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THE GEOLOGY AND OIL AND GAS POTENTIAL OF THE FLATHEAD AREA, SOUTHEASTERN BRITISH COLUMBIA

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Monahan Petroleum Consulting, December 2000

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ABSTRACT

The Flathead area in the Rocky Mountains of southeastern British Columbia has a long history of petroleum exploration. Drilling activity began in the early 1900's, based on oil seeps in Precambrian metasediments, and resulted in some minor oil production. Subsequently, $17x10^9m^3$ (600BCF) of CO_2-rich gas have been discovered in thrust faulted Paleozoic reservoirs beneath the Lewis thrust, in pools similar to those hosting large gas reserves in adjacent parts of Alberta. Significant potential remains in this area in a variety of geological settings, several of which are unusual for Western Canada.

The greatest remaining potential is in additional traps in thrust faulted Mississippian and Devonian reservoirs beneath the Lewis thrust. Undrilled structures have been identified on seismic data northwest of the productive structural trend, and Devonian strata have not been tested in structures to the east. In addition, the Peechee Member shelf-edge reef could form stratigraphic traps where it changes facies updip into interbedded shelf dolomites and anhydrites. Sour hydrocarbon gases could occur east of the CO_2-rich productive trend. Paleozoic strata have minor potential on structures above the Lewis thrust sheet because they are widely exposed and have been subjected to flushing by fresh water. The potential is greatest where they have been more protected from flushing by surface waters beneath Mesozoic and Tertiary strata in the Kishenehn Basin, but there Paleozoic strata were downfaulted into their current position after peak hydrocarbon generation and migration. Devonian Peechee Member pinnacle reefs could occur above and below the Lewis thrust, and because of their stratigraphic isolation, may have been less susceptible to flushing and introduction of CO_2-rich gases.

Cretaceous strata have modest potential beneath the Lewis thrust sheet in combination structural-stratigraphic traps. The principal targets in this setting are in conglomerate-rich trends, where they cross structures, and to a lesser extent in marine, fluvial and deltaic sandstones. Cretaceous objectives could be gas or oil bearing, although gas is more likely in the lower parts of the Cretaceous. Above the Lewis thrust, Jurassic and Cretaceous strata have minor potential where they are buried beneath the Kishenehn Basin.

The Oligocene Kishenehn Formation is an important hydrocarbon objective in the Flathead area. It is up to 4750m thick and fills a post-Laramide extensional basin. Potential reservoirs include fluvial and lacustrine sandstones and conglomerates, and megabreccias. Lacustrine oil shales in the lower part of the formation have probably generated liquid hydrocarbons where deeply buried in the axis of the basin. These strata have been tested by only two deep modern wells. Similar small lacustrine basins in China are prolific oil producers.

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[1] Monahan Petroleum Consulting, December 2000.

Two smaller extensional basins occur in the southern Rocky Mountain Trench. The basin fill succession may be similar to the Kishenehn Formation, and potential reservoirs are likely to be comparable. In addition to biogenic gas, these strata may have been buried deeply enough to generate liquid hydrocarbons locally.

The coals of the Jura-Cretaceous Mist Mountain Formation are the targets of an active coalbed methane play north of the Flathead area. However, in the Flathead area, the coal-bearing section in the Lewis thrust sheet is thinner and has a more restricted areal extent. In addition, the coals may be undersaturated and require further investigation. Locally, the Mist Mountain coals may have some potential below the Lewis thrust.

INTRODUCTION

The Flathead area of southeastern British Columbia has long intrigued petroleum explorers. Oil seeps in Precambrian metasediments in this area stimulated some of the earliest drilling for oil and gas in British Columbia in the early 1900's, and during the 1980's large volumes of CO_2-rich gas were established in pools similar to those hosting large gas reserves in adjacent parts of Alberta. Additional potential remains in this area in a variety of settings, some of which are unusual for Western Canada. 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 2850 km^2 and extends along the international boundary from the Alberta border to the west side of the Rocky Mountain Trench. The northern boundary follows the outcrop belt of Jurassic and Triassic strata at the southern margin of the Fernie Basin between latitude 49°15'N and 49°20'N (North Kootenay Pass Monocline; Map 1) west to the Elk River, which it follows to the Rocky Mountain Trench. In the Rocky Mountain Trench, the area investigation of extends north as far as the Bull River. The geology and oil and gas potential of the Fernie-Elk Valley area immediately to the north is addressed in a separate report (Monahan, 2000).

Between the Alberta border and the Rocky Mountain Trench, the Flathead area is entirely within the Border Ranges of the southern Rocky Mountains (Holland, 1976). The Border Ranges are generally underlain by gently dipping Precambrian to Paleozoic strata (Map 1; Cross section 1). From east to west, they are subdivided into the Clarke, MacDonald and Galton Ranges, in which peaks attain elevations of 2600m, 2300m, and 2300m respectively. These ranges are separated by the valleys of the Flathead and Wigwam Rivers, from the east to the west respectively. The Flathead River occupies a broad intermontane valley underlain by Tertiary sedimentary rocks, and is up to 15km wide with elevations generally between 1250 and 1500m. In contrast, the Wigwam River Valley is generally less than 1km wide and is at elevations of 1000 to 1250m. The Rocky Mountain Trench is an extensive intermontane valley that is almost 1500km long in British Columbia. In the area of this investigation, it separates the Rocky Mountains on the east from the Purcell Mountains on the west, forms an area of low relief between 12 and 15km wide at an elevation of approximately 900 m, and is drained by the Kootenay River.

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 this area at scales of 1:63,360 and 1:126,720 by Leech (1960) and Price (1962a, 1965). Following current practice in British Columbia, well names in this report use surface rather than bottomhole locations. Where they differ from surface locations, the bottomhole locations are provided in Table 3.

STRUCTURAL AND TECTONIC FRAMEWORK

The Flathead 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 on a west-facing continental margin, overlain by an Upper Jurassic to Upper Cretaceous foreland succession derived from rising highlands to the west (Table 1; Price, 1981). These stratigraphic successions were deformed during the Late Jurassic to Early Tertiary Laramide Orogeny[2]. Tertiary sediments form the fill of a series of post-Laramide extensional basins.

The platformal to miogeoclinal and the foreland successions have been deformed by easterly verging thrust faults and attendant folds. 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 (ramps). Hanging wall strata are consequently folded above hanging wall and footwall ramps. Within the sedimentary succession, a major zone of detachment occurs in shales of the Jurassic Fernie Formation, so that the structure of the platformal and foreland successions can be significantly different. 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 in the Cambrian strata just above the crystalline basement beneath most of the Rocky Mountains. However, it cuts down into the Precambrian sedimentary succession, because a thick Precambrian succession is incorporated in thrust sheets in the Flathead area and in the Purcell Mountains (Map 1; Cross section 1). Crystalline basement, which is undeformed by Laramide structures, dips westward beneath the Rocky Mountains and is between 7 to 12 km below sea level beneath the Flathead area (van der Velden and Cook, 1994, 1996). Deformation progressed from west to east across the Foreland Belt[3]. Deposits of the Upper Jurassic to Upper Cretaceous foreland succession in

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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 Flathead area were derived from structures rising in the west, and were subsequently deformed during the Late Cretaceous and Early Tertiary.

The principal thrust fault in the Flathead area is the Lewis thrust (Map 1; Cross section 1). Displacement on the Lewis thrust reaches a maximum of 75 to 90km in the vicinity of the international boundary, and diminishes to zero at Mount Kidd in the Alberta Front Ranges 160km to the north (Dahlstrom *et al.*, 1962; van der Velden and Cook, 1994; Fermor, 1999). In the Flathead area, the hanging wall of the Lewis thrust is in Precambrian strata, and the Lewis thrust sheet includes a thick relatively undisturbed succession of Precambrian to Cretaceous strata. Upper Cretaceous strata occur in the footwall of the Lewis thrust, both where it is exposed east of the British Columbia border along the mountain front, as well as in most of the Flathead area east of the Flathead Valley.

At the north end of the Flathead area, the Lewis thrust abruptly cuts 2000m upsection to the north in the Precambrian succession on a lateral ramp in the hanging wall (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 northern boundary of the Flathead area, as used here. Further north in the Fernie-Elk Valley area, the Lewis thrust cuts upsection more gradually from the upper part of the Precambrian succession to Mississippian strata.

Immediately to the east of the Flathead Valley, the Lewis thrust is folded above a northwest-trending duplex of Paleozoic strata, and Upper Cretaceous strata are locally exposed in windows through the thrust (Maps 1 and 2; Olsson, 1934b; Dahlstrom *et al.*, 1962; Price, 1962a, 1965; Bally *et al.*, 1966; Jones, 1969b; Fermor and Price, 1976, 1987; Gordy *et al.* 1977; Fermor and Moffat, 1992). As a consequence of this folding of the Lewis thrust, the Lewis sheet in the Clarke Range east of the sub-Lewis duplexes forms a gentle syncline, referred to as the Akamina syncline.

A series of normal faults occurs in the Lewis thrust sheet and records a period of post-Laramide extension (Maps 1 and 2, Cross section 1; Price, 1962a, b). The largest of these is the Flathead fault, a west-dipping listric normal fault that merges downdip with the Lewis thrust (Bally *et al.*, 1966; Fermor 1999). It is located immediately west of the sub-Lewis duplexes noted above and defines the eastern margin of the Flathead Valley. 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 and Price, 1980; McMechan, 1981; Constenius 1981, 1982, 1988; McMechan and Thompson, 1991; Fermor and Moffat, 1992).

The Flathead fault forms the eastern margin of a northwest oriented extensional basin that is 150km long, up to 18km wide, and contains up to 4270m of Kishenehn sedimentary fill (Maps 1 and 2, Cross section 1; Jones, 1969a; Johns, 1970; McMechan, 1981; Constenius, 1981, 1982; 1988; Harrison *et al.*, 1992). The northwesternmost 30km of this length is in British Columbia, where the Kishenehn Basin has the form of a half graben in which Kishenehn strata dip northeast at an average of 32°. To the southeast, the basin is a graben bounded on the southwest as well as on the northeast by normal faults. This basin occurs in the area of maximum displacement on the

Lewis thrust and probably formed in response to the large displacement. Maximum displacement on the Flathead fault is 15km (Constenius, 1988; van der Velden and Cook, 1994).

The Lewis-Flathead fault has been interpreted to merge with the basal detachment to the west of the Flathead Valley beneath the MacDonald Range (Map 1, Cross section 1; Yoos *et al.*, 1991; Fermor and Moffat, 1992; van der Velden and Cook, 1994; Fermor, 1999). On the basis of seismic data, the footwall cutoff of Precambrian strata beneath the Lewis thrust has been interpreted by Van der Velden and Cook (1994, 1996) to occur further west, immediately west of the Rocky Mountain Trench in the easternmost Purcell Mountains.

The Lewis sheet in the MacDonald Range forms a broad dome exposing primarily Paleozoic strata, and is interpreted to represent a roll-over anticline related to slip on the Flathead and other related faults (Map 1; Jones, 1969a; Fritts and Klipping, 1987a, b – their Trail Creek structure). Several secondary domal culminations occur on this structure. The largest of these is cored by Precambrian strata that have been brought to the surface along a minor thrust in the Lewis sheet, and may have been further uplifted by Lower Cretaceous igneous intrusions. This dome is also associated with an enigmatic occurrence of Upper Cretaceous strata in fault contact with older strata - the Howell Creek structure – which has been most successfully interpreted as a slide block of Upper Cretaceous strata, subsequently modified by normal faulting (Jones, 1977). The north dipping North Kootenay Pass monocline (*see* above) separates the MacDonald Range from the Fernie Basin, a gently folded synclinal basin of Upper Jurassic and Cretaceous strata in the Lewis thrust sheet in the Fernie-Elk Valley area (Monahan, 2000).

A series of smaller thrust and normal faults occur above the Lewis sheet in the western part of the MacDonald Range and the Galton Range (Map 1; Cross section 1; Price, 1962a; Yoos *et al.*, 1991; van der Velden and Cook, 1994). At the surface, the MacDonald thrust and the Hefty thrust, which is a splay of the MacDonald, carry Precambrian to Mesozoic strata over Paleozoic and Mesozoic strata in the Lewis sheet. The MacDonald-Hefty thrust is both cut and folded by movement on the Couldrey listric normal fault. To the west, the Wigwam thrust carries Precambrian over Precambrian and Paleozoic strata.

The MacDonald thrust is the southward continuation of the Bourgeau thrust, on which several tens of kilometres of displacement can be inferred further north in the Rocky Mountains (Map 1; Mott, 1989; Wheeler and McFeely, 1991; Root *et al.*, 2000). Displacement on the Bourgeau-MacDonald thrust system diminishes southward. In outcrop north of latitude 50°10’, the Bourgeau thrust carries Triassic and older strata in the hanging wall over Upper Jurassic and younger strata in the footwall (Price, 1962a; Wheeler and McFeely, 1991; Price *et al.*, 1992a; Grieve, 1993; McMechan, 1998). Conversely, to the south both the hanging wall and footwall of the Bourgeau-MacDonald thrust are in the Jurassic Fernie Shale in outcrop at most localities (Cross section 1). Furthermore, Paleozoic strata occur in what appear to be windows in the MacDonald thrust a few kilometres west of its surface trace, suggesting displacement in the order of 1 to 2km in the Flathead area.

The Rocky Mountain Trench is a half graben bounded on the east by a listric normal fault that has up to 12km of displacement and merges at depth with the basal detachment (Map 1; Cross section 1; Bally *et al.*, 1966; Yoos *et al.*, 1991; van der Velden and Cook, 1994, 1996).

Continuity of thrust faults and other structures across the Rocky Mountain Trench (e.g. Moyie and Dibble faults) demonstrate that little strike slip movement has occurred in this area[4] (Bally *et al.*, 1966; Benvenuto and Price, 1979). Consequently, the Rocky Mountain Trench formed as a result of post-Laramide extension and is similar to the Kishenehn Basin. The presence of Miocene non-marine strata assigned to the St. Eugene Formation suggests that extension in this part of the Rocky Mountain Trench occurred in part later than in the Kishenehn Basin, but only the uppermost part of the post-Laramide sequence is known (Clague, 1974). Gravity data demonstrate that the Rocky Mountain Trench is further segmented along strike into a series of basins up to 10km wide and 25km long in which the post-Laramide sequence is at least 1500m thick (Map 2; Garland *et al.*, 1961; Thompson, 1962). These basins are separated by areas where block faulted Paleozoic strata are exposed or covered by thin sequences of Tertiary strata.

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 southern British Columbia and Montana (Norris and Price, 1966; Benvenuto and Price, 1979; McMechan and Thompson, 1989; Richards, 1989; Richards *et al*., 1994; Price, 1994). All of the Flathead area, as defined in this report, is within Montania. Within 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 of Montania and the Flathead area 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 northern 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 6 km of Lower Cambrian to Silurian strata are preserved beneath Devonian strata.

