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Heartland Area Redwater Project: Geological and Hydrogeological Characterization for Saline Aquifer CO_2 Storage in the Redwater Leduc Reef, Alberta, Canada

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Setting

The Devonian Redwater Leduc carbonate reef, located northeast of Edmonton in Alberta, Canada (Figure 1), represents an excellent opportunity for the storage of several hundred megatonnes (Mt) of CO_2 captured from large stationary sources in the region such as oil sands upgraders, refineries and chemical and petrochemical plants. The reef is located at a depth of approximately 1000 metres (m) at its shallowest. The reef structure is a bioherm, having a massive areal extent of roughly 600 km^2 with a stratigraphic thickness of up to 290 m. The reef established itself on a topographic high of the shallow platform carbonates of the Cooking Lake Formation. The shales of the Ireton Formation encase the reef laterally and form a competent caprock.

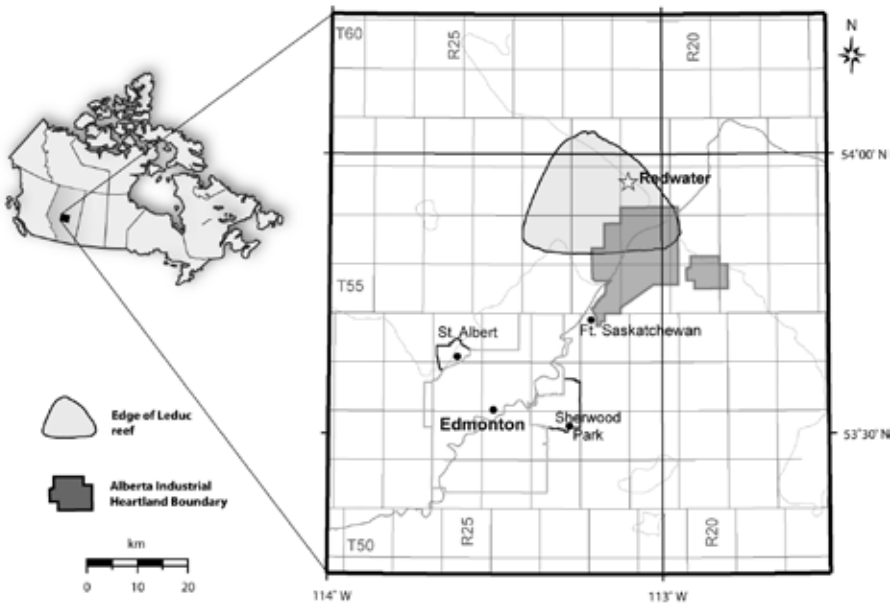

Figure 1 – Location of the Redwater Leduc reef with respect to the city of Edmonton and the Alberta Industrial Heartland (AIH). The AIH is a major source of CO_2 emissions in Alberta.

Devonian strata in the basin dip at an angle of ~0.44^{o} to the southwest due to structural loading during mountain building. Oil generated from organic-rich Devonian argillaceous limestones has migrated into the reef, resulting in the accumulation of oil in the up-dip areas of the reef margin to the northeast (Figure 2). Accumulation of 1.3 Bbl original oil in place (OOIP) makes the Redwater pool the third largest conventional oil reservoir in Canada, which has been in production since the late 1940s. Currently, a CO_2-EOR pilot project operation is active in the oil leg of the reef (at the updip northeastern margin). In parallel with this CO_2-EOR pilot, a Carbon Capture Storage (CCS) project is in the initial phase of characterization and site selection for implementing a CCS pilot in the downdip, water-saturated leg of the reef (Heartland Area Redwater Project – HARP). If proven successful, plans are to upscale this pilot operation to reach a storage rate of 1 Mt CO_2 per year by 2015, contributing significantly to Canada's commitment to reducing greenhouse gas emissions through CCS technologies.

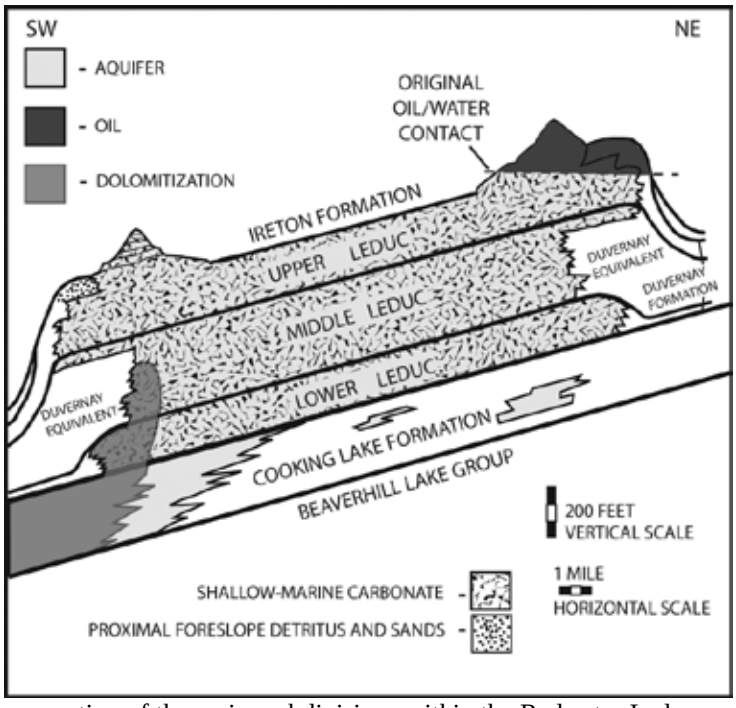

Figure 2 – Schematic cross-section of the major subdivisions within the Redwater Leduc reef. The original oil-water contact and the dolomitized area are shown (modified from Wendte, 1983).

