Petroleum evaluation of the Bob Marshall Wilderness and adjacent study areas, Lewis and Clark, Teton, Pondera, Flathead, Lake, Missoula, and Powell Counties, Montana

by

Dudley D. Rice

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Introduction

This report discusses the petroleum potential of the Bob Marshall Wilderness and adjacent wilderness study areas (fig. 13), which will be collectively referred to as the study area in much of the following discussion. This study will eventually be published as a chapter in a report on the mineral resources of the study area. The numbering of figures begins with 13 and those of tables begin with 8.

In general, the study area has a good potential for natural gas accumulations from Mississippian carbonate rocks. Reservoirs may also be present in the underlying Devonian carbonates, but these are unevaluated. Clastic rocks of Mesozoic age are secondary objectives because their reservoir qualities are generally poor. Likely source beds are marine shales in the Jurassic Ellis Group, the Mississippian Allan Mountain Formation, and the Mississippian-Devonian Bakken Formation, where present. Prospective traps are primarily structural. The faulted eastern edge of reservoir rocks in the upper plate of a thrust block is the primary type of trap; associated folds are a secondary type. Structural and stratigraphic changes associated with northeasterly-trending lineaments are especially favorable for hydrocarbon accumulations.

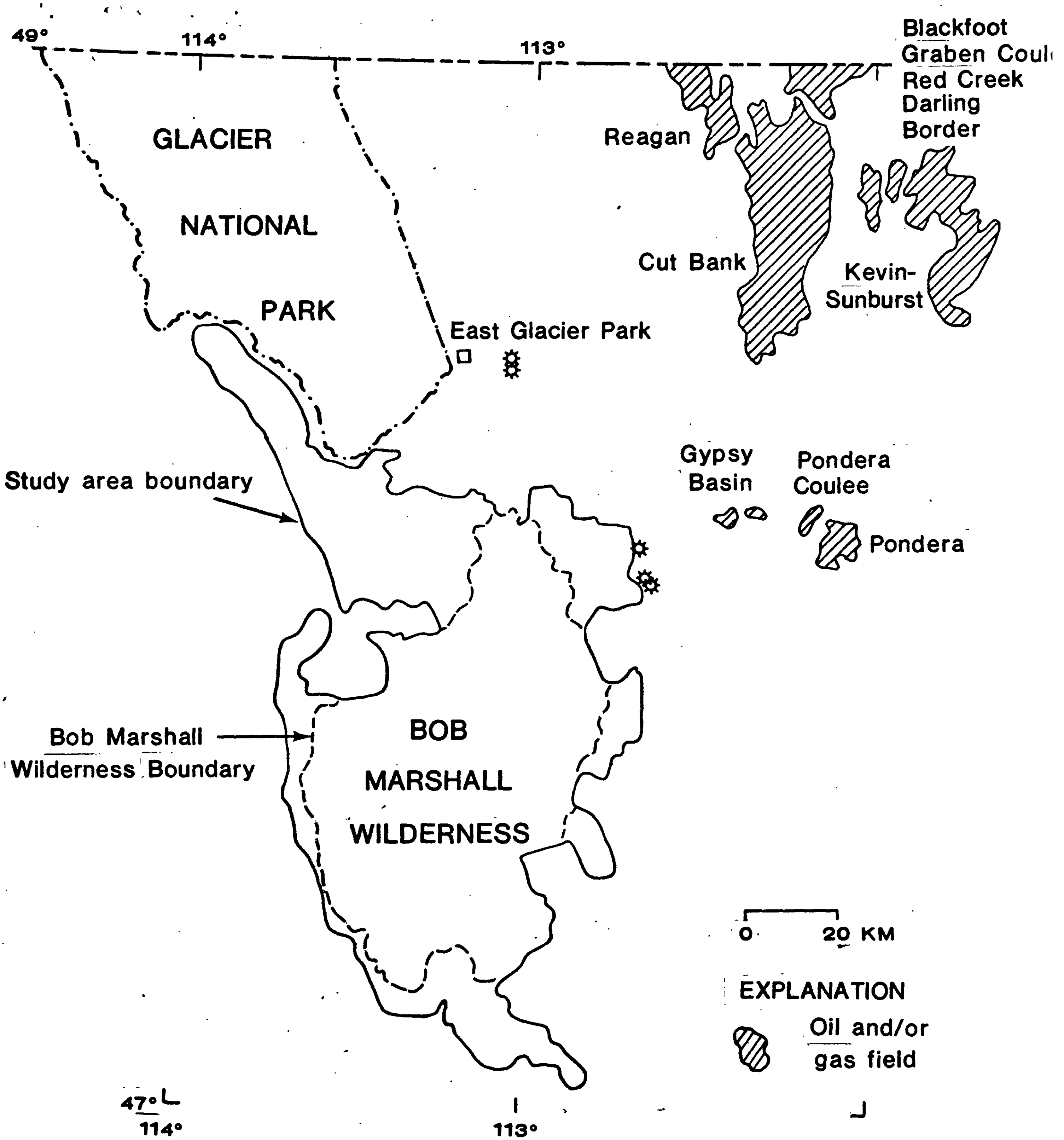

Figure 13.-Map showing location of Bob Marshall Wilderness and proposed additions with nearby oil and gas fields and wells in Montana (cross hashed pattern)

Although exploration for hydrocarbons has been limited within the study area, the petroleum potential has been assessed by: (1) surface mapping, because all of the prospective reservoir and source rocks which are probably present in the subsurface are exposed, and (2) examining productive areas in the southern Alberta Foothills to the north, which lie along the same structural trend as the eastern part of the study area, and on the Sweetgrass arch to the east. However, more detailed exploration efforts in the future, to include geophysical surveys and drilling, will be necessary to evaluate the potential fully.

The area is geologically divided into two parts. The eastern part is in the northern disturbed belt of Montana, which is characterized by numerous closely-spaced thrust faults and folds involving Paleozoic and Mesozoic rocks. The central and western section, west of the Continental Divide, contains mostly Precambrian belt rocks in thrust plates, with normal faults and broad open folds.

The search for hydrocarbons in the Montana disturbed belt and the mountains to the west has had limited success due to three factors. First, gas was discovered in several wells drilled in the 1950's near the southeastern boundary of the eastern part of the Great Bear study area, and in the vicinity of East Glacier Park (fig. 13). These wells were never produced because it was not economical at that time to transport the gas to markets. Second, the inaccessibility of the mountains has discouraged exploration. Third, previous exploration has been directed toward simple structural traps, such as anticlines, at relatively shallow depths. Potential hydrocarbon accumulations in the study area are probably structurally complex and at greater depths. The recent discovery of major hydrocarbon accumulations in southwestern Wyoming and northeastern Utah has renewed interest in the northern disturbed belt. These discoveries are important because they are large enough to offset the high costs of seismic surveys needed to interpret complex structures and of deep drilling. These discoveries, combined with the past success in the Canadian portion of the disturbed belt, suggest that the study area should be evaluated for its hydrocarbon potential.

