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Petroleum Geology of the

Wind River and Bighorn Basins, Wyoming and Montana

by

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and

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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 Wind River and Bighorn basins are large, asymmetrical, intermontane basins of the Rocky Mountain foreland and are located in central and northcentral Wyoming and contiguous Montana (figure 1). These two basins have been productive of oil and gas from rocks ranging in age from Cambrian to Eocene. Resources discovered total more than 2.9 billion barrels of recoverable oil and 3.6 trillion cubic feet of natural gas. This report provides a brief summary of the geologic framework used in the assessment of oil and gas resources for this area, reported in USGS/MMS Open-File report 88-373 (1988). Important plays are defined, geologically characterized, and oil and gas occurrences are identified.

STRUCTURAL SETTING

The two basins are separated from one another by the Owl Creek Mountains and are surrounded by major basement highs. Uplifts around the Wind River basin include the Wind River Mountains to the southwest, the Owl Creek Mountains and the Big Horn Mountains to the north, the Casper arch to the east, and the Granite Mountains (Sweetwater arch) to the south (figure 1). The Wind River basin is markedly asymmetrical, with the axis of the basin lying near the Owl Creek Mountains and Casper arch (figures 1 and 2). Maximum depths to the top of Permian strata are in excess of 25,000 ft (-20,000 ft)(Keefer, 1965a; 1970). Uplifts surrounding the Bighorn basin include the Beartooth, Pryor, Big Horn, and Owl Creek Mountains (figure 1). The basin is asymmetrical with the axis along the west-central side (figures 1 and 2). Present elevations of the Precambrian surface range from about 11,000 ft in the Bighorn mountains to -30,000 ft in the deepest part of the Bighorn basin (Stearns, 1975; Fanshawe, 1971; Thomas, 1965). In addition, a high volcanic upland, the Absaroka Volcanic Plateau, lies on the west side of the Bighorn basin, overlapping folded sedimentary rocks. Strata along the uplifts range in dip from 10-20 degrees to overturned.

The basins are bounded by overthrust, high-angle reverse, and normal faults. Anticlinal flexures, many of which are faulted, occur within the basin margins and are generally asymmetrical, typically with the steeper limb toward the adjacent mountain uplift.

The present structural setting is basically a product of Laramide deformation, which began in latest Cretaceous time, with tectonic movements continuing intermittently and decreasing in intensity through the Paleocene, culminating in earliest Eocene time with the uplift of mountains along reverse faults. Broad outcrop belts of folded and faulted Paleozoic and Mesozoic rocks surround the resulting crustal depressions.

Nevertheless, Permian facies, along with thickness patterns of other stratigraphic units are interpreted by Peterson (1984) as evidence that pre-Laramide tectonic movement took place along or in the vicinity of what later became major Laramide structures and is inferred to have had an important bearing on migration paths of Bighorn and Wind River basin hydrocarbons. Structural growth prior to Laramide is also documented by Merewether and Cobban (1986) for the mid-Cretaceous and also may have had significant effect on early migration paths.

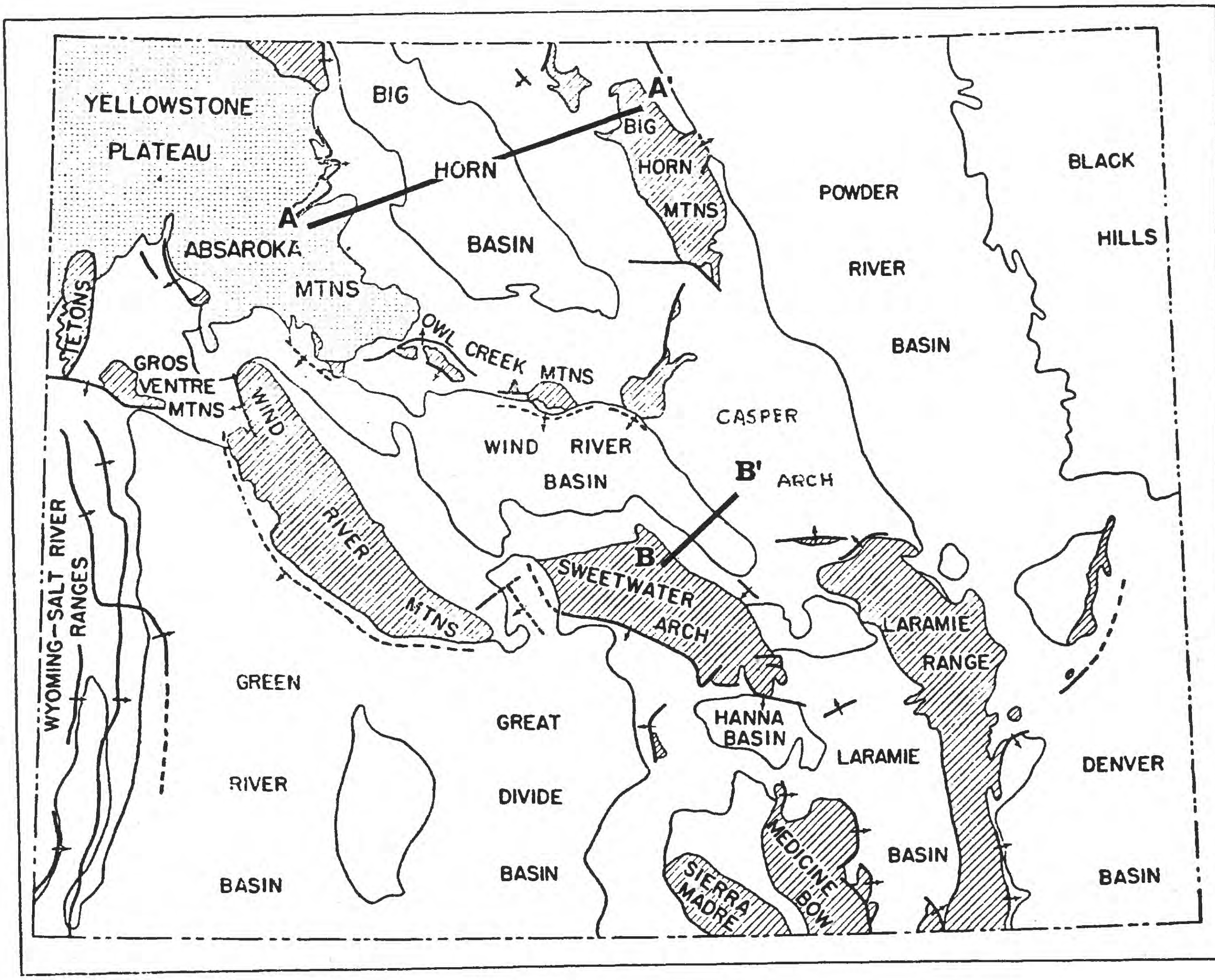

Figure 1. Index map of Wyoming showing major structural features. Faults are shown as heavy lines with arrows showing direction of movement of hanging wall of thrust fault. From Thomas (1957).

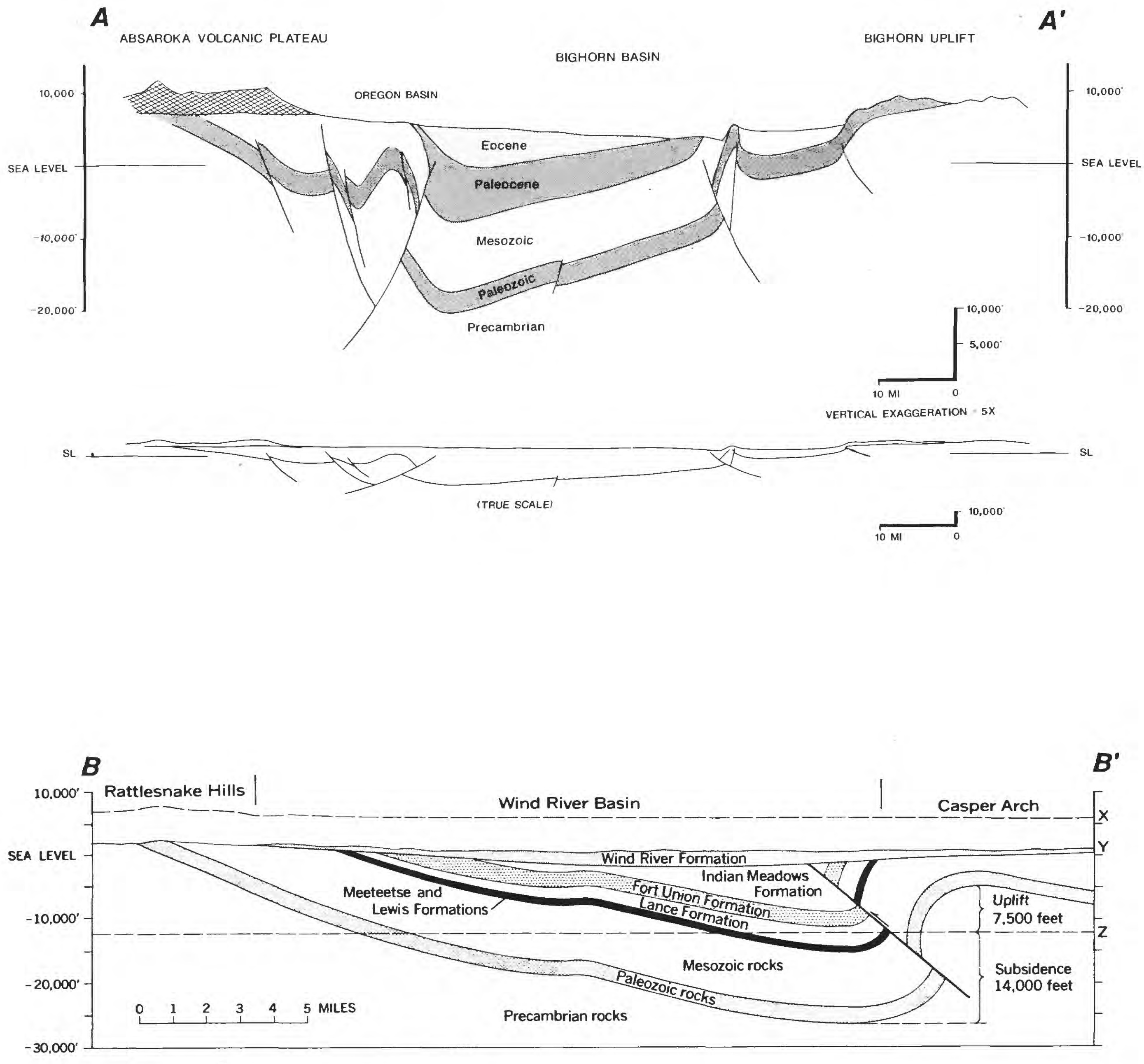

Figure 2. Cross sections of the Bighorn (A-A′) and Wind River (B-B′) basins, Wyoming and Montana. B-B′ from Keefer (1965b). X, present topographic profile; Y, postulated position of topographic profile at end of early Eocene time; Z, top of Precambrian rocks at beginning of deformation. Cross-section traverses are shown on figures 1, 4, and 5.

STRATIGRAPHY

A relatively complete sequence of Phanerozoic strata is present in both basins. Although rocks from all systems of the Phanerozoic, except the Silurian are present, the sequence is much thinner and more discontinuous than the sedimentary accumulations in the foreland of the Cordilleran region farther west. Lower Eocene strata, which are relatively underformed, cover the basins and unconformably overlap folded older rocks along the margins (figure 2). The stratigraphic sequences are shown on figure 3. A series of 5 electric-log cross sections by Fox and Priestly (1983) illustrate stratigraphic relationships in the Wind River basin.

The majority of Paleozoic and lower Mesozoic rocks of the region were deposited as sediment in shallow seas covering a gently westward-sloping shelf. Growth of late Paleozoic structural elements may have influenced the distribution of Permian cyclic lithofacies and carbonate reservoir belts in Wyoming and southeastern Idaho and is inferred to have had an important bearing on the relation between Permian-Pennsylvanian source rock-reservoir rock facies and migration paths.

In response to uplift in the west the western margin of the seaway moved eastward by Late Cretaceous, resulting in deposition of thick sequences of alternating marine and nonmarine strata in central Wyoming (Frontier, Cody, Mesaverde, Lewis, Lance, and Meeteetse Formations) (figure 3). Laramide mountain building and basin subsidence began during the Late Cretaceous and continued intermittently through the Paleocene. As it culminated in early Eocene time, extensive mountainous areas had been uplifted along reverse faults. More than 18,000 ft of marine, fluviatile, and lacustrine strata accumulated in areas of greatest subsidence in these basins (Meeteetse, Mesaverde, Lance, Fort Union, Indian Meadows, and Wind River Formations) (figure 3). During this time of major mountain building and subsidence, most of the petroleum-bearing structures were formed. Keefer (1969) presents evidence that after culmination of the Laramide orogeny, the entire region was elevated about 5,000 ft above its previous level and contemporaneous normal faulting resulted in the partial collapse of some Laramide uplifts. Subsequent erosion has removed younger strata so only lower Eocene and older strata of the basin fill remain in the central parts of the basins.

