

# THE POTENTIAL FOR CO<sub>2</sub> SEQUESTRATION IN BRITISH COLUMBIA COAL SEAMS

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**KEYWORDS:** Carbon dioxide phase diagram, coal macerals, carbon dioxide isotherms, coal rank.

## INTRODUCTION

Most people accept that climate change resulting from human activity is a reality. The details as to causes and progress are much in dispute, but again most people accept that increase in the concentration of carbon dioxide (CO<sub>2</sub>) in the atmosphere is one of the causes. The amount of carbon dioxide released when any fossil fuel is burned is substantially dependent on the ratio of carbon to hydrogen in the fuel. This ratio is a maximum for coal and a minimum for natural gas (mainly methane CH<sub>4</sub>) with oil having an intermediate ratio. The amount of CO<sub>2</sub> produced per unit of heat (in this case 10<sup>6</sup> BTU) for the various fossil fuels (Table 1) is a maximum for coal, but it is not zero for natural gas. The true impact of using the various fossil fuels requires an analysis of the efficiency of turning them into more useful forms of energy; often electricity or in the case of oil often momentum. Natural gas and conventional oil reserves will be substantially depleted in the next 50 years leaving coal as the most readily available fossil fuel. Technology that uses the energy from coal, while minimizing or eliminating the release of CO<sub>2</sub> to the environment, will become critically

important. This means sequestering CO<sub>2</sub> as a gas, liquid, or as a solid, or in the adsorbed state on coal.

In recent years there has been a lot of discussion on the possibility of sequestering carbon dioxide (CO<sub>2</sub>) in coal seams or using CO<sub>2</sub> to aid in the recovery of coalbed methane (CH<sub>4</sub>). The basis of both these ideas is the fact that CO<sub>2</sub> is more strongly adsorbed onto coal surfaces than CH<sub>4</sub>. Once adsorbed, if temperature and pressure conditions do not change, then the CO<sub>2</sub> is permanently sequestered. There are of course two concerns, firstly pressure and temperature conditions must not change and secondly and more importantly there are limited pressure and temperature ranges over which CO<sub>2</sub> is a gas. At higher temperatures and pressures conditions CO<sub>2</sub> becomes a super critical fluid and under these conditions it is not clear whether it is adsorbed by coal, occupies the pore spaces acting like a fluid with very low viscosity or infuses into the coal matrix. Under these conditions it is probably not realistic to talk of sequestering the CO<sub>2</sub> because it might be mobile.

Studies have looked at the potential to sequester CO<sub>2</sub> in a number of areas. Pashin *et al.*, (2003) studied the Black Warrior Basin. Bachu and Stewart (2002) and Hughes (in press) have studied the potential for CO<sub>2</sub> sequestration in the Western Canadian Sedimentary Basin. These studies involve analysis of the coal basins and measurement of CO<sub>2</sub> isotherms from representative coal seams. This report is an initial study of the CO<sub>2</sub> sequestration potential for coals in British Columbia. British Columbia ranks fourth in total greenhouse gas emissions of the provinces in Canada but ranks eighth in terms of tonnes of CO<sub>2</sub> per person per year (Figure 1). The province does not generate electricity by burning coal so that the more obvious point sources of anthropogenic CO<sub>2</sub> emissions are less readily identifiable in the province. In fact the largest sources of CO<sub>2</sub> emissions are commercial and private transportation (Table 2). The easiest way for the province to reduce CO<sub>2</sub> emissions may be to improve the efficiency of fuel consumption in diesel and gasoline engines. Smaller point sources may be located close to coal deposits and it may be possible to sequester some of the CO<sub>2</sub> that they generate in seams. Ideal candidates maybe cement plants and natural gas processing plants because they produce relatively pure streams of CO<sub>2</sub>.

**TABLE 1  
CARBON DIOXIDE PRODUCED BY  
BURNING VARIOUS FOSSIL FUELS**

	oil	gas	coal
unit	barrel	cubic M	tonne
cost \$US	30	5\$/1000scf	25
exchange rate	0.76	0.76	0.76
cost US\$ per unit	30.00	0.177	25.00
cost can\$ per unit	39.47	0.23	32.89
wt of unit in kg	136.40	0.7142	1000
heat GJ per unit	6.12	0.0373	29.30
heat kcals per unit	1462007	8899	6999477
btu 10 <sup>6</sup> per unit	5.801	0.035	27.771
kcals/kg	10719	12460	6999
GJ/tonne	44.87	52.16	29.30
cost GJ \$can	6.45	6.24	1.12
cost Kcal 10 <sup>6</sup> \$can	27.0	19.8	4.7
cost btu 10 <sup>6</sup> \$can	6.81	6.58	1.18
CO2 emissions in kg from one million BTU			
coal	92.4		
oil	77.6		
gas	56.1		
Note Assumptions are made concerning heat value of each fuel and carbon content. Numbers are only approximate			

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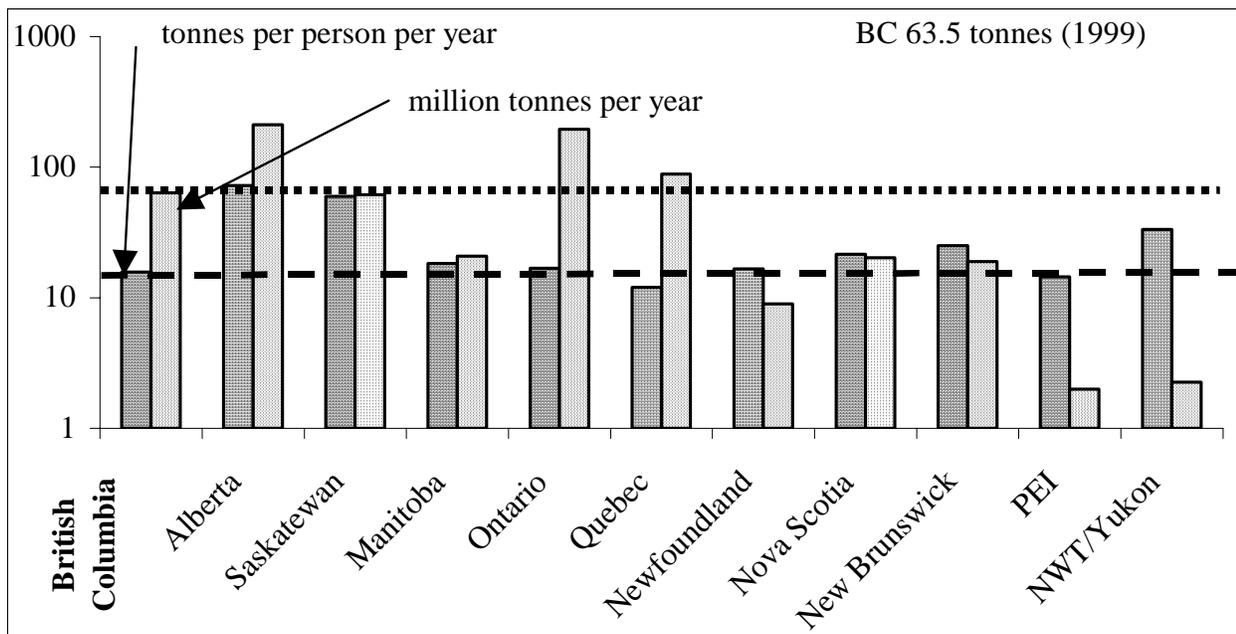


Figure 1. Total CO<sub>2</sub> emissions and CO<sub>2</sub> emissions per person for the provinces.

Data from Environment Canada 2000; Canada Greenhouse gas inventory 1990-1999.

The predominance of literature refers to the extraction of coalbed methane (CBM) from coal. This is not scientifically correct as the gas extracted from coal is a mixture of methane carbon dioxide and other gases. The British Columbia government is adopting the term coalbed gas (CBG). The abbreviations CBM and CBG both refer to the commercial gas extracted from coal at depth. To avoid confusion with existing scientific literature this paper uses the term CBM.

**TABLE 2**  
**CO<sub>2</sub> EMISSIONS BY SOURCE IN BC FOR 1999**

Kg CO <sub>2</sub> equivalent			
Energy	industry combustion		12.7
	transportation		26.1
	non commercial combustion		7.95
	fugative	coal mines	0.5
oil and gas		5.4	
industry process		2.9	
Agriculture		2.6	
waste		4.9	
Forestry		0.8	
total		63.85	

Data from Environment Canada 2001,  
Canada Greenhouse gas inventory 1990-1999.

## SAMPLES AND SAMPLE LOCATIONS

Samples for this study were collected from a number of formations and from a single seam to provide some indication of the variation of CO<sub>2</sub> adsorption with changes in rank, maceral content and temperature. A number of samples were collected from the Gething Formation in northeast British Columbia at the same location as samples collected for a previous study of CH<sub>4</sub> adsorption characteristics (Ryan and Lane, 2002). Also in the northeast, two samples were collected from the Gates Formation from the Bullmoose Mine, which is now closed. In southeast British Columbia, one sample was collected from the Mist Mountain Formation. Two samples were collected from the Quinsam Coal mine on Vancouver Island. Tertiary coal deposits were represented by a drill core sample from the Princeton Basin.

The Gates and the Gething formations, which are both Lower Cretaceous in age, are the two major coal-bearing formations in the Peace River Coalfield in northeast British Columbia. The formations outcrop extensively throughout the coalfield (Figure 2). Coal seams of economic interest in the Gates Formation occur exclusively south of the Sukunka River (Figure 2) and in the Gething Formation mainly north of the Sukunka River.

