Screening and ranking of sedimentary basins for sequestration of CO_2 in geological media in response to climate change

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Abstract Sedimentary basins are suitable to different degrees for CO_2 geological sequestration as a result of various intrinsic and extrinsic characteristics, of which the geothermal regime is one of the most important. Warm basins are less favorable for CO_2 sequestration than cold basins because of reduced capacity in terms of CO_2 mass, and because of higher CO_2 buoyancy, which drives the upward CO_2 migration. A set of 15 criteria, with several classes each, has been developed for the assessment and ranking of sedimentary basins in terms of their suitability for CO_2 sequestration. Using a parametric normalization procedure, a basin's individual scores are summed to a total score using weights that express the relative importance of different criteria. The total score is ranked to determine the most suitable basin or region thereof for the geological sequestration of CO_2. The method is extremely flexible in that it allows changes in the functions that express the importance of various classes for any given criterion, and in the weights that express the relative importance of various criteria. Examples of application are given for Canada's case and for the Alberta basin in Canada.

Keywords Canada · CO_2 geological sequestration · Screening and ranking · Sedimentary basins

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Introduction

As a result of anthropogenic carbon dioxide (CO_2) emissions, atmospheric concentrations of CO_2, a major greenhouse gas, have risen from pre-industrial levels of 280 to 360 ppm, primarily as a consequence of fossil fuel combustion for energy production (Bryant 1997). Increasing concentrations of CO_2 affect the Earth–atmosphere energy balance, enhancing the natural greenhouse effect and thereby exerting a warming influence at the Earth's surface. The changes anticipated during the next few hundred years are well within the range experienced during the Pleistocene Era, and the rates of change projected for the next 100 years are no more rapid than those experienced on half-century scales, but the magnitudes may be significant (Jenkins 2001). Although the detailed response of the climate system is uncertain because of its inherent complexity and natural variability, the close coupling between the carbon cycle and climate suggests that a change in the former will be accompanied by a change in the latter (AGU 1999). Because of uncertainties regarding the Earth's climate system, there is much public debate over the extent to which increased concentrations of greenhouse gases have caused or will cause climate change, and over potential actions to limit and/or respond to climate change. Planetary cooling forces that are intensified by warmer temperatures and by strengthening of biological processes, which would be enhanced by the same rise in atmospheric CO_2 concentrations, may cancel the predicted climate warming (Idso 2001). Nevertheless, there is almost general acceptance that the world cannot wait for definitive answers on this subject and that preventive and mitigating actions have to take place concurrently.

Reducing anthropogenic CO_2 emissions into the atmosphere in response to global climate change involves basically three approaches, expressed best by examination of the following relation between carbon emissions (C), energy (E) and economic growth as indicated by the gross domestic product (GDP):

$$\text{Net C} = \text{GDP} \times \text{E/GDP} \times \text{C/E} - \text{S} \quad (1)$$

where E/GDP is the "energy intensity" of the economy, C/E is the "carbon intensity" of the energy system, and S

represents carbon removed from the atmosphere (carbon sinks).

Historical evidence shows that, on aggregate, the emissions intensity (*C/GDP*) decreased continuously since the beginning of the industrial revolution, the carbon removed from the atmosphere (*S*) decreased slightly as a result of deforestation and agricultural practices, but the net carbon emissions (*C*) increased, mainly as a result of the increase in economic growth (*GDP*) at a faster rate than the decrease in emissions intensity. Since the GDP is increasing, except maybe for short-duration, local, situations caused by economic and/or political collapse, a reduction in net CO_2 emissions into the atmosphere can be achieved by: (1) lowering the energy intensity of the economy E/GDP (i.e., increase the efficiency of primary energy conversion and end use); (2) lowering the carbon intensity C/E of the energy system by substituting lower-carbon or carbon-free energy sources for the current sources; and (3) by artificially increasing the capacity and capture rate of carbon sinks. However, short of revolutionary, large-scale new technological advances and major expenditures, the energy intensity of the economy will continue to decrease at a lower rate than the rate of GDP increase and mitigation strategies will have a limited impact (Turkenburg 1997). Similarly, fossil fuels, which currently provide more than 75% of the world's energy, will likely remain a major component of world's energy supply for at least this century (Jepma and Munasinghe 1998; Bajura 2001) because of their inherent advantages, such as availability, competitive cost, ease of transport and storage, and large resources. Thus, the carbon intensity of the energy system is not likely to decrease in any significant way in the medium term. This leaves the increase of carbon sinks S and of their capture rate in a significant way as the single major means of reducing net carbon emissions into the atmosphere in the short term, although it is recognized that no single category of mitigation measures is sufficient (Turkenburg 1997). Any viable carbon sink must be safe, environmentally benign, effective, economic and acceptable to the public.

Large, natural CO_2 sinks are terrestrial ecosystems (soils and vegetation) and oceans with retention times of the order of 10–10^5 years, respectively (Gunter and others 1998). Terrestrial ecosystems and the ocean surface represent a diffuse natural carbon sink that captures CO_2 from the atmosphere after release from various sources. The capacity, but not the capture rate, of terrestrial ecosystems can be increased by changing forestry and agricultural practices. However, population increase and other land uses compete with expanding these natural CO_2 sinks. The natural, diffuse and slow exchange of CO_2 between the atmosphere and oceans can be artificially enhanced at concentrated points by injecting CO_2 at great depths where it will form either hydrates or heavier-than-water plumes that will sink at the bottom of the ocean (Aya and others 1999). However, ocean disposal involves issues of poorly understood physical and chemical processes, sequestration efficiency, cost, technical feasibility and environmental impact, while the technology of disposing of CO_2 from either ships or deep pipelines is only in the development stage. In addition, ocean circulation and processes may bring to the fore legal, political and international limitations to large-scale ocean disposal of CO_2.

In contrast, the geological storage and/or sequestration of CO_2 currently represent the best short-to-medium term option for significantly enhancing CO_2 sinks, thus reducing net carbon emissions into the atmosphere. In this context, the meaning is the *removal of CO_2 directly from anthropogenic sources (capture) and its disposal in geological media, either permanently (sequestration), or for significant time periods (storage)*.

The carbon dioxide disposal in geological media, more specifically in sedimentary basins, does not compete with agriculture, fishing, other industries and land use. The technology for the deep injection of CO_2, acid gases (CO_2 and H_2S) and industrial liquid waste is well developed and currently practiced mainly by the energy and petrochemical industries (e.g., Gale and others 2001; Moritis 2002; Tsang and others 2002; Bachu and Gunter 2003). Generally, there are no associated environmental problems unless there is significant leakage, and it can be safely undertaken within national boundaries, thus avoiding potential international issues. Fossil fuels and power generation are intrinsically and serendipitously linked with sedimentary basins (Hitchon and others 1999), consequently lowering overall transportation costs. Thus, while the CO_2 capture from anthropogenic sources still poses some technological challenges because of its high cost, the issues related to CO_2 disposal in geological media strictu-senso are not technological, but rather fall into the following categories (Bachu 2002): (1) geoscience (site selection, capacity and safety); (2) economic (cost, fiscal and taxation policy, credits); and (3) public (perception and acceptance).

