Oil & Gas Science and Technology – Rev. IFP, Vol. 60 (2005), No. 1, pp. 51-65

IFP International Workshop
Rencontres scientifiques de l'IFP

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Geological and Hydrogeological Evaluation of the Nisku Q-Pool in Alberta, Canada, for H_2S and/or CO_2 Storage

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Résumé — Évaluation géologique et hydrogéologique du champ Nisku-Q de l'Alberta (Canada) en vue d'un stockage de l'H_2S et/ou du CO_2 — Au Canada occidental, plus de quarante sites géologiques sont aujourd'hui utilisés pour l'injection de gaz acide ($H_2S + CO_2$). Le champ Nisku-Q est localisé dans le centre-ouest de l'Alberta (zone de Brazeau). Il s'agit d'un gisement de gaz *déplété*, dont le réservoir, situé dans la formation de Nisku (Dévonien supérieur), est constitué pour l'essentiel de dolomite et d'anhydrite. La formation de Nisku offre un prospect à huile et gaz à condensat, le gaz étant plus ou moins acide. Son enfouissement, inférieur à 2300 m au nord-est, atteint environ 4200 m au sud-ouest. Son épaisseur est de 80 à 100 m. Une particularité de ce prospect est que les hydrocarbures sont répartis dans un assez grand nombre de gisements proches l'un de l'autre, et pourtant isolés sur le plan hydrodynamique depuis leur migration et leur piégeage, datés entre 30 et 60 Ma. Cet isolement, mis en évidence par la distribution des compositions et des pressions naturelles des gisements, rend ceux-ci propices à l'injection de gaz acide, et en particulier à la séquestration de dioxyde de carbone.

Une investigation détaillée des caractères stratigraphiques, diagénétiques, minéralogiques et hydrogéologiques de la formation de Nisku permet de penser que le gaz injecté resterait confiné, pour des durées géologiques, au sein de la structure qui contient le champ Nisku-Q. Et même si par fait extraordinaire le gaz s'en échappait, il ne manquerait pas de se disperser et de se dissoudre dans les eaux de formation situées en profondeur, le long des chemins de migration. Le seul risque de fuite sérieux, à l'échelle humaine, serait le fait d'un puits mal équipé, et/ou abandonné sans surveillance.

Abstract* — *Geological and Hydrogeological Evaluation of the Nisku Q-Pool in Alberta, Canada, for H_2S and/or CO_2 Storage — *The Brazeau Nisku Q-Pool in west-central Alberta is one of more than forty acid gas injection operations currently active in western Canada. The Nisku Q-Pool, mineralogically essentially dolomite and anhydrite, is a depleted sour gas reservoir in the Upper Devonian Nisku Formation. The Nisku is an oil, sweet and sour gas condensate play at depths ranging from about 2300 m in the northeast to more than 4200 m in the southwest, with a thickness of about 80 to 100 m. A unique feature of this play is that the hydrocarbons are contained in numerous closely spaced pools that have been essentially isolated hydrodynamically from one another since hydrocarbon migration and entrapment about 50-60 Ma ago, as shown by initial reservoir pressures and gas compositions. The hydrodynamic isolation renders these pools suitable for acid gas ($H_2S + CO_2$) injection and/or carbon dioxide (CO_2) sequestration.*

A thorough stratigraphic, diagenetic, mineralogical, and hydrogeological evaluation of the Nisku Formation suggests that the injected acid gas will remain in the structure that contains the Nisku Q-Pool on a geological time scale. In the highly unlikely case of migration out of the Q-Pool, the acid gas plume would disperse and dissolve in deep formation waters along the flow path. The only possibility for upward leakage of acid gas rapid enough to be of human concern is through wells that were improperly completed and/or are abandoned and are not monitored.

INTRODUCTION

Over the past two decades, oil and gas producers in western Canada have been faced with a growing challenge to reduce atmospheric emissions of produced H_2S from sour hydrocarbon pools. Since surface desulphurization through the Claus process is uneconomic and the surface storage of the produced sulphur constitutes a liability, increasingly more operators are turning to H_2S gas disposal by injection into deep geologic formations. H_2S is commonly injected as acid gas, a mixture of H_2S and CO_2 that is a byproduct of "sweetening" sour hydrocarbons. Injection of acid gas reduces the emissions of a highly toxic and a major greenhouse gas at the same time through geological storage. By extension, acid gas injection also serves as an analogue for the geological sequestration of CO_2.

As of November 2003, there were 42 active acid-gas injection operations in western Canada in depleted oil or gas reservoirs *(Figs. 1 and 2)*, and other locations are under consideration for acid gas injection. Gas injection of one type or another has been used for more than 20 years in some of these pools to sustain production (Bachu and Gunter, 2004). The maximum injection pressures are kept equal to or lower than the virgin reservoir pressures, and below the pressure necessary to fracture the rocks, so as to minimize the possibility of leakage. To date no leakage has been reported from any of these sites. Injection gas composition varies from about 4 to 95% in H_2S-CO_2 or CO_2-H_2S mixtures, which are the byproducts of sour gas processing. One of these injection sites is the Brazeau Nisku Q-Pool, a carbonate reef buildup in the Upper Devonian Nisku Formation. The Nisku Q-Pool is a depleted sour gas reservoir, in operation as an injection site

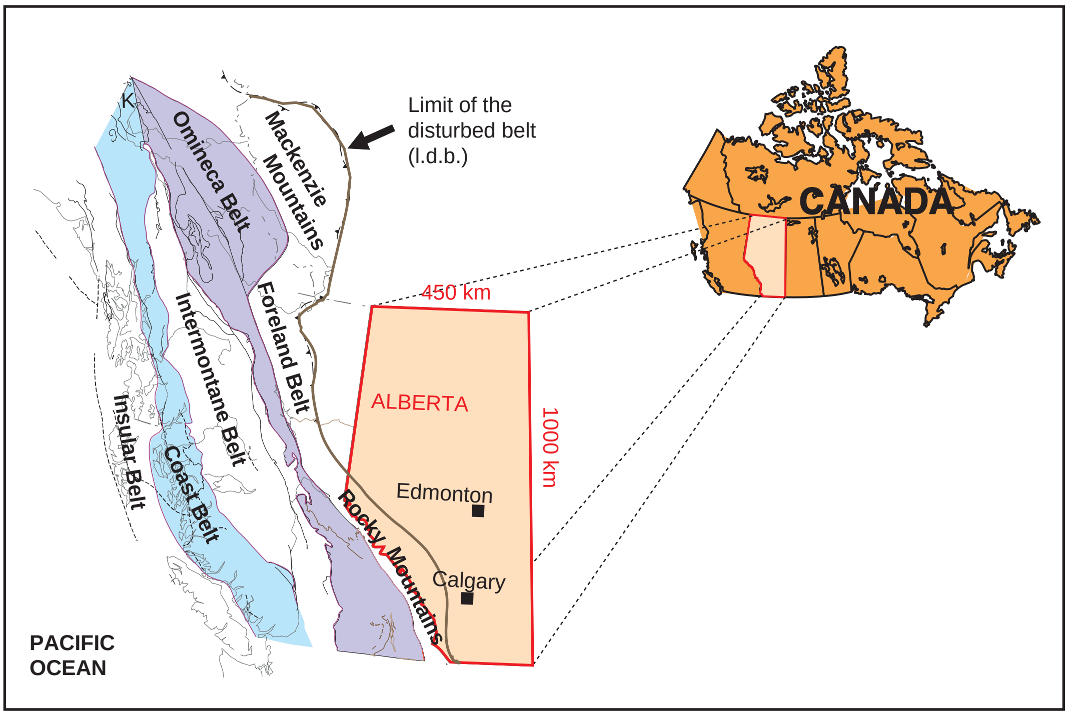

Figure 1

Geographic overview map of western Canada. Note the location and outline of the province of Alberta. The Cordilleran orogen is located largely to the west of Alberta. The limit of the disturbed belt marks the easternmost thrust fault(s).

