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# THE GEOLOGY AND OIL AND GAS POTENTIAL OF THE FERNIE - ELK VALLEY AREA, SOUTHEASTERN BRITISH COLUMBIA

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Monahan Petroleum Consulting, December 2000

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**P.A. MONAHAN, P.GEO.**[1]

## ABSTRACT

The Fernie-Elk River Valley area is a geologically complex and relatively unexplored area in the Front Ranges of the southern Rocky Mountains. Although no conventional hydrocarbon reserves have been found in the area to date, large reserves have been established in adjacent parts of Alberta and British Columbia. Furthermore, the Fernie-Elk Valley area is the foremost coal mining area of British Columbia, and an active coalbed methane exploration program is currently underway.

The most significant conventional hydrocarbon objectives are in thrust faulted Mississippian and Devonian carbonates beneath the Lewis thrust. Two major structural trends occur in this setting: an essentially untested 100km long trend of sub-Lewis duplexes beneath a belt of Paleozoic outcrop in the Lewis thrust sheet; and a poorly tested trend of duplexes beneath the leading edge of the Lewis thrust sheet. Both duplex trends could contain large reserves. Mississippian and Devonian strata also have potential in structures on the Lewis thrust sheet, principally west of the Flathead and Erickson normal faults. The Devonian Peechee Member (Leduc-equivalent) shelf-edge reef is prospective where it crosses structures both above and below the Lewis thrust, and stratigraphic traps could occur in this reef trend in the Lewis thrust sheet where it is deeply buried beneath the Bourgeau thrust sheet. Stratigraphic traps could also occur in the Lewis thrust sheet in Peechee pinnacle reefs and possibly in reefs in the Devonian Borsato and Nisku Formations. In most areas, Paleozoic reservoirs are potentially gas-bearing, although gases are likely to be sour and may contain high concentrations of $CO_2$ in the southern and western parts of the area. However, oil could occur locally in Devonian strata in the hanging wall of the Lewis thrust where Cretaceous strata are present in the footwall. Mesozoic strata have potential for modest conventional hydrocarbon resources in a band a few kilometres wide beneath the leading edge of the Lewis thrust sheet. There, structural-stratigraphic traps could occur in Triassic dolomite and Jurassic and Cretaceous conglomerates and sandstones. Triassic and Jurassic reservoirs would probably be gas-bearing, but Cretaceous reservoirs could contain either gas or oil.

A vast coalbed methane resource is present in the Jura-Cretaceous Mist Mountain Formation. Drilling activity for which data are available has not resulted in commercial production, due in part to incomplete well testing. Furthermore, drilling locations were not optimally located on gentle folds, where permeability could be enhanced, or to evaluate the upper coal seams of the Mist Mountain Formation, which have better developed cleat systems. A current drilling program in the Elk Valley Coalfield is still confidential but appears to include wells better located to evaluate the coalbed methane potential of the area.

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[1] Monahan Petroleum Consulting, December 2000.

## INTRODUCTION

The Fernie-Elk Valley area is a geologically complex and relatively unexplored area located in the southern Rocky Mountains of British Columbia. Although no hydrocarbon reserves have been established in this area, several large gas fields have been found in adjacent parts of Alberta, and wells capable of producing significant volumes of $CO_2$ have been drilled immediately to the south in the Flathead area of British Columbia. The Fernie-Elk Valley area is also the most important coal-mining region in the province, and recent attention has been directed to the coalbed methane potential of the area (Johnson and Smith, 1991; Dawson, 1995; Dawson *et al.*, 1998, 2000). The objective of this report is to describe the geology and the oil and gas potential of the area in order to assist future exploration.

The area of this investigation comprises approximately 3600 $km^2$ and extends from the mountain range west of the Elk River Valley to the Alberta border. The southern boundary follows the outcrop belt of Jurassic and Triassic strata at the southern margin of the Fernie Basin, between latitude 49$^{o}$15'N and 49$^{o}$20'N (North Kootenay Pass Monocline; Map 1). The geology and oil and gas potential of the Flathead area immediately to the south is addressed in a separate report (Monahan, 2000).

The Fernie-Elk Valley area is entirely within the Front Ranges of the southern Rocky Mountains (Holland, 1976). Regionally, the Front Ranges are characterized by rugged strike-oriented mountain ranges of resistant Paleozoic carbonates separated by valleys and areas of more subdued topography, generally underlain by less resistant Mesozoic clastics. In the Fernie-Elk Valley area, the principal ranges of the Front Ranges are the Highrock and Flathead Ranges, to the east along the British Columbia-Alberta border, and the western Front Ranges to the west (informal term; Map 1; Cross sections 1, 2 and 3). Peaks in these ranges are commonly between 2500 and 3000m. These ranges are separated by the Fernie Basin, a pear-shaped outlier of Mesozoic strata 110km long and up to 30km wide. Elevations in the Fernie Basin range from 1000 to 1200m in the valley of the Elk River, which flows along the western margin of the basin, to 2100m on strike-oriented ridges. The southern and widest part of the Fernie Basin forms a gently sloping upland above 1500m elevation, and is deeply incised by the Elk and Flathead Rivers and their tributaries. To the north, the Fernie Basin narrows to a strike valley between the Highrock and western Front Ranges.

This investigation is based on published reports, industry well data and unpublished reports in the files of the British Columbia Ministry of Energy and Mines. In addition, an unpublished resource assessment by the Geological Survey of Canada (Hannigan *et al.*, 1993) has been particularly helpful. Bedrock geology maps have been prepared for most of the area at scales of between 1:50,000 and 1:126,720 by Leech (1960, 1979), Price (1962a, 1965), Grieve and Price (1985), Grieve (1993), Price *et al.* (1992a, b) and Norris (1993a).

## STRUCTURAL AND TECTONIC FRAMEWORK

The Fernie-Elk Valley area is in the Rocky Mountain Foreland Fold and Thrust Belt (Foreland Belt), which is the deformed western margin of the Western Canada Sedimentary Basin

(Gabrielse *et al.*, 1991; Price, 1994). The deformed sedimentary succession consists of a westward thickening Precambrian to Jurassic platformal to miogeoclinal succession deposited in a passive continental margin setting, overlain by an Upper Jurassic to Upper Cretaceous foreland succession derived from rising highlands to the west (Table 1; Price, 1981).

These stratigraphic successions have been deformed by easterly verging thrust faults and attendant folds during the Late Jurassic to Early Tertiary Laramide Orogeny[2]. Excellent descriptions of the structural style of the southern Canadian Rocky Mountains have been written by Bally *et al.* (1966), Dahlstrom (1970), Price (1981, 1994), McMechan and Thompson (1989, 1991), Fermor and Moffat (1992) and Fermor (1999), and the principal characteristics can be summarized as follows. Thrust faults cut upsection in the direction of tectonic transport (i.e. to the east) and place older upon younger strata. In incompetent strata, thrust faults typically follow bedding planes or cut bedding at low angles, whereas they cut competent strata at higher angles. Hanging wall strata are consequently folded above steps in the footwall. Within the sedimentary succession, a major zone of detachment occurs in the Jurassic Fernie Formation, so that the structure of the platformal and foreland successions can be significantly different (Cross sections 2 and 3). All the west-dipping thrusts are linked to a basal detachment, so that as one thrust fault diminishes along strike, displacement is transferred to another. The basal detachment is near the basement, and is in the Cambrian in most of the Rocky Mountains. However, it cuts down into the Precambrian sedimentary succession to the west, because Precambrian strata are incorporated in thrust sheets in parts of the Rocky Mountains (e.g. the southern part of the Fernie Elk Valley area and the Flathead area to the south) and in the Purcell Mountains to the west (Map 1; Cross section 3). Crystalline basement, which is undeformed by Laramide structures, dips westward beneath the Rocky Mountains and is between 6 to 10 km below sea level beneath the Fernie-Elk Valley area. Deformation progressed from west to east across the Foreland Belt[3]. Deposits of the Upper Jurassic to Upper Cretaceous foreland succession in the Fernie-Elk Valley area were derived from structures rising in the west, and were subsequently deformed during the Late Cretaceous and Early Tertiary.

The principal thrust faults in the Fernie-Elk Valley area are the Lewis and Bourgeau thrusts (Map 1). The Lewis thrust is exposed immediately east of the British Columbia border, and Paleozoic and older strata exposed in the hanging wall form the Highrock and Flathead Ranges (Map 1; Cross sections 1, 2 and 3). Displacement on the Lewis thrust reaches a maximum of 75-90km along the international boundary, and diminishes to zero at Mount Kidd in the Alberta Front Ranges 35km north of the Fernie-Elk Valley area (Dahlstrom *et al.*, 1962; van der Velden and Cook, 1994; Fermor, 1999). Adjacent to the Fernie-Elk Valley area, Upper Cretaceous strata are exposed in the footwall of the Lewis thrust. However, in the hanging wall the Lewis thrust cuts gradually downsection southward along strike from the Mississippian to the upper part of

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[2] Gabrielse and Yorath (1991) recommended discontinuing use of the term Laramide, which has been used elsewhere for the Late Cretaceous to Early Tertiary deformation only. Deformation probably occurred more or less continuously from the Late Jurassic to the Early Tertiary.

[3] Paleomagnetic studies by Enkin *et al.* (1997, 2000) also show that deformation proceeded from west to east.

the Precambrian succession. Immediately to the south in the Flathead area, the Lewis thrust cuts sharply further downsection in the Precambrian on a lateral ramp in the hanging wall, exposing an additional 2000m of Precambrian strata (Dahlstrom *et al.*, 1962; Price, 1962a, 1965; Childers, 1964). The north-dipping North Kootenay Pass monocline is the surface expression of this lateral ramp in the Lewis thrust sheet (Price, 1965), and forms the southern boundary of the Fernie-Elk Valley area as used here.

The Lewis thrust is folded above a northwest-trending duplex of Paleozoic strata to the south in the Flathead area, where Upper Cretaceous strata are locally exposed in windows through the thrust (Maps 1 and 2; Dahlstrom *et al.*, 1962; Price, 1962a, 1965; Bally *et al.*, 1966; Jones, 1969b; Gordy *et al.* 1977; Fermor and Moffat, 1992). A similar duplex of Paleozoic strata has folded the Lewis thrust east of the Calstan Fording Mountain d-61-L/82-G-15 well (Cross section 2; Dahlstrom *et al.*, 1962; Price *et al.* 1992a, b), and is interpreted to represent the north end of a trend of duplexes that underlies the belt of Paleozoic outcrop in the Wisukitsak Range, Erickson Ridge, and the southern part of the Taylor Range (Fitzgerald, 1969).

A series of normal faults occurs in the Lewis thrust sheet and records a period of post-Laramide extension (Price, 1962a, b). The largest of these is the Flathead fault, a west-dipping listric normal fault located immediately west of the sub-Lewis duplexes noted above in the Flathead area and the southern part of the Fernie-Elk River Valley area (Maps 1 and 2; Cross section 3). The Flathead fault merges downdip with the Lewis thrust. In the Flathead area, strata of the contemporaneously deposited non-marine Oligocene Kishenehn Formation occur in the hanging wall of the Flathead fault, and establish a minimum age for the termination of thrust faulting in the area (Russell, 1964; Bally *et al.*, 1966; Jones, 1969a; Gordy *et al.* 1977; McMechan, 1981; Constenius 1981, 1982, 1988; McMechan and Thompson, 1991; Fermor and Moffat, 1992). To the north, the Erickson fault is a similar west-dipping listric normal fault, also located immediately west of the sub-Lewis duplex trend[4]. It is interpreted to merge west with either the Lewis thrust (Cross section 2; Dahlstrom *et al.*, 1962; Mott, 1989), or a thrust fault on the backlimb of the Lewis thrust sheet (Price *et al.*, 1992a). West of the Flathead and Erickson faults lies the Fernie Basin, a gently folded synclinal basin of Upper Jurassic and Cretaceous strata in the Lewis thrust sheet.

A series of overturned concentric anticlines and synclines carrying Mississippian to Triassic strata plunges beneath the gently dipping west limb of the Fernie Basin (Cross section 3; Dahlstrom, 1969). This limb is underlain by an east-dipping, west-verging thrust fault that forms the upper detachment of an extensive triangle zone (Dahlstrom, 1969; Root *et al.*, 2000). The triangle zone is cored by shale of the Fernie Formation, which has been structurally thickened to over 2600m in the B.A. CNP Fernie d-42-I/82-G-6 well from a stratigraphic thickness of 300 to 400m. The overturned anticlines and synclines are carried on a thrust fault that probably merges with the Lewis thrust to the west.

[4] The Erickson fault may be the northward continuation of the Flathead fault (Ollerenshaw, 1981b).

The surface trace of the Bourgeau thrust follows the west side of the Elk River valley, and is interpreted to be continuous with the MacDonald thrust to the south in the Flathead area (Map 1; Wheeler and McFeely, 1991; Root *et al*., 2000). In outcrop north of latitude 50°10’, Triassic and older strata in the hanging wall are thrust over Upper Jurassic and younger strata in the footwall, and displacement on the thrust is large. West of this area, the Western Front Ranges and Main Ranges of the Rocky Mountains have been interpreted by Mott (1989) to be underlain by a large ramp anticline on the Bourgeau thrust (Cross section 1). This anticline is cored by a thick succession of Cambrian to Silurian strata not represented in the footwall. Consequently, Mott interpreted the hanging wall cutoff of these strata to have been formed on a west-side-down normal fault that was active during the Early Paleozoic and later followed by the Bourgeau thrust during the Laramide. Displacement on the Bourgeau-MacDonald thrust appears to diminish to the south, where both the hanging wall and footwall are in the Jurassic Fernie Shale at most localities (Cross sections 1-3; Price, 1962a; Wheeler and McFeely, 1991; Price *et al.*, 1992a; Grieve, 1993; McMechan, 1998).

Deposition and preservation of Paleozoic and possibly Triassic strata were strongly influenced by Montania, a positive element represented by rocks now located in the Rocky Mountains of southernmost British Columbia and Montana (Norris and Price, 1966; Benvenuto and Price, 1979; McMechan and Thompson, 1989; Richards, 1989; Richards *et al*., 1994; Price, 1994). In Montania, the Lower Paleozoic is represented by a relatively thin Middle Cambrian shallow water succession that is up to 330m thick in British Columbia and does not thicken westward across the Rocky Mountains[5] (Fritz and Norris, 1966; Norris and Price, 1966; Slind *et al*., 1994). In contrast, the Lower Paleozoic to the north is represented by a Lower Cambrian to Silurian shallow water succession that thickens westward to over 2000m in the Bow Valley area, where the Middle Cambrian alone exceeds 600m (Fritz and Norris, 1966; Slind *et al*., 1994). This succession thickens further to the west, where much of it changes facies to basinal clastics and carbonates in the Main Ranges of the Rocky Mountains (Aitken, 1971). The northwestern margin of Montania was a north-dipping monocline that was reactivated during the Laramide Orogeny by the Dibble fault, which is located east of the Rocky Mountain Trench (Map 1; Leech, 1958, 1960; Norris and Price, 1966; Benvenuto and Price, 1979). North of this margin, up to 6km of Lower Cambrian to Silurian strata are preserved beneath Devonian strata. The margin of Montania appears to trend eastward across the Fernie-Elk Valley area, because the thick Lower Paleozoic clastic and carbonate succession is present west of the Fernie-Elk Valley area north of 49°35’ (Leech, 1979; Mott, 1989). As noted above, the Bourgeau thrust may be a reactivated shelf margin fault north of Montania (Mott, 1989).