Carbon dioxide can be sequestered in geological media by geological (stratigraphic and structural) trapping in depleted oil and gas reservoirs, solubility trapping in reservoir oil and formation water, adsorption trapping in uneconomic coal beds, cavern trapping in salt structures, and by mineral immobilization (Fig. 1) (Blunt and others 1993; Gunter and others 1993, 1997; Hendriks and Blok 1993; Dusseault and others 2002). Use of CO_2 in enhanced oil and gas recovery (EOR and EGR; Holtz and others 2001; Koide and Yamazaki 2001) and in enhanced coalbed methane recovery (ECBMR; Gunter and others 1997; Gale and Freund 2001), and hydrodynamic trapping in deep aquifers (Bachu and others 1994) represent actually forms of CO_2 geological storage with retention times of a few months to potentially millions of years, depending on flow path and processes. In all cases of enhanced recovery of hydrocarbons, CO_2 ultimately breaks through at the producing well and has to be separated and recirculated back into the system, thus reducing the storage and sequestration capacity and efficiency of the operation, notwithstanding the additional CO_2 produced during the separation and compression stages. However, the economic benefits of incremental oil and gas production make EOR, EGR, and ECBMR operations most likely to be implemented first.

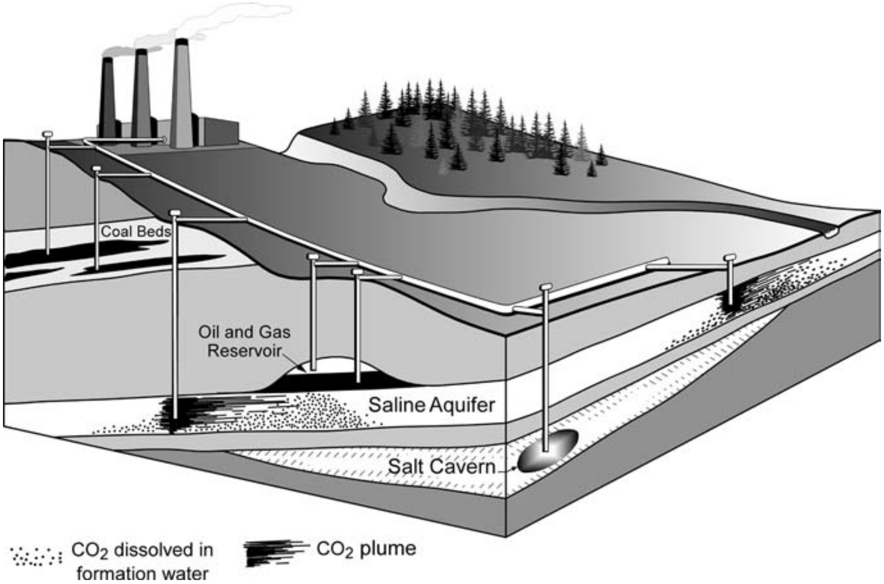

Fig. 1
Diagrammatic representation of various means of CO_2 sequestration or storage in geological media

Only sedimentary basins contain geological media generally suitable for CO_2 storage and/or sequestration: oil and gas reservoirs (geological and solubility trapping), deep sandstone and carbonate aquifers (solubility, hydrodynamic and mineral trapping), coal beds (adsorption storage and trapping), and salt beds and domes (cavern trapping). In addition, these media have both the space (porosity) and injectivity (permeability) necessary for CO_2 injection, and, by and large, have the ability to either prevent or delay for geologically significant periods of time the CO_2 return to the atmosphere. Crystalline and metamorphic rocks, such as granite, on continental shields, are not suitable for CO_2 storage and sequestration because they lack the porosity and permeability needed for CO_2 injection, and because of their fractured nature. Volcanic areas and orogenic belts (mountains) are also unsuitable mainly because they lack capacity and are unsafe. Fortunately and serependitously, sedimentary basins are also where fossil energy resources are found, produced and, by and large, used for power generation (Hitchon and others 1999).

There are more than 800 sedimentary provinces in the world (St John and others 1984) distributed on and along continents (Fig. 2), however, they are variously suited for CO_2 storage and sequestration. The first step in the process of site selection for CO_2 sequestration is the basin- and regional-scale suitability assessment (Bachu 2002), to identify the best sedimentary basins or regions thereof. A series of suitability criteria were previously developed (Bachu 2000, 2002), which can be broadly classified into:

1. Basin characteristics, such as tectonism, geology and geothermal and hydrodynamic regimes (these are "hard" criteria because they do not change).
2. Basin resources (hydrocarbons, coal, salt), maturity and infrastructure (these "semi-hard" or "semi-soft" criteria because they may change with new discoveries, technological advances and/or economic development).
3. Societal, such as level of development, economy, political structure and stability, public education and attitude (these are "soft" criteria because they can rapidly change or vary from one region to another).

The first two categories were qualitatively applied for the regional-scale assessment of the Western Canada Sedimentary Basin, where, within the same basin, regions vary from not suitable near the shallow basin edge, to very suitable near the Rocky Mountains (Bachu and Stewart 2002). The third category of criteria applies uniformly across the basin, and scores at the top, such that it did not provide a differential factor. Similarly, the sedimentary basins in Australia were assessed in the GEODISC program in terms of their potential for geological sequestration of CO_2 (Bradshaw and Rigg 2001; Bradshaw and others 2002). However, the Australian suitability assessment went a step further by considering much more specific data and information, such as storage capacity and injectivity potential (estimated based on porosity and permeability), specific CO_2 source location, sequestration site characteristics, and economic and risk factors (Bradhsaw and others 2002). The information used in the analysis and selection of Australian basins generally is either not available or it requires significant effort and resources for processing. The suitability criteria developed and applied to the Western Canada Sedimentary Basin can be expanded to include other factors that can be assessed in a qualitative manner without requiring specific and detailed information that needs significant processing, and can be applied in a quantitative algorithm for the identification, ranking and selection of best-suited sedimentary basins or regions thereof for geological storage and sequestration of CO_2. This methodology is particularly applicable in the case of large, continental-scale countries such at the US, Canada, Australia, Russia, Brazil, Argentina, China, and India, with several sedimentary basins within their territory and territorial waters, but it can be applied also to the case of smaller countries and/or regions, and to the regional-scale analysis of a single, large sedimentary basin where significant variability exists in one or more of the characteristics used as assessment criteria.

