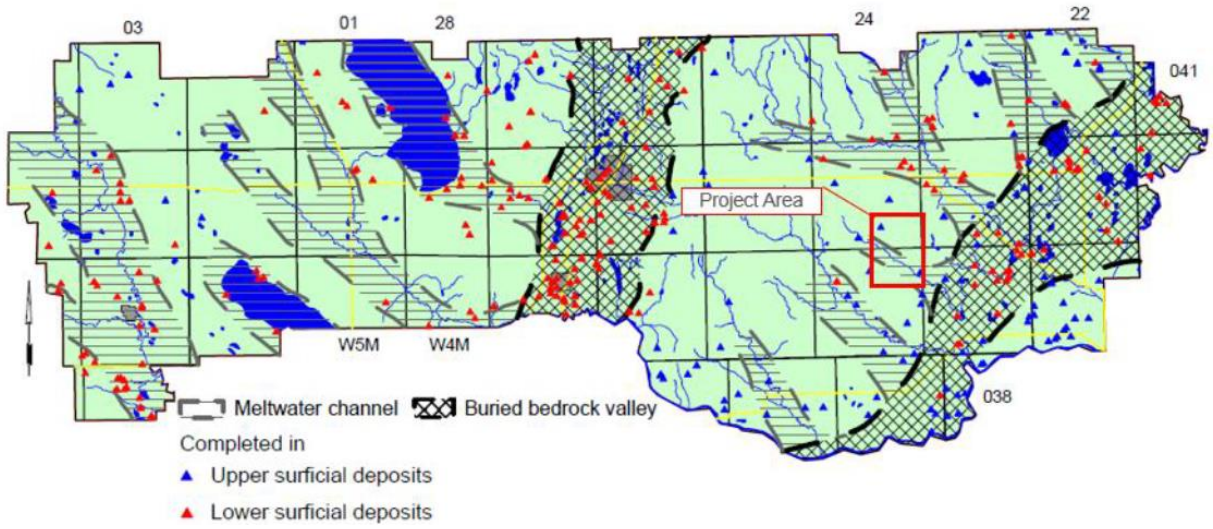


Figure 2-13: Water Wells Completed in Surficial Deposits (HCL 2001)

Bedrock Geology

The upper bedrock in the County consists of the Paskapoo, Scollard, Whitemud, Battle, and Upper Horseshoe Canyon Formations (HCL 2001). Of these, the project area is underlain by the Lower Lacombe and Haynes Member, both of which are members of the Paskapoo Formation (Figure 2-14).

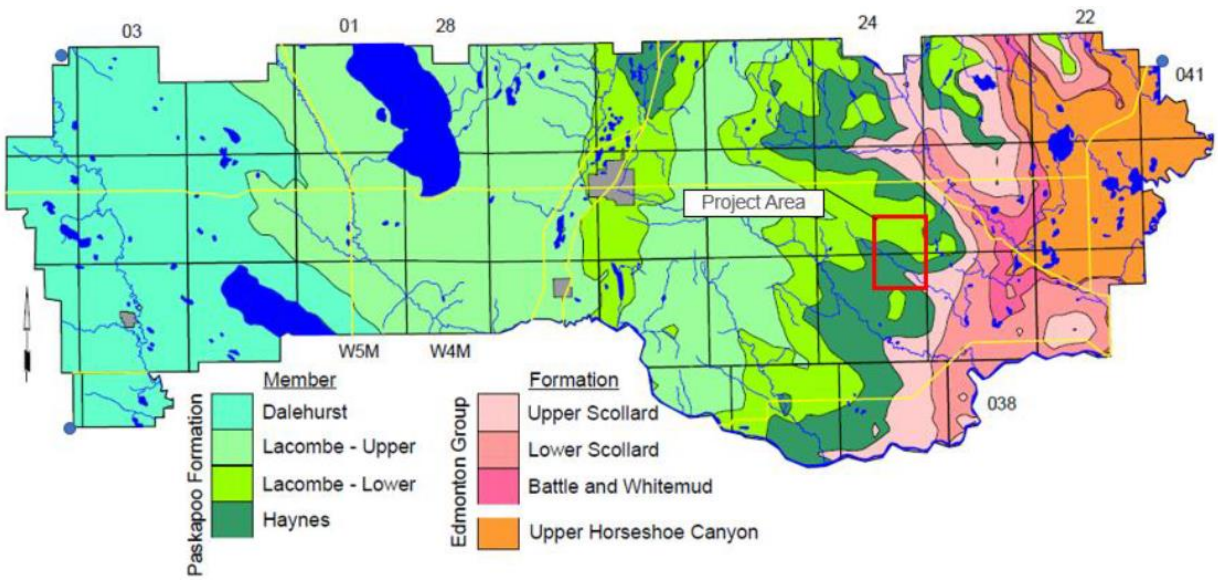


Figure 2-14: Bedrock Geology (HCL 2001)

The Lower Lacombe Member has a maximum thickness of approximately 100 m (average is 50 m) and is comprised of sandstone and a coal zone in the middle. The depth to the top of the Lower Lacombe Member ranges from less than 10 metres below ground surface (mbgs) in the eastern part of the County (**MMV Plan Area**) to more than 250 mbgs in the western side of the County.

The Haynes Member (which lies underneath the Lacombe Member) has a maximum thickness of approximately 100 m (average is 40 m) and is comprised of sandstone with some siltstone, shale and coal. The depth to the top of the Haynes Member ranges from less than 10 mbgs in the eastern part of the County (Project area) to more than 300 mbgs in the western side of the County.

Bedrock water wells within Project area (Figure 2-15) are completed in the Lower Lacombe Member and Haynes Member, as previously shown in Figure 2-14.

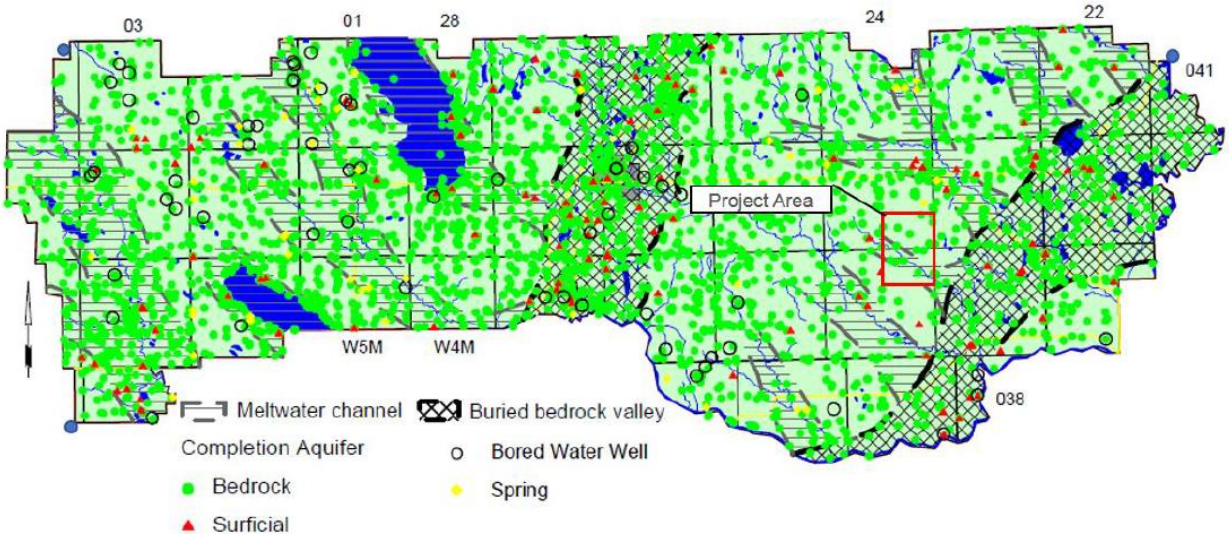


Figure 2-15 Water Wells Location (HCL 2001)

GEOCHEMICAL EFFECTS ON DEEP FORMATIONS IN CASE OF CO_2 LEAKAGE

The following summarizes the findings of AITF's report entitled *Geochemical Effects on the Deep Strata in Case of CO_2 Leakage from the Clive Leduc and Clive Nisku Oil Reservoirs in the Clive Oil Field in Alberta* (authors Stephen Talman, Ph.D.; and Stefan Bachu, Ph.D., P.Eng), which evaluates the potential CO_2 interactions with reservoir rock and brine in the unlikely event of containment loss. Please refer to **Appendix C** for full document and updated information.

The study's objective was to assess the likely geochemical interactions between the injected CO_2 and the rocks and water contained in the Leduc and Nisku oil reservoirs and in overlying saline aquifers, assuming that CO_2 or CO_2-rich water leakage from the reservoir may occur.

Within the oil reservoirs, in both of which the host rock is relatively pure dolomite, the interaction between CO_2 and reservoir minerals will lead to the breakdown of feldspars, present in minor amounts, to form clays. There is also some transformation of the carbonate minerals within the reservoir; however, this will be minor. Overall, the predicted geochemical reactions will lead to a trivial decrease in porosity in the oil reservoirs, with no expected impact on reservoir characteristics, particularly permeability.

Leaking fluids would interact with formation water and minerals in a succession of saline aquifers. These are, in ascending order: Lower Mannville, Viking, Basal Belly River and Upper Belly River. These overlying aquifers, being of siliciclastic nature, are mineralogically more complex than the carbonate oil reservoirs, therefore the resultant geochemical reactions are accordingly more complex. In the case of pure CO_2 leakage into these aquifers, the general tendency will be for the pre-existing feldspars and complex clays to break down, forming the simpler, more acidic clay mineral kaolinite and a pure silica phase. As well, significant quantities of the magnesium carbonate, magnesite, are predicted to form within the Basal and Upper Belly River aquifers.

The capacity of the aquifers overlying the oil reservoirs to trap CO_2, either within mineral phases or as bicarbonate in the water, is greater in the upper two aquifers (Basal and Upper Belly River) than in the lower ones (Lower Mannville and Viking). One reason is the markedly lower salinity in the former than in the latter. Calculations indicate that, following equilibration with a free-phase CO_2, free CO_2 will continue to exist within the Mannville and Viking aquifers but not in the Basal and Upper Belly River aquifers. Leakage through any of these aquifers would also result in some dispersion and dilution of any vertical CO_2 **FLUX** into each of these aquifers.

Acidified brines leaking into these aquifers would result in a more complex set of reactions. The flow of cation-laden brines can induce acid-forming reactions. As such, the pH of waters resulting from the mixing of CO_2-enriched, reservoir-derived water with that from the overlying aquifers will generally be lower (the water will be more acidic) than in the case of pure CO_2 flow. This has implications when considering trace metal mobility within affected aquifers; generally, the mobility increases as pH decreases.

The hydraulic gradient and water chemistry analyses completed in this study show strong evidence of five effective aquitards which would prevent upward migration of CO_2 and four significant aquifers that are isolated from one another, which could absorb and dissipate any CO_2 should upward migration occur. The planned monitoring program's chemistry-related components will provide additional assurance of containment

through independent and complementary analysis of soil, water well and CBM gases, and analysis of water samples from domestic wells.

GEOMECHANICAL ANALYSIS OF THE EFFECTS OF CO_2 INJECTION

The following summarizes the findings of the AITF report entitled *Geomechanical Analysis of the Effects of CO_2 Injection in the Clive Leduc and Clive Nisku Reservoirs in the Clive Field, Phase 2 Report* (authors Hamidreza Soltanzadeh, Ph.D., P.Eng.; Alireza Jafari, Ph.D.; and Tyler Hauck, M.Sc., P.Geol), which assesses potential geomechanical effects from CO_2 injection. Please refer to **Appendix D** for full document and updated information.

Injecting CO_2 into a hydrocarbon reservoir or deep saline aquifer results in pore pressure and temperature changes, both of which may induce deformations and stresses in the injection zone and the rocks that surround it. Geomechanical analysis is required to predict the effects of these induced deformations and stresses on the injection zone's bounding seal mechanical, or hydraulic, integrity. The study's primary objective was to characterize the rock mechanical properties and in situ stresses within the sedimentary succession above the Leduc and Nisku oil reservoirs in the **MMV Plan Area** (more specifically, from the base of the Calmar Formation to ground surface), and to construct a two-dimensional mechanical earth model (2D MEM). This model included geomechanical characterization of the geological units from the Cooking Lake Formation to the surface. Then, 3D numerical modelling was conducted to study the geomechanical response of the Clive Leduc and Clive Nisku reservoirs to historical oil and gas production and future CO_2 injection.

To study the effects of pressure changes, a 3D geomechanical model was developed for the entire study area. The results indicated the potential for fracturing and fault reactivation has been low during the historical producing life of the field. Therefore, it is less likely the integrity of the cap rock has been disturbed during this period. The results also showed low potential for fracturing or fault reactivation induced by future CO_2 injection. The modelling predicted a maximum surface heave of 2.4mm as a result of CO_2 injection pressure build-up.

Sensitivity analysis confirms the variations in the mechanical rock properties do not lead to meaningful changes in the modelling results regarding the low potential for fracturing and fault reactivation induced by pressure changes. The effects of these variations on the predicted reservoir deformation and surface heave are only in order of millimetres.

To study the effects of temperature changes induced by CO_2 injection at temperatures lower than reservoir temperature, a single vertical well geomechanical model was developed. The modelling was performed based on two scenarios: of 15°C and 30°C for the injected CO_2 temperatures. The results indicate that, for both cases, tensile fractures are likely to occur due to cooling effects within the reservoir. However, simulation of the cap rock's integrity, which is a key factor contributing to the Leduc being an ideal storage container, was not considered under these conditions. To mitigate these effects, Enhance will exclusively use horizontal injection wells, for which the long-term impacts of cold CO_2 injection on cap rock integrity have been modelled through a variety of different geological scenarios, with results showing cooling *does not significantly affect the cap rock* (Vilarrasa *et al*., 2014). Further to this, Enhance's simulation modelling shows injection pressures with horizontal wells will be 75% lower than what was modelled in the AITF geomechanical study, further mitigating risk of injection-induced fracturing.

CLIVE LEDUC PRESSURE HISTORY AND BASHAW PLATFORM AQUIFER SUPPORT

The Bashaw Platform's **HYDROGEOLOGY** has been researched at length (Tsang and Springer, 1983; Hearn, 1995; Hearn *et. al*, 2011; Rostron *et. al*, 1997; Paul, 1994; Schwark and Laenen, 2000), not least because of the role it played in the conveyance of massive volumes of hydrocarbons between Duvernay source and Upper Cretaceous deposits. The Clive Leduc pool, like other pools along the reef complex, receives pressure support from the Bashaw Platform Aquifer. In 1962, it was first recognized pressures were dropping in all of the platform's D3 pools and the cause was extensive gas drawdown in the Nevis Field (Figure 2-16). The drawdown was recognized as far away as Innisfail, 100km from Nevis (Tsang and Springer, 1983). In response to the pressure decline, the Clive Leduc pool was **UNITIZED** in 1970 and a bottom-water injection pressure maintenance scheme was approved. Clive's original reservoir pressure was 17,485 kPa (2,535 psi). Fresh-source water, as well as produced water, was injected to supplement the bottom-water drive until 1996, but the injected volumes did little to offset the pressure decline. In 1996, fresh-source water injection was discontinued and only produced water was injected. The reservoir pressure stabilized at approximately 13,500 kPa (1,960 psi) in the early 1990s and, since then, pressure has changed little, as hydrocarbon production and natural recharge appear to be balanced.

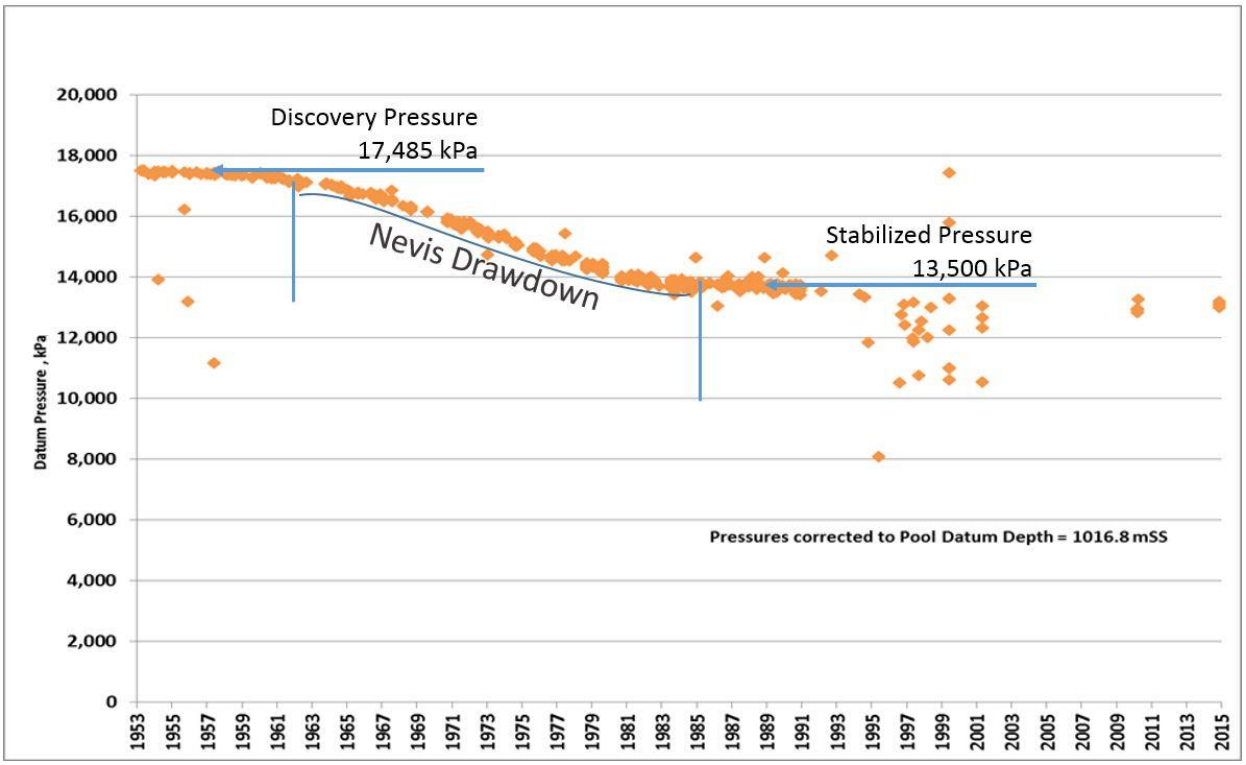


Figure 2-16: Clive Leduc Pressure History

Pressure decline due to the Nevis Field blow-down confirms the connectivity of reservoirs on the Bashaw platform. Post-Nevis blow-down, natural recharge has been sufficient to stabilize pressure.

Despite the drawdown causing issues on the Bashaw Platform's other fields, its effects highlighted three aspects of the aquifer. First, the aquifer is extremely well connected throughout its extent, allowing for pressure communication over large distances. Second, the aquifer is very large but finite. The Bashaw Platform's pore volume is massive (30km^3 based on an average porosity of 4%). However, this was not enough to prevent the pressure drop of the entire aquifer, which in turn suggests that, third, external connectivity is limited. This final aspect suggests the Cooking Lake Formation does not significantly support the platform.

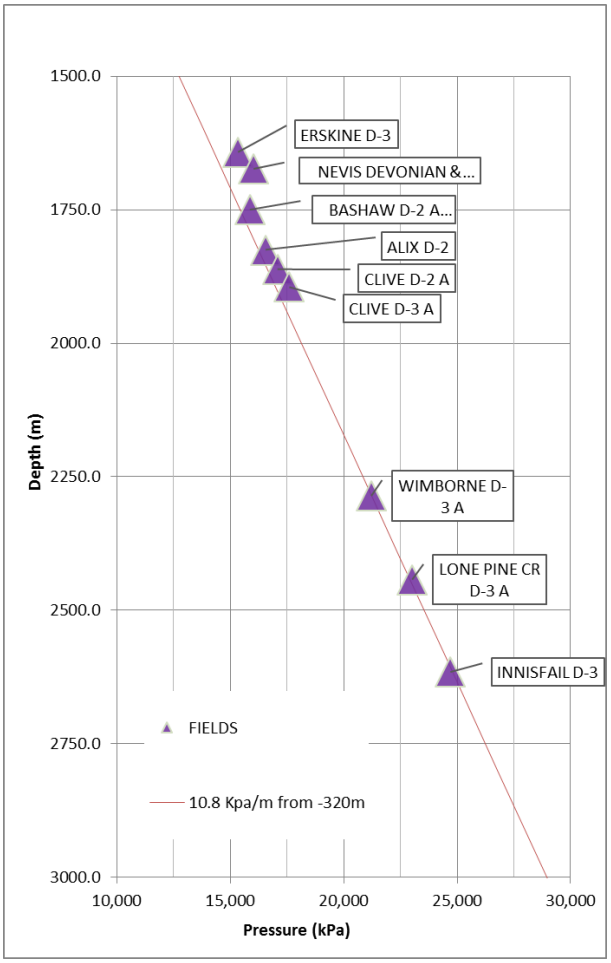


Figure 2-17: Pressure/Depth Chart of Bashaw Platform Fields

Alignment of the fields suggests they have a common Leduc aquifer, while the match of the gradient and the brine density suggest the waters are static (adapted from Tsang and Springer, 1983).

Hydrogeological conditions of discoveries on the platform provide further evidence of a lack of significant drive. Figure 2-17 shows discovery pressure for all of Bashaw Platform's major D2 and D3 fields (and Erskine, which is separate). Fields mostly align on a **GRADIENT** of 10.8 Kpa/m, which conforms to the weight of the average Leduc brine. A match between gradient and fluid weight suggests the aquifer is static and there is no significant mobility in the system on discovery. Additionally, elevated brine salinities indicate there has been little fresh water dilution, as might be the case if the aquifer was open to freshwater circulation from the surface.

The Bashaw Platform Aquifer is both vast and isolated. Historical pressure measurements at Clive and other fields connected to the aquifer suggest there was little natural fluid drive prior to development and, despite connectivity in the aquifer, under-pressured conditions caused by the Nevis Drawdown have been very slow to recover.

CLIVE LEDUC PRODUCTION HISTORY

The Clive Leduc discovery well was drilled in 1952. The pool has since been delineated and developed, with the drilling of 168 wellbores. At peak production in 1979, the daily oil rate was 912 m^3/d (5,735 bopd) from 82 wells (Figure 2-18). Three **STATIC GRADIENTS** taken in November 2014 confirm the current reservoir pressure remains at 13,500 kPa (1,960 psi). Enhance conducted **SLIM TUBE TESTS**, the results of which confirmed CO_2 will be **MISCIBLE** with the oil at this pressure, supporting the feasibility of CO_2 EOR at Clive. Furthermore, there will be no need to increase pressure to achieve miscibility. This means that Enhance can conduct the CO_2 flood at close to current conditions, eliminating any risk of containment issues related to over-pressuring the reservoir.

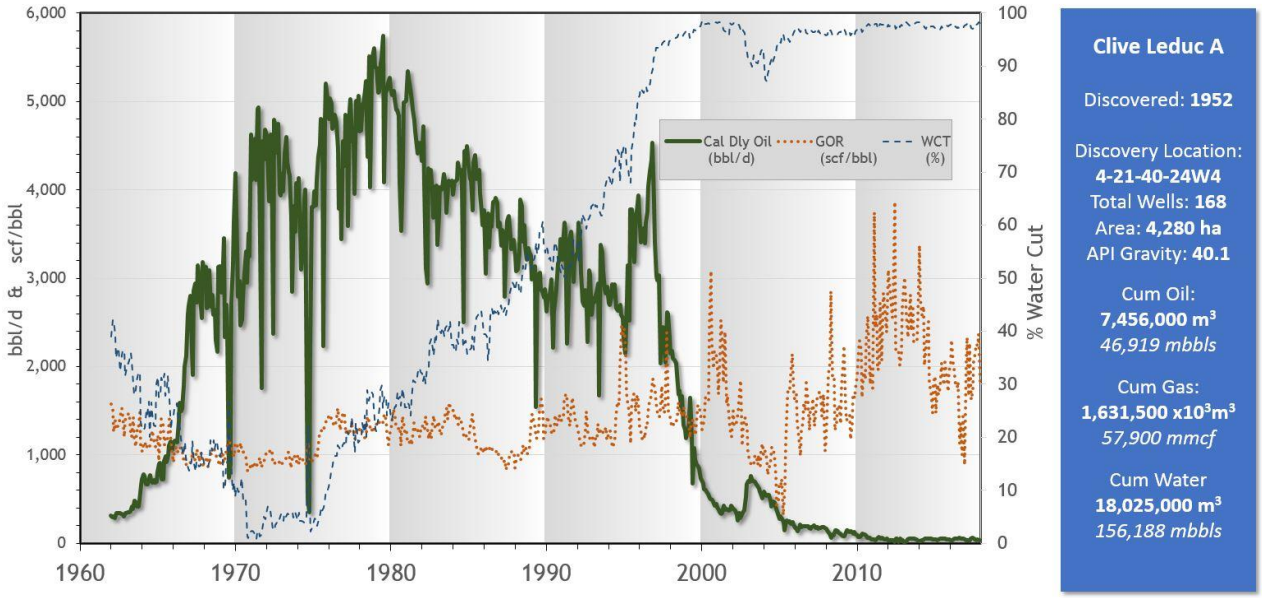


Figure 2-18: Clive Leduc Production History

The field was rapidly developed in the 1960s and continued to improve until 1980. From that point on, water production has increased, resulting in many wells to water out and reduced oil recovery. Recent production is concentrated along the highest points of the reservoir, as the field approaches its end of life.

CLIVE GEO-MODEL

The geological study's primary goal was to understand and characterize fluid flow through the reservoir. Building a Clive geo-model, which can be used to test different development scenarios, was the most successful way to achieve the goal. Complex relationships that recorded constantly fluctuating conditions during platform growth at Clive have to be distilled from observations from core and well logs.

Included Geological Components in this Study:

1. A detailed 16-well Leduc core study describing depositional and diagenetic fabrics and establishing an environmental framework. Dr. Jeff Packard conducted this study. Ongoing observations of the remaining central Clive cores have used the designations and framework set forth in the initial study.

2. Petrophysical analysis of 180 well logs at Clive, with a range of vintages from the 1950s to the late 2000s. An in-house processing tool was developed to calibrate core data with various petrophysical analysis methods on a well-by-well basis. Output from the tool included porosity, permeability (lateral and vertical) and water saturation (SW).

3. Construction of a geo-model. The geological study's ultimate goal was to construct a geo-model that can be used to build a reservoir model with the highest degree of confidence possible. This constrains the simulation to ensure the best possible history match and predictions. As well as input from the petrophysical analysis, the geo-model incorporated lateral facies distribution parameters and vertical facies associations, and a particular focus was made on baffles and aquitard lenses to better approximate the reservoir's true flow dynamic in simulation.

Petrophysical Study

Existing wells at Clive provide outstanding coverage of the Leduc complex that, coupled with over 50 years of production and injection data, allow for an excellent understanding of the formation's properties. Using Petrel geological modelling software that allows input of geological and petrophysical properties into a framework, Enhance has constructed a refined geological model of the Clive Leduc pool based on log and core data from 180 wells. Petrophysical analysis was conducted on 2,800m of log data, and permeability and porosity data extracted from 3,700 core samples. Advanced modelling techniques were used to construct a 3D geological model based on porosity, permeability, water saturation and facies correlations.