SOURCE ROCKS, THERMAL MATURITY AND TIMING OF MIGRATION

Carbon-rich rocks of the Phosphoria, Mowry, Frontier, Niobrara, Mesaverde, and Fort Union Formations are potential petroleum source rocks in the Wind River and Bighorn basins (Keefer, 1969; Meissner, Woodward, and Clayton, 1984). Oil prone source rocks are mostly found in mid-Cretaceous and older strata, particularly in the Mowry and Phosphoria Formations, while rocks of the Late Cretaceous and early Tertiary age tend to be largely gas prone.

Laramide folding was the primary controlling factor for entrapment of petroleum in reservoirs of latest Cretaceous and early Tertiary ages (Keefer, 1969), as well as important for the large accumulations in Paleozoic and older Mesozoic reservoirs. However, Keefer believes this folding to be only the final concentrating process in a long and complex history of generation, migration, and accumulation of hydrocarbons.

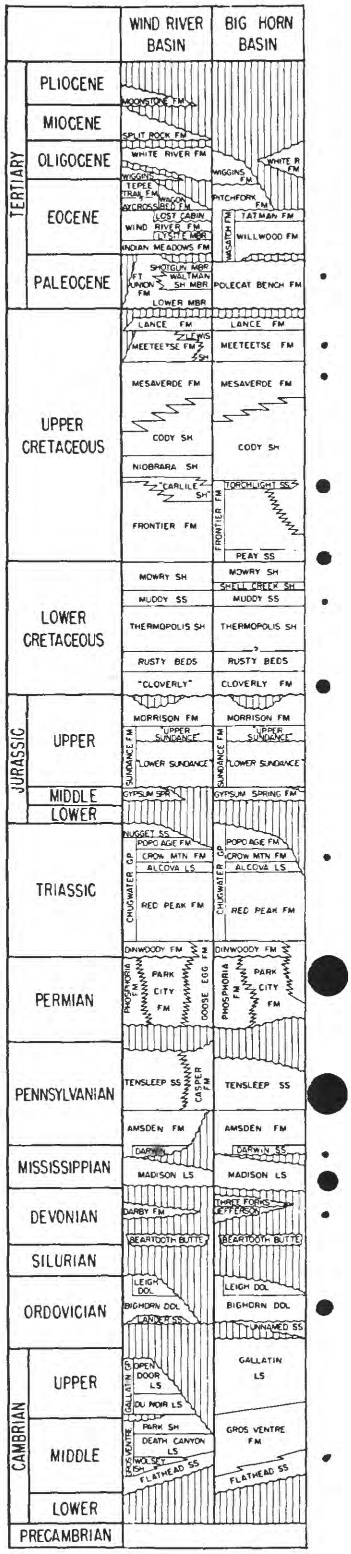

Figure 3. Stratigraphic sections of the Wind River and Bighorn basins, Wyoming and Montana (Wyoming Geological Association, 1983). Principal oil and gas producing intervals are indicated; relative importance is shown by size of circles.

The Phosphoria may be the origin of much of the Paleozoic oil in both the Wind River and Bighorn basins. Sheldon (1967) and Claypool, Love, and Maughan (1978) propose that long-distance migration of petroleum sourced from the Phosphoria in the area of western Wyoming occurred prior to basin formation and that this oil was trapped as far east as the eastern Powder River basin, Wyoming in the Pennsylvan-Permian Minnelusa Formation. Stone (1967) and others have suggested early entrapment and remigration during the Laramide. Lateral migration in the Bighorn basin is supported by McCaleb and Willingham's (1967) evidence that the source rocks for the Cottonwood Creek field Phosphoria reservoir are equivalent downdip organic-rich facies. However, Clayton and Ryder (1984) have indicated that Minnelusa Formation oil in the Powder River basin is geochemically different from Phosphoria Formation oil produced from the Bighorn basin and, based on the organic geochemical composition, could have been derived from Pennsylvanian black shales in the Powder River basin. Phosphoria source rocks are present within the Bighorn and Wind River basins for local generation of oil without invoking long distance migration, whose problems include barriers to migration caused by early structural growth and discontinuouities in the Park City and Weber-Tensleep carrier beds (Peterson, 1984).

Hagen and Surdam (1984) demonstrated that Cretaceous source rocks reached maturity by early Paleocene time in deep parts of the Bighorn basin and younger rocks later entered the hydrocarbon generation window. Structural growth apparently coincided with this Laramide stage of maturation. Burtner and Warner (1984) also demonstrate maturity of Lower Cretaceous source rocks in these same areas. By inference, Phosphoria source rocks for generation within the basins achieved maturity by Late Cretaceous.

HYDROCARBON OCCURRENCE

Stratigraphic and structural habitat of petroleum

Approximately .5 billion barrels of recoverable oil and 2.1 trillion cubic feet of gas had been discovered in the Wind River basin to the end of 1983, and about 2.5 billion barrels of oil and 1.6 trillion cubic feet of gas in the Bighorn basin. Major oil and gas fields of the basins are shown on figures 4 and 5 and are listed on Tables 1 and 2. Oil and gas resources in the Wind River and Bighorn basins occur chiefly in structural traps around their margins, some of large size. Two of the largest fields in the Rocky Mountains (Elk basin and Oregon basin fields) are found in this setting in the Bighorn basin and account for about 1 billion barrels of oil. Many structural traps have strong surface anticlinal expression; other pools, such as Madden field, occur in deep structures along the northern axial part of the Wind River basin and along a northwesterly-trending structure within the Bighorn basin. Major exceptions to structural entrapment are Grieve field (Lawson, 1962) in the Wind River basin and Cottonwood Creek field (McCaleb and Willingham, 1967; Rogers, 1971; Pedry, 1975) in the Bighorn basin which produce from updip facies changes in the Lower Cretaceous Muddy Sandstone and Permian Phosphoria Formation, respectively. A number of fields appear to be combination traps.

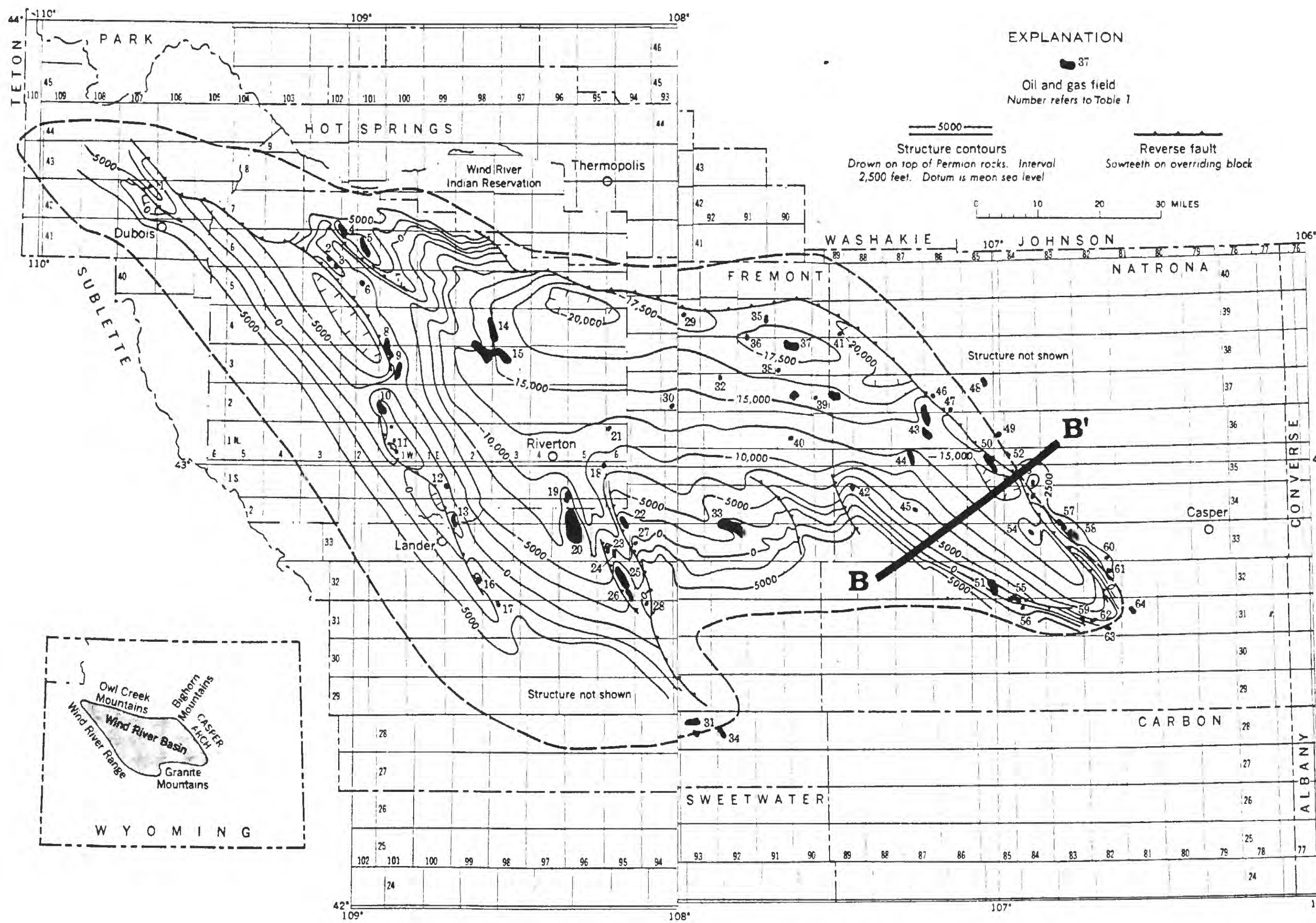

Figure 4. Index map of the Wind River basin, outlined by dashed line, and showing locations of oil and gas fields. The numbers next to the fields are indexed to field name and production information on Table 1. Structure contour lines are on top of Permian rocks (from Keefer, 1969).

Table 1. Wind River basin oil and gas fields. Fields are shown on Figure 4 (from Keefer, 1969).