Figure 2

Geographic overview map of the Alberta Basin and adjacent areas, marking the locations of acid gas injection sites presently in operation (solid circles). The two heavy, lobate lines mark the limit of the disturbed belt *(see Fig. 1)* and the limit of erosion of the sedimentary succession in the Alberta Basin. The box to the west of Edmonton is the Nisku study area, enlarged in Figures. 4, 7, and 8.

for acid gas with 85% H_2S and 15% CO_2 since 2003, and the main subject of this study.

A geologic formation is deemed suitable in principle for acid gas or other waste gas disposal, if the formation (pool) is and remains hydraulically sealed over at least hundreds, if not thousands, of years. Ideally, the geologic formation is hydraulically sealed over geologic times, and geochemical reactions within the formation would serve to sequester waste gases without leading to dissolution of the rock matrix and/or the well casings. Thus, the most favorable conditions for acid gas disposal and/or carbon dioxide sequestration can be summarized as follows:

– effective hydraulic seals at the time of injection;
– absence of or very slow geochemical reactions within the formation that could lead to breaching of the surrounding seals over long periods of time;
– the well casings are especially tight and monitored over time for leakage.

Within this framework, the Nisku Formation is uniquely suited for the permanent disposal of waste gases in depleted carbonate reservoirs. This is because the Nisku Formation contains a number of closely spaced pools that have been essentially isolated hydrodynamically from one another and from the surface since hydrocarbon entrapment about 50-60 Ma ago (Machel *et al.* 1995). If these pools were hydrodynamically isolated for this long, they will remain so after acid gas injection, unless the initial formation pressures are exceeded considerably and/or the sealing formations are carelessly fractured, or when there is leakage from well casings.

Another important aspect in this context is that the Nisku is one of the most thoroughly investigated and documented plays in the entire Alberta Basin. Hence, the Nisku play provides an exceptional data base for assessment and interpretation of hydraulic integrity, as well as for geochemical modeling of possible in-situ reactions after acid gas injection. Almost all aspects that are of interest to the oil and gas industry, including extensive geochemical data and modeling that were utilized in the genetic interpretation(s) of the diagenesis, dolomitization, and the genesis of sour gas, are documented in Anderson (1985), Machel (1985, 1986a, 1986b, 1987, 1988, 1993, 2004), Anderson and Machel (1988), Machel and Anderson (1989), Machel and Burton (1991), Riciputi *et al.* (1994, 1996), Machel *et al.* (1995, 1997), and Manzano *et al.* (1997). Some data from these studies are included in this paper, supplemented by extant drill stem test data and formation water salinities.

The main objective of this paper is to demonstrate the suitability of the Nisku Formation (and thereby of similar depleted hydrocarbon reservoirs elsewhere) for acid gas and/or carbon dioxide storage in terms of geological and hydrogeological trapping, *i.e.*, to document the overall geometry of the pools, aquifers and aquitards, petrology (mineral composition, abundance, and distribution), as well as porosity and permeability. Some results of this study are used to assess the geochemical trapping of acid gas, *i.e.*, acid gas dissolution in the formation water followed by ion complexing and reaction of the formation water with the minerals in the surrounding rocks (Gunter *et al.*, 2003, 2004).

1 GEOLOGIC FRAMEWORK

The Upper Devonian (Frasnian) Nisku reef trend is located in west-central Alberta, Canada, between townships 46 and 52, and between ranges 8 through 16 west of the fifth meridian (*Figs. 1, 2, 3, 4 and 5*). The initial discovery of a hydrocarbon-bearing pool in this reef trend was made in January 1977 by *Chevron Exploration* (Chevron Exploration Staff, 1979). Since that time, more than 50 producing pools have been discovered in the Nisku Formation by *Chevron* and other companies.

Geographically the study area is subdivided into the Bigoray, Pembina, and Brazeau (also called Brazeau River) Areas (*Fig. 4*). Today the reef trend and the enclosing strata are located in the undeformed Alberta Basin in front of the Rocky Mountains (*Fig. 1*) and form a structural homocline

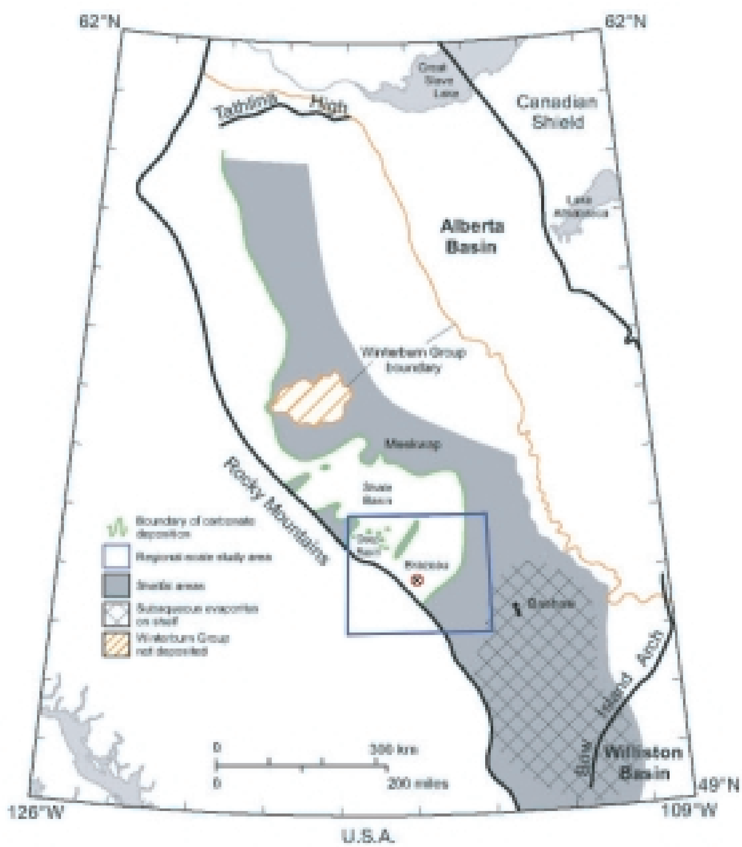

Figure 3

Geologic overview map of the Upper Devonian Winterburn Group in the subsurface of the Alberta Basin and adjacent areas. The grey-shaded areas are carbonate platforms that are surrounded by deeper, basinal areas in the west and north (up to the limit if the disturbed belt/ Rocky Mountains), and that give way to shallow-marine and lagoonal evaporites toward the southeast. The box to the west of Edmonton is the Nisku study area, enlarged in Figures. 4, 7, and 8.

that dips at about 1° toward the southwest. The average burial depth of the top of the Nisku Formation ranges from about 1500 m below sea level (2300 m below ground level) in the Bigoray Area to more than 2800 m below sea level (4200 m below ground level) in the Brazeau Area. The Nisku Formation thickens southeast to northwest from about 60 m in the carbonate shelf region to more than 100 m in the outer shelf region toward the Winterburn shale basin *(Figs. 4, 6)*.