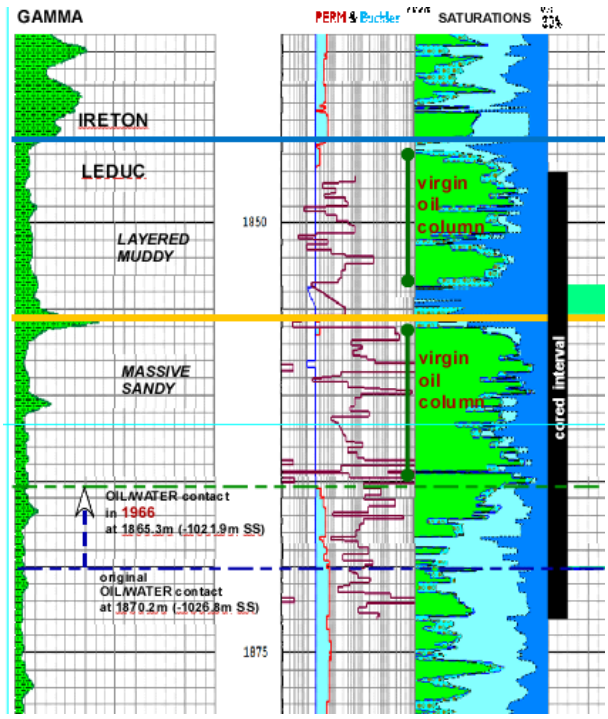


Figure 2-19; Example of Log Analysis Data

The results are graphically presented in the saturations column, where the dark blue fill represents irreducible water, the light blue fill; represents movable water and the light green fill represents hydrocarbons. From 2-35-039-24W4.

To standardize output data from greatly varying input data, a number of challenges had to be addressed, including the need to utilize and cross-calibrate log suites of various vintages (ranging from the 1950s to 2000s). Only 31% of the penetrations were drilled after 1985 and have a relatively complete log suite available. Specific challenges with the older logs included reliance on thermal neutron logs for porosity (if available) for wells drilled in the 1950s and correcting sonic logs for wells drilled in the 1960s where porosities are grossly underestimated as the result of sonic logs' inability to detect vuggy porosity.

Integration of core and log data, utilization of Archie variable 'm' and 'n' methods in solving for water saturations and utilization of the Buckles method (Buckles, 1965) allowed for the identification of various fluid contacts at the time of drilling (Figure 2-19). As well, the recognition of an original oil/water contact in many wells, despite hydrocarbon migration and water flooding, coupled with the identification of residual water saturation profiles for differing pore system types, has allowed for a reassessment of the original hydrocarbon in place.

The Clive field is split into three separate models, each with a grid size of 25m by 25m by 1m at a 45-degree angle to match horizontal well azimuth. Grid cells are bound to structural surfaces and extend to a base at -1,040m, giving 17m of aquifer.

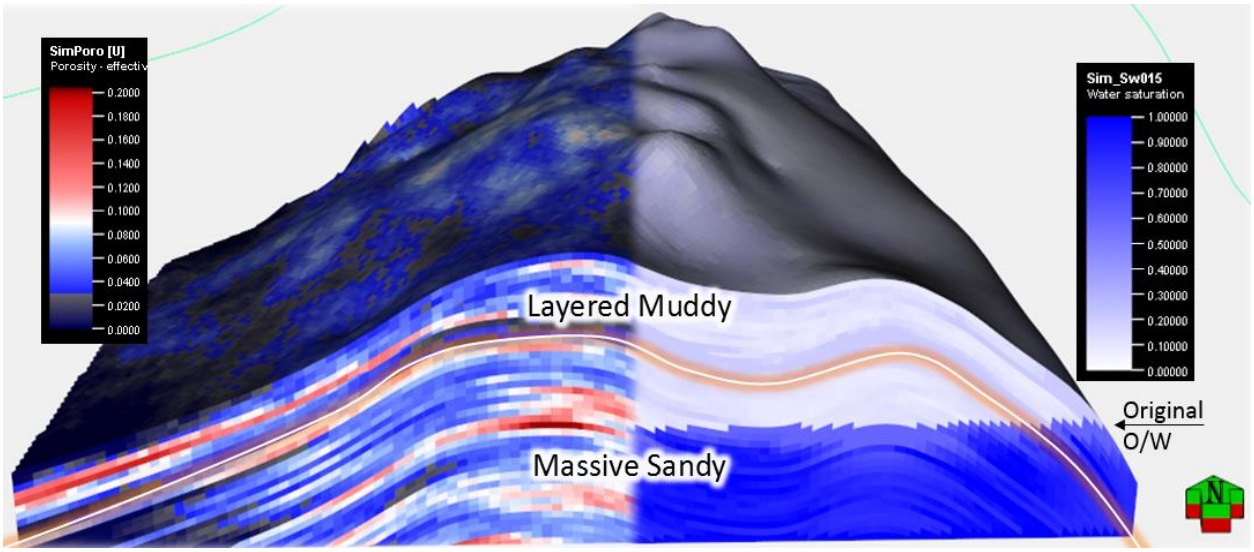


Figure 2-20: Clive Central Area Petrel Geo-Model Looking North

The porosity model is on the left and the saturation model is on the right. 25x vertical exaggeration.

Primary facies distribution at Clive is vertical, so the model was split into four vertical layers: three representing the Layered Muddy Zone and one for the Massive Sandy Zone. A **GAUSSIAN RANDOM FUNCTION** simulation method was used to grid the porosity model, with a *well search area* set to encompass the typical 400m inter-well distance. Lateral and vertical permeability were gridded in conjunction with the porosity grid to maintain a porosity/permeability relationship in calculated cells. As fluid saturation varies according to the date of logging, well data was not used to build the saturation model. Instead, Buckles formula was used, applying an inverse relationship between porosity and water saturation to create an on-discovery water saturation average of 0.15. A transition zone is included in the water saturation grid below the oil/water contact to aid in the integration of the aquifer with the oil zone during simulation (Figure 2-20).

The completed geo-model was exported to CMG's reservoir simulator, IMEX.

SIMULATION MODELLING

Enhance constructed a robust simulation model of the entire Central Area. The model was history matched to over 50 years of production and injection history, with minimal adjustment to geological and fluid property data.

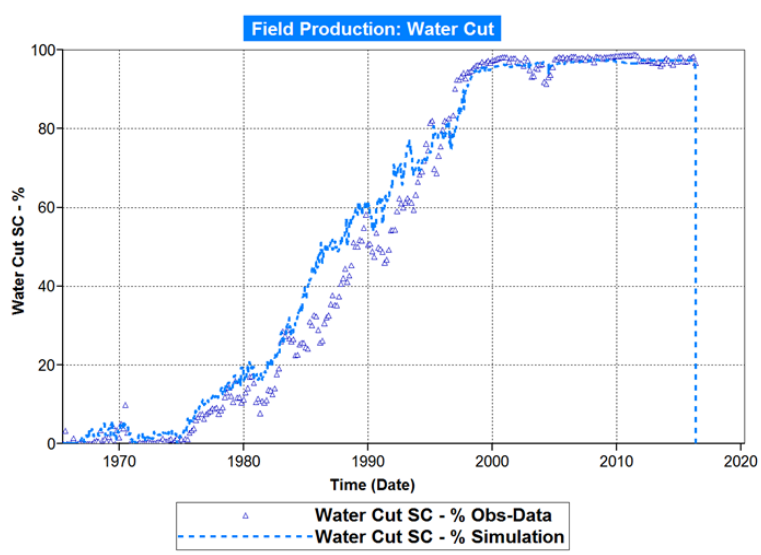
History Matching and CO_2 EOR Prediction

In addition to rock properties, the other important factors to consider in reservoir simulation are the properties and interaction of fluids within the reservoir; initially oil, gas and water, during historical production, followed by the addition of CO_2 during the planned EOR project. The initial oil, gas and water properties for Clive were determined based on produced fluid samples adjusted to reservoir temperature and pressure conditions and were used during the **BLACK OIL MODEL** history match phase of the project. Core Labs conducted slim tube tests and other studies to predict properties during CO_2 EOR. The slim tube tests confirmed that CO_2 is miscible with Clive Leduc oil at current reservoir conditions and provided the data needed to model **COMPOSITIONAL BEHAVIOUR** of oil, gas and CO_2. These relationships were input to the simulator for CO_2 EOR performance

prediction. Core testing derived relative permeability and **RESIDUAL SATURATION**. Modelling of these parameters in the simulator was performed in consultation with Avasthi & Associates Inc., an organization that provided expert review and assistance in appropriately describing these properties in the simulator.

The aforementioned data related to rock and fluid properties and interactions is necessary to construct a valid reservoir model and has been obtained from actual logs, core and fluid analyses. Enhance considers this hard data and has honoured these inputs to the simulation model by making minimal changes to them when **HISTORY MATCHING**. The high-quality history match that was obtained gives confidence in the predictive capability of the simulation model. The Petrel 3D geological model and basic fluid properties were imported into simulation software that Enhance then used to conduct a black oil history match, where the model was tuned to over 50 years of historical oil, water and gas production and pressures.

The Clive Leduc history match was achieved through the application of liquid rate constraint matching historical oil rate, water rate, gas rate, water cut (percentage of water in total produced liquid) and gas-oil-ratio (GOR) at individual wells. Pressure within the model was matched to historical measurements. Changes to the geological model parameters and the relative permeability curves determined from laboratory testing on core samples were deliberately avoided. History was matched through reasonable adjustments to the Leduc aquifer properties and some minor adjustments to permeability at the wells to allow fluid rates to be matched. As shown in Figure 2-21, a good match on produced water cut indicates the aquifer adjustments were valid. Gas and oil profiles offer similarly close results with very minimal differences for the first 25 years. After 1980, there is some divergence, but the close agreement between the overall shapes of the actual and simulated production curves, and only a minor difference in cumulative recovery over the long production history, give confidence the model will provide reliable predictive capability for the CO_2 flood.



This match was obtained with minimal adjustments to the geological model and relative permeability curves, providing additional assurance of its validity.

Figure 2-21 Cumulative Water Production History Match

A very close match between simulated and actual confirms the geo-model is representative of the Clive Leduc pool and can be used as a predictive tool in ongoing planning.

The initial oil, gas and water saturations (i.e. after history matching with the black oil model) for the GEM model are shown in Figure 2-22.

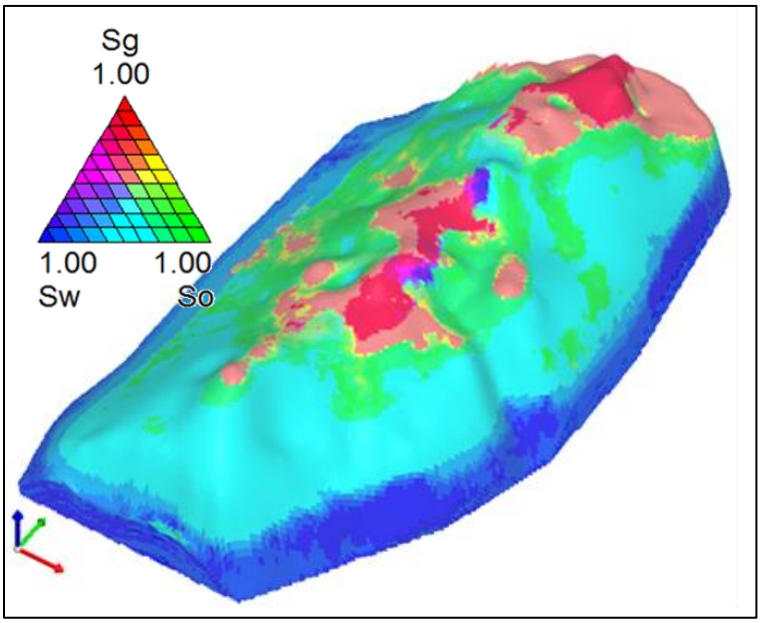


Figure 2-22: Clive Central Model showing Fluid Distribution at end of Black Oil History Match

Free gas, represented by red areas, occurs at the top of the reservoir due to its low density. Water tends to lie towards the bottom and the oil occurs in varying saturations between the free gas and free water phases.

The phase and composition distribution from the final state of the history match model was used to build the initial state of the forecast scenario for compositional modelling; this is referred to as explicit initialization. Incorporation of the CO_2 interaction with oil requires compositional (equation of state) simulation with a modified fluid model that can account for CO_2-hydrocarbon interactions such as the oil swelling effect (density alteration) and oil **VISCOSITY** reduction as a function of CO_2 solubility in oil. The history matched reservoir simulation was used to initialize the compositional model in CMG's **GEM SOFTWARE**; compositional modelling was chosen for CO_2 injection forecast scenarios because it best captures the interactions between the CO_2 and the oil under miscible reservoir conditions. Enhance contracted CMG to derive the inputs required to describe these interactions in their simulator.

GEM simulations predict CO_2 movement and interactions across the model by applying relatively simple calculations to realize the relative density, and therefore movement, of water, oil and CO_2 between every cell in a model, of which there are millions. Figure 2-23 shows the density of CO_2, brine and oil at reservoir temperature and a range of pressures. Of note, the CO_2 curve shows much greater density dependence on pressure than it does on oil (oil density decreases with increasing pressure, as these calculations are for a live oil containing natural gas; as pressure increases, more gas dissolves into the oil and decreases its density). Although the CO_2 will be injected in dense phase, having some properties similar to a liquid, it is still highly compressible and behaves like a gas, in some respects.

At the expected range of EOR operating pressures, Clive Leduc brine is double the density of CO_2. This will cause CO_2 to rise to the top of the reservoir, where it will be structurally trapped against the confining Ireton cap rock.

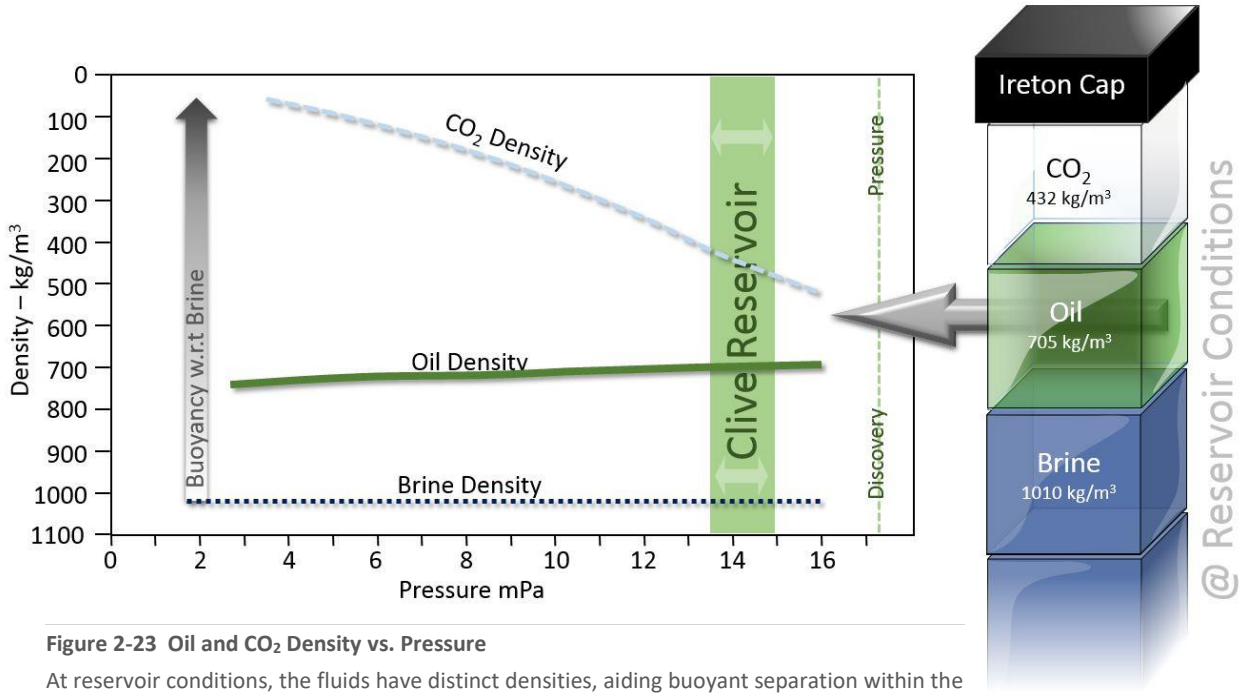


Figure 2-23 Oil and CO_2 Density vs. Pressure

At reservoir conditions, the fluids have distinct densities, aiding buoyant separation within the reservoir. CO_2 trapping long after EOR has finished is assured because CO_2 has less than half of the brine density.

Development Planning

Enhance's goal with EOR is to use CO_2 as efficiently as possible, while maintaining the long-term storage of CO_2 in the formation. To that end, a multitude of different well configurations and production scenarios have been run in the model, each evaluating sequestered CO_2, recycled gas, water production and oil recovery, among others, to establish the best possible development plan. Having considered almost every conceivable development scenario, the chosen plan is to drill horizontal injection and production wells oriented in a northeast-southwest direction; this orientation was selected to take advantage of the reservoir's orientation. Horizontal wells offer broad reservoir access with minimal surface disturbance and achieve higher injectivity and productivity than vertical wells due to the amount of reservoir penetrated. Simulation was run based on the planned schedules for Nutrien and NWR CO_2 supply tie-in. The Central Area model, or Clive Phase 1 development, consists of eight injection wells and eight producing wells (Figure 2-24). Central Area development will commence in the **MMV Plan Area** with six injection wells and six production wells.

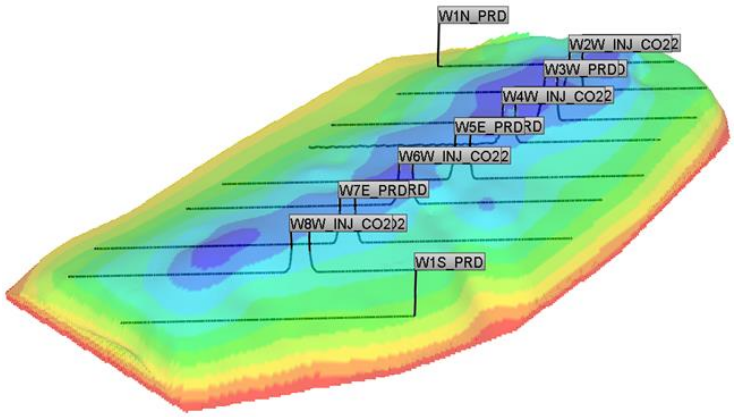


Figure 2-24 Clive Central (MMV Plan Area) Model As Seen From the Southeast

Eight injection wells and eight producing wells, all horizontal, are to be drilled in the NE-SW direction, mostly in the form of well pairs from the central axis.

Injection rates will be maintained at an equivalent injection rate of 30% **HYDROCARBON PORE VOLUME (HCPV)** per year to accommodate the planned volumes.

CO_2 injection will continue for 25 months, until the total injected CO_2 volume reaches approximately 0.50 of the HCPV. Thereafter, a **WATER-ALTERNATING-GAS (WAG)** process starts with conversion of the CO_2 injectors on the east pattern to water injectors. Six months later, the water injection begins on the west injectors, while the east injectors convert back to gas injection. This cyclic conversion happens every six months and injection proceeds until a total injection gas volume of 3.5 HCPV is realized.

To track and account for fluid mobility over the program life cycle, the simulation was run for decades until the reservoir reaches its economic limit, and then for 475 years after development. Figure 2-25 shows the results in three snapshots of CO_2 distribution to represent the initial state during injection (two years), at the end of injection (25 years), and the long-term state (500 years). The decrease in CO_2 saturation from 25 to 500 years is due to continued CO_2 dissolution into the residual oil and water phases in the model, which will diminish as local brines become more saturated.

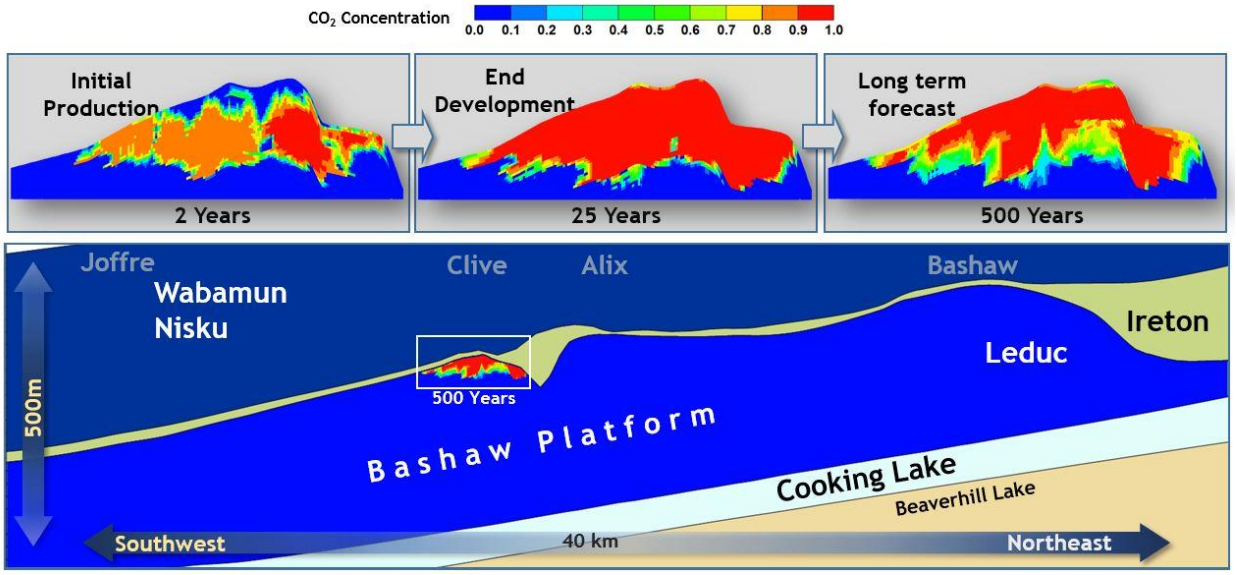


Figure 2-25 Structural Containment of CO_2 for the Long Term

Simulated CO_2 distribution slice-through Central Clive at two, 25 and 500 years, in context of the entire Bashaw Platform (bottom).

The limited CO_2 mobility from end of development through the following 475 years shows containment is stable in the Clive Leduc pool. Enhance concludes there is little risk for loss of geological containment, even over geological time scales.

For this study, Enhance used a version of GEM that does not account for mineralization or ionic trapping of CO_2. However, AITF investigated these phenomena and found they trapped approximately 9% of CO_2 in rock containing only CO_2 and residual water.

Careful injection and production volume monitoring, which can be compared to the simulator's predictions, will achieve pressure maintenance during EOR. The injected fluids volume will be balanced with the produced fluids volume, eliminating the chance of over-pressuring the reservoir and resulting in the reservoir pressure being approximately 20% below initial conditions. Active monitoring and injection/production management allow Enhance to understand CO_2 distribution in the reservoir and to identify any anomalous conditions as a possible early indication of containment or conformance issues. Average reservoir pressure is expected to remain relatively stable and well below the discovery pressure of 17,400 kPa (2,535 psi). Once injection ceases, in approximately 25 to 30 years, pressure declines and stabilizes at slightly over 14,100 kPa (2,050 psi). It is worth noting that deliberate attempts at pressurizing the pool during the 1980s and 1990s failed because of the Bashaw Platform Aquifer's influence. Therefore, it is extremely unlikely that any part of the reservoir will exceed the initial pressure state.

Enhance has constructed a robust simulation model of the entire Central Area, which includes the **MMV Plan Area**. The model was history matched to over 50 years of production and injection history with minimal adjustment to hard input data, such as the geo-model and fluid properties and saturation-dependent behaviours such as relative permeability. The high-quality history match obtained means the model will be a valuable tool for reservoir and CO_2 containment and conformance monitoring. The model's predictive capabilities have shown that CO_2 will rise to the top of the reservoir and remain trapped by the impenetrable Ireton seal.

SECTION SUMMARY

Enhance conducted extensive regional and local geological analyses of the Clive Leduc zone, confirming it to be an ideal storage reservoir for CO_2. Highlights from the analyses include the following conclusions:

- The Ireton Formation's impermeable tight lime shales separate the Clive Leduc and Clive Nisku pools in the Clive area, which are distinctly separate hydrocarbon accumulations.
- Ireton seal integrity is confirmed by the existence of a gas cap of up to 11m and an oil column of 18.5m on discovery in the Leduc, overlain by water in the Nisku.
- Secondary seals ensure there is *no quantifiable likelihood of geological containment failure* of CO_2 to the surface at Clive. These seals include the Nisku and Wabamun anhydrites, Joli Fou, Colorado and McKay shales.
- To understand the effects and dynamics of CO_2 injected into the reservoir, Enhance has built and simulated a detailed geological model of the Clive Leduc pool. The geological model was built using all available core and log data, with petrophysical input from 180 wells. Core and fluid properties for

the CO_2 EOR predictions were derived from Core Labs' laboratory analysis and reviewed and validated by Avasthi & Associates.

- Results of the fluid analysis shows that sequestered dense-phase CO_2 will remain significantly buoyant with respect to the Leduc aquifer brine. This ensures the confining Ireton cap rock will keep CO_2 trapped in the Clive Leduc pool.
- The simulation model was history matched to over 50 years of production and injection history, with minimal adjustment to geo-model and fluid properties, thereby validating the accuracy of the geo-model.
- Periodic updates to the history match as the CO_2 EOR scheme progresses will provide a means of understanding and optimizing EOR performance and will also provide evidence of containment or conformance issues, should matches be unobtainable with reasonable adjustments to the simulation parameters.
- Results of the simulation validate CO_2 will remain contained in the Clive Leduc pool throughout the period of EOR and beyond. Simulations run to 500 years in the future show no appreciable CO_2 migration from the scheme area, validating containment within the storage reservoir.

3 EXISTING WELLBORES

The Clive Leduc Unit includes 163 existing wells drilled over the last 55 years for the purpose of primary oil recovery. Existing wells will not be used for EOR, with the exception of monitoring purposes. Currently, Clive is an operating oil field with producing oil wells, water injection wells, suspended wells and zonally and fully **ABANDONED WELLS.** Producing Leduc wells or wells where the Leduc has not been zonally abandoned, will require conversion to monitoring or abandonment prior to CO_2 injection. Furthermore, the physical condition of all Leduc and Nisku penetrations has been investigated to assess risk of cross-formational flow and CO_2 surface leakage.

In addressing the risks associated with future CO_2 storage at Clive, it should be noted the presence of naturally occurring H_2S in the Leduc and Nisku of Clive has historically required the highest safety standards to be employed when drilling, completing, operating, suspending or abandoning wells. As the Alberta government's regulations that govern H_2S management are designed to prevent even the smallest containment failure of this gas, the Clive field benefits from already meeting these stringent safety and regulatory standards. The AER specifies well design and operating practices through established directives and guidelines that ensure the safe operation of sour oil and gas fields.

By meeting or exceeding regulatory compliance governing H_2S, Enhance can demonstrate the highest-possible safety standards for CO_2 containment at Clive.

Enhance's review of existing wellbores has been conducted in two stages: AITF's initial study and Enhance's more recent detailed review. The AITF review employed public domain data to provide an initial screening of wells (Please see **Appendix E**, *Characterization of the Wells that Penetrate the Clive Leduc and Clive Nisku Oil Reservoirs in the Clive Oil Field in Alberta* by Faltinson, Jafari, Hauk and Bachu.). This work used software developed by TL Watson and Associates Ltd. that calculates an empirically derived risk score for a well, based on vintage, well type, and construction details. **AITF concluded the only possible risk to CO_2 containment at Clive is through existing wellbores**. Enhance has addressed AITF's recommendations and completed more exhaustive and detailed analysis, using proprietary information from internal well records.

Enhance has reviewed the 163 existing wells in the Clive Unit, inclusive of the 71 wells in the **MMV Plan Area**, using proprietary data for well integrity and CO_2 containment in the Leduc Formation to ensure appropriate engineered passive safeguards are in place. The study evaluated the history and current status of the wellbores, cement integrity via **CEMENT BOND LOGS (CBLs)**, identification and cataloguing of SCVF events, and surface casing depths.

As further assurance, Enhance contracted a third-party engineering firm, VZFox Canada, to facilitate a formal independent risk analysis. This work has detailed a well-specific monitoring and mitigating plan for every existing well in the **MMV Plan Area** (Figure 3-1).