Stratigraphy as related to petroleum potential

Sedimentary rocks ranging in age from Precambrian to Tertiary crop out in the study area; strata from the Ordovician, Silurian, Pennsylvanian, Permian, and Triassic systems are not represented. Details of lithologies and thicknesses are given by Mudge (1972A) and Mudge, Earhart, and Rice (1977). For the purposes of petroleum evaluation, Devonian and younger rocks are briefly discussed in reference to known reservoir and source rocks. Older rocks are not included in the discussion because of their lack of hydrocarbon production or significant shows in the adjacent areas. Figure 14 shows correlations of productive stratigraphic intervals in the Sweetgrass arch and in the southern Alberta Foothills with potential reservoir rocks in the study area.

Devonian rocks unconformably overlie Cambrian rocks in the study area, and range in thickness from 950 ft (290 m) in eastern outcrop to more than 1,500 ft (457 m) in western outcrop. The sequence is mostly carbonate rocks; mudstone is in the lower part, and the upper part contains evaporite solution breccia.

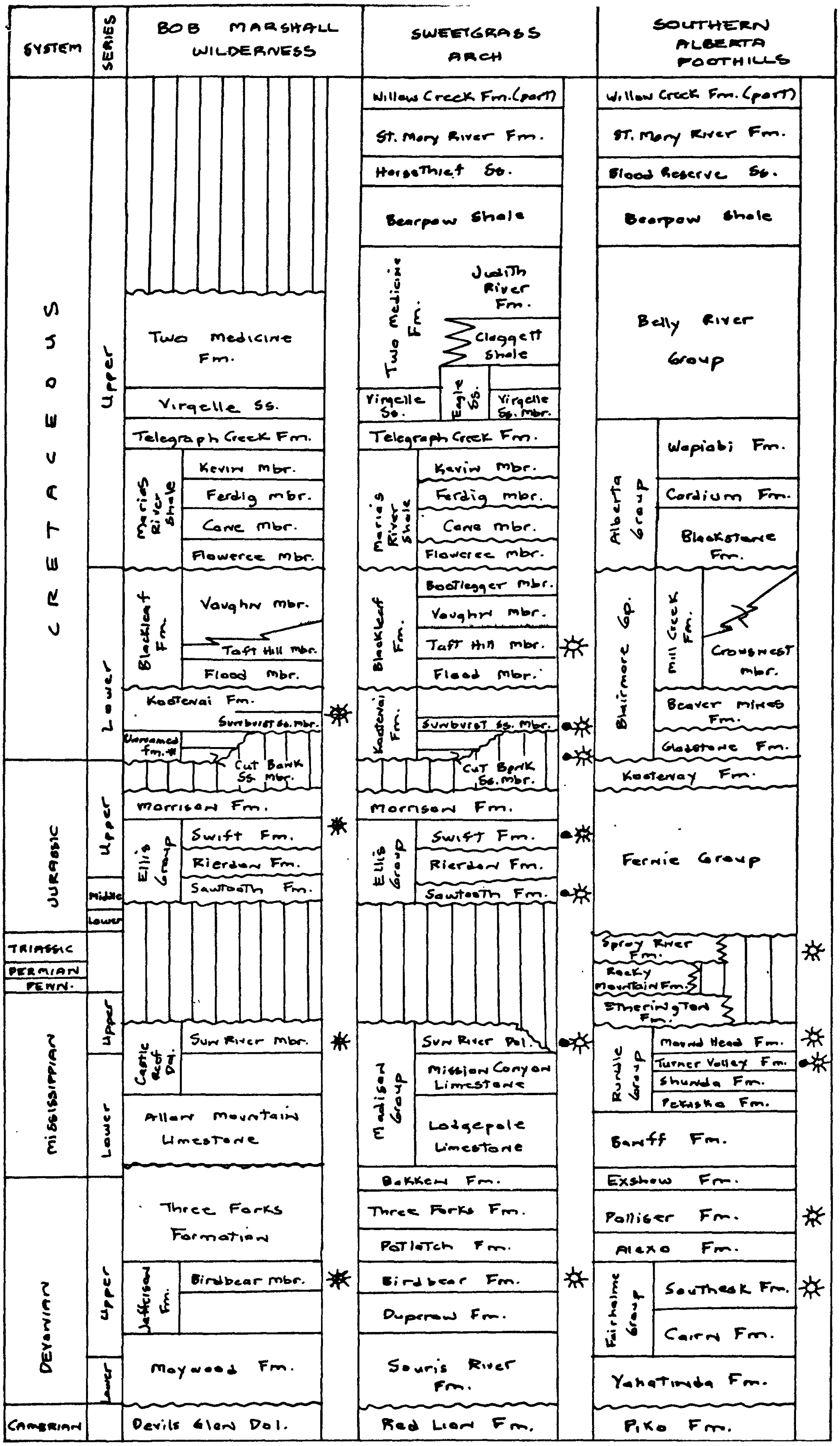

Figure 14.-Correlation chart for Bob Marshall Wilderness, Sweetgrass Arch, and southern Alberta Foothills showing productive intervals. (● oil, ☼ gas) and prospective intervals (✷).

*Unnamed formation crops out northeast of the study area and may be present in the subsurface to the north.

In the 1950's natural gas was tested from a well in the Jefferson, and lower part of Three Forks Formations east of the Great Bear study area. The Palliser Formation and upper part of the Fairholme Group are secondary reservoirs for natural gas in a field in the southern Alberta Foothills. Recently, commercial quantities of gas were discovered in the Birdbear Formation on the Kevin-Sunburst dome (Sweetgrass arch). Generally, however, exploration efforts have overlooked Devonian carbonates because they are deeper than the major Mississippian reservoirs.

The Mississippian section, which ranges in thickness from 900 ft (274 m) to 1,700 ft (518 m), is primarily carbonate and unconformably overlies the Devonian. The lower part of the Allan Mountain Limestone contains numerous interbeds of shale.

Mississippian carbonates are an important hydrocarbon reservoir in the Rocky Mountain region. On the Sweetgrass arch, Chamberlain (1955) reported that Mississippian rocks are the primary reservoir in several fields. Several shut-in wells east of the study area tested natural gas in the Sun River Member of the Castle Reef Dolomite. In the Alberta Foothills, Mississippian rocks are the primary reservoir in all of the fields.

