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COALBED METHANE: A COMPARISON BETWEEN CANADA AND THE UNITED STATES

F.M. Dawson

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Cover Illustration

Methane gas bubbling to the surface from the base of the Anderson coal seam, Eagle Butte Mine, near Gillette, Wyoming.

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PREFACE

Canada is blessed with abundant coal resources, many of which lie at depths too great to be considered for conventional mining. These resources, however, contain substantial volumes of methane gas that represent a significant portion of the total natural gas resources for the country. Canadian coalbed methane resources are undeveloped at present in contrast to the United States where coalbed methane has been in production since the mid 1970s. Exploration for coalbed methane in Canada began in the late 1980s with most of the activity concentrated in Nova Scotia, Alberta and southeastern British Columbia.

This paper presents a summary of the geological framework of the San Juan and Black Warrior basins, the two major coalbed methane producing basins in the United States, and provides a geological overview of the potential coalbed methane basins in Canada for comparison.

Critical geological and production factors are discussed and an assessment of the coalbed methane opportunities in Canada is presented, providing a valuable reference for industry to use in future coalbed methane exploration activities.

Elkanah A. Babcock
Assistant Deputy Minister
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PRÉFACE

Au Canada, les ressources en charbon sont abondantes; cependant, une bonne partie se trouve beaucoup trop en profondeur pour être exploitée par les méthodes classiques. De plus, les ressources renferment un volume important de méthane, lequel correspond à une part considérable des ressources totales en gaz naturel au pays. Le méthane dans les couches de charbon est actuellement inexploité au Canada, alors qu'aux États-Unis, il est mis en valeur depuis le milieu des années soixante-dix. C'est à la fin des années quatre-vingts qu'a commencé l'exploration visant à trouver du méthane dans les couches de charbon. Elle s'est surtout concentrée en Nouvelle-Écosse, en Alberta et dans le sud-est de la Colombie-Britannique.

Le présent document décrit sommairement le contexte géologique des bassins de San Juan et de Black Warrior, les deux plus importantes sources de méthane dans les couches de charbon en exploitation aux États-Unis, et le compare à ceux des bassins houillers du Canada les plus propices à contenir ce combustible.

Sont considérés les facteurs géologiques et techniques importants, mais aussi évaluées les possibilités d'exploitation de méthane dans les couches de charbon au Canada, procurant ainsi à l'industrie un précieux outil de référence pour les futurs travaux d'exploration pour ce combustible.

Elkanah A. Babcock
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Abstract

Coalbed methane is rapidly becoming a major source of natural gas hydrocarbons in the United States. Cumulative annual gas production was in excess of 550 BCF (end of 1992) and technically recoverable resource estimates for the United States are placed at 62 to 135 TCF.

Canada also contains abundant coal resources spread throughout numerous basins in British Columbia, Alberta, Saskatchewan, the Maritimes, Yukon and the Northwest Territories. Many of these basins contain coal of suitable quality and at sufficient depth to be considered for coalbed methane reservoirs, but the coalbed methane resource potential is essentially undefined.

Although limited exploration for coalbed methane resources has been ongoing since the late 1970s and in excess of 80 boreholes have been drilled to test for coalbed methane, only one well is currently in production.

This paper presents a detailed overview of the geological characteristics of the San Juan and Black Warrior basins of the United States and highlights geological criteria that have allowed the development of economic coalbed methane production from these regions.

A similar overview of the major Canadian coal basins and their coalbed methane potential is also presented. Using a set of numerical criteria based upon cumulative coal thickness and theoretical gas capacity, the Canadian coal basins are ranked to highlight the regions with the highest coalbed methane potential.

The paper also presents a general discussion on production parameters such as coal quality and maceral composition, depth of reservoir, water tables and reservoir pressures, reservoir permeability, and infrastructure. These elements are of equal importance to the coal seam's thickness and gas content in the successful development of an economic coalbed methane well.

Résumé

Aux États-Unis, le méthane dans les couches de charbon devient rapidement une importante source d'hydrocarbures gazeux. La production annuelle totale de gaz dépassait 550 milliards de pieds cubes à la fin de 1992 et les estimations des ressources techniquement récupérables aux États-Unis se situent entre 62 et 135 billions de pieds cubes.

Le Canada possède également d'abondantes ressources en charbon réparties entre de nombreux bassins en Colombie-Britannique, en Alberta, en Saskatchewan, dans les Maritimes, au Yukon et dans les Territoires du Nord-Ouest. Par la qualité et la profondeur de leur charbon, beaucoup de ces bassins pourraient être considérés comme des réservoirs de méthane dans les couches de charbon, mais le potentiel en ressources de ce combustible n'est pratiquement pas défini.

Bien que le méthane dans les couches de charbon ait fait l'objet de travaux d'exploration depuis la fin des années soixante-dix et que plus de 80 sondages aient été effectués à cette fin, un seul puits est actuellement en exploitation.

Le présent document donne un aperçu des caractéristiques géologiques des bassins de San Juan et de Black Warrior, aux États-Unis, et souligne les paramètres géologiques qui ont permis d'en venir à une mise en valeur économique à partir du méthane dans les couches de charbon de ces régions.

De même, on dresse un portrait des grands bassins houillers du Canada et de leur potentiel en méthane dans les couches de charbon. À l'aide d'un ensemble de paramètres numériques fondés sur l'épaisseur totale de charbon et la capacité théorique en gaz, les bassins houillers canadiens sont classés afin de mettre en évidence les régions qui présentent le meilleur potentiel.

Le document traite également des paramètres de production comme la qualité du charbon, sa composition macérale, la profondeur du réservoir, la pression hydrostatique et celle du réservoir, sans oublier la perméabilité du réservoir et les infrastructures en place. Ces paramètres sont aussi importants que l'épaisseur et la teneur en gaz des couches de charbon lorsqu'il s'agit du succès de la mise en valeur d'un puits de méthane.

Summary

Coalbed methane is rapidly becoming a major source of natural gas hydrocarbons in the United States. Cumulative annual gas production was in excess of 550 BCF (end of 1992) and coalbed gas accounted for up to 20 per cent of New Mexico's hydrocarbon production. Technically recoverable resource estimates for the United States are placed at 62 to 135 TCF.

Canada also contains abundant coal resources spread throughout numerous basins in British Columbia, Alberta, Saskatchewan, the Maritimes, Yukon and the Northwest Territories. Many of these basins contain coal of suitable quality and at sufficient depth to be considered for coalbed methane reservoirs. In most of the coal-bearing basins, the distribution of the coals is well defined at or near the surface, in response to the historical mining of coal for domestic or export utilization. However, the coals that lie at depth are poorly defined, both qualitatively and volumetrically, leading to a high degree of uncertainty in resource estimates for coalbed methane resources. Coupled with a general lack of knowledge of the actual gas contents and gas capacities of the coal, the resource potential of coalbed methane in Canada is essentially undefined.

Although limited exploration for coalbed methane resources has been ongoing since the late 1970s and in excess of 80 boreholes have been drilled to test for coalbed methane, only one well is currently in production. Current exploration efforts by various oil and gas companies have, for the most part, been centred in southeastern British Columbia, central Alberta and the Cumberland Basin of Nova Scotia.

The first section of this paper presents a detailed overview of the geological characteristics of the San Juan and Black Warrior basins of the United States and highlights geological criteria that have allowed the development of economic coalbed methane production in these regions.

The second section provides a similar overview of the major coal basins of Canada and highlights the coalbed methane potential of each. Gas capacity values of adsorbed methane, where available, and theoretical gas capacity values based upon representative coal quality are presented for a depth range for each basin. These values represent the theoretical gas capacity of the coal that may be present based upon depth, coal quality, and coal rank. Actual gas contents that are present in situ may vary dependent on local geological conditions.

Using a set of numerical criteria based upon cumulative coal thickness and theoretical gas capacity, the coal basins are ranked to highlight the regions with the highest coalbed methane potential. The ranking system places the highest potential on the coal deposits of the foothills and mountain regions of southeastern and northeastern British Columbia. Criteria used in this preliminary assessment (cumulative seam thickness and gas capacity) are restricted to the geology of the potential reservoir. If other production criteria such as permeability and infrastructure are imposed, the ranking of the basins may change slightly.

The third section of the paper presents a general discussion on production parameters such as coal quality and maceral composition, depth of reservoir, water tables and reservoir pressures, reservoir permeability, and infrastructure. These elements are of equal importance to the coal seam's thickness and gas content in the successful development of an economic coalbed methane well.

Sommaire

Aux États-Unis, le méthane dans les couches de charbon devient rapidement une importante source d'hydrocarbures gazeux. La production annuelle totale de gaz dépassait 550 milliards de pieds cubes à la fin de 1992 et le gaz dans les couches de charbon représentait jusqu'à 20 p. 100 de la production d'hydrocarbures au Nouveau-Mexique. Les estimations des ressources techniquement récupérables aux États-Unis se situent entre 62 et 135 billions de pieds cubes.

Le Canada possède également d'abondantes ressources en charbon réparties entre de nombreux bassins en Colombie-Britannique, en Alberta, en Saskatchewan, dans les Maritimes, au Yukon et dans les Territoires du Nord-Ouest. Par la qualité et la profondeur de leur charbon, beaucoup de ces bassins pourraient être considérés comme des réservoirs de méthane dans les couches de charbon. Dans la plupart des bassins houillers, la répartition des charbons est bien définie en surface et près de la surface, l'exploitation de ce combustible à des fins d'exportation ou de consommation intérieure étant un fait historique. Cependant, la qualité et le volume des charbons en profondeur sont mal définis, ce qui a pour effet de rendre très incertaine l'évaluation des ressources en méthane dans les couches de charbon. Cette incertitude conjuguée à une absence générale de connaissances sur la teneur en gaz et la capacité en gaz du charbon fait que le potentiel en ressources de ce combustible n'est pratiquement pas défini.

Bien que le méthane dans les couches de charbon ait fait l'objet de travaux d'exploration depuis la fin des années soixante-dix et que plus de 80 sondages aient été effectués à cette fin, un seul puits est actuellement en exploitation. Pour le moment, les diverses sociétés pétrolières et gazières qui s'intéressent au méthane dans les couches de charbon ont surtout concentré leurs efforts d'exploration dans le sud-est de la Colombie-Britannique, dans le centre de l'Alberta et dans le bassin de Cumberland de la Nouvelle-Écosse.

La première partie du présent document donne un aperçu des caractéristiques géologiques des bassins de San Juan et de Black Warrior, aux États-Unis, et souligne les paramètres géologiques qui ont permis d'en venir à une mise en valeur économique du méthane dans les couches de charbon de ces régions.

De même, dans la deuxième partie, on dresse un portrait des grands bassins houillers au Canada et de leur potentiel en méthane dans les couches de charbon. On donne, pour une gamme de profondeurs et pour chacun des bassins, la valeur de la capacité en gaz du méthane adsorbé, lorsqu'elle existe, et celle de la capacité théorique en gaz correspondant à une qualité de charbon

représentative. Ces valeurs représentent la capacité théorique en gaz du charbon susceptible d'être présent selon la profondeur, la qualité et le rang du charbon. Les teneurs réelles en gaz in situ peuvent varier selon les conditions géologiques locales.

À l'aide d'un ensemble de paramètres numériques fondés sur l'épaisseur totale de charbon et la capacité théorique en gaz, les bassins houillers canadiens sont classés afin de mettre en évidence les régions qui présentent le meilleur potentiel. Selon le système de classification, ce sont les gisements de charbon des régions montagneuses et des contreforts des parties sud-est et nord-est de la Colombie-Britannique qui remportent la palme. Les paramètres utilisés dans cette évaluation provisoire (épaisseur totale des couches et capacité en gaz) sont limités à la géologie de l'éventuel réservoir. Si on fait entrer en ligne de compte d'autres paramètres de production comme la perméabilité et les infrastructures existantes, la classification des bassins peut changer légèrement.

La troisième partie traite des paramètres de production comme la qualité du charbon, sa composition macérale, la profondeur du réservoir, la pression hydrostatique et celle du réservoir, sans oublier la perméabilité du réservoir et les infrastructures en place. Ces paramètres sont aussi importants que l'épaisseur et la teneur en gaz des couches de charbon lorsqu'il s'agit du succès de la mise en valeur d'un puits de méthane.

INTRODUCTION

Exploration activity for coalbed methane (CBM) in the United States, primarily as a result of the Section 29 Tax Credit, has led to the growth of coalbed methane production from a minor resource in the 1970s to a major source of natural gas in the 1990s. Coalbed methane production accounts for over 10% of total natural gas production in Colorado and 20% in New Mexico. To date, over 5000 coalbed methane wells have been permitted in the United States. Cumulative gas production to the end of 1992 was in excess of 15.6 x $10^9 m^3$ (550 BCF); equivalent to almost 50% of Canada's gas exports to the United States (Gas Research Institute, 1993). In Canada, the prospect of similar gas resources and production capability has led to new exploration efforts in Western Canada and the Maritimes to tap the potential coalbed methane resources that may lie at depth within the Western Canada Sedimentary Basin and the Cumberland, Pictou and Sydney basins of Nova Scotia.

This report will outline and compare the geological setting of the coal resources from the two major coalbed methane producing basins in the United States (San Juan and Black Warrior) with the coal distribution and resources of Canada.

Numerous studies have been completed that have provided an assessment of the coalbed methane potential of various basins of the United States but to date no compilation has been undertaken in Canada. Regional coalbed methane assessment reports have been completed for the foothills and mountain regions of southeastern and northeastern British Columbia for the B.C. government. In Alberta, several overview papers prepared by the Alberta Geological Survey have addressed the coalbed methane potential for the Alberta Plains, while in Nova Scotia a preliminary assessment has been completed based upon exploration work conducted in the Cumberland Basin. These reports are very general in scope and were prepared prior to significant adsorption and desorption data being available. Previously reported resource estimates should be used with caution. It is the opinion of the author that a reliable assessment of Canadian coalbed methane potential is not possible at the present time because fundamental resource information, such as estimates of coal volumes and gas contents for potential Canadian coalbed methane reservoirs, has not been evaluated. As a result, the comparative elements of this report will be restricted to geological criteria, such as coal distribution, seam depth and thickness, petrographic characteristics, structural setting and theoretical gas capacity.

UNITED STATES COAL BASINS

The continental United States contains numerous coal basins ranging in age from Pennsylvanian to Paleocene (Fig. 1). Conservative estimates of in situ coalbed methane resources and number of producing wells (Gas Research Institute, 1993) are summarized in Table 1. Exploration for coalbed methane in the United States has been conducted in many of these basins, but most activity and subsequent coalbed methane production has occurred in two major basins, the San Juan in the western United States and the Black Warrior in the eastern United States. The geological setting, age of formation and resource potential for these two basins essentially encompass the range and type of coalbed methane production in the United States and serve as good benchmarks to compare with similar types of basins in Canada.

Table 1

Coalbed methane resource estimates for major coal-bearing basins of the United States

Basin	Number of Producing Wells (Dec. 1992)	1992 Coalbed Methane Production (BCF)
Western Basin		
San Juan	2087	436
Piceance	95	3.2
Powder River	29	0.9
Uinta	8	0.2
Green River	9	0.02
Raton	0	0
Western Washington	0	0
Western Interior Coal Region		
Arkoma	103*	1.9**
Cherokee	232*	5**
Forest City	10*	0.1**
Eastern Basins		
Black Warrior	2627	91.8
Central Appalachian	287	10.5**
Northern Appalachian	6	0.03**
Illinois	4	0.08**
Total	**5497**	**550**

*Estimated from number of wells drilled and completed and from operator information.
**Estimated from number of producing wells and from operator information on average production per well.

San Juan Basin

The San Juan Basin is located near the "Four Corners" region of the southwestern United States (Fig. 2) and forms an elliptical basin roughly 160 km long by 150 km wide (Choate et al., 1984). Most of the basin lies within northern New Mexico and southern Colorado. The basin is bounded on the east by the

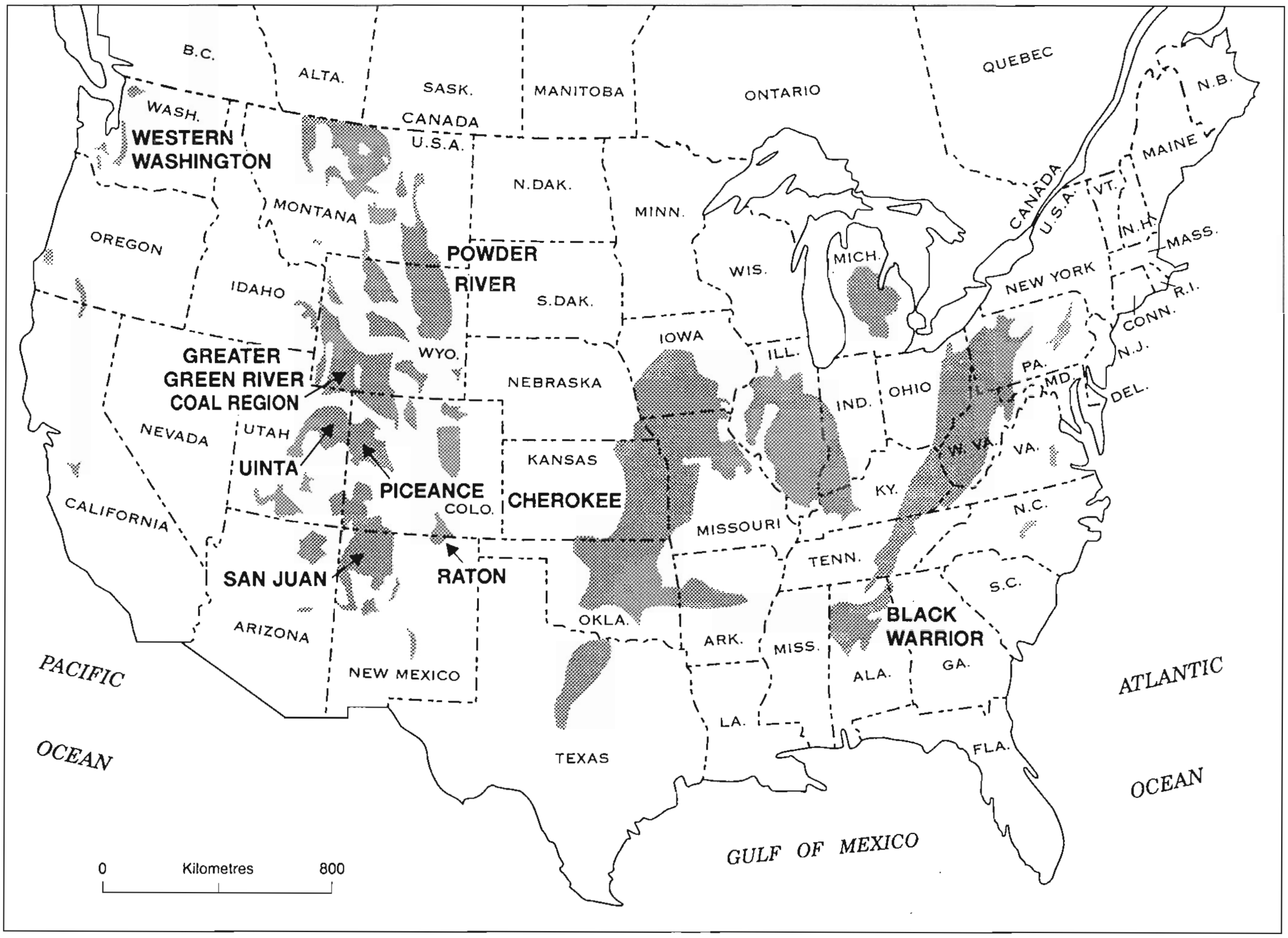

Figure 1. *Major coal basins of the continental United States (from Gas Research Institute, 1993).*

Nacimiento and Archuleta uplifts and on the west by the Defiance and Zuni uplifts. The limits of the San Juan Basin are generally defined by the surface outcrops of the Upper Cretaceous Fruitland Formation. Older sediments extend beyond these defined limits but in the context of this paper the basin margins will be constrained by the Fruitland Formation (op. cit.). The rocks of the San Juan Basin are mostly of Cretaceous and Tertiary age, sedimentary in origin and form broad plateaus and mesas dissected by steep canyons. The land is very arid, mostly consisting of scrub, brush and desert. One major river, the San Juan, cuts through the northern part of the basin.

Stratigraphy

The San Juan Basin forms an asymmetrical synclinal basin, the axis of which trends essentially southeast, from Durango, Colorado into New Mexico. To the northeast, the San Juan Mountains form the edge of the basin with coal-bearing strata dipping steeply to the southwest. In the south, the beds dip gently to the north. Gentle folds and minor normal faulting occur throughout the basin.

During the Late Cretaceous, the region of the San Juan basin lay along the edge of the Western Interior Seaway, giving rise to sedimentary strata being deposited in coastal conditions (Ayers and Kaiser, 1992). The principal coal-bearing formations of the basin are the Upper Cretaceous Fruitland and Menefee formations. Strata consist of interbedded sandstone, siltstone, shale and coal of both marine and nonmarine origin. Both formations lie above coarsening upward sandstone sequences (Pictured Cliffs and Point Lookout formations), which represent marginal marine/shoreline conditions above the underlying thick marine strata of the Lewis and Mancos shales respectively (Choate et al., 1984). The Pictured Cliffs

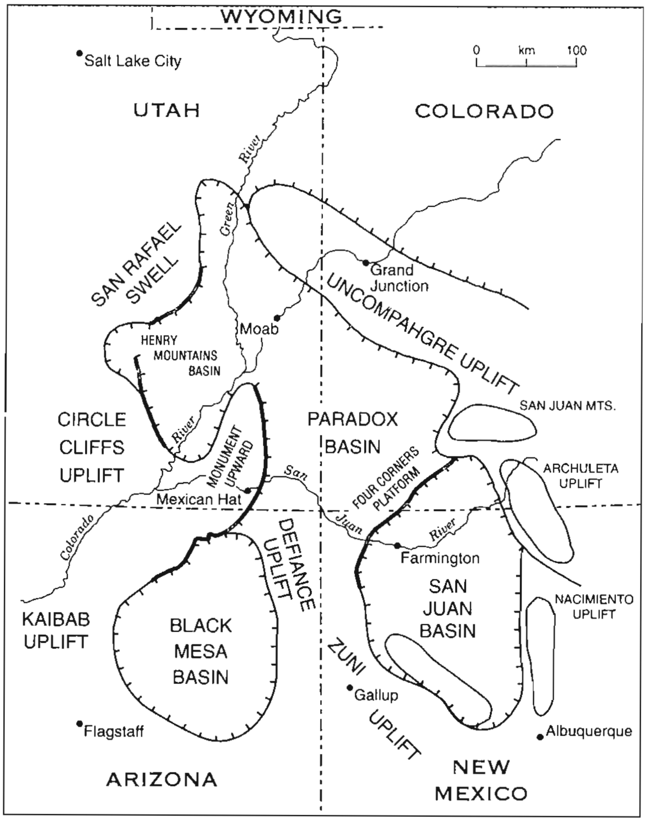

Figure 2. *Four Corners area: major uplifts and basins (after Peterson et al., 1965).*

and Point Lookout formations form the shoreline barrier behind which the peat deposits of the Fruitland and Meneffee formations were deposited. Coals of the Meneffee Formation are thin and discontinuous and will not be considered in this report.

The central portion of the basin, as exemplified by structural contours on the Huerfanito Bentonite bed (at the base of the Pictured Cliffs Formation) lies near the Colorado/New Mexico border and is orientated in a northwest direction (Fig. 3; Fassett, 1987). Along the southwest edge of the depocentre, a structural hingeline is inferred, possibly representing a series of basin-wide normal faults which appear to have controlled the rate of sedimentation in the basin. North of this structure, the basin flattens, whereas to the southwest it appears to have had a relatively constant slope to the northeast. It is postulated that the hingeline is responsible for the stacking of the Pictured Cliffs shoreline sandstone deposits prior to the deposition of the Fruitland Formation immediately to the north of the inferred structure. This, in turn, allowed thick peat deposits to form immediately shoreward due to the stalling of the progradation of continental facies and resulted in the formation of thick coals trending in a northwest direction parallel to the sandstones of the Pictured Cliffs Formation (Ayers and Kaiser, 1992).

The Fruitland Formation averages 100 m thick, with most of the productive coal zones within the lower half of the stratigraphic interval (Fig. 4). The coals have been divided into four major groups, A to D, with the most extensive coals lying within group C (Fig. 5). Isopach maps of the Pictured Cliffs Formation clearly demonstrate the relationship between underlying sandstone thickness and coal distribution (Ayers and Kaiser, 1992). The sediments are believed to have prograded in a northeasterly direction into the interior seaway, giving rise to strandline and beach deposits oriented in a northwest-southeast direction. Coals within the Fruitland Formation are oriented in a northwest direction, with a northeast directional overprinting due to local depositional features. The maximum number and thickness of coal seams in local depocentres are separated by northeast-trending channel sediments. Within these areas, 8 to 14 seams are present, with the total net coal thickness exceeding 25 m. Seam thicknesses range from 2 to 10 m, averaging 4 to 5 m. The coals are laterally continuous within these local depocentres but thin toward the margins within these small areas (Fig. 6), and to the southwest and northeast parts of the basin (Fig. 7).

Structural geology

The San Juan Basin is asymmetrical in shape with steeply dipping beds (40–60°) northeast of the basin axis and beds dipping less than 10° in the southwest. The axis of the basin trends northwest, extending from northwestern New Mexico to southwestern Colorado. The structural hingeline often reported in geological papers appears to contain a series of normal faults paralleling the basin's axis (Ambrose and Ayers, 1991). Vertical displacement along these faults is commonly greater than 70 m and offsets the coals of the Fruitland Formation (Fig. 8). Smaller scale antiforms and synforms plunge into the main structural axis on the flanks of the basin axis. Relief on these secondary structures ranges from 15 to 30 m in amplitude. These features, along with the normal faults of the hingeline, appear to be the main controlling mechanisms for the local regions of enhanced permeability and overpressured regimes for the coalbed methane production in the San Juan Basin. The Fruitland Formation coals extend from outcrop to greater than 1200 m depth. Much of the coalbed methane production occurs between depths of 900 to 1050 m.

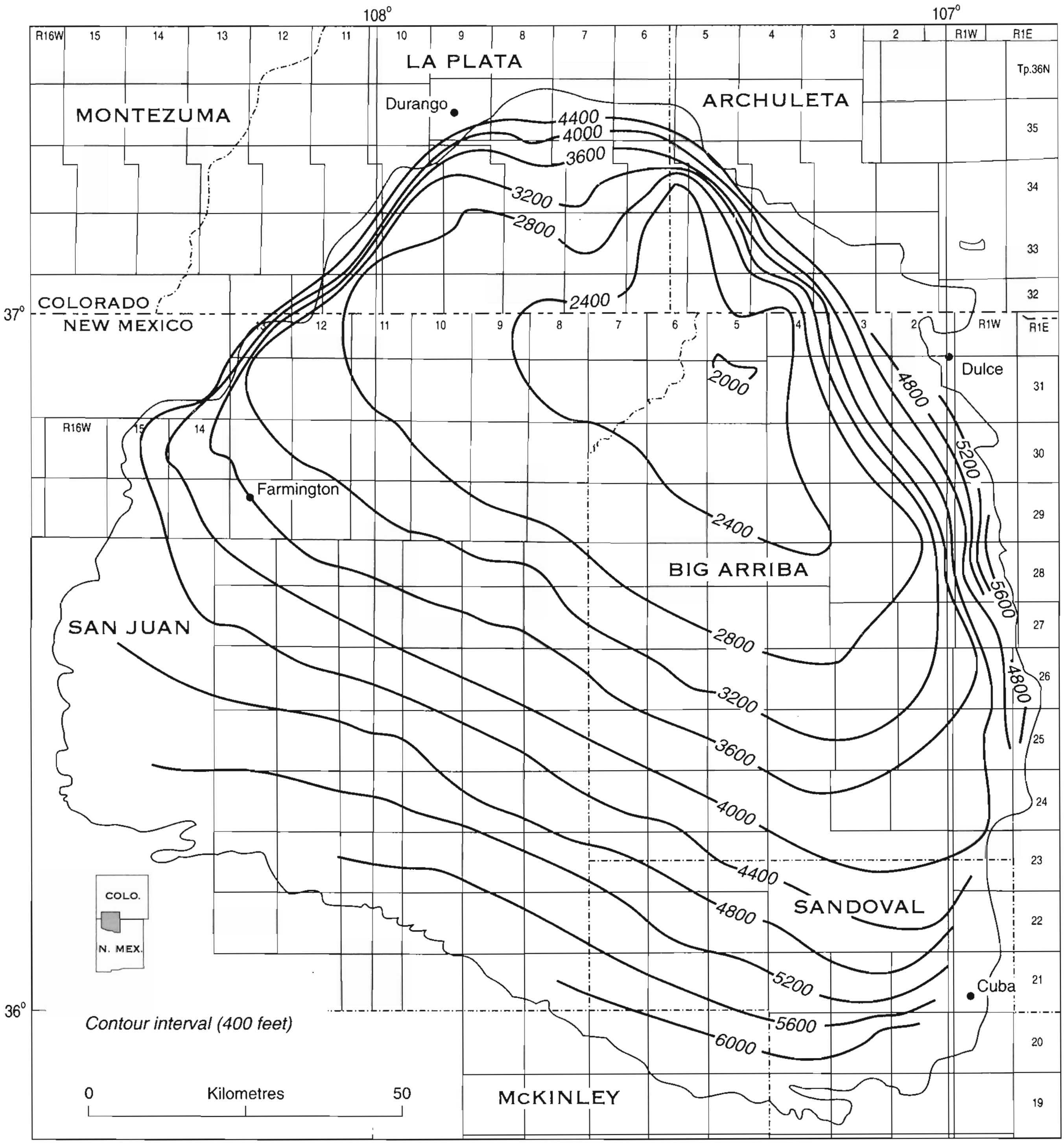

Figure 3. *Structure contour map of the Huerfanito Bentonite bed (after Fassett, 1987).*

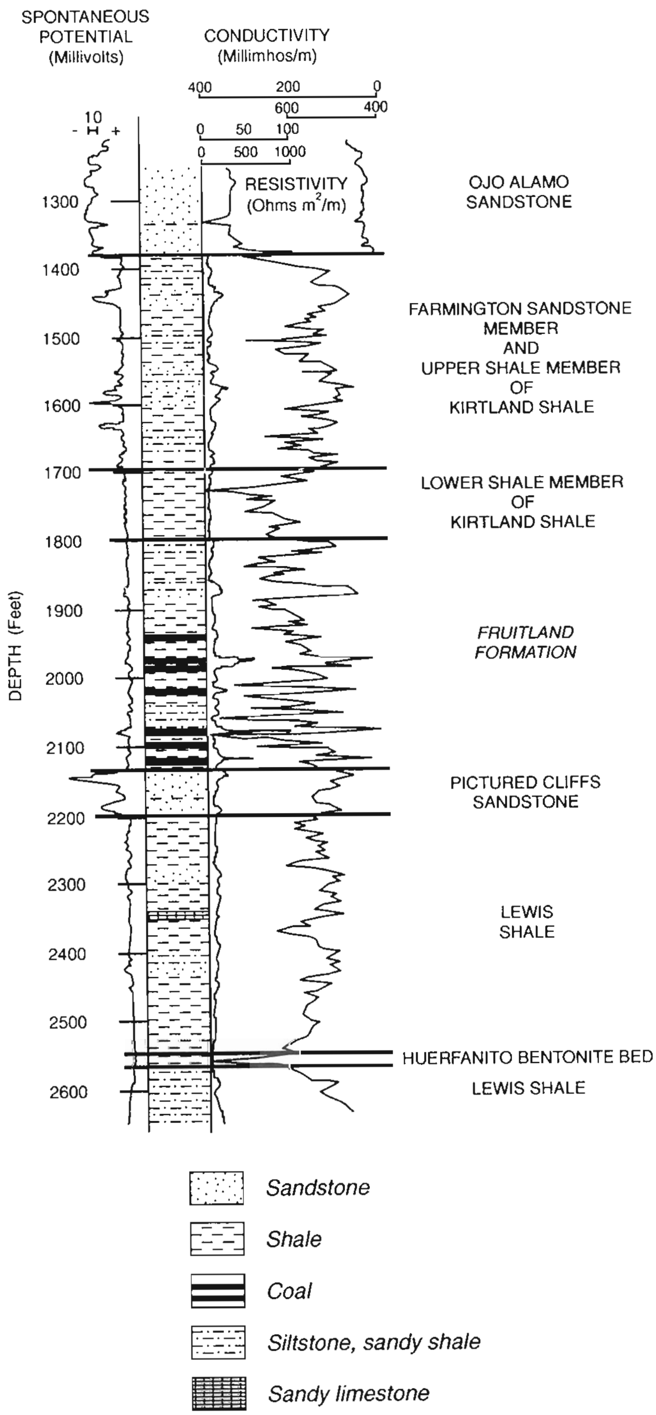

Figure 4. *Generalized stratigraphic section of the Fruitland Formation, San Juan Basin (from Fassett, 1987).*

Coal quality

The coals of the Fruitland Formation range from subbituminous B to medium volatile bituminous rank. Coal rank increases from outcrop toward the central portion of the basin, consistent with the increase in overburden depths. Rank trends parallel the structure contours of the basin, with the highest rank attained in the basin axis near the Colorado/New Mexico border (Fig. 9). Ash content for the coals ranges from 15% to 30%.