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 in Montania than they do further north (*see* Price, 1964b (Devonian); Oswald, 1964b, Bamber *et al.*, 1981, Richards, 1989, and Richards *et al.*, 1994 (Mississippian); Scott, 1964, Norris, 1965, and McGugan and Rapson, 1961, (Pennsylvanian and Permian); MacRae and McGugan, 1977 (Permian); and Gibson, 1974, (Triassic)).

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[4] Between 750 and 900km of strike-slip movement has been documented on the northern Rocky Mountain Trench in northern British Columbia (Gabrielse, 1991).

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

STRATIGRAPHY AND RESERVOIR DEVELOPMENT:

Precambrian Purcell Supergroup

A conformable succession of Middle Proterozoic strata assigned to the Purcell Supergroup occurs in the Lewis and higher thrust sheets[6] (Aitken and McMechan, 1991). Seismic data suggest that Purcell strata are thin or absent below the basal detachment as far west as the Rocky Mountain Trench (Yoos *et al.*, 1991; van der Velden and Cook, 1994, 1996). However, Purcell strata may be present locally below Cambrian strata in sub-Lewis structures (Cross section 2, Shell Sage a-56-E/82-G-1 well, *see* Cross section 1).

The Purcell Supergroup thickens westward from 2.1km in the eastern part of the Clarke Range to 11km in the Purcell Mountains. The westward thickening is in part depositional and in part because progressively older strata occur above the Lewis thrust in that direction. The Purcell Supergroup is informally subdivided herein at the top of the Purcell Lava into lower and upper parts (cross section 1).

In the Clarke Range, the base of the Purcell Supergroup consists of a succession of shallow water dolomites, limestones and argillites, comprising, in ascending order, four unnamed basal units, and the Haig Brook, Tombstone Mountain, Waterton, and Altyn Formations (Table 1, Part C; Price, 1964a; Fermor and Price, 1983, 1990b, c, d, e; Aitken and McMechan, 1991). These units have an aggregate thickness greater than 1.7km. This sequence is replaced in the western Rocky Mountains and the Purcell Mountains by the Aldridge Formation[7], which consists of thin to thick bedded quartzite, siltstone and argillite deposited primarily in deeper water, largely from turbidity currents (McMechan, 1981; Aitken and McMechan, 1991). The Aldridge Formation has a maximum thickness of 4.2km in the Purcell Mountains. In addition, the Aldridge includes abundant diorite sills (Moyie intrusions) that form distinct reflectors on seismic data (Harrison *et al.*, 1985; Boberg, *et al.*, 1989; Yoos, *et al.*, 1991; van der Velden and Cook, 1994, 1996). On the basis of such reflectors, Aldridge strata have been interpreted to be present in the Lewis and higher thrust sheets beneath the MacDonald and Galton Ranges (Cross section 1; van der Velden and Cook, 1994).

In the Flathead area, the Altyn and Aldridge Formations are overlain, in ascending order, by the Appekunny and the Grinnell Formations. These units consist of dominantly green and grey (Appekunny) and red (Grinnell) argillites and siltstones interbedded with sandstones deposited in shallow water (Table 1, Part C; Price, 1964a; Fermor and Price, 1983; 1990a; Aitken and McMechan, 1991). The Appekunny and the Grinnell Formations thicken westward from 500 to 1500m across the Rocky Mountains, and are replaced to the west in the Purcell Mountains by the Creston Formation (Price, 1964a; McMechan, 1981; Aitken and McMechan, 1991). The Creston Formation consists of up to 2350m of green, grey and purple shallow water siltstone, argillite and sandstone.

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[6] The Purcell is synonymous with the Belt, which is the preferred term in the United States.

[7] The Pritchard Formation in the United States.

The Grinnell Formation is overlain by the Siyeh Formation, which consists of platformal to basinal argillaceous limestone and dolomite with green, grey and black argillite, siltstone and sandstone. This formation thickens southwest across the Rocky Mountains from 350 to 1000m (Table 1, Part C; Price, 1964a; McMechan, 1981; Aitken and McMechan, 1991). It is replaced in the Purcell Mountains by the uppermost part of the Creston Formation, the dolomites, dolomitic siltstones, siltstones and argillites of the Kitchener Formation (over 1500m), and the siltstones and argillites of the Van Creek Formation (up to 750m). The Siyeh Formation is in turn overlain by the Purcell Lava, a succession of chloritized andesite flows that is up to 150m thick (Price, 1964a; McMechan, 1981; Aitken and McMechan, 1991). This unit forms an important stratigraphic marker in the Purcell succession, but it is locally absent in the Galton Range due to erosion that preceded deposition of the succeeding Sheppard Formation. To the west in the Purcell Mountains, it is replaced by volcanics of the Nichol Creek Formation, which are up to 750m thick.

The Purcell Lava is conformably to unconformably overlain by a sequence of shallow water to subareal green to red sandstones, dolomites and argillites comprising, in ascending order, the Sheppard, Gateway, Phillips and Roosville Formations (Table 1, Part C; Price, 1964a; Aitken and McMechan, 1991). These units are truncated northward beneath the sub-Cambrian unconformity (Norris and Price, 1966). Where preserved beneath the Roosville Formation, the Sheppard, Gateway and Phillips Formations collectively thicken south and west from 650 to 1100m across the Clarke Range, and are 1000m thick in the Galton Range. The Roosville Formation has a maximum preserved thickness of 1300m in the Galton Range.

Strata of the Purcell Supergroup are not well known in the subsurface. Useful reference sections in the Flathead area are in the Shell Grouse d-66-G/82-G-1 well in the axis of Akamina syncline in the Clarke Range (Tombstone Mountain to Gateway Formations) and the Shell MacDonald b-30-H/82-G-2 well in the MacDonald Range (Sheppard to Roosville Formations; Cross section 1; Hein and McMechan, 1994).

Purcell strata were metamorphosed to greenschist grade during the Precambrian and have no primary porosity. However, fractured reservoirs occur in these strata (Fritts and Klipping, 1987a, b; Boberg *et al.*, 1989; Greenwood *et al.*, 1991; Read *et al.*, 1991; Hannigan *et al.*, 1993). Several oil and gas seeps occur in Purcell strata in the Clarke Range in the Flathead area and Waterton National Park, and small quantities of oil were produced from Purcell reservoirs in these areas in the early 1900's (Map 2; Table 2; Selwyn, 1893; British Columbia Department of Mines, 1904; Kirkpatrick, 1913; Johnson, 1913; Nichols, 1914; Arnold, 1915; Kirkham, 1925; Estlin; 1927; Link, 1932; Hume, 1933a, b, 1964; Power, 1933; Olsson, 1934a; Boberg, 1984). Shows have also been reported from Purcell strata in recent wells in the area (Table 3). In British Columbia, the seeps and shows occur primarily where Purcell strata are folded above the sub-Lewis duplex of Paleozoic strata on the east side of the Flathead Valley, although in Waterton, the shows have less obvious connection to structure. The oil appears to have been sourced from the shales of the Upper Cretaceous Alberta Group beneath the Lewis thrust (Hannigan *et al.*, 1993).

Shows of gas in drilling mud and lost circulation zones have also been reported from fractured quartzites and diorite sills in the Aldridge Formation in two wells that were drilled entirely in the Purcell Supergroup west of the Rocky Mountain Trench: ARCO Marathon No. 1 Paul Gibbs, a

5418m test located in nw ne 2-28N-27W, Flathead County, Montana (Boberg, 1985; Shirley, 1985; Boberg *et al.*, 1989); and DEI *et al.* Moyie d-8-C/82-G-5 well, a 3476m test located to the west of the Flathead area in British Columbia (Map 1). Fractures appear to be concentrated adjacent to major thrusts and at the tops and bases of diorite sills. Recoveries in successful drill stem tests vary from 29m of mud to 2874m of gas cut water in the ARCO well (Boberg *et al.*, 1989), and from 76m of mud to gas, too small to measure (61%N_2 and 38%C_1), with 652m gas cut mud in the DEI well. In addition, Boberg (*in* Shirley, 1985) has reported that a mining corehole in southeast British Columbia flowed gas at $0.8x10^3m^3/d$ (30Mcf/d) from a fractured zone in the Lower Purcell at a depth of 1067m.

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

A Middle Cambrian succession unconformably overlies the Purcell Supergroup (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 overlying Gordon Shale consists of 45 to 90m of green shale, variegated with brown or red near the base, and with 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 the 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 of the Bow River succession to the north, and the Windsor Mountain is equivalent to the Stephen and Eldon Formations of that area (Fritz and Norris, 1966; Slind *et al*., 1994). This succession has been beveled northward beneath the sub-Devonian unconformity toward the northwestern margin of Montania, and immediately south of the Dibble Creek Fault Devonian strata directly overlie the Purcell (Leech, 1958, 1960).

Cambrian rocks have not been generally regarded as exploration targets in the Foreland Belt, and no reserves have been assigned (Fermor and Moffat, 1992). However, an oil show in Cambrian strata has been described by Fermor and Moffat (1992) in the Foreland Belt north of the Flathead area, and vuggy and intercrystalline porosity occurs in the Elko Formation in outcrop (Price, 1965; Norris and Price, 1966). Consequently, the Elko Formation and possibly the Flathead sandstone could be potential reservoirs on structures.

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

The lower part of the Devonian succession consists of the Yahatinda Formation, the Fairholme Group, and the overlying Alexo and Sassenach 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 filling 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 beneath the Lewis thrust in the Flathead 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, 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 2).

Carbonates and evaporites of the Beaverhill Lake Group and the lower part of the Cooking Lake Formation extend palinspastically to the west into the Lewis and higher thrust sheets, where they constitute the Hollebeke Formation (Cross section 2; Price, 1964b, 1990b). The Hollebeke Formation thickens westward from 120m thick in outcrop and wells in the eastern part of the Lewis sheet, to 240m west of the Fernie Basin, immediately north of the Flathead area[8]. The Hollebeke Formation is sandy and argillaceous and lacks anhydrite on the west side of the Fernie Basin. 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 eastern part of the Lewis sheet (Cross section 2). 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 175m thick in the eastern part of the Lewis sheet where it overlies the Borsato Formation (Cross section 2; 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).

The Nisku Formation extends westward beyond the limit of the Peechee-Leduc shelf carbonates and evaporites. In the eastern part of the Lewis sheet, it overlies the Mount Hawk Formation and can be subdivided in outcrop into the Grotto and Arcs Members[9], 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.

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

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

The Fairholme Group is overlain by the Famennian (late Late Devonian age) Alexo and Sassenach Formations (Cross section 2; Table 1, Part B). The Alexo Formation consists of 5 to 30m of silty dolomite, limestone and anhydrite (expressed in outcrop as solution breccia) that overlies the Nisku Formation[10] (Price, 1964b, 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 170m of sandstones, siltstones and sandy and silty carbonates on the west side of the Fernie Basin (Price, 1964b).

The Fairholme Group is a prime exploration target in the Flathead 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). Furthermore, the Perdrix Formation is the temporal and lithological equivalent of the Duvernay Formation in the Alberta Plains, 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 has been penetrated by wells that tested the sub-Lewis duplex of Paleozoic strata east of the Flathead Valley and appears to be reefal in part (Map 2; Cross section 2). In the Shell Flathead c-12-A/82-G-7 and Shell Honolulu Flathead d-22-A/82-G-7 wells, 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 upper dolomite and anhydrite shelf deposits. The middle Peechee shelf-edge reef drill stem tested gas with 98% CO_2 at a rate of $52x10^3m^3/d$ (1.9MMcf/d) in the d-22-A well. In the wells to the south in the sub-Lewis duplex, the lower and middle parts of the Peechee consist of limestone as well as slightly argillaceous dolomite, and are interpreted to represent a slightly more basinward part of the shelf margin than the c-12-A and d-22-A wells. Consequently, the middle Peechee shelf margin reef is interpreted to trend northwest, in a more westerly orientation than the sub-Lewis duplex. Furthermore, the shelf edge has a prograding aspect, so that upper and lower Peechee shelf edge reef trends could also be anticipated southwest and northeast of the middle Peechee shelf-edge reef trend, respectively. Further north in the Fernie-Elk Valley area, the Peechee shelf-edge generally trends northwest across the Lewis thrust sheet (Moore, 1989; Geldsetzer, 1991; Monahan, 2000).

Southwest of the Peechee shelf edge, at least five Peechee pinnacle reefs occur in outcrop in the Flathead Range, immediately north of the Flathead area (Map 2; Cross section 2; 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 also 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 of northeast dips in the pinnacles. Peechee pinnacle reefs are potential targets southwest of the Peechee shelf edge below the Lewis thrust and in the Lewis thrust sheet. The western limit of the prospective area is conjectural. However, the underlying

[10] 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.

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, the Borsato is present in the Lewis thrust sheet in the MacDonald Range, 50 km south of the Peechee shelf edge (Cross section 2; Price, 1962a, 1964b, 1965).

Peechee dolomite has also been reported at an isolated Devonian outlier in the Lewis thrust sheet at Windsor Mountain in the Clarke Range east of the British Columbia border (Map 1; Price, 1964b). Because of its location, this occurrence probably represents an isolated bank or pinnacle reef rather than promontory on the Peechee shelf edge.

Porosity also occurs in outcrop in the Borsato and Nisku Formations (Reynolds, 1971), and porous intervals up to 10m thick occur in these units and in the Hollebeke Formation in the Shell MacDonald b-30-H/82-G-2 well in the MacDonald Range. Consequently, these units could be prospective locally on structures in the Lewis thrust, 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 2). In the Waterton area, east of the Flathead 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 open marine limestones in the Lewis and higher thrust sheets (Price, 1965; McMechan, 1998). The thickness increases concomitantly to the west, from 175m below the Lewis thrust, to 220m within the Lewis thrust sheet (Price, 1965). In outcrop in the latter areas 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 northwest of the Flathead area, the Palliser is replaced by dark basinal shales (Savoy, 1992; Savoy and Harris, 1993).

The Palliser is an important hydrocarbon reservoir in the Foreland Belt. The Palliser Formation 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[11] between interbedded dolomite and anhydrite intervals, and is near the middle of the

[11] 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 2; *see* Eliuk, 1984).

To the west at Coleman in Alberta and below the Lewis thrust in the Flathead area, where most of the Palliser Formation is dolomite, effective reservoir may occur throughout the formation (Cross section 2). 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 east of the Flathead Valley. There, three wells were completed in the Palliser Formation, and flowed gas with 90% CO_2 at final 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 thrust sheet, the Palliser is primarily limestone and has little reservoir potential. However, effective reservoir could possibly occur west of the MacDonald Range in a dolomite facies west of the limit of the basal dolomite and anhydrite unit (*see* Cross section 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 strata deposited on a westerly prograding complex ramp (Martindale and Boreen, 1997). 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 sharply but apparently conformably overlies the Palliser and 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 the Flathead area (Cross sections 2 and 3; Price, 1962a, 1965; Oswald, 1964b; Savoy, 1992; Savoy and Harris, 1993). However, in the Fernie-Elk Valley area north of Montania, it thickens westward to as much as 150m in the Bourgeau thrust sheet (Mamet and Mason, 1968; Bamber *et al.*, 1981; Monahan, 2000).

