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Geothermal Reservoir Characterization in Carbonate-Hosted Oil and Gas Fields from the Western Canada Sedimentary Basin

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ABSTRACT

We investigate the potential for geothermal energy production and characterize geothermal reservoirs from two active oil and gas fields in the Western Canada Sedimentary Basin, Alberta and British Columbia. These fields have had a long history of hydrocarbon production and are now evaluated for electric power production from hot water, in one case for public power consumption and the second for power to drive downhole pumps. Formation water temperatures locally in excess of 100°C suggest that electric power can be economically generated. Characterization of the subsurface reservoir is a critical step in geothermal development of the field. We present static and dynamic reservoir models that describe the distribution of reservoir properties and the flow of hot water from the reservoir with various production and injection well scenarios.

The Clarke Lake field in northeastern British Columbia occurs in carbonate sediments of the Middle Devonian Slave Point Formation, which were deposited within a rimmed carbonate platform environment flanking the Horn River Basin. The development of porous and permeable reservoir resulted from hydrothermal alteration of parent limestone to dolomite. High quality reservoir zones exist at the reef margin due to hydrothermal alteration preferentially occurring in more porous and permeable sediments that are stratigraphically trapped by shales of the Horn River and Muskwa formations. High quality reservoir zones also extend some distance into the back-reef within porous and permeable carrier beds of back-reef facies, which display average porosity and permeability of 6.4% and 124 mD, respectively. The field displays anomalously high reservoir temperatures and strong water drive. Clarke Lake field has shown water production rates upward of 2800 m^3/day between in two wells, with an average reservoir temperature taken from DST measurements of 98.2°C. Simple flow simulations show that to the reservoir at Clarke Lake field is capable of sustaining 25 years of hot water production. Estimates of geothermal power potential are 300 kW using a doublet well model and 2400 kW using a four injector and eight producer well model.

The South Swan Hills oil field in central Alberta is developed in the Upper Devonian Swan Hills Formation, which is composed of two units, a regionally extensive carbonate platform and an overlying unit that comprises a series of atoll reef complexes. Several controls affect the porosity and permeability of the reef: the lateral and vertical distribution of lithofacies, sedimentation stacking patterns and diagenetic cement cycles. We use core data to identify key lithofacies and assemble them into a depositional model that distinguishes zones of high porosity and permeability, specifically reef flat and reef margin deposits. We apply a sequence stratigraphic analysis to a "rim-bounded reef" depositional model and recognize three sequences distinguished by exposure surfaces. At paleo-water tables, porosity is enhanced by heavy strong dissolution. Porous and permeable zones are also developed in reef margin facies that stack vertically as the reef aggraded. Active wells in the field produce annually over 200,000 m^3 of hot (≥100°) Celsius water. This heat energy of the water has potential for conversion to electrical power. A 3D geo-cellular model is created in order to simulate the flow of water through the effective aquifer and eventually model the complicated rock-water chemical interactions of cool-water brine injection.

1. INTRODUCTION

Exploitation of thermal energy present in sedimentary basins has historically been minimal, although developments such as Groβ Schönebeck in the Molasse Basin, Germany, is a notable exception (Zimmerman and Reinicke, 2010; Blöcher et al., 2015). At least in part, the general lack of development results from the low temperature (enthalpy) of these resources. Geothermal gradients are typically low (typically 25-30°C/km); thus, it is necessary to drill to considerable depths to find fluids of sufficient temperature for economic energy production. Nonetheless, exploitation of geothermal resources in sedimentary basins has considerable advantages, specifically in the deep understanding of hydraulic architecture that, in some basins, has resulted from decades of oil and gas exploration and production.

We present two case studies from the Western Canada Sedimentary Basin, western Canada, in which there is potential for geothermal production from carbonate formations in fields that have an extensive historic record of oil and/or gas production. Our work emphasizes the development of geology-based reservoir models to predict fluid flow and energy production as hot water is produced and cooler water is reinjected.

2. GEOLOGICAL BACKGROUND

2.1 Basin history and architecture

The Western Canada Sedimentary Basin (WCSB) is a foreland basin located primarily in the provinces of Alberta and Saskatchewan in western Canada, but extends to the east into southwestern Manitoba, to the west into northeastern British Columbia and to the north into the Northwest Territories, and is geologically bounded by metamorphic and igneous rocks of the Precambrian Shield to the east and the Mesozoic deformation front to the west. It contains a sequence of sedimentary rocks ranging in age from Cambrian

to Paleocene, with restricted and thin younger Tertiary and Quaternary deposits. Sedimentary units were deposited under two fundamentally different tectonic regimes. From Cambrian through the Late Jurassic, sediments were deposited on a west-facing passive margin. Lower Cambrian deposits consisted primarily of sandstones, but sedimentation then underwent a transition to platform and reefal carbonates, basinal shales that persisted through the Middle Jurassic, with subordinate intervals of evaporite deposits in the Lower to Middle Devonian and clastic rocks in the Permian through Middle Triassic. Prominent carbonate intervals, including important petroleum reservoirs were deposited in the Late Devonian through Mississippian.