The Gething Formation overlies the Cadomin Formation (Table 3). Therefore it is slightly younger than the Mist Mountain Formation, which underlies the Cadomin in the southeast British Columbia coalfields (Table 4). The Gething Formation samples were collected

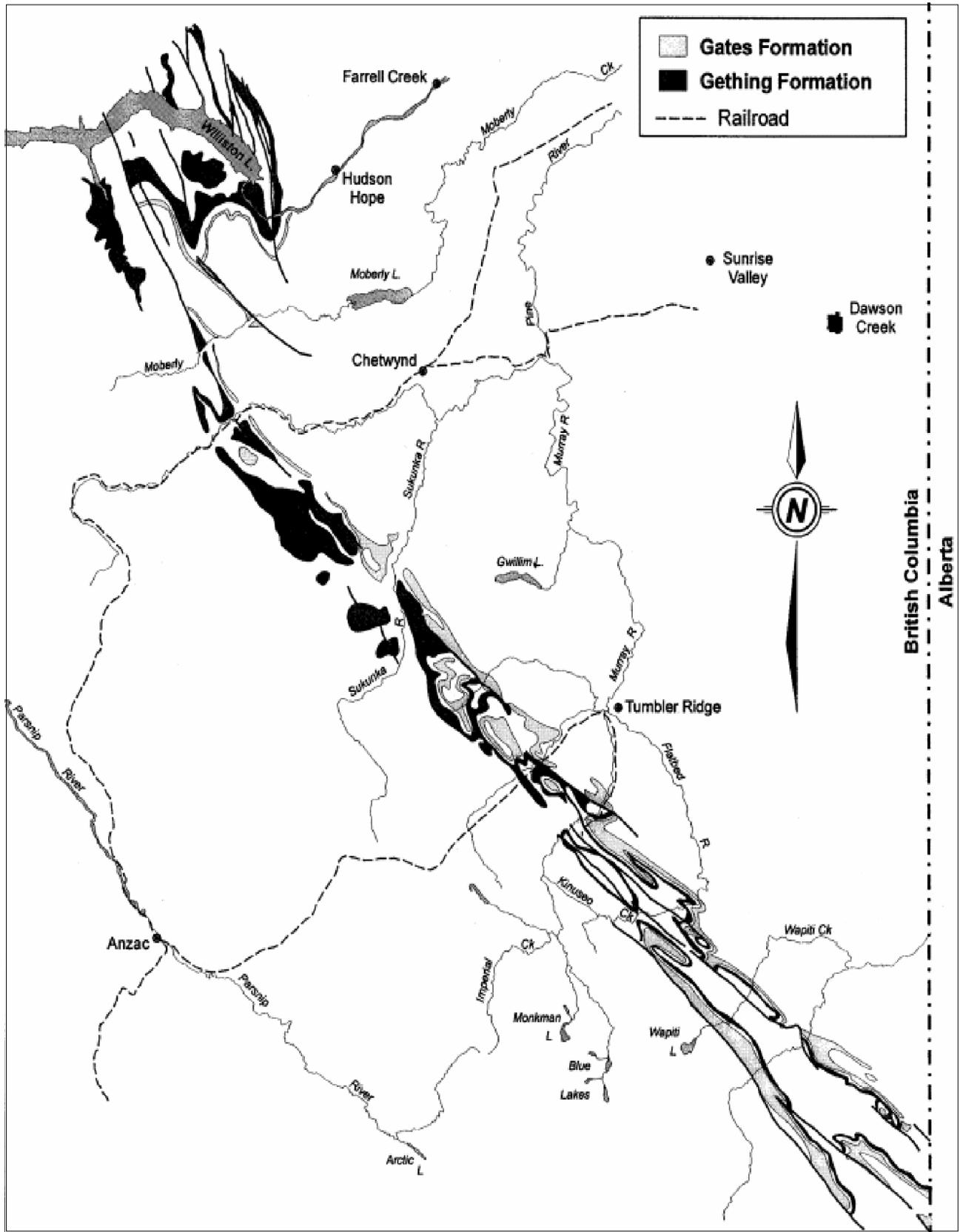


Figure 2. Outcrop pattern of the Gething and Gates formations in the Peace River Coalfield.

**TABLE 3  
GENERALIZED LOWER  
CRETACEOUS STRATIGRAPHY**

		Pine River Area.	metres
Jurassic to lower Cretaceous	FORT ST JOHN'S GROUP	CRUISER FORMATION	
		marine shale	115
		GOODRICH FORMATION	
		fine grained sandstone and shale	350
		HASLAR FORMATION	
		marine shale	260
		BOULDER CREEK FORMATION	
		sandstone and conglomerates	150
	HULCROSS FORMATION		
	grey marine shale	100	
	GATES FORMATION		
non marine sandstones and coal seams	110		
MOOSEBAR FORMATION			
marine shale	250		
BULLHEAD GROUP	GETHING FORMATION		
	non marine sediments and coal	500	
	CADOMIN FORMATION		
		conglomerates	150

from the Willow Creek property located on the south side of the Pine River about 40 kilometres west of Chetwynd (Figure 2). The Pine Valley Mining Corporation plans to initiate mining in the formation at Willow Creek and has excavated a test pit. In this area the Gething Formation has 8 coal seams ranging in thickness from 1 to over 5 metres and numbered from 1 downwards from the top of the formation. Six samples were collected from seam 7-0 (Figure 3). The samples were collected from various locations in the seam with the intention of representing a wide range of maceral composition. Samples were collected in the same area as the samples used in a previous methane adsorption study (Ryan and Lane, 2002).

The younger Gates Formation is separated from the older Gething Formation by the marine Moosebar Formation (Table 3). The formation hosts two major coalmines, both now closed. Western Canadian Coal Corporation proposes to renew mining in the formation. There are some CH<sub>4</sub> adsorption data available for the formation (Lamberson and Bustin, 1993) but no published CO<sub>2</sub> isotherm data. Samples of Gates Formation coal (B seam) were collected from the Bullmoose Mine and from the Western Canadian Coal Corporation property (J seam). Coal in the Gates Formation is generally restricted to 4 zones that are numbered from A counting up section to D. However convention at the Quintette Mine and properties in the vicinity is to number the basal seam as K and with letters decreasing up section. Consequently B seam at Bullmoose and J seam at in the Quintette area occupy similar stratigraphic levels in the Gates Formation.

The Mist Mountain Formation of Upper Jurassic to Lower Cretaceous age (Table 4) outcrops extensively in

the Elk Valley and Crowsnest coalfields. The coal geology of the Elk Valley Coalfield is summarized by Grieve (1993) and, to a lesser extent, Ryan (2003) has summarized the CBM potential of the Crowsnest Coalfield. Both these publications list many other useful references. EnCana has drilled 17 CBM holes in the Elk Valley Coalfield and at the moment is operating two pilots. As a consequence there exists a lot of CH<sub>4</sub> and CO<sub>2</sub> isotherm data, which are not yet public. Dawson *et al.*, (2000) have summarized public data available for the two coalfields. In this study Dave Endicott/Pat Gilmar (Elkview coal mine) provided a sample of the basal seam (10 seam) from the Mist Mountain Formation.

On Vancouver Island Upper Cretaceous coals occur in the older Comox Formation in the Comox Coal Basin and in the younger Protection and Extension Formations in the Nanaimo Coal Basin. There are four seams in the Comox Formation, unfortunately some papers number the seams from 1 at the base counting up and some papers start at 4 at the base counting down. The Quinsam mine extracts coal from 2 seams in the Comox Formation, the basal (1 seam) and the third seam up section (3 seam). Steve Gardner (chief geologist, Quinsam Coal Mine) provided samples of 1 Seam and 3 Seam.

There are a number of Tertiary coal basins in British Columbia however it is difficult to get fresh samples. John Hodgins of Connaught Energy provided a drill core sample from the Princeton Coal Basin. Four coal zones are contained in the Allenby Formation. The sample was collected from the lowest zone, designated as the Black-Jack, Princeton or Blue flame zone.

**TABLE 4  
GENERALIZED JURASSIC-CRETACEOUS  
STRATIGRAPHY, EAST KOOTENAYS**

LOWER CRETACEOUS	CADOMIN FORMATION		
JURASSIC AND CRETACEOUS	KOOTENAY GROUP	ELK FORMATION minor coal	
		MIST MOUNTAIN FORMATION coal seams	
		MORRISSEY FORMATION	MOOSE MOUNTAIN MEMBER
			WEARY RIDGE MEMBER
JURASSIC	FERNIE FORMATION	PASSAGE BEDS	



## SAMPLE PETROGRAPHY AND RANK

Karst and White (1979), Kalkreuth and McMechan (1988), Kalkreuth, *et al.*, (1989) and Marchioni and Kalkreuth (1992) have all discussed coal rank in the Gething Formation. Rank varies from semi-anthracite to high-volatile bituminous. Along the outcrop belt in the foothills the rank is high, in places reaching semi-anthracite. To the north and east it decreases to high-volatile bituminous. There is some evidence that outcrops at the western outcrop edge of the formation have lower ranks. Rank was established prior to deformation and variations are related to changes in the thickness of the Gething plus post Gething sedimentary package (Leckie, 1983).

The rank at Willow Creek, where the samples were collected ranges from medium to low-volatile bituminous. The rank of the 7 seam samples is low-volatile bituminous  $R_{max}=1.64\%$  (Table 5). Ryan (1997) and Ryan and Lane (2002) discuss the petrography of Gething Formation coal. Coal from the formation is characterized by variable reactive content and often low ash concentrations, which make it ideal for providing samples for studies investigating the influence of maceral content on adsorption of various gases. Reactive maceral contents range from approximately 80% to less than 50%. Samples (Table 5) have a high collodetrinite content, which

contains fragments of non-structured inert macerals such as macrinite and inertodetrinite. Structured macerals, such as semifusinite and fusinite are less common. Generally, compared to coals from the Mist Mountain Formation, there is less fusinite and semifusinite and consequently less preserved cell structure and this limits the possible content of dispersed mineral matter, which often fills cell lumen in these macerals. Some of the collotelinite contains the eye-shaped slits characteristic of pseudovitrinite, the origin of which is discussed by Ryan (2002).

The petrography of the three Gates Formation samples (Table 5) is similar to that of the Gething Formation samples though the rank is lower (1.06% and 1.23%). The samples contain liptinite that is not present in the Gething samples but they do contain pseudovitrinite that appears to be characteristic of most samples from the two formations in samples collected from surface and at depth in drill holes. Lamberson *et al.*, (1991) emphasize the importance of fires in forming inertinite in Gates coals. There is no obvious explanation for the variable and sometimes high content of inertinite in Gething coals. Gething coal swamps may have experienced more episodes of drying and a greater frequency of forest fires than Gates swamps.

Grieve (1993) and others have studied the petrography of seams from the Mist Mountain. Rank

**TABLE 5  
PETROGRAPHY AND MEAN MAXIMUM REFLECTANCE  
OF SAMPLES ANALYZED FOR CO<sub>2</sub> ISOTHERMS**

Data as volume percent	telinite	collo telinite	collo detritite	vitro detritite	liptinite	pseudo Vitrinite	semi fusinite	fusinite	macrinite	micrinite	inert detritite	mineral matter	R <sub>max</sub> %	total reactives	total inerts	TR mmfb
Gething Formation																
7 seam -7	0	43	38	0	0	0	8	0	5	0	5	2	1.64	81	17	82
-2	0	37	52	0	0	0	1	0	0	0	3	6	1.64	90	4	96
-4	0	5	26	0	0	0	41	0	10	1	11	6	1.64	32	63	34
-3	0	3	28	0	0	0	34	0	17	1	14	2	1.64	31	67	31
-8	0	5	37	0	0	0	27	1	14	0	14	3	1.64	42	56	43
-5	0	14	39	0	0	0	35	0	3	0	5	3	1.64	53	44	55
Gates Formation																
B seam fine	2	10	31	0	3	0	24	0	12	0	14	4	1.06	45	51	47
B seam coarse	0	3	32	0	3	0	30	0	10	0	16	5	1.06	39	57	41
J seam	0	26	26	1	0	0	18	0	5	0	8	16	1.23	53	31	63
Mist Mountain Formation																
10 seam	0	20	25	1	0	0	26	0	6	0	8	13	1.28	46	41	53
Comox Formation																
Quinsam 1 seam	5	18	47	0	5	1	9	0	2	0	6	9	0.68	75	17	82
Quinsam 3 seam	6	21	44	1	4	1	10	0	2	0	6	5	0.71	78	18	81
Allenby																
Black-jack zone	1	21	57	0	7	0	0	0	0	0	0	14	0.70	85	0	100

varies from high-volatile bituminous to low-volatile bituminous. Generally, seams are characterized by variable and higher inert maceral contents than Carboniferous coals and are similar to Permian coals from Australia. They are similar in many aspects to coals in the Gething and Gates formations, though they tend to contain more semifusinite and less macrinite than these formations. One of the more conspicuous differences is the near absence of psuedovitrinite.

