OVERVIEW OF REGIONAL OPPORTUNITIES FOR GEOLOGICAL SEQUESTRATION OF CO$_2$ AS GAS HYDRATE IN CANADA

J. F. Wright *, M. M. Côté, S. R. Dallimore

Geological Survey of Canada
Natural Resources Canada
9860 West Saanich Rd. Sidney BC, V8L 4B2
CANADA

ABSTRACT
The responsible management and reduction of carbon dioxide (CO$_2$) emissions to the atmosphere requires consideration of alternative options for disposal and long-term sequestration of CO$_2$ generated at hydrocarbon-fueled power plants and large industrial sources. A number of “conventional” options for geological sequestration of CO$_2$ are currently being evaluated worldwide, including disposal of CO$_2$ in depleted oil and gas reservoirs, in deep saline aquifers, and in unrecoverable coal beds, typically in gaseous or liquid form or as a supercritical fluid. Although these geological settings may constitute the most readily accessible sites for immediate utilization, it is unlikely that they represent sufficient cumulative storage capacity to keep pace with global CO$_2$ production and future disposal requirements. In addition, the requirement for long-term maintenance of CO$_2$ sequestered in fluid form, raises concerns regarding the possible mobility of the disposed CO$_2$ over the longer term. The Geological Survey of Canada (GSC) has investigated potential opportunities to sequester CO$_2$ in solid form in Canadian geologic reservoirs having pressure and temperature conditions suitable for the formation and long-term stability of CO$_2$ hydrate. Initial screening of candidate reservoirs has identified substantial potentials for CO$_2$ sequestration as gas hydrate in extensive porous sandstone and limestone formations beneath portions of the Canadian Great Lakes, and in areas of the Mackenzie-Beaufort hydrocarbon development region in northern Canada. A significant but less robust capacity has been identified in the oil and gas production regions of northeastern Alberta.

Keywords: geological sequestration; carbon dioxide; gas hydrates

INTRODUCTION
Continuing concern regarding the impacts of atmospheric carbon dioxide (CO$_2$) on the global climate system has provided an impetus for the development of methods for the long-term disposal of CO$_2$ produced by industrial activities. The Geological Survey of Canada (GSC) in partnership with the Climate Change Action Plan (CCAP 2000) has conducted an initial assessment of Canadian options for geologic sequestration of CO$_2$ as a solid gas hydrate. CO$_2$ hydrate is an efficient medium for CO$_2$ storage, with one volume of CO$_2$ hydrate containing the equivalent of up to 160 volumes of free gas under standard pressure and temperature conditions. Furthermore, sequestering CO$_2$ as solid gas hydrate has the obvious advantage of greatly reduced mobility of the sequestered CO$_2$ over the longer term.

The broader GSC research program strives to advance scientific understanding of CO$_2$ hydrate occurrence in porous geological media, to identify geological settings suitable for sequestration of

* Corresponding author: Phone: +1 250 363 6498 Fax +1 250 363 6565 E-mail: fwright@gsc.nrcan.gc.ca
CO₂ as gas hydrate, and to evaluate the utility of conventional oilfield methodologies and engineering technologies for long-term CO₂ injection and reservoir monitoring. At present the concept of CO₂ sequestration as gas hydrate is largely based on theoretical precepts and limited laboratory studies, and therefore considerable additional research is required to fully evaluate the feasibility of this option. The scope of this paper will be limited to the presentation of the results of an initial assessment of regional potentials for CO₂ sequestration as gas hydrate in three regions of Canada, based on the presence of geothermal and geopressure conditions conducive to the formation and long-term stability of CO₂ hydrate.