The influence of Montania can be seen to a lesser extent in younger strata. Devonian, Mississippian, Pennsylvanian, Permian and possibly Triassic strata show less westward thickening across the Lewis and Bourgeau-MacDonald thrust sheets in Montania than they do to the north (Cross sections 4, 5 and 5a; see Price, 1964b (Devonian); Oswald, 1964b, Bamber *et al.*, 1981, Richards, 1989, and Richards *et al.*, 1994 (Mississippian); McGugan and Rapson,

[5] The Middle Cambrian succession thins northward across Montania beneath the sub-Devonian unconformity (Leech, 1958, 1960; Norris and Price, 1966).

1961; Scott, 1964, Norris, 1965, and MacRae and McGugan, 1977, (Pennsylvanian; Permian); and Gibson, 1974, (Triassic)). However, the greater rate of westward thickening to the north has probably been exaggerated by the northward increase in displacement along the Bourgeau thrust.

## STRATIGRAPHY AND RESERVOIR DEVELOPMENT

### Precambrian Purcell Supergroup

The upper part of the Precambrian Purcell Supergroup is present in the hanging wall of the Lewis thrust north of the North Kootenay Pass Monocline, in the southernmost part of the Fernie–Elk Valley area (Map1; Cross section 3). There, Purcell strata are 900m thick and consist of, in ascending order, the Siyeh, Purcell Lava, Sheppard, Gateway and Phillips Formations (Table 1, Part C; Price, 1964a, 1965). To the south, Purcell strata thicken to over 2000m on a lateral ramp in the hanging wall of the Lewis thrust (Price 1962a, 1965; Childers, 1964). At the Shell North Kootenay Pass b-58-H/82-G-7 well[6], which is on the monocline, 1300m of Purcell strata occur and include strata as old as the Grinnell Formation (Table 1, Part C). Both older and younger formations of the Purcell Supergroup are exposed to the south in the Clarke Range of the Flathead area and are also shown on Table 1, Part C (Fermor and Price, 1983; Aitken and McMechan, 1991)

Purcell strata have been metamorphosed to greenschist grade and have no primary porosity (Fritts and Klipping, 1987a, b; Hannigan *et al.*, 1993). However, several oil and gas seeps from these strata are known in the Flathead area and Waterton National Park, where limited oil production was established in the early 1900's (Hume, 1933a, b, 1964; Boberg, 1984; Hannigan *et al.*, 1993; Monahan, 2000). The oil occurs in fractured reservoirs, both related and unrelated to folds in the Lewis thrust sheet, and appears to have been sourced from the Upper Cretaceous Second White Specks zone of the Alberta Group beneath the Lewis thrust (Hannigan *et al.*, 1993). In the Shell North Kootenay Pass b-58-H/82-G-7 well, gas flow rates up to $19.9 \times 10^3 m^3/d$ (700mcf/d)[7] have been reported from the Siyeh Formation and Purcell Lava.

### Cambrian Flathead Sandstone, Gordon Shale, Elko and Windsor Mountain Formations

A Middle Cambrian succession unconformably overlies the Purcell Supergroup, and is known from surface and subsurface data around the southern margins of the Fernie-Elk Valley area (Table 1, Part C; Fritz and Norris, 1966; Norris and Price, 1966). At the base, the Flathead Sandstone consists of quartz sandstones and varies in thickness from 2 to 45m. The gradationally

[6] Following current practice in British Columbia, well names in this report use surface rather than bottomhole locations. Where they differ from surface locations, bottomhole locations are listed in Table 2.

[7] Reported on the scout ticket. This report could not be verified with the data provided by Shell to the British Columbia Ministry of Energy and Mines.

overlying Gordon Shale consists of 45 to 90m of green shale, variegated with brown or red near its base, and includes interbeds of sandstone and limestone. The Gordon Shale is gradationally overlain by the Elko Formation, which consists of up to 160m of dolomite with dolomite-mottled limestone near its base. The Windsor Mountain Formation sharply overlies the Elko Formation and is up to 70m thick. A unit of silty dolomite occurs at the base, and is overlain by mottled limestone and dolomite like that at the base of the Elko Formation. The Gordon Shale and the Elko Formation are equivalent to the Cathedral Formation in the Bow River succession to the north, and the Windsor Mountain is equivalent to the Stephen and Eldon Formations in that area (Fritz and Norris, 1966; Slind *et al*., 1994). This succession has been beveled northward beneath the sub-Devonian unconformity toward the northern margin of Montania, and immediately south of the Dibble Creek fault Devonian strata directly overlie the Purcell (Leech, 1958, 1960).

The succession described above is representative only of Montania. In the northern part of the Fernie-Elk Valley area, Cambrian strata are unknown, with the possible exception of a dolomite and limestone interval between 3036 and 3124m (9960' and 10250') in the Calstan Fording Mountain d-61-L/82-G-15 well. Cambrian strata probably occur in thrust sheets in this area (Cross sections 1 and 2), and may be more like the thicker succession of Middle and Upper Cambrian carbonates and shales exposed in the Bow Valley (Slind *et al.*, 1994).

Cambrian rocks have not been generally regarded as exploration targets in the Foreland Fold and Thrust Belt, and no reserves have been assigned (Fermor and Moffat, 1992). However, vuggy and intercrystalline porosity occurs in the Elko Formation in outcrop (Price, 1965; Norris and Price, 1966), so that the Elko and possibly the Flathead sandstone could be potential reservoirs.

## Middle and Upper Devonian Yahatinda, Fairholme Group, Alexo and Sassenach Formations

The Devonian succession consists of the Yahatinda Formation, the Fairholme Group and the overlying Alexo, Sassenach and Palliser Formations (Table 1, Part B). The Yahatinda Formation is a thin discontinuous unit of dolomite and dolomitic sandstone and siltstone of probable Givetian (late Middle Devonian) age. It fills erosional lows incised into underlying Cambrian strata (Price, 1964b, Norris and Price, 1966; Aitken, 1990).

The Fairholme Group is primarily Frasnian (early Late Devonian) in age and is characterized by pronounced facies changes from shallow water carbonates and evaporites in the east to deeper water limestones and shales in the west (Table 1, Part B). In southwestern Alberta and the eastern part of the Fernie-Elk Valley area, the Fairholme Group and its equivalents form the western part of a carbonate-evaporite succession deposited on a shallow water shelf that extended eastward into the Williston Basin (Kent, 1994; Switzer *et al.*, 1994). In ascending order, this succession is comprised of the Beaverhill Lake Group and the Cooking Lake Formation, which both consist of limestone, dolomite and anhydrite and are 100m and 60m thick, respectively; the Leduc Formation (Peechee Member of the Southesk Formation), which consists of 200m of dolomite and anhydrite; the Ireton Formation (Mount Hawk Formation equivalent), which consists of up to 3m of argillaceous carbonate; and the Nisku Formation, which consists of 25 to 50m of dolomite with minor anhydrite (Cross section 4; Monahan, 2000).

Carbonates and evaporites of the Beaverhill Lake Group and the lower part of the Cooking Lake Formation extend west across the Fernie Elk Valley area as the Hollebeke Formation, which thickens westward from 120m in outcrop in the Flathead Range in the eastern part of the Lewis thrust sheet, to 240m on the west side of the Fernie Basin[8] (Price, 1964b; Price 1990b). The upper part of the Hollebeke Formation becomes argillaceous and lacks anhydrite to the west. In the White River area, which is in the hanging wall of the Bourgeau thrust west of the Fernie-Elk Valley area, the Hollebeke Formation may be represented by an interval of gypsum and solution breccia beneath Fairholme Group shales and limestones (see Mott, 1989). The Hollebeke Formation is equivalent to the Flume Formation in the Rocky Mountains to the north.

The upper part of the Cooking Lake Formation is replaced to the west by the Borsato Formation in the Flathead Range outcrop area (Table 1, Part B; Cross section 4; Monahan, 2000). The Borsato Formation is a dark crystalline dolomite 15 to 60m thick and in turn passes westward into dark basinal shales of the Perdrix Formation on the west side of the Fernie Basin (Price, 1964b, 1965, 1990a; Reynolds, 1971). The Borsato Formation is equivalent to the upper part of the Cairn Formation in the Rocky Mountains to the north.

The Peechee-Leduc carbonate-evaporite shelf deposits are replaced to the west by basinal argillaceous limestones of the Mount Hawk Formation, which is up to 150m thick in outcrop in the Flathead Range where it overlies the Borsato Formation (Cross section 4; Price 1964b, 1965; Workum, 1988). The Mount Hawk Formation thins to the west, and on the west side of the Fernie Basin the combined thickness of the basinal Perdrix and Mount Hawk Formations is 60 to 120m (Price, 1964b). In the White River area, which is in the Bourgeau thrust sheet west of the Fernie-Elk Valley area, the Fairholme Group includes dark basinal limestones and shales equivalent to the Maligne[9], Perdrix and Mount Hawk Formations, overlying the possible Hollebeke-equivalent evaporitic deposits noted above (Mott, 1989).

The Nisku Formation extends west beyond the limit of the Peechee-Leduc shelf carbonates and evaporites. In the Flathead Range, it overlies the Mount Hawk Formation and can be subdivided into the Grotto and Arcs Members[10], which consist of dark grey dolomite and light grey coarse dolomite, respectively (Price, 1964b, 1965). The Nisku Formation is not present on the west side of the Fernie Basin, where its equivalents are included in the upper part of the Mount Hawk Formation.

The Fairholme Group is overlain by the Famennian (late Late Devonian age) Alexo or Sassenach Formations (Cross section 4). The Alexo Formation consists of 5 to 30m of silty dolomite,

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[8] Anhydrite is expressed as solution breccia in outcrop.

[9] The Maligne Formation consists of dark shaly limestones between the Flume and Perdrix Formations in basinal Fairholme Group successions in the Rocky Mountains to the north (Coppold, 1990).

[10] The Grotto and Arcs Members were initially defined as members of the Southesk Formation.

limestone and anhydrite (expressed in outcrop as solution breccia) that overlie the Nisku Formation[11] (Price, 1964a, 1965; Workum, 1988). To the west, where the Mount Hawk thins and the Nisku is absent, the Alexo Formation is replaced by the Sassenach Formation, which consists of 150 to 200m of sandstones, siltstones and sandy and silty carbonates (Price, 1964b; Leech, 1979; Mott, 1989).

The Fairholme Group is a prime exploration target in the Fernie-Elk Valley area. Beaverhill Lake, Leduc and Nisku reefs and related carbonates are prolific oil and gas reservoirs in the Alberta plains and the Foreland Belt (e.g. Fermor and Moffat, 1992; Switzer *et al.*, 1994). In addition, the lithological equivalent of the Perdrix Formation in the Alberta plains, the Duvernay Formation, is one of the principal hydrocarbon source rocks of the Western Canada Sedimentary Basin (Creaney and Allan, 1990, 1992; Creaney *et al.*, 1994).

The Peechee-Leduc shelf margin appears to be reefal in part. The Peechee shelf margin has been penetrated by wells beneath the Lewis thrust in the Flathead area, immediately south of the Fernie-Elk Valley area (Map 2; Cross section 4; Monahan, 2000). There, the Peechee consists of a lower slightly argillaceous dolomite interpreted as a forereef deposit, a middle clean porous dolomite interpreted as a shelf-edge reef, and an upper dolomite and anhydrite shelf succession. The middle Peechee shelf-edge reef drill stem tested gas with 98% $CO_2$ at a rate of $52x10^3m^3/d$ (1.8mmcf/d) in the Shell Honolulu Flathead d-22-A/82-G-7 well, where it is incorporated in the sub-Lewis duplex of Paleozoic strata. Beneath the Lewis thrust, the middle Peechee shelf-edge reef trends northwest, in a slightly more westerly direction than the Flathead sub-Lewis duplex (Map 2). It lies west of the Shell North Kootenay Pass b-58-H/82-G-7 well and is prospective in the sub-Lewis Paleozoic duplex beneath the Taylor Range. Upper and lower Peechee shelf-edge reef trends could also occur parallel to the middle Peechee reef, west and east of the middle Peechee reef trend, respectively. In the Lewis thrust sheet, the Peechee shelf edge trends west-northwest, south of carbonate-evaporite shelf deposits in the Northstar *et al.* Highrock c-67-B and Calstan Fording Mountain d-61-L/82-G-15 wells and north of the Flathead Range, where basinal equivalents outcrop (Map 2). In this setting shelf-edge reefs are prospective in folds, secondary thrust sheets and on the downthrown side of normal faults. To the west in the Bourgeau thrust sheet, the Peechee shelf edge can be traced into the Kananaskis area (immediately north of the Fernie-Elk Valley area) trending northwest between Peechee outcrops in the leading edge of the thrust sheet and basinal outcrops 10 km to the west (Map 2; McMechan, 1998).

Southwest of the Peechee shelf edge, at least five Peechee pinnacle reefs occur in the Flathead Range outcrop area (Map 2; Cross section 4; Price, 1964b, 1965, Workum, 1988). These pinnacles consist of light grey coarse crystalline dolomite, and are 100 to 150m thick and up to 1 km across. They overlie the Borsato Formation and interfinger laterally with the Mount Hawk Formation, which overlies some of them. Price (1964b) had initially interpreted these as protuberances on the Peechee shelf edge, but Workum (1988) interpreted them to be pinnacles on the basis of the open marine character of the underlying Borsato Formation and the presence

[11] The Alexo Formation in outcrop includes solution breccias that may correlate in part with anhydrites in the lower part of the Palliser Formation in the subsurface.

of northeast dips in the pinnacles. Peechee pinnacle reefs are potential targets southwest of the Peechee shelf edge, both below the Lewis thrust and in the Lewis thrust sheet. The southwest limit of the prospective area is conjectural. However, the underlying Borsato dolomite is likely to have been the platform for the pinnacle reefs, so that its western limit may also be the limit of pinnacle reef development (Reynolds, 1971). Although the western limit of the Borsato Formation is poorly defined, south of the Fernie–Elk Valley area the Borsato is present in the Lewis thrust sheet in the MacDonald Range, 50 km south of the Peechee shelf edge (Price, 1962a, 1964b, 1965; Monahan, 2000).

Porosity also occurs in outcrop in the Borsato and Nisku Formations (Reynolds, 1971). In the Shell MacDonald b-30H/82-G-2 well in the Lewis thrust sheet in the MacDonald Range, porous intervals up to 10m thick occur in these units and in the Hollebeke Formation (Monahan, 2000). Consequently, these units could be prospective locally on structures in the Lewis thrust sheet, particularly south of the Peechee shelf edge. In addition, thicker porous intervals could occur in shelf-edge reefs developed at the edge of the Borsato Formation, and in pinnacle reefs at the western margin of the Nisku Formation, where the Nisku descends into and is replaced by basinal deposits. Nisku and equivalent pinnacle reefs occur in this setting throughout the Western Canada Sedimentary Basin (e.g. Switzer *et al.*, 1994).