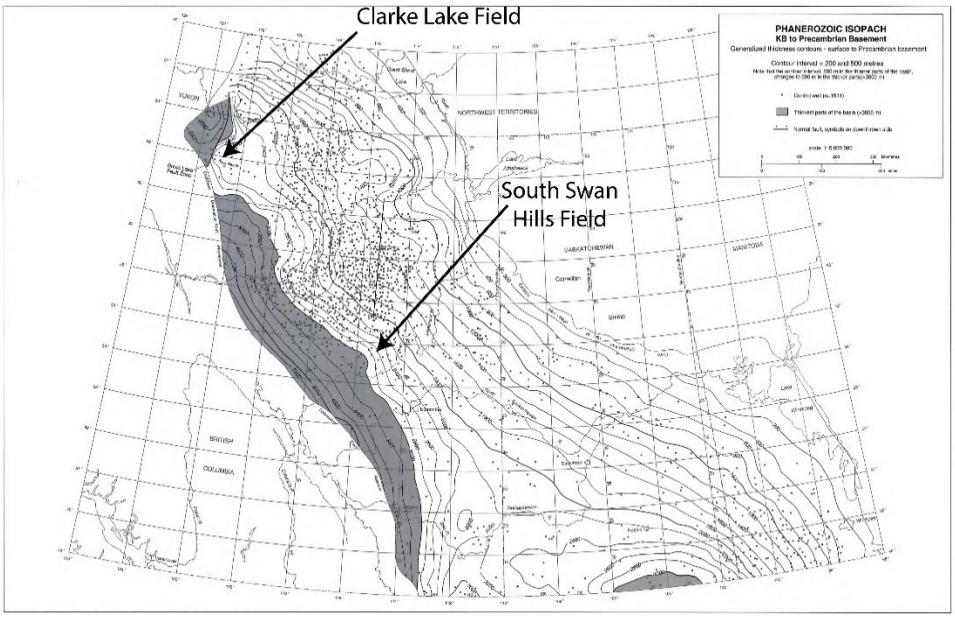

Figure 1: Isopach map of Cambrian through Recent strata in the Western Canada Sedimentary Basin. Locations of the two fields in this study are indicated. Modified after Wright et al. (1994).

Deformation along the western margin of North America began with the docking of exotic terranes in the late Early Jurassic, marking a transition from passive margin to foreland basin tectonics and from carbonate-dominated to clastic-dominated sedimentation. Thin skinned deformation associated with the Larimide Orogeny began in the Late Cretaceous, resulting in deposition of a thick package of sandstones and shales in an interior seaway that extended from the proto-Gulf of Mexico to the Arctic Ocean.

The present-day architecture of the basin is that of a wedge, thin in northeastern Alberta, eastern Saskatchewan and southeastern Manitoba where sediments onlap Precambrian basement rocks, dipping and thickening to the southwest toward the deformation front in southwestern Alberta and northeastern British Columbia, where depths of more than 5000 meters are commonly reached. Sedimentary rocks typically exhibit monoclinal dips to the southeast except near the deformed zone, where complex systems of thrust faults are encountered; these typically transported sedimentary formation from west to east during Larimide deformation.

2.1 Thermal regimes in the Western Canada Sedimentary Basin

Extensive oil and gas development, beginning in the late 1800s, has resulted in the accumulation of vast knowledge of the subsurface geology of the WCSB, including knowledge of temperatures and geothermal gradients. In general, geothermal gradients are relatively low in the southern part of the basin (from the U.S. border to latitude 52°N), generally less than 35°C/km (Weides and Majorowicz, 2014). An east-west-trending belt of somewhat higher gradients (30-40°C/km) is present between 52°N and 56°N. Much higher gradients are present in the northwestern part of the basin (northwestern Alberta, northeastern British Columbia, southwestern Northwest Territories), locally exceeding 50°/km. Majorowicz and Grasby (2019) show that temperatures in excess of 120°C are present at the base of the sediment column in a belt near the deformation extending from approximately 53°N to 59°N.

3. STUDY AREAS, DATA SETS AND METHODS

We present results from two petroleum fields in the WCSB. The Clarke Lake gas field is located near the town of Fort Nelson in northeastern British Columbia (Figures 1 and 2). This field, discovered in 1957 by Gulf States Oil Company of Canada, is a largely depleted gas field developed in dolomitized parts of the Middle Devonian Slave Point Formation (Gray and Kassube, 1963; Lonnee and Machel, 2006). The South Swan Hills field is a producing oil field northwest of Edmonton, Alberta (Figures 1 and 2), developed in a limestone reef within the Middle to Upper Devonian Swan Hills Formation, one of a cluster of fields discovered initially by Home Oil Company in 1957. South Swan Hills field is currently operated by Razor Energy Corporation and as of 2018 produced approximately 5000 barrels of light oil per day.