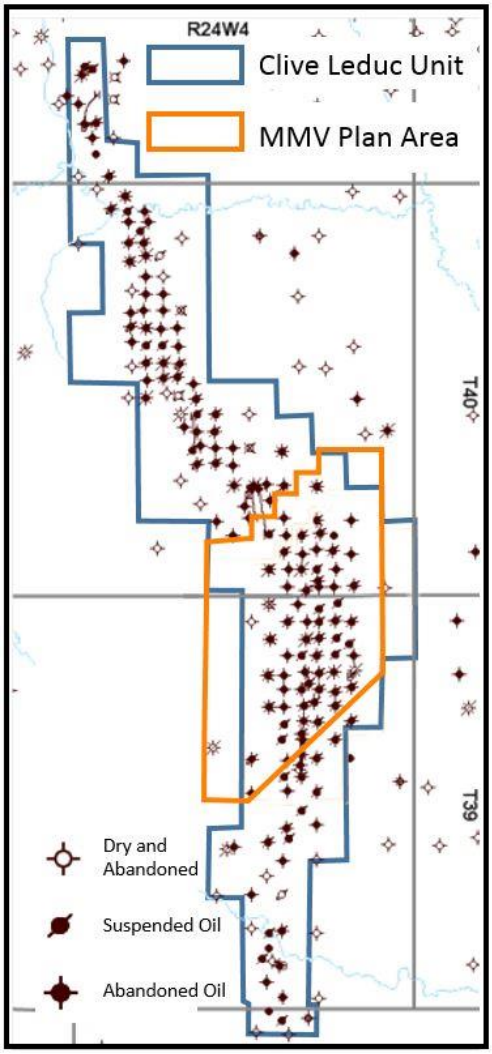


Figure 3-1 Existing Well Review / MMV Plan Area

This map shows the area Enhance reviewed for the categorization of existing wells.

CLIVE WELLBORE STATUS

As part of the risk assessment, Enhance has reviewed every existing well in the Clive Leduc Unit to assure that all wells conform to current provincial regulatory standards.

Enhance divided existing wells into four categories for review purposes:

- **Abandoned:** Wells that are fully abandoned and cut and capped.
- **Zonally Abandoned:** Wells that have previously been abandoned in the Leduc Formation.
- **Suspended:** Wells that have not been zonally abandoned. These typically have had a **BRIDGE PLUG** set but no cement cap.
- **Currently Operating**: Operating wells that are currently producing oil or disposing water.

Of the above, the **Zonally Abandoned** wells were further divided according to the AER Directive 20 versions that were applicable at the time of their **ZONAL ABANDONMENT**. Directive 20, the directive governing well abandonments, has had three revisions, effective December 7, 2007, July 1, 2010, and March 15, 2016. A major change occurred in the July 1, 2010, revision with the introduction of Level A intervals. Level A intervals are zones that contain hazardous fluids, including those with an H_2S concentration over 15%, and require specific abandonment safeguards. Wells that have been zonally abandoned before July 1, 2010, are not subject to be re-abandoned but may require additional remediation. Enhance will bring these wells into compliance (minimum 30m cement column or 1 m3 of cement on top of the existing abandonment) with current D-20 requirements.

Review of existing Unit wells found that:

Total Unit Wells					
Leduc Formation					
Well Mode	# of Wells	D20 2016/03/15	D20 2010/07/01	D20 2007/12/07	CBL Log
Abandoned	23	0	0	23	8
Zonally Abandoned	108	6	5	90	72
Suspended	24	0	0	0	15
Operating	8	8	0	0	2
Totals	**163**	**14**	**5**	**113**	**97**

Table 3- 1 Summary of Enhance's Study of Clive Unit Wells

- 23 of the wells were abandoned prior to the introduction of the July 1, 2010, Level A wells.
- 90 of the wells were zonally abandoned prior to the introduction of the July 1, 2010, Level A wells.
- 11 of the wells were abandoned or zonally abandoned following the introduction of the Level A wells on July 1, 2010.

Although the pool H_2S level averages 12.6%, the individual well gas and fluid analysis can exceed the H_2S limit of 15%.

Enhance Energy has, and will, continue to zonally abandon Clive Unit wells to the Level A standards set out in Directive 20, which, in most cases, exceeds the current regulatory requirements.

Wells that were zonally abandoned with a bridge plug capped with cement, prior to the introduction of Level A intervals, are acceptable for containment and are considered a low risk for failure as no failure of this type of well has been observed to date. Any of these wells lacking sufficient cement column above the bridge plug will be brought into compliance (minimum 30m cement column or 1 m^3 of cement on top of the existing abandonment) with current D-20 Level A requirements. As the project progresses, inactive wells will be zonally abandoned or fully abandoned per current requirements. Any wells lacking a cement bond log will have one run to determine cement tops at the time of abandonment. Furthermore, any porous zones (as defined by AER D-20) above the cement top will have remedial cementing completed per AER D-20. All wells will be monitored during operations for possible failures; any failures would be addressed immediately.

Full abandonment of wells per AER D-20 Level A will meet regulatory requirements for closure of the project. Monitoring of wells during project operation will ensure that any issues are detected and dealt with in an expedient fashion and provide learnings to assist in project closure. As per the AER D-65 EOR Approval, all non-abandoned wells that are completed in the Leduc and/or Nisku zones and within the Approval Area must be abandoned by a Level A method in accordance with Directive 020 upon completion of the CO_2 injection operations. The abandonment program must be submitted to the Closure & Liability (Oil & Gas) Group in the AER Closure and Liability Branch and approved by the AER.

ENHANCE'S WELLBORE REVIEW

Potential Leak Paths in Existing Wells

Enhance's formal wellbore review incorporated every well in the **MMV Plan Area** to evaluate its construction method and each component's likelihood of failure. Potential leakage pathways can be broadly grouped into four types, as shown in Figure 3-2 and discussed below.

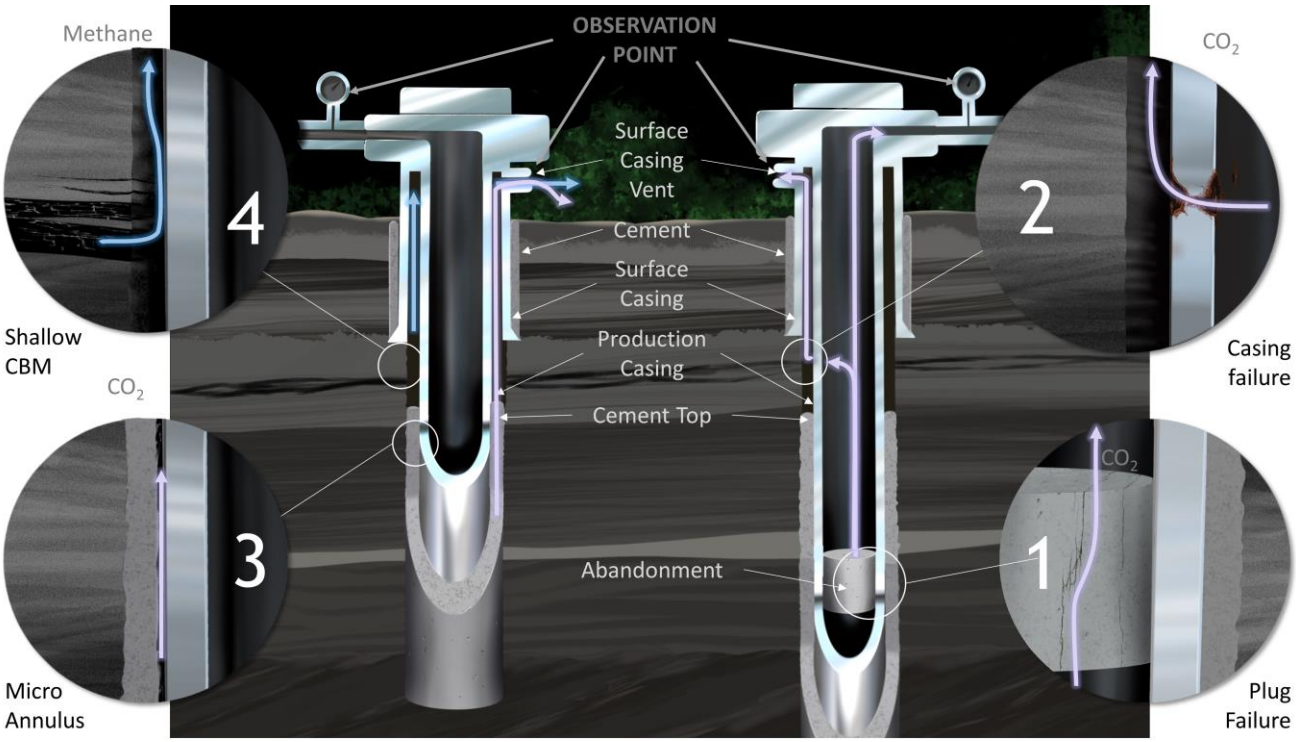


Figure 3-2 Potential Wellbore Leakage Scenarios

1. Abandonment Plug Leak: CO_2 leaks past the abandonment plug within the production casing.
2. Abandonment Plug Leak and Production Casing Failure: As above, but the CO_2 encounters a casing failure up-hole.
3. Leak through Micro-Annulus Flow in the Production Casing: CO_2 enters a micro-annulus.
4. Shallow Gas Zone Annular Flow: Shallow sweet gas, likely CBM, enters the annulus above the cement top.

1. Abandonment Plug Leak

In this scenario, CO_2 leaks past the **ABANDONMENT PLUG** within the production casing and would be detected as pressure build-up on the production casing pressure gauge.

2. Abandonment Plug Leak and Production Casing Failure

Like the first scenario, CO_2 leaks past the abandonment plug within the production casing but encounters a casing failure above the cement top up-hole, enabling CO_2 to leak into the annulus. In this case, the leak would be detected as a SCVF.

3. Leak through Micro-Annulus Flow in the Production Casing

CO_2 enters a micro-annulus, a small gap between the casing and the surrounding cement. In this case, the CO_2 would be detected as a SCVF, or Nisku monitoring wells would detect cross-flow into the overlying Nisku zone.

4. Shallow Gas Zone Annular Flow

Shallow sweet gas, likely CBM, enters the annulus above the cement top. This would be identified as a SCVF and gas analysis would confirm the source is from a shallow zone rather than the Leduc; this would not pose a threat to CO_2 storage. Enhance would follow the requirements of AER ID 2003-1.

Enhance's detailed review of existing wellbore risks indicates that the first and third scenarios are extremely unlikely, while the second and fourth scenarios have limited likelihood of occurrence.

Cement Top and Bond Log Review

Typical drilling methods at Clive involved cementing the production casing from the total depth up to the Cretaceous Joli Fou and Colorado Shales. This method isolated the producing Leduc and Nisku zones from porous intervals at the base of the Cretaceous. VZFox has reviewed all wells that indicate a cement top to show, on average, Clive existing wells have a cement column of 619m, isolating the Leduc from shallow producing zones (Figure 3-3).

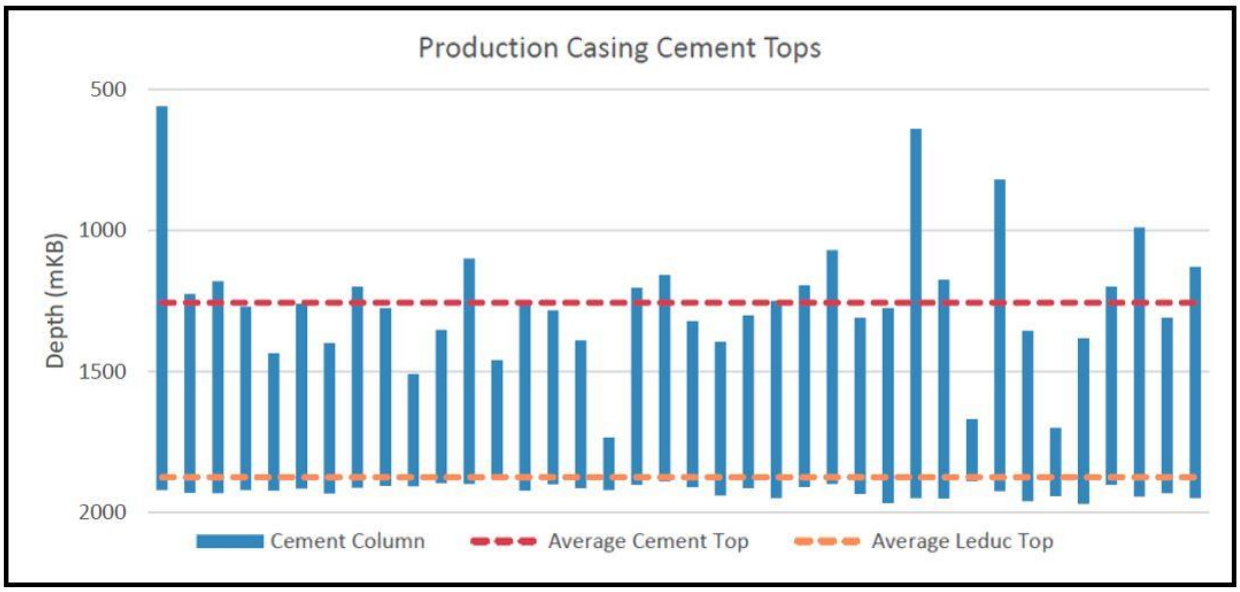


Figure 3-3 Results of Production Casing Cement Tops Review.

Thirty-eight wells indicated cement top depth with an average top at 1,256m Kb. This gives an average cement column of 619m, isolating the Leduc from up-hole zones. Courtesy of VZFox.

Existing CBLs were reviewed to understand cement quality in these wells. CBLs use an acoustic signal to gauge the quality of cement behind the casing. Good cement, as CBLs indicate, provides assurance the cement is an effective seal against fluid migration between the well casing and rock formations.

Enhance has reviewed the available CBLs from 97 existing wells and confirmed they have hydraulic isolation. The Company also provided CBLs from 10 randomly chosen wells to Reliance Oilfield Services for expert review, which confirmed Enhance's analysis.

Surface Casing Vent Flows (SCVF)

A SCVF is the flow of gas out of the surface casing/casing annulus. As the surface casing is purely a secondary barrier to protect from leakage into shallow aquifers, a flow of gas from inside the surface casing indicates a failure of either the well casing or cement (Figure 3-4). Casing breaches are the most common SCVF cause, as failure can be a single point, typically via localized corrosion, above the cement top. In comparison, cement failures are less common, as they require a continuous path of failure between the cement lining and the casing from the reservoir to the cement top. Clive existing wells have an average distance of 619m between the Ireton top and the cement top, rendering this type of failure less likely.

All SCVF events at Clive have been investigated, with particular attention given to sour gas events (containing H_2S) that would suggest Devonian gasses were a component. SCVF of sour gas was noted in only six cases where the casing had failed above the cement top, allowing gas to pass through the breach in the casing and to migrate to the surface casing vent; the wells were not plugged at the time. These wells have been repaired by squeezing cement. All recorded SCVF events were due to casing failure above the cement top (i.e. where the casing was not protected by cement), not cement failure. The absence of any cement-failure-related SCVF confirms existing cement has hydraulically isolated the Leduc for over 50 years. The absence of any casing

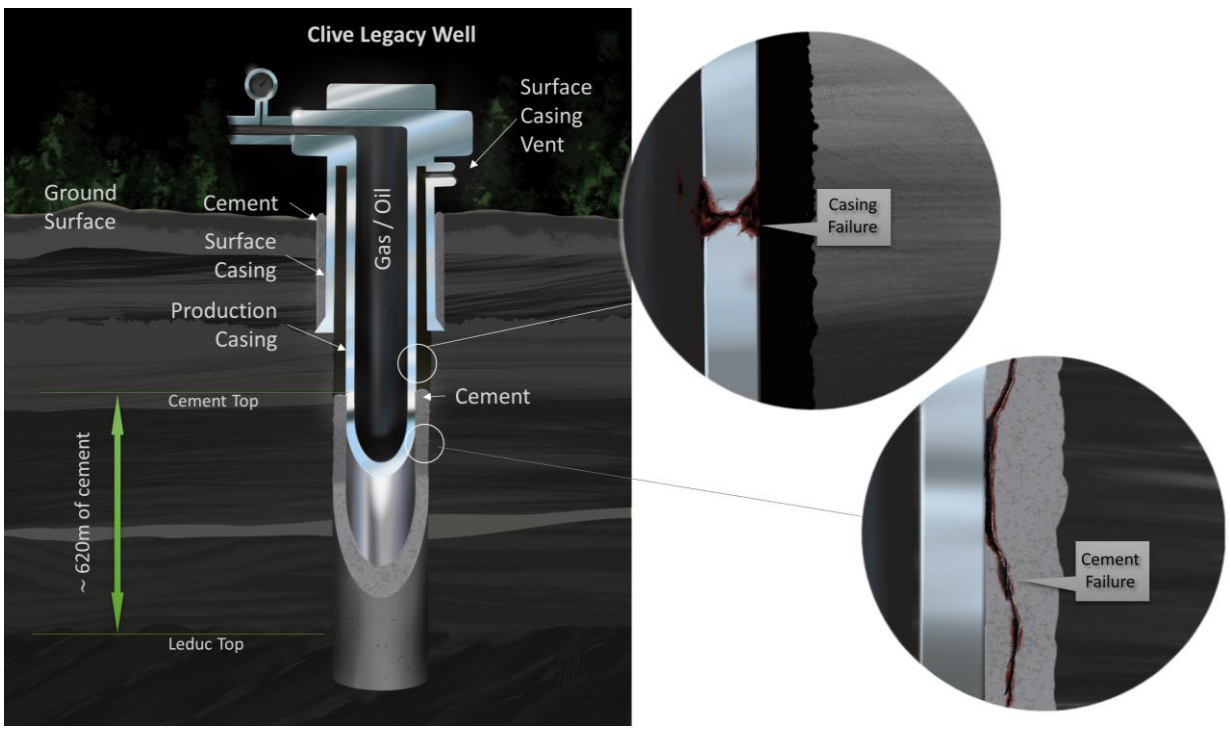


Figure 3-4 Possible Wellbore Leakage Scenarios

Existing wells represent the only possible containment risk. Casing failures accounted for all previous SCVF events at Clive involving sour gas. In each case, the production string was open to Leduc or Nisku fluids. Those fluids escaped via a breach in the production casing, migrated up and were detected at the surface casing vent. Every instance has since been mitigated. Enhance has recorded no instances of a cement failure at Clive. The absence of any cement-failure-related SCVF indicates that existing cement has hydraulically isolated the Leduc for over 50 years.

failures below the cement top also indicates that cement protects the casing from external corrosion. Since cement protects casing from external corrosion and the inside of abandoned wells will be protected by bridge

plugs, cement caps and inhibited fluids, the possibility of casing corrosion will be limited to sections of the well where cement has degraded sufficiently to enable CO_2 to make contact with the steel. Studies by the International Energy Agency (IEA Greenhouse Gas R&D Programme, "Long Term Integrity of CO_2 Storage – Well Abandonment) concluded that penetration of CO_2 through cement over a 10,000 year period would range from a few centimeters to 12.6 m. This study included a 2007 paper (Carey, *et al., 2007*) that examined cement cores taken from a 55-year-old well with more than 30 years of CO_2 exposure in the SACROC field in West Texas; the paper concluded that Portland cement will withstand and prevent CO_2 migration. The SACROC field is comparable to the Clive Unit in age, well design, temperature and pressure, although the Clive Unit will be operating at a lower pressure, approximately 14 MPa vs 18 MPa at SACROC. Studies by Watson and Bachu (2007, 2008) have generally concluded that well vintage and CO_2 or H_2S content have little to no influence on leakage potential. Based on these studies and experience to date at Clive, Enhance concludes that properly abandoned wells present a low level of risk of containment failure.

As Enhance brings all existing wells in the Unit up to current AER D-20 requirements, the presence of 30m of cement inside the well and the existing cement columns, minimum 186m identified within the VZFox wellbore risk assessment, will protect the casing from corrosion and provide adequate hydraulic isolation of the uphole horizons.

Enhance has also reviewed existing wellbore surface casing setting depths in the Central Area and found the shallowest surface casing to be set at approximately 190m. The deepest domestic/agricultural water wells in the area are approximately 100m deep. Therefore, the existing wells adequately protect the aquifers that are being used for domestic/agricultural purposes.

EXISTING WELLBORE RISK ASSESSMENT

Enhance retained the services of engineering firm VZFox to undertake a formal third-party risk assessment of existing wells within the **MMV Plan Area** (see **Appendix F**). Wells were investigated for current status,

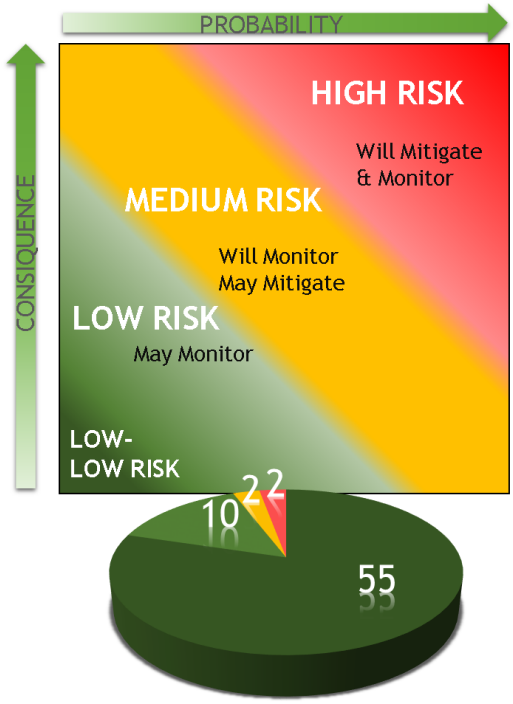


Figure 3-5 Risk Matrix Field

Enhance will identify the risk associated with every existing well and make plans to mitigate and/or monitor each, depending on the need. Enhance's goal is to move all existing wells into the *Low Risk* category. VZFox assessed 69 wells, including 65 deemed to be, at most, *Low Risk*.

abandonments, abandonment methodology, and casing and cement integrity. At the time of publication, the review-assessed 69 wells within the **MMV Plan Area** (Figure 3-1). Fifty-five of the wells are deemed Low-Low Risk, where the Leduc Zone has been abandoned and the Leduc is hydraulically isolated from zones above. Ten wells are Low Risk, where the Leduc has been suspended with a bridge plug and the Leduc is hydraulically isolated from above zones. All Low Risk wells will be monitored for SCVFs. Two wells are characterized Medium Risk, in which the Leduc Zone is open and capable of production or there may be segregation issues between the Leduc and above Nisku. Finally, VZFox characterized two wells High Risk.

The *Medium Risk* and *High Risk* wells were deemed such because the Leduc Zone is open and capable of production, with the *High Risk* wells in closer proximity (within 800 m) to the new injectors. Enhance will either mitigate these wells to a lower risk category prior to commencement of CO_2 injection, or convert them to monitoring wells as required by the AER in the D-65 EOR Approval.

VZFox advises casing pressures should be regularly monitored for the wells characterized as medium and high risk, wellheads pressures tested, and in the event communication with the injection wells is observed, the Leduc zone be suspended or abandoned with a bridge plug. Enhance will follow the monitoring procedures recommended by VZFox, and is currently evaluating these wellbores for full mitigation to low risk prior to commencement of CO_2 injection.

Inclusive within the risk assessment, VZFox also reviewed coverage of porous intervals in wells with CBL and concluded, in every case, the cement is providing hydraulic isolation between the Leduc and all porous intervals above it. VZFox also concluded that it is reasonable to assume that this isolation holds true for the wells that do not have a CBL.

CONCLUSIONS

Based on the detailed assessments undertaken on existing wellbores at Clive, Enhance submits the following conclusions:

- By meeting or exceeding regulatory compliance governing H_2S, Enhance can demonstrate the highest-possible safety standards for CO_2 containment at Clive.
- Existing wells represent the only possible risk to CO_2 containment at Clive.
- Enhance has completed a comprehensive well-by-well review of existing wells at Clive. All information collected and analyzed during this review concludes that existing and planned abandonments on these wells will mitigate risk of CO_2 containment loss to the maximum practical extent.
- As further assurance, Enhance contracted VZFox Canada, a third-party engineering firm, to facilitate a formal independent risk analysis of all wells in the **MMV Plan Area**. An assessment of wells in the **MMV Plan Area** concluded that 65 wells are *Low Risk* or *Low-Low Risk*, while two wells are *Medium Risk* and two wells are characterized *High Risk*. The *Medium Risk* and *High Risk* wells were deemed such because the Leduc Zone is open and capable of production with the *High Risk* wells simply being closer (within 800 m) to the new injectors. Enhance will either mitigate these wells to a lower risk category prior to commencement of CO_2 injection, or convert them to monitoring wells as required by the AER in the D-65 EOR approval.

- Enhance has completed extensive work evaluating the existing wells within the project area, concluding existing wells present the only possible risk to CO_2 containment, the active monitoring program will focus on these wells.
- Ninety-seven (~60%) of 163 wells in the field were found to have cement bond logs (CBLs), all of which confirmed hydraulic isolation between the Nisku/Leduc and uphole porous zones. The fact that 100% of wells with CBLs proved isolation, combined with the fact that no cases of sour SCVFs have been noted due to cement failure over the life of the field, supports the conclusion that the Nisku/Leduc is hydraulically isolated from uphole horizons in all existing wells. An independent Engineering assessment completed by VZFox confirmed this conclusion.
- Existing wells not in compliance with AER D-20 requirements will be brought into compliance as the project progresses. As per the AER D-65 EOR Approval, all non-abandoned wells that are completed in the Leduc and/or Nisku zones and within the approval area must be abandoned to Level A method in accordance with Directive 20 upon completion of the CO_2 operations.

4 CENTRAL CLIVE LEDUC AREA MEASUREMENT, MONITORING AND VERIFICATION (MMV) PLAN

The MMV plan outlines actions and responsibilities Enhance will undertake to ensure the Clive Leduc pool is safe for long-term storage of CO_2. Enhance has developed this plan in consultation with industry experts and consideration of current literature. The MMV plan has been designed to account for the Clive Leduc reservoir's unique setting and the characteristics of CO_2 EOR.

Protecting the environment, particularly soil, potable water sources and atmospheric emission, is the MMV Plan's primary purpose at Clive. Enhance also has financial incentive to effectively utilize every tonne of CO_2 for EOR. In the context of EOR, high-purity CO_2 is a commodity that requires resources and infrastructure, resulting in cost to the operator. Therefore, dual incentives – environmental protection and good resource management – drive the need for careful monitoring and accounting of CO_2 in the reservoir.

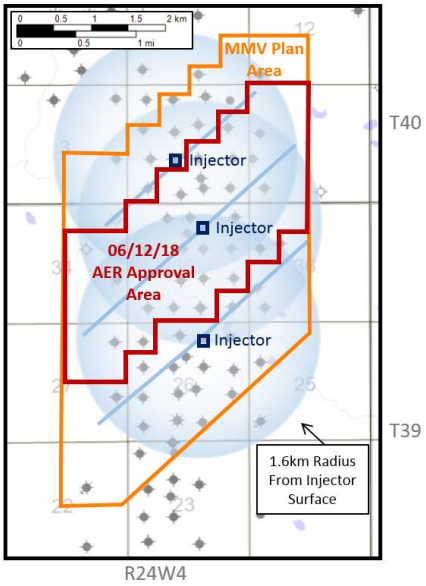
The MMV plan is built upon passive safeguards that will ensure safe, long-term storage. The plan utilizes a proven existing geological hydrodynamic trap in the Clive Leduc pool. The sealing Ireton Formation has prevented upward migration of oil and gas from the Leduc for millions of years – and will offer the same containment for future CO_2 storage. Above the Ireton, impenetrable and self-sealing anhydrite sheets cap another hydrocarbon trap in the Nisku, providing a secondary level of containment. Above this, numerous aquitards and aquifers present barriers to upward migration of fluids, ensuring the probability of CO_2 migration into potable water through natural pathways is effectively zero. By safely managing the EOR scheme – in particular, maintaining reservoir pressure to below original levels -- Enhance will preserve these inherent safeguards throughout the project's lifetime.