No.	Field	Producing Formation	Average Depth (ft)	Oil	Gas	Cond.
1	Dubois	Park City Formation	2,150	X		
2	Rolff Lake	Chugwater Group (Crow Mountain Sandstone)	3,450	X		
		Park City Formation	4,660	X		
3	Northwest Sheldon	Chugwater Group (Crow Mountain Sandstone)	3,330	X		
		Park City Formation	4,375	X		
		Tensleep Sandstone	4,750	X		
4	Circle Ridge	Park City Formation	950	X		
		Tensleep Sandstone	1,200	X		
		Amsden Formation (Darwin Sandstone Member)	1,600	X		
		Madison Limestone	1,700	X		
5	Maverick Springs	Park City Formation	1,100	X		
		Tensleep Sandstone	1,600	X		
6	Sheldon Dome	Frontier Formation	2,750		X	
		Chugwater Group (Crow Mountain Sandstone)	5,250	X		
		Park City Formation	6,450	X		
		Tensleep Sandstone	6,760	X		
7	Little Dome[2]	Chugwater Group (Crow Mountain Sandstone)	1,275		X	
8	Steamboat Butte	Frontier Formation	3,250		X	
		Cloverly Formation	4,325	X		
		Sundance Formation	5,100	X		
		Nugget Sandstone	5,175	X		
		Chugwater Group (Crow Mountain Sandstone)	5,525	X		
		Park City Formation	6,730	X		
		Tensleep Sandstone	6,980	X		
9	Pilot Butte	Cody Shale	800	X		
		Thermopolis Shale (Muddy Sandstone Member)	3,300	X	X	
		Park City Formation	5,760	X		
		Tensleep Sandstone	6,200	X		
10	Winkleman Dome	Cloverly Formation	530		X	
		Park City Formation	2,790	X		
		Tensleep Sandstone	2,980	X		
11	Sage Creek[2]	Park City Formation		X		
12	Plunkett	Mowry Shale	450	X		
13	Lander-Hudson	Park City Formation	1,250	X		
		Tensleep Sandstone	1,750	X		
14	Muddy Ridge	Wind River Formation	4,400		X	
15	Pavillion	do	3,700		X	
16	Dallas Dome	Park City Formation	700	X		
		Tensleep Sandstone	1,000	X		
17	Derby Dome	Park City Formation	700	X		
		Tensleep Sandstone	1,000	X		
18	Riverton East	Frontier Formation	10,000		X	X
		Thermopolis Shale (Muddy Sandstone Member)	10,925		X	X
		Cloverly Formation	11,240		X	X
19	Riverton	Frontier Formation	8,275		X	
		Park City Formation	11,580		X	X
		Tensleep Sandstone	11,750	X		
20	Beaver Creek	Cody Shale	3,930	X		
		Frontier Formation	7,700		X	X
		Thermopolis Shale (Muddy Sandstone Member)	8,000		X	
		Cloverly Formation	8,300		X	X
		Park City Formation	10,900	X	X	X
		Tensleep Sandstone	10,990	X		
		Madison Limestone	11,200	X		
21	Indian Butte	Fort Union and Lance Fms.	6,425		X	X
		Mesaverde Formation	8,430		X	X
22	Alkali Butte	Frontier Formation	2,485		X	
		Thermopolis Shale (Muddy Sandstone Member)	4,200	X		
		Cloverly Formation	4,575		X	
23	North Sand Draw[2]	Tensleep Sandstone	10,775	X		
24	Kirby Draw[2]	Frontier Formation	4,485		X	
		Cloverly Formation	5,500		X	
25	Big Sand Draw	Frontier Formation	2,750		X	
		Cloverly Formation	4,310		X	
		Morrison Formation	4,380		X	
		Park City Formation	6,850		X	X
		Tensleep Sandstone	7,105	X		
26	South Sand Draw	Frontier Formation	4,000		X	
		Thermopolis Shale (Muddy Sandstone Member)			X	
		Park City Formation		X		
		Tensleep Sandstone		X		
27	Rogers Mountain[2]	Cloverly Formation	4,100		X	
28	Long Creek	Park City Formation	5,220		X	X
29	Howard Ranch	Fort Union and Lance Fms.	8,735		X	X
30	Poison Creek	do	5,425		X	X
31	Happy Springs	Frontier Formation	4,750	X		
		Thermopolis Shale (Muddy Sandstone Member)	4,450	X		
		Cloverly Formation	4,530	X		
		Park City Formation	6,200	X		
32	Dinty Moore Reservoir	Fort Union and Lance Fms.	4,300		X	X
33	Muskrat	Frontier Formation	4,000		X	
		Cloverly Formation	5,500		X	
		Park City Formation	7,320	X		
34	Crooks Gap	Frontier Formation	3,400	X		
		Thermopolis Shale (Muddy Sandstone Member)	4,800	X		
		Cloverly Formation	5,000	X		
		Nugget Sandstone	5,600	X		
35	Dolis Hills	Lance and Fort Union Fms.	6,780		X	X
36	Lysite	Wind River Formation	3,600	X	X	
37	Lost Cabin	Wind River Formation	3,700	X	X	
		Fort Union and Lance Fms.	8,870		X	
38	Moneta Hills[2]	do	10,500		X	
39	Frenchie Draw	do	9,325		X	X
40	Squaw Butte	do	6,700		X	
41	Badwater[2]	do	15,210		X	
42	Raderville	Cody Shale	2,120	X		
43	Waltman	Fort Union and Lance Fms.	5,650	X	X	
44	Cooper Reservoir	do	3,660		X	
45	Wallace Creek	Thermopolis Shale (Muddy Sandstone Member)	10,345	X		
46	Arminto[2]	Frontier Formation	1,860		X	
47	Lox[2]	do	2,075		X	
48	Notches	Mowry Shale	325		X	
		Tensleep Sandstone	2,750	X		
49	Powder River[2]	Frontier Formation	925	X	X	
		Thermopolis Shale (Muddy Sandstone Member)	2,280			
		Sundance Formation	3,000		X	
50	Boone Dome	Cody Shale	1,550		X	
		Frontier Formation	6,800		X	
51	Grieve	Thermopolis Shale (Muddy Sandstone Member)	6,700	X	X	
52	Clark Ranch	Frontier Formation	915		X	
		Chugwater Group (Crow Mountain Sandstone)	3,190	X		
		Tensleep Sandstone	4,685	X		
53	Pine Mountain[2]	Goose Egg Formation	1,800	X	X	
		Tensleep Sandstone	1,800		X	
54	West Poison Spider	Mesaverde Formation	9,230	X		
		Cody Shale	10,400	X		
		Frontier Formation	14,200	X		
		Morrison Formation	15,920	X		
55	Poison Spring Creek[2]	Thermopolis Shale (Muddy Sandstone Member)	6,880	X		
56	Fish Creek[2]	Cloverly Formation	1,400	X		
57	South Casper Creek	Sundance Formation	1,450		X	
		Tensleep Sandstone	2,450	X		
58	Poison Spider	Thermopolis Shale (Muddy Sandstone Member)	550	X		
		Sundance Formation	1,375	X	X	
59	Tipps	Cloverly Formation	5,400	X		
60	Oil Mountain	Tensleep Sandstone	2,650	X		
61	Iron Creek	Frontier Formation	200	X		
		Thermopolis Shale (Muddy Sandstone Member)	750	X		
		Cloverly Formation	700	X	X	
62	Government Bridge	Cody Shale	2,200	X		
		Thermopolis Shale (Muddy Sandstone Member)	3,800	X		
63	Schrader Flats	Sundance Formation	3,330	X		
64	Bates Creek	Frontier Formation	1,150	X		

[1] Information based on Wyoming Geological Association (1957), Biggs and Espach (1960), International Oil Scouts Association (1966), published releases of Petroleum Information, Inc., Denver, Colorado, and files of Conservation Division, U. S. Geological Survey, Denver, Colorado.

[2] Noncommercial or abandoned field.

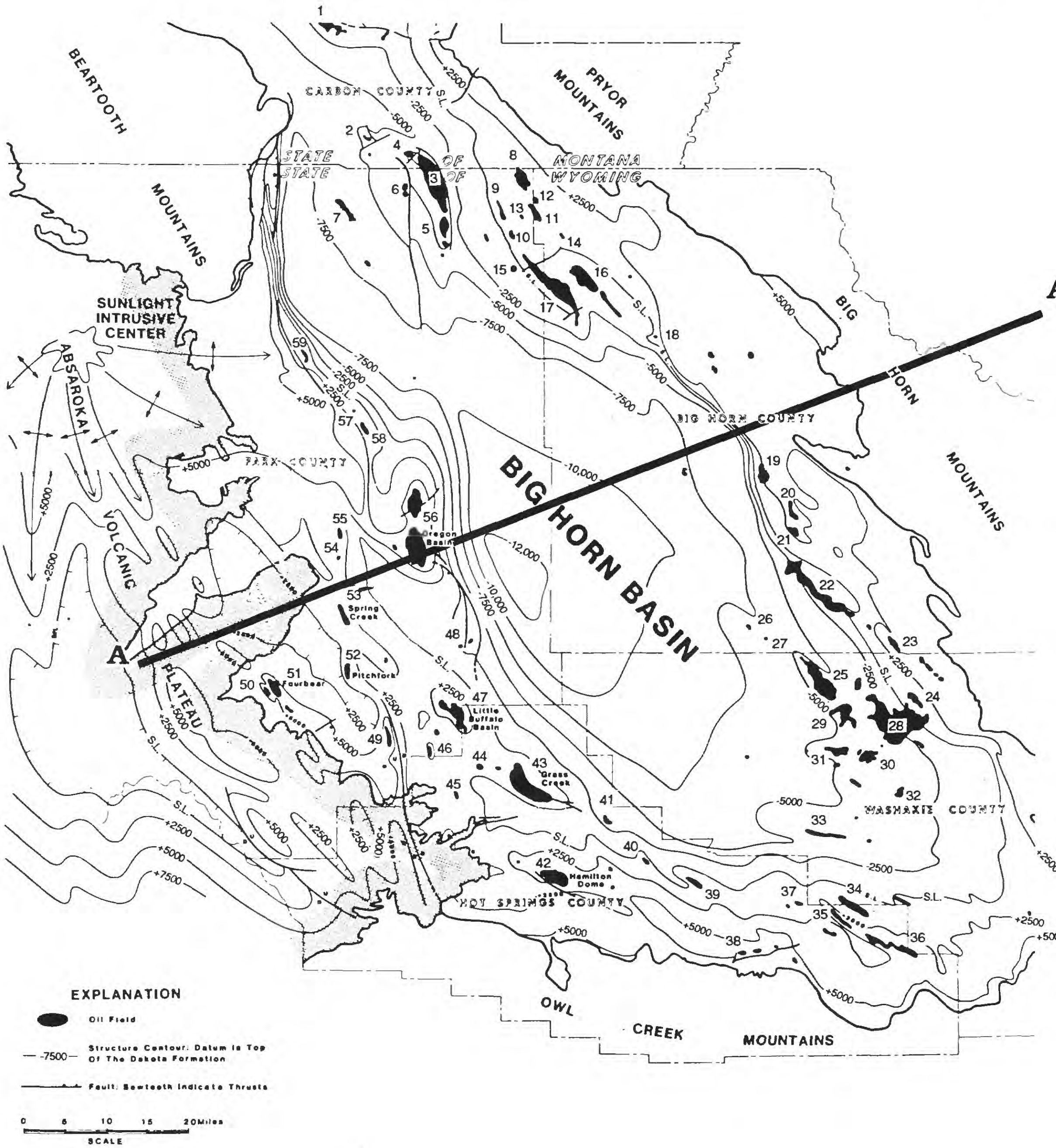

Figure 5. Index map of the Bighorn basin, showing locations of oil and gas fields. The numbers next to the fields are indexed to field name and production information on Table 2. Structure contour lines are on top of the Dakota Formation (from Brittenham and Tadewald, 1985).

Table 2. Bighorn basin oil and gas fields larger than one million barrels of oil equivalent. Fields are shown on figure 5. Data from: NRG Assoc. (1986); Wyoming Oil and Gas Conservation Commission (1986); Stephenson and others (1984); Montana Oil and Gas Conservation Commission (1986).

Number	Field Name	State	Field Size MMBO	Field Size BCFG	Producing Formation
1	Dry Creek	Montana	4.1	72.0	Mesaverde Fm. Frontier Fm. Lakota Fm.
2	Clarks Fork North	Montana	1.0	1.8	Lakota Fm.
3	Elk Basin	Wyo-Mont	532.0	333.6	Frontier Fm. Dakota Ss. Tensleep Ss. Madison Ls. Jefferson Fm. Bighorn Dol.
4	Elk Basin Northwest	Montana	1.2	0.1	Phosphoria Fm. Tensleep Ss. Madison Ls. Bighorn Dol.
5	Elk Basin South	Wyoming	19.2	35.4	Frontier Fm. Dakota Ss. Lakota Fm. Morrison Fm. Tensleep Ss. Madison Ls.
6	Silver Tip	Wyoming	4.7	24.6	Mesaverde Fm. Frontier Fm. Phosphoria Fm. Tensleep Ss. Madison Ls.
7	Badger Basin	Wyoming	2.8	4.6	Frontier Fm. Dakota Ss.
8	Frannie	Wyo-Mont	120.8	0.5	Tensleep Ss. Madison Ls.
9	North Danker	Wyoming	0.6	2.7	Frontier Fm. Dinwoody Fm. Tensleep Ss.
10	Big Polecat	Wyoming	6.6		Frontier Fm. Tensleep Ss.
11	Deaver North	Wyoming	1.4		Tensleep Ss.
12	Sage Creek	Wyoming	11.8		Tensleep Ss. Madison Ls.
13	Sage Creek West	Wyoming	1.3		Tensleep Ss.
14	Homestead	Wyoming	1.6		Tensleep Ss.
15	Whistle Creek	Wyoming	5.2	2.1	Tensleep Ss.
16	Byron	Wyoming	128.0	13.5	Frontier Fm. Sundance Fm. Tensleep Ss. Amsden Fm.
17	Garland	Wyoming	178.0	138.0	Frontier Fm. Cloverly Fm. Morrison Fm. Phosphoria Fm. Tensleep Ss. Madison Ls.
18	Alkali Anticline	Wyoming	2.7		Phosphoria Fm. Tensleep Ss. Dinwoody Fm. Madison Ls.
19	Greybull	Wyoming	1.0		Frontier Fm. Muddy Ss. Lakota Fm.
20	Lamb	Wyoming	1.0	0.2	Phosphoria Fm. Tensleep Ss. Madison Ls.
21	Torchlight	Wyoming	16.8	4.0	Meeteetse Fm. Phosphoria Fm. Tensleep Ss. Madison Ls. Bighorn Dol.
22	Manderson	Wyoming	3.9	84.0	Muddy Ss. Phosphoria Fm. Tensleep Ss.
23	Bonanza	Wyoming	41.7		Meeteetse Fm. Tensleep Ss.
24	Hidden Dome	Wyoming	6.8	22.3	Frontier Fm. Phosphoria Fm. Tensleep Fm.
25	Worland	Wyoming	18.2	387.0	Frontier Fm. Phosphoria Fm. Tensleep Ss.
26	Dobie Creek	Wyoming		15.0	Frontier Fm. Muddy Ss.
27	Five Mile	Wyoming		15.0	Frontier Fm. Muddy Ss. Phosphoria Fm.
28	Cottonwood Creek	Wyoming	54.4	37.6	Phosphoria Fm. Tensleep Ss.
29	Frisbee, S. Rattlesnake	Wyoming	12.0	7.2	Phosphoria Fm.
30	South Fork	Wyoming	1.0	0.1	Phosphoria Fm.
31	Slick Creek-No Water Creek	Wyoming	9.5	8.4	Phosphoria Fm.
32	Sand Creek	Wyoming	1.5	5.1	Frontier Fm. Muddy Ss. Phosphoria Fm.
33	Neiber Dome	Wyoming	3.6	6.4	Phosphoria Fm. Tensleep Ss.
34	Murphy Dome	Wyoming	38.4		Curtis Ss. Tensleep Ss.
35	Lake Creek and Northwest	Wyoming	9.8	0.2	Tensleep Ss. Amsden Fm.
36	Black Mountain	Wyoming	17.2	0.1	Phosphoria Fm. Tensleep Ss. Madison Ls.
37	Zimmerman Butte	Wyoming	1.2		Frontier Fm. Phosphoria Fm. Tensleep Ss.
38	Warm Springs	Wyoming	3.7		Phosphoria Fm.
39	Gebo	Wyoming	29.5	0.9	Chugwater Gp. Phosphoria Fm. Tensleep Ss.
40	Little Sand Draw	Wyoming	10.2		Phosphoria Fm. Tensleep Ss.
41	Golden Eagle	Wyoming	13.5	2.5	Mesaverde Fm. Muddy Ss. Cloverly Fm. Phosphoria Fm. Tensleep Ss.
42	Hamilton Dome	Wyoming	250.0	0.1	Chugwater Gp. Phosphoria Fm. Tensleep Ss. Madison Ls. Bighorn Dol.
43	Grass Creek	Wyoming	195.0	0.7	Frontier Fm. Chugwater Gp. Phosphoria Fm. Tensleep Ss. Darwin Ss. Madison Ls.
44	Walker Dome	Wyoming	3.2	0.8	Frontier Fm. Phosphoria Fm.
45	Enos Creek	Wyoming	0.8	0.5	Phosphoria Fm.
46	Gooseberry	Wyoming	7.6		Phosphoria Fm. Tensleep Ss.
47	Little Buffalo Basin	Wyoming	145.0	119.4	Frontier Fm. Muddy Ss. Dakota Ss. Phosphoria Fm. Tensleep Ss.
48	Meeteetse	Wyoming	0.3	12.0	Frontier Fm. Muddy Ss. Phosphoria Fm.
49	Sunshine North	Wyoming	2.5		Phosphoria Fm. Tensleep Ss.
50	Willow Draw	Wyoming	2.2		Dinwoody Fm. Phosphoria Fm. Tensleep Ss.
51	Fourbear	Wyoming	25.0		Muddy Ss. Chugwater Gp. Phosphoria Fm. Tensleep Ss. Amsden Fm.
52	Pitchfork	Wyoming	36.0		Phosphoria Fm. Tensleep Ss. Madison Ls.
53	Spring Creek South	Wyoming	18.2	.1	Phosphoria Fm. Tensleep Ss. Dinwoody Fm. Madison Ls.
54	Ferguson Ranch	Wyoming	4.0		Tensleep Ss.
55	Half Moon	Wyoming	8.5		Phosphoria Fm. Tensleep Ss.
56	Oregon Basin	Wyoming	440.0	186.0	Frontier Fm. Cloverly Fm. Chugwater Gp. Phosphoria Fm. Tensleep Ss. Madison Ls. Bighorn Dol. Flathead Ss.
57	Shoshone	Wyoming	3.4		Phosphoria Fm. Tensleep Ss.
58	Cody	Wyoming	5.2		Tensleep Ss.
59	Heart Mountain	Wyoming		51.0	Frontier Fm.