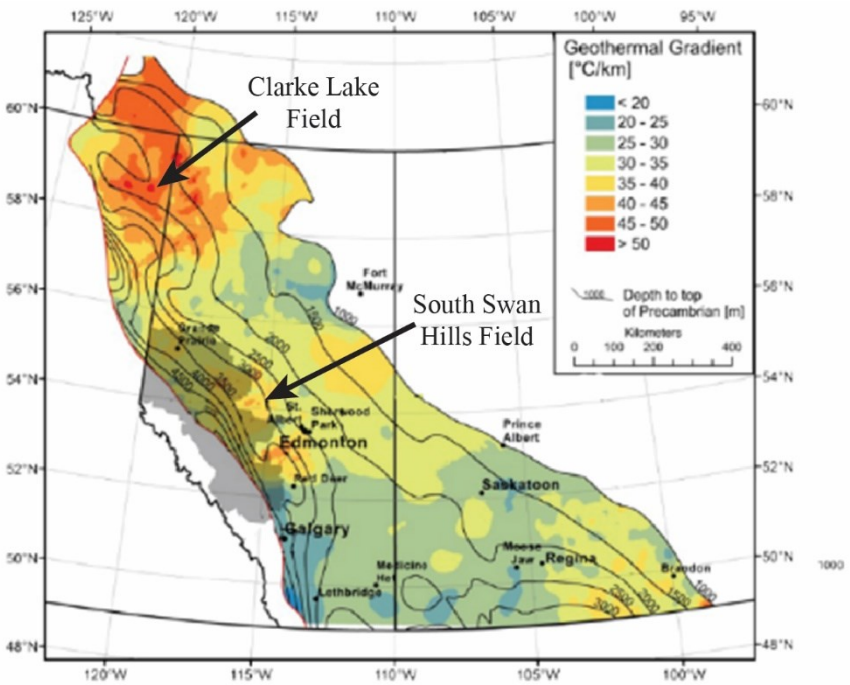

Figure 2: Geothermal gradients in the Western Canada Sedimentary Basin (modified after Weides and Majorowicz, 2014).

Both Clarke Lake Field and South Swan Hill Field have been extensively drilled. Datasets utilized in this study include spatially registered well logs for the fields, enabling us to identify and map stratigraphic markers for definition of field architecture and reservoir zones. These were imported into Petrel and manipulated to make cross-sections and various types of maps. Numerous long cores through the reservoir were available from the fields through the Alberta Energy Regulator (South Swan Hills) and the British Columbia Oil and Gas Commission (Clarke Lake); several cores from each field were described in details, recording information on lithology, fabric, presence and type of bioclasts, sedimentary structures such as bedding and bioturbation, fractures, vugs and other types of porosity, and diagenetic features such as dolomite cement. Core descriptions were correlated in detail to well logs, providing critical control for log-based maps. A selection of representative petrographic thin sections was made to document further sedimentological and diagenetic details and to characterize pore systems. Finally, porosity and permeability data were available from several wells in each field; these were assigned to appropriate depositional or diagenetic facies and applied to field-scale maps of reservoir properties.

Dynamic flow models were developed and implemented for the Clarke Lake Field using the PetroSim software.

4. CLARKE LAKE FIELD

4.1 Geologic features

The reservoir at Clarke Lake Field is developed in carbonates of the Slave Point Formation, which forms a platform on the southern margin of the Horn River shale basin (Figure 3). Slave Point carbonates are laterally equivalent to shales of the Horn Rive Group; they are underlain by Upper Keg River Formation carbonates and overlain by shales of the Muskwa Formation.

Depositional facies identified in core examination follow a rimmed platform model proposed originally for the Judy Creek Field in Alberta by Wendte (1992) (Figure 4). Facies range from laminated muddy carbonates deposited in tidal flats in the platform interiors, *Amphipora* wackestones and packstones in lagoons and on reef flats, Stromatoporoid boundstones at the reef margin, transitioning to grainstones and packstones down the slope into deeper water, and wackestones and organic-rich mudstones in deep water settings outboard from the reefs. Vertical stacking of facies is dictated by changes in relative sea level and sedimentation rates, in which rises in sea level (at different time scales) typically result in superposition of basinward facies on top of platform facies. As rates of sea level rise slow and sedimentation catches up to sea level, facies belts shift back toward the basin, placing shallower water facies on top of deeper water facies. These depositional cycles are expressed at a range of cycles. Sea level falls, however, are primarily expressed as erosion surfaces, with development of karst features and the deposition of green clays.

Dolomite bodies are controlled by large-scale reef geometry and by smaller-scale features such as permeable and impermeable beds.