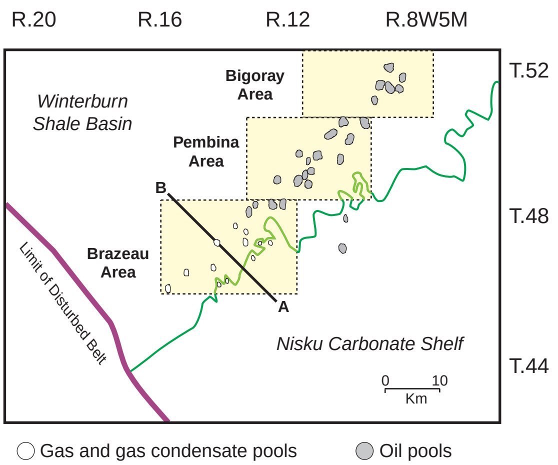

Figure 4

Subsurface geologic overview map of the Nisku Formation *(see Figs 2 and 3* for location). The margin of the Nisku carbonate shelf (lobate line trending SW-NW) and the isolated reefs along the ramp to the Winterburn Basin (gas, gas condensate, and oil pools) are seismically defined. The study area is geographically subdivided into the Bigoray, Pembina, and Brazeau Areas. Details of the Brazeau Area are shown in Figure 5, a schematic cross section along line A-B is shown in Figure 6.

Nisku reefs, the principal porous and permeable reservoir rocks, were deposited during the last known period of Upper Devonian reef development in the Western Canada Sedimentary Basin as part of the Winterburng Group. The Nisku reefs occur in two types. One type is small, pancake-shaped bodies that measure about 1.5 to 2 km in diameter and are up to about 90 m thick. These bodies are located on the ramp (slope) to the Winterburn Basin *(Fig. 5)*. The other type of reef is an elongate buildup along the carbonate shelf margin, called the bank-edge reef *(Fig. 5)*. Both reef types are underlain, surrounded, and overlain by fine-grained, relatively impermeable marls that are 200 - 300 m thick *(Fig. 6)*. The bank-edge reef formed, and to some degree still forms, a regional aquifer along the carbonate shelf margin (further discussed below).

2 VIRGIN RESERVOIR CONDITIONS

The Nisku reefs in the Bigoray and Pembina Areas contain oil with associated sweet gas. In the downdip Brazeau Area, the reefs contain oil, sweet condensate, and then sour gas condensate in a general downdip direction *(Fig. 5)*. The initial volume of oil in place for the whole reef trend was originally estimated as 325.1 Mm^3, with initial estimated reserves of 167 Mm^3 and remaining reserves at 51.5 Mm^3 (ERCB, 1985). Early estimates of gas reserves exceeded 14 Gm^3 (Watts, 1987). Recent recalculation reveals much higher reserves. For the Brazeau Area they are as follows: gas in Brazeau Nisku pools C, F, G, I, J, K, L, M, N, P, Q, R, S, U, V, W, X, Y, Z, AA, BB: over 700 Bcf OGIP (original gas in place), and about 220 Bcf produced to date; oil in Brazeau Nisku pools A, B, C, D, E, G, H, I, L: over 95 000 mbbl OOIP (original oil in place), and about 65 000 mbbl produced to date (Machel, 2004).

Significant porosity and permeability are limited to the reefs. In the limestone and partly dolomitized reefs, located almost exclusively in the Bigoray and Pembina Areas, porosity is mostly primary and consists of interparticle, intraparticle, and shelter voids. Fracture porosity is minor. Secondary porosity due to dissolution of calcium carbonate is rare and restricted to the upper parts of a few reefs. Porosities range from about 3-5%, and permeabilities range from several tens of mD to about 1 D. In contrast, porosity in the completely dolomitized reefs, concentrated in the downdip Brazeau Area, is mostly secondary, *i.e.*, moldic, vuggy, intercrystalline, and in fractures. Average porosites range from 5 to 11%, exceeding 20% in places, and average permeabilities range from 1 to several darcies.

The subcircular reef pools in the Brazeau Area are encased and surrounded by relatively impermeable marls, and are hydraulically isolated from one another. This is shown by their virgin pressures (original reservoir pressures prior to production), many of which are significantly above hydrostatic and vary drastically from pool to pool, in some cases even within a single township (*Fig. 5*: compare the virgin pressures to pressures expected based on present day depths at a normal hydrostatic gradient of about 10 MPa/km). Also, there was no pressure drawdown from pool to pool during production. As a result of this hydraulic isolation, the hydrocarbon distribution and certain organic geochemical parameters in the subcircular reef pools display increased thermal maturation downdip (Manzano *et al.*, 1997). The hydrological isolation of the pools from one another is also manifested in the virgin H_2S contents that generally increase downdip and vary drastically, *e.g.*, from about 7 to 31% even among closely spaced pools *(Fig. 5)*.

The reservoir characteristics in the bank-edge reef of the Brazeau Area are strikingly different. Firstly, this reef contains only sour gas, even directly adjacent to the oil pools in the updip part of this area *(Fig. 5)*. Secondly, the pressures

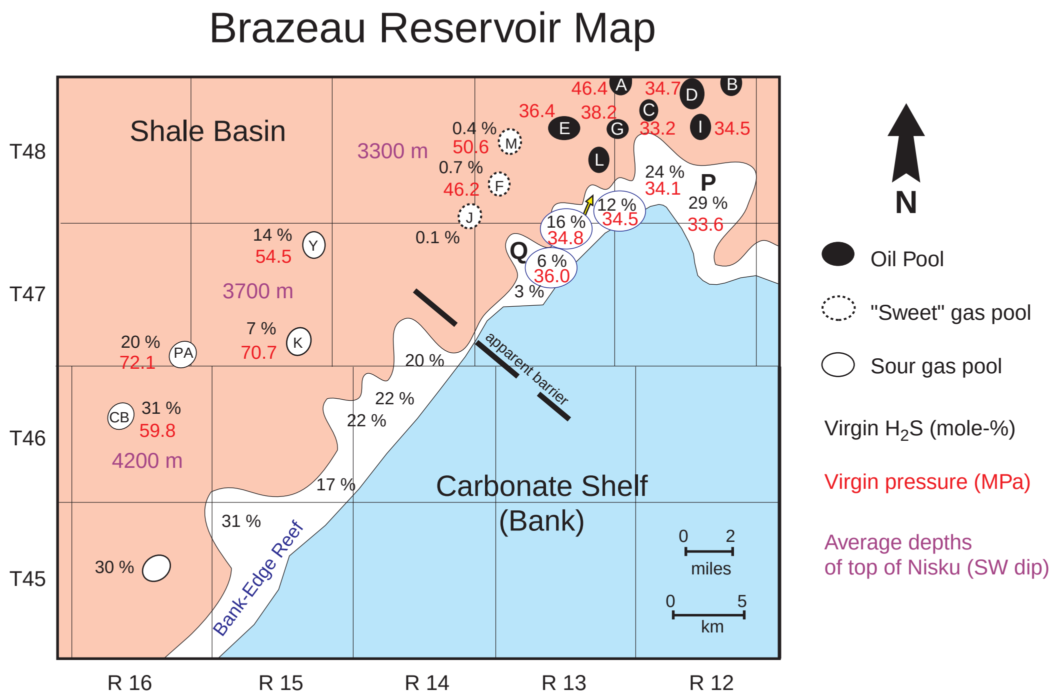

Figure 5

Brazeau Area reservoir map, enlargement of box labeled Brazeau Area in Figure 4. See text for further explanation.