Enhance and AITF have identified existing wellbore leakage as the only possible containment risk associated with the project. Enhance has mitigated, and will continue to mitigate, this risk and will undertake a monitoring program designed to verify and provide confidence in containment.

The monitoring component of the project will encompass every geological level, from the reservoir to the surface, and include a variety of techniques. Prior to injection, a **BASELINE** of carbon isotope samples will be taken to serve as a carbon fingerprint database. These samples will then be compared to both injected gas samples and future samples of unknown origin, should the need arise. Reservoir monitoring and simulation will ensure the Leduc responds within expected parameters to the introduction of CO_2. Furthermore, Nisku Formation production monitoring will verify Ireton seal containment. Shallow production monitoring in the Cretaceous CBM zones will monitor CO_2 at the **BASE OF GROUNDWATER PROTECTION (BGWP)**. Sampling domestic potable water wells and dedicated monitoring wells will ensure public safety and confidence in containment. Soil gas sampling will take place throughout the **MMV Plan Area** as to give full public assurance. As wellbores have been identified as the only possible risk to containment, they will be the main focus of monitoring efforts; all wellheads will be monitored for surface casing vent flow events, as this is the most probable outcome of downhole failure. At surface, **SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)** systems will monitor and shut down injection wells, should a failure be detected. Air quality and safety systems designed to alert and prevent an escape of H_2S, which is present in Leduc and Nisku production, will inherently monitor for CO_2 leakage.

AER D-65 EOR APPROVAL

In December 2018, the Alberta Energy Regulator granted Scheme Approval No. 12832 for enhanced recovery of oil by miscible displacement using miscible fluid (CO_2) and/or water injection in the Clive D-3 A (Leduc) Pool and containment of CO_2 within the Clive D-3 A and D-2 A (Nisku) Pools. The December 2018 Approval Area is incorporated entirely within the boundary of the MMV Plan Area (See Right). Prior to CO_2 injection, Enhance will apply to expand the AER Approval Area to coincide with the MMV Plan Area.



The approval is subject to several terms and conditions. Many of these conditions are specifically stated within the MMV Plan. Inherent within Enhance's MMV Plan is to meet or exceed all conditions specified within the approval, or subsequent amendments to the approval. The full details of the conditions contained with the AER D-65 Approval is included within the MMV Plan as **Appendix N**.

The approval specifies 1) required baseline and project data gathering requirements in the Leduc, Nisku, overlying aquifers and CBM, 2) baseline seismic data and reservoir simulation requirements, 3) deep Leduc and Nisku monitoring well requirements, 4) minimum reservoir operating pressures to ensure miscibility is achieved and maximum reservoir pressure constraint to ensure cap rock integrity maintained, 5) injection wellbore design and operational monitoring requirements.

Prior to commencement of CO_2 injection, the approval requires Enhance to complete and submit a risk assessment of all the Leduc and/or Nisku wells, including abandoned, suspended or active, in the approval area to assess the possibility of leakage based on the vintage of the wells, diagnostic tools run and abandonment practice applied (including porous zone isolation). Wellbores found to have medium and high risks as detailed within the MMV Plan should be mitigated prior to the expected time of CO_2 reaching the locations.

All suspended wells that are completed in the Leduc and/or Nisku zones and within the Approval Area must meet the High-Risk Type 2 suspension requirements of Directive 013 prior to commencement of CO_2 injection.

All non-abandoned wells that are completed in the Leduc and/or Nisku zones and within the approval area must be abandoned to Level A method in accordance with Directive 20 upon completion of the CO_2 operations. The abandonment program must be submitted to the Closure & Liability (Oil & Gas) Group in the AER Closure and Liability Branch and approved by the AER.

As specified in Clause 4)l) of the approval, if injection facilitates the movement of injected fluids into any zone above the base of groundwater protection or any zone other than the Leduc and Nisku zones, Enhance will immediately inform the Resource Compliance Group in the AER Environmental & Operational Performance Branch, and the AER Red Deer Field Centre.

Clause 9 of the approval provides detailed requirements for annual reporting and presentation on the CO_2 EOR scheme to the Resource Compliance Group in the AER Environmental & Operational Performance Branch. The first report is required within one year of commencement of injection.

ENVIRONMENTS AND AREA OF OBSERVATION

In terms of monitoring, five environments are discussed: reservoir, geosphere, hydrosphere, biosphere and atmosphere (Figure 4-1). The reservoir is defined as the area that hydrocarbon accumulation dominates – the Leduc reservoir – whereas the geosphere is everything else in the deep subsurface that brines dominate. The hydrosphere overlies the geosphere from the BGWP, locally defined by the AER as the Base of the Edmonton Group, at approximately 500-600m to the surface. The biosphere comprises soils and surface biota, while the atmosphere overlaps this environment, up from the surface.

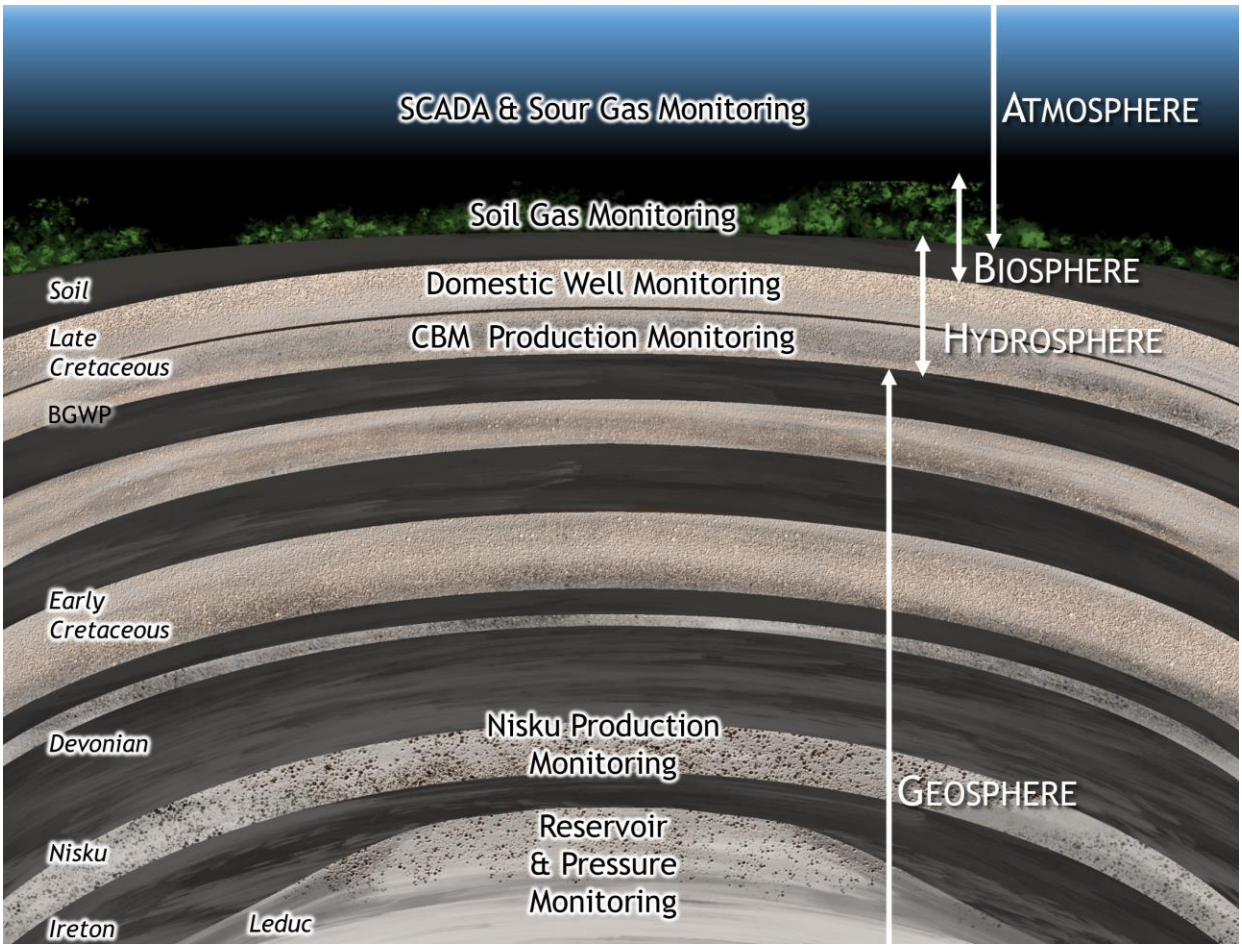


Figure 4-1 The Clive MMV Plan's Fluid Environments and Observation Targets

The MMV plan targets key intervals around the reservoir, geosphere, hydrosphere, biosphere and atmosphere. Deep geosphere observation is established through careful Leduc and Nisku production monitoring, as well as Leduc pressure monitoring. A series of safeguards – CBM, domestic water wells and soil gas monitoring – protects the hydrosphere and biosphere shallow aquifer systems. The continued use of H_2S monitoring will provide atmospheric monitoring in key areas.

RISK ASSESSMENT

Enhance has undertaken a formal risk assessment of the Clive project in order to select appropriate monitoring techniques. The focus of the risk assessment is the failure of the Clive Leduc reservoir to contain the CO_2, resulting in leakage into the geosphere, hydrosphere, biosphere or atmosphere. Expertise in all areas of project development were utilized in this assessment, including CO_2 EOR, drilling, completions and workovers, geology,

geo-modelling, geomechanics, reservoir engineering, reservoir simulation and project development. Furthermore, the assessment was informed by studies conducted internally be Enhance Energy, AITF and VZFox. A total of 61 possible leakage scenarios through geological and wellbore pathways were categorized by the two deterministic properties of risk; probability and consequence, and the resulting assessment is summarized in the matrix shown in Figure 4-2. The risk assessment is produced in full in **Appendix G**.

In describing safeguards within the MMV plan, it is necessary to evaluate **RISK** as a product of **PROBABILITY OF OCCURRENCE AND CONSEQUENCE**, where some degree of both components must be present to establish meaningful risk**.** Numerical values of probability and consequence were assigned as follows:

PROBABILITY:

1. Extremely unlikely to occur
2. Unlikely to occur
3. Chance of taking place
4. Likely to occur
5. Almost certain to manifest

CONSEQUENCE:

1. No Impact
2. Leak identified and mitigated
3. Contained to geosphere with no environmental impact
4. Potential temporary shut-down of pattern or project resulting from environmental concern
5. Unacceptable environmental impact with no feasible mitigation

Final risk scores were calculated by multiplying the probability ranking by the consequence ranking.

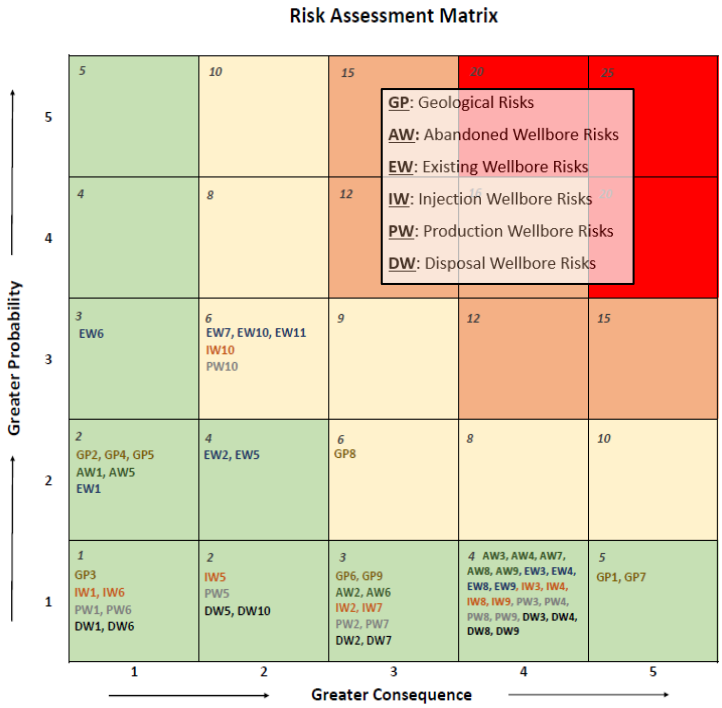


Figure 4-2: Risk Assessment Matrix

Green: Low Risk- 1/25 to 5/25; extremely unlikely to occur and/or low consequence. No monitoring or mitigation required.

Yellow: Medium Low Risk – 6/25 to 10/25; some probability of occurrence and/or high consequence. Monitoring required.

Orange: Medium High Risk 11/25 to 15/26; reasonable chance of occurrence with higher consequences. Mitigation and/or monitoring required.

Red: High Risk - Score exceeding 20/25; high probability of occurrence and high consequence. Mitigation required.

There are no high or medium high-risk scenarios identified in the Clive EOR scheme.

Six scenarios received the Medium-Low *risk score* value of 6 out of 25. Three of these scenarios related to existing wellbores, particularly, casing failure into a saline aquifer (EW7) or atmosphere (EW10), and a possible leak at the wellhead (EW11). In these cases, historical records show that similar failure types have occurred at Clive, justifying a *probability score* of 3/5. The consequence score for each scenario was 2/5, reflecting the likely speed of detection based on planned monitoring, and a variety of engineering mitigation options available. Two scenarios depicting leakage in new wellheads for production and injection wells, scored a *Risk level* of 6/25 (IW10, PW10). As with existing wellbores, historical evidence suggests that there is a chance of leakage, this time with the installation of new equipment, however, in-place monitoring will quickly detect a leak of this type and mitigation options are available. The last of the six Medium Low Risk scenarios is that of CO_2 loss through migration beyond the reservoir spill point (GP8). Clive's spill point is in the south end of the field with its boundary to the Haynes D3 Pool. Aside from the actual loss of containment, there is unlikely to be any environmental damage, as any leak would be absorbed into the vast Bashaw Platform aquifer. Probability of occurrence of spill point loss is low, as this type of containment breach can be prevented by close reservoir supervision.

Monitoring Tool Cost Benefit Analysis and Selection

Selection of monitoring techniques for Clive was driven by the unique characteristics of the reservoir, geology, existing infrastructure and the planned CO_2 EOR and storage process, guided by the formal risk assessment and studies by AITF. Some of the potential monitoring techniques considered were based on the National Energy Technology Laboratory (NETL) Best Practices Manual for Monitoring (BPM), Verification, and Accounting (MVA) for Geologic Storage Projects 2017 Revised Edition (BPM-MVA-2012.pdf). As the BPM was written for geologic storage projects it does not include additional techniques available for CO_2 EOR; these were also included in the selection process. The Monitoring Tool Cost Benefit Analysis and Selection are reproduced in full in **Appendix H**. The selected monitoring techniques are discussed in the remainder of this section.

As Clive is a sour field (H_2S present) and will be a CO_2 EOR field, a number of techniques are mandated by regulation for safety and flood management. These techniques include H_2S detection, monitoring of new injection and production wells drilled for the project, monitoring of existing production wells (Nisku and Leduc), monitoring of zonally abandoned existing wells and ongoing simulation and history matching of the flood response. Enhance will meet or exceed regulatory requirements. Since these techniques provide a strong foundation of monitoring techniques, additional methods were evaluated on both a stand-alone basis and based on the incremental cost and benefit provided.

Tools and procedures selected prior to the commencement of the EOR flood are considered to be relevant to that stage of development. Over time, all tools should be evaluated for effectiveness and assessed on an ongoing basis.

Routine Monitoring Techniques

Routine Monitoring Techniques encompass those techniques that Enhance has chosen to implement for baseline and ongoing monitoring. Should these techniques identify a possible containment issue or trigger

event that cannot be resolved using the information that they provide, additional or contingent methods can be employed. Some potential contingent techniques are discussed in the 'Monitoring Techniques Considered but Deemed Unnecessary' section.

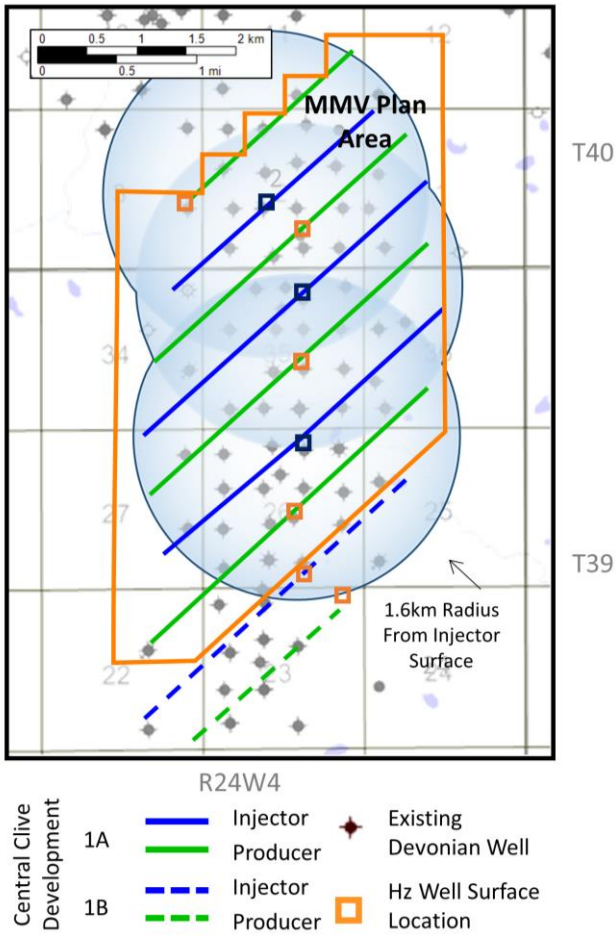


Figure 4-3: Phase 1 Monitoring Area

Enhance will focus monitoring efforts within a 1.6 km radius around the planned injection well surface locations, as the injection wells will represent the highest-pressure points during EOR operations.

Geographic Area Extent of Monitoring

Enhance will focus monitoring efforts within a 1.6 km radius around the planned injection well surface locations, as the injection wells will represent the highest-pressure points during EOR operations. Due to the structural trap's relatively narrow nature, the 1.6 km radius will essentially cover the entire reservoir (Figure 4-3).

Carbon Isotope Analysis

Enhance will establish a baseline analysis of $\delta^{13}C$ and ^{14}C contained within the source CO_2 prior to injection and compare it to baseline $\delta\ ^{13}C$ and ^{14}C in produced gas CO_2 from existing Leduc, Nisku and CBM wells, soil gas and headspace gas from domestic water wells, and dissolved inorganic carbon (DIC) in water samples.

Different CO_2 sources may exhibit different amounts of carbon isotopes ($\delta^{13}C$ and ^{14}C) that effectively allow samples to be fingerprinted. ^{14}C can also be used to differentiate **BIOGENIC** and **PETROGENIC** sources. The ratio of CO_2 to O_2 and N_2 in samples can also provide independent attribution to the source of CO_2 in soil gas samples (discussed further in the ***Soil Gas Monitoring*** section).

RESERVOIR MONITORING

Active Reservoir Monitoring and Simulation

Enhance has constructed detailed geological and reservoir models of the entire Clive Central Area. These models have been validated through history matching and will be used as an active tool for reservoir management, and for containment and conformance monitoring. As the CO_2 flood continues to progress, the compositional simulation model will enable Enhance to conduct further history matching to actual CO_2 flood performance. Not only is history matching a useful tool for flood optimization, but 'anomalies vs. expected' performance can also serve as a means of detecting issues with CO_2 conformance or containment.

To illustrate how simulation could detect issues with containment or conformance, Enhance ran a scenario on 10% leakage of CO_2. The leakage is quickly reflected in actual vs. expected gas-to-liquids ratio response for the production wells offset to the injectors (Figure 4-4, left). Similar differences can be seen in instantaneous oil response (Figure 4-4, right). If the actual delayed response could not be matched by reasonable adjustments to the model, an indication of potential containment or conformance issues would be identified and Enhance would investigate and evaluate data from other monitoring techniques.

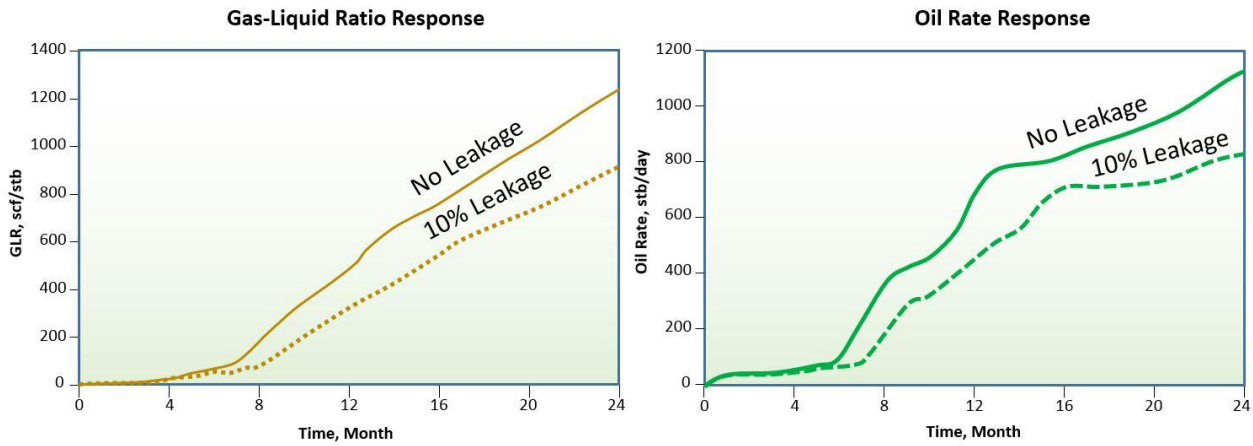


Figure 4-4: Simulation of 10% Leakage Scenario

At left, predicted gas-liquid ratio, base case and 10% leakage results show Enhance's simulation model will quickly identify issues with CO_2 conformance or containment. The difference between the actual and expected gas-to-liquids ratio response in producing wells would trigger investigation. At right, predicted oil rate, base case and 10% leakage simulations show that, similarly, differences in actual and expected oil rate responses in producing wells would indicate potential containment issues and prompt further investigation.

Injection Well Pressure Monitoring

Simulation modeling predicts the CO_2 flood will operate approximately 20% below original reservoir pressure, and the peak maximum pressure at an injection well to be approximately 5,100 kPa above the average reservoir pressure, operating safely below formation fracture pressure. The pressure at these wells will be continuously monitored and will not exceed the reservoir or seal fracture pressure (simulation shows the peak injection pressure to be approximately 55% of the mean formation fracturing pressure). Furthermore, the injection wells themselves will be constructed to meet or exceed regulatory requirements, resulting in minimal leakage risk. Enhance is required by the AER D-65 EOR Approval to provide evidence that the most suitable surface and downhole casing, tubulars and equipment are employed in the new wells drilled for injection.

As per the AER D-65 EOR Approval, Enhance must immediately report any loss of containment, anomalies that indicate fracturing out of the Leduc and Nisku formations, or anomalous pressure changes occurring anywhere within the Clive D-3 A Pool to Resource Compliance.

Project injection wells will be equipped with continuous monitoring of pressure on the injection string and annulus at the wellhead. Output will be tied to the project's SCADA system, which will be continuously monitored and set to alarm if pressures fall outside expected operating ranges or experience sudden changes not correlated to changes in injection volume. Continuous monitoring will provide immediate indication of any issues with these wells so that remedial action can occur.

Integrity of the injection wells will be further verified by annual packer isolation tests and zonal isolation logging every five years.

Measuring Produced and Injected Fluid Volumes

Enhance will follow approved oilfield well test and measurement techniques to ensure produced and injected fluid volumes are accurately measured. In AER's Directive 17, standards are established for what and how volumes must be measured and the expected level of measurement accuracy. While based on a regulatory requirement, it is a necessary component of field monitoring and provides a basis for flood management, as well as for reservoir simulation model updates to improve recovery and storage while monitoring for containment issues.

Analyzing Produced, Recycle and Source Gas

Gas sourced from Nutrien and NWR will be analyzed annually for carbon isotopes and continuously for CO_2 concentration. An extensive database of historical analyses from the Nutrien source is provided in **Appendix I**, it is expected to be 99% pure CO_2 with traces of CH_4, H_2 and N_2. It is expected that the NWR CO_2 stream will be 99.5% CO_2 with traces of H_2, CO, CH_4, N_2, MeOH and AR. Likewise, gas produced at individual production wells will be sampled quarterly and the composite recycle stream sampled monthly. These gases will contain increasing proportions of the reservoir gas (which consists primarily of CH_4, C_2-C_6, H_2S and CO_2) as the EOR project progresses. Understanding the gas stream compositions aids in identifying the source of any anomalous readings from the active monitoring techniques. Baseline gas analysis of existing Leduc producers will include isotopic testing.

GEOSPHERE MONITORING

Nisku Monitoring Wells

Monitoring the overlying Nisku will verify Ireton seal containment. Enhance will use a combination of passive and active Nisku monitoring wells within the **MMV Plan Area**. The designated Nisku monitoring wells and requirements are prescribed within the AER D-65 EOR Approval (**Appendix N**), they are:

- 02/02-35-039-24W4/02
- 00/16-02-040-24W4/00
- 00/01-02-040-24W4/02
- 00/12-01-040-24W4/02

Baseline data will include Nisku water chemistry, reservoir pressure and carbon isotope signature ($\delta^{13}C$ and ^{14}C) in the produced gas. During the monitoring phase reservoir pressure will be obtained annually in accordance with AER D-40 requirements, annual isotope analysis ($\delta^{13}C$ and ^{14}C) on the produced fluids and bi-annual gas samples for chemical compositional analysis.

Enhance will immediately inform the Resource Compliance Group in the AER Environmental & Operational Performance Branch if the injection into the Leduc facilitates the movement of fluids into the Nisku zone, observed in any Nisku monitoring well. If an event was triggered, Enhance would continue to monitor the

movement of fluids within the Nisku zone while taking direction from the AER to continue, suspend, or reverse the injection.

Leduc Monitoring Well

Enhance has identified an existing Leduc vertical well, located within the **MMV Plan Area** at 00/10-35-039-24W4/0, that will be utilized as a Leduc monitoring well. Enhance will continue to produce this well until economically viable, and thereafter convert to a static monitoring well.

As per the AER D-65 EOR Approval, Enhance will include Leduc water chemistry, reservoir pressure and carbon isotope signature ($\delta^{13}C$ and ^{14}C) in the produced gas as baseline data gathering requirements. During the monitoring phase reservoir pressure will be obtained annually in accordance with AER D-40 requirements and bi-annual gas samples for chemical compositional analysis.

Gas Chromatograph Logging of New Drills

Gas chromatographic logging instrumentation will be employed during the drilling of Enhance's first three wells (03/06-02-40-24W4, 16-02-40-24W4 and 15-34-39-24W4) to record various gas concentrations throughout the subsurface. This continuous gas sampling analyzed for C_1-C_5 (i.e. methane, ethane, propane, butane, pentane and hexane, which are low-density hydrocarbons), including isomers (different arrangements of the hydrogen and carbon atoms) and CO_2. This data will be added to the baseline library for consultation in the event of a future anomaly.

Seismic Baseline Gathering

Enhance has obtained a 2004 3D Seismic program across a large portion of the Clive Field (Figure 4-5), including the entire **MMV Plan Area**. This survey will act as a baseline for comparison if an event triggers requirement for further investigating into possible containment loss into shallower porous intervals.

As per the AER D-65 EOR Approval, Enhance will evaluate the baseline seismic data to indicate that no faults transect the seals in the Approval Area.