**Background**

Gas hydrates are ice-like crystalline solids composed of water and gas. In general terms, gas hydrates occur and remain thermodynamically stable under conditions of high pressure and relatively low temperature (Figure 1). In cases where CO₂ is the only hydrate-forming gas, CO₂ will form structure I (sI) hydrate. The formula for sI CO₂ hydrate is CO₂ • 5.75 H₂O (or 8 CO₂ • 46 H₂O for a repeatable molecular unit cell). In theory, if all of the hydrate cages were occupied by CO₂, then each m³ of CO₂ hydrate would contain approximately 164 m³ of CO₂ gas at standard conditions. However, in reality generally less than 100% of hydrate cages are actually occupied by guest molecules of gases [1][2][3][4]. Experimental determination of the ratio of water molecules to CO₂ molecules reported in the literature ranges from 5.82 to 7.8 [4], suggesting that 1 m³ of CO₂ hydrate may contain between 120-162 m³ of CO₂ at standard conditions. This corresponds to a CO₂ density of between 0.28-0.37 tonne·m⁻³ of CO₂ hydrate. Detailed descriptions of the structure and properties of CO₂ hydrate can be found in Sloan and Koh [5] and Makogon [6].

**Criteria for reservoir assessment**

Specific criteria for assessing the suitability of individual sedimentary formations for long-term geological sequestration of CO₂ are still under development, although in a general sense the major elements that should be considered in the screening process have been reasonably well defined [7][8]. Although of major importance, geological suitability is only one of a number of factors that must be evaluated in the screening of candidate reservoirs. In the case of CO₂ sequestration as gas hydrate, the primary requirement is that pressure-temperature (P-T) conditions within the target reservoir must be conducive to the formation and maintenance of stable CO₂ hydrate. Other major screening factors include:

- **Porosity**: the host sediment has adequate pore volume for storage of CO₂ as gas, supercritical fluid, or gas hydrate.
- **Permeability**: pore size distribution and connectivity are adequate to ensure reasonable CO₂ injectivity rates and efficient reservoir filling.
- **Thickness and extent**: sufficiently large storage capacity to be economical within the constraints of available technology.
- **Geochemistry**: injection of CO₂ is unlikely to induce chemical reactions which degrade the structural integrity of the host reservoir.
- **Hydrodynamic regime**: formation waters are sufficiently isolated from fresh water aquifers comprising the domestic water supply.
- **Proximity**: candidate reservoirs are close to CO₂ generation source and/or suitable CO₂ transport infrastructure (e.g. pipelines).
- **Accessibility**: the reservoir can be accessed readily and economically using existing drilling and injection technologies.
In addition, the future response of the ground temperature regime to ongoing climate change is an important factor affecting the long-term stability of the CO₂ hydrate sequestered in geologic reservoirs.

This work primarily considers local/regional geothermal and geopressure conditions, coupled with the presence of suitable porous reservoir sediments (in terms of porosity, permeability, thickness and extent) as a basis for evaluating inherent geological potentials for CO₂ sequestration as gas hydrate. Other practical factors such as accessibility, extent and capacity of CO₂ transportation infrastructure, economics and socio-political considerations are also important in the broader feasibility context, but are given only cursory attention in this paper. Extensive data collection efforts will be required to document the detailed characteristics of potential candidate reservoirs prior to the consideration of any practical CO₂ sequestration operations within these study areas.

METHODS
Detailed descriptions of the methodologies employed will not be given here, but are available in Wright et al. [9] and Shaw [10]. Geological formations beneath Lake Superior, in northeastern Alberta, and in the Mackenzie-Beaufort region were evaluated with respect to the presence of suitable geothermal and geopressure conditions necessary to support the in situ formation of CO₂ hydrate, assuming successful injection of CO₂ into fully or partially water-saturated reservoirs.

A simplified, regional-scale approach to the analysis was adopted, reflecting the nature of currently-available information regarding geological and geothermal conditions at depth. Mean annual ground surface temperatures (or bottom-water temperature in the case of lakes), local/regional geothermal heat flux values, and estimates of sediment thermal conductivity served as a basis for assessing geothermal conditions and CO₂ hydrate stability potentials within the candidate reservoirs. For each study area, regional stratigraphic data were evaluated to identify suitably-extensive sedimentary units with sufficient permeability and porosity to support practical CO₂ injection rates and a significant CO₂ storage capacity.