**Upper Devonian Palliser Formation**

The Famennian Palliser Formation (equivalent to the Wabamun of the Alberta plains) overlies the Alexo and Sassenach Formations. The Palliser Formation varies from carbonates and evaporites in the east to limestones in the west (Cross section 4). In the Waterton area, east of the Fernie-Elk Valley area, the Palliser consists primarily of dolomites and anhydrites. Although a basal dolomite and anhydrite unit extends westward into the Lewis thrust sheet, most of the formation changes facies westward to primarily dolomite east of and below the Lewis thrust, and then to shallow water marine limestones in the Lewis and Bourgeau thrust sheets (Price, 1965; McMechan, 1998). The thickness increases concomitantly to the west, from 175m below the Lewis thrust, to between 200 and 220m in the Lewis thrust sheet (Price, 1962a, 1965), and up to 500m in the Bourgeau thrust sheet north of Montania (McMechan, 1998). In outcrop in the Lewis thrust sheet, the Palliser Formation is divisible into the lower Morro Member, which consists of 150m of primarily massive dolomite-mottled limestone, and the upper Costigan Member, which consists of 50m of medium bedded limestone (Price, 1965). In the Lussier syncline, located in the Main Ranges of the Rocky Mountains west of the Fernie-Elk Valley area, the Palliser is replaced by dark basinal shales (Savoy, 1992; Savoy and Harris, 1993).

The Palliser Formation is an important hydrocarbon reservoir in the southern Foreland Belt, and forms the lower part of the principal gas pool at the giant Waterton gas field in Alberta (Hall, 1969; Gordy and Frey, 1977). There, the main Palliser reservoir occurs in a dolomite facies 25 to 35m thick[12] between interbedded dolomite and anhydrite intervals, and is near the middle of the

[12] Average porosity in the combined Rundle Group and Palliser Formation reservoir is 5.7% (Hall, 1969).

formation in a position analogous to that of the Crossfield Member of Alberta (Cross section 4; see Eliuk, 1984).

To the west at Coleman in Alberta and below the Lewis thrust in the Flathead area of British Columbia, where most of the Palliser Formation is dolomite, effective reservoir may occur throughout the formation[13]. In the Flathead area, the Palliser Formation is the main reservoir in the $CO_2$-rich gas field established in the sub-Lewis duplex of Paleozoic strata. There, three wells were completed in the Palliser Formation and flowed gas with 90% $CO_2$ at final test rates of 81 to $311x10^3m^3/d$ (2.8 to 11mmcf/d). Net pay thickness in these wells varies from 21 to 48m and the reservoir varies in quality and stratigraphic position from well to well. However, the reservoir is generally concentrated in two zones approximately 50m thick, one below the middle and the other near the top of the formation.

In the Lewis and Bourgeau thrust sheets, the Palliser is primarily limestone and has little reservoir potential. However, a few thin streaks of porous dolomite occur in the Northstar *et al.* Highrock c-67-B/82-G-15 well. Effective reservoir may also be developed in a dolomite facies west of the basal dolomite and anhydrite unit. The base of the Palliser Formation appears to be limestone in the Bourgeau thrust (McMechan, 1998).

Consequently, the Palliser Formation is a prime exploration target in the Fernie-Elk Valley area on structures beneath the Lewis thrust, where reservoir may be present (Map 2).

**Uppermost Devonian and Mississippian Exshaw Formation, Mississippian Banff Formation and Rundle Group**

The Mississippian sequence consists of a broadly shoaling upward succession of basinal to shallow marine shelf deposits. This sequence is comprised of the Exshaw Formation, which spans the Devonian-Mississippian Boundary, the Banff Formation and the Rundle Group (Table 1, Part B).

The Exshaw Formation sharply but apparently conformably overlies the Palliser Formation. It consists of organic-rich black shale, calcareous siltstone and chert, and is characterized by a high gamma ray log signature. The Exshaw Formation is 2 to 10m thick in Montania (Price, 1962a; 1965; Oswald, 1964b; Savoy, 1992; Savoy and Harris, 1993). North of Montania, however, it thickens westward from 6m below the Lewis thrust to as much as 150m in the Bourgeau thrust sheet, although part of the westerly thickening may be due to a facies change of the lower part of

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[13] Control is sparse in the Palliser Formation east of the northern part of the Fernie-Elk Valley area. It consists mainly of dolomite with some limestone at the Coseka *et al.* Savanna Creek 9-31-12-4W5 and Phillips Savanna Creek #3A 5-32-14-4W5 wells (Kubli *et al.*, 1995), and of tight dolomite and anhydrite to the east in the Gulf *et al.* Stimson Creek 9-36-16-4W5 well.

the Banff Formation into the upper part of the Exshaw Formation[14] (Cross sections 5 and 5a; Norris, 1958; Mamet and Mason, 1968; Bamber *et al.*, 1981).

The Banff Formation gradationally overlies the Exshaw Formation, and consists of dark cherty argillaceous limestone, chert, siltstone and shale. The Banff Formation represents basinal deposits overlain by a prograding ramp in which westerly dipping clinoforms can be commonly recognized (Chatellier, 1988; Savoy, 1992; Savoy and Harris, 1993; Monahan, 2000). It thickens westward from 250m in the footwall of the Lewis thrust to 365m on the west side of the Fernie Basin in Montania, and to 850m in the Bourgeau thrust sheet north of Montania (Cross sections 5 and 5a; Norris, 1958; Mamet and Mason, 1968; Oswald, 1964b).

The Rundle Group conformably overlies the Banff Formation, and consists of the Livingstone, Mount Head, and Etherington Formations. The Livingstone Formation is characterized by fine to coarse massive crinoidal grainstone and packstone, with fine crystalline dolomite interbeds (Norris, 1958; Price, 1962a, 1965; Mamet and Mason, 1968). The latter occur throughout the Livingstone Formation, but they occur more commonly toward the top. The Livingstone is 200 to 280m thick below the Lewis thrust, and thickens westward to approximately 450m in the Bourgeau thrust sheet north of Montania (Cross sections 5 and 5a). Some of the westward thickening is due to westward facies change of the lower part of the overlying Mount Head into the Livingstone Formation, but this thickening is partly offset by a westward facies change of the lower part of the Livingstone into the upper part of the underlying Banff Formation. In Montania, the Livingstone Formation is 300 to 400m thick in the Lewis and higher thrust sheets (Price, 1962a, 1965; Oswald, 1964b).

The overlying Mount Head Formation consists of crinoidal grainstone like those of the Livingstone Formation, interbedded with peloidal, oolitic and fine-grained limestones, silty dolomite and anhydrite, which is expressed in outcrop as solution breccias. The Mount Head thickens westward from 200m below the Lewis thrust to 270m in Montania, and to 680m in the Bourgeau thrust sheet north of Montania (Cross sections 5 and 5a; Norris, 1958; Price, 1962a, 1965; Oswald, 1964b; Mamet and Mason, 1968).

The Mount Head has been subdivided into members dominated by silty dolomite and anhydrite alternating with those dominated by lime grainstone and packstone (Table 1, Part B). In the eastern parts of the Fernie-Elk Valley area and adjoining areas, the following are recognized in ascending order: the Wileman Member (8 to 25m of mainly silty dolomite and anhydrite); the Baril Member (11 to 39m of mainly oolitic, micritic and crinoidal limestones); the Salter Member (29 to 67m of mainly silty and sandy dolomites and anhydrite); the Loomis Member (30 to 100m of oolitic, crinoidal and micritic limestones, and fine to medium crystalline dolomites); the Marston Member (18 to 68m of silty dolomite and anhydrite with lesser amounts of

[14] In the Bourgeau thrust sheet, the Exshaw thickness varies from 33m in the Shell Forsyth d-25-A/82-J-6 well to 151m at the Connor Lakes section (Mamet and Mason, 1968), and in the Lewis thrust sheet it is as much as 43m thick (Cross section 5). These relationships may reflect the westerly thinning of individual units of the Exshaw, combined with a westward facies change of the lower Banff into the upper Exshaw.

limestone and shale); and the Carnarvon Member (23 to 90m of micritic and skeletal limestones with lesser amounts of calcareous shale; Price, 1965; Macqueen and Bamber, 1986). The Wileman, Baril, and possibly the lower part of the Salter Members pass westward into crinoidal grainstones and packstones of the upper Livingstone Formation below the Lewis thrust (Cross sections 5 and 5a). Although the upper part of the Salter and Loomis Members also change westward into crinoidal limestone like those of the Livingstone Formation (Macqueen and Bamber, 1986), these intervals can be distinguished in the Lewis thrust sheet on wireline logs by the presence of silty carbonates (represented by higher gamma ray log response) and anhydrite in the Salter Member (Cross section 5). The Marston Member and the lower part of the Carnarvon Member pass westward into the Opal Member, which is a distinct unit of dark grey-weathering skeletal, oolitic, micritic and argillaceous limestones and calcareous shale, and is 200m thick in the Lewis thrust sheet. The Opal Member is overlain by the westward continuation of the upper part of the Carnarvon Member (Macqueen and Bamber, 1968). In the Bourgeau thrust sheet, the Mount Head Formation consists of peloidal, oolitic and crinoidal grainstones and packstones, wackestones and dolomites (Mamet and Mason, 1968).

The Etherington Formation, which is a diverse assemblage of carbonates, clastics and evaporites, abruptly overlies the Mount Head Formation. The unit thins to a zero edge beneath the sub-Triassic and sub-Jurassic unconformities east of the Fernie-Elk Valley area, but in the Fernie-Elk Valley area itself, it is disconformably overlain by the Pennsylvanian and Permian Rocky Mountain Supergroup. The Etherington Formation thickens westward to 170m on the west side of the Fernie Basin in Montania, and to over 469m in the Bourgeau thrust sheet to the north (Cross section 5a; Price, 1962a; Oswald, 1964b, Mamet and Mason, 1968). In the thinner eastern occurrences, the Etherington Formation consists primarily of coarse crystalline dolomite and green to maroon shale, interbedded with anhydrite, sandstone and siltstone. In the Lewis thrust sheet, the Etherington Formation consists of a lower unit of crinoidal and oolitic limestones and green shale with minor dolomite and sandstone, and an overlying unit of silty and cherty dolomite with lesser amounts of sandstone and siltstone (Cross section 5; Norris, 1958; Oswald, 1964b; Scott, 1964; Price, 1965; Lerand, 1990a). In these areas, the Etherington Formation can be distinguished from the underlying Mount Head Formation by the presence of green shale interbeds in the lower part of the formation and more shale interbeds throughout, giving the Etherington Formation a more serrate log character. In addition, the Todhunter Member, a distinct unit of brightly coloured interbedded siltstone, dolomite and calcareous sandstone can be recognized in outcrop at the top of the Etherington Formation (Norris, 1958, 1965; Scott, 1964; Lerand, 1990b). To the west, in the Bourgeau thrust sheet, the Etherington Formation consists of crinoidal grainstones and packstones, silty wackestones and calcareous sandstones (Mamet and Mason, 1968).

The Rundle Group is the principal gas reservoir in most of the fields in the Foreland Belt, including the Waterton and Savanna Creek gas fields east of the Fernie-Elk Valley area, and is the upper reservoir in the high $CO_2$ gas field in the Flathead area to the south (Fuglem, 1969; Hall, 1969; Gordy and Frey, 1977; Fermor and Moffat, 1992; Kubli *et al.*, 1995; Monahan, 2000). The principal pay zones occur in the Livingstone and Mount Head Formations, and to a lesser extent the lower part of the Etherington Formation (Cross section 5). The high initial porosity of the grainstones in these units has been cemented by calcite, probably during early diagenesis, and matrix porosity is best developed in the clean dolomitized lime mudstones and wackestones that are interbedded with grainstones (Price; 1962a, 1965; Klassen, 1972; Kubli *et al.*, 1995). In a general way, porosity in the Rundle Group diminishes from east to west across the Foreland Belt.

Porous dolomite occurs at least locally in outcrop and wells throughout the Fernie-Elk Valley area (e.g. Klassen, 1972), although the amount varies considerably between wells. In the Lewis thrust sheet in the Calstan Fording Mountain d-61-L/82-G-15 well, up to 70m of porosity occurs in the Livingstone Formation and up to 20m occurs in the Mount Head Formation, although these thicknesses may have been enhanced by dissolution by surface waters (Cross section 5). However, net porous dolomite thins to near zero in wells to the east and west. In the high $CO_2$ gasfield below the Lewis thrust in the Flathead area, porous dolomite in the Rundle Group varies in thickness and stratigraphic position from well to well, and locally similar dolomites occur in the upper part of the Banff Formation (Monahan, 2000). Net pay thickness varies from 8 to 27m in the Livingstone Formation, and is up to 9m in the Mount Head and 7m in the Etherington Formations. Final test gas flow rates range from 25 to $141x10^3m^3/d$ (0.9 to 5.0mmcf/d).

Consequently, the Rundle Group, particularly the Livingstone Formation, is prospective on structures above and below the Lewis thrust, although the variability of the reservoir presents a risk throughout the Fernie-Elk Valley area. In addition, the Exshaw Formation is one of the principal source rocks of the Western Canada Sedimentary Basin (Creaney and Allen, 1990, 1992; Creaney *et al.*, 1994).

**Pennsylvanian and Permian Rocky Mountain Supergroup**

Pennsylvanian and Permian strata are grouped together in the Rocky Mountain Supergroup, which is subdivided into the Pennsylvanian Spray Lakes Group and the Permian Ishbel Group (Table 1, Part B)

The Spray Lakes Group is comprised of the Misty and Kananaskis Formations. The Misty Formation disconformably overlies the Rundle Group (Scott, 1964; Henderson, 1989), and consists of sandstone with minor amounts of siltstone and dolomite[15]. The Misty Formation thins eastward to a zero edge beneath the sub-Triassic and sub-Jurassic unconformities east of the Fernie-Elk Valley area. The Misty Formation thickens westward to 610m in the Bourgeau thrust sheet north of Montania, but to only 200m in Montania (Cross sections 5 and 5a; McGugan and Rapson, 1961; Scott, 1964; Norris, 1965). The Kananaskis Formation consists of up to 60m of silty and sandy dolomites[16] (Scott, 1964; Norris, 1965), conformably overlying the Misty Formation.

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[15] Strata assigned to the Misty Formation have also been subdivided into the Tyrwhitt, Storelk and Tobermory Formations. The contact between the Storelk and overlying Tobermory Formations may be disconformable (Scott, 1964; Henderson, 1989).

[16] The thickness of 85m reported at the Inexco *et al.* Tornado b-9-J/82-G-15 well is probably structurally thickened (Cross sections 5 and 5a).

The Ishbel Group unconformably overlies the Spray Lakes Group. However, it is not well developed in most of the Fernie-Elk Valley area, where thin condensed sections with a high gamma ray log signature may be locally recognized (Cross section 5; McGugan and Rapson, 1964; MacRae and McGugan, 1977). The Ishbel Group thickens westward. On the west side of the Fernie Basin in Montania, it consists of 30m of phosphatic siltstone assigned to the Johnson Canyon Formation and is distinguished by its high gamma ray log signature (395m to 425m, or 1296' to 1394', in the B.A. CNP Fernie b-81-D/82-G-7 well; MacRae and McGugan, 1977). However, to the north of Montania, the Ishbel Group thickens westward to 500m in the Bourgeau thrust sheet, and consists of the Johnson Canyon Formation (up to 60m), the Telford Formation (up to 240m of fossiliferous limestones and dolomites), the Ross Creek Formation (up to 150m of phosphatic siltstones, with limestone and chert) and the Ranger Canyon Formation (up to 36m of chert with sandstone and siltstone; Table 1, Part B; McGugan and Rapson, 1964; MacRae and McGugan, 1977).