Dow (1974, p. 1257) identified the Lower Mississippian-Upper Devonian Bakken Formation as the principal hydrocarbon source bed for Mississippian reservoirs in the Williston basin in eastern Montana and western North Dakota. The Bakken is present on the Sweetgrass arch, and is locally present and included in the Three Forks Formation just east of the study area. These black, organic-rich shales along with those in the lower Allan Mountain Limestone are likely source beds for hydrocarbons entrapped in Devonian and Mississippian rocks. Gallup (1951, p. 814) considered the Banff Formation and upper part of the Rundle Group as the source bed for the oil and gas in the Turner Valley field in Alberta.

Jurassic rocks unconformably overlie the Mississippian carbonates, and range in thickness from 485 ft (148 m) in the east to 1,175 ft (358 m) in the west. Most of this sequence is assigned to the Ellis Group, which is mostly shale, with some sandstone, siltstone, and limestone. The Ellis Group is overlain by the nonmarine Morrison Formation of Late Jurassic-Early Cretaceous age.

The upper member of the Swift Formation of the Ellis Group contains interbedded sandstone which is the main oil producer at Flat Coulee field in Liberty County (Radella and Galuska, 1966). Both this interval in the Swift, and porous zones in the Sawtooth Formation, locally produce hydrocarbons in several fields on the Sweetgrass arch where the main reservoirs are Mississippian or Cretaceous rocks.

Dark, organic-rich shales in the Sawtooth, Rierdon, and lower part of the Swift Formations, are potential hydrocarbon source beds in the study area. My investigations indicate that the Sawtooth and lower Rierdon shales are the source for the oil and gas in Cretaceous and Mississippian reservoirs at the Cut Bank field (fig. 13).

The Cretaceous system in the study area is a clastic sequence as much as 7,000 ft (2,134 m) thick that is mainly marine except for the Kootenai Formation, Vaughn Member of the Blackleaf Formation, and Two Medicine Formation. As discussed by Mudge (1972A), the thickening of many units to the west indicates proximity to a source area. Igneous sills of very Late Cretaceous to Early Tertiary age, which average 500 ft (152 m) thick, intruded strata of the Kootenai and Blackleaf Formations. The lack of intense metamorphism associated with the intrusion of the sills suggests that they probably did not affect potential hydrocarbon accumulations.

Discontinuous channel sandstones in the Kootenai Formation, including the Cut Bank, Sunburst, and Moulton Members, are the primary producing horizons in the Cut Bank field (Blixt, 1941) and other fields on the Sweetgrass arch. In addition, gas has been produced from shallow wells in marine sandstones in the Taft Hill Member of the Blackleaf Formation in several fields in this area. Although these sandstones produce hydrocarbons to the east, abundant clay plus other diagenetic effects caused by deformation has greatly reduced the reservoir potential of these sandstones in the study area.

Marine shales in the Blackleaf and Marias River Formations are potential source beds in the Cretaceous sequence. Stebinger (1918, p. 161-162) noted the source rock characteristic of the Cone Member of the Marias River Formation in the Birch Creek-Sun River area, and reported that distillation tests from these shales yielded the equivalent of 1 to 2 gallons of oil per ton (4.2 to 8.3 liters per tonne).

Structural geology

The structure of the study area as interpreted from surface mapping is important to the evaluation of hydrocarbon potential. Evidence from producing fields in the Alberta Foothills suggests that potential traps in the study area are structurally controlled and locally enhanced by facies changes.

The structural setting of the eastern part of the study area is comparable to that in the foothills of Alberta. This part consists of numerous northerly-trending, westerly-dipping thrust faults with some folds and normal faults. The ridges are composed of Paleozoic carbonate rocks; the valleys are clastic rocks of Mesozoic age. The central and western part contains northerly-trending normal faults and broad open folds composed of Precambrian belt rocks locally overlain by Paleozoic rocks. Northwesterly-trending folds, part of a sequence of folded thrust plates, are along the eastern and western sides of the Sawtooth Range. Similar folded plates may lie beneath Lewis and South Fork thrust plates in the Lewis and Clark Range. Many of the structures have been described in chapter A of this report, and by Childers (1963), Deiss (1943), Sommers (1966), and Mudge (1972B).

Most of the northerly-trending faults and folds in the study area are a result of gravitational gliding from a western uplift that was formed during an early Tertiary (Paleocene-late Eocene) orogeny (Mudge, 1970). Structural closures resulting from this tectonism are the primary traps for major hydrocarbon accumulations in the Alberta Foothills, and similar traps are present in the study area, particularly in the eastern part.

Northeasterly lineaments and trends are in the study area. The lineaments are an alignment of topographic and structural features that may result from structures older than the northwesterly-trending early Tertiary faults and folds. The trends are an alignment of gravity and magnetic features that may not necessarily be related to lineaments. The Lick Creek-Pendroy fault trend is also represented by a lineament.

In the study area, the southernmost trend is the Brown Sandstone-Brady trend (Kleinkopf and Mudge, 1972). The Lick Creek trend may tie with the Pendroy fault in the plains, where it appears to be related to hydrocarbon occurrences. The Pondera oil field lies south of the zone in the upthrown block (Leskela, 1955, p. 168). Farther west, gas wells just east of the eastern Great Bear study area are probably on the downthrown block of the southwesterly extension of this fault zone. The Schafer Meadows-Cox Creek trend is near the north edge of the wilderness. Mudge, Earhart, and Rice (1977, p. 21-22) pointed out significant structural and stratigraphic changes which occur in the northern part of the Sawtooth, and Lewis and Clark Ranges which may occur north of the eastern extension of the Schafer Meadows-Cox Creek trend.

Thomas (1974) described a major northeasterly and northwesterly-trending lineament block system in the greater Williston basin-Blood Creek syncline area in eastern Montana. He documented with examples the proven effect these trends had on local stratigraphy and petroleum occurrences in northeastern Montana (Thomas, 1974, p. 1319-1320). More detailed studies may show the influence of similar lineaments in the study area on both stratigraphy and structure, and possible hydrocarbon entrapment.