Overlay of the assumed geographic extents of candidate sedimentary formations with areas having P-T conditions suitable for CO₂hydrate formation and stability yielded estimates of the potential volumetric capacity available for CO₂ storage. The actual utility of this capacity depends on a variety of other factors, including accessibility, cost, geochemical factors, and hydrodynamics.

LAKE SUPERIOR
The Canadian Great Lakes are located in the industrial heartland of North America, and thus are in comparatively close proximity to both Canadian and American sources of industrial CO₂. In addition, an extensive network of pipelines link the major industrial centers, and some of these pipelines or their rights-of-way may be suitable for future utilization as conduits for transporting industrial CO₂ to potential disposal sites.

Potentials for CO₂ sequestration as gas hydrate were evaluated for all four of the Great Lakes (including Lake Michigan). No significant sequestration potentials were determined for Lake Ontario and Lake Erie, due to high sub-bottom geothermal gradients and insufficient water depths, respectively. A modest but significant potential was determined for Lake Huron [9], and a very substantial sequestration capacity was determined for Lake Michigan. The following sections outline the major steps in the determination of potentials for CO₂ sequestration as gas hydrate beneath Lake Superior, for which a potentially very large sequestration capacity was identified.

Geology
The Lake Superior basin was a feature of positive relief (the Wisconsin Arch) through the last 500 Ma of the Proterozoic Eon and the Cambrian Period. Sediments from Ordovician and Silurian seas of the Michigan Basin were deposited in the southeastern part of the region. It is thought that

Figure 2: Cross section along a seismic transect in eastern Lake Superior showing thickness of major sedimentary and volcanic rock formations [21].
the whole region was submerged during the early Mississippian, but that deposits from that time were eroded through the 250 Ma of the Mesozoic Era [11][12]. River valleys may have occupied the axis of the rift prior to a series of glaciations beginning approximately 3 million years ago which subsequently eroded the basin. By the end of the last glaciation, melt waters filled the basin above present levels. Outlets to the south and east opened over time and the lake levels subsided to current levels. The northwest shore and Keweenaw Peninsula consist of Proterozoic volcanics, intrusive rocks, and sandstones. The northeast shore is Archean bedrock. The bedrock of the south shore and parts of the eastern shore is comprised of Proterozoic to Cambrian sandstones and Paleozoic rock. The Sault Ste Marie area is underlain by massive to cross-bedded sandstone and Proterozoic volcanics.

Table 1: Properties of the Jacobsville Sandstone

<table>
<thead>
<tr>
<th>Site</th>
<th>Quartz / Feldspar (%)</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Michigan outcrops</td>
<td>75/&lt;15 (medium)</td>
<td></td>
<td></td>
<td>[13]</td>
</tr>
<tr>
<td>Ontario outcrops</td>
<td>65-85/5-25 (fine-medium)</td>
<td></td>
<td></td>
<td>[14]</td>
</tr>
<tr>
<td>Michigan quarry</td>
<td></td>
<td>13.8</td>
<td>8.11</td>
<td>[15]</td>
</tr>
<tr>
<td>Sault Ste. Marie area</td>
<td>70/18</td>
<td></td>
<td></td>
<td>[16]</td>
</tr>
<tr>
<td>Northern Michigan</td>
<td>67/17 (medium)</td>
<td>5.1-9.8</td>
<td></td>
<td>[17]</td>
</tr>
</tbody>
</table>

The Jacobsville Sandstone is a fluvial to lacustrine sequence of quartzose and feldspathic siliciclastics, and is considered to be the most desirable geologic unit for sequestration of CO₂ as gas hydrate in the Lake Superior area. Interpretation of seismic refraction studies [18], suggests that Jacobsville-Bayfield sandstones underlie most of Lake Superior. A minimum thickness of 1100 m has been recorded from a drill hole on the Keweenaw Peninsula, with a potential thickness of at least 3 km near the Keweenaw fault [19][20] and an estimated thickness of up to 6 km beneath Lake Superior [21] (Figure 2).