Little porosity is developed in the sandstones, dolomites and associated strata of the Rocky Mountain Supergroup (MacRae and McGugan, 1977). However, sandstones of the Misty Formation are porous and tested salt water in the Shell North Kootenay Pass b-58-H/82-G-7 well at the south end of the Fernie-Elk Valley area (Monahan, 2000). Consequently, these sandstones are a potential secondary objective on structures in the area.

**Triassic Spray River Group**

Triassic strata overlie older strata unconformably and consist of the Sulphur Mountain and the Whitehorse Formations of the Spray River Group (Table 1, Part A). The Sulphur Mountain Formation consists of a lower dark siltstone and shale member (Phroso Siltstone Member), a middle member of calcareous and dolomitic siltstone, silty limestone, and shale (Vega Siltstone Member), and an upper member of sandy dolomite, dolomitic siltstone, shale and sandstone (Llama Member; Gibson, 1974). Below the Lewis thrust, where the overlying Whitehorse Formation is not present, the Sulphur Mountain Formation is truncated to the east beneath the sub-Jurassic unconformity. The subsurface zero edge is located between the Lewis thrust sheet and Savanna Creek gas field (Cross section 5). However, it trends southward beneath the Lewis thrust sheet, so that the Sulphur Mountain Formation is absent beneath the Lewis thrust in the Shell North Kootenay Pass b-58-H/82-G-7 well. In the Lewis and higher thrust sheets, the Sulphur Mountain Formation thickens westward to over 157m on the west side of the Fernie Basin in Montania, and to 496m in the Bourgeau thrust sheet north of Montania (Gibson, 1974). The conformably overlying Whitehorse Formation consists of calcareous and dolomitic sandstone and siltstone, sandy dolomite and limestone and solution breccia (Gibson, 1974; Price, 1992a, b). In the Fernie-Elk Valley area, the Whitehorse Formation is less than 10m thick and has been recognized only in the Lewis thrust sheet.

Most Spray River strata are not porous and have little reservoir potential. However, a dolomite unit 6 to 10m thick has been recognized in thinner eastern occurrences of the Sulphur Mountain Formation (Cross section 5; Gibson, 1974). The dolomite unit is locally porous in wells (e.g. 2m with up to 6% porosity in the Getty Union *et al.* Oyster 9-21-13-5W5 well between 2970m and 2972m, or 9744' and 9750'), and pyrobitumen has been observed in vugs in outcrop (Gibson, 1974). This dolomite is similar to the Mackenzie Dolomite Lentil of the Sulphur Mountain Formation, which is gas productive in the Foreland Belt north of the Fernie-Elk Valley area, and represents a potential objective on structures east of and below the Lewis thrust. Furthermore, the dark shales and siltstones of the Sulphur Mountain Formation are the lithological equivalents of the Doig and Montney Formations of the Alberta and British Columbia plains, which include one of the principal hydrocarbon source beds of the Western Canada Sedimentary Basin (Creaney and Allen, 1990, 1992; Creaney *et al.*, 1994).

**Jurassic Fernie Formation**

The Jurassic Fernie Formation overlies Triassic and older strata unconformably. The Fernie Formation consists primarily of dark shales, with lesser amounts sandstone, siltstone and limestone (Price, 1962a, 1965; Price, *et al.*, 1992a, b; Norris, 1993a). It thickens westward from less than 175m east of the Lewis thrust (Cross section 9) to 300 to 400m in the Lewis thrust sheet (Price, 1962a, 1965; Weihmann, 1964; Ollerenshaw, 1981b; Stronach, 1984; Hall, 1984). However, the Fernie Formation is a major zone of detachment in the Foreland Belt, and is commonly structurally thickened to several times its stratigraphic thickness (Dahlstrom, 1969, 1970). For example, it has been thickened to 530m and to over 1000m in the Getty Union *et al.* Oyster 9-21-13-5W5 and the Sinclair *et al.* Racehorse 16-29-9-5W5 wells respectively east of the leading edge of the Lewis thrust (Cross section 2), and to over 2600m in the B.A. CNP Fernie d-42-I/82-G-6 well in the triangle zone on the west side of the Fernie Basin (Cross section 3; Dahlstrom, 1969).

The internal stratigraphy of the Fernie Formation is complex and may include one or more disconformities (Hall, 1984; Poulton, 1989). Several members have been recognized in the Fernie-Elk Valley area, including a thin unnamed basal coquina and phosphate pebble conglomerate, which is in part the equivalent of the Nordegg Member to the north and is characterized by a high gamma ray signature on logs, the Poker Chip Shale, the Rock Creek Sandstone, the Highwood Member, the Grey Beds, the Green Beds, the Ribbon Creek Member and the Passage Beds (Price, 1965; Stronach, 1984; Hall, 1984; Norris, 1993a, b). Because of the stratigraphic and structural complexities, these members have not been differentiated on the cross sections.

The Fernie Formation does not appear to be a significant conventional hydrocarbon objective in the Fernie-Elk Valley area, although the Rock Creek Sandstone Member is an objective in parts of the Alberta plains. The Rock Creek is argillaceous and has low porosity in most wells east of the Lewis thrust, but 2m of Rock Creek gas pay is reported from the Shell Gulf Sullivan 6-15-18-5W5 well, and the Rock Creek interval tested gas too small to measure from a 0.6m thick zone in the Shell 5 Waterton 6-28-4-1W5 well. The Fernie Formation did produce gas on drill stem tests at rates declining from $42x10^3m^3$/d (1.5mmcf/d) to 7 $x10^3m^3$/d (250mcf/d) in the Sinclair *et al.* Racehorse 16-29-9-5w5 well east of the Lewis thrust. This test was from a structurally thickened shale section that probably represents an uneconomic fractured shale reservoir. However, the organic-rich Poker Chip Shale, and possibly the Nordegg-equivalent basal phosphatic member, are potential hydrocarbon source rocks in this area (Stronach, 1984; Creaney and Allen, 1992, 1994).

**Jurassic and Lowermost Cretaceous Kootenay Group**

The Fernie Formation is conformably overlain by the Upper Jurassic to Lower Cretaceous Kootenay Group, which consists of the Morrissey, Mist Mountain and Elk Formations (Table 1, Part A; Gibson, 1977, 1979, 1984, 1985; Dunlop and Bustin, 1987; Grieve, 1993). The Morrissey Formation consists of a 25 to 65m thick coarsening upward sequence of fine to medium-grained sandstone, with some conglomeratic sandstone in the upper part, and rare interbeds of mudstone, siltstone and coal (Cross section 9). The Morrissey Formation is sharply overlain by the Mist Mountain Formation, which consists of dark siltstone interbedded with fine to locally coarse sandstone, conglomerate, mudstone, shale and thick coal seams. In the subsurface east of the Lewis thrust, the Mist Mountain Formation thins eastward beneath the sub-Blairmore unconformity (Cross section 9; Gibson, 1985; Monahan, 2000). To the west, where the Elk Formation conformably overlies it, the Mist Mountain Formation thickens to the north and west from 100 to 665m (see Cross sections 7 and 8; Gibson, 1985; Grieve and Kilby, 1989; Johnson and Smith, 1991; Grieve, 1993; Dawson *et al.*, 1998). The Elk Formation consists of fine to coarse sandstone, siltstone, mudstone, shale, conglomerate, which is abundant in the west side of the Fernie Basin, and thin coal beds. The contact between the Mist Mountain and Elk Formations is picked at the base of the first major sandstone or conglomerate above the highest significant coal seam and is probably diachronous (Cross sections 7 and 8; Gibson, 1985; Grieve and Ollerenshaw, 1989). The Elk Formation thickens westward beneath the sub-Blairmore unconformity from a zero edge east of the surface trace of the Lewis thrust to 475m in the Lewis thrust sheet. However, the upper contact could be conformable where the Elk Formation is thickest (Gibson, 1977, 1985; Leckie and Cheel, 1997)

Sandstones in the Kootenay Group are generally tight, although 1m thick streaks of porous sandstone occur in a thick sandstone unit in the Getty Union *et al.* Oyster 9-21-13-5W5 well, and may be associated with conglomerate beds (Cross section 9). Mist Mountain and Elk Formation conglomerates may have reservoir potential locally.

However, the coal seams of the Mist Mountain Formation are an important potential coalbed methane target (Johnson and Smith, 1991; Dawson, 1995; Dawson *et al.*, 1998, 2000). Coal rank varies from low volatile to high volatile B bituminous, individual coal seams are generally 1 to 8m thick, and cumulative thickness of coal varies from 23 to 86m (Pearson and Grieve, 1985; Grieve and Kilby, 1989; Johnson and Smith, 1991).

**Lower Cretaceous Blairmore Group**

The Lower Cretaceous Blairmore Group is a thick sequence of continental sandstone, conglomerates, mudstones, siltstones and shales. It thickens westward depositionally from 635m below and east of the Lewis thrust, to over 2400m in the Fernie Basin (Price, 1962a; Norris, 1964; Ollerenshaw, 1981b). The Blairmore Group has been subdivided into the Cadomin, Gladstone, Beaver Mines and Ma Butte Formations (Table 1, Part A; McLean, 1982, 1990a, b, c, d). In the westernmost part of the Fernie Basin, where the Blairmore Group overlies thick sections of the Elk Formation of the Kootenay Group, the lower contact may be either conformable or disconformable (Gibson, 1977, 1985; Leckie and Cheel, 1997). Elsewhere, Kootenay Group strata are truncated eastward beneath the Blairmore Group, and the contact is clearly unconformable (Cross section 9).

The Pocaterra Creek Member forms the base of the Blairmore Group in the westernmost part of the Fernie Basin, where the base may be conformable. This member consists of up to 90m of sandstone, siltstone and mudstone with minor chert pebble conglomerate (Gibson, 1977, 1985).

Elsewhere, the Cadomin Formation forms the base of the Blairmore Group. The Cadomin Formation consists of chert pebble conglomerate and sandstone, commonly organized into decameter-scale coarsening upward sequences that are interbedded and laterally replaced by grey, green and or red mudstone (Ollerenshaw, 1981a, b). It is 15 to 75m thick and, at least locally, the thicker sections have greater proportions of conglomerate and lower proportions of mudstone (Cross section 9[17]; Monahan, 2000). The Cadomin was deposited by braided streams that flowed northeast from upland areas to the west, and then converged into a north to northwest-oriented drainage system [18] (McLean, 1977; Leckie and Cheel, 1997). The Cadomin Formation is gradationally overlain by the Gladstone Formation.

The Gladstone Formation[19] consists of a lower member of fine quartz-chert sandstone, green and red mudstones and minor amounts of conglomerate, and an upper member of fresh water limestone and calcareous mudstone (Price, 1962a; Norris, 1964, Ollerenshaw, 1981b; McLean 1982, 1990c). The Gladstone thickens westward from 82m east of the Lewis thrust to over 450m in the Fernie Basin.

The succeeding Beaver Mines[20] and Ma Butte Formations[21] consist of sandstone interbedded with siltstone and grey to red mudstone (Price, 1962a; Norris, 1964, Ollerenshaw, 1981b; McLean, 1982, 1990a, d). The two formations are distinguished by their sandstones, which are

[17] The greater proportion of conglomerate in the thick Cadomin section in the Husky Savanna Creek 13-26-13-4W5 well is inferred from the ability of the zone to produce gas at economic rates.

[18] In outcrops east of the Lewis thrust, the upper part of the Cadomin is replaced by sandstones that Leckie and Cheel (1997) have assigned to the Dalhousie Formation, which they interpret as being separated from the Cadomin by an unconformity. However, palynological data suggests that the Cadomin and Dalhousie Formations are broadly correlative (White and Leckie, 1999), and they are treated that way here.

[19] The Gladstone Formation is equivalent to some or all of the Lower Blairmore of Price (1962a), Norris (1964) and Ollerenshaw (1981b).

[20] The Beaver Mines Formation is equivalent to the Middle Blairmore of Price (1962a) and Norris (1964).

[21] The Ma Butte Formation is equivalent to the Upper Blairmore of Price (1962a) and Norris (1964), and the Mill Creek Formation of other workers (McLean, 1982, 1990d).

grey to green feldspathic and arkosic in the Beaver Mines Formation and consist of quartz and chert in the Ma Butte Formation. In addition, igneous and chert pebble conglomerates up to 60m thick occur filling channels incised into finer sediments in the upper part of the Beaver Mines and the Ma Butte Formations and form a series of east-oriented conglomerate-rich trends crossing the foothills (Price, 1962a; Norris, 1964; Ollerenshaw, 1981b; Leckie and Krystinik, 1995a, b; Leckie and Craw, 1995). These conglomerates equate to the McDougal-Segur Conglomerate, a group of conglomerates that occur at a variety of stratigraphic levels in the upper part of the Blairmore Group in the Turner Valley area of the Alberta foothills. East of the Lewis thrust, the Beaver Mines and Ma Butte Formations are 450 and 120m thick respectively (MacLean, 1990a, d), and they thicken westward to a combined thickness of 1875m in the Fernie Basin (Ollerenshaw, 1981b).

Porosity is generally low in the Blairmore Group clastics, but sufficient permeability for commercial production may occur in conglomerates. The Cadomin Formation (and its equivalents) has yielded gas shows in several wells in the adjacent parts of Alberta, at Savanna Creek and Waterton[22]. In particular, the Cadomin section in the Husky Savanna Creek 13-26-13-4W5 is unusually thick (63m) and tested gas at a rate of $25x10^3m^3/d$ (887mcf/d), of which $21.6x10^3m^3/d$ (767mcf/d) was $N_2$, with water (i.e. $3.4x10^3m^3/d$, or 121mcf/d, net gas). Although this does not represent a commercial well, it does indicate the presence of effective reservoir in Cadomin Formation “thicks” deposited along major fluvial trends. The orientation of such trends is unknown, but may vary from northeast to northwest. A high gas detector response was reported in a similar thick Cadomin Formation conglomerate in the Flathead area (Monahan, 2000).

Similarly, the conglomerates in the Beaver Mines and Ma Butte Formations may provide effective reservoirs (Leckie and Krystinik, 1995a, b). The equivalent McDougal-Segur conglomerates produce oil in the Turner Valley field, north of the Fernie-Elk Valley area in Alberta. In the Calstan Crowsnest 6-14-8-5W5 well, gas was tested at rates declining from 4 to $2x10^3m^3/d$ (142 to 71mcf/d) from a 3m sand or conglomerate in the upper part of the Blairmore Group that may be from this zone, and sand or conglomerate beds up to 15m thick in the upper part of the Blairmore Group in the Savanna Creek field may also represent these conglomerates. Savanna Creek is located on one of the east-oriented conglomerate trends identified by Leckie and Krystinik (1995a, b).

**Lower Cretaceous Crowsnest Formation**

The Crowsnest Formation has an interfingering lower contact with the Ma Butte Formation. It consists of bedded alkaline volcanic rocks composed of tuffs, volcanic breccias, volcanic conglomerates and trachyte, and was deposited largely by pyroclastic flows, surges, lahars and

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[22] The Cadomin (Dalhousie) Formation tested gas through perforations in the Chevron Canadian Superior Waterton 16-5-6-1W5 and Encounter *et al.* Waterton 7-12-6-2W5 wells, at rates of $28x10^3m^3/d$ (994mcf/d) and $17x10^3m^3/d$ (603mcf/d), respectively. The Cadomin Formation is 12 and 15m thick in these wells, respectively.

minor flows (Adair, 1990; Adair and Burwash, 1996). The thickness varies from over 400m near Coleman east of the Lewis thrust and thins in all directions from there. It is not recognized in outcrop north of Township 10. However, it is 175m thick in the Sinclair *et al.* Racehorse 16-29-9-5w5 well and 67m thick in the Getty Union *et al.* Oyster 9-21-13-5W5 well, north of which it is not recognized in the subsurface. It is not present in the Lewis thrust sheet. The formation is disconformably overlain by the Blackstone Formation of the Alberta Group (Norris, 1964; Adair, 1990). The Crowsnest Formation has yielded a K-Ar date of 95 MA (Follinsbee *et al.*, 1957).