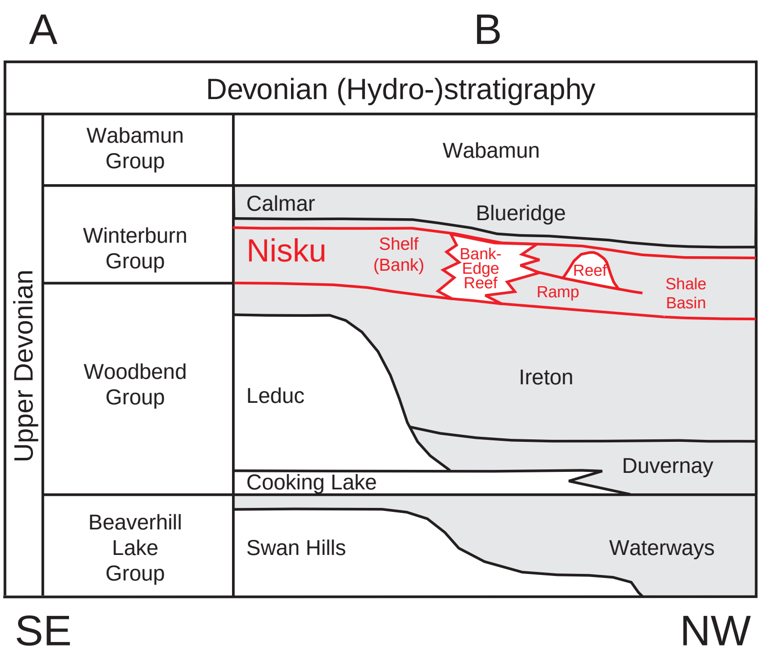

Figure 6

Hydrostratigraphic cross section that also serves as a schematic geologic cross section A-B *(see Fig. 4)*. The shaded stratigraphic intervals are marls and shales that act as aquitards. The porous and permeable Nisku reefs are effectively enclosed in these aquitards.

are nearly hydrostatic. Thirdly, although the bank-edge reef has been divided into a number of small pools by the reservoir engineers, from a geologic and hydrogeologic point of view the entire reef is one, at best two pools. Specifically, the P- and Q-Pools, both located within the bank-edge reef, must be hydraulically connected at least over geologic times, as shown by certain organic-geochemical parameters (Manzano *et al.*, 1997). The closure of this combined pool is the "nose" protruding northeastward around the P-Pool *(Fig. 5)*. The virgin H_2S contents in this combined pool vary from nearly 34 to about 3% southwestward (downdip) over a distance of about 25 km. Farther southwestward there is an abrupt jump back to about 20% H_2S right around the line labeled "apparent barrier" in Figure 5. Downdip from this line, the bank-edge reef appears to form another large sour gas pool that stretches all the way to the southwest corner of the study area *(Fig. 5)*. Although no physical evidence has been found, there must be a permeability barrier (probably a tightly cemented interval or fault), or else there is no explanation for the jump in H_2S contents. However, it is certain that the entire bank-edge reef was in hydrologic communication over geologic times, *i.e.*, during and some time after hydrocarbon migration in the Late Cretaceous to Early Tertiary. This is indicated by the gas compositions that demonstrate that the hydrocarbons contained today in the Q- and P- Pools were at least partially derived from much farther downdip (Manzano *et al.*, 1997).

The Nisku Q-Pool is located within the bank-edge reef at a subsurface depth of its top of 3348 m, and with the following virgin reservoir conditions: temperature: 110°C; pressure: 36 MPa; average porosity: 6.6%; average horizontal/vertical permeability: 63.4 /54.7 mD; gas composition: 93% hydrocarbons, 6% H_2S, 1% CO_2. At the time the pool was depleted and considered for acid gas injection, the reservoir pressure was about 11 MPa.

3 HYDROLOGICAL DATA

Extant, publicly available drill stem test data have been used to further characterize the hydraulic integrity of the seals and possible hydraulic interconnection between the pools. The salinity of the formation waters in the Winterburn Group in the Brazeau Area and the surrounding region is very high, *i.e.*, ranging from about 120 g/l to more than 240 g/l (TDS = total dissolved solids). When mapped, there is an overall yet weak trend toward lower salinities northeastward *(Fig. 7)*. The Brazeau Area shows closed contours with relatively uniform salinities around 120 g/l, suggesting sluggish if any flow of the formation waters.

The hydraulic heads in the same region support and refine this conclusion. The heads vary from more than 1100 m to less than 300 m and indicate the potential for general northeastward flow *(Fig. 8)*. Interestingly, the head contours are very tightly spaced near the northeast corner of the Brazeau Area, indicating that there is some form of hydraulic barrier. Hence, the bank-edge reef in this area does not appear to act as a regional aquifer today, a conclusion reached previously

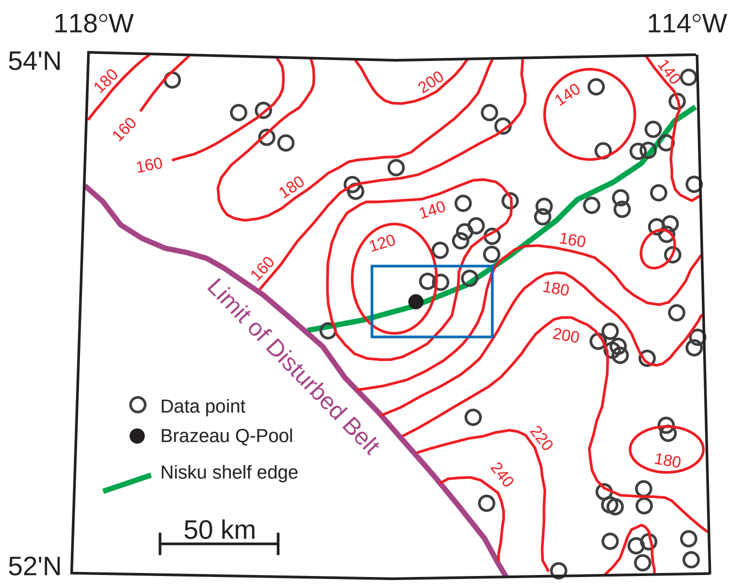

Figure 7

Salinity map of the formation waters of the Winterburn Group in the region surrounding the Brazeau area (rectangle near center - *see Figs. 2 and 3*).

