Screening and Ranking of Hydrocarbon Reservoirs for CO_2 Storage in the Alberta Basin, Canada

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Introduction

Human activity since the industrial revolution has had the effect of increasing atmospheric concentrations of gases with a greenhouse effect, such as carbon dioxide (CO_2) and methane (CH_4), leading to climate warming and weather changes (Bryant, 1997; Jepma and Munasinghe, 1998). Because of its relative abundance compared with the other greenhouse gases, CO_2 is by far the most important, being responsible for about 64% of the enhanced "greenhouse effect" (Bryant, 1997). Given their inherent advantages, such as availability, competitive cost, ease of transport and storage, and large resources, fossil fuels which today provide about 75% of the world's energy (84% in the US and 73% in Canada) are likely to continue to remain a major component of world's energy supply for at least this century (Jepma and Munasinghe, 1998; Bajura, 2000). Thus, the world, including Canada and the US, needs to reduce CO_2 emissions into the atmosphere while at the same time ensuring sustainable economic development.

One of the possible approaches in mitigating anthropogenic climate change is carbon sequestration through the capture and diversion to secure storage of anthropogenic carbon emissions. Large CO_2 sinks are terrestrial ecosystems (soils and vegetation), oceans and geological media, with retention times of the order of 10-10^5 years, respectively (Gunter et al., 1998). Terrestrial ecosystems represent a diffuse natural carbon sink that captures CO_2 from the atmosphere after release from various sources. The oceans represent possibly the largest potential global sink, but ocean disposal involves issues of poorly understood physical and chemical processes, sequestration efficiency, cost, technical feasibility and environmental impact (Herzog et al, 1997). For landlocked regions, such as Alberta and the North American mid continent, ocean disposal is not an option for reducing CO_2 emissions. Biomass fixation of CO_2 is an option for the mid-term reduction of CO_2 emissions, but, besides some cost issues, factors of practicality and uncertainty make this an improbable solution as yet (Herzog et al, 1997). In addition, biomass CO_2 fixation through forest growth depends on climatic conditions and competes with agriculture, fishing, other industries, and land use. This leaves CO_2 sequestration in geological media as the best option currently available for the long-term sequestration of CO_2.

Storage of CO_2 in geological media is likely to provide the first large-scale opportunity for concentrated sequestration of CO_2, being immediately applicable as a result of the experience already gained in oil and gas production, storage of natural gas, and groundwater resource management. Currently, CO_2 is used in enhanced oil recovery (EOR) operations at more than 70 sites in the world, of which more than 40 are in west Texas (Moritis, 1998, 2000), and in enhanced coalbed methane recovery (ECBMR) in the San Juan basin (Byrer and Guthrie, 1999; Stevens et al., 1999). Acid-gas, a mixture of CO_2 and H_2S produced by gas plants, is already being injected into depleted hydrocarbon reservoirs and deep saline aquifers at more than 20 locations in the Alberta basin (Wichert and Royan, 1997; Davidson et al., 1999), and produced CO_2 is injected in the Utsira aquifer in the North Sea (Korbol and Kaddour, 1995; Baklid and Korbol, 1996).

Various CO_2 physical properties and other criteria play a role in the selection of the appropriate means and sites for CO_2 storage in geological media (Bachu, 2000; 2001a,b). Depending on in-situ temperature and original pressure, CO_2 can be stored in geological media either as a gas, as a liquid or in supercritical phase by several mechanisms (Bachu 2001a): 1) geological trapping in depleted hydrocarbon reservoirs and other stratigraphic and structural traps; 2) solubility trapping in oil reservoirs and in EOR, and in brines in deep aquifers; 3) hydrodynamic trapping in regional-scale aquifers; 4) mineral trapping through carbonate precipitation; 5) adsorption trapping onto the coal matrix in uneconomic coal beds and in ECBMR; and 6) cavern trapping in mined salt caverns. The method of geological storage, available volumes and retention time depend on media characteristics and in-situ conditions (Bachu, 2000). These factors play an intrinsic role in the identification of potential sites for CO_2 sequestration. Extrinsic (surface) factors, such as CO_2 availability, infrastructure for capture and transport, and cost, further narrow down the candidate sites for CO_2 sequestration in geological media (Bachu, 2000).