**Upper Cretaceous Alberta Group and Belly River Formation**

The Upper Cretaceous Alberta Group consists of marine shales and sandstones and disconformably overlies the Crowsnest Formation and the Blairmore Group. Regionally, the Alberta Group thickens westward, and is up to 700m thick in the footwall of the Lewis thrust (Wall and Rosene, 1977; Leckie *et al.*, 1994). To the west on the Lewis thrust sheet, outliers are preserved in the axis of the Fernie Basin and in slide deposits south of the Fernie-Elk Valley area (Map 1; Price, 1962a; Jones, 1977). The Alberta Group is comprised of the Blackstone, Cardium and Wapiabi Formations (Table 1, Part A).

The Blackstone Formation consists of dark shale, fine sandstone, siltstone and calcareous shale (Wall and Rosene, 1977). East of the Lewis thrust, the Blackstone Formation is over 250m thick in wells in the Savannah Creek area, and thins southeastward. It is 85 to110m thick in wells beneath the Lewis thrust in the Flathead area, immediately south of the Fernie Elk Valley area, and as thin as 30m in the Waterton gas field (Herr, 1967) and possibly in the Fernie Basin. In the Flathead area, a 15m thick basal sandstone occurs in several wells, and a decameter-scale coarsening upward sandstone sequence like those of the overlying Cardium Formation is developed locally in the middle of the formation (Monahan, 2000).

In outcrop, the Blackstone has been subdivided into the Sunkay, Vimy, Haven and Opabin Members (Stott, 1963; 1990a, b, c, d; Wall and Rosene, 1977). The Sunkay Member, consists of shale, siltstone and sandstone, and may equate with the basal sandstone observed in the Flathead area. The Vimy Member consists of calcareous shale and limestone, and is the equivalent of the Second White Specks, an important source rock zone in the Alberta plains (Creaney and Allen, 1990, 1992; Creaney *et al.*, 1994). The Haven Member consists of dark shale and siltstone; and the Opabin Member consists of silty mudstone with sideritic concretions.

The Cardium Formation gradationally overlies the Blackstone Formation. It consists of marine sandstone, siltstone and shale, and is organized into decameter-scale coarsening upward cycles. The thickness of individual sand units is 3 to 10m. Some cycles coarsen up to siltstone rather than sandstone, so that the relative amount of sandstone in the Cardium Formation is low. The Cardium Formation is 100 to 150m thick in the footwall of the Lewis thrust west of Savanna Creek and in the Flathead area, and thins eastward, where fewer coarsening upward cycles occur.

The Wapiabi Formation conformably overlies the Cardium Formation. It is 600 to 700m thick beneath and immediately to the east of the Lewis thrust, and consists of dark shales with lesser amounts of siltstone and fine sandstone (Price, 1962a; Wall and Rosene, 1977). A calcareous shale and limestone member near the middle is the equivalent of the First White Speckled Shale Member, an important hydrocarbon source rock in the Alberta plains (Creaney and Allen, 1990, 1992; Creaney *et al.*, 1994).

The Belly River Formation conformably overlies the Wapiabi Formation and consists of interbedded continental sandstones, shales and minor amounts of coal (Price, 1962a; Wall and Rosene, 1977). In the Fernie-Elk Valley area, it occurs only below and east of the Lewis thrust, where it is up to 1370m thick.

The Cardium and Belly River sandstones are important hydrocarbon objectives in the Alberta plains and foothills, and condensate has been drill stem tested from the Cardium Formation in two wells at Waterton[23]. However, sandstones observed in the Blackstone, Cardium and Belly River Formations are generally fine grained, and have low porosity. Nonetheless, discontinuous conglomerates in the Cardium Formation provide sufficient permeability for economic production in other areas, and could possibly occur here locally. Most Cardium trends in Alberta are oriented northwest. Fractured shale in the Vimy member of the Blackstone Formation (Second White Specks zone equivalent) is another potential objective. This zone is locally a prolific, if unpredictable, reservoir in Alberta.

## INTRUSIVE ROCKS

Intrusive rocks are not common in the Fernie-Elk Valley area, but some occur and may have some bearing on the hydrocarbon potential. Some thin altered gabbro sills occur in Cambrian to Ordovician Mackay Group west of the Fernie-Elk Valley area (Leech, 1979; Mott, 1989). In the same area, Leech (1979) mapped the Bull River amygdaloid, a volcanic rock of unknown age also in contact with the Mackay Group. These intrusive rocks are interpreted here to be roughly equivalent in age to the rocks that they intrude.

In addition, about 40 intrusive breccia diatremes have been identified in the western Front Ranges and Main Ranges of the Rocky Mountains in southeastern British Columbia. Most lie in a north-trending belt west of the Fernie-Elk Valley area, and were emplaced between the Middle Ordovician and the Middle Devonian (Pell, 1987; Helmstaedt *et al.*, 1988; Mott, 1989). However, the Cross diatreme, the only one identified as a kimberlite, intrudes strata of the Pennsylvanian to Permian Rocky Mountain Supergroup in the hanging wall of the Bourgeau Thrust 10 km northwest of Elkford, and has yielded a Rb-Sr date of 240-250 Ma, close to that of the host rock (Map 1; Grieve, 1981, 1982; Ijewliw, 1987; Helmstaedt *et al.*, 1988; Smith *et al.*, 1988). The lack of thermal alteration of the wall rock indicates that it was intruded 'cold'.

[23]The Shell Waterton 11-4-6-1W5 and Chevron Canadian Superior 16-5-6-1W5 wells drill stem tested 300m and 200m of condensate, respectively, from a 1m sandstone. In both wells, other Cardium sandstones occur, including fault repeats, and one of these was also tested and did not produce hydrocarbons.

Several granitic stocks have been mapped on the west side of the Rocky Mountains and in the Rocky Mountain Trench (Map 1; Leech, 1958, 1960). Of these, the Reade Lake stock in the Rocky Mountain Trench has yielded a U-Pb date of 94 Ma (Hoy and van der Heyden, 1988), and the others have been interpreted to be of similar age (Leech, 1958, 1960).

South of Fernie-Elk Valley in the Flathead area, a suite of primarily alkaline intrusive rocks occurs in the Lewis thrust sheet (Map 1; Price, 1962a, 1965; Spukinsky and Legun, 1989; Goble *et al.*, 1993, 1999; Brown and Cameron, 1999). These intrusives vary from dykes and sills to stocks with a maximum surface area of 7 $km^2$. The most reliable age estimate is provided by a U-Pb date of 98.5$\pm$5 Ma, and additional K-Ar dates range from 72-119 Ma (Gordy and Edwards, 1962; Spukinsky and Legun, 1989; Brown and Cameron, 1999). These rocks are both contemporaneous with and compositionally similar to the Lower Cretaceous Crowsnest Formation and have similar origins (Price, 1962a, 1965; Spukinsky and Legun, 1989; Goble *et al.*, 1993, 1999; Brown and Cameron, 1999). However, they are unlikely to represent a single igneous centre, because they are separated by the Lewis Thrust, on which there has been in excess of 75 km of displacement in the Flathead area (van der Velden and Cook, 1994; Fermor, 1999).

## EXPLORATION ACTIVITY

Since 1961, only 8 conventional exploratory wells have been drilled in the area, the most recent having been completed in October 1999 (Table 2). Although none of these wells were successful, several large gas fields have been found in thrust faulted Devonian and Mississippian carbonates in adjacent parts of the Cordillera. Currently, most exploration interest is focused on the coalbed methane potential of the area. Since 1990, 13 testholes and 2 wells have been drilled to evaluate this resource (Table 3). In 2000, two new testholes and 13 new wells have been licenced and are confidential at the time of writing.

## SOURCE ROCKS AND MATURATION

Several of the established hydrocarbon source rocks in the Western Canada Sedimentary Basin are known or inferred to be present in the Fernie-Elk Valley area (Creaney and Allan, 1990, 1992; Creaney *et al.*, 1994). In Paleozoic strata, these include the Upper Devonian Perdrix Formation, the lithological and temporal equivalent of the Duvernay Formation, and the Upper Devonian-Lower Mississippian Exshaw Formation. The Triassic Sulphur Mountain Formation is the equivalent of the Montney and Doig Formations, which include source rocks elsewhere in the Western Canada Sedimentary Basin. However, the highly radioactive phosphate zone, which is the most prolific source, does not appear to be present in the area. In the Jurassic Fernie Formation, potential source rocks occur in the Poker Chip Shale Member (Stronach, 1984), and possibly the basal phosphatic member, which is the equivalent of the Nordegg Member, an important source rock further north in the Foreland Belt. Lastly, hydrocarbon source rocks also occur in the shales of the Upper Cretaceous Alberta Group. The most important of these are the Second and First White Specks zones, but shale units between these horizons are also potential source rocks. Alberta Group source rocks occur only below the Lewis thrust in the Fernie-Elk

Valley area. In addition to these source rocks, coal in the Jurassic Mist Mountain Formation of the Kootenay Group has generated gas in this area (see section below on coalbed methane potential).

Vitrinite reflectance data obtained in the course of exploration and development of the Mist Mountain coals and other studies show that maturation increases westward and northward in the foothills and Rocky Mountains. In addition, peak maturation was broadly contemporaneous with thrust faulting and folding, but pre-dates normal faulting[24] (Hacquebard and Donaldson, 1974, Pearson and Grieve, 1985; England and Bustin, 1986; Grieve, 1987, 1991; Bustin and England, 1989; Osadetz *et al.*, 1992; Fermor and Moffat, 1992). Vitrinite reflectance generally exceeds 1.0% in the lower part of the Mist Mountain Formation in the Fernie-Elk Valley area and adjacent parts of Alberta (generally >1.2% at the base of the Mist Mountain in the Lewis thrust sheet; see also Grieve, 1993). Consequently, only Cretaceous source rocks are likely to be in the oil window in this area. Consistent with this conclusion, in the parts of the Alberta Foothills and Rocky Mountains adjacent to the Fernie-Elk Valley area, the Paleozoic is gas-bearing, whereas both oil and gas shows occur in Cretaceous strata.

## CONVENTIONAL PROSPECTIVE ZONES AND PLAY TYPES

### Thrust Faulted Paleozoic Strata Below the Lewis Thrust

Thrust faulted Paleozoic strata beneath the Lewis thrust represent the most prospective conventional hydrocarbon targets in the Fernie-Elk Valley area. This play type is well established in adjacent parts of Alberta, where the Waterton, Coleman and Savanna Creek gas fields have initial recoverable reserves of $73x10^9m^3$ (2600BCF), $7x10^9m^3$ (249BCF) and $4.4x10^9m^3$ (153BCF) respectively (Fuglem, 1969; Hall, 1969; Alberta Energy and Utilities Board, 1997). In addition, $17x10^9m^3$ (600BCF) of $CO_2$-rich gas has been discovered in thrust faulted Paleozoic carbonates to the south in the Flathead area of British Columbia (Hannigan *et al.*, 1993).

The principal reservoirs in this setting are in the Devonian Palliser and the Mississippian Livingstone Formations, and to a lesser extent in the Devonian Peechee Member and the Mississippian Mount Head and Etherington Formations. Reservoir rocks in these formations vary in quality and stratigraphic position from well to well and are not present in all places. By comparison with wells in the Flathead area, average net pay thicknesses could be 30m in the Palliser and 20m in the Livingstone Formation. In addition, the prospective Peechee Member shelf-edge reef facies in this setting is restricted to the southern part of the area. The Cambrian Elko and the Pennsylvanian Misty Formations may have some minor reservoir potential locally.

Fracturing is an important contributor to the reservoir quality of these low porosity reservoirs, enhancing permeability and establishing communication between stratigraphically separated

[24] A similar conclusion can be drawn from paleomagnetic data, which record a late tectonic cooling event (Enkin *et al.*, 2000).

intervals (Gordy and Frey, 1977). Fracturing is generally better developed in dolomite than limestone (e.g. Kubli *et al.*, 1995). However, fracturing alone is generally insufficient for economic production and matrix porosity is necessary. Lewchuk *et al.* (1988) showed that the dolomite reservoir in the Mount Head Formation at Waterton Field recrystallized in part from an early diagenetic dolomite during the Laramide orogeny, probably as hydrocarbons were migrating into the trap. Furthermore, as noted above, porous dolomites in the Mississippian were derived from lime mudstones and wackestones rather than grainstones and packstones (Kubli et al., 1995), and reservoir quality varies considerably from well to well on a structure in this setting. These factors demonstrate that although reservoir quality may be enhanced on the crest of a structure, the presence of reservoir is usually dependent upon depositional and/or relatively early diagenetic facies.

In the largest pool in the Waterton field, the Palliser and Rundle reservoirs are in communication and behave as a single reservoir as a result of extensive fracturing in the Banff Formation, (Gordy and Frey, 1977), which has been attributed to the high chert content of the Banff in this area (K. Osadetz, 2000, personal communication). However, in the Flathead area, the compositional differences between the gas in the Palliser Formation and the Rundle Group[25] indicate that these reservoirs need not be in communication in all structures in the region (Monahan, 2000). Nonetheless, communication between the Peechee and Palliser reservoirs may occur at Flathead, and be a partial explanation for the smaller area under closure at the Peechee level. Although the Palliser is gas-bearing in both the Shell Flathead c-12-A and the Shell Honolulu Flathead d-22-A/82-G-7 wells at the north end of the Flathead field, the Peechee is gas-bearing only in the d-22-A well and is lower and wet at c-12-A. Communication could occur between these horizons on other structures.

Two major prospective structural trends can be defined beneath the Lewis thrust, although other structures could also be present. The belt of Paleozoic outcrop in the Wisukitsak Range, Erickson Ridge and the south Taylor Range is interpreted to be the surface expression of a trend of sub-Lewis duplexes that have folded the Lewis thrust sheet (Maps 1 and 2; Cross sections 2 and 3; Fitzgerald, 1969). The Calstan Fording Mountain d-61-L/82-G-15 well is the only well on this structural trend (Table 2). It is located on the west flank of the structure and confirms the duplex and folded thrust model, at least at the north end of the trend (Dahlstrom, 1962; Price, 1992a, b). Seismic data confirm the existence of sub-Lewis thrust sheets beneath the southernmost end of the Taylor Range (Charters, 1989)[26].

[25] In the gas wells at Flathead, the $CO_2$ content of the gas in the Palliser Formation is 90% or greater, whereas in the Rundle Group it ranges from 20 to 90%.

[26] On the seismic line shown by Charters (1989), the surface antiform of Paleozoic strata is less pronounced than further north, and the Lewis thrust sheet appears to be monoclinally rather than anticlinally folded. An additional line east of the Chevron Shell Mansfield c-72-D/82-G-15 well indicates that the Lewis thrust may be monoclinally rather than anticlinally folded at this location as well (Davitt and Kushnir, 1986).