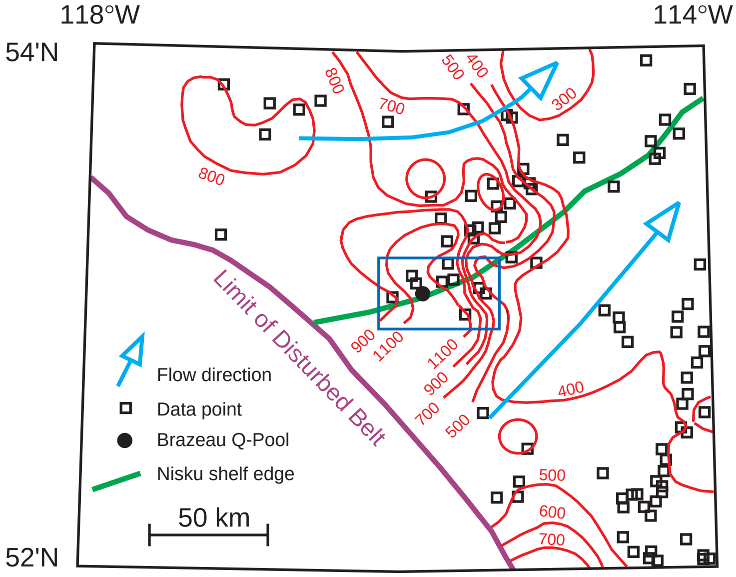

Figure 8

Hydraulic head map of the Winterburn Group in the region surrounding the Brazeau area (rectangle near center - *see Figs. 2 and 3*).

on the basis of gas compositions and virgin pressure data (see above). If there is any significant fluid flow within the Winterburn Group today, it would be around the Brazeau Area, *i.e.*, roughly along the arrows shown in Figure 8.

The pressure-depth and especially elevation-depth plots of various Nisku pools *(Fig. 9)* further refine these findings. The data from the shallow shelf margin and the deep shelf margin (bank-edge reef in the Bigoray and Brazeau Areas, respectively) plot along the hydrostatic gradient of about 10 MPa/km *(Fig. 9b)*. However, the data from the Brazeau Area are shifted toward higher values, indicating hydraulic communication within the bank-edge reef yet disconnection from the surface and from higher aquifers. A third pressure regime is represented by the small pools located along the ramp. The data from these pools are strikingly above hydrostatic and plot along a much steeper hydraulic gradient *(Fig. 9b)*, further proof of their effective hydraulic isolation from the surface, from higher aquifers, and from one another.

4 LITHOLOGY AND MINERALOGY

The spatial distribution of the various rock types and minerals is heterogeneous across the study area, with an overall inverse relationship between textural and mineralogic heterogeneity. The greatest diversity of textures, including porosity and permeability, exists in the reefs of the updip Bigoray Area. However, these reefs are almost monomineralic, consisting almost exclusively of calcite (limestone). In contrast, the reefs in the Pembina and Brazeau Areas consist essentially of dolomite with an average of about 20% anhydrite. Additionally, several other diagenetic minerals occur in small amounts (commonly less than 1 wt%): namely, elemental sulphur, celestite, authigenic clay minerals, pyrite, quartz, and ankerite.

The bulk mineralogy in the Nisku Q-Pool is dominated by dolomite and anhydrite (about 54 and 39%, respectively), with minor amounts of calcite, pyrite, and elemental sulfur, as well as trace amounts of the other minerals. Oxides were not present prior to drilling because of the prolonged (tens of Ma) contact of the rocks with hydrocarbons and H_2S, both dissolved in the formation waters and as gases phases. Small amounts of oxides now present in some drill cores formed after the cores were retrieved and put in storage. However, it is possible that small amounts of oxides formed within the reservoir(s) during the last 20 years due to oxygenated injection waters. This aspect may play a role (however small) in the sequestration of acid gas and should be considered in geochemical modeling. The following discussion ignores these small, “man-made”changes in mineralogy.

The dominant rock types are shown in Figure 10. There are four types of dolomite in the Nisku Formation:

– replacive grey matrix dolomite (GMD), which appears “tight” in most hand specimens;
– replacive brown porous matrix dolomite (BPMD), which appears porous in most hand specimens;
– white saddle dolomite cement;
– limpid dolomite cement.

The two matrix dolomites GMD and BPMD together comprise about 95 to 98 volume % of all dolomite in the Nisku Formation, and thus represent the typical reservoir rocks in the Nisku Formation.

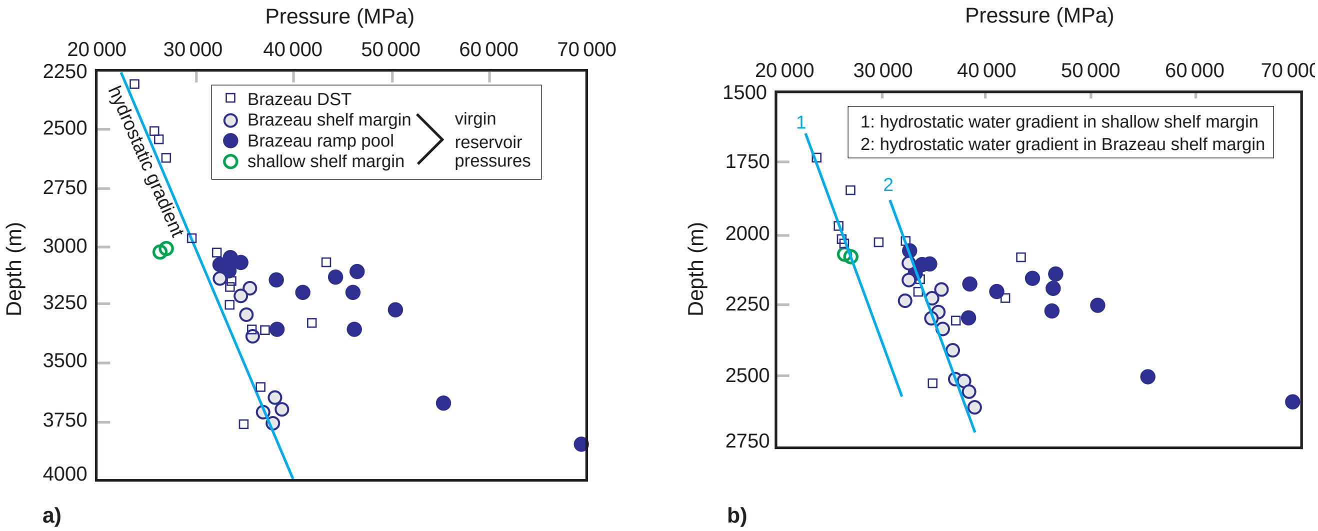

Figure 9

Pressure-depth and elevation-depth plots of drill stem test data of the Winterburn Group in the Brazeau Area.

GMD *(Fig. 10a-f)* is variably grey to greygreen in hand specimens, depending on the amount and color of clay impurities, which usually make up less than 1 wt% (determined by acid digestion). GMD occurs in place of the lime mud/micrite matrix. Large calcite skeletons, such as cemented tabular stromatoporoids, mollusks, and even delicate uncemented corals *(Fig. 10a)*, as well as various calcite cements, remained unaffected by this type of replacement dolomite in most places. BPMD occurs either instead of, or is intimately associated with, GMD. The contacts between these two dolomite types are sharp yet irregular *(Figs. 10d, e)*.