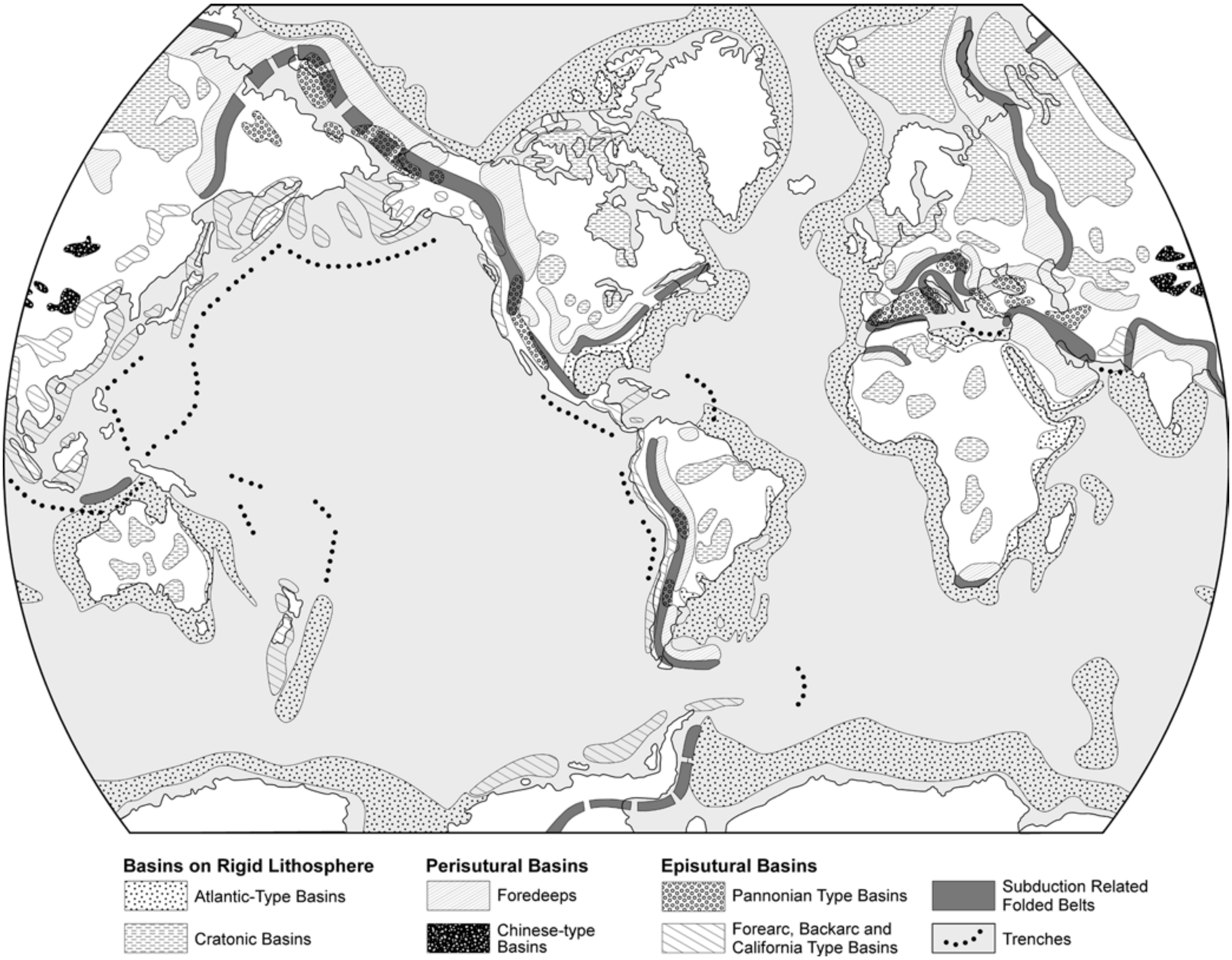

Fig. 2
Major types and distribution of sedimentary basins around the world (produced based on St. John and others 1984)

Geothermal effects on CO_2 storage and sequestration

In developing some of the criteria for suitability assessment, the phase behavior and variation of CO_2 properties with temperature and pressure, hence with depth, is one of the most important elements. At normal atmospheric conditions, CO_2 is a thermodynamically very stable gas heavier than air (density of 1.872 kg/m^3). For temperatures greater than T_c=31.1 °C and pressures greater than P_c=7.38 MPa (critical point), CO_2 is in a supercritical state (Fig. 3). At these pressure and temperature conditions, CO_2 behaves still like a gas by filling all the available volume, but has a "liquid" density that increases, depending on pressure and temperature, from 150 to >800 kg/m^3 (Fig. 4). Subcritical CO_2 is either a gas or a liquid, depending on temperature and pressure (Fig. 3). The higher the density of CO_2, the more efficiently the pore space can be used to sequester or store CO_2 as a separate phase. In addition, buoyancy forces, which would drive

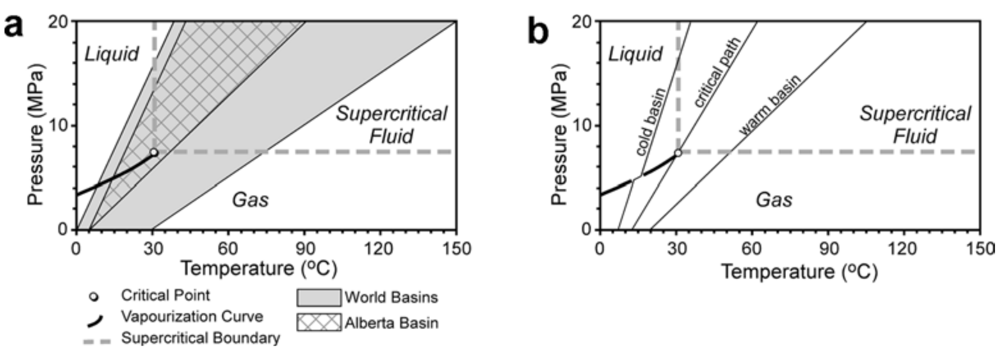

Fig. 3
Phase behavior of CO_2 for conditions characteristic of sedimentary basins: **a** phase envelope for worldwide conditions, and for the Alberta basin, Canada, in particular; and **b** loci of CO_2 in the P–T space for various conditions of surface temperature T_s and geothermal gradient G, assuming hydrostatic pressure conditions

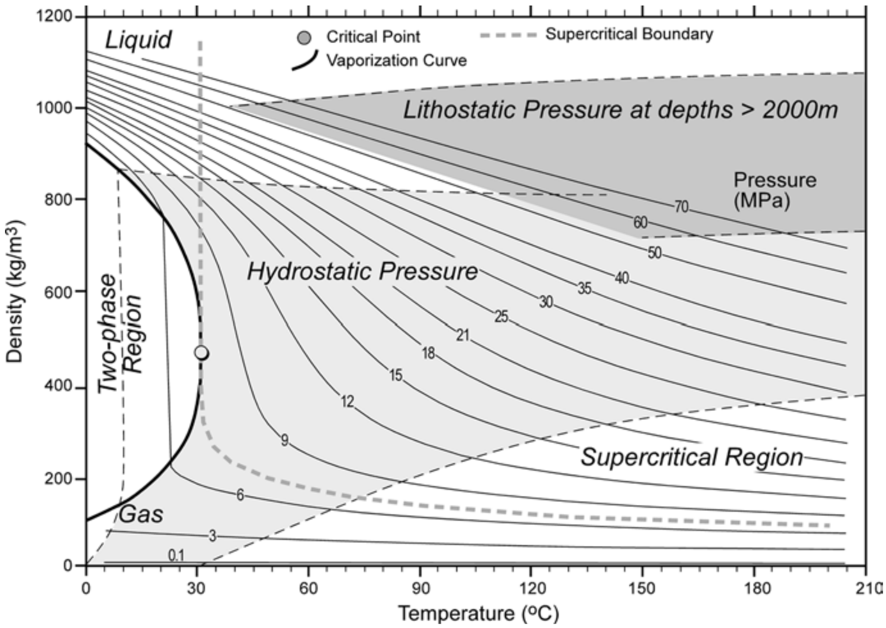

Fig. 4
Variation of CO_2 density as a function of temperature and pressure, showing the range of density that would be encountered in sedimentary basins around the world for various surface temperatures and geothermal gradients, assuming hydrostatic and lithostatic pressure conditions

CO_2 upward and updip, decrease with increasing CO_2 density. Thus, to increase the efficiency and safety of geological sequestration or storage, it was previously deemed necessary to inject CO_2 at depths greater than 800 m, where supercritical conditions would be met assuming a hydrostatic pressure gradient and a geothermal gradient of 25 °C/km (Holloway and Savage 1993). However, the depth at which CO_2 supercritical conditions are met is highly variable, depending on surface temperature and geothermal gradients (Bachu 2000, 2002). Even within a single basin this depth can vary significantly, as in the case of the Western Canada Sedimentary Basin, where it varies from <700 m in the north, where geothermal gradients reach 50 °C/km, to >1,200 m in the south, where geothermal gradients are in the 20 °C/km range (Bachu and Stewart 2002).