The sub-Lewis duplex beneath the Wisukitsak Range, Erickson Ridge and south Taylor Range is a large untested structure 100km long. Although the Calstan Fording Mountain d-61-L/82-G-15 well did not encounter porous dolomite in the Livingstone, Mount Head or Etherington Formations below the Lewis thrust, porous dolomite occurs palinspastically west in the Lewis thrust sheet (Cross section 5). Furthermore, the d-61-L well penetrated little more than half the sub-Lewis Livingstone Formation. In the Lewis thrust sheet section of the Livingstone in the Inexco *et al.* Tornado b-9-J/82-G-15 well, palinspastically the closest well with a complete Livingstone penetration to d-61-L, the principal porous dolomite development is below the stratigraphic level reached in the d-61-L well (Cross section 6). Neither the Peechee Member nor the Palliser Formation have been tested on this structural trend, although the Peechee is likely to be prospective only in the south Taylor Range, west of the Shell North Kootenay Pass b-58-H/82-G-7 well (Map 2). The Palliser and Rundle were tested unsuccessfully in this well, which is located east of the south Taylor Range on another structural trend (Table 2; see also discussion in next paragraph).

Another trend of duplexes is interpreted to underlie the leading edge of the Lewis thrust (Map 2; Cross sections 1, 2 and 3). The northern part of this trend is based on a seismic time structure high on the regional Cambrian event (Semkow, 1969, 1973). The time structure high extends beneath the Highrock Range from 82-J-7 to 82-G-15 and in general plunges south. Closure to the north is suggested by a surface syncline in Cretaceous strata that wraps around the north end of the trend (Map 1; Ollerenshaw, 1975). Two wells have been drilled on this part of the trend. In the Inexco *et al.* Tornado b-9-J/82-G-15 well, the sub-Lewis duplex involved the Mount Head and Etherington Formations and the Rocky Mountain Supergroup, but not the Livingstone Formation (Cross section 2; Table 2). In the Northstar *et al.* Highrock c-67-B/82-G-15 well, both the Livingstone and Mount Head Formations occur in the structure but are tight, and the Palliser was not penetrated. To the south, sub-Lewis duplexes beneath the leading edge of the Lewis thrust are less well defined with the data available, but the Shell North Kootenay Pass b-58-H/82-G-7 well at the southernmost part of the project area was drilled on a sub-Lewis structure in this setting (Table 2; Charters, 1989). It encountered marginal reservoir in the Rundle Group and the Palliser Formation, shelf dolomite and anhydrite in the Peechee Member, and tested salt water[27] from the Misty Formation. This well does not appear to have been favourably located structurally. The Shell North Kootenay Pass 3-23-5-5W5 well, located approximately 1km north in Alberta (Maps 1 and 2), encountered Paleozoic strata 300m higher (in the same sheet?), but failed to encounter effective reservoir in either Rundle or Misty strata[28]. Although these results are not encouraging, the trend of duplexes beneath the leading edge of the Lewis thrust is too large to be discounted on the basis of only four wells. The better-defined northern part is over 60km long in British Columbia. Although reservoir is a significant risk in this setting, reservoir does occur in the Livingstone Formation in the Lewis sheet, as noted above (Cross sections 5 and 6).

[27] Although the scout ticket reports salinities of 6,000 and 11,000 ppm, water analyses from these tests report 18,000 to 21,000 ppm total dissolved solids.

[28] The Shell North Kootenay Pass 3-23-5-5W5 well drill stem tested $4x10^3m^3/d$ (135mcf/d) from the Livingstone Formation. The Palliser Formation was not penetrated.

Gas composition is also a significant risk in prospects in Paleozoic strata beneath the Lewis thrust. Gases in the Flathead area have $CO_2$ concentrations that vary between 89 to 100% in the Devonian reservoirs and between 20 and 90% in Mississippian reservoirs. The source of the $CO_2$ there may be contact metamorphism of Paleozoic carbonates by Cretaceous intrusives, in particular the trachyte intrusives in the Flathead area and the roots of the Crowsnest Formation volcanics. $CO_2$ generated by these intrusives could then have remigrated into structural traps during the Laramide orogeny. However, the variable $CO_2$ concentrations in the Mississippian reservoirs at Flathead suggest that gas composition could change rapidly laterally as well as stratigraphically (Monahan, 2000). The sub-Lewis duplexes beneath the south Taylor Range are likely to have high $CO_2$ concentrations, because of proximity to the Flathead area. However, to the north, the closest large Cretaceous downdip igneous sources are on the west side of the Rocky Mountains (Map 1). With the exception of the small Permian Cross diatreme, other intrusive rocks are small and older than the prospective reservoirs. Consequently, hydrocarbon gases could be anticipated in sub-Lewis structures in most of the Fernie-Elk Valley area. As in other areas of the Foreland Belt, hydrocarbon gases in carbonate reservoirs are likely to be associated with $H_2S$. Reports of sulphur in samples below the Lewis thrust in the Calstan Fording Mountain d-61-L/82-G-15 well suggest that hydrocarbons have migrated through the area and reacted with anhydrite, producing sulphur and $H_2S$ (Cross section 6; Orr, 1977; Eliuk, 1984).

Osadetz *et al.* (1995)[29] have estimated the mean resource potential for thrust faulted Paleozoic reservoirs structurally below the Lewis thrust in southwestern Alberta, southeastern British Columbia and northwestern Montana to be $752 \times 10^9 m^3$ (26,677BCF) raw initial gas in place (RIGIP), of which $221 \times 10^9 m^3$ (7,833BCF) has been discovered. Although much of the remaining $531 \times 10^9 m^3$ (18,844BCF) may be in Montana, a significant volume could be in the poorly tested structural trends in the Fernie-Elk Valley area.

## Faulted and Folded Paleozoic Strata Above the Lewis Thrust

Faulted and folded Paleozoic strata are prospective in the Lewis thrust and higher thrust sheets, although no hydrocarbons have been discovered to date in this or similar settings in British Columbia, Alberta or Montana. The principal prospective horizons in this play type are in the Mississippian Rundle Group, which has a higher reservoir risk than in the sub-Lewis structures, the Devonian Fairholme Group and possibly the Cambrian Elko Formation (Hannigan *et al.*, 1993). In the Fairholme Group, the main targets are the Peechee Member shelf-edge reef and the Borsato and the Nisku Formations, particularly south of the Peechee shelf edge. Traps could occur in five distinct settings: along the leading edge of the Lewis thrust sheet; to the east of, along and west of the Flathead and Erickson normal faults; and in the footwall of the Bourgeau thrust (Maps 1 and 2).

Traps could occur along the leading edge of the Lewis thrust sheet, north of the Flathead Range. Because the Mississippian strata are exposed here, potential reservoirs are restricted to the

[29] Their Waterton Rundle/Wabamun Foothills gas play.

Cambrian Elko Formation, which has vuggy porosity locally, and the Devonian Fairholme Group, particularly where the Peechee shelf-edge reef is truncated by the Lewis thrust (Map 2). Prospects in this setting have high risk because the reservoirs are not well defined and they are not deeply buried, and thus could have been subject to flushing by surface waters. However, where these potential reservoirs are thrust over Cretaceous shales, they could have been charged with oil rather than gas. Analogues for oil in this setting occur to the south in the Flathead and Waterton areas, where minor oil production has been established from Precambrian metasediments thrust over Cretaceous shales (see below; Hume, 1933a, b, 1964; Boberg, 1984; Hannigan *et al.*, 1993; Monahan, 2000), and an oil show in Cambrian strata described by Fermor and Moffat (1992) in the Alberta foothills north of the Fernie-Elk Valley area.

A series of folds and faults is present in the Lewis thrust sheet east of the Flathead and Erickson normal faults (Map 1; Price, 1962a, b, 1994a; Fitzgerald, 1969; Ollerenshaw, 1981b). Reservoir is at least locally well developed in the Mississippian Rundle Group. However, the Rundle is widely exposed and the high porosity in the Livingstone in the Inexco *et al.* Tornado b-9-J and Calstan Fording Mountain d-61-L/82-G-15 wells has probably been enhanced by dissolution by surface waters, so that the Rundle Group probably has been flushed (Cross sections 5 and 6). The Fairholme Group may be prospective in this setting, particularly where the Peechee shelf-edge reef crosses structures, but flushing is a risk in these strata as well (Map 2; Fitzgerald, 1969). However, the gas kick encountered in folded Devonian Palliser carbonates in the Northstar *et al.* Highrock c-67-B/82-G-15 well shows that hydrocarbons can at least locally be preserved in this setting. The Palliser consists of limestones with a few thin streaks of porous dolomite in this well and has limited reservoir potential here.

The Rundle Group, the Peechee shelf-edge reef and locally the Borsato and Nisku Formations could also be prospective on the downthrown side of the Flathead, Erickson and other normal faults. The Calstan Fording Mountain d-61-L/82-G-15 well is located on the crest of a roll-over anticline on the downthrown side of the Erickson fault, and similar anticlinal structures have been interpreted on the basis of seismic data west of the Flathead fault in the Fernie Basin (Cross section 2; Table 2; Blancher, 1984)[30]. However, as noted above, the very high porosity in the d-61-L well is probably indicative of flushing by surface waters, so that flushing is likely to be a significant risk at least in the Rundle Group in the northern part of the Flathead-Erickson fault system. In addition, normal faulting appears to have post-dated thrust faulting and peak maturation (Pearson and Grieve, 1985), so that these structures may have formed after significant hydrocarbon migration occurred.

Between the Flathead-Erickson normal fault system and the Bourgeau thrust, Mississippian and Devonian strata are more deeply buried beneath Mesozoic strata (Map 1; Cross sections 2 and 3). Three wells have been drilled in this setting (Table 2), and several untested structures remain (e.g. immediately west of Fernie; Blancher, 1984). Flushing is still locally a risk in this setting. On the west side of the Fernie Basin, the B.A. CNP Fernie b-81-D/82-G-7 is 3 km downplunge from a surface anticline exposing Mississippian strata, and encountered a steeply dipping

[30] These structures are mapped on the basis of a reflector within the Jurassic, and so may not be present in Paleozoic strata (Blancher, 1984).

Mississippian section that drill stem tested 2028m fresh water from a solution-enhanced porous zone (Table 2). Similarly, the Chevron Shell Mansfield c-72-D/82-G-15 well, which appears to have been located on a seismically interpreted minor backlimb thrust sheet on the Lewis thrust sheet (see Davitt and Kushnir, 1986)[31], produced brackish water from two 1 to 2m thick porous zones in the Mount Head Formation, showing that flushing is a risk here as well (Cross section 5). Reservoir is also a risk in this setting. The c-72-D well encountered primarily tight limestone and dolomite in the Livingstone and Mount Head Formations, although it did not reach the lower part of the Livingstone, where porosity is developed in the Inexco *et al.* Tornado b-9-J/82-G-15 well (Cross sections 5 and 6). The third well in this setting, B.A. CNP Fernie d-42-I/82-G-6 well, encountered over 2600m of structurally thickened Fernie Formation in the triangle zone on the west side of the Fernie Basin, so that structural interpretation is also a risk in this setting. None of these wells penetrated Devonian or Cambrian strata. In addition to the Peechee shelf-edge reef and the Borsato and Nisku Formations, the basal Palliser may also be prospective where the basal anhydrite-dolomite facies is replaced to the west by dolomite.

The Mississippian Rundle Group, Devonian basal Palliser Formation, Nisku Formation, Peechee shelf-edge reef and Borsato Formation, and the Cambrian Elko Formation could also be prospective in the footwall of the Bourgeau thrust, although exploration in this setting would be very difficult due to the thickness and structural complexity of the Bourgeau thrust sheet. These strata could be prospective both in sub-Bourgeau duplexes, particularly near their footwall cutoff below the Bourgeau thrust (similar to those beneath the Lewis thrust), and where they are folded above hanging wall ramps in the Lewis thrust (Cross section 1; Root *et al.*, 2000).

The westward extent of Mississippian and Devonian strata beneath the Bourgeau thrust is undefined, but west of the southern Fernie Basin, Root *et al.* (2000) have proposed that they extend 60km, as far as the Moyie anticline in the Purcell Mountains. If correct, Mississippian and Devonian strata could be prospective beneath the Purcell Mountains. However, displacement on the MacDonald fault, the southern continuation of the Bourgeau thrust in the Flathead area, does not appear to be of this order of magnitude, suggesting that their model may not be correct. In the Flathead area, Mississippian and Devonian strata are in fault contact with Precambrian strata in windows through the MacDonald thrust a few kilometers southwest of where both hanging wall and footwall occur in the Fernie Formation (Map 1; Price, 1962a; Harrison *et al.*, 1992; Monahan, 2000). Although displacement on the Bourgeau-MacDonald thrust increases northward and may be in the order of tens of kilometers in the northern part of the Fernie-Elk Valley area, it is unlikely to be 60km in the southern Fernie Basin if it is only 2 to 5 km at locations 25 km to the south. Neither Yoos *et al.* (1991) or van der Velden and Cook (1994, 1996) interpret large displacement on the MacDonald thrust.

Another possibility deserves mention. Hunt (1961, 1967, 1970, 1973; Brechtel, 1961) proposed that the Bourgeau thrust is folded above a duplex of prospective Devonian and Mississippian strata at a surface anticline in the Bourgeau thrust sheet west of the Kananaskis area. A corehole

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[31] The Triassic top in the c-72-D well is 600m high to a $12^{o}$ downdip projection of this contact from outcrop (see geological map by Price *et al.*, 1992a, who do not show a thrust sheet at this location).

located on this structure in b-85-C/82-J-11 penetrated 945m of thrust repeated Ordovician strata, failing to confirm or disprove this structural model (Hunt, 1973). However, others have interpreted this structure differently. Wind and Gronberg (1968) found no evidence of a folded thrust, although the prospect was rejected because of the reservoir risk. Mott (1989) interpreted the projection of this structure as a thrusted fold on the east flank of the large ramp anticline in the Bourgeau thrust sheet.

With the possible exception of the Peechee Member, which is discussed below, Devonian and Mississippian strata are widely exposed in the Bourgeau thrust sheet and have little potential there. The Shell Forsyth d-25-A/82-J-6 well encountered the leading edge of the Palliser Formation in this thrust sheet, but no reservoir was encountered (Table 2).

Hannigan *et al.* (1993)[32] have estimated the mean gas resource potential for structural traps in Paleozoic carbonates above the Lewis thrust to be $5.1x10^9m^3$ (183BCF) RIGIP, which would be almost entirely in British Columbia. They estimate a population of 9 pools, the largest of which has a median size of $1.5x10^9m^3$ (53BCF). However, this is a conceptual play and is subject to large uncertainties, so that the play size could be significantly higher or lower than their mean estimate. As with prospects in Paleozoic carbonates beneath the Lewis thrust, gas composition is a significant risk here, and the probability of encountering $CO_2$ increases to the west. However, the closest significant downdip Cretaceous igneous sources are on the west side of the Rocky Mountains, so that in Paleozoic reservoirs above the Lewis thrust hydrocarbon gases could be also be expected, if not assured. Such gases are likely to include $H_2S$.