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 single prograding ramp in which westerly dipping clinoforms can be commonly recognized (Cross section 3; Price, 1962a, 1965; Oswald, 1964b; Chatellier, 1988; Savoy, 1992; Savoy and Harris, 1993). The Banff Formation is 250 to 280m thick in the footwall of the Lewis thrust and thickens westward to 365m west of the Fernie Basin north of the Flathead area. To the north of Montania, the Banff Formation thickens westward to 850m in the Bourgeau thrust sheet (Mamet and Mason, 1968; Bamber *et al.*, 1981; Monahan, 2000).

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 grainstones, packstones and wackestones with fine crystalline dolomite interbeds (Cross section 3; Norris, 1958; Price, 1962a, 1965; Oswald, 1964b; Klassen, 1972; Martindale and Boreen, 1997). The latter occur throughout the Livingstone Formation, but they occur more commonly toward the top. Below the Lewis thrust, the Livingstone Formation thickens westward from 200 to 280m, primarily due to a westward facies change of the lower members of the Mount Head Formation into the Livingstone (Cross section 3; Macqueen and Bamber, 1968). In the Lewis and higher thrust sheets, it appears to thin westward from 400 to 300m thick, probably due to westward facies change of the lower part of the Livingstone into the upper part of the underlying Banff Formation. To the north of Montania, the Livingstone thickens westward to approximately 450m in the Bourgeau thrust sheet (Mamet and Mason, 1968; Monahan, 2000).

The overlying Mount Head Formation consists of crinoidal grainstones like those of the Livingstone Formation, interbedded with peloidal, oolitic and fine-grained limestones, silty dolomites, and anhydrite, which is expressed in outcrop as solution breccia. The Mount Head thickens westward from 200 m below the Lewis thrust to 270m on the west side of the Fernie Basin (Oswald, 1964b; Price, 1965). North of Montania, the Mount Head thickens westward from 200m below the Lewis thrust to 680m in the Bourgeau thrust sheet (Mamet and Mason, 1968; Monahan 2000).

Beneath the Lewis thrust in the easternmost part of the Flathead area, the Mount Head can be divided into, in ascending order, the Wileman, Baril, Salter, Loomis, Marston and Carnarvon Members (Cross section 3; Table 1, Part B). The Wileman Member consists of 9 m of silty carbonate and anhydrite, and the Baril Member is represented by 18 to 25 metres of oolitic and skeletal grainstones (Macqueen and Bamber, 1968). Beneath the Lewis thrust and west of the Shell Grouse d-66-G/82-G-1 and Shell Kishinena b-56-C/82-G-1 wells, the Wileman and Baril Members pass westward into crinoidal grainstones of the upper part of the Livingstone Formation (Cross section 3; Price 1965; Macqueen and Bamber, 1968). The Salter Member consists of 20 to 50m of silty dolomite and anhydrite (Price, 1965). The lower part of the Salter member also passes west into the crinoidal grainstones of the upper part of the Livingstone Formation, but the remainder of the formation can be traced to west of the Fernie Basin (Oswald, 1964b). The Loomis Member is 45 to 80m thick, and is characterized by oolitic, crinoidal and micritic limestone, with fine and coarse dolomite, and some anhydrite in the lower part in eastern occurrences below the Lewis thrust. The Loomis Member can be traced across the Flathead area to the west side of the Fernie Basin (Oswald, 1964b; Price, 1965). The Marston Member consists of 13 to 30m of interbedded silty dolomite, anhydrite and limestone, and the Carnarvon Member consists of 55 to 90 m of argillaceous limestone, black crinoidal limestone and calcareous black shale (Price, 1965). The Marston and Carnarvon Members can be recognized beneath the Lewis thrust and in the eastern edge of the Lewis thrust sheet (Price, 1965). To the west, they pass into dark weathering pelmicrites that probably equate to the Opal Member, which was defined in the Front Ranges of Alberta north of the study area as the westerly equivalent of the Marston Member and the lower part of the Carnarvon Member (Oswald, 1964b; Macqueen and Bamber, 1968). The upper part of the Carnarvon is continuous over the Opal in the Front Ranges of Alberta (Macqueen and Bamber, 1968), but this unit is not obvious on the data presented by Oswald (1964b) on the west side of the Fernie Basin.

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-Jurassic unconformity below the Lewis thrust (Cross section 3). Where it is overlain by the

Pennsylvanian Misty Formation, the Etherington thickens westward from 70m below the Lewis thrust to 170m on the west side of the Fernie Basin (Price, 1962a; Oswald, 1964b). North of Montania, the Etherington Formation thickens westward to over 470m in the Bourgeau thrust sheet (Mamet and Mason, 1968; Monahan, 2000). 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 (Cross section 3). 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 that thickens westward at the expense of an overlying unit of silty and cherty dolomite with lesser amounts of sandstone and siltstone (Norris, 1958; Oswald, 1964b; Scott, 1964; Price, 1965; Lerand, 1990a). 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).

The Rundle Group is the principal gas reservoir in most of the fields in the Foreland Belt, including Waterton and Savanna Creek gas fields in Alberta, and is the upper reservoir in the CO_2–rich gas field established in the sub-Lewis duplex east of the Flathead Valley (Fuglem, 1969; Hall, 1969; Gordy and Frey, 1977; Fermor and Moffat, 1992; Kubli *et al.*, 1995; Martindale and Boreen, 1997). The principal gas pay zones occur in the Livingstone Formation, and to a lesser extent in the Mount Head and the lower part of the Etherington Formations (Cross section 3). Much of the high initially porosity of the grainstones has been cemented by calcite during early diagenesis, and matrix porosity is best developed in clean dolomitized packstones, wackestones and mudstones, particularly those interbedded with grainstones and deposited in a mid-ramp environment (Price, 1965; Klassen, 1972; Al-Aasm and Lu, 1994; Kubli *et al.*, 1995; Martindale and Boreen, 1997). These strata were dolomitized during shallow burial, prior to the Laramide Orogeny (Al-Aasm and Lu, 1994). Porosity has also been reported in bryzoan grainstones of Waulsortian mound character in an outer ramp setting in the Banff and Lower Livingstone Formations north of the Flathead area (Martindale and Boreen, 1997). In a general way, porosity in the Rundle Group diminishes from east to west across the Foreland Belt.

In the sub-Lewis duplex in the Flathead area, porous dolomite in the Rundle Group varies in thickness and stratigraphic position from well to well, and similar dolomites occur locally in the upper part of the Banff Formation (Cross section 3). 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 gas flow rates vary from 25 to $141x10^3m^3$/d (0.9 to 5.0MMcf/d). In the Lewis thrust sheet, porous dolomite occurs in the Rundle Group, particularly in the Livingstone Formation and the Loomis Member of the Mount Head Formation (Price, 1965; Klassen, 1971). However, in wells in the Lewis thrust sheet to the north in the Fernie-Elk Valley area, the net thickness of porosity in the Rundle Group varies from almost zero to over 90m (Monahan, 2000). Furthermore, much of the porosity observed in wells and outcrop has probably been enhanced by dissolution by surface waters. For example, in the B.A. CNP Fernie b-81-D/82-G-7 well, which is located on the west side of the Fernie Basin immediately adjacent to the Flathead area, an interval of porous dolomite in the Rundle Group produced 2028m of fresh water on a drill stem test. This well is down plunge on a surface anticline in which the Rundle is exposed (Map 1).

Consequently, the Rundle Group, particularly the Livingstone Formation, has reservoir potential on structures above and below the Lewis thrust, although the variability of the reservoir presents a risk throughout the Flathead area. In addition, the lower part of the Banff Formation tested gas at final flow rate of $60x10^3m^3/d$ (2.1MMcf/d) in the Shell Flathead c-12-A/82-G-7 well and is a secondary target in the area. 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 has been 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[12]. The Misty Formation thins eastward to a zero edge beneath the sub-Jurassic unconformity below the Lewis thrust sheet (Cross sections 3 and 4). The Formation is 75 to 100m thick in the sub-Lewis duplex east of the Flathead Valley and 150 to 200m thick in the Lewis thrust sheet. North of Montania, the Misty Formation thickens westward to 610m in the Bourgeau thrust sheet (McGugan and Rapson, 1961; Scott, 1964; Norris, 1965; Monahan, 2000). The Kananaskis Formation consists of up to 30m of silty and sandy dolomites in the Flathead area (Scott, 1964; Norris, 1965; Price, 1965). It conformably overlies Misty Formation and is recognized only in the Lewis thrust sheet.

The Ishbel Group unconformably overlies the Spray Lakes Group. It is not recognized beneath the Lewis thrust in the Flathead area. In the eastern part of the Lewis thrust sheet, it is locally represented by thin condensed sections. The Ishbel thickens to the west side of the Fernie Basin, where it consists of 30m of phosphatic siltstone assigned to the Johnson Canyon Formation (McGugan and Rapson, 1964; MacRae and McGugan, 1977). Ishbel strata are characterized by a high gamma ray log signature (e.g. 1296' to 1394' in the B.A. CNP Fernie b-81-D/82-G-7 well). 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).

[12] The interval between the Todhunter Member and the Kananaskis Formation has 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).

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. Consequently, these sandstones are a potential secondary objective on structures in the area.

Triassic Spray River Group

Triassic strata consist of the Sulphur Mountain and the Whitehorse Formations of the Spray River Group, and overlie older strata unconformably (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). In the Flathead area, the Sulphur Mountain Formation is not present below the Lewis thrust. In the Lewis thrust sheet, the Sulphur Mountain Formation thickens to the northwest from 100 to 157m on the west side of the Fernie Basin (Price, 1962a; Gibson, 1974). To the north of Montania, the Sulphur Mountain Formation thickens westward to 496m in the Bourgeau thrust sheet. The conformably overlying Whitehorse Formation consists of up to 6m of sandy dolomite and limestone, calcareous and dolomitic sandstone and siltstone, and solution breccia. It has been recognized only in the Lewis thrust sheet in the Flathead area (Gibson, 1974).

Most Spray River strata are not porous and have little reservoir potential in the Flathead area. However, 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 170m below the Lewis thrust (Cross section 4) 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 fold and thrust belt, and is commonly structurally thickened to several times its stratigraphic thickness (Dahlstrom, 1969, 1970). For example, it has been thickened to 331m in the Shell Grouse d-66-G/82-G-1 well beneath the Lewis thrust (Cross section 4), to 1294m in the Shell West Castle 5-7-4-3W5 well beneath the Lewis thrust in Alberta, 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, immediately north of the Flathead area (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, only some of these members have been differentiated on Cross sections 3 and 4.

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 the Alberta Plains. The Rock Creek is argillaceous and has low porosity in most wells below the Lewis thrust (Cross section 4). However, 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 east of the Flathead area. In addition, the Fernie Formation tested gas in two wells east of the Flathead area in Alberta: the Sinclair *et al.* Racehorse 16-29-9-5w5 well flowed gas at rates declining from $42x10^3m^3/d$ (1.5MMcf/d) to $7x10^3m^3/d$ (0.25MMcf/d) on drill stem tests, and Shell West Castle 5-7-4-3W5 well produced gas at a rate of $7x10^3m^3/d$ (0.25MMcf/d) gas in a production test. These tests produced gas from structurally thickened shale sections that probably represent uneconomic fractured shale reservoirs. More importantly, 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). The Morrissey Formation forms a coarsening upward sequence of fine- to medium-grained sandstone, with some conglomeratic sandstones in the upper part, and rare interbeds of mudstone, siltstone, and coal (Cross section 4). In the Flathead area, the Morrissey Formation is 15 to 25m thick below the Lewis thrust, and thickens northwest from 25 to 40m in the Lewis thrust sheet. 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. Below the Lewis thrust in the Flathead area, the Mist Mountain Formation thins eastward beneath the sub-Blairmore unconformity from 80m immediately east of the Flathead Valley to 20m in the Shell Grouse d-66-G/82-G-1 well (Cross section 4; Gibson, 1985). In the Lewis thrust sheet, where it is conformably overlain by the Elk Formation, the Mist Mountain Formation thickens to the northwest from 120 to 400m in the southern part of the Fernie Basin (Gibson, 1985; Grieve and Kilby, 1989; Johnson and Smith, 1991; Monahan, 2000). The Elk Formation consists of fine to coarse sandstone, siltstone, mudstone, shale, conglomerate, 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 (Gibson, 1985; Grieve and Ollerenshaw, 1989). The Elk Formation thickens to the north and west beneath the sub-Blairmore unconformity to 275m in the southern part of the Fernie Basin (Gibson, 1985). At Cabin Creek, on the west side of the Flathead Valley, the Mist Mountain and Elk Formations are 190m and 45m thick, respectively (Johnson and Smith, 1991).

Sandstones in the Kootenay Group are generally tight, although Mist Mountain and Elk Formation conglomerates may also 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). In the Flathead area, individual coal seams are generally 1 to 10m thick. Cumulative thicknesses of coal vary from 18 to 29m above the Lewis thrust (Grieve and Kilby, 1989; Johnson and Smith, 1991) and diminish to the east where the Mist Mountain is truncated beneath the sub-Blairmore unconformity (Cross section 4). Coal rank varies from generally medium volatile bituminous above the Lewis thrust (Ro= 1.11% to 1.30%; Grieve, 1981a, 1987; Johnson and Smith, 1991) to high volatile bituminous A below the Lewis thrust in the Shell Middlepass a-95-L/82-G-1 well (Ro=0.86% to 1.05%; England and Bustin, 1986; Bustin and England, 1989).

Lower Cretaceous Blairmore Group

The Kootenay Group is unconformably overlain by continental sandstones, conglomerates, mudstones, siltstone and shales of the Lower Cretaceous Blairmore Group. Beneath the Lewis thrust, the Blairmore Group thickens westward depositionally from 300m in the Shell Grouse d-66-G/82-G-1 well to 650m in the Shell Flathead c-12-A/82-G-7 and Shell Honolulu Flathead d-22-A/82-G-7 wells. In the Lewis thrust sheet, it is over 2400m thick in the Fernie Basin, immediately north of the Flathead area (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).