The Upper Cretaceous coals on Vancouver Island are generally sub-bituminous to high-volatile A bituminous in rank. They are characterized by high vitrinite contents with moderate contents of liptinite and minor amounts of semifusinite. Psuedovitrinite is present but not common. They are less deformed than the coals in the Rocky Mountain foothills and often well cleated though sometimes the seams low in the section have carbonate coating on cleat surfaces.

There are a number of Tertiary coal deposits varying in size from Hat Creek, which could contain 30 billion tonnes of lignite and higher rank coals, to Coal River, which may contain about 100 million tonnes of lignite. Coal rank varies from lignite at Coal River to medium-volatile bituminous at Seaton near the town of Smithers. Most of the Tertiary coals are sub-bituminous to high-volatile C bituminous. Coals in the Princeton Basin are sub-bituminous (Rmax= 0.7%, Table 5 and characterized by a very high percentage of vitrinite with minor amounts of liptinite. Mineral matter is finely dispersed in the vitrinite.

## SAMPLE DATA

Fifteen samples were submitted for CO<sub>2</sub> isotherm analysis (Table 6). The ash contents of the samples range from 1% to 20% and are generally low. Moisture contents are in the range of 2.5% to 12% and generally decrease as rank increases. The exception is the J Seam sample, which was collected from an exploration outcrop and probably contains some oxidation. Most of the samples were analyzed at 25°C but two were also run at 30°C. The Langmuir volumes (DAF basis) range from 34 to 58 cc/g though these values should not be taken as representative of the samples adsorption ability because at pressures over about 7.4 Mpa CO<sub>2</sub> is not a gas. Langmuir pressures for samples analyzed at 25°C range from 1.1 to 2.6 Mpa with a tendency to decrease as coal rank increases. The Langmuir pressures increase as temperatures of the isotherms increase.

## CARBON DIOXIDE PHASE DIAGRAM AND CO<sub>2</sub> ADSORPTION POTENTIAL

The CO<sub>2</sub> phase diagram is well documented in terms of the boundaries between liquid, solid and gas fields (Figure 4). However the boundary between the gas and

**TABLE 6**  
**CO<sub>2</sub> ISOTHERM ANALYSIS RESULTS**

	as received		dry ash free		temperature (°C)	Ash (%)	as received moisture (%)	SG	Rmax
	AR Lang Vol (cc/g)	AR Lang Pres (Mpa)	DAF Lang Vol(cc/g)	DAF Lang Pres (Mpa)					
<b>Gething</b>									
7 seam -7	45.56	1.34	48.49	1.34	30	2.7	3.31	1.339	1.64
-7	48.15	1.23	51.25	1.23	25	2.7	3.31	1.345	1.64
-2	50.54	1.48	55.59	1.48	25	6.2	2.83	1.382	1.64
-4	54.66	1.27	57.49	1.27	25	1.1	3.85	1.338	1.64
-3	50.02	1.44	53.33	1.44	25	2.5	3.69	1.369	1.64
-8	51.95	1.44	55.69	1.44	25	2.9	3.88	1.369	1.64
-5	47.31	1.35	49.81	1.35	25	1.3	3.76	1.359	1.64
<b>Gates</b>									
B seam fine	31.14	1.15	34.45	1.15	25	6.9	2.74	1.370	1.06
B seam coarse	31.60	1.28	35.09	1.28	25	7.5	2.48	1.407	1.06
J seam	23.58	2.45	34.28	2.45	25	20.4	10.77	1.528	1.23
<b>Mist Mountain</b>									
10 seam	28.17	2.04	35.28	2.04	25	17.8	2.37	1.468	1.28
<b>Comox</b>									
Quinsam 1 seam	41.80	4.27	48.99	4.27	30	8.4	6.28	1.466	0.68
Quinsam 1 seam	31.40	1.32	36.80	1.32	25	8.4	6.28	1.444	0.68
Quinsam 3 seam	40.35	2.61	47.12	2.61	25	8.5	5.92	1.375	0.71
<b>Allenby</b>									
Black-jack zone	44.44	4.65	55.98	4.65	25	8.5	12.15	1.351	0.7

supercritical fluid fields at high temperatures and moderate pressures is less well defined and is probably represented by a zone. It is therefore difficult to determine the maximum depth at which coal can sequester CO<sub>2</sub> by adsorption in conditions where there is a high geothermal gradient. Figure 4 assumes that the super critical fluid is separated from gas by a horizontal line implying no temperature sensitivity, in fact the line should probably have a negative slope.

The vertical axis of Figure 4 is pressure and, consequently, to plot a depth tract for a stratigraphic section onto the figure one must have both temperature and pressure gradients. Once this is done, the point at which the depth tract crosses the gas-liquid or gas-critical fluid phase lines can be determined. The pressure at this point is then converted to a depth, based on the pressure gradient, and this is the maximum depth for CO<sub>2</sub> sequestration by adsorption on coal. By selecting a number of geothermal and pressure gradient pairs, it is possible to construct a diagram (Figure 5) in which the X

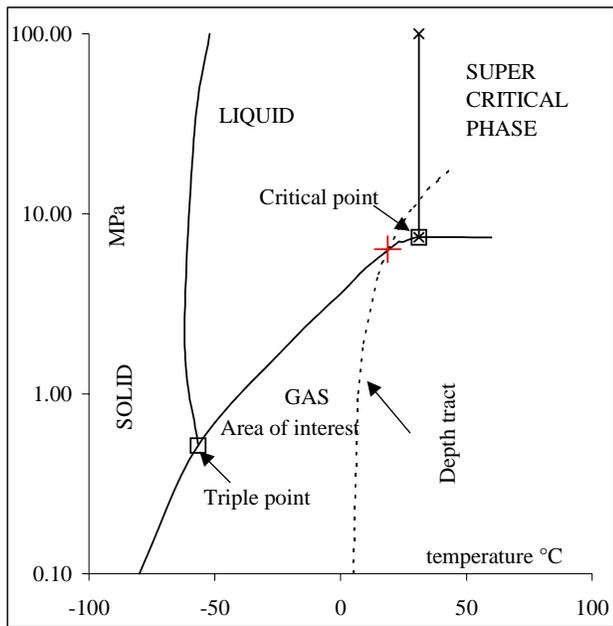


Figure 4. Carbon dioxide phase diagram

axis is the pressure gradient and the Y axis is the geothermal gradient and the contour lines represent the approximate maximum depths for sequestration by adsorption.

The area probably occupied by pressure and temperature gradients in British Columbia coal basins is plotted into Figure 5, based on geothermal gradients for various coalfields in British Columbia (Table 7). Generally temperature data are available for holes drilled for oil and gas exploration. Often this is bottom hole temperature so that an average temperature gradient is calculated based on assuming that the single temperature value is representative. Temperature gradients range from

18°C/Km to 36°C/Km this compares to gradients in the Black Warrior basin that range from 11°C/Km to 22°C/Km (Pashin and McIntyre, 2003). Pressure gradient information is not readily available from drill holes. If there is a normal hydrostatic gradient the pressure gradient varies slightly based on the salinity of the water and will increase from 0.009818 Mpa/metre for fresh water to 0.00984 Mpa/metre for water with 3000 mg/L total dissolved solids. In a lot of sedimentary basins normal hydrostatic gradients do not apply. Gradients in parts of the Western Canadian Sedimentary Basin are as low as 0.005 Mpa/metre. In The Black Warrior Basin gradients range from normal (.00984 Mpa/metre to as low as 0.004 and lower (Pashin and McIntyre, 2003). In areas of complex structure such as northeast British Columbia, there can be considerable over pressuring, and hydrostatic pressure gradients can approach lithostatic gradients of 0.2 Mpa/metre or more.

The maximum depth of sequestration is estimated using the contour lines in Figure 5. The effect of the temperature gradient is minimal for low pressure gradients though it increases as pressure gradients increase. The depth tract depends on the interrelationship of geothermal and pressure gradients and the depth at which CO<sub>2</sub> becomes supercritical or liquid can vary from about 400 metres to over 1000 metres. At shallow depths conditions are defined by a low geothermal gradient matched to a high pressure gradient. At maximum depths conditions are defined by a high geothermal gradient and low-pressure gradient. These conditions may allow for adsorption of CO<sub>2</sub> at greater depth but the increased temperature will greatly reduce the ability of coal to adsorb any gas. The window for potential CO<sub>2</sub> sequestration is probably below 200 metres and above a depth defined in part by the CO<sub>2</sub> phase diagram.

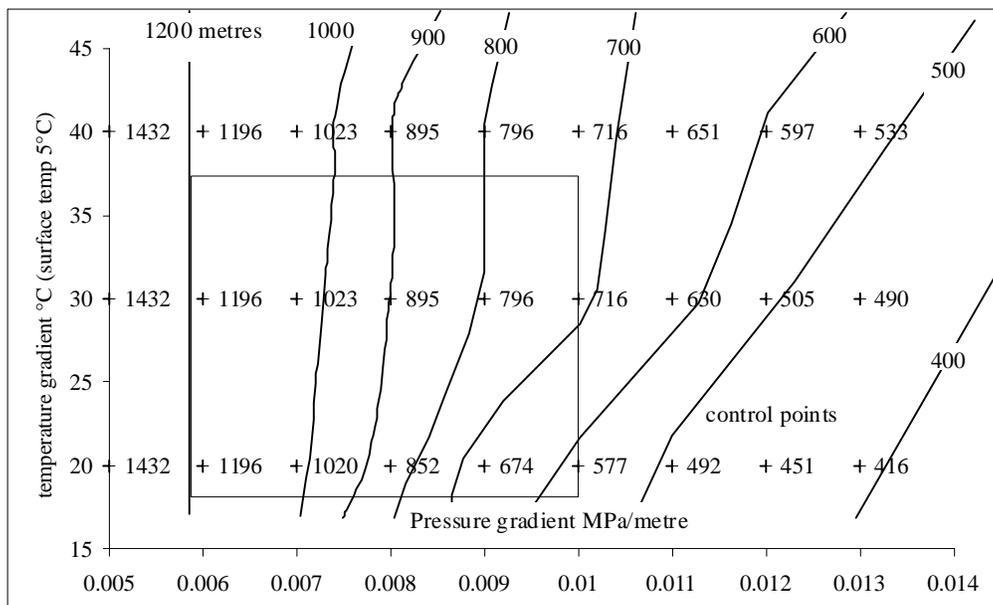


Figure 5. Diagram illustrating the approximate relationship between temperature and pressure gradients and the depth to the liquid or critical fluid fields for carbon dioxide.