Numerous formations, ranging in age from Cambrian to early Eocene, produce hydrocarbons in the Wind River and Bighorn basins (figure 3). The principal producing formations include the Madison Limestone, Tensleep Sandstone, Phosphoria Formation (Park City Formation), Cloverly Formation, Muddy Sandstone and Frontier Formation. Approximately 90% of the oil in the Bighorn basin and 70% of that in the Wind River basin is found in Late Paleozoic reservoirs. In the Wind River basin, however, much of the gas is found in younger formations. Many of the structural trap fields contain multiple pay zones and many contain common oil-water contacts within the Paleozoics. Sandstone is the dominant rock type for most of the reservoirs except for carbonate rocks of the Madison Limestone, Phosphoria Formation, and most older Paleozoics. Rocks older than the Mississippian Madison Limestone have been tested in many fields, but contain significant quantities of oil and/or gas in only a few, including Elk Basin and Oregon Basin, where Flathead (Cambrian), Bighorn (Ordovician), and Jefferson-Darby (Devonian) reservoirs are variously productive.

Depth of production ranges from a few hundred feet along basin margins to more than 23,000 ft in the deep axial portion of the Wind River basin at Madden anticline (figure 4) (Reid, 1978; Dunleavy and Gilbertson, 1986, 1987).

Basis for play definition

Principal plays in the Wind River and Bighorn basins are subdivided into structural and stratigraphic types. Plays within each of these categories are defined based on known or anticipated favorable geologic conditions for undiscovered resources.

Structural plays have been defined in both basins to include (1) basin margin subthrust, (2) basin margin anticline, and (3) deep basin structure plays. A fourth structural play has been defined in the Bighorn basin area as the sub-Absaroka play. Most structures have demonstrated production from more than one formation; as wells are drilled into deeper formations on these structures, petroleum production from heretofore untested Paleozoic formations may become more significant in terms of future field growth. For instance, in 1985, gas was discovered in the Madison in Madden Field, an anticline in the deeper northern axial part of the Wind River basin (Reid, 1978; Dunleavy and Gilbertson, 1986, 1987). This well, completed from the lower Madison at a depth of 23,758 ft, deepened the Rocky Mountain region depth-of-production record. It also produces gas from six other younger stratigraphic intervals. Such added resources are not considered part of the undiscovered category, but rather part of field growth.

Principal stratigraphic plays in the Wind River basin include: (1) central basin Cretaceous and Tertiary (basin center "tight" gas sands), (2) Muddy Sandstone, and (3) Phosphoria Formation; those in the Bighorn basin include: (1) central basin Cretaceous and Tertiary (basin center "tight" gas sands) and (2) Phosphoria Formation. These plays will be discussed in detail later in this report.

Discussion of other prospective associations

Several formations and associations, not considered in this assessment as formal plays, may become significantly petroleum-productive in the future. A summary of these formations or associations anticipated to have potential are briefly noted in the following discussion. Some already produce relatively small quantities of oil or gas. These were assessed collectively.

Oil may be trapped in wedge-edge or beveled-edge pinchouts of the Ordovician Bighorn Dolomite as well as granular dolomite beds of the Devonian Darby Formation (Keefer and Van Lieu, 1966). These beveled edges of dolomite abut the base of the Madison Limestone, providing a possibly favorable geologic setting for petroleum entrapment. Stratigraphic traps may also exist in the Cambrian Flathead and Ordovician Lander Sandstones. Stratigraphic entrapment within, or at the top of the Madison or in porous strata of the Amsden and Darwin Formations also has potential.

Porosity and permeability of the Tensleep Sandstone are highly variable, contributing to the favorable possibilities for local internal stratigraphic entrapment of petroleum (Fox and others, 1975; Mankiewicz and Steidtman, 1979; Andrews and Higgins, 1984). Also, structural and paleotopographic irregularities at the boundary between the Tensleep Sandstone and the Park City Formation may have caused entrapment of petroleum in the Tensleep in both the Wind River and Bighorn basins (Lawson and Smith, 1966; Curry, 1984).

Stratigraphic traps may be present in Triassic and Jurassic formations such as the Crow Mountain Sandstone and equivalent Jelm Formation of the Chugwater Group, Nugget Sandstone, Sundance Formation, and Morrison Formation. For example, the wedge edges of the Nugget Sandstone occur along the east and north sides of the Wind River basin. Petroleum may be entrapped locally in porous zones that parallel the wedge edges (Keefer, 1969).

The Lower Cretaceous Cloverly Formation, which includes the highly variable "Lakota sandstone", Cat Creek Sandstone, "Dakota sandstone" ("Rusty beds"), and Greybull Sandstone in the Bighorn and Wind River basins, is already modestly petroleum productive and may become a significant stratigraphic trap exploration target in the future, as perhaps, will the Muddy sandstone of the Bighorn basin.

In addition, less conventional resources exist in both the Bighorn and Wind River basins, including heavy oils and tar sands, such as exposed in Cretaceous outcrops along the north flank of the Sweetgrass uplift and elsewhere. Bailey and Sundell (1986), for instance, have estimated a minimum of 10 million barrels of asphaltum within the basal Absaroka volcanic sequence on the west side of the Bighorn basin, in addition to the possibility of resources in truncation traps in the underlying Paleozoic strata which probably involve low gravity oil as well as "conventional" hydrocarbons.

Sandstones within the Cody Shale and Frontier Formation have potential for conventional and nonconventional tight gas sand reservoirs deep within both the Wind River and Bighorn basins. The Frontier Formation is a highly variable sequence of interbedded sandstone and shale of both marine and nonmarine origin ranging from about 650 to 1,000 ft in thickness. In the Wind River basin, petroleum geologists have named the sandstones the First, Second, Third, Fourth, and Fifth Frontier Sands or the First Wall Creek Sand, Second Wall Creek Sand, and Third Wall Creek Sand (Tonnsen, 1980; Goodell, 1962; Keefer, 1972). In the Bighorn basin the major productive intervals are known as Torchlight and Peay sandstones.

The Cody Shale is a sequence of marine shale and fine-grained sandstone ranging in thickness from 3,600 to 5,000 ft. Petroleum productive sandstones in the eastern part of the basins are termed the Shannon and Sussex Sandstone Members (Keefer, 1972), although Cody "strays", such as the "Pilot" sandstone are locally productive.

PETROLEUM PLAY DESCRIPTIONS

Basin-margin subthrust play - Wind River and Bighorn basins:

Play description and type - As discussed by Berg (1962) and Gries (1981), nearly all of the Laramide basins of the Rocky Mountain Foreland have thrust faults along at least part of their margins. In this play, petroleum is trapped in deformed Phanerozoic strata below the thrust. A trap in this play may occur where structures with closure beneath the thrust are sealed by impermeable rocks of the hanging wall of the fault or are concealed by the thrust block. Figures 6 and 7 illustrate the boundaries of this play in the Wind River and Bighorn basins, respectively.

Reservoirs - Reservoir type and quality in this play are highly variable. Porous and permeable sandstone and carbonate facies may have good reservoir quality. Also, some of the less conventional lithotypes may have good reservoir quality due to extensive fracturing associated with thrusting. Essentially any age of rock formation may provide reservoirs.

Traps and seals - The trapping mechanism is the overthrust wedge of impermeable rocks creating a trap and seal of fluids in the underlying Phanerozoic sedimentary rocks or in folds concealed beneath the thrust wedges. In the thrusting process, the underlying beds are folded and often upturned or overturned with fault slivers typically present.

Source rocks and geochemistry - Petroleum source rocks for this play are numerous, including essentially any of the carbon-rich shale formations within the basin. The best source rocks are carbon-rich rocks of the Phosphoria, Mowry, Frontier, Mesaverde, and Fort Union Formations (figure 3) (Meissner, Woodward, and Clayton, 1984; Hagen and Surdam, 1984).

Timing and migration - Because Laramide thrust faults have thrust Precambrian rocks over Phanerozoic rocks, the depth of the source shales is usually great enough to have generated hydrocarbons locally or to have migrated from mature areas in deeper parts of the basin. Hydrocarbon generation in this case occurred during and after the Laramide Orogeny when the structures formed. Some early or pre-Laramide migration may have taken place, moving hydrocarbons into sandstone reservoirs before tectonic development of basin margin folds and faults. If these sandstones were sealed by facies changes, stratigraphic traps may have developed prior to basin-margin thrusting. Faulting could then have superimposed structural control on these stratigraphic traps.