The hydrostatic variation of pressure with depth is described by:

$$P = \rho_w g z \qquad (2)$$

where ρ_w is water density, g is the gravitational constant, and z is depth. In most sedimentary basins pressure conditions are hydrostatic or close to it, such that, for the purpose of this analysis, this assumption is sufficient. For lithostatic conditions, the water density is replaced in relation (2) by the density of the water-saturated overburden. For a given surface temperature T_s and geothermal gradient G, temperature T varies with depth according to:

$$T = T_s + Gz \qquad (3)$$

Thus, the CO_2 phase behavior in a sedimentary basin is described by the linear relation:

$$P = \frac{\rho_w g}{G}(T - T_s) \qquad (4)$$

Considering that surface temperatures vary between ~0 °C for arctic and sub-Arctic basins (actually it may reach −2 °C at the base of the permafrost and of glaciers) and ~30 °C for low-altitude tropical basins, and assuming hydrostatic pressure gradients and typical geothermal gradients that vary between 20 and 60 °C/km, a general envelope of CO_2 phase behavior in sedimentary basins can be identified using relation (4) (Fig. 3a). Because geothermal gradients vary also within sedimentary basins, basin-specific CO_2-phase envelopes can be constructed, as illustrated in Fig. 3a for the Alberta basin.

A similar envelope for the range of conditions encountered in worldwide sedimentary basins can be constructed for CO_2 density (Fig. 4). The "density envelope" shows that the maximum CO_2 density that can be attained in normally pressured sedimentary basins is ~850 kg/m^3, and that greater pressures, i.e., depths, are needed to reach high CO_2 density in warm basins than in cold basins, with corresponding increasing costs for injection. Overpressures, sometimes approaching lithostatic, are generated and maintained in some sedimentary basins at great depths, usually >2,000 m, as a result mainly of disequilibrium compaction, transformation of gypsum to anhydrite, and/or gas generation (Osborne and Swarbrick 1997). This is the case, for example, of compacting basins on the continental shelf, such as Beaufort, Nova Scotian Shelf, and the Gulf (e.g., Hitchon and others 1990; Rogers and Yassir 1993; Ortoleva 1994). In such cases, higher CO_2 densities can be achieved, up to 1,060 kg/m^3 (Fig. 3), but the cost of injection and safety issues may prohibit using overpressured zones as CO_2 sequestration targets.

At a given location, where T_s is known, and the variations of pressure P and geothermal gradient G with depth z are also known, the locus of CO_2 in the P–T space can be constructed. For the purpose of this analysis P is considered hydrostatic and G is considered constant, in which case the locus of CO_2 is along a straight line which may or may not cross the CO_2 vaporization curve (Fig. 3b). If CO_2 injected at a certain depth, characterized by local P and T, migrates upward, it will cool and decompress along its physical path as the depth decreases, a process that is represented by a move down along a P–T trajectory in the CO_2 phase space. If the trajectory is to the right of the vaporization curve (Fig. 3b), CO_2 will just change phase from supercritical to compressed gas, and, if it reaches shallow depths and the surface, to gas at normal conditions, with potentially adverse effects on groundwater, vegetation and life, as is the case of natural CO_2 releases at Lake Nyasos in Cameroon in 1987 (Evans and others 1993) and at Mammoth Mountain in California (Farrar and others 1995). If the trajectory crosses the vaporization curve, CO_2 will change phase from liquid to gaseous with significant absorption of heat from the surrounding medium, to account for the needed latent heat of vaporization, which will result in local cooling. As CO_2 changes phase from liquid to gaseous, CO_2 moves in the two-phase region from the bubble curve to the dew curve (Fig. 4), as the gas saturation S_g increases from 0 to 100%. In the P–T space, the CO_2 trajectory follows the vaporization curve until the phase change to gaseous is complete, after which it returns to the (linear) downward movement as depth decreases (Fig. 3b).

In some instances it is possible for the CO_2 trajectory in the P–T space to pass through the CO_2 critical point (T_c, P_c; Fig. 3b). This may happen for a wide combination of surface temperature and geothermal gradients values that satisfy relation (4) for P=P_c and T=T_c. In the context of CO_2 sequestration or storage in geological media, the surface temperatures and geothermal gradients that lead to CO_2 passing through the critical point (T_c, P_c) are henceforth called "critical geothermal characteristics". Analysis of relation (4) shows that a critical surface temperature T_s^c exists only if G<42 °C/km. Conversely, a critical geothermal gradient G^c exists only if T_s<16 °C. For G>=42 °C/km or T_s>=16 °C the CO_2 trajectory in the P–T space will always be to the right of the critical point (Fig. 3b), i.e., CO_2 will change phase from supercritical to gaseous as it moves upwards. For G<42 °C/km and T_s<16 °C, the trajectory will be from supercritical to gaseous if, for a given geothermal gradient, T_s is greater than the critical surface temperature T_s^c that corresponds to that geothermal gradient, or if, for a given surface temperature, G is greater than the corresponding critical geothermal gradient G^c. Otherwise CO_2 will change phase from supercritical to liquid and then from liquid to gaseous across the vaporization curve (Fig. 3b) through the two-phase region (Fig. 4).

Representative curves of CO_2-density variation with depth, based on the temperature and pressure increase with depth, can be constructed for each basin or region thereof by transforming the geological space into the CO_2 phase space (Bachu 2002). The effect of geothermal conditions, T_s and G, on CO_2 behavior in the geological space is illustrated in Fig. 5. For conditions, henceforth defined as "warm", where the corresponding CO_2 trajectory in the P–T space is to the right of the critical point, CO_2 density always increases with depth, at the beginning rapidly as a result of pressure effects, after which strong temperature effects on density (Fig. 4) counteract pressure effects, such that the density increase with depth is very small (Fig. 5). For the same depth, the density of CO_2 decreases as either the geothermal gradient or surface temperature increases. For opposite geothermal conditions, henceforth defined as "cold", where the corresponding CO_2 trajectory in the P–T space crosses the vaporization curve and liquid CO_2 exists, CO_2 density variation with depth has generally a different behavior. Temperature effects on density are stronger than pressure effects, such that in most, but not all cases, CO_2 density actually decreases with depth, or remains almost constant, as illustrated in Fig. 5a for the case of G=25 °C/km and T_s<T_s^c=12.27 °C. Figure 5b illustrates the same concept for the case of sedimentary basins where T_s=5 °C, like in temperate-to-sub-Arctic regions, and various possible geothermal gradients. The CO_2 density variation with depth is different for the cases when CO_2 passes through a liquid phase (G<G^c=34.7 °C/km), actually it decreases or is almost constant with increasing depth, from the cases when CO_2 passes directly from supercritical to gaseous (G>G^c), in which case density increases with depth (Fig. 5b).