Oil and gas fields in adjacent areas

Hydrocarbons have not been produced within the study area, although several shut-in gas wells are adjacent to the eastern part of Great Bear study area, and in the vicinity of East Glacier Park (fig. 13). These wells, mostly drilled in the 1950's, are listed in table 8 with production data. Hurley (1959) reviewed the exploration history of these and other wells in the northern disturbed belt. Core analyses from the Northern Natural Gas No. 1 Blackleaf-Federal "A" well, which tested 6.3 million cubic feet (178 thousand cubic meters) of gas per day, indicate a net productive interval of 135 ft (41 m) in the Sun River Member of the Castle Reef Dolomite, with porosity ranging from 2.9 to 11.6 percent and permeability ranging from 0.1 to 37 millidarcies (Hurley, 1959, p. 106). These reservoir characteristics are similar to those in fields in the Alberta Foothills. There has been relatively no exploration since these wells were drilled.

Table 8.--Shut-in gas wells in the northern disturbed belt of Montana

Name	Location	Producing formation and depth	Initial potential flowing
Northern Natural gas 1 Blackleaf - Federal "B"	NE¼ SW¼ sec. 19, T. 26 N., R. 8 W.	Sun River Mbr. Castle Reef Dol. 5280-5300 ft (1609-1615 m)	969 MCFGPD (27 MCMGPD)
Northern Natural Gas 1 Blackleaf - Federal "A"	SE¼ NE¼ sec. 13, T. 26 N., R. 9 W.	Sun River Mbr. Castle Reef Dol. 3794-3830 ft (1156-1167 m)	6293 MCFGPD (178 MCMGPD)
Texaco 1 Government - Pearson	SW¼ SW¼ sec. 26, T. 27 N., R. 9 W.	Three Forks Fm. Jefferson Fm. 2068-3360 ft (630-1024 m)	280 MCFGPD (8 MCMGPD)
Union Oil 1 Morning Gun	SW¼ SW¼ sec. 18, T. 31 N., R. 11 W.	Sun River Mbr. Castle Reef Dol. 8962-9087 ft (2732-2770 m)	500 MCFGPD (14 MCMGPD) 13 bbls. condensate
Great Northern Drilling 1 Two Medicine	SE¼ NW¼ sec. 19, T. 31 N., R. 11 W.	Sun River Mbr. Castle Reef Dol. 8895-9018 ft (2711-2749 m)	771 MCFGPD (22 MCMGPD) 13.6 bbls. condensate

MCFGPD - thousand cubic feet of gas per day.
MCMGPD - thousand cubic meters of gas per day.
bbls. - barrels.

East of the disturbed belt, significant oil and gas fields have been discovered on the Sweetgrass arch. Figure 13 shows the location of some of these fields with respect to the study area. Figure 14 shows the correlation of units on the arch with those in the study area and producing intervals. Production is mainly from stratigraphic traps locally enhanced by structure in Mississippian and Cretaceous reservoir rocks. Traps in the Upper Mississippian carbonates, such as the one at the Pondera field (Leskela, 1955), are caused by pinchouts of porous and permeable zones, and irregular erosion on the Jurassic-Mississippian unconformity. Lenticular channel sandstones in the Kootenai Formation are the primary type of trap for accumulations in Cretaceous rocks. Natural gas has recently been discovered in the Devonian Birdbear Formation in traps that resulted from updip porosity pinchouts (R. E. Near, oral commun., 1977). Similar stratigraphic traps may have been effective initially in the study area, but any hydrocarbon accumulations in them were later redistributed during the early Tertiary orogeny and now occur primarily in structural traps.

A review of the production in the Alberta Foothills is even more pertinent to the hydrocarbon evaluation of the study area, because the structure is comparable, and the stratigraphy and geologic history are similar. Figure 15 shows the location of the fields in the southern Foothills, with respect to the study area. Figure 14 is a correlation chart of the area showing productive zones. Fox (1959) and Wells (1968) provide detailed summaries of the petroleum geology of the region.

Twenty fields have been discovered in the Alberta Foothills; all are gas except for Turner Valley, which produces oil and gas. Seventeen of these fields are listed in table 9 with reserve data. These fields have in-place gas reserves totalling more than 15 trillion cubic feet (424 billion cubic meters) with recoverable reserves of approximately 12 trillion cubic feet (339 billion cubic meters). It is significant to note that two of the larger fields, Pincher Creek and Waterton, are just north of the international border.