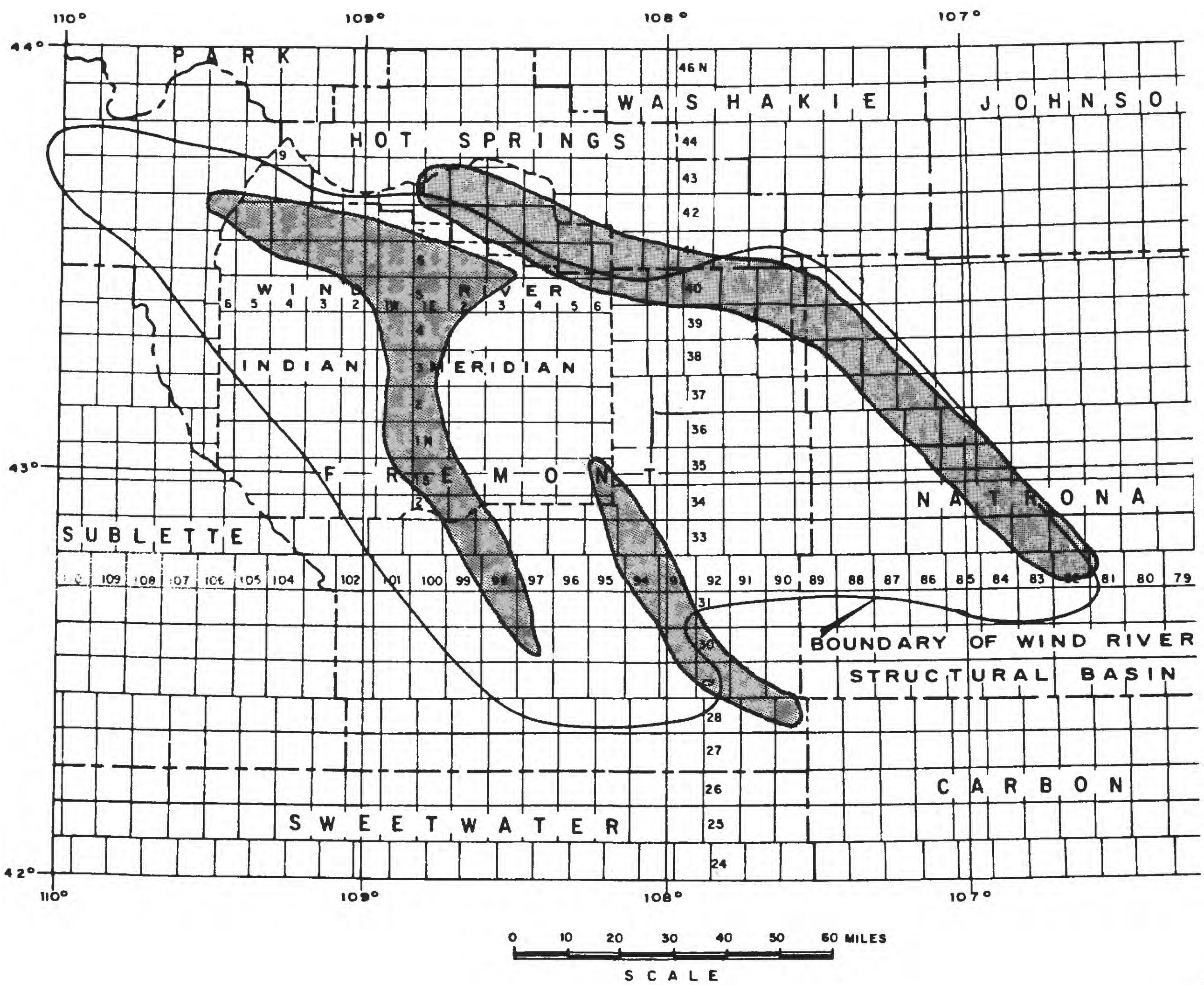

Figure 6. Base map of the Wind River basin showing the limits of the basin margin subthrust play.

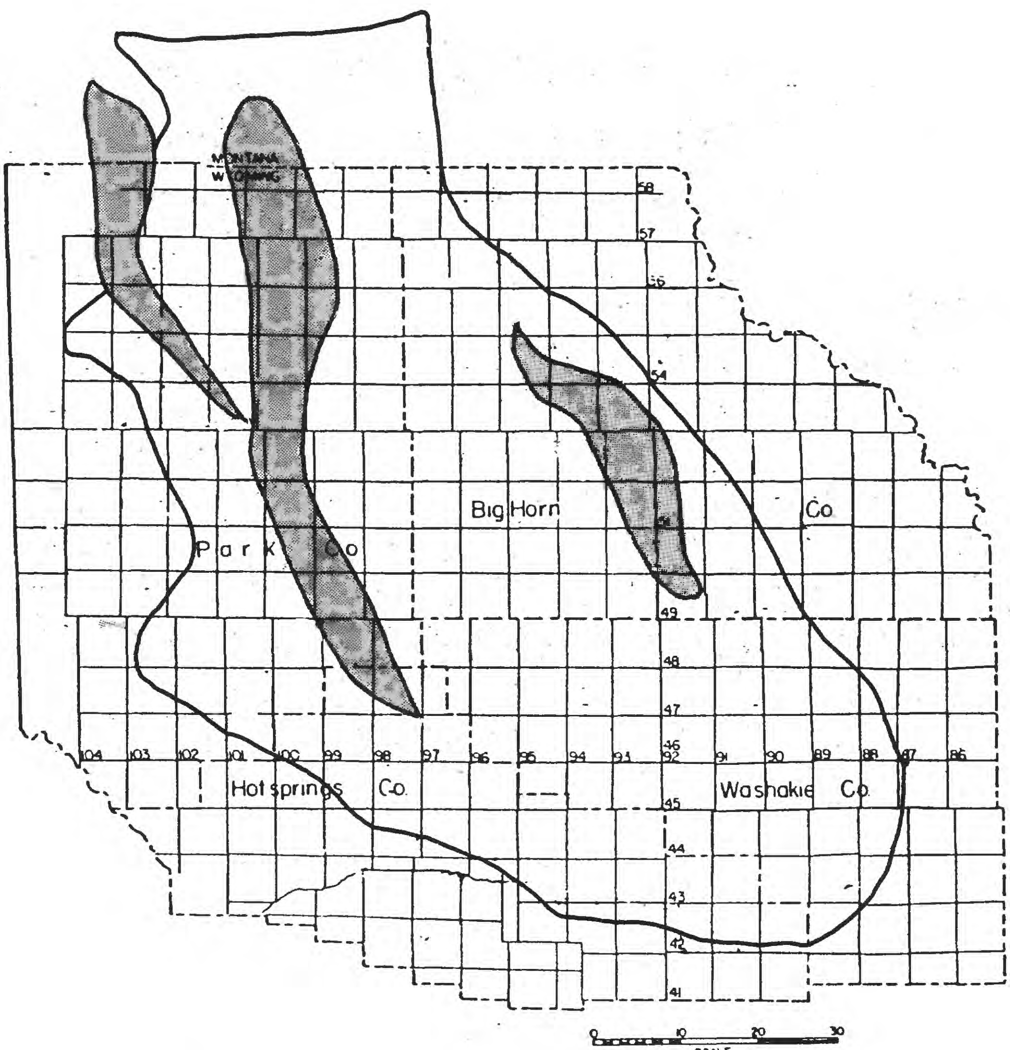

Figure 7. Base map of the Bighorn basin showing the limits of the basin margin subthrust play.

Depth of occurrence - Depth of occurrence is highly variable depending on the thickness of the Precambrian wedge (dip angle of the thrust plane) and orientation and thickness of the underlying Phanerozoic strata. The depth could be in excess of 20,000 ft where thrusting takes place over the structurally deep side of the asymmetrical basins and less than 10,000 ft in other basin-margin areas.

Exploration status - The basin-margin subthrust play is a demonstrated play. The level of exploration is in the category of very lightly explored to unexplored. One field, Tepee Flats field in the Wind River basin, is currently producing gas from the Frontier Formation at a depth of about 12,000 ft (Ray and Berg, 1985). The NRG Associates "Significant Oil and Gas Fields of the United States" (1986) data base estimates 21 billion cubic feet of gas (BCFG) ultimately recoverable from this field. It is anticipated that about 70% of the fields in this play will be gas fields occurring in the deeper parts of the basins, and the remaining 30% will be oil fields in areas where entrapment is shallower.

Basin margin anticlinal play - Wind River and Bighorn basins:

Play description and type - The basin margin anticlinal play is a structural play, the anticlines having formed as a result of compression during the Laramide Orogeny. This play is best developed along the shallower margins of the basins, as shown on figures 8 and 9.

Reservoirs - Numerous formations, ranging in age from Cambrian to early Eocene, are productive and many fields contain multiple pay zones. Formations that have produced petroleum from these structures include: Flathead, Bighorn, Jefferson, Madison, Tensleep, Phosphoria, Crow Mountain, Nugget, Lakota, Cloverly, Muddy, Thermopolis, Frontier, Cody, Mesaverde, Fort Union, and Wind River. Primary production has been out of the Madison, Tensleep and Phosphoria. Many of the fields with multiple pay zones are associated with faulted anticlines and in some cases show common oil-water contacts for the Paleozoic reservoirs (Stone, 1967). Sandstone is the dominant reservoir lithology; however, substantial hydrocarbons have been produced from carbonate reservoir rocks in the Madison and Park City (Phosphoria) Formations.

Two fields in the western part of the Wind River basin produce oil from the Madison Limestone, namely Circle Ridge and Beaver Creek (figure 4). As discussed by Keefer (1969), properties of the oil in these two fields are nearly identical to those of the Tensleep and Park City oil in the same areas, indicating petroleum in the Madison in these two fields may have been derived from the younger Paleozoic reservoirs. In the Bighorn basin, several fields produce Madison oil, often in common reservoirs with other Paleozoic rocks, particularly the Phosphoria and Tensleep. Oil types in all these formations have similar geochemical parameters (Stone, 1967).

Traps and seals - The trapping mechanism is closure in both anticlines and domes. In many cases the anticlines and domes are faulted. Within these structures, interbedded impermeable beds act as seals.

Source rocks and geochemistry - Within the thick sequence of hydrocarbon-bearing strata are numerous organic-rich argillaceous sedimentary rocks. Oil and gas in the Cretaceous and younger reservoirs appear to be

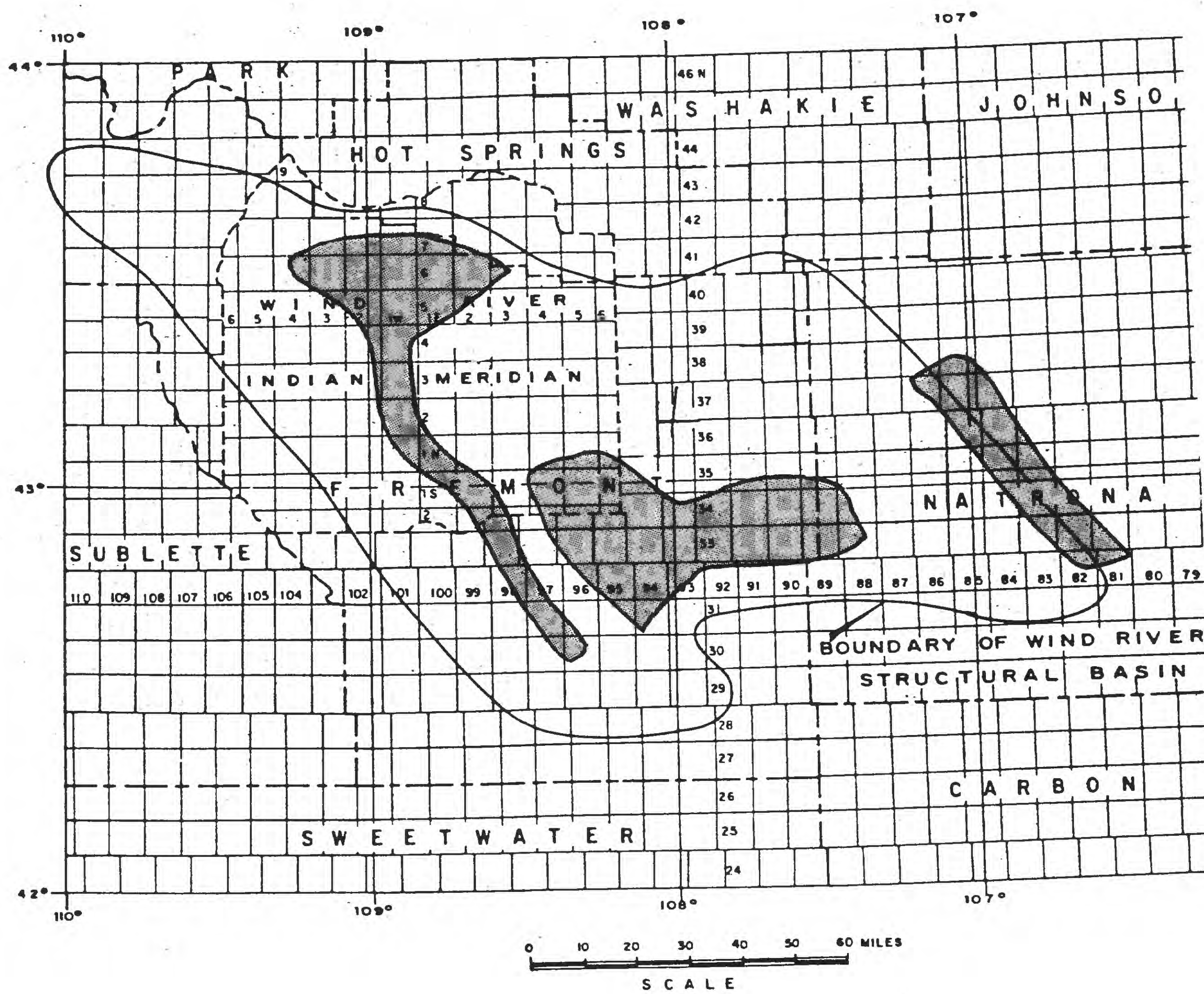

Figure 8. Base map of the Wind River basin showing the limits of the basin margin anticlinal play.