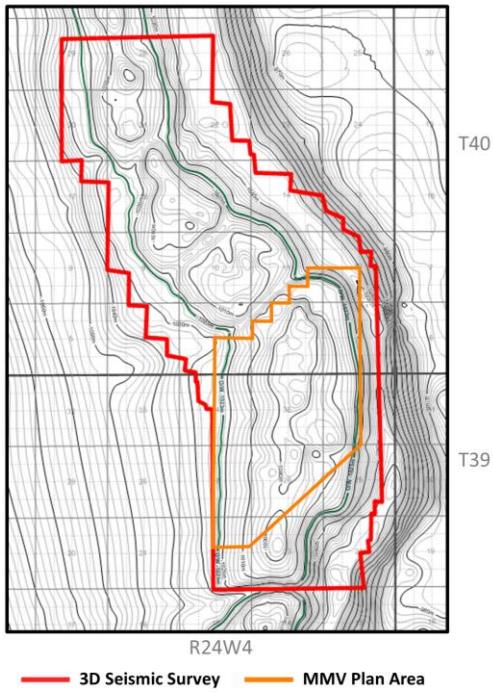


Figure 4-5: Location of Enhance's 3D Seismic Survey

A geophysical study was undertaken at Clive to investigate the geophysical response of entry of CO_2 into various stratigraphic intervals (Leduc reservoir, Manville, Viking, Belly River). The study report is attached as **Appendix J**. Seismic response is determined by the physical and elastic properties of rocks and their constituent fluids. If the reservoir changes from a static to dynamic state, changes in pressure, temperature, and fluid content can cause measurable changes to the seismic response.

At Clive, the trade 3D survey serves as the baseline, and various concentrations of CO_2 fluid replacement modelling was conducted to determine at what concentration, and in what zones would CO_2 injection result in a change in the seismic response. This would allow the determination of CO_2 movement outside of the reservoir zone. Fluid replacement modelling was used to determine the theoretical response of adding varying concentrations of CO_2 as a function of total reservoir fluid at *InSitu* temperatures and pressure. An example synthetic trace from the study in Figure 4-6 shows modelled responses of CO_2 emplacement into the Mannville, Viking and Belly River intervals, based off the 100/06-02-040-24W4 sonic and density logs. In the Leduc and Nisku reservoirs, as the effective pressure is such that the CO_2 remains in a liquid state, the slight change in bulk modulus (replacing a portion of one liquid with a different liquid with similar physical properties) results in a very slight change in the acoustic impedance. The strength of signal by the fluid change may not necessarily be identifiable by comparison with a new 3D shoot. However, in the shallower horizons (Mannville, Viking and Belly River) as the effective pressure on the fluids in the reservoir lessens and causes the CO_2 to transition to a gaseous state, the bulk modulus of the reservoir is reduced significantly, resulting is a more pronounced seismic response.

There are considerations to be made when translating from model to real world application. The primary of these is the use of an existing trade seismic survey as a baseline. Best results for '4D seismic' are typically gained when baseline and repeat shoots are acquired with the same method and spacing. Divergence from this ideal will result in noise created by the differences in acquisition that have no association with the underlying strata. In order to justify the use of trade data, it is important that the signal of CO_2 emplacement is stronger than the expected noise. This study suggests that a weaker signal in the Nisku and Leduc intervals, a product of CO_2 maintained in a liquid state and a very low porosity, will be difficult to interpret by comparing the 2004 baseline shoot with a future 3D. However, the combination of CO_2 filling far greater pore space in a gaseous state in shallower Cretaceous zone would result in a far stronger signal to noise ratio, and would make detection and even quantification of CO_2 possible.

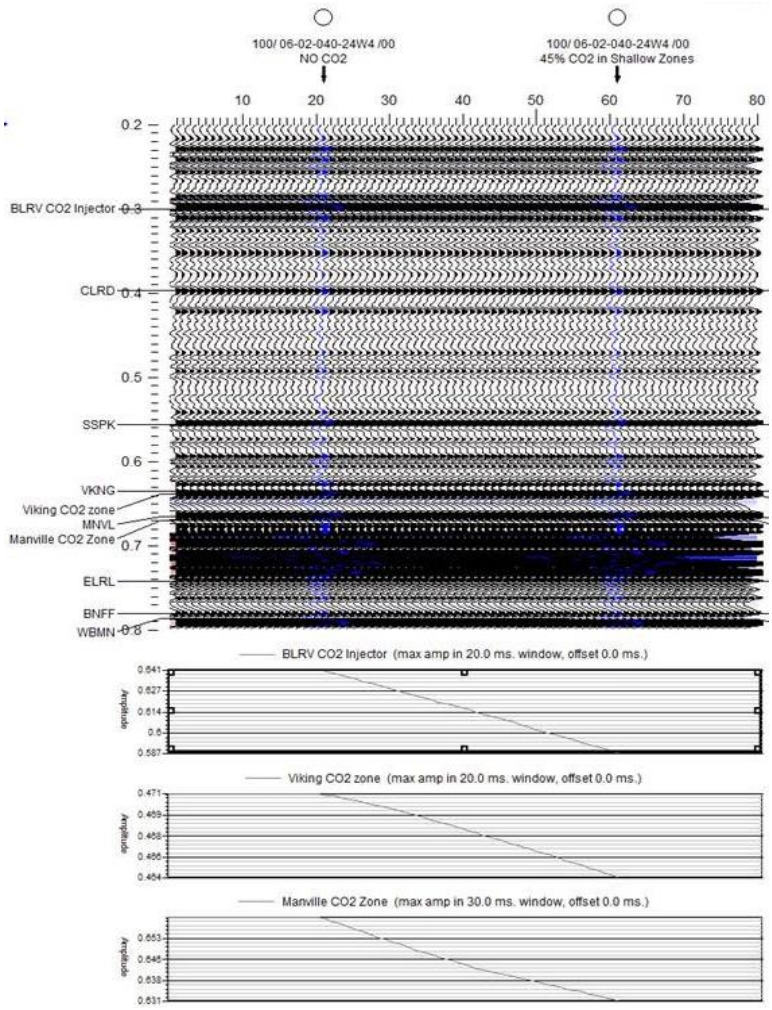


Figure 4-6: Amplitude response to fluid change in three shallow porous intervals above the Clive Leduc Field. Modelling based of the central Clive location of 100/06-02-040-24W4

The results of the Seismic Study show that a leak into any of the Cretaceous porous zones would be detectable as a marked amplitude change from the 3D Seismic Baseline. The strength of the expected amplitude change is significant enough to surpass noise generated by differences in acquisition, rendering the acquired 3D seismic baseline suitable to task.

Availability of the 2004 Clive 3D gives Enhance the option for a future 4D investigation. If widespread leakage of CO_2 into shallow intervals were suspected at Clive, and no other monitoring methods were able to adequately describe the extent of loss, Enhance would be able to shoot a new survey for comparison and to create a snapshot of fluid distribution at that time. The study outlined above suggests that this would prove an effective tool in determining CO_2 distribution and concentrations in shallow zones, if the need arose.

HYDROSPHERE MONITORING

The protection afforded to the geosphere will, for the most part, be inherent for the hydrosphere. However, due to the consequences of contamination, it is necessary to add further safeguards. The purpose of the groundwater monitoring program is to establish baseline conditions for groundwater quality in the area, which can then be compared to sampling during the project conditions in the event of possible CO_2 migration.

From the Base of Groundwater Protection at around 600m depth to the surface, hydrosphere monitoring program will commence on three fronts; Coalbed Methane Monitoring, Landowner Water Well Monitoring and a Dedicated Groundwater Monitoring Well nest, located in the center of the **MMV Plan Area**.

Coal Bed Methane (CBM) Monitoring

CBM production in the area offers an excellent opportunity to provide sampling over a large area from geological horizons above the EOR complex. CBM wells will sample three geological horizons, namely the Belly River, Edmonton and Horseshoe Canyon. CBM wells are generally completed within, the BGWP at 600m depth (Figure 4-7) having an average depth of approximately 450 m.

Enhance operates compression on behalf of the CBM operator and has extensive historical records of CBM sales gas analysis on a monthly basis. Enhance will continue to collect this data but will also collect data from a more focused area largely coincident with the **MMV Plan Area**. This more focused sampling is possible as the CBM gas gathering system collects from segregated areas in the Clive area; one of these collection areas largely overlays the **MMV Plan Area**. As shown by the existing analyses, the CBM gas has a stable composition, contains little CO_2 (<0.2%) and no detectable H_2S, making monitoring of CBM well gas analyses an ideal early detection tool for loss of CO_2 containment before it can reach the shallow hydrosphere. CBM well sampling over a wide area will provide a reliable method of detecting CO_2 containment loss while the gas is still within hydrocarbon-producing horizons. This monitoring technique has a high probability of identifying containment loss, such that leakage can be mitigated prior to any impacts on the biosphere or the shallower hydrosphere.

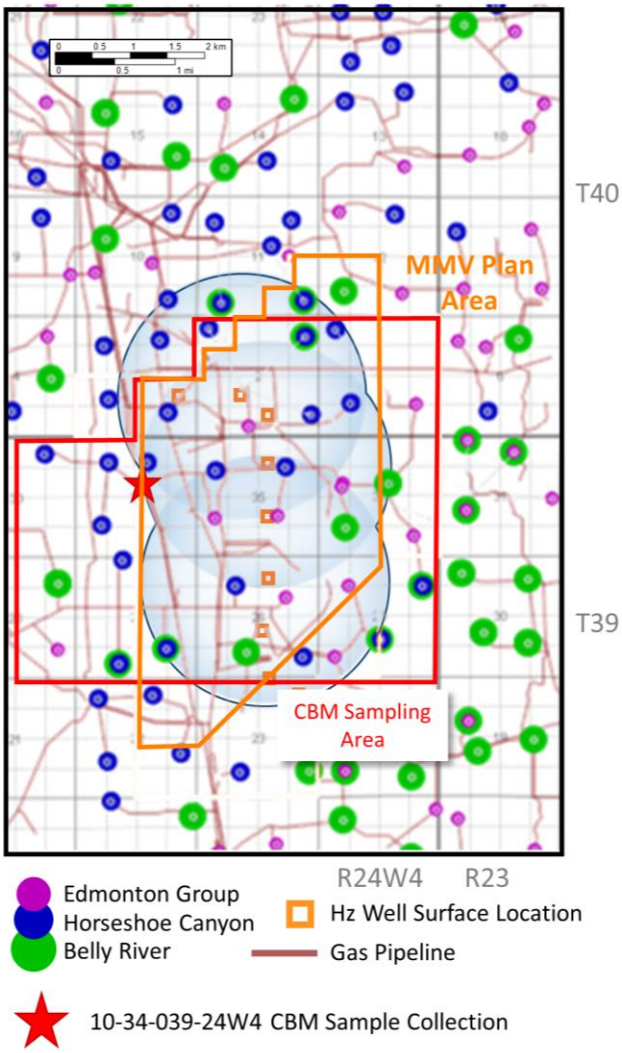


Figure 4-7: CBM Wells and Phase 1 Monitoring Area

Active coal bed methane wells within the **MMV Plan Area** will provide an excellent opportunity to sample produced gas from zones above the EOR complex. This monitoring technique will provide independent and complementary assurance of CO_2 containment.

Enhance will gather baseline carbon isotopes. During project operations, Enhance will sample annually for isotopic analysis and monthly for gas composition.

Registered Landowner Water Well Monitoring

Landowner water well selection and monitoring methods are detailed in full in **Appendix L***: Baseline Shallow Groundwater Monitoring*. The selection of Landowner water wells for baseline groundwater monitoring included the following approach:

- Review the hydrogeological conditions of the project area to identify sampling locations that are representative of the local groundwater system;

- identify all registered water wells within 1.6km radius from the injection pad sites;
- review available water well drilling reports to identify completion zones; and
- select Landowner water wells that are representative of local hydrogeological conditions and are spatially distributed throughout the project area.

According to Alberta's Water Well Information Database (AEP WWID 2019, internet site), there are currently 45 registered water wells within a 1.6-km radius from the Project injection well pads. Of these, 25 were completed for domestic and/or stock use. The remaining wells (20) are listed as being primarily for industrial (17) purposes, as well as investigation (1), other (1) or unknown (1).

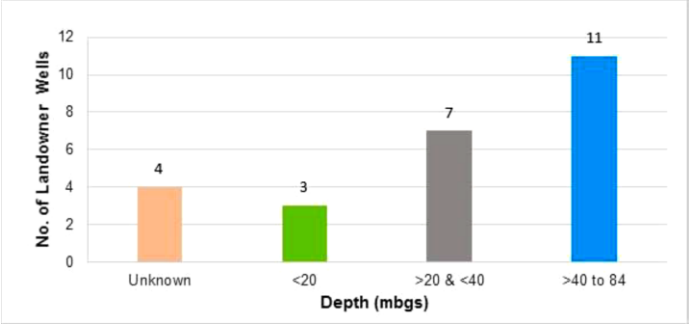


Figure 4-8: Number of Registered Landowner Water Wells within a 1.6-km Radius from Surface Injection Pads

Based on the available drilling reports, the depth of the Landowner water wells (domestic & stock) ranges between 15 and 84 mbgs, with the majority (18) being completed in upper bedrock and below 20 mbgs. Figure 4-8 illustrates the number of Landowner water wells (domestic & stock) for different reported depths, including: <20 mbgs, >20 and <40 mbgs, >40 to 84 mbgs, and unknown.

Selected Landowner Water Wells

A review of the hydrogeological information and the available water well drilling reports indicated that most Landowner water wells within the **MMV Plan Area** are completed in the Lower Lacombe Aquifer or Haynes Aquifer, both of which are members of the Paskapoo Formation. On this basis, a representative number (>25%) of Landowner water wells were selected for each depth ranges outlined earlier (i.e., <20 mbgs, >20 and <40 mbgs, >40 to 84 mbgs). In total, nine Landowner water wells (36% of the total wells) have been selected for baseline groundwater monitoring. The wells are representative of local geological conditions, are spatially distributed throughout the area of interest at a density of about four wells per 1.6-km radius, cover the depth range of domestic wells, and include the two members of the Paskapoo Formation that are intersected by the registered domestic wells. A list of the selected wells is included in Table 4-1 (redacted) and the associated drilling reports are attached.

Table 4-1: Recommended Landowner Water Wells for Baseline Sampling- Redacted

The locations of the selected nine Landowner water wells are illustrated in Figure 4-9 (redacted). It should be noted that the selected Landowner water wells may be subject to change following an assessment of their current condition and/or Landowner commitment to participate in the baseline monitoring program.

Figure 4-9: Location of Selected Domestic Water Wells for Baseline Monitoring (WWID 2019, internet site)- Redacted

Water will be analyzed for routine potability: pH, alkalinity, bicarbonate, carbonate, hydroxide, electrical conductivity, fluoride, chloride, nitrite, nitrate, sulphate, calcium, magnesium, potassium, sodium, iron, manganese, Total Dissolved Solids (TDS), hardness, ion balance, nitrate+nitrite-N, nitrate-N, Nitrite-N and Sodium Adsorption Ratio (SAR). Since leaking CO_2 may not initially appear as free gas due to dissolution in water or interactions with various minerals, baseline analysis will also include dissolved metals: aluminum, antimony, arsenic, barium, beryllium, boron, cadmium, calcium, chromium, cobalt, copper, iron, lead, lithium, magnesium, manganese, molybdenum, nickel, phosphorus, potassium, selenium, silicon, silver, sodium, strontium, thallium, tin, titanium, uranium, vanadium and zinc. If practical, headspace gas will be captured for isotopic analysis, or alternatively measurements can also be made from water samples. These analyses will establish initial conditions, allow monitoring for potential interactions of injected CO_2 with brines and/or rock matrices and fingerprint various formation waters based on their chemical profiles. Following review and analysis of initial results, monitoring plans for these wells will be finalized. Water well sampling will follow methodology established by the Alberta Research Council; *The Free Gas Sampling Standard for BWWT* (ARC, March, 2009).

Enhance will collect three events per year (spring/summer/fall) for two years. Enhance will re-evaluate at the end of 2020.

Baseline Water Well Testing for Coalbed Methane Development

Enhance will supplement its own analysis with the *Baseline Water Well Testing for Coalbed Methane Development*, a database of water samples taken from the mid-2000s as a baseline for CBM development. When choosing candidate wells for its program, Enhance will preference wells included in the database (pink locations in Figure 4-9, adding complementary information on long-term variability of gas composition).

These historic analysis, which includes seventeen wells within the **MMV Plan Area**, were conducted beginning in 2006 and include parameters such as bicarbonate, Ca, carbonate, Cl, conductivity, I. Coli, FI, hydroxide, ionic balance, Fe, iron related bacteria, Mg, Mn, Nitrate, pH, k, Na, sulphate, sulphate reducing bacteria, alkalinity, total coliforms, TDS and total hardness.

Three of the Landowner water wells selected to be sampled within Enhance's program have been tested as part of the Baseline Water Well Testing (BWWT) for CBM development in the area. Copies of these historic analyses are included in **Appendix O**.

Dedicated Monitoring Well Nest

Enhance will drill three nested observation wells completed in the surficial, Lacombe and Haynes aquifers (~20, 40 and 80 mBGS) to allow sampling and monitoring of fluid levels and temperatures to in these horizons (full details in **Appendix L**). These wells will be located on an inactive well lease at 11-35-39-24W4 (Figure 4-10-Redacted) and completed in the Lower Lacombe and Haynes Aquifers. Given that the bedrock and topographic positions are similar amongst the registered Landowner water wells, the main differentiator is depth. Therefore, the three nested dedicated water wells (completed at different screen intervals) will serve to capture water quality changes with depth. These wells will be sampled three times per year,

spring/summer/fall during baseline and monitoring operations. Enhance will re-evaluate frequency after two years.

Figure 4-10: Groundwater Monitoring Program in the MMV Plan Area. Nine domestic wells will be sampled, in addition to 3 stacked Monitor wells in the centre of the Area that sample at 20, 40 and 80m below ground surface.- Redacted

BIOSPHERE MONITORING

Soil Gas Monitoring

Soil gas sampling is a proven and reliable means of providing additional assurance CO_2 is not migrating to surface. Enhance will install 21 permanent soil sample probes at 19 well locations within the **MMV Plan Area** (due to overlap of the monitoring areas, this will provide 10 sample points within 1,600m of each injection pad), which will be sampled three times per year prior to CO_2 injection (in spring, summer and fall) to establish the baseline. No sampling will be conducted in the winter due to frozen soil conditions. Seasonal sampling of these wells is important because soil gas composition may change with seasons due to variations in biological activity in the soil (Romanak, 2016). Sampling will continue for two years to provide enough data to characterize soil gas concentrations. Monitoring frequency will be re-evaluated after two years, depending on the results seen to that time. Further details of the soil gas monitoring program can be found in **Appendix K**.

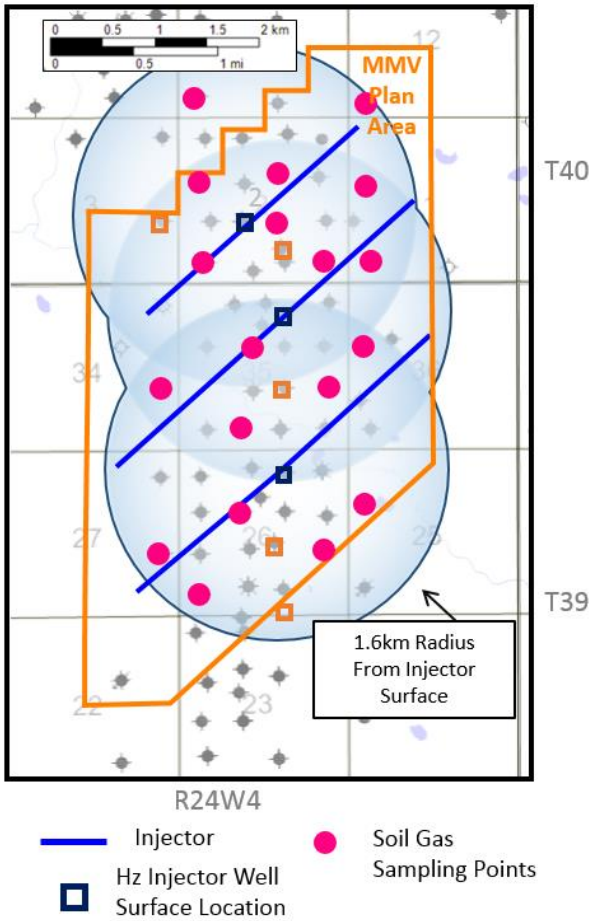


Figure 4-11: Nineteen Soil Gas Monitoring Locations

During each field program the soil vapour probes will be sampled in-situ in real time for CH_4 and CO_2 concentrations using a Los Gatos Research Ultra-portable GHG Analyzer. Including the ability to detect methane (CH_4) in soil gases is recommended since: surficial deposits in central Alberta may contain coal seams that naturally produce methane (i.e., coal bed methane); and, methane oxidation by soil microbes can elevate soil gas CO_2 concentrations.

Off-site laboratory analysis of the soil gas samples will include determinations of their N_2, O_2, CO, CH_4, CO_2 and, if applicable, F1 hydrocarbon (nC_6-nC_{10}) concentrations. Analysis of F1 hydrocarbons helps to confirm the presence of an exogenous geological (i.e., coal bed methane may contain F1 hydrocarbons) or biological methane source (e.g., from methanogenesis).

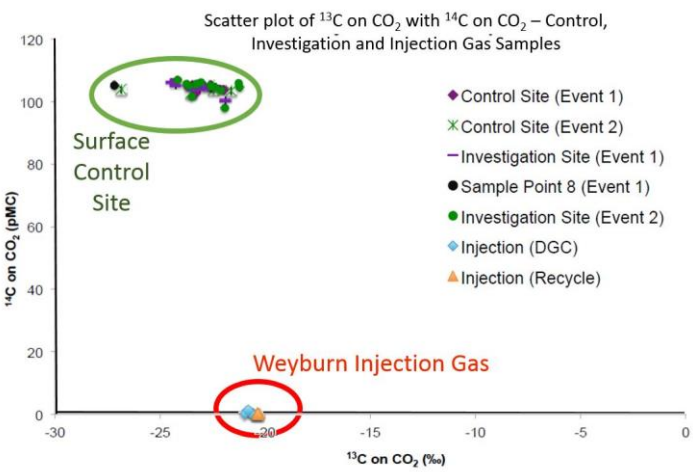
Selected well locations are tabulated below.

User-Format Well ID	Prod./Inject. Frmtn	Date Well Spudded	Surf-Hole Latitude (NAD83)	Surf-Hole Longitude (NAD83)	Ground Elevation (m)
100/12-25-039-24W4/00	Dleduc	1966/08/16	52.38570N	113.33720W	838.2
100/04-26-039-24W4/00	Dleduc	1967/08/19	52.37783N	113.36029W	882.7
100/08-26-039-24W4/00	Dleduc	1984/07/04	52.38180N	113.34281W	860.9
100/11-26-039-24W4/00	Dleduc	1985/10/23	52.38509N	113.35435W	870.3
100/08-27-039-24W4/00	Dleduc	1967/06/15	52.38144N	113.36562W	865.3
100/08-34-039-24W4/00	Dleduc	1968/01/06	52.39591N	113.36537W	855
100/03-35-039-24W4/00	Dleduc	1985/10/23	52.39153N	113.35435W	856.4
100/08-35-039-24W4/00	Dleduc	1984/07/02	52.39598N	113.34239W	856.8
100/11-35-039-24W4/00	Dleduc	1988/02/23	52.39957N	113.35253W	850.5
100/12-36-039-24W4/00	Dnisku	1966/05/29	52.39958N	113.33718W	864.1
100/04-01-040-24W4/00	Dleduc	1966/07/29	52.40700N	113.33624W	891.5
100/12-01-040-24W4/00	Dleduc	1966/08/28	52.41366N	113.33711W	909.8
100/01-02-040-24W4/00	Dleduc	1985/12/31	52.40698N	113.34301W	891.2
100/04-02-040-24W4/00	Dleduc	1966/07/11	52.40696N	113.35936W	855.9
100/07-02-040-24W4/00	Dleduc	1988/02/07	52.41059N	113.34931W	879.1
100/10-02-040-24W4/00	Dleduc	1965/05/23	52.41475N	113.34927W	897
100/12-02-040-24W4/00	Dleduc	1965/10/02	52.41419N	113.36028W	864.4
100/04-11-040-24W4/00	Dleduc	1965/01/28	52.42150N	113.36040W	875.1
100/04-12-040-24W4/00	Dnisku	1967/02/12	52.42089N	113.33706W	905
Note: Highlighted wells 11-35 and 4-1 will have radioisotope testing at each sampling event.					

The soil gas monitoring program will provide excellent coverage, with approximately 75 baseline data points prior to injection.

Soil Isotopic Baseline

In the event anomalous soil gases are detected outside of expected levels, complimentary geochemical techniques will be used to determine the CO_2 source in soil gas samples. Cenovus Energy Inc. successfully applied such geochemical techniques at its Weyburn CO_2 flood in Saskatchewan.



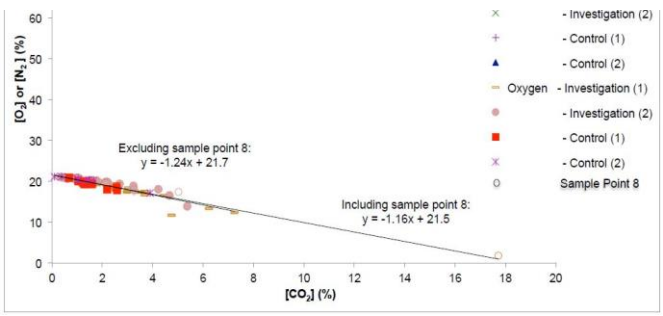


Figure 4-12: ^{14}C on CO_2 vs. ^{13}C on CO_2 from Cenovus Weyburn Study

Soil gas samples (upper left quadrant of the graph) show approximately 100% modern ^{14}C, indicating a biogenic source (i.e. no DGC or recycle gas is present in the soil gas, as this would dilute the values below 100% modern ^{14}C). The soil gases also show a slight difference in $\delta^{13}C$ vs. the DGC and recycle streams, providing additional evidence the CO_2 in soil gas is biogenic in origin.

producing CO_2. If leaking CO_2 were displacing soil gas, both nitrogen and oxygen would decline as CO_2 concentration increases.

In the study, the origin of gas samples recovered from soils close to the injection site were in question. To resolve the problem, Cenovus turned to carbon isotopes present in the samples. Carbon 14 (^{14}C) is an unstable carbon isotope that is taken up by plants through photosynthesis. Over long periods of time, the unstable isotope reverts to more stable Carbon 13 (^{13}C). As this rate of decay is predictable (the half-life of ^{14}C is 5,730 years), the ratio of ^{14}C and ^{13}C can be used to date a sample. Analysis results (Figure 4-12) showed that ^{14}C levels were consistent with CO_2 generated by modern plant decay, as well as with that of baseline samples. Conversely, samples taken from the Weyburn injection gas stream have virtually zero ^{14}C, as the constituent carbon was synthesised millions of years ago.

Cenovus furthered its case by testing the relative elemental gasses abundances. Microbial activity in soils consumes oxygen (O_2), converting it to CO_2, which means that biogenic CO_2 will have an inverse relationship with O_2, while nitrogen (N_2) will remain constant and consistent with atmospheric concentrations. If leaking CO_2 displaces soil gas, both O_2 and N_2 will show an inverse relationship to CO_2 (Figure 4-13). Cenovus's example demonstrated these geochemical techniques provide a definitive means of differentiating CO_2 sources independent of environmental variability.

The planned Clive program to establish baseline soil gas will provide a sufficient data set to compare with that obtained during the monitoring phase. To institute a baseline independent of seasonal variability, Enhance will take isotopic samples to provide the most valid and concise means of differentiating CO_2 from fossil fuel sources, versus that from biological activity. Baseline CO_2 concentration and $\delta^{13}C$ will also be established.

Carbon isotopes will be analyzed for all locations during the spring baseline program and then a sub-set of 2 locations for the summer and fall baseline program. Sampling and analyses for project monitoring will follow the same procedures as the baseline program and will be re-evaluated after two years.

Although there have been no recorded instances of sour gas migration outside the surface casing at Clive (i.e. gas migration), this soil gas monitoring program, along with ongoing H_2S monitoring and surveillance will provide detection of this type of event should it occur.