Local Stratigraphy and Geological Architecture of the Reef

The sedimentary succession in the reef area, residing on a Proterozoic crystalline basement, comprises cratonic Cambrian and Devonian consolidated sediments overlain by foreland-basin Cretaceous and unconsolidated Quaternary sediments. In the region of the Redwater Leduc reef, the Paleozoic succession is dominated by carbonates with intervening shales and evaporites. In addition to the thick Paleozoic Ireton shales lateral to and overlying the Redwater Leduc reef, thick Mesozoic Mannville and Colorado Group shales represent additional significant barriers to the upward migration of CO_2 in the area.

The Redwater Leduc reef comprises three major units distinguished by facies types and overall facies stacking patterns (Figure 2). The three units are the Lower, Middle and Upper Leduc, each

of which are further subdivided into recognizable cycles of growth. All three units consist predominantly of foreslope, reef margin, and interior lagoon sediments. The Lower Leduc formed on a depositional high of the underlying Cooking Lake Fm. platform, representing a shallow ramp-like unit consisting dominantly of thin coalescing patch reefs overlain by micritic reefal deposits. During Middle Leduc deposition, the reef attained an atoll form with conspicuous reef-margin relief, consisting of a number of backstepping cycles that formed during an overall transgressive event, followed by widespread progradation of the uppermost Middle Leduc. During the backstepping of the Middle Leduc unit, embayments formed at the western and eastern margins of the reef, in which distal basinal sediments were deposited. The delineation of the nature and extent of these embayments has been crucial as these sediments comprise ineffective porosity and contribute negatively to the overall usable storage volume of the reef. Overlying the backstepping units and the embayments is a progradational cycle formed during a fall in sea-level, culminating in a widespread subaerial unconformity at the top of the Middle Leduc. This exposure led to infilling of near-surface porosity with green argillaceous clays, resulting in overall flow impedance at this level of the reef. The Upper Leduc unit contains the oil pool and is therefore the most well resolved unit in the reef. This unit maintains an atoll form with a pronounced reef margin, and consists of a series of cycles ranging from aggradational at the base to backstepping for the remainder of reef growth. The unit is capped by a number of shoals with small areal extents which formed as a last gasp in reef growth.

Some time during shallow burial of Devonian sediments the basin was subject to a phase of diagenetic alteration by dolomitizing fluids. The dolomitizing front was restricted to the western-most margin of the Redwater Leduc reef and the underlying Cooking Lake platform (Figure 2). The dolomitized area of the reef contains significant porosity and permeabilities and represents the main conduit for fluid flow from the underlying Cooking Lake aquifer.

Hydrogeology

Hydrogeological mapping has been completed to determine the natural and current hydraulic regimes in the reef and underlying and overlying aquifers in order to determine the degree of hydraulic communication and its impact on CO_2 storage. A new local hydrostratigraphic model has been generated for the Woodbend Group, which contains the Redwater reef, and the overlying Winterburn Group. Refinements to the hydrostratigraphic framework included subdividing the Cooking Lake Formation from the overlying Leduc Formation reefs. A detailed hydrogeological characterization of the Winterburn and Woodbend groups has been undertaken to properly evaluate the fate of the injected CO_2 and to assess CO_2 containment. Secure CO_2 geological storage includes having an effective trapping mechanism, competent bounding seal, hydraulic isolation from overlying aquifers, and a favorable hydrogeological regime.

The Redwater Leduc reef, like many other reefs of similar age in east central Alberta, is in hydraulic communication with the underlying Cooking Lake aquifer. At a regional scale, salinity of formation waters in the Cooking Lake aquifer decreases northeastward from more than 240 g/L to less than 60 g/L. In the overlying Leduc Formation reefs, salinity of formation waters is comparable to that in the underlying Cooking Lake aquifer in composition and distribution. Hydraulic heads calculated with a reference density of 1070 kg/m^3 vary from more than 425 m in the southeast to less than 325 m in the northwest, indicating north-northwestward flow of

formation water towards and beyond the Redwater Leduc reef. Porosity in the Redwater Leduc reef varies in the 3 to 12% range, and permeability varies from a few millidarcies in the interior lagoon facies of the buildup to several hundred millidarcies in the dolomitized portions and the underlying Cooking Lake aquifer. The Cooking Lake aquifer and the overlying Leduc reefs in east-central Alberta are confined by the competent shales (caprock) of the Ireton Fm., which varies in thickness from 20 to 65 m above the Redwater buildup and up to 300 m surrounding it in basinal locations. This strong aquitard separates the Cooking Lake – Redwater hydraulic system from the overlying Nisku aquifer, which in turn is capped by the Calmar aquitard that forms a secondary barrier to CO_2 leakage.

Summary

The Redwater Leduc reef has the potential to store several decades of CO_2 emissions from large stationary sources in central and northeastern Alberta. The reef size, the potential for high injectivity rates into permeable zones, and its location in close proximity of large CO_2 sources make it an ideal candidate for CO_2 storage. The geological architecture external and internal to the reef present a unique opportunity to study the potential for CO_2 storage in such a setting and to understand the fate of CO_2 stored in a carbonate system.

References

Wendte, J.C. and Callow, G.O., 1983, Geological Evolution and Facies Framework of the Redwater Reef Complex: unpublished report, Esso Resources Canada Ltd.