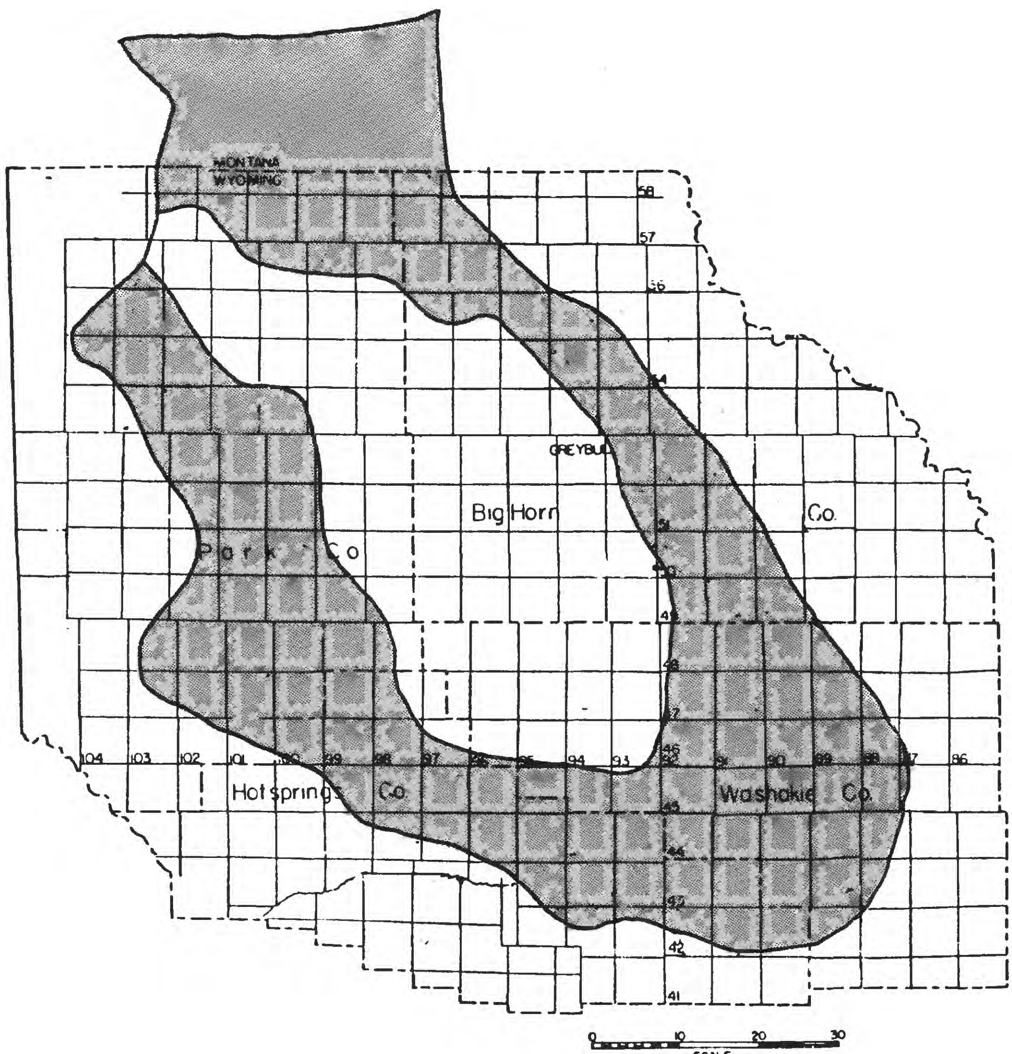

Figure 9. Base map of the Bighorn basin showing the limits of the basin margin anticlinal play.

sourced from associated Cretaceous organic-rich beds while Paleozoic oil and gas appear to be derived primarily from a distinct Phosphoria source. The thermal maturity is high in many areas of the basins, especially where source beds are very deeply buried and in these areas gas predominates (Hagen and Surdam, 1984).

Timing and migration - Some hydrocarbon source beds may have been generating hydrocarbons long before the Laramide Orogeny when most of the shallow hydrocarbon-bearing structures of this play formed. These basin-margin structures formed at about the same time as the basin was deepening (Keefer, 1969). This deepening in the basin center at the same time as anticlinal structures were forming around it resulted in the remobilization of previously generated hydrocarbons into these developing structures (Lawson and Smith, 1966; Keefer, 1969). Many of these anticlines are faulted allowing migrating hydrocarbons to move into multiple levels of porous and permeable reservoirs (Stone, 1967; Stauffer, 1971).

Depth of occurrence - Depth of production in this play ranges from a few hundred feet to more than 12,000 ft.

Exploration status - The first commerical oil well in Wyoming was drilled in 1884 on a basin margin anticlinal structure named Dallas dome along the west edge of the Wind River basin. In fact, most of the oil and gas in the Wind River and Bighorn basins is produced from structural traps which are mapped along the basin margins. Most of these traps had been explored by 1950 resulting in about 50 fields greater than 1 MMBOE size in the Bighorn basin, and about 20 in the Wind River.

In the Wind River basin, field sizes range from about 90 million barrels of oil (MMBO) recoverable in Winkleman dome and about 810 BCF of nonassociated gas at Beaver Creek field (figure 4, Table 1) to fields in the category of less than 1 million barrels of oil equivalent (MMBOE). Approximately 500 MMBO and 1250 BCF of nonassociated and associated gas have been discovered in the basin to date.

In the Bighorn basin, field sizes range from over 500 MMBO at Elk Basin and 387 BCFG at Worland (figure 5, Table 2) to less than 1 MMBOE; about 2400 MMBO and 1400 BCFG have been found in the basin in structural traps and 8 fields are of giant size (>100 MMBO).

This play has been extensively explored and developed throughout both basins and future prospects for new significant discoveries are not good, although new production could occur in extensions and secondary features related to larger structural trends. Small fields are likely. The mix of oil and gas should be in about the same proportion as historic.

Deep basin structure play - Wind River basin:

Play description and type - Several large anticlinal, domal, and fold nose trap structures are proven to be petroleum productive within the deeper axial portion of the Wind River basin (figure 4). More of these Laramide structures may exist within the play (figure 10). It is primarily a gas play because of the great depth of burial.

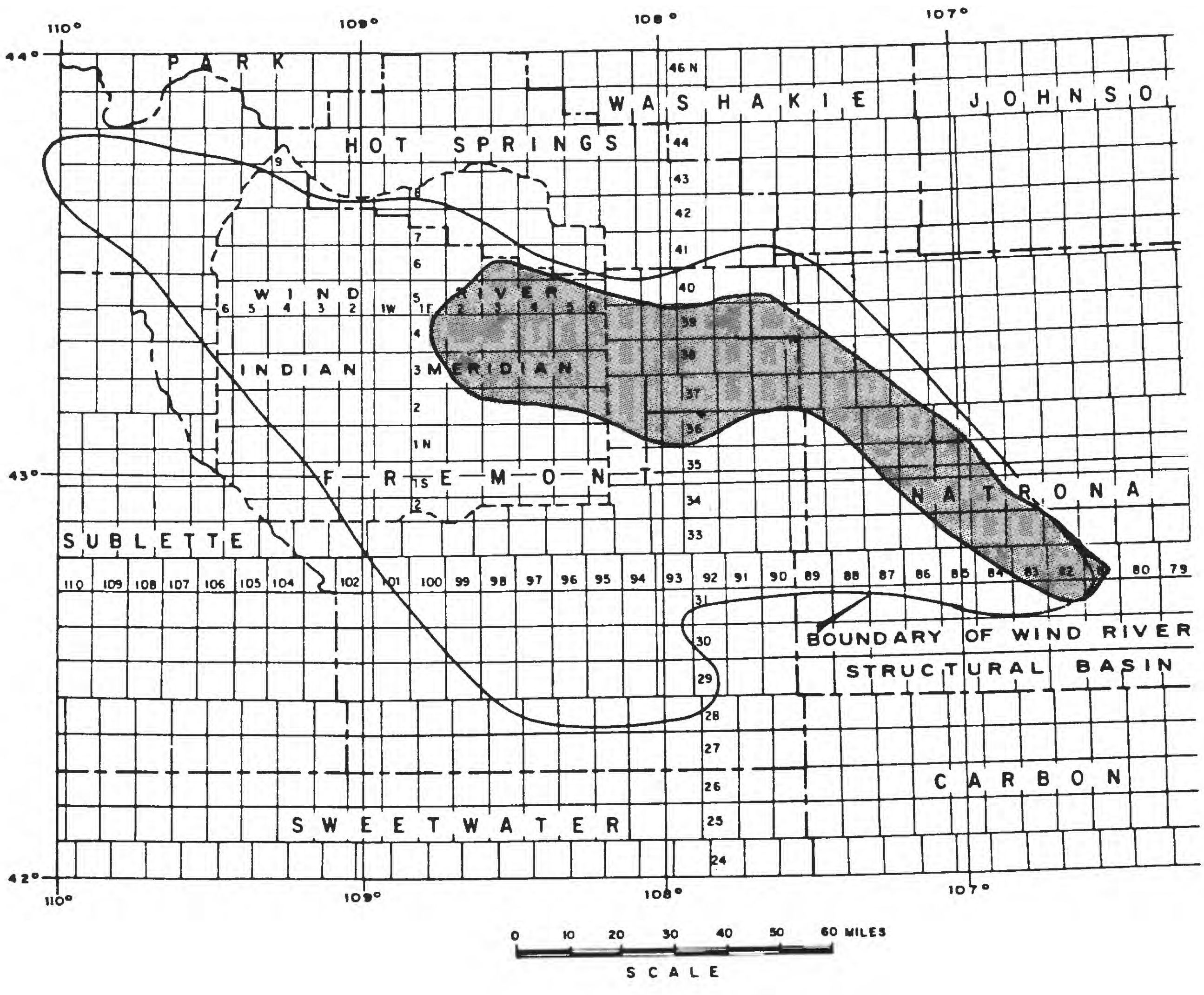

Figure 10. Base map of the Wind River basin showning the limits of the deep basin structure play.

Reservoirs - Reservoir rocks are composed primarily of Cretaceous or Tertiary sandstones, deposited in a variety of depositional environments including deltaic, marginal marine, and fluvial. The compositional and textural maturity varies from immature to mature. The great depth of burial has reduced porosity and permeability through compaction and cementation. Where oil migrated into the reservoir sandstones early in burial history, some of the original porosity and permeability may have been preserved. Structures produce primarily gas from Cretaceous and Tertiary age formations including the Frontier, Cody, Mesaverde, Lance, Fort Union, and Wind River Formations. As evidenced by Madden field, Mississippian carbonate reservoirs may also be important. Fracturing may be important.

Traps and seals - The trapping mechanisms in this play are intrabasin anticlinal structures and fold noses. Seals include fine-grained facies interbedded with the reservoirs, some of which may also be hydrocarbon source beds.

Source rocks and geochemistry - Hydrocarbon source rocks are abundant in the Upper Cretaceous and lower Tertiary formations throughout the deep portions of the basins which are the areas of this play. Source rocks include carbon-rich shales in the Permian Phosphoria and the Cretaceous Frontier, Mesaverde, Lance, and Tertiary Fort Union Formations (figure 3) and are thermally mature to supermature (Hagen and Surdam, 1984). Source rocks may only yield gas, which is the hydrocarbon resource in many of the producing fields of this area.

Timing and migration - As discussed by Keefer (1969) some of the hydrocarbon source beds may have been buried deeply enough to generate hydrocarbons before the time of the Laramide orogeny, when most of the hydrocarbon-bearing structures formed. However, continuing generation during Laramide is also evident. The reservoir rocks are interbedded with the source rocks facilitating easy migration from the source rocks into the reservoir rocks.

Depth of occurrence - The area of this play is the deep axial portion of the basin where source and reservoir strata occur at depths to in excess of 23,000 feet. At Madden field (figure 4), the depth of the Precambrian has been reported to be at 24,813 ft and there is gas production from the Madison Limestone at about 23,700 ft (Reid, 1978; Dunleavy and Gilbertson, 1986, 1987).

Exploration status - The deep basin structure play in the Wind River basin is a demonstrated play. The level of exploration is moderate and there is good potential for future gas discoveries. In fact, reserve estimates of many of the currently discovered fields in this play do not take into consideration Paleozoic strata such as the Madison Limestone which is productive at Madden field. With the addition of this newly discovered pool, the reserve estimates have increased considerably.

About 10 fields with ultimate production in the category of greater than 1 MMBOE are currently producing in this play in the Wind River basin. The size of these fields exceeds 500 BCFG ultimately recoverable at Madden. These volumes are based on NRG Associates "Significant Oil and Gas Fields of the United States" data base. Major fields in the Wind River basin include West Poison Spider, Waltman, Madden, and Pavillion (figure 4). West Poison Spider field also produces oil from the Morrison Formation. Gas is currently being produced from the Mississippian Madison Limestone at Madden field.