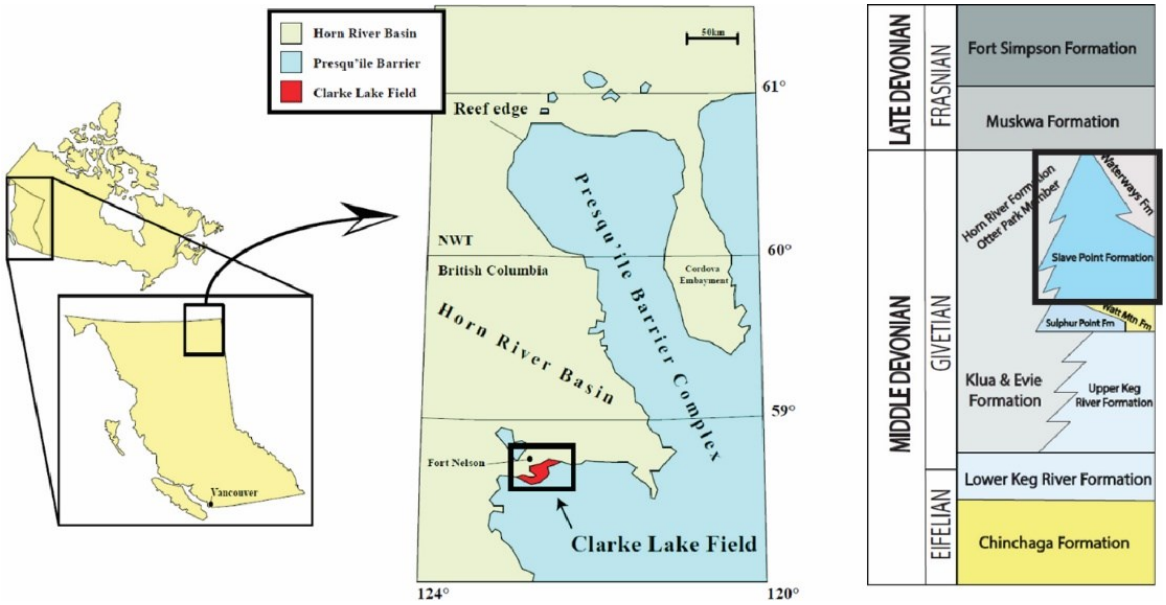

Figure 3: (Left) Location map for Clarke Lake Field. (Right) Stratigraphic column identifying the Slave Point Formation, the primary reservoir at Clarke Lake Field.

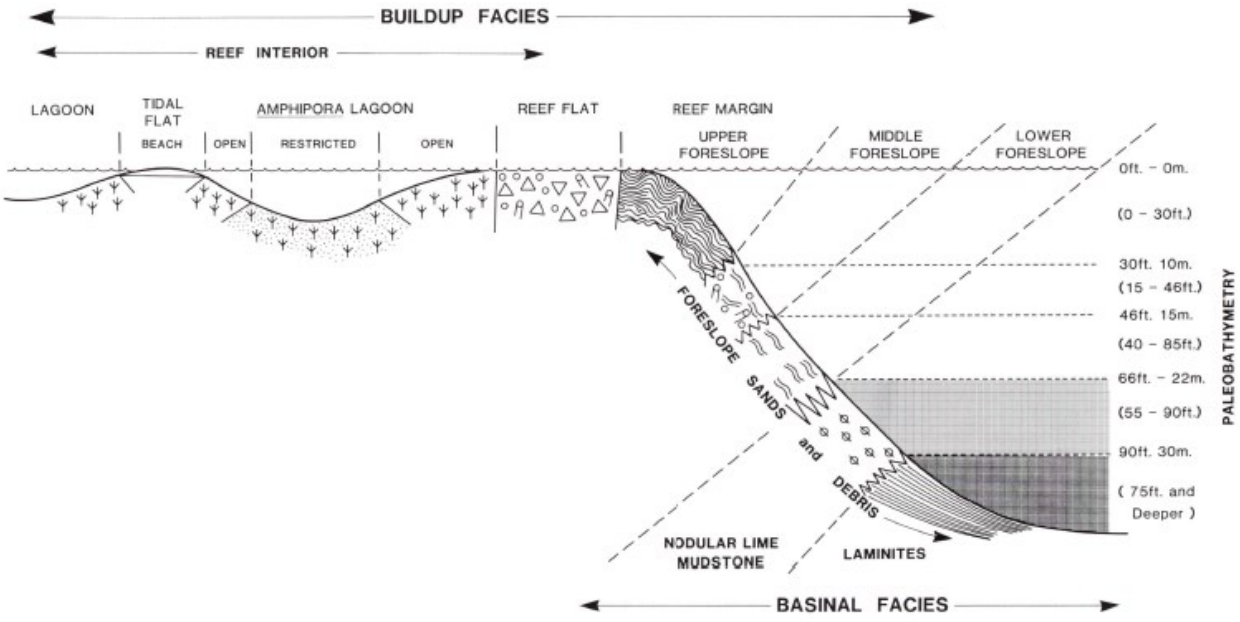

Figure 4: Sedimentary facies associated with Devonian rimmed carbonate platforms and reefs. Model from Wendte (1992) for the Judy Creek Field, but applied in this study to both Clarke Lake Field and South Swan Hills Field.

Dolomitization has locally strongly affected the rock fabric, especially near the platform margin, in places obliterating the original depositional fabric. Two varieties of dolomite are present, a grey matrix dolomite and a white saddle dolomite. These commonly occur in brecciated zones associated with hydrothermal alteration. Dolomitization is most pervasive at the northern margin of the reservoir (Figure 5), at the platform edge adjacent to the shale basin. Lonnee and Machel (2006) interpreted this distribution as the product of migrating brines saturated with salt by contact with evaporites to the south and east of the field.