GMD has average crystal diameters of 50 to 100 μm (total range is about 5 to 300 μm). In partially dolomitized strata, GMD is matrix-selective and occurs as euhedral to subhedral rhombs scattered in the micrite matrix, but rarely in microspar or pseudospar matrix. BPMD forms coarser-crystalline mosaics, with average crystal diameters of 100 to 500 μm (*Figs. 10d, 10e*). BPMD consists of two populations: one is cloudy in the center with clear(er) overgrowth (similar to GMD), commonly with crystal diameters of 100 to 350 μm; the other population is clear throughout, commonly with diameters of 250 to 500 μm. These two populations are randomly intergrown, or they form small clusters of less than 10 crystals dominated by one or the other crystal type. Both GMD and BPMD contain molds and vugs from the dissolution of unreplaced calcite (one example is shown in *Fig. 10b*).

Anhydrite is an important accessory to both replacive dolomite types in the Nisku. Occurring in various textural subtypes, most anhydrite is milky-white in hand specimens. White anhydrite occurs as cements in molds that postdate dolomitization *(Fig. 10b)*, as well as replacing dolomite *(Figs. 10c1, 10c2)*. Furthermore, the amount of anhydrite varies with the degree of dolomitization. Limestones and partially dolomitized reefs are devoid of anhydrite, which appears in small quantities wherever the dolomite content exceeds 70 to 80 volume %. Most completely dolomitized reefs contain about 20 volume %.

Saddle dolomite is very rare in the Nisku Formation and restricted to two modes of occurrence. The more common occurrence, which is present in the Pembina and the Brazeau Areas, is as a cement in molds and vugs adjacent to stylolites *(Fig. 10f)*. The other occurrence is texturally almost identical but differs in the geochemical composition (Machel, 1985, 1987) and spatial distribution, *i.e.*, it is restricted to the water-saturated parts of the sour gas wells in the Brazeau Area.

5 DISCUSSION

The capacity of the Nisku reefs for storage of H_2S and/or CO_2 over extended, preferably geologic periods of time can be evaluated on the basis of the data presented above. There are two dimensions to this problem: what is the hydraulic integrity of the formation now, and what was it in the past?

5.1 Present Reservoir Characteristics

The first dimension is characterized by the virgin pressure conditions. The data clearly show that the small, pancake-shaped Nisku pools located on the ramp into the Winterburn basin are hydraulically isolated from one another, or else they would not display such tremendous and highly variable overpressures. Furthermore, the bank-edge reef is now effectively sealed hydraulically by the surrounding strata, and it once acted as an aquifer. The latter is shown by the gas compositions that demonstrate long-distance updip migration and

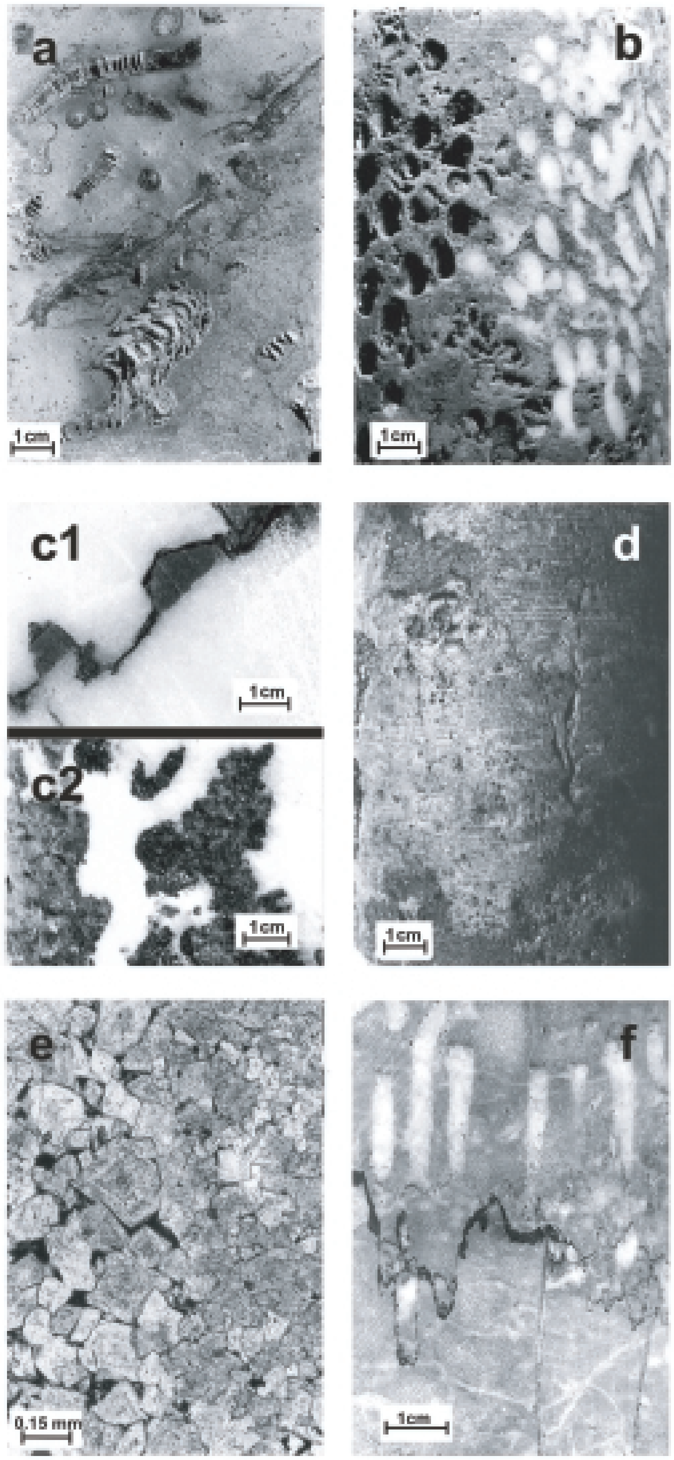

Figure 10

Typical reservoir rock types in the Nisku Formation: grey matrix dolomite GMD and brown matrix dolomite BPMD, and common associated textures. a: GMD selectively replacing matrix; the delicate corals are preserved as calcite. b: Moldic porosity in GMD, partially plugged with white anhydrite. c1: Replacive anhydrite postdating stylolitization, note "islands" of unreplaced GMD entirely encased in anhydrite; c2: similar to sample shown in c1, showing extensive anhydritization in dolostone. d: core photograph of GMD (light) abutting against BPMD (dark). e: thin section of sample shown in d; BPMD on left, GMD on right; inter-crystalline pores in BPMD contain dead oil. f: Saddle dolomite plugging coral molds in GMD near stylolite. Similar molds are open about 50 cm away from the stylolite.

mixing of gases within the bank-edge reef (Manzano *et al.*, 1997). This finding also explains why the subdivision of the bank-edge reef into numerous pools, which was made by reservoir engineers on the basis of the lack of short-term pressure draw-down, is erroneous. The Q- and P-Pools, located near the updip margin of the bank-edge reef in Figure 5, are not hydraulically isolated from one another. Rather, any gas injected into the Q-Pool will migrate into the P-Pool over relatively short periods of time, *i.e.*, probably within well under 100 years.

5.2 Evolution of Reservoir Characteristics

The question as to when the hydraulic isolation of the Nisku Pools happened is more difficult to answer and involves unraveling the diagenetic history of the Nisku Formation. At the time of deposition during the late Devonian, the Nisku Formation certainly was highly permeable throughout (as are all freshly deposited carbonate-marl/shale sequences), and the reefs consisted of calcite and/or its metastable polymorphs aragonite and/or high-Mg calcite. Subsequent diagenesis changed porosity, permeability, and mineralogy to the present state.