**TABLE 7  
TEMPERATURE GRADIENTS IN  
COAL BASINS IN BRITISH COLUMBIA**

Region	Local area	Surface temperature	gradient C/Km
SW BC	Comox	7	20.8
SW BC	Naniamo	7	27.5
SW BC	Naniamo	7	28.3
SW BC	Naniamo	7	23.3
SW BC	Naniamo	7	22.1
SE BC	Crowsnest area	8	25.4
SE BC	Crowsnest area	8	20.5
SE BC	Crowsnest area	8	18
SE BC	Elk Valley	8	23.6
SE BC	Elk Valley	8	36.2
NE BC	Bullmoose area	4	23.1
NE BC	Bullmoose area	4	30.2
NE BC	Bullmoose area	4	31.5
NE BC	Grizzly area	5	26
NE BC	Grizzly area	5	25.7
NE BC	Willow Creek	5	25.6
NE BC	Hudson Hope	5	30
NE BC	Hudson Hope	5	28.6
NE BC	Hudson Hope	5	36.4
NE BC	Hudson Hope	5	22.8

### CARBON DIOXIDE AS A FREE GAS OR IN SOLUTION IN WATER OR AS A SUPER CRITICAL FLUID

When CO<sub>2</sub> is injected into seams some of the CO<sub>2</sub> goes into solution in the water associated with the coal. Water associated with coal occurs in three forms defined in different ways and given different names. In simple terms the three forms may be referred to as free and mobile water in fractures, surface water loosely bound to coal surfaces and structural water, which forms part of the coal structure. Surface water is the difference between equilibrium moisture and inherent moisture. The amount of surface water depends on rank (Figure 6) and on the amount of porosity. The amount of CO<sub>2</sub> that can be held in solution in water therefore depends on rank, porosity and temperature pressure conditions. The solubility of CO<sub>2</sub> in water increases with pressure but decreases with temperature. There are numerous sources of data describing CO<sub>2</sub> solubility, unfortunately there are as many

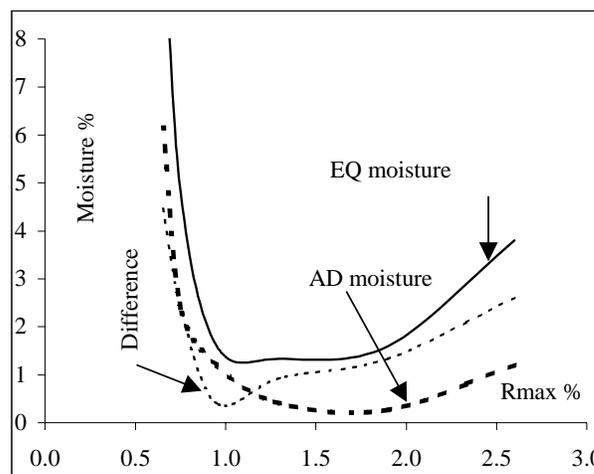


Figure 6. Air-dried, Equilibrium and free water versus rank

combinations of units as there are examples of CO<sub>2</sub> solubility plots. The plots (Figure 7) are adapted from Jarrell (2002) and Rightmire (1984). Based on the interplay of geothermal and temperature gradients the amount of CO<sub>2</sub> held in solution ranges from about 25 to 35 cubic metres gas in solution in 1 cubic metre water. The actual amount held in 1 tonne of coal depends on rank and water-filled porosity. For low rank coals the amount of CO<sub>2</sub> in solution can range up to 8 cc/g and for higher rank coals probably is not more than 1 cc/g.

Below the critical point, CO<sub>2</sub> is contained in the coal by adsorption, in part by solution in the interstitial water and as free gas. The amount of CO<sub>2</sub> held in a free gas phase can be estimated from the ideal gas law and ranges up to about 8 cc/gm for 15% gas-filled porosity at a depth less than that equivalent to the critical point (Figure 8). Obviously the amount held by adsorption is much greater than that held in solution or as free gas for all ranks of coal.

The density of CO<sub>2</sub> gas as it approaches critical conditions is in the range of 0.15 gm/cc. Once CO<sub>2</sub> enters the supercritical phase the density increases rapidly to about 0.7 gm/cc (Figure 9) and maintains this value as pressure and temperature increase as predicted by normal hydrostatic and geothermal gradients. Density tends to stay in a narrow range above the critical point because of the opposing effects of increasing pressure and increasing temperature. The rapid change in density as conditions approach the critical point makes it very difficult to determine the adsorption characteristics of CO<sub>2</sub> at temperatures approaching critical conditions.

### GENERAL COMMENTS REGARDING ADSORPTION OF CO<sub>2</sub> ON COAL

As pressure increases, CO<sub>2</sub> becomes a liquid or a supercritical fluid as indicated by the CO<sub>2</sub> phase diagram (Figure 4). The diagram indicates the limited pressure-temperature field in which CO<sub>2</sub> is a gas and therefore,

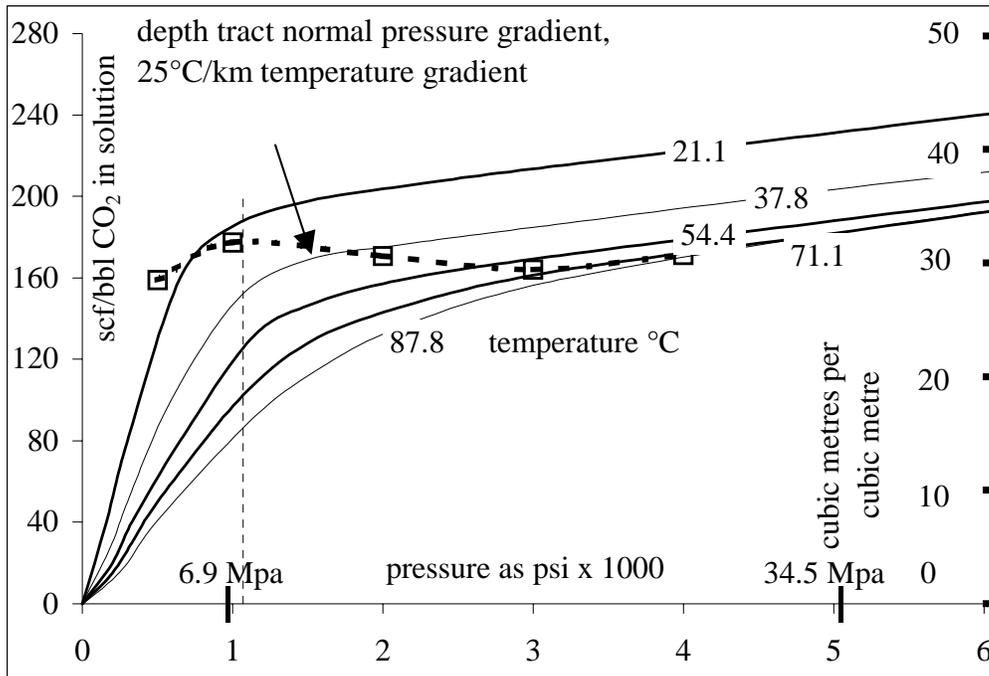


Figure 7. Plots of CO<sub>2</sub> solubility versus depth and temperature; data from Jarell *et al.*, (2002) and Rightmire (1984).

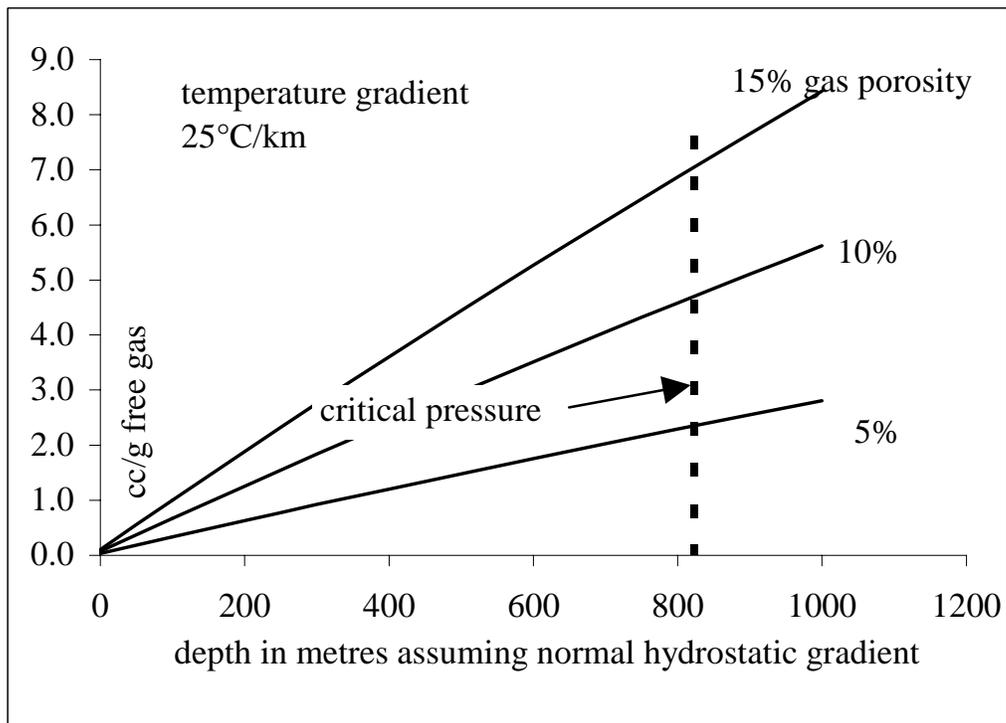


Figure 8. Potential free gas based on porosity assuming a normal hydrostatic gradient and a geothermal gradient of 25°C.

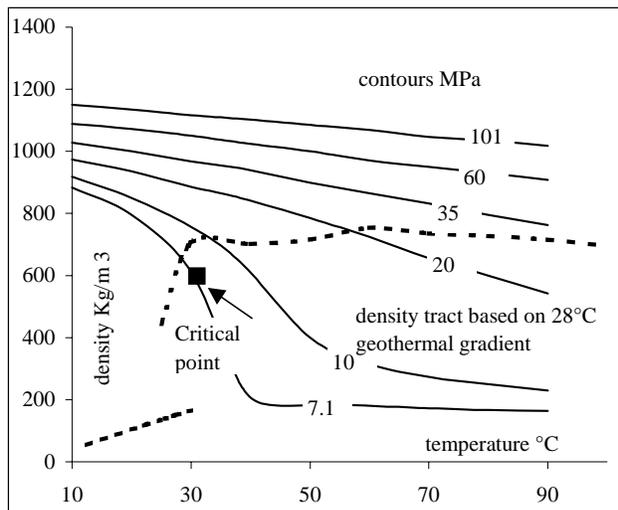


Figure 9. Density of CO<sub>2</sub> as a gas and in the super critical phase plots adapted from Bachu and Stewart, (2002) and Pruess *et al.*, (2001).

based on pressure and temperature gradients, defines the depth range through which CO<sub>2</sub> can be sequestered by adsorption. The diagram is for pure CO<sub>2</sub> and the addition of other gases will change the field boundaries, probably increasing the size of the gas field in terms of pressure. This is important because it may not always be cost effective to obtain a pure CO<sub>2</sub> gas for injection.