**Fairholme Group Stratigraphic and Combined Stratigraphic-Structural Traps**

As described above, the Peechee shelf-edge reef trend could be prospective where it crosses the sub-Lewis duplex in the south Taylor Range, the leading edge of the Lewis thrust, the Erickson normal fault, and structures on the backlimb of the Lewis thrust (Map 2). Further west, the shelf-edge reef probably swings to a more northerly orientation in order to connect with the trend in the Bourgeau thrust sheet (see Moore, 1989, Figure 9-21b; Geldsetzer and Morrow, 1991, Figure 8.6). In the footwall of the Bourgeau thrust, gas could be trapped in structures as well as stratigraphically, updip against tight dolomites and anhydrites of the Peechee shelf facies. A shelf-edge reef could also be prospective at the leading edge of the Bourgeau thrust sheet, if separated from the Fairholme Group outcrop in the Kananaskis area structurally or by a reentrant on the reef front[33]. Although this play type has a significant stratigraphic risk, because the shelf-edge reef facies is very poorly defined and seismic interpretation of stratigraphic changes is difficult in this environment, potential reserves could be large.

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[32] Their Fernie-Elk Valley Paleozoic Structural gas play.

[33] The Peechee shelf edge is poorly defined in the Bourgeau thrust sheet south of Kananaskis. However, immediately west of the Shell Forsyth d-25-A/82-J-6 well, the Fairholme Group is interpreted to be in a basinal facies, because of the tight folding and the probability of a detachment in the Fairholme Group (Cross section 1).

As with the plays previously described, gas composition is a significant risk in Peechee shelf-edge reefs. In the south Taylor Range, high $CO_2$ gas could be expected. At the leading edge of the Lewis thrust sheet, oil derived from structurally lower Cretaceous strata is a possibility, although flushing is a risk. Further north, hydrocarbon gases are likely to be present, but the $CO_2$ risk probably also increases to the west beneath the Bourgeau thrust sheet. As with the plays previously discussed, $H_2S$ is likely to occur in the gases.

Peechee pinnacle reefs occur in outcrop in the Lewis thrust sheet, so that a pinnacle reef play could exist southwest of the bank edge facies in the Lewis thrust sheet and in a small area below it. If the Borsato Formation acted as the platform for pinnacle growth, the pinnacle reef play could extend at least 50 km southwest of the Peechee shelf-edge reef in the Lewis Sheet. Pinnacle reefs may have been less susceptible to introduction of $CO_2$-rich gases because of their stratigraphic isolation, and hydrocarbon gases, probably associated with $H_2S$, are more likely to have been retained. Pinnacles near the leading edge of the Lewis thrust sheet could have been charged with oil from underlying Cretaceous shales, as suggested above for the Peechee shelf-edge reefs, but flushing could be a problem. However, reserves in Peechee pinnacle reefs may not be large (e.g. $470 \times 10^6 m^3$ – or 17BCF for $1 km^2$ pool with 60m of pay at a depth of 2km), and exploration for pinnacle reefs would be risky. Interpretation of stratigraphic changes on seismic data would be very difficult in this environment, particularly below the Lewis thrust.

Additional potential stratigraphic or structural-stratigraphic traps could occur in shelf-edge reefs where the Borsato Formation passes laterally into the Perdrix Formation, and in pinnacle reefs where the Nisku Formation passes laterally into the upper part of the Mount Hawk Formation.

No separate resource estimate has been made for Fairholme Group stratigraphic and stratigraphic-structural traps by the Geological Survey of Canada.

## Mesozoic Structural-Stratigraphic Traps Below the Lewis Thrust

The Triassic Sulphur Mountain Formation, the Jura-Cretaceous Mist Mountain Formation, the Lower Cretaceous Blairmore Group and the Upper Cretaceous Alberta Group have potential beneath the leading edge of the Lewis thrust in a band that is up to 6 km wide in British Columbia (Cross sections 1, 2 and 3). In all cases, plays have a strong stratigraphic component.

A thin locally porous dolomite unit occurs in the lower part of the Sulphur Mountain Formation (Gibson, 1974), and 2m of porosity has been observed in wells. Sulphur Mountain strata occur beneath the major detachment surface in the Fernie Formation, so that the structural style is close to that of Paleozoic strata. Consequently, the Sulphur Mountain has potential above structures involving Paleozoic strata and could provide a secondary objective (Cross section 1). Where a duplex of Mount Head Formation to Rocky Mountain Group strata occurs, as in the Inexco Tornado *et al.* b-9-J/82-G-15 well, the duplex is likely to involve Sulphur Mountain strata to the east, where the Sulphur Mountain Formation dolomite could form multiple stacked reservoirs. No separate resource assessment of the Sulphur Mountain has been prepared by the Geological

Survey of Canada. The Sulphur Mountain Formation is likely to be gas rather than oil-bearing, and may contain $H_2S$.

Thin porous zones may occur in sandstones in the Mist Mountain Formation and locally be prospective on structures above the Fernie detachment. Potential in this interval appears to be minor, but sands are close to thick coal seams, which are a significant potential gas source.

Conglomerates in the Cadomin, Beaver Mines and Ma Butte Formations of the Blairmore Group locally produce both oil and gas at Waterton, Turner Valley and other fields in the Foreland Belt. These strata are prospective where thick fluvial conglomerate trends cross structures. The Blairmore Group reservoirs occur above the major detachment in the Fernie Formation, so that the structural style may differ from that of the underlying Paleozoic strata. For example, a broad fold is interpreted above the duplex of Mount Head Formation through Sulphur Mountain strata encountered by the Inexco *et al.*, Tornado b-9-J/82-G-15 well (Cross section 2). The orientation of the prospective trends in the Cadomin may vary from northeast to northwest (Leckie and Cheel, 1997), and the established prospective trend closest to British Columbia occurs in the Husky Savanna Creek 13-26-13-4W5 well. Additional trends may occur to the west in British Columbia. Potentially prospective conglomerate trends in the Beaver Mines and Ma Butte Formations are oriented east-west (Leckie and Krystinik, 1995a, b) and likely occur on structures beneath the Lewis thrust in British Columbia. Blairmore Group reservoirs may have been locally breached where they have been brought to the surface along thrust faults. However, the degree of beaching is probably less in the Cadomin because some of the trends may be oriented parallel rather than perpendicular to structural strike.

Hannigan *et al.* (1993)[34] have estimated mean gas resource potential of 11.9 $x10^9m^3$ (424BCF) RIGIP and a mean oil resource potential of 78 $x10^6m^3$ ($491x10^6$ barrels) original oil in place (OOIP) for the Blairmore Group in the Foreland Belt in southwestern Alberta, southeastern British Columbia and northwestern Montana. They estimate that these resources would be distributed in 33 pools. Of these totals, $0.459x10^9m^3$ (16BCF) and $0.455x10^6m^3$ ($2.86x10^6$ barrels) have been discovered. Only 4.5% of the play area is in British Columbia, and because of the greater maturation of sediments to the west, the play there is likely to be have more gas than oil. Furthermore, the Blairmore conglomerates overlie the Mist Mountain coals, which are a major potential gas source. Gas in the Blairmore Group is unlikely to be sour.

The Alberta Group could be prospective where porous marine sandstones and conglomerates in the Cardium and Blackstone Formations cross structures, and some condensate drill stem test recoveries have been reported from the Cardium Formation at Waterton. However, Alberta Group sandstones and conglomerates are discontinuous and have low porosity, so prospects in these strata have a high reservoir risk and have the greatest potential where conglomerates are

[34] Their Waterton Mannville Foothills gas and oil plays. Osadetz *et al.* (1995) estimate a mean gas resource potential of $34.5x10^9m^3$ (1226BCF), and the median size of the largest pool as $1.3x10^9m^3$ (46BCF).

present. Like most Cardium trends in Alberta, potential reservoirs are likely to trend northwest, nearly parallel to structural strike.

Hannigan *et al.* (1993)[35] have estimated a mean gas resource potential of 6.7 $x10^9m^3$ (239BCF) RIGIP in 20 pools for marine sandstones in the Alberta Group Foreland Belt in southwestern Alberta, southeastern British Columbia and northwestern Montana. Of this total, $0.199x10^9m^3$ (7BCF) has been discovered. Only 4.5% of the play area is in British Columbia, where the prospect risk is higher than other areas of the play because the Cardium Formation is widely exposed in thrust sheets nearby. However, the Cardium Formation is above the base of the oil window here and could be oil as well as gas-bearing. The gas in this play is unlikely to be sour.

Fractured reservoirs may also occur in the calcareous shales of the Vimy Member of the Blackstone Formation (Second White Specks equivalent). These reservoirs are locally prolific in Alberta, but are very difficult to predict.

Sandstones in the Upper Cretaceous Belly River Formation are potential reservoirs, but are not likely to have significant potential because they are widely exposed in the foothills.

## Mesozoic Structural Traps Above the Lewis Thrust

Above the Lewis thrust, potential Mesozoic reservoirs occur only in the Fernie Basin, where they may be prospective locally. The principal reservoirs in this setting would be conglomerates in the Cadomin Formation, and to a lesser extent in the Mist Mountain, Elk, Beaver Mines and Ma Butte Formations. These potential reservoirs are interbedded with and overlie the thick Mist Mountain coals, which are a significant potential gas source. Traps in this setting could be stratigraphic or structural-stratigraphic. As noted above, some structures have been mapped in the Fernie Basin immediately west of the Flathead fault (Blancher, 1984). Hannigan *et al.*, (1993) [36] estimate the mean gas resource potential in Mesozoic strata above the Lewis thrust to be $0.2x10^9m^3$ (7BCF), and this would be entirely in British Columbia. They estimate that this potential would be in 5 pools, the largest of which would be 0.08 $x10^9m^3$ (3BCF). However, this potential does not include coalbed methane resources in the Mist Mountain Formation.

## Hydrocarbons in Fractured Precambrian Metasediments

South of the Fernie-Elk Valley area, fractured metasediments in the Purcell Supergroup are locally hydrocarbon-bearing in the Lewis thrust sheet where they have been thrust over

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[35] Their Waterton Colorado Foothills gas and oil play. Osadetz *et al.* (1995) estimate a mean gas resource potential of $27.6x10^9m^3$ (980BCF), and the median size of the largest pool as $6.6x10^9m^3$ (234BCF).

[36] Their Fernie-Elk Valley Mesozoic Structural gas play.

Cretaceous strata. Minor oil production was established in this setting early in the 20th Century at Sage Creek and Waterton Park (Map 1; Hume, 1933a, b, 1964; Boberg, 1984). The source of the oil is likely to have been the Vimy Member of the Blackstone Formation (i.e. Second White Specks zone; Hannigan *et al.*, 1993). Purcell strata occur in the Lewis thrust sheet along the southern margin of the Fernie-Elk Valley area, and gas flows on drill stem tests have been reported from these strata in the Shell North Kootenay Pass b-58-H/82-G-7 well (see footnote 7). Hannigan *et al.* (1993)[37] have estimated the mean oil resource potential of $4.5x10^6m^3$ (28MMBO) OOIP and mean gas resource potential $0.6x10^9m^3$ (22BCF) RIGIP for fractured reservoirs in the Purcell Supergroup. However, most of this would occur in the Flathead area of British Columbia, the Waterton area of Alberta and the Glacier Park area of Montana.

## COALBED METHANE POTENTIAL IN THE MIST MOUNTAIN FORMATION

The thick coal seams in the Jura-Cretaceous Mist Mountain Formation have high potential for coalbed methane, and are currently the focus of an active exploration program (Johnson and Smith, 1991; Dawson, 1995; Dawson *et al.*, 1998, 2000). Coalbed methane differs from conventional gas in that the coal is both the hydrocarbon source and reservoir. Coalbed methane is formed during burial thermogenically above a temperature of $50^oC$, equivalent to a high volatile bituminous rank or vitrinite reflectance of ~0.6% (Rightmire, 1984, Dawson *et al.*, 1998). Peak generation occurs in the high to medium volatile bituminous range, or at vitrinite reflectance of ~1%. In the reservoir, most methane is adsorbed onto coal particles and does not occur in gas form, and the amount of adsorbed gas is dependent upon the coal rank and the reservoir pressure and temperature. At the shallow depths where coalbed methane production is feasible, the volume of gas that can be adsorbed by coal is much greater than the volume of gas that could be contained in a conventional gas reservoir. As reservoir pressure is reduced, the coal desorbs gas, which diffuses or flows through micropores to a system of cleats, or fractures. These provide permeability to produce gas. Cleat systems are commonly water saturated, so that they must be dewatered before economic gas production can occur.

The economic limits of coalbed methane production are generally between 250 and 2000m (Dawson *et al.*, 1998). Shallower than 250m, insufficient gas is stored in the coal, and greater than 2000m, high effective overburden pressure reduces the permeability of the cleat system. In addition, the amount of gas adsorbed by coal levels off with depth, so that at greater depths not much extra gas is available, yet a greater reduction in reservoir pressure is required to establish economic gas flows. In the Mist Mountain coals, for example, there is little increase in gas adsorption at reservoir pressure equivalent to a depth of approximately 400m, so that this would represent an optimum depth for coalbed methane exploitation here.

Topography and structure are significant factors that can affect the producibility of methane from coal seams in mountainous structurally disturbed areas like Fernie-Elk Valley. Reservoir pressure is a function of depth below the water table, so that where the water table is deep

[37] Their Belt Purcell Immature Structural oil and gas plays.

adjacent to major valleys, low reservoir pressure and gas content would prevail in spite of the depth of burial[38] (Dawson and Clow, 1992; Dawson *et al.*, 1998). Consequently, coalbed methane targets should be below the base elevation of major rivers. Shearing of coal seams can obliterate the cleat system, eliminating the permeability for economic production, and generally occurs where faults follow coal seams (Dawson *et al.*, 1998). Because relatively thicker coal seams form more pronounced zones of weakness, they are more likely to be sheared, so that paradoxically, relatively thinner coal seams may be better exploration targets. Conversely, permeability of the cleat system can be enhanced where coal seams are gently flexed across open anticlinal and synclinal axes (Dawson *et al.*, 1998).

Coal seams of the Mist Mountain are commonly between 1 and 8m thick, and are up to 19m thick in pre-deformational thickness (Pearson and Grieve, 1985; Grieve and Kilby, 1989, Johnson and Smith, 1991; Grieve, 1993). Net coal thickness in the Mist Mountain Formation varies from 23 to 86m. In the Fernie-Elk Valley area, the Mist Mountain Formation coals are high volatile B bituminous to low volatile bituminous (vitrinite reflectance from 0.71%-1.85%), and thus within the thermogenic gas window. However, at most locations the lower part of the formation is medium volatile bituminous and the upper part is high volatile A bituminous. The vitrinite content of the coals varies from 45% to 90% and, with the exception of the basal coal zone, generally increases upsection, (Pearson and Grieve, 1985; Johnson and Smith, 1991; Grieve, 1993; Dawson, *et al.*, 1998). Vitrinite-rich coals have better developed cleat systems, so that the higher coals are better exploration targets (Laubach *et al.*, 1998; Dawson *et al.*, 1998). However, the upper Mist Mountain appears to be a preferred zone of structural detachment in parts of the Crowsnest Coalfield (Ollerenshaw, 1981b), so that the upper Mist Mountain coals may have locally experienced more shearing than those in the lower part of the formation.

The presence of large volumes of gas in the Mist Mountain Formation coals has been known for a long time and was a hazard for early mining operations (Johnson and Smith, 1991). In the early part of the 19th Century, methane was being vented from individual active mines around the margins of the Fernie Basin at rates of 10 to $118 x 10^3 m^3/d$ (0.35 to 4.18mmcf/d), or 43 to $250 m^3$ per tonne mined (1300 to 8000scf per ton mined; Rice, 1918). Johnson and Smith (1991) have estimated the total coalbed methane resource potential of southeastern British Columbia within the economic depth range to be approximately $577 x 10^9 m^3$ (20.5TCF).