ATMOSPHERIC MONITORING

Surface Facility Monitoring

Injection and production facilities will be equipped with H_2S alarms. Since leaking CO_2 would contain H_2S from the reservoir, these alarms will provide a robust method of potential leak detection.

WELLHEAD MONITORING

Monitoring existing wells for SCVF will provide the primary protection against leakage out of the geosphere at its most likely point. Should this prove not to be the case (meaning one of the secondary techniques shows that leakage has occurred that was not detected by SCVF monitoring), Enhance will first locate and repair the leak and then evaluate why the SCVF monitoring did not detect the leakage. Should this evaluation show that SCVF monitoring does not provide a reliable means of leakage detection, Enhance will evaluate additional techniques to provide detection while CO_2 is still in the geosphere.

Surface Casing Vent Flow and Casing Pressure Buildup on Existing Wells

To monitor for potential of CO_2 leakage, all of the existing wells within the active MMV Plan Area will be monitored for SCVF and pressure build-up in the production casing a minimum of twice per year, using procedures as outlined in AER ID 2003-1 and D-20 ..

Small vent flows require specialized detection methods (SCVF testing involves running a tube from the surface casing vent into a jar of water and watching for bubbles for 10 minutes; if any are observed, a meter must then be installed to quantify the vent rate) unless they are apparent due to odours from carried H_2S. High volumes of CO_2 leakage would be apparent from any or all of the following:

- odour;
- noise from the vent;
- visible shimmer caused by the differing optical properties of vented gas versus the atmosphere; and
- ice plumes associated with cooling CO_2 as it expands to atmospheric pressure from the casing vent.

Operations staff are trained and qualified to observe these conditions during their daily field surveillance.

If SCVF and/or pressure build-up is noted, Enhance will follow response procedures outlined in AER Interim Directive ID 2001-03, which directs how the magnitude of the issue is to be determined and the corrective actions required. These procedures are discussed in *Action Triggers and Mitigation Plans* section.

Based on an extensive review of the cement bond integrity of the 64 existing wells within the planned Phase 1 development area, the leakage risk is extremely low. This work has shown excellent cement bond across the Leduc, Nisku and Ireton cap rock zones, confirming strong zonal and cap rock isolation. Approximately 75% of all zonally abandoned or fully abandoned wells had a cement bond log, and no wells had any history of SCVF from the Nisku or Leduc formations due to cement failure. No history of SCVF in more than 50 years of operation is a strong indication of good cement bonding and integrity through the Leduc, Ireton , Nisku and overlying cap rock.

Gas from the Leduc reservoir is sour, containing over 12% H_2S. Any leakage from the reservoir would be obvious due to the strong odour of this gas; none has been noted to date, except for those wells where casing failure above the cement top was detected and repaired. During EOR operations, CO_2 will blend with existing gas and make odour detection of leaks possible. If the source of any SCVF is not obvious, Enhance will sample the flow for chemical and/or isotopic analysis and may conduct downhole investigation.

Changes Due to Formal Risk Assessment

Enhance will continue its undertaking a formal risk assessment on existing wells outside the **MMV Plan Area**. Should this assessment identify wells that cannot be mitigated to a low-risk, Enhance will implement additional monitoring.

Timing of Baseline Data Gathering

Baseline soil and domestic water well sampling is planned for the spring, summer and fall, prior to any CO_2 injection, based on the current project schedule. Baseline sampling of the CBM wells, gathering system and the CO_2 sources (Nutrien and the Sturgeon Refinery) will occur prior to CO_2 injection, in conjunction with the soil and water well sampling program. Existing wells within the **MMV Plan Area** will be monitored for SCVF and casing pressure prior to CO_2 injection.

Summary of Planned Monitoring Program

The following table provides a summary of the monitoring techniques to be used within Enhance's MMV Plan.

GEOSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During ACTIVE EOR**	**Frequency of Testing POST INJECTION**
Most recent AER D-65 EOR Approval	Meet all clauses and requirements specified within Approval No. 12832	As per approval	As per approval	N/A
Monitor physical status of all wells per AER Directives 13, 20, 51 and 65, ID2003-1 or as applicable at the time	All Enhance wells within **MMV Plan Area**.	Verify no SCVF or casing pressure on existing wells prior to CO_2 injection.	Monitor SCVF and casing pressure on existing wells minimum two times per year. Evaluate frequency after two years, if no issues seen.	Per AER requirements at time. SCVF and casing pressure to be checked and remediated (if required) at final abandonment.
Conduct reservoir simulation and day-to-day flood management	Entire EOR operation with focus in specific areas, as required.	History match of Central Leduc Area prior to CO_2 injection and baseline CO_2 EOR performance prediction.	Day-to-day monitoring of EOR performance. Annual (minimum) updates to simulation for two years, then as required. Monitor voidage replacement ratio (not to exceed 1.0 cumulative).	N/A
Seismic	Acquire existing 3D seismic over project area as per AER D65 project approval.	Process and Interpret baseline seismic. Confirm no faults	Evaluate as required based on event trigger.	N/A

		transects the seals.		
Nisku monitoring wells	Isotope & gas analysis, water chemistry and reservoir pressure as per AER D65 project approval.	Once. Gas carbon isotope. Water chemistry (from Nisku pool).	Isotopes annually, and gas analysis bi-annually. Evaluate frequency of isotope and gas analysis after two years. Annual reservoir pressure.	N/A
Leduc monitoring well	Isotope & gas analysis, water chemistry and reservoir pressure as per AER D65 project approval.	Once. Gas carbon isotope. Water chemistry (from Leduc pool).	Isotopes annually, and gas analysis bi-annually. Evaluate frequency of isotope and gas analysis after two years. Annual reservoir pressure.	N/A
Leduc and Nisku Reservoir Pressure	Annual stabilized formation pressure per AER D-40 requirements and D-65 project approval.	Once.	Annual.	N/A
Monitor tubing and annulus pressure on injection wells	All injection wells.	N/A	Continuous tied into SCADA.	N/A
Injection well hydraulic isolation testing	All injection wells.	Pressure test packer, hydraulic isolation log and cement bond log.	Annual pressure test packer, hydraulic isolation log every five years.	N/A
MUD LOG new surface and build drills	Three project new drills within the **MMV Plan Area**	Once C_1-C_5, including isomers and CO_2.	N/A- may be considered if infill or replacement well required.	N/A
Measure injected and produced fluids	All injection and production wells.	N/A	Follow measurement requirements	N/A

			as outlined by AER D-17.	
Analyze produced liquids and gas	All production wells.	N/A	Periodically prior to breakthrough, every three months post breakthrough.	N/A
Analyze injected source gas	Nutrien and Northwest Redwater Partnership (NWR).	Once for chemistry and carbon isotopes.	Annual isotopic and continuous CO_2 concentration.	N/A
Analyze produced and recycled gas	Produced gas at individual wells and recycle streams.	Baseline (including isotope) on existing Leduc producers.	Minimum quarterly gas analysis on production wells and monthly on recycle stream & combined injection stream.	N/A

BIOSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During Active EOR**	**Frequency of Testing Post Injection**
Conduct soil gas surveys	19 locations within **MMV Plan Area**. Planned during unfrozen ground conditions to obtain the most reliable and representative samples	Spring, summer and fall prior to injection. Gas chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set.	Spring, summer and fall. Evaluate frequency after two years. Analyses per baseline.	Evaluate frequency based on results to date.

HYDROSPHERE				
Routine Monitoring Technique	**Testing Technique Details**	**Frequency of Testing to Establish Baseline**	**Frequency of Testing During Active EOR**	**Frequency of Testing Post Injection**

Monitor CBM wells for CARBON ISOTOPE SIGNATURE	Gas-gathering system encompassing well clusters for the entire **MMV Plan Area** and at main gas plant.	Once	Annual isotope analysis and monthly composition.	Annually
Conduct landowner water well surveys	9 Landowner water wells within **MMV Plan Area**.	Spring, summer and fall prior to injection. Water and headspace gas (if obtainable) chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set. Supplement with Baseline Water Well Testing for Coalbed Methane Development.	Quarterly in 2020. Evaluate frequency at YE 2020. Analyses per baseline.	Evaluate frequency based on results to date.
Dedicated monitoring wells	Three dedicated monitoring wells completed at 20, 40 and 80m BGS for chemistry and pressure monitoring. Low flow sampling and downhole pressure recorder.	Spring, summer and fall. Water and headspace gas (if obtainable) chemistry at each event. Isotopes once on all samples and spring, summer, fall on sub-set.	Quarterly. Evaluate after two years.	Evaluate frequency based on results to date.

Action Triggers and Mitigation Plans

As part of MMV planning and preparedness, Enhance has undertaken analysis of potential action triggers and mitigation plans in the risk assessment (**Appendix G**). The list of triggers, actions and mitigations in **Appendix G** is not intended to include every conceivable scenario but gives examples of these events and steps that could be taken to understand and respond any CO_2 migration.

Action triggers and mitigation plan details listed in this section are in addition and complementary to those stipulated in the AER D-65 EOR Approval (**Appendix N**). Foremost of these is that, Enhance will immediately suspend injection operations if the injection facilitates the movement of injected fluids into any zone above the base of groundwater protection or any zone other than the Leduc and Nisku zones, and immediately inform the Resource Compliance Group in the AER Environment & Operational Performance Branch, and the AER Red Deer Field Centre.

The two most likely scenarios that would trigger action, as well as the general approach that would be taken if anomalous monitoring results are observed are discussed below.

As a general rule, unexpected or anomalous results from any of the active safeguards would trigger action beyond routine monitoring activities. Unless the issue is readily apparent, the first step will be to confirm the data to verify that an issue exists. This could involve re-sampling and analysis, for techniques such as soil gas monitoring, or re-calibrating pressure sensors, for techniques such as injection well pressure monitoring. This step is necessary to ensure that actions are not being taken based on a false positive.

If the anomaly is confirmed, further steps will be taken to identify and remediate the source of the suspected CO_2 leak. As each technique being used is independent of the others, results from the trigger technique would be compared to the other monitoring methods. If necessary, for techniques where only periodic measurements are taken, new samples or measurements would be taken to compare to the trigger event.

If the preceding actions indicate the trigger event is valid, Enhance will conduct tighter areal sampling to determine the leak's source. For example, should project CO_2 be detected at the inlet to the CBM gas plant, the event would trigger systematic sampling along the gathering system and sampling of individual wells to isolate the leak's geographic location so that remediation could occur. If it was suspected that CO_2 had migrated above the CBM producing zones, Enhance would conduct soil and/or water well sampling, or use technologies such as additional shallow aquifer dedicated monitoring wells, as an alternative to, or complement for, individual well checking.

Should Enhance be unable to resolve the issue itself, external resources and support will be engaged, such as service companies, consultants, academia, regulators or other specialists.

Enhance has provided examples of two possible well-related that would be readily apparent, how they would manifest, and how the Company would respond.

1. ***The first potential trigger event would be the presence of SCVF.***

   There are two potential sources that have the highest probability of manifesting as a SCVF in the Clive field. The first potential source is sweet methane gas from the shallow coalbed zones that are being produced in the area (Scenario 4 in Figure 3-2). This scenario is possible because existing wells did not have full cement coverage over these zones. The second potential source is a leaking plug in the wellbore combined with a possible casing leak. This scenario would result in sour gas and CO_2 being detected at surface (Scenario 2 in Figure 3.2).

   The AER defines SCVFs in two classifications, serious and non-serious, both of which are detailed in ID2003-01.

   In the event a SCVF is detected, Enhance would take the following action:

   - If there was any danger to the public or environment, Enhance's Emergency Response Plan would be activated, and the SCVF would be tested to determine its classification.
   - Enhance would report the SCVF to the AER through the Digital Data Submission Surface Casing Vent Flow/Gas Migration (DDS SCVF/GM) system.
   - If the SCVF were deemed to be serious (based on several criteria, including flow rate, presence of

H_2S and/or liquids and proximity of potable water wells), the problem would be repaired as soon as possible and not later than 90 days from discovery. The type of repair required would depend on the leak's source. In general, the gas would be sampled and analyzed to determine the geological zone that it is likely leaking from. A service rig would be moved onto the well and downhole sensing tools (logging tools) would be used to confirm the leak's source. The actual repair method would depend on where the leak occurred, equipment in the well and the condition of the well, but it would usually involve placing and/or squeezing additional cement into the well or using mechanical sealing devices such as a bridge plug or casing patch. All of these are routine well-repair methods.

2. ***The second potential trigger event would be any abnormal annulus or tubing pressure readings from injection wells.***

The injection wells will have an initial tubing/casing annulus pressure test of 7,000 kPa prior to injection. The packer will be tested annually to 1,400 kPa and reported to the AER. These testing requirements are specified by AER D-51. The tubing and casing/tubing annulus pressures will be continuously monitored through SCADA, which exceeds regulatory requirements.

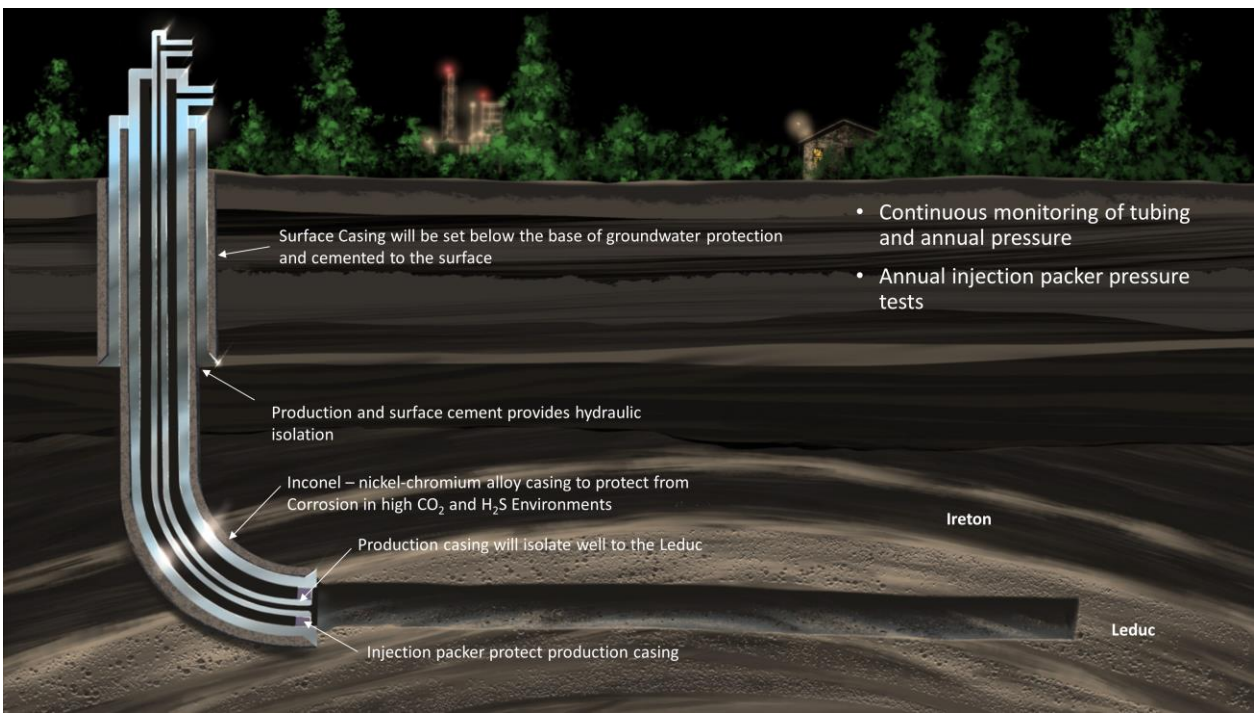


Figure 4-14 CO_2 EOR Injection Well Diagram

Any abnormal annulus or tubing pressure would result in troubleshooting and repair to remediate the issue. The wells will be equipped with an Emergency Shut-Down technology that will shut-in the well, in the event of a failure. Enhance will then diagnose the problem and develop a plan to remediate the issue. Operations to repair the issue will commence within 90 days.

Monitoring Techniques Considered but Deemed Unnecessary

In establishing the appropriate and optimal monitoring techniques to be used within the MMV Plan, Enhance conducted an extensive review of all available monitoring technologies. Based on this review, the Company determined the following techniques were not necessary to implement on a routine basis to achieve its MMV goals. However, should routine monitoring techniques identify issues that cannot be resolved using the data they provide, some of these methods or others not identified could be implemented to assist in analysis. These methods are considered contingent techniques.

1. Routine Time Lapse (4D) Seismic

Enhance investigated using 4D seismic as a routine tool for tracking the progress of CO_2 in the reservoir over the period of injection, primarily to understand the efficiency of the flood. A geophysical study conducted by Enhance (see above - Seismic Baseline Gathering) (**Appendix J**), showed tracking CO_2 at Leduc and Nisku depth would be difficult due to the lack of acoustic variation between the supercritical (liquid) CO_2, and the water it would displace. The capability of the tool is further debilitated by the low porosity of these zones, as this reduces the amount of fluid that can be recognised. Furthermore, a cost-benefit analysis of repeat 3D seismic shoots showed that the information gained would be too late to have any actionable consequence. To make a meaningful impact on EOR management, a desired tool would require a quicker rate than would be feasible from repeat 3D surveys, with much of the required information obtainable using downhole real time surveillance.

Having understood the limitations of routine 4D seismic, Enhance has chosen to utilize it as a contingent monitoring tool in the specific case of suspected CO_2 loss into Cretaceous horizons.

2. Areal atmospheric monitoring techniques

Areal atmospheric monitoring tools generally measure changes in infrared light transmission due to varying CO_2 concentration in the atmosphere. Any reservoir-sourced leakage of CO_2 will contain H_2S in quantities high enough to be detected by H_2S monitors currently employed at Clive. Furthermore, the pipeline that will be used to transport CO_2 from the source to Clive will also be equipped with a comprehensive leak detection system incorporating pressure, temperature, and input and outlet volume measurement, and SCADA will continuously monitor surface systems. Combined, the personnel safety systems that are designed for H_2S leakage detection provide superior coverage for CO_2 monitoring versus a dedicated atmospheric system making this an unlikely tool for contingent monitoring purposes.

3. *Dedicated Lower Mannville Aquifer observation wells*

Enhance has studied the theoretical effect of CO_2 migration into the Lower Mannville Aquifer, which is the deepest aquifer above the **MMV Plan Area**, in order to evaluate the potential utility of deep observation wells above the Leduc. The methodology and assumptions used for the purposes of this study are discussed in **Appendix M**.

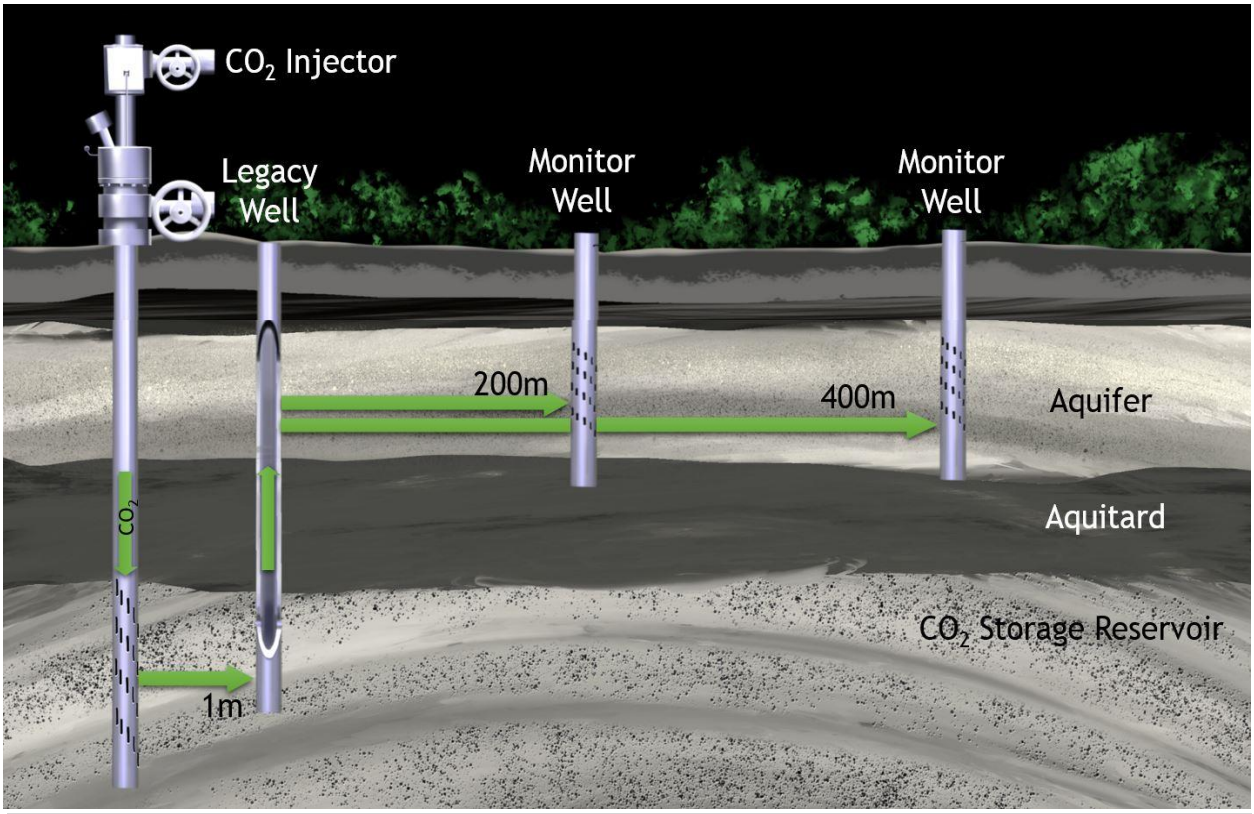


Figure 4-15: A Worst-Case Scenario Pressure Response Model

Enhance has analyzed expected pressure changes due to injection into a reservoir cross-flowing into an aquifer through a leaky pathway (a well) and found them too small for the instrument to detect at a monitoring well.

A potential worst-case scenario was evaluated (Figure 4-15), which assumed that a well is leaking within 1m of the injection well and there is a casing failure or channel in the existing cement. This work concludes pressure changes in the aquifer would be extremely small (Figure 4-16) and would be below the tolerance of instrument accuracy (piezometers are generally accurate within 0.1% of full scale with a resolution of 0.025%)[1]. Calculated pressure changes for this CO_2 migration would not be detectable. As a result, the observation well would not be effective.

[1] http://www.geokon.com/Piezometers

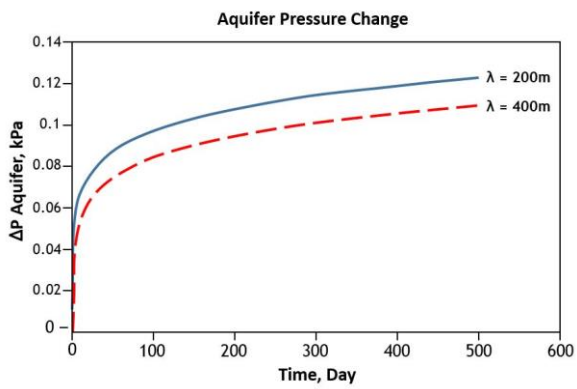


Figure 4-16: Aquifer Pressure Change vs. Time at 200m and 400m Offset

Based on these analyses, Enhance determined that dedicated Lower Mannville observation wells are impractical from both logistics and economic viability perspectives, are disruptive from a surface impact perspective, and, most importantly, have an extremely low chance of detecting CO_2 migration. Plans to monitor existing wells, Nisku producing wells, CBM wells, domestic and the planned dedicated groundwater well(s) and response from the CO_2 flood will provide extensive and dependable coverage.

4. Remote sensing techniques

There are many possible remote sensing techniques that could be used to monitor conditions such as changes in surface elevations or vegetation health. Given that average reservoir pressure will remain relatively constant during operations, Enhance does not expect to see changes in surface elevation. Changes in vegetation health could be due to factors other than CO_2 leakage to the biosphere, such as climate conditions, agricultural practices or other natural causes. The monitoring techniques Enhance plans to use will provide more immediate and reliable indication of containment issues than these methods could afford.

ACCURACY TARGETS

Monitoring techniques selected by Enhance are typical of oilfield practice. Accuracy targets, where appropriate, are specified below:

Technique	Accuracy
SCVF testing	No bubbles observed in 10 minutes flow into water filled container.
Tubing and casing pressure	Gauge pressure typically accurate to 0.02% of full scale.
Isotopic analysis	Dependent on variation in isotope signature which is not yet established and the relative concentration of gases. Utility TBD once baseline analyses are complete.
Soil gas analysis	Dependent on isotopic data. Ratios of O_2, N_2 and CO_2 can provide independent attribution of CO_2 source.
Production and injection volumes	Enhance will meet or exceed provisions of AER D-17. Flow computers calculating gas volumes and densities will use AGA-3 and NIST-14 calculations.
CO_2 concentration	Grab samples by accredited laboratories. Continuous analysis device not yet selected but IR devices typically accurate to 1% with resolution to 0.1%.
H_2S detection	Commercially available detectors have resolution of +/- 1 ppm.

All chemical analyses will be conducted by laboratories accredited to ISO/IEC 17025 using procedures based on recognized Provincial, Federal or US method compendia such as ASTM, CGSB, EN, GPA and/or SM.

PIPELINE AND PROJECT MASS BALANCES

Accurate measurement and accounting for injection and production fluids is critical from both a CO_2 storage perspective and to ensure accurate data is available for ongoing assessment of project performance.

Each source (NWR and Nutrien) will be equipped with continuous flow meters and CO_2 analyzers to accurately measure the mass of CO_2 delivered to the ACTL (Figure 4-17). A continuous flow meter will be installed at the delivery point of Clive to enable accurate measurement as close to injection site as practically possible. The concentration of CO_2 delivered to Clive will be calculated based on a mass averaged concentration delivered to the pipeline by the two sources. Further discussion of pipeline leak detection is outside the scope of the Clive MMV Plan.

New CO_2 delivered to Clive from the ACTL will be blended with recycled gas from the EOR production wells, which will be composed of a mixture of solution gas and CO_2. Injection wells will be equipped with continuous flow meters. A mass balance between injection at each of the individual well meters and the total combined new and recycle stream will account for any CO_2 losses encountered within the field injection system. The recycle gas stream will be sampled monthly and individual production wells quarterly post-CO_2 breakthrough for compositional analysis. Gas compositional sampling and analysis will assist in understanding reservoir performance, and in estimated mass of CO_2 lost in the event of a leak. CO_2 from the NWR source is expected to be approximately 99.5% pure with traces of H_2, CO, CH_4, N_2, MeOH and AR. Post dehydration, Nutrien CO_2 is 99% pure with traces of CH_4, H_2 and N_2. Recycle gas will be dehydrated and will contain varying proportions of the source gases and reservoir gas which consists primarily of methane, C_2-C_6, H_2S and CO_2 with trace amounts of helium and nitrogen. None of these substances represent potential added risks; produced gas is successfully handled in the field today.