The Cadomin Formation forms the base of the Blairmore Group and consists of chert pebble conglomerate and sandstone, commonly organized into decametre-scale coarsening upward sequences that are interbedded and laterally replaced by grey, green and/or red mudstone (Ollerenshaw, 1981a, b). It is 15 to 35m thick below the Lewis thrust (Cross section 4) and up to 75m thick in Lewis thrust sheet in the Fernie Basin. At least locally, the thicker sections have greater proportions of conglomerate and lower proportions of mudstone (e.g. in the Shell Grouse d-66-G/82-G-1 well; Cross section 4; Monahan, 2000). The Cadomin Formation 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[13] (McLean, 1977; Leckie and Cheel, 1997). The Cadomin Formation is gradationally overlain by the Gladstone Formation.

[13] 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.

The Gladstone Formation[14] 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 in outcrop east of the Lewis thrust to over 450m in the Fernie Basin.

The succeeding Beaver Mines[15] and Ma Butte Formations[16] 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 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, which forms a number of conglomerate units occurring at a variety of stratigraphic levels in the upper part of the Blairmore Group in the Turner Valley area of the Alberta Foothills. In outcrop east of the Lewis thrust, the Beaver Mines and Ma Butte Formations are 280 and 120m thick respectively (MacLean, 1982, 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. A high gas detector response was reported in the Cadomin in the thick conglomeratic section in the Shell Grouse d-66-G/82-G-1 well (Figure 4). A similar thick Cadomin section in the Husky Savanna Creek 13-26-13-4W5 in Alberta flowed gas at $25x10^3m^3/d$ (887Mcf/d), of which $21.6x10^3m^3/d$ (766Mcf/d) was injected N_2, with water (i.e. $3.4x10^3m^3/d$ or 121Mcf/d net formation 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. In addition, the Cadomin Formation (and its equivalents) has yielded gas shows in several wells at Waterton[17] in Alberta. The orientation of such trends is unknown, but may vary from northeast to northwest.

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

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

[16] Equivalent to the Upper Blairmore of Price (1962a) and Norris (1964), and the Mill Creek of other workers (McLean, 1990d).

[17] 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.

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 in Alberta, north of the Flathead area. 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. Conglomerate units greater than 25m thick occur in the subsurface at Waterton, which is located on one of the east-oriented conglomerate trends (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 minor flows (Adair, 1990; Adair and Burwash, 1996). The Crowsnest Formation is 40 to 100 m thick beneath the Lewis thrust in the Flathead area, and 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 900m thick in the footwall of the Lewis thrust (Stott, 1963; 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 in the MacDonald Range (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 (Stott, 1963; Wall and Rosene, 1977). It is 85 to 110 m thick beneath the Lewis thrust in the Flathead area[18], and as thin as 30m in the Waterton gas field to the east (Herr, 1967). In the Flathead area, a 15m thick basal sandstone occurs in the wells drilled along the sub-Lewis Paleozoic duplex, but this sandstone is not present in the Shell Grouse d-66-G/82-G-1 well to the east. In addition, a decametre-scale coarsening upward sandstone sequence like those of the overlying Cardium Formation is developed in the middle of the formation in the Shell Flathead d-26-L/82-G-1 well.

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

[18] The Blackstone is 150m thick at the Shell Grouse d-66-G/82-G-1 well, but is overlain by an apparently inverted Cardium section, and may be structurally thickened.

shale, siltstone and sandstone, and may equate with the basal sandstone observed in the Flathead. The Vimy Member consists of calcareous shale and limestone, and is the equivalent of the Second White Specks zone, an important source rock of 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 decametre-scale coarsening upward cycles. The lowest cycle is best developed in the Flathead area, and has up to 5m of net clean sandstone at the top. Overlying cycles coarsen up to siltstone rather than sandstone, and the thickness of individual sandstone beds is 3 to 10m, so that the relative amount of sandstone in the Cardium Formation is low. The Cardium Formation is 100m thick below the Lewis thrust in the Flathead area and thins eastward in Alberta, where fewer coarsening upward cycles occur.

The Wapiabi Formation conformably overlies the Cardium Formation. It is approximately 500m thick in the Shell West Castle 5-7-4-3W5 well below the Lewis thrust immediately east of the Flathead area. Thicker sections in some of the Flathead wells are likely due to structure. The Wapiabi Formation 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 Flathead area, up to 350m of Belly River strata is reported in wells beneath the Lewis thrust. The Belly River Formation is up to 1370m thick to the east in Alberta. A 40m thick sandstone unit occurs at the base of the Belly River in the Shell Middlepass a-95-L/82-G-1 and Shell West Castle 5-7-4-3W5 wells. Elsewhere in the Foreland Belt, relatively continuous fluvial and/or deltaic sandstones occur at the base of the Belly River Formation.

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[19]. 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. 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.

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

Oligocene Kishenehn Formation

The Kishenehn Formation forms the fill of the half graben created by displacement on the Flathead fault (Russell, 1964; Bally *et al.*, 1966; Jones, 1969a; Gordy *et al.* 1977; McMechan, 1981; Constenius, 1981, 1982, 1988; Constenius and Dyni, 1983; Constenius *et al.*, 1989). The Kishenehn Formation overlies earlier deposits unconformably, and this unconformity has at least 300m of local relief on the west side of the Flathead Valley (Jones, 1969a; McMechan, 1981). In British Columbia, the Kishenehn dips eastward into the Flathead fault at an average dip of 32^{o} (range 18^{o} to 43^{o}; McMechan, 1981), and dips of over 50^{o} are reported in Montana (Constenius, 1981). In general dips decrease toward the Flathead fault, reflecting both eastward stratigraphic thickening and deposition of the Kishenehn contemporaneously with displacement on the Flathead fault (McMechan and Price, 1980).

Estimates of the stratigraphic thickness of the Kishenehn vary from 3600 to 4750m in British Columbia (Jones, 1969a; McMechan, 1981). Because of dip on the Flathead fault, the total thickness of basin fill would be less than the stratigraphic thickness. However, based on gravity data, the thickness of basin fill in Montana has been interpreted to be at least 4270m and may be greater (Constenius, 1988). On the northwestern margin of the Kishenehn Basin, the thickness of the Kishenehn Formation is greater than 2145m in the Chevron Mobil Flathead d-22-H/82-G-2 well (Table 3). This thickness appears to be anomalously high at this location, which could be in an erosional low on the sub-Kishenehn unconformity (Cross section 1).

The Kishenehn Formation is divisible into three members (MacKenzie, 1916; Jones, 1969a; Constenius, 1981; McMechan, 1981; Constenius and Dyni, 1983; Constenius *et al.*, 1989). The basal member is discontinuous and up to 140m thick. It consists of pebble and cobble conglomerates and sandstones deposited in a braided fan environment.

The lower member[20] is up to 2500m thick and consists of varicoloured clays, mudstones and shales, sandstones, calcareous oil shales and bituminous marls, fine argillaceous and commonly fossiliferous limestones, scattered lignitic coal and locally conglomerates, deposited in a variety of fluvial, floodplain, lacustrine and paludal environments (Jones, 1969a; Hopkins and Sweet, 1976; Constenius, 1981; McMechan, 1981; Constenius and Dyni, 1983). In particular, the oil shales and bituminous marls were deposited in a stratified freshwater lacustrine basin or basins with anoxic bottom waters. They are present the entire length of the Kishenehn Basin, but are best developed in southern part where they have a cumulative thickness of 85m (MacKenzie, 1916; Constenius, 1981; Constenius and Dyni, 1983; Curiale *et al.*, 1988). Early diagenetic gypsum occurs in some of the floodplain deposits (McMechan, 1981). In the classification of ancient lacustrine deposits of Carroll and Bohacs (1999) and Bohacs *et al.* (2000), the lower member has the characteristics primarily of the Fluvial-Lacustrine Facies Association (fluvial and lacustrine deposits, and both terrestrial and algal organic matter; *see* Curiale *et al.*, 1988).

[20] The lower member (McMechan, 1981) is lithologically equivalent to the Coal Creek and Kintla Members of Constenius (1981) and Constenius and Dyni (1983). The lower member of Jones (1969a) includes strata assigned to both the basal and lower members as defined by McMechan (1981) and used here.

The fluvial-Lacustrine Facies Association represents the fill of hydrologically open lacustrine systems (i.e. filled to the spill point and with fluvial outflow).

The upper member[21] is up to 2100m thick and consists of conglomerates interbedded with sandstones, varicoloured mudstones and coal, and breccias and megabreccias that include individual blocks with dimensions up to several hundred metres (Jones, 1969a). The upper member was deposited in an alluvial fan environment, and the megabreccias are interpreted to represent slide deposits. The members are gradational, probably laterally as well as vertically, and not all members may be present locally. For example, the Chevron Mobil Flathead d-22-H/82-G-2 well noted above penetrated 2221m of conglomerate and breccia, without penetrating strata assignable to the lower member.

The Kishenehn Formation has a diverse fauna and flora that suggests a range of ages between late Eocene and early Miocene (Russell, 1954, 1964; Hopkins and Sweet, 1976; Constenius *et al*., 1989). However, a fission track age of 33.2$\pm$1.5Ma in the lower member in the Kishenehn Basin, and a K/Ar date of 29.9$\pm$5.3Ma in similar strata in a nearby basin indicate that the lower part of the Kishenehn is early to middle Oligocene (Constenius and Dyni, 1983; Constenius *et al*., 1989). The Kishenehn Formation is at least in part the equivalent of the Renova Formation, which forms the lower part of the fill of similar post Laramide extensional basins in Montana (Fields *et al.*, 1985). The Renova Formation consists of dominantly fine clastics, including lacustrine deposits similar to the lower member of the Kishenehn Formation.

The fluvial and lacustrine[22] sandstones and conglomerates are potential reservoirs in this sequence. Although reservoirs of this type are characteristically discontinuous, friable sandstone units greater than 30m thick occur in outcrop near the base of the lower member (Jones, 1969a).

In addition, the megabreccias may provide significant potential reservoirs. Intensely brecciated Paleozoic carbonates that have been interpreted to be slide blocks form prolific reservoirs in the Railroad Valley area of Nevada, a Tertiary graben similar to the Kishenehn Basin (Read and Zogg, 1988; French, 1991, 1993, 1996; Montgomery *et al*., 1999). There, reservoirs occur both within and at the base of the Tertiary valley fill. Read and Zogg (1988) estimate that 60% to 90% of the reservoir volume at Grant Canyon field, the most prolific in Railroad Valley, is due to fracturing and brecciation. Investigations of megabreccias exposed in other basins shows that individual megaclasts can be up to 2500m long and 200m thick, that brecciation is concentrated on the outer 8 to 15m of individual megaclasts, and that the average porosity of brecciated zones is 8% in carbonate blocks (Morris and Hebertson, 1996). Rock avalanche deposits can retain source area stratigraphy, albeit attenuated (Melosh, 1987), so that in the subsurface,

[21] The upper member (Jones, 1969a; McMechan, 1981) is lithologically equivalent to the Pinchot Conglomerate Member of Constenius (1981) and Constenius and Dyni (1983).

[22] McMechan (1981) and Constenius and Dyni (1983) interpret graded sandstone interbedded with lacustrine oil shales and argillaceous and fossiliferous limestones as overbank fluvial deposits. However, some have load and dewatering structures and may also be interpreted as lacustrine turbidites.

distinguishing between megabreccia beds, individual megaclasts within them, or isolated coherent slide blocks[23] could be exceedingly difficult. However, the presence of Tertiary lithologies mixed with Paleozoic lithologies suggests that at least some of the Railroad Valley reservoirs are megabreccia beds rather than individual slide blocks (Montgomery *et al.*, 1999). In the Kishenehn Formation, Jones (1969a) describes a complete gradation from fractured and brecciated megaclasts to monolithological breccia of Precambrian clastics and Paleozoic carbonates.

Miocene St. Eugene Formation and older Tertiary deposits in the Rocky Mountain Trench

The St. Eugene Formation forms the uppermost part of the post-Laramide fill in the Rocky Mountain Trench south of Cranbrook in British Columbia (Clague, 1974, 1990). The exposed section is approximately 50m thick, and consists of a lower unit of colluvium and fanglomerate, a middle unit of floodplain silt and sand, and an upper unit of fluvial gravel and sand. These strata have been tilted and are locally cut by normal faults. The St. Eugene Formation has a Middle Miocene flora. It is equivalent in part to the Sixmile Formation, which forms the upper part of the fill of similar post Laramide extensional basins in Montana and consists of coarse clastics (Fields *et al.*, 1985).

Gravity data indicate that this part of the Rocky Mountain Trench is segmented into basins up to 10km wide and 25km long (Map 2; Garland *et al.*, 1961; Thompson, 1962). Two such basins occur south of the Bull River in British Columbia and are called, from south to north, the Waldo and Jaffray gravity lows. Assuming an average density of 2.2g/cc (2200kg/m^3) for the Tertiary deposits, Thompson (1962) estimated their thickness to be 1500m in the Waldo gravity low and 1150m in the Jaffray gravity low. However, Constenius (1988) has shown that in similar post-Laramide extensional basins in Montana, the density of Tertiary basin fill is between 2.1 and 2.2g/cc at a depth of 900m and increases with depth to 2.6 to 2.7g/cc at a depth of 3000m. He also estimated a similar density structure for the Kishenehn Basin based on seismic data, and showed that the average density of outcrop samples generally ranged from 2.47 to 2.62g/cc in conglomerates and 2.25 to 2.35g/cc in other lithologies. Furthermore, on the basis of seismic refraction data, Lamb and Smith (1962) estimated the thickness of Tertiary fill to be 1500m across the northern part of the Waldo gravity low, where the gravity data suggested a thinner Tertiary section, so that the maximum thickness would be greater. The basins may also be underlain by Paleozoic carbonates, which are exposed in the Rocky Mountain Trench west of the Bull River (Cross section 1) and are denser than the Purcell strata on either side of the Trench. These factors suggest that the thicknesses of Tertiary fill estimated by Thompson in the Waldo and Jaffray lows are minimum values, and that the true thicknesses could be significantly greater. Two shallower gravity lows are present in the Rocky Mountain Trench north of the Jaffray gravity low (Garland *et al.*, 1961; Thompson, 1962).

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[23] Large catastrophic slides of coherent bedrock blocks can occur. See Anders *et al.* (2000) for a recent discussion on the mode of emplacement of ancient examples, and Semenza and Ghirotti, (2000) for a description of a modern example at Vaiont in Italy in 1963.

The nature of the Tertiary fill in the Rocky Mountain Trench is unknown. However, similar post-Laramide extensional basins occur throughout Western Montana and have up to 4500m of Tertiary fill (Fields *et al.*, 1985). The stratigraphic successions of these basins are generally similar and consist of three units separated by angular unconformities: a discontinuous basal Early to Middle Eocene fanglomerate unit; the Middle Eocene to Early Miocene Renova Formation, which consists of fine fluvial and lacustrine sediments rich in volcanic ash and with localized coarse clastics; and the Middle to Late Miocene Sixmile Formation, which consists of coarse clastics. The approximate comtemporaneity of depositional episodes in these basins has been attributed to climate, with sedimentation occurring primarily during periods of aridity (Thompson *et al.*, 1982; Fields *et al.*, 1985). The interbasinal extent of these stratigraphic units in Western Montana and the presence of the Renova-equivalent Kishenehn Formation nearby suggests that the following stratigraphic succession could be present in the Rocky Mountain Trench basins: an Oligocene fine-grained fluvial and lacustrine unit, similar to the Kishenehn and Renova Formations, and a Miocene coarse-grained unit, represented by the St. Eugene Formation and similar to the Sixmile Formation. As in the Kishenehn Formation, potential reservoirs in this succession would include fluvial sands and conglomerates, and megabreccias.