In the case of oil reservoirs suitable for CO_2 flooding, CO_2-storage is already achieved during the EOR operation. US experience shows that approximately 40% of the originally injected CO_2 is being produced at the pump and re-injected (Hadlow, 1992), which suggests a "gross" CO_2-retention efficiency of ~60%. This matches the 66% CO_2 retention obtained in numerical simulations (Holt et al., 1995). The US CO_2 utilization of ~17 mcf per incremental barrel of oil (3000 m^3/m^3) includes the reinjected CO_2 (Hadlow, 1992). If one takes into account that additional CO_2 is being produced in EOR operations, mainly during compression, the actual, or "net" CO_2-retention efficiency is of the order of 30-40%, which corresponds to the estimate of average storage of CO_2 of ~ 1080 Sm^3/m^3 stock tank oil (Holt et al., 1995). The incremental oil recovery from CO_2 flooding, estimated to increase the ultimate oil recovery by 8-14% of the Original Oil in Place (OOIP) (e.g., Holt et al., 1995), is achieved by oil swelling, reduction of oil viscosity, contribution to internal solution gas drive, and vaporization of crude. The economic benefit of additional oil production, when applied against the cost of injecting and storing CO_2, leads to a "negative-cost", or benefit, of storing CO_2 first in EOR operations (Freund, 2000; Stevens et al., 2000).

Fossil fuels are serendipitously linked with sedimentary basins in which CO_2 can be sequestered (Hitchon et al., 1999). In this respect, the Alberta basin is no exception, being rich in conventional oil and gas, heavy oil and oil sands, coal and coalbed methane, and salts (Bachu and Gunter, 1999). Most anthropogenic CO_2 emissions in the Alberta basin come from large point sources associated with power generation from fossil fuels and large industrial processes such as refineries and steel, cement and petro-chemical plants. Carbon dioxide separated from flue gases, effluents, and during fuel-decarbonization processes could be captured and concentrated into a liquid or gas stream that could be transported and injected into deep geological formations.

Objective

Having established that geological storage of anthropogenic CO_2 is immediately applicable, and in some case the best or only option for the large scale reduction of CO_2 emissions into the atmosphere, the objective is to identify where, how much and by what means CO_2 could be stored for significant periods of time. While the main mechanisms for CO_2 storage have been identified, and a series of criteria for site assessment and selection has been developed (e.g., Bachu 2000, 2001b), there are still many geoscience, engineering, economic and public issues that require addressing before full-scale implementation (Herzog et al., 1997), such as: volumes available for sequestration; identification of sequestration sites and appropriate methods; long-term integrity of sequestration; liability and cost associated with CO_2 capture, transport and injection; environmental impact and safety; and public perception, education and acceptance (Bachu, 2001a,b; Lenstra and van Engelenburg, 2000). Using a proper roadmap and strategy for resolving these issues (Bachu, 2001b) will lead to an early and successful implementation of large-scale storage of CO_2. Because not all geological media everywhere are suitable for CO_2 storage, site selection, one of the first steps in this process, should be based on an analysis that includes geoscience, engineering and economic criteria. The geoscience aspects comprise (Bachu, 2001b): 1) basin- and regional-scale suitability assessment; 2) inventory, selection and characterization of disposal sites; 3) safety and long-term fate assessment of the injected CO_2; and 4) capacity determination. Surface-based criteria, such as CO_2 capture, transport and injection, and cost and benefits can be applied after the geoscience-based screening of potential CO_2-storage sites.