Coalbed methane potential

Large volumes of coalbed methane being produced from single wells or small fields has drawn attention to the San Juan Basin, and to some extent, spurred worldwide exploration for coalbed methane. Unique geological and hydrological conditions appear to have combined to produce local reservoirs that enable large volumes of coalbed methane to be produced. Sustained production rates in excess of 28.3 x $10^3m^3/d$ (1 MMCF/d) have been recorded from numerous wells, with maximum production in excess of 424 800 m^3/d (15 MMCF/d). Daily production rates are widely variable throughout producing fields with most of the wells producing in the 8500 to 16 990 m^3/d (300-600 MCF/d) range. Prior to 1993, in excess of 1900 coalbed methane wells were producing from the basin with total annual gas production exceeding 12.17 x 10^9m^3 (430 BCF) (Gas Research Institute, 1993).

The coals of the San Juan Basin are of a rank (high volatile B bituminous to medium volatile bituminous) that has the potential to generate and store significant volumes of coalbed methane. Gas contents range from 14.8 to 20.3 cm^3/g (dry, ash free basis; Gas Research Institute, 1993). Within the San Juan Basin, actual gas contents for Fruitland coal intersections are highly variable and dependent on gas saturation levels, residual hydrocarbons, local hydrogeology and pressure regimes.

Coalbed methane producing fields, such as the Meridian 400 and Cedar Creek fields where gas production is extremely high, appear to be located in geographical regions where coal thickness, rank, structure and hydrology have combined to allow overpressuring of the coalbed reservoir. Production from wells in these gas fields consists of high volumes of gas in addition to large volumes of formation water.

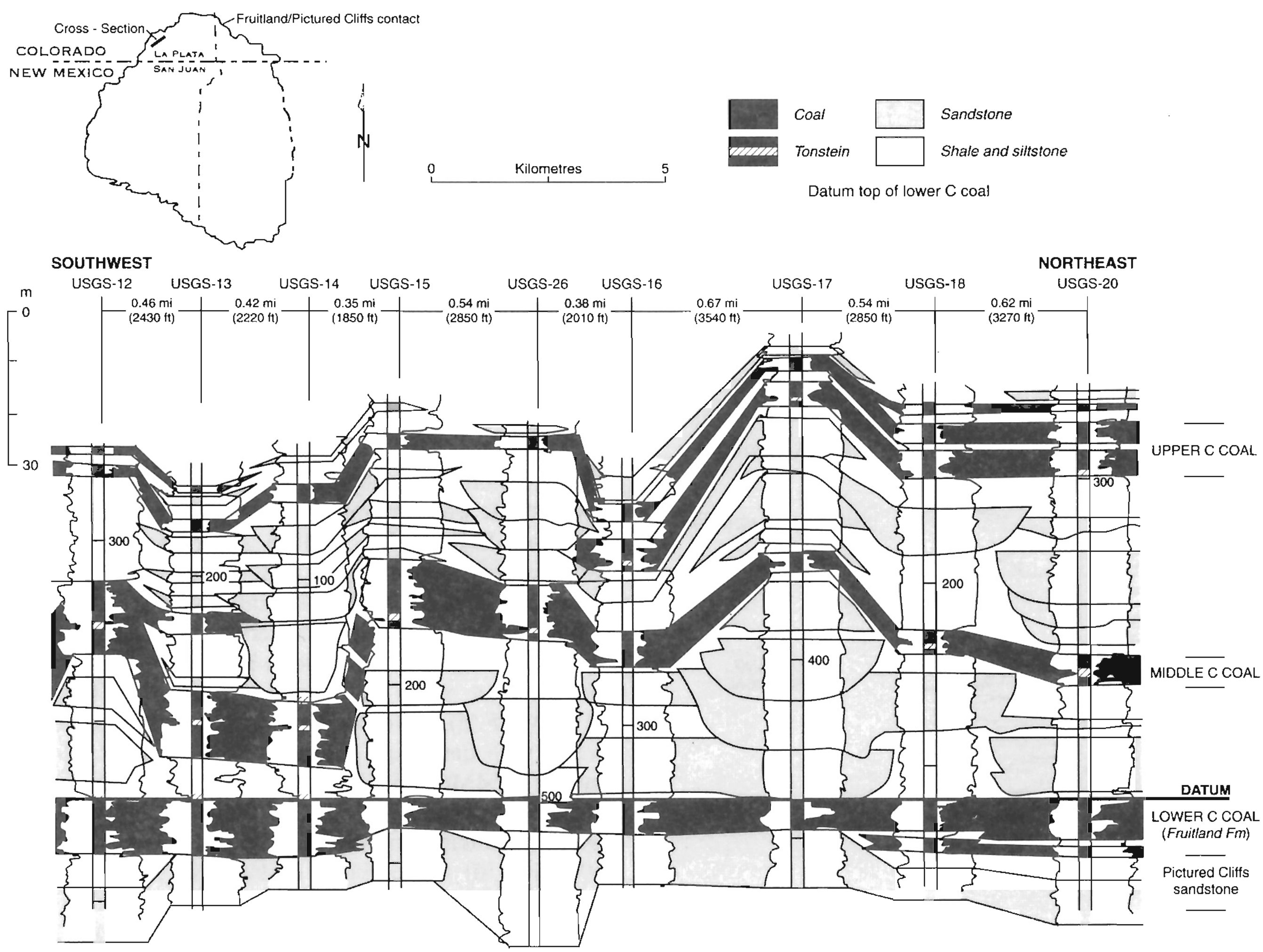

Figure 5. Detailed correlation of seams in the Fruitland C coal group (from Ambrose and Ayers, 1991).

A structural analysis of the basin by the Texas Bureau of Economic Geology (Ayers et al., 1991) suggests that the overpressuring of the Fruitland Formation at depth is caused by the hydrological recharge of the basin from the San Juan Mountains in the north. Immediately to the south of the major producing fields, the northwest trending normal faults have displaced the Fruitland coals, thus forming an impermeable barrier to the hydrologic flow pattern of the groundwater. This structural offset has created a zone of high hydrological pressure with corresponding high coalbed methane reservoir pressures, resulting in the storage of large volumes of both free and adsorbed methane gas in the coal immediately to the north of the faults. A simplified map of San Juan Basin pressure regimes illustrates the region of overpressuring north and northeast of the hingeline, in comparison to that of underpressuring to the south and southwest (Fig. 10).

In addition to the enhanced hydrogeological conditions, the areas north of the hingeline also represent the maximum coal development within the Fruitland Formation. Maximum number of seams and thickness of seams are orientated along a northwest trend parallel to the hingeline, with net coal thicknesses greater than 25 m. To the north and south of this trend, the coals tend to pinch out. Maximum gas production from the Fruitland coal reservoirs is located along this thick isopach trend.

Detailed reservoir studies indicate that the Navajo Lake area of the San Juan Basin contains local areas where conventionally trapped free gas is present within the fracture system of the coal reservoir, in addition to the adsorbed gas. In these regions, up to 425 x $10^6 m^3/d$ (15 MMCF/d) of coalbed methane has been recorded. Average gas production in the overpressured

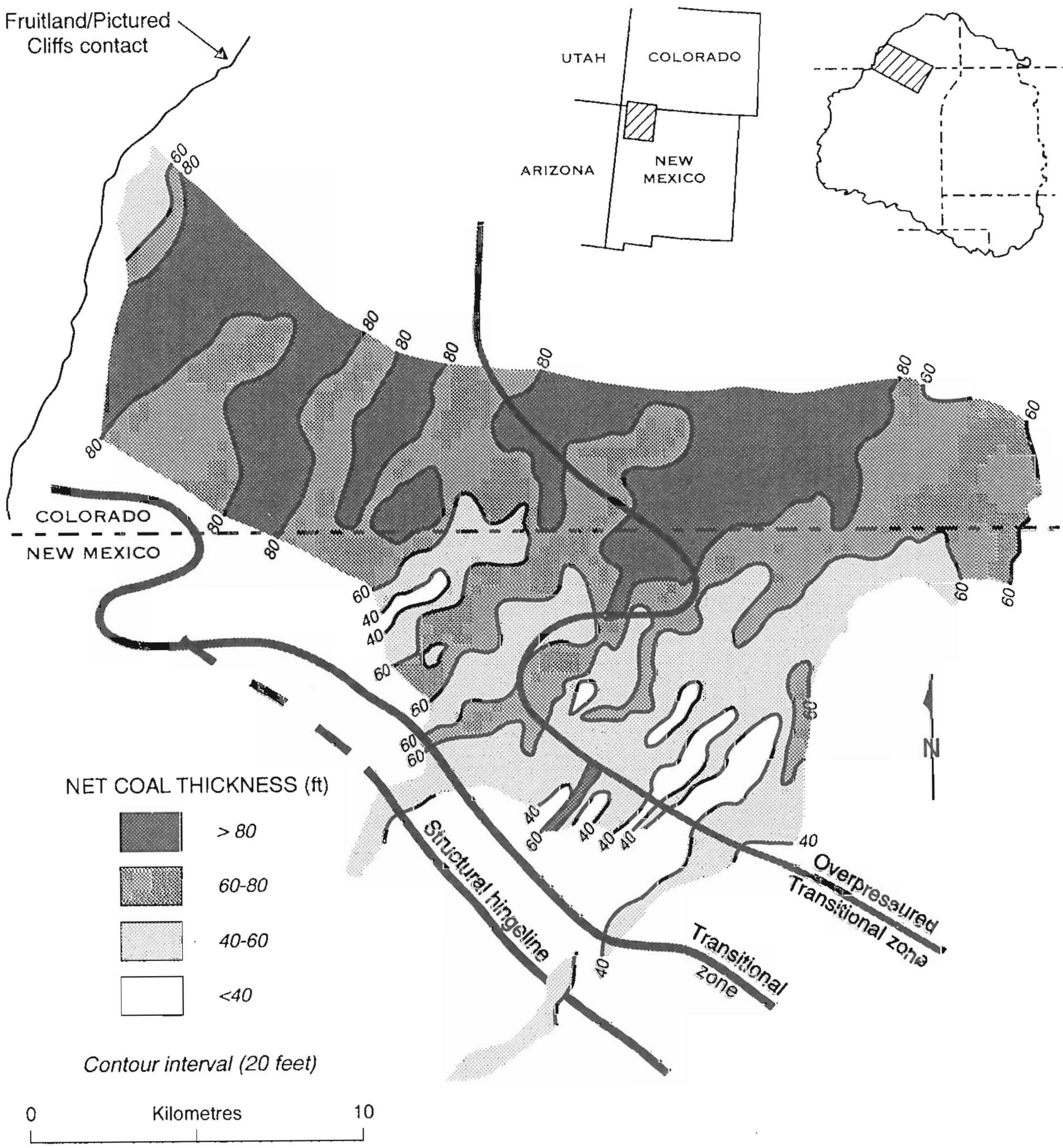

Figure 6. Isopach of regional net coal thickness in the Fruitland Formation (after Ayers, 1991).

regions where free coalbed gas is not present ranges from 8.5 to 425 x $10^3 m^3/d$ (300–15 000 MCF/d) (Ayers and Kaiser, 1992). South of the hingeline, gas production is lower, averaging less than 8.5 x $10^3 m^3/d$ (300 MCF/d).

Black Warrior Basin

The Black Warrior Basin of the eastern United States represents a foreland basin lying west of the Appalachian Orogenic belt and northeast of the Ouachita Front (Fig. 11). The basin contains Carboniferous strata partially overlain by younger sediments of the Gulf Coastal Plain. The Black Warrior Basin is roughly triangular in shape, covering approximately 91 000 km^2, and lies within northern Alabama and northeastern Mississippi (Hewitt, 1984). Throughout most of the basin, strata is flat-lying or gently inclined. Along the eastern margin, similar rocks are steeply dipping to overturned and lie within the Appalachian Fold Belt.

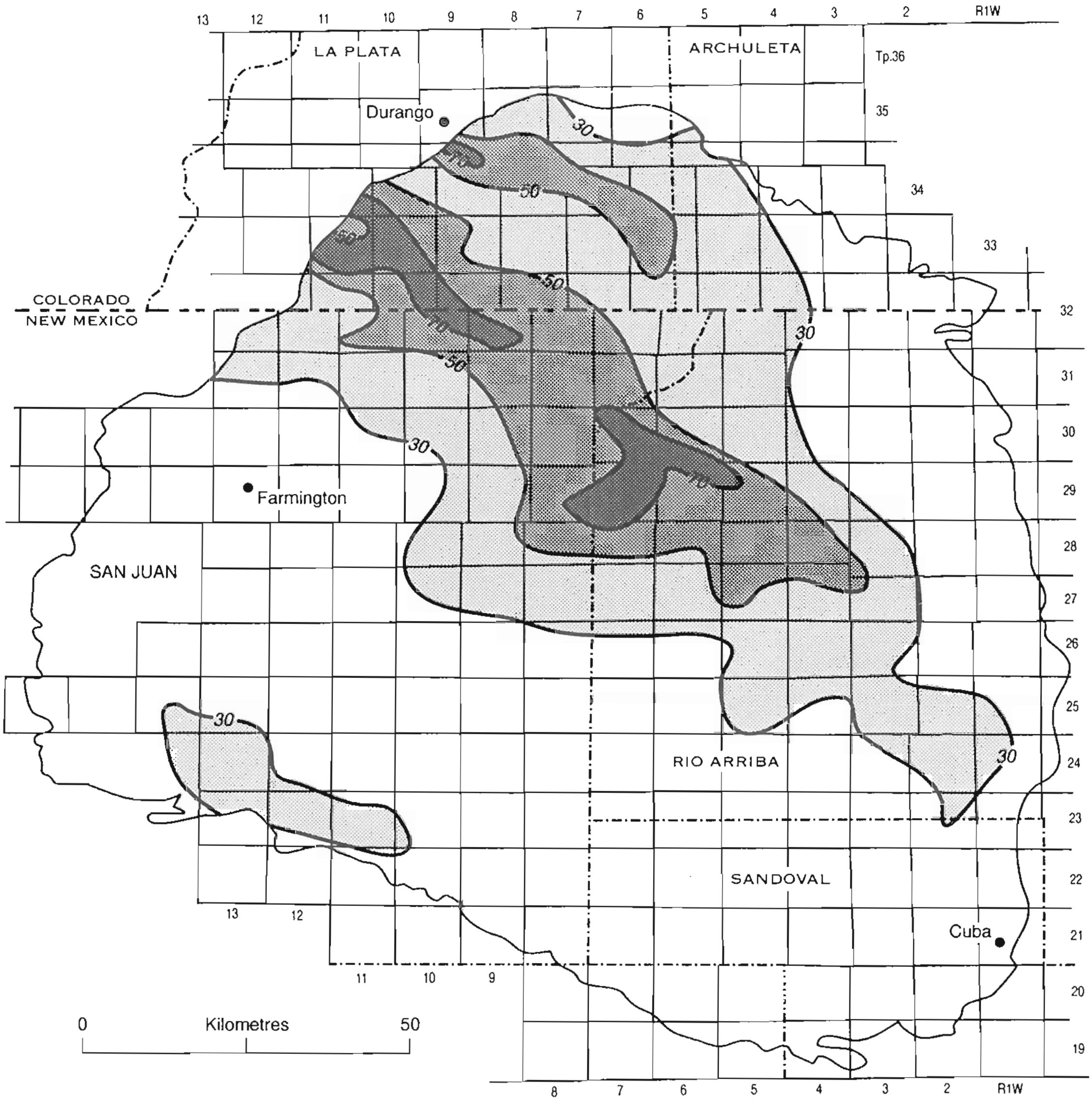

Figure 7. Generalized isopach map of Fruitland Formation coals (after Choate et al., 1984).

The Black Warrior River and the eroded remnants of the Appalachian Fold Belt form the major geographic features along the eastern edge of the basin. Coal has been mined extensively in this region of Alabama for over 100 years and the Black Warrior River serves as a major transportation route to ship the coal to the Gulf Coast. Throughout this historical mining period, the release of coalbed methane from underground mining operations posed a safety hazard and a problem in maintaining production levels. In the early 1970s drainage of methane in advance of mining operations was initiated. It was found that the methane gas, originally vented to the atmosphere, could be gathered, compressed and sold to various utility companies for heat and power generation. Since these initial trial projects, the production of coalbed methane in Alabama now accounts for over 28% of the state's natural gas sales (Gas Research Institute, 1993).

Stratigraphy

The Black Warrior Basin is underlain by a thick coal-bearing sequence of the lower Pennsylvanian/Pottsville Formation. The lower portion of the formation is barren of coal, while the upper Pottsville contains up to 40 coalbeds within seven major

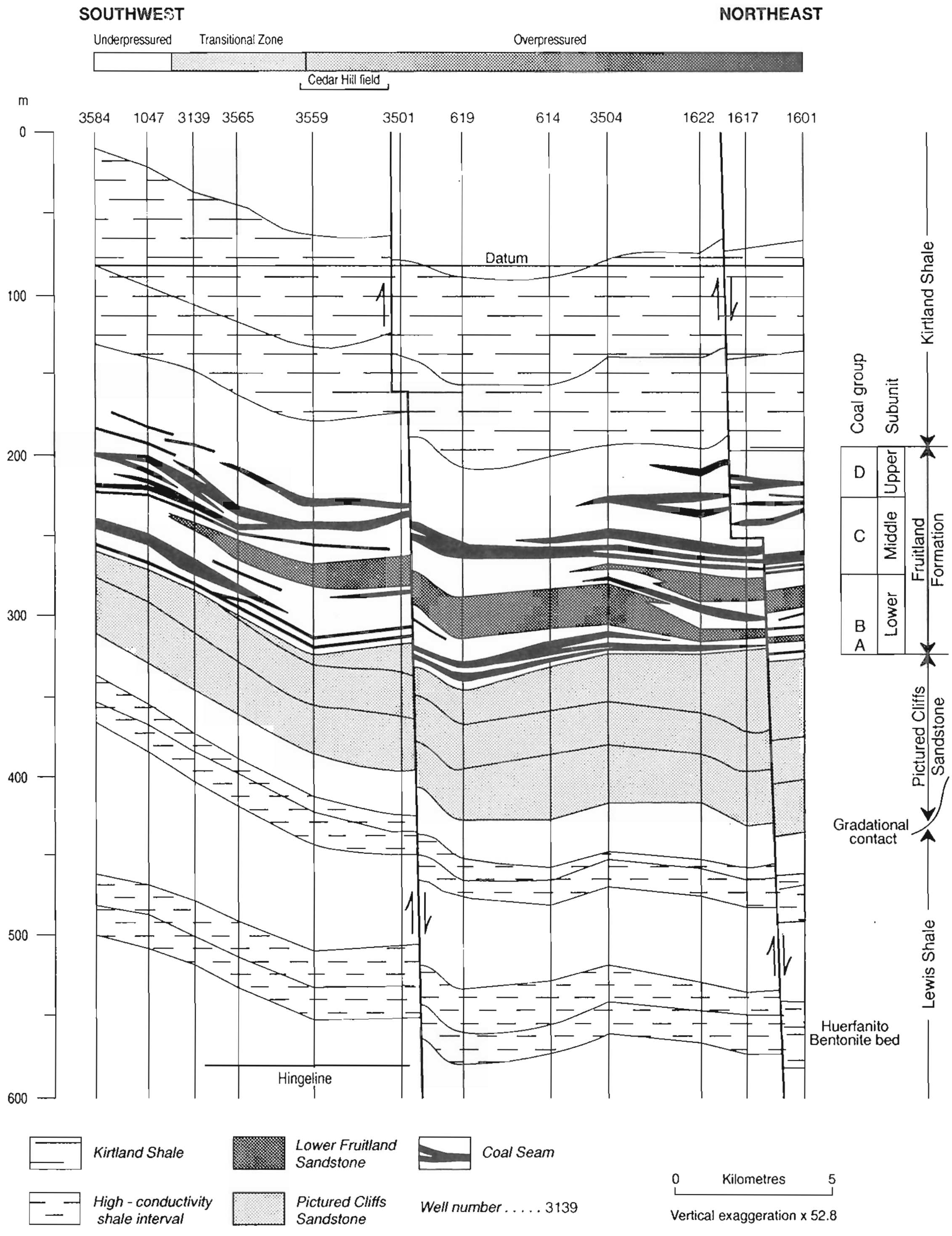

Figure 8. *Representative cross-section across the hingeline in the San Juan Basin illustrating the typical offset of the Fruitland coals due to normal faulting (after Ambrose and Ayers, 1991).*

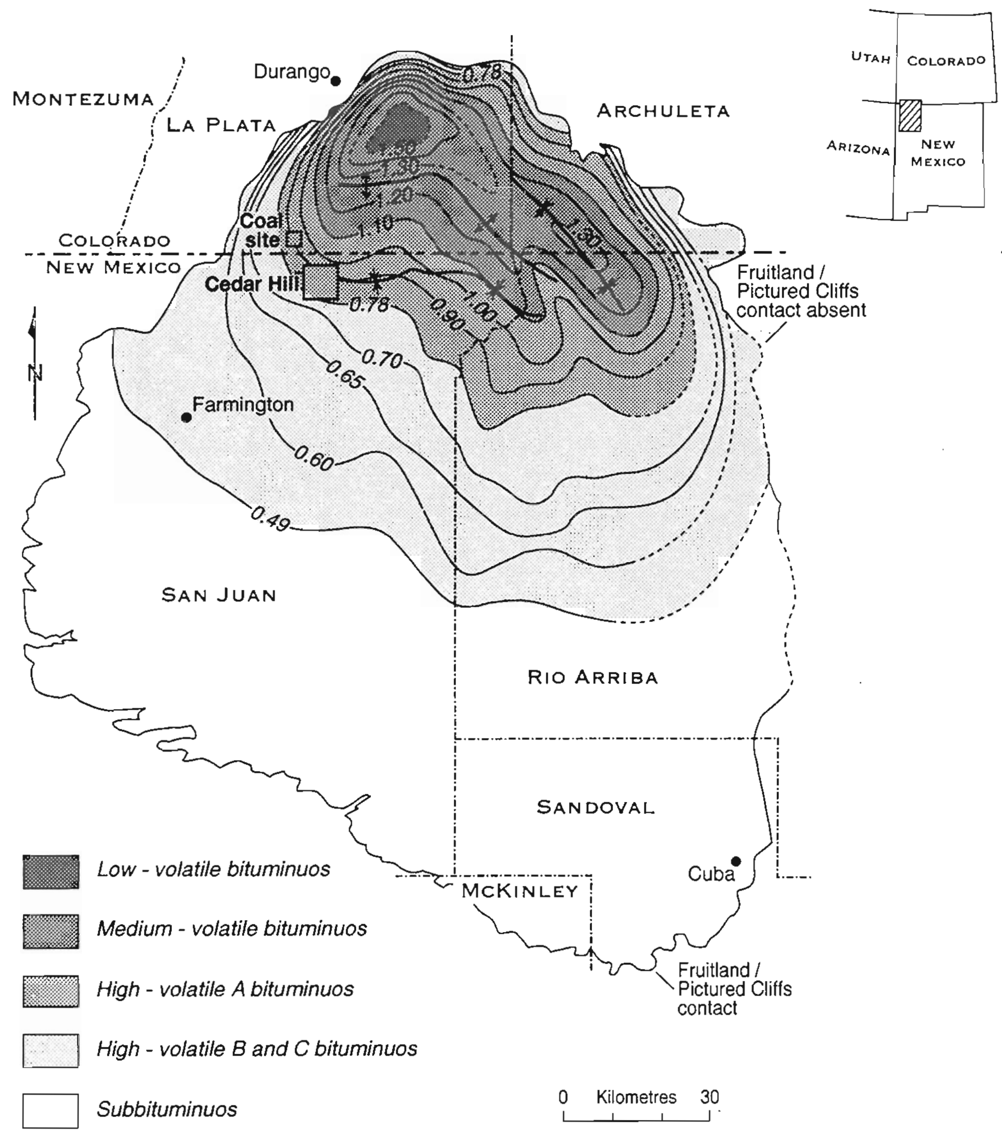

Figure 9. *Rank of Fruitland Formation coals (after Scott et al., 1991).*

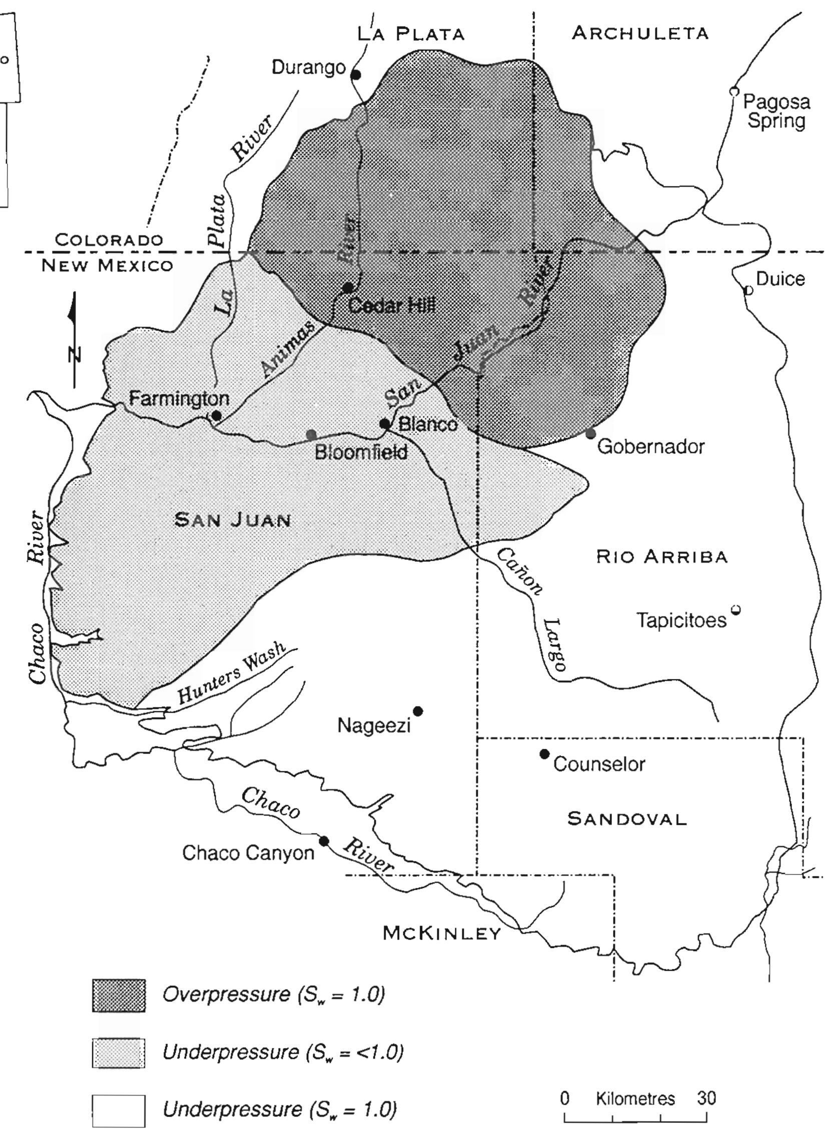

Figure 10. *Simplified map illustrating pressure regimes within the San Juan Basin (after Paul and Boyer, 1991).*

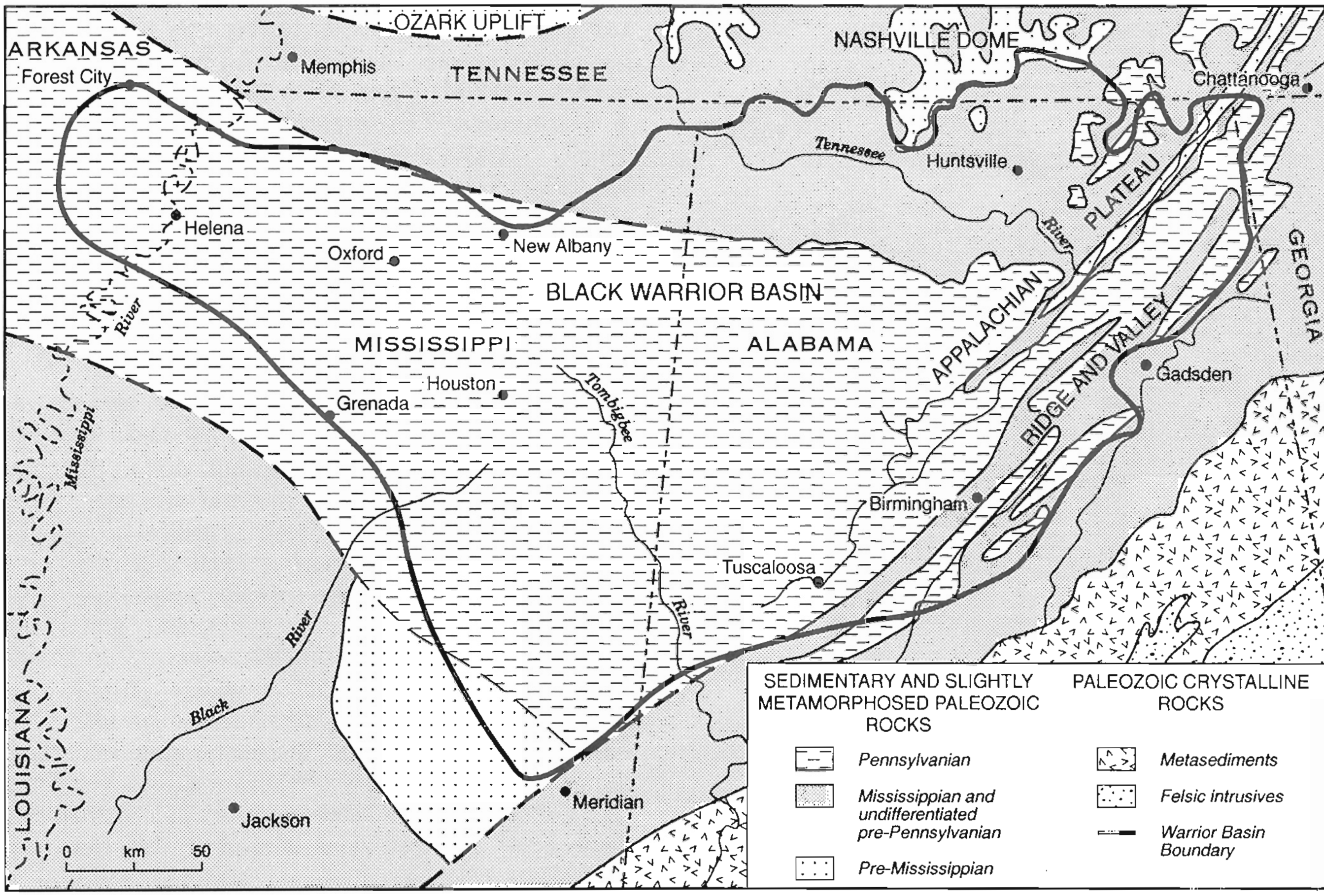

Figure 11. *General location and geology map of the Black Warrior Basin (after Hobday, 1974).*

depositional cycles and with a cumulative net coal thickness of 9 to 15 m (Ellard and Roark, 1991). The upper Pottsville Formation outcrops along the eastern edge of the Black Warrior Basin and is traceable westward into Mississippi where it is unconformably overlain by up to 1800 m of Cretaceous and Tertiary strata. The upper Pottsville Formation exceeds 1500 m, with the Black Creek–Cobb interval accounting for 700 m. Each depositional cycle thickens toward the axis of the foreland basin in the southeast. In addition, the number of coal seams in each cycle increases in a similar manner. Coals were formed in a series of transgressive-regressive cycles, consisting of marine sediments overlain by a coarsening-upward succession of arenaceous material and capped by coal or carbonaceous beds (Hewitt, 1984). Each cycle contains several coalbeds, each ranging in thickness from less than 0.3 m to greater than 2.0 m. The seams commonly split and coalesce to form thicker coalbeds with thin rock partings. The major coal-bearing cycles that contribute to conventional coal production and coalbed methane production are the Brookwood, Utley, Gwin, Cobb, Pratt, Mary Lee and Black Creek. Of these, the upper three, Brookwood, Utley and Gwin, are considered to be too shallow for coalbed methane production but contribute substantially to the coal resources extracted by surface mining methods. In this paper, only the lower four coal cycles will be examined in detail (Fig. 12).