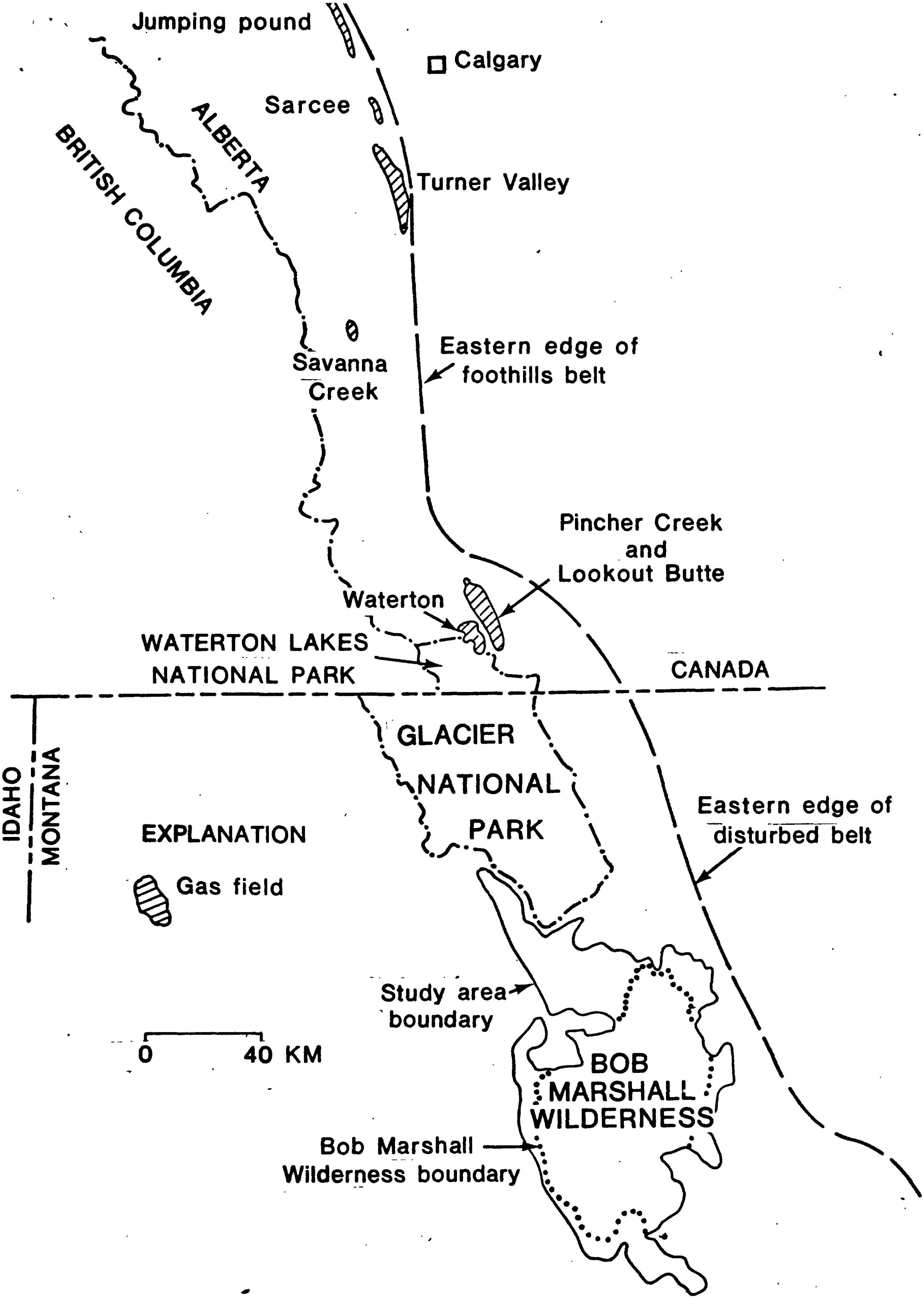

Figure 15.-Map showing Bob Marshall Wilderness and gas fields in southern Alberta Foothills (cross hashed pattern)

Table 9.--Gas fields of the Alberta Foothills (north to south)[1/]

	Initial in-place reserves billion cu. ft.	Initial in-place reserves billion cu. mtrs.	Recovery rate
Mountain Park	21	0.6	0.90
Lovett River	72	2	0.80
Brown Creek	59	1.7	0.85
Stolberg	550	15.6	0.80
Nordegg	34	1	0.85
Hunter Valley	78	2.2	0.85
Burnt Timber	780	22	0.85
Panther River	201	5.7	0.75
Wildcat Hills	1070	30.3	0.85
Jumping Pound	2817	79.7	0.85
Sarcee	190	5.4	0.90
Moose Mountain	50	1.4	0.80
Turner Valley	2870	81.2	0.75
Savanna Creek	240	6.8	0.85
Waterton	4137	117.1	0.80
Pincher Creek	1590	45	0.30
Lookout Butte	530	15	0.55

Source: Reserves of crude oil, gas, natural gas liquids, and sulfur, Province of Alberta: Energy Resources Conservation Board 1975.

[1/] Not all gas fields shown on index map (fig. 15).

In most of the fields, Mississippian carbonates of the Rundle Group are the principal reservoir. Secondary reservoirs are the Triassic Spray Mountain Formation and the Devonian Palliser Formation and Fairholme Group. The reservoir usually consists of dolomitized limestone with buildups of organic debris such as crinoids. The better fields have a producing zone of 100-200 ft (30-61 m) at an average depth of 10,000 ft (3,048 m): The rocks have 6 to 7 percent porosity (Wells, 1968, p. 1253).

All fields except Turner Valley appear to produce from structural traps associated with thrust faulting. The faulted eastern edge of Paleozoic carbonate rocks in the upper plate of a thrust block is the primary type of trap; associated folding is a secondary type. For example, the Savanna Creek field, as summarized by Scott, Hennessey, and Lamon (1957), is an anticlinal closure resulting from a pile of folded Paleozoic thrust sheets. Devonian and Mississippian strata are in the lower part of each thrust plate, and the main production is from the Rundle Group.

The Turner Valley structure is described by Gallup (1951) as being a relatively simple anticline in Mississippian rocks that is thrust over Jurassic and Cretaceous rocks. Gallup (1951, p. 817) believed that the structure began to form at the close of the Paleozoic, and additional folding occurred at the end of the Jurassic. The folding and associated faulting was accentuated by the early Tertiary orogeny.

Fox (1959, p. 1024), in his study of the hydrocarbon accumulations of the Alberta Foothills, concluded that: (1) the traps, with the exception of Turner Valley, are associated with faulting, (2) these faults are not always recognizable as major breaks at the surface, and (3) the structure of the reservoir block is generally simpler than the overlying strata. These conclusions emphasize the need for seismic surveys and drilling to evaluate fully the petroleum potential of the study area.

Oil and gas potential

A few basic concepts of hydrocarbon generation must be understood before the potential of any area can be properly assessed. The generation and accumulation of hydrocarbons is a multistage process which begins during the deposition of sediments. Each successive stage is critical in the ultimate formation of a hydrocarbon accumulation. The stages are as follows:

1) Deposition of organic-rich, fine-grained sediments and/or carbonates, and the preservation in them of abundant organic matter.

2) Conversion of this organic matter by biological and chemical processes into hydrocarbons.

3) Expulsion of the hydrocarbons from the source rock.

4) Migration along horizontal and vertical pathways.

5) Entrapment in porous and permeable reservoirs by a variety of stratigraphic and structural conditions, capped by an impervious cover.

The occurrence of these stages can be determined or predicted by studies in the Bob Marshall Wilderness and adjacent areas.

The preservation of organic matter in ancient sediments can be determined by measuring the amount of organic carbon. Figure 16 shows the location of potential source rocks sampled east of the study area, which are considered representative of the study area. Table 10 lists the organic carbon content of these samples. Momper (1972) set a minimum requirement of 0.4 percent organic carbon for petroleum source beds. All but one of the listed samples satisfy this requirement.