It is not reasonable to consider the Langmuir volume (adsorbed volume at infinite pressure) as a measure of the CO<sub>2</sub> adsorption ability of a sample, because CO<sub>2</sub> becomes a super critical fluid at quite low pressures. It is therefore best to compare the adsorption of CO<sub>2</sub> at a fixed depth and not at infinite pressure. In this study isotherms were run at 25°C and 30°C, temperatures typically seen at depths of 600 to 900 metres in sedimentary basins in British Columbia. The temperature at which isotherms are run combined with temperature and pressure gradients in an area combine to provide the specific depth at which the isotherm is predicting real gas contents. Adsorption data from a number of isotherms should be compared based on calculated gas contents at this depth.

Some of the earliest investigations of the CO<sub>2</sub> adsorption capacity of coal were conducted by Ettinger *et al.*, (1966). They recognized the stronger adsorption of CO<sub>2</sub> onto coal compared to CH<sub>4</sub> and suggested that the relative adsorption of gases such as H<sub>2</sub>S, CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub> and H<sub>2</sub>O is related to their liquefaction temperature. They also point out that there is an increased danger of mine outbursts when coals contain a higher proportion of adsorbed CO<sub>2</sub>. Levy *et al.*, (1997) documented the difference in Langmuir volumes for nitrogen, methane and carbon dioxide for isotherms measured on moist coal at 30°C. Working with Bowen Basin coals covering a rank range of high-volatile bituminous to low-volatile bituminous, Levy *et al.*, (1997) found that the CO<sub>2</sub>/CH<sub>4</sub> molar ratio for adsorbed gases decreased consistently from 1.82 to 1.37 as rank increased. They suggest that the

greater adsorption of CO<sub>2</sub> is probably related to the increased polar nature of the molecule compared to CH<sub>4</sub> (Levy *et al.*, 1997).

Krooss *et al.*, (2001) studied the adsorption behaviour of CO<sub>2</sub> at high pressures and temperatures, in part above the critical point. They discuss the difficulty of interpreting experimental results above the critical point. The density of the adsorbed phase and of the phase occupying the void in the canister are both difficult to determine. They assumed a density of 1.028 gm/cc for the adsorbed CO<sub>2</sub>. In addition the coal probably swells which makes it even harder to correct for the component of CO<sub>2</sub> that is not adsorbed. Adsorption experiments do not generally confine the coal as it is loosely packed as fine grains and therefore they do not model the competing effects of matrix swelling and adsorption that occur in nature. In general the results of Krooss *et al.*, (2001) conform to Langmuir adsorption below the critical point but above pressures of about 6 Mpa (similar to the critical point pressure 7.47 MPa) results are inconsistent with normal adsorption. Even after data are corrected for the assumed volume of the adsorbed phase using a density of 1.028 gm/cc, adsorption is negative. This probably indicates swelling of the coal and use of an overly large void space in the canister to correct for the non adsorbed CO<sub>2</sub> phase. As Krooss *et al.*, (2001) state, it is difficult to interpret the results above the critical point and even more difficult to predict what they might mean for a seam at depth.

Larsen (2004) documented the solution of CO<sub>2</sub> in coal over a wide range of pressure and temperature conditions extending below the critical point. Solution of CO<sub>2</sub> causes coal to expand but also increases the plasticity of coal. These two effects are potentially devastating to the permeability needed to inject CO<sub>2</sub> into coal. The amount of CO<sub>2</sub> dissolved in coal increases as pressure increases and as rank decreases. At pressures equivalent to depths of 150 to 200 metres about half the CO<sub>2</sub> contained in medium or low rank coals is in solution (Reucroft and Sethuraman, 1987). The softening temperature of coal appears to decrease to about 31°C at the critical pressure (Figure 10) implying that the coal becomes a plastic solid above critical conditions of temperature and pressure.

The stronger adsorption of CO<sub>2</sub> affects the relative rate of desorption of CO<sub>2</sub> relative to CH<sub>4</sub> and the CO<sub>2</sub> content of produced gases generally increase over time. The effect is predicted by the extended Langmuir equation (Arri *et al.*, 1992).

## INFLUENCE OF RANK AND PETROGRAPHY ON CO<sub>2</sub> ADSORPTION

Adsorption of methane tends to increase as rank increases, initially rapidly and then more slowly at high ranks, though the relationship of adsorption to rank for medium-volatile coals is less well-defined. For example

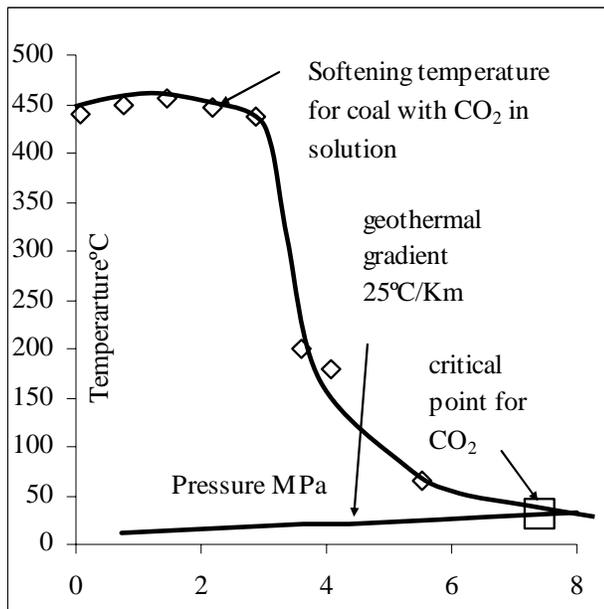


Figure 10. Softening temperature of Lower Kittanning coal (89.6 % C daf) at increasing pressure; plot adapted from Khan and Jenkins (1985) in Larsen (2004).

coals from the Bowen Basin (Levy *et al.*, 1997) have higher adsorption capacities than coals of similar rank from the USA (Levy *et al.*, 1997). Some of the variation may be caused by variable maceral content in the samples. Despite the fact that many diagrams (Ryan, 1992) imply a consistent relationship between rank and adsorption ability for CH<sub>4</sub> the reality is much more complicated.

Carbon dioxide adsorption capacity has a weak correlation with rank, increasing at high rank but there are indications that adsorption is higher for lignite and sub-bituminous coals than for bituminous coals. This is hinted at in the data from Gluskoter *et al.*, (2003) and from data in this study (Figure 11). Volume data from Gluskoter *et al.*, are plotted at 300 psi and as scf/t daf basis so that data from this study (Figure 11) are recalculated to the same pressure. Gluskoter *et al.*, (2003) do not specifically identify rank by reflectance so that some assumptions are made in incorporating their data into Figure 11. However it is obvious that both data sets imply higher adsorption for low and high rank coals than for medium-rank coals. The present data set was generated at 25°C. The temperature of the Gluskoter *et al.*, data set is not stated.

The adsorption behaviour of CO<sub>2</sub> at low rank is different from that of CH<sub>4</sub> and this probably relates to the distribution of micro, meso and macro porosity by rank and the stronger polarity of the CO<sub>2</sub> molecule compared to the CH<sub>4</sub> molecule. Rightmire (1984), Bustin and Clarkson, (1999) and Levine (1993) have all summarized the distribution of porosity in coal (Figure 12). Total porosity is a minimum for medium-volatile rank coals and macro porosity decreases as rank increases. At low ranks the increased meso porosity allows CO<sub>2</sub> to adsorb, possibly as a volume filling in meso sized pores whereas

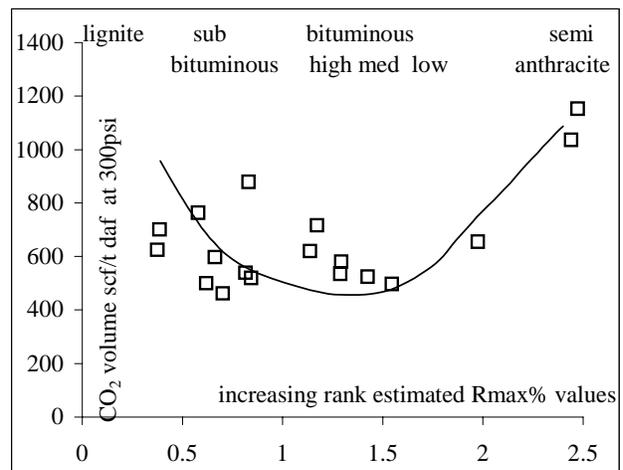
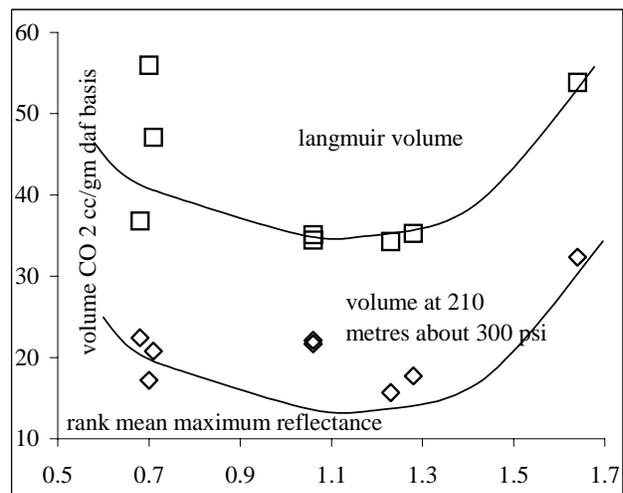


Figure 11. Carbon dioxide adsorption versus rank. Data from this study and from Gluskoter *et al.*, (2002).

CH<sub>4</sub> with lower polarity forms layer adsorption in micro pores. The selectivity of CO<sub>2</sub> over CH<sub>4</sub> is high and the amount of CO<sub>2</sub> adsorbed high, despite low rank. As rank increases the amount of meso porosity decreases, CO<sub>2</sub> adsorption decreases and CH<sub>4</sub> adsorption increases. Consequently the selectivity for CO<sub>2</sub> decreases. At high rank the increase in micro porosity causes increases in the adsorption of both CO<sub>2</sub> and CH<sub>4</sub> without a major increase in the selectivity for CO<sub>2</sub>. Determining the effective porosity distribution in coals is difficult because experiments are often not done on moisture equilibrated coal at insitu pressures. Also the structure of low rank coals is less predictable than that of higher rank coals and this results in a wider variation of porosity distribution. It is therefore hard to predict the CO<sub>2</sub> and CH<sub>4</sub> adsorption characteristics of low rank coals.