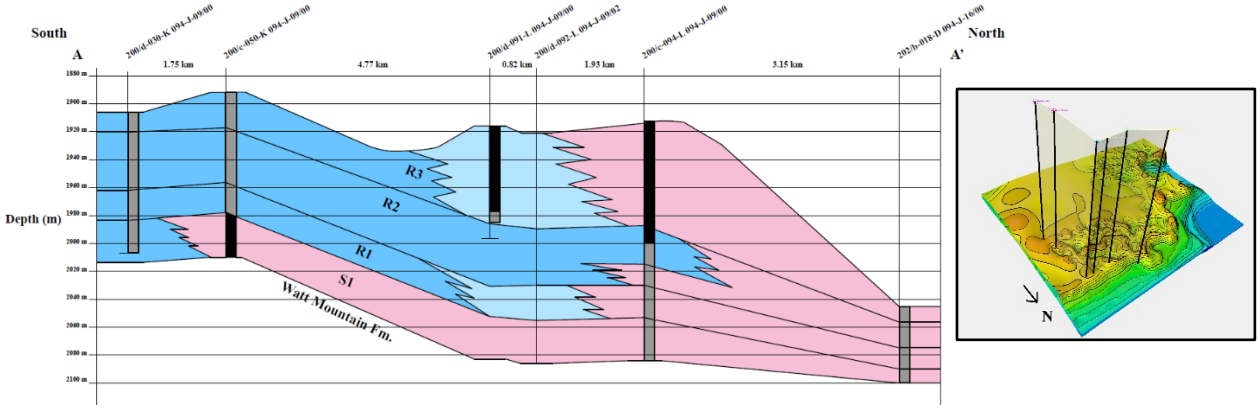

Figure 5: Distribution of dolomite bodies (pink) in the reservoir at Clarke Lake Field. Dark blue represents limestone, and light blue represents partially dolomitized limestone.

4.2 Reservoir properties

Porosity and permeability are largely dependent on the extent of dolomitization and thus on geographic position in the reservoir. Dolomite samples have porosities ranging from less than 1% to 15% and permeabilities ranging from 0.1 to 4000 mD (Figure 6). Limestone samples, in contrast, have porosities from 0 to 6% and permeabilities from less than 0.1 to 20 mD. Mixed lithologies have reservoir properties comparable to pure dolomites.

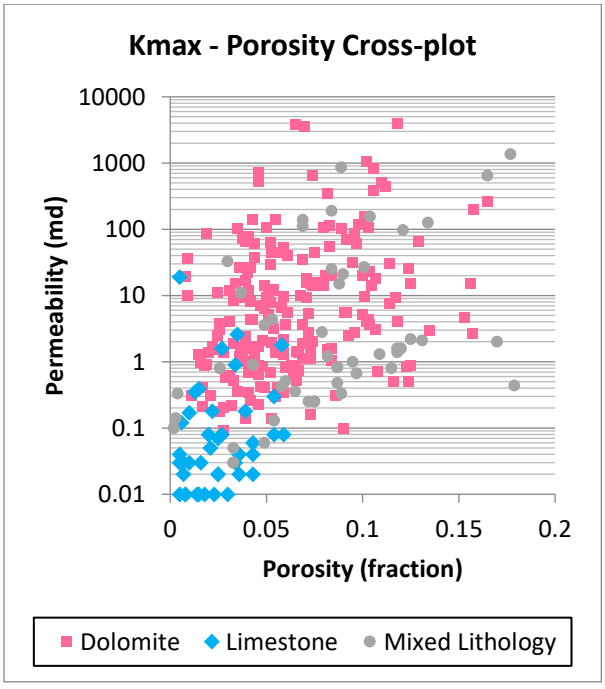

Figure 6: Porosity and permeability data for carbonate samples from Clarke Lake Field.

4.3 Hot water production and flow simulations

Average reservoir temperatures in the Clarke Lake reservoir are 96.2°C, with local hot spots at which temperatures exceed 110°C. Field operators have long recognized the presence of a strong water drive in the field. Petro-Canada, which operated the field through part of the 2000s, attempted to increase the gas cut by depleting water in the reservoir; to do so, they pumped approximately 2800 m^3/day for a period of 10 months, expecting a pressure drop of 1 MPa. In the end, they achieve a temporary drop in pressure of 100 KPa, indicating that much of the water produced in this experiment was replaced by subsurface flow.

We have created dynamic flow models for the dolomitized part of the reservoir to test whether a simple doublet injector-producer well pair and 12 well array (4 injectors – 8 producers) could produce water at present-day reservoir temperatures with produced water temperatures being affected by the nearby injector well. In our models, a 2500 X 2500 X 250 polygonal array was used, in which cell size was smallest closest to the well bores and expanded outward. Reservoir properties for the grid blocks were assigned based on different statistical distributions drawn from the petrophysical data presented in Figure 6. The doublets were assumed to be 500 meters apart, with flow rates of 25 kg/sec. The 12 well patterns with simulated with total injection and production rates of 200 kg/sec.

Examples of model outputs are shown in Figure 7. In this instance, the maximum porosity and permeability values were used to populate the cells. This model was considered successful because cold water from the injector well did not reach the producer within the 25 year period of the model experiment.