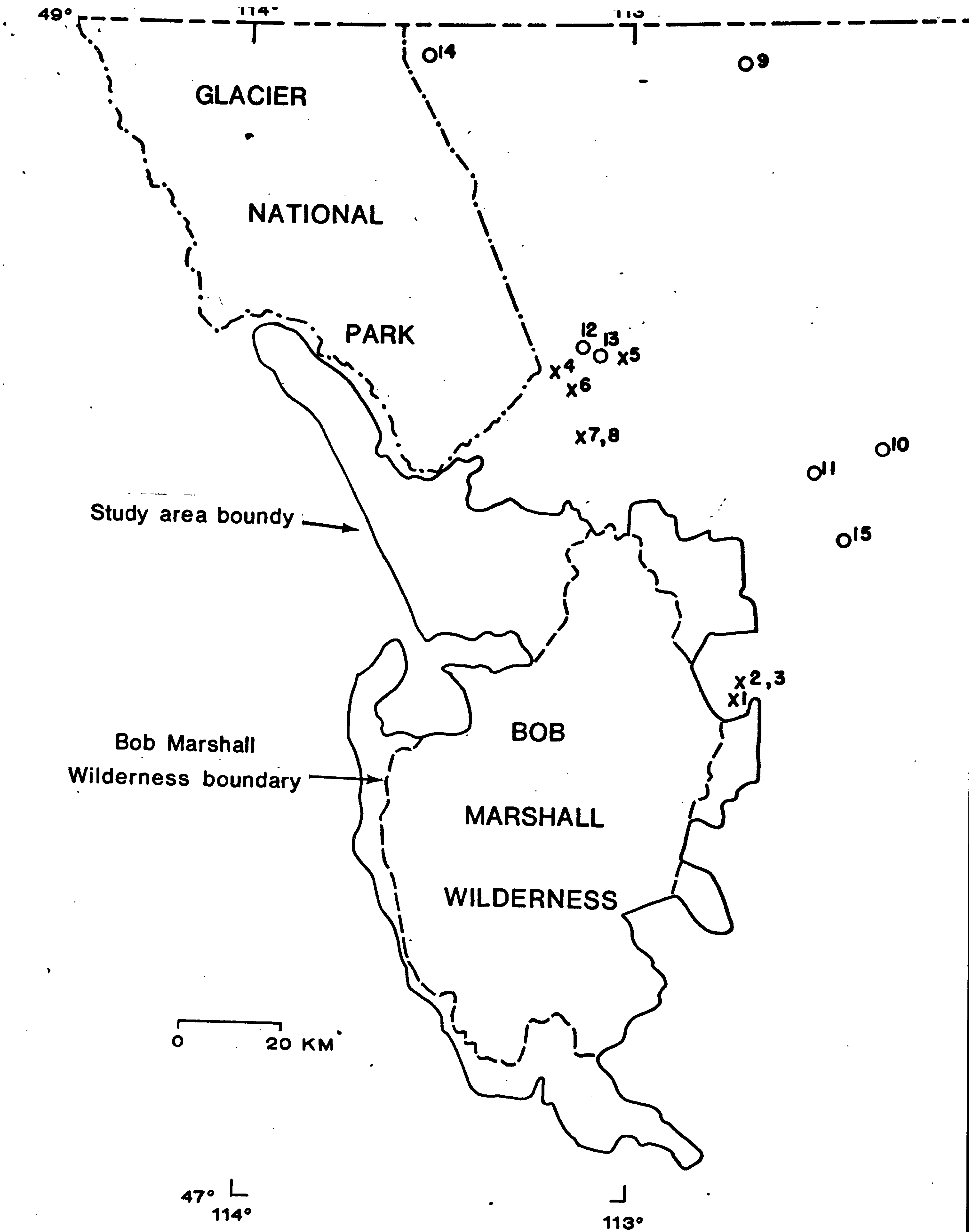

Figure 16.-Map showing location of source rock samples
(x-outcrop O-subsurface core)

Table 10.--Organic carbon content of outcrop and core samples east of the Bob Marshall Wilderness and study areas

Number	Age and formation	Location section/township/range - core samples quadrangle - outcrop samples	Depth (core samples)	Organic carbon weight percent
1.	Jurassic Sawtooth Fm.	Ear Mountain Quad.		0.76
2.	Miss. Allan Mountain Ls.	Ear Mountain Quad.		1.39
3.	Miss.-Dev. Bakken Fm.	Ear Mountain Quad.		7.23 - 7.29
4.	Cret. Cone Mbr., Marias River Sh.	East Glacier Park Quad.		4.90
5.	Cret. Kevin Mbr., Marias River Sh.	Big Rock Quad.		3.60
6.	Cret. Flood Mbr., Blackleaf Fm.	East Glacier Park Quad.		0.95
7.	Jurassic Rierdon Fm.	Hyde Creek Quad.		1.51
8.	Jurassic Sawtooth Fm.	Hyde Creek Quad.		0.52 - 0.56
9.	Mississippian Castle Reef Dol.	19/37N/8W	5785-5790 ft (1763-1765 m)	0.62
10.	Jurassic Sawtooth Fm.	11/29N/6W	3425 ft (1044 m)	0.37
11.	Jurassic Sawtooth Fm.	28/29N/7W	4121-4125 ft (1256-1257 m)	0.77
12.	Jurassic Ellis Group	11/31N/12W	9555-9567 ft (2912-2916 m)	3.55
13.	Mississippian Castle Reef Dol.	18/31N/11W (gas well)	8959-8960 ft (2731 m)	1.88 - 1.90
14.	Jurassic Ellis Group	14/37N/15W	12,315-12,319 ft (3754-3755 m)	2.44
15.	Jurassic Sawtooth Fm.	1/27N/7W (oil well)	3308 ft (1008 m)	0.66

In the Williston basin, Williams (1974, p. 1249) identified the Ordovician Winnipeg, Mississippian-Devonian Bakken, and Pennsylvanian Tyler shales as the major source beds for oil. The average organic carbon values for these units are 0.42, 3.84, and 0.80 percent, respectively. Of the samples analyzed adjacent to the study area, all but one sample have organic carbon values greater than the Winnipeg and Tyler shales, and two samples have values greater than the Bakken shales. Considering these criteria, marine shales in the Upper Devonian, Lower Mississippian, Jurassic, and Cretaceous are considered as excellent petroleum source beds in the study area.

Once organic-rich sediments have been deposited and preserved, the organic matter is converted into hydrocarbons by biological and chemical processes. The occurrence and type (oil or gas) of hydrocarbons is related to the different origins within the three stages of petroleum generation and thermal maturation of organic matter: (1) immature--biological processes at shallow depths in accumulating sediments generate gas consisting chiefly of methane, (2) mature--thermal cracking processes generate liquid hydrocarbons (oil) and high molecular-weight gas, (3) post-mature--gas, mostly methane, is generated by the destruction of liquid hydrocarbons and higher molecular-weight gases, and by the conversion of organic matter to carbon-rich residues and volatile compounds in response to increasingly severe thermal cracking. Thermal cracking processes are controlled by temperature (depth of burial) and geologic time. The relationship of these factors is discussed by Hunt (1975).

Various methods were employed to determine the stage of hydrocarbon generations or level of maturation of the organic matter in the study area. These techniques, which will be briefly discussed, are: (a) burial and temperature history, (b) vitrinite reflectance, and (c) carbon isotope ratios of natural gases.

a) Burial and temperature history

Maturation levels may be estimated by reconstructing the burial and temperature history of an area, assuming the past and present temperature gradients are similar. In the study area, the present temperature gradient is 1.5°F (1°C) per 100 ft (30 m), using an average surface temperature of 60°F (16°C).