INTRUSIVE ROCKS

Intrusive rocks occur at several levels in the Flathead area and may have some bearing on the hydrocarbon potential. In addition to the numerous sills in the Aldridge Formation of the Purcell Supergroup noted above, chloritized diorite sills have been reported by Price (1962a, 1964a, 1965) throughout the Purcell sequence in the Flathead area. These are truncated beneath the sub-Cambrian unconformity and would not affect the hydrocarbon potential of Phanerozoic strata.

However, a suite of primarily alkaline intrusive rocks occurs in the Lewis thrust sheet and intrudes strata as young as the Cretaceous Blairmore Group (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 largest intrusive bodies occur in the domal culminations in the MacDonald Range west of the Flathead Valley and may contribute to the uplift of these domes ("Howell Creek Intrusives"). Smaller intrusive bodies occur in the Clarke Range. 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 to 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).

SOURCE ROCKS AND MATURATION

Several of the established hydrocarbon source rocks in the Western Canada Sedimentary Basin are known or inferred to have been present in the platformal and foreland successions in the Flathead area (Creaney and Allan, 1990, 1992; Creaney *et al.*, 1994). The Upper Devonian Perdrix Formation is the lithological and temporal equivalent of the Duvernay Formation. Although it is probably no longer preserved in the Flathead area, it is present on the west side of the Fernie Basin and could have acted as a source prior to significant thrusting. The Upper Devonian-Lower Mississippian Exshaw Formation occurs throughout the Flathead area. 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 Flathead area, and these strata are preserved only above the Lewis thrust. 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 Flathead area. In addition to these source rocks, coal in the Jurassic Mist Mountain Formation of the Kootenay Group is known to have generated gas in this area.

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). In the Flathead and Waterton areas, vitrinite reflectance in the Mist Mountain Formation generally exceeds 1.1% in the Lewis thrust sheet (Grieve, 1981a, 1987), but generally varies between 0.6% and 1.3% below it (England and Bustin, 1986; Bustin and England, 1989). Similarly, vitrinite reflectance in Mississippian strata beneath the Lewis thrust varies between 0.8% and 1.7%, indicating a complex maturation history with pre-, syn- and post-orogenic components (Chagnon *et al.*, 1975; England and Bustin, 1986; Bustin and England, 1989). These data indicate that the oil window includes Cretaceous strata in this area, but below the Lewis thrust locally includes strata as old as Mississippian. In the parts of the Alberta Foothills and Rocky Mountains adjacent to the Flathead area, the Paleozoic is gas-bearing, whereas both oil and gas shows occur in Cretaceous strata.

In addition, the lacustrine oil shales and bituminous marls in the lower member of the Kishenehn Formation are a significant potential hydrocarbon source (MacKenzie, 1916; Constenius, 1981; Constenius and Dyni, 1983; Veres, 1985; Curiale, 1987; Curiale and Sperry, 1987; Curiale *et al.*, 1988). The oil shales occur throughout the Kishenehn Basin, but are best developed in the

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

southern part, where they have a cumulative thickness of 85m. Oil yield varies between 34 and 155 l/tonne (8.1 to 37.2 gal/ton; Constenius and Dyni, 1983) and total organic carbon content varies between 0.13% and 35.53% (Curiale *et al.*, 1988). These source rocks generally contain type I kerogen in the southern part of the basin and types II and III in the northern part. Vitrinite reflectance varies between 0.25% and 0.51% and averages 0.39%, so that these source rocks are generally immature at surface. However, if they are present in deeper parts of the basin they are likely to have generated liquid hydrocarbons (Curiale *et al.*, 1988). Oil and gas shows have been observed in shallow wells in the basin, providing direct evidence of hydrocarbon generation (Tables 2 and 4; Boberg, 1983, 1984).

As noted above, minor gas shows have been reported from fractured Precambrian strata west of the Rocky Mountain Trench. Organic-rich intervals occur within the Aldridge Formation and may have been the source rocks for this gas (Boberg, 1985; Shirley, 1985).

EXPLORATION HISTORY[25]

Early petroleum explorers were drawn to the Flathead region by the oil seeps in metasediments of the Precambrian Purcell Supergroup and oil shales in the Tertiary Kishenehn Formation. The principal oil seeps in Precambrian strata in British Columbia are on Sage and Kishinena Creeks where they cross anticlines developed in the Lewis sheet above the sub-Lewis duplex of Paleozoic strata, immediately east of the Flathead fault (Map 2; Selwyn, 1893[26]; British Columbia Department of Mines, 1904; Kirkpatrick, 1913; Johnson, 1913; Nichols, 1914; Arnold, 1915; Kirkham, 1925; Estlin; 1927; Link, 1932; Hume, 1933a, b, 1964; Power, 1933; Olsson, 1934a; Boberg, 1984). Of these, the Sage Creek seeps were significantly larger and recoveries of 1.25 to 1.5 gallon per day were reported. Another small seep occurs to the southeast on this structural trend between Upper and Lower Kintla Lakes in Montana (British Columbia Department of Mines, 1904; Johnson, 1913; Arnold, 1915; Boberg, 1984). Oil seeps from Precambrian strata also occur at Cameron and Lineham Brooks in Waterton National Park in Alberta, although these do not appear to be related to anticlines in the Lewis sheet (Selwyn, 1893; Kirkpatrick, 1913; Johnson, 1913; Nichols, 1914; Link, 1932; Hume, 1933a, b, 1964; Boberg, 1984).

[25] For further details, the reader should refer to the excellent historical review by Boberg (1984).

[26] Selwyn (1893) referred to Kishinena Creek as Akamina Brook, a name that is now used for a tributary of Kishinena Creek. The oil seep he describes on "Akamina Brook" occurs in northeast-dipping strata at a beaver dam pool "15 miles in a direct line, west 10^{o} south, from the occurrence on Cameron Falls Creek" (i.e. oil seeps in Alberta). The distance from Cameron Creek places this seep on Kishinena Creek, where it crosses the anticline developed in the Lewis sheet above the sub-Lewis duplex of Paleozoic strata, and immediately east of the Flathead fault (British Columbia Department of Mines, 1904). Nichols (1913) also reported a beaver dam at this site. Consequently, this seep is *not* located in the vicinity of the wells in Block B/82-G-1, which are on Akamina Creek and near the axis of the Akamina syncline.

The earliest drilling in the region occurred in Montana and Alberta. Between 1901 and 1910, at least 13 wells were drilled in the vicinity of the Cameron Brook oil seeps in Alberta, which became known as “Oil City” (British Columbia Department of Mines, 1904; Daly, 1912; Kirkpatrick, 1913; Johnson, 1913; Nichols, 1914; Dowling, 1921; Link, 1932; Hume, 1933a, b, 1964; Power, 1933; Boberg, 1984). Oil shows were reported and some limited oil production was established from one well[27]. Drilling in the area continued between 1919 and 1933 (Hume, 1933b). Hume also reports that 4 wells were drilled in the vicinity of the Lineham Brook seeps and had shows of oil in Purcell strata (Map 2).

Between 1901 and 1906, 2 wells were drilled in Precambrian strata in the Lewis sheet in Montana in what is now Glacier National Park (Map 2; Table 4; Daly, 1912; Kirkpatrick, 1913; Johnson, 1913; Arnold, 1915; Boberg, 1984). Of these, the Butte Oil well, which was located approximately 3km west of the Kintla Lake seeps, encountered gas and oil shows in the Purcell Supergroup and flowed gas until the 1950’s. In 1902, 2 wells were drilled in the Flathead Valley adjacent to exposures of Kishenehn oil shales, and minor oil and gas shows were reported (Table 4; Daly, 1912; Boberg, 1984).

The earliest drilling in British Columbia occurred at Akamina Creek on the axis of the Akamina syncline, where the Purcell Supergroup is more than 3000m thick (Block B/82-G-1; Table 2). The only first hand report of oil seeps here is by Nichols (1914), although both Selwyn (1893) and Hume (1933a, b) attributed reports of seeps to others. Two shallow wells were drilled between 1908 and 1914, and oil shows and minor production were reported in the Purcell Supergroup in one of them (Kirkpatrick, 1913; Nichols, 1914, Power, 1933). However, Johnson (1913) and Arnold (1915) discounted these favourable reports. Three additional shallow wells were drilled here without success, the latest in 1952.

The first well in the Flathead Valley in British Columbia was drilled as early as 1913, and was abandoned at a depth of 183m (B.C. Oil and Coal #1 d-86-D/82-G-1; Table 2; Kirkpatrick, 1913; Johnson, 1913; Nichols, 1914; Arnold, 1915). Between 1931 and 1950, the Canadian Kootenay #1 b-50-D/82-G-1 and Border Oils #1 d-55-A/82-G-1 wells, located on the west side of the valley, were drilled to depths of 1097m and 549m respectively and encountered minor shows in Kishenehn Formation and possibly Jurassic strata (Table 2; Boberg, 1984).

In spite of the significant oil seeps at Sage Creek, the first wells at Sage Creek were not drilled until 1913 or 1914, because the federal government withheld lands from leasing until 1905 and subsequent lawsuits further delayed exploration (Boberg, 1984). However, between 1913 and 1915, at least 7 wells were drilled in Precambrian strata at these oil seeps to depths of 55 to 296m (Table 2; British Columbia Department of Mines, 1914, 1916; Nichols, 1914; Arnold, 1915). Oil and gas shows were reported in several of these. Drilling resumed in 1919, and at least 3 deeper wells were drilled[28] between then and 1938 (Table 2; Kirkham, 1925; Estlin, 1927; British

[27] Although the reported production volumes vary widely, the most credible report is that of Hume (1933a), which reports that 36.6m^3 (230 bbl), of which 3m^3 (700 gallons) was sold.

[28] Including a possible re-entry (British Columbia Coal and Oil Development #5; Table 2; Boberg, 1984)

Columbia Department of Mines, 1930, 1931; Hume, 1933a,b, 1964; Power, 1934; Olsson, 1934a; Boberg, 1984). The deepest of these was Columbia #1, which reached a true vertical depth of 1356m but did not penetrate the Lewis thrust (Hume, 1964; Boberg, 1984). Oil and gas shows were reported from the Purcell Supergroup in these wells, although commercial production was not established. However, sufficient oil was produced while drilling the Columbia #1 to operate the camp generator. Many of the wells drilled at Sage Creek continued to flow small volumes of oil and gas for decades, and oil could be recovered from at least three during the 1980's[29] (Table 2; Boberg, 1984).

The early phase of exploration at Sage Creek came to a close in 1953 with the Pacific Atlantic Flathead d-34-E/82-G-1 well, which penetrated the Lewis thrust and tested CO_2-rich gas from the underlying duplex of Mississippian strata (Tables 3 and 5; Map 2). The next well in the region was the Shell Honolulu Flathead d-22-A/82-G-7 well, which was drilled in 1960, and established the presence of CO_2-rich gas 18 km to the northwest on the same sub-Lewis duplex trend.

Although only one well was drilled between 1960 and 1980, regional geological and geophysical studies of the area conducted by Shell, Chevron, and others contributed to the development of structural models that have been successfully applied throughout the Foreland Belt (e.g. Bally *et al.*, 1966; Dahlstrom, 1969, 1970). During this time, the CIGOL IOE *et al.* Howell a-16-B/82-G-7 well was drilled on the Howell Creek structure and demonstrated the occurrence of significant normal faults in the Lewis sheet west of the Flathead fault (Table 3; Labrecque and Shaw, 1973).

During the 1980's, Shell drilled nine wells, partly to extend plays successfully developed by them in thrust-faulted Paleozoic carbonates in adjacent parts of Alberta, and partly to evaluate the CO_2 reserves for use in enhanced oil recovery projects in Saskatchewan and Alberta (Tables 3; Oil and Gas Journal, 1985; Oilweek, 1985). Eight of the wells were drilled to test thrust faulted Paleozoic carbonates beneath the Lewis thrust east of the Flathead fault. Of the five that were located on the sub-Lewis duplex trend tested by the Pacific Atlantic and Shell Honolulu Flathead wells, four were completed as CO_2 gaswells (Map 2). These wells established the sub-Lewis duplex as a potential CO_2 gas field with estimated gas reserves of $21x10^9m^3$ (600BCF; Hannigan *et al.*, 1993). However, the wells have subsequently been abandoned because reserves were insufficient to justify development in the oil price regime of the late 1980's, and the rights are currently available. The other four wells drilled east of the Flathead fault were abandoned, although the Shell Kishinena b-56-C/82-G-1 well, which was located on the Kishinena Creek oil seep, did test minor amounts of oil and gas from Purcell strata (Map 2). One of the Shell wells was drilled well west of the Flathead Valley on a domal culmination in the MacDonald Range, and abandoned after penetrating an unfaulted section of Mississippian to Lower Purcell strata in the Lewis sheet (Cross section 1; Boberg, 1984).

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[29] Oil was used for local use (Hume, 1933a, b, 1964). The Hungry Horse News reported on Oct. 17, 1947 that a local trapper ran his Model T for 15 years on the oil from one of the 1913/1914 wells.

Renewed interest was also expressed in the Kishenehn Formation during the 1980's, with several geophysical and geochemical studies being directed toward this objective (Kulik, 1982; Constenius and Dyni, 1983; Veres, 1984, 1985; Strauss, 1984; Lee, 1986; Curiale, 1987; Curiale and Sperry, 1987; Curiale *et al.*, 1988; Constenius, 1988). Subsequently, the Chevron Mobil Flathead d-22-H/82-G-2 well was drilled in 1990 to test the Kishenehn Formation on the west side of the Flathead Valley and abandoned (Table 3). Two unsuccessful wells were also drilled to test the Kishenehn Formation in Flathead Valley in Montana during the 1980's (Table 4).

Also during the 1980's, several companies considered the possibility of hydrocarbons being trapped in Paleozoic strata beneath overthrust Purcell Supergroup west of the Rocky Mountain Trench. The most significant wells drilled west of the Trench during this time were the ARCO Marathon #1 Gibbs well in se nw ne 2-28N-27 west in northwest Montana, which was drilled to 5417m (Boberg *et al.*, 1989), and the DEI Moyie d-8-C/82-G-5 well in southeast British Columbia, which was drilled to 3477m. These wells were drilled on large surface anticlines, and neither well encountered Paleozoic strata beneath the Purcell Supergroup. However, both encountered minor gas shows and demonstrated that several prominent seismic reflectors were diabase sills in the Aldridge Formation of the Purcell Supergroup. The concept of Paleozoic strata existing beneath overthrust Purcell west of the Rocky Mountain Trench has recently been renewed by Root *et al.* (2000).