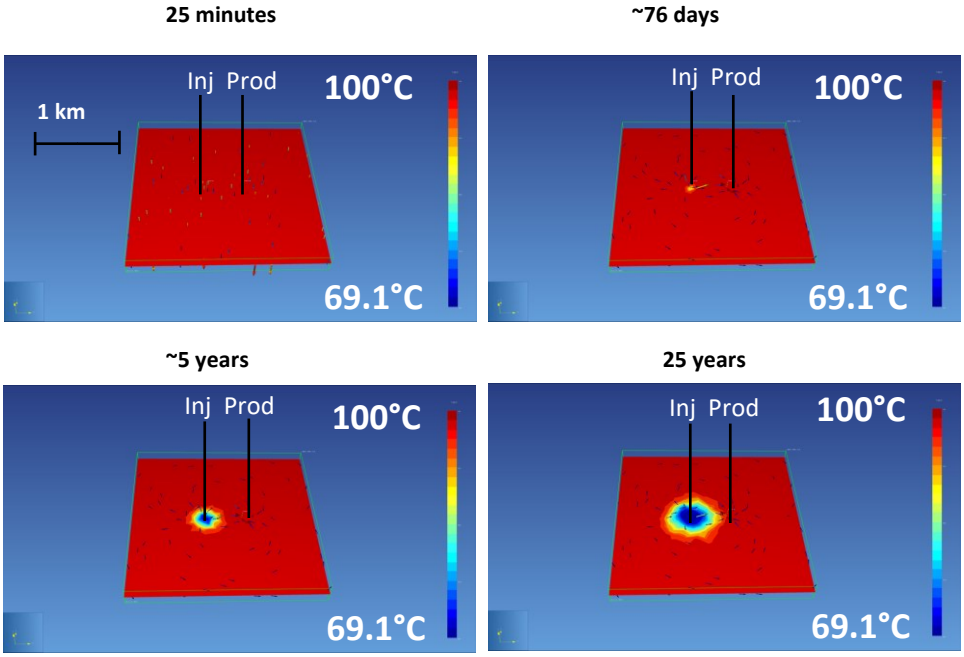

Figure 7: Output from flow simulations of the Clarke Lake Field, based on reservoir properties in dolomite facies.

Simulations failed, in the sense that cold water from the injector reached the producer within 25 years, only when minimum or bottom quartile values for porosity and permeability were used as input. Assuming mean, median, Q3 and maximum porosity and permeability arrays, model runs were successful.

For the doublet well pair, we calculate electrical power production of 300 kW_{equiv}, assuming a generation efficiency of 16% (from equation 8 in Banks and Harris, 2018). The 12 well configuration produced 2400 kW_{equiv}.

5. SOUTH SWAN HILLS FIELD

5.1 Geologic features

The reservoir at South Swan Hills Field is developed in the Swan Hills Formation, part of the Beaver Hill Lake Group. This formation, part of the Beaver Hill Lake Group, overlies the clastic Watt Mountain Formation and underlies carbonates of the Leduc Formation. It is laterally equivalent to mudstones of the Waterways Formation. Two phases of Swan Hills carbonate are identified in the Swan Hills area, an underlying platform phase in which an extensive carbonate platform developed, and an overlying reefal phase in which several isolated pinnacle reefs grew from the platform. Oil accumulations are present in the South Swan Hills reef, the Virginia Hills and other reefs.

The South Swan Hills reef is an irregular shaped body of approximately 120 square kms (Figure 8), from 30 to 70 m thick. Depositional facies are similar to those observed at Clarke Lake and are described by the rimmed carbonate reef model presented earlier (Figure 4). In this case, bioclasts in the interior of the platform (tidal flats and lagoons) consist primarily of *Amphipora*, whereas the reef margin and slope are dominated by various forms of Stromatoporoids. In the platform interior, similar to the Clarke Lake reservoir, numerous shoaling upward cycles are evident, characterized by coarsening upward sedimentary fabrics and basinward shifts in facies belts. Cycle tops are represented by flooding events that abruptly place deeper-water, muddier sediment on coarse sediment. A few through-going unconformities are present, typically represented by dissolution surfaces and the accumulation of green clays. On the platform margins, facies tend to stack vertically rather than shifting laterally through sea level cycles, because of the steeper bathymetric slope.