**Bathymetry and bottom water temperature**

Figure 3 shows the location of extensive deep basins (>200 m depth) within Lake Superior, which occupy approximately 30% of the entire lake area [22]. More than 85% of the lake area has water depths of greater than 100 m. Water temperature measurements for Lake Superior are available from 32 research cruises carried out between 1968 and 1997 by Environment Canada and are available in databases maintained by the Centre for Inland Waters at Burlington, Ontario. Sounding depth and temperature were obtained at each station using a mechanical bathythermograph and an echo sounder [23]. Although there is no published year-round temperature record for the deep basins of Lake Superior, measurements obtained in the spring and early fall show that bottom water temperatures in areas deeper than 100 m are relatively constant, ranging from 3.80°C to 4.15°C, and that temperatures below 200 m remain at the temperature of maximum density 3.83°C [24]. This suggests that for the purpose of estimating ground temperature profiles beneath Lake Superior, we can assume stable bottom water temperatures of approximately 3.8°C for basin depths greater than 200 m, and mean annual

**Figure 3: Generalized bathymetry of Lake Superior, showing deep basins [22].**

Superior, measurements obtained in the spring and early fall show that bottom water temperatures in areas deeper than 100 m are relatively constant, ranging from 3.80°C to 4.15°C, and that temperatures below 200 m remain at the temperature of maximum density 3.83°C [24]. This suggests that for the purpose of estimating ground temperature profiles beneath Lake Superior, we can assume stable bottom water temperatures of approximately 3.8°C for basin depths greater than 200 m, and mean annual
bottom water temperatures near 4°C at depths greater than 100 m.

**Potential for CO₂ sequestration as hydrate**

The assessment of the potential for CO₂ sequestration as gas hydrate beneath Lake Superior was based on available information about water depths, geothermal heat flows, and the thermal conductivity of sub-lake sedimentary formations, resolved to a 1 km² spatial grid. Ground temperature profiles for sediments beneath Lake Superior were estimated based on the assumption of stable or near-stable mean annual bottom water temperatures of about 4°C for basins of greater than 100 m depth.

Figure 4 presents regional heat flow values beneath Lake Superior, as determined by spatial interpolation of point measurements. In general heat flux values range between a low of about 20 mW·m⁻² along the western shoreline to more than 60 mW·m⁻² in east-central portions of the lake [25][26].

Figures 5a,b present two examples in which, bottom water temperature, geothermal heat flow, and formation thermal conductivity have been integrated to derive sub-bottom ground temperature gradients for water depths of 100 m and 200 m, respectively. Using an average sub-bottom heat flux of 41 mW·m⁻² and a thermal conductivity of 3.5 W·m⁻¹·K⁻¹ representative of a low-porosity sandstone [27], a geothermal gradient of 0.012 °C·m⁻¹ was determined for sub-bottom lake sediments. Alternative gradients based on ±20% uncertainty in thermal conductivity values are also presented.

The intersections (upper and lower) of the theoretical CO₂ hydrate phase-equilibrium curve with the estimated ground temperature profile defines a zone of potential CO₂ hydrate stability in sediments beneath Lake Superior. Note that in areas of the lake where the geothermal heat flux is greater than 41 mW·m⁻², higher geothermal gradients will result in decreased thickness of the zone of CO₂ hydrate stability. Conversely, where geothermal fluxes are less than 41 mW·m⁻², the thickness of the CO₂ hydrate stability zone will increase proportionally.