The selectivity of CO<sub>2</sub> versus CH<sub>4</sub> of coals decreases as rank increases but may increase again at high ranks. Data from this study include only CO<sub>2</sub> isotherms but in most cases CH<sub>4</sub> isotherms exist for the coals from previous studies so that it is possible to construct an approximate plot of CO<sub>2</sub>/CH<sub>4</sub> ratio versus rank (Figure

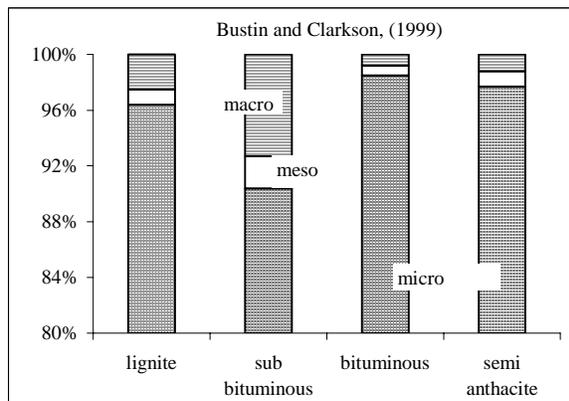
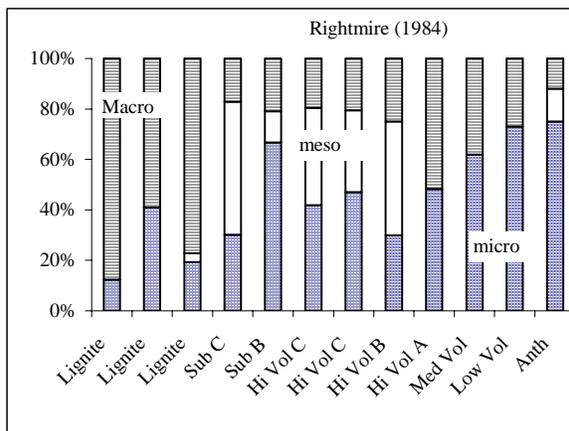
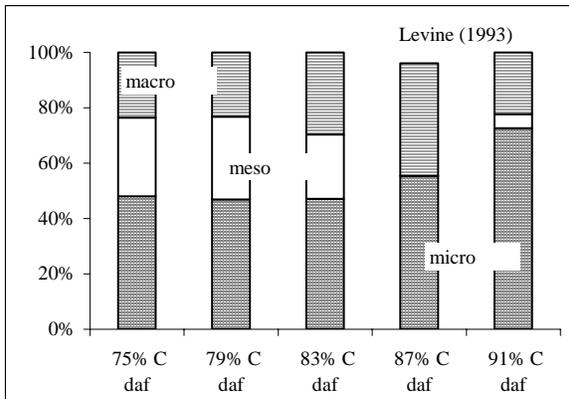
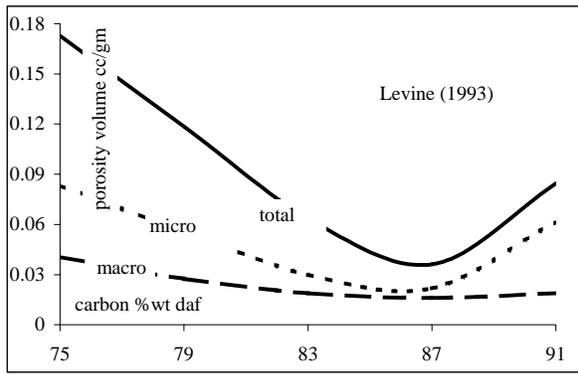


Figure 12. Distribution of porosity in coal data adapted from Rightmire (1984), Bustin and Clarkson (1999) and Levine (1993).

13). Ratios in Figure 13 are calculated at a pressure of 300 psi to conform to the data from Gluskoter *et al.*, (2003), which is also reproduced in Figure 13. The ratio is very high for low rank coals, approaching 20, and then decreases to a range of 1.5 to 2 for medium rank coals. It might increase slightly in high rank coals. For coals of all ranks the volume ratio of CO<sub>2</sub>/CH<sub>4</sub> decreases as pressure increases (Gluskoter *et al.*, 2003) and probably also as temperature increases.

It is important to recognize the difference between molecule for molecule replacement and weight for weight replacement when comparing the adsorption capacity of CO<sub>2</sub> and CH<sub>4</sub>. If there is a one for one molecule replacement then 2.75 grams of CO<sub>2</sub> will replace 1 gram of CH<sub>4</sub> (the ratio of the molecular weights). In terms of greenhouses gases one is interested in sequestering a weight of CO<sub>2</sub> not a volume. The increased selectivity and adsorption of low rank coals may make them better candidates for CO<sub>2</sub> sequestration than higher rank coals.

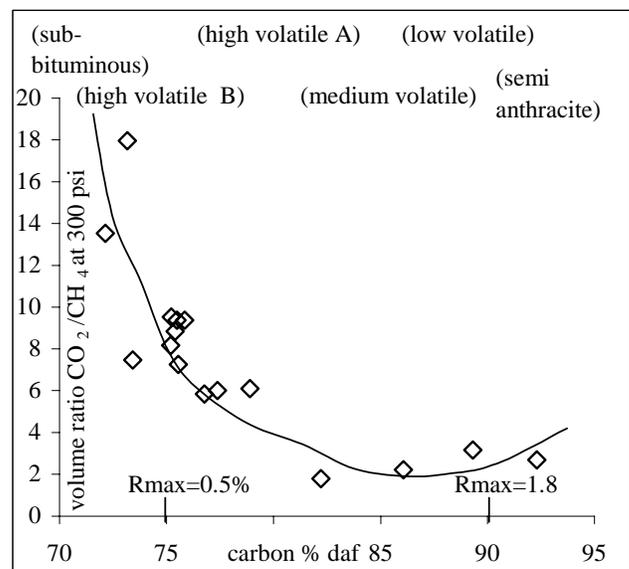
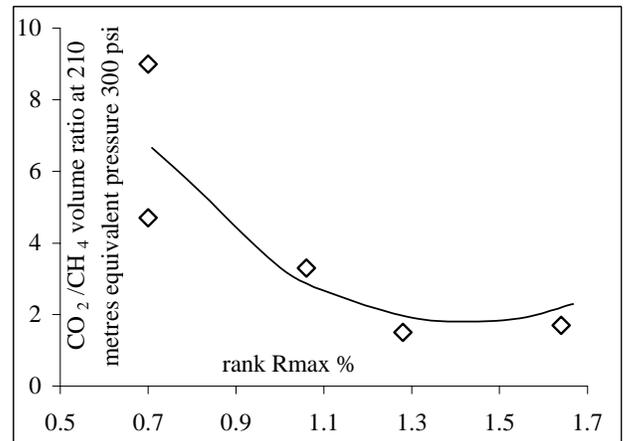


Figure 13. Plot of CO<sub>2</sub>/CH<sub>4</sub> ratio calculated at 210 metres equivalent pressure versus rank. Data from this study from Gluskoter *et al.*, (2003).

This of course assumes that they are not already saturated with CO<sub>2</sub>. Low rank coals have better diffusivity and should maintain permeability and accommodate matrix swelling better than higher rank coals.

Macerals are not minerals and do not have defined crystal structures like minerals. However there are generalizations that hold about the different characteristics of macerals. Inert macerals have more meso porosity and less micro porosity than reactive macerals (Harris and Yust, 1976; Gan *et al.*, 1972). At constant rank the effect of petrography on methane adsorption has been studied by a number of authors (Ryan and Lane, 2002) (Lamberson and Bustin, 1993). There is either no correlation or adsorption ability tends to increase as the percentage of reactive macerals increases. These studies were done on medium or low-volatile coals. In British Columbia many of the Tertiary low rank coals are composed, on a mineral matter free basis, of almost 100% reactive macerals making it difficult (and less relevant) to study the effects of petrography on the adsorption characteristics of low rank coals.

Studies of the maceral influence on the adsorption of CO<sub>2</sub> are more limited. Gluskoter *et al.*, (2002) presented data, which indicate no correlation between inert maceral content and adsorption of CO<sub>2</sub> for a range of 0% to 25% inerts in low rank coals. In this study a number of samples with a rank of 1.64% and varying petrography were analysed (Table 5) as well as two samples (rank 1.06%) with somewhat different petrography. These were actually the same sample screened to different sizes to provide a partial concentration of vitrinite. The Gething Formation samples with R<sub>max</sub> of 1.64% (Figure 14) are plotted on a total reactivities *versus* gas plot with the CO<sub>2</sub> gas contents plotted as gas contents at 210 metres (300psi) or as Langmuir volumes. The data indicate a weak negative correlation of gas content with increasing reactivities content. This is the reverse of the situation for samples of the same coal analysed for CH<sub>4</sub> adsorption (Figure 15). One of the Gething samples (Table 5) has distinctly higher ash than the other samples and it is highlighted in

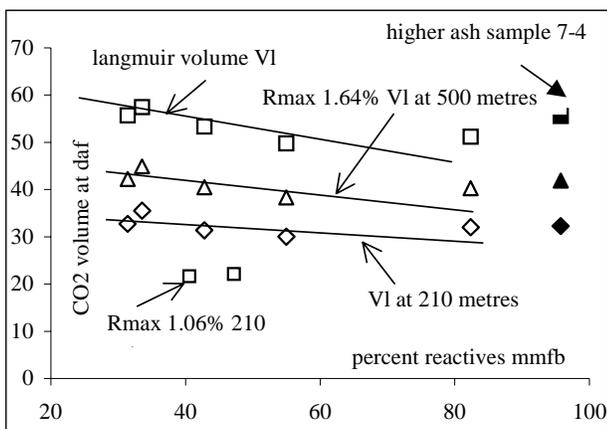


Figure 14. Plot of CO<sub>2</sub> adsorption at different depth versus reactive content for the Gething Formation samples.

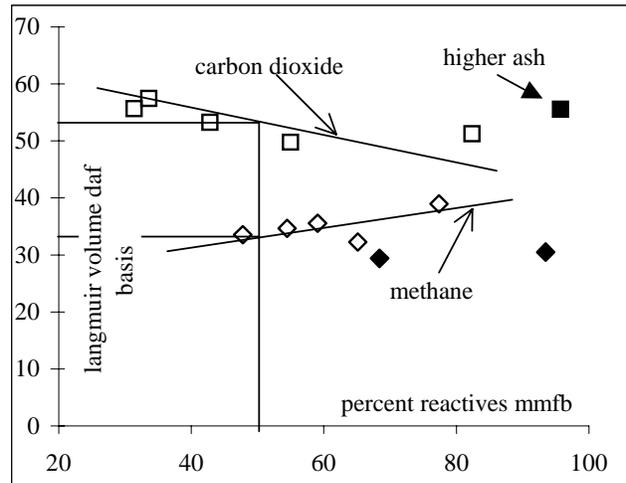


Figure 15. Plot CH<sub>4</sub> and CO<sub>2</sub> adsorption versus content for Gething Formation samples. CH<sub>4</sub> data are from Ryan and Lane (2002).

the plot (Figure 14). It appears that the effect of petrography on CO<sub>2</sub> and CH<sub>4</sub> adsorption is different for high rank coals. The CO<sub>2</sub>/CH<sub>4</sub> ratio increases as the inert maceral content increases. This means that some of the Jurassic-Cretaceous coals of BC, which are characterized by moderately high inert maceral contents, may have improved ability to sequester CO<sub>2</sub>. At lower ranks it appears that CO<sub>2</sub> adsorption does not vary much with maceral content as indicated by the two samples (rank 1.06%) also plotted into Figure 14 and by the Gluskoter data for sub-bituminous coals.