Deep basin structure play - Bighorn basin:

Play description and type - A deep-basin structure play also exists within the deep portion of the Bighorn basin where structures similar to those discussed in the Wind River basin deep-basin structure play and may prove to be petroleum productive. The play boundary in the Bighorn basin is shown on figure 11. It is primarily a gas play because of the great depth of burial.

Reservoirs - Reservoir rocks are primarily sandstones of a variety of facies including deltaic channel and bar, marginal marine, and fluvial channel. All of these facies have potentially good primary porosity and permeability. The great depth of burial has very likely reduced the quality of the reservoirs. If hydrocarbons were being generated and the structure began forming prior to excessive burial, they could have become trapped within the reservoirs and helped to preserve some of the original porosity and permeability. Carbonates are considered secondary reservoirs.

Traps and seals - The primary trapping mechanism in this play is an intrabasin "anticlinal" structure feature, fault bounded on the north side and often referred to as the "Five Mile Trend". It extends northwest diagonally across the center of the basin (figure 11) and is the only structure in the play. The anticline plunges in a northwesterly direction. Depth to the top of the Tensleep exceeds 25,000 ft at the northwest end. At the southeast end, close to the Cottonwood Creek, Worland, and Rattlesnake fields, the depth to the Tensleep is about 11,000 ft. Petroleum may be sealed in reservoirs by interbedded fine-grained beds that are interbedded with the reservoirs and that may also have been source rocks.

Source rocks and geochemistry - A thick section of marine shales has potential as source rocks and include the following: Permian Phosphoria Formation and Cretaceous Thermopolis Shale, Mowry Shale, Frontier Formation, and Cody Shale. Paludal shales within the Mesaverde, Meeteetse, Lance, and Fort Union Formations (figure 3) are also carbon-rich and may be a good source for natural gas. Most of these formations are very deeply buried in this play area and may be beyond the maturity range of oil generation and into the gas zone.

Timing and migration - Some of the stratigraphically lowest Cretaceous shale formations and the Phosphoria Formation may have been buried deeply enough in the area to the west for hydrocarbon migration to begin even before the onset of the Laramide Orogeny in Late Cretaceous time and migrate into this area. The area of this play cuts diagonally across the deep axial part of the basin (figure 11) where source beds may be as deep as 15,000 ft or more on the northwest end of the play trend. The reservoir sandstones in the Frontier and Mesaverde Formations are interbedded with marine shale; reservoir sandstones in the Lance and Fort Union Formations are interbedded with source rocks of nonmarine origin. This interbedded relationship favored easy migration from source rock to reservoir rock. The Tensleep Sandstone, the major producer in the basin, is buried very deeply and its potential as a producer in this play is minimal. On the "shallow" southeast end, gas is produced in part from the Phosphoria at Five Mile field at a depth of 11,650 ft.

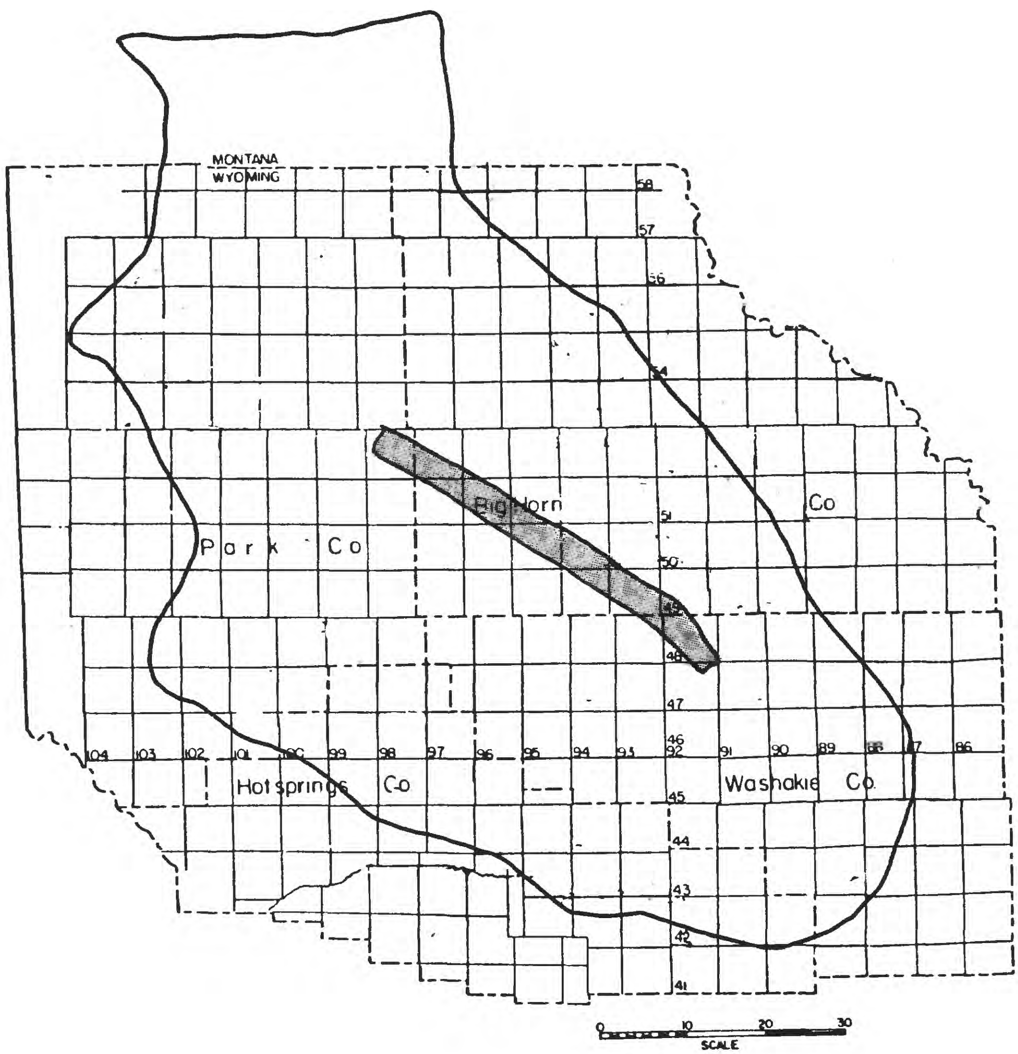

Figure 11. Base map of the Bighorn basin showing the limits of the deep basin structure play.

Depth of occurrence - The depth of potential production ranges from about 11,000 ft on the southeast end of the structure to in excess of 20,000 ft on the northwest end.

Exploration status - This play is not very well demonstrated. The level of exploration is minimal and the potential for future discoveries is uncertain; structures at equivalent depths in the Wind River basin are gas productive. One field, Five Mile field, is in the category of greater than 1 MMBOE ultimately recoverable. Two fields are in the category of less than 1 MMBOE ultimately recoverable. Approximately 3 BCFG have been discovered to date and ultimately recoverable reserves are estimated to be about 10.4 BCFG from the Phosphoria and Frontier Formations.

Muddy Sandstone play - Wind River basin:

Play description and type - The Muddy Sandstone play is a stratigraphic play with anticipated entrapment of oil and gas in pinchouts of the Muddy sandstone. The Muddy was deposited as a complex series of sand bodies, interpreted as fluviatile, deltaic, beach, and offshore bar (Curry, 1962; 1978) and estuarine (Mitchell, 1978). The distribution of these facies of the Muddy may have been controlled by paleotopography and structure during Muddy deposition (Mitchell, 1978). The limits of this play, as assessed, are shown on figure 12. The actual sandstone may, in fact, extend beyond the limits shown, but the play is restricted due to excessive depth and anticipated reservoir degradation of the formation in the deeper Wind River basin, and to the infrequent and generally poor development of sandstone in the Bighorn basin.

Reservoirs - The reservoir sandstone is closely associated with thick petroleum source beds so the conditions for primary stratigraphic entrapment of hydrocarbons are ideal. The thickness of the Muddy sandstone is as much as 150 ft in places along the west margin of the basin, locally thinning and grading almost completely into shale and siltstone (Keefer, 1969). The effective pay zone averages only about 15-20 ft but the high porosity and permeability and the high quality of the oil make it a prime drilling objective.

Traps and seals - The trapping mechanism is updip pinchout of discontinuous reservoirs, such as Grieve field (figure 4), the largest Muddy field, where production is from an unusually thick section of estuarine sandstone (Mitchell, 1978) which thins abruptly updip on the west where the petroleum is trapped (Lawson, 1962).

Source rocks and geochemistry - Source beds for Muddy hydrocarbons are the black shales of the Mowry and Shell Creek Shale that overlie, and the Thermopolis Shale that lies below Muddy Sandstone reservoir rocks (figure 3).

Timing and migration - As overburden accumulated, petroleum was squeezed out of the thick overlying and underlying fine grained source rocks and into the intervening sandstone reservoir rocks. Depth of burial of the Muddy is in excess of 5,000 ft throughout the play area, a depth sufficient for generation of hydrocarbons.

Depth of occurrence - The depth range of the Muddy interval in the play area is from approximately 5,000 to 12,000 ft.

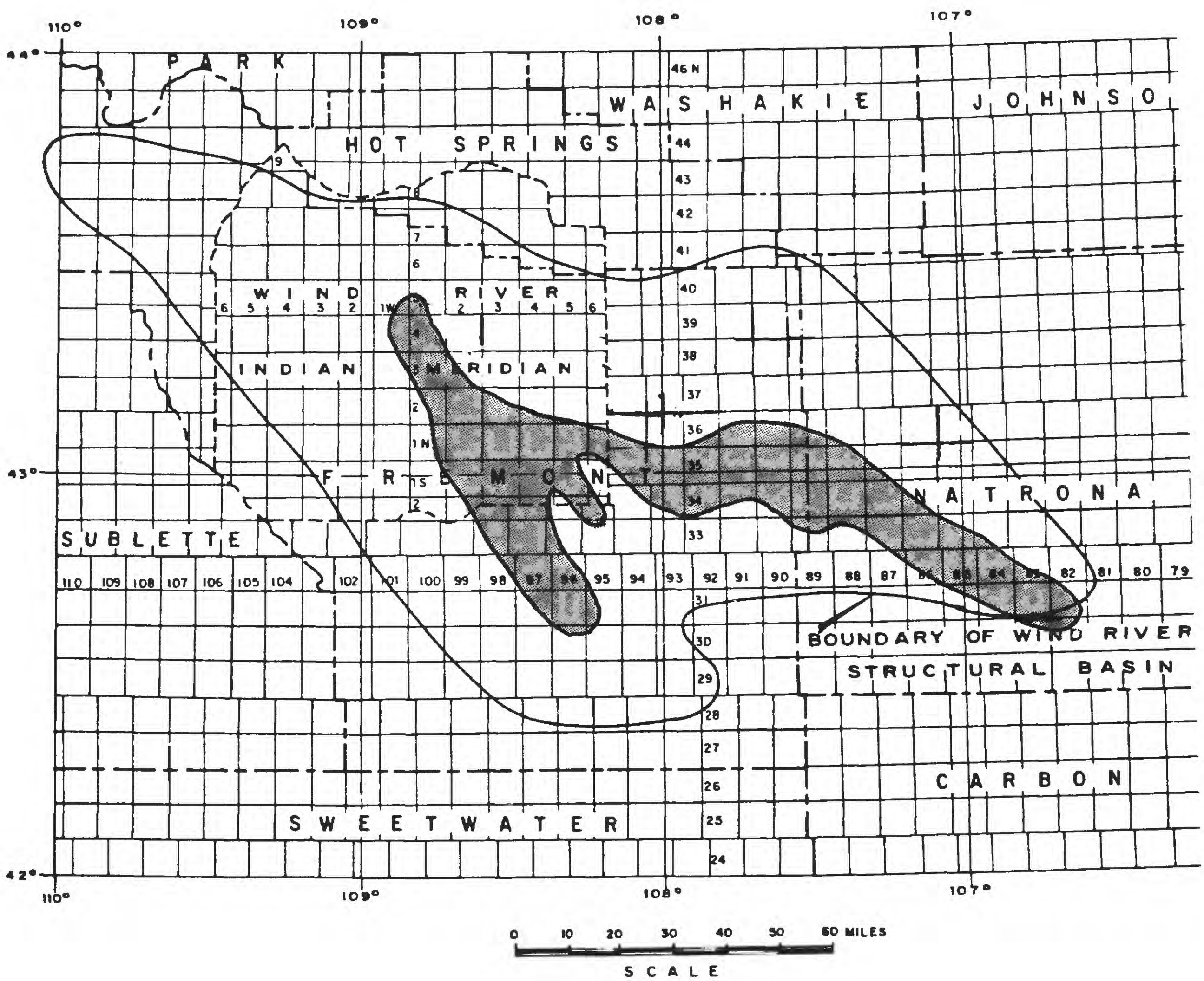

Figure 12. Base map of the Wind River basin showing the limits of the Muddy Sandstone play.