Little exploration activity has occurred in the Flathead area in the last decade. However, to the north in the Fernie-Elk Valley area, coal in the Jura-Cretaceous Mist Mountain Formation has attracted interest as a potential coalbed methane source (Johnson and Smith, 1991; Dawson, 1995; Dawson *et al.*, 1998, 2000; Monahan, 2000). An active exploration program is underway, and could potentially lead to activity in the Flathead area.

CONVENTIONAL PROSPECTIVE ZONES AND PLAY TYPES

Hydrocarbons in Fractured Precambrian Metasediments

Oil in fractured metasediments of the Purcell Supergroup was the earliest play type to be pursued in the Flathead area. As described in more detail in the section on exploration history, oil seeps in Precambrian Purcell strata attracted the interest of petroleum explorers in the early 20th Century. These occurrences of oil are located east of the Flathead Valley, where Purcell strata in the Lewis thrust sheet structurally overlie Paleozoic and Mesozoic strata (Map 2; Cross section 1). The oil seeps occur in two trends: in folded Purcell strata above the sub-Lewis duplex on the east side of the Flathead Valley, and in Waterton National Park in Alberta, where production has a less obvious connection to structure (Hume, 1933a, b, 1964). Drilling activity at "Oil City" in Waterton resulted in minor production – 36.6m^3 (230 bbl) from one well, according to the most credible estimate (Hume, 1933a). Eleven wells were drilled on the anticlinal structure at Sage Creek in British Columbia between 1913 and 1938 to depths 55 and 2438m, and sufficient oil was produced for camp use (Table 2; Boberg, 1984). Five (?) wells were drilled in the Akamina syncline between 1908 and 1952 (Kirkpatrick, 1913; Nichols, 1914; Power, 1933). However, several authors expressed skepticism about the reports of oil seeps and shows in the wells in the Akamina syncline (Johnson, 1913; Arnold, 1915). Hydrocarbon shows have been reported in

Purcell strata in some of the recent drilling in the Flathead area (Table 3). The Shell Kishenena b-56-C/82-G-1 well, which is on an anticlinal structure above the sub-Lewis duplex, produced up to 1.5m^3/d (9bopd) oil and 3x10^3m^3 (110Mcf/d) gas on a completion attempt. In the Shell North Kootenay Pass b-58-H/82-G-7 well, gas flow rates up to 19.9x10^3m^3/d (700Mcf/d)[30] were reported in drill stem tests from the Siyeh Formation and the Purcell Lava.

The character of the oil is not the same at all locations. Dark 30^o oil occurs at Waterton and similar oil was reported at Kishenena Creek, whereas at Sage Creek the oil includes dark green 40^o oil, amber 42^o oil, and clear 50^o to 60^o oil (Selwyn, 1893; British Columbia Department of Mines, 1904; Arnold, 1915; Dowling, 1921; Estlin, 1927). In addition to hydrocarbon gases occurring with oil, non-flammable sulphur-bearing gas occurred in one well at Sage Creek (Estlin, 1927; Hume, 1933a, b, 1964; Power, 1933). The source of the oil has been attributed to the Vimy Member, or Second White Specks zone, of the Blackstone Formation, which is an important source rock in the Alberta Plains (Creaney and Allan, 1990, 1992; Creaney *et al.*, 1994; Hannigan *et al.*, 1993). In addition, the equivalent Greenhorn Formation is locally an oil reservoir on structures in the Foreland Belt in Montana (e.g. Garner, 1985). However, the Blackstone is thin beneath the Lewis thrust in the Flathead area and the Vimy Member is not distinct. Other Alberta Group shales are potential source rocks in the Foreland Belt (Creaney and Allan, 1990, 1992; Creaney *et al.*, 1994), and locally Jurassic and Mississippian strata appear to be within the oil window beneath the Lewis thrust (Chagnon *et al.*, 1975; England and Bustin, 1986; Bustin and England, 1989), so that source rocks in these strata may have also contributed to the oils in the Purcell Supergroup. The sour gas seep at Sage Creek is probably derived from the underlying CO_2-rich gas field.

Hannigan *et al.* (1993)[31] have estimated the mean oil resource potential to be 4.5x10^6m^3 (28MMBO) original oil in place (OOIP) in 55 pools (mean estimate) and the mean gas resource potential to be 0.6x10^9m^3 (22BCF) raw initial gas in place (RIGIP) in 35 pools (mean estimate) for fractured Purcell reservoirs in the Lewis thrust sheet thrust above Paleozoic and Mesozoic strata. Their median estimates for the largest pools are 0.8x10^6m^3 (5MMBO) and 0.2x10^9m^3 (4BCF). Only 3% of the play area is in British Columbia, mainly in the Flathead area. Because of the fractured reservoir, this play type has limited reserve potential and production rates and thus only minor potential.

As noted above, minor gas shows have also been reported from fractured diorite sills and quartzites in the Aldridge Formation of the Purcell Supergroup in two wells drilled on large surface anticlines west of the Rocky Mountain Trench – the ARCO Marathon No. 1 Paul Gibbs well in nw ne 2-28N-27W in Flathead County Montana (Boberg *et al.*, 1989) and the DEI *et al.* Moyie d-8-C/82-G-5 well located west of the Flathead area in British Columbia. Drill stem tests in these wells indicated low to good permeability in fractured zones. In addition, Boberg (*in* Shirley, 1985) has reported that a mining corehole in southeast British Columbia flowed gas at 0.8x10^3m^3/d (30Mcf/d) from a fractured zone in the Lower Purcell. Purcell strata west of the

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

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

Flathead fault probably have very limited hydrocarbon potential due to the lack of matrix porosity and effective seals in this metamorphosed sequence. Furthermore, significant hydrocarbon accumulations may have not been preserved due to the high metamorphic grade and the late timing of structural trap development with respect to maturation of possible Purcell source rocks. However, if fractured sills in the Aldridge Formation are to be considered an exploration target, they could be tested in the large roll-over anticline in the Lewis sheet in the MacDonald range (Cross section 1; *see* van der Velden and Cook, 1994). At this location, Paleozoic strata beneath the Lewis thrust may also have acted as hydrocarbon sources.

Thrust Faulted Paleozoic Strata Below the Lewis Thrust

Thrust faulted Paleozoic strata beneath the Lewis thrust have been the target of most recent drilling activity in the Flathead area, and all of the recent success (Tables 3 and 5). Ten wells have been drilled in this setting. Of these, four were completed as gaswells, and two more tested gas at rates exceeding $28x10^3m^3/d$ (1MMcf/d). These wells define a CO_2-rich gas field in the sub-Lewis duplex east of the Flathead fault with a raw gas volume of $17x10^9m^3$ (600BCF; Hannigan *et al.*, 1993). 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 $73x10^9m^3$ (2,600BCF), $7x10^9m^3$ (249BCF), and $4.4x10^9m^3$ (153BCF) respectively (Fuglem, 1969; Hall, 1969; Alberta Energy and Utilities Board, 1997).

The principal reservoirs in the CO_2-rich gas field are in the Devonian Palliser Formation and the Mississippian Livingstone Formations, and to a lesser extent in the Mississippian Mount Head and Etherington Formations (Cross sections 2 and 3; Tables 3 and 5). Reservoir rocks in these formations vary in quality and stratigraphic position from well to well and are not present in all places. For example, the Shell Kishinena b-56-C/82-G-1 well at the southern end of the sub-Lewis duplex failed to encounter significant reservoir in the Livingstone Formation. In the three Palliser gaswells, net pay averages 34m and final flow rates vary from 81 to $311x10^3m^3/d$ (2.8 to 11.0MMcf/d). In the Livingstone Formation[32] net pay averages 18m in four gaswells, and in the Mount Head and Etherington Formations net pay averages 4m and 5m, respectively, in 3 wells. Final test flow rates from the Livingstone, Mount Head and Etherington Formations combined range from 25 to $141x10^3m^3/d$ (0.9 to 5.0MMcf/d). In addition, the porous Devonian Peechee Member shelf-edge reef, which is developed only at the north end of the gas field, drill stem tested gas at a rate of $52x10^3m^3/d$ (1.9MMcf/d) from one well, and the Banff Formation flowed gas at a rate of $60x10^3m^3/d$ (2.1MMcf/d) from another. The reported CO_2 content of the gas in this field is between 89% and 100% in the Devonian reservoirs, and between 20% and 90% in the Mississippian reservoirs (Table 5). The methane content of gas in the Mississippian reservoirs is as high as 53%.

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

[32] In the Shell Sage a-56-E/82-G-1 well the Livingstone net pay zone and the completed intervals include part of the upper Banff Formation.

(Gordy and Frey, 1977; Kubli *et al.*, 1995; Martindale and Boreen, 1997). Fracturing is better developed in dolomite than in limestone. However, fracturing alone is generally insufficient for economic production, and matrix porosity is necessary. The Rundle Group dolomite reservoirs formed primarily during shallow burial, prior to the Laramide Orogeny (Al-Aasm and Lu, 1994; Martindale and Boreen, 1997), although Lewchuk *et al.* (1998) showed that dolomite in the Mount Head Formation reservoir at the Waterton gas field recrystallized in part during the Laramide Orogeny, probably as hydrocarbons were migrating into the trap. Furthermore, as noted above, reservoir quality varies considerably from well to well on a structure in this setting. These factors demonstrate that, although reservoir quality is enhanced on the crest or leading edge of a structure, the presence of effective reservoir is usually dependent upon the presence of favourable depositional and relatively early diagenetic facies (*see* Martindale and Boreen, 1997).

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, the compositional differences between the gas in the Palliser Formation and gas in the Rundle Group indicate that these reservoirs are not in communication in the Flathead gas field, which is segmented vertically and horizontally into several pools (Table 5). Even in the Shell Flathead c-12-A/82-G-7 well, in which the Palliser and the Rundle gases both contain ~90% CO_2, the CO_2 content of the gas in the intervening Banff reservoir is 68%, indicating that the Palliser and Rundle reservoirs are separate. Communication between the Peechee and Palliser reservoirs may occur, and this may offer 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. The gas composition is similar in the Peechee and the Palliser. Communication could occur between these horizons on other structures.

Additional potential remains in thrust faulted Paleozoic strata below the Lewis thrust. In addition to the Mississippian Rundle Group, the Devonian Palliser Formation and the Peechee shelf-edge reef, potential reservoirs in this setting locally include the Pennsylvanian Misty and Cambrian Elko Formations. In British Columbia, hydrocarbon potential in this setting is restricted to the area east of the MacDonald Range, where the Lewis-Flathead fault system appears to merge with the basal detachment (Map 1, Cross section 1; Yoos *et al.*, 1991; Fermor and Moffat, 1992; van der Velden and Cook, 1994; Fermor, 1999).

The sub-Lewis duplex trend that forms the Flathead gas field is interpreted to continue to the northwest, parallel to the Flathead fault, and into the Fernie-Elk Valley area, where it constitutes a major exploration target (Map 2; Monahan, 2000). Charters (1989) has identified the southernmost part of the extension of this trend on the basis of seismic data in the northeast part of Block G/82-G-7, and has identified another undrilled structure in the northeast part of Block B/82-G-7, west of the surface trace of the Flathead fault. Potential reservoirs on these structures include the middle Peechee Member shelf-edge reef, as well as the Palliser Formation and the Rundle Group. The marginal development of these reservoirs in the Shell North Kootenay Pass b-58-H/82-G-7 well to the east further points to the reservoir risk in this setting. This duplex trend also continues to the south into Montana.

North of the Flathead gas field, the Shell North Kootenay Pass b-58-H/82-G-7 well was drilled on a duplex trend that diverges from the Flathead gas field and follows the leading edge of the Lewis thrust to the north. It encountered marginal reservoir in the Rundle Group and the Palliser Formation, shelf dolomite and anhydrite in the Peechee Member, and tested salt water[33] 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 (Map 1), encountered Paleozoic strata 300m higher (in the same sheet?), but did not encounter effective reservoir in either Rundle or Rocky Mountain strata. It drill stem tested $4x10^3m^3/d$ (135Mcf/d) from the Livingstone Formation.

East of the Flathead gas field, only two wells have been drilled to test thrust faulted Paleozoic strata beneath the Lewis thrust in the Flathead area (Cross section 1), and another has been drilled immediately to the east in Alberta. None encountered economic reservoir in the Rundle Group, although the Shell West Castle 5-7 well flowed gas at rates of $2x10^3m^3/d$ (83Mcf/d), and the Shell Middlepass a-95-L/82-G-1 well flowed gas from the Livingstone with a 2m flare[34] (Tables 3 and 5). These results underscore the reservoir risk in the Rundle in this part of the Flathead area, but the two wells in British Columbia are 20km apart. Furthermore, Devonian strata were not encountered in these wells, so that the Palliser Formation and locally the middle Peechee Reef trend are prime objectives on structures in this area.

Gas composition is a significant factor in prospects in Paleozoic strata beneath the Lewis thrust. As noted above, the CO_2 content of the gases in the Flathead gas field varies between 20% and 100% (Table 5). The source of the CO_2 may be contact metamorphism of Paleozoic carbonates by Cretaceous intrusives, in particular the alkaline 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 demonstrate that gas composition varies over short distances laterally as well as stratigraphically. Furthermore, the gas composition in Mississippian strata appears to be 9% CO_2 and 76% methane in the Shell Middlepass a-95-L/82-G-1 well, 4km east of the Flathead gas field (Table 5), and 0.1% CO_2 and 92% methane in the Shell West Castle 5-7-4-3W5 well further east in Alberta (*see* footnote 34). The Flathead gas field may have trapped the CO_2 migrating updip from igneous source areas to the west, such that hydrocarbon gases could predominate east of the Flathead gas field. If this hypothesis is correct, the untested sub-Lewis structures northwest of the Flathead gas field identified by Charters (1989) and other

[33] 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.

[34] The tests on both wells may include a contribution from the Fernie Formation. The gas flow in the Shell Middlepass well occurred in the annulus behind casing and was interpreted, on the basis of a noise log, to be from the Livingstone Formation immediately above a thrust fault over Fernie strata. The drill stem test interval in the Shell West Castle included Fernie as well as Paleozoic strata, and the gas analysis is reported to be from a gas kick in Fernie strata 60m *above* the test interval. The kick is close enough to the test interval to appear to have been the basis for the test.

potential structures west of it are likely to be CO_2–prone. As in other areas of the Foreland Belt, hydrocarbon gases in carbonate reservoirs are likely to be associated with H_2S.