In the Lewis thrust sheet, Mist Mountain strata occur in three principal coalfields: the Elk Valley Coalfield, in the Alexander Creek and Greenhills synclines; the Crowsnest Coalfield, in the Fernie Basin; and the Flathead Coalfield which occurs as a series of erosional remnants south of the Fernie-Elk Valley area (Map 3; Johnson and Smith, 1991). Most of the resources estimated by Johnson and Smith, as well as all of the coalbed methane exploration activity to date, are in the Elk Valley and Crowsnest Coalfields, which are discussed in more detail below. Below the Lewis thrust, Mist Mountain strata are buried too deeply for economic coalbed methane production in the Fernie-Elk Valley area.

[38] In addition, effective overburden pressure would be high in such settings, further reducing cleat permeability.

The Elk Valley Coalfield occurs in an 85km long outlier of the Kootenay Group in the core of the Alexander Creek and Greenhills synclines in the north part of the Fernie-Elk Valley area[39] (Maps 1 and 3). The Kootenay Group outcrops in most of the coalfield, so that the prospective Mist Mountain coal seams are everywhere at depths less than 1500m, shallower than the coalbed methane economic basement (Cross sections, 1, 1a and 2). Johnson and Smith (1991) estimate the total coalbed methane resource potential to be $222x10^9m^3$ (7.9TCF) in the Elk Valley Coalfield. Most of the coalbed exploration activity has occurred in this area, and programs have been conducted by Norcen, Fording Coal, Symmetry and AEC (Tables 3 and 4).

The Norcen program consisted of 4 testholes and one well drilled in 1991 and 1992 on the east limb of the Alexander syncline (Cross section 1a; Table 3). The testholes were located in two pairs (c-54-E and b-63-E/82-J-7, and c-5-L and d-5-L/82-J-7), each of which penetrated a full Mist Mountain section at depths less than 500m (Cross section 8; Dawson *et al.*, 2000). The well was located in a-64-E/82-J-7 between the southern pair of testholes. Desorption tests in the coal seams indicate gas contents generally between 10 and 20 cc/g dry, ash-free (320 to 640 scf/t; Table 3). Adsorption tests in selected coals demonstrate that these are close to saturation values, although in some cases coals appear to be oversaturated due to the high $CO_2$ concentrations in the desorbed gas (Dawson, *et al.*, 2000). The $CO_2$ concentrations average $16\pm10\%$ (one standard deviation) and reach a maximum of 39%. The highest $CO_2$ concentrations tend to occur in the middle of the Mist Mountain Formation[40].

Two intervals in the lower part of the Mist Mountain Formation were completed in the Norcen Elkford a-64-E well (Cross section 8). An open-hole completion attempt was made across 3 coal seams at the base of the hole. Injection test data indicated a permeability of 0.7md in these seams, and a limited production test generated a minor gas flow (Dawson *et al.*, 2000). A higher coal seam (#10 seam on Cross section 8) was tested through casing. Because of a borehole washout in the coal seam, the zone was perforated and hydraulically fractured *below* the coal seam. Gas flow peaked at $21x10^3m^3/d$ (750mcf/d) and the final gas flow rate was $1.75x10^3m^3/d$ with $5m^3/d$ of water (62mcf/d with 31 bwpd). Pressure buildup analysis indicated a permeability of 0.9mD (Dawson *et al.*, 2000). The produced water exceeded environmental standards for lead, manganese, total suspended solids, and some organic compounds, but met standards for other constituents.

The Fording Coal Greenhills a-53-L/82-J-2 testhole was drilled and tested in 1993, and was located on the east limb of the Greenhills syncline. Coal gas contents were similar to those encountered in the Norcen testholes and well (Cross section 8; Table 3). Injection tests in 3 coal seams in the middle and lower parts of the Mist Mountain indicated permeabilities varying from 1 to 6md. The borehole was completed open hole below 265m. Pump problems caused several

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[39] Large scale (1:10,000) geological maps have been prepared for parts of the Elk Valley Coalfield by Grieve and Pearson (1983), Grieve and Fraser (1985) and Morris and Grieve (1990). Geological compilation maps (1:50,000) have been prepared for the Elk Valley Coalfield by Grieve and Price (1985) and Grieve (1993).

[40] Harrison and Barker (2000) report that there may be active bacterial generation of methane and $CO_2$ in the Mist Mountain Formation in the vicinity of the Norcen testholes and well.

interruptions in the test. Gas flow peaked at 197m$^3$/d (7mcf/d) and declined to 28m$^3$/d (1mcf/d) at the end of the test, and water production remained relatively constant at ~15 to 17m$^3$/d (94 to 107 bwpd.

The Symmetry Fording d-15-C/82-J-2 well was drilled in 1999 to a depth of 805m and was located on the axis of the Alexander Creek syncline (Table 3). Four intervals between 519 and 725m were tested through a slotted liner. The final flow rates averaged 50 to 70m$^3$/d gas (1.8 to 2.5mcf/d) with 2 to 3m$^3$/d water (13 to 19bwpd), and the production test was suspended due to a hole in the liner. A nearby followup well in d-5-F/82-J-2 has not been drilled

The low gas production rates in the Norcen, Fording Coal, and Symmetry completion attempts in part reflect completion problems as well as low *relative* permeability during two-phase flow. The water production rates and results of the injection tests, particularly in the Fording Coal testhole, suggest moderate permeability in the tested interval and that continued dewatering of the coal could have lead to significantly improved, and possibly economic gas production. Furthermore, the Fording Coal testhole completion was an open hole test, so that the water production could reflect permeabilities of lithologies other than coal. If so, water flow from these lithologies would certainly have impeded dewatering of the coal. The possibility of water flow from other lithologies is supported by well testing by Harrison and Barker (2000) in the Elk valley, who report that there is pressure communication from the surface to about 500m.

Furthermore, none of the tests focused on the upper coals of the Mist Mountain Formation, which are richer in vitrinite and may have better developed cleat systems than the lower coals, nor were the tests located on gentle fold axes, where permeability may have been enhanced by folding. Although the Symmetry well was located on the axis of the Alexander syncline, the syncline is tightly folded at this location, and the coals may be sheared. Dawson *et al.* (1998), have suggested that where dips exceed 45$^o$, shearing is commonly present in the coals.

In the fall of 2000, AEC initiated an exploration program, initially licencing two testholes and 13 wells (Table 4). The results of this program are currently confidential, but the activity is concentrated near the axis of the Greenhills syncline where it is more gently folded, in the vicinity of the Fording Coal testhole. Thus, these wells are well located to encounter permeability enhanced by gentle flexing, as well as to evaluate coals in the upper part of the Mist Mountain Formation.

The Crowsnest Coalfield encompasses a 60 by 25 km area in the Fernie Basin[41] (Maps 1 and 3). The Blairmore Group outcrops over much of this area, so that the Mist Mountain Formation coal seams are more deeply buried than in the Elk Valley Coalfield, and are locally below the economic basement (Cross section 3; Johnson and Smith, 1991; Dawson *et al.*, 1998). In addition, lands in the Dominion Coal Block (Parcels 73 and 82 on Maps 1 and 3; Ollerenshaw,

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[41] Large scale (1:10,000) geological maps have been prepared for parts of the Crowsnest Coalfield by Pearson *et al*. (1977), Pearson and Grieve (1978, 1981) and Gigliotti and Pearson (1979). A geological compilation map (1:50,000) for the Crowsnest Coalfield has been prepared by Dawson *et al*. (1998).

1977, 1981; Grieve and Kilby, 1989; Dawson *et al.*, 1998) are not currently available for coalbed methane exploitation. Johnson and Smith (1991) estimated the total coalbed methane resource potential of the Crowsnest Coalfield to be 344x10$^9$m$^3$ (12.2TCF). However, Dawson *et al.* (1998) estimated the coalbed methane resource potential of the Dominion Coal Block, which is a fraction of the size of the Crowsnest Coalfield, to be 195x10$^9$m$^3$ (6.9TCF), using a higher average gas content but excluding some areas of high dip.

Eight testholes have been drilled in the Crowsnest Coalfield (Table 3). However, one of them did not penetrate the Mist Mountain Formation. Of the remaining seven, 3 were near offsets of earlier holes, so that only four locations were effectively tested (Maps 1 and 2; Cross section7). These testholes encountered thick coal seams, and the Norwest and Beacon Hill a-65-E testholes penetrated the entire Mist Mountain Formation. However, the measured gas contents in most testholes are very low, less than 1.5g/cc (48scf/t) at the Norwest c-80-B and the Norwest and Lornel a-72-C/82-G-7 testholes, and commonly less than 10cc/g (320scf/t) at the a-65-E testholes, indicating severe undersaturation with respect to gas. The low gas contents have been attributed to strong water flows that were encountered in some testholes and may have removed methane, and to being in an area of high topographic relief on the margin of the Fernie Basin where gas content is limited by the base level of major streams (Dawson *et al.*, 1998). Only in the Norwest and Lornel c-12-L/82-G-7 testholes and the deeper seams of the a-65-E/82-G-2 testholes, where the coal is more deeply buried, are the gas contents generally between 10 and 15 cc/g (320 to 480scf/t). Dawson *et al.* (1998) did not consider the low gas contents representative of the Crowsnest Coalfield and used saturation values for their resource assessment of the Dominion coal block. The high gas volumes vented from the early 20$^{th}$ Century mining operations (Rice, 1918) support his interpretation.

In the Crowsnest Coalfield, only the Beacon Hill Morrissey a-65-E testhole was tested (an offset to TH#43, Cross section 7; Dawson *et al.*, 2000). On the basis of injection tests conducted in the equivalents of seams 4 and 5 in TH#43, permeability in these zones has been estimated to be 0.3 and 0.1mD respectively. However, seam 5 is 13m thick, compared to 3m thick in TH#43, and is probably structurally thickened and sheared. An openhole test produced free gas (rates not reported) with water at 29m$^3$/d (182bwpd). Most of the produced water was from seam 2, where the gas content averages 15.5cc/g (496scf/t). Dawson *et al.* (2000) report that the produced gas was probably from the cleat system, because the pressure had not been reduced sufficiently for methane desorption from the coal matrix. Nonetheless, this test confirms the presence of a permeable coalbed methane reservoir in the Crowsnest Coalfield. No drilling programs are underway in the Crowsnest Coalfield, and most rights are available. Gentle surface anticlines and synclines provide attractive exploration targets. However, topography in this area is more rugged than in the Elk Valley Coalfield.

Another factor to be considered in the economics of coalbed methane is the potential synergy with the $CO_2$ resources of the area. Because coal has a greater affinity for $CO_2$ than methane, $CO_2$ could potentially be used to replace methane in coal in enhanced recovery schemes.

## CONCLUSIONS

Hydrocarbon potential occurs in a variety of settings in the Fernie-Elk Valley area.

The most significant conventional hydrocarbon objectives are those in thrust faulted Paleozoic carbonates beneath the Lewis thrust. The principal potential reservoirs are the Mississippian Rundle Group and the Devonian Palliser Formation, although the Devonian Peechee Member shelf-edge reef could be locally significant and the Cambrian Elko Formation and the Pennsylvanian Misty Formation may also have some potential. Two major structural trends occur in this setting. A trend of sub-Lewis duplexes is interpreted to underlie a belt of Paleozoic outcrop in the Lewis thrust sheet. Only one well is located on this trend, and although it is located on its flank, it does confirm the sub-Lewis structure. Although no reservoir was encountered, it did not penetrate a full section of the Mississippian Livingstone Formation, nor test the Devonian. This duplex trend is a major and essentially untested structure over 100km long, and could contain large reserves. Another trend of duplexes underlies the leading edge of the Lewis thrust, and has been tested unsuccessfully by four wells. However, it too is a major structural trend that has been poorly tested.

The Mississippian Rundle Group and locally the Devonian Peechee Member shelf-edge reef, the Borsato and Nisku Formations also have potential in structures on the Lewis thrust sheet and higher structures below the Bourgeau thrust. The potential is greatest west of the Flathead and Erickson normal faults, where the structures are more deeply buried and are less susceptible to flushing by surface waters. Traps could also occur adjacent to the Flathead and Erickson faults, although these may have formed after hydrocarbon migration. The westward extent of prospective Mississippian and Devonian strata beneath the Bourgeau thrust is unknown.

Devonian stratigraphic and structural-stratigraphic traps could also occur. The Peechee Member shelf-edge reef trend is prospective on structures, both above and below the Lewis thrust, as noted above. In addition, stratigraphic traps could occur in the Peechee Member shelf-edge reef below the Bourgeau thrust, where it may be oriented parallel to strike and is replaced updip by tight shelf dolomite and anhydrite. Southwest of the shelf edge, Peechee Member pinnacle reefs occur and could also be prospective. More speculative stratigraphic traps could occur in Borsato Formation shelf-edge reefs and Nisku pinnacle reefs.

Paleozoic reservoirs are below the oil window and thus potentially gas rather than oil-bearing in most areas. However, oil could occur locally in Peechee and Cambrian reservoirs along the leading edge of the Lewis thrust, where potential oil source rocks occur in the footwall. Gas composition is a significant factor in Paleozoic reservoirs. Gas with up to 100% $CO_2$ occurs in the Flathead gas field to the south, and may be derived from the contact metamorphism of Paleozoic carbonates by mid-Cretaceous intrusive and volcanic rocks. The igneous centres are located in the Flathead area and southern part of the Fernie-Elk Valley area, so that the risk of $CO_2$ may diminish to the north, where hydrocarbon-dominated gases could prevail. However, the risk of $CO_2$ probably increases again to the west, approaching volcanic centers on the west side of the Rocky Mountains. Gases in Paleozoic reservoirs are likely to be sour.

In the Fernie-Elk Valley area, Mesozoic strata have potential for conventional hydrocarbons in a band a few kilometres wide beneath the leading edge of the Lewis thrust. There, structural-stratigraphic traps could occur in dolomite in the lower part of the Triassic Sulphur Mountain Formation, sandstones of the Jura-Cretaceous Mist Mountain Formation, conglomerates in the Lower Cretaceous Cadomin, Beaver Mines and Ma Butte Formations, and sandstones and conglomerates in the Upper Cretaceous Cardium Formation. These reservoirs present high stratigraphic risks and modest potential. Triassic reservoirs would probably contain gas, which could be sour, Jura-Cretaceous reservoirs would likely contain gas, and Cretaceous reservoirs could contain either gas or oil. The Mist Mountain, Cadomin, Beaver Mines and Ma Butte Formations have minor potential in the Fernie Basin in the Lewis thrust sheet.

A huge coalbed methane resource is present in coals in the Jura-Cretaceous Mist Mountain Formation and has been estimated to be in the order of $566x10^9m^3$ (20.1TCF; Johnson and Smith). Drilling activity in the last decade has confirmed the existence of gas-saturated coals and at least locally permeable cleat systems. However, commercial production has not been established in any of the wells for which data are available, partly because of production testing problems and partly because production testing was terminated while *relative* permeability was low in the cleat system due to production of both water and gas. In addition, most wells and testholes were not located to test areas where permeability could be enhanced by gentle folding, or to test the upper coal seams of the Mist Mountain Formation, which are richer in vitrinite and have better developed cleat systems. A current drilling program that is still confidential appears to include wells better located to evaluate the coalbed methane potential of the area. Most activity has focused on the Elk Valley Coalfield. However, the potential of the Crowsnest Coalfield appears to be similar and most of the rights are available at the time of writing.

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