In comparison to the coals of Cretaceous age in both the San Juan Basin and the Western Canada Sedimentary Basin, the Pennsylvanian coals of the Black Warrior Basin are generally thin. Total coal thickness for the lower four coal groups ranges from 6 to 10 m and usually is distributed over numerous thin discontinuous beds. The Black Creek Group is the lowest coal-bearing sequence in the Pottsville Formation. Three seams are present ranging in thickness up to 1.5 m over a stratigraphic interval of up to 45 m. Coal rank is high volatile bituminous A, with relatively low ash (as low as 6%) and variable sulphur contents. The thickest and most laterally persistent horizon is the Mary Lee Group. This interval

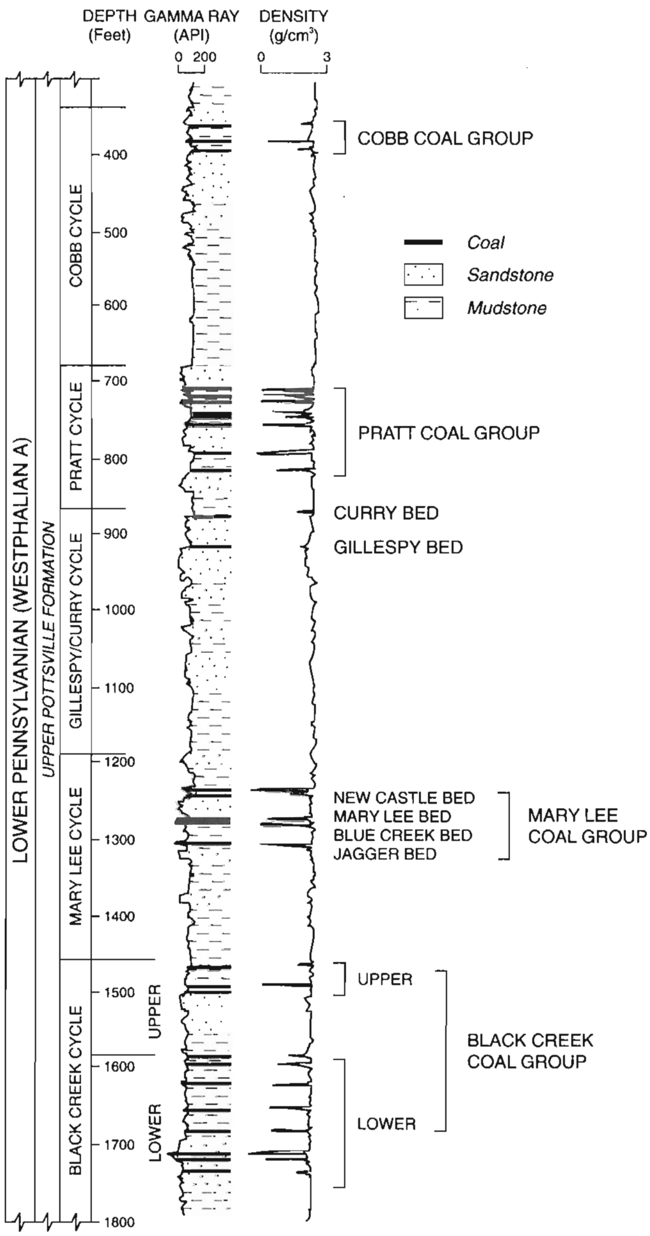

Figure 12. Stratigraphic column of the Pottsville Formation illustrating the major coal-bearing cycles (from Pashin et al., 1991).

contains up to five seams with a combined thickness averaging 3.0 m. The thickest seam is the Mary Lee, averaging 1.5 to 2.0 m and thickening toward the structural margin of the basin to the southeast. In some localities, the Blue Creek seam coalesces with the Mary Lee to form a coal zone up to 3.0 m thick. Rank of the coals are variable, ranging from high volatile A bituminous to medium volatile bituminous. The Pratt coal group lies approximately 150 m above the Mary Lee group and contains up to five coal seams with a cumulative average thickness of 2.5 m. Coal is similar in rank to the Mary Lee, being medium to high volatile A bituminous. The uppermost coal group that is usually considered for coalbed methane extraction is the Cobb. Three seams have been reported which are generally discontinuous and thin, averaging less than 0.6 m thick.

Structure

The Black Warrior Basin represents a foreland basin associated with the Appalachian Fold Belt. Strata is essentially flat-lying except within the tectonically disturbed zone, where steep dips and overturned beds have been reported. Smaller scale structures are present throughout the basin, varying from antiforms and synforms to normal faults forming small-scale horst and graben structures. On a regional scale, the structures are relatively simple, however, on closer examination structural relief is widely variable. An example of the detailed structure is presented in Figure 13, which illustrates the small normal faults and folds that affect the Mary Lee coal measures within the Oak Grove coalfield. Detailed studies by the Alabama Geological Survey have demonstrated that the variability of coal thickness and distribution is controlled to a large extent by these smaller scale structures (Pashin et al., 1990). The fault structures appear to be oriented perpendicular to the Appalachian Fold Belt to the east, whereas the axes of the major folds appear to be parallel to the belt. Displacement on the faults can be as much as 50 m. Structural complexity increases in proximity to the edge of the disturbed belt.

Coal quality

The coals of the Black Warrior Basin tend to be classified as ''gassy'', partially due to the relatively low ash content and high rank. The Mary Lee and the Black Creek coals range from high volatile B bituminous to low volatile bituminous in rank. Generally the rank increases toward the southwest, with maximum reflectances being observed in the axis of the Colburg Syncline, subparallel to the Birmingham Anticlinorium (Pashin et al., 1990). Vitrinite reflectance approaches a maximum of 1.4% to 1.5% Ro_{max} in the axis of the synclinal structure and decreases in a northwesterly direction. Most of the current coalbed methane production is concentrated in the region bounded by the 0.9% Ro_{max} line (Fig. 14).

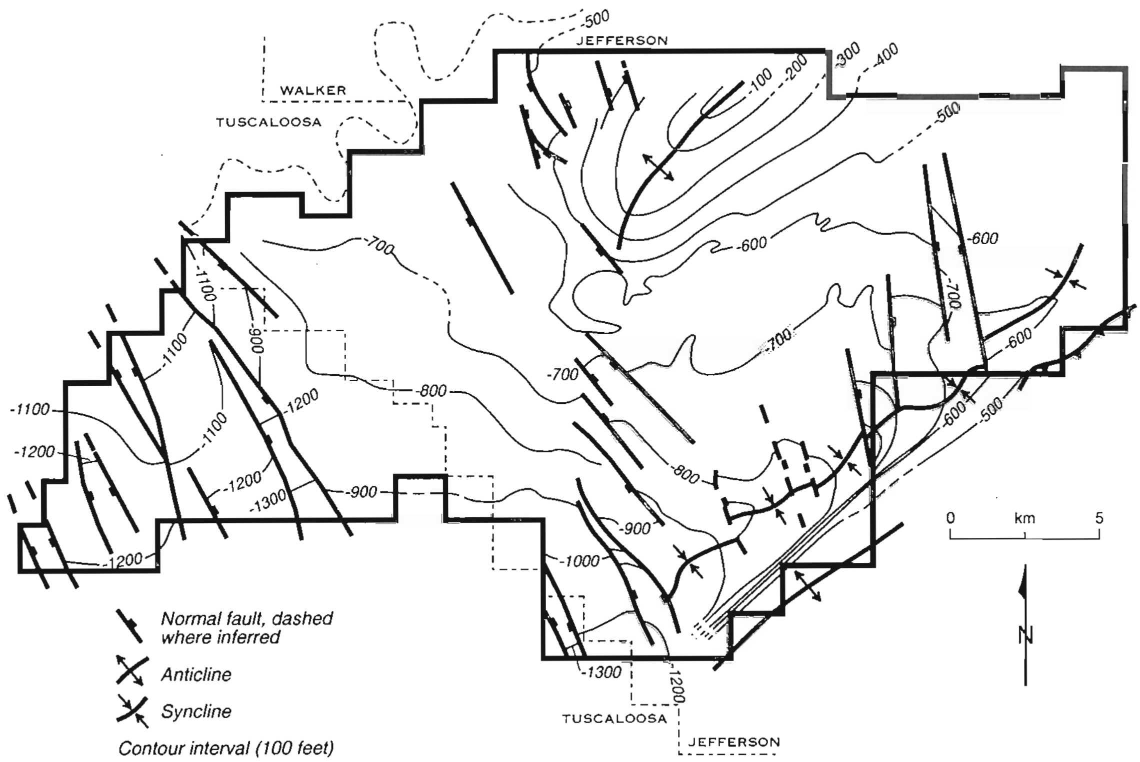

Figure 13. *Structure contour map of the Mary Lee coal seam in the Oak Grove coalfield (after Pashin et al., 1991).*

As with the rank, ash content of the Mary Lee and Black Creek coals follows similar trends. Low ash values (generally less than 12%) are located in the southeast portion of the basin, near the fold and fault belt of the Birmingham Anticlinorium. Toward the northwest, ash contents increase to 18% (Pashin et al., 1990).

Coalbed methane potential

Coalbed methane has been produced commercially from the Black Warrior Basin since 1980. The first coalbed methane field developed was at the Oak Grove coalfield, where initial gas production was derived from drainage boreholes, both vertical and horizontal, in advance of underground mining. Development of degasification fields was slow, until the introduction of the section 29 Tax Credit in the late 1980s. Since then, development has undergone a boom with over 4000 wells having been permitted for coalbed methane production. Seventeen coalbed methane fields have been defined (Fig. 15) and as of February, 1993, over 2900 wells were in production (Gas Research Institute, 1993). Total coalbed methane production for 1992 exceeded 2.6 x $10^9 m^3$ (92 BCF). Cumulative production of coalbed methane from the Black Warrior Basin to the end of 1992 was in excess of 6.7 x $10^9 m^3$ (237 BCF) (Gas Research Institute, 1993).

The coals of the Pottsville Formation are generally considered prime targets for coalbed methane. Rank ranges from high volatile A bituminous to medium volatile bituminous and gas contents are variable, ranging up to 21.3 cm^3/g (Ellard and Roarke, 1991). Most of the coalbed methane reservoirs lie at depths ranging from 180 m to greater than 1200 m. Reservoir pressure, unlike the productive fields in the San Juan Basin, appears to be normal hydrostatic. Average production from the wells in the basin is variable. Many degasification wells drilled in advance of mining operations have a very short production span and tend to produce at low volumes. In contrast some of the "Gob" coalbed methane wells in production at the underground mines produce in excess of 113 x $10^3 m^3/d$ (4 MMCF/d). Cumulative gas production from these wells is currently in excess of 849 x $10^3 m^3/d$ (30 MMCF/d) (Mills and Stevenson, 1991).

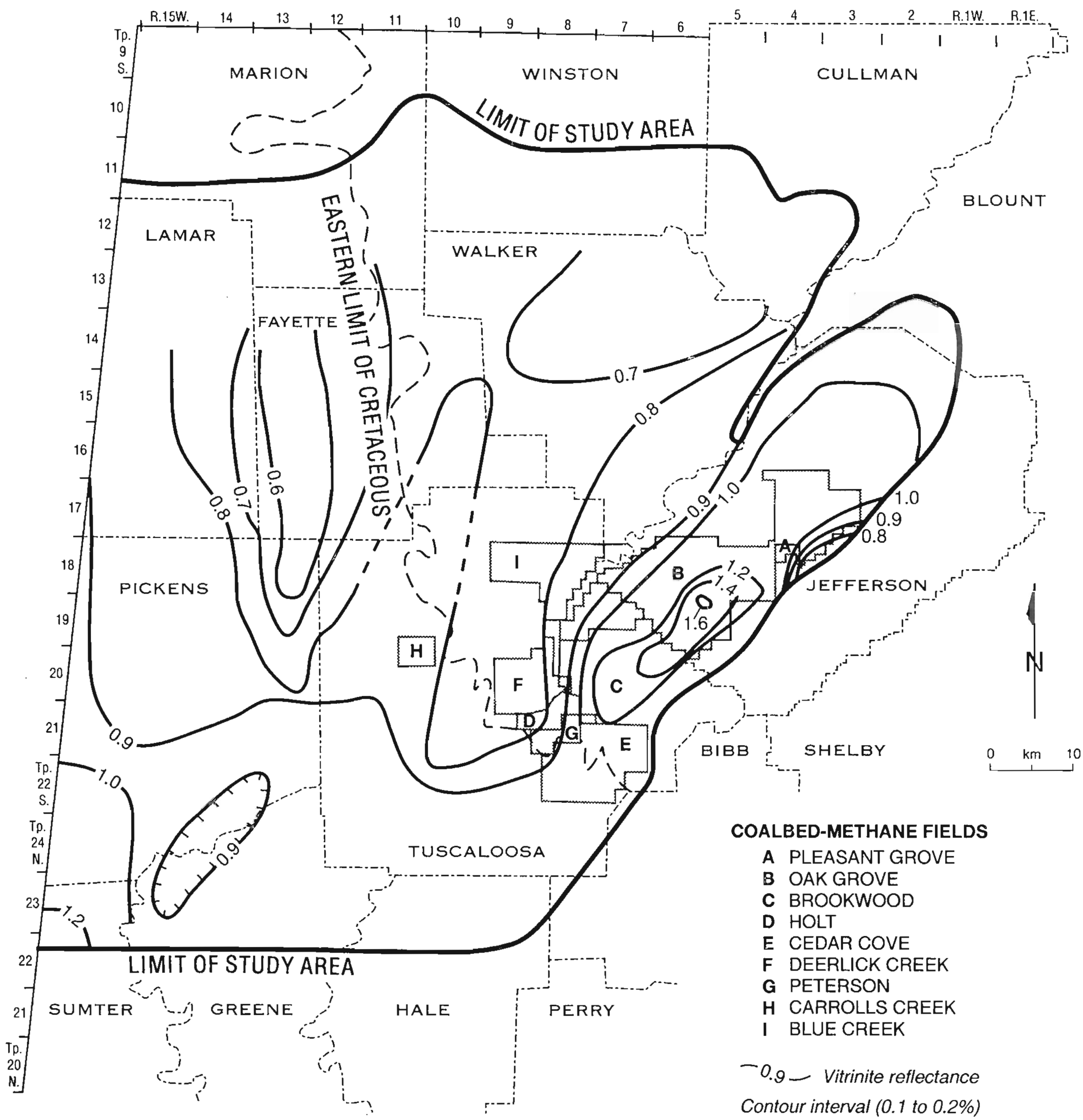

Figure 14. *Map of vitrinite reflectance in the Mary Lee coal group (after Pashin et al., 1990).*

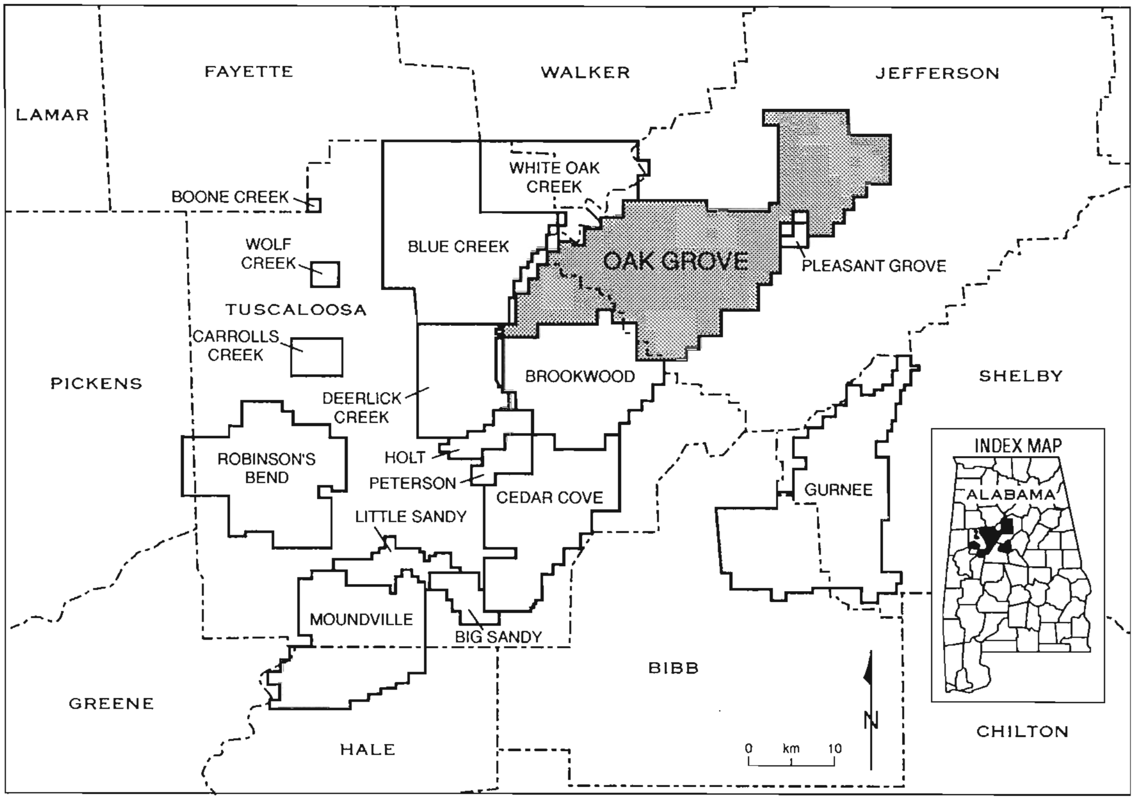

Figure 15. *Coalbed methane fields of the Black Warrior basin (from Pashin et al., 1991).*

In conventional wells drilled specifically for the recovery of coalbed methane, production rates are generally lower than those of the San Juan Basin, averaging 3.7 x $10^3 m^3/d$ (130 MCF/d). Some wells are more productive, producing up to 28.3 x $10^3 m^3/d$ (1 MMCF/d) and are generally located along northwest trending features that may be related to enhanced permeability along fractures associated with normal faulting (Ellard and Roarke, 1991). Detailed studies of several coalbed methane fields, excluding those involved in "Gob" gas production, indicate that the primary control of coalbed methane production is coal seam thickness. High coalbed methane production rates coincide with areas of thick coal.

CANADIAN COAL BASINS

Coal-bearing basins in Canada are widespread, extending from Vancouver Island in the west to the Sydney coalfield in Nova Scotia in the east (Fig. 16). A summary of coal characteristics for these areas is presented in this report. More detailed information may be obtained from Smith (1989). Much of the information presented in the following section is drawn from Smith (op. cit.). Coalbed methane data used to assess the various basins has been drawn from field testing programs undertaken by the Geological Survey of Canada (GSC) and the British Columbia Geological Survey (BCGS), and from summary data provided by the Nova Scotia Department of Mines.

The coal-bearing basins or areas that appear to have the greatest coalbed methane potential in Canada are, from west to east, as follows:

Vancouver Island,
Intermontane British Columbia,
Rocky Mountains and Foothills,
Western Interior Plains, and
Maritimes.

There are other coal deposits in Ontario, Manitoba, Northwest Territories and Yukon, but the coalbed methane opportunities in these regions may be limited. A brief discussion will be presented on the regions of northern Canada under the section Coalbed Methane Opportunities, Exploration Potential.

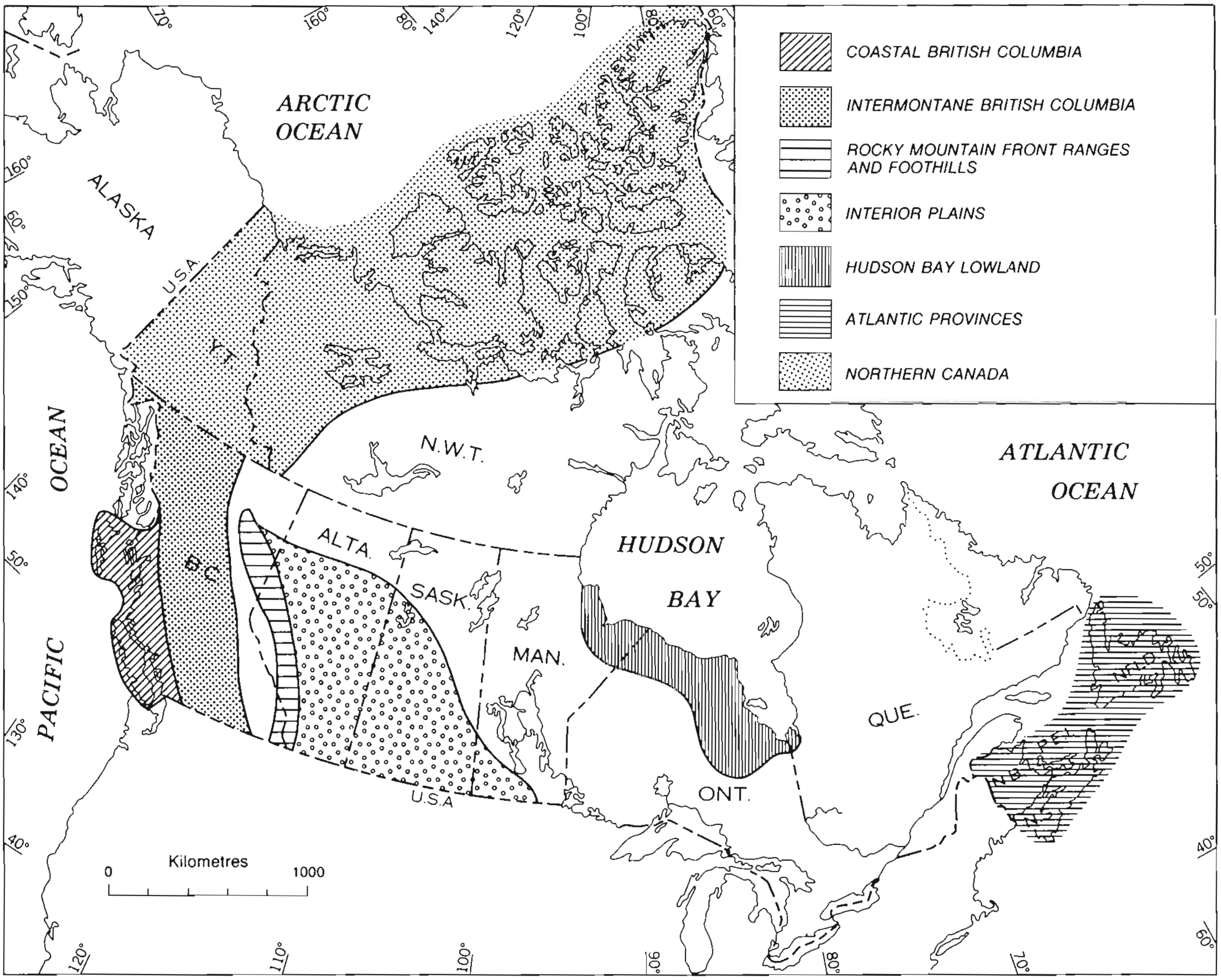

Figure 16. Major coal-bearing regions of Canada (from Smith, 1989).

Theoretical gas capacity

Theoretical gas capacity values, presented in various tables in this report, are based on a mathematical equation developed by Ryan (1992), which, in turn, represents the theoretical gas storage capacity curves developed by Eddy et al. (1982) and Kim (1977). The gas capacity curves that Eddy produced estimate the desorbed gas from samples gathered from the United States Geological Survey coalbed methane database. Ryan (1992) used these curves to develop a series of equations that allows the use of coal quality parameters and depth criteria to predict the theoretical gas capacity of any coal of a given rank at a variety of depth ranges.

For each coal-bearing basin or area, representative rank and depth criteria are used to produce a table that provides a range of what the theoretical gas capacity may be for potential coalbed methane reservoirs in the area. The data in these tables was facilitated by the use of a computer program developed by B.D. Ryan (unpublished data, 1992). For each table there is a depth range for the optimum coalbed methane target. Theoretical gas capacity values are estimated for these depths, based upon rank of the coal, ash content and equilibrium moisture content. The calculated values represent the capacity of the coal to hold methane and do not reflect what actually may be present in the coal reservoir. Local geological conditions such as water table, geothermal gradient, structural complexity and geological history control the actual volumes of gas present for each individual reservoir.

In most depositional profiles, the rank of the coal increases with increased depth. Hence a coal that has a rank of 0.6% Ro_{max} at a depth of 300 m may increase in rank to greater than 1.0% Ro_{max} at a depth of 2000 m. The tables presented in this paper do not adjust for rank variability with increasing depth. Rather, they illustrate a rank and quality range for assumed equilibrium moisture values. The tables do, however, allow estimates of the theoretical gas capacity values for a range of depths using Ro_{max} values that reflect the range of rank variability.

Vancouver Island

Coals on Vancouver Island are present in Upper Cretaceous strata and are concentrated in four main coalfields: Nanaimo, Comox, Quinsam and Suquash (Fig. 17). Coal distribution and seam quality suggest that only the first three are suitable for coalbed methane exploration. The coals vary in thickness, averaging 2 to 3 m, although in specific areas individual coal seams have been structurally thickened to greater than 20 m (Cathyl-Bickford, 1991). The two principle coalfields, Nanaimo and Comox, have been extensively mined in the past and have a history of being very "gassy". Each coalfield contains numerous coal seams of variable rank, ranging from high volatile B bituminous to anthracite. Structure in the Nanaimo and Comox fields is relatively simple, consisting of gently dipping open folds offset by several large-scale shear zones. The main coal seam in the Nanaimo coalfield is the Douglas seam which extends from outcrop to a depth greater than 1500 m. Much of the coal has been mined out at depths shallower than 450 m but the coals below this depth have, for the most part, not been exploited. In the Comox field, the main coal seam is the No. 1 seam which lies at similar depth ranges.

Both the Nanaimo and Comox coalfields have had a history of methane emissions associated with underground mining operations. As the mines extended to greater depths, coalbed methane became more prevalent and problematic. Several coalbed methane wells have been drilled in the Nanaimo and Comox coalfields with mixed success (Cathyl-Bickford, 1991). One well, drilled near Royston in the Comox field, produced gas from the early 1900s to the 1980s. The volume of gas produced is unknown. Gas content estimates for the coals range from 6 to 18 cm^3/g (Proudlock, 1990). Emission rates from the collieries in the Comox coalfield were reported to be substantially higher with some exceeding 128 cm^3/g (Cathyl-Bickford et al., 1992). Gas analyses indicate that the gas consists of greater than 95% methane.

Based upon coal quality and rank data from the Quinsam deposit, theoretical gas capacity values for a range of depths are presented in Table 2.

Table 2

Theoretical gas capacity values for coals of the Quinsam coal deposit, Vancouver Island

Depth (m)	Gas Capacity (cm^3/g)	
	Rank 0.6% Ro_{max}	Rank 0.6% Ro_{max}
	Ash 15%	Ash 25%
500	2.56	2.27
750	3.64	3.22
1000	4.41	3.90
1250	5.01	4.42
1500	5.49	4.85
Assumed Equilibrium Moisture 4.7%		

Coal rank at the Quinsam deposit averages 0.6% Ro_{max} indicating that the gas generation capacity of the coals is at the bottom of the gas generation window. An adsorption isotherm has been derived for a coal sample from the Quinsam deposit (Fig. 18) which indicates that the coal has a gas capacity of up to 17.6 cm^3/g at a Langmuir pressure of 9205 Kpa. Actual gas storage capacity is projected to be less (Table 2) because the rank of the coal is too low to generate sufficient methane to reach ultimate gas capacity and the coal is too shallow for sufficient reservoir pressures to be developed (Ryan and Dawson, 1993b, c).

Intermontane British Columbia

Within the intermontane region of British Columbia are the numerous coal-bearing basins with deposits that range in age from Jurassic to Eocene (Fig. 19; Table 3). Each of these coal-bearing basins contain substantial coal resources that range in rank from lignite A to high volatile B bituminous. Coals that have rank values greater than high volatile C bituminous may contain significant coalbed methane resources.