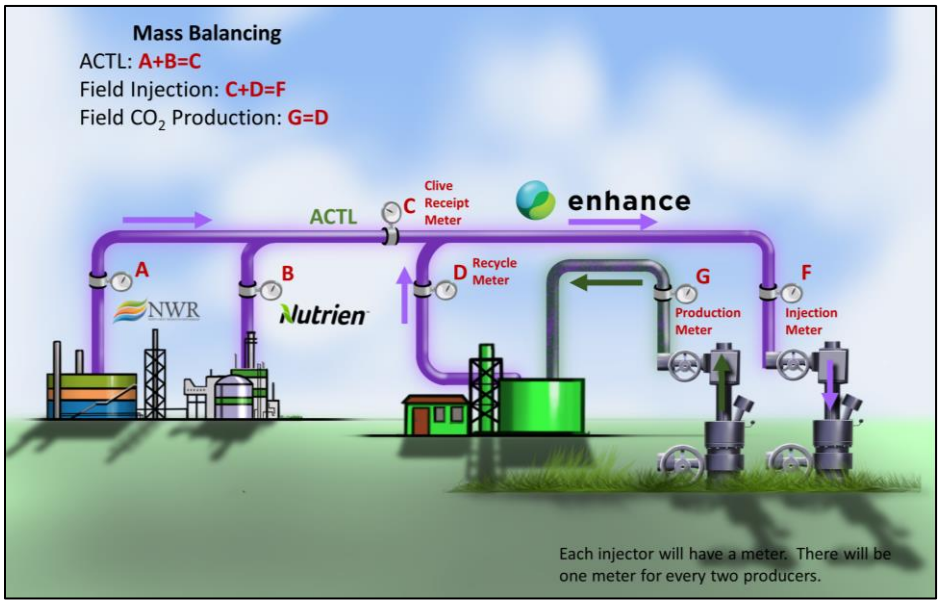


Figure 4-17: Mass Balance Calculation of the ACTL Project

The Clive Leduc reservoir contains an average of 12.6% H_2S, requiring all wells and production facilities meet high standards of fluid containment to prevent release of this gas. As blended gas is produced from the CO_2 EOR project, it will contain H_2S and must be contained to meet regulatory standards. All production facilities, from the initial free water knockout and plant inlet separator to the sales tanks will be equipped with vapour recovery to ensure all gas evolved is recovered and routed to the recycle compressor for re-injection. As produced gas is blended with source gas from NWR and Nutrien, the blended stream going from the Clive battery to the injection wells will also contain H_2S. The presence of H_2S in both produced fluids and injected CO_2 will provide an additional means of ensuring the system does not leak, as even small leaks will be readily detected by odour.

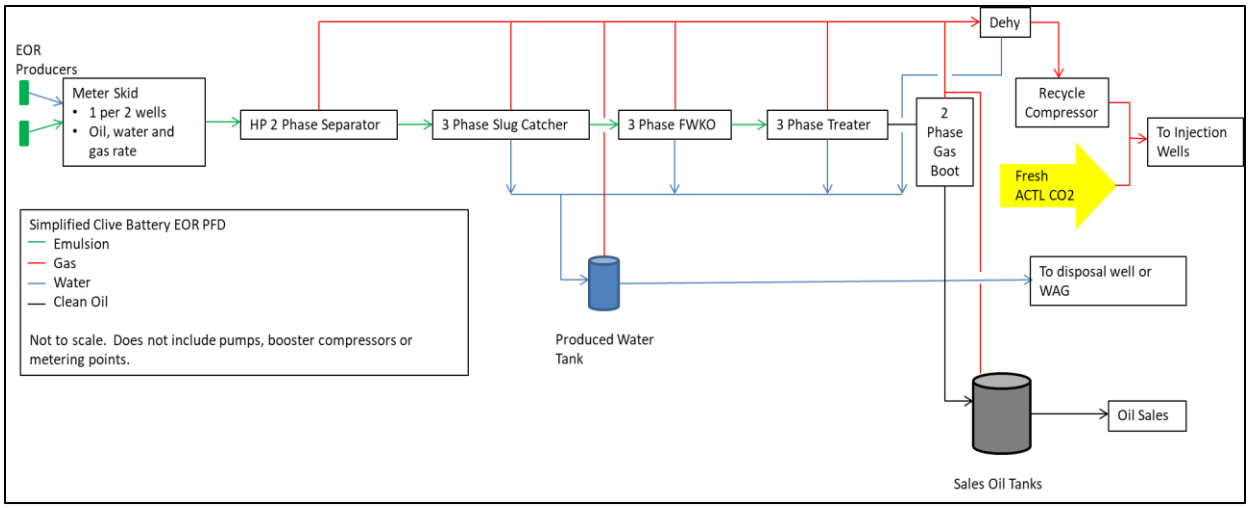


Figure 4-18: Fluid Management at Clive

Figure 4-18 shows a simplified process flow diagram (PFD) of facilities design for the Clive CO_2 EOR project. All vessels used in emulsion separation and oil treating will be tied-into a vapour recovery system, as will the produced water and sales oil tanks. As the gas blanket on the tanks will operate at approximately 0.5 oz/in^2 gauge, entrained gas in these liquids will be minimal. The gas blanket on the tanks will have pressure safety valves set to 4 oz/in^2, and will vent to a low-pressure flare, not shown, to protect against tank rupture; this system would only operate under upset conditions and CO_2 losses would be accounted for following procedures outlined in AER D-60. As noted in the Figure 4-18, there are a number of booster compressors not shown on the diagram that allow the various vessels and tanks to operate at differing pressures and balance pressures feeding into the recycle compressor. The recycle stream will be dehydrated using the DexPro^{TM} process, and water content monitored to ensure that no free water accumulates in injection lines that could lead to corrosion and failure. Other than a facility upset flare condition, the entire system is closed loop, all CO_2 and gas produced will be captured, compressed, dehydrated and combined with the new CO_2 stream for re-injection.

CONCLUSIONS

The MMV Plan outlines actions and responsibilities that Enhance will undertake to ensure the ***safe and long-term containment of CO_2 in the Clive Leduc pool. The plan is designed to verify CO_2 is contained within the Leduc reservoir and to provide public assurance the hydrosphere and biosphere are protected.*** Enhance considered AITF's recommendations, its own expertise and that of expert consultants in assessing the probability of different potential leakage pathways, the monitoring techniques that could be used (as well as those deemed unnecessary), and in crafting a monitoring plan that will provide assurance CO_2 remains contained in the reservoir for the duration of the project and beyond. This plan has been developed to address areas of the project that present a material probability of occurrence and/or a high consequence of leakage.

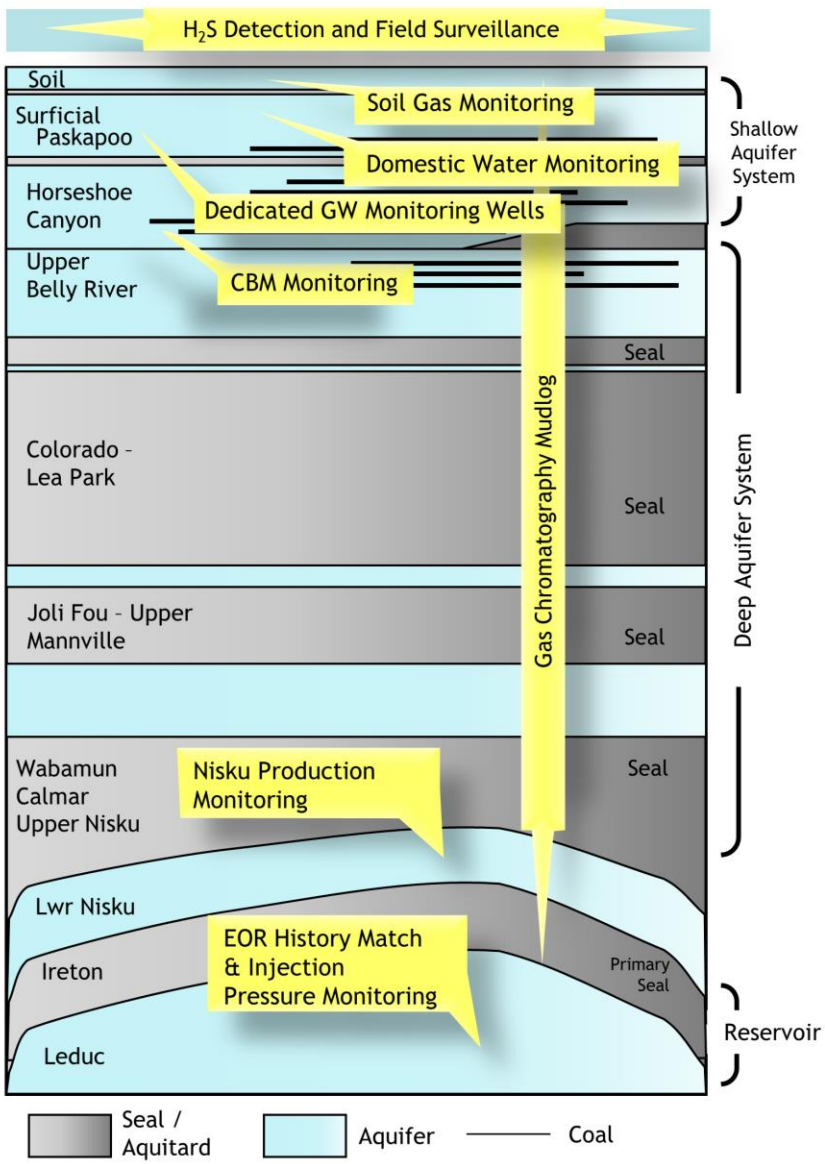


Figure 4-19: Clive Field MMV Plan Summary

Enhance evaluated all monitoring tools and techniques for this project; the MMV plan is designed for the Clive's unique properties and the attributes of CO_2 EOR (see Figure 4-19 Clive Field MMV Plan Summary).

- The plan is designed to maximize EOR project performance, verify Ireton seal containment, provide public assurance of hydrosphere and biosphere protection, and monitor existing wellbores, which present the only reasonable leakage probability.
- Enhance employed a risk-based approach to designing the MMV plan, considering both probability and consequence of occurrence in selecting the appropriate monitoring environments.
- Carbon isotope analysis is the most powerful tool available for monitoring and verification, and it will be utilized in every aspect of the MMV plan. Baseline carbon isotopes will be established for source CO_2, Leduc, Nisku and CBM gas, soil gas and headspace from

domestic water wells.

- Extensive data gathering and analysis from reservoir monitoring techniques will ensure Ireton seal integrity is not compromised and enable simulation modelling as a means of detecting possible CO_2 conformance or containment issues.
- Nisku production monitoring will verify Ireton seal containment or potential cross-flow through existing wellbores.
- Coal bed methane sampling will monitor three geological horizons above the Leduc pool over a large geographic area.
- Dedicated water wells, landowner wells and soil gas sampling within 1,600m of the injection well sites will provide public assurance CO_2 is contained within the geosphere. Baseline samples will be collected spring, summer and fall prior to CO_2 injection.
- The Leduc is a sour field. Therefore, a CO_2 leak from the reservoir would contain H_2S. Surface facilities will be equipped with H_2S alarms, providing a robust method of leak detection. As well, operations staff are trained and qualified to detect an H_2S leakage.
- Surface casing vent flow monitoring on existing wells will provide the primary protection against potential leakage out of the geosphere.

5 ALBERTA REGULATIONS AND INDUSTRY EXPERIENCE

In addition to the passive safeguards provided by the characteristics of the site itself and the active safeguards that Enhance will implement, the regulatory regime in Alberta provides ancillary safeguards that afford significant benefit.

HIGH STANDARDS OF OIL AND GAS REGULATION IN ALBERTA

Current industry practices and AER well drilling, completion, repair, monitoring and abandonment requirements have been continually refined and updated based on experience gained from operating and regulating wells in Alberta. Including its predecessors, the AER has been in existence for almost 80 years and is widely recognized for its excellence in regulating industry to promote efficient and effective resource development while, at the same time, ensuring environmental and public protection. This is especially important given the extensive sour gas and oil production and sour gas disposal operations in the province. Meanwhile, operating and service companies have been continually learning how best to drill, complete and operate wells; a failed well represents a loss of potential oil or gas production, as well as a liability requiring repair, providing additional incentive to ensure that industry best practices are used and continually upgraded. Enhance Energy staff includes experts in drilling and completions, facility design, construction and operation, and reservoir management, with experience gained at the Cenovus (now Whitecap) Weyburn project and other oil and gas developments.

OPERATION, TESTING AND MONITORING OF WELLS PER AER DIRECTIVES

The AER prescribes extensive operational, testing and monitoring requirements for production, injection and suspended wells, or those wells on which operations have been discontinued. These requirements ensure well integrity to protect against contamination of the hydrosphere, biosphere or atmosphere. Enhance's MMV plan focuses on well integrity, ensuring containment and protecting potable groundwater. Enhance will meet or exceed all requirements, current and future, for operated and owned wells in the EOR project. Current requirements include:

- **Directive 13 Suspension Requirements for Wells:** Deals with suspension of wells that are not to be immediately abandoned (i.e. they are retained for potential future use) and specifies down-hole suspension methods and ongoing monitoring requirements specific to the well type. https://www.aer.ca/rules-and-regulations/directives/directive-013.

- **Directive 20 Well Abandonment**: Specifies how wells that are no longer required must be tested, remediated (if leakage is apparent during testing) and abandoned, with the ultimate goal of protecting potable groundwater. Enhance will meet or exceed all of these requirements when abandoning existing wells as active EOR areas are developed. https://www.aer.ca/rules-and-regulations/directives/directive-020.

- **Directive 051 Injection and Disposal Wells – Well Classifications, Completions, Logging, and Testing Requirements**: Specifies how injection wells are to be constructed, monitored and operated. Enhance will meet or exceed all the Directive 051 requirements, which include ensuring wellbore isolation of the CO_2 to the injection zone (Leduc), injecting below formation fracture pressure, confirming casing

and cement integrity, and ensuring the injection packer and tubing are not leaking. This directive requires an initial pressure test on the casing-tubing annulus and annual pressure tests to confirm integrity of the annulus. Enhance will exceed these requirements by having continuous pressure monitoring tied to the SCADA and alarm system for the project. https://www.aer.ca/rules-and-regulations/directives/directive-051.

- **Interim Directive 2003-1 1) Isolation Packer Testing, Reporting, and Repair Requirements 2) Surface Casing Vent Flow / Gas Migration Testing, Reporting and Repair Requirements 3) Casing Failure Reporting and Repair Requirements**: Specifies testing, reporting and remediating requirements for wells with SCVF, gas migration or casing issues. Enhance will exceed these requirements by monitoring existing wells in the EOR area for SCVF and casing pressure a minimum of twice per year. https://www.aer.ca/rules-and-regulations/interim-directives/id-2003-01.

Enhance will also follow a number of additional guidelines and regulations that ensure safe and efficient recovery of resources. These regulations are not specific to the MMV plan and include, but are not limited to:

- **Directive 65 Resources Applications for Oil and Gas Reservoirs**: Establishes requirements to ensure efficient resource recovery.
- **Directive 56 Energy Development Applications and Schedules**: Sets out procedures to be followed for petroleum industry energy development that includes facilities, pipelines or wells.
- **Directive 8 Surface Casing Depth Requirements**: Sets requirements for the surface casing depth on new wells to assist in well control and groundwater protection.
- **Directive 9 Casing Cementing Minimum Requirements**: Prescribes required cementing procedures for casing strings.
- **Directive 10 Minimum Casing Design Requirements**: Establishes standards for casing design to ensure well integrity.
- **Directive 60 Upstream Petroleum Industry Flaring, Incinerating and Venting**: Deals with requirements to eliminate or reduce the potential and observed impacts and to ensure that public safety concerns and environmental impacts are addressed.
- **Directive 71 Emergency Preparedness and Response Requirements**: Establishes a decision framework and action plan to ensure quick and effective emergency response in order to protect public safety and minimize environmental impacts through implementation of an Emergency Response Plan.
- **Directive 80 Well Logging**: Establishes minimum logging requirements to ensure relevant geological data is collected to allow evaluation of aquifers, to confirm the completion/production intervals and to provide sufficient data to estimate resources and reserves of the well and allow assessment of other zones penetrated by the well. Also establishes format for submission of this data to the AER.

These directives may be viewed at the AER website: https://www.aer.ca/rules-and-regulations/directives.

EXTENSIVE EXPERIENCE WITH INJECTION IN ALBERTA

Alberta has a long-standing practice of successfully utilizing the deep sedimentary sequence for a variety of fluid injection purposes, while protecting potable groundwater and ensuring orderly and efficient resource development. As of March 2017, the following statistics were available for active wells (not suspended or abandoned) licensed for various injection and disposal purposes in Alberta (source IHS AccuMap):

MODE	FLUID	NUMBER
Disposal	Acid Gas	44
Disposal	Waste	78
Disposal	Water Disposal	1,783
Industrial	Waste	28
Injection	Air	5
Injection	CO_2	46
Injection	Gas	3
Injection	Gas Injection	57
Injection	Solvent	144
Injection	Steam	354
Injection	Water Injection	7,026
SAGD	Steam	1,661
Storage	Gas Storage	174
Storage	LPG	58
Cyclical	Oil	3
Cyclical	Heavy Oil	5,631
TOTAL		17,095

Table 2 Injection and Disposal Wells in Alberta

AccuMap shows a total of over 17,000 wells licensed for various types of injection. This includes solvent and CO_2 injection wells associated with 59 projects as of June 2011. The high level of injection activity – without widespread or persistent issues – speaks to the effectiveness of well construction, abandonment requirements and regulation in Alberta. The CO_2 EOR flood at SACROC, which has been in operation for more than 45 years, also has a low incidence of wellbore-related issues (as reported by Carey, *et al*, 2016*)*. The success at SACROC, with wells that are a similar vintage to the wells at Clive, provides additional confidence that historic drilling and completions methods are competent in providing CO_2 containment.

DIFFERENCES BETWEEN CO_2 INJECTION FOR EOR SCHEMES AND SALINE AQUIFER STORAGE

The risk profile for CO_2 EOR is different than for saline aquifer storage. Clive Leduc pool and most other CO_2 EOR projects are proven containers that have stored hydrocarbons for millions of years, and have tight well control and decades of production and injection history, allowing for detailed geological and history matched simulation models to be constructed. These models, as Enhance has built, provide a thorough understanding and response prediction during CO_2 injection; the models will trigger investigation when they cannot explain variations in field performance during CO_2 EOR. Saline aquifers, on the other hand, generally have poor well

control and limited understanding of hydrodynamics, as they have been of little economic interest prior to using them for storage.

As the AITF studies referenced in this plan have noted, and as Hovorka (2009) recently noted, existing wellbores in a CO_2 EOR scheme represent the most likely risk for containment loss. Conversely, Hovorka also noted, existing wells and the EOR process allow for much better monitoring and management of reservoir pressure than saline aquifer storage due to the presence of tighter well control and fluid production and recycling (Figure 5-1).

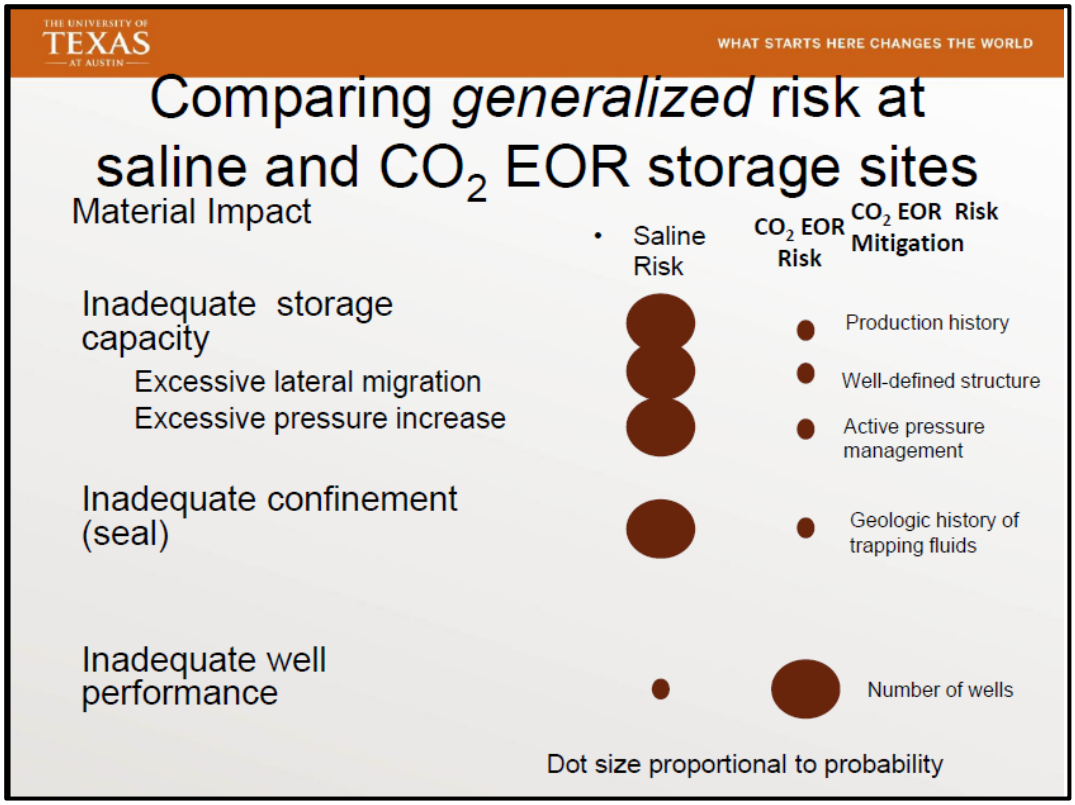


Figure 5-1: General Risks of Aquifer Storage versus CO_2 EOR
(From Hovorka's presentation, used with permission)

Deep saline aquifer storage typically has less containment loss risk from existing wells, but it does not benefit from the detailed reservoir information these wells provide in terms of understanding and predicting storage performance. In EOR storage, distribution of injected CO_2, or conformance, can be monitored and interpreted through production well response and reservoir simulation matching. Aquifer storage does not offer extensive injection or production history, leaving much more uncertainty in forecasting performance. The lack of production means that injection tracking typically requires the use of time lapse (4D) seismic and/or dedicated observation wells. Since aquifers are not proven hydrocarbon traps, the expected ultimate distribution of injected CO_2 may be less certain.

Hovorka also notes that "fluids produced from shallower zones may be (an) ideal and low-cost monitoring option", which is consistent with AITF's conclusions and Enhance's plan to use analysis from Nisku producers and CBM wells as a monitoring technique.

In both types of storage schemes, however, if the geological setting can be shown to provide a strong passive safeguard for CO_2 containment, wellbores are the biggest risk. Enhance recognizes this risk and has built a comprehensive plan to minimize potential leakage from existing wells through rigorous risk assessment that has provided engineered passive safeguards, as well as the suspension and/or abandonment procedures for inactive wells within EOR development areas. Existing wells represent a lower risk in saline aquifer storage because, typically, there are fewer of them that penetrate the storage horizon. In both cases, drilling and completing new wells to meet or exceed regulatory requirements mitigates the risk associated with wells drilled for injection – and, in the case of EOR, production – and/or for observation.

Enhance has designed its MMV program factoring in all of these considerations.

NORTH AMERICAN CO_2 EOR EXPERIENCE

CO_2 EOR is well understood and has been utilized safely for decades in North America. In the continental U.S. alone, injecting CO_2 for EOR has been a successful practice for nearly 50 years. As of 2012, it is estimated that CO_2 EOR operations in North America have injected up to 65 million tonnes per year of CO_2 through more than 7,200 CO_2 injection wells. Cumulative CO_2 injection in the United States is estimated at 800 to 900 million tonnes and annual incremental production at over 128 million barrels (http://hub.globalccsinstitute.com/sites/default/files/publications/118951/bridging-gap-analysis-comparison-legal-regulatory-frameworks-eor-ccs.pdf).

One of the most comprehensive studies of shallow aquifer protection was conducted by the Gulf Coast Carbon Center of the University of Texas at Austin on the SACROC project. SACROC is located in the Permian Basin in Scurry County, Texas, was discovered in 1948, and was rapidly developed over the following two years, making many of the wells in the field over 65 years old (older than the majority of Clive wells, which were largely drilled in the mid-1960s). CO_2 EOR began in 1972 and more than 175 million tonnes of CO_2 have been injected to date. The SACROC oil reservoir ranges in depth between 1,830 and 2,130 metres (6,000 to 7,000 feet), which is a similar depth range to Clive. The Gulf Coast Carbon Center concluded:

"Our field-based study of shallow (<500 ft) groundwater overlying and within an ~1,000 mi^2 area of SACROC shows no impacts to drinking water quality as a result of over 35 years of deep subsurface (6,000 to 7,000 feet) CO_2 injection. Modelling of stable carbon isotopes (d13C) of injectate CO_2 gas, DIC in shallow and deep groundwater, carbonate mineral matrix, and soil zone CO_2 suggests that no significant injectate CO_2 has been introduced to the shallow groundwater."

The success in the SACROC oil reservoir, which is of a similar depth and vintage to the Clive field, and numerous other studies provide confidence that drilling and completion practices provide excellent CO_2 containment.

CONCLUSIONS

Alberta is one of the best-regulated oil and gas producing areas in the world. Enhance's CO_2 EOR project and MMV plan will benefit from the following:

- Current industry practices and AER well drilling, completion, repair, monitoring and abandonment requirements have been continually refined and updated based on experience gained from operating and regulating wells in Alberta. They have proven highly effective in safeguarding the public, oil and gas workers, and the environment.
- Including its predecessors, the AER has been in existence for almost 80 years and is widely recognized for its excellence in regulating industry to promote safe, efficient and effective resource recovery. CO_2 EOR and other injection processes are proven, safe and effective techniques.
- There are over 17,000 wells licensed for various forms of injection in Alberta with no evidence of widespread or persistent containment issues, speaking to the efficacy of regulations and industry practices in the province. Enhance's Phase 1 project will make use of this industry expertise to meet or exceed regulatory requirements to ensure safe and effective CO_2 EOR and storage at Clive.
- CO_2 EOR has been practiced safely for decades in North America, is well understood, and has had no widespread or persistent containment or conformance challenges.
- CCS in deep saline aquifers and storage in EOR projects both provide for excellent opportunities to remove greenhouse gases from the atmosphere through capture and geological storage. There are similarities in the injection wells but there are differences in the storage risks and mitigation procedures, meaning different MMV plans are required.

6 FINAL CONCLUSIONS

Enhance is confident the Clive CO_2 EOR and storage project will be safe, effective and environmentally responsible, and will provide a number of outstanding benefits to Albertans.

The Enhance team created this MMV plan with great care for the public, the environment and all stakeholders. The plan relies on a thorough understanding of the EOR storage reservoir, developed through decades of production, tight well control and third-party expert review of the Clive Leduc pool's suitability for CO_2 storage. Enhance personnel have extensive CO_2 EOR experience and have engaged industry experts to assist in constructing and validating the Company's models and plans.

In addition to its environmental benefits, injecting CO_2 into the Clive field will profoundly increase oil recovery. In terms of expected EOR results, the project will extend the Clive unit operational life for more than 20 additional years. Using CO_2 to produce oil will create a new revenue stream for the Alberta Government of up to $15 billion in royalties, based on up to one billion barrels of CO_2 EOR potential along the first leg of the ACTL pipeline system for which Clive is the anchor project. All Albertans will benefit from the royalties and taxes the ACTL EOR projects will generate, in the form of education, essential services, health care, infrastructure, social programs and transportation.

Job creation will be another significant project win. Based on a Canadian Energy Research Institute study, construction and operation of EOR projects enabled by the ACTL will create more than 30,000 man-years of employment, directly and indirectly. These jobs will be heavily concentrated in rural Alberta and will provide local community members with opportunities for construction jobs, full-time operating and maintenance positions, local contracting and procurement roles, leadership in green technology for Alberta, and more.

CO_2 EOR and other injection processes are proven, safe and effective techniques. There are over 17,000 wells licenced for various forms of injection in Alberta and over 7,200 CO_2 injection wells operating in North America, with some CO_2 EOR projects having been in operation for over 40 years, and no evidence of widespread or persistent containment issues.

Both Enhance and AITF conducted geological analysis of the Clive Phase 1 area confirming the Clive Leduc pool's suitability as an excellent CO_2 storage container. The overlying Ireton Formation's role in containing gas and oil within the Leduc reservoir for geologically significant periods of time demonstrates effective primary sealing. Enhance also operates the Nisku Formation, which is directly above the Ireton and is unitized, and has plans to flood it with CO_2 in the future. Four strong aquitards overlying the Nisku's anhydrite-rich top provide secondary barriers and five saline aquifers could absorb and dissipate any leakage that might occur.

Enhance's interpretation of core and petrophysical log data from 163 existing wells has enabled a robust geological model to be built. The geo-model was imported into a reservoir simulation model in which over 50 years of production and injection data was used to derive a history match, while adjustments to data from the geo-model and laboratory fluid studies were avoided. This provides a high degree of confidence in the model's quality and predictive capability. The simulator will be used to compare production and injection well response with predictions; the model will provide an understanding of CO_2 distribution that is not available in dedicated storage projects with no production.