The *basin-scale suitability* assessment for CO_2 sequestration needs to consider geological, geothermal, hydrodynamic, hydrocarbon potential and basin maturity, economic, and political and societal criteria (Bachu, 2000). The *regional-scale suitability* assessment should identify which regions in a “generally-suitable” basin are indeed suitable and which are not, and by what means of sequestration. This stepwise analysis should address (Bachu, 2001b): 1) basin geology and hydrostratigraphy, 2) basin hydrodynamics, 3) temperature and pressure distributions, 4) oil and gas reservoirs and in-situ conditions, including suitability for enhanced oil recovery (EOR), 5) coal beds and their characteristics, and 6) salt beds. The regional-scale suitability analysis further narrows down the regions, strata and means of CO_2 sequestration in a sedimentary basin. For example, although the Alberta basin in western Canada is generally one of the most suitable basins in the world for CO_2 storage in geological media (Bachu and Gunter, 1999; Bachu, 2000), the eastern shallow part of the basin is not suitable at all, the northwestern and southeastern parts are of medium suitability because of intermediate depth, fewer hydrocarbon reservoirs and no coal beds, and the deep southwestern and central parts of the basin are extremely suitable, with potential for sequestration by all geological means (Bachu and Stewart, 2002).

Inventory of potential CO_2-storage sites is the next step after suitability analysis (Bachu, 2001b) in the identification and selection of storage sites. Wherever more than one way of storing CO_2, and more than one site are available, the selection should take into account cost and potential economic benefits. From this point of view, CO_2 storage in oil reservoirs and coal beds by use in EOR and ECBMR should take priority over other means of geological storage. This is the case of the Alberta basin, rich both in oil, gas and coals, or of Nova Scotia basins in eastern Canada that are rich in coals. After the preliminary inventory of feasible storage sites, some potential sites may be eliminated after site-specific characterization, if they do not meet all the criteria for site selection, particularly with respect to CO_2 injectivity and site integrity (Bachu, 2001a).

Developing tools for screening and ranking of oil reservoirs for CO_2 storage in hydrocarbon-rich sedimentary basins, such as Alberta and Texas, and their large-scale application, is therefore one of the first steps in the selection of sites for CO_2 storage in geological media.

Approach

A “zoom-in” approach is used in the identification, selection and capacity evaluation of sites for CO_2 storage in geological media. After the basin- and regional-scale evaluation of a sedimentary basin (Bachu, 2000, 2001b), the next scaling-down step is the reservoir-scale analysis based on in-situ characteristics, such as temperature, pressure, rock-volume, porosity and oil gravity, and on in-situ CO_2 characteristics, such as phase, density and viscosity. Previous studies assumed that CO_2 will reach supercritical state at depths of ~ 800 m (van der Meer, 1993; Holloway and Savage, 1993); however, the temperature and pressure regimes in a sedimentary basin are highly variable, being a function of many factors whose interplay can produce a wide range of situations with respect to the state and fate of the injected CO_2 (Bachu, 2000). Depending if a basin is “warm” or “cold”, and underpressured or overpressured, the conditions for supercritical CO_2 are reached at various depths, from very shallow (a few hundred meters) to very deep (>1200 m), with implications for drilling and CO_2 compression and injection (Bachu, 2001b). Using bottom hole temperatures and pressures from drill stem tests, the geological space can be transformed into the CO_2-phase space that indicates the CO_2 state in various strata (Bachu, 2001), hence in the hydrocarbon reservoirs, coal beds and/or aquifers contained in the respective strata. The amount of stored CO_2 in the pore space is maximized if the in-situ conditions allow higher CO_2 density, which occurs for low geothermal gradients and high pressures (Bachu, 2001b). Injection in areas and at depths close to the temperature and pressure conditions that correspond to a CO_2 phase change will result in transition to the gaseous phase if CO_2 reaches slightly shallower depths. This may happen if CO_2 is injected below the spill point in hydrocarbon reservoirs, if it overrides quickly at the top of an aquifer, or through cross-formational flow. In the absence of geological traps, CO_2 bouyancy will lead to its relatively rapid raise or flow through the sedimentary column and escape to the surface. Thus, this methodology allows the identification of sites with significant storage capacity, while avoiding CO_2 injection into unsafe places.

Application of the space transform from geological to CO_2 phase allows the screening out of oil reservoirs that are not suitable for EOR using CO_2 flooding. An additional screening criterion is that the reservoir pressure at the start of a CO_2 flood should be at least 1.38 MPa (200 psi) above the minimum miscibility pressure (MMP) to achieve miscibility between CO_2 and reservoir oil (Rivas et al., 1994). This means that ratio between reservoir pressure and minimum miscible pressure (P/MMP) normally should be >1. In reality, CO_2-flood EOR is still possible for P/MMP >0.9. Thus, reservoirs for which P/MMP <0.9 were also deemed as not suitable for CO_2-flood EOR. The unsuitable reservoirs become available for geological storage of CO_2 only after they are “depleted” using primary and other secondary recovery methods, if applicable.

The reservoirs suitable for EOR using CO_2 flooding have various degrees of suitability, depending on the intrinsic reservoir and oil characteristics. The range of reservoir and fluid properties suitable for CO_2 miscible injection is quite wide; however, ideal reservoirs should have oil API gravity >27^o (light oils with density <900 kg/m^3), oil saturation S_o >25%, reservoir pressure >7.6 MPa and ideally 1.4 MPa (200 psi) higher than the minimum miscible pressure (MMP) at the time of CO_2 injection, porosity >15% and permeability >1 md (10^{-15} m^2). Immiscible CO_2 flooding is much less common; nevertheless it has being applied to heavy and medium oils (10-25^o API; 900-1000 kg/m^3 density) and in-situ viscosities of 100 to 1000 mPa·s (cp). Thus, some oil reservoirs will be better suited, hence more economic, than others, for CO_2 flooding, and these reservoirs should be used first for CO_2 storage. Of course, the final ranking and choice of oil reservoirs for CO_2 storage depends also on extrinsic conditions, such as surface facilities, source and cost of CO_2 and other economic considerations.

Using various criteria for the application of CO_2 miscible and immiscible flooding (Lewin and Associates Inc., 1976; Klins and Farouq Ali, 1982; Taber et al., 1997; Thomas, 1998), the oil reservoirs suitable for EOR can be ranked using parametric optimization methods (Rivas et al., 1994; Diaz et al., 1996). The ranking method is based on determining for each reservoir property a corresponding normalized parameter by comparison with fictitious best (optimum) and worst (not suited) reservoirs for EOR operations. The effect of normalization is that it transforms reservoir and fluid properties that vary in various ranges and have different physical meaning and units, into new dimensionless variables that vary linearly between 0 and 1, which can subsequently be added to produce a score used in reservoir ranking. The relative importance of each reservoir parameter is taken into account by using different weigthing factors, of which the highest is assigned to oil gravity, and the lowest to reservoir porosity (Diaz et al., 1996). The scores obtained using this parametric optimization method vary between 1 and 100, with 100 representing the best possible reservoir for CO_2-flood EOR for a given set of weighting factors. The optimum reservoir values for CO_2 EOR operations are based on the results of numerical reservoir simulations by Rivas et al. (1994). The minimum miscibility pressure (MMP), which is one of the screening and ranking criteria, can be estimated using the National Petroleum Council method (1976). Previous screening methods for CO_2 flooding were designed with the purpose of maximizing oil recovery and screening out of uneconomic reservoirs (e.g., Taber et al., 1998; Thomas, 1998; Edwards, 2000), while the screening and ranking methodology developed here, although similar, has the objective of maximizing CO_2 storage in oil reservoirs, identifying at the same time potential economic benefits. Application of this method for CO_2 flooding in EOR operations provides an indication as to which reservoirs should be considered first in the context of maximizing the economic benefit of CO_2 storage.

The process of screening and ranking of oil reservoirs for EOR and CO_2 storage based on the transform of the geological space into the CO_2-phase space and on reservoir suitability for CO_2-flooding is presented graphically in the flowchart of Figure 1. The process is entirely based on geoscience and reservoir-engineering in the sense that only reservoir and fluid properties are considered. Other technical, engineering and economic criteria can be added, or overlain, to provide industry with a tool for site selection for CO_2 storage in EOR operations in oil reservoirs.

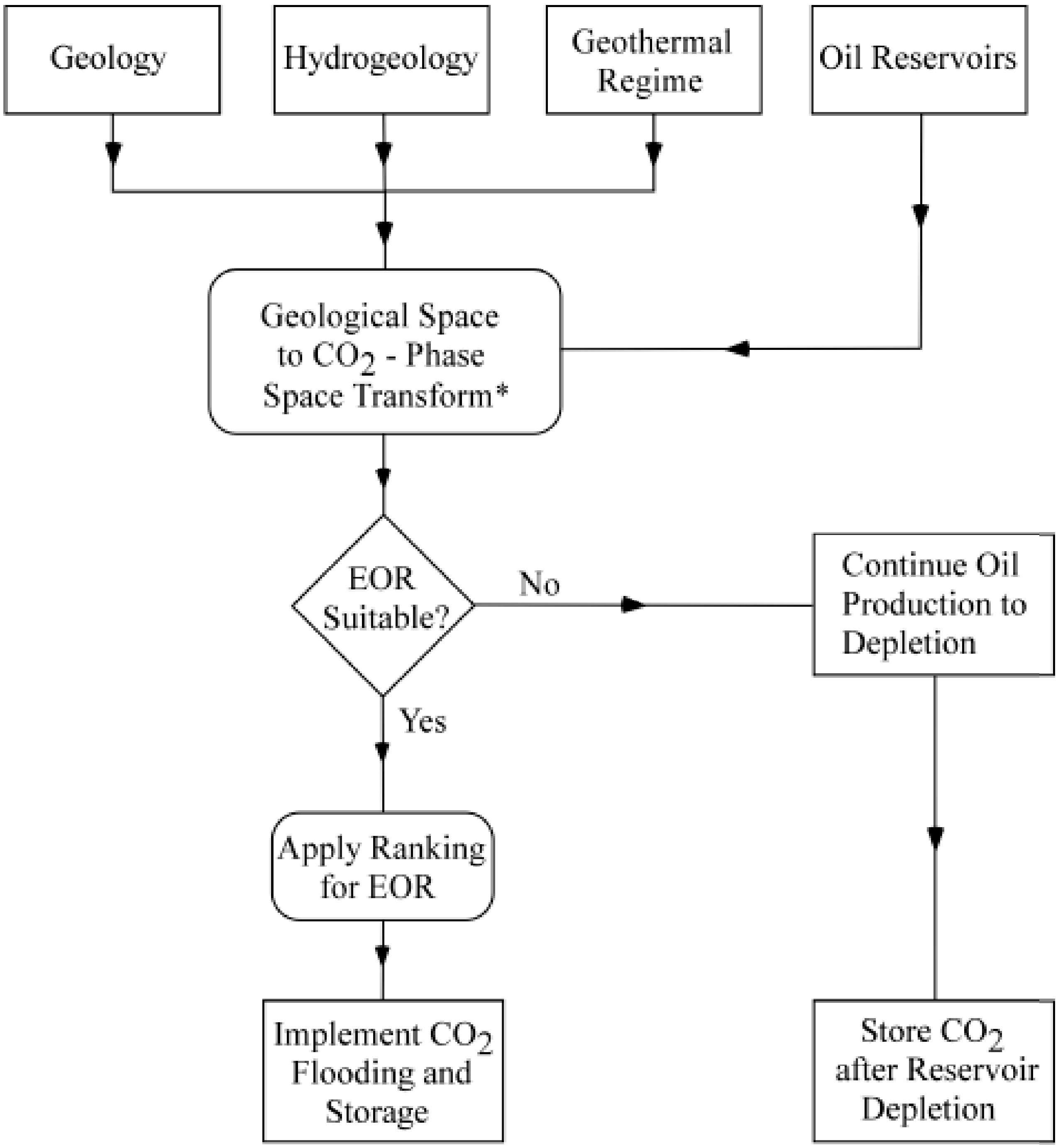

Figure 1: Diagrammatic representation of the process of screening and ranking of oil reservoirs for CO_2 - flood EOR and CO_2 storage (* for details see Bachu, 2001b)

Application

The method developed for the screening and ranking of oil reservoirs for CO_2 storage (Shaw and Bachu, 2001) was applied to the oil fields of the sandstone Viking Formation in the Alberta basin (Figure 2). This formation was chosen because there is already a miscible CO_2 flood operation at Joffre (Stephenson et al., 1993). Approximately 90 oil fields, the largest at Provost with 93.6×10^6 m^3 original oil in place (OOIP), and containing 331 pools, are found in the Viking Formation. According to the records of the Alberta Energy and Utilities Board, the original oil in place (OOIP) in the Viking Fm. is 328.9×10^6 m^3, of which 45.33×10^6 m^3 are primary initial reserves, and 16.88×10^6 m^3 are enhanced initial reserves. To date, 11.6×10^6 m^3 of oil have been produced from the Viking Fm. The following are the characteristics of Viking oil reservoirs relevant for the screening and ranking process:

Reservoir Characteristics	Minimum	Maximum
API Gravity	16	53
Oil Saturation (%)	0.49	1.00
Temperature (deg. C)	20	108
Initial Pressure P (MPa)	3.56	46.16
MMP (kPa)	8.27	28.94
P/MMP	0.13	3.94
Porosity (%)	0.02	0.33
Av. Pay Thickness (m)	0.46	24.8

Temperatures and pressures in the deep southwestern part of the Viking Fm. are both higher than the supercritical point for CO_2 (Figure 2). Many oil fields, including some of the largest, such as Caroline, Gilby, Crystal and Joffre, are found in this region. In the regions where $T<31.1^oC$ and $p>7.38$ MPa CO_2 will be in liquid state, while if $T>31.1^oC$ and $p<7.38$ MPa, then CO_2 will remain a gas (Figure 2). Conditions in the eastern, shallower part of the basin are such that CO_2 will be a gas. Based on the transform from the geological space to the CO_2-phase space, 98 reservoirs in the Viking Fm. were eliminated as being not suitable for tertiary recovery because of low temperature and/or low pressure. Oil fields in the eastern, shallow part of the basin, including some of the largest such as Provost, Kerrobert, Smiley and Cessford (Figure 2), are not suitable for CO_2-flood EOR operations. Another 27 reservoirs are not suitable for CO_2 flooding because of low P/MMP ratios. The 125 reservoirs not suitable for EOR CO_2 storage had initial oil reserves of 26.2×10^6 m^3. After depletion, the pore space in these reservoirs can be used for CO_2 storage. The 206 reservoirs suitable for CO_2 flooding, including the very large Caroline, Crystal, Joffre and Gilby fields (Figure 2), and ranking in absolute score between 27.62 and 77.52, had primary and enhanced initial oil reserves of 25.6×10^6 m^3 and 10.5×10^6 m^3, respectively. Considering the net efficiency of CO_2 storage in EOR operations (e.g., Holt et al., 1995), some $11{,}294 \times 10^6$ Sm^3 CO_2, or 21.45 Mt CO_2 can be stored in Viking Fm. oil reservoirs in the Alberta basin while recovering oil that produces an economic benefit that offsets the cost of storing CO_2.

