Mineral Resources of the McCullough Peaks Wilderness Study Area, Park County, Wyoming

U.S. DEPARTMENT OF THE INTERIOR GEOLOGICAL SURVEY

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF MINES

U.S. DEPARTMENT OF THE INTERIOR BUREAU OF LAND MANAGEMENT

U.S. GEOLOGICAL SURVEY BULLETIN 1756–F

Chapter F

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MINERAL RESOURCES OF WILDERNESS STUDY AREAS—NORTHERN WYOMING

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

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Dallas L. Peck, Director

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STUDIES RELATED TO WILDERNESS

Bureau of Land Management Wilderness Study Areas

The Federal Land Policy and Management Act (Public Law 94–579, October 21, 1976) requires the U.S. Geological Survey and the U.S. Bureau of Mines to conduct mineral surveys on certain lands to determine the mineral values, if any, that may be present. Results must be made available to the public and submitted to the President and the Congress. This report presents the results of a mineral survey of the McCullough Peaks Wilderness Study Area (WY–010–335), Park County, Wyoming.

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[Plate is in pocket]

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Mineral Resources of the McCullough Peaks Wilderness Study Area, Park County, Wyoming

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ABSTRACT

The McCullough Peaks Wilderness Study Area (WY-010-335) is located near the western edge of the Bighorn Basin, Park County, Wyoming. The area is about 10 miles northeast of Cody. Mineral and energy resource assessment of the McCullough Peaks Wilderness Study Area indicates a total of 52 million tons of measured and indicated subbituminous coal resources. There are no other identified resources in the study area. There is low resource potential for metals, sand and gravel, bentonite, glass and sand, oil, and geothermal sources, a low resource potential for gas in Paleozoic (see geologic time chart in Appendix) rocks, lower Mesozoic rocks, and some conventional sandstone reservoirs of Late Cretaceous to early Tertiary age, a moderate resource potential for gas in some conventional sandstone reservoirs of Late Cretaceous to early Tertiary age, and a high resource potential for gas in low-permeability sandstone reservoirs of Cretaceous and early Tertiary age. The study area has a high resource potential for undiscovered paleontological resources.

SUMMARY

The U.S. Geological Survey and the U.S. Bureau of Mines studied the McCullough Peaks Wilderness Study Area (WY-010-335) in Park County, Wyoming, in the summer of 1986. The area covers 25,200 acres situated about 10 mi (mile) northeast of Cody and can be reached by unpaved roads from U.S. and State highways to the south, north and east (fig. 1).

A rugged, deeply dissected topography characterizes the McCullough Peaks Wilderness Study Area. The highest point in the vicinity is the northwest McCulloch Peak (spelled this way on topographic base for plate 1), less than 0.5 mi south of the study area (elevation 6,546 ft (feet)), and the lowest point is at the northeast corner of the study area (elevation 4,395 ft). The study area is located along the western flank of the Bighorn Basin. To the west, the rocks are turned up against the flanks of the Absaroka Range and are structurally complex. Within the study area, the rock units are flat lying and are composed at the surface of only the Tertiary (Paleocene and lower Eocene) Willwood Formation. Subsurface formations are thrust-faulted and folded; this deformation possibly includes the lowermost part of the Fort Union Formation. Two thrust faults, the Oregon Basin thrust fault and the Elk Basin thrust fault, underlie the study area and influence traps for possible gas accumulations.

The Willwood Formation is 2,822 ft thick and consists of variable-colored mudstone, shale, siltstone, sandstone, conglomerate, and thin lignite. Erosion of the formation has produced a badlands-type topography similar to that in Badlands National Park in South Dakota.

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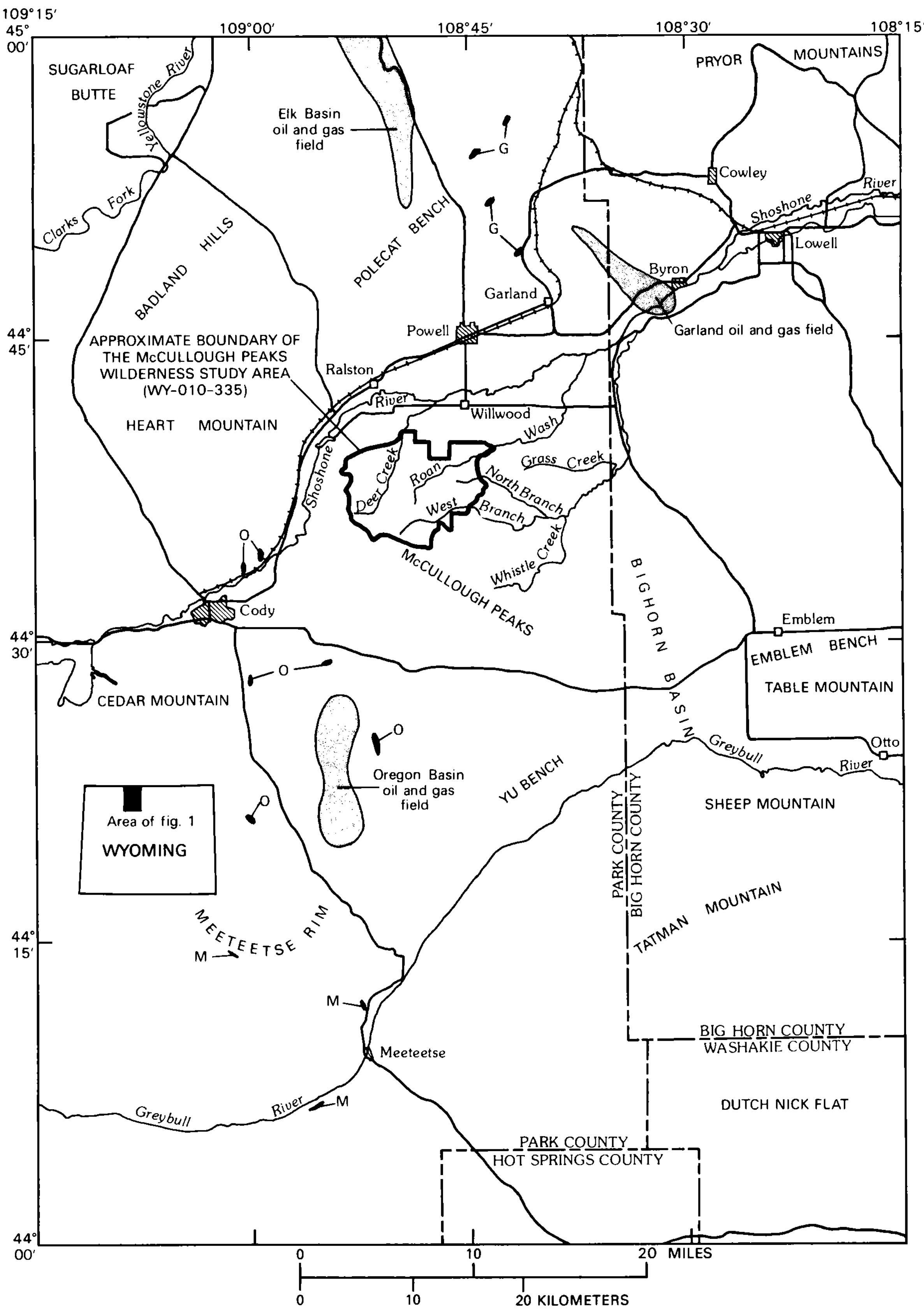


Figure 1. Index map showing location of the McCullough Peaks Wilderness Study Area and some nearby oil, gas, and coal fields, western Bighorn Basin, Park County, Wyoming. Coal fields are identified as follows: G, Garland; M, Meeteetse; O, Oregon Basin.

Identified and undiscovered mineral, energy, and paleontologic resources of the McCullough Peaks Wilderness Study Area were assessed by visual inspection during field traverses and measurement of a stratigraphic section, by geochemical methods based on stream-sediment and rock-sample analyses, by evaluation of subsurface data acquired from gravity and aeromagnetic surveys and acoustic and density well logs, and by review of existing records.

Identified Resources

There has been no mining activity or oil and gas production within the study area. Sand and gravel are present, but sources outside the study area are much larger and closer to market. Although clays occur throughout the Willwood Formation, analyses showed them to be of poor quality for commercial bentonite. Fossils are present in the Willwood Formation and are an important paleontological resource.

One coal prospect was found along Deer Creek (fig. 2), but the coal is thin and is enclosed mostly by shale. Based on examination of the Deer Creek prospect and surface inspection of the entire study area, coal resources are estimated to be low. However, on the basis of subsurface acoustic and density log data, the sum of measured and indicated subbituminous coal resources beneath the study area is estimated to be 52 million tons.

Mineral Resource Potential

Metals in the McCullough Peaks Wilderness Study Area were assessed by geochemical methods. This work revealed anomalous arsenic and uranium in some rock specimens and barium values exceeding 10,000 ppm (parts per million) in several pan concentrate samples. Barium values from rock geochemistry, however, are not greater than 1,000 ppm and thus are low. Metallic values were low at most rock- and stream-sediment sample sites even where panned concentrates of the stream-sediment samples exceeded background value for one or more of the 31 elements analyzed. The anomalous metallic values were not concentrated within a geographic area. Thus, the mineral resource potential for metals is rated low.

Nonmetals in the study area, such as sand and gravel, bentonite, and glass sand have a low resource potential. Deposits of these nonmetals in the study area are thin and small.

On the basis of oil and gas plays, and a proximity to producing oil and gas fields, the McCullough Peaks Wilderness Study Area has a low to high potential for undiscovered oil and gas. Three oil and gas plays have been assessed in the McCullough Peaks Wilderness Study Area. The first play involves gas primarily trapped in the upper Paleozoic Phosphoria Formation, Tensleep Sandstone, and Madison Limestone. Due to probable low porosity and permeability of the play formations, the likelihood of undiscovered gas is considered low (fig. 2). A second play involves Cretaceous and lower Tertiary rocks in the northwest part of the study area between the Oregon Basin and Elk Basin thrust faults. Reservoirs in this play probably include sandstones of the Mesaverde and Meeteetse Formations, Fox Hills Sandstone, and Lance and Fort Union Formations. Because the potential oil and gas source rocks in this play are probably situated in the zone of gas generation, the potential for undiscovered oil resources is rated low (fig. 2). The potential for undiscovered gas resources appears more favorable and is given a moderate rating. The third play covers the entire study area and involves possible gas accumulations trapped in tight, low permeability, overpressured Cretaceous and lower Tertiary sandstone reservoirs. The likelihood of undiscovered gas in the rocks of this play is rated high (fig. 2).

Based on geological, geochemical, and geophysical data collected for this report, the potential for geothermal sources is rated low.

The Willwood Formation in the Bighorn Basin is known for an abundance and diversity of vertebrate fauna. Because of this, paleontologic resources of the study area are rated high.

INTRODUCTION

The U.S. Geological Survey (USGS) and the U.S. Bureau of Mines (USBM) studied the McCullough Peaks Wilderness Study Area (WY–010–335) in Park County, Wyoming (fig. 1) at the request of the U.S. Bureau of Land Management (USBLM) in order to evaluate the mineral resource potential of the study area. In this report, the area studied is referred to as the "study area."

The study area is located about 10 mi northeast of Cody, Wyoming. The terrane is rugged and deeply dissected by several small, mostly intermittent streams that flow mostly east or northeast into the Shoshone River or its tributaries. The McCullough Peaks Wilderness Study Area consists of about 25,200 acres between latitudes 44°34′30″N. and 44°40′30″N. and longitudes 108°44′W. and 108°55′W. It is accessible by good private and USBLM roads from the south (U.S. routes 14, 16, and 20), north (U.S. Alt. 14), and northeast (State 32) (fig. 1). Inside the study area, vehicular traverse is difficult and may be hazardous due to washed-out sections of road, steep slopes, and slippery conditions when wet.

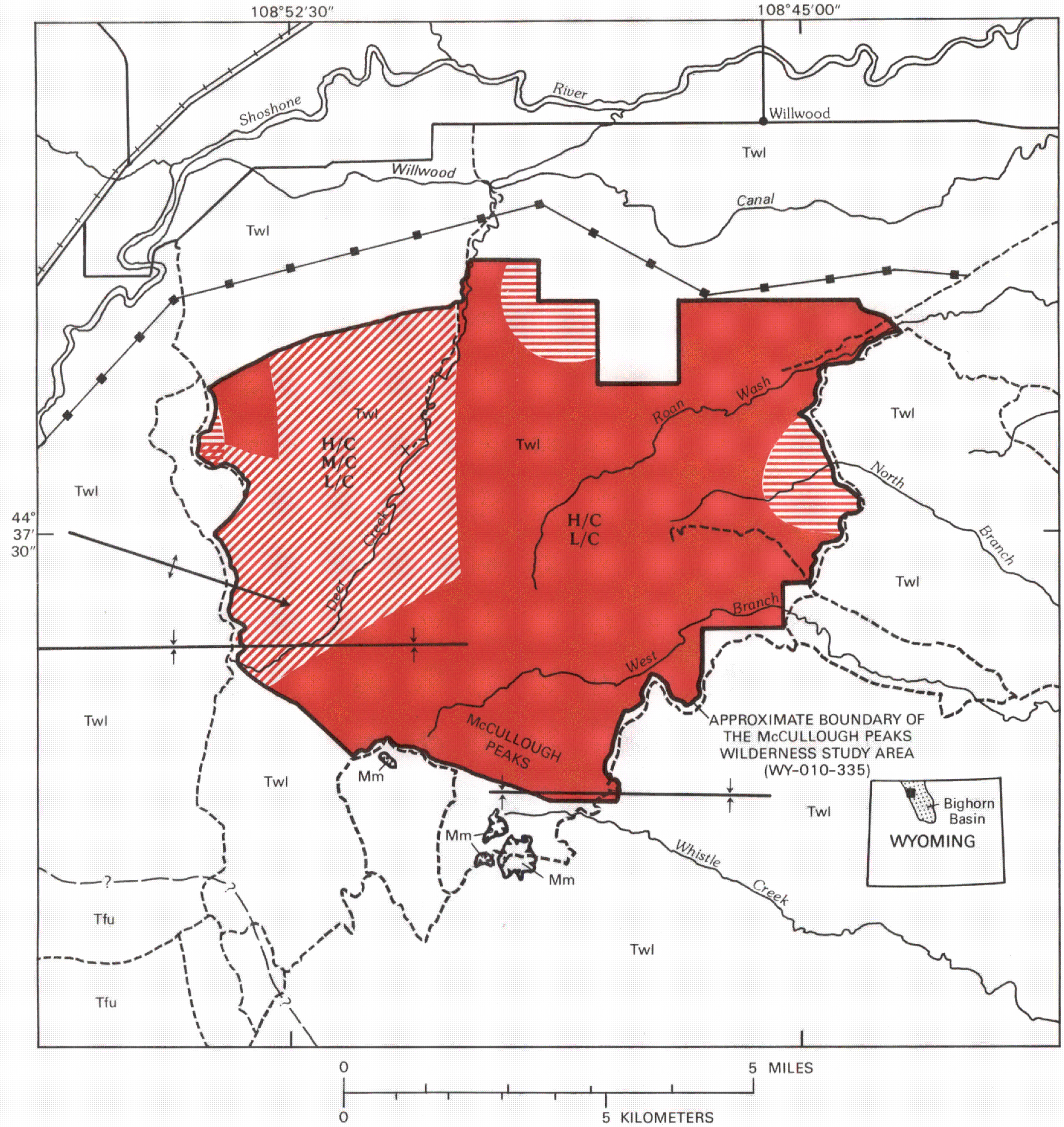


Figure 2 (above and facing page). Summary map showing mineral resource potential and generalized geology of the McCullough Peaks Wilderness Study Area, Park County, Wyoming. The contact between the Willwood and Fort Union Formations is generalized.