The variation of CO_2 density with depth has implications for both CO_2 storage or sequestration and CO_2 flow and fate. The lack of a significant increase in the density of CO_2 below certain depths in warm basins, and the actual decrease in the case of cold basins, suggests the existence of an optimum depth for CO_2 sequestration in free phase (i.e., not dissolved in formation water or reservoir oil). For the same available pore or cavern space, the sequestration or storage capacity increases with increasing CO_2 density, hence the optimum depth is that depth that maximizes this capacity while, at the same time, minimizes the cost of well drilling and CO_2 compression and injection to that depth. Figure 5b suggests that the optimum depth varies from 800–1,000 m for cold basins to 1,500–2,000 m for warm basins. For cold basins, any depth greater than that is going to be less efficient and more costly. For warm basins, a marginal increase in capacity will probably be offset by higher costs and likely higher CO_2 emissions during CO_2 compression to attain these depths, such that the net incremental gain in sequestered CO_2 may be very small or null. In reality, the minimum, optimal and maximum injection and sequestration depths will be determined by other factors, such as basin characteristics, CO_2 confinement, and drilling, injection and monitoring costs. As a result, the maximum sequestration or storage depth will most likely be limited to several kilometers.

Besides effects on capacity, the "cold" or "warm" nature of a sedimentary basin has significant effects on the phase and flow behavior of free CO_2 (Bachu 2002). The phase and density envelopes for CO_2 in sedimentary basins (Figs. 3 and 4) and the variation of CO_2 density with depth (Fig. 5) show first that the upward buoyancy forces acting on CO_2 will be much stronger in warm basins than in cold basins. This is because the CO_2 density is lower in the former, resulting in a larger difference between the density of the injected CO_2 and that of formation water (brines), which varies between ~1,000 and 1,300 kg/m^3, depending on

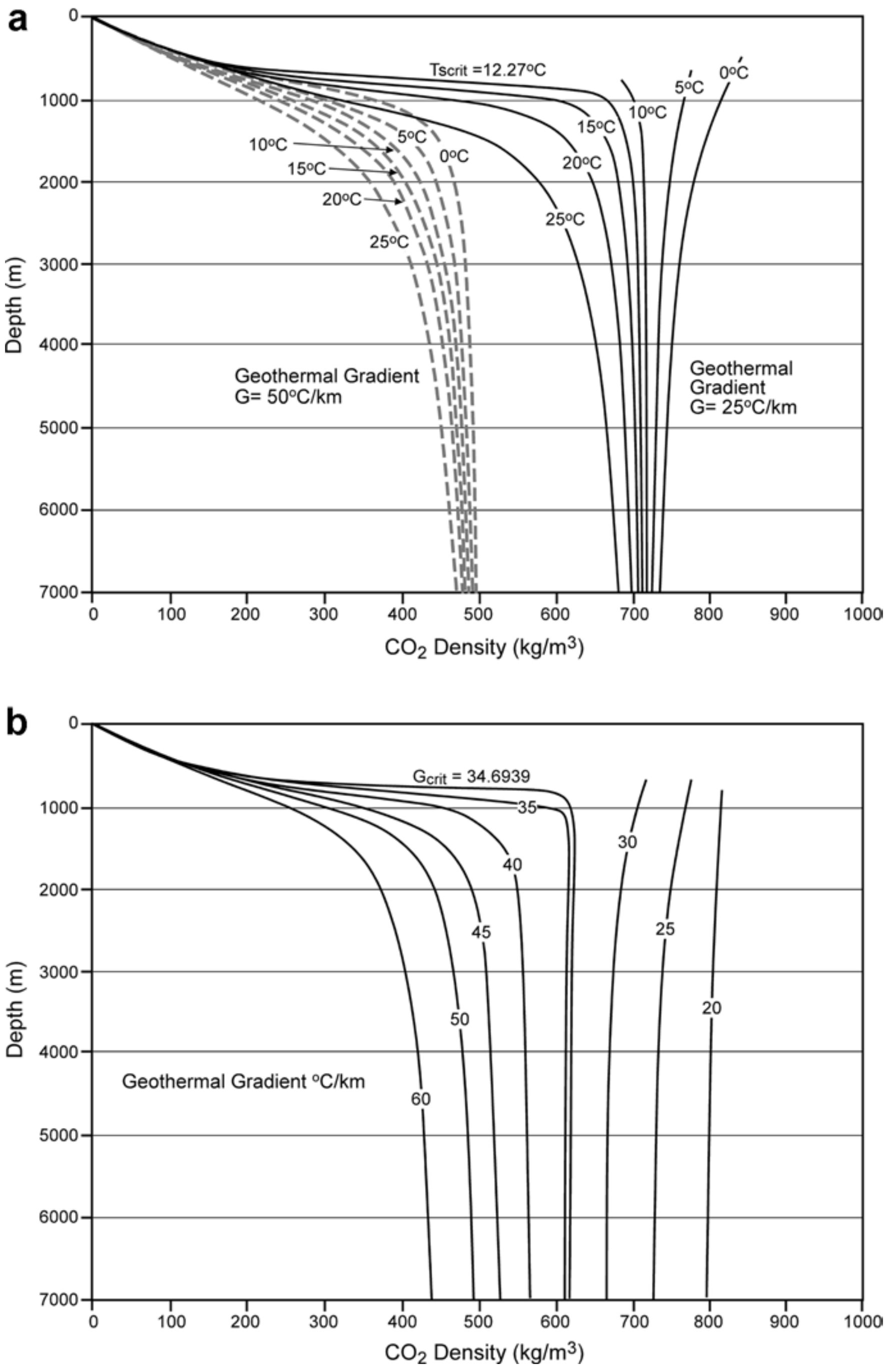

Fig. 5
Variation of CO_2 density with depth in sedimentary basins: **a** assuming hydrostatic pressures and various surface temperatures T_s and geothermal gradients representative of "cold" and "warm" basins; and **b** for T_s=5 °C and a range of possible geothermal gradients

salinity (Adams and Bachu 2002). Second, in warm basins, as CO_2 decompresses when it moves upward and pressure and temperature decrease, its density decreases continuously, enhancing its buoyancy in a self-accelerating, auto-reinforcing process. In cold basins, CO_2 density increases slightly as it moves upward as long as it is supercritical or liquid; thus, buoyancy will remain generally constant or will slightly decelerate. This difference in flow behavior may become significant in terms of CO_2 upward flow and potential leakage to the surface. Of course, once CO_2 becomes gaseous in either case, these major differences disappear, although its density will still be lower in the case of warm basins than in the case of cold basins. Thus, buoyancy and its gradient are comparatively weaker in cold sedimentary basins than in warm basins, decreasing the flow drive and increasing the sequestration safety.