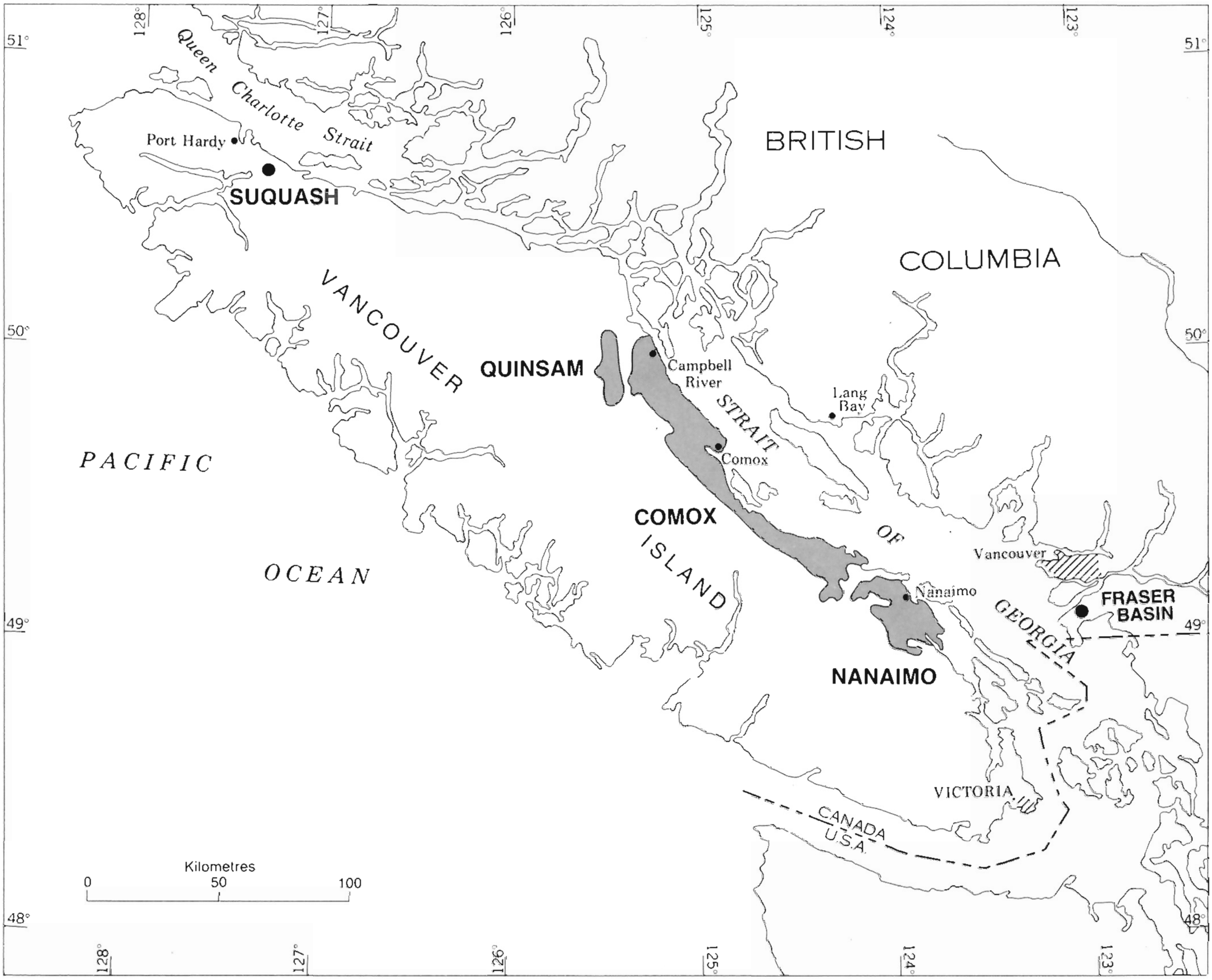

Figure 17. *Coalfields of Vancouver Island (from Smith, 1989).*

Table 3

Major coal basins within the Intermontane Region of British Columbia

Coal Basin	Location within Province	Coal Rank
Bowser Basin	northern	Semianthracite
Skeena Basin	northern	High to medium volatile bituminous
Bowron River	northeast	High volatile C bituminous
Quesnel	central	Lignite A
Hat Creek	southern	Lignite A
Merritt	southern	High volatile B/C bituminous
Tulameen	southern	High volatile C bituminous
Princeton	southern	Subbituminous B/A

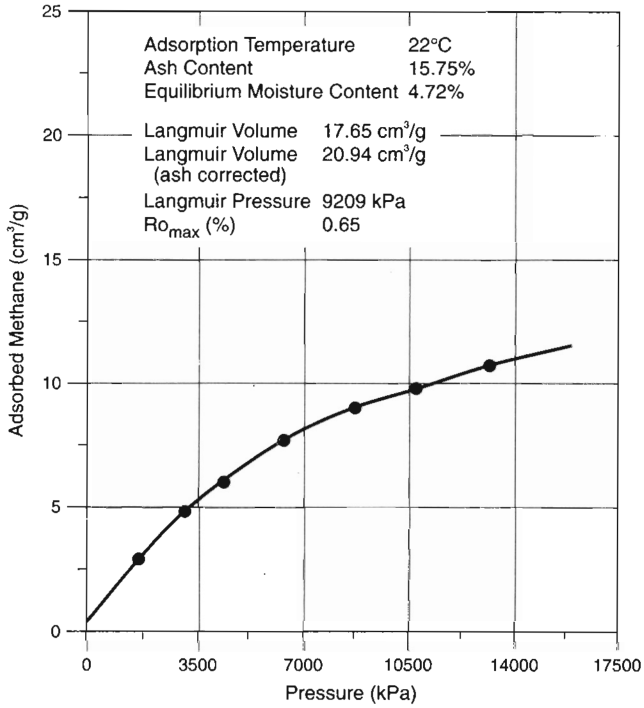

***Figure 18.** Adsorption isotherm of a sample from Quinsam coal deposit.*

Bowser Basin

Bowser Basin in northern British Columbia encompasses approximately 50 000 km^2. The Groundhog coalfield, located in the east-central region of the basin, contains the majority of the potentially exploitable coal deposits. Coals occur in the Jurassic to Lower Cretaceous Currier Formation and range in thickness up to 6 m (Bustin and Moffat, 1983). The region is extensively folded and faulted, and in some localities the coal seams have been structurally thickened. Coals tend to be relatively high in ash (15-35%) and extremely high in rank. Throughout the coalfield, the coals range from semi-anthracite to meta-anthracite rank with reflectance values ranging from 2.5% to 5.3% Ro_{max} (Dawson and Ryan, 1992). One isotherm has been computed for a coal from the Mount Klappan deposit in the northern part of the basin (Fig. 20). The Langmuir volume totalled 46 cm^3/g (ash free basis) and provides some indication of the overall adsorptive capacity of high rank coals. This high gas capacity value however does not reflect the overall gas content capability for coals of the Bowser Basin (Ryan and Dawson, in press). Resource estimates using theoretical gas content estimates of approximately 6.8 cm^3/g indicate that the basin has the potential to contain up to 228 x 10^{9}m^3 of coal gas.

The coal measures have been subjected to extensive tectonism complicating the entrapment of gas within the seams and the development of coalbed methane reservoirs. However, several coal exploration boreholes on the Mount Klappan deposit encountered the presence of coalbed methane (V. Duford, pers. comm., 1992). Infrastructure in the region is essentially nonexistent and any coalbed methane development would have to be site specific for local power or heat generative needs. The potential for coalbed methane resources is unknown at present.

Skeena Basin

The Skeena Basin contains coal-bearing nonmarine sediments of the Lower Cretaceous Red Rose Formation. Although strata of the Bowser Lake Group extend as far south as this basin, it appears that sediments were derived from different sources. The largest, and potentially mineable, coal deposit in the basin is the Telkwa coalfield, immediately south of the town of Smithers. Coal seams are from 1 to 7 m thick and of high to medium volatile bituminous rank (Ryan and Dawson, 1993a). The coal seams are cut by numerous northwesterly trending normal faults. Other coal deposits of the Skeena Basin are small and appear to have limited resource potential. Desorption tests conducted by the GSC and BCGS indicate that coalbed methane is present within the Telkwa coals. Shallow exploration boreholes were sampled and gas content averaged 4.25 cm^3/g (ash free basis) at depths of approximately 100 m. Two adsorption isotherms were derived for core samples and yielded Langmuir volumes of approximately 11 cm^3/g (ash free basis) (Fig. 20).

Coalbed methane resource estimates for the Telkwa deposit are estimated at 4.4 x 10^{9}m^3 (Ryan and Dawson, in press). The Telkwa deposit is in close proximity to the Bulkley and Telkwa rivers, suggesting that sufficient hydrostatic pressures may exist to have retained significant volumes of methane gas at depth. Permeability studies undertaken by Crowsnest Resources during the 1980s indicate that the coals have permeability values from 3 to 50 mD. This, in conjunction with the regional extensional faulting, may provide sufficient reservoir permeability for economic extraction of this potential resource.

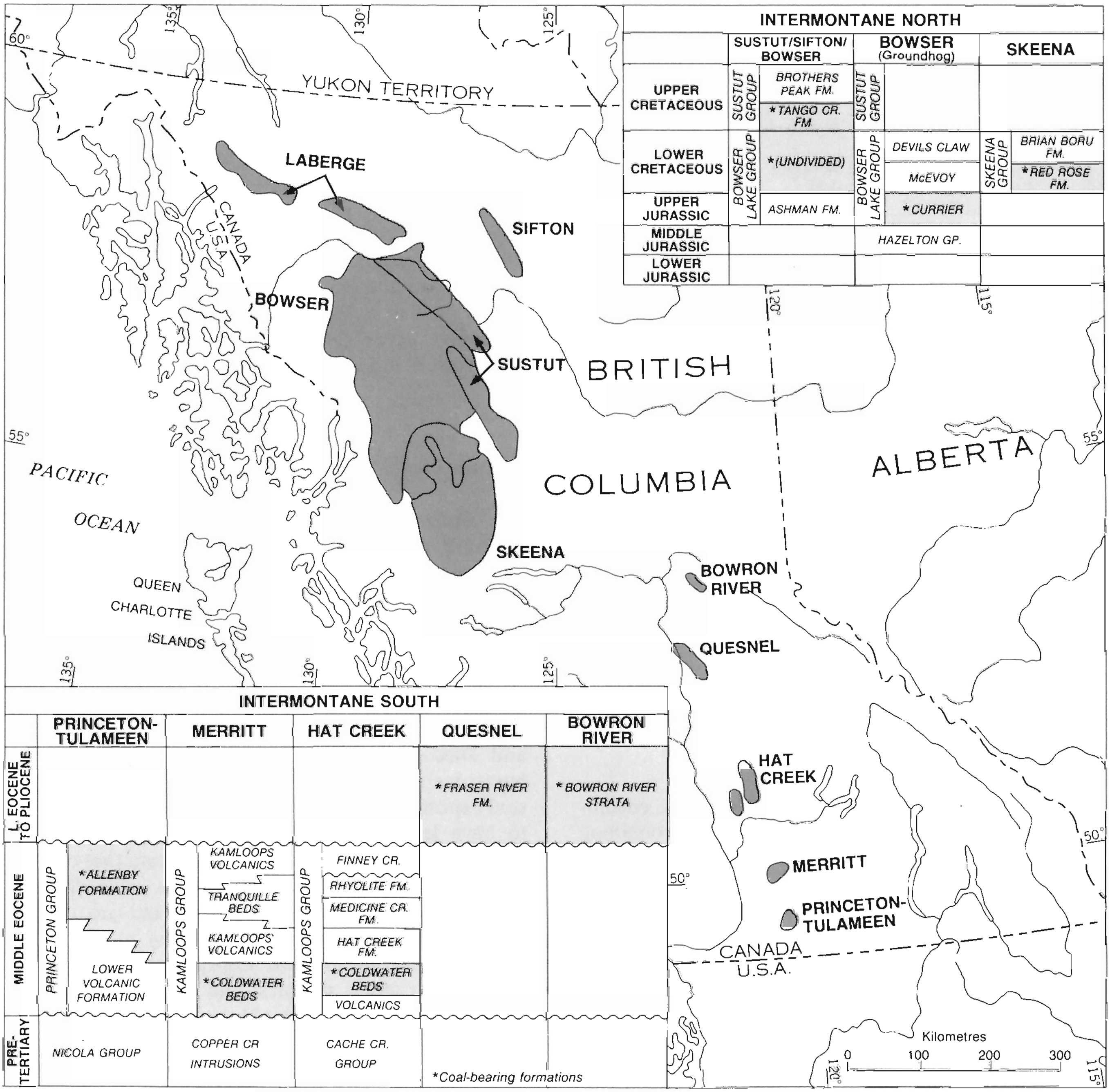

Figure 19. *Coal-bearing intermontane sedimentary basins of British Columbia (from Smith, 1989).*

Bowron River

The Bowron River coal basin lies within an elongate graben-type structure, approximately 25 km long and 2.5 km wide. Sedimentary strata up to 700 m thick, consisting of interbedded sandstone, shale, conglomerate and minor coal have been reported. The coal zone, which is up to 35 m thick and contains coal seams up to 3.5 m thick, lies in the lower part of the succession. Analyses of samples indicate that the coals are high volatile C to B bituminous in rank with widely variable ash contents due to interbedded partings. The British Columbia Geological Survey conducted exploratory drilling for coalbed methane in the region during 1989 (Matheson and Sadra, 1990). Boreholes were shallow (maximum depth 140 m) and gas contents were low (averaging less than 0.5 cm^3/g). Drilling was concentrated along the western edge of the basin and

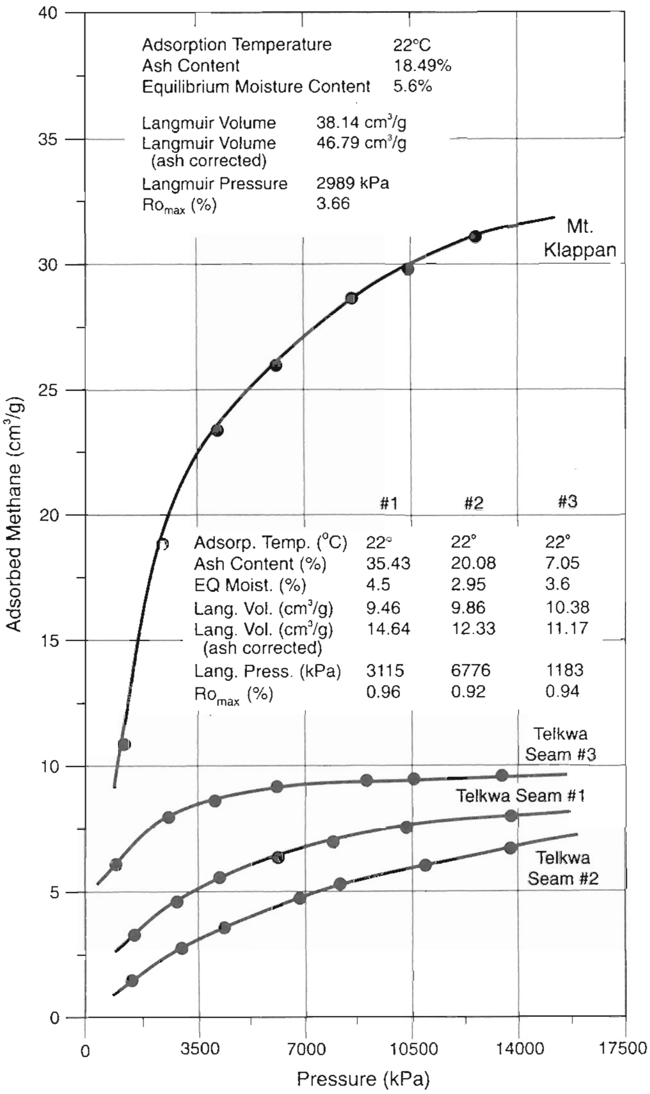

Figure 20. *Adsorption isotherms of coal samples from the Telkwa and Klappan coalfields.*

no exploratory boreholes have penetrated the centre of the basin where coalbeds are shallow dipping and reported to lie at depths greater than 200 m. It may be possible that coal rank increases within the centre of the basin in response to increased depth of the coal measures, thus presenting a coalbed methane target that, although small, may have reasonable potential.

Merritt

The Merritt coal deposit occupies a northwest trending depression approximately 11 km long by 5 km wide. The coal-bearing rocks are highly faulted and folded on the western edge of the basin and coal seams appear to be widely variable in distribution and thickness. Rank of the coal varies from high volatile C to B bituminous with a wide range of ash concentrations. To date no coalbed methane exploration has been undertaken in this basin. Future coalbed methane exploration will have to address the structural complexity of the basin, lateral variability of the coal seams and the shallow depths of the coal measures.

Tulameen

The Tulameen coal deposit, lying in southern British Columbia, is approximately 5 x 3 km in size. Sedimentary rocks comprise a stratigraphic sequence in excess of 800 m thick, with a middle section approximately 140 m thick containing the coal resources. Coal seams up to 9 m thick have been reported, with some structurally thickened sections in excess of 25 m (Graham, 1979). The coalfield generally forms a synclinal structure with limbs dipping at 45°. Underground mining in the coalfield frequently encountered faults that offset the coal seams. The coals within the Tulameen deposit range in rank from high volatile B to C bituminous. The coal demonstrates a wide range in rank due, in part, to high and variable geothermal gradients and varying depths of burial (Williams and Ross, 1979). The coals tend to be relatively high in ash and are commonly crushed and sheared. To date no coalbed methane exploration has been undertaken within this deposit.

Rocky Mountain Front Ranges and Foothills

The region defined as the Rocky Mountain Front Ranges and Foothills (Smith, 1989) contains more than 95% of Canada's bituminous coal resources. Coal deposits extend from the United States border northwestward for a distance in excess of 1100 km (Fig. 21). The region is divisible into three distinct subdivisions: Rocky Mountain Front Ranges, Inner Foothills, and Outer Foothills (located along the eastern side of the cordillera).

Coal deposits of the Rocky Mountain Front Ranges are of late Jurassic to early Cretaceous age and belong to the Kootenay Group located in the southeast region of British Columbia and the southwest region of Alberta. The Rocky Mountain Front Ranges are characterized by folded and faulted Paleozoic carbonates thrust over the predominantly clastic Mesozoic to Tertiary rocks.

The Inner Foothills belt contains coals of Cretaceous age and extends from the central Alberta Foothills northwest into British Columbia near the Yukon border. The rocks are predominantly

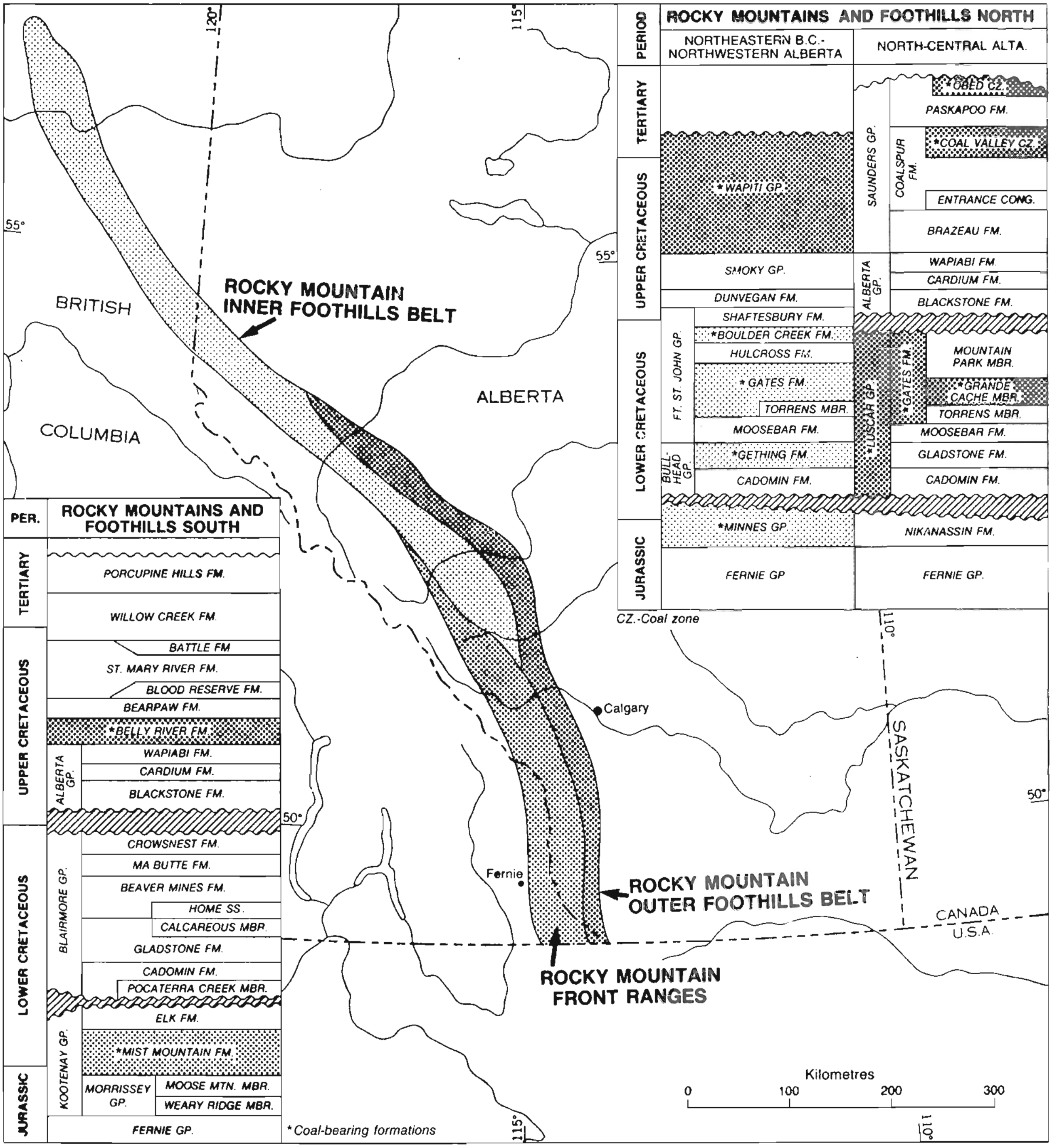

Figure 21. *Regional subdivisions of major coal-bearing formations in the Rocky Mountain Front Ranges and Foothills of British Columbia and Alberta (from Smith, 1989).*

structurally deformed Mesozoic rocks that form a series of linear ridges of relatively high relief caused by the resistant nature of the coarser grained sediments.

The Outer Foothills belt is present along the edge of the deformed belt and extends from the United States border to northwestern Alberta. This region contains less resistant Upper Cretaceous to Tertiary sedimentary rocks.

Each of these three regions contains substantial coal resources that may be suitable for coalbed methane exploration. For each, coal rank and depth ranges are used to calculate theoretical coalbed methane gas capacity values that are presented in tabular form to illustrate the potential for each geographic region. Resource estimates have not been made because insufficient data of gas contents are available.

Rocky Mountain Front Ranges

The region defined as the Rocky Mountain Front Ranges, containing coal deposits of the Jura-Cretaceous Kootenay Group, can be subdivided into four main districts: East Kootenay, Crowsnest, Cascade, and Panther/Clearwater (Fig. 22). Of these districts, the East Kootenay contains the thickest section of coal measures and corresponding cumulative thickness of coal. The Kootenay Group thins progressively to the east and north into the other districts. To date, most of the coalbed methane exploration activity in the Rocky Mountain Front Ranges region has been concentrated in the East Kootenay district.

East Kootenay district

The East Kootenay district can be divided into three coalfields: Elk Valley, Fernie, and Flathead. Numerous coal deposits containing extensive coal resources lie within each of these fields. To date all of the coalbed methane exploration has occurred in the Elk Valley and the Fernie coalfields. In these regions, the Kootenay Group attains a thickness of greater than 1100 m and consists mainly of interbedded siltstone, shale, sandstone, conglomerate, and coal (Gibson, 1977). The coal-bearing Mist Mountain Formation, lying near the base of the group, averages 500 to 600 m thick (Grieve, 1985) and contains up to 29 coal seams and a cumulative coal thickness up to 75 m. Individual seams are up to 18 m thick (normal stratigraphic thickness), with most of the thicker coals lying near the base of the formation (Fig. 23).

The East Kootenay coal district lies within a region of the Rocky Mountain cordillera that is structurally complex, with extensive folding and faulting. Coal seams are frequently fault repeated or thickened with several deposits containing structurally thickened seams in excess of 100 m thick (Mammoth seam at Corbin). In the East Kootenay district, the coal-bearing strata lie within structural or erosional remnants associated with the Lewis Thrust. The major structural features of the East Kootenay district are large open synclinoria bounded by low- to high-angle thrusts or normal faults (Bustin, 1982). These synclinal structures may be attractive coalbed methane targets.

The Mist Mountain Formation coals range from high to low volatile bituminous rank in the East Kootenay district. Rank variability extends within individual seams both along strike and down dip as well as between structural domains (Abercrombie

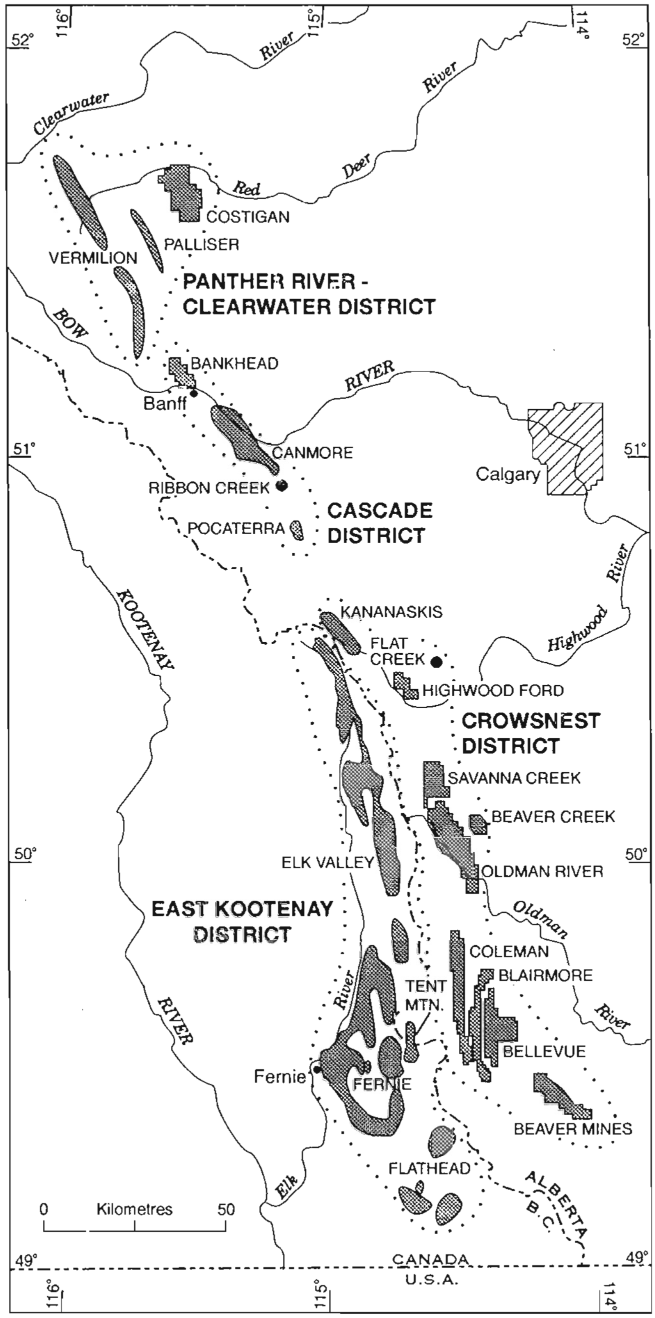

Figure 22. *Coal districts of the southern Canadian Rocky Mountains (from Smith, 1989).*

et al., 1992). Maceral composition trends suggest an increase in vitrinite content and decrease in inertinite from the base of the formation upward (Cameron, 1972). Ash content of the coals ranges from 15% to 25% (Grieve, 1985). The influence that the higher inertinite contents may have on the coalbed methane potential of the lower seams in the Mist Mountain Formation is unknown at this time and is part of an ongoing research project by the Geological Survey of Canada and the British Columbia Geological Survey.

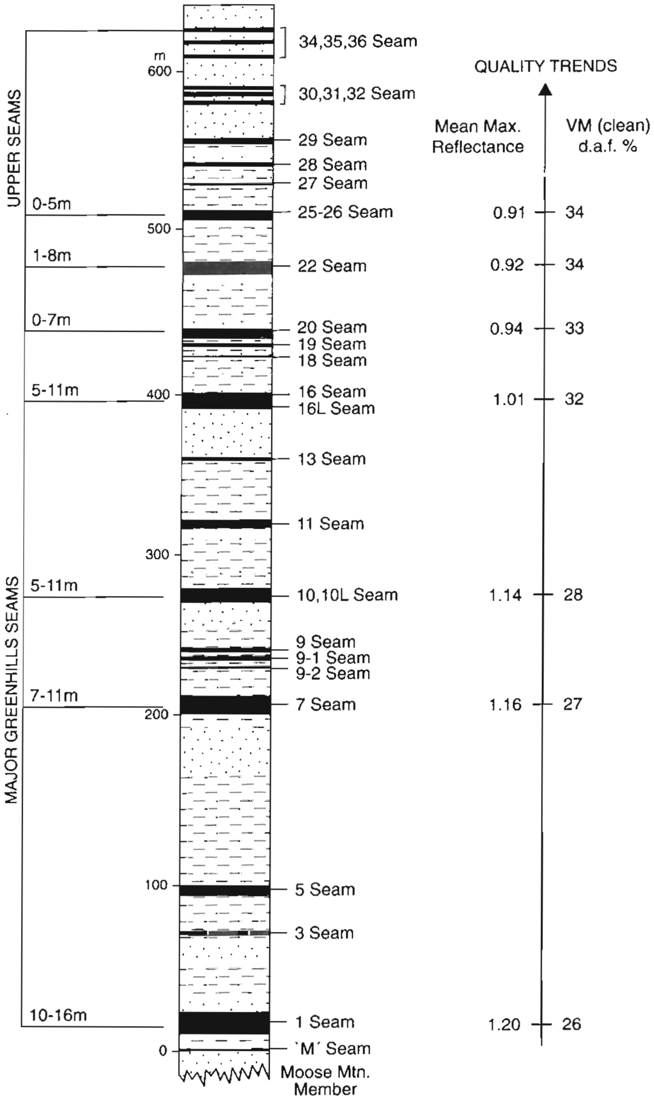

Figure 23. *Typical stratigraphic section of the Mist Mountain Formation, Fernie coal district (from Westar Mining Ltd., pers. comm., 1992).*

This region has been the focus for much of the recent coalbed methane exploration in Canada. The combination of numerous thick coal seams of sufficient rank for gas generation and retention has led to at least seven exploration companies drilling in excess of 10 wells specifically for coalbed methane. The distribution of these wells is split between the Elk Valley coalfield to the north and the Fernie coalfield to the south. In all cases, the companies have targeted the lower seams of the Mist Mountain Formation.

Ash contents are widely variable, ranging from 7% to 23%, and equilibrium moisture content is low, averaging less than 5%. Theoretical gas capacity values have been calculated based upon the Ryan equation (Ryan, 1992) for coals with a rank variation from 0.9% to 1.4%Ro_{max}, an average ash content of 15% and a depth range of 200 to 2000 m (Table 4). Adsorption isotherm curves for coal samples from the Elk Valley (Fig. 24) support the theoretical values generated using the Ryan equation. Langmuir volumes range from 16.8 cm^3/g (ash free basis) for coals of low volatile bituminous rank (Ro_{max} 1.36), to 24.3 cm^3/g (ash free basis) for coals of medium volatile bituminous rank (Ro_{max} 1.14).

Table 4

Theoretical gas capacity values for coals of the Mist Mountain Formation, southeastern British Columbia

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 0.9% Ro_{max}		Rank 1.4% Ro_{max}	
	Ash 7%	Ash 23%	Ash 7%	Ash 23%
200	6.63	5.46	10.93	9.00
400	8.78	7.23	13.11	10.79
600	10.03	8.26	14.39	11.84
800	10.92	3.99	15.29	12.59
1000	11.61	9.56	15.99	13.17
1200	12.18	10.02	16.57	13.64
1400	12.65	10.42	17.05	14.04
1600	13.07	10.76	17.47	14.38
1800	13.43	11.06	17.84	14.69
2000	13.76	11.33	18.17	14.96
Assumed Equilibrium Moisture 2.5%				

Crowsnest coal district

The Crowsnest coal district lies in southwestern Alberta and extends from the United States border to Sheep River (Fig. 22). The area is characterized by a series of northwesterly trending, west dipping thrust plates associated with the Lewis Thrust. Kootenay Group rocks are fault repeated numerous times to produce at least eight bands of strata paralleling the major ranges of the Rocky Mountains to the west.

Coal is present within the 67 to 380 m thick Mist Mountain Formation (Gibson, 1985a). Up to 11 coal seams have been measured, with a cumulative thickness in excess of 17 m. The top of the Mist Mountain Formation is disconformably overlain by the conglomeratic beds of the Cadomin Formation (Fig. 25).