The McCullough Peaks Wilderness Study Area owes its scenic badlands landscape to the wide variation in color and erosional shape of its sedimentary rocks. Except for some low-lying stream bottoms and sloped terraces, nearly all the terrain is mountainous. Elevations in and immediately adjacent to the study area range from 6,546 ft on the highest of the McCullough Peaks at the south boundary of the study area to 4,395 ft at the northeast corner.

Previous studies bearing directly on the mineral and hydrocarbon resource potential of the McCullough Peaks Wilderness Study Area were evaluated. These included a geology, energy, and mineral resource assessment of the area by Tetra Tech, Inc. (1983), an

EXPLANATION OF MINERAL RESOURCE POTENTIAL

H/C — Geologic terrane having high resource potential for gas in low-permeability Cretaceous and Tertiary rocks, with certainty level C; and for paleontological resources in the Willwood Formation, with certainty level C—Applies to entire study area

M/C — Geologic terrane having moderate resource potential for gas in porous and permeable Cretaceous and Tertiary rocks, with certainty level C—Applies to northwest part of study area

L/C — Geologic terrane having low resource potential, with certainty level C, for metals; for sand and gravel, bentonite, and glass sand; for oil and geothermal sources; and for gas in Paleozoic, lower Mesozoic, and porous and permeable Cretaceous and Tertiary rocks—Applies to entire study area except for gas in porous and permeable Cretaceous and Tertiary rocks in area marked M/C

Levels of certainty

C — Available information gives a good indication of the level of mineral resource potential

Area underlain by measured and indicated subbituminous coal resources

DESCRIPTION OF MAP UNITS

Twl — Willwood Formation (lower Eocene and Paleocene)—Claystone, mudstone, siltstone, conglomerate, sandstone, coal, lignite, and carbonaceous shale

Tfu — Fort Union Formation (Paleocene)—Sandstone, siltstone, conglomerate, coal, and carbonaceous shale

Mm — Madison Limestone (Mississippian)—Massive, blue-gray limestone and dolomitic limestone

Contact

Contact, generalized

Anticline—Arrows show dip and direction of plunge

Syncline—Arrows show dip

Detachment fault; at surface. Sawteeth on upper plate

X — Coal prospect

Paved road

Unpaved road

Power line

assessment of the petroleum potential (Spencer, 1983a, b), and a mineral resource assessment of Bighorn Basin wilderness study areas aided by remote sensing techniques (Barrell and others, 1984).

This report presents an evaluation of the mineral endowment (identified resources and mineral resource potential) of the study area and is the product of several separate studies by the USBM and the USGS. The U.S. Bureau of Mines appraised the identified mineral, energy, and paleontological resources of the McCullough Peaks Wilderness Study Area, including the surface coal resources. The U.S. Geological Survey assessed the undiscovered mineral and energy resources of the study area and the identified subsurface coal resources of the study area to a depth of 6,000 ft.

Identified resources are classified according to the system of the U.S. Bureau of Mines and the U.S. Geological Survey (1980), which is shown in the Appendix of this report. Identified coal resources are classified according to Wood and others (1983). Mineral resource potential is the likelihood of occurrence of undiscovered metals and nonmetals, industrial rocks and minerals, and of undiscovered energy sources (coal, oil, gas, oil shale, and geothermal sources). It is classified according to the system of Goudarzi (1984) and is shown in the Appendix.

Investigation by the U.S. Bureau of Mines

The USBM investigation of the McCullough Peaks Wilderness Study Area included a literature search and a field investigation. Literature pertaining to the area was reviewed, and personnel at the U.S. Bureau of Land Management Cody Resource Area office were interviewed. The USBM examined USBLM records of mining claims and oil and gas leases inside and adjacent to the study area.

Field studies were conducted during August 1986. Roads were driven and foot traverses were made to check for mineralized rock. Scintillometer readings were taken on traverses. Forty-two rock samples were collected (Jeske, 1987, fig. 2). Of these, 34 mudstone samples were submitted for bentonite analysis. Channel samples of mudstones averaged 4 ft in length and were taken from 1-ft-deep cuts perpendicular to bedding. They were tested by the USBLM laboratory in Worland, Wyoming, for apparent viscosity, plastic viscosity, water loss, barrel yield, and moisture, using procedures described in American Petroleum Institute (1984). These tests were used to determine the suitability of the material for drilling muds. A semiquantitative multielement inductively coupled plasma-atomic emission spectrometry (ICP) analysis for 30 elements was performed by Chemex Labs Ltd., Sparks, Nevada, on all samples. Results of these studies have been published by the USBM (Jeske, 1987).

Investigation by the U.S. Geological Survey

Prior to geologic field work in the study area, D.G. Hadley, R.H. Hill, D.M. Kulik, and R.T. Ryder collected and reviewed published and unpublished reports and maps related to the McCullough Peaks Wilderness Study Area. D.G. Hadley and K.E. McLeod spent 4 weeks in the field followed by an additional week by Hadley, which included 2 days of helicopter support. Field work consisted of mapping geologic features, measuring a stratigraphic section, and collecting 302 rock samples from 167 field stations. R.H. Hill, assisted by David Fey and Clifford Taylor, collected 43 rock and 53 stream-sediment and pan-concentrate samples during the course of a geochemical survey of the area. Preparation and analysis of the geochemical samples were done by R.H. Hill, Betty Adrian, Olga Erlich, R.T. Hopkins, and T.A. Roemer; interpretation of the results was by R.H. Hill. D.M. Kulik conducted a reconnaissance geophysical survey of the study area, evaluated existing data from various sources related to subsurface structure and stratigraphy, and interpreted the results. Using surface and subsurface geologic and geophysical data, R.T. Ryder evaluated the likelihood of undiscovered oil, gas, and coal resources and identified coal resources based on subsurface well logs within and immediately adjacent to the study area.

APPRAISAL OF IDENTIFIED RESOURCES

By Rodney E. Jeske, U.S. Bureau of Mines

Oil and Gas

Oil and gas leases cover much of the McCullough Peaks Wilderness Study Area, and several wells have been drilled near or in the study area. One producing well (Atlantic and Alpine No. 1 McCulloch Peak Government) located ½ mi west of the boundary (well 13, figs. 3, 7) was drilled in 1961–1962 by Atlantic Refining Company. Total production has been about 500 million ft^3 (cubic feet) of gas from the Paleocene Fort Union Formation at depths between 3,492 and 4,387 ft, the shallowest productive zone in the area (Fred Crockett, U.S. Bureau of Land Management, Worland, Wyo., unpub. data, 1986).

In 1967, a well (well 16, figs. 3, 7) was drilled within the northern boundary but had no shows of oil and gas (Fred Crockett, U.S. Bureau of Land Management, Worland, Wyo., unpub. data, 1986). A well (well 17, figs. 3, 7) drilled along the eastern boundary to 10,508 ft in 1969 was reported to have had a show of gas in the Fort Union Formation (U.S. Bureau of Land Management, Worland, Wyo., unpub. data, 1987).

Mining and Mineral Exploration History

There has been no mineral production from, and there are no mines or mineral claims in or near the study area. One coal prospect is along Deer Creek (fig. 3).

Prospects and Mineral Occurrences

Along Deer Creek, a 6-ft by 6-ft by 2-ft hole was dug into a shale outcrop containing lignite stringers and lenses. In the study area, thin lenses (4 ft thick or less) of carbonaceous shales rich in plant fragments occur locally in the Willwood Formation. Thin lignite lenses (less than 1 in. (inch) thick) occur within the carbonaceous shale, but they are too small and discontinuous to be considered a coal resource (as classified by Wood and others, 1983).

Sandstone-hosted uranium deposits associated with carbonaceous material are known in this part of Wyoming, but scintillometer readings taken on the traverses revealed no areas of anomalous radioactivity. A semiquantitative, 30-element ICP analysis on 42 samples revealed no anomalously high metal concentrations (Jeske, 1987, appendix 1).

Industrial Mineral Resources

Sand and Gravel

Sand and gravel are found in small deposits in the study area. However, sources outside the study area are much larger and closer to market.

Bentonite

Although clays occur throughout the Willwood Formation, analyses of 34 samples showed them to be of poor quality as commercial bentonite (Jeske, 1987, table 1) and they would not be suitable for any industrial applications (Regis, 1978). Drilling-mud requirements for American Petroleum Institute (April 1984) state that a minimum yield of about 91 barrels of 15-cp (centipoise) mud result from each ton of bentonite used. No sample had a barrel yield greater than 46. Large reserves of high-grade bentonite are more readily available elsewhere in the Bighorn Basin.

Paleontological Resources

The Paleocene to lower Eocene Willwood Formation is well known for its abundance of vertebrate fossils (Jepsen, 1930). Fossils have been recovered throughout the Willwood Formation; those from Roan Wash east of the study area and in Rough Gulch southwest of the study area have been described in the scientific literature as cited by the U.S. Bureau of Land Management (unpub. data, 1987). During the USBM field investigation, fossilized bone fragments, teeth, and turtle shell fragments were found at several localities. These fossils are an important paleontological resource for the scientific community and private collectors.

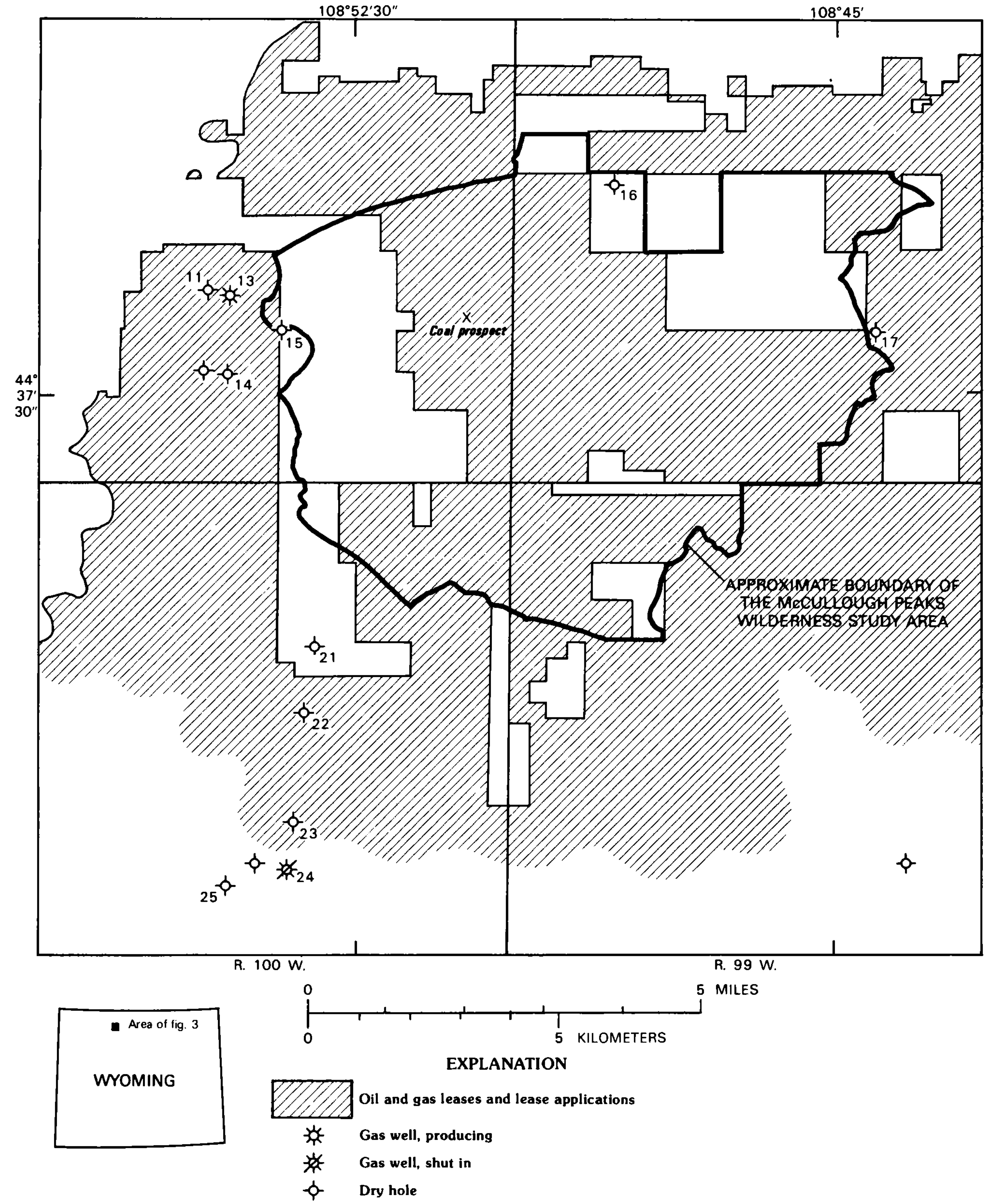


Figure 3. Map showing oil and gas leases, wells, and coal prospect in and near the McCullough Peaks Wilderness Study Area, Park County, Wyoming. Oil and gas lease and well information from the U.S. Bureau of Land Management; current as of July 1986. Gas wells and dry holes with accompanying numbers are identified in table 3. Many of these gas wells and dry holes (with the same identifying numbers) are shown on figures 7 and 8.