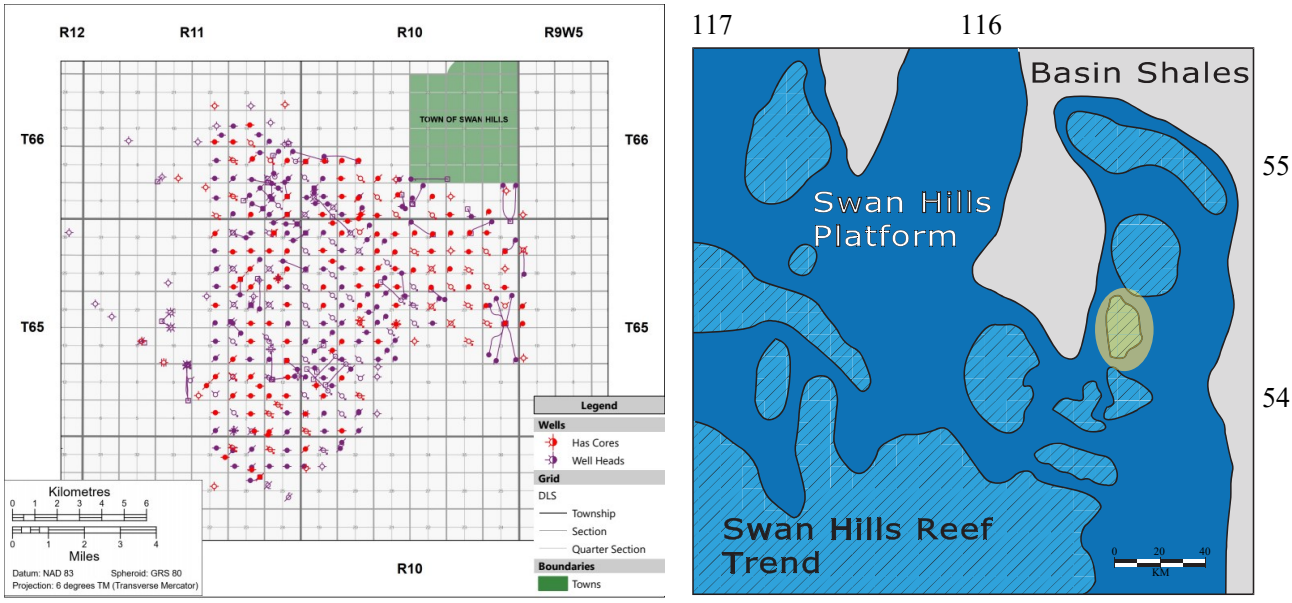

Figure 8: (left) Outline of the South Swan Hills Field, indicated the concentration of well symbols (red symbols indicate wells with core). (right) Map of the Swan Hills reef trend, developed on the underlying Swan Hills platform. The South Swan Hills field is indicated in yellow.

In contrast to Clarke Lake Field, the carbonates at South Swan Hills have effectively experience no dolomitization, and rocks consist of either limestone or mudstone.

5.2 Reservoir properties

Because dolomitization is absent in the South Swan Hills reservoir, reservoir properties are determined by depositional facies instead of diagenesis (Figure 9). Foreslope carbonate sands develop the best reservoir quality, typically in the range of 14 to 17% porosity and 10 to 200 mD. Talus and reef flat carbonates also develop high quality reservoir, only slightly below the foreslope facies. Lagoon and tidal flat deposits from the platform interior generally have lower quality.

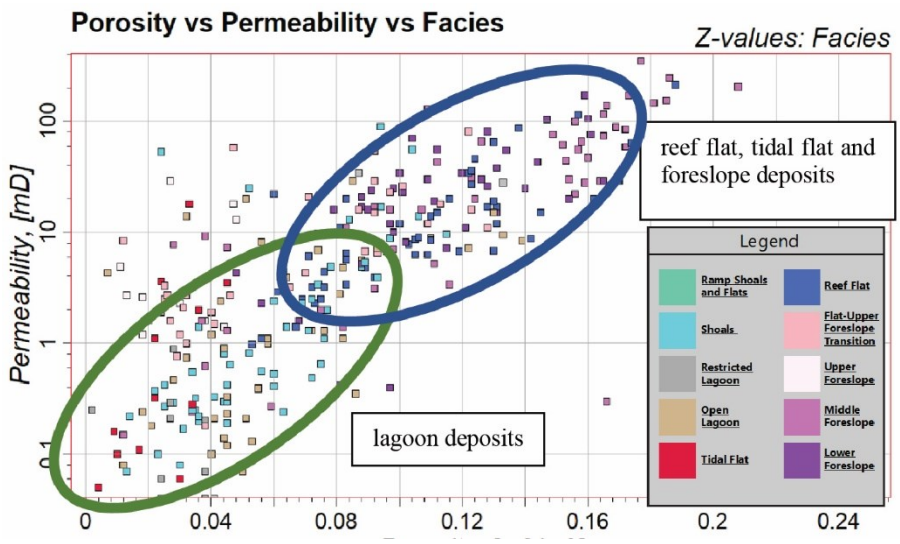

Figure 9: Cross-plot of porosity versus porosity for depositional facies at South Swan Hills Field.

The more porous and permeable facies at South Swan Hills Field were deposited on the platform rim and slope and, in addition, reef flat cap across the top of the reef before it was finally drowned. The best reservoir zones thus form a sort of upside-down cup, surrounding poorer quality reservoir in the reef interior (Figures 10). In detail, patterns are more complex, related to sea level cycles including major sea level rises that forced the reef to backstep and major sea level falls that created unconformities and porous karsted surfaces.