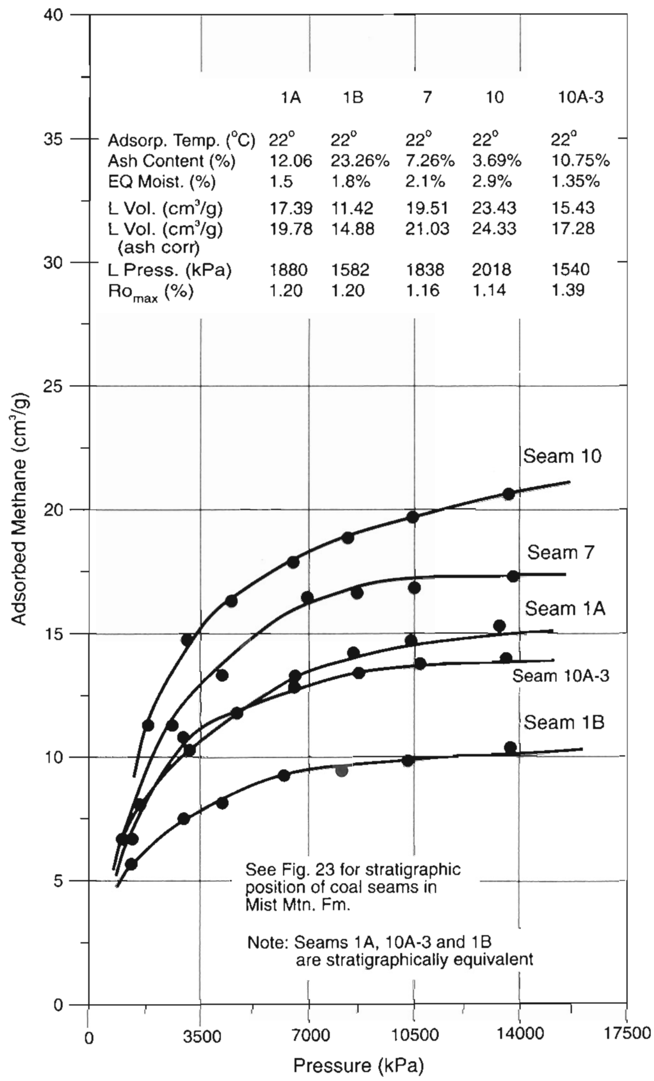

***Figure 24.** Adsorption isotherms of coal samples from the Mist Mountain Formation, Elk Valley coalfield.*

The coals range from high to low volatile bituminous in rank and appear to be higher in rank toward the northern part of the district. Refer to Smith (1989) for details of coal quality variability. The coals have commonly been subject to deformation associated with the tectonic processes of the Laramide Orogeny. Structural thickening of a 6 to 9 m thick seam to greater than 25 m has been observed at Grassy Mountain (Fig. 26). In many cases the high degree of deformation and bedding plane slip within the coals has overprinted both the face and butt cleat, producing highly sheared and friable coal seams. Coalbed methane potential for the region, based upon exploration potential, has been estimated by the Alberta Geological Survey for two mapsheets (NTS 82G/8, 9) for southern Alberta (Richardson et al., 1992a, b).

To date, two companies have been active in drilling for coalbed methane in the Crowsnest coal district. Three boreholes were completed in the vicinity of the Coleman coalfield, while one hole was completed in the region of the Savanna Creek deposit. All boreholes were less than 1000 m deep and drilled to test the coalbed methane potential of steeply dipping Mist Mountain Formation strata. No commercial production has been initiated from these wells. Gas capacity of the Mist Mountain strata in this region is similar to that of the Elk Valley isotherms (Fig. 24).

Cascade coal district

The coals of the Cascade coal district have the highest rank within the Mist Mountain Formation. Most of the coal measures lie within the overturned Mount Allan syncline paralleling the Bow River corridor near Canmore (Fig. 22). In this area, the Mist Mountain Formation is approximately 400 m thick and contains up to 13 seams with a cumulative thickness of greater than 20 m (Norris, 1971). The coal-bearing strata outcrop near the Bow River and dip moderately to the west (25-40°) toward the Rundle Thrust to depths exceeding 1500 m. The area has been extensively mined in the past and many of these underground workings were reported to be "gassy". The coal ranges from low volatile bituminous (1.33% Ro_{max}) to semianthracite (2.65% Ro_{max}) and the ash content is relatively low (less than 20%) (Hughes and Cameron, 1985). During the early 1980s, Algas Limited, a division of Novacorp, drilled several holes into the coal-bearing strata of the Mist Mountain Formation near Canmore to test the coalbed methane potential. These holes are reported to have encountered coalbed methane but no commercial production was achieved. No gas content values are available for this district, but based upon the coal rank and quality, and using the Ryan equation (Ryan, 1992), gas capacity values for this area range from 12 to 15 cm^3/g for a depth range of 500 to 1500 m (Table 5).

Panther/Clearwater district

The Panther/Clearwater coal district represents the northern extension of the coal-bearing Kootenay Group, (Fig. 22). Further to the north, equivalent strata are referred to as the Nikanassin Formation and have limited coal development. In the Panther/Clearwater area, the Mist Mountain Formation is approximately 400 m thick and contains up to six coal seams with a cumulative thickness of less than 10 m. The coal is of similar rank to the Cascade district: low volatile bituminous coal to anthracite. Much of the

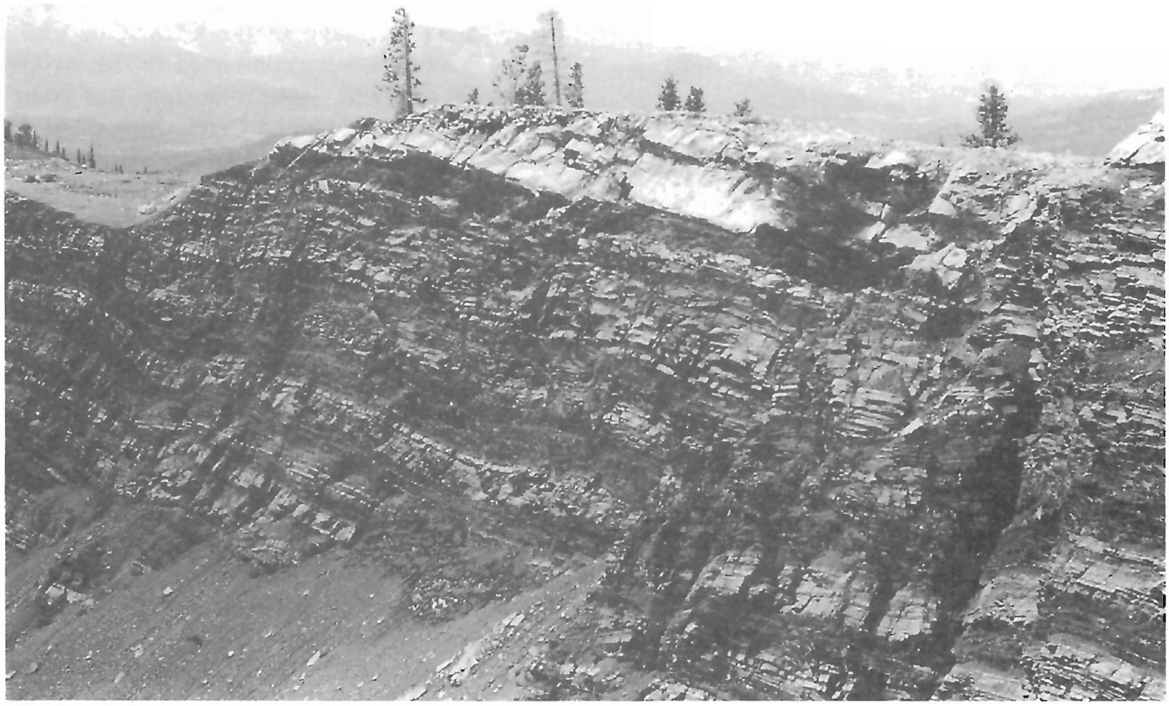

Figure 25. Cadomin conglomerate unconformably overlying coal-bearing strata of the Mist Mountain Formation at Grassy Mountain, southwestern Alberta. (ISPG photo. 4225-4.)

Figure 26. Structural thickening of the No. 2 seam at Grassy Mountain, southwestern Alberta. (ISPG photo. 4225-3.)

Panther/Clearwater district lies either in Banff National Park or within areas designated as environmentally sensitive by the Alberta Government, resulting in limited opportunities to develop the coalbed methane potential.

Table 5

Theoretical gas capacity values for coals of the Mist Mountain Formation, Cascade coal district, Canmore, Alberta

Depth (m)	Gas Capacity (cm^3/g)	
	Rank 1.3% Ro_{max}	Rank 2.6% Ro_{max}
500	12.00	17.44
750	13.16	18.62
1000	13.99	19.45
1250	14.63	20.10
1500	15.15	20.63
Equilibrium Moisture 1.5% Assumed Ash Content 15%		

Inner Foothills

The Inner Foothills belt extends from south of the Clearwater River to north of the Peace River in northeastern British Columbia (Fig. 27). The region has been divided into two blocks, northern and southern Inner Foothills, the boundary is defined by the Kakwa River near the Alberta/British Columbia border. In the southern Inner Foothills, coal is present within the Gates Formation of the Lower Cretaceous Luscar Group. In the northern Inner Foothills, coals are contained within the Gates Formation as well as the Gething Formation of the Fort St. John Group (Langenberg and McMechan, 1985).

There are three major areas of coalbed methane potential within the southern inner foothills: Nordegg, Cadomin-Luscar, and Smoky River. All three coalfields contain thick seams (up to 13 m) within the Grande Cache Member of the Gates Formation (Fig. 28). These deposits have been subjected to tectonic stresses associated with the Laramide orogeny, causing the coal seams to be commonly folded and faulted. In the axis of the tightly folded structures, it is common for the coal seams to display tectonic thickening and shearing.

Nordegg coalfield

The Nordegg coalfield lies in the west-central Alberta Foothills, approximately 200 km west of the city of Red Deer. The area was extensively mined in the past and several of the underground mines were referred to as "gassy". Up to six coal seams are present with a cumulative thickness of greater than 15 m (Fig. 29). Coal is medium to low volatile in rank with 1.2% to 1.6% Ro_{max}. Ash content is variable, ranging from 7% to 25% (air dried basis, ADB). Several geological structures have been defined as potential coalbed methane exploration targets for this area (Dawson and Kalkreuth, 1994), but to date, no boreholes have been drilled to examine the coalbed methane potential. Theoretical gas capacity values for coals of the Nordegg area, based upon the Ryan equation (Ryan, 1992), are presented in Table 6. One adsorption isotherm has been completed for a representative coal sample from the Nordegg area and the data are presented in Figure 30. Langmuir volume is estimated at 20.5 cm^3/g at a Langmuir pressure of 2320.2 kPa. The calculated theoretical gas capacity of the coal using the Ryan equation at 1000 m depth and a rank of 1.52% Ro_{max} yields a value of 14.02 cm^3/g. The measured value as derived from the adsorption isotherm for the same depth interval is approximately 16.2 cm^3/g. The difference between the two numbers may be due to adsorption isotherm temperatures and variation in moisture content.

Table 6

Theoretical gas capacity values for coals of the Grande Cache Member of the Gates Formation, Nordegg, Alberta

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 1.2% Ro_{max}		Rank 1.6% Ro_{max}	
	Ash 7%	Ash 25%	Ash 7%	Ash 25%
600	12.96	10.37	15.56	12.46
800	13.86	11.09	16.47	13.18
1000	14.56	11.65	17.18	13.75
1200	15.13	12.11	17.75	14.21
1400	15.62	12.50	18.24	14.59
1600	16.03	12.83	18.66	14.93
1800	16.40	13.13	19.03	15.23
2000	16.73	13.34	19.36	15.50
2200	17.03	13.63	19.66	15.74
2400	17.30	13.85	19.94	15.96
2600	17.55	14.05	20.19	16.16
Assumed Equilibrium Moisture 2.9%				

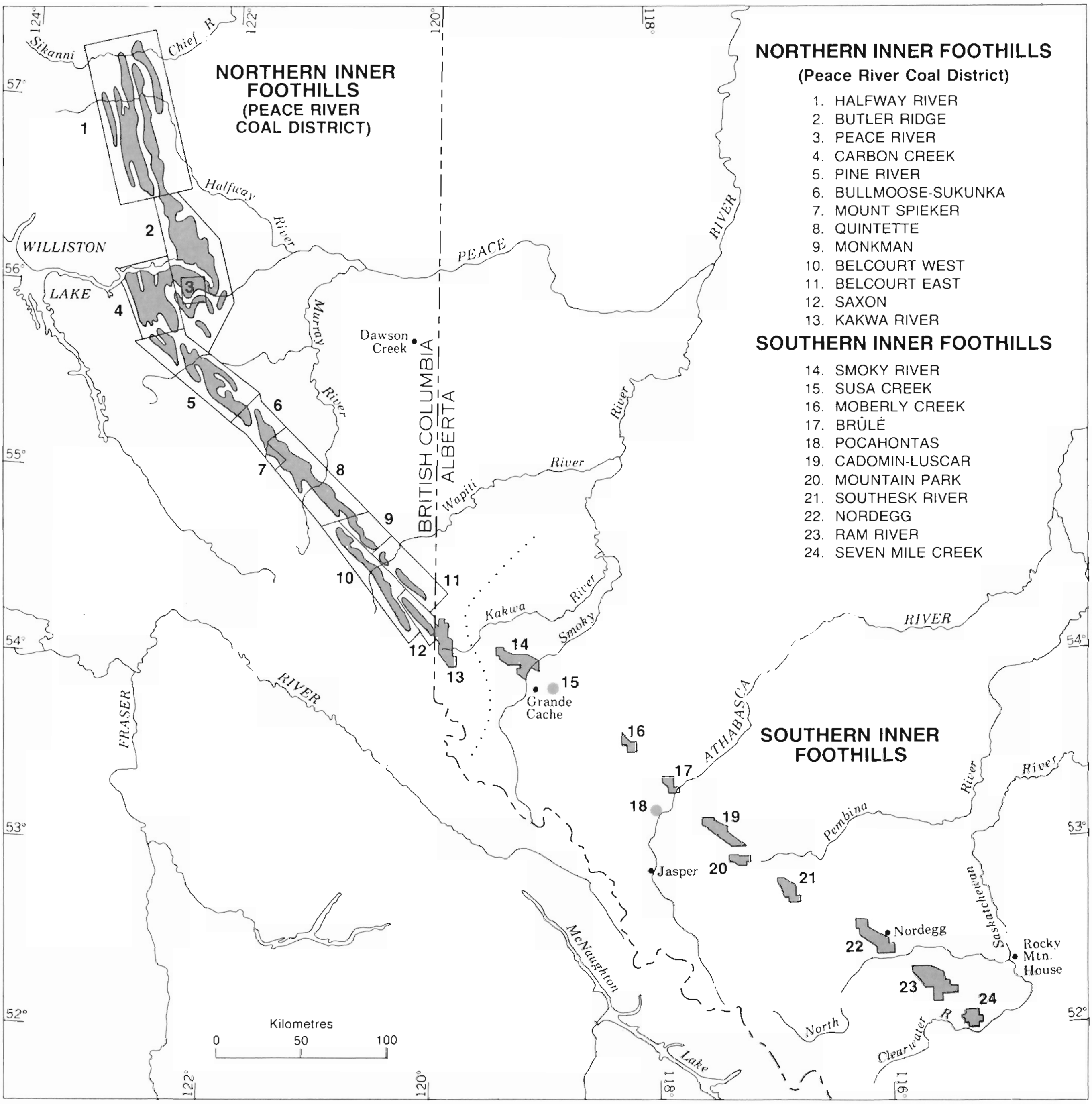

Figure 27. Coal districts and coalfields of the Inner Foothills Belt of the Rocky Mountains (from Smith, 1989).

Cadomin-Luscar coalfield

In the Cadomin-Luscar coalfield, one major coal seam (Jewel seam) lies at the base of the Grande Cache Member, immediately above the Torrens Member. Several thinner coal seams are developed higher in the stratigraphic section but are not currently being exploited commercially. The Jewel seam is variable in thickness, up to 10 m thick, and tends to split into several thinner seams toward the north (Langenberg, 1992). The Cadomin-Luscar region lies immediately to the east of the McConnell thrust of the Rocky Mountains, and has been subjected to widespread folding and faulting. Commonly the Jewel seam is structurally thickened due to folding or faulting, resulting in shearing of the coal. The ash content of the Jewel seam averages 14% and the rank varies from 0.97% to 1.43% Ro_{max} (Dawson and Kalkreuth,

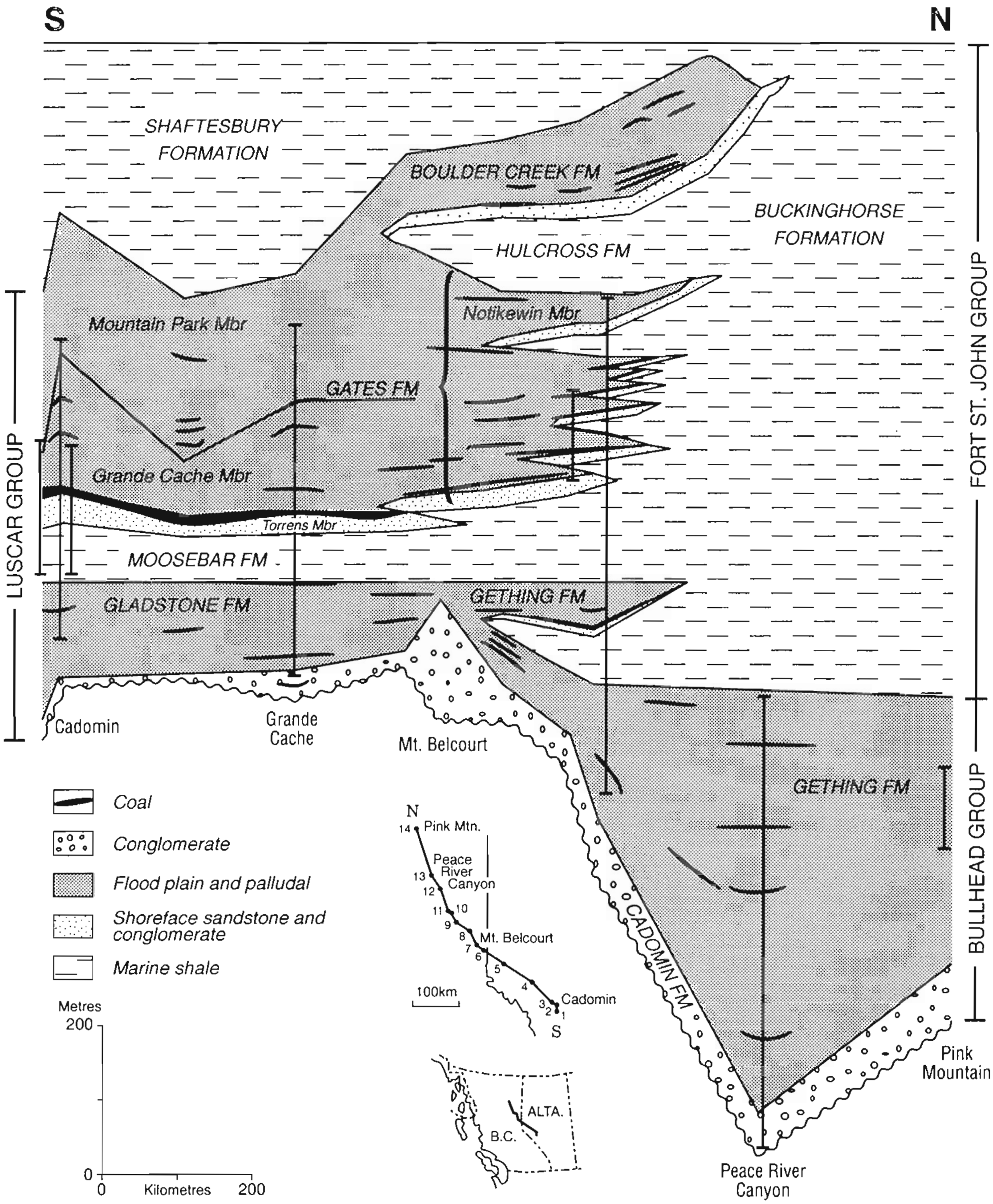

Figure 28. *Generalized stratigraphic cross-section of the Gates Formation from northeastern British Columbia to the Cadomin-Luscar coalfield (from Kalkreuth et al., 1989).*

1993). Theoretical gas capacity values based upon these rank ranges and average coal quality for a depth range of 500 to 2600 m are presented in Table 7. Two adsorption isotherms have been completed on samples collected from the Jewel seam at Cardinal River and Gregg River open pit coal mines (Fig. 31). The Langmuir volumes and pressures for the two isotherms are 23.1 cm^3/g and 1628 KPa, and 34.7 cm^3/g and 3372 KPa respectively, indicating that the coals have a very high gas capacity. Exploration drilling in 1980 at the Cardinal River mine indicated that the Jewel seam contains significant volumes of coalbed methane at depths greater than 300 m. Desorption testing produced in situ values of greater than 17.7 cm^3/g for samples collected at 400 m depth (Feng and Augsten, 1980). These values are significantly higher than

Table 7

Theoretical gas capacity values for coals of the Grande Cache Member of the Gates Formation, Cadomin/Luscar coalfield, west-central Alberta

Depth (m)	Gas Capacity (cm^3/g)	
	Rank 0.97% Ro_{max}	Rank 1.43% Ro_{max}
500	9.49	12.93
750	10.66	14.11
1000	11.48	14.94
1250	12.12	15.59
1500	12.64	16.12
1750	13.09	16.57
2000	13.47	16.96
Equilibrium Moisture 2.1% Average Ash Content 14%		

obtained using the Ryan equation and it appears that the coals at the base of the Gates Formation may exhibit unique characteristics that allow significant volumes of coalbed methane to be adsorbed. Samples collected from other Gates Formation localities confirm these high gas capacity isotherm curves. Research by the author is currently underway to study this apparent anomaly. To date no other coalbed methane exploration has been conducted in the region.

Smoky River coalfield

The Smoky River coalfield, located in the northwest corner of the Alberta Foothills, contains up to four major seams within the Grande Cache Member of the Gates Formation. The most laterally continuous of these are the No. 4 and 10 seams that have an average thickness of 6 and 3 m respectively (Langenberg et al., 1987). The No. 3 and 11 seams are more variable in thickness, contain numerous partings and are usually less than 3 m thick. In the Smoky River coalfield, the coal-bearing strata have been folded and faulted in a similar manner to other areas of the Inner Foothills to the south. Structural thickening of coal seams in the axes of antiforms along with small-scale imbricate thrust faults and duplex structures are common (op. cit.).

The rank of the coal seams ranges from 1.3% to 1.7% Ro_{max} and is classified as medium to low volatile bituminous. Kalkreuth and McMechan (1984) have demonstrated that the rank of the coal has been controlled more by preorogenic depth of burial rather than postorogenic activity, in contrast to coalification studies conducted by Pearson and Grieve (1980) for the

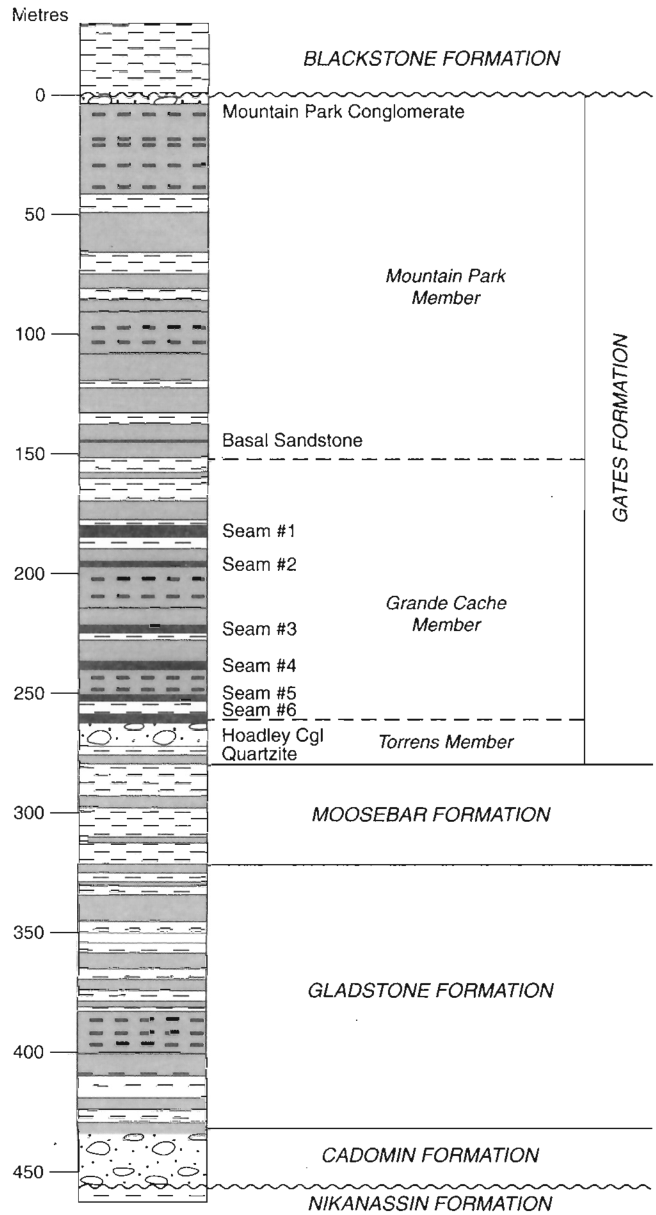

Figure 29. *Stratigraphic section of the Gates Formation, Nordegg area (from Dawson and Kalkreuth, 1993).*

Crowsnest coalfield. In essence, the lower coal seams of the Grande Cache Member (No. 3 and 4 seams) have a higher rank than those near the top (No. 10 and 11 seams).

Some coalbed methane exploration has been undertaken in the Smoky River coalfield. To date two exploration boreholes have been completed, upon which desorption tests were undertaken. One of these boreholes was subjected to a limited production test. Data for these boreholes is held confidential by the Alberta Energy Resources Conservation Board.

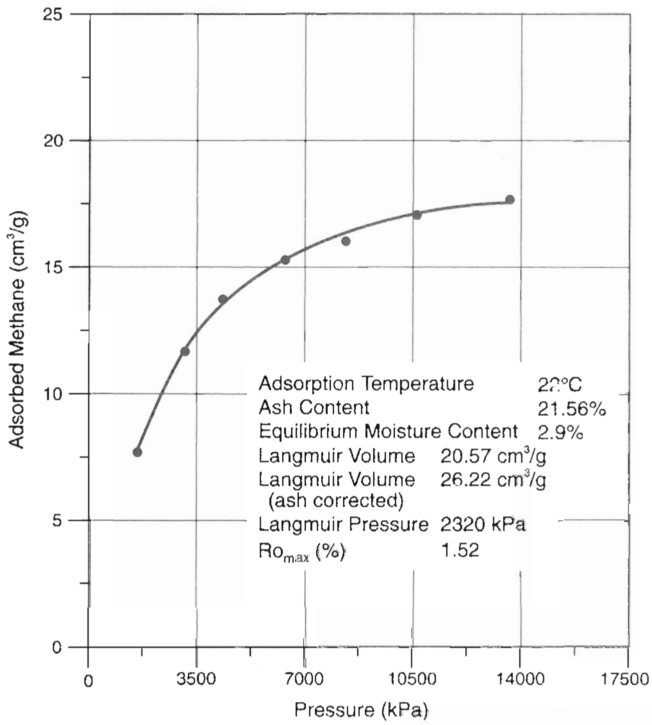

***Figure 30.** Adsorption isotherm of coal from No. 2 seam, Nordegg mine site.*

Theoretical gas capacity values have been calculated for the Smoky River coalfield assuming an ash and moisture content of 12% and 5% respectively and a rank range listed above (Table 8). One isotherm of seam No. 4 was calculated (Fig. 32) yielding a Langmuir volume and pressure of 27.6 cm^3/g and 2377 KPa. Comparing the actual isotherm values to the theoretical values of the Ryan equation reveals a similar trend to that of the Luscar-Cadomin coalfield to the south.

Peace River coal district

The northern extension of the Inner Foothills belt is referred to as the Peace River coal district and extends from the Kakwa River, near the Alberta/British Columbia border, to the Sikanni Chief River, north of Fort St. John (Fig. 27). In the northern half of the coal district, coals are present in the Lower Cretaceous Gething and in the southern half of the coal district in the Gates Formation. Minor coal is also present in the Upper Jurassic/Lower Cretaceous Minnes Group.

The Gething Formation is up to 1050 m thick with up to 100 coalbeds reported (Gibson, 1985b). Coal seams are generally less than 2 m thick and cumulative coal thickness for the formation is between 20 and 30 m (Duff and Gilchrist, 1981).

Table 8

Theoretical gas capacity values for coals of the Grande Cache Member of the Gates Formation, Smoky River coalfield, northwestern Alberta

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 1.3% Ro_{max}		Rank 1.7% Ro_{max}	
	Ash 10%	Ash 20%	Ash 10%	Ash 20%
500	12.71	11.27	15.02	13.32
750	13.95	12.37	16.26	14.41
1000	14.82	13.14	17.14	15.19
1250	15.50	13.74	17.82	15.80
1500	16.05	14.23	18.38	16.29
1750	16.52	14.65	18.85	16.71
2000	16.93	15.01	19.26	17.07
Equilibrium Moisture 1.8%				

The Gates Formation is separated from the older Gething Formation by the predominantly marine Moosebar Formation. The widespread deposition of coals within the lower portion of the Gates Formation is associated with the transition from marine to continental rocks. The formation is up to 280 m thick and contains up to 11 coal seams with a cumulative thickness of up to 46 m (Fig. 33). Several seams, each in excess of 4 m thick, are laterally extensive between the Kakwa and Sukunka rivers (Duff and Gilchrist, 1981).

Coals of the Gething and Gates formations range from high volatile A bituminous to low volatile bituminous with the average being medium volatile bituminous (Kalkreuth and McMechan, 1988). Proximate analyses for the coals is variable with ash and moisture contents ranging from 5% to 20% and 1% to 3% respectively.

Coalbed methane potential of the coals varies depending on rank, ash and moisture content. Theoretical gas capacity values, based upon the Ryan equation (Ryan, 1992), have been calculated for the range of quality and rank characteristics and are presented in Table 9.

Two isotherms have been completed for these coals, one from the Gates Formation at Quintette and the other from the Gething Formation from Carbon Creek (Fig. 34). Langmuir volume and pressure for the Gates Formation sample are 55.2 cm^3/g (ash free) and 6250 KPa, while 23.2 cm^3/g (ash free) and 2519 KPa for the

Table 9

Theoretical gas capacity values for coals of the Gething and Gates formations, Peace River coal district, northeastern British Columbia

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 1.0% Ro_{max}		Rank 1.5% Ro_{max}	
	Ash 5%	Ash 20%	Ash 5%	Ash 20%
250	7.36	7.12	10.52	10.52
500	10.80	8.94	14.76	12.40
750	12.08	10.00	16.07	13.50
1000	13.00	10.76	16.99	14.20
1250	13.70	11.34	17.71	14.89
1500	14.20	11.82	18.30	15.38
1750	14.77	12.22	18.80	15.80
2000	15.19	12.57	19.23	16.16
	Assumed Equilibrium Moisture 8%		Assumed Equilibrium Moisture 1%	

Gething sample were obtained. Ash content and equilibrium moisture content for the two samples were 5.65% and 2.1%, and 17.09% and 2.8% respectively. There appears to be a reasonable correlation between theoretical gas capacity and adsorption isotherm capacity for the Gething Formation sample but again the Gates Formation sample is much higher than the theoretically determined value.