Table 1. As-received coal analyses (in percent) from Garland, Meeteetse, and Oregon Basin coal fields, Bighorn Basin, Wyoming (from Glass and others, 1975)

[Btu, British thermal unit]

Coal field	No. of analyses	Moisture		Volatile matter		Fixed carbon	
		Range	Average	Range	Average	Range	Average
Garland----	1		13.3		29.2		50.8
Meeteetse--	10	14.2-17.6	15.7	27.2-35.8	32.9	37.7-47.4	40.9
Oregon-----Basin.	6	13.4-17.2	15.2	31.3-35.9	34.2	39.3-45.8	41.8

Coal field	No. of analyses	Ash		Sulfur		Btu/pound	
		Range	Average	Range	Average	Range	Average
Garland----	1		6.7		0.8		10,870
Meeteetse--	10	7.5-14.7	10.6	0.2-1.0	0.6	9,270-9,925	9,568
Oregon-----Basin.	6	5.4-11.8	8.9	0.3-0.9	0.6	9,266-10,214	9,894

Coal Resources

By Robert T. Ryder, U.S. Geological Survey

Fields

The Oregon Basin coal field (formerly Cody coal field) is along the west edge of the Bighorn Basin between 8 and 18 mi south and southwest of the McCullough Peaks Wilderness Study Area (fig. 1). A northern extension of the field is about 15 mi northwest of the study area (fig. 1). Production from this coal field yielded less than 3,000 tons from 13 mines (Glass and others, 1975). None of the mines is currently active. Nine of the thirteen mines in the Oregon Basin coal field are located on coal beds in the Mesaverde Formation that range in thickness from 10 in. to 7.8 ft (Glass and others, 1975). Outcrop studies by Hewett (1926) and Pierce and Andrews (1941) showed that Mesaverde coal beds in the Oregon Basin coal field occur in two zones, the Wilson coal zone and the overlying Buffalo coal zone, both in the lower part of the Mesaverde Formation. Two mines in the Oregon Basin coal field are in the Meeteetse Formation on coal beds that have a maximum thickness of about 3.5 ft (Glass and others, 1975). Hewett (1926) and Pierce and Andrews (1941) showed that outcrop coal beds in the Meeteetse Formation occur in the upper half of the formation and are more lenticular than the coal beds in the Mesaverde Formation. Two mines in the Oregon Basin field are in the Fort Union Formation on coal beds that range in thickness from 2 to 4.5 ft (Glass and others, 1975).

The Meeteetse coal field is located along the west edge of the Bighorn Basin about 25–35 mi south of the study area (fig. 1). The Garland coal field is located along the east edge of the Bighorn Basin about 12–18 mi northeast of the study area (fig. 1). The geology and production history of the Meeteetse and Garland coal fields are similar to those of the Oregon Basin coal field (Glass and others, 1975).

Quality

According to Glass and others (1975), coal beds in the Oregon Basin, Meeteetse, and Garland fields are subbituminous in rank. A summary of the quality of selected coal beds in those fields is listed in table 1. The values in table 1 probably are derived from Cretaceous coal, but judging from other published coal analyses in the western Bighorn Basin (Fisher, 1903; Glass and others, 1975; Hewett, 1926) the values also are representative of Fort Union coal.

As demonstrated in the discussion about gas-prone source rocks, coal beds exposed along the west edge of the Bighorn Basin extend into the subsurface beneath the study area where possibly they increase in number and thickness. Beneath the western and northern parts of the study area, the Fort Union through Mesaverde coal-bearing sequence is buried to between 3,000 and 12,000 ft, whereas in the southern part of the study area the coal-bearing sequence is buried to between 4,000 and 15,000 ft. Based on vitrinite analyses by Hagen and Surdam (1984) and time-temperature reconstructions from Waples (1980), most of the coal beds buried to a depth greater than 6,000 ft beneath the study area probably are high-volatile bituminous to medium-volatile bituminous in rank (Tissot and Welte, 1978; fig. 7–49, p. 345). Coal beds buried to a present-day depth of less than 6,000 ft beneath the study area are considered to be subbituminous in rank.

Subbituminous Coal Resources

Many of the coal beds beneath the McCullough Peaks Wilderness Study Area are buried deeper than 6,000 ft and therefore are excluded from coal resource consideration (Wood and others, 1983; fig. 4). Only those coal beds indentified on acoustic and density logs in the Fort Union and possibly the Willwood Formation beneath the study area are considered to be a coal resource. Coal resources are estimated using the method derived by Wood and others (1983). Acoustic and density logs from four drill holes—Atlantic and Alpine No. 1 McCulloch Peak Government, Miami Oil No. 1 Miami Federal 509, Gulf Oil No. 1 Red Point, and Midwest Oil No. 1 USA (holes 13, 16, 17, and 21, table 3; fig. 7)—were used to identify coal beds and their thickness. Depending on the distance from these control points, coal resources were calculated for two areas of reliability: measured and indicated (fig. 5). Inferred and hypothetical coal resouces (fig. 5) were not calculated beneath the study area because postulated coal beds at depth are probably lenticular. No coal beds thicker than 5 ft were identified in the Fort Union and Willwood Formations in the four drill holes. Coal beds less than 2.5 ft thick were excluded from the resource calculations. Strata beneath the study area generally dip less than 10 degrees, and thus the coal resources here were calculated as if the strata were flat (Wood and others, 1983).

Total measured and indicated subbituminous coal resources beneath the study area are estimated to be 52 million tons (table 2). The sum of the measured and indicated subbituminous coal resources calculated in this study (52 million tons) is about one-tenth of the measured and inferred subbituminous coal resource estimate by Berryhill and others (1950) for the entire Bighorn Basin. The estimate by Berryhill and others (1950) only accounted for the marginal areas of the basin and did not include coal beds having greater than 3,000 ft of overburden. Wood and others (1983) cautioned that coal resource estimates based on geophysical logs, as done in the present study, are probably not as reliable as those based on outcrop and (or) corehole data. Moreover, the calculated coal resources would be greatly reduced if many of the postulated Fort Union and Willwood coal beds have an ash content greater than 33 percent—the

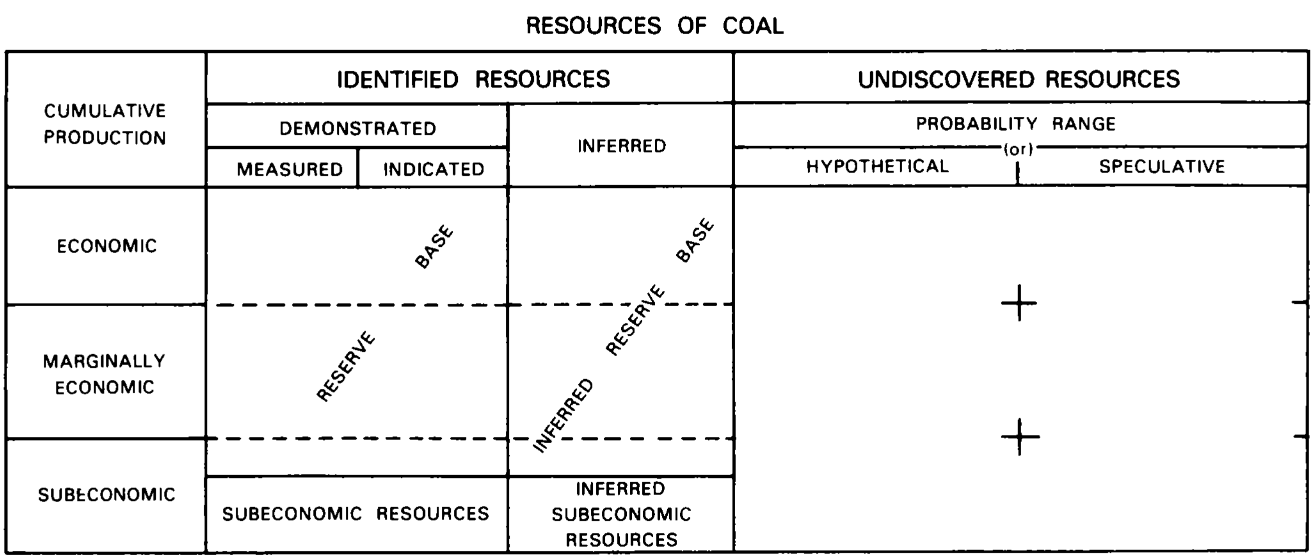


Figure 4. Format and classification of coal resources and inferred reserve bases and subeconomic and inferred subeconomic resource categories (Wood and others, 1983).

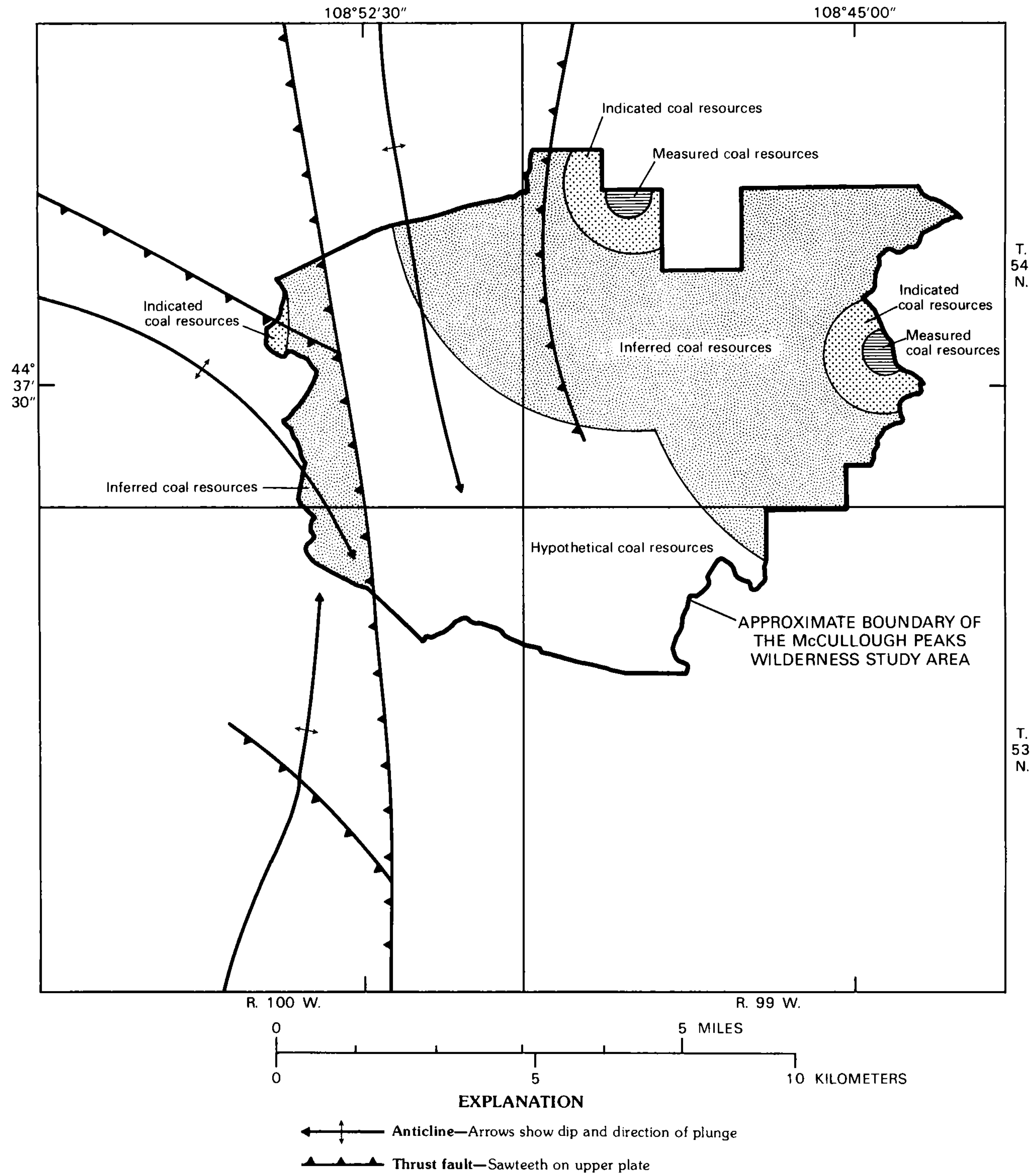


Figure 5. Sketch map of McCullough Peaks Wilderness Study Area showing areas of measured, indicated, inferred, and hypothetical subbituminous coal resources. Structures shown are confined to the subsurface.

upper limit for a coal resource (Wood and others, 1983). Although the subbituminous coal resources beneath the study area may have been overestimated, the probability is high that Fort Union and possibly Willwood coal beds between 2.5 and 5 ft thick and with an ash content less than 33 percent are present.

Table 2. Measured (M) and indicated (In) subbituminous coal resources, in millions of tons, estimated for McCullough Peaks Wilderness Study Area listed by depth of overburden

0-1,000 feet	
M------ } In-----	7
1,000-2,000 feet	
M------ } In-----	15
2,000-3,000 feet	
M------ } In-----	15
3,000-6,000 feet	
M------ } In-----	15

ASSESSMENT OF POTENTIAL FOR UNDISCOVERED RESOURCES

By D.G. Hadley, R.T. Ryder, R.H. Hill, D.M. Kulik, and K.E. McLeod

Geology

Local and Regional Setting

The McCullough Peaks Wilderness Study Area is located near the western edge of the Bighorn Basin (figs. 1, 2). The Bighorn Basin consists of a thick succession of sedimentary strata of Paleozoic to Tertiary age in northwest to north-central Wyoming and south-central Montana (Andrews and others, 1947; Love, 1960; Love and Christiansen, 1985). The surface strata are generally upturned and faulted around the flanks of the basin, but are mostly flat lying or gently dipping elsewhere.

The study area contains surface exposures of only the Paleocene and lower Eocene (about 66 to 52 Ma) Willwood Formation (Neasham and Vondra, 1972; Pierce, 1966; Rohrer, 1964; Rohrer and Smith, 1969; Van Houten, 1944). The Willwood Formation conformably overlies the Paleocene Fort Union Formation 1.2 mi southwest of the study area (fig. 2; pl. 1). Along the western edge of the Bighorn Basin, the contact between the Willwood and Fort Union is angular; and along the flanks of mountain ranges to the west and north, the Willwood rests unconformably on Cretaceous strata (Neasham and Vondra, 1972). At the contact with the Fort Union Formation to the southwest of the study area, the Willwood dips about 20° to the northeast. The Fort Union-Willwood contact identified on figure 2 and plate 1 is about 1 mi southwest of the contact identified by Pierce (1978).

Within the study area, the Willwood rarely dips more than 5° and mostly dips less than 2°. To the south of the study area at Tatman Mountain (fig. 1), the Willwood Formation is conformably overlain by the Eocene Tatman Formation. The contact between the Willwood and Tatman Formations is gradational from the rich red, purple, and yellow beds of the Willwood to the drab gray and green lithologic units of the Tatman. Nowhere was the top of the Willwood Formation or contact with the Tatman Formation observed in the study area.