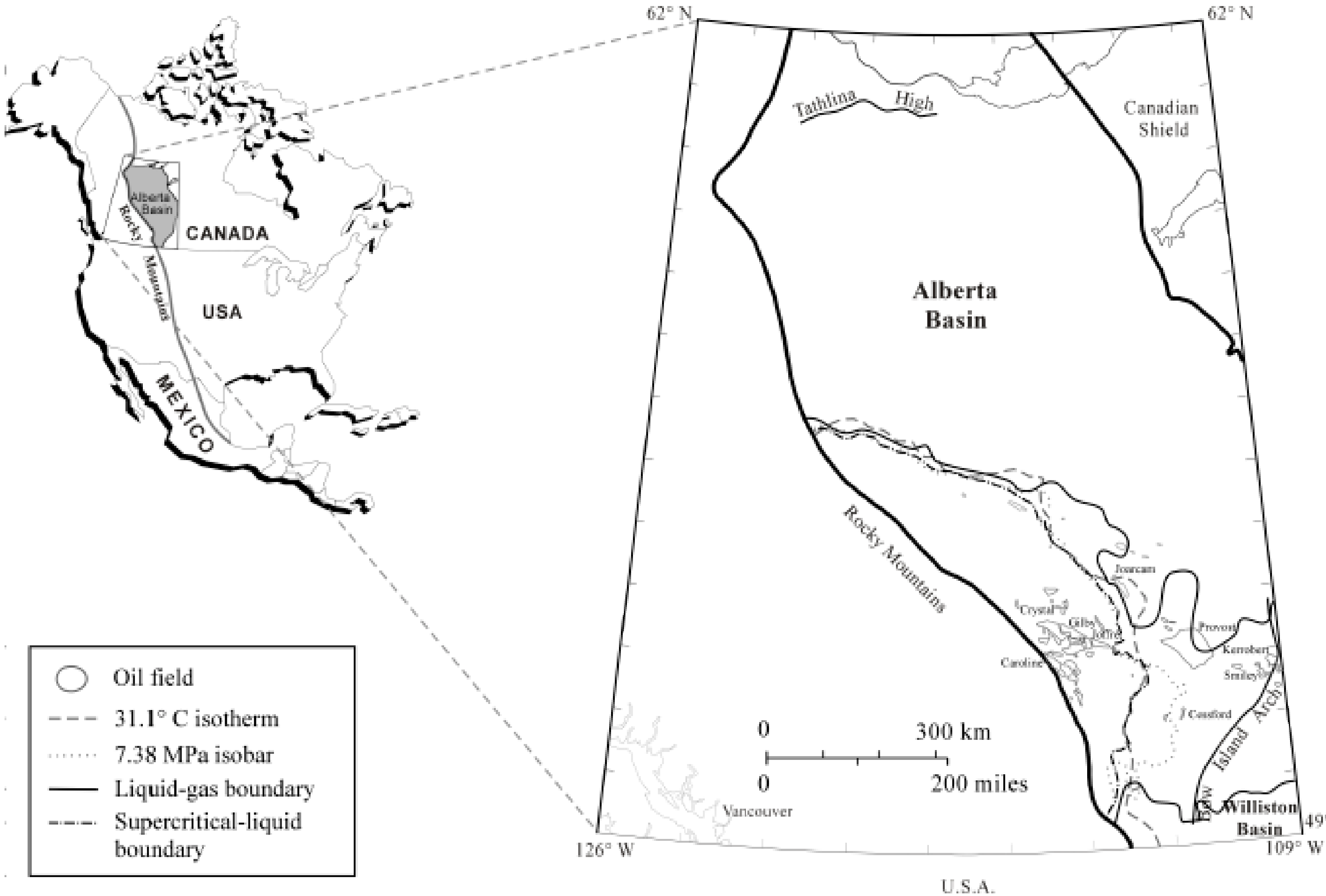

Figure 2: Position of the 31.1°C isotherm, 7.38 MPa isobar, and CO_2 phase boundaries and location of oil reservoirs in the Viking Formation in the Alberta Basin.

Conclusions and Future Work

Geological storage of CO_2 is an immediately-available means of reducing CO_2 emissions into the atmosphere from major point sources, which is particularly suited to landlocked sedimentary basins. Among the issues that need addressing is the selection of potential sites, means of sequestration and capacity evaluation based on in-situ characteristics and CO_2 properties and behavior at these specific conditions.

The geological space in each sedimentary basin can be transformed into the CO_2-phase space using data that are usually collected by the energy industry. The CO_2 space can then be mapped and used for the identification of sites with significant storage capacity, and of unsafe sites because of CO_2 phase instability or potential migration and escape. In the case of oil reservoirs, application of this space transform, together with an additional criterion of CO_2 miscibility, provides a powerful tool for screening out reservoirs that are not suitable for CO_2-flood EOR, and identification of the CO_2-storage capacity of the reservoirs that are suited. In addition, application of a ranking system based on parametric optimization methods provides an indication of a reservoir relative suitability. Surface engineering and economic criteria should be applied to this geoscience-and-engineering based reservoir ranking, to select the best sites for geological storage of CO_2. The methodology developed and applied on 331 oil pools in the Viking Fm. in the Alberta basin will be applied to the more than 10,000 pools in the basin to identify all the reservoirs suitable for CO_2 flooding and estimate their storage capacity as a result of EOR operations.

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