Basin-scale criteria for CO_2 storage and sequestration

The significant effect of the geothermal regime in a sedimentary basin on the capacity and safety of CO_2 sequestration and storage operations indicates the need to introduce climatic conditions, hence surface temperature, geothermal conditions, and depth as separate criteria for the ranking and selection of sedimentary basins for CO_2 injection. Climatic conditions express also in an indirect way difficulties or lack thereof with regard to developing the necessary infrastructure for CO_2 capture, transportation, and injection. Also, depending on the geothermal regime in a basin, an optimum depth range for CO_2 sequestration and storage can be identified in each basin, for which the capacity is maximized through maximizing CO_2 density, while the costs for drilling, compression, and injection are minimized. For shallower depths, CO_2 sequestration and storage is inefficient (low CO_2 density) and/or unsafe because of very high CO_2 buoyancy. For greater depths, the cost of the operations increases without realizing a corresponding increase in sequestration or storage capacity, as a result of the leveling off of CO_2 density increase with depth or even decrease, depending on the basin type. Of course, the need for sequestration space and safety issues may require CO_2 injection deeper than the optimum depth range.

The on- or offshore location of a sedimentary basin is also an important criterion because of the implications regarding access and infrastructure, notwithstanding the level of exploration. Existing infrastructure and major CO_2 point sources make also a difference in that it allows for lower transportation costs. The effect of geothermal conditions on the capacity for and fate of CO_2 in sedimentary basins leads to a paradox. It is obvious that, for increased capacity and decreasing buoyancy, basins whose surface temperature is low, such as those in cold regions and offshore, are preferable to those on-shore in temperate-to-warm climates. However, from an operational point of view (CO_2 sources, infrastructure, access, etc.), the former would rank low compared with the latter. Thus, an overall ranking score would take these and other criteria into account, to arrive at a quantitative evaluation in terms of a basin's suitability for CO_2 sequestration. Table 1 presents a set of 15 criteria for the assessment and ranking of sedimentary basins in terms of their suitability for CO_2 sequestration or storage. These represent an expansion of the six criteria in the first two categories, basin characteristics and resources, introduced previously: geology, hydrodynamics, geothermics, oil and gas reservoirs, coal beds, and salt structures (Bachu 2000, 2002). The list can be expanded further if more criteria are developed.

In each category, three to five classes have been defined, listed in Table 1 from the least favorable to the most favorable for CO_2 sequestration or storage. Most of them are obvious, such as size and depth, or have been discussed previously, and, except for tectonic setting, do not require further explanation. Oceanic convergent basins (episutural forearc, back arc and California type; Fig. 2), such as circum-Pacific ones, are the least favorable because they are located in tectonically active areas, mostly along subduction zones where oceanic plates move toward and dip under continental plates. Convergent intramontane basins (also episutural; Fig. 2) are not very favorable, mainly because of structure (faulting and folding). Thus, for these basins the safety of CO_2 sequestration may become an issue, with a significant potential and risk for either catastrophic escape or significant continuous leakage of CO_2 to the surface. Divergent basins on the rigid lithosphere (cratonic and Atlantic-type; Fig. 2) are the most suited for CO_2 sequestration as a result of their stability and favorable structure (Bachu 2000). All circum-Atlantic, circum-Arctic and circum-Antarctic basins, around the Indian Ocean and Australia, and mid-continent basins, are of this type (Fig. 2). Perisutural basins, mainly foredeeps on the

Table 1
Criteria for assessing sedimentary basins for CO_2 geological sequestration

	Criterion	Classes				
		1	2	3	4	5
1	Tectonic setting	Convergent oceanic	Convergent intramontane	Divergent continental shelf	Divergent foredeep	Divergent cratonic
2	Size	Small	Medium	Large	Giant	
3	Depth	Shallow (<1,500 m)	Intermediate (1,500–3,500 m)	Deep (>3,500 m)		
4	Geology	Extensively faulted and fractured	Moderately faulted and fractured	Limited faulting and fracturing, extensive shales		
5	Hydrogeology	Shallow, short flow systems, or compaction flow	Intermediate flow systems	Regional, long-range flow systems; topography or erosional flow		
6	Geothermal	Warm basin	Moderate	Cold basin		
7	Hydrocarbon potential	None	Small	Medium	Large	Giant
8	Maturity	Unexplored	Exploration	Developing	Mature	Over mature
9	Coal and CBM	None	Deep (>800 m)	Shallow (200–800 m)		
10	Salts	None	Domes	Beds		
11	On/Off Shore	Deep offshore	Shallow offshore	Onshore		
12	Climate	Arctic	Sub-Arctic	Desert	Tropical	Temperate
13	Accessibility	Inaccessible	Difficult	Acceptable	Easy	
14	Infrastructure	None	Minor	Moderate	Extensive	
15	CO_2 Sources	None	Few	Moderate	Major	

continental side of orogens (Fig. 2), are also favorable for CO_2 sequestration. Such are Rocky Mountain, Appalachian and Andean basins in the Americas, European basins north of the Alps and Carpathians in Europe, west of the Urals, and south of the Zagros and Himalaya in Asia (Fig. 2). Basin location on- or offshore, climate, accessibility and infrastructure reflect the variability in conditions in terms of getting the captured anthropogenic CO_2 from source to the point of sequestration, and translate ultimately into technology and cost, without directly depending on fluctuating economic elements.

Screening and ranking of sedimentary basins

Currently there are no large-scale operations for the geological sequestration or storage of CO_2, and whatever operations exist, they were driven by other considerations, such as increasing oil production, avoiding a carbon tax, or complying with regulations regarding sulfur emissions. However, if CO_2 geological sequestration or storage are to be implemented on a large scale, then there is need for a systematic, quantitative analysis of sedimentary basins in terms of their suitability to serve as enhanced CO_2 sinks. A method for such a quantitative analysis, based on parametric normalization and ranking, is proposed here, which can be further developed or adapted to more specific conditions.

For each criterion i (i=1,..15) in Table 1 for evaluating a basin suitability, a monotonically-increasing numerical function F_i is assigned, which can be continuous or discrete, to describe a value placed on the specific class j for that criterion. The lowest and highest values of this function characterize the worst and best class in terms of suitability for that criterion, i.e. $F_{i,1}$=min(F_i) and $F_{i,n}$=max(F_i), where n is the number of classes in that category (n=3, 4, or 5). If the classes have a relatively equal importance assigned to them, then a linear function is probably best for F_i. If increasing value (or importance) is placed on increasingly favorable classes, then geometric or exponential functions are probably better. Table 2 presents the numerical values assigned here to the various classes for the criteria in Table 1.

For any sedimentary basin k that is evaluated in terms of its general suitability for CO_2 sequestration or storage, the corresponding class j for each criterion i is identified (see Table 1), resulting in a corresponding score $F_{i,j}$ (see Table 2). Because the function F_i has different ranges of values for each criterion, making comparisons and manipulations difficult, the individual scores $F_{i,j}$ are normalized according to:

$$P_i^k = \frac{F_{i,j} - F_{i,1}}{F_{i,n} - F_{i,1}} \qquad (5)$$

such that P_i=0 for the least favorable class and P_i=1 for the most favorable class for all the criteria i=1,...15. As a result of this process, each sedimentary basin k being evaluated is characterized by 15 individual scores P_i^k.