The diagenesis of the Nisku Formation forms a paragenetic sequence of at least 17 petrographically and/or geochemically distinct phases *(Fig. 11).* Not included are authigenic clay minerals, pyrite, celestite, quartz, and ankerite, because they do not significantly contribute to the diagenetic interpretation of the study area, although they may be important reactants during and after acid gas injection because the injected gas differs significantly in composition from that of the original reservoir gas (Gunter *et al.*, 2003, 2004).

The two replacive dolomite types, GMD and BPMD, constitute phase 9. Their generation was preceded by a number of limestone-diagenetic phases that effectively indurated (lithified) the original sediment and removed all metastable calcium carbonate phases. After dolomitization the Nisku was affected by several other diagenetic processes, including oil migration and entrapment, and sour gas formation via thermochemical sulfate reduction. In all, the diagenesis of the Nisku Formation in the study area can be grouped into six diagenetic stages that are distinguished by significant changes in the subsidence rate, the diagenetic fluid flow regime, and/or distinctive geochemical reactions. The five important stages I-V are indicated in Figure 11, and are briefly summarized below. Further details of these stages are documented in Anderson (1985), Machel (1985) and Anderson and Machel (1988). Stage VI is the most recent stage and encompasses the period of uplift from the Paleocene/Eocene to the Recent. No significant mineral reactions have been identified for this period.

Stage I encompasses phases 1 to 7 and includes deposition and shallow burial to about 300 m, reached near the end of Devonian time. This stage resulted in limestone induration and lithification.

Stage II encompasses phases 8 to 12 during shallow to intermediate burial, *i.e.*, about 300 to 1100 m. Based on regional burial curves (Anderson, 1985; Machel, 1985), a burial depth of about 1100 m was reached near the end of Mississippian time in most parts of the study area. The regional southwesterly dip must have been instigated during Stage II, leading to a slightly greater depth in the downdip part of the reef trend. Major diagenetic processes were chemical compaction leading to stylolites I in the limestones (phase 8), matrix dolomitization (phase 9), mold and vug

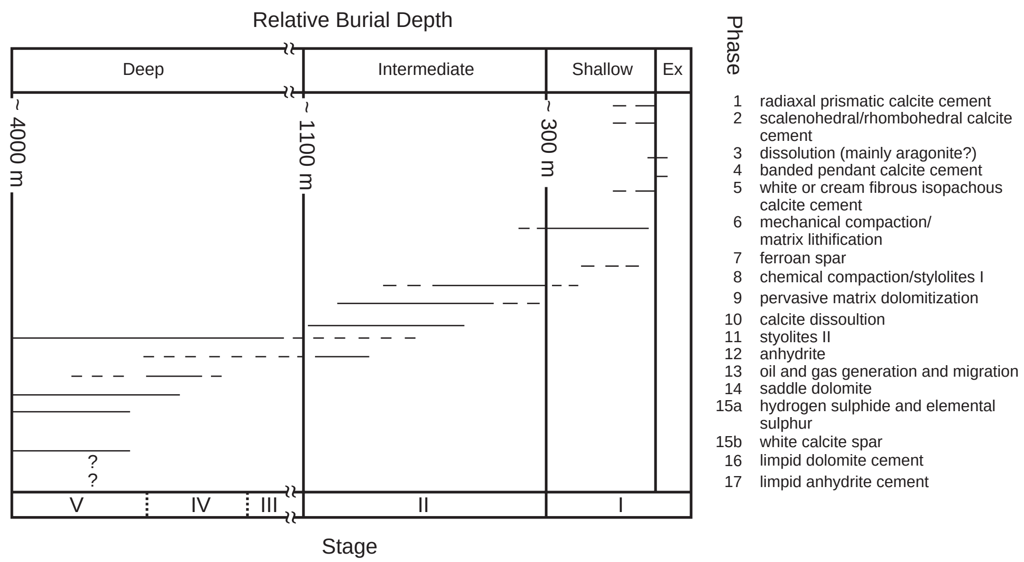

Figure 11

Diagenetic paragenetic sequence of the Nisku Formation. See text for further explanation.

formation (phase 10), renewed/continued pressure solution (phase 11), and replacive anhydritization (phase 12). Pressure solution must have begun near the Devonian/Carboniferous boundary and continued throughout Mississippian time, which was a period of relatively rapid burial. Stylolitization of limestones requires a minimum depth of about 300 m (Lind, 1993; Fabricius, 2000), which defines the boundary between Stages I and II. Furthermore, the sulfates provide two more indications for burial depth. One is the fact that most anhydrites formed originally as gypsum. The gypsum-anhydrite conversion takes place in the burial range of about 600 to 1100 m, which coincides with the depth of dolomitization inferred from the isotope data and stylolitization. Secondly, the sulfate isotopes indicate advanced bacterial sulfate reduction prior to or during gypsum emplacement, which is possible from the surface to about 2 km of depth (Machel and Foght, 2000).

Pervasive dolomitization proceeded in such a way that the porous and permeable matrix was replaced first, forming GMD, and the previously well cemented and recrystallized matrix domains were the last to become replaced, forming BPMD. The time difference between "first" and "last" probably was very small. On a geologic time scale GMD and BPMD are cogenetic and formed during one continuous replacement process. Calcite dissolution leading to vugs and molds appears to be an integral part of the dolomitization process, as it is common in the dolostones but virtually absent in the partially or undolomitized strata. Similarly, calcium sulfate (originally as gypsum, recrystallized to anhydrite during increased burial) appears to be an integral byproduct of the dolomitization process, as anhydrite is common in the completely dolomitized parts of the Nisku but virtually absent in the limestone areas. Pervasive dolomitization may have happened by thermal convection, compaction-driven flow, or a combination of these two (Machel, 2004). Whatever the dominant fluid drive, at least two additional factors modified the generally ascending flow pattern during dolomitization in the study area: one is the presence of subvertical faults with very low throws (undetectable in cross sections) that focused and deflected fluid flow, as suggested by the localized asymmetrical dolomitization of some reefs. The other is locally variable flow directions due to permeability variations, which account for the irregular distribution of dolomite in the partially dolomitized strata. Considering the present pressure distribution in the Nisku Formation, these faults appear to be sealed today (further discussed below).

Stage III encompasses a long period of nondeposition, erosion, and minor sedimentation (note that the time scale is not linear in *Fig. 11*). No significant diagenetic processes have been identified for this stage.

Stage IV includes intermediate to deep burial from about 1500 to 2400 m in the Bigoray Area, and from about 2000 to 3400 m in the Brazeau Area, reflecting a second period of rapid burial between Upper Cretaceous and lower Tertiary time. Phases 11 and 12, which began in Stage II, extended into stage IV. The pressure solution that formed stylolites II (phase 11) took place throughout most of stage IV. This phase of pressure solution dissolved some matrix dolomites, generating thin clay residues and leading to the localized precipitation of a few volume % of saddle dolomite in the vicinity of the stylolites. Hence, the $CaMg(CO_3)_2$ for the precipitation of the saddle dolomite cements was locally redistributed from the preexisting matrix dolomites, and did not require fluid flow to import Mg. Some anhydrite cements that now contain oil filled fluid inclusions formed during this stage. The sulphate for these cements was derived locally from pressure solution, *i.e.*, the $CaSO_4$ for the precipitation of these late-formed anhydrite cements was locally redistributed from the preexisting anhydrites. Another major event during Stage IV was oil generation and migration (phase 13).