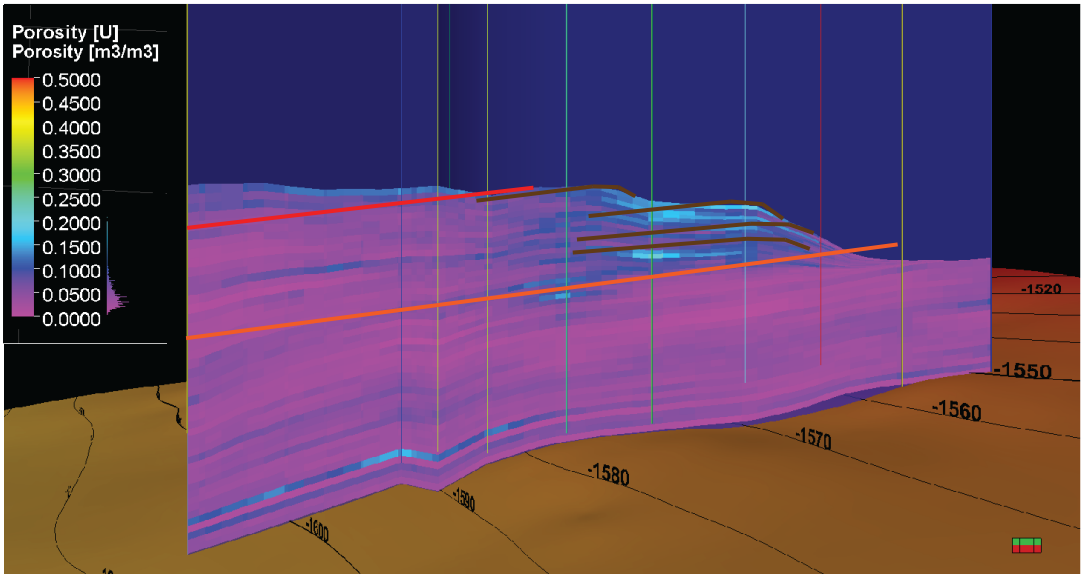

Figure 10: Cross-section through South Swan Hills Field, illustrating the development of porous and permeable zones particularly on the reef margin.

4.3 Reservoir temperatures and potential power production.

Temperatures across most of South Swan Hills Field are in excess of 95°C. Much of the eastern margin of the field has water temperatures between 100°C and 120°C with local hot spots up to 135°C (Figure 11), suggesting that these are represent optimal locations for geothermal well placement. Preliminary calculations suggest that electric power production of 4 to 12 MW is possible for a 50-year period. One application for this power is for 'behind-the-fence' power needs associated with oil production, for example downhole pumps. Currently, electrical power for this purpose is purchase from the provincial power grid.

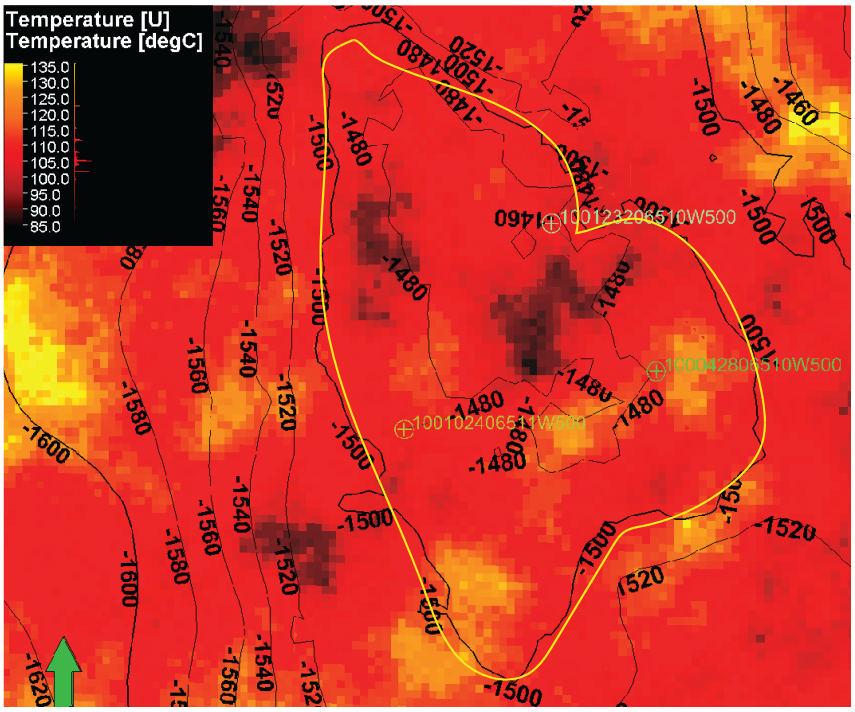

Figure 11: Map of temperatures at the South Swan Hills Field, from corrected bottom hole logging temperatures.

5. CONCLUSIONS

Geological reservoir studies and calculations of electric power potential suggest that power generation from geothermal resources is possible from producing or depleted oil and gas fields. We illustrate both the potential and challenges of such developments in analyses of two fields from the Western Canada Sedimentary Basin. In both cases, production of water with temperatures at or above 100°C is feasible, yield power production in the range of a few MW, based on small clusters of wells. Operations are potentially scalable with addition of more wells.

Our studies also illustrate the critical nature of geological reservoir studies. In one case, optimal reservoir zones are related to diagenetic alteration of the original carbonate rock and form massive zones cross-cutting stratigraphy on one margin of the field. In the other case, optimal reservoir zones are related to original depositional facies. Thus, models for predicting reservoir zonation, flow patterns and power production require classic reservoir analysis, using the same geologic skills that the oil and gas industry has applied to optimizing petroleum production for decades.

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