Table 2
Scores and weight assigned to the criteria and classes for assessing sedimentary basins in terms of their suitability for CO_2 sequestration in geological media

	Criterion	Scores					Weight
		j=1	j=2	j=3	j=4	j=5	
i=1	Tectonic setting	1	3	7	15	15	0.07
i=2	Size	1	3	5	9		0.06
i=3	Depth	1	3	5			0.07
i=4	Geology	1	3	7			0.08
i=5	Hydrogeology	1	3	7			0.08
i=6	Geothermal	1	3	7			0.10
i=7	Hydrocarbon potential	1	3	7	13	21	0.06
i=8	Maturity	1	2	4	8	10	0.08
i=9	Coals and CBM	1	2	5			0.04
i=10	Salts	1	2	3			0.01
i=11	On/offshore	1	4	10			0.10
i=12	Climate	1	2	4	7	11	0.08
i=13	Accessibility	1	3	6	10		0.03
i=14	Infrastructure	1	3	7	10		0.05
i=15	CO_2 Sources	1	3	7	15		0.09

The effect of parameterization and normalization is that it transforms various basin characteristics, which have differing meanings and importance, into dimensionless variables that vary between 0 and 1. These can subsequently be added to produce a general score R^k, used in basin ranking, which is calculated using:

$$R^k = \sum_{1}^{15} w_i P_i^k \qquad (6)$$

where w_i are weighting functions that satisfy the condition:

$$\sum_{1}^{15} w_i = 1 \qquad (7)$$

The weights w_i assigned in this study to the various suitability criteria are shown in Table 2. The number of criteria (currently 15), the functions F_i (i=1,..15) and the weights w_i can be changed and/or adapted to changing conditions and priorities. Using this methodology, sedimentary basins, or parts thereof, within a given jurisdiction or geographic region can be assessed and ranked in terms of their suitability for the geological sequestration or storage of CO_2. This ranking can be then used in making decisions for the large-scale implementation of such operations.

Example of application: Canada's case

Canada is a continental-size country, the second largest in the world by area after Russia, which spans the northern half of the western hemisphere, from 45°N to close to the North Pole, and six time zones from the Atlantic to the Pacific (Fig. 6). The climate varies from temperate to arctic, and from maritime to continental. There are 68 sedimentary basins in Canada that can be

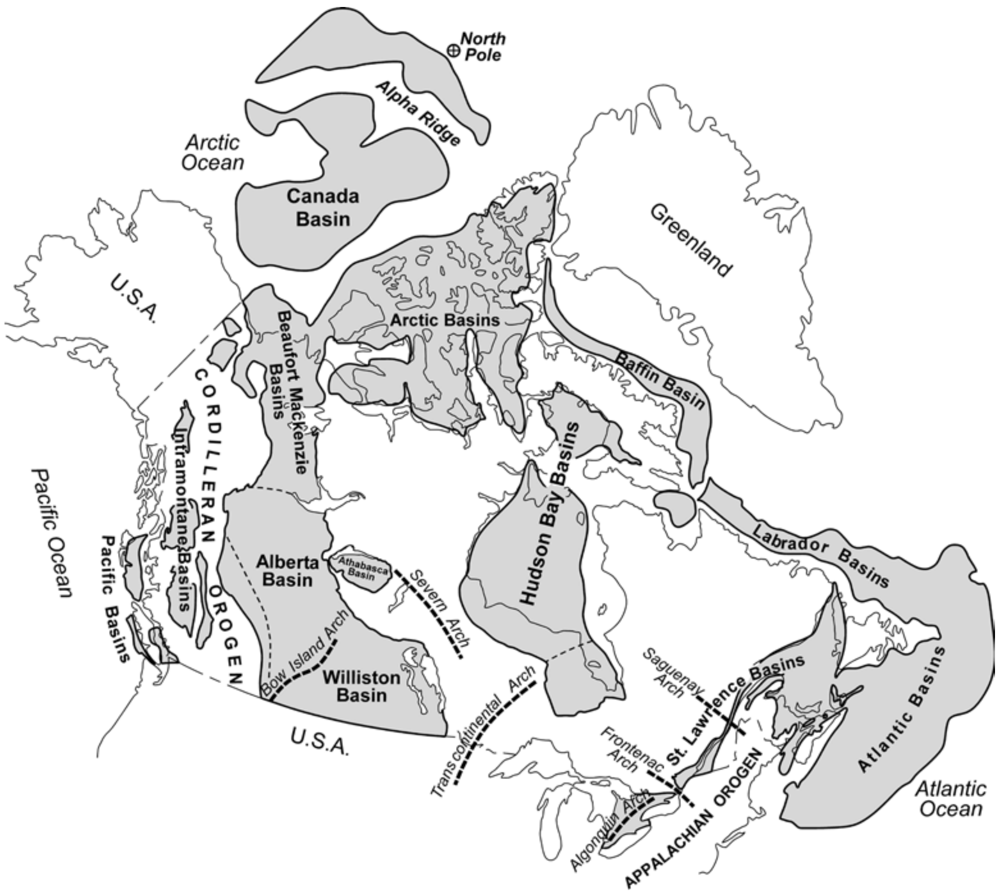

Fig. 6
Distribution of sedimentary basins in Canada

Table 3
Ranking of Canada's sedimentary basins in terms of suitability for CO_2 geological sequestration

Rank	Basin(s)	Characteristics	Score
1	Alberta	Foredeep, giant, deep, mature, coals and salts, good infrastructure, temperate, large point CO_2 sources, large CO_2 emissions	0.96
2	Williston	Intracratonic, large, deep, mature, coals, good infrastructure, temperate, large point CO_2 sources	0.88
3	Beaufort-Mackenzie	Foredeep, large, deep, exploring, sub-arctic, large hydrocarbon potential	0.60
4	SW Ontario	Arch, shallow, small, over mature, good infrastructure, temperate, CO_2 sources	0.52
5	Atlantic shelf	Offshore, developing, oil and gas, coals, large CO_2 point sources	0.35
6	St. Lawrence River	Foredeep, small, temperate, CO_2 sources, no hydrocarbons and coals	0.31
7	Gulf of St. Lawrence	Off-shore, small, no CO_2 sources	0.26
8	Arctic islands	On/off shore, arctic, coals, no CO_2 sources and infrastructure	0.24
9	Intramontane	Convergent, small, coals, no CO_2 sources and infrastructure	0.20
10	Hudson Bay	Mostly offshore, intracratonic, sub-Arctic, no potential, no CO_2	0.18
11	Eastern Arctic	Offshore, arctic, no potential no CO_2 sources	0.13
12	Pacific	Convergent trench, off-shore, unexplored, no CO_2 sources, no infrastructure	0.09

grouped in 12 groups based on type and geographic location (Fig. 6). The Pacific and intramontane basins in the west are convergent (episutural) in type, whereas the basins east of the Rocky Mountains are divergent: cratonic (e.g., Williston, Athabasca, Hudson Bay, Arctic Islands), Atlantic-type (e.g., Atlantic and eastern-Arctic shelves), and foredeeps (e.g., Alberta, Beaufort-Mackenzie, and St Lawrence). Of these, the Alberta basin has world-scale hydrocarbon and coal resources, with advanced production and infrastructure, followed by the Williston basin. Atlantic basins recently started oil and gas production from a few offshore fields (Hibernia, Sable Island), and have a long history of coal production. The Beaufort basin at the Mackenzie Delta and Beaufort Sea in the north also has significant oil and gas potential. Table 3 shows the main characteristics of these basin groups and the scores attained by each according to the method presented previously for ranking in terms of suitability for CO_2 sequestration in geological media.