Stage V includes deep and maximum burial to about 2500 to 3000 m in the Bigoray Area, and to about 4000 m in the Brazeau Area. The major diagenetic process was thermochemical sulphate reduction in the deepest reefs at temperature of about 135 to 140°C. Saddle dolomite precipitation from the formation waters associated with oil and gas began in Stage IV, driven by chemical compaction and was enhanced in Stage V by increased carbonate alkalinity in those wells affected by thermochemical sulfate reduction (Machel *et al.*, 1995). The structural dip increased to its present value of about 1° to the southwest during Stage V, the latter part of which coincided with the Laramide Orogeny in the Rocky Mountains 200 to 400 km to the west.

Stage VI is the period of erosion and relative uplifting of the study area since the Laramide orogeny. Diagenetic processes during this time period were negligible in importance.

The analysis reveals that the most significant mineralogic transformations and reorganization of porosity and permeability happened about 360-330 Ma ago during the Late Devonian to Early Carboniferous in phases 9-12, *i.e.*, during pervasive matrix dolomitization and concurrent calcite dissolution, anhydritization, and stylolitization. Dolomitization *stricto sensu* generated intercrystalline porosity and permeability, as did the associated calcite dissolution that formed macroscopic molds and vugs *(Fig. 10)*. On the other hand, anhydritization and stylolitization destroyed porosity and created locally effective permeability barriers. This is shown by several reef cores that contain 1 to 2 m thick intervals of solid anhydrite, texturally similar to the one shown in Figure 10c1, some of which appear to be anhydrite-cemented fractures. In short, diagenetic phases 9-12 probably led to the present reservoir conditions across most of the study area.

The exception is the apparent permeability barrier that now separates the bank-edge reef into two large sour gas pools *(Fig. 5)*, and that must be much younger. This barrier must postdate regional hydrocarbon migration and sour gas formation via thermochemical sulphate reduction, which happened some 50-70 Ma ago during the Late Cretaceous to Early Tertiary. Otherwise the combined QP-Pool would not contain hydrocarbons and H_2S that were generated more than 50 km farther downdip (Manzano *et al.*, 1997). Although there is no direct evidence, the permeability barrier in the bank-edge reef most probably is a tightly anhydrite-cemented subvertical fracture or fault, texturally similar to that shown in Fig. 10c1 but thicker. Circumstantial evidence for subvertical faulting in the study area is present in some Nisku reefs that are dolomitized only on their downdip side, such as the Brazeau D-Pool close to the QP-Pool *(Fig. 5)*. Such faults have been essentially inactive since the waning of the Laramide orogeny some 30 Ma ago. Also, mobility of anhydrite during and after the Laramide orogeny has been documented from several other locations in the deep part of the basin (Machel, 1993). Taking these lines of evidence together, it stands to reason that the apparent permeability barrier in the bank-edge reef is a tightly anhydrite-cemented fracture or fault that was last active about 30 Ma ago.

5.3 Implications for Acid Gas Injection and Carbon Dioxide Sequestration

The Nisku Formation contains many pools that are suitable for acid gas injection and carbon dioxide sequestration. One such pool is the Brazeau Q-Pool. The finding that the Nisku Q- and P-Pools are hydraulically connected is considered an advantage. The combined QP-Pool has a much greater capacity for acid gas storage than either of its components. The small pools located on the ramp could also be considered for acid gas disposal. They obviously are extremely well sealed over geologic times, as shown by their significant overpressures and the pressure gradients with depth *(Fig. 9)*.

In the highly unlikely case of migration out of the Nisku Q-Pool, the acid gas plume would disperse and dissolve in deep formation waters along the flow path. This is suggested by the regional hydrogeological evaluation (*Figs. 7 and 8*). The only possibility for upward leakage of acid gas rapid enough to be of human concern is through wells that were improperly completed and/or are abandoned and are not monitored. There are six wells near the injection well site that could cause problems (*Fig. 12*: circled). These wells should be closely monitored for leakage through cracked well casings, mineral reactions that may corrode them, or spalling of the casings from the rock formations.

CONCLUSIONS

The most favorable conditions for acid gas disposal and/or carbon dioxide sequestration are:

– effective hydraulic seals at the time of injection;
– absence of or very slow geochemical reactions within the formation that could lead to breaching of the surrounding seals over long periods of time; and
– the well casings are especially tight and monitored over time for leakage.

The Nisku Formation contains numerous pools that meet the above criteria. One such pool is the Nisku Q-Pool. Other, and potentially even better pools for acid gas disposal are the small, pancake-shaped pools along the ramp.

The Nisku Q-Pool is hydraulically connected to the Nisku P-Pool, forming what is here informally called the QP-Pool. This is considered an advantage, as the combined pool has a much higher storage capacity than the Q-Pool alone.

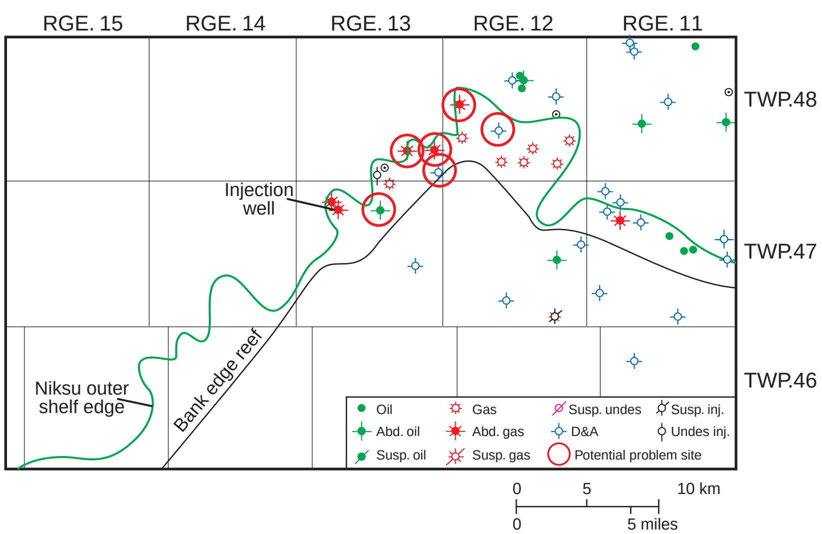

Figure 12

Injection and potential problem sites in the Brazeau bank-edge reef. Abd.: abandoned; Susp.: suspended; D&A: drilled and abandoned; Inj.: injection.

In the highly unlikely case of acid gas leakage out of the Nisku Q-Pool, the contaminant plume would disperse and dissolve in deep formation waters along the flow path. The only possibility for upward leakage of acid gas rapid enough to be of human concern is through wells that were improperly completed and/or are abandoned and are not monitored.

ACKNOWLEDGEMENTS

This research was supported by the *Natural Sciences and Enginnering Council of Canada (NSERC)*, the *Alexander von Humboldt Foundation (AvH)*, and by several oil companies, most notably *Petro Canada Resources*. The author further acknowledges the contribution by the *Alberta Geological Survey* on the hydrogeology of the Nisku Q-Pool and the Winterburn Group. Comments by E. Brosse and two anonymous reviewers are appreciated.

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Final manuscript received in November 2004