**Figure 5: Estimated ground temperature gradients (examples) beneath Lake Superior and inferred CO₂ hydrate stability within the Jacobsville Sandstone formation for water depths of: a) 100 m and b) 200 m.**

**Figure 6: Estimated thickness of the zone of CO₂ hydrate stability beneath Lake Superior.**

GIS-based computations at 1 km resolution generated estimates of sub-bottom geothermal gradients for all water depths greater than 100m.
Assuming mean annual bottom water temperatures of 4°C and a formation thermal conductivity of 3.5 W·m⁻¹·K⁻¹, we predict the presence of a zone of CO₂ hydrate stability beneath extensive portions of Lake Superior, ranging from about 200 m to more than 1000 m thicknesses (Figure 6). Indeed, for some areas along the western shoreline (US territory), the zone of CO₂ hydrate stability may approach 2 km in thickness.

**CO₂ sequestration capacity**
The area of Lake Superior having stable or near-stable bottom water temperatures of about 4°C is approx. 57,320 km² (5.7x10¹⁰ m³). Assuming a nominal average thickness of the CO₂ hydrate stability zone of 300 m, and average porosity of 10%, the total pore volume available for sequestration of CO₂ as gas hydrate is 1.7x10¹³ m³. However, it is reasonable to consider that practical constraints may dictate that only 50% of the local pore volume can be filled with gas hydrate (S_h=0.5), reducing the total volumetric capacity to 8.5x10¹² m³ of CO₂ hydrate. Based on a CO₂ density of 0.3 tonne·m⁻³ of hydrate (70% cage occupancy), the gross sequestration capacity beneath Lake Superior may be as high as 256 Gigatonnes (Gt) of CO₂. If only areas having water depths of 200 m or greater are considered in this calculation, the gross capacity for CO₂ sequestration as gas hydrate decreases to about 85 Gt.

Note that we have not partitioned this capacity according to the Canada-US international boundary. Also, given the absence of detailed information regarding the properties of the underlying reservoir rocks (porosity, permeability, salinity, thermal conductivity, etc.), considerable uncertainty remains with respect to the precise thickness of the zone of CO₂ hydrate stability and the actual sequestration capacity at any given location.

Overall, it is clear that a very large CO₂ sequestration potential exists beneath Lake Superior, with a capacity to store up to 256 Gt or more of CO₂. However, given current technological and economic constraints, it is likely that little of this capacity is presently accessible at reasonable cost. Continuing advances in drilling technologies and/or the implementation of strategic economic and policy incentives may create conditions under which significant portions of the Lake Superior basin becomes accessible for CO₂ sequestration as stable gas hydrate.

**Source-sink proximity**
The effective capture of CO₂ from industrial process streams generally requires that these sources be stationary and generate relatively large quantities of CO₂. Ideal targets are power plants, refineries, and manufacturing plants. In contrast, emissions from small, mobile, and distributed sources such as those associated with road, rail, and air transportation are not well-suited to current CO₂ capture and storage technologies [28].

In 2005, CO₂ emissions in Ontario totaled about 174 Mt, of which ~55% (97Mt) was generated by stationary sources [29]. Emissions from fossil fuel, electricity, and heat generation industries account for about 42 Mt per year. Utilization just 1% of Lake Superior’s estimated gross CO₂ sequestration capacity of 256 Gt could accommodate 50% of Ontario’s CO₂ emissions from power generation and fossil fuel industries for a period of 120 years.

![Figure 7: Location of 5 major stationary CO₂ emission sources in Ontario, in relation to potential deep water sites for CO₂ sequestration as gas hydrate beneath the Canadian Great Lakes [30].](image)

Figure 7 shows elements of an extensive network of Ontario pipelines [30]. Some of these pipelines (or their rights-of-way) may be suitable for transporting CO₂ from generation sources to potential sequestration sites. Under a coordinated North American strategy for CO₂ capture and storage, the utilization of a much denser pipeline network in the industrial heartland of the US could be considered.