For Cretaceous rocks, the mature stage occurs between approximately 180° to 300°F (82° to 149°C), which corresponds to depths of burial ranging between 8,000 and 16,000 ft (2,438-4,877 m) in the study area. The mature stage for Paleozoic rocks generally takes place within the temperature range of 130° to 220°F (54°-104°C), which coincides with burial depths ranging between 4,600 and 10,600 ft (1,402-3,231 m) in the study area. The mature stage for Jurassic rocks lies somewhere between these ranges.

Because the Cretaceous sequence is approximately 7,000 ft (2,134 m) thick in the study area, Jurassic and older rocks have been buried deep enough to have generated hydrocarbons of the mature stage. With the added thickness of Mississippian carbonates, source beds in the Upper Devonian and Lower Mississippian have been buried to at least 9,000 ft (2,743 m), which places them in the lower part of the mature stage. Burial depths for the Paleozoic may be underestimated because Pennsylvanian, Permiam, and Triassic rocks may have covered the study area and been eroded before Jurassic sedimentation.

This burial and temperature history is complicated by the increased pressures and temperatures associated with the early Tertiary deformation and burial beneath thrust plates. Hoffman, Hower, and Aronson (1976, p. 12) concluded that the Cretaceous shale mineralogy in the northern disturbed belt resulted from heating in the temperature range between 212° and 347°F (100°-175°C). Thus, although burial depths before the early Tertiary orogeny indicate that Jurassic and older rocks are mature and have probably generated oil, the increased temperatures associated with thrust faulting may have increased the maturity level for the entire stratigraphic section.

b) Vitrinite reflectance

The reflectance intensity, measured in R_o, of the vitrinite fraction of disseminated coaly material in sediments is a sensitive measure of the thermal maturation of sediments. Hacquebard (1975) studied the correlation between vitrinite reflectance, paleotemperatures, and petroleum occurrences in Alberta. He (Hacquebard, 1975, p. 7-8) concluded that most Alberta oil pools have vitrinite reflectance values between 0.5 to 0.9 percent R_o. Except for immature gas of the Cretaceous, most of the gas is in Paleozoic reservoirs. Of the total gas, 47 percent occurs in fields where vitrinite reflectance values range between 0.8 and 1.2 percent R_o. Table 11 shows vitrinite reflectance data for four selected Cretaceous and Jurassic samples east of the study area. Three of the four samples lie within the oil range, as determined by Hacquebard (1975, p. 7), and the fourth, sample 7, which has been involved in thrust faulting, is in the gas range. Because of the increased burial and geologic time, Paleozoic source beds would probably be in the gas range. Based on this vitrinite reflectance data, Jurassic and older source beds have probably generated gas, and Cretaceous rocks, where deeply buried below thrust plates, may have locally generated oil.

Table 11.--Vitrinite reflectance, values for selected samples

Number	Age and formation	Minimum reflectance (% R_o)	Maximum reflectance (% R_o)	Average reflectance (% R_o)
6.	Cretaceous Flood Mbr. Blackleaf Fm.	0.52	1.03	0.75
7.	Jurassic Rierdon Fm.	0.77	1.01	0.91
11.	Jurassic Sawtooth Fm.	0.44	0.79	0.60
12.	Jurassic Ellis Group	0.36	0.96	0.56

c) Carbon isotope ratios of natural gas.

Carbon isotope ratios of the methane fraction of natural gas are a useful tool in determining the origin and thermal history of a gas accumulation. Gases were sampled from the pipeline and a well in the Jumping Pound field (fig. 15) in the southern Alberta Foothills, which produces from the Mississippian Turner Valley Formation (fig. 14). The carbon isotope ratios, which are expressed as δC^{13} values, are -41.99 $^{o}/oo$ and -41.65 $^{o}/oo$ for these gases, respectively. Stahl and Carey (1975, p. 263), in studying Paleozoic gases of west Texas concluded that gases within this range occur in the late mature stage. This gas, which often is associated with condensate, results from the initial thermal cracking of some of the heavier hydrocarbons, mainly oil, which are converted to methane. In the Jumping Pound field, the gas is 85 to 90 percent methane (C_1) with 10-15 percent C_2-C_5. In the west Texas area, gases with a δC^{13} of -42 $^{o}/oo$ are generated from beds having a vitrinite reflectance value of 0.8 to 0.9 percent R_o. In the study area, this would correspond to the maturity level of sample 7 (table 11). Assuming the thermal history of the study area is similar to the Alberta Foothills, the Bob Marshall Wilderness will probably contain mostly natural gas accumulations, rather than oil.

Liquid hydrocarbons (oil) in the study area were probably generated in Jurassic and older marine shales and were expelled, migrated, and accumulated in stratigraphic traps prior to the early Tertiary orogeny. Some of these traps were associated with northeasterly-trending lineaments. This oil was thermally cracked, converted to methane-rich gas, and was redistributed into primarily structural traps associated with the thrust faulting and associated structures. The faulted eastern edge of reservoir rocks in the upper plate of a thrust block is probably the primary type of structural trap; associated folding is a secondary type.

The primary reservoir targets in the study area are Mississippian carbonate rocks, which are the primary reservoirs in the Alberta Foothills and the northern disturbed belt east of the study area. Porous zones are developed in areas of secondary dolomitization or organic buildups, such as encrinites. Previously unevaluated reservoirs may be present in the underlying Devonian carbonates, such as the Birdbear Member of the Jefferson Formation. Potential reservoirs in clastic rocks such as the Swift and Kootenai sandstones are secondary, because of clay infilling and diagenetic effects associated with the deformation.

Areas with hydrocarbon potential, based on knowledge derived from surface stratigraphic and structural data, are shown numerically in decreasing order of importance on figure 17. It is important to emphasize that the boundaries between these areas are indefinite. Detailed exploration, including seismic surveys and drilling, will be necessary to evalute more precisely the petroleum potential of the areas.

Area 1 has a high hydrocarbon potential because it contains hydrocarbon source and reservoir rocks, and possible structural traps. The northern and central parts of the area also contain northeasterly-trending lineaments (older structures) which may have affected petroleum accumulations. Northwest-trending folded thrust plates are along the east and west sides of the Sawtooth Range, and very likely are west of the present eastern edge of the Lewis and South Fork thrust plates in the Lewis and Clark Range.

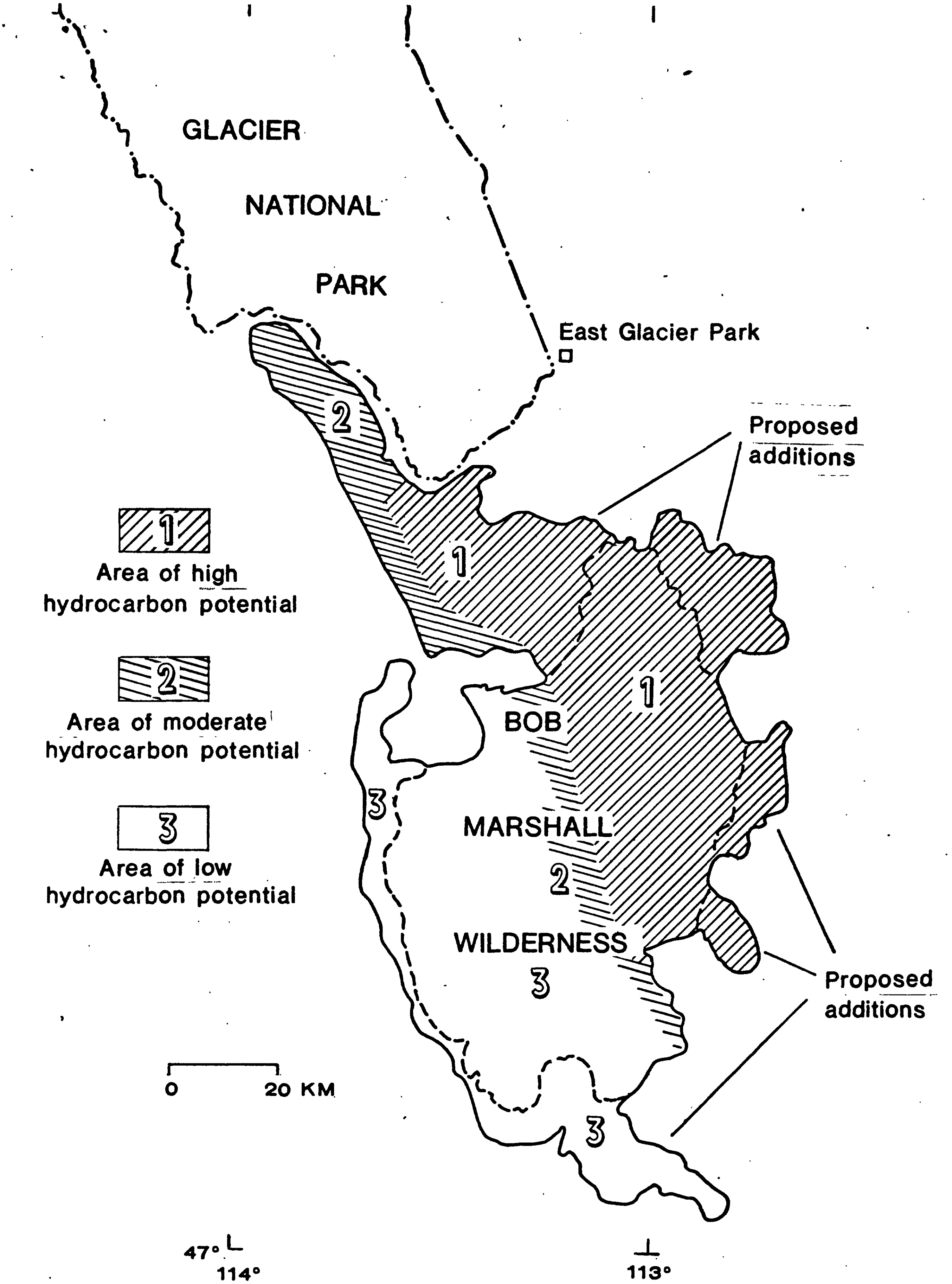

Figure 17.-Potential areas for hydrocarbon accumulations in the Bob Marshall Wilderness and proposed additions.

Present geologic data indicate that the areas of the northeasterly-trending lineaments (fig. 8) have the greatest potential for hydrocarbons. In the east-central part of the area the northeastern extension of the northern lineament appears to connect with the Pendroy fault zone east of the study area. The Pondera oil field lies on the south side of the fault. Three wells containing gas are essentially on this lineament, along the east side of the study area, between Blackleaf Creek and the North Fork of Dupuyer Creek. The lineament extends southwest to Lick Creek in the Bob Marshall Wilderness. An unpublished gravity survey in Lick and Route Creeks indicates the area is structurally high, and the first Mississippian sequence may be at relatively shallow depth (M. D. Kleinkopf, oral commun., 1977). Folded thrust plates extend northwest through the upper reaches of Route Creek where they are structurally higher than in adjacent areas.

The northern part of area 1 also contains a northeast-trending lineament, excellent source and reservoir rocks, as well as northwesterly-plunging folded thrust plates. A northeastern extension of the area contains gas wells, in the vicinity of East Glacier Park. In the western part of the area, east of the crest of the Flathead Range, potential reservoirs underlie a thick Precambrian sequence, and deep drilling would be necessary to penetrate potential accumulations. The thickness of the Precambrian strata ranges from a few meters near the exposed Lewis thrust fault to more than 12,000 ft (3,658 m) in the Flathead Range.

Elsewhere in the Sawtooth Range, Mississippian and Devonian rocks are involved in narrow linear thrust fault blocks. This close spacing may break up the continuity of potential reservoirs at depth, and reduce the occurrence of sizeable accumulations. Seismic studies are necessary to determine if potential structures lie beneath the imbricate surface structures of the range.

The unpublished gravity survey along Cox Creek indicates the area may contain potential structures with Mississippian rocks at relatively shallow depths, although these same rocks are exposed at the head of Cox Creek (M. D. Kleinfopf, 1977), and the hydrocarbons may have escaped. However, favorable reservoirs may very likely be present in other fault blocks at greater depth, as folded thrust plates are present in the eastern part of the area.

The hydrocarbon potential of area 2 is considered to be moderate because structures beneath the Lewis thrust block are not known. Potential petroleum accumulations would lie beneath at least 12,000 ft (3,658 m) of Precambrian rocks present in the Lewis thrust plate.

Area 3 is classified as having a low petroleum potential because of the thick sequence of Precambrian rocks in the Lewis thrust plate, and the lack of known reservoir rocks in the subsurface in most of the area. Precambrian rocks range in thickness from more than 10,000 ft (3,048 m) near the Continental Divide in the central part of the Wilderness, where there are two thrust plates, to more than 32,000 ft (9,754 m) in the Swan Range. Paleozoic and Mesozoic rocks probably do not extend more than a few miles beneath these thrust plates, and no known reservoir or source rocks are present in the Precambrian sequence.

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