Enhance has also conducted a detailed review of the existing wells within the Central Clive Area and concluded they show good hydraulic sealing, indicating an extremely low chance of leakage. Engineering company VZFox has completed a third-party risk assessment of all existing wells in the **MMV Plan Area**. More wells will be added to the risk assessment prior to injection outside of the **MMV Plan Area**. This work has detailed a well-specific monitoring and mitigating plan for every existing well within the **MMV Plan Area**. New wells will be drilled and completed using industry best practices to meet or exceed regulatory requirements, thereby mitigating leakage risks. As additional assurance, Enhance will undertake Nisku and CBM production, soil gas and domestic water well sampling.

Enhance is dedicated to the success of the Clive project and to the implementation of its robust MMV plan. Although both CO_2 EOR and saline aquifer storage present opportunities to mitigate CO_2 emissions through geological storage of CO_2, they each have unique challenges and strengths that dictate the most appropriate and effective monitoring techniques to be used. Enhance's plan relies on multiple proven and practical techniques geared specifically towards CO_2 EOR that will provide redundant and complementary early detection of potential containment issues. The safe and effective use of CO_2 injection will reduce greenhouse emissions, enhance oil recovery, and create significant societal and economic benefits for Albertans.

Annual project updates will be provided to Alberta Energy and the AER. These updates will present data and interpretations to date, and they will inform updates to this MMV plan based on new information and learnings.

7 ENHANCE AND CONSULTANT EXPERTISE AND RESEARCH

For the design and development of the Clive Project, as well as the associated MMV Plan, Enhance enlisted its internal team of engineers and geologists, and numerous external consultants.

Enhance Energy: Enhance has extensive internal expertise in all aspects of CO_2 EOR. Key team members provided expertise in drilling, completions and workovers, facility construction and operations, carbonate geology, reservoir modelling, simulation and management, and CO_2 storage verification for the Weyburn project and other CO_2 pilots.

Alberta Innovates Technology Futures (AITF): AITF is now known as InnoTech Alberta, a subsidiary of Alberta Innovates. For more information about AITF and InnoTech, including its expertise and research teams, please see InnoTech Alberta's website at http://www.innotechalberta.ca/. Dr. Stefan Bachu, a recognized authority in the area of CCS and co-winner of a 2007 Nobel Peace Prize for his work with the Intergovernmental Panel on Climate Change, contributed to and/or oversaw much of the work that AITF developed. Dr. Bachu's biography can be found at: http://www.albertatechfutures.ca/Corporate/StefanBachubio.aspx.

Avasthi & Associates Inc.: Avasthi & Associates is a Houston-based international group of over 100 consultants with specialization in many areas, including CO_2 EOR. Dr. Sam Avasthi is an engineering alumnus of the Indian Institute of Technology (Indian School of Mines), Imperial College London, and Texas A&M University (where he earned a Ph.D. degree in Petroleum Engineering). Dr. Avasthi has over 45 years of worldwide oil and gas industry experience in petroleum engineering, reservoir engineering and simulation/modelling, EOR/IOR project design, evaluation and optimization, revitalizing mature oil fields, and related projects. He has been providing consulting and training services to the worldwide oil and gas industry since 1970 and has been involved in conducting reservoir engineering and simulation studies of some of the major EOR/IOR projects. The organization completed a full review of Enhance's simulation modelling for correctness of inputs, specifically residual oil saturations, relative permeability curves and rock fluid interactions.

Bill May and Dr. Jeffrey Packard: Bill May is a geologist and petrophysicist who has worked on every major play in the basin over a career of 40 years. Mr. May has been V.P. for Excite Energy, Circumpacific Energy and more recently for W.R. May & Associates and has also been president of the Canadian Society of Petroleum geologists. Jeff Packard has had an established career in the Canadian oil patch for over 35 years. Dr. Packard's work has been instrumental in understanding of hydrothermal reservoirs in the Wabamun and Devonian, as well as understanding of Devonian reef systems. He has held positions of Senior Geologist at Conoco Phillips and Senior Carbonate Specialist for Talisman Energy, and co-founder of Rhomb Carbonate Consulting. He has also been president of the Canadian Society for Petroleum Geologists and is a research associate for the Pembina Institute. Mr. May and Dr. Packard completed the petrophysical work and the core correlations for the geo-model.

Golder Associates (Golder): Golder is an employee-owned, global organization of more than 6,500 people operating from 165 offices providing consulting, design, and construction services in specialist areas of earth, environment, and energy through technical excellence, innovative solutions and award winning client service. Golder's clients represent the world's major industries and drivers of development: Oil and Gas, Mining, Manufacturing, Power, and Infrastructure. Golder has extensive experience in hydrosphere and biosphere

monitoring for CO2 injection projects in Alberta developed through their involvement with the Shell Quest Aquifer Storage Project.

Computer Modelling Group (CMG): The organization completed the equation of state modelling utilized in the compositional simulation. CMG also developed and supports the simulation software Enhance uses for history matches and CO_2 EOR performance predictions.

Core Laboratories (Core Labs): Core Laboratories has been in business for over 80 years and has developed many of the techniques used to describe the properties of oil and gas reservoirs and the properties of hydrocarbon fluids. Core Labs completed all laboratory testing for the project.

Reliance Oilfield Services: With headquarters in Tulsa, Oklahoma, Reliance provides drilling, completions, and production services to the oil and gas industry. Reliance provided expert review of cement bond logs for a sub-set of Clive existing wells to confirm Enhance's interpretation of excellent cement bond.

The University of Saskatchewan: The University of Saskatchewan team that developed the geomechanical earth model subsequently used by AITF worked under the supervision of Dr. Christopher Hawkes, Associate Professor of Civil and Geological Engineering. Dr. Hawkes specializes in petroleum geomechanics, rock mechanics and numerical modelling and conducted geomechanical investigations for the Cenovus Weyburn CO_2 EOR project.

VZFOX Canada Engineering: VZFOX assists clients with developing strategies and navigating across various regulations to obtain the necessary regulatory approvals and permits. It also provides regulatory consulting and application services tailored to various regulatory bodies in Canada, such as the AER.

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GLOSSARY

NOTE: Enhance has chosen the definition of these terms most relevant to oil and gas operations, CO_2 EOR and storage, and the Alberta regulatory environment as the terms are used in this document.

Abandoned well: An abandoned well has been completely abandoned, the wellhead removed, and the casing strings cut and capped below ground level.

Abandonment plug: An abandonment plug is a device or substance placed in a well when the well is no longer needed for production, injection, observation or other purposes. There are many types of plugs that can be used, dependent on the type and condition of the well; abandonment requirements in Alberta are specified by the AER in Directive-20. The primary purpose of abandonment is to seal-off all deep formations that could potentially produce fluids that could contaminate potable groundwater, ensure the potable groundwater is sealed-off and protected, and to prevent flow of these fluids to the surface.

Active EOR: Period during which the CO_2 EOR project is injecting CO_2 and recovering oil until all injection and/or production has ceased and project abandonment has commenced.

Active safeguard: This includes active monitoring techniques that would indicate potential loss of containment or conformance and would allow further investigation and remedial action, if required.

Amphipora: A sponge-like creature with a calcium carbonate exoskeleton that contributed to carbonate rock formation (much like coral reef building).

Amplitude Curve: The distance between the peak and trough of a sound wave. The greater the distance, the louder the sound.

Anhydrite: A calcium sulfate mineral ($CaSO_4$) deposited during evaporation of sea water. The ductile properties and low-to-zero permeability of anhydrite make it an ideal seal for CO_2 storage.

Aquifer: A permeable geological formation that is water-saturated. The water may be either saline or non-saline. In Alberta, non-saline (potable) water is defined as having a Total Dissolved Solids content of less than 4,000 ppm.

Aquitard: A geological formation of low- to non-existent permeability (i.e. highly resistant or impervious to fluid flow) that forms a barrier to fluid movement.

Argillite: A massive (non-layered) rock composed of fine grained (muddy) materials. A precursor to shale. Argillite has low-to-zero permeability.

Atmosphere: The gaseous envelope surrounding the earth.

Base of groundwater protection (BGWP): This marks the transition between potable and non-potable (saline) water in the earth. In Alberta, the BGWP is defined at the level where TDS in groundwater exceeds 4,000 mg/l (ppm w/V).

Baseline: Condition prior to CO_2 injection.

Biogenic: Produced by biological activity.

Biosphere: The realm that supports living organisms. The shallow geosphere, where soil microbes and other organisms are found, is also considered part of the biosphere.

Bioturbated: Refers to sediments that have been disturbed (i.e. churned-up) by biological activity. An example would be sediment disturbed by worm burrows.

Black Oil Model: A type of fluid model that simulates the different interactions of fluid within a reservoir at different pressures and temperatures. A Black Oil Model is a relatively simple fluid model that considers only three fluids: oil, gas and water. A Compositional Model is more complex, and tracks more fluids, including various hydrocarbons, CO_2, H_2S, and more.

Bridge plug: A mechanical device which grips the inside of the casing and which has sealing elements that press against the inside of the casing to prevent fluid flow.

Brine: In Alberta, brine is defined as saline or brackish water having more than 4,000 mg/l of total dissolved solids.

Buckles Method: Method for estimating the amount of unmovable (irreducible) water in a rock with a given porosity (Porosity x Irreducible Water Saturation = Buckles Constant).

Calcareous: Describes rock containing calcium carbonate.

Carbon isotope signature analysis: This is a generic term Enhance uses to refer to any number of techniques that rely on differences and/or known relationships of various isotopes of carbon in the CO_2 molecule. Atoms contain a balanced number of protons and electrons but may contain varying numbers of neutrons. Carbon has 6 electrons and 6 protons. The most common isotope, carbon 12 or ^{12}C, contains 6 neutrons as well (12 is the total count of protons and neutrons). In keeping, carbon 13 (^{13}C) has 7 neutrons and carbon 14 (^{14}C) has 8. The amount and ratios of isotopes can provide fingerprints, or signatures, that allow different sources of CO_2 (or other elements or molecules) to be uniquely identified.

Carbonate: Rock having a carbonate molecule (CO_3) as part of its composition. Examples include limestone ($CaCO_3$) and dolomite ($Ca\text{-}Mg\text{-}CO_3$).

Cement bond log (CBL): A wellbore logging technique that uses acoustic energy to provide an assessment of the quality of the cement bond between the steel casing of the well and geological formations. This cement provides the primary sealing mechanism that prevents vertical fluid movement in this area. The Cement Bond Log is a valuable source of data about the effectiveness of the cement sheath surrounding the casing. This data is obtained by evaluating the effect of the casing, the cement sheath, and the formation on an acoustic wave emanating from the CBL instrument. The amplitude curve (i.e. the strength) of the reflected acoustic wave is maximum in unsupported casing (i.e. it "rings") and minimum in those sections in which the cement is well-bonded to the casing and the formation (since this dampens any "ringing" effect).

The CBL uses conventional sonic log principals of refraction to make its measurements. The sound travels from the transmitter, through the wellbore fluid, refracts along the casing-fluid interface and refracts back to the receivers. In fast formations (faster than the casing), the signal travels up the cement-formation interface, and arrives at the receiver before the casing refraction. To get formation arrivals, there must be good bond from cement to casing and cement to formation, therefore if there is fast formation arrival there is good bond on both sides of the cement.

CO_2 enhanced oil recovery (CO_2 EOR): The process of injecting CO_2 into an oil reservoir to improve oil recovery. Under the proper conditions of reservoir temperature and pressure and oil properties, the CO_2 acts as a solvent mobilizing oil that cannot be produced by conventional primary and waterflood techniques. This process has been used extensively in the Permian Basin of Texas for over 40 years and is also being used in the world's largest CO_2 EOR and storage project at Weyburn, Saskatchewan, which began CO_2 injection in 2000.

The CO_2 EOR process involves seven steps, as follows:

1. CO_2 is injected into the reservoir via injection wells.
2. The CO_2 reduces the oil viscosity (i.e. makes it more like water than honey) and swells the trapped oil so it flows more easily.
3. Produced water can be injected in alternating cycles (known as WAG) with CO_2 to help sweep the oil

to the producing wells.

4. Production wells pump the oil, along with CO_2, produced water and any associated natural gas to the surface.
5. The CO_2 and associated natural gas are separated at the production satellite facility so that volumes of each substance produced at individual wells can be measured. The fluids then flow to the central treating facility.
6. The oil, gas (which consists of both solution gas from the reservoir and CO_2) and produced water are separated at the central treating facility. The oil is piped to holding tanks where it is metered and sold. CO_2 and solution gas are recycled for reinjection. No CO_2 is released to the atmosphere; this is a closed-loop system.
7. The produced water is also re-injected.

Coal bed methane: Natural gas that is adsorbed onto the surface of coal and that is produced when the pressure in the coal seam is reduced via a production well.

Compositional behaviour: Describes how fluids such as oil, water, CO_2 and natural gas interact and behave at various mixing ratios, temperatures and pressures.

Conformance: This relates to the areal distribution of CO_2. Ensuring conformance, whereby CO_2 stays within an EOR project area, maximizes the efficient use of CO_2 within the EOR operations and protects against offset producer risks. This requires an understanding of the expected areal distribution of CO_2 during and after active EOR (i.e. where is the CO_2 plume?). The structure, or underground topography of the pool, can be an important determinant of conformance. Buoyancy effects will cause injected CO_2 to rise towards the top of this structural trap due to its low density. This will prevent it from migrating into the water leg which connects various oil pools on this geological trend.

Containment: Maintaining containment, or ensuring that CO_2 does not leak vertically out of an EOR and storage reservoir, is the primary goal of a MMV program. Keeping CO_2 in the reservoir protects against biosphere and/or hydrosphere contamination, safety risks, and CO_2 contamination of vertically offset hydrocarbon resources. Containment also ensures CO_2 is being efficiently used for EOR; containment of the CO_2 to the injection zone is critical for the technical and economic success of the EOR project, as it is the miscible action of CO_2 on the oil that improves recovery to offset the added costs of implementing CO_2 EOR. As part of any EOR scheme, regardless of a storage component, the scheme operator would focus significant resources, capital and technology to ensure CO_2 is contained to the injected zone to ensure the best possible oil production response.

Container: A term used in this document to define a geologic horizon in which CO_2 can be stored. In order to ensure long-term, safe storage, a solid container is better than a leaky one.

Core: Samples of the reservoir obtained while drilling a well using a specialized core barrel. Rock plugs may be cut from the core to measure physical rock properties such as porosity and permeability. Core- and log-derived reservoir properties can be compared to confirm the validity of the log correlations.

Density: The weight or mass of a given volume of material.

Dip: The direction and angle of the highest upwards and downwards changes in elevation of a geological formation. Analogous to the fall line in skiing. The direction at right angles to dip is known as the strike.

Dolomite: A calcium-magnesium carbonate ($Ca\text{-}Mg\text{-}CO_3$).

Dolomitization: The process whereby calcium in limestone is replaced by magnesium, creating dolomite.

Drillstem: Drillstem test is a measurement of fluid inflow and formation pressure obtained during drilling by isolating a portion of the hole and reducing pressure. This allows a fluid sample to be obtained and formation permeability and pressure to be calculated as pressure builds up after the initial inflow.

Enhanced oil recovery (EOR): EOR is an improved hydrocarbon recovery method that usually occurs after all possible oil is pumped out of the ground using traditional methods. Primary and secondary recovery methods have been used for over a hundred years, while EOR—also termed tertiary recovery— has been used commercially for over 50 years. Numerous EOR methods can be used, dependent on reservoir properties and the costs of the various options. There are many methods: heating, surfactant flooding, polymer flooding, solvent flooding and CO_2 flooding are among the options.

Evaporite: Minerals laid down through the evaporation of sea water. Examples include halite (NaCl) and anhydrite ($CaSO_4$).

Facies: A term that describes a geological environment such as offshore, near shore, beach, etc.

Flux: The rate of fluid flow.

Gaussian Random Function: A mathematical function used to generate a statistical variation of properties between known points. The function is used to fill in the unmeasured rock properties between wells.

GEM Software: An industry-leading equation of state model that allows the complex fluid interactions associated with CO_2 EOR to be simulated. GEM has been referenced in over 770 technical papers. See https://www.cmgl.ca/gem/resource-library for more information.

Geo-model: A geo-model (short for geological model) incorporates rock properties developed through petrophysical analysis of log and core data to develop a digital model that provides a framework of rock properties and initial fluid saturations that are used to initialize a reservoir model for simulation studies.

Geosphere: All geological horizons located below the BGWP. The term shallow geosphere is sometimes used to refer to the shallow subsurface where soil microbes and other organisms are found and where seasonal and climatic variations can impact conditions (and may be above the BGWP). The shallow geosphere is also considered part of the biosphere

Gradient: The change in pressure over a given distance.

History matching: This is the replication of the historical performance of a reservoir via a numerical model to ensure the validity of predictions that it might make; if a model cannot match historical data, then predictions cannot be considered valid. However, as a complex non-linear inverse problem it is critical to constrain the model to some actual measured values in order to have confidence in predictions. In other words, the more measured hard data used, the better confidence there will be in predictions.

Hydrocarbon pore volume (HCPV): This is the amount of hydrocarbon (oil and/or gas) contained with the pore space of a given volume of rock.

Hydrodynamic: Pertaining to fluid movement (within the geosphere).

Hydrogeology: The study of fluid distribution and flow within the geosphere.

Hydrosphere: Geological horizons within the groundwater protection zone containing water with a TDS less than 4,000 mg/l (defined as potable water in Alberta). The deepest horizon within the hydrosphere is considered the BGWP.

Initial solution gas oil ratio (Initial GOR): The amount of gas that is dissolved in the oil at initial reservoir temperature and pressure much like the CO_2 dissolved in a carbonated beverage. Just like a carbonated beverage, reducing the pressure (opening the bottle or can) allows the gas to evolve from the liquid.

Isopach: Thickness of a geological layer. Isolines connects points of equal thickness to create an isopach map.

Log: Data obtained from specialized tools run into wells that infer rock properties based on magnetic, natural and/or induced radioactive response and electrical properties.

Miscible: Capable of forming a single fluid when mixed. In terms of CO_2, this fluid is miscible with oil under pressure, deep underground, but is immiscible – will not mix – at surface conditions.

MMV Plan Area: The geographic area of Clive for which the monitoring, measurement and verification plan has been designed. The MMV Plan Area is located within the Clive Central Area, and consists of the initial development utilizing six horizontal injection wells and six horizontal production wells.

Moldic porosity: Porosity that is created in a rock through dissolution of a component of the rock. An example would be dissolution of shell fragments within a sedimentary rock. The dissolution leaves behind molds of the original fragment.

Mud log: Mud logging is the creation of a detailed record, or well log, of a borehole by examining the cuttings of rock and fluids brought to the surface by the circulating drilling medium (most commonly drilling mud).

Passive safeguard: This includes site-specific geological considerations as well as engineered safeguards built into project wells.

Permeability: A rock property that controls the ease with which fluids can flow through the reservoir. Usually expressed as Darcies (D) or milliDarcies (mD).

Petrogenic: Produced from a petroleum source.

Petrophysical: Petrophysics is the study of rock and fluid properties that defines interactions between the two, meaning how fluids flow (or not) through rock, and the rock features that control flow and correlations between core and log properties.

Pool: In oil and gas terminology, a pool is a distinct and separate oil and/or gas reservoir. Production from a pool will not produce oil and/or gas from another pool. In Alberta, pools are designated by the AER.

Porosity: The space between grains of rock. Expressed as a percentage of the total volume.

Post-abandonment: Not specifically addressed in this document but is the period in which the Crown holds liability for CO_2 storage. The Crown may choose to conduct new MMV activities or continue ones initiated by Enhance.

Post-injection: Period during which injection in a phase has ceased. Depending on reservoir response, there may be a short period of continued production (any produced CO_2 would be recycled into a following phase) until an economic limit is reached and facility and well de-commissioning and abandonment are completed.

Primary seal: The seal or cap rock immediately above the storage formation. The Ireton is the primary seal for Phase 1 of Enhance's project.

Probability of occurrence and consequence: Enhance's MMV plan is built on a foundation of understanding failure risks. Risk is the product of probability of occurrence and consequence, so high risk is the product of high probability and high consequence and vice versa.

Relative permeability: Relative permeability controls how various fluids flow through the reservoir as relative saturations of the fluids changes. For example, if part of the pore space is occupied by water, the effective (or relative) permeability for other fluids is reduced, since the water restricts the size of pore openings left for the other fluids to move through.

Reservoir: A geological formation containing economically recoverable quantities of oil and/or gas (reserves).

Reservoir simulation: This is a tool used by petroleum engineers and geo-scientists to understand and monitor fluid flow and displacement mechanisms and pathways, in order to optimize economic hydrocarbon recovery. Simulation considers rock and fluid properties, initial saturations of oil, water and gas in the rock and the

interactions that occur as conditions change. Once a model is constructed, the first step is to conduct a history match to validate the input parameters and tune them to actual reservoir performance. The validated, history matched model is then used to project future performance. It is also possible to construct a purely predictive model where there is no production history, but this type of simulation has a much higher degree of uncertainty and is not applicable to Clive Leduc given the extensive production history.

A well-developed reservoir simulation can also provide a valuable monitoring tool. As reservoir development continues, variations between actual vs. predicted performance can provide early warning of containment or conformance issues that can then be investigated through additional field monitoring.

Residual saturation: The amount of a given fluid left in a pore space after maximum practical displacement of that fluid has occurred. For example, CO_2 EOR reduces the amount of residual oil left in a reservoir after waterflood.

Risk: Potential harm or loss resulting from a failure. Risk is characterised with this MMV plan as a product of probability and consequence.

SCADA (Supervisory Control And Data Acquisition): This is a control system that uses a network of local and remote sensing and control devices for process control and alarm functions.

Secondary seal: Permeability barriers (cap rocks) located above the primary seal that would prevent upward CO_2 migration in the unlikely event the primary seal leaks.

Shale: A low- to zero-permeability layered sedimentary rock derived from fine grained muddy materials.

Slim tube test: A test of the displacement characteristics of oil saturated rock samples with CO_2 at reservoir conditions (temperature and pressure). This test is used to confirm miscibility under expected CO_2 EOR conditions.

Spill point: A low point in a cap rock. As long as buoyant fluid stays above the spill point, it is trapped. Once the fluid fills to the level of the spill point, it can flow under it and continue moving up-dip.

Static gradient: A pressure measurement taken in a shut-in well by lowering a pressure recording device into the well. This allows the reservoir (pool) pressure to be determined at a point in time.

Surface casing vent flow (SCVF): A surface casing vent flow is a condition where fluid or gas is flowing from the surface casing vent assembly. A well that has an integrity problem may exhibit signs of SCVF.

Terrigenous: A sediment or rock originating from a terrestrial (land-based) source as opposed to marine (sea), lacustrine (lake) or fluvial (river).

Total dissolved solids (TDS): This is the total amount of solids (e.g. salt) dissolved in a volume of water. In Alberta, a TDS over 4000 mg/l (or parts per million on a weight/volume basis) is considered saline or non-potable.

Unitization: A consolidation of interests of mineral lease holders within a pool to allow efficient development and conservation of the resource.

Viscosity: The thickness of a fluid that controls how easily it can flow. For example, molasses is more viscous than water.

Water-alternating-gas (WAG): WAG is a widely used and proven technique that assists in achieving more uniform movement of CO_2 through the reservoir to improve oil recovery. CO_2 and water are injected in alternating slugs. The water moves preferentially into channels in the rock with higher gas saturation, reducing the relative permeability to the subsequent slug of gas. This forces the gas into new areas of the rock, improving contact with un-swept oil, thereby increasing recovery.

Wellbore basics: Although it has been documented that some of the earliest oil wells were drilled in China over 1,650 years ago (https://en.wikipedia.org/wiki/Oil_well) using percussion spring pole methods, the most relevant description of drilling techniques applicable to Clive is that of rotary drilling.

Rotary drilling uses a rotating drill bit to drill through subsurface rock formations to reach oil reservoirs, just like one would use a cordless drill to drill a hole in a piece of wood. The main difference (apart from the size, cost, power and complexity of the equipment), is that rotary drilling uses hollow pipe "joints" (generally approximately 10m long and screwed together) to allow drill bit extension as it penetrates further into the earth. The hollow pipe also allows circulation of drilling mud, a liquid which can be water- or hydrocarbon-based and which contains specialized additives to control its viscosity and density. Circulation of drilling mud means pumping the mud down through the drill pipe and circulating it back up to surface through the space between the hole and the drill string (the entire assembly of pipe joints and the drill bit). The space between the drill string and the hole is termed the annulus. Drilling mud serves four main purposes:

1. It provides cooling to the drill bit (drilling through solid rock generates tremendous frictional heat that would otherwise damage the bit);
2. It carries the rock fragments dislodged by the bit (cuttings) back to surface where they are separated from the mud (and often mud logged to determine the geology of the subsurface and assist in determining what formations are being drilled through and the types of fluids encountered). The mud is then pumped back into the hole by mud pumps;
3. It provides stability to the hole by exerting hydrostatic pressure (i.e. the pressure exerted by the weight of the column of mud) against the sides of the open hole; and
4. It prevents influx of unwanted fluids from formations that are being drilled through by exerting hydrostatic pressure to hold the fluids in their formations.

In some cases, the mud is also used to drive a mud motor, which rotates the drill bit downhole, making it unnecessary to rotate the entire drill string, using energy provided by the mud pumped through the drill string by the mud pumps.

After a section of the well has been drilled, joints of hollow pipe called casing are run into the hole and cemented in place. Casing serves five main purposes:

1. To protect potable aquifers from contamination by produced oil, water and gas;
2. To stabilize the section of the hole that has just been drilled so that material does not fall, or slough, into the hole as the hole is deepened;
3. To provide a means of well control within the well should an unexpected flow of oil, water or gas from other underground formations occur;
4. To provide a conduit that allows production to surface or facilitates the injection of fluids into the reservoir; and
5. To prevent flow between formations.

There are three main types of casing that are generally used in Alberta wells. Each series of pipes is referred to as a string, which is the basis for the term casing string(s). The three types of casing are as follows:

1. **Conductor pipe**: This casing string is generally set to 10 to 20 metres depth to prevent excess sloughing of poorly cemented surface formations (i.e. the crumbly layers of soil that could easily become unstable and fall into the hole) for the surface hole drilling.
2. **Surface casing**: This casing string provides primary protection of aquifers and well control while drilling the next section of the well. The surface casing is set or run to a depth that is calculated based on the maximum reservoir pressure expected to be encountered while drilling the next section of the well or

to a minimum depth of 25m below the depth of the deepest potable water well within 200m of the well, whichever is greater. If the preceding calculation shows the surface casing could be set shallower than the BGWP, the owner of the well may elect to set the surface casing deeper in order to isolate the BGWP (the typical procedure). Alternately, the owner must ensure the BGWP is completely protected when cementing the next casing string.

3. **Production casing**: This casing string is run into or slightly below the formation targeted by the well to allow the production or injection of fluids. In very deep or complex wells, intermediate casing strings may be run to a shallower depth than the final production string to improve the stability of the hole and to provide well control.

Casing strings are cemented in place after being run to a programmed depth. While there are many different types of oil field cement and additives depending on the specific application, using cement prevents fluid from moving on the outside of each casing string by providing a strong bond between the string and the rock formation. Once the casing has been run into the hole, cement is circulated down inside the casing and displaced with fluid, pushing it upwards outside the casing until the space (or annulus) between the outside of the casing string and the rock formations is fully covered by cement. Once the cement sets, it provides a seal along the length of the casing string to prevent unwanted fluid movement along the well.

Oil field cements have different compositions and physical properties than cements used in typical construction projects and are formulated for quick curing time and high strength to provide hydraulic isolation.

Zonal abandonment: This is the plugging of a specific interval that was formerly open to a geological horizon inside or down hole in a given well.