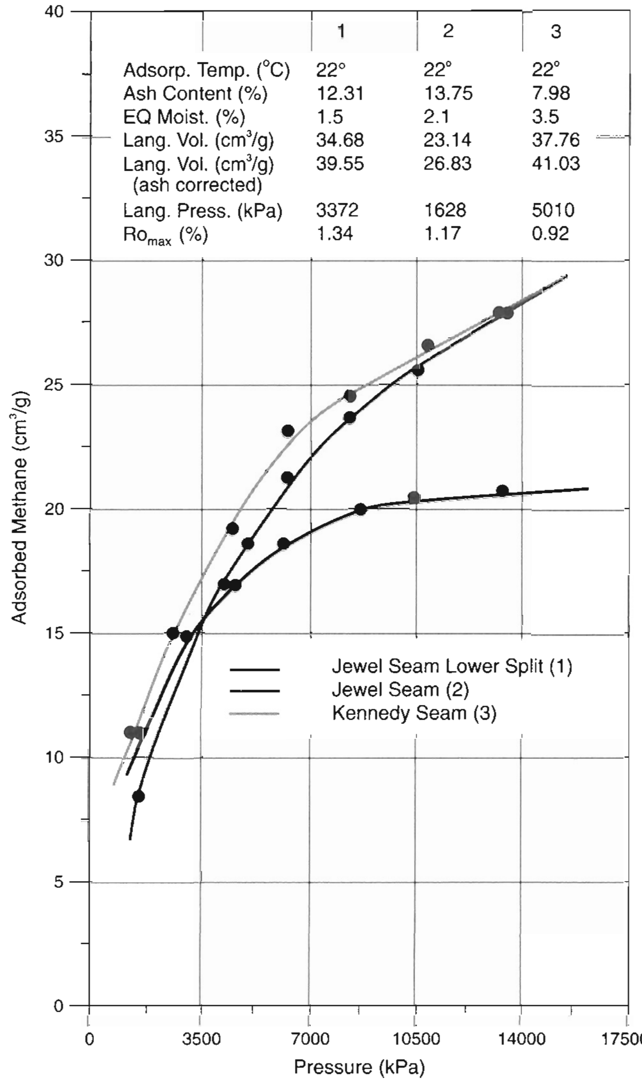

Figure 31. Adsorption isotherms of two samples of the Jewel seam from Cardinal River and Gregg River mines.

Outer Foothills

Coals of the Outer Foothills occur in Upper Cretaceous to Tertiary strata and lie within a narrow belt (10–30 km wide) extending from the United States border to north of the Athabasca River, parallel to the Rocky Mountains to the west (Fig. 35). Coal is present throughout this trend, with maximum development occurring in the region between the Pembina River in the south and the Athabasca River in the north (commonly referred to as the Coalspur trend).

Coals in the southern portion of the Outer Foothills are present in the Upper Cretaceous Belly River Formation. This formation ranges from 700 to 900 m thick and contains two major coal-bearing intervals, the lower, approximately 120 m above the formation base, and the upper, within 45 m of the top of the formation (Douglas, 1951). Seams are generally thin and discontinuous with a maximum reported thickness of 3 m (Allan, 1943). Further to the north, equivalent strata of the Brazeau Formation contain thin coals of similar thickness and distribution.

In the region south and east of Hinton, thick coals are present within the Palaeocene Coalspur Formation (Jerzykiewicz and McLean, 1980). Numerous seams in excess of 6 m thick lie within a 250 m thick sequence of interbedded sandstone, siltstone and shale (Fig. 36). Coal zones are laterally continuous and have been correlated to be equivalent to the Ardley Coal Zone of the Alberta Plains. Cumulative coal thickness for the Coalspur Formation is up to 40 m. North of the Athabasca River, the major coal zones within the Coalspur Formation (Val d'Or, Mynheer and Silkstone) tend to split and become more

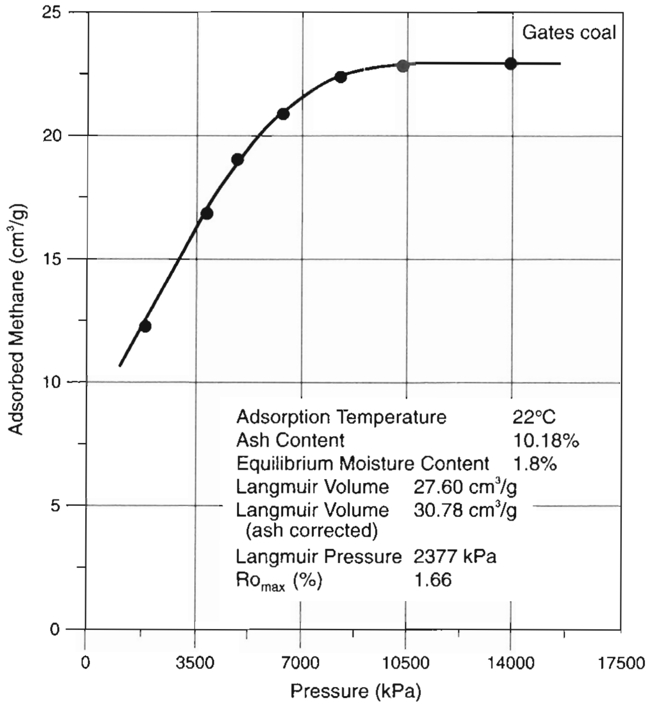

Figure 32. Adsorption isotherm of a coal sample from seam No. 4 from Smoky River mine, Smoky River coalfield.

discontinuous. Equivalent strata in the region of the Smoky River is called the Kakwa coal measures (Dawson and Kalkreuth, 1989).

The Belly River and Coalspur coals are generally high volatile bituminous in rank with Ro_{max} values ranging from 0.6% to 0.7%. Ash and moisture contents are variable, ranging from 10% to 20%, and 4% to 10% respectively. Table 10 illustrates the theoretical gas capacity values for these coals based upon the quality and rank characteristics presented above, at a depth range of 500 to 2000 m. Isotherms were completed for two Coalspur Formation samples (Fig. 37). The ash and equilibrium moisture contents were 9.11% and 8.3% for one sample, and 15.34% and 8.3% for the other. By comparing the gas capacity values with the adsorption isotherms, it can be seen that a wide discrepancy is present. It appears that even though the adsorption isotherms predict that the coals of the Coalspur Formation have the capacity to hold large quantities of methane (Langmuir volumes of 21.6 cm^3/g and 16.3 cm^3/g at Langmuir pressures of 4101 and 4636 KPa), the coals may be of insufficient rank to have generated sufficient thermogenic methane to produce saturated gas conditions.

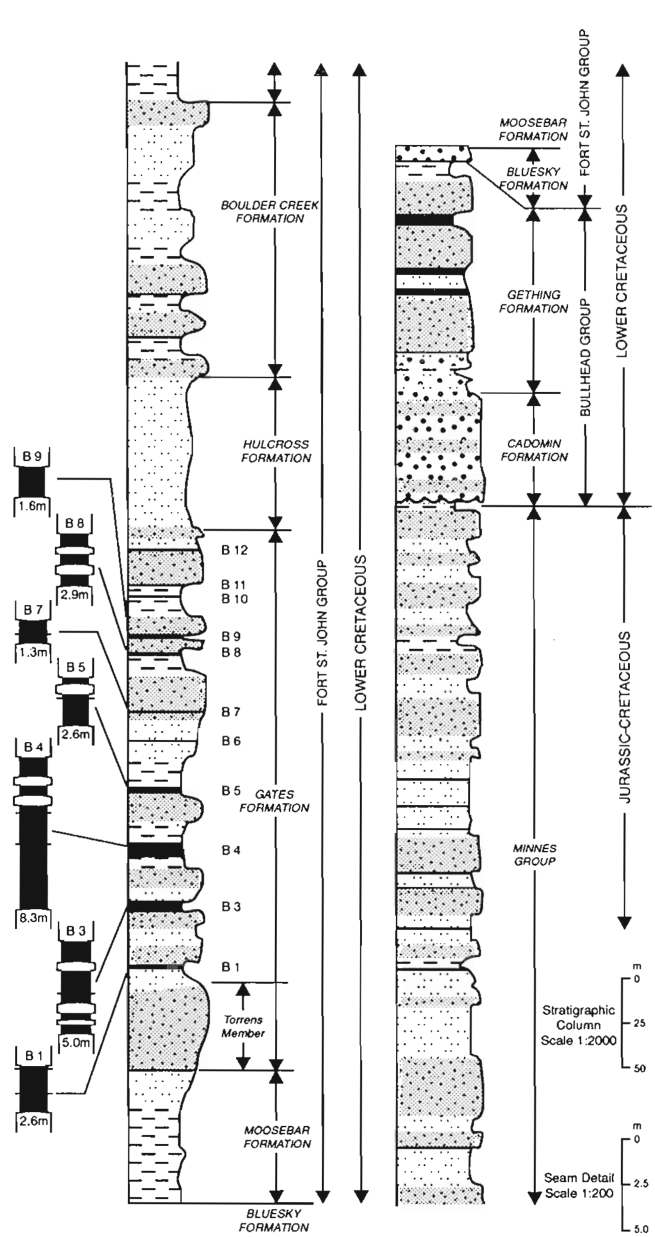

***Figure 33.** Stratigraphic sections illustrating distribution of coal seams in the Gething and Gates formations (from Smith et al., 1990).*

Western Interior Plains

Coals of the Western Interior Plains cover an area extending from the edge of the disturbed belt in western Alberta and northeastern British Columbia to the Saskatchewan/Manitoba border (Fig. 38). The seams are essentially flat-lying to gently dipping to the west and occur at depths ranging from the surface to greater than 3000 m (Fig. 39). The coals occur in Lower Cretaceous to Paleocene strata and are widely variable in thickness and lateral extent.

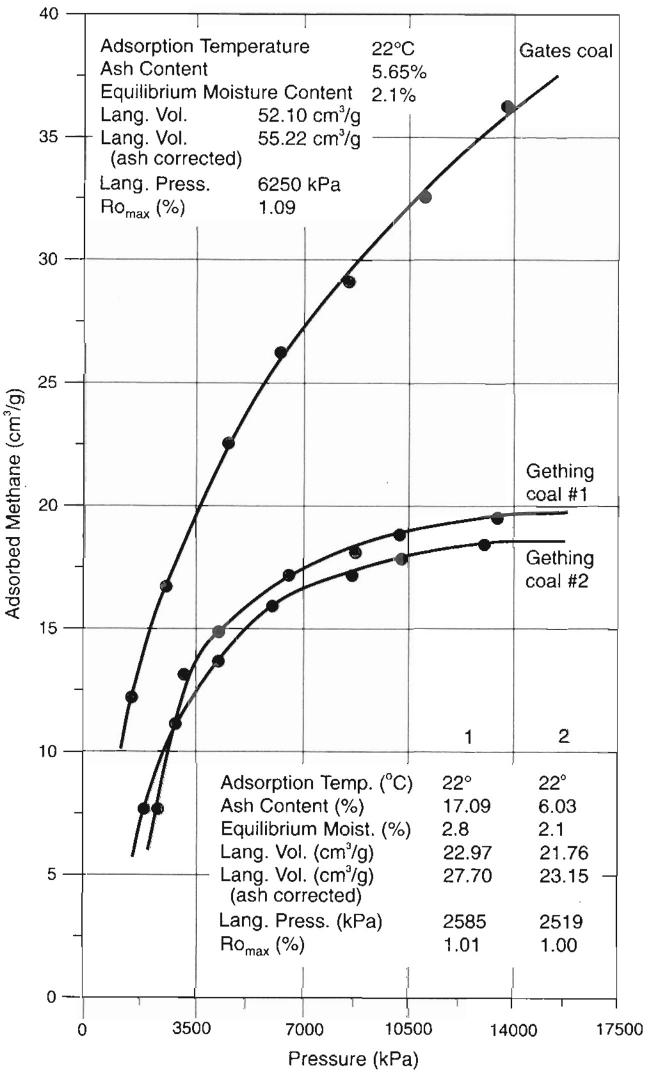

Figure 34. *Adsorption isotherms of coal samples from the Gething and Gates formations, Peace River coal district. Gates coal samples collected from Quintette mine; Gething coal samples collected from Carbon Creek deposit.*

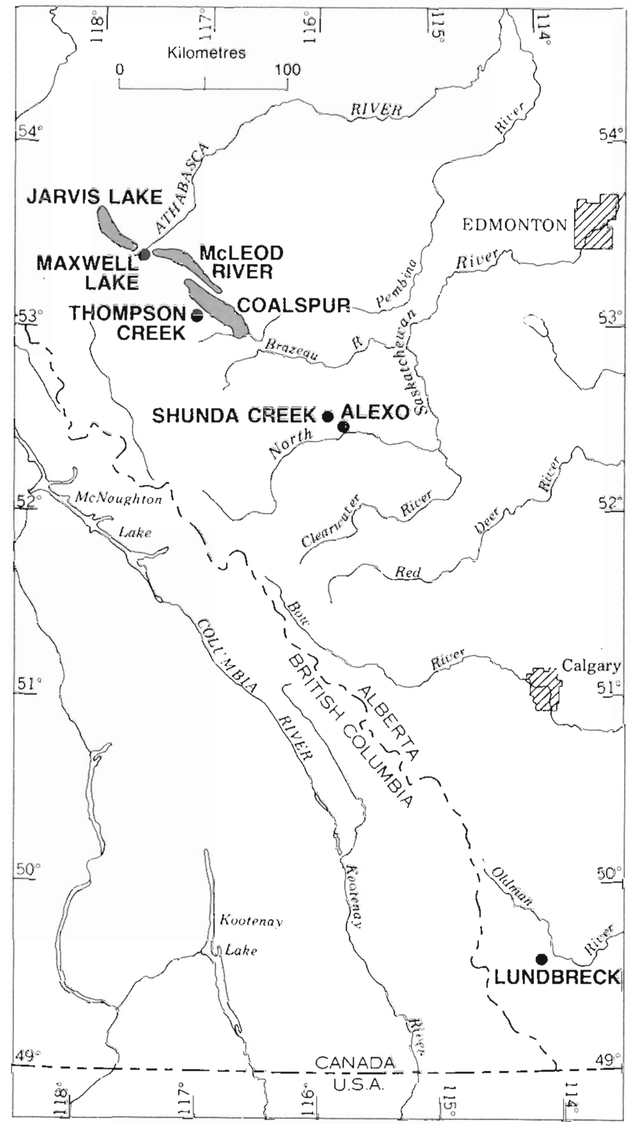

Figure 35. *Coalfields and isolated deposits of the Outer Foothills Belt of the Rocky Mountains (from Smith, 1989).*

The major coal-bearing formations are the Mannville (Lower Cretaceous), Oldman (Upper Cretaceous), Horseshoe Canyon (Upper Cretaceous) and Scollard (Tertiary). The coals range from lignite to bituminous in rank, generally increasing in rank from east to west. The coals of the Oldman and Horseshoe Canyon formations are thin, discontinuous and believed to be of too low a rank to be considered for coalbed methane potential. In addition, the coals present in Saskatchewan, Manitoba and eastern Alberta are of low rank (less than 0.5% Ro_{max}) and are not considered to contain areas of significant coalbed methane potential. The coals of the Mannville and Scollard formations are considered to be the main coalbed methane targets of the Interior Plains.

Mannville Formation

The coals of the Mannville Formation are widespread throughout the Alberta Plains and are stratigraphically equivalent to the coals of the Gates Formation of the Rocky Mountain Inner Foothills. Individual seams are laterally persistent but variable in thickness (Williams and Murphy, 1981). Up to seven seams are present, with cumulative coal thickness up to 15 m (Fig. 40). Individual seams range from less than 1 m to greater than 11 m in thickness. The coals of the Mannville Formation are usually low in ash (less than 20% ash) with a highly variable sulphur content. Rank increases from lignite in the east (Alberta/Saskatchewan border) to bituminous in the west (axis of the Alberta

Table 10

Theoretical gas capacity values for coals of the Coalspur Formation, west-central Alberta Foothills

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 0.6% Ro_{max}		Rank 0.75% Ro_{max}	
	Ash 10%	Ash 20%	Ash 10%	Ash 20%
250	0.76	0.67	4.14	4.91
500	2.73	2.39	6.95	6.14
750	3.88	3.40	8.14	7.20
1000	4.70	4.11	8.99	7.95
1250	5.33	4.67	9.65	8.53
1500	5.85	5.12	10.19	9.00
1750	6.29	5.50	10.64	9.40
2000	6.67	5.83	11.03	9.75
	Assumed Equilibrium Moisture 10%		Assumed Equilibrium Moisture 4%	

Syncline). Depth of the coal correspondingly increases from east to west (<600->3000 m).

The coalbed methane potential of the Mannville Formation has been the focus of exploration by numerous oil and gas companies over the past two to three years. In many cases the testing for coalbed methane from the Mannville Formation has taken the form of secondary testing of wells being drilled for conventional hydrocarbons from deeper formations. Several wells have been drilled specifically for coalbed methane and to date limited commercial production has been achieved. Using the Ryan equation, theoretical gas capacity values have been calculated for the Mannville Formation assuming an ash and moisture content of 15% and 5% respectively. The rank of the coal ranges from 0.5% to 1.2% Ro_{max} over a depth range of 500 to 3000 m (Table 11). An attractive element of the coalbed methane potential of the Alberta Plains is the number of existing wells that may be utilized for recompletion. Numerous companies are currently evaluating the engineering and economic viability of using these existing wells in developing the coalbed methane potential.

Scollard Formation

The Scollard Formation contains the laterally extensive Ardley coal measures, stratigraphically equivalent to the Coalspur coal measures of the Alberta Foothills. The coals fall within a 60 to 150 m interval of interbedded sandstone, siltstone, shale and coal (Baofang and Dawson, 1988; Fig. 41). Individual

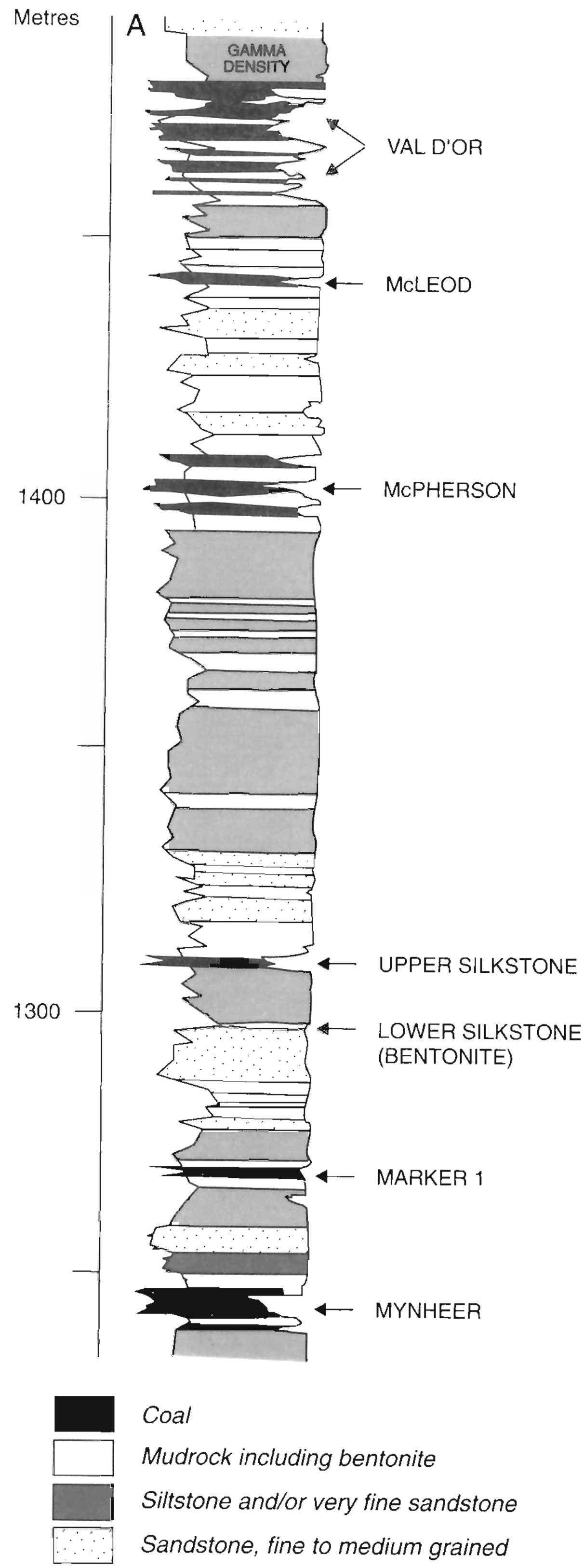

***Figure 36.** Representative stratigraphic section of the Coalspur Formation in the northern Outer Foothills (from Jerzykiewicz and McLean, 1980).*

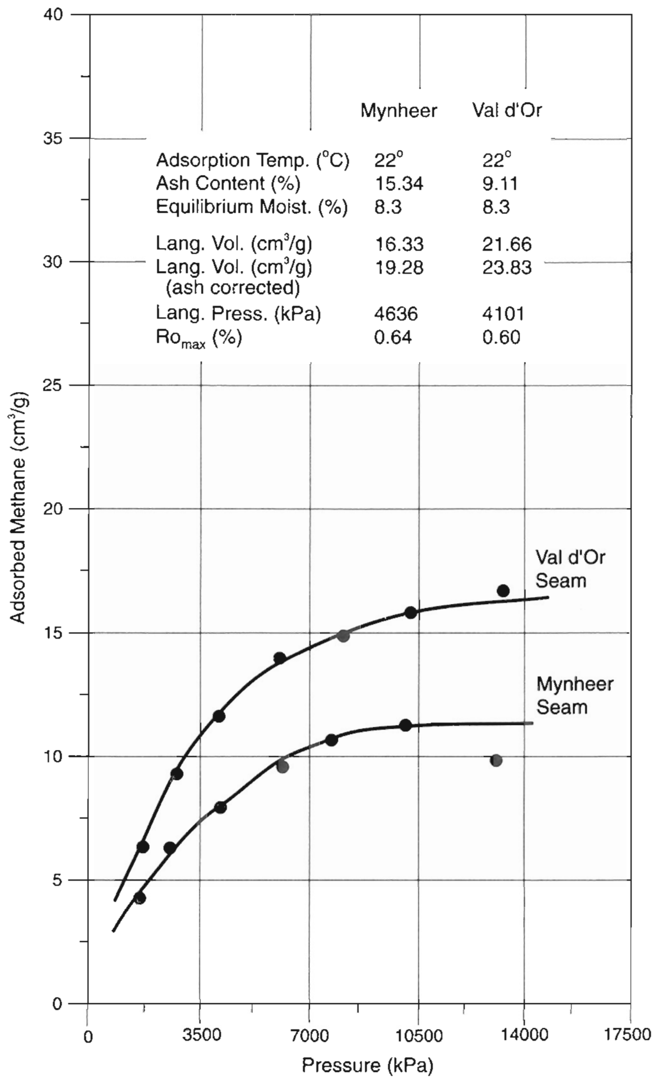

Figure 37. *Adsorption isotherms of the Coalspur Formation coals. Samples collected from the Val d'Or and Mynheer seams at the Coal Valley mine site.*

seams display remarkable continuity, extending from Three Hills in the south to north of Swan Hills in the north. Up to 24 m of coal are present within the Ardley coal measures, with individual seams up to 4 m thick (Richardson, 1991; Fig. 42). Coal seams commonly contain thin partings of kaolinitic mudstone. The Ardley coals subcrop along a belt extending from Three Hills, northward to Wabamum Lake and Whitecourt, then toward the west near the Kakwa and Smoky rivers (Dawson and Kalkreuth, 1989). Strata are essentially flat-lying or dip gently to the west. Near the axis of the Alberta Syncline (parallel to the front ranges of the Rocky Mountains), the Scollard Formation coals are at depths greater than 800 m.

Table 11

Theoretical gas capacity values for coals of the Mannville Formation of the Alberta Plains

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 0.6% Ro_{max}		Rank 1.2% Ro_{max}	
	Ash 10%	Ash 20%	Ash 10%	Ash 20%
500	2.59	2.73	11.99	10.63
1000	4.70	4.11	14.09	12.49
1500	5.85	5.12	15.32	13.58
2000	6.67	5.83	16.19	14.35
2500	7.30	6.39	16.87	14.95
3000	7.82	6.84	17.42	15.44
	Assumed Equilibrium Moisture 10%		Assumed Equilibrium Moisture 2%	

The Ardley coal measures range from subbituminous C to high volatile C bituminous in rank with reflectances ranging from 0.4% Ro_{max} in the central plains region to 0.75% Ro_{max} near the foothills. Rank of the coal increases from east to west in response to increased depth of burial. The coal seams are widely variable in ash content (10–25%) and equilibrium moisture of the coals ranges from 10% to 20%. The lower rank of the coals at shallow depths suggests that major coalbed methane potential target areas for Ardley coals lie at depths greater than 800 m near the edge of the foothills. Rank of the coals is generally greater than 0.65% Ro_{max}. Table 12 presents theoretical gas capacity values (based upon the Ryan equation) for the range of Ardley coal quality to a depth of 2000 m. Desorption tests conducted by the GSC on several Ardley coal tests appear to collaborate these estimates.

Maritimes

Nova Scotia

The coal-bearing strata in the Maritimes are of Carboniferous age and are contained in four major groups: Riversdale, Cumberland, Pictou/Stellarton, and Sydney Mines. The sedimentary basins containing these coal measures at shallow depths are present in New Brunswick, Newfoundland, and Nova Scotia (Fig. 43). The Sydney and Cumberland basins of Nova Scotia are the largest of the coal-bearing areas and have the longest history of coal mining in the region. Coalbed methane exploration was undertaken by Algas Limited during the mid 1970s and early 1980s in the

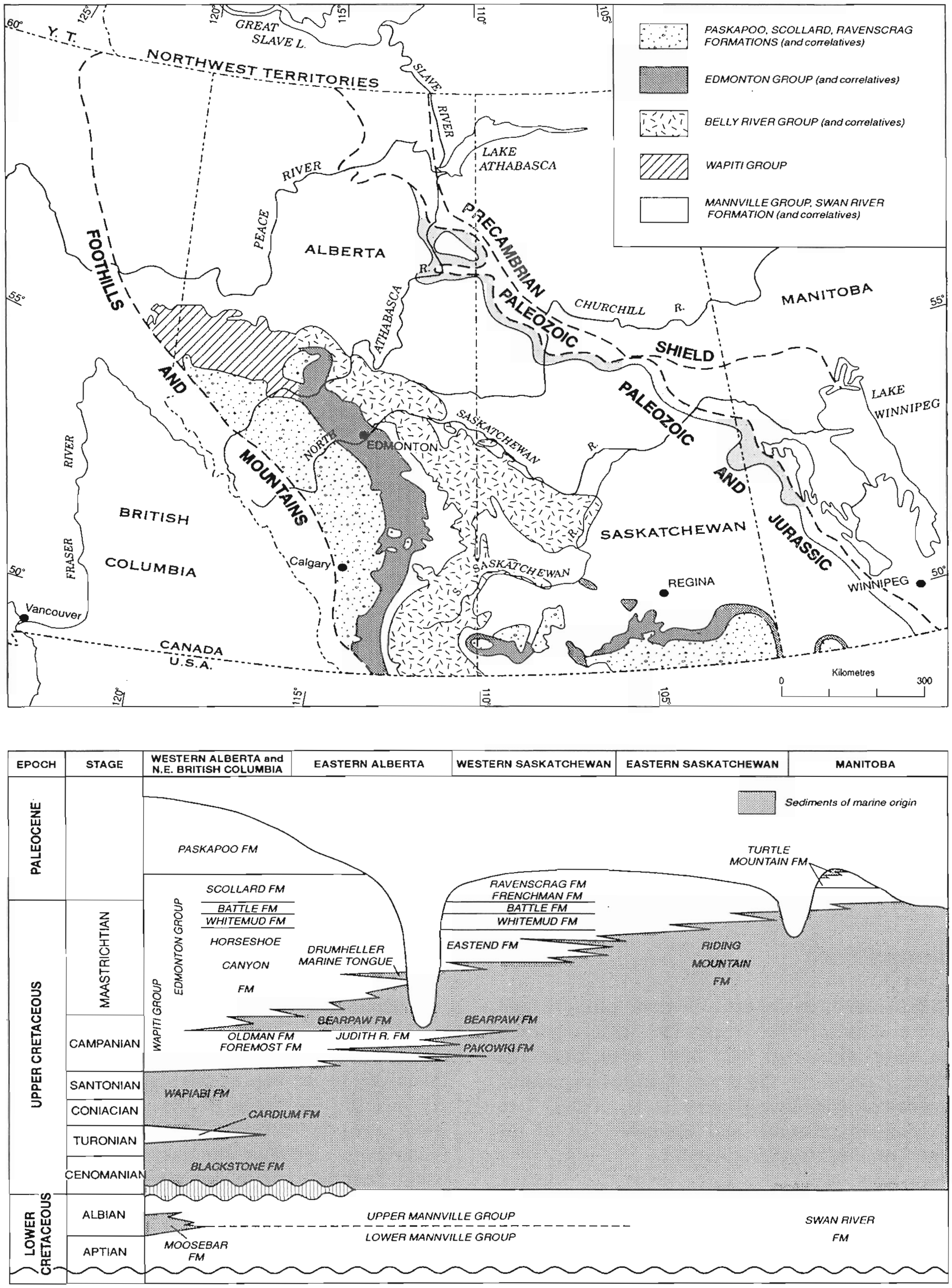

Figure 38. *Generalized map and stratigraphic section showing major coal-bearing formations of the Interior Plains (from Smith, 1989).*

Table 12

Theoretical gas capacity values for coals of the Scollard Formation of the Alberta Plains

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 0.55% Ro_{max}		Rank 0.75% Ro_{max}	
	Ash 10%	Ash 20%	Ash 10%	Ash 20%
250	0.00	0.00	4.03	4.88
500	0.00	0.00	6.91	6.07
750	0.00	0.00	8.10	7.11
1000	0.18	0.16	8.95	7.86
1250	0.80	0.70	9.60	8.43
1500	1.31	1.14	10.14	8.90
1750	1.74	1.51	10.59	9.30
2000	2.11	1.84	10.98	9.64
	Assumed Equilibrium Moisture 12%		Assumed Equilibrium Moisture 8%	

Cumberland Basin and Pictou County coalfield, but no commercial production was achieved. In recent years there has been a renewed interest in these basins with several coalbed methane exploration licenses being acquired and exploration boreholes planned for the next two years.

Coal seams within the Riversdale Group are thin and discontinuous. Coalfields containing these coal measures commonly are limited in lateral extent due to structural complications. Coals of this group are not considered for coalbed methane potential.

Cumberland Basin

The Cumberland Basin extends both onshore and offshore in western Nova Scotia. The onshore portion covers approximately 5000 km^2 with only the southwest region near the Athol Syncline containing significant coal measures (Naylor et al., 1992). Two major coalfields, Joggins and Springhill, lie in the proximity of this structural feature.

The Cumberland Group is comprised of the Joggins and Springhill Mines formations and contains up to 2200 m of coal-bearing strata (Ryan et al., 1991). These sedimentary rocks are preserved in the asymmetrical east/west trending Athol syncline which appears to have served as a local depocentre during Westphalian A-B time (Naylor et al., 1992; Fig. 44). As many as 32 coal zones are present within the Coal Mine Point Member of the Joggins Formation, with seams ranging in thickness from 0.6 to 1.5 m (Naylor et al., 1992; Fig. 45). In the Springhill Mines Formation (up to 800 m thick), the Coal Mine Brook Member contains up to 60 coal seams (up to 4.3 m thick) with maximum development at the north end of the Athol Syncline near the town of Springhill. Coal-bearing strata outcrop along the northern limb of this structure on what is called the Joggins trend. To the south, the coal-bearing sequence thins dramatically to less than 150 m near the pre-Carboniferous Cobequid Highlands (Smith, 1989).

The northern limb of the Athol Syncline and the area surrounding the town of Springhill have been exploited for coal since the 1700s and much of the region's coal resources have been mined. Remaining coal resources lie at depth, downdip from the existing workings. The coals at depth generally increase in rank from high volatile bituminous A to medium volatile bituminous. The seams are variable in ash and moisture content, ranging from 5% to 30%, and 1% to 10% respectively. Vitrinite content is high, averaging 80 to 85%.