CO_2 has potential application in enhanced oil recovery and possibly in coalbed methane projects. The Flathead CO_2–rich gaswells were abandoned because reserves were insufficient to justify development in the oil price regime of the late 1980's. However, this gas field represents a significant established CO_2 resource, and the rights there are currently available.

Osadetz *et al.* (1995)[35] have estimated the mean resource potential for thrust faulted Paleozoic reservoirs below the Lewis thrust in southwestern Alberta, southeastern British Columbia and northwestern Montana to be $752x10^9m^3$ (26,677BCF) RIGIP, of which $221x10^9m^3$ (7,833BCF) has been discovered. They estimated that the remaining $531x10^9m^3$ (18,844BCF) occurs in 172 pools (mean estimate) and that the largest pool has a median potential reserve of $291x10^9m^3$ (10,325BCF). They predicted that much of this potential might be in untested parts of the Montana thrust belt. However, a significant volume could also be in structures adjacent to established gas pools in southeastern British Columbia.

Faulted and Folded Paleozoic Strata Above the Lewis Thrust

In the Flathead area, Paleozoic strata are present in Lewis and higher thrust sheets below the MacDonald thrust (Map 1, Cross section 1). The principal potential reservoirs in this setting are the Cambrian Elko Formation, the Devonian Hollebeke, Borsato and possibly the Nisku Formations, and the Mississippian Rundle Group. Paleozoic strata are widely exposed in the MacDonald Range, so that flushing by surface waters is a major risk in this area. Furthermore, Lower Cretaceous alkaline intrusives outcrop widely, and could have provided the Paleozoic reservoirs with an initial charge of CO_2–rich gas. Two wells, both unsuccessful, have been drilled in this setting (Table 3). The CIGOL IOE *et al.* Howell a-16-B/82-G-7 was drilled on the Howell Creek structure. Below an Upper Cretaceous sequence interpreted to be a slide block (Jones, 1977), this well penetrated a normally faulted Paleozoic sequence intruded by igneous rocks, and terminated in Precambrian strata (Labreque and Shaw, 1973). The Shell MacDonald b-30-H/82-G-2 well was drilled in the southern part of the MacDonald Range on a culmination exposing Mississippian strata. This well penetrated an unfaulted sequence down to the Grinnell Formation of the Purcell Supergroup (Boberg, 1984), and tested fresh water from the Hollebeke Formation (Cross sections 1 and 2).

Paleozoic strata in the Lewis thrust sheet have more potential beneath Mesozoic and Tertiary strata in the Kishenehn Basin, where they may have been protected from flushing by surface waters. Potential traps in this setting are likely to be controlled primarily by normal faulting. Although source rocks are present in the Exshaw Formation, the Fernie Formation, and the Mist Mountain Formation coals, hydrocarbon migration preceded structural trap development (Hannigan *et al.*, 1993). These source rocks reached peak maturation before and during the Laramide Orogeny. The potential Paleozoic reservoirs were uplifted along the Lewis thrust

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

during the Laramide Orogeny, and were downfaulted to their present position later. Consequently, structural trapping of hydrocarbons from pre-Laramide sources in this setting would likely have involved remigration from stratigraphic and Laramide structural traps. However, deeply buried oil shales of the Kishenehn Formation could also potentially provide a hydrocarbon source.

Hannigan *et al.* (1993)[36] have estimated the mean gas resource potential for structural traps in Paleozoic carbonates above the Lewis thrust to be $3.4 \times 10^9 m^3$ (121BCF) RIGIP. They estimated a mean population of 5 pools, the largest of which has a median size of $1.8 \times 10^9 m^3$ (65BCF). Only 12% of the play area is in British Columbia and the remainder is in Montana. However, this is a conceptual play (terminology used by Hannigan *et al.* (1993) where no pools have yet been discovered), and is subject to significant risks, including reservoir, timing of migration, and gas composition. As with prospects in Paleozoic carbonates beneath the Lewis thrust fault, gases may be rich in CO_2 and include H_2S.

Another possible setting for hydrocarbons in Paleozoic strata above the Lewis thrust not included in the Hannigan *et al.* (1993) appraisal is west of the Rocky Mountain Trench in structures beneath thrust sheets of the Purcell Supergroup. Both the ARCO Marathon No. 1 Paul Gibbs well in nw ne 2-28N-27W in Montana and the DEI *et al.* Moyie d-8-C/82-G-5 well in British Columbia, were drilled to test structures in this setting (Boberg, 1985; Harrison *et al.*, 1985; Fritts and Klipping, 1987a, b; Boberg *et al.*, 1989). As described above, these wells penetrated only Purcell rocks, and demonstrated that the diorite sills in the Aldridge Formation were the sources of both the prominent seismic reflectors and positive gravity anomalies observed in structures in that area. More recently, Root *et al*., (2000) have revived this concept and proposed that west of the southern Fernie Basin, Paleozoic strata could be prospective beneath the MacDonald thrust as far as the Moyie anticline in the Purcell Mountains, below the DEI *et al.* Moyie well. This interpretation requires 60km of displacement on the MacDonald thrust. However, displacement on the MacDonald thrust in the Flathead area may not be of this order of magnitude. Mississippian and Devonian strata are in fault contact with Precambrian strata in windows through the MacDonald thrust a few kilometres southwest of where both hanging wall and footwall occur in the Fernie Formation (Map 1; Cross section 1; Price, 1962a; Harrison *et al.*, 1992). Unless these Paleozoic outcrops represent horses, Paleozoic strata are unlikely to extend far west beneath the MacDonald thrust. Although displacement on the Bourgeau-MacDonald thrust increases northward and may be in the order of tens of kilometres in the northern part of the Fernie-Elk Valley area, it is unlikely to increase to 60km adjacent to the southern Fernie Basin if it is only 2 to 5 km at locations 25 km to the south because the fault parallels regional strike between these locations. Neither Yoos *et al.* (1991) or van der Velden and Cook (1994, 1996) interpret large displacement on the MacDonald thrust in the Flathead area or adjacent parts of Montana. In addition to the structural risks presented by this concept, significant reservoir risk exists because Paleozoic strata were deposited in progressively deeper water to the west and the prospective reservoirs appear to deteriorate in that direction.

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[36] Their MacDonald Paleozoic Structural Gas Play.

Fairholme Group Stratigraphic and Combined Stratigraphic-Structural Traps

As described above, the middle Peechee shelf-edge reef trend could be prospective where it crosses sub-Lewis structures northwest and to the east of the Flathead gas field (Map 2). Because the middle Peechee shelf-edge reef is a prograding feature, parallel shelf-edge reefs may occur in the lower and upper Peechee, respectively to the east and to the west of the middle Peechee reef trend (Cross section 2). Furthermore, if structures east of the Flathead gas field do not involve Devonian strata, stratigraphic traps could occur in the middle and lower shelf-edge reefs where they change facies to the east into shelf dolomites and anhydrites. As with the plays previously described, gas composition is a significant risk in Peechee shelf-edge reefs. To the north and west of the Flathead gas field CO_2–rich gas could be anticipated, but hydrocarbon gases could predominate to the east. H_2S is likely to occur with hydrocarbon gases.

Peechee pinnacle reefs occur in outcrop in the Lewis thrust sheet, so that a pinnacle reef play could exist southwest of the shelf-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 flushing and to the 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. However, potential reserves in Peechee pinnacle reefs may not be large (e.g. $470x10^6m^3$ – or 17BCF for $1km^2$ 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. Such prospects could occur in the Lewis thrust sheet in the western MacDonald Range, but as with the Peechee pinnacles, would be difficult to pursue.

Mesozoic Structural-Stratigraphic Traps Below the Lewis Thrust

The Jura-Cretaceous Mist Mountain Formation, the Lower Cretaceous Blairmore Group, the Upper Cretaceous Alberta Group and the Upper Cretaceous Belly River Formation have potential beneath the Lewis thrust east of the Flathead gas field (Map 2; Cross section 1). In all cases, plays have a strong stratigraphic component. Thin porous zones may occur in sandstones and conglomerates in the Mist Mountain Formation and locally be prospective on structures above the Fernie detachment. However, this interval is thin and the proportion of sandstone is low, so that potential in this interval appears to be minor (Cross section 4).

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 (Cross section 1). The orientation of the prospective trends in the Cadomin may vary from northeast to northwest (Leckie and Cheel, 1997). The Shell Grouse d-66-G/82-G-1 well appears to have encountered a thick and possibly productive conglomerate trend. The Cadomin in this well is thicker (35m) and richer in conglomerate than in other wells in this setting and a gas detector response increase was reported in this interval (Cross section 4). Although porosity is low, the conglomerate may provide sufficient permeability for economic production. 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.

Hannigan *et al.* (1993)[37] 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) 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 (mean estimate). 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 contain more gas than oil. Furthermore, Blairmore conglomerates overlie 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 are discontinuous and have low porosity, so prospects in these strata have a high reservoir risk and have the greatest potential where conglomerates are present. Like most Cardium trends in Alberta, potential reservoirs are likely to trend northwest, parallel to structural strike. A gas show is reported in deformed Cardium strata immediately beneath the Lewis thrust in the Shell Grouse d-66-G/82-G-1 well.

Osadetz *et al.* (1995)[38] have estimated a mean gas resource potential of $27.6x10^9m^3$ (980BCF) RIGIP in 212 pools (mean estimate) for marine sandstones in the Alberta Group in the Foreland Belt in southwestern Alberta, southeastern British Columbia and northwestern Montana. They estimated the median size of the largest pool to be $6.6x10^9m^3$ (234BCF). Of this total, $0.199x10^9m^3$ (7BCF) has been discovered. Only 4.5% of the play area is in British Columbia. 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

[37] Their Waterton Mannville Foothills gas and oil plays. In a later revision of this work, Osadetz *et al.* (1995) estimated a mean gas resource potential of $34.5x10^9m^3$ (1226BCF) in 118 pools (mean estimate). They estimated the median size of the largest pool to be $1.3x10^9m^3$ (46BCF).

[38] Their Waterton Colorado Foothills gas and oil play.

Alberta, but are very difficult to predict. The equivalent Greenhorn Formation is locally an oil reservoir on structures in the Foreland Belt in Montana (e.g. Garner, 1985)

Sandstones in the Upper Cretaceous Belly River Formation are potential reservoirs, in particular the fluvial and/or deltaic sandstone at the base, which appears to be a unit that is correlatable between wells. However, the porosity in this sandstone is low, and the potential minor.

Mesozoic Structural-Stratigraphic Traps Above the Lewis Thrust

In the Flathead area, potential reservoirs in Mesozoic strata above the Lewis thrust would occur only where these strata are preserved beneath the Kishenehn Basin. 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. As with the Paleozoic strata above the Lewis thrust, potential traps in this setting would be partly controlled by normal faulting, which postdated peak hydrocarbon generation from the pre-Laramide source rocks. However, there could also be a stratigraphic component to trapping in this setting. These potential reservoirs are interbedded with and overlie the thick Mist Mountain coals, which are a significant potential gas source, although the coals may now be undersaturated due to reburial. Lacustrine oil shales of the Kishenehn Formation could also provide a source for these potential reservoirs. The hydrocarbon potential in this setting is probably minor.

Hydrocarbons in the Oligocene Kishenehn Formation

The Oligocene Kishenehn Formation forms the fill of the half graben created by slip on the Flathead fault, and is an important exploration target in the Flathead area (Map 2; Cross section 1). The total basin fill is locally up to 4270m.

In the lower member, potential reservoirs include fluvial sandstones and conglomerates, and friable sand units greater than 30m thick occur near the base of the member (Jones, 1969a). The megabreccias of the upper member, which are interpreted to represent slide deposits, could also be significant reservoirs. Analogous deposits in a similar tectonic setting in Railroad Valley, Nevada form prolific reservoirs (Read and Zogg, 1988; French, 1991, 1993, 1996; Montgomery *et al.*, 1999). The largest of these fields is Grant Canyon, in which the estimated primary recovery is $3.2x10^6m^3$ (20mmbo) from 3 wells in a 120ha (300 acre) area (Johnson and Schalla, 1996). In the Kishenehn Formation, both structural traps, related to normal faulting, and stratigraphic traps could be anticipated. Normal faults in the MacDonald Range extend into the Kishenehn Basin, and cut Kishenehn strata at the basin margin (Map 1; Cross section 1; McMechan, 1981). The thick sandstone units in the lower part of the lower member would probably provide the best reserve potential in fault traps, whereas megabreccia could provide large reserves in stratigraphic traps. Stratigraphic traps could also occur in fluvial and lacustrine sandstones interbedded with lacustrine shale and marl deposits in the lower member. Gravity anomalies within the Kishenehn Basin in British Columbia (*see* Strauss, 1984) could represent either fault or slide blocks.

The lacustrine oil shales and bituminous marls of the lower member of the Kishenehn are excellent source rocks (MacKenzie, 1916; Constenius and Dyni, 1983; Veres, 1985; Curiale, 1987; Curiale and Sperry, 1987; Curiale *et al.*, 1988). Although they are generally immature where exposed on the western side of the Kishenehn Basin, they are likely to have generated liquid hydrocarbons to the east where they are buried in deeper parts of the basin. The quality and maturity of the source rock is greatest in the southern parts of the basin but significant hydrocarbon source potential is present in the northern part - oil shale with up to 35.63% total organic carbon occurs in British Columbia. Oil and gas shows have been observed in shallow wells in the basin, indicating that hydrocarbons have been generated (Tables 2 and 4; Boberg, 1983, 1984).

Eight wells have been drilled in the Kishenehn Formation, but only 3 are more than 1000m deep and all of them are near the western margin of the basin (Map 1; Tables 2, 3, and 4). The Canadian Kootenay #1 b-50-D/82-G-1 well was drilled in 1950 and was located primarily on the basis of access (Boberg, 1984). It bottomed in the Kishenehn Formation at 1097m[39]. The Chevron Mobil Flathead d-22-H/82-G-2 well is located at the northwest end of the basin, and penetrated 2221m of Kishenehn conglomerate and breccia without encountering the base. The coarse-grained facies encountered by this well probably reflects its marginal position in the basin, possibly on a major stream channel entering the basin. This interpretation is consistent with the apparent location of this well on a pre-Kishenehn erosional low (*see* section on reservoir development). Only log data are available for the Cenex Ladenburg #4-13 se nw nw 13-34N-21W well in Montana, which is located on the western margin of the basin and it is interpreted to have penetrated 993m of Kishenehn strata before encountering Purcell strata. None of the deeper wells have been drilled on seismically defined targets in the deeper parts of the basin where greater interbedding of fine source rocks and coarse potential reservoirs could be anticipated.