The results are expected, given the extreme conditions found in most of Canada's basins, particularly harsh climatic conditions and the lack of CO_2 sources and infrastructure, and one could claim that this tool barely confirms what one would intuitively know. However, the situation is not so clear cut in the case of sedimentary basins in the United States, where most sedimentary basins are in advanced stages of exploration and production, where CO_2 sources are abundant and where infrastructure is already in place. Such basins, to name only a few, are Michigan, Illinois, Permian, and other Texas basins, Denver, Appalachian. Thus, the proposed system of assessing and ranking sedimentary basins could prove very useful prior to proceeding with a more detailed analysis based on specific geological data (e.g., pore space, injectivity) and economic analysis, as it was applied for Australian basins (Bradshaw and others 2002). Furthermore, the method can be easily applied to regions within a sedimentary basin. For example, although the Alberta basin (Fig. 6) scores at the top in Canada, not all regions are equally suitable for CO_2 sequestration (Bachu and Stewart 2002), and top-ranked regions in the Williston basin score higher than lower-rank regions in the Alberta basin. Table 4 shows the characteristics and corresponding scores of various regions in the Alberta basin. Because tectonic setting, size, geology, maturity and onshore location are non-discriminatory criteria in this case, they were assigned a null weight, and the weights for the other criteria were re-assigned to meet the condition expressed by relation (7) and to reflect local circumstances and priorities.

Local-scale issues and applicability

Geological sequestration of CO_2 is technologically feasible and is being practiced today on a very limited scale for enhanced oil recovery, mainly in Texas where more than 65 EOR operations are currently active, for acid gas disposal, mainly in the Alberta basin where 39 operations are currently active, and at Sleipner West in the North Sea. While the main mechanisms for CO_2 sequestration have been identified, and a series of criteria for site assessment and selection have been developed, there are still many issues that require addressing before full-scale implementation (Bachu 2001). It is not yet possible to predict with confidence storage volumes, sequestration integrity, and the fate of injected CO_2 over long periods of time. The potential leakage of CO_2 from the injection medium into shallower formations and to the surface, either along natural fractures or through improperly completed wells adds an element of risk (Celia and Bachu 2002) that needs considering and that could be added as an additional criterion for basin suitability assessment. Some of these issues are:

1. Medium characterization. The sequestration medium (hydrocarbon reservoir, aquifer, coal bed or salt structure) and the sealing unit (shale or salt bed) require full characterization in terms of depth, geometry, internal architecture, lithology and mineralogy, porosity and permeability, heterogeneity, geomechanical properties, degree of fracturing and overall integrity, including well penetration.
2. In-situ conditions. The sequestration medium and contained fluids also need characterization, such as: stress, pressure, temperature, flow direction and water salinity in the case of aquifers, oil and gas properties in the case of hydrocarbon reservoirs, and coal rank, quality and gas content in the case of coal beds.
3. Fate of the injected CO_2. There is insucient knowledge about the long-term fate of the CO_2 injected in geological media. Adequate numerical models need developing, and monitoring programs put in place, to predict and determine the long-term fate of the injected CO_2 outside the immediate vicinity of the injection well (flow paths and rate, dissolution, mineral reactions), and for the detection of potential leakage.
4. Long-term integrity and safety of CO_2 injection operations, mainly wells and cements.
5. Performance assessment, addressing mainly the net CO_2 sequestration, as a result of energy consumption during CO_2 capture, transportation and injection, and of CO_2 leakage.
6. Public acceptance, which is absolutely critical for the large-scale implementation of geological sequestration of CO_2. The public must be credibly convinced that it is a safe operation, with no risks for environment, property and life.

Considering the current uncertainty with regard to the characteristics of the sequestration medium and the fate of the injected CO_2, the elements of uncertainty and risk need

Table 4
Ranking of various regions in the Alberta basin in terms of suitability for CO_2 geological sequestration

Rank	Region	Characteristics	Score
1	SW Alberta	Deep; cold basin; regional and erosional flow; oil, gas, coal and salts; major CO_2 sources and infrastructure	1.00
2	SE Alberta	Intermediate depth; cold basin; regional flow; oil, gas and coal; major CO_2 sources and infrastructure	0.71
3	Eastern Alberta	Intermediate-to-shallow depth; cold-to-warm basin; regional and local flow; oil, gas and salts; major CO_2 sources and infrastructure	0.53
4	NW Alberta	Deep; high geothermal gradients; regional flow; oil, gas and coal; less accessible; few CO_2 sources and infrastructure	0.40
5	NE Alberta	Shallow; warm basin; local flow; bitumen, gas and salts; a few very large sources and limited infrastructure	0.30

quantification from the site-specific to the basin scale, and may be included in the evaluation and ranking of sites, regions and basins with respect to their suitability for CO_2 geological sequestration.

Conclusions

Geological sequestration or storage of CO_2 is a means for avoiding the release into the atmosphere of anthropogenic CO_2 emitted by large point sources such as power plants, refineries, and petrochemical plants. Experience to date with enhanced oil recovery and acid gas and CO_2 injection shows that the necessary technology already exists and the main barriers to large-scale implementation are the high cost of CO_2 capture and the identification of geological sinks for CO_2. Sedimentary basins, which are targets for CO_2 geological sequestration because they posses the needed pore space and injectivity, are suitable to various degrees for CO_2 disposal as a result of a series of intrinsic and extrinsic characteristics, such as tectonism and geology in the first category, and infrastructure in the second. One of the most important intrinsic characteristics of a basin with regard to CO_2 sequestration is the geothermal regime, which is controlled by the surface temperature and geothermal gradient. The temperature at any depth determines CO_2 density, which in turn affects the sequestration capacity and the buoyancy forces driving the upward movement of CO_2. All other conditions being equal, the storage capacity is less and the buoyancy force is stronger for higher temperatures than for lower ones. Thus, warm basins are less favorable for CO_2 sequestration than cold basins, the latter being characterized by low surface temperature and low geothermal gradients.

A set of 15 intrinsic and extrinsic criteria has been developed for the assessment and ranking of sedimentary basins in terms of their suitability for CO_2 sequestration and storage. For each criterion, several classes have been defined, which then have been assigned a numerical value, with the least and most favorable classes being assigned the lowest and highest values, respectively. The function defining the range of numerical values for the classes in a given category can take various forms (e.g., linear, geometric, exponential), depending on the relative importance of the higher classes with respect to the lower ones. Any sedimentary basin being analyzed will score in a particular class for each criterion, depending on its specific characteristics. Using a parametric normalization procedure, all the individual scores are transformed into dimensionless scores that vary between 0 and 1, allowing thus inter-criterion comparisons. Finally, the individual scores are summed using weights that express the relative importance of different criteria in the general assessment, leading to a single total score for each basin. The total scores of sedimentary basins or parts thereof can then be compared and ranked to determine the most suitable basin or region for the geological sequestration of CO_2. The method is extremely flexible in that it allows changes in the functions that express the importance of various classes for any given criterion, and in the weights that express the relative importance of various criteria. Furthermore, the criteria can be changed according to specific circumstances. The methodology for suitability assessment and selection of sedimentary basins or parts thereof for CO_2 sequestration or storage is particularly applicable in the case of large, continental-scale countries such as the US, Canada, Australia, Russia, Brazil, Argentina, China, and India, with several sedimentary basins within their territory and territorial waters, but it can be applied also to the case of smaller countries and/or regions, and to the regional-scale analysis of a single, large sedimentary basin where significant variability exists in one or more of the characteristics used as assessment criteria. Examples of application are given for Canada's case and for the Alberta basin in Canada.

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