Pure gas isotherms illustrate the ultimate replacement potential of CO<sub>2</sub> for CH<sub>4</sub>. Unfortunately they give no hints as to how to achieve this. The extended Langmuir Equation predicts the ratio of adsorbed gases based on the mole ratio of gases in the free phase (Figure 16). For example, if the mole ratio of CO<sub>2</sub> in the gas phase is 0.5 then the mole ratio in the adsorbed phase will be 0.7 and

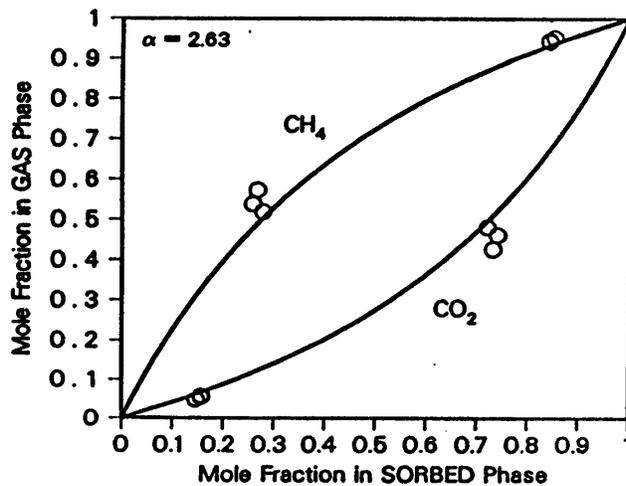


Figure 16. CO<sub>2</sub>/CH<sub>4</sub> mole fraction in gas and adsorbed phase; data from Arri *et al.*, (1992).

this requires a mole ratio of 0.3 CH<sub>4</sub> in the adsorbed phase and 0.45 in the gas phase. Figure 16 is coal and temperature specific but it does indicate trends as predicted by the extended Langmuir Equation. Arri *et al.*, (1992) found that the CO<sub>2</sub> data had at best a moderate fit to curves predicted by the extended Langmuir Equation. Crosdale (1999) analysed the composition of adsorbed gas for increasing pressure steps for a gas phase of 52.9% CO<sub>2</sub> and 47.1% CH<sub>4</sub>. The results do not conform to the extended Langmuir Equation. The amount of CO<sub>2</sub> adsorbed was in agreement with a pore filling model influenced by the faster diffusion of the smaller CH<sub>4</sub> molecule. The CH<sub>4</sub> molecule was able to diffuse into the coal faster than the CO<sub>2</sub> molecule and block or occupy adsorption sites. During desorption, as pressure drops, CH<sub>4</sub> desorbs faster leaving an increased concentration of adsorbed CO<sub>2</sub>. Based on Crosdale's work, increasing the pressure of CO<sub>2</sub> in coal not desorbed of CH<sub>4</sub> may not release as much CH<sub>4</sub> or adsorb as much CO<sub>2</sub> as is predicted by the extended Langmuir Equation. If the coal is under saturated with CH<sub>4</sub> then it should be possible to predict CO<sub>2</sub> adsorption based on a CO<sub>2</sub> isotherm. The mechanics of getting the CO<sub>2</sub> to permeate coal depends on permeability, and as the coal adsorbs CO<sub>2</sub> on matrix swelling. If the coal seam has limited permeability then CO<sub>2</sub> flooding and adsorption may not be possible.

Some of the early studies on CO<sub>2</sub> adsorption were interested in the potential of using CO<sub>2</sub> for enhanced coalbed methane recovery (ECBMR). In this case a coal with low CO<sub>2</sub> selectivity is better than one with a high CO<sub>2</sub>/CH<sub>4</sub> selectivity ratio. In all cases for ECBMR it is important that the recovered gas does not have a high CO<sub>2</sub> component as this adds to the costs of upgrading the gas to pipeline quality. In many situations ECBMR may not be practical because of low permeability and high concentration of CO<sub>2</sub> in the recovered gas. The results of the Allison CO<sub>2</sub> injection project of Burlington are somewhat inconclusive. Injection of CO<sub>2</sub> certainly increased water production in part probably because CO<sub>2</sub> went into solution in the water decreasing its viscosity. In low rank coals this may have the effect of drying the coals, which would then increase their adsorption ability. In an ECBMR situation this may mean production of water and temporary sequestration of CO<sub>2</sub> and minimal release of CH<sub>4</sub>. When water re-enters the seam adsorption ability may decrease causing CO<sub>2</sub> to be released.

## INFLUENCE OF TEMPERATURE ON CO<sub>2</sub> ADSORPTION

Any temperature increase below the critical temperature decreases the ability of samples to adsorb CO<sub>2</sub>. This effect has to be paired with a geothermal and pressure gradient to attempt to construct real adsorption *versus* depth tracts. In this study two samples were analysed at 25°C and 30°C (Table 6, Figure 17). The Langmuir pressures increase as the temperature increases.

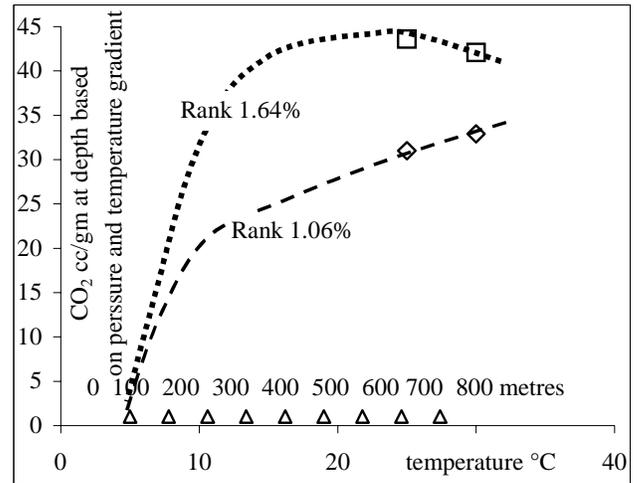


Figure 17. Plot of CO<sub>2</sub> adsorption at different temperatures. Data volumes calculated based on a normal hydrostatic gradient and a geothermal gradient of 28°C/Km with surface temperature of 5°C.

The same effect is seen for CH<sub>4</sub> isotherms, however the CO<sub>2</sub> Langmuir volumes do not consistently decrease as temperature increases. When the CO<sub>2</sub> gas contents are calculated at the depth/pressure that corresponds to the temperature of the isotherm, the adsorption for the high rank coals decreases as depth increases and for the low rank coals the adsorption increases with depth (Figure 17). This is in a depth window of about 700 to 800 metres. Higher rank coals have lower Langmuir pressures indicating curves that are steeper at the origin than curves for low rank coals. This combined with the effect of increasing temperature means that for low rank coals the adsorption still tends to increase with depth and temperature whereas for high rank coals the adsorption decreases as depth and temperature increase.

It is very important to construct adsorption *versus* depth tracts for different rank coals for the depth range that corresponds to temperatures below the critical temperature. The implication of Figure 17 is that it might be better to sequester CO<sub>2</sub> in lower rank coals at depth than to sequester it in higher rank coals.

## SEQUESTERING CO<sub>2</sub> IN BRITISH COLUMBIAN COALS

One of the most understated facts about sequestering CO<sub>2</sub> in coal is that it can only happen by first displacing the CH<sub>4</sub> already adsorbed by the coal. The coal may or may not be saturated with adsorbed CH<sub>4</sub> but it will certainly have some that will be released when the CO<sub>2</sub> is adsorbed. On a weight basis the amount of CO<sub>2</sub> adsorbed is between 5 and 30 times the amount of CH<sub>4</sub> desorbed, calculated at a depth of 210 metres (Table 8). The ratio of CO<sub>2</sub>/CH<sub>4</sub> decreases as pressure (depth) increases though the situation is more complicated when the effect of increasing temperature is factored in. This sounds very

**TABLE 8.**  
**THE RATIO OF CO<sub>2</sub>/CH<sub>4</sub> ADSORBED**  
**ON COALS OF DIFFERENT RANKS**

Rank	R <sub>max</sub> %	volume ratio	wt ratio	CO <sub>2</sub> scf/t daf at 300psi =213 m depth	CO <sub>2</sub> cc/g	CH <sub>4</sub> cc/g
Gluskoter						
lignite	9.4	25.9	800	25.0	2.7	
sub bit	7.6	20.9	900	28.1	3.7	
high vol	5	13.8	700	21.8	4.4	
medium vol	2.4	6.6	600	18.7	7.8	
low vol	2	5.5	800	25.0	12.5	
Semi anth	2.6	7.2	1000	31.2	12.0	
this paper						
Low vol	1.64	1.7	4.7	998	31.2	18.3
medium vol	1.28	1.5	4.1	550	17.2	11.4
High vol A	1.06	3.3	9.1	685	21.4	6.5
High vol B	0.7	4.7	12.9	527	16.4	3.5
High vol B	0.7	9	24.8	611	19.1	2.1

Data calculated at a pressure of 300 psi, equivalent to a depth of 210 metres.

favourable in terms of sequestering CO<sub>2</sub>. Unfortunately the CH<sub>4</sub> released is about 20 times more powerful as a greenhouse gas. Consequently unless CO<sub>2</sub> sequestration is paired with CH<sub>4</sub> recovery, there is likely to be, over the long term, a net increase in the release of greenhouse gases.

Many coals are under saturated with respect to CH<sub>4</sub> and CO<sub>2</sub>. In these cases CO<sub>2</sub> injected will initially be adsorbed without any release of CH<sub>4</sub>. The coal matrix will expand, decreasing permeability and making it even more difficult for CO<sub>2</sub> to infuse coal and for CH<sub>4</sub> to escape. In situations where the coal is partially desorbed of CH<sub>4</sub>, because of production, the pressure is reduced and there will be some matrix shrinkage hopefully to improve permeability. In this case CO<sub>2</sub> should be able to permeate coal and be adsorbed however because the coal is under saturated with respect to CH<sub>4</sub>, there may not be an immediate release of additional CH<sub>4</sub> as the pressure increases and the composition of the gas phase becomes more CO<sub>2</sub> rich.

One of the best ways of locally sequestering CO<sub>2</sub> is to inject it into abandoned or mature CBM wells. It is possible to use the CBM at site to generate electricity either by burning it or by using a fuel cell. If a relatively pure stream of CO<sub>2</sub> is derived from these processes, then it can be injected back into the CBM well to be adsorbed on under saturated coal or to replace CH<sub>4</sub> on saturated coal. As an added advantage the gas may be hot, which would increase the release of CH<sub>4</sub>. It is interesting to compare the amount of CO<sub>2</sub> produced by oxidizing or burning the CH<sub>4</sub> produced from a well with the amount of CO<sub>2</sub> that coal in the well could adsorb (Table 9). As an

example, CO<sub>2</sub> and CH<sub>4</sub> isotherms for a medium-volatile coal are used (Bustin, 2001). The two isotherms run at 25°C indicate the actual adsorption conditions at a depth where the temperature is 25°C (assumed to be 300 metres). The adsorption amounts are therefore high for depths greater than 300 metres and low for depths shallower than 300 metres. However the data do illustrate trends. The CO<sub>2</sub> derived from oxidizing the CH<sub>4</sub> produced from one tonne of coal can be adsorbed onto about 0.5 tonnes. But based on estimating the matrix shrinkage caused by desorption of CH<sub>4</sub> and expansion caused by adsorption of CO<sub>2</sub> there will be about a 2% volume increase in the tonne of coal. These estimates are made assuming densities of the adsorbed gases and may change considerably but it is probably valid to assume that there will be a matrix expansion.