Lacustrine basins can be prolific hydrocarbon producers, notably in the western United States[40] (e.g. Uinta Basin), China and in rift basins in offshore Brazil and Angola (e.g. Katz, 1990, Smith, 1990; Caroll *et al.*, 1992; Gierlowski-Kordesch and Kelts, 2000; Bohacs *et al.*, 2000). The optimum conditions for preservation of source rocks in ancient lake systems occur in the Fluctuating-Profundal Facies Association, as defined by Carroll and Bohacs (1999) and Bohacs *et al.* (2000). However, good source rocks can be preserved in the Fluvial-Lacustrine Facies Association, such as in the lower member of the Kishenehn Formation, where deposition occurred in a thermally stratified lacustrine basin. Source rocks in the Fluvial-Lacustrine Facies Association are capable of generating both gas and oil, which is generally very waxy. Many productive lacustrine basins are larger than the Kishenehn Basin, but several productive basins of

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[39] The presence of sub-bituminous coal at the bottom of this well confirms that it did not reach Cretaceous or Jurassic strata, in which coals have higher rank.

[40] Although the Kishenehn Basin is similar structurally to the Railroad Valley of Nevada and may contain similar reservoirs, the distribution of source rocks is different. Potential source rocks occur *within* the Kishenehn Basin fill, but the slide block reservoirs in the Railroad Valley are sourced from extrabasinal Mississippian strata that are separated from Tertiary basin fill by several unconformities and variably preserved beneath the basin (Poole and Claypool, 1984; Barker and Peterson, 1991; Peterson, 1994).

similar size, structure and facies occur in eastern China (Hu, 1985; Li and Luo, 1990). These basins are commonly less than 1000km^2 in area, are structurally half grabens, have mixed organic matter, and produce waxy oils. Pools occur in both stratigraphic and structural traps, involving reservoirs in alluvial, deltaic and lacustrine sandstones, carbonates and pre-basinal rocks. Production volumes are very high, with 2.3x10^{6}m^3 (14.5x10^6 barrels) being produced annually from one field. Although the east China basins have thicker source beds, these basins demonstrate that small lacustrine basins with effective source rocks, such as the Kishenehn Basin, can be significant hydrocarbon producers. Hu (1985) reported that defining the oil-generating area was the key to finding hydrocarbons in these basins.

Hannigan *et al.* (1993)[41] have estimated mean gas resource potential of 17.88 x10^{9}m^3 (635BCF) RIGIP and a mean oil resource potential of 61 x10^{6}m^3 (382x10^6 barrels) OOIP in the Kishenehn Formation in Montana and British Columbia. They estimate that 50 gas and oil pools (mean estimate) could be present, the largest of which would contain 3.1x10^{9}m^3 (110BCF) and 9.1x10^{6}m^3 (57x10^6 barrels), respectively. Seventeen percent of the play is in British Columbia. Although this play is unproven, it represents a high potential objective in the Flathead area. Oils in the Kishenehn Basin are likely to be waxy.

Hydrocarbons in the Rocky Mountain Trench

The Miocene St. Eugene Formation forms the upper part of the post Laramide sedimentary fill of the Rocky Mountain Trench. This sedimentary fill probably exceeds 1500m in the basins defined by the Waldo and Jaffray gravity lows (Map 2; Cross section 1; Garland *et al.*, 1961; Thompson, 1962). By comparison with the Kishenehn Formation and Tertiary sequences in the post Laramide basins of western Montana the fill of the Rocky Mountain Trench basins could consist of an Oligocene fine-grained fluvial and lacustrine unit and a Miocene coarse-grained unit, represented by the St. Eugene Formation. As in the Kishenehn Formation, potential reservoirs in this succession would include fluvial sands and conglomerates as well as megabreccias, potential source rocks could occur in the lower lacustrine unit, and potential traps are likely to be both structural, related to normal faulting, and stratigraphic.

Several wells have been drilled in post Laramide basins in southwestern Montana to depths up to 4800m (Fields *et al*., 1985; Bryant, 1985; Constenius, 1988). Although commercial hydrocarbon production has not been established, oil and gas shows have been reported in some of these wells, particularly from the fine-grained lower section below 2000m[42]. Closer to the Flathead area, two water wells in the Rocky Mountain Trench in Montana flowed gas that was probably

[41] Their Kishenehn Tertiary graben gas and oil plays

[42] Fields *et al.* (1985) and Bryant (1985) report recovery of oil and gas on a drill stem test in the Amoco Production Co. #1 Carl Johnson sw sw 31-7N-9W well in Powell County, Montana. Although this oil recovery is reported on the State of Montana well completion report, it could not be verified on the drill stem test report, which did not indicate the type of fluid recovered. The drill stem test indicated low permeability.

biogenic in origin and was used for domestic purposes (Boberg, 1984; Hannigan *et al*., 1993). A significant factor in the hydrocarbon potential of the Rocky Mountain Trench in British Columbia is whether potential source rocks have been buried deeply enough to generate liquid hydrocarbons. Fritts and Klipping (1987b) report that a soil geochemical survey in the Rocky Mountain Trench in the vicinity of the Spectra Energy #1 Stoltze Lumber well in nw ne sw 26-31N-21W, south of the Flathead area in Montana, suggests the presence of mature oil-prone source rocks. Although the Spectra well penetrated only 450m of Tertiary strata, they interpret the thickness of the Tertiary section to be up to 1800m in this part of the Rocky Mountain Trench, similar to the thickness of Tertiary fill in the Waldo and Jaffray sub-basins.

Hannigan *et al.* (1993)[43] have estimated mean gas resource potential of $0.8x10^9m^3$ (30BCF) RIGIP distributed in 170 pools (mean estimate), the largest of which has a median volume of $0.08x10^9m^3$ (3BCF). This estimate is based on the assumption that hydrocarbons in this setting are primarily biogenic gas, so that if source rocks were buried sufficiently deeply for liquid hydrocarbons to be generated, the potential reserves could be greater. However, the Rocky Mountain Trench basins are small, and their hydrocarbon potential is modest. Twenty-six percent of this play is in British Columbia.

COALBED METHANE POTENTIAL IN THE MIST MOUNTAIN FORMATION

The coal seams in the Jura-Cretaceous Mist Mountain Formation have high potential for coalbed methane in southeast British Columbia. The presence of gas in the coal in this area is well known, and has been a significant hazard for mining operations (e.g. Rice, 1918). Johnson and Smith (1991) have estimated the potential coalbed methane resource in the Elk Valley and Crowsnest Coalfields[44], north of the Flathead area, to be $222x10^9m^3$ (7.7TCF) and $344x10^9m^3$ (12.2TCF), respectively. Their estimate of the resource potential of the Flathead Coalfield, which is in the Flathead area as defined in this report, is much lower - $11x10^9m^3$ (0.4TCF). All the coalbed methane exploration activity in southeast British Columbia has occurred in the Elk Valley and Crowsnest Coalfields. The results of this activity and the local controls over economic coalbed methane production have been discussed in detail by Dawson *et al.* (1998, 2000) and Monahan (2000). These are not repeated in the following discussion, which summarizes the potential of the Flathead coalfield only.

The coalbed methane resource in the Flathead Coalfield occurs in 3 isolated areas – a faulted outlier of Kootenay strata on the North Kootenay Pass monocline (Map 1), and two areas of Kootenay Group outcrop on the north and west sides of the Flathead Valley (Map 3; Johnson and Smith, 1991). The coalbed methane resource estimates of the latter areas by Johnson and Smith include their downdip extensions beneath Kishenehn strata to a depth of 1500m. A fourth area of Kootenay outcrop in the Flathead Coalfield west of the Flathead Valley in the MacDonald Range was not included because coal is not buried deeply enough to retain adsorbed gas.

[43] Their Rocky Mountain Trench Cenozoic graben play.

[44] The Crowsnest Coalfield forms the axis of the Fernie Basin.

The Mist Mountain Formation is 110 to 185m thick in the Flathead Coalfield, less than half of its thickness in the Elk Valley and Crowsnest Coalfields (Johnson and Smith, 1991). Similarly, the average cumulative coal thickness in the Flathead Coalfield is 23m (range 18 to 29m), compared to greater than 50m in the coalfields to the north. Individual coal seams are generally 1 to 10m thick. Coal is generally medium volatile bituminous (Ro=1.11% to1.30%; Grieve, 1981a, 1987; Johnson and Smith, 1991), which is within the thermogenic gas generation window, like the Mist Mountain coals to the north. Consequently, coal in the Flathead coalfield has generated gas. However, coals in the margins of the Flathead Valley could be undersaturated. These strata reached peak maturation prior to and during the Laramide Orogeny. During the Laramide Orogeny, they were uplifted along the Lewis thrust, when they could have degassed, and they were downfaulted to their current position later. The effect of degassing during uplift could potentially be offset by biogenic methane generation, which has been reported in the Elk Valley Coalfield (Harrison and Barker, 2000).

The Mist Mountain Formation may have some coalbed methane potential beneath the Lewis thrust. The Mist Mountain Formation is thinner there due to truncation beneath the sub-Blairmore unconformity, but cumulative coal thicknesses are 10 to 30m (Cross section 4). Coal rank varies from high volatile bituminous C to medium volatile bituminous (Ro=0.6% to 1.3%; England and Bustin, 1986; Bustin and England, 1989), within the thermogenic gas window. The greatest potential in this setting occurs where these strata are both gently folded above the duplex of Paleozoic strata, potentially enhancing permeability (Cross section 1), and are less deeply buried beneath windows in the Lewis thrust. The Shell Honolulu Flathead d-22-A/82-G-7 well satisfies these criteria, and has a cumulative thickness of coal of 17m at an approximate depth of 1400m. This depth may not be within the limits of economic production. However, another factor to be considered in the economics of coalbed methane is the potential synergy with the CO_2 resources of the area, particularly in the Flathead gas field. 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

The Flathead area has significant hydrocarbon potential in several varied play types, which are summarized below in stratigraphic order. The most attractive exploration targets are Paleozoic and Mesozoic strata in structures below the Lewis thrust, and the Oligocene Kishenehn Formation.

Oil and gas seeps occur in metasediments of the Precambrian Purcell Supergroup, where they are thrust over Mesozoic and Paleozoic strata. These seeps sparked the earliest drilling activity in the area in the first part of the 20th Century, which resulted in minor production. Purcell strata have limited hydrocarbon potential because they have no matrix porosity, and production is entirely from fractures. The oil was probably sourced from Cretaceous and possibly older source rocks beneath the Lewis thrust

The greatest potential is in thrust faulted Paleozoic reservoirs beneath the Lewis thrust. In this setting, $17x10^9m^3$ (600BCF) of CO_2-rich gas has been discovered in a northwest-oriented trend of duplexes immediately east of the Flathead Valley. The principal reservoirs are the Mississippian Rundle Group, the Devonian Palliser Formation, and the Devonian middle Peechee Member shelf-edge reef, which trends northwest across the northern end of the duplex trend. Undrilled structures have been identified on seismic data northwest of the productive duplexes, and Devonian strata have not been tested on structures east of the productive duplexes in British Columbia. In addition to thrust faulted traps, the Peechee Member shelf-edge reef could form stratigraphic traps where it changes facies to interbedded shelf dolomites and anhydrites east of the productive duplex trend, if it is not involved in structures in that area. Peechee pinnacle reefs could also be present beneath the Lewis thrust, but could be very difficult to locate. Gases in this setting are probably CO_2-rich north and west of the productive duplexes, but may consist predominantly of hydrocarbons to the east. Hydrocarbon gases in Paleozoic carbonates would be sour. CO_2 has potential application in enhanced oil recovery projects and possibly in coalbed methane projects. The Flathead CO_2–rich gas field represents a significant established CO_2 resource, and the rights there are currently available.

Paleozoic strata have minor potential on structures in the Lewis thrust sheet, where the principal potential reservoirs are the Cambrian Elko Formation, the Devonian Hollebeke and Borsato Formations, and the Mississippian Rundle Group. In the MacDonald Range, Paleozoic strata are widely exposed and have been subjected to flushing by fresh water. Paleozoic strata in the Lewis thrust sheet have more potential beneath Mesozoic and Tertiary strata in the Kishenehn Basin, where they have been protected from flushing by surface waters. However, Paleozoic strata here were rotated and downfaulted into their current position after peak hydrocarbon generation and migration, which occurred during the Laramide Orogeny. Trapping here would require remigration of earlier pooled hydrocarbons, or contribution from Tertiary source rocks. Furthermore, these strata are close to igneous sources that could have provided reservoirs with an early charge of CO_2-rich gas. Peechee Member pinnacle reefs could occur in the Lewis thrust sheet, and because of their stratigraphic isolation, may have been less susceptible to flushing and the introduction of CO_2-rich gas.

Cretaceous strata have modest potential beneath the Lewis thrust sheet in combination structural-stratigraphic traps. The principal target in this setting is the Cadomin Formation, which is potentially productive on thick conglomeratic trends where they cross structures. One such thick trend appears to have been encountered in the eastern part of the Flathead area. Other potential Cretaceous objectives include conglomerate trends in the Beaver Mines and Ma Butte Formations of the Blairmore Group, sandstone or conglomerate trends in the Cardium Formation, and possibly the Belly River Formation, particularly the fluvial and/or deltaic basal sandstone. Cretaceous objectives could be gas or oil bearing, although gas is more likely in the lower parts of the Cretaceous.

Jurassic and Cretaceous strata have minor potential in the Lewis thrust sheet where they are buried beneath the Kishenehn Basin. The principal reservoir 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.

The Oligocene Kishenehn Formation fills the half graben formed by slip on the Flathead fault, and is locally up to 4750m thick. Potential reservoirs include fluvial and lacustrine sandstones and conglomerates, and megabreccias, which form prolific reservoirs in a similar setting in Nevada. In addition, lacustrine oil shales and bituminous marls in the lower part of the formation have probably generated liquid hydrocarbons where buried in the axis of the basin. These strata have been tested by only two deep wells that were based on modern exploration methods. These factors, as well as the production of significant volumes of oil in similar small lacustrine basins in China, indicate that the Kishenehn Formation has significant hydrocarbon potential in the Flathead area. Oil in this setting is likely to be very waxy.

Two smaller extensional basins, in which the basin thickness probably exceeds 1500m, occur in the southern Rocky Mountain Trench. The basin fill succession may be similar to the Kishenehn Formation, and potential reservoirs are likely to be comparable. The occurrence of biogenic gas in water wells in the Rocky Mountain Trench in Montana suggests that the hydrocarbon potential in these basins may be minor. However, lacustrine source rocks may be present, and locally may have been buried deeply enough to generate liquid hydrocarbons.

The coals of the Jura-Cretaceous Mist Mountain Formation are the targets of an active coalbed methane play in the Fernie-Elk Valley to the north. The prospective coal-bearing section is thinner and has a more restricted areal extent in the Flathead area. Furthermore, coals on the margins of the Flathead Valley may be undersaturated and this possibility should be evaluated. The Mist Mountain coals may have some potential below the Lewis thrust, particularly where they are arched over the duplex of Paleozoic strata and less deeply buried beneath windows in the Lewis thrust.

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