**Climate change**
Because CO₂ hydrate is thermodynamically unstable at warmer temperatures, any feasibility study of CO₂ sequestration as gas hydrate in
natural geological reservoirs must consider the response of the sequestered gas hydrate to regional climate warming. Changes in bottom water temperatures and lake levels (i.e. pressure) associated with climate warming can potentially affect the stability of CO₂ sequestered as gas hydrate in sediments beneath the lakes. Numerous simulations of global climate have been applied to the Great Lakes region [31]. Because changes in bulk water temperature are governed primarily by the high specific heat of water, the Great Lakes have a very large capacity to store heat, and therefore it is expected that water temperatures in the Great lakes will respond slowly to changes in air temperature.

For deep water basins, stable bottom water temperatures of ∼4°C will persist when mean annual air temperatures are between −7°C and +8°C [26]. Simulations using General Circulation Models for the Great Lakes area under a 2×CO₂ scenario predict a warmer regional climate by 2050, with most of this warming in winter [32][33][34][35]. Current mean annual air temperatures at Thunder Bay and Sault Ste. Marie range from 2.5°C to 4.3°C respectively, but reach 9.4°C in Toronto. Therefore, it may be reasonable to assume that bottom water temperatures in the deeper basins of lakes Superior and Huron will remain relatively stable in response to anticipated magnitudes of climate warming, while those of Lake Erie and Lake Ontario may undergo significant warming.

The geological sequestration of CO₂ as gas hydrate is considered potentially viable over the longer-term because the CO₂ hydrate formed in sub-lake geologic settings will be insulated by the overlying sediments from the effects of modest perturbations of bottom water temperature. Furthermore, geothermal modeling by Taylor et al. [36] suggests that the time lag at depth due to a temperature change at the sediment/water interface may be in the order of millennia, providing a buffer against possible regional climate warming.

**OTHER REGIONAL POTENTIALS FOR CO₂ SEQUESTRATION AS GAS HYDRATE**

Regional opportunities for the sequestration of CO₂ as gas hydrate were also investigated in the Alberta and the Mackenzie-Beaufort hydrocarbon development regions. Detailed descriptions of the methods and assumptions employed in these assessments are available in Côté et al. [37] and Wright et al. [38] and will not be presented here.

The following sections provide a brief summary of the results of these assessments

**Northeastern Alberta**

Alberta is underlain almost entirely by the extensive Western Canada Sedimentary Basin (WCSB), which consists primarily of relatively porous reservoir rock, typically sandstone, limestone, and dolomite [39]. More than a half-century of oil and gas production in Alberta has produced a large number of depleted or partially-depleted oil/gas reservoirs that may potentially be utilized for geological storage of CO₂ from industrial sources. On this basis Alberta is already considered a premier world-class CO₂ sequestration site with respect to its geological capacity to store waste CO₂ in the fluid (gas, liquid or supercritical) state.

*Figure 8: Map showing areas of Alberta having potential for geological sequestration of CO₂ as gas hydrate. Inset presents gas hydrate stability conditions at 62 Alberta gas pools satisfying initial screening criteria.*
According to Environment Canada [29], CO₂ emissions Alberta totaled about 179 Mt in 2005, largely from oil/gas production and power generation. This represents about 30% of total Canadian CO₂ emissions (583 Mt). Approximately 95 Mt of CO₂ was generated by Alberta’s power generation and fossil fuel industries. The Alberta share of Canadian CO₂ production is likely to substantially increase during the next several decades as new oil sands meg-projects are developed.

We have investigated the potential for CO₂ sequestration as gas hydrate within the Alberta extent of the Western Canadian Sedimentary Basin (WCSB), through screening of pressure-temperature conditions recorded for more than 26,000 Alberta gas pools [40], and through GIS-based geothermal modeling, as summarized in Figure 8. Modeling results indicate an area of northeastern Alberta for which geothermal and geopressure conditions may be suitable for CO₂ sequestration as gas hydrate, and that ground temperatures within these reservoirs would be insulated from the effects of continuing climate warming for a period of about 1000 years.

The inset in Figure 8 plots P-T conditions at 62 Alberta gas pools (which satisfied initial screening criteria) in relation to the CO₂ hydrate stability curve. The geographical location of these 62 gas pools are indicated on the map as red circles. Although these represent only a very small percentage of Alberta gas pools overall, almost all of these pools are located within the general region of northeastern Alberta for which geothermal modeling also indicates a potential for CO₂ sequestration as gas hydrate.

While considerable work remains to evaluate the actual CO₂ sequestration capacity in this region, Shaw [10] suggests that these 62 pools alone could sequester 30% of annual CO₂ production from the Syncrude and Suncor oil sands operations (i.e. 30% of 16.5 Mt or 5 Mt) for about 60 years. Given its general accessibility and proximity to large CO₂ generation sources, we consider that this region of northeastern Alberta may provide an ideal location for future field trials and/or pilot projects for evaluating the practical feasibility of geological sequestration of CO₂ as gas hydrate.

Mackenzie-Beaufort Region
The Mackenzie valley and Beaufort coastal region is currently geographically isolated from major Canadian sources of industrial CO₂. However, the region contains substantial oil and gas resources, and plans for large-scale resource development are expected to be realized within the next decade, commencing with the construction of a pipeline to deliver natural gas from the Mackenzie delta area to southern markets. The presence of a pipeline connecting to the CO₂ generating regions of Alberta raises the possibility for the transport of CO₂ from southern sources for subsequent disposal in the thick sedimentary formations of the Mackenzie-Beaufort area. Given the cold regional climate, it is conceivable that CO₂ could potentially be sequestered as stable gas hydrate beneath the extensive permafrost of the region.

The Beaufort-Mackenzie basin is underlain by thick deposits of Upper Cretaceous to Holocene sediments deposited during four large-scale tectono-stratigraphic phases [42]. During each of these phases the centre of deposition shifted, resulting in a 12-16 km thick succession of northward-prograding deltaic complexes. Many of these formations are of highly porous (commonly 20-30%) sands and sandstone formations, which are considered ideal for the formation and storage of CO₂ hydrate. These include sands and gravels.
of Pliocene-Pleistocene Iperk sequence, thick accumulations of Kugmallit Bay sands and gravels, non-marine and marginal marine sands and gravels of Reindeer Formation, and sandstones of Fish River Sequence.

As was the case in the Lake Superior and Alberta studies, regional geologic and geothermal data were evaluated against the theoretical phase-equilibrium threshold for CO₂ hydrate stability. Figure 9 identifies an extensive area of the northern Mackenzie valley and Beaufort coastal region for which a good potential for CO₂ sequestration as gas hydrate is indicated. In general, the widespread occurrence of suitable porous and permeable geologic reservoirs in this area further supports the practical consideration of potential opportunities CO₂ sequestration as gas hydrate in this region.

TECHNOLOGY
A comprehensive assessment of technology issues related to the geological sequestration of CO₂ as gas hydrate is beyond the scope of this paper. However, over the past few decades there have been significant advances in the transport and utilization of CO₂ for Enhanced Oil Recovery projects in North America and elsewhere. As such, there is considerable experience with the design and maintenance of materials and systems for CO₂ transport, flow control, and injection into geologic structures, which will have direct application to geologic sequestration projects in general, and to CO₂ sequestration as gas hydrate in particular.

In recent years there has been considerable research and development into methods and technologies for CO₂ capture and storage from point source producers (e.g. power plants, refineries). Several large-scale pilot projects have been implemented to assess issues of technology performance and the maintenance of reservoir integrity over extended operational time-frames (e.g. Weyburn project in Saskatchewan, Sleipner project in the Norwegian North Sea). These projects also incorporate intensive monitoring programs to track accumulation and propagation of CO₂ within the host reservoir.

A currently unpublished study commissioned by the GSC and conducted by the Alberta Research Council assessed a wide range of technologies for CO₂ capture and storage, including CO₂ capture form stationary sources (power plants, refineries and upgraders, gas purification plans, etc.), CO₂ delivery systems (pipelines, long distance ocean transport), well completion and injection systems, and reservoir monitoring. The review found no prohibitive technological impediments to the application of existing technologies for CO₂ transportation and subsequent geological sequestration of CO₂ as gas hydrate.

However, significant technical challenges constrain the immediate utilization of the CO₂ sequestration potential beneath the Great Lakes. These include a limited practical drilling capability for accessing reservoirs located beneath deepwater lakes, either by shipboard or platform drilling, or by horizontal drilling from land. Shipboard drilling and completion of multiple well configurations is technically difficult and is likely prohibitively expensive under current CO₂ economics. Land-based extended-reach drilling is also technically challenging, but advances during the past decade have extended the range of this technique beyond 10 km horizontal distance [43], and this range will probably continue to expand in the future. At the current realized limit of 10 km, reservoirs beneath most of the deeper basins (>200 m) of Lake Superior would be beyond the reach of current land-based drilling technology. However, a considerable portion of the reservoirs beneath basins of greater than 100 m depth might be sufficient accessible for utilization in the immediate or near future.

NUMERICAL SIMULATION
Numerical studies can provide an integrated understanding of the process mechanisms affecting the viability of geological sequestration CO₂ as gas hydrate, especially when realistic geological reservoir characteristics are utilized in the models. A series of numerical simulations sponsored by the GSC and conducted at the Alberta Research Council using the Thermal Advanced Process Reservoir Flow Simulator - CMG STARS® 2006 shows that numerical modeling can effectively capture the spatial and temporal dynamics of CO₂ hydrate formation in geological reservoirs by injection of CO₂ gas [44].

Although this research has identified some practical limitations to CO₂ hydrate formation by gas injection, it also provides useful insights that ultimately will contribute to improved efficiency of the CO₂ injection/sequestration process. For example, observations regarding the propagation of the pressure pulse (overshoot) in reservoirs having different porosity and permeability
characteristics suggest potential problems in maintaining sufficient pressure overshoot (the primary driver for hydrate formation) in high-permeability reservoirs (~1000 mD), as compared to reservoirs of relatively lower permeability (10-100 mD). It is likely that additional modeling based on such insights will facilitate the specification of a range of optimal reservoir parameters supporting sustained, long-term sequestration of CO₂ as gas hydrate, thereby assisting in the identification of potential candidate geologic formations for future utilization.

SUMMARY AND CONCLUSIONS

The potentials for geological sequestration of CO₂ in three different environmental settings in Canada have been investigated by evaluating geologic, geothermal, and geopressure conditions with respect to their suitability for the in situ formation and long-term maintenance of CO₂ hydrate. A large and robust capacity for CO₂ sequestration as gas hydrate was determined for the extensive Jacobsville Sandstone formation beneath Lake Superior. A potentially vast sequestration capacity was identified for a broad area of the Mackenzie valley-Beaufort coastal region, although this region is distant from industrial sources of CO₂. A more modest and less robust capacity was determined for portions of the WCSB in northeastern Alberta, however this region likely affords an ideal location for future field trials and/or pilot projects given the generally good regional infrastructure development and excellent CO₂ source-sink proximity in the vicinity of the Fort McMurray heavy oil development area.

ACKNOWLEDGEMENTS

This project was funded by the Climate Change Action Plan of Canada (CCAP 2000), with additional financial and in-kind contributions from the Geological Survey of Canada, Natural Resources Canada. Comprehensive datasets describing geologic conditions within a gas hydrate-bearing reservoir at the Mallik site in Canada’s Mackenzie Delta were provided by the Mallik 2002 Gas Hydrate Production Research Well consortium.

REFERENCES


[37] Côté MM, Wright JF. Regional opportunities for CO2 sequestration as gas hydrate in the
[38] Wright JF. Côté MM, Regional Opportunities for CO₂ sequestration as gas hydrate in the Mackenzie-Beaufort hydrocarbon development region; GSC Open File. In Preparation.
www.ags.gov.ab.ca/publications/ATLAS