Sequestration of CO<sub>2</sub> is simpler if a pure stream of CO<sub>2</sub> is obtained. Natural gas processing plants can produce relatively pure streams of CO<sub>2</sub>. Power plants and coal gasification produce mixtures of N<sub>2</sub>, CO<sub>2</sub> and other gases. However a pure stream of CO<sub>2</sub> can be obtained by trapping CO<sub>2</sub> using CaO to produce CaCO<sub>3</sub> and then liming the CaCO<sub>3</sub> in a separate reactor. The process can be self-sustaining in terms of CaCO<sub>3</sub> or may require inputs of fresh CaCO<sub>3</sub>, in which case sequestration may require a location where coal and limestone are both available. The locations of the coal deposits in British Columbia and brief description of their size and CBM potential can be found in Ryan (2003).

British Columbia releases about 63.5 million tonnes equivalent of CO<sub>2</sub> annually (Environment Canada, 2001). If this is assumed all to be CO<sub>2</sub> it is possible to estimate the amount of coal that would be required to sequester it all (Table 10) and the amount is in the range 100 to 200 billion tonnes. This amount of coal is similar to the total amount of coal in the province above a depth of 2000 (estimated to be about 250 billion tonnes). Sequestering CO<sub>2</sub> in coal will only be applicable for very specific point sources.

Sequestering CO<sub>2</sub> in coal is often discussed in the context of coal-fired power plants. Spath *et al.*, (1999) studied greenhouse gas emissions resulting from all aspects of generating electricity from coal. A present day 360 MW power plant burns about 1.4 million tonnes of coal per year. About 100 to 200 million tonnes of coal is required to sequester the CO<sub>2</sub> produced (Table 11). It is probably unrealistic to envisage the CO<sub>2</sub> produced from a power plant being sequestered in the same coal resource that is providing coal to the power plant.

One of the few places where it might be possible to sequester the CO<sub>2</sub> generated by a power plant adjacent to the plant is in the Hat Creek area in south central British Columbia. This deposit was explored by BC Hydro as a possible site for a large power plant and the area contains a large resource of lignite to sub-bituminous coal, which is estimated to be between 10 to 30 billion tonnes. Data from Gluskoter *et al.*, (2003) indicates that sub-bituminous

**TABLE 9  
COMPARISON OF THE AMOUNTS OF CH<sub>4</sub> AND CO<sub>2</sub> ADSORBED  
ONTO A MEDIUM-VOLATILE COAL OVER A RANGE OF DEPTHS**

		CH <sub>4</sub>	CO <sub>2</sub>	SG coal					1.2
SG liquid estimated		0.466	0.6	CO <sub>2</sub> from burning 1 tonne coal					
density of gas g/m <sup>3</sup>		714.3	1964	2567 Kg					
	mole wt	16	44	cc/g to scf/t					32.04
	psi	1000	800	600	400	300	200	100	
	depth metres	704	563	422	282	211	141	70	
CH <sub>4</sub>	scf/t	340	323	300	260	228	184	120	
CH <sub>4</sub>	cc/g	10.6	10.1	9.4	8.1	7.1	5.7	3.7	
CH <sub>4</sub>	wt kg /tonne	7.6	7.2	6.7	5.8	5.1	4.1	2.7	
CH <sub>4</sub>	moles	0.5	0.5	0.4	0.4	0.3	0.3	0.2	
CO <sub>2</sub>	scf/t	604.0	587.0	560.0	510.0	467.0	400.0	283.0	
CO <sub>2</sub>	cc/g	18.9	18.3	17.5	15.9	14.6	12.5	8.8	
CO <sub>2</sub>	wt kg /tonne	37.0	36.0	34.3	31.3	28.6	24.5	17.3	
CO <sub>2</sub>	moles	0.8	0.8	0.8	0.7	0.7	0.6	0.4	
CO <sub>2</sub> /CH <sub>4</sub>	volume ratio	1.8	1.8	1.9	2.0	2.0	2.2	2.4	
CO <sub>2</sub> /CH <sub>4</sub>	wieght ratio	4.9	5.0	5.1	5.4	5.6	6.0	6.5	
CO <sub>2</sub> /CH <sub>4</sub>	mole ratio	1.8	1.8	1.9	2.0	2.0	2.2	2.4	
wt kg CO <sub>2</sub>	from burning CH <sub>4</sub>	20.8	19.8	18.4	15.9	14.0	11.3	7.4	
m <sup>3</sup> vol of resultant CO <sub>2</sub>		10.6	10.1	9.4	8.1	7.1	5.7	3.7	
tonnes coal required to sequester		0.56	0.55	0.54	0.51	0.49	0.46	0.42	
liquid vol m <sup>3</sup> /t of adsorbed CH <sub>4</sub>		0.016	0.015	0.014	0.012	0.011	0.009	0.006	
liquid vol m <sup>3</sup> /t adsorbed CO <sub>2</sub>		0.062	0.060	0.057	0.052	0.048	0.041	0.029	
% vol increase if all CH <sub>4</sub> desorbed and replaced by CO <sub>2</sub>		5.453	5.343	5.144	4.76	4.417	3.848	2.781	
liquid volume m <sup>3</sup> /t of CO <sub>2</sub> resultant from burning CH <sub>4</sub>		0.035	0.033	0.031	0.027	0.023	0.019	0.012	
% volume change if CO <sub>2</sub> adsorbed onto 1 tonne coal		2.2	2.1	2.0	1.7	1.5	1.2	0.8	

Data is approximate in part because isotherms do not recognize the change of temperature with depth.

**TABLE 10  
THE AMOUNT OF COAL REQUIRED TO SEQUESTER THE  
CO<sub>2</sub> PRODUCED IN BRITISH COLUMBIA IN ONE YEAR**

British Columbia CO <sub>2</sub> equivalent emissions (million tonnes per year (1999))	63.8	estimated assuming all greenhouse gas CO <sub>2</sub>					
CO <sub>2</sub> produced (billion cubic metres per year)	32.5						
depth (metres)	704	563	422	282	211	141	70
CO <sub>2</sub> adsorption cubic metres/tonne billion tonnes of coal to sequester	18.9	18.3	17.5	15.9	14.6	12.5	8.8
CO <sub>2</sub> produced in 1 year	91	94	98	108	118	137	194

Estimated using 1999 data.

**TABLE 11**  
**THE AMOUNT OF COAL REQUIRED TO SEQUESTER**  
**THE CO<sub>2</sub> PRODUCED BY A 360 MW POWER PLANT**

coal fired power plant MW	360						
efficiency %	32						
coal consumption/yr million tonnes	1.413						
% carbon	65						
CO <sub>2</sub> produced million tonnes	3.37						
CO <sub>2</sub> produced million cubic metres	1715						
depth metres	704	563	422	282	211	141	70
adsorption cubic metres/tonne	18.9	18.3	17.5	15.9	14.6	12.5	8.8
million tonnes of coal to sequester CO <sub>2</sub>	91	94	98	108	118	137	194
ratio coal needed for sequestering versus coal burnt	64	66	69	76	83	97	137

Data from Spath et. al. (1999).

and lignite coals can adsorb about 10 cc/g CO<sub>2</sub> at intermediate depths (300 metres). When this is compared to the amount of carbon in the coal it is apparent that, for a tonne of coal burnt, the amount of CO<sub>2</sub> produced is less than for high rank coals and can be sequestered in fewer tonnes of in situ coal. At Hat Creek coal delivered to a power plant would be less than 30% carbon and would require less than 100 tonnes in situ to sequester the CO<sub>2</sub> produced from 1 tonne burned. Because of the size of the Hat Creek resource, a power plant using 10 million tonnes/year for 25 years would require about 25 billion tonnes to sequester the CO<sub>2</sub> generated. The sequestering of CO<sub>2</sub> may also result in the recovery of CH<sub>4</sub> that can be used in the power plant or sold as natural gas.

Isotopic studies of the C<sup>13</sup>/C<sup>12</sup> isotopic ratios of CBM indicate that the gas is often a mixture of biogenic and thermogenic methane. Biogenic methane may originate from early coalification or during uplift of the coal bearing formation. Generation of biogenic methane requires a consortium of bacteria and a series of biochemical reactions that in part require H<sub>2</sub> and CO<sub>2</sub>. This raises the possibility that injection of CO<sub>2</sub>, if associated with bacteria or nutrients may stimulate generation of biogenic methane at the same time that CO<sub>2</sub> is sequestered (Budwill, 2003). The best candidates for synchronous CO<sub>2</sub> sequestration and generation of biogenic methane are low rank coals at shallow depth. Deposits such as Coal River or Tuya River as well as the much larger Hat Creek deposit could be candidates.

## CONCLUSIONS

The connection is made; climate change is at least in part related to increasing concentration of CO<sub>2</sub> in the atmosphere and we are responsible for the most recent increase. The incentive to limit fossil fuel use or sequester the CO<sub>2</sub> produced by fossil fuel use is here and will not go away.

Sequestration of CO<sub>2</sub> in coal seams requires a clear understanding of the CO<sub>2</sub> phase diagram and the implications for the maximum depth of sequestration. The maximum depth varies based on combinations of geothermal and pressure gradients but is generally in the range of 500 to 900 metres. Below this depth and in part above it, CO<sub>2</sub> goes into solution in coal and causes an increase in plasticity and swelling (Larson, 2004).

It is essential to understand the CO<sub>2</sub> and CH<sub>4</sub> adsorption behaviour in coals of different ranks and for different combinations of temperature and pressure. The mole ratio of CO<sub>2</sub>/CH<sub>4</sub> adsorption varies from over 10 for low rank coals to under 2 for medium and high rank coals. The CO<sub>2</sub> adsorption is moderately high for low rank coals, decreases for medium rank coals and then increases substantially for high rank coals. The interaction of adsorption and selectivity of CO<sub>2</sub> and CH<sub>4</sub> means that for maximum CO<sub>2</sub> sequestration with minimum production of CH<sub>4</sub> one should use lignite whereas for maximum sequestration of CO<sub>2</sub> with maximum production of CH<sub>4</sub> one should use a high rank coal.

Sequestration of CO<sub>2</sub> without collection of the released CH<sub>4</sub> may result in a net increase in the emission of green house gases over time.

Actual sequestration of CO<sub>2</sub> and release of CH<sub>4</sub> is predicted by binary gas isotherms and may not obey the extended Langmuir Equation. It will also be influenced by permeability, matrix swelling and initial saturation.

Conditions of sequestration of CO<sub>2</sub> in coal may best be applied to small point sources; as an example where CBM is being burned on site to produce electricity.

Most discussions of CO<sub>2</sub> sequestration do not consider the implications of an impure gas stream composed of CO<sub>2</sub> and N<sub>2</sub>. Addition of N<sub>2</sub> to the gas decreases the adsorption of CO<sub>2</sub>.

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