In addition to bedrock of the Willwood Formation, much of the study area (pl. 1) is covered by upland pediment deposits, ancestral Shoshone River terrace deposits, alluvial silt and gravel in stream bottoms (not shown), and, in one place, several acres of landslide debris. Landslide deposits are found in areas underlain by the Willwood and Tatman Formations where relief is moderate to steep. A large part of Tatman Mountain (fig. 1) is flanked by landslide and slump deposits derived from the Willwood and Tatman Formations (Rohrer, 1964). The tendency of these formations to fail may pose a hazard to humans and manmade structures in populated areas.

Angular blocks of limestone (probably Madison Limestone) are found in nearly every stream bed of the study area. The blocks are clearly allochthonous (transported) from some distance away, for there are no similar limestones in the immediate area that are younger than the Willwood Formation (Love and Christiansen, 1985). Immediately south of the study area are four areas of limestone outcrop and rubble (fig. 2; pl. 1) that have been interpreted by Pierce (1978) as detachment blocks of Madison Limestone derived from Heart Mountain (Pierce, 1957, 1966). Detachment masses of Madison Limestone were probably on top of the high peak at the western headwaters of Deer Creek (pl. 1) and on other, now eroded, peaks and ridges.

Stratigraphy and Rock Units

A number of known oil and gas source and reservoir rocks are in the Paleozoic, Mesozoic, and Paleocene formations of the Bighorn Basin; many, if not all, probably underlie the study area. The formations are not discussed in this report, as they do not crop out in the study area, but their sequence and importance as oil-, gas-, and coal-bearing units in the basin are noted on figure 6.

According to Van Houten (1944) and Neasham and Vondra (1972), the Willwood Formation ranges in thickness from about 1,319 ft to 2,500 ft. Torres (1985) stated that the Willwood exceeds 3,300 ft in the Clarks Fork Basin. The thickness obtained by Van Houten (1944) was from the central part of the Bighorn Basin. Neasham and Vondra (1972) measured an east-west decrease in thickness of about 1,000 ft (2,300–1,320 ft) across the Bighorn Basin from Basin to Meeteetse. Hadley and McLeod in the present study measured 2,822 ft of Willwood Formation along the southwest boundary of the study area (pl. 1). The axis of the Bighorn Basin lies within about 4.3 mi of the Hadley and McLeod section, which may explain why we obtained a greater thickness than Van Houten (1944) and Neasham and Vondra (1972). We delineated three members of the Willwood Formation on the basis of color differences. The members are informally termed lower, middle, and upper. From bottom to top, they are 1,295 ft, 482 ft, and 1,045 ft thick. The lower and upper members are dominated by bright-colored lithologic units, whereas the middle member is composed primarily of drab gray and green lithologic units. Two stratigraphic parts are described in the Willwood Formation along the North Fork of the Shoshone River by Torres (1985), who did not formally assign them as members of the formation. The lower part consists of 98 ft of lacustrine mudstone, sandstone, and carbonaceous shale. The upper 1,540 ft is fluvial sandstones, mudstones, thin coal, and one red to gray bentonite bed (Torres, 1985).

Rock types in the Willwood Formation consist of mudstone, shale, siltstone, sandstone, pebbly sandstone, minor conglomerate, lignite, and coal. Some authors described a bentonite bed and a gastropod- and pelecypod-rich claystone in the Willwood Formation (Rohrer, 1964; Torres, 1985). A greenish-gray bentonite bed, 1.6 ft thick, was measured in about the middle part of the lower member in the measured section, but the fossiliferous claystone was not seen in the study area nor in the measured section. The Willwood rock types will be discussed according to their general order of abundance.

The Willwood Formation is one of the richest formations for vertebrate fossils in the world. A wide variety of plant and animal fossils have been collected from the formation, including mammals, birds, and reptiles (Gingerich, 1980; Bown, 1980; Gingerich and others, 1980; Butler and others, 1980). We collected a number of mammalian bone parts, teeth, jawbones, and so forth during our summer field season. The specimens are under study but are not treated in this report.

The Willwood Formation is prominent because of the wide variety of brightly colored mudstone beds in the formation. Mudstone beds are the most abundant lithology followed by sandstone units. The mudstone beds are various hues of purple, red, yellow, tan, brown, orange, gray, and green. Weathered beds are invariably lighter in hue than freshly quarried rock. Fresh sampled mudstone always breaks into inch- to fist-size fragments that are far more mottled than weathered outcrop faces. Individual beds range in thickness from a few inches to as much as 13 ft and average 6.5 ft in thickness. Units containing several mudstone beds may be as thick as 23 ft.

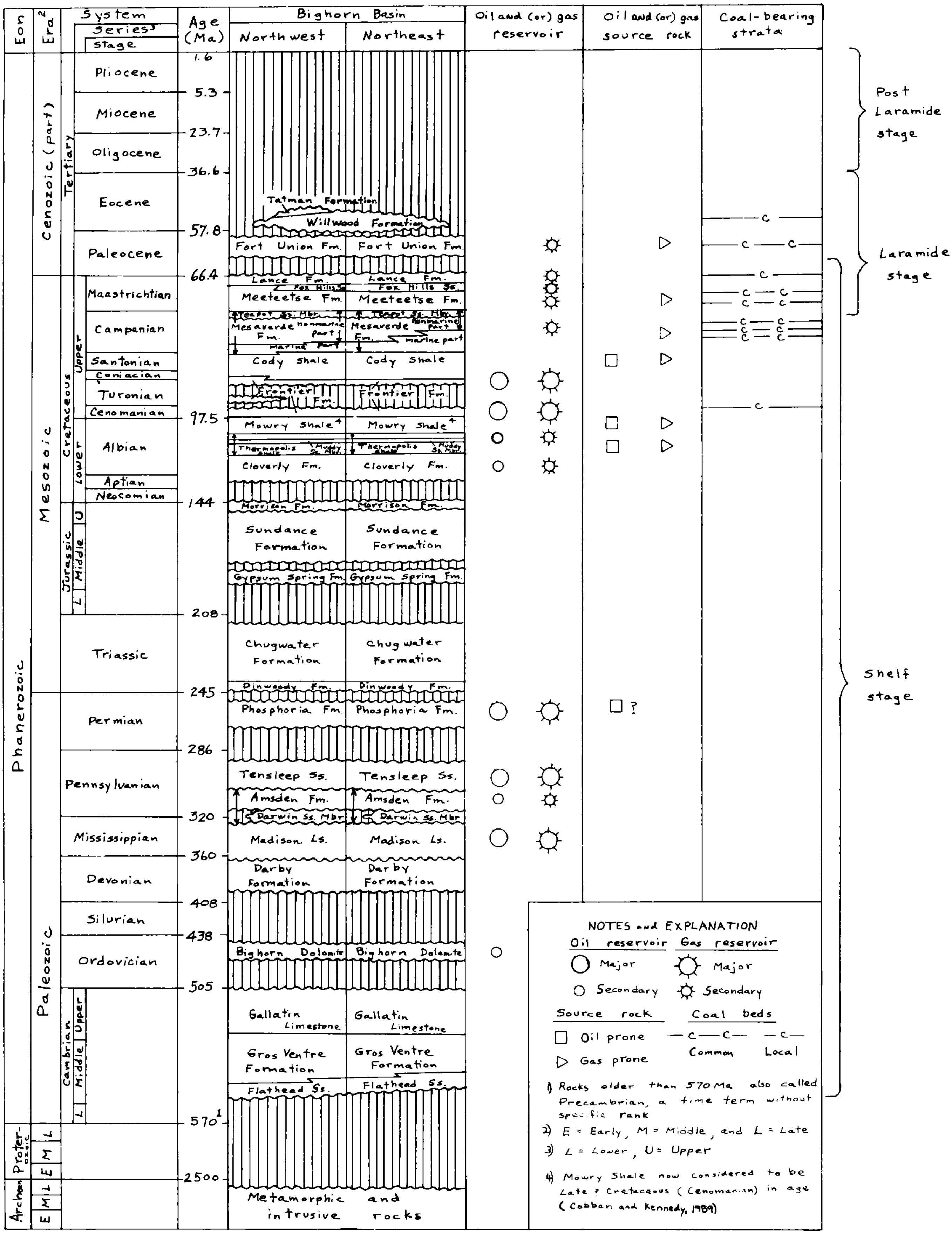
Sandstone is the second-most abundant rock type in the Willwood Formation of the study area. Units or individual beds of sandstone range in thickness from less than 3 ft to 39 ft and average about 11 ft based on our measured section. Like shales of the Willwood, the sandstones are restricted in their color range; they are light gray, green, or tan. Bedding is undulatory; pebble-filled channels along the base of sandstone units are common.

The sandstones are pebbly to very fine grained. In general, they are moderate to well sorted. Pebble fragments include chert, vein quartz, several sedimentary rock types (such as mudstone, shale, and siltstone), and rare plutonic pebbles. Volcanic fragments were not identified readily by hand-lens inspection. The pebbles and finer grained detritus are angular to subrounded and are mostly subangular. Quartz, feldspar, and minor rock fragments are the primary constituents of the sandstones of the Willwood. Accessory minerals include hornblende, biotite, rare pyroxene, glauconite, and opaque minerals.

Siltstone is of about equal thickness to shale in the Willwood. Apart from it and the lithologic units just discussed, all other rock types in the Willwood are of minor importance in the study area. In the Willwood measured section, there are 12 siltstone units that total about 46 ft thick compared with 8 units of shale that total 39 ft.

Siltstone beds are gray, green, and greenish gray. They range from 1.3 ft to 8.2 ft thick, are massive to thinly

Figure 6 (facing page). Stratigraphic chart of the rocks of the Bighorn Basin, showing oil and gas source and reservoir rocks and coal-bearing strata. Chart is mostly from Love and Christiansen (1980) and the Wyoming Geological Association Stratigraphic Nomenclature Committee (1975). Absolute age (in Ma) is from the geological time scale compiled by Palmer (1983). Time scale is nonlinear.


Eon
Era[2]
System
Series[3]
Stage
Age (Ma)
Bighorn Basin
Northwest
Northeast
Oil and (or) gas reservoir
Oil and (or) gas source rock
Coal-bearing strata
Phanerozoic
Cenozoic (part)
Mesozoic
Paleozoic
Proterozoic
Archean
Tertiary
Cretaceous
Jurassic
Cambrian
Upper
Lower
U
Middle
L
E
M
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Neocomian
Triassic
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
1.6
5.3
23.7
36.6
57.8
66.4
97.5
144
208
245
286
320
360
408
438
505
570[1]
2500
Tatman Formation
Willwood Formation
Fort Union Fm.
Lance Fm.
Fox Hills Ss.
Meeteetse Fm.
Teapot Ss. Mbr.
Mesaverde Fm.
nonmarine part
marine part
Cody Shale
Frontier Fm.
Mowry Shale[4]
Thermopolis Shale
Muddy Ss. Mbr.
Cloverly Fm.
Morrison Fm.
Sundance Formation
Gypsum Spring Fm.
Chugwater Formation
Dinwoody Fm.
Phosphoria Fm.
Tensleep Ss.
Amsden Fm.
Darwin Ss. Mbr.
Madison Ls.
Darby Formation
Bighorn Dolomite
Gallatin Limestone
Gros Ventre Formation
Flathead Ss.
Metamorphic and intrusive rocks
?
c
Post Laramide stage
Laramide stage
Shelf stage
NOTES and EXPLANATION
Oil reservoir
Gas reservoir
Major
Secondary
Source rock
Coal beds
Oil prone
Gas prone
Common
Local
1) Rocks older than 570 Ma also called Precambrian, a time term without specific rank
2) E = Early, M = Middle, and L = Late
3) L = Lower, U = Upper
4) Mowry Shale now considered to be Late ? Cretaceous (Cenomanian) in age (Cobban and Kennedy, 1989)

laminated, are mostly lenticular, and are thinly cross-laminated in some beds. In rare cases, vertebrate fossils were found weathering out of the siltstones. Siltstone beds intertongue with mudstone, shale, and sandstone beds of the Willwood in most instances.

Shale is a minor component of the Willwood Formation. It is massive in most places and is associated with most of the carbonaceous units. In general, the color of shale of the Willwood is more muted than the mudstones and is mostly gray and green. Individual beds range from 6 in. to 6.5 ft in thickness. Like the mudstones, the shales are mostly lenticular.

Minor pebbly sandstone and conglomerate are found in the Willwood Formation in the study area and measured section. A unit of pebbly sandstone 36 ft thick is in the lower member, and conglomerate beds, each 3 ft thick, are in the Willwood measured section. Pebbles in the pebbly sandstone and conglomerate are of the same general size, composition, and degree of maturity, but are not as concentrated as in pebble layers in the sandstones of the Willwood.

Minor lignite, coal, and bentonite were present in the Willwood measured section or at localities within the study area. Three thin lignite beds were observed in the two lowest members of the Willwood totaling 12.5 ft thick, and one 1.6 ft greenish-gray bentonite(?) bed was noted in the lower member. Coal was not seen in the measured section, but was examined at two localities (stations HSMP–27 and 29, pl. 1) within the study area, one of which was prospected in the past. It consists of thin lenses of coal 0.08–0.8 in. thick set in carbonaceous shale rich in plant fragments. The coaly beds are 6 in. to 5 ft thick, and because they are predominantly shale and only locally distributed, they are unminable.

Surface Structure

The strata in the McCullough Peaks Wilderness Study Area are everywhere shallow dipping and are tilted no more than 5°. Just outside the study area as the contact with the Fort Union is approached, the strata are upturned to as much as 20°. Because of minor surface flexures in the strata due to subsurface faulting and associated deformation, three very shallow plunging open folds were noted along the southwest and southern boundary of the study area (fig. 7; pl. 1). The subsurface structures (thrust faults) responsible for the two broad synclines and one anticline in the area are shown in figures 7 and 8. The surface synclines trend east-west and the anticline plunges about 4° S. 75° E. The thrust faults offset pre-Fort Union strata in the subsurface beneath and adjacent to the study area; surface strata are not offset by these faults. Oil and gas traps have formed as a result of the subsurface faulting and folding, and traps containing gas are likely in the study area (see "Hydrocarbon Resources" in section on "Assessment of Potential for Undiscovered Resources").

Geochemistry

Sample Media

Fifty-three minus-80-mesh stream sediments collected from active alluvium and 53 heavy-mineral panned concentrates derived from stream sediments were selected as primary sample media as they represent a composite of rock and soil exposed in the drainage basin upstream from the sample site. Chemical analyses of these stream sediments provide data useful in identifying those basins that contain unusually high concentrations of elements that may be related to mineral occurrences. In addition, studies have shown that heavy-mineral concentrates derived from stream sediments are a useful sample medium in arid and semiarid environments or in areas of rugged topography where mechanical erosion predominates over chemical erosion (Overstreet and Marsh, 1981; Bugrov and Shalaby, 1975).

Forty-three unaltered rock samples were collected to represent the rocks exposed in the vicinity of the stream-sediment sample sites. The actual areal extent of influence of the geochemical information provided by a specific rock sample is not known; the sampling program

EXPLANATION

Field

Oil Gas

Field abbreviation

bt, Bridger trail

c, Coulee

g, Garland

mp, McCulloch Peak

pg, Penney Gulch

u, unnamed

wcs, Whistle Creek, South

Major tectonic feature

EBA, Elk Basin anticline

EBF, Elk Basin thrust fault

MPA, McCulloch Peak anticline

OBA, Oregon Basin anticline

OBF, Oregon Basin thrust fault

Well or drill hole (see table 3)

Thrust fault—Sawteeth on upper plate

Anticline—Arrows show direction of dip and plunge

A——A′ Line of geologic cross section

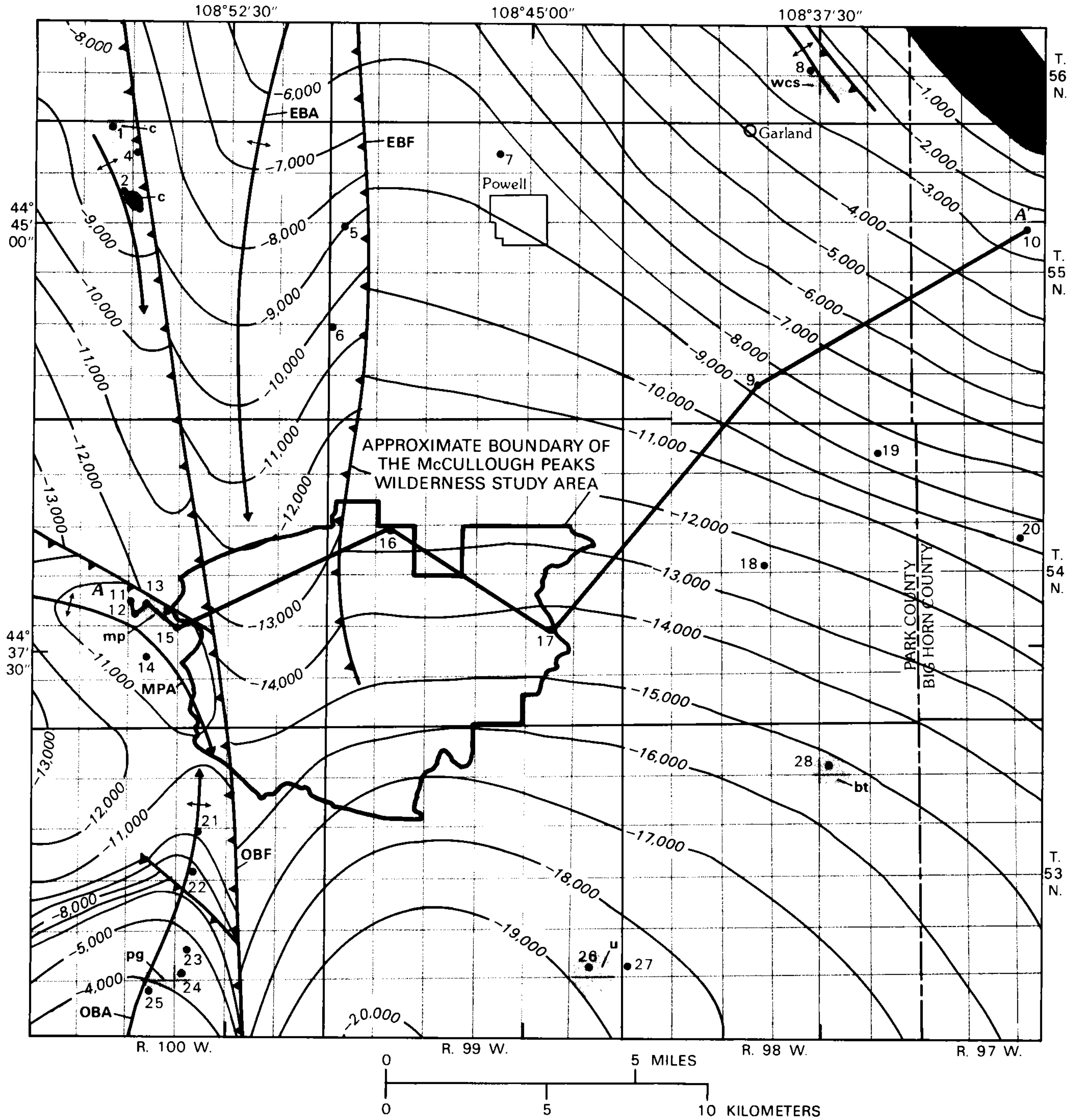


Figure 7 (above and facing page). Structure contour map of the McCullough Peaks Wilderness Study Area and surrounding region. Contours, in feet below mean sea level, are drawn on top of the Pennsylvanian Tensleep Sandstone. Contour interval, 1,000 ft. Map from Petroleum Information Corporation and Barlow and Haun Incorporated. (Permission to publish map granted April 24, 1987.)

was designed only to provide some general information on the geochemical nature of the rock units present. Single grab samples of rock from outcrop were collected at these sites.

In addition to the rock samples collected at the stream-sediment sample sites, 302 rock, ant-hill, sand, and carbonaceous (lignitic) samples were collected during the geologic mapping phase of field work. Of the latter samples, 197 were collected from geologic field stations throughout the study area, and 105 were collected along the line of section measured southwest of the study area (pl. 1).

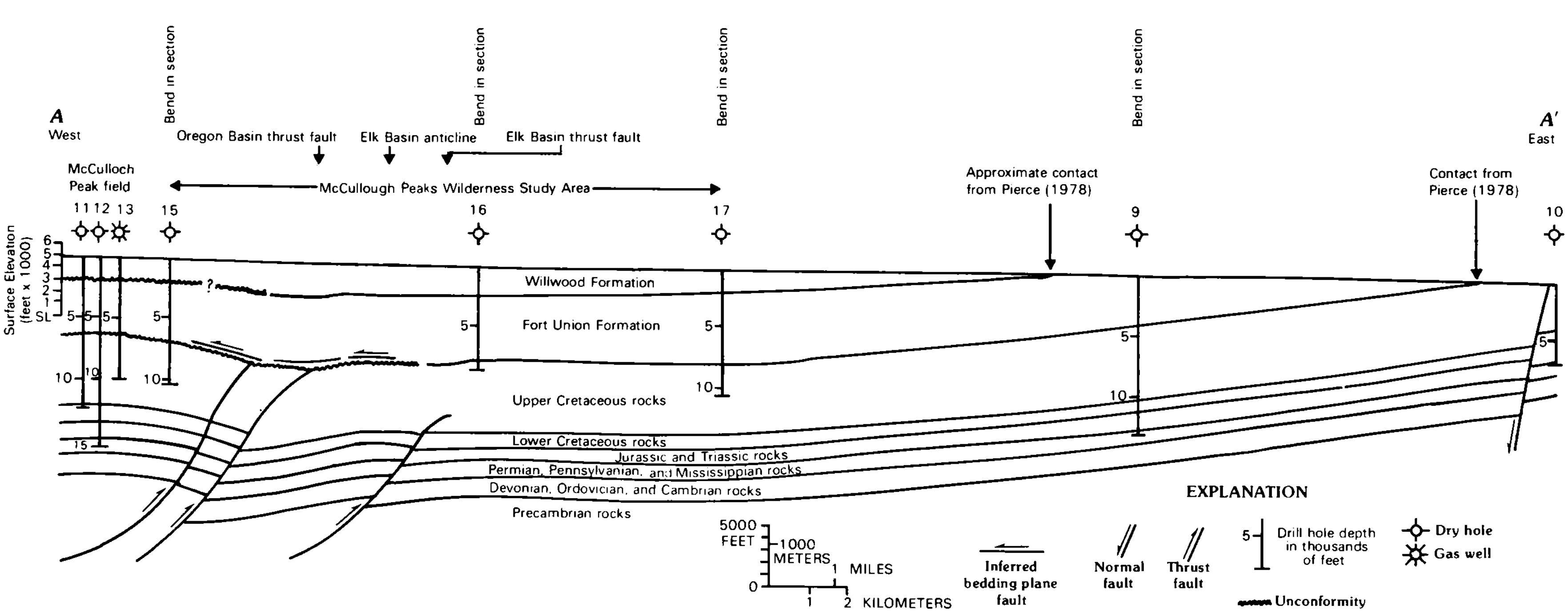


Figure 8. Geologic cross section through the McCullough Peaks Wilderness Study Area and parts of the surrounding area. Well and drill hole depths are in thousands of feet. Wells and drill holes are identified in table 3; line of section is shown in figure 7.

Sample Preparation

The dry stream-sediment samples were sieved through 80-mesh (0.17-mm) stainless-steel sieves. The minus-80-mesh material was retained from analysis and pulverized with ceramic plates to at least minus-100 mesh prior to analysis.

To produce the heavy-mineral concentrate, bulk stream sediment from active alluvium was first sieved through a 10-mesh (2.0-mm) screen. About 10–15 pounds of the minus-10-mesh sediment were panned to remove most of the quartz, feldspar, and organic and clay-size material. The panned concentrate was then separated into light and heavy fractions using bromoform (heavy liquid, specific gravity 2.86). The light fraction was discarded. The material of specific gravity greater than 2.8 was further separated into three fractions (highly magnetic, weakly magnetic, and nonmagnetic) using a modified Frantz Isodynamic Separator. The nonmagnetic fraction was hand-ground and saved for analysis. These procedures resulted in a sample that represents a concentration of heavy minerals that may be ore-forming or ore-related, such as pyrite, galena, cassiterite, sphalerite, chalcopyrite, stibnite, free gold, barite, and scheelite. This selective concentration of heavy minerals permits determination of some elements that are not easily detected in bulk stream-sediment samples.

Rock samples were crushed and then pulverized to at least minus-100 mesh with ceramic plates prior to analysis.

Sample Analysis

All three types of sample media were analyzed for 31 elements using a six-step semiquantitative emission spectrographic method (Grimes and Marranzino, 1968). Due to the limited amount of sample material, the nonmagnetic heavy-mineral concentrates were only analyzed spectrographically. The 43 rock and minus-80-mesh stream-sediment samples were also analyzed for arsenic, bismuth, cadmium, antimony, and zinc using an inductively coupled argon plasma-atomic emission spectrograph (Crock and others, 1987), for uranium by fluorometric methods, and for gold by atomic absorption spectrometry (O'Leary and Meier, 1984). In addition, 23 selected samples from the mapping-phase set were analyzed also for arsenic, bismuth, cadmium, antimony, zinc, and uranium by fluorometric and atomic absorption spectrometry methods (R.H. Hill, unpub. data).

Results and Discussion

Threshold values, defined as the upper limit of normal background values, were determined for each element by inspection of frequency distribution histograms for all three sample media. A geochemical value higher than the threshold values is considered anomalous and worthy of scrutiny as a possible indication of mineralization.

Analytical values for the rock and minus-80-mesh stream-sediment samples are well within normal background values with some exceptions. Ten of the rock samples revealed arsenic values between 28 and 115 parts per million (ppm) and one was 600 ppm. Fluorapatite is the most likely source of the arsenic (Palache and others, 1951) as determined from several of the samples by X-ray diffraction and is not considered to be related to any mineralization. Eight rock samples revealed uranium values between 7.3 and 14.0 ppm. The source of the uranium is not known; however, the areal extent of the uranium is quite limited as no other rock or stream-sediment samples were above threshold values.

Analytical values in nonmagnetic heavy-mineral concentrates reflect high concentrations of barium (all samples were 10,000 ppm or greater) and zirconium (98 percent of the samples were greater than 2,000 ppm). Barite and zircon were identified as the major mineral constituents of the heavy-mineral concentrates by X-ray diffraction analysis. The barite is considered to be authigenic; the zircon probably is a product of mechanical weathering and transportation of a rock accessory mineral concentrated in active stream alluvium and further concentrated by panning. The nominally high strontium values in heavy-mineral concentrates (700–3,000 ppm) may be related to the barite and to another major constituent of the heavy-mineral concentrate, fluorapatite (Palache and others, 1951), as determined by X-ray diffraction analysis. The yttrium values (98 percent of the values ranged from 150 to 700 ppm) are also likely to be related to the fluorapatite (Palache and others, 1951). The source of the detectable tin values (20–100 ppm) in the heavy-mineral concentrate is not known; however, the tin is most likely to be disseminated throughout the rock in the area and is concentrated by mechanical erosion and weathering in the active stream alluvium and further concentrated by panning.

One gold and silver value (gold detectable at 20 ppm, silver at 10 ppm) was detected in the heavy-mineral concentrates. Gold with a lower detection limit of 50 parts per billion was not detected by atomic absorption spectrometry in either the rock or minus-80-mesh stream-sediment samples. Silver with a lower detection limit of 0.5 ppm was detected in the minus-80-mesh stream sediment by emission spectrometry at only one other stream-sediment site.

Geophysics

Gravity and magnetic studies were undertaken as part of the mineral resource evaluation of the McCullough Peaks Wilderness Study Area to provide information on the subsurface distribution of rock masses and the structural framework. The gravity and magnetic data are of a reconnaissance nature and are adequate only to define regional structural features, such as the basin axis and bounding faults.

Data and Methodology

The gravity data were obtained in and adjacent to the study area in 1986 and 1987 and were supplemented by data maintained in the files of the U.S. Defense Mapping Agency of the Department of Defense. Stations measured by the author were established using Worden gravimeter W–177. The data were tied to the International Gravity Standardization Net 1971 (U.S. Defense Mapping Agency, Aerospace Center, 1974) at the base station ACIC 1651–1 at Cody, Wyoming. Station elevations were obtained from benchmarks, spot elevations, and estimates from topographic maps at 1:24,000 and 1:62,500 scales and are accurate to ±20–40 ft. The error in the Bouguer anomaly is less than 2.5 mGal (milligal) for errors in elevation control. Bouguer anomaly values were computed using the 1967 gravity formula (International Association of Geodesy, 1971) and a reduction density of 2.67 g/cm^3 (gram per cubic centimeter). Mathematical formulas are given in Cordell and others (1982). Terrain corrections were made by computer for a distance of 104 mi from the station using the method of Plouff (1977). The data are shown on figure 9 as a complete Bouguer anomaly map with a contour interval of 5 mGal.

Magnetic data are from U.S. Department of Energy (1982). Flight lines were flown east-west at 2-to 5-mi intervals and 400 ft above the ground surface. The data are shown on figure 10 as a residual intensity magnetic map with a contour interval of 20 nT (nanotesla).

Interpretation

The gravity data (fig. 9) primarily reflect low-density sedimentary rocks deposited in synclinal depressions in front of developing eastward-directed thrust faults (fig. 8). The southern half of the study area is located within the regional gravity low that follows a depositional axis of the Bighorn Basin. The northern half of the study area is located on the gravity gradient that regionally defines the eastern flank of the basin and, immediately northeast of the study area, reflects an area of shallowing basement and suggests that the anticlines on the basin flank are basement-cored. Low gravity anomalies A and B, north and south of the study area, coincide with a synclinal axis that probably formed during eastward movement of subsurface thrust faults. These thrust faults trend N. 10° W. to N. 10° E. at roughly a 50° angle to the major basin axis defined by the gravity data.

The Oregon Basin thrust fault is a major basement-involved fault that follows the western edge of the Bighorn Basin from an area west of Thermopolis, Wyoming, to an area about 10 mi south of the study area (Stone, 1985). At this point, the Oregon Basin thrust fault continues northward along the western edge of the study area but with less vertical separation of basement rocks; a second fault trends northwest and is shown in the southwest part of map area on figure 8 (VerPloeg, 1985). The gravity low that defines the basin axis and the gravity gradient that defines the basin edge are associated with the northwest-trending fault and suggest that this fault (unnamed) is the major basin-bounding fault in the vicinity of the study area. The saddle between the –225 mGal contours at the northwest corner of the study area coincides generally with the structurally complex area of the McCulloch Peak anticline (fig. 7), but the data are not sufficient to define the structure here or to determine the extent of the Elk Basin thrust fault beneath the study area.

Because there is no evidence of either magnetic, mineral-enriched sedimentary rocks or intrusive rocks, magnetic data (fig. 10) only reflect relative depth to crystalline basement rocks or changes in lithology and magnetic susceptibility within the basement, or both. Higher magnetic values in the eastern half of the map area partly reflect the rise of crystalline basement on the eastern flank of the Bighorn Basin (fig. 10). The magnitude of the north-south-trending gradient, however, suggests either relief on the basement surface (for which there is no evidence in the gravity data) or, more likely, a contrast in lithology and magnetic susceptibility. The gradient coincides with the north-trending fault and suggests that basement inhomogeneity may have had some control on fault location.

Mineral Resource Potential

Metals and Nonmetals

With the exception of a few isolated sites, geochemical samples from the McCullough Peaks Wilderness Study Area are within background values and show no anomalous values other than noted in the geochemistry section. Those values that are anomalous are neither sufficiently above normal background value nor sufficiently concentrated geographically to identify metallic mineral deposits within the study area. Barium values in the pan concentrates are the most notable, consistently high, metallic minerals values, but none of the barium values from outcrop samples are above background value. Therefore, a barite or barium resource in the

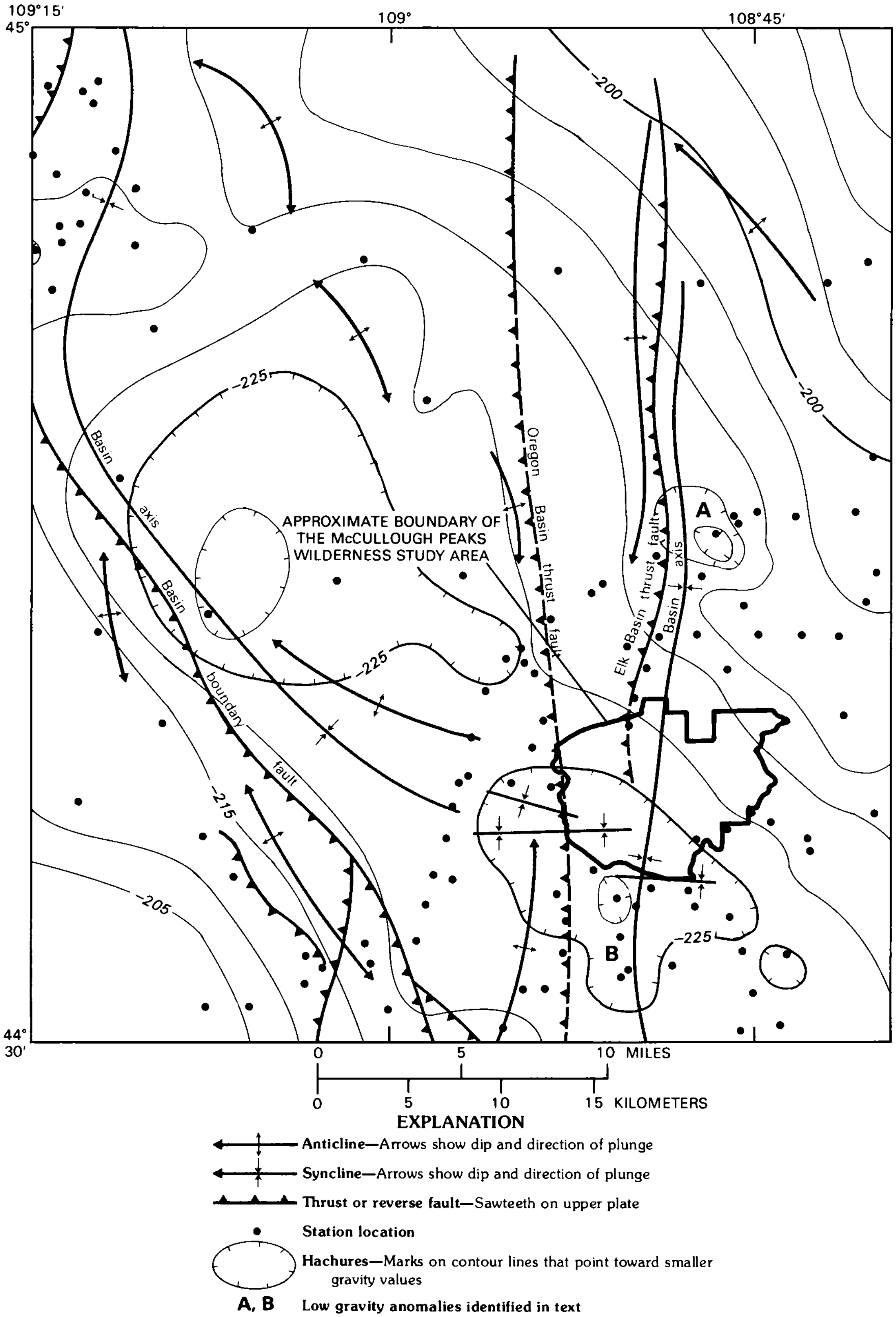


Figure 9. Complete Bouguer gravity anomaly and generalized structure map of McCullough Peaks Wilderness Study Area and vicinity. Contour interval 5 milligals. Structure from VerPloeg (1985).

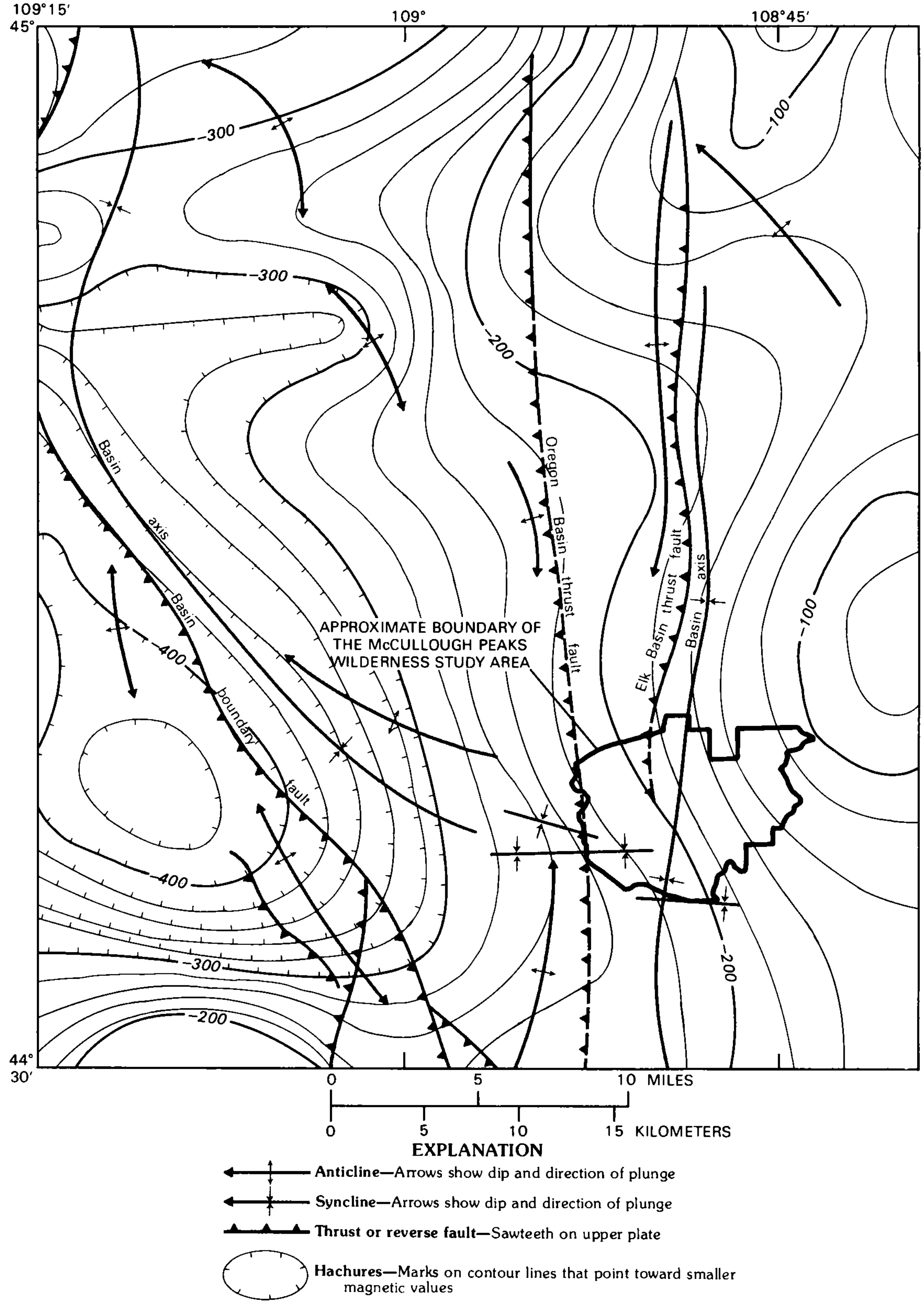


Figure 10. Residual intensity magnetic anomaly and generalized structure map of McCullough Peaks Wilderness Study Area and vicinity. Contour interval 20 nanoteslas. Structure from VerPloeg (1985). Hachures on contour lines point toward smaller magnetic values.

study area is not likely. Geochemistry from the study area indicates a low potential for metals, with a certainty level of C.

Sand and gravel, bentonite, and glass sand are present as thin and small deposits in the study area, and, therefore, they have a low resource potential, with a certainty level of C.

Hydrocarbon Resources

Introduction

The McCullough Peaks Wilderness Study Area is located approximately midway between two giant anticlinal oil fields—Elk Basin and Oregon Basin (fig. 1). Each of these fields originally contained recoverable oil resources of about 450 million barrels (Richard Nehring, unpub. data). A third major anticlinal oil field—Garland, with ultimate recoverable oil of about 180 million barrels (Richard Nehring, unpub. data)—is located 15 mi northeast of the study area on the east flank of the Bighorn Basin (figs. 1 and 7).

The McCullough Peaks Wilderness Study Area overlies the deeply buried northwest side of the Bighorn Basin whose Precambrian basement rocks have been dislocated by the east-verging Oregon Basin and Elk Basin thrust faults (fig. 7). Thus, the structural style beneath the study area closely resembles the structural style of other basins in the Rocky Mountain region where deep, elongate depressions of compressional origin are flanked on one or more sides by uplifted Precambrian basement rocks underlain by thrust faults.

In a recent study of wilderness lands in Wyoming, Spencer (1983a,b) estimated that the McCullough Peaks Wilderness Study Area has a high potential for undiscovered petroleum, a conclusion that the U.S. Bureau of Land Management (1984), Jeske (1987), and Fred Crockett (unpub. data) have supported. The objective of the present study was to assess the potential for undiscovered oil and gas resources in the McCullough Peaks Wilderness Study Area using previous work by Spencer (1983a,b), Barrell and others (1984), and Fred Crockett (unpub. data) and a variety of subsurface data. The total area of 410 mi^2 (square miles) from which subsurface data were gathered in support of the oil and gas resources evaluation includes the study area and surrounding region as shown on figure 7. A more comprehensive discussion of the subsurface geology and resource assessment of the expanded study area is presented by Ryder (1987).

Oil and Gas

Fields and Shows

In addition to its location near the giant Elk Basin, Garland, and Oregon Basin oil and gas fields, the McCullough Peaks Wilderness Study Area is located near five small gas fields and one small oil and gas field (fig. 7). Three of the fields occur in anticlinal structures along the eastern margin of the hanging-wall block of the Oregon Basin thrust fault (fig. 7). Of these three fields, the McCulloch Peak gas field is closest to the study area. Gas was initially produced from the Atlantic and Alpine No. 1 McCulloch Peak Government (well 13, table 3) discovery well at 495 MCF (thousand cubic feet) per day from a 15-ft-thick sandstone in the Paleocene Fort Union Formation (fig. 6). Between 1962 and 1974, 191,475 MCF of gas were produced from the McCulloch Peak field (Reaves, 1975); through 1984, 485 MMCF (million cubic feet) of gas had been produced (Wyoming Oil and Gas Commission, 1985). In addition, gas and (or) oil shows in the McCulloch Peak field are reported from the Mesaverde Formation, Fox Hills Sandstone, and Frontier Formation (table 3; fig. 6). Minimum reservoir pressures derived from drill-stem tests and mud-weight pressures from well-log mud weights indicate that the Frontier Formation and Muddy Sandstone Member of the Thermopolis Shale in the McCulloch Peak field are slightly overpressured with respect to a normal hydrostatic gradient of 0.43 psi/ft (pound per square inch per foot). The top and base of the overpressured zone is estimated to be at about 11,000 ft and 14,000 ft, respectively. The significance of these slightly overpressured rocks is discussed in the section on "Reservoir Characteristics."

About 6 mi southeast of the study area, two marginally commercial, one-well gas fields (Bridger Trail and unnamed) occur in the deeply buried part of the basin (fig. 7). Gas in the more northerly of these fields (Bridger Trail) initially flowed at a rate of 261–822 MCF per day from the 20-ft-thick Muddy Sandstone Member, whereas gas in the southerly field (unnamed) initially flowed at a rate of 350 MCF per day from 55- to 75-ft-thick sandstones in the Mesaverde Formation. Initial testing in the unnamed field also produced condensate and 132 barrels of water from the Mesaverde Formation. Gas shows in the Fort Union, Lance, and Meeteetse Formations and an oil show in the Meeteetse Formation have been reported from these fields and from the nearby Texas Pacific Oil No. 1 Red Point II drill hole (hole 27, table 3; fig. 7). Minimum pressure derived from drill-stem tests and mud-weight pressures from well-log mud weights indicate that the Meeteetse Formation, Mesaverde Formation, and Cody Shale in the unnamed field and the adjacent Texas Pacific Oil No. 1 Red Point II drill hole are significantly overpressured with respect to a normal hydrostatic gradient of

Table 3. Name and depth of wells and drill holes in the vicinity of McCullough Peaks Wilderness Study Area

[No., number used to identify holes on figures 3, 5, and 6]

Well or hole No.	Name	Total depth (feet)
1	Davis No. 1 Coulee	13,375
2	Stanolind Oil No. 1 Big Sand Coulee	13,447
3	Davis No. 2 Coulee	10,551
4	Phillips No. 1 Rose-B	8,620
5	Marathon Oil No. 1-67 Cary	12,450
6	Amoco No. 1 Burgener Trust	13,100
7	Tidewater No. 1 Atteberry	13,100
8	Dow, Manning and Anadarko	6,700
9	Houston No. 41-33 McCullough	12,966
10	Shell Oil No. 1 State	6,921
11	Hamm-Trigood No. 1 Government	12,299
12	Husky Oil No. 1 McCulloch Peak	15,627
13	Atlantic and Alpine No. 1 McCulloch Peak Government	9,904
14	Atlantic and Alpine No. 1 Rogers	8,140
15	Amoco No. 3-27 McCulloch II	13,800
16	Miami Oil No. 1 Miami Federal 509	8,612
17	Gulf Oil No. 1 Red Point	10,508
18	Amoco No. 2 Bridger Trail	8,000
19	Continental Oil No. 1 Farwell	11,350
20	Anadarko No. 1 Bridger Butte	10,121
21	Midwest Oil No. 1 USA	9,650
22	Chambers No. 1-15 Federal	15,355
23	California Oil No. 1 Corbett	11,198
24	Davis Oil No. 1 Buttercup	10,427
25	Davis Oil No. 1 Catfish	10,500
26	Husky Oil No. 14-25 Stonebarn	15,914
27	Texas Pacific Oil No. 1 Red Point II	18,500
28	Amoco No. 2-A Bridger Trail	17,060

0.43 psi/ft. Pressure data from the Bridger Trail field are too scant to accurately define a pressure gradient; however, because of its proximity to the unnamed field, the Bridger Trail field is also considered to be overpressured. The top of the overpressured zone in the unnamed and Bridger Trail fields is probably between 11,000 and 12,000 ft. The significance of these overpressured rocks is discussed in the following section on "Reservoir Characteristics."

Reservoir Characteristics

Traditionally, the best oil and gas reservoir rocks in the northern Bighorn Basin have been the Frontier Formation (sandstone), Phosphoria Formation (dolomite and limestone), Tensleep Sandstone, and Madison Limestone (fig. 6). These reservoirs are less than 5,000 ft deep in the Elk Basin, Garland, and Oregon Basin fields, and they commonly have porosity values greater than 15 percent and permeability values greater than 10 mD (millidarcy). Beneath the westernmost margin of the McCullough Peaks Wilderness Study Area, in the upper plate of the Oregon Basin thrust fault, the Frontier Formation is estimated to lie between 12,000 and 13,000 ft, and the upper Paleozoic sequence is estimated to lie between 15,000 and 16,000 ft (figs. 6, 7, and 8). East of the Oregon Basin thrust fault, beneath the rest of the study area, the Frontier Formation is estimated to lie between 13,500 and 17,000 ft, and the upper Paleozoic sequence is estimated to lie between 16,500 and 20,000 ft (figs. 7 and 8). At these depths, the traditional high-yield reservoirs (Frontier, Phosphoria, Tensleep, and

Madison) on the flanks of the Bighorn Basin probably have greatly reduced porosity and permeability. Special circumstances such as tectonic fracturing, secondary leaching of unstable mineral grains, and early oil migration may have locally improved the porosity and permeability of these deeply buried units.

The expansion of oil and gas exploration into deeper parts of basins has led to the discovery of gas fields in lower quality reservoirs—compared to stratigraphically equivalent reservoirs on the flanks of basins—whose reserves are commonly measured in trillions of cubic feet (Masters, 1979). Gas fields of this type in the Rocky Mountain region commonly are characterized by tight (low permeability) overpressured reservoirs (Spencer, 1985, 1987) and by traps that resulted from zones of high water saturation (Masters, 1979). These tight (low permeability) gas reservoirs are considered by Spencer (1985) to be unconventional reservoirs, and gas from them is considered by Dolton and others (1981) to be an unconventional resource.

Beneath the southern part of the study area, where the drilling depth to Precambrian basement rocks is as much as 22,000 ft, an approximately 8,000-ft-thick lower Tertiary and Cretaceous sequence contains many shallow marine to nonmarine sandstone bodies that seem to have the characteristics of tight gas reservoirs (figs. 6, 7, and 8). This thick sequence, marked by the Lower Cretaceous Cloverly Formation at the base and by the lower part of the Paleocene Fort Union Formation at the top, is intercalated with coal beds and several thick, dark-gray to black marine shale units. According to Law and others (1980), Law (1984), and Meissner (1978, 1980), the coal beds and shale units combined with a high temperature (200 °F) are responsible for the production of gas and abnormally high formation pressures in tight (low permeability) reservoirs. The top and bottom of the lower Tertiary and Cretaceous sequence are presently at 10,000 ft and 18,000 ft, respectively, beneath the southern part of the study area, and thus the sequence is largely incorporated into the higher-than-normal pressure zone recorded in the nearby unnamed gas field.

Overpressured, tight (low permeability) gas reservoirs of the variety described by Spencer (1985, 1987), Law and others (1980), and Law (1984) very likely occur beneath the study area. Beneath the southern part of the study area, the prospective sequence extends from the lower part of the Fort Union Formation to the base of the Cloverly Formation, whereas beneath the rest of the study area, where the overburden is thinner, the prospective sequence extends from the top of the Frontier Formation to the base of the Cloverly Formation. Moreover, some sandstones in the Mesaverde Formation, Meeteetse Formation, Fox Hills Sandstone, Lance Formation, and Fort Union Formation (lower part) could be suitable conventional oil and (or) gas reservoirs beneath the western and northern parts of the study area.

Traps

Structural traps beneath the study area, if present, would most likely occur along the trend of the Oregon Basin and Elk Basin thrust faults (fig. 7). The overthrust blocks associated with these Laramide-age faults (fig. 6) have been warped, internally faulted, and folded in response to local stresses created during their net eastward tectonic transport (figs. 7 and 8). An example of such a structure is the McCulloch Peak faulted anticline that forms the trap for the McCulloch Peak field and plunges southeastward beneath the western part of the study area (fig. 7). If the structure of the McCulloch Peak anticline is more complex than is shown by available structure contour maps (fig. 7; Blackstone, 1986), additional areas of closure may exist. Another anticline on the upper plate of a major thrust fault (the Elk Basin anticline, fig. 7) forms the trap for the Elk Basin, South Elk Basin, and Bearcat fields to the north and plunges southward beneath the northern part of the study area (figs. 7 and 8). Available structure contour maps suggest that the Elk Basin anticline plunges gently southward without major structural complications (fig. 7; Blackstone, 1986). However, drill-hole data are sparse in this part of the Bighorn Basin and there is disagreement as to whether or not the Elk Basin thrust fault extends beneath the wilderness study area (compare fig. 7 with Blackstone (1986) and Stone (1985)). Seismic surveys, which were unavailable for the present study, are required to resolve the structural details at the southern extremities of the Elk Basin and McCulloch Peak anticlines and to determine whether or not prospective structures are present.

Gas trapped in low-permeability reservoirs, as discussed previously, probably underlies the entire study area. In accumulations of this type, water-saturated, low-permeability rocks seem to prevent the gas from migrating updip, and the trap may also be assisted by a large hydrostatic head behind it (Masters, 1979).

Gas and (or) oil accumulations may also be trapped beneath the McCullough Peaks Wilderness Study Area in facies-change traps caused by lenticular sandstones in the Fort Union Formation, Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Mesaverde Formation. The updip permeability barrier for these traps most likely is shale and (or) siltstone, but locally the barrier may be caused by tightly cemented sandstone rather than shaly rocks. Those porous sandstone bodies whose pinchout edges trend normal to the axial planes of the plunging Elk Basin, McCulloch Peak, and Oregon Basin anticlines (fig. 6) would be the most effective stratigraphic traps.

Source Rocks and Thermal Maturity

Dark-gray to black shale of marine origin, which comprises all or part of the Lower Cretaceous Thermopolis Shale and Upper Cretaceous Mowry Shale, Frontier Formation, and Cody Shale, is present throughout the subsurface of the study area and the area surrounding it (fig. 6). In the Marathon Oil No. 1–67 Cary drill hole (hole 5, table 3; fig. 7), the total organic carbon (TOC) content of these shale units, measured in weight percent, ranges from 0.96 to 1.10 in the Thermopolis Shale, 0.88 to 1.42 in the Mowry Shale, 0.42 to 1.11 in the Frontier Formation, and 0.77 to 1.00 in the Cody Shale (Hagen and Surdam, 1984). Rock-Eval pyrolysis yields indicate that these marine shales are moderately good source rocks that have the capacity to generate both oil and gas (Hagen and Surdam, 1984) (fig. 6). Hagen and Surdam (1984) concluded that, in the Bighorn Basin, this predominantly shale sequence contains moderately good quality source rocks over an aggregate thickness of about 2,000 ft and probably was the major source of oil in Cretaceous and Tertiary reservoirs.

The Meade Peak and Retort Phosphatic Shale Members of the Lower Permian Phosphoria Formation are excellent oil-prone source rocks in the thrust belt of western Wyoming, eastern Idaho, and southwest Montana (Claypool and others, 1978). Isopach maps by Maughan (1984) and Peterson (1984) indicate that the Meade Peak Phosphatic Shale Member (lower part of Phosphoria) and Retort (upper part of Phosphoria) are thickest in western Wyoming, eastern Idaho, and southwest Montana and thin eastward into central Wyoming and adjoining states. These maps also indicate that the Meade Peak Member pinches out along the western margin of the Bighorn Basin, whereas the Retort Member extends across the Bighorn Basin and, according to Peterson (1984), contains a net thickness of organic shale as much as 25 ft. According to Sheldon (1967) and Stone (1967), the abundant oil in Phosphoria Formation, Tensleep Sandstone, and Madison Limestone reservoirs in the Bighorn Basin probably migrated there from the Phosphoria Formation in western Wyoming where black shale beds attain a net thickness of several hundred feet. Possible migration pathways of this oil into the Bighorn Basin have been suggested by Maughan (1984). In contrast, Peterson (1984) suggests that the oil in Paleozoic reservoirs in the Bighorn Basin was locally derived from organic shale in the Retort Member of the Phosphoria Formation. Although the long-distance versus local transport controversy is unresolved, the conclusion seems inescapable that Phosphoria-derived oil was available in late Mesozoic to early Tertiary time for charging Paleozoic reservoirs in the Bighorn Basin.

Outcrop studies by Hewett (1914, 1926), Pierce (1965, 1966), and Pierce and Andrews (1941) indicate that the Fort Union, Meeteetse, and Mesaverde Formations along the western edge of the Bighorn Basin are coal bearing. These coal beds also extend into the subsurface beneath the study area and reappear in outcrop on the east side of the basin. Coal-bearing intervals of secondary importance in the northern Bighorn Basin occur in the Willwood Formation, Lance Formation, and the Frontier Formation (fig. 6). Coal beds, such as those present beneath the study area are excellent gas-prone source rocks (Tissot and Welte, 1978). Meissner (1984) has demonstrated that many lower Tertiary and Cretaceous coal beds in the Rocky Mountain region, including those in the Bighorn Basin, have been buried deep enough to have generated gas.

Vitrinite (Hagen and Surdam, 1984) and theoretically derived maturation levels (Ryder, 1987) suggest that, beneath the southern part of the study area, the marine source rocks are in the zone of dry gas generation and the coal-bearing source rocks are in the zones of oil and wet gas generation. Beneath the northern and western parts of the study area, the marine source rocks are in the zone of wet gas generation and the coal-bearing source rocks are within, to slightly above, the zone of oil generation.

Potential

Three major oil and (or) gas exploration plays (a group of prospects having common geologic characteristics that may contain oil and (or) gas) are identified and assessed in the McCullough Peaks Wilderness Study Area. The upper Paleozoic play for structurally trapped gas involves primarily gas trapped in the Phosphoria Formation, Tensleep Sandstone, and Madison Limestone on or near the southern extremities of the Elk Basin and McCulloch Peak anticlines. Judging from probable low porosity and permeability values of the Phosphoria Formation, Tensleep Sandstone, and Madison Limestone at the expected 15,000–20,000 ft depth of burial and the absence of proven anticlinal closure beneath the study area, the potential for undiscovered gas resources in this play and in upper Paleozoic rocks in the remaining part of the study area is rated low, with certainty level C (fig. 2; pl. 1).

The Upper Cretaceous and lower Tertiary play involves oil and gas trapped in moderately porous and permeable conventional sandstone reservoirs by anticlinal closure along the southern extremities of the Elk Basin and McCulloch Peak anticlines and (or) by facies changes across the noses of these anticlines. Sandstones in the Mesaverde Formation, Meeteetse Formation, Fox Hills Sandstone, Lance Formation, and Fort Union Formation are the most likely reservoirs in this play. Judging from the absence of proven anticlinal closure and the less-than-optimum conditions for gas generation, the potential for undiscovered gas resources in the Upper Cretaceous and lower Tertiary play is rated moderate, with certainty level C (fig. 2; pl. 1). The potential for undiscovered oil resources in this play is rated low, with certainty level C, because the oil-prone source rocks beneath the study area are situated in the zone of gas generation. In the remainder of the study area, the potential for undiscovered oil and gas resources in porous and permeable conventional sandstone reservoirs of Upper Cretaceous and lower Tertiary age is rated low, with certainty level C.

The Cretaceous and lower Tertiary play involves stratigraphically trapped gas accumulations in tight (low permeability), overpressured sandstone reservoirs that underlie the entire study area—reservoirs similar to those described by Law (1984) and Spencer (1987). The potential for undiscovered gas in this play is rated high, with certainty level C (fig. 2; pl. 1).

Lower Paleozoic and lower Mesozoic (Triassic and Jurassic) strata have not been assigned to specific plays because of their low-quality reservoirs, absence of known source rocks, and low petroleum productivity in the Bighorn Basin. Therefore, the potential for undiscovered oil and gas resources in lower Paleozoic and lower Mesozoic (Triassic and Jurassic) rocks in the study area is rated low, with certainty level C.

Other Energy Resources

Based on the geological, geochemical, and geophysical data collected for this report, there is a low resource potential (certainty level C) for undiscovered geothermal sources in the study area.

Paleontological Resources

Because a wide variety of plant and animal fossils have been collected from the Willwood Formation, the study area has a high potential for undiscovered paleontological resources, with a certainty level of C.

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APPENDIX

DEFINITION OF LEVELS OF MINERAL RESOURCE POTENTIAL AND CERTAINTY OF ASSESSMENT

Definitions of Mineral Resource Potential

LOW mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics define a geologic environment in which the existence of resources is unlikely. This broad category embraces areas with dispersed but insignificantly mineralized rock as well as areas with few or no indications of having been mineralized.

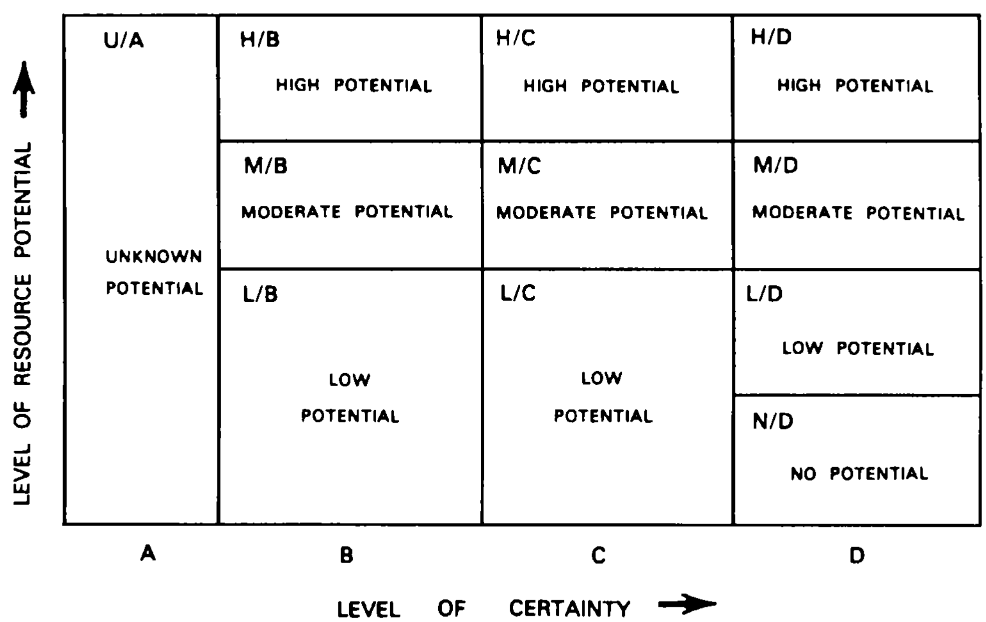
MODERATE mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a reasonable likelihood of resource accumulation, and (or) where an application of mineral-deposit models indicates favorable ground for the specified type(s) of deposits.

HIGH mineral resource potential is assigned to areas where geologic, geochemical, and geophysical characteristics indicate a geologic environment favorable for resource occurrence, where interpretations of data indicate a high degree of likelihood for resource accumulation, where data support mineral-deposit models indicating presence of resources, and where evidence indicates that mineral concentration has taken place. Assignment of high resource potential to an area requires some positive knowledge that mineral-forming processes have been active in at least part of the area.

UNKNOWN mineral resource potential is assigned to areas where information is inadequate to assign low, moderate, or high levels of resource potential.

NO mineral resource potential is a category reserved for a specific type of resource in a well-defined area.

Levels of Certainty



A. Available information is not adequate for determination of the level of mineral resource potential.
B. Available information suggests the level of mineral resource potential.
C. Available information gives a good indication of the level of mineral resource potential.
D. Available information clearly defines the level of mineral resource potential.

Abstracted with minor modifications from:

Taylor, R. B., and Steven, T. A., 1983, Definition of mineral resource potential: Economic Geology, v. 78, no. 6, p. 1268–1270.

Taylor, R. B., Stoneman, R. J., and Marsh, S. P., 1984, An assessment of the mineral resource potential of the San Isabel National Forest, south-central Colorado: U.S. Geological Survey Bulletin 1638, p. 40–42.

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RESOURCE/RESERVE CLASSIFICATION

	IDENTIFIED RESOURCES			UNDISCOVERED RESOURCES	
	Demonstrated		Inferred	Probability Range (or)	
	Measured	Indicated		Hypothetical	Speculative
ECONOMIC	Reserves		Inferred Reserves		
MARGINALLY ECONOMIC	Marginal Reserves		Inferred Marginal Reserves		
SUB-ECONOMIC	Demonstrated Subeconomic Resources		Inferred Subeconomic Resources		

Major elements of mineral resource classification, excluding reserve base and inferred reserve base. Modified from McKelvey, 1972, Mineral resource estimates and public policy: American Scientist, v.60, p.32-40, and U.S. Bureau of Mines and U.S. Geological Survey, 1980, Principles of a resource/reserve classification for minerals: U.S. Geological Survey Circular 831, p.5.

GEOLOGIC TIME CHART

Terms and boundary ages used in this report

EON	ERA	PERIOD		EPOCH	BOUNDARY AGE IN MILLION YEARS
Phanerozoic	Cenozoic	Quaternary		Holocene	0.010
				Pleistocene	1.7
		Tertiary	Neogene Subperiod	Pliocene	5
				Miocene	24
			Paleogene Subperiod	Oligocene	38
				Eocene	55
				Paleocene	66
	Mesozoic	Cretaceous		Late	96
				Early	138
		Jurassic		Late Middle Early	205
		Triassic		Late Middle Early	~ 240
	Paleozoic	Permian		Late Early	290
		Carboniferous Periods	Pennsylvanian	Late Middle Early	~ 330
			Mississippian	Late Early	360
		Devonian		Late Middle Early	410
		Silurian		Late Middle Early	435
		Ordovician		Late Middle Early	500
		Cambrian		Late Middle Early	~ 570[1]
Proterozoic	Late Proterozoic				900
	Middle Proterozoic				1600
	Early Proterozoic				2500
Archean	Late Archean				3000
	Middle Archean				3400
	Early Archean				3800?
pre-Archean[2]					4550

[1] Rocks older than 570 m.y. also called Precambrian, a time term without specific rank.

[2] Informal time term without specific rank.

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Mineral Resources of Wilderness Study Areas— Northern Wyoming

This volume was published as
separate chapters A–F

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DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, JR., Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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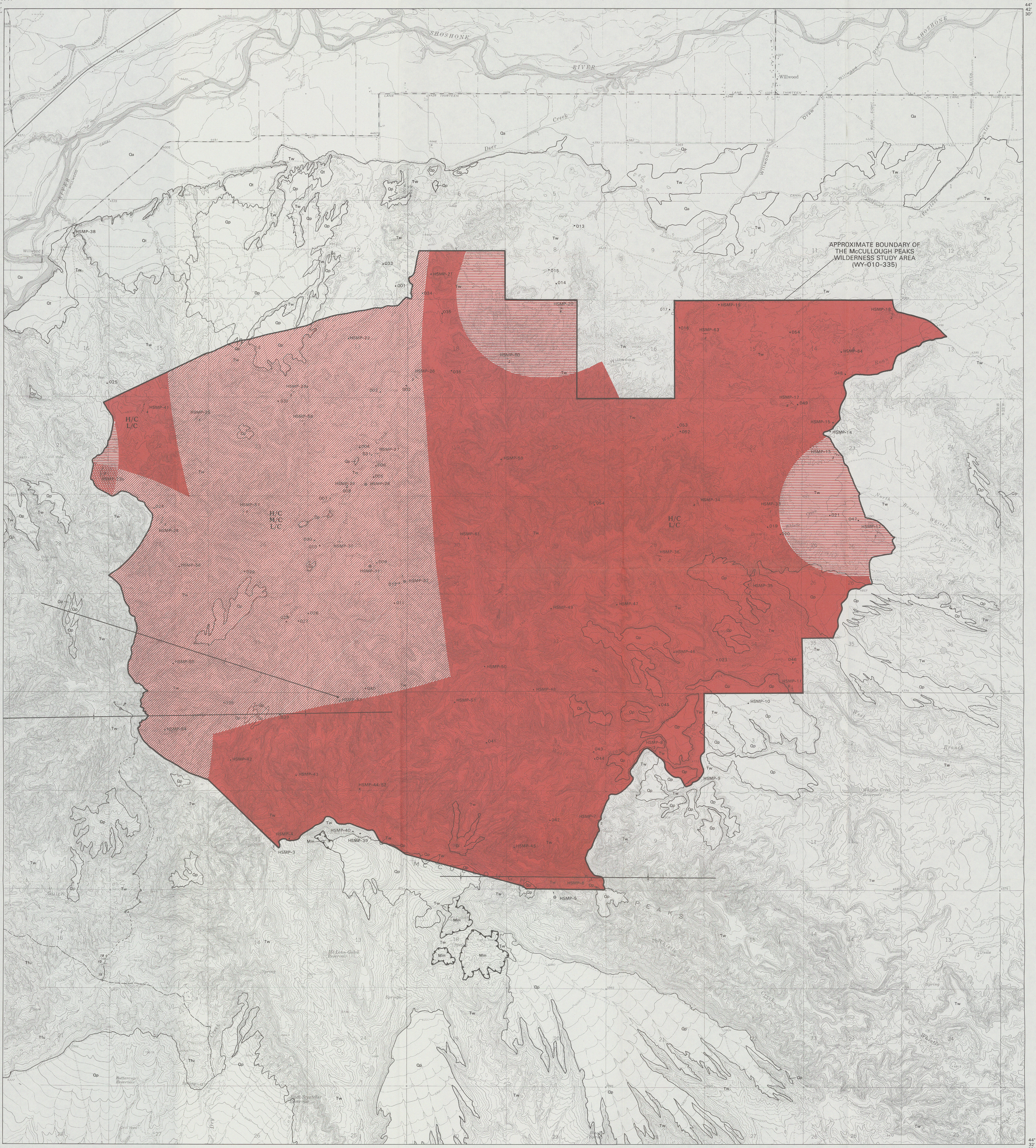
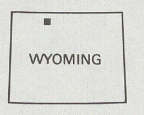
[Letters designate the chapters]



Base from U.S. Geological Survey
Corbett Dam, Stone Barn Camp, Gilmore Hill,
Vocation, Ralston, and Gilmore Hill NW
7.5 minute quadrangles

16½°
TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 1975

SCALE 1:24 000
1 ½ 0 1 MILE
1 .5 0 1 KILOMETER
CONTOUR INTERVAL 20 FEET
DATUM IS MEAN SEA LEVEL



Geology mapped by Donald G. Hadley and K.E. McLeod.

EXPLANATION OF MINERAL RESOURCE POTENTIAL

- **H/C** — **Geologic terrane having high resource potential for gas in low-permeability Cretaceous and Tertiary rocks, with certainty level C; and for paleontological resources in the Willwood Formation, with certainty level C**—Applies to entire study area
- **M/C** — **Geologic terrane having moderate resource potential for gas in porous and permeable Cretaceous and Tertiary rocks, with certainty level C**—Applies to northwest part of study area
- **L/C** — **Geologic terrane having low resource potential, with certainty level C, for metals; for sand and gravel, bentonite, and glass sand; for oil and geothermal sources; and for gas in Paleozoic, lower Mesozoic, and porous and permeable Cretaceous and Tertiary rocks**—Applies to entire study area except for gas in porous and permeable Cretaceous and Tertiary rocks in area marked M/C
- **Area underlain by measured and indicated subbituminous coal resources**

CORRELATION OF MAP UNITS

Ql
Qt
Qp
} Quaternary

Tw
Tfu
} Tertiary

Mm
} Mississipppian

LIST OF MAP UNITS

Ql	**Landslide deposit (Quaternary)**—Failed Willwood Formation
Qt	**Alluvial terraces (Quaternary)**—Developed along ancestral Shoshone River
Qp	**Pediment surfaces (Quaternary)**
Tw	**Willwood Formation (Tertiary)**
Tfu	**Fort Union Formation (Tertiary)**
Mm	**Madison Limestone (Mississippian)**
========	**Unpaved road**
	Paved road
--------	**Trail**
	Stream
	Power line
	Syncline—Arrows show dip
	Anticline, shallow plunge—Arrows show dip and direction of plunge
	Detachment fault—Sawteeth on upper plate
	Contact
——?——	**Contact, generalized**
5	**Strike and dip of bedding, inclined**
⊕	**Strike and dip of bedding, horizontal**
←	**Azimuth of paleocurrent measurement**
x	**Coal prospect**
•042	**Stream sediment and rock geochemical sample locality and number**
HSMP-51	**Rock, thin-section, and geologic data sample locality from mapping field stations (number)**
	Measured outcrop section (dashed where offset)

LEVEL OF RESOURCE POTENTIAL ↑

	A	B	C	D
	U/A UNKNOWN POTENTIAL	H/B HIGH POTENTIAL	H/C HIGH POTENTIAL	H/D HIGH POTENTIAL
		M/B MODERATE POTENTIAL	M/C MODERATE POTENTIAL	M/D MODERATE POTENTIAL
		L/B LOW POTENTIAL	L/C LOW POTENTIAL	L/D LOW POTENTIAL
				N/D NO POTENTIAL

LEVEL OF CERTAINTY →

LEVELS OF RESOURCE POTENTIAL

- **H** High mineral resource potential
- **M** Moderate mineral resource potential
- **L** Low mineral resource potential
- **U** Unknown mineral resource potential
- **N** No known mineral resource potential

LEVELS OF CERTAINTY

- **A** Available data not adequate
- **B** Data indicate geologic environment and suggest level of resource potential
- **C** Data indicate geologic environment, give good indication of level of resource potential, but do not establish activity of resource-forming processes
- **D** Data clearly define geologic environment and level of resource potential and indicate activity of resource-forming processes in all or part of the area

Diagram showing relationships between levels of mineral resource potential and levels of certainty. Shading shows levels that apply to this study area

MINERAL RESOURCE POTENTIAL, GEOLOGIC, AND SAMPLE LOCALITY MAP OF THE McCULLOUGH PEAKS WILDERNESS STUDY AREA, PARK COUNTY, WYOMING