Pictou/Stellarton coalfield

The Pictou/Stellarton coalfield lies within a fault-bounded graben measuring approximately 18 x 9 km in central Nova Scotia (after Naylor et al., 1992; Fig. 46).

The coals within the Pictou/Stellarton coalfield belong to the Stellarton Formation, a thick (2600 m) stratigraphic sequence of red and grey siliciclastics with numerous coals and oil shales (Naylor et al., 1992). The major coals are present within the Albion and Coal Brook members with up to 15 major coal seams present, ranging in thickness from 1 to 14 m (Fig. 47).

Numerous surface and underground mines have exploited these coal resources over the last 200 years and as a result most of the remaining higher quality resources lie at depths between 600 and 1200 m. Historically, the mines in the Pictou coalfield have been noted for being "gassy" and further work is required to determine the gas capacity of the these coals. Coal rank and quality are similar to those of the Cumberland Basin (Paul et al., 1989).

Sydney Basin

The Sydney Basin, located on the northern tip of Nova Scotia, contains most of the coal resources of the Maritimes region (Smith, 1989). The coals are present within the Sydney Mines Formation, a 2000 m thick

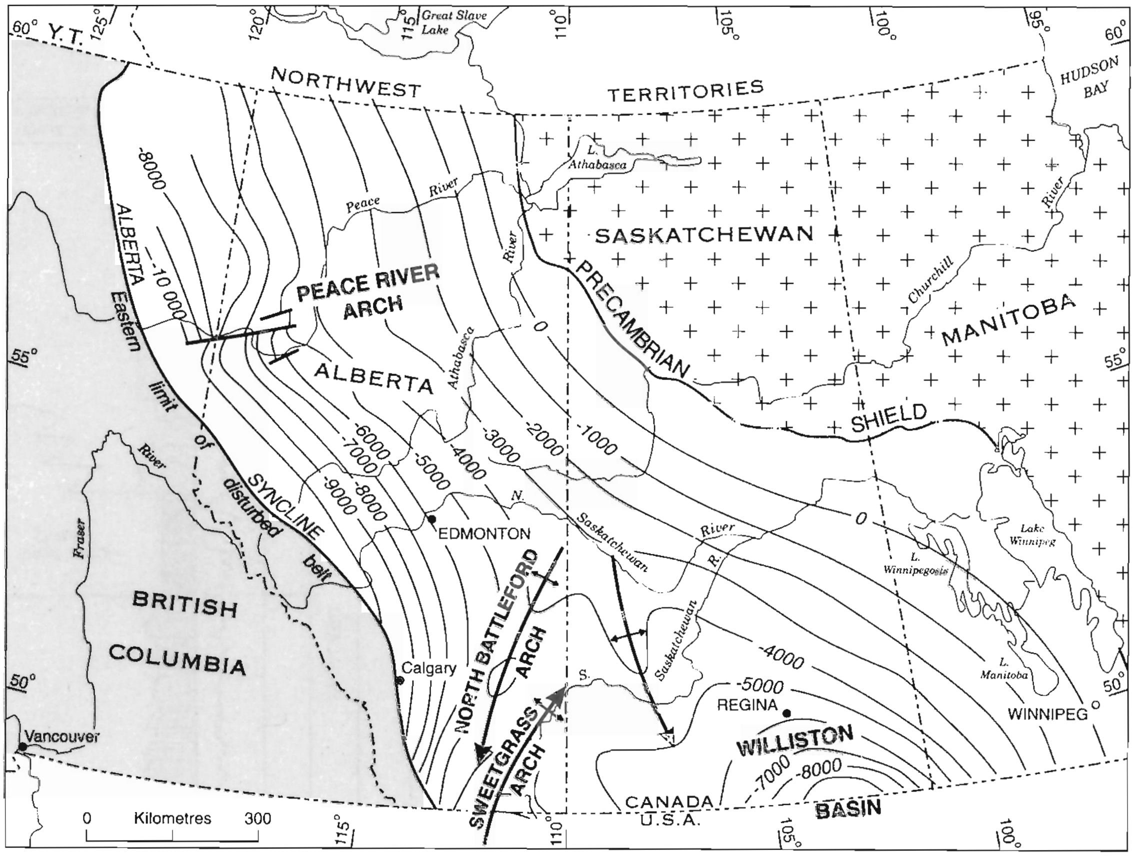

Figure 39. Major structural features of the Interior Plains (from Herbaly, 1974).

sequence of interbedded sandstone, shale and coal. Thirteen major coal seams have been identified ranging in thickness from 1 m to greater than 10 m (Fig. 48). Strata are essentially flat-lying, with dips averaging less than 5° toward the offshore basin centre. Several local flexures increase the dips up to 15°. Although all of these seams outcrop on land, 98% of the basin lies offshore (Fig. 49). Currently Cape Breton Development Corporation (DEVCO) operates several underground mines with coal being extracted from the Harbour and Phalen seams. The coals are generally classified as high volatile A bituminous in rank with similar quality characteristics as those of the Cumberland Basin. Several gas recovery projects have been proposed to recover the methane gas liberated from the underground mining activities of DEVCO's operations but no commercial production has been achieved to date.

Coalbed methane potential

Coalbed methane potential of the Carboniferous coals of the Maritimes region can be estimated based upon rank, quality and depth. The three major coal-bearing basins that have significant potential are the Cumberland Basin, Pictou/Stellarton coalfield and Sydney Basin. Both the Cumberland and Pictou target areas appear to be suitable for conventional coalbed methane exploration because the potential reservoirs are onshore. In contrast, most of the potential coalbed methane reservoir area for the Sydney Basin is offshore, thus precluding surface exploration for this potential resource. Active underground mining from this basin does allow for coalbed methane extraction from underground drilling into either existing workings (gob gas recovery) or surrounding coal-bearing strata to extract the methane gas from seams that are currently not being mined.

Early efforts to explore and develop coalbed methane resources were undertaken by Algas Resources Ltd. between 1979 and 1982. A total of 27 boreholes were drilled in selected coalfields with the Cumberland Basin and Pictou/Stellarton coalfield being the primary targets.

Results of the exploration drilling from Pictou County indicate that desorbed gas contents are widely variable, ranging from 0 to 6 cm^3/g (Algas Resources

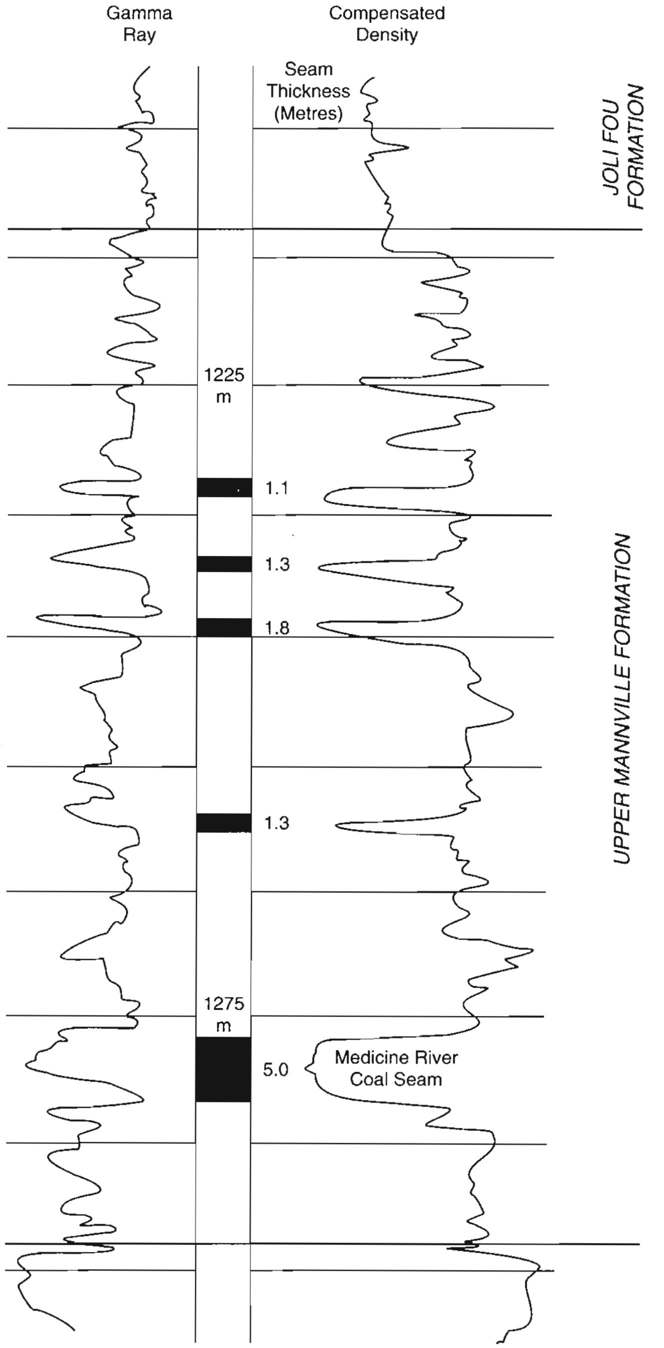

***Figure 40.** Representative stratigraphic section of the Mannville Formation, illustrating the distribution of coal seams.*

Ltd., 1981). This variability and suggested low potential may be due to the high ash content of the coals and the relatively shallow depths (less than 450 m) at which the coals were intersected.

In the Cumberland Basin, eight boreholes were drilled for coalbed methane by Algas Resources Ltd. in

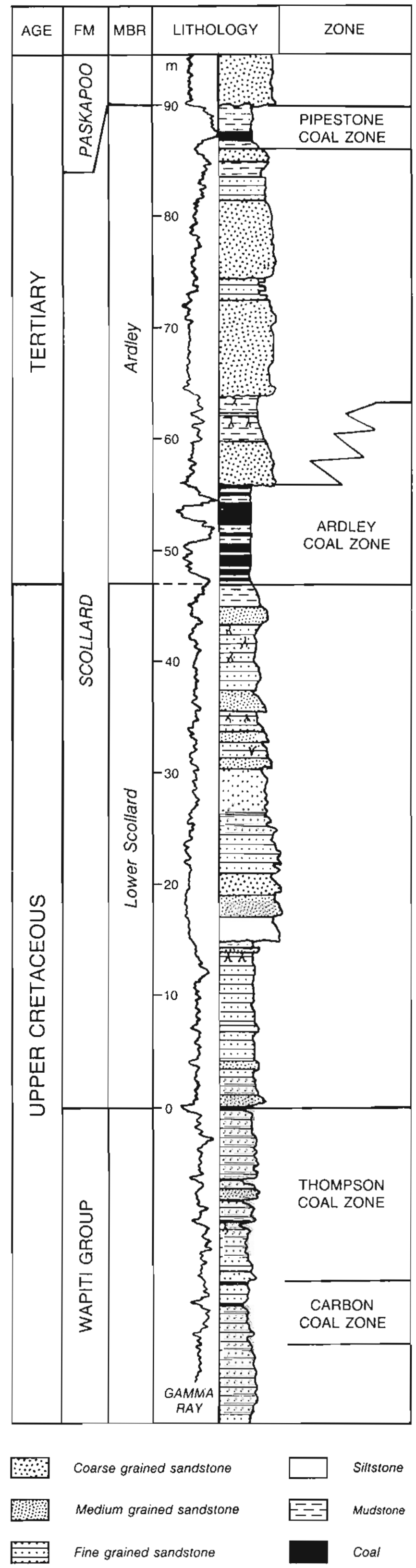

***Figure 41.** Regional stratigraphic section of the Scollard Formation, illustrating the Ardley Coal Zone (from Baofang and Dawson, 1988).*

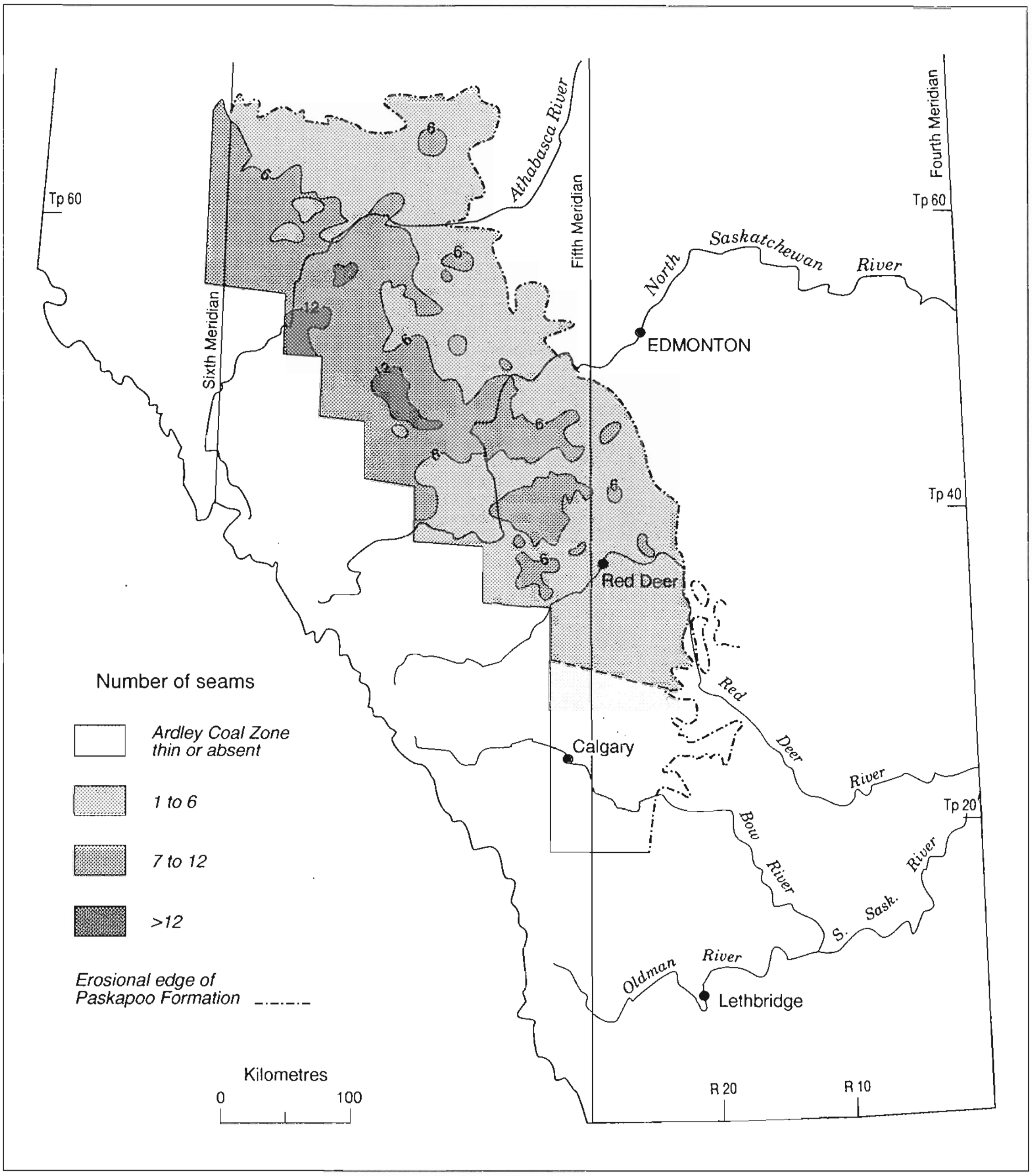

Figure 42. *Map illustrating the number of coal seams in the Ardley Coal Zone in west-central Alberta (from Richardson, 1991).*

1980. These holes were relatively shallow (less than 450 m) and placed to intersect the downdip extension of the Joggins and Springhill Mines formations near Joggins and Springhill respectively. Desorbed gas content ranges from 0 to 3 cm^3/g (Thompson, 1981). The coal seams intersected appear to be thin, ranging from 0.6 to 4m. Ash and sulphur content of the coals is variable and rank varies from 0.75% Ro_{max} at Joggins to 0.97% Ro_{max} at Springhill (Mukhopadhyay et al., 1993).

In the Sydney Basin much of the coal resources lie offshore, precluding conventional coalbed methane exploration and development. Active underground mining by Cape Breton Development Corporation (DEVCO) has provided the opportunity to explore for in situ coalbed methane resources by using horizontal boreholes and gob well collection systems. An initial feasibility study was conducted by DEVCO and partners in 1992 to assess the coalbed methane potential of the Donkin coal resource block (Mavor

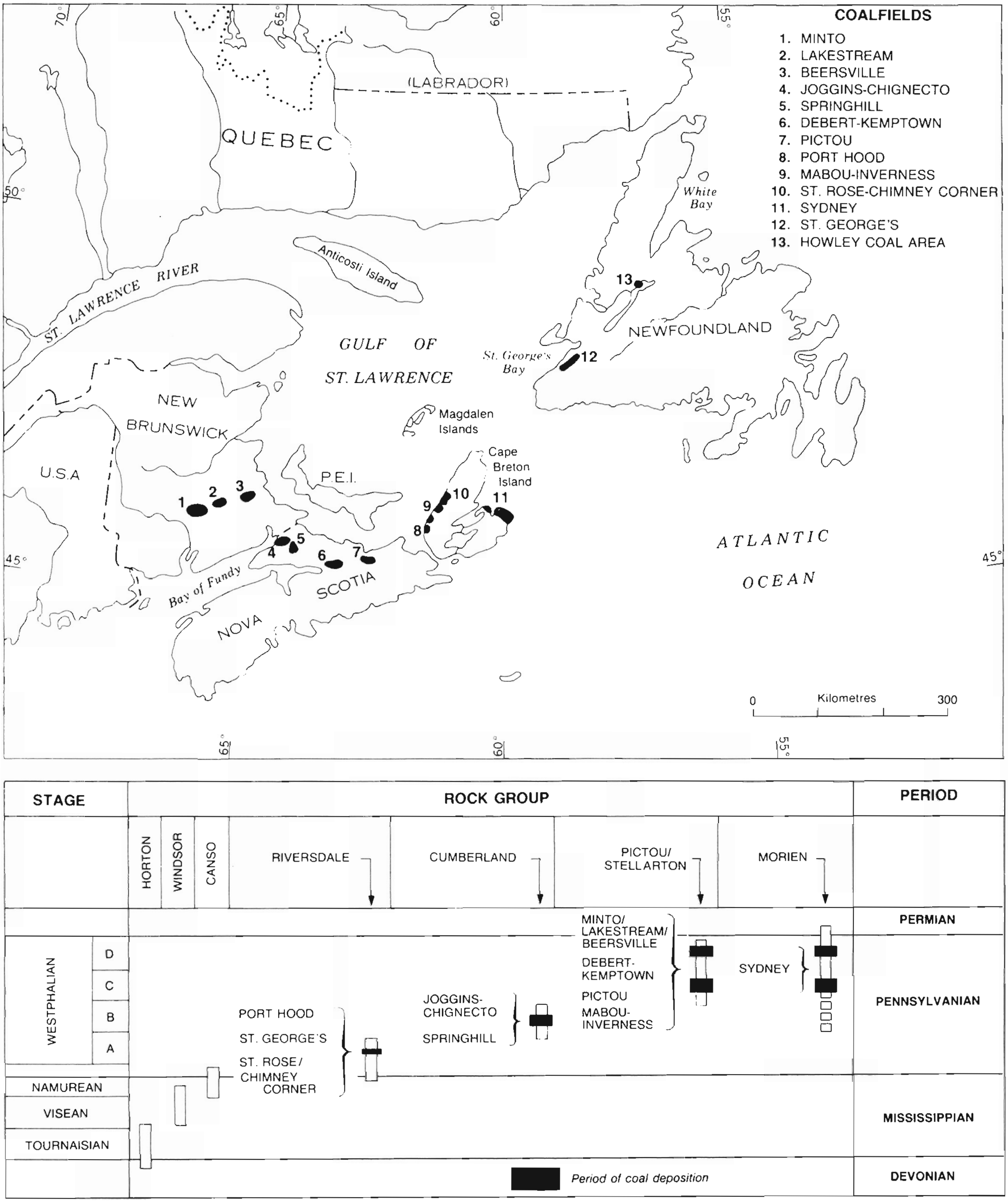

Figure 43. *Location of the major coalfields in the Atlantic provinces (from Naylor et al., 1992).*

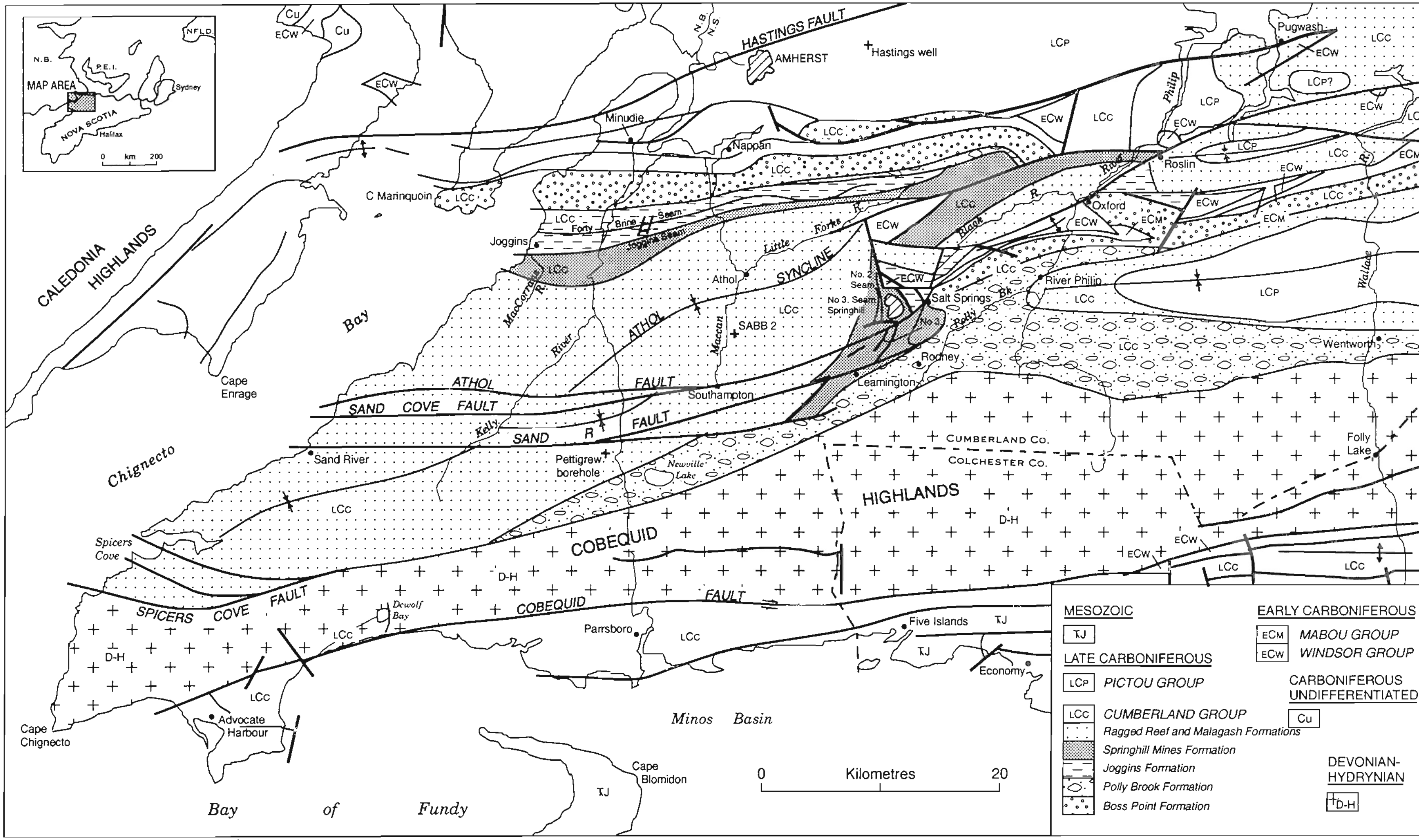

Figure 44. *Generalized geology of the western Cumberland Basin (after Naylor et al., 1992).*

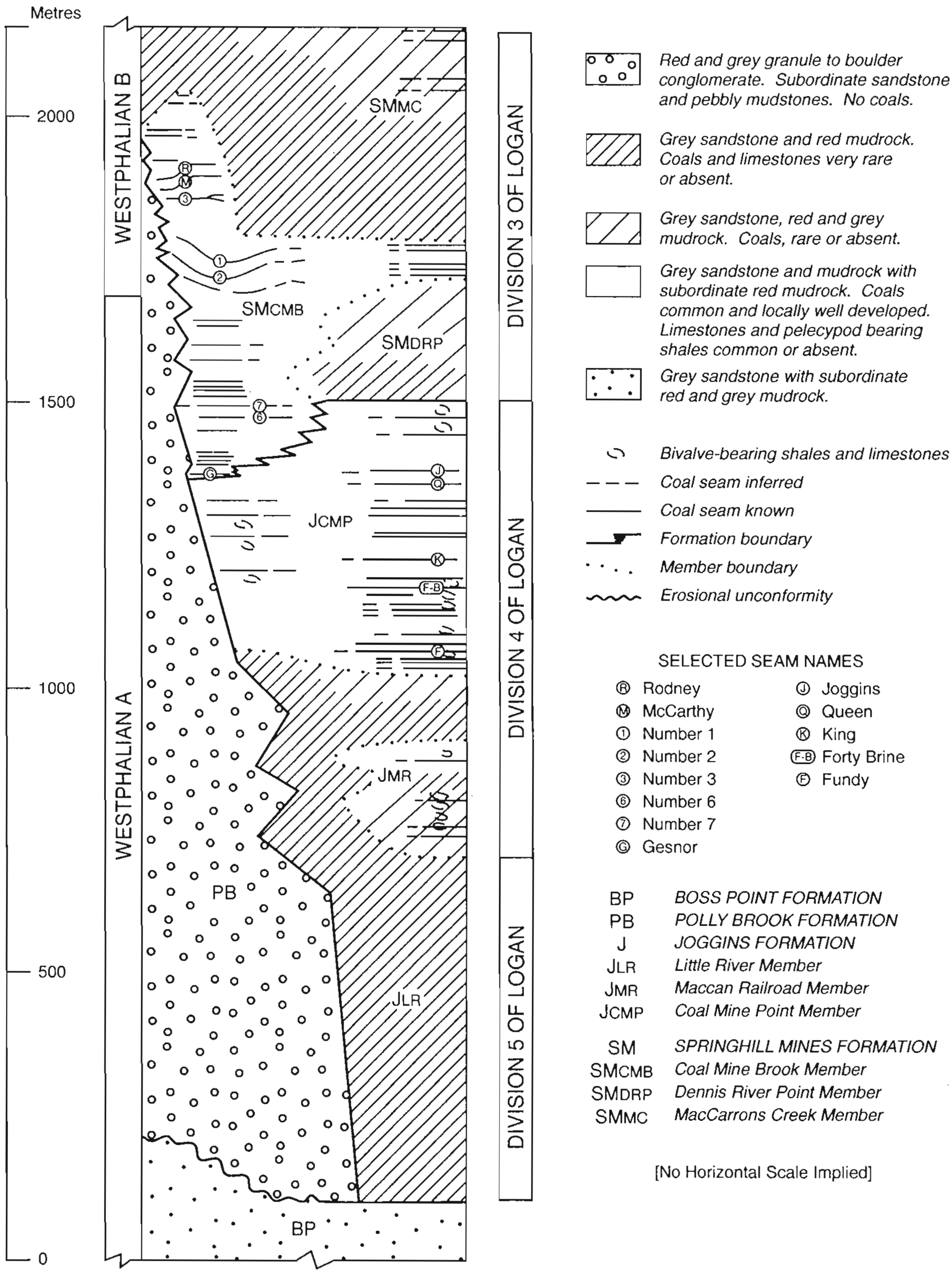

Figure 45. *General stratigraphy of the Joggins and Springhill Mines formations in the Athol Syncline in the Cumberland Basin (from Naylor et al., 1992).*

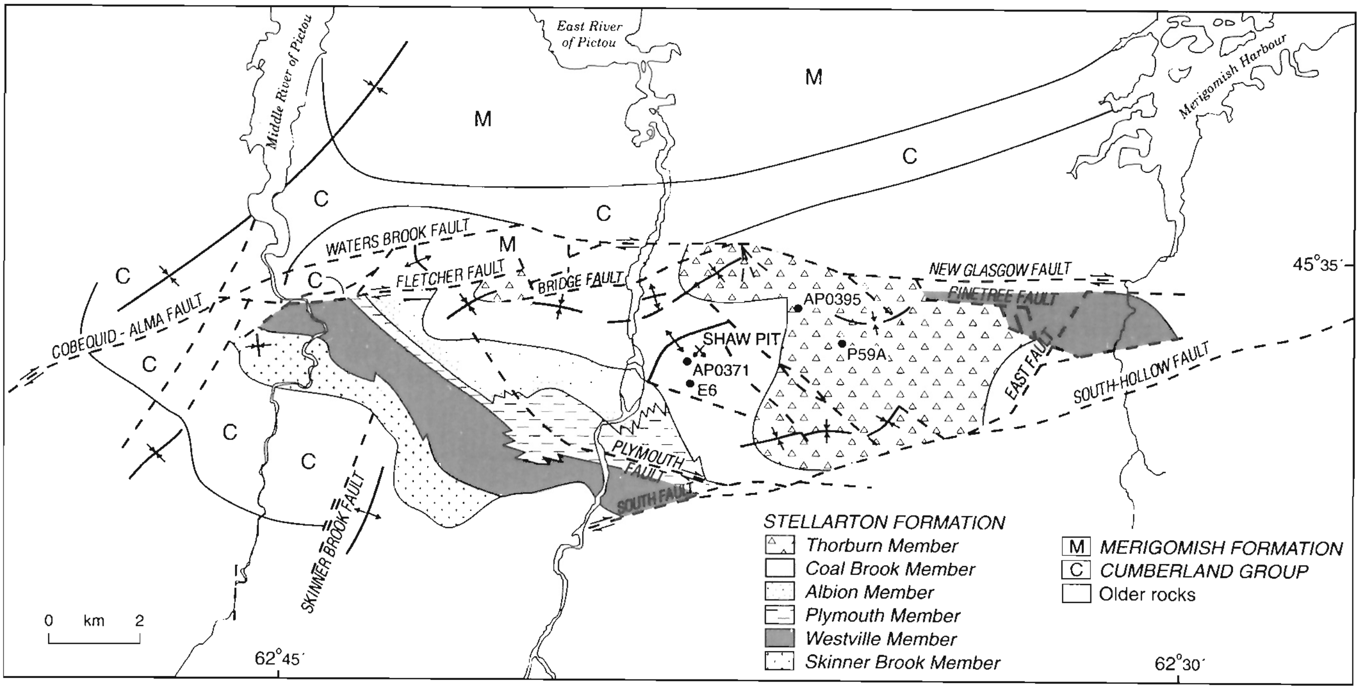

Figure 46. *Regional geology map of the Pictou County/Stellarton coalfield (after Naylor et al., 1992).*

et al., 1993). A horizontal well was drilled to penetrate the Harbour seam and samples were collected for desorption and adsorption isotherm experiments. Desorbed gas contents range from 4.15 to 8.29 cm^3/g (dry mineral-matter-free basis; DMMF). Ash content ranges from 1.44% to 17.7%. Moisture content averages 2.4% and mean maximum reflectance is 0.92% Ro_{max}. Adsorption isotherm data indicates a Langmuir volume of 16.92 cm^3/g (DMMF).

Theoretical gas capacity values have been calculated using the Ryan equation (Table 13) for a depth range of 500 to 2000 m. Rank variability is assumed to be from 0.9% to 1.2% Ro_{max}, and ash content ranges from 5% to 20%. Moisture content is assumed to be 5%. It can be seen that the gas capacity values estimated using the Ryan equation are in reasonable agreement with the measured adsorption isotherm value calculated for the Harbour seam sample collected from the Sydney Basin.

Table 13

Theoretical gas capacity values for coals of Carboniferous age, Maritime provinces

Depth (m)	Gas Capacity (cm^3/g)			
	Rank 0.9% Ro_{max}		Rank 1.2% Ro_{max}	
	Ash 5%	Ash 20%	Ash 5%	Ash 20%
500	9.66	8.05	10.41	8.69
750	10.94	9.12	13.95	11.62
1000	11.85	9.88	14.87	12.39
1250	12.56	10.46	15.58	12.98
1500	13.13	10.94	16.61	13.47
1750	13.62	11.35	16.66	13.88
2000	14.04	11.70	17.08	14.24
Assumed Equilibrium Moisture 5%				

Coalbed methane opportunities

Current status

Coalbed methane exploration was pioneered in Canada by Algas Limited, a subsidiary of Nova (an Alberta corporation). Exploration boreholes were drilled in western Canada in the Crowsnest Pass and Canmore regions in the mid 1970s and in the Cumberland Basin and Pictou County coalfields in Nova Scotia during the late 1970s and early 1980s. At the same time, several coal companies were exploring the feasibility of capturing the methane released from underground mining operations. Several joint venture projects with the Canadian Centre for Mineral and Energy Technology (CANMET) (Feng et al., 1984) gathered

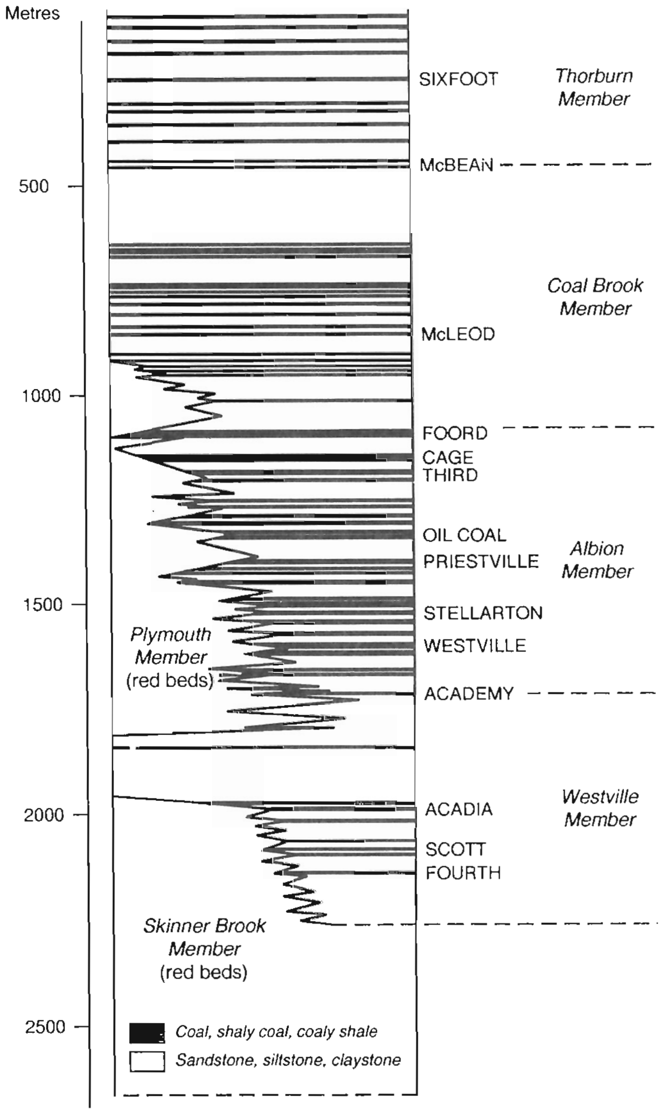

Figure 47. *Regional stratigraphy of the Stellarton Formation illustrating member boundaries and major coal seams (after Naylor et al., 1992).*

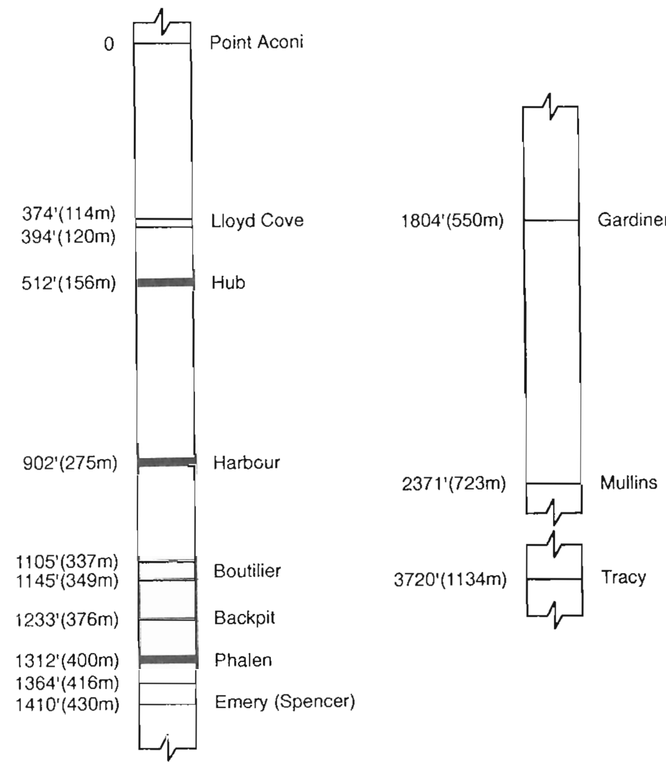

Figure 48. *Regional stratigraphic section of the Sydney Mines Formation, Sydney Basin (from Calder, 1985).*

methane desorption data from coal mines in western Canada and preliminary studies were being undertaken by DEVCO at their underground mines in the Sydney Basin in Nova Scotia. Subsequent to these early exploration efforts there was a brief hiatus until renewed activity by several oil and gas companies in the late 1980s to present. During the early 1990s, many oil and gas companies initiated coalbed methane exploration projects in Western Canada. Activities were concentrated, for the most part, in the Fernie and Elk Valley coalfields of southeastern British Columbia as well as the Alberta Plains. In the former, companies undertook exploration drilling projects to determine gas content and reservoir characterization. Wells were generally shallow and truck mounted drilling rigs were used. In the plains region, many of the coalbed methane tests were conducted as "piggyback" projects on deeper conventional hydrocarbon targets. Coal samples were obtained (either core or chips) to determine the gas content of the seams. In most cases no reservoir tests were conducted. Several regional studies that provide new rank data from cuttings samples have been completed by the Alberta Research Council and the Institute of Sedimentary and Petroleum Geology (Rottenfusser et al., 1991).

Based upon these preliminary results, numerous exploration licenses were applied for in Alberta and southeastern British Columbia, which led to a brief period of active exploration in 1990 and 1991. In the Alberta Plains region, most of the lands were already held by the exploration companies and a similar "land rush" did not occur.

Since 1991, exploration activity for coalbed methane has subsided and many of the companies that were originally involved in coalbed methane exploration have either retrenched or stopped their activities. The rationale for this change in direction may be due to the limited success of their efforts and/or change in management philosophy. Several companies remain

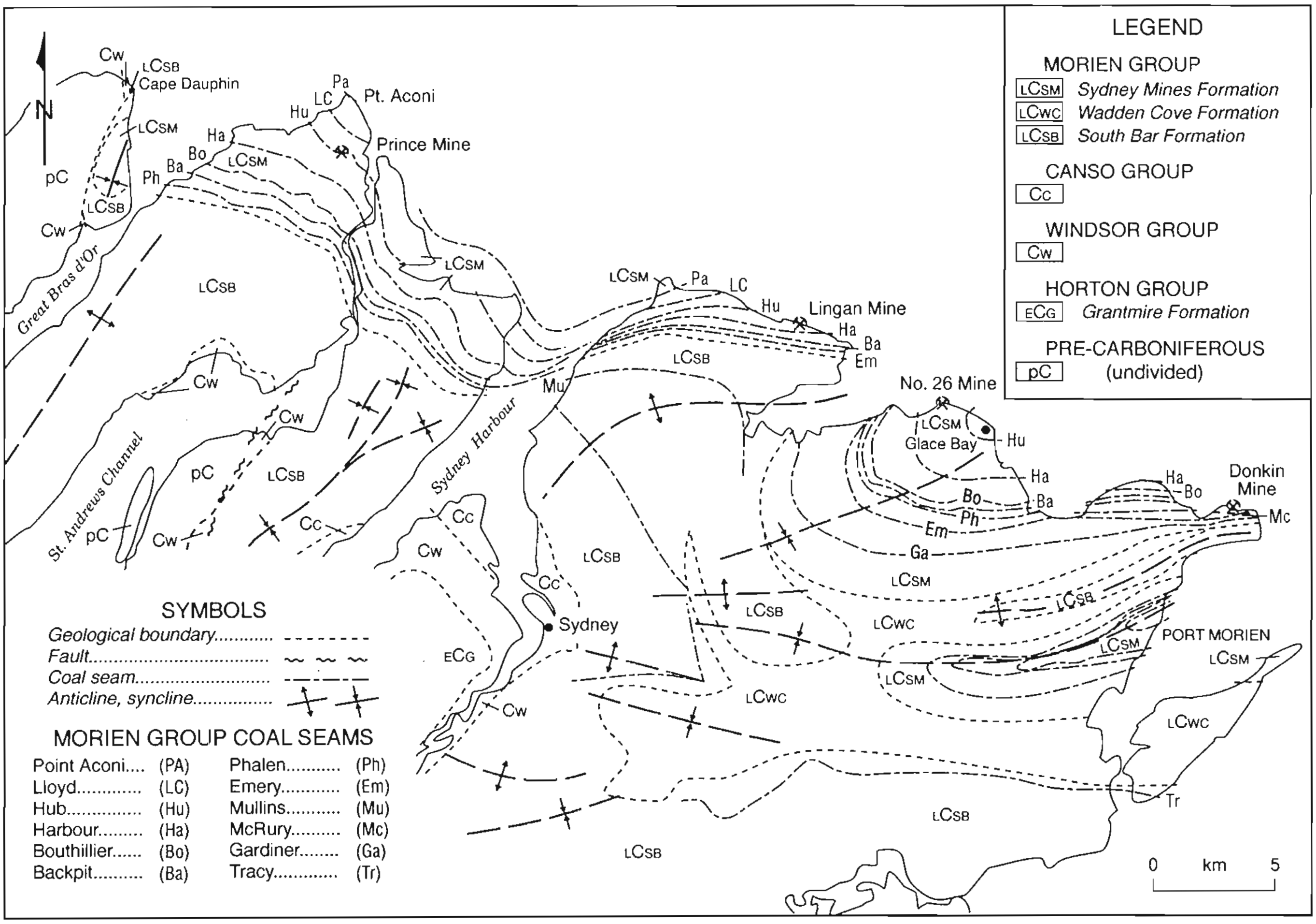

Figure 49. Regional geology map of the onshore portion of the Sydney Basin (from Calder, 1985).

active, but exploration efforts are modest, pending the increase in natural gas prices and or decreased availability of inexpensive natural gas supplies.

In summary, the major exploration efforts for coalbed methane in Canada occurred in the early 1970s in both western Canada and Nova Scotia by Algas Limited. Renewed interest in this potential resource occurred during 1990 to 1991 with numerous boreholes being drilled in Western Canada. Since then activities have slowed but there are still companies active in exploration for this resource. To date, more than 105 boreholes have been drilled from which coal samples have been gathered for coalbed methane testing (Table 14). Of these, desorption data were obtained for 98 holes (Figs. 50, 51). Many of these wells were drilled for deeper hydrocarbon targets. A total of 53 wells have been drilled specifically for coalbed methane purposes, of which 17 wells have undergone limited production testing. Some of these wells were tested with conventional pump tests while others have been stimulated using fracing techniques or cavity completion. At present, two wells are producing coalbed methane gas on a commercial basis. Much of these data remain confidential with the provincial government regulatory agencies.

Exploration potential

Canadian coal basins are known to contain substantial resources of coal at depths that appear to be attractive for the retention of coalbed methane. Potential coalbed methane reservoirs are present in most coalfields, but to date, limited exploration has been undertaken to determine the viability of extraction of the coalbed methane from these target areas.

In the past few years, several papers have been published that have attempted to quantify the coalbed methane resource potential for various regions in Canada (Nikols and Rottenfusser, 1991; Richardson, 1991; Smith et al., 1992). This paper, rather than providing a resource assessment based upon a limited

Table 14

Summary table of coalbed methane (CBM) exploration (up to 1993) in Canada

Area	Number of Wells with Coal Samples for CBM	Number of Wells with CBM Desorption Data	Number of Wells with Production Data for CBM	Number of Wells Currently Producing CBM Gas
Alberta	64	50	8	0
B.C.	24	21	2	0
Maritimes	27	27	7	0
Total	**105**	**98**	**17**	**0**

database, attempts to rank the potential target areas based upon coalbed methane capacity. The theoretical gas capacity values generated using the Ryan equation provide a numerical estimate upon which potential coalbed methane exploration areas can be ranked. Using these values and an average cumulative thickness of coal for the coal-bearing formations for each region (Table 15), the exploration areas are ranked from highest to lowest (Table 16). Ranking is determined by assigning numerical values for threshold levels of cumulative seam thickness and theoretical gas capacity. Table 15 presents the threshold criteria used for ranking of the potential coalbed methane exploration areas. It must be stressed that the cumulative coal thicknesses are averaged and will vary throughout the region. As well, gas capacity values are theoretical and do not necessarily represent the volumes of gas that are actually present in the coal seams. Table 16 ranks the potential coalbed methane exploration areas but does not take exploration or production costs into account. Some of the areas, such as the Fernie Basin or Peace River region, would incur higher exploration and production costs than would be expected for wells drilled in the Alberta Plains. Given the right conditions, it may be more feasible to explore for lower ranked (from a geological perspective) coalbed methane targets due to cost savings in exploration and production than to concentrate on the higher cost regions of the foothills of Alberta or British Columbia. In Nova Scotia, the lack of onshore conventional natural gas supplies provides an economic climate that may make coalbed methane production more attractive than in western Canada where abundant conventional natural gas supplies are present and prices tend to be lower.

Table 15

Threshold criteria for ranking potential coalbed methane exploration areas

Cumulative Coal		Theoretical Gas Capacity	
Thickness (m)	Rating	Capacity (cm^3/g)	Rating
0 - 10	1	0 - 3	1
10 - 20	2	3 - 6	2
20 - 30	3	6 - 9	3
30 - 40	4	9 - 12	4
40 - 50	5	12 - 15	5
50 - 60	6	15 - 18	6
>60	7	>18	7

It can be seen from Table 16 that the coal deposits of southeastern British Columbia have high exploration potential based upon coal seam thickness and gas capacity. It follows that much of the exploration activity for coalbed methane in Western Canada has taken place in this region. Other areas that have a high potential are the Peace River District and the Cascade District regions near Canmore. Both of these areas have undergone some limited coalbed methane exploration. Intermediate rank target areas are the coal basins of the Maritimes and several other coal-bearing areas of the Rocky Mountains and Inner Foothills belt. Nova Scotia coalbed methane target areas may have some inherent advantages over other similarly ranked prospects due to the lack of competition of conventional natural gas supplies and the favourable political climate for coalbed methane in the province. The lowest ranked areas are regions where the coals are thinner and of lower rank, where insufficient volumes of thermogenic methane may have been generated during the coalification process.

In addition to the ranking of the major coal-bearing regions listed in Table 16, there are also smaller scale coalbed methane exploration opportunities in northern Canada. In this region, the supply of coalbed methane for fuel and heat may be an attractive hydrocarbon exploration target due to the economics of other alternative fuel sources. In numerous small com-

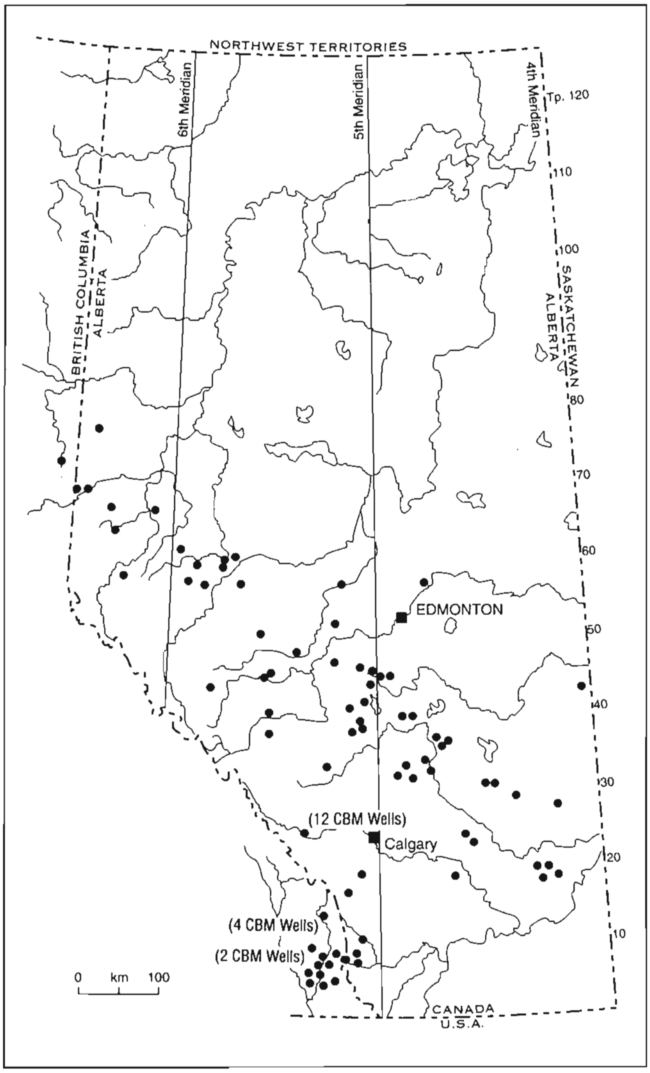

Figure 50. *General location map of coalbed methane exploration wells in Western Canada.*

munities in northern Canada, much of the fuel used for electrical power generation and heat is diesel fuel, commonly trucked in at high cost. Small-scale coalbed methane production to supply gas for these purposes may be economically attractive given the low volumes of gas that would be required.

In Yukon, some preliminary assessment of several coal deposits near Whitehorse has been initiated by the Geological Survey of Canada to determine the coalbed methane potential but to date no wells have been drilled specifically for that purpose. In Northwest Territories there are numerous coal deposits suitable for coalbed methane exploration, which are relatively close to small markets.

Production factors

The potential of each exploration area is often difficult to measure because economical production of coalbed methane from wells is dependent on many variables. Factors such as coal quality and maceral composition, depth of reservoir, regional water table and reservoir pressures, reservoir permeability and fracturing, infrastructure availability, and drilling and completion costs all play major roles in determining the viability of producing coalbed methane economically.

Coal quality and maceral composition

Coal quality and maceral composition play an important role in the producibility of coalbed methane reservoirs. The coal must be of sufficient rank in order to lie within the thermogenic gas generation window. Studies conducted in the United States have demonstrated that coals with a rank of less than 0.6% Ro_{max} generally fall below the generation window and have not produced significant volumes of thermogenic methane. Adsorption isotherms completed on lower rank samples (Fig. 37) suggest that these types of coals may have high adsorptive capacities, but these adsorptive volumes are not achieved in situ because there are limited volumes of methane generated due to the lower rank of the coal. Using the Ryan equation, theoretical gas capacities more closely approach desorption values measured in field tests (F.M. Dawson, unpublished data, 1992). It should be noted, however, that in Wyoming coalbed methane production is achieved from lower ranked coals in the Powder River Basin where, although the methane gas being desorbed from the coals is relatively low, the thickness (greater than 30 m) of the coal seams offsets the lower capacity.

Mineral matter and ash content also control the volumes of adsorbed methane gas retained within the coal seam. Desorption data from the United States coal basins has demonstrated that ash acts as a dilutent in gas content (i.e., the higher the ash content the lower the gas content). Adsorption isotherms completed on Mist Mountain Formation samples (Dawson and Clow, 1992) indicate that even after the isotherms are corrected for ash content (based upon proximate analyses data) there still appears to be an ash or mineral matter effect on the overall gas capacity of the coals. Current research being conducted by B.D. Ryan and F.M. Dawson (unpublished data, 1993) is attempting to understand the relation between mineral matter and gas capacity.

Table 16

Index ranking of coalbed methane potential of coal deposits, based upon theoretical gas capacity

Rank	Score	Potential Coalbed Methane Exploration Target Area	Total coal (m)	Theoretical Gas Capacity (cm^3/g) at Depth (m)		
				500	1000	1500
1	21	Fernie/Elk Valley	75	8.6	14.6	15.7
2	20	Peace River	>20	9.9	13.8	17.7
3	20	Cascade	>20	14.7	16.7	17.9
4	17	Cadomin/Luscar	>10	9.5	13.2	16.1
5	17	Smoky River	>12	12.0	14.0	17.3
6	16	Cumberland	>40	8.9	10.9	15.0
7	16	Sydney	>40	8.9	10.9	15.0
8	15	Pictou County	>30	8.9	10.9	15.0
9	15	Nordegg	>10	10.8	13.1	14.7
10	13	Skeena Basin	>10	8.0	10.6	11.5
11	11	Outer Foothills	>30	2.6	4.4	9.6
12	9	Plains - Mannville	>10	2.6	4.4	9.5
13	8	Plains - Ardley	>10	0	4.4	9.5
14	8	Bowser Basin	>10	6.8	6.8	6.8
15	7	Quinsam/Nanaimo	>10	2.56	4.4	9.6
16	7	Princeton - Tulamee	>20	<1	<3	<6
17	6	Bowron River	>10	<1	<3	<6

Note: Gas content values were averaged between the ash content ranges for each depth interval.
Rank values were adjusted to reflect increasing rank with depth.

Another element of coal composition that impacts on coalbed methane gas capacity and producibility is maceral composition. Lamberson and Bustin (1992, 1993) demonstrated that for the Gates Formation of northeastern British Columbia, the highest gas capacity values were obtained for vitrinite-rich coalbeds. In contrast, adsorption isotherms completed by Dawson and Clow (1992) for the Mist Mountain Formation in southeastern British Columbia indicate that coals rich in semifusinite and fusinite have an equal or higher adsorptive gas capacity. At this stage, the relationship between maceral composition and overall gas capacity is unclear. Field studies conducted by F.M. Dawson and B.D. Ryan (unpublished data, 1993) indicate that vitrinite-rich coals tend to be more highly cleated than the fusinite- and semi-fusinite-rich coals. Observations made on fresh coal faces of seams in the Mist Mountain Formation, from open pit mines in southeastern British Columbia, indicate that, in general, the lower seams in the formation are higher in inertinite content and tend to have a poorly developed cleat system while seams in the upper half of the formation have a higher vitrinite content and display a well developed cleat system (F.M. Dawson and B.D. Ryan, unpublished data, 1993). Cleat development as demonstrated in the San Juan Basin appears to be a critical component for coalbed methane production. Ongoing research studies are attempting to address the relation between maceral composition and cleat development.

Depth of reservoir

Many studies have addressed the relation between depth and gas capacity. All adsorption isotherms are a plot of the increase in gas content with increasing pressure, in effect depth. To some extent, the adsorption characteristics of the coal controls the net effect of depth on gas content. Coals of the Mist Mountain Formation, southeastern British Columbia, appear to have fast diffusion rates with large volumes of coalbed gas capable of being stored at lower pressures (F.M. Dawson, unpublished data, 1993).

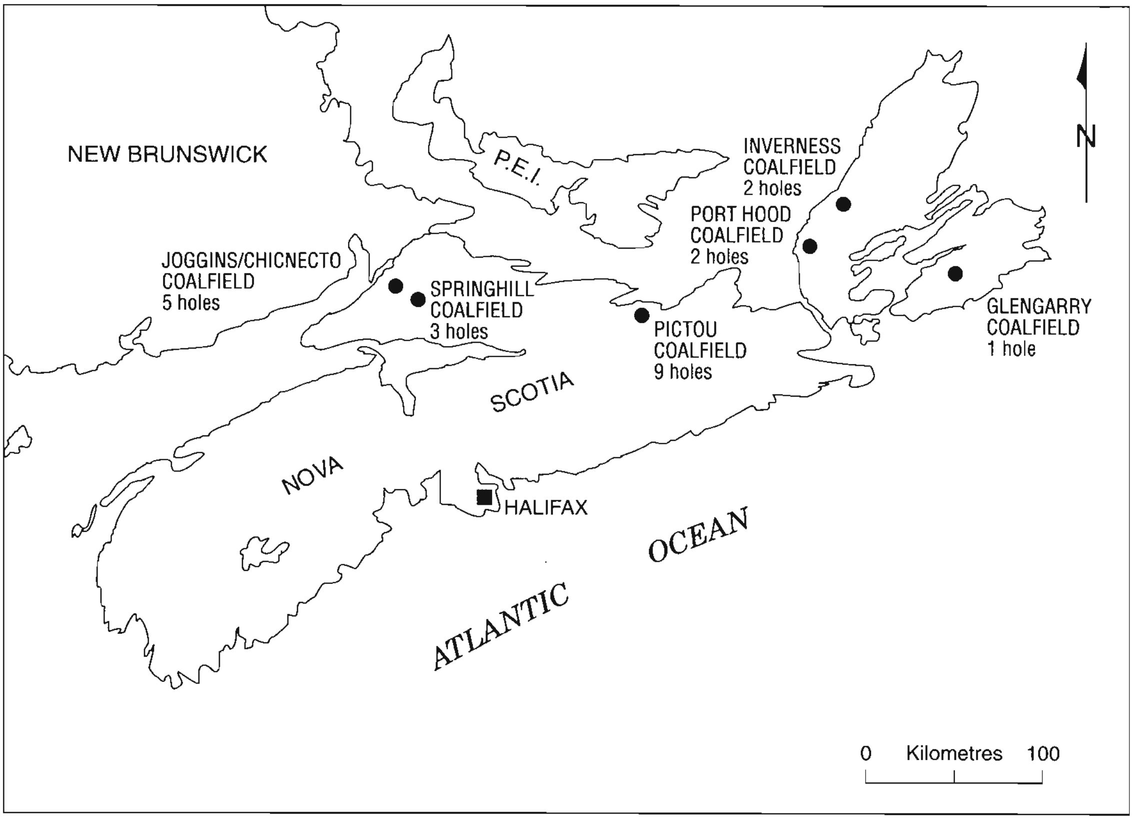

Figure 51. *General location map of coalbed methane exploration wells in Nova Scotia (from J. MacDonald, pers. comm., 1993).*

Typical adsorption isotherm curves indicate that as much as 70% of the total methane gas is adsorbed within 0 to 4480 KPa (approximately 450 m depth equivalent). Desorption curves gathered from field testing have similar trends, suggesting that large volumes of gas may be present at shallower depths (300–500 m). In contrast, desorption curves for coals of the Mannville Formation in the Alberta Plains are more gradual, indicating that to achieve similar in situ gas contents, the coals must lie at greater depths.

Regional water table and reservoir pressures

Coalbed methane exploration targets in the mountainous terrain of British Columbia and the foothills and mountain regions of Alberta are commonly defined by topographic constraints. Topography not only controls the distribution of the coals but also the elevation of the regional water table. Dawson and Clow (1992) demonstrated that for the Elk Valley coalfield, the volume of adsorbed coalbed methane present in the coals of the Mist Mountain Formation was controlled by the elevation of the seams relative to the elevation of the Fording and Elk river valleys. It appears that in mountainous terrain, the coals must lie below the regional water table (i.e., major river valleys) in order for the methane gas to be retained in the coal seam. Desorption samples have been collected from a number of coal seams in both southeastern British Columbia and northwestern Alberta that have yielded gas content values less than 1 cm^3/g at depths greater than 250 m. In all cases the coals lay at elevations higher than the regional water table.

Reservoir permeability and fracturing

Reservoir permeability is the second most important criteria that determines the viability of a coalbed methane reservoir, after in situ gas content. Coalbed methane wells in the "fairway" region of the San Juan Basin are successful mainly due to the high permeability of the reservoir. The Fruitland coals are highly cleated (both face and butt cleat) with overprinting by a secondary regional fracture pattern (Close and Mavor, 1991). For Canadian coals to demonstrate equal productivity, a similar geological regime must be found, one of well developed cleating with some degree of structural overprinting to enhance the permeability. Many of the coalbed methane exploration projects that were undertaken in the early 1990s were based upon land holdings or existing infrastructure, rather than on the geological potential of the target. As a result, many of the exploration target areas were not optimized, with corresponding disappointing results. Future exploration efforts should be concentrated in regions where both the face and butt cleat of the coal seams are well developed and where local structures may have enhanced the permeability. Current research studies being conducted by the GSC in conjunction with the BCGS are directed toward determining the relation between coal composition and cleat generation.

Infrastructure

A major component of the economic viability of coalbed methane wells is the relative cost of installing the infrastructure to recover the resources. The cost of drilling and installation of gathering systems is an integral part each borehole's economics. In Canada, the primary coalbed methane exploration target areas lie in mountainous terrain where limited hydrocarbon exploration has been undertaken. Access and water disposal costs can easily be greater than the cost of drilling the well. In addition, pipeline systems for transporting the produced methane are rare and installation of new gathering facilities can become cost prohibitive if the distance from the coalbed methane field to an existing pipeline is large. One of the factors that makes the Fernie Basin attractive as a coalbed methane target is the proximity to the Westcoast Transmission Limited pipeline to the United States.

In contrast to the high infrastructure cost of the foothills and mountain regions, coalbed methane exploration in the Alberta Plains has relied heavily on the presence of existing conventional oil and gas fields. Several companies have initiated projects to explore the feasibility of extracting coalbed methane from existing wells in both the Mannville and Scollard formations. Many of these wells are nearing the end of production from the conventional hydrocarbon pool. Rather than abandoning the well, the companies are considering recompleting for coalbed methane. The advantages of this approach are several, the foremost being that recompletion costs are incidental relative to the cost of drilling a new well. In addition, other wells in the existing field may be used for water disposal. One of the drawbacks of this approach is that the existing well bores dictate the location of the coalbed methane exploration target, which may not be optimal for gas content, seam thickness or permeability. As well, previous drilling and completion methods used for the deeper conventional hydrocarbon pool may have inflicted significant formation damage to the potential coal seam reservoirs. This in turn may severely inhibit the coal zone's permeability.

In Western Canada, coalbed methane exploration activities have tended to be polarized between the two geographic areas: the mountains and foothills, where coal seams are thicker and have the potential for higher gas contents due to increased rank, but existing infrastructure is limited; or in the plains, where gas contents are lower and coals are thinner but the infrastructure is well developed.

CONCLUSIONS

Coalbed methane production from both the San Juan and Black Warrior basins in the United States in 1992 was in excess of 15.6 x $10^9 m^3$ (550 BCF), an increase of over 300% since 1990. In situ recoverable reserves for the United States, excluding Alaska, are placed at 2.29 to 2.92 x $10^{12} m^3$ (80.8 to 103.1 TCF) (Gas Research Institute, 1993).

Canada is blessed with numerous coal basins that may contain resources of coalbed methane. To date, in excess of 80 wells have been drilled which involve tests of the coalbed methane potential, although limited economic production has been achieved. Exploration activity has, for the most part, been concentrated in southeastern British Columbia and central and northwestern Alberta, partially due to the extensive coal resources that are present in the subsurface as well as the existence of an established infrastructure.

Research efforts by government agencies such as the Geological Survey of Canada and its provincial counterparts have concentrated on determining the distribution of coalbed methane throughout the numerous coal deposits in Canada and relating the in situ variability to the characteristics of the coals themselves. Further research efforts by both industry and government are needed to establish a reliable database to allow resource assessments to be undertaken and to continue the scientific studies into the relation between coal chemistry and coalbed methane production criteria, such as gas content and permeability.

The potential for coalbed methane in Canada is great but much more scientific research coupled with exploration efforts by private industry will be required to determine the economic potential and viability of this fledgling resource.

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