Exploration status - The Muddy Sandstone play is a demonstrated play. The level of exploration ranges from heavily explored along the southern margin of the Wind River basin to lightly explored in the central part of the basin. Four fields greater than 1 MMBOE ultimately recoverable have been discovered through 1983, the largest being Grieve. Cumulative production from the Muddy is approximately 40 MMBO and 80 BCF associated gas. Potential for large discoveries exists, but is not high.

Basin center "tight" gas sandstone play - Wind River and Bighorn basins:

Play description and type - Potential for significant accumulations of nonassociated gas exists in the deep parts of the basins. However, because of reservoir characteristics it is treated as a "tight" gas sandstone play. Shallow, conventional gas reservoirs in these sequences are treated in the collective assessment of other occurrences. Figures 13 and 14 illustrate the limits of these plays in the Wind River and Bighorn basins, respectively. The plays are characterized by discontinuous reservoirs and stratigraphic pinchouts forming traps at great depths within the basins where gas is anticipated as the hydrocarbon resource. Facies with the necessary characteristics to form pinchout traps in combination with shale source rocks are present in a number formations in this play, including sandstones within the Mesaverde, Lance, Fort Union, Wind River, and Indian Meadows formations (figure 3).

Reservoirs - Several formations have potential as petroleum reservoirs. The permeability of these reservoirs is highly varied. Individual sandstone units in the Frontier Formation are varied in thickness and lithology and potential as hydrocarbon reservoirs. Sandstone and shale intertongue extensively along the Cody-Mesaverde contact. This zone of intertonguing extends northward across the Wind River basin and is connected with similar trends in the Bighorn basin (Gill and Cobban, 1966; Keefer, 1969; Keefer 1972; Miller and others, 1965; Barwin, 1961). In locations where structural uplift took place during deposition of the Lance and Fort Union, favorable reservoir rock facies were deposited, the patterns of sedimentation influenced by the uplift (Gillespie, 1984).

Cody, Frontier, and older arenaceous rocks were not assessed in this play because of general lack of available information. Though they not assessed, they probably have significant resource potential.

The Mesaverde Formation, which overlies the Cody Shale, contains about 700 to 2,000 ft of interbedded fine-to medium-grained sandstone, shale, siltstone, and coal deposited in interfingering nearshore, brackish-water, swampy, and fluvial environments (Severn, 1961; Miller and others, 1965; Barwin, 1961; Keefer, 1972). The reservoir quality of these complex facies is highly variable.

The Lance and Fort Union Formations reach a maximum thickness of about 14,000 ft (Keefer, 1969; Gillespie, 1984). Strata, consisting chiefly of shale, claystone, siltstone, and fine-grained sandstone, occur in the central parts of the basins. This includes the lacustrine Waltman Shale in the Wind River basin. Near the basin margins, these fine-grained strata grade into and intertongue with coarse-grained sandstone and conglomerate derived from uplifted nearby mountain blocks and deposited in alluvial and lacustrine environments

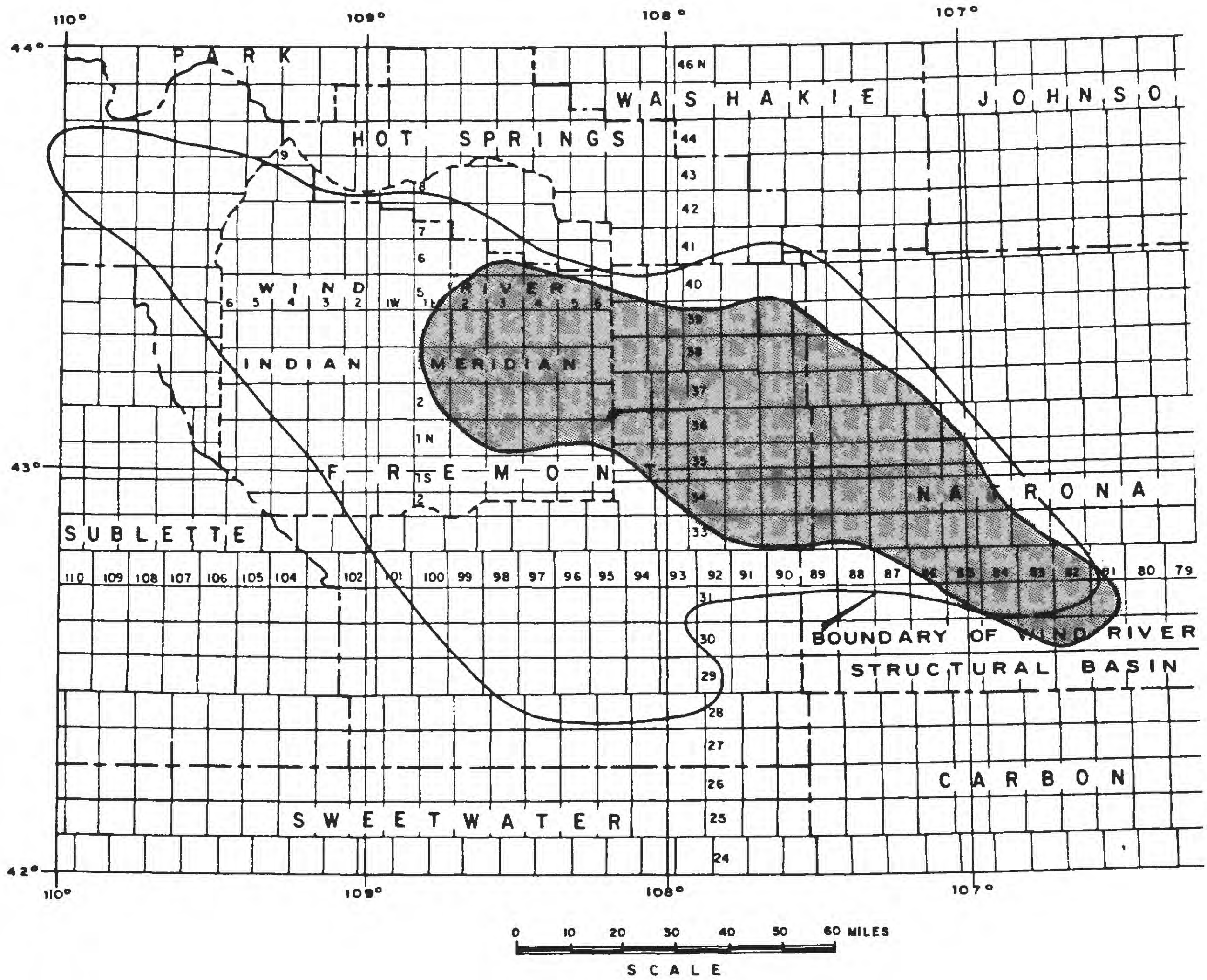

Figure 13. Base map of the Wind River basin showing the limits of the basin center gas play.

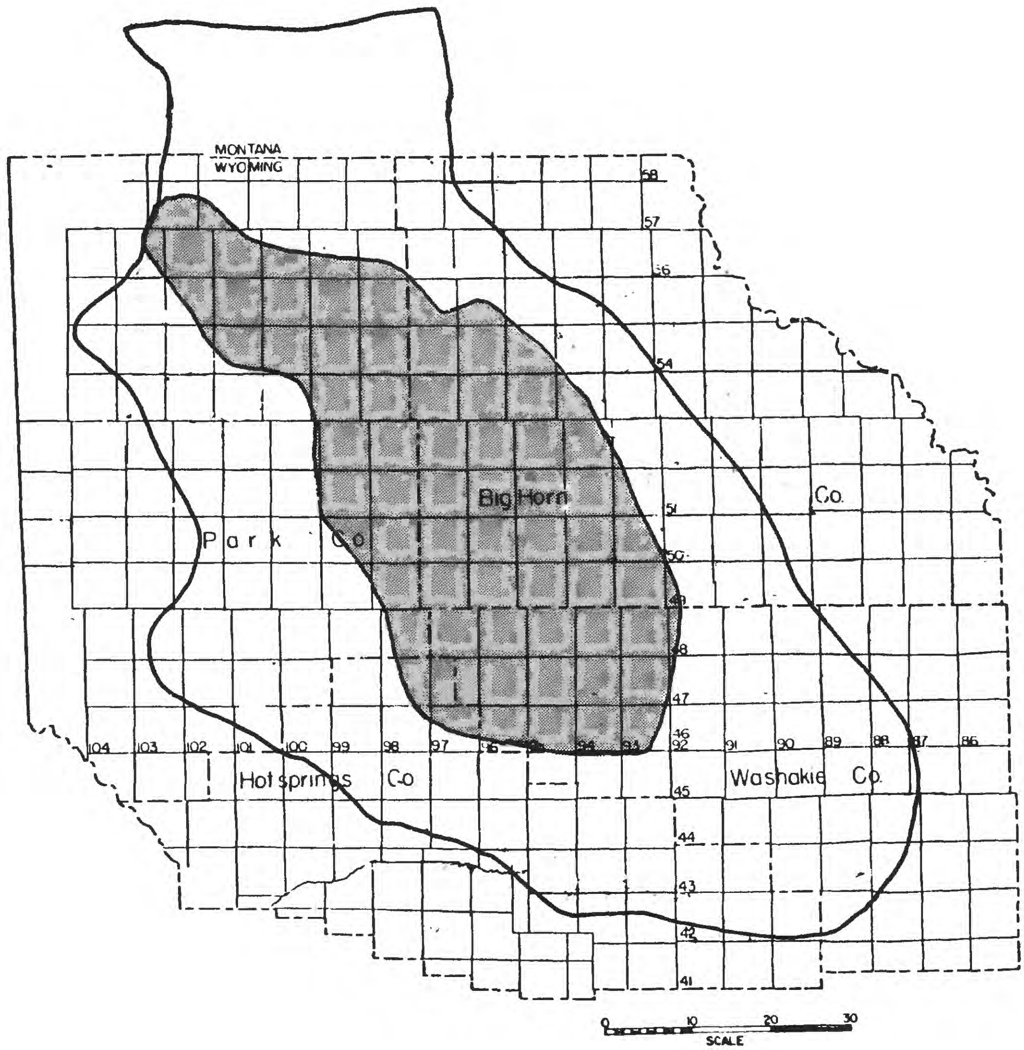

Figure 14. Base map of the Bighorn basin showing the limits of the basin center gas play.

(Gillespie, 1984; Keefer, 1969). Several gas fields in the central and northeastern parts of the Wind River basin have reservoirs that are lenticular sandstone bodies within the Lance and Fort Union Formations.

The Wind River and Indian Meadows Formations of early Eocene age (figure 3) in the Wind River basin consist of varicolored claystone and siltstone interbedded with fine- to coarse-grained, partly conglomeratic sandstone. These formations are thin along the flanks of the basin and thicken to about 9,000 ft in the central, structurally deepest parts where deposition was most continuous (figure 2) and subsidence was greater. The two formations cannot be differentiated in most subsurface sections. Production is from sandstone beds in the lower part of the sequence. In some cases production may actually be from the upper part of the Paleocene Fort Union Formation (Keefer, 1969). By contrast, in the Bighorn basin no significant production has been recorded from Eocene (Wilwood or Wasatch) rocks.

Traps and seals - Traps are developed in this play area as a result of updip pinchouts of porous and permeable reservoir sandstones into impermeable seals of shale. The complex nature of facies relationships in these formations makes exploration for these subtle reservoirs challenging.

Source rocks and geochemistry - An abundance of both organic-rich shale source rocks and porous and permeable sandstone reservoir rocks provides for seemingly favorable conditions for the generation and accumulation of hydrocarbons from the Frontier, Cody, and Mesaverde Formations. However, even though the Cody Shale is very thick, it is probably not very good source rock for petroleum and the record of production of hydrocarbons in this extensive zone of intertonguing of sandstone and shale is not very good. Thermal maturity appears to have been achieved in deeper parts of the basins and most of the sequence is in the thermal gas window.

Dark shales and siltstones in the upper part of the Lance Formation and in the lower part of the Fort Union were probable source rocks of petroleum in the associated lenticular sandstone reservoirs. The Waltman Shale Member of the Fort Union Formation in the Wind River basin is up to 2,500 ft thick and consists of black organic-rich shale and siltstone of lacustrine origin. It covers a large area of the central and northeastern part of the basin. Organic content is reportedly up to to 2.5-6.5% (Keefer, 1969). In spite of the great mass of potential source rock, the amount of hydrocarbons discovered to date in associated sandstone beds has not been significant. The organic matter is composed of minute particles of lignite and coal and may not readily convert to oil and gas under available heat and pressure conditions.

The basal Eocene Wind River and Indian Meadows Formations contain gray to black carbonaceous shale and mudstone that grade downward into upper Fort Union strata. These organic-rich rocks provide a potential source for petroleum in sandstone beds that interfinger laterally toward the basin margins. In some places hydrocarbons may have been derived from source beds in the underlying Fort Union Formation.

Timing and migration - The major hydrocarbon type is gas. The major period of generation of hydrocarbons from source beds was probably during the deposition of shale and sