DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

Oil, Gas, and Coal Resources of the McCullough Peaks Wilderness Study Area, Bighorn Basin, Wyoming

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Open-File Report 87-646

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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INTRODUCTION

The McCullough Peaks Wilderness Study Area (WY-010-335) is located in the northern Bighorn Basin about 15 mi (25 km) northeast of Cody, Wyoming, midway between two giant anticlinal oil fields, Elk Basin and Oregon Basin (fig. 1). Each of these fields originally contained recoverable oil resources of approximately 450 million barrels. A third major anticlinal oil field, Garland, with ultimate recoverable oil of approximately 180 million barrels, is located 15 mi (25 km) northeast of the wilderness study area on the east flank of the Bighorn Basin. The small Oregon Basin and Meeteetse coal fields occur 9 mi (14 km) south and 30 mi (48 km) southwest of the wilderness study area, respectively, and the small Garland coal field occurs about 18 mi (29 km) northeast of the wilderness study area (fig. 1).

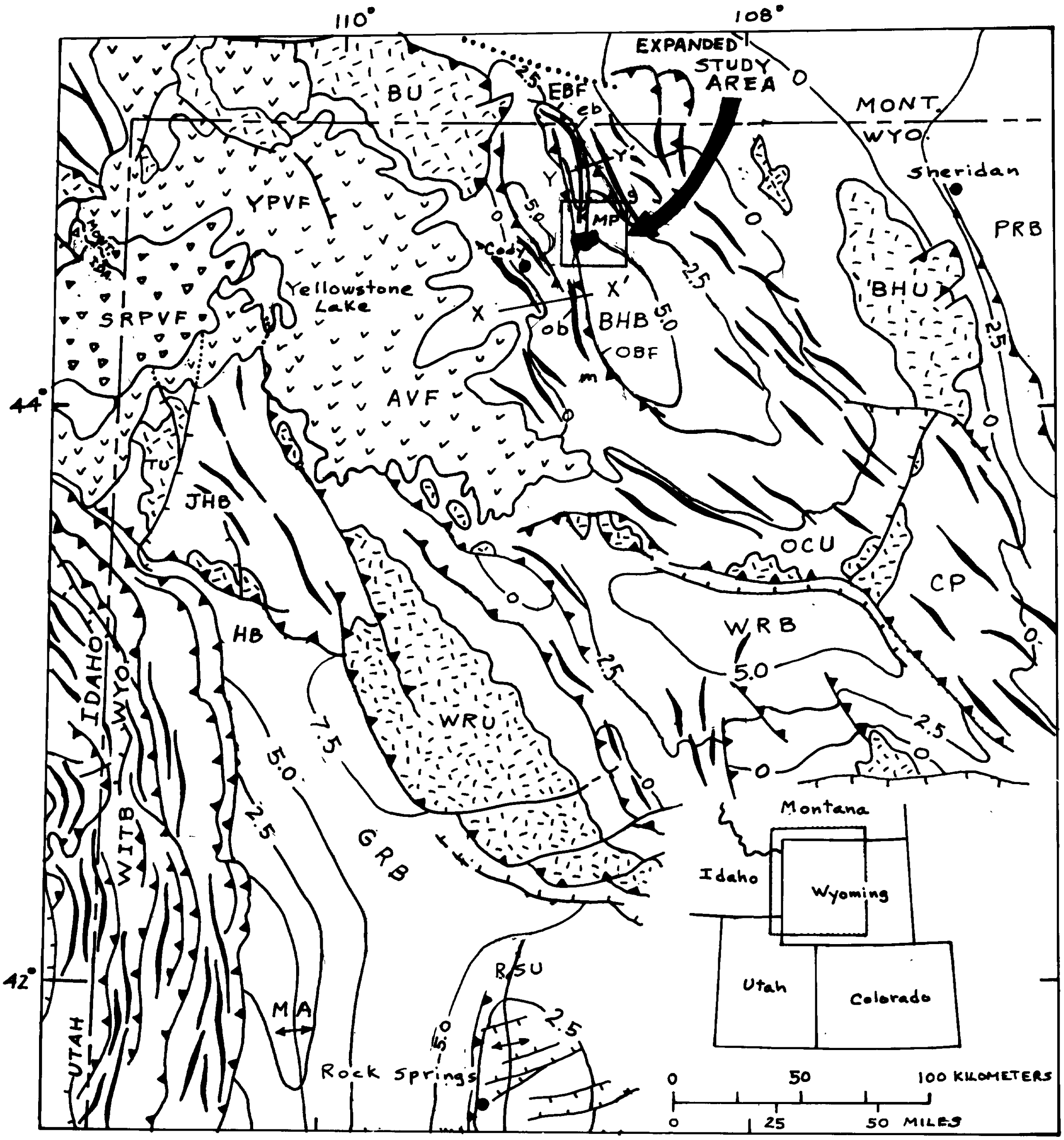
The McCullough Peaks Wilderness Study Area overlies the deeply buried northern end of the Bighorn Basin whose Precambrian basement rocks have been dislocated by the east-verging Oregon Basin and Elk Basin thrust faults (fig. 1). Thus, the structural style beneath the wilderness study area closely resembles the structural style in other basins of 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 listric-shaped thrust faults.

The Oregon Basin thrust fault is very conspicuous on tectonic maps of the Bighorn Basin, extending for as much as 75 mi (125 km) along the western side of the basin (fig. 1). In the deepest part of the Bighorn Basin, adjoining the Oregon Basin field, seismic and drill hole data indicate that the vertical separation of Precambrian basement rocks across this fault is as much as 4 mi (6.5 km) (Stone, 1985; fig. 2). Also at this locality, Precambrian basement rocks and their sedimentary cover on the hanging wall of the thrust have overridden the sedimentary sequence on the foot wall by 3 to 6 mi (5 to 10 km) (fig. 2). Northward, where the Oregon Basin fault extends beneath the western part of the McCullough Peaks Wilderness Study Area, the vertical separation of Precambrian basement rocks is reduced to less than 1 mi (1.6 km). The Elk Basin thrust fault, underlying the east-vergent Elk Basin anticline (fig. 2), probably extends southward into the north-central part of the wilderness study area where vertical separation of basement rocks across it is probably less than 300 ft (91 m).

Fragmentation of the Precambrian basement rocks that controlled, in large part, the structural configuration of the northern Bighorn Basin and its sedimentary deposits is Laramide in age (Campanian through late Eocene). However, prior to Laramide deformation and sedimentation, the region now occupied by the Bighorn Basin was the site of continental shelf sedimentation, broad warping, extensive erosion and (or) non-deposition. Post-Laramide sedimentation, preserved in other basins of the Rocky Mountain region, is absent in the northern part of the Bighorn Basin owing to post-middle Miocene uplift and erosion. In the deepest part of the Bighorn Basin, adjoining the Oregon Basin thrust fault, the sedimentary record is 5 mi (8 km) thick (fig. 2). Approximately two-thirds of the sedimentary record here consists of Laramide-stage deposits whereas the remainder consists of shelf-stage deposits. Rocks of Paleozoic age account for less than 15 percent of the total record.

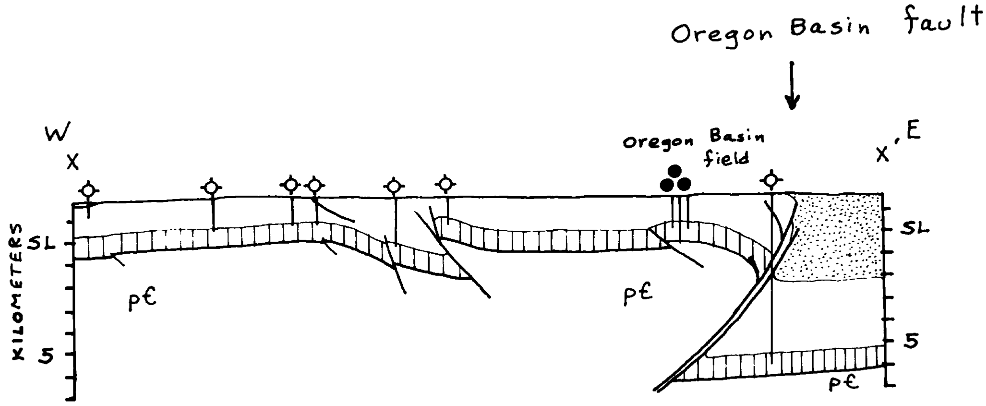
Carbonate rocks of shallow marine and peritidal origin, identified as the Gallatin Limestone, Bighorn Dolomite, Darby Formation, Madison Limestone, LIST OF ILLUSTRATIONS AND TABLES (Cont.)

Figure 1. Tectonic map of northwestern Wyoming and adjacent states showing the McCullough Peaks Wilderness Study Area (MP), the expanded study area, and major tectonic elements of the Bighorn Basin. The map is taken from King (1969). Minor modifications have been added based on the work of Blackstone (1979, 1986), Love and Christiansen (1985), and Stone (1983, 1985). Structure contours, in kilometers below mean sea level, are drawn on top of Precambrian basement rocks. Oil, gas, and coal fields are identified as follows: eb, Elk Basin oil and gas field; g. Garland oil, gas, and coal field; m, Meeteetse coal field; ob, Oregon Basin oil, gas, and coal field. Major tectonic and geologic features are identified as follows: AVF, Absaroka volcanic field; BHB, Bighorn Basin; BHU, Bighorn uplift; BU, Beartooth uplift; CP, Casper platform; eb, Elk Basin anticline; EBF, Elk Basin fault; g, Garland anticline; GRB, Green River Basin; HB, Hoback basin; JHB, Jackson Hole basin; MA, Moxa arch; ob, Oregon Basin anticline; OBF, Oregon Basin fault; OCU, Owl Creek uplift; PRB, Powder River Basin; RSU, Rock Springs uplift; SRPVF, Snake River Plain volcanic field; TU, Teton uplift; WITB, Wyoming and Idaho thrust belt; WRB, Wind River Basin; WRU, Wind River uplift; YPVF, Yellowstone Plateau volcanic field. Basement rocks of Archean age are identified by a random-dash pattern. Tertiary volcanic rocks are identified by a random V pattern. Quaternary volcanic rocks are identified by an open triangle pattern. X-X' and Y-Y' locate geologic cross sections shown in figure 2.

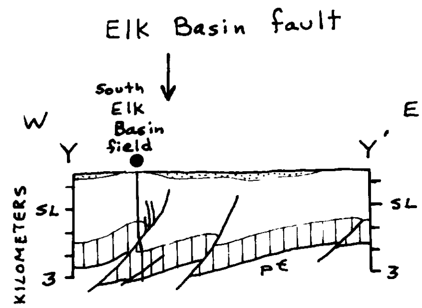


110°
108°
EXPANDED STUDY AREA
MONT.
WYO.
Sheridan
PRB
BU
EBF
eb
YPVF
MP
Cody
Yellowstone Lake
SRPVF
X
X'
BHB
OBF
ob
BHU
AVF
44°
TU
JHB
OCU
CP
WRB
HB
WRU
GRB
IDAHO
WYO
WITB
UTAH
42°
RSU
MA
Rock Springs
Montana
Idaho
Wyoming
Utah
Colorado
100 KILOMETERS
50 MILES

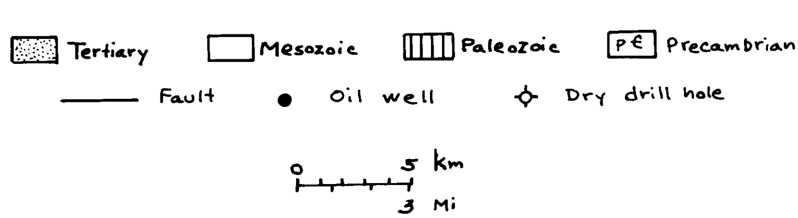
Figure 2. Geologic cross sections through the Oregon Basin (X-X') and South Elk Basin (Y-Y') fields, Bighorn Basin, Wyoming. Lines of section are located on figure 1. Section X-X' is from Stone (1985) and section Y-Y' is from Stone (1983).



Oregon Basin fault
W
X
Oregon Basin field
X', E
SL
5
KILOMETERS
pЄ
pЄ
pЄ



Elk Basin fault
South Elk Basin field
W
Y
E
Y'
SL
3
KILOMETERS
pЄ



Tertiary
Mesozoic
Paleozoic
pЄ Precambrian
Fault
Oil well
Dry drill hole
0
5 km
3 Mi

Amsden Formation (part) and Phosphoria Formation, dominate the Paleozoic deposits in the vicinity of the wilderness study area (fig. 3). Quartz sandstones in the Paleozoic sequence are represented by the Pennsylvanian Tensleep Sandstone, the Mississippian (?) Darwin Sandstone Member of the Amsden Formation, and the Cambrian Flathead Sandstone. Regional unconformities bound most of the major stratigraphic units of Paleozoic age (fig. 3).

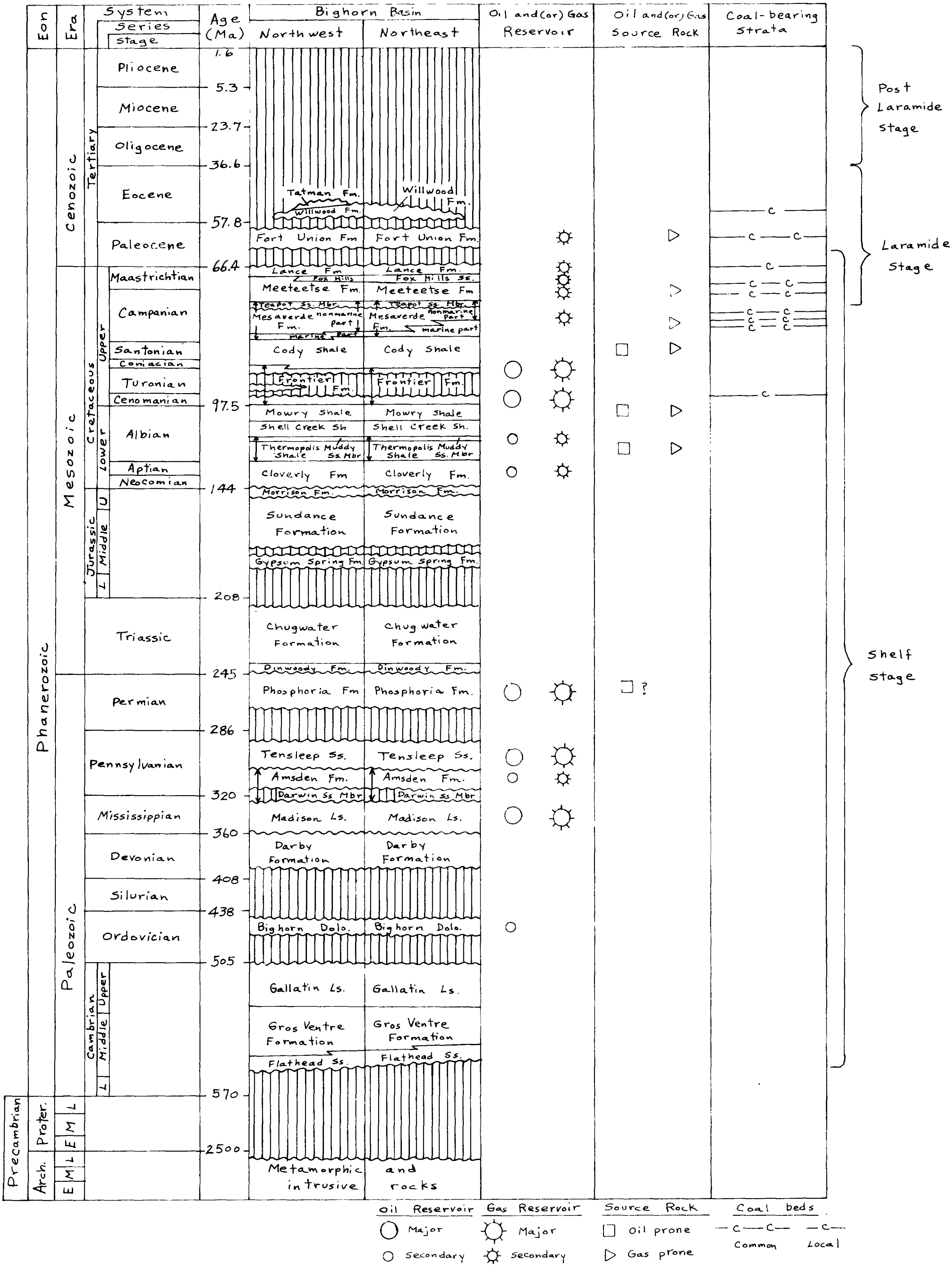
Nonmarine red beds (Chugwater Formation, Gypsum Spring Formation, Morrison Formation, and the lower part of the Cloverly Formation) and shallow marine shale, sandstone, and limestone of the Sundance Formation characterize the deposits of Triassic, Jurassic, and earliest Cretaceous age in the vicinity of the wilderness study area (fig. 3). Many of these stratigraphic units are bounded by regional unconformities. The upper part of the Cloverly Formation and the overlying Thermopolis Shale (lower Albian) document the arrival of the Western Interior seaway into the area now occupied by the northern Bighorn Basin.

For the remainder of Early Cretaceous time and most of Late Cretaceous time, the area of the present-day wilderness study area was either covered by or was peripheral to the Western Interior seaway. Sandstone-dominated, nonmarine to nearshore marine regressive sequences (Frontier, Mesaverde, Meeteetse, and Lance Formations) were derived from tectonically active uplands in the thrust belt to the west. The Cody Shale of offshore marine origin, located stratigraphically between the Frontier and Mesaverde Formations, represents a late Coniacian to early Campanian transgression of the Western Interior seaway.

The onset of Laramide tectonism in the present-day Bighorn Basin is probably recorded by the regional unconformity in the upper part of the Mesaverde Formation and the subsequent deposition of westerly derived fluvial sandstone and conglomeratic sandstone of the middle Campanian Teapot Sandstone Member (Gill and Cobban, 1966). Regional unconformities of Cenomanian and Turonian age in the Frontier Formation of the Bighorn Basin (Merewether and Cobban, 1986) are precursors to the Laramide events. Laramide tectonism was greatly accelerated in Paleocene and early Eocene time, causing sedimentation of the Fort Union and Willwood Formations in the rapidly subsiding Bighorn Basin and thrust faulting, uplift, and erosion along its margins. Thick Paleocene and early Eocene syntectonic deposits of sandstone and local conglomerate formed adjacent to the active uplifts whereas finer grained deposits of sandstone, siltstone, mudstone, and coal formed near the basin center. The appearance of feldspathic detritus in the Willwood Formation suggests that at least some of the uplifts west of the basin had been eroded to Precambrian basement rocks by early Eocene time (Neasham and Vondra, 1972). Although now absent, the eastern margin of the Absaroka volcanic field (fig. 1) may have extended across all or part of the McCullough Peaks Wilderness Study Area in late Eocene time.

In a recent study of the Wilderness Lands in Wyoming, Spencer (1983a,b) estimated that the McCullough Peaks Wilderness Study Area has a high potential for undiscovered oil and gas, a conclusion which the U.S. Bureau of Land Management (1984; Crockett, Fred, unpub. data, 1986) supports. The objectives of this investigation are to augment the preliminary oil and gas resource appraisals by Spencer (1983 a,b) and the U.S. Bureau of Land Management (1984; Crockett, Fred, unpub. data 1986), by analyzing a variety of subsurface data

Figure 3. Stratigraphic correlation chart for Phanerozoic and Precambrian rocks of the Bighorn Basin. Also identified on the chart are oil and gas reservoirs, oil and gas source rocks, and coal-bearing strata. The chart is based largely on published stratigraphic correlation charts by Love and Christiansen (1980) and the Wyoming Geological Association Stratigraphic Nomenclature Committee (1975). Absolute age (in Ma) is taken from the Geological Time Scale compiled by Palmer (1983). The time scale is nonlinear.


Eon
Era
System
Series
Stage
Age (Ma)
Bighorn Basin
Northwest
Northeast
Oil and(or) Gas Reservoir
Oil and(or) Gas Source Rock
Coal-bearing strata
Phanerozoic
Cenozoic
Tertiary
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Mesozoic
Cretaceous
Upper
Lower
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Neocomian
Jurassic
U
Middle
L
Triassic
Paleozoic
Permian
Pennsylvanian
Mississippian
Devonian
Silurian
Ordovician
Cambrian
Upper
Middle
L
Precambrian
Proter.
Arch.
L
M
E
L
M
E
1.6
5.3
23.7
36.6
57.8
66.4
97.5
144
208
245
286
320
360
408
438
505
570
2500
Tatman Fm.
Willwood Fm.
Willwood Fm.
Fort Union Fm
Fort Union Fm.
Lance Fm
Fox Hills
Lance Fm.
Fox Hills Ss.
Meeteetse Fm.
Meeteetse Fm
Teapot Ss. Mbr.
Mesaverde Fm.
nonmarine part
marine part
Teapot Ss. Mbr.
Mesaverde Fm.
nonmarine part
marine part
Cody Shale
Cody Shale
Frontier Fm.
Frontier Fm.
Mowry Shale
Mowry Shale
Shell Creek Sh
Shell Creek Sh.
Thermopolis Shale
Muddy Ss. Mbr
Thermopolis Shale
Muddy Ss. Mbr
Cloverly Fm
Cloverly Fm.
Morrison Fm.
Morrison Fm.
Sundance Formation
Sundance Formation
Gypsum Spring Fm.
Gypsum Spring Fm.
Chugwater Formation
Chugwater Formation
Dinwoody Fm.
Dinwoody Fm.
Phosphoria Fm
Phosphoria Fm.
Tensleep Ss.
Tensleep Ss.
Amsden Fm.
Amsden Fm.
Darwin Ss Mbr
Darwin Ss Mbr
Madison Ls.
Madison Ls.
Darby Formation
Darby Formation
Bighorn Dolo.
Bighorn Dolo.
Gallatin Ls.
Gallatin Ls.
Gros Ventre Formation
Gros Ventre Formation
Flathead Ss.
Flathead Ss.
Metamorphic and intrusive rocks
?
c
Post Laramide stage
Laramide Stage
Shelf stage
Oil Reservoir
Major
Secondary
Gas Reservoir
Major
Secondary
Source Rock
Oil prone
Gas prone
Coal beds
Common
Local

recorded in drill holes in the vicinity of the wilderness study area, and to modify their resource appraisals if necessary. An additional objective is to assess the potential coal resources in the wilderness study area. The total area of 410 sq mi (1050 sq km) from which subsurface data were gathered in support of the oil, gas, and coal resource evaluation of the McCullough Peaks Wilderness Study Area is referred to as the expanded study area (fig. 1).

OIL AND GAS

Fields and Shows

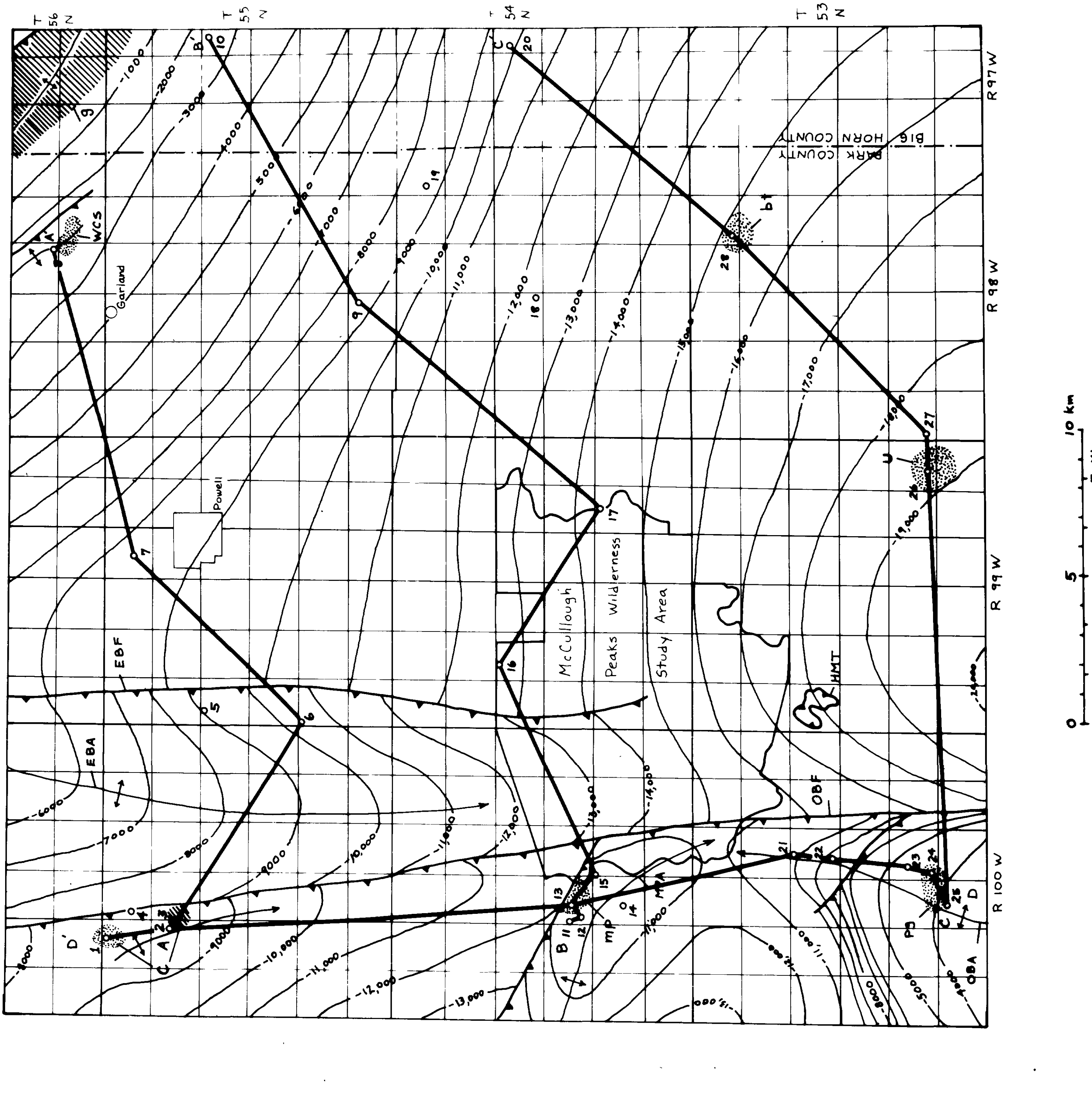
In addition to its location near the giant Elk Basin, Garland, and Oregon Basin oil and gas fields, the McCullough Peaks Wilderness Study Area is located near five small gas fields and one small oil and gas field (figs. 1 and 4). Most of these fields consist of 1 or 2 wells and are presently shut in or abandoned. Three of the fields occur in anticlinal structures distributed along the eastern margin of the hanging wall block of the Oregon Basin thrust fault (figs. 4 and 5). The northernmost of these fields, Coulee, initially produced condensate at 131 barrels/day, gas at 1.069 million cubic ft(MMCF)/day, and water at 55 barrels/day from two 45- to 60-ft-thick (14 to 18 m) sandstones in the upper part of the Frontier Formation. The Coulee field also initially produced oil at 36 barrels/day and water at 39 barrels/day from two 15- to 30-ft.-thick (4.5 to 9 m) sandstones near the base of the Lance Formation (table 1; fig. 5, sec. A-A'; fig. 6, sec. D-D'). Gas shows in the Coulee field are reported from the Fox Hills Sandstone and Mesaverde Formation and oil shows are reported from the Mesaverde Formation, Phosphoria Formation and Tensleep Sandstone (table 1). Minimum reservoir pressures derived from drill-stem tests and mud-weight pressures from well-log mud weights indicate that the Frontier and Cloverly Formations are slightly overpressured with respect to a normal hydrostatic gradient of 0.43 psi/ft (fig. 7). The reservoir pressures derived from these drill-stem tests and tests in subsequent fields are minimum pressures because they have not been extrapolated. The top and base of the overpressured section are located, respectively, at about 10,000 and 12,000 ft (3.05 and 3.65 km).

The McCulloch Peak gas field, situated about 8 mi (13 km) south of the Coulee field and less than 1 mi (1.6 km) west of the wilderness study area, intially produced gas at 495 thousand cubic ft(MCF)/day from a 15-ft-thick (4.5 m) sandstone in the Fort Union Formation (table 1). Between 1962 and 1974, 191,475 MCF of gas were produced from the McCulloch Peak field (Reaves, 1975). Through 1984, 485 MMCF of gas were produced from the field (Wyoming Oil and Gas Commission, 1985). In addition, gas shows in the McCulloch Peak field are reported from the Mesaverde Formation and oil and gas shows are reported from the Fox Hills Sandstone and Frontier Formation (table 1; fig. 5, sec. B-B'; fig. 6 sec. D-D'). 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 are slightly overpressured with respect to a normal hydrostatic gradient of 0.43 psi/ft (fig. 8). The top and base of the overpressured zone in the McCulloch Peak field are not as well defined as in the Coulee field, but are estimated to be at about 11,000 ft (3352 m) and 14,000 ft (4267 m), respectively (fig. 8).

The third field located along the margin of the Oregon Basin thrust fault is Penney Gulch (fig. 4; fig. 6; sec. D-D'). This field initially produced

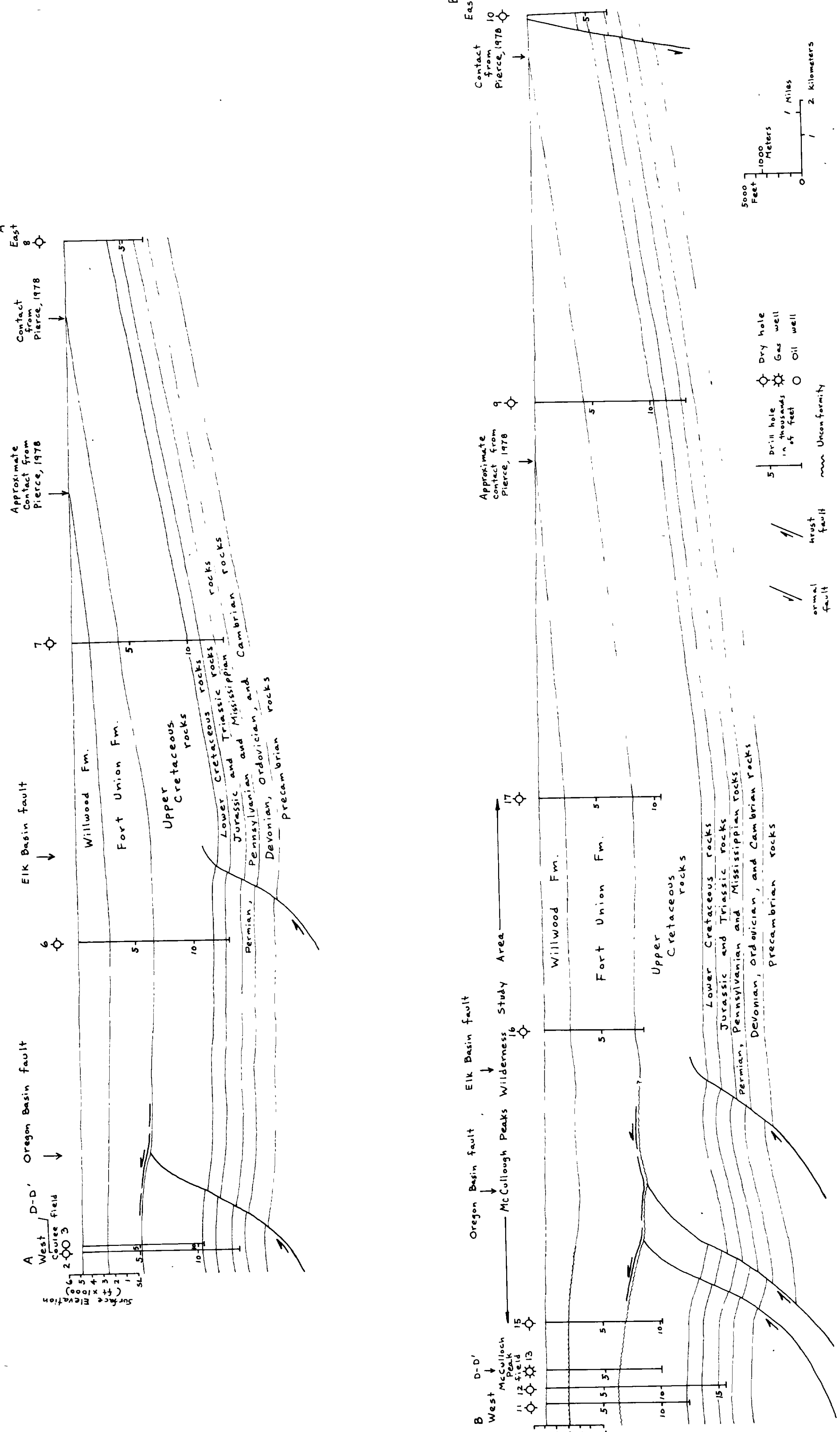
Figure 4. Structure contour map of the McCullough Peaks Wilderness Study Area and the expanded study area. Contours, in feet below mean sea level, are drawn on top of the Tensleep Sandstone. The contour interval is 1000 ft. This map was acquired from Petroleum Information Corporation and Barlow and Haun, Incorporated. Drill holes are located with a small circle and an accompanying number which is identified in Table 1. Oil (diagonal line pattern) and gas (stippled pattern) fields are identified as follows: bt, Bridger Trail; c, Coulee; g, Garland; mp, McCulloch Peak; pg, Penney Gulch; u, unnamed; wcs, Whistle Creek South. Major tectonic features are identified as follows: EBA, Elk Basin anticline; EBF, Elk Basin fault; HMT, Heart Mountain thrust; MPA, McCulloch Peak anticline; OBA, Oregon Basin anticline; OBF, Oregon Basin fault. A-A', B-B', C-C', and D-D' locate lines of geologic cross section shown in figures 5 and 6.

Figure 5. Geologic cross sections A-A' and B-B' through the expanded study area. Well and drill hole depths are in thousands of feet. Wells and drill holes are identified in Table 1. Lines of section are shown on figure 4.



McCullough Peaks Wilderness Study Area
Powell
Garland
BIG HORN COUNTY
PARK COUNTY
R 97 W
R 98 W
R 99 W
R 100 W
T 56 N
T 55 N
T 54 N
T 53 N
EBF
EBA
OBF
OBA
HMT
WCS
10 km
5 Mi

Figure 6. Geologic cross sections C-C' and D-D' through the expanded study area. Well and drill hole depths are in thousands of feet. Wells and drill holes are identified in table 1. Lines of section are shown on figure 4.


A
West
Coulee Field
D-D'
Oregon Basin fault
Elk Basin fault
Contact from Pierce, 1978
Approximate Contact from Pierce, 1978
A'
East
Surface Elevation (ft x1000)
SL
Willwood Fm.
Fort Union Fm.
Upper Cretaceous rocks
Lower Cretaceous rocks
Jurassic and Triassic rocks
Permian, Pennsylvanian, and Mississippian rocks
Devonian, Ordovician, and Cambrian rocks
Precambrian rocks
B
West
McCulloch Peak field
McCullough Peaks Wilderness Study Area
Drill hole in thousands of feet
Dry hole
Gas well
Oil well
Unconformity
Normal fault
Thrust fault
5000 Feet
1000 Meters
1 Miles
2 Kilometers

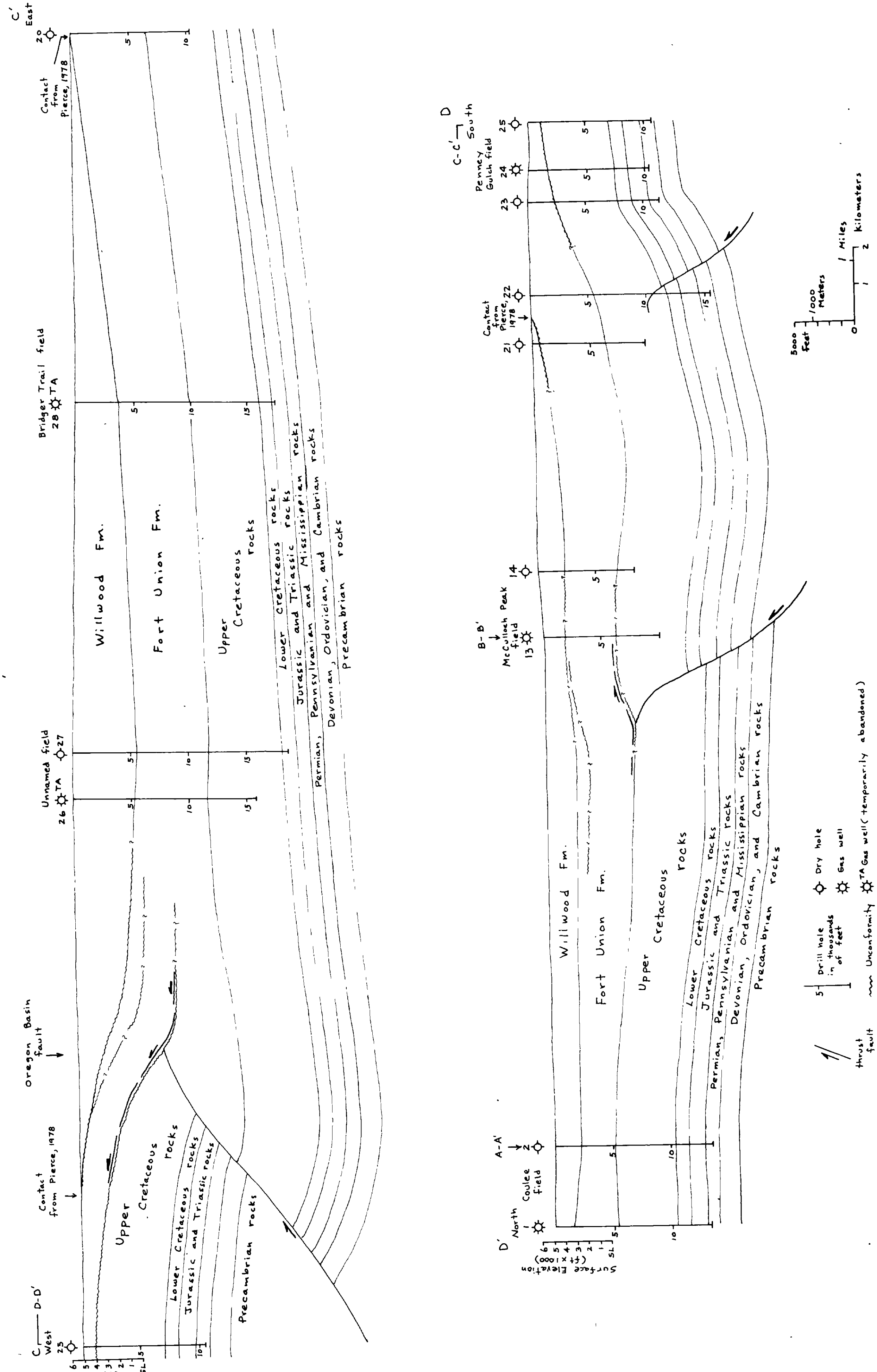
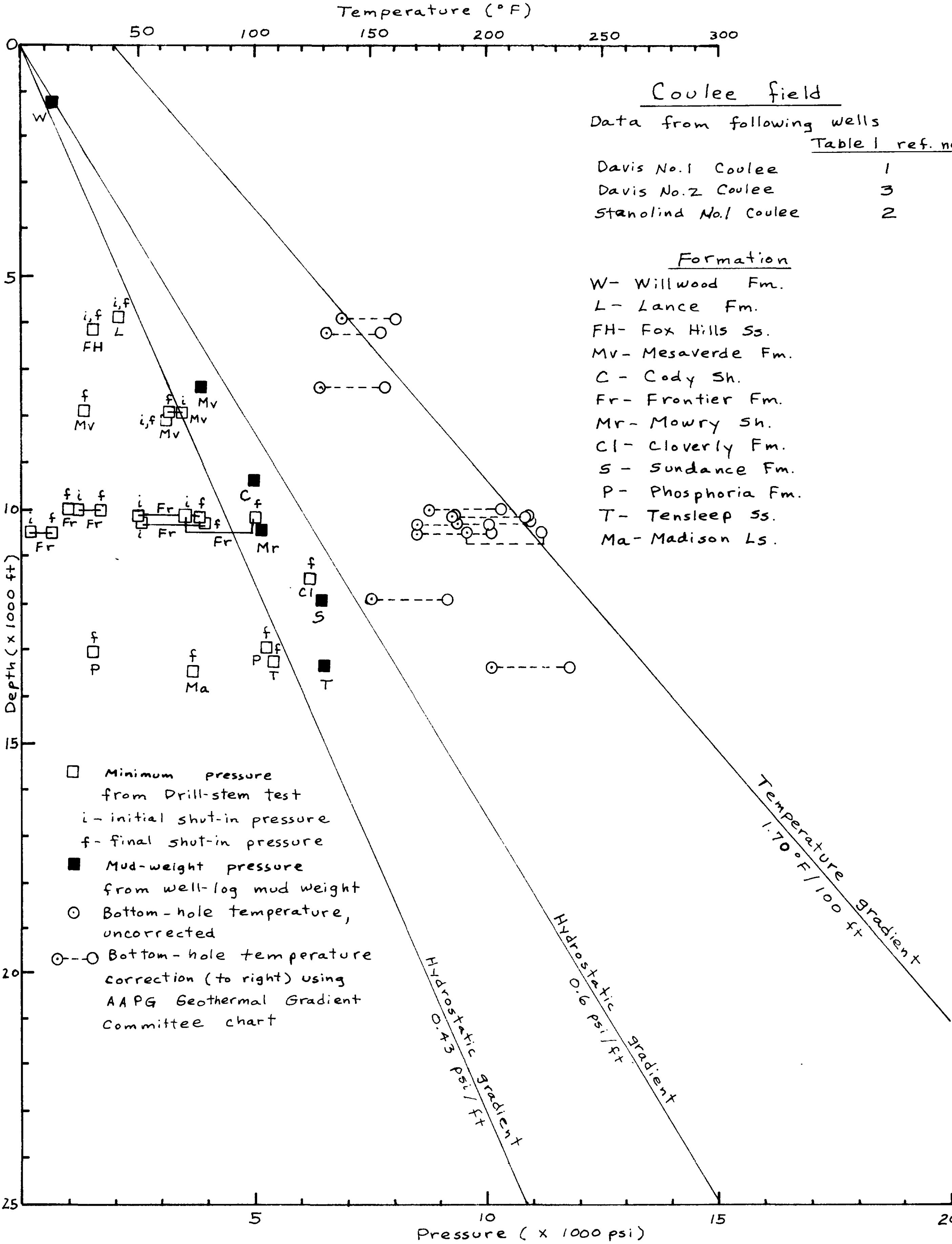
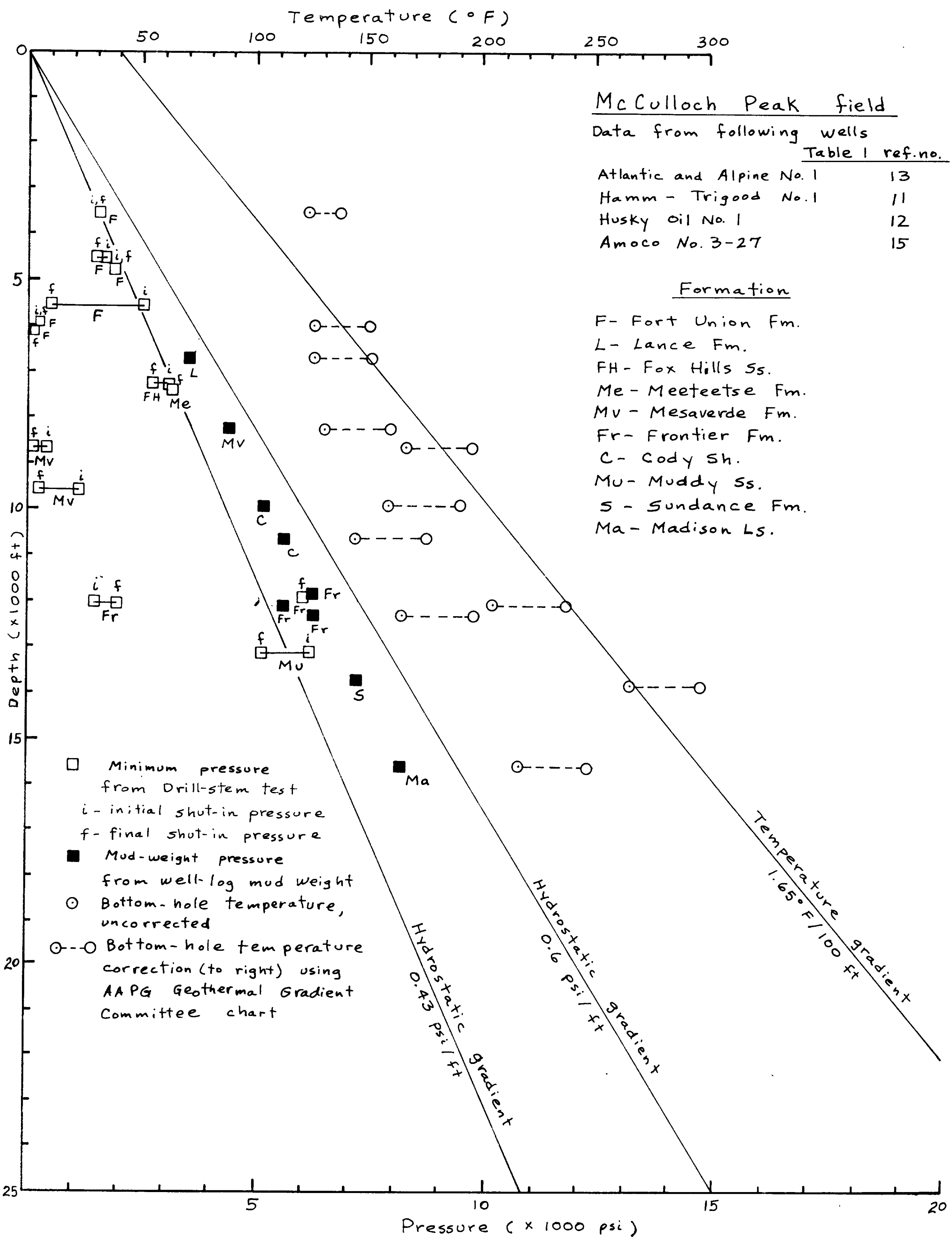

C
West
D-D'
C'
East
Contact from Pierce, 1978
Oregon Basin fault
Unnamed field
26 TA
27
Bridger Trail field
28 TA
20
Upper Cretaceous rocks
Lower Cretaceous rocks
Jurassic and Triassic rocks
Precambrian rocks
Willwood Fm.
Fort Union Fm.
Permian, Pennsylvanian and Mississippian rocks
Devonian, Ordovician, and Cambrian rocks
Surface Elevation (ft x1000)
D'
North
Coulee field
A-A'
B-B'
McCulloch Peak field
C-C'
D
South
Penney Gulch field
Drill hole in thousands of feet
Dry hole
Gas well
TA Gas well (temporarily abandoned)
Unconformity
thrust fault
5000 Feet
1000 Meters
1 Miles
2 kilometers

Figure 7. Pressure and temperature profiles for selected drill holes in the Coulee field. For location of drill holes and field see table 1 and figure 4.

Figure 8. Pressure and temperature profiles for selected drill holes in the McCulloch Peak field. For location of drill holes and field see table 1 and figure 4.


Temperature (°F)
50
100
150
200
250
300
Coulee field
Data from following wells
Table 1 ref. no.
Davis No. 1 Coulee 1
Davis No. 2 Coulee 3
Stanolind No. 1 Coulee 2
Formation
W- Willwood Fm.
L- Lance Fm.
FH- Fox Hills Ss.
Mv- Mesaverde Fm.
C- Cody Sh.
Fr- Frontier Fm.
Mr- Mowry Sh.
Cl- Cloverly Fm.
S- Sundance Fm.
P- Phosphoria Fm.
T- Tensleep Ss.
Ma- Madison Ls.
Depth (x 1000 ft)
Minimum pressure from Drill-stem test
i - initial shut-in pressure
f - final shut-in pressure
Mud-weight pressure from well-log mud weight
Bottom-hole temperature, uncorrected
Bottom-hole temperature correction (to right) using AAPG Geothermal Gradient Committee chart
Hydrostatic gradient 0.43 psi/ft
Hydrostatic gradient 0.6 psi/ft
Temperature gradient 1.70°F/100 ft
Pressure (x 1000 psi)



Temperature (°F)
50
100
150
200
250
300
McCulloch Peak field
Data from following wells
Table 1 ref. no.
Atlantic and Alpine No. 1 13
Hamm - Trigood No. 1 11
Husky Oil No. 1 12
Amoco No. 3-27 15
Formation
F - Fort Union Fm.
L - Lance Fm.
FH - Fox Hills Ss.
Me - Meeteetse Fm.
Mv - Mesaverde Fm.
Fr - Frontier Fm.
C - Cody Sh.
Mu - Muddy Ss.
S - Sundance Fm.
Ma - Madison Ls.
Minimum pressure from Drill-stem test
i - initial shut-in pressure
f - final shut-in pressure
Mud-weight pressure from well-log mud weight
Bottom-hole temperature, uncorrected
Bottom-hole temperature correction (to right) using AAPG Geothermal Gradient Committee chart
Hydrostatic gradient 0.43 psi/ft
Hydrostatic gradient 0.6 psi/ft
Temperature gradient 1.65°F/100 ft
Depth (x1000 ft)
Pressure (x 1000 psi)

gas at 313 MCF/day from a 30-ft-thick (9 m) sandstone near the base of the Lance Formation (Table 1; fig. 6, sec. D-D'). Oil and gas shows are reported from the Phosphoria Formation (table 1). Although the field is located on the north-plunging nose of the Oregon Basin anticline, the apparent lack of structural closure suggests that the gas accumulation here may be in part stratigraphically controlled. Minimum reservoir pressures derived from drill-stem tests and mud-weight pressures from well-log mud weights indicate a normal hydrostatic pressure gradient of 0.43 psi/ft at this field (fig. 9).

The Whistle Creek South gas field and part of the Garland oil and gas field are located in the northeast corner of the expanded study area (fig. 4). Accumulations at both fields have been trapped by northwest-trending anticlines which are the first major structures updip from the McCullough Peaks Wilderness Study Area on the east flank of the basin. At Garland field, oil and gas are produced from the Frontier Formation, Phosphoria Formation, Tensleep Sandstone, Amsden Formation, and the Madison Limestone. The small Whistle Creek South field produces gas from the Cloverly Formation. The down-plunge position of the Cloverly gas accumulation suggests that it is in part stratigraphically controlled. Between 1951 and 1974, 383,080 MCF of gas have been produced from the Whistle Creek South field (Reaves, 1975). Minimum pressures derived from drill-stem tests and mud-weight pressures from well-log mud weights indicate a normal hydrostatic pressure gradient at the Whistle Creek South field and the moderately buried east flank of the basin (fig. 10).

Approximately 6 mi (10 km) southeast of the wilderness study area, two marginally commercial one-well gas fields occur in the deeply buried part of the basin (fig. 4; fig. 6, sec. C-C'). Gas in the more northerly of these fields (Bridger Trail) initially flowed at a rate of 261 to 822 MCF/day from the 20-ft-thick (6 m) Muddy Sandstone whereas gas in the southerly field (unnamed) initially flowed at a rate of 350 MCF/day from 55- to 75-ft-thick (17-23 m) sandstones in the Mesaverde Formation (table 1). Initial testing in the unnamed field also produced condensate and 132 barrels of water from the Mesaverde Formation (table 1). 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 No. 1 drill hole (table 1). Minimum pressures 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 No. 1 drill hole are significantly overpressured with respect to a normal hydrostatic gradient of 0.43 psi/ft (fig. 11). 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 (fig. 11). The top of the overpressured zone in the unnamed and Bridger Trail fields is probably located between 11,000 and 12,000 ft (3.35 - 3.65 km) (fig. 11).

Oil and gas shows in the expanded study area are not confined to small fields. For example, gas and(or) oil was reported from the Meeteetse Formation in the Gulf Oil No. 1 near the eastern boundary of the wilderness study area and from the Meeteetse and Cloverly Formations in the Amoco No. 1 Burgener approximately 4 mi (6 km) north of the wilderness study area (fig. 4; table 1). In addition, live and dead oil shows and gas shows are reported from the Tensleep Sandstone and Phosphoria Formation in the Tidewater No. 1 and Houston Oil and Minerals No. 41 - 33 drill holes located on the moderately

Figure 9. Pressure and temperature profiles for selected drill holes in the Penney Gulch field. For location of drill holes and field see table 1 and figure 4.

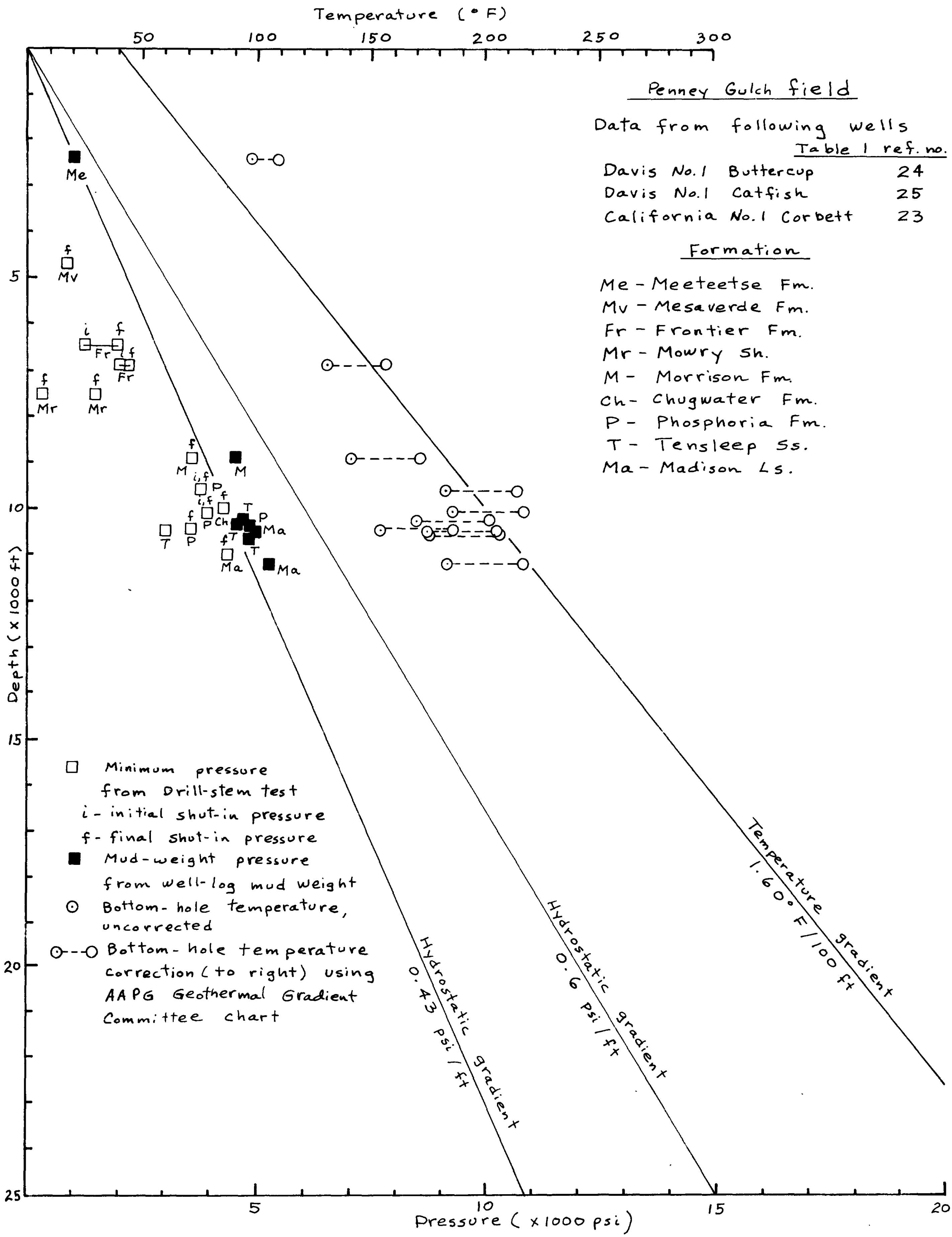

Temperature (°F)
50
100
150
200
250
300
Penney Gulch field
Data from following wells
Table I ref. no.
Davis No. I Buttercup 24
Davis No. I Catfish 25
California No. I Corbett 23
Formation
Me - Meeteetse Fm.
Mv - Mesaverde Fm.
Fr - Frontier Fm.
Mr - Mowry Sh.
M - Morrison Fm.
Ch - Chugwater Fm.
P - Phosphoria Fm.
T - Tensleep Ss.
Ma - Madison Ls.
Depth (x1000 ft)
5
10
15
20
25
Minimum pressure from Drill-stem test
i - initial shut-in pressure
f - final shut-in pressure
Mud-weight pressure from well-log mud weight
Bottom-hole temperature, uncorrected
Bottom-hole temperature correction (to right) using AAPG Geothermal Gradient Committee chart
Hydrostatic gradient 0.43 psi/ft
Hydrostatic gradient 0.6 psi/ft
Temperature gradient 1.60° F/100 ft
5
10
15
20
Pressure (x1000 psi)

Table 1.--Well and drill hole data* in vicinity of McCullough Peaks Wilderness Study Area

Ref. No.	Name	Location	Total Depth (ft)	Formation at total depth	Formation with oil and/or gas show or production; depth(s) (ft)
1	Davis Oil Company No. 1 Coulee Unit	NW 1/4, NE 1/4 Sec. 5, T.55 N., R.100 W.	13,375	Tensleep Ss	Mesaverde Fm, oil and gas show, 8060 - 8150 Frontier Fm, gas production at 1.069 MMCFPD, 131 BCPD and 55 BW, 10,153 - 10,202 Phosphoria Fm, oil show, 13,133 - 13,139
2	Stanolind Oil and Gas Company No. 1 Big Sand Coulee Unit	SE 1/4, NE 1/4 Sec. 8, T.55 N., R.100 W.	13,447	Madison Ls.	Frontier Fm, oil show, 10,028 - 10,057, gas show, 10,316 - 10,372 Tensleep Ss., oil show, 12,972 - 13,111
3	Davis Oil Company No. 2 Coulee Unit	SE 1/4, NE 1/4 Sec. 8, T.55 N., R.100 W.	10,551	Mowry Sh.	Lance Fm, oil production at 36 BOPD, 39 BW, 5873 - 5959 Fox Hills Ss, gas show, 6138 - 6139 Mesaverde Fm, gas show, 7864 - 7964 Frontier Fm, gas shows, 10,026 - 10,059, 10,130 - 10,183
4	Phillips Petroleum Company No. 1 Rose-B	NW 1/4, SW 1/4 Sec. 4, T.55 N., R.100 W.	8,620	Cody Sh.	NS
5	Marathon Oil Company No. 1-67 Cary	NE 1/4, NW 1/4 Sec. 18, T.55 N., R.99 W.	12,450	Tensleep Ss.	Frontier Fm., gas show, 9360, 9500 Muddy Ss., gas show, 10,385 Cloverly Fm, gas show, 10,700
6	Amoco Production Company No. 1 Burgener Trust	NW 1/4, NW 1/4 Sec. 30 T.55 N., R.99 W.	13,100	Sundance Fm	Meeteetse Fm., oil and gas show, 7695 - 7751 Cloverly Fm., gas show, 12,652 - 12,902

Table 1 (cont.)

Ref. No.	Name	Location	Total Depth (ft)	Formation at total depth	Formation with oil and/or gas show or production; depth(s) (ft)
7	Tidewater Oil Company No. 1 Atteberry	NE 1/4, SE 1/4 Sec. 3, T.55 N., R.99 W.	13,100	Madison Ls.	Phosphoria Fm., gas and dead oil show, 12,434 - 12,532 Tensleep Ss., live and dead oil shows, 12,560 - 12,780
8	Dow, Manning, and Anadarko Production Company	SE 1/4, SE 1/4 Sec. 27, T.56 N., R.98 W.	6700	Madison Ls.	NS
9	Houston Oil and Minerals No. 41-33 McCullough	NE 1/4, NE 1/4 Sec. 33, T.55 N., R.98 W.	12,966	Tensleep Ss.	Phosphoria Fm. and(or) Tensleep Sandstone, gas show, 12,770 - 12,962
10	Shell Oil Company No. 1 State	NE 1/4, NW 1/4 Sec. 16, T.55 N., R.97 W.	6,921	Tensleep Ss.	Phosphoria Fm., gas and oil show, 6708 - 6762
11	Hamm-Trigood No. 1 Government	NW 1/4, SW 1/4 Sec. 21 T.54 N., R.100 W.	12,299	Mowry Sh.	Fort Union Fm., oil show, 5200 - 5400 Frontier Fm., gas show, 11,871 - 12,035, oil show, 12,030 - 12,110
12	Husky Oil Company No. 1 McCulloch Peak	NW 1/4, SW 1/4 Sec. 21, T.54 N., R.100 W.	15,627	Madison Ls.	No record
13	Atlantic Refining Company and Alpine Oil Company, Inc. No. 1 McCulloch Peak Government	NE 1/4, SW 1/4 Sec. 21, T.54 N., R.100 W.	9904	Cody Sh.	Fort Union Fm., gas production at 495 MCFPD, 3487 - 3492, gas show, 4425 - 4514, 4753 - 4825, 5902 - 5970 Fox Hills Ss., oil and gas show, 7236 - 7255 Mesaverde Fm., gas show, 8632 - 8663
14	Atlantic Refining Company and Alpine Oil Company, Inc. No. 1 Rogers Government	NE 1/4, SW 1/4 Sec. 28, T.54 N., R.100 W.	8140	Meeteetse Fm.	Fort Union Fm., gas show, 4063 - 4102, 5728 - 5758, 6522 - 6564

Table 1 (cont.)

Ref. No.	Name	Location	Total Depth (ft)	Formation at total depth	Formation with oil and/or gas show or production; depth(s) (ft)
15	Amoco Production Company No. 3-27 McCulloch II	NW 1/4, NW 1/4 Sec. 27, T.54 N., R.100 W.	13,800	Morrison Fm.	Fort Union Fm., gas show, 5615 - 5662
16	Miami Oil Producers Inc. No. 1 Miami Federal 509	NE 1/4, NW 1/4 Sec. 17, T.54 N., R.99 W.	8612	Lance Fm.	NS
17	Gulf Oil Company No. 1 Red Point Unit	NW 1/4, NE 1/4 Sec. 26, T.54 N., R.99 W.	10,508	Mesaverde Fm.	Meeteetse Fm., gas show, 9582 - 9614
18	Amoco Production Company No. 2 Bridger Trail Unit	SE 1/4, SE 1/4 Sec. 16, T.54 N., R.98 W.	8,000	Not reported	NS
19	Continental Oil Company No. 1 Conoco - Farwell	NW 1/4, SW 1/4 Sec. 1, T.54 N., R. 98 W.	11,350	Mowry Sh.	Meeteetse Fm., gas show, 5640 - 5643, 5862 - 5865 Mesaverde Fm., gas show, 8060 - 8063 Frontier Fm., gas show, 10,239 - 10,242
20	Anadarko Production No. 1 Bridger Butte	SW 1/4, NW 1/4 Sec. 16, T.54 N., R.97 W.	10,121	Cody Sh.	NS
21	Midwest Oil No. 1 USA	NE 1/4, NW 1/4 Sec. 15, T.53 N., R. 100 W.	9650	Mesaverde Fm.	Lance Fm., gas show, 7067 - 7324 Mesaverde Fm., gas show, 8246 - 8290
22	Chambers No. 1-15 Federal	SE 1/4, SW 1/4 Sec. 15 T.53 N., R. 100 W.	15,355	Madison Ls.	NS
23	California Oil Company No. 1 Corbett Unit	SE 1/4, NW 1/4 Sec. 27, T.53 N., R. 100 W.	11,198	Madison Ls.	Mesaverde Fm., gas show, 4590 - 4720 Frontier Fm., gas show, 7600 - 7627 Morrison Fm., gas show, 8925 - 8977 Phosphoria Fm., oil show, 10,396 - 10,467 Madison Ls., gas show, 10,963 - 10,999

Table 1 (cont.)

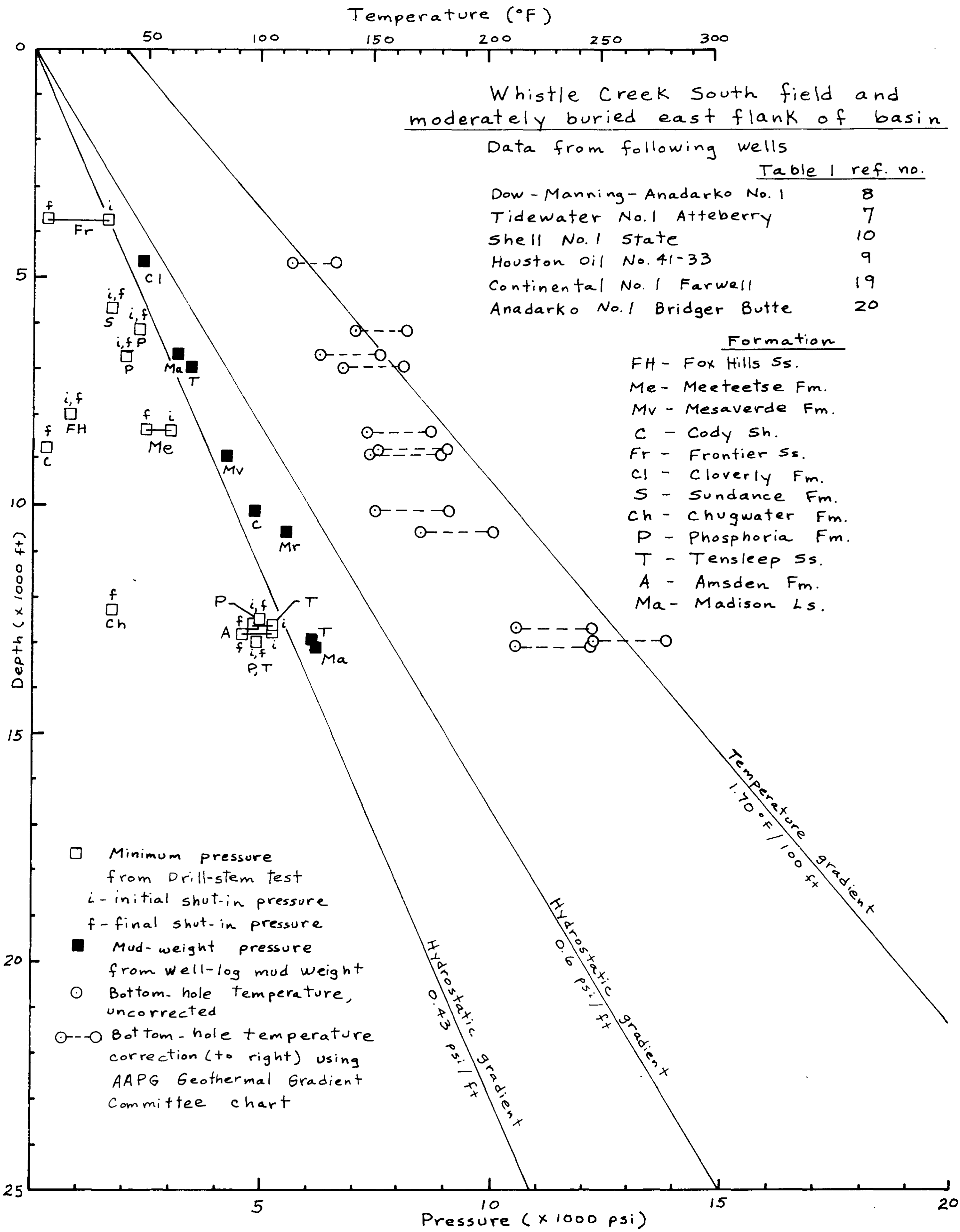
Ref. No.	Name	Location	Total Depth (ft)	Formation at total depth	Formation with oil and/or gas show or production; depth(s) (ft)
24	Davis Oil Company No. 1 Buttercup Reservoir Unit	SW ¼ , SW ¼ Sec. 27, T.53 N., R.100 W.	10,427	Tensleep Ss.	Lance Fm., gas production at 313 MCF, 1951 - 1964 Phosphoria Fm., oil and gas show, 10,066 - 10,096
25	Davis Oil Company No. 1 Catfish Unit	NE ¼ , NW ¼ Sec. 33, T.53 N., R.100 W.	10,500	Madison Ls.	Frontier Fm., gas show, 6421 - 6935, oil show, 6770 - 6935 Phosphoria Fm., oil and gas show, 9645 - 9674
26	Husky Oil Company No. 14-25 Stonebarn Unit	SE ¼ , SW ¼ Sec. 25, T.53 N., R.99 W.	15,914	Cody Sh.	Fort Union Fm., gas show, 9882 - 10,082 Meeteetse Fm., gas show, 13,790 - 13,964 Mesaverde Fm., gas and condensate production at 20 BCPD, 350 MCFPD, 132 BW, 14,722 - 14,972; gas production at 349 MCFPD, 195 BW, 15,268 - 15,368
27	Texas Pacific Oil No. 1 Red Point II Unit	SW ¼ , SW ¼ Sec. 30, T.53 N., R. 98 W.	18,500	Mowry Sh.	Meeteetse Fm., gas and oil show, 14,324 - 14,384 Mesaverde Fm., gas show, 15,212 - 15,286
28	Amoco Production Company No. 2-A Bridger Trail Unit	SW ¼ , SW ¼ Sec. 2 T.53 N., R.98 W.	17,060	Morrison Fm.	Lance Fm., gas and condensate show, 11,191-11,262 Muddy Ss., gas production at 261-822 MCF, 16,412 - 16,442

Abbreviations:
BOPD - Barrels of oil per day
MCFPD - Thousand cubic feet of gas per day
MMCFPD - Million cubic feet of gas per day
BCPD - Barrels of condensate per day
BW - Barrels of water
NS - No shows

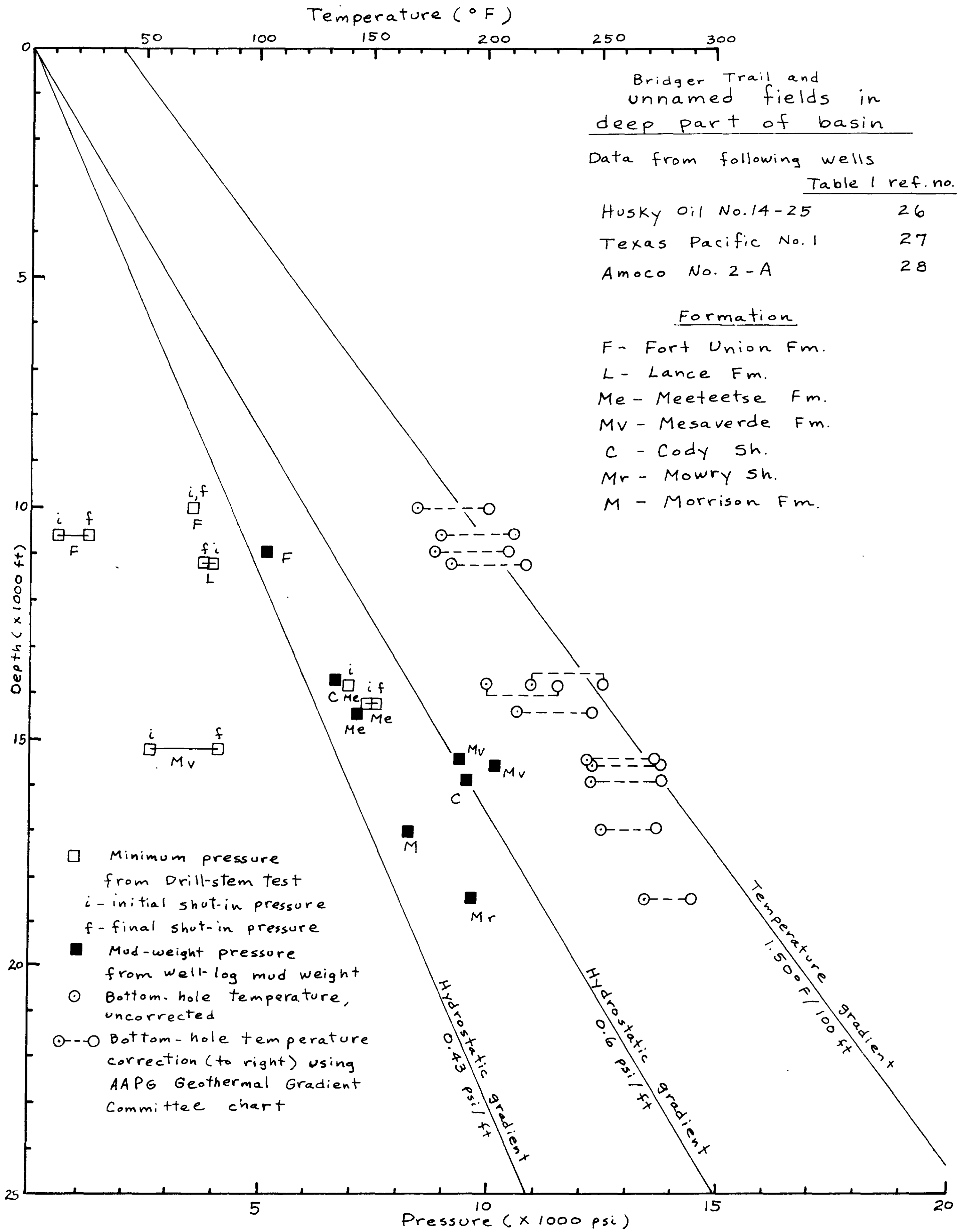
*Data from Petroleum Information Inc. Completion Report File.

Figure 10. Pressure and temperature profiles for selected drill holes in the Whistle Creek South field and the moderately buried east flank of the basin. For location of drill holes and field see table 1 and figure 4.

Figure 11. Pressure and temperature profiles for selected drill holes in the Bridger Trail and unnamed fields in the deep part of the basin. For location of drill holes and fields see table 1 and figure 4.



Temperature (°F)
50
100
150
200
250
300
Whistle Creek South field and moderately buried east flank of basin
Data from following wells
Table 1 ref. no.
Dow - Manning - Anadarko No. 1 8
Tidewater No. 1 Atteberry 7
Shell No. 1 State 10
Houston Oil No. 41-33 9
Continental No. 1 Farwell 19
Anadarko No. 1 Bridger Butte 20
Formation
FH - Fox Hills Ss.
Me - Meeteetse Fm.
Mv - Mesaverde Fm.
C - Cody Sh.
Fr - Frontier Ss.
Cl - Cloverly Fm.
S - Sundance Fm.
Ch - Chugwater Fm.
P - Phosphoria Fm.
T - Tensleep Ss.
A - Amsden Fm.
Ma - Madison Ls.
Depth (x 1000 ft)
0
5
10
15
20
25
Pressure (x 1000 psi)
5
10
15
20
Temperature gradient 1.70 °F / 100 ft
Hydrostatic gradient 0.6 psi / ft
Hydrostatic gradient 0.43 psi / ft
Minimum pressure from Drill-stem test
i - initial shut-in pressure
f - final shut-in pressure
Mud-weight pressure from well-log mud weight
Bottom-hole temperature, uncorrected
Bottom-hole temperature correction (to right) using AAPG Geothermal Gradient Committee chart



Temperature (°F)
50
100
150
200
250
300
Bridger Trail and unnamed fields in deep part of basin
Data from following wells
Table 1 ref. no.
Husky Oil No. 14-25 26
Texas Pacific No. 1 27
Amoco No. 2-A 28
Formation
F - Fort Union Fm.
L - Lance Fm.
Me - Meeteetse Fm.
Mv - Mesaverde Fm.
C - Cody Sh.
Mr - Mowry Sh.
M - Morrison Fm.
Depth (x 1000 ft)
0
5
10
15
20
25
Minimum pressure from Drill-stem test
i - initial shut-in pressure
f - final shut-in pressure
Mud-weight pressure from well-log mud weight
Bottom-hole temperature, uncorrected
Bottom-hole temperature correction (to right) using AAPG Geothermal Gradient Committee chart
Hydrostatic gradient 0.43 psi/ft
Hydrostatic gradient 0.6 psi/ft
Temperature gradient 1.50°F/100 ft
Pressure (x 1000 psi)
5
10
15
20

buried east flank of the basin, about 6 to 8 mi (10 - 13 km) northeast of the wilderness study area (fig. 4; table 1).

In summary, from the perspective of proximity to existing oil and(or) gas fields and shows, the McCullough Peaks Wilderness Study Area has high potential for oil and gas resources. The fact that the wilderness study area is located over a more deeply buried part of the basin than the prolific Elk Basin, Garland, and Oregon Basin oil fields and is more closely aligned with small gas fields suggest that it is in a more favorable setting for gas than oil.

Reservoir Characteristics

Conventional Reservoirs

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 (McCabe, 1947; Walton, 1947; Wyoming Geological Association, 1957). These reservoirs are less than 5000 ft (1.5 km) 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. Beneath the westernmost margin of the wilderness study area, along the hanging wall of the Oregon Basin thrust fault, the Frontier Formation is estimated to lie between 12,000 ft (3.65 km) and 13,000 ft (4 km) and the upper Paleozoic sequence is estimated to lie between 15,000 ft (4.6 km) and 16,000 ft (4.9 km) (fig. 4; fig. 5, sec. B-B'). East of the Oregon Basin fault, beneath the remainder of the wilderness study area, the Frontier Formation is estimated to lie between 13,500 ft (4.1 km) and 17,000 ft (5.2 km) and the upper Paleozoic sequence is estimated to lie between 16,500 ft (5 km) and 20,000 ft (6.1 km) (fig. 4; fig. 5, sec. B-B'). These present-day burial depths are minimum values because the Bighorn Basin has experienced post-Laramide uplift and erosion as have other basins in the Rocky Mountain region.

Fox and others (1975) showed that, throughout the Bighorn Basin, the porosity of the Tensleep Sandstone varies between 2 and 8 percent for burial depths between 10,000 ft (3 km) and 12,250 ft (3.7 km), but the porosity is less than 1 percent for burial depths greater than 17,000 ft (5.2 km). Porosity reduction in the deeply buried Tensleep Sandstone is attributed to the precipitation of quartz cement by migrating solutions rather than to pressure solution processes (Fox and others, 1975).

Average porosity and permeability values of 1.4 percent and 0.02 md for the gas-and-condensate-producing Pennsylvanian Weber Sandstone between 17,000 and 18,000 ft (5.2 and 5.5 km) in the greater Green River basin (Colburn, 1979) are consistent with the values cited by Fox and others (1975). In addition, Colburn (1979) indicates that fractured intervals in the Weber Sandstone have porosity values up to 5 percent. Similar zones of fracturing may enhance the porosity of the Tensleep Sandstone beneath the deeply buried wilderness study area.

Thirty-three core plugs taken from a 41-ft-thick (12.5 m) limestone unit in the Phosphoria Formation (13,133 - 13,174 ft, 4003 - 4015 m) in the Davis No. 1 Coulee well yielded porosity values ranging from 1.0 to 18.2 percent (avg. 2.8 percent) and permeability values ranging from 0.01 to 11.0 md (avg. 0.58 md).

Madison Limestone cores recovered from the Tidewater No. 1 (12,893 - 12,916 ft, 3930 - 3937 m) and from the California No. 1 Corbett (10,935 - 10,956 ft, 3333 - 3339 m; 11,152 - 11,160 ft, 3399-3402 m; 11,188 - 11,196 ft, 3410 - 3413 m) drill holes appear to have low porosity and permeability. However, based on 13 percent porosity values and gas production from the Madison Limestone in the greater Green River basin (Colburn, 1979) at about 18,000 ft (5486 m), the Madison Limestone could be a potential reservoir beneath the wilderness study area.

Core recovered from the Frontier Formation in the Stanolind No. 1 Coulee (10,027 - 10,057 ft, 3056 - 3065 m; 10,145 - 10,155 ft, 3092 - 3095 m; 10,323 - 10,347 ft, 3146 - 3154 m; 10,362 - 10,395 ft, 3158 - 3168 m), Amoco No. 3-27 (11,965 - 12,070 ft, 3647 - 3679 m; 12,037 - 12,096 ft, 3669 - 3687 m), and Manning and Goodstein No. 1 (11,810 - 11,855 ft, 3600 - 3613 m; 11,906 - 11,931 ft, 3629 - 3637 m; 11,952 - 11,995 ft, 3643 - 3656 m) drill holes suggest that sandstone units in the Frontier Formation have low porosity and permeability below 10,000 ft (3 km). A major reason for the marked porosity and permeability reduction in the Frontier sandstones below 10,000 ft (3 km) is their relatively high percentage of chemically unstable feldspar grains and volcanic rock fragments (Siemers, 1975). In the Stanolind No. 1 Coulee core, porosity values of 3.4 and 4.2 percent were measured in the Peay sandstone, the lowermost sandstone in the Frontier and the best oil-producing Frontier reservoir at the Elk Basin field. The Peay sandstone is present beneath the northwest corner of the expanded study area, but it does not extend beneath the wilderness study area (Rea and Barlow, 1975).

In summary, the traditional high-yield reservoirs (Frontier, Phosphoria, Tensleep, and Madison) on the flanks of the Bighorn Basin probably have greatly reduced porosity and permeability beneath the wilderness study area. 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.

Unconventional Reservoirs and Post-Frontier Conventional Reservoirs

The expansion of oil and gas exploration into deeper parts of basins has led to the discovery of gas fields in lower quality reservoirs in comparison to reservoirs on the flanks of basins, but whose reserves are commonly measured in trillions of cubic feet (Masters, 1979). Gas fields of this type are trapped under stratigraphic conditions and their reservoirs in the Rocky Mountain region commonly are tight (low permeability) and are overpressured (Spencer, 1985, 1987). 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 wilderness study area, where the drilling depth to Precambrian basement rocks is as much as 22,000 ft (6.7 km), an approximately 8000-ft-thick (2.4 km) lower Tertiary and Cretaceous sequence contains numerous marginal marine to nonmarine sandstone bodies which seem to have the characteristics of tight gas reservoirs (fig. 4; fig. 5, sec. B-B'). This thick sequence, marked by the Cloverly Formation at the base and by the lower part of the 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 pressure in tight reservoirs. The top and bottom of the lower Tertiary and Cretaceous sequence are presently situated approximately at 10,000 ft (3 km) and 18,000 ft (5.5 km), respectively, beneath the southern part of the wilderness study area and thus the sequence is largely incorporated into the higher-than-normal pressure zone recorded in the nearby unnamed gas field (fig. 11).

Beneath the remainder of the wilderness study area, the depth to Precambrian basement rocks decreases such that sandstone units in the Fort Union Formation, Lance Formation, Fox Hills Sandstone, Meeteetse Formation, and Mesaverde Formation are normally pressured and may behave as normally pressured to slightly underpressured tight-gas reservoirs and(or) conventional reservoirs. This suggestion is consistent with the statement by Spencer (1985) that "many sandstone reservoirs that are tight in the deep parts of basins have conventional reservoir characteristics at shallow burial depth." Also, overpressuring is not a necessary condition for tight (low permeability) gas reservoirs, but it does help to increase gas productivity. Probable examples of normally pressured tight-gas and(or) conventional reservoirs in the vicinity of the wilderness study area are the oil- and gas-bearing sandstones in the Fort Union Formation and Fox Hills Sandstone at the McCulloch Peak field and the Lance Formation at the Coulee field.

In summary, 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 wilderness study area. Beneath the southern part of the wilderness study area, the prospective sequence extends from the lower part of the Paleocene Fort Union Formation to the base of the Lower Cretaceous Cloverly Formation whereas beneath the remainder of the wilderness study area, where burial is less, the prospective sequence extends from the top of the Frontier Formation to the base of the Cloverly Formation. Moreover, some sandstones in the Fort Union Formation (lower part), Fox Hills Sandstone, Lance Formation, Mesaverde Formation, and Meeteetse Formation could be suitable conventional oil and(or) gas reservoirs beneath the western and northern parts of the wilderness study area.

Traps

Structural traps beneath the wilderness study area, if present, would most likely occur along the trend of the Oregon Basin and Elk Basin thrust faults (fig. 4). The hanging wall blocks of these Laramide-age faults have been warped, internally faulted, and folded in response to local stresses created during their net eastward tectonic transport (fig. 4; fig. 5, secs. A-A' and B-B'; fig. 6, secs. C-C' and D-D'). An example of such a structure is the McCulloch Peak faulted anticline which forms the trap for the McCulloch Peak field and plunges southeastward beneath the western part of the wilderness study area (figs. 4 and 5). If the structure of the McCulloch Peak anticline is more complex than is shown by available structure contour maps (fig. 4; Blackstone, 1986), additional areas of closure may exist. Another anticline located on the hanging wall of a major thrust fault is the Elk Basin anticline. This anticline 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 wilderness study area (fig. 4). Available structure contour maps suggest that the Elk Basin anticline plunges gently southward without major structural complications (fig. 4; 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. 4 with Blackstone, 1986 and Stone, 1985). Seismic surveys, which were unavailable for this 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.

If structural closure can be identified beneath the wilderness study area along the Elk Basin and McCulloch Peak anticlinal trends, the major group of exploration objectives would be conventional sandstone reservoirs in the Fort Union Formation, Lance Formation, Fox Hills Sandstone, Mesaverde Formation, and Meeteetse Formation. Sandstones in the Frontier Formation, Muddy Sandstone, and Cloverly Formation may also be potential reservoirs in structurally controlled traps along the Elk Basin and McCulloch Peak anticlinal trends. Although these sandstones are largely unconventional reservoirs in the wilderness study area, tectonic fracturing and (or) diagenetic processes along the anticlinal trends may convert them to conventional reservoirs. A third group of exploration targets would be tectonically fractured reservoirs in the deeply buried Phosphoria Formation, Tensleep Sandstone, and Madison Limestone. Cores from the Davis No. 1 Coulee well and Davis No. 1 Catfish drill hole indicate that, at least locally, the porosity and permeability of the Phosphoria Formation has been enhanced by tectonic fracturing. A close inspection of geophysical logs from the Husky No. 1 drill hole, a 15,627 ft (4.8 km) test to the Madison Limestone in the McCulloch Peak anticline, may provide additional data concerning the reservoir quality and degree of fracturing in the lower Paleozoic sequence along the McCulloch Peak and Elk Basin anticlinal trends.

Gas trapped in low-permeability reservoirs, as discussed previously, probably underlies the entire wilderness study area. In accumulations of this type, the gas seems to be prevented from migrating updip by water-saturated, low-permeability rocks (Masters, 1979). The gas 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, Mesaverde Formation and Meeteetse 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 by pelitic 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 would be the most effective stratigraphic traps.

In summary, a barrier caused by high-water saturation in low-permeability sandstone may have trapped large quantities of gas in lower Tertiary and Cretaceous sandstones beneath the McCullough Peaks Wilderness Study Area. Traps of secondary importance that may exist beneath the wilderness study area are anticlines along the Oregon Basin, Elk Basin, and McCulloch Peak anticlinal trends and facies-change traps across the noses of these anticlines.

Source Rocks and Thermal Maturity

Dark gray to black shale of nearshore to offshore marine origin which comprises all or part of the Lower Cretaceous Thermopolis, Shell Creek, and

Mowry Shales and the Upper Cretaceous Frontier Formation and Cody Shale, is present throughout the subsurface of the expanded study area. In the Marathon No. 1-67 Cary drill hole (table 1; fig. 4), 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). This range of TOC values in the Mowry Shale is consistent with the 1.3 TOC content of the Mowry measured in the Tidewater No. 1 Atteberry (table 1; fig. 4) and with maps showing the regional distribution of TOC in the Mowry Shale (Burtner and Warner, 1984). Hydrogen index values (S2, integral of second hydrocarbon peak in Rock-Eval pyrolysis yield/TOC X100) between 49 and 315 indicate that the Thermopolis Shale, Mowry Shale, Frontier Formation, and Cody Shale contain a mixture of type II (oil and gas prone) and type III (gas prone) kerogen (Hagen and Surdam, 1984; Burtner and Warner, 1984; fig. 3). Thus, these marine shales are moderately good source rocks which have the capacity to generate both oil and gas. In fact, S1 values (integral of first hydrocarbon peak on Rock-Eval pyrolysis) between 0.32 and 1.85 in the Marathon No. 1-67 Cary drill hole indicate that liquid hydrocarbons have already been expelled from the Thermopolis Shale, Mowry Shale, Frontier Formation, and Cody Shale. Moreover, Hagen and Surdam (1984) conclude that, in the Bighorn Basin, this predominantly shale sequence contains moderately good quality source rocks over an aggregate thickness of about 2000 ft (0.6 km) and probably was the major source of oil in Cretaceous and Tertiary reservoirs. Burtner and Warner (1984) conclude, from a regional geochemical investigation, that the Mowry and Skull Creek (lower part of Thermopolis Shale) Shales are an important source of oil and gas in Cretaceous reservoirs in the northern Rocky Mountain region.

The Meade Peak and Retort Phosphatic Shale Members of the Phosphoria Formation are excellent oil-prone source rocks in western Wyoming, eastern Idaho, and southwest Montana (Claypool and others, 1978). Isopach maps by Maughan (1975, 1984) and Peterson (1984) indicate that the Meade Peak Shale (lower part of Phosphoria) pinches out west of the Bighorn Basin, whereas the Retort Shale (upper part of Phosphoria) is present in the Bighorn Basin and, according to Peterson (1984), contains a net thickness of organic shale up to 25 ft (7.5 m). The absence of shale beds in cores taken from parts of the Phosphoria Formation in the Tidewater No. 1 Atteberry, California No. 1 Corbett, Davis No. 1 Coulee, and Davis No. 1 Catfish drill holes suggests that organic shale beds in the Retort Member, if present in the expanded study area, are located east of the Oregon Basin fault and south of T.55 N. According to Sheldon (1967) and Stone (1967), the abundant oil in Phosphoria Formation, Tensleep Sandstone, and Madison Limestone reservoirs in the Bighorn Basin 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 of the Bighorn Basin was locally derived from organic shale in the Retort Member of the Phosphoria Formation. Although the long-distance vs. local transport controversy is unresolved, the conclusion seems inescapable that Phosphoria-derived oil was available in middle to late Mesozoic time for charging Paleozoic reservors 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 margin of the Bighorn Basin are coal bearing. These coal beds also extend into the subsurface beneath the wilderness study area and reappear in outcrop on the east side of the basin (fig. 3). Coal-bearing intervals of secondary importance in the northern Bighorn Basin occur in the Willwood Formation, Lance Formation, and the Frontier Formation (fig. 3). Coal beds, such as those present beneath the expanded study area, are rich in type III kerogen and therefore are an excellent source of dry gas (Tissot and Welte, 1978). Meissner (1984) has demonstrated that many lower Tertiary and Cretaceous coal beds in the Rocky Mountain region, including those on the Bighorn Basin, have achieved sufficient burial to have generated gas.

Geochemical studies by Hagan and Surdam (1984) and Burtner and Warner (1984) indicate that the Lower and Upper Cretaceous marine source rocks in the northern part of the expanded area are mature with respect to oil generation. Specific measurements which support this conclusion are S1 values between 0.32 and 1.85, a vitrinite reflectance (Ro) of 0.69 in the Marathon No. 1-67 Cary drill hole, and a Tmax (temperature at which the S2 peak occurs) of 440 in the Tidewater No. 1 Atteberry drill hole. According to Hagen and Surdam (1984), the 0.69 Ro value in the Marathon No. 1-67 Cary probably is not a true representation of the thermal maturation level of the Frontier Formation from which it was sampled because of bitumen impregnation in the vitrinite particles. They suggest that a 1.36 Ro value, derived from an associated population of nonimpregnated vitrinite particles, gives a more realistic appraisal of the thermal maturation level of the sample from the Frontier Formation. A Ro vs. depth plot by Hagen and Surdam (1984) of the Marathon No. 1-67 Cary bitumen-free sample and 8 additional Frontier Formation and Mowry Shale bitumen-free samples from selected drill holes throughout the Bighorn Basin, indicate that the approximate top of the zone of oil generation is between the present-day depths of 2000 to 3000 ft (0.6 - 0.9 km) and the approximate bottom is between the present-day depths 11,000 to 12,000 ft (3.35 - 3.65 km).

Throughout the wilderness study area the marine shale source-rock interval is buried at or below 12,000 ft and thus is largely in the zone of gas generation. In contrast, the burial depths of the lower Tertiary and Upper Cretaceous coal-bearing sequence beneath the wilderness study area range between 4000 and 15,000 ft (1.22 - 4.57 km) in the southern part and between 3000 and 12,000 ft (0.9 - 3.66 km) in the northern and western parts (figs. 5 and 6). Using the boundaries of the zone of oil generation defined by Hagen and Surdam (1984), the coal-bearing sequence is probably largely in the zone of oil generation beneath the northern and western parts of the wilderness study area whereas the coal-bearing sequence spans the boundary between the zones of oil and gas generation beneath the southern part of the wilderness study area.

Time-temperature reconstructions following Waples (1980) provide an independent check of the position of the zones of oil and gas generation derived from vitrinite data by Hagen and Surdam (1984). A geothermal gradient of 1.65°F/100 ft (30°C/km), which closely approximates the present-day thermal gradient (figs 7-11), was used in the reconstructions. The present-day geothermal gradient is assumed to closely approximate the paleogeothermal gradient. In most instances, the amount of erosion which accompanied unconformities in the Paleozoic and Mesozoic sequences were not accounted for in the models. Major erosional episodes accounted for in the models are 600 ft (183 m) of erosion at the top of the Lance Formation on the Oregon Basin fault block and a minimum of 2500 ft (0.8 km) of erosion resulting from post-early to middle Miocene uplift of the northern part of the basin (Hagen and Surdam, 1984, based on evidence from Mackin, 1937; Ritter, 1967, 1975; McKenna and Love, 1972; McKenna, 1980; and Bown, 1980).

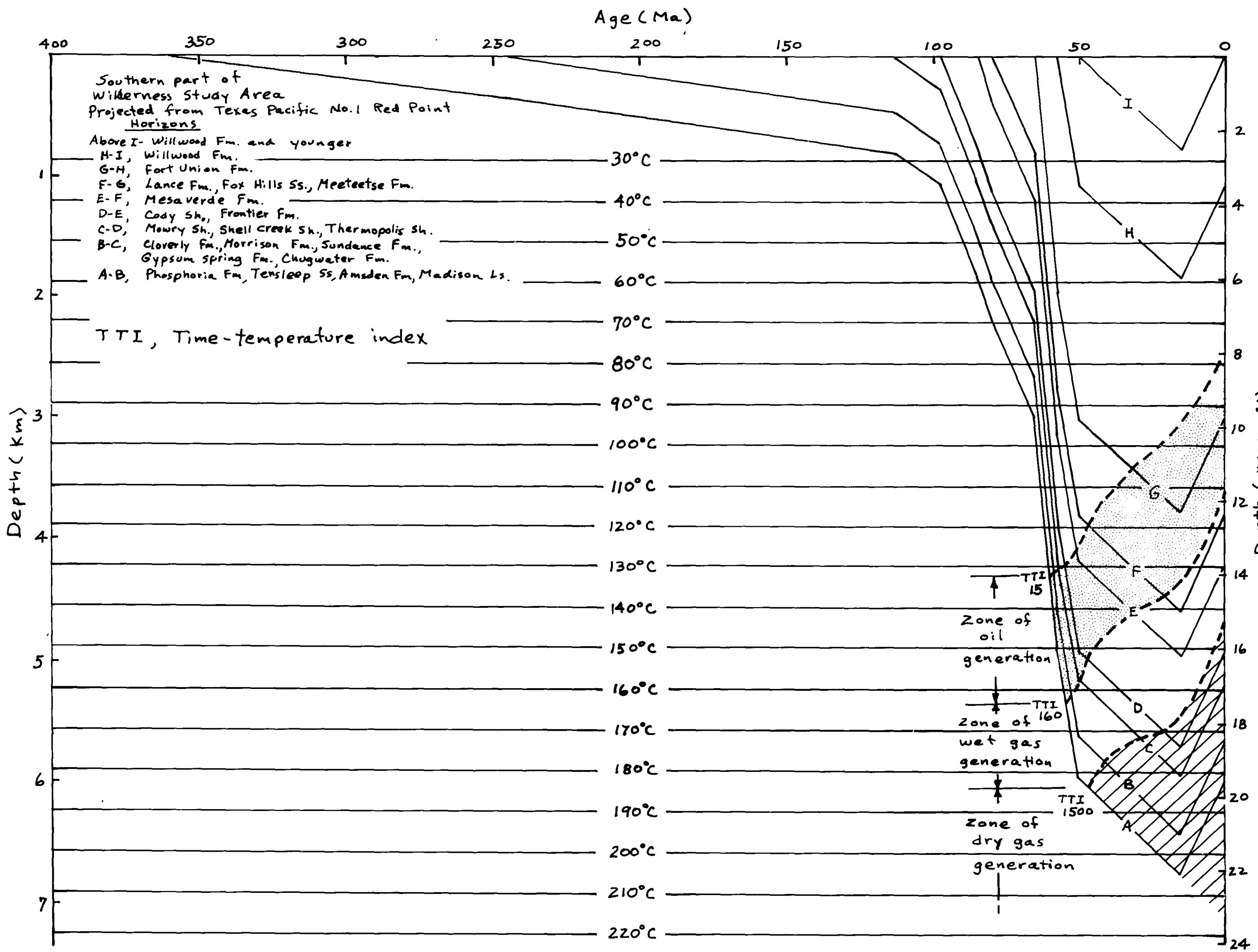
The time-temperature reconstruction indicates that for the southern part of the wilderness study area, the zone of oil generation is between the depths of 8000 ft and 11,500 ft (2.44 - 3.51 km), the zone of wet gas generation is between about 11,500 ft and 15,000 ft (3.51 - 4.57 km), and the zone of dry gas generation is below about 15,000 ft (4.57 km) (fig. 12). This reconstruction further indicates that the marine source rocks in the southern part of the wilderness study area are located in the zone of dry gas generation whereas the coal-bearing source rocks are located in the zones of oil and wet gas generation (fig. 12).

For the western and northern parts of the wilderness study area, the present-day depths to the zones of oil, wet gas, and dry gas are similar to those for the southern part of the wilderness study area (fig. 13). However, in contrast to the southern part, the marine source rocks in the northern and western parts of the wilderness study area are located in the zone of wet gas generation, the coal-bearing source rocks of the Mesaverde Formation are located in the zone of oil generation, and the coal-bearing source rocks of the Meeteetse, Lance, and Fort Union Formations are above the zone of oil generation (fig. 13). The base of the present-day zone of oil generation (12,000 ft, 3.66 km) derived from time-temperature reconstructions agrees rather well with the base of the zone (11,500 ft, 3.51 km) derived from the vitrinite measurements of Hagen and Surdam (1984). However, the top of the present-day zone of oil generation (8000 ft, 2.44 km) derived from time-temperature reconstructions differs significantly from the top of the zone (2000 to 3000 ft, 0.61 to 0.91 km) derived from vitrinite measurements. The different positions of the top of the oil window as defined by the two approaches cannot be simply explained by a paleogeothermal gradient which is greater than the present-day geothermal gradient. If this explanation were true, there would also be a discrepancy in the position of the base of the oil window as determined by the two methods. Moreover, for the same reason, the different positions of the top of the oil window cannot be attributed to underestimating the amount of post-Miocene uplift in the time-temperature reconstructions. Vitrinite data collected only from the expanded study area may reconcile the differences between the two techniques.

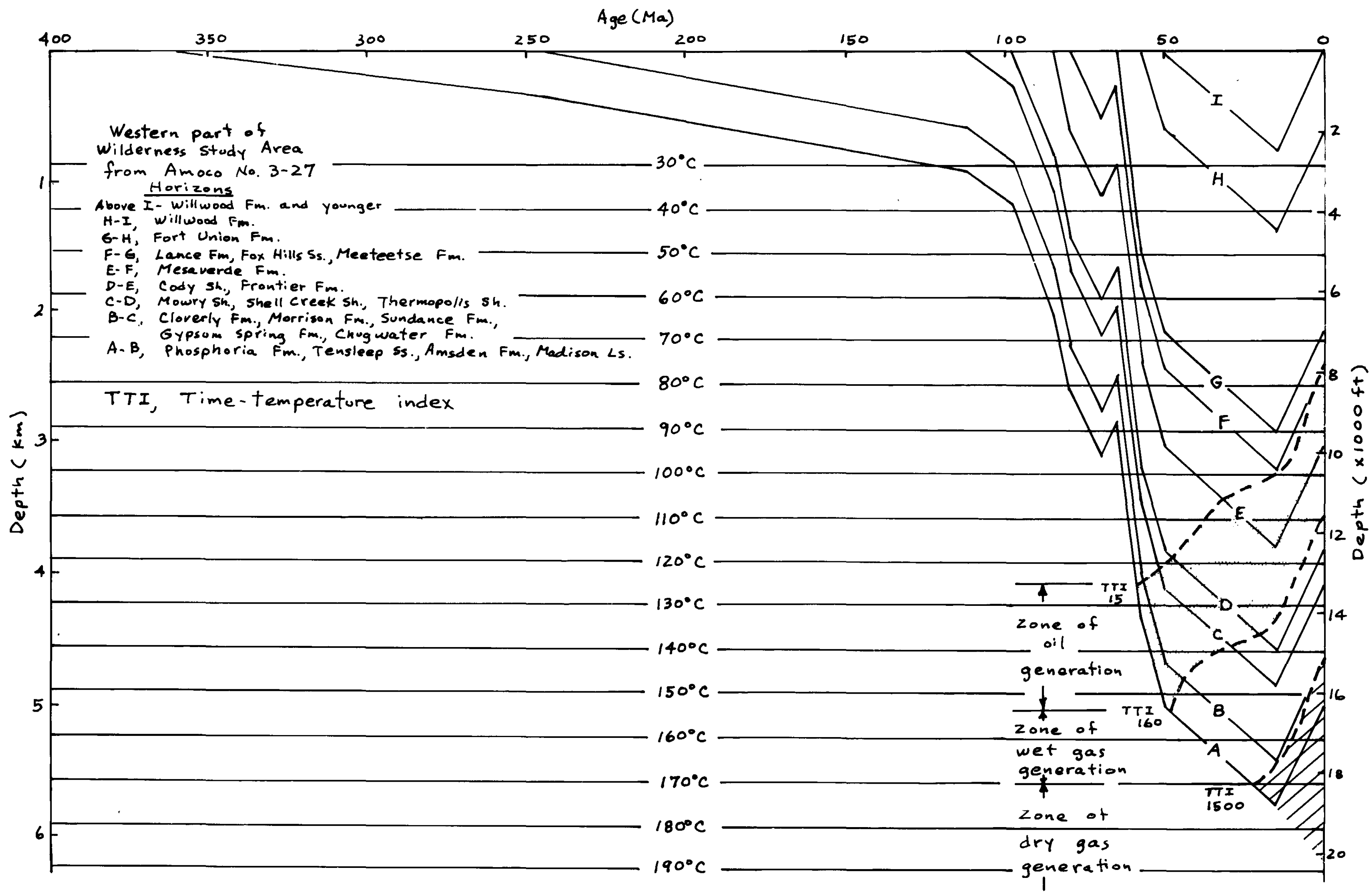
In summary, the wilderness study area is underlain by the marine Mowry, Thermopolis, Shell Creek, and Cody Shales which are moderately good oil- and gas-prone source rocks (fig. 3). Coal-bearing strata in the Mesaverde, Meeteetse, and Fort Union Formations, which are good gas-prone source rocks, also underlie the wilderness study area. Vitrinite and theoretically derived maturation levels suggest that, beneath the southern part of the wilderness study area, the marine source rocks are located in the zone of dry gas generation and the coal-bearing source rocks are located in the zones of oil and wet gas generation (fig. 12). Beneath the northern and western parts of the wilderness study area the marine source rocks are located in the zone of wet gas generation, and the coal-bearing source rocks are located within to slightly above the zone of oil generation (fig. 13).

Figure 12. Time-temperature reconstruction for the southern part of the wilderness study area projected from the Texas Pacific No. 1 Red Point drill hole. Temperature gradient used in reconstruction is 1.65°F/100 ft (30°C/km). Average surface temperature is 40°F(4°C).

Figure 13. Time-temperature reconstruction for the western part of the wilderness study area using the Amoco No. 3-27 drill hole. Temperature gradient used in reconstruction is 1.65°F/100 ft (30°C/km). Average surface temperature is 40°F(4°C).



Age (Ma)
400
350
300
250
200
150
100
50
0
Depth (Km)
1
2
3
4
5
6
7
Depth (x1000 ft)
2
4
6
8
10
12
14
16
18
20
22
24
Southern part of
Wilderness Study Area
Projected from Texas Pacific No. 1 Red Point
Horizons
Above I- Willwood Fm. and younger
H-I, Willwood Fm.
G-H, Fort Union Fm.
F-G, Lance Fm., Fox Hills Ss., Meeteetse Fm.
E-F, Mesaverde Fm.
D-E, Cody Sh., Frontier Fm.
C-D, Mowry Sh., Shell Creek Sh., Thermopolis Sh.
B-C, Cloverly Fm., Morrison Fm., Sundance Fm.,
Gypsum Spring Fm., Chugwater Fm.
A-B, Phosphoria Fm, Tensleep Ss, Amsden Fm, Madison Ls.
TTI, Time-temperature index
30°C
40°C
50°C
60°C
70°C
80°C
90°C
100°C
110°C
120°C
130°C
140°C
150°C
160°C
170°C
180°C
190°C
200°C
210°C
220°C
TTI 15
Zone of oil generation
TTI 160
Zone of wet gas generation
TTI 1500
Zone of dry gas generation
I
H
G
F
E
D
C
B
A


Age (Ma)
400
350
300
250
200
150
100
50
0
Depth (km)
1
2
3
4
5
6
Depth (x1000 ft)
2
4
6
8
10
12
14
16
18
20
Western part of
Wilderness Study Area
from Amoco No. 3-27
Horizons
Above I- Willwood Fm. and younger
H-I, Willwood Fm.
G-H, Fort Union Fm.
F-G, Lance Fm, Fox Hills Ss., Meeteetse Fm.
E-F, Mesaverde Fm.
D-E, Cody Sh., Frontier Fm.
C-D, Mowry Sh., Shell Creek Sh., Thermopolis Sh.
B-C, Cloverly Fm., Morrison Fm., Sundance Fm.,
Gypsum Spring Fm., Chugwater Fm.
A-B, Phosphoria Fm., Tensleep Ss., Amsden Fm., Madison Ls.
TTI, Time-temperature index
30°C
40°C
50°C
60°C
70°C
80°C
90°C
100°C
110°C
120°C
130°C
140°C
150°C
160°C
170°C
180°C
190°C
I
H
G
F
E
D
C
B
A
TTI 15
TTI 160
TTI 1500
Zone of oil generation
Zone of wet gas generation
Zone of dry gas generation

Potential for Undiscovered Oil and Gas Resources

Three major oil and(or) gas plays are identified in the McCullough Peaks Wilderness Study Area: 1) upper Paleozoic play for structurally trapped gas, 2) Upper Cretaceous and lower Tertiary play for structurally and(or) stratigraphically trapped oil and gas, and 3) Cretaceous and lower Tertiary play for gas in tight (low permeability), overpressured sandstone reservoirs. In the discussion that follows, each play is assessed qualitatively using the rating methods defined by Goudarzi (1984) based on the work of Miller (1983) and Taylor and Steven (1983). A rating of high potential indicates a geologic environment highly favorable for the occurrence of oil and gas accumulations; the area is near or on trend with existing production from structural and(or) stratigraphic traps. A medium potential indicates a geologic environment favorable for the occurrence of oil and gas accumulations. The area of medium potential contains known reservor rocks and hydrocarbon source rocks and includes some areas of sparse subsurface control. A low potential indicates a geologic environment interpreted to have low potential for the occurrence of oil and gas accumulations. The area of low potential probably contains low-quality hydrocarbon source rocks and(or) reservoirs and may include areas of sparse or no drill-hole control and an expected thin sedimentary sequence.

The upper Paleozoic play primarily involves 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. Gas in this play most likely was derived by thermally cracking oil which originally was expelled from Phosphoria source beds and was trapped in upper Paleozoic reservoirs. Porosity and permeability of the Phosphoria, Tensleep and Madison are likely to be very low at the expected 15,000 to 20,000 ft (4.57 to 6.10 km) depths of burial beneath the wilderness study area. Improved reservoir quality would depend on tectonically induced fractures and(or) secondary porosity owing to burial diagenesis. Judging from probable low porosity and permeability values of the Phosphoria Formation, Tensleep Sandstone, and Madison Limestone and the absence of proven anticlinal closure beneath the wilderness study area, the potential for undiscovered gas resources in the upper Paleozoic play is rated low (L/C).

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, Fox Hills Sandstone, Meeteetse Formation, Lance Formation, and Fort Union Formation are the most likely reservoirs in this play. In the western and northern parts of the wilderness study area where anticlinal closure and anticlinal noses are most likely to be present, coal-bearing units associated with potential reservoirs in the Mesaverde Formation, Fox Hills Sandstone, Meeteetse Formation, and Lance Formation are predominantly in the zone of oil generation (fig. 13). Moreover, coal beds associated with potential reservoirs in the Fort Union Formation in the western and northern part of the wilderness study area are situated above the zone of oil generation (fig. 13). Therefore, it seems that major gas-prone source rocks beneath the western and northern parts of the wilderness study area have not been buried deep enough for peak gas generation. Probably some gas has been generated from the coal-bearing units in the zone of oil generation but the volume is significantly less than that which could be formed in the zone of gas generation. Other potential sources of gas for sandstone reservoirs in the Fox Hills Sandstone, Mesaverde Formation, Meeteetse Formation, Lance Formation, and Fort Union Formation located in or above the zone of oil generation are 1) biologically generated gas, 2) vertically migrated thermogenic gas generated from underlying marine source rocks, and 3) laterally migrated thermogenic gas generated in the southern part of the wilderness study area from the lower part of the coal-bearing sequence.

Although burial conditions are optimum for the generation of oil in the uppermost Cretaceous-lower Tertiary sequence beneath the western and northern parts of the wilderness study area, the paucity of oil-prone source rocks in this sequence suggests that very little oil can be expected here. The minor amounts of oil that type III kerogen is capable of generating most likely accounts for the local oil shows and production reported in the upper Cretaceous and lower Tertiary sequence. 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 medium (moderate, M/C). The potential for undiscovered oil resources in this play is rated low (L/C) because the majority of the oil-prone source rocks beneath the wilderness study area are situated in the zone of gas generation.

The Cretaceous and lower Tertiary play involves stratigraphically trapped gas accumulations in tight (low permeability), overpressured sandstone reservoirs similar to those described by Law (1984) and Spencer (1987). Overpressuring is known to exist in the Cretaceous sequence 25 mi (40 km) south of the wilderness study area (fig. 11) and most probably this zone of overpressure extends beneath at least the southern part of the wilderness study area. Law and others (1980), Law (1984), and Spencer (1987) conclude that hydrocarbon generation is the major cause of overpressuring in the Rocky Mountain region, and currently active hydrocarbon generation--such as that which seems to be present in the Bridger Trail and unnamed fields south of the wilderness study area (fig. 11)--is required to maintain the high pressure. The zone of overpressure probably also extends across the northern and western parts of the wilderness study area, but is limited to the Frontier Formation, Muddy Sandstone and Cloverly Formation. Cretaceous and lower Tertiary sandstones sampled by cores and drill-stem tests below about 10,000 ft (3 km) in the expanded study area generally seem to have low porosity and permeability.

The time-temperature reconstruction for the southern part of the wilderness study area (fig. 12) suggests that all of the potential tight gas reservoirs here have a temperature at or above 200°F (93°C), the present-day minimum temperature required for active overpressuring (Law, 1984; Spencer, 1987). Based on the time-temperature reconstruction from the Amoco No. 3-27 drill hole (fig. 13) and the pressure and temperature profiles from the McCulloch Peak field (fig. 8), the Frontier Formation, Muddy Sandstone, and Cloverly Formation are probably the only potential tight gas reservoirs which are actively overpressured in the western and northern parts of the wilderness study area. The degree to which the Oregon Basin and Elk Basin thrust faults may have caused leakage of abnormally high pressure and whether or not open fractures are present in the prospective tight sandstone sequence are aspects of the play which are presently unknown. Overall, the potential for undiscovered gas in tight, overpressured sandstone reservoirs in the Cretaceous and lower Tertiary play is rated high (H/C).

COAL

Stratigraphic Position

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 margin of the Bighorn Basin are coal bearing (fig. 3). The coal-bearing sequence in the Mesaverde Formation on the west side of the basin directly overlies a nearshore marine sandstone sequence at the base of the formation. Eastward, this coal-bearing sequence in the Mesaverde Formation extends into the subsurface which includes the area beneath the expanded study area, and reappears in a higher stratigraphic position on the east flank of the Bighorn Basin (Severn, 1961; Glass and others, 1975). The west to east stratigraphic rise of the coals in the Mesaverde Formation across the basin is caused by the net eastward regression of the Mesaverde shoreline. Coal-bearing strata of the Fort Union and Meeteetse Formations which crop out along the west side of the basin also extend into the subsurface beneath the expanded study area and crop out on the east side of the basin (Rioux, 1958; Glass and others, 1975). Acoustic and density logs used to construct the geologic cross sections in figures 5 and 6 suggest that coal beds in the Fort Union and Meeteetse Formations become more abundant in the subsurface. Similar observations were made by Rea and Barlow (1975) for Fort Union coal beds in the Bighorn Basin and by Windolph and others (1986) for Meeteetse coal beds in the Wind River Basin. These observations imply that the rate of subsidence in the developing Bighorn and Wind River Basins, during Meeteetse and Fort Union time, commonly may have exceeded the rate of sedimentation, thus allowing peat sedimentation in the resultant topographic depressions.

Coal-bearing intervals of secondary importance in the northern Bighorn Basin occur in the Willwood Formation (Pierce, 1965, 1966), Lance Formation (Rioux, 1958; Glass and others, 1975), and the Frontier Formation (Siemers, 1975; Merewether and others, 1975) (fig. 3). In general, coal beds are uncommon in the Willwood Formation and those that are present are thin and discontinuous. Coal beds in the Lance Formation are most commonly found in the lowermost part of the formation directly overlying the Fox Hills Sandstone and in the uppermost part of the formation directly beneath the Fort Union Formation. Although Lance coal beds crop out along the east side of the Bighorn Basin, the majority of them--in a manner similar to the Meeteetse and Fort Union coal beds--seem to be located in the subsurface. Frontier coal beds have been identified in outcrop along the west side of the Bighorn Basin (Siemers, 1975; Merewether and others, 1975) and in a core from the Amoco No. 3-27 drill hole. Based on the outcrop and subsurface study of the Frontier Formation by Merewether and others (1975) and the presence of coal in the Amoco No. 3-27 drill hole, coal beds in the Frontier Formation probably underlie only the western half of the expanded study area.

Fields

The Oregon Basin coal field (formerly Cody coal field) is distributed along the west margin of the Bighorn Basin between 9 and 32 mi (14 to 51 km) south and southwest of the wilderness study area (fig. 1). A northern extension of the field is located about 25 mi (40 km) northwest of the wilderness study area. This coal field is small, having recorded production less than 3000 tons from 13 mines (Glass and others, 1975). None of the mines are presently active. Nine of the 13 mines in the Oregon Basin coal field are located on coal beds in the Mesaverde Formation, ranging in thickness from 10 in (25.4 cm) to 7.8 ft (2.38 m) (Glass and others, 1975). Outcrop studies by Hewett (1926) and Pierce and Andrews (1941) show that Mesaverde coal beds in the Oregon Basin coal field occur in two zones, the Wilson coal group and the overlying Buffalo coal group, both in the lower part of the Mesaverde Formation. Two mines in the Oregon Basin coal field are located on coal beds in the Meeteetse Formation which have a maximum thickness of about 3.5 ft (1.07 m) (Glass and others, 1975). Hewett (1926) and Pierce and Andrews (1941) show that, in outcrop, the coal beds in the Meeteetse Formation occur in the upper half of the formation and are more lenticular than the coal beds in Mesaverde Formation. Two mines in the Oregon Basin field are located on coal beds in the Fort Union Formation (Glass and others, 1975). Fisher (1903) and Glass and others (1975) report that the thickness of the mined Fort Union coal beds ranges from 2 to 4.5 ft (0.61 to 1.37 m).

The Meeteetse coal field is distributed along the west margin of the Bighorn Basin about 25 to 40 mi (40 to 64 km) south of the wilderness study area (fig. 1). This coal field is small, having recorded production slightly greater than 8000 tons from 6 mines (Glass and others, 1975). None of the mines in the Meeteetse coal field are active today. Four of the 6 mines in the Meeteetse coal field are located on coal beds ranging in thickness from 4.8 to 8 ft (1.46 to 2.43 mi) in the Mesaverde Formation (Glass and others, 1975). In outcrop, the Mesaverde coal beds in the Meeteetse coal field occupy two major zones in the lower part of the formation (Hewett, 1926; Pierce and Andrews, 1941). One mine was located on a 4 ft (1.21 m) thick coal bed in the lowermost part of the Fort Union Formation (Hewett, 1926; Glass and others, 1975), and another mine was located on a 1- to 2-ft (0.30 to 0.61 m) thick coal bed probably in the uppermost part of the Meeteetse Formation (Fisher, 1903; Pierce and Andrews, 1941).

The Garland coal field is distributed along the east margin of the Bighorn Basin about 16 to 24 mi (26 to 38 km) northeast of the wilderness study area (fig. 1). This coal field is small and has no recorded production (Glass and others, 1975). None of the 6 coal mines in the field are presently active. Five of the 6 coal mines in the Garland coal field are located on 4.4- to 7-ft-(1.34 to 2.13 m) thick coal beds in the basal part of the Fort Union Formation (Glass and others, 1975). One mine is located on a coal bed of unrecorded thickness in the Mesaverde Formation (Glass and others, 1975).

Quality

According to Glass and others (1975), the coal beds in the Oregon Basin, Meeteetse, and Garland fields are subbituminous in rank. A summary of the quality of selected coal beds in these fields is listed in Table 2. The values in Table 2 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 concerning gas-prone source rocks, coal beds exposed along the west margin of the Bighorn Basin extend into the subsurface beneath the wilderness study area where possibly they increase in number and thickness. Beneath the western and northern parts of the wilder-

Table 2.--As-received coal analyses (in percent) from Garland, Meeteetse, and Oregon Basin coal fields, Bighorn Basin, Wyoming (Glass and others, 1975).

	Number 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

	Number 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

ness study area the Fort Union through Mesaverde coal-bearing sequence is buried to between 3000 and 12,000 ft (0.9 to 3.66 km) whereas in the southern part of the wilderness study area the coal-bearing sequence is buried to between 4000 and 15,000 ft (1.22 to 4.57 km). Based on vitrinite studies by Hagen and Surdam (1984) and time-temperature reconstructions, most of the coal beds buried to a depth greater than 6000 ft (1.83 km) beneath the wilderness 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 less than 6000 ft (1.83 km) beneath the Wilderness Study Area are considered to be subbituminous in rank.

Identified and Undiscovered Subbituminous Coal Resources

Many of the coal beds beneath the McCullough Peaks Wilderness Study Area are buried deeper than 6000 ft (1.8 km) and therefore are excluded from coal resource consideration (Wood and others, 1983). Only those coal beds in the Fort Union and Willwood Formations beneath the wilderness 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, Miami Oil No. 1, Gulf Oil No. 1, Atlantic Refining and Alpine Oil No. 1, and Midwest Oil No. 1 (table 1), were used to identify coal beds and their thickness. Depending on the distance from these control points, coal resources were calculated for four areas of reliability (fig. 14). No coal beds thicker than 5 ft (1.5 m) were identified in the Fort Union and Willwood Formations. Coal beds less than 2.5 ft (0.75 m) thick were excluded from the resource calculations. Strata beneath the wilderness study area generally have dips less than 10 degrees and thus the coal resources here were calculated as if the strata were flat lying (Wood and others, 1983).

Total identified and undiscovered subbituminous coal resources beneath the wilderness study area are estimated to be 805 million tons and 275 million tons, respectively (Table 3). The sum of the identified and undiscovered subbituminous coal resources calculated in this study exceeds by a factor of two the subbituminous coal resource estimate by Berryhill and others (1950) for the entire Bighorn Basin. However, 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 3000 ft (0.91 km) of overburden. Wood and others (1983) caution that coal resource estimates based on geophysical logs, as done in this 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 Fort Union and Willwood coal beds have an ash content greater than 33 percent, the upper limit for a coal resource (Wood and others, 1983). Although the subbituminous coal resources beneath the wilderness study area may be overestimated, the probability is high that numerous Fort Union and Willwood coal beds between 2.5 and 5 ft thick (0.75 to 1.5 m) and with an ash content less than 33 percent are present.

CONCLUSIONS

Three major oil and(or) gas plays are identified in the McCullough Peaks Wilderness Study Area (fig. 15). Each play and its qualitative assessment(s) using the terminology of Goudarzi (1984) which is based on Miller (1983) and Taylor and Steven (1983) is listed below:

Figure 14. Map of McCullough Peaks Wilderness Study Area showing areas of reliability (A-J) used for subbituminous coal resource estimates. Miami Oil No. 1 drill hole (16, table 1) was used to calculate coal resources in areas of reliability A, D, H, J. Gulf Oil No. 1 drill hole (17, table 1) was used to calculate coal resources in areas of reliability B, E, I. Atlantic and Alpine No. 1 gas well (13, table 1) was used to calculate coal resources in areas of reliability C, F. Midwest Oil No. 1 drill hole (21, table 1) was used to calculate coal resources in area of reliability G. Areas of reliability are determined by using 1/4-mi radius (measured), 3/4-mi radius (indicated), 3-mi radius (inferred), and more-than-3-mi radius (hypothetical) from drill hole where thickness of coal was measured. Structure contours, in feet below mean sea level, are drawn on top of Tensleep Sandstone. The contour interval is 1000 ft. Drill holes are located with a small circle and an accompanying number which is identified in table 1. The base map with the structure contours was acquired from Petroleum Information Corporation and Barlow and Haun, Incorporated. Major tectonic features are identified as follows: EBA, Elk Basin anticline; EBF, Elk Basin fault; MPA, McCulloch Peak anticline; OBA, Oregon Basin anticline; OBF, Oregon Basin fault.

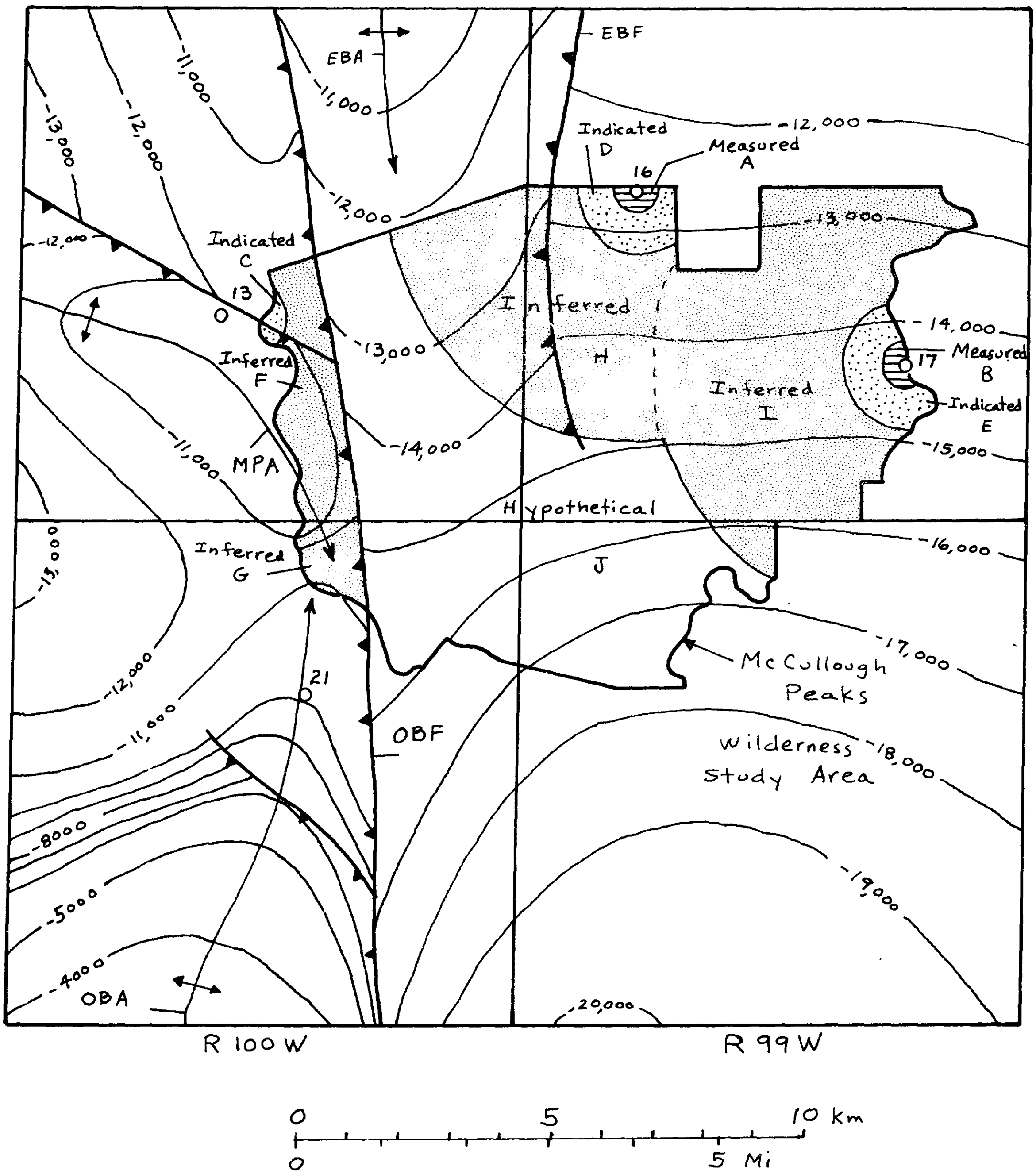

EBA
EBF
11,000
12,000
13,000
Indicated D
Measured A
16
Indicated C
13
Inferred F
MPA
Inferred
H
Inferred
I
14,000
Measured B
17
Indicated E
15,000
Hypothetical
Inferred G
J
16,000
17,000
McCullough Peaks
Wilderness Study Area
18,000
21
11,000
OBF
-8000
-5000
-4000
OBA
19,000
20,000
T 54 N
T 53 N
R 100 W
R 99 W
0 5 10 Km
0 5 Mi

Table 3.--Identified and undiscovered subbituminous coal resources estimated for McCullough Peaks Wilderness Study Area listed by depth of overburden. Identified resources are the sum of the measured (M), indicated (In), and inferred (Inf) resources. Undiscovered resources are equal to the hypothetical (H) resources.

	0-1000 ft	
Identified Resources	M - 1,031,910 In - 6,899,460 Inf - 87,216,750	95 million tons
Undiscovered Resources	H - 39 million tons	
	1000 - 2000 ft	
Identified Resources	M - 2,270,910 In - 15,793,710 Inf - 197,700,150	216 million tons
Undiscovered Resources	H - 39 million tons	
	2000 - 3000 ft	
Identified Resources	M - 2,690,400 In - 17,646,900 Inf - 221,034,060	241 million tons
Undiscovered Resources	H - 79 million tons	
	3000 - 6000 ft	
Identified Resources	M - 2,784,210 In - 18,174,500 Inf - 231,958,500	253 million tons
Undiscovered Resources	H - 118 million tons	

1) Upper Paleozoic play for structurally trapped gas (fig. 15A). Prospective upper Paleozoic reservoirs are located at depths greater than 15,000 ft (4.57 km). The potential for undiscovered gas resources is rated low (L/C).

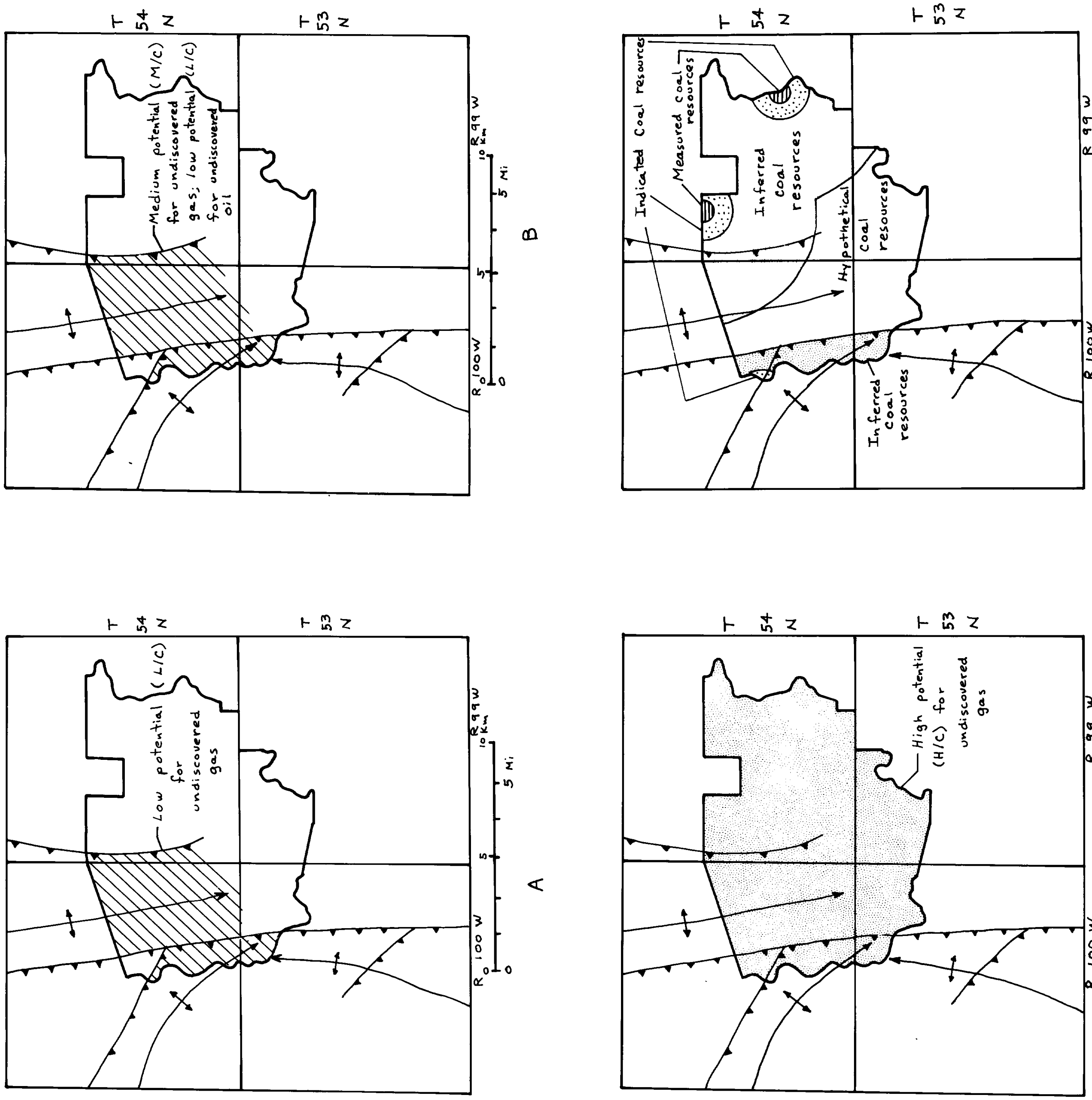
2) Upper Cretaceous and lower Tertiary play for structurally and(or) stratigraphically trapped oil and gas (fig. 15B). The potential for undiscovered gas resources is rated medium (moderate M/C). The potential for undiscovered oil resources is rated low (L/C).

3) Cretaceous and lower Tertiary play for gas in tight (low permeability), overpressured reservoirs (fig. 15C). The potential for undiscovered gas resources is rated high (H/C).

Mineable subbituminous coal is identified in the Fort Union and Willwood Formations beneath the McCullough Peaks Wilderness Study Area. The estimated tonnage of coal having between 0 and 6000 ft. of overburden is listed below at four levels of resource assurance (fig. 15D).

1) Measured subbituminous resources, 8.5 million tons
2) Indicated subbituminous resources, 58.5 million tons
3) Inferred subbituminous resources, 738 million tons
4) Hypothetical subbituminous resources, 275 million tons

Figure 15. Maps of McCullough Peaks Wilderness Study Area showing areas of potential undiscovered oil and gas resources and identified and undiscovered subbituminous coal resources. A. Area of upper Paleozoic play for structurally trapped gas; B. Area of Upper Cretaceous and lower Tertiary play for structurally and(or) stratigraphically trapped oil and gas; C. Area of Cretaceous and lower Tertiary play for gas in tight (low permeability), overpressured reservoirs; D. Areas of Measured, Indicated, Inferred, and Hypothetical subbituminous coal resources. Measured + Indicated + Inferred = Identified coal resources. Hypothetical = Undiscovered coal resources.



A
Low potential (L/C) for undiscovered gas
T 54 N
T 53 N
R 100 W
R 99 W
0 5 10 Km
5 Mi
B
Medium potential (M/C) for undiscovered gas; low potential (L/C) for undiscovered oil
C
High potential (H/C) for undiscovered gas
D
Indicated Coal resources
Measured coal resources
Inferred coal resources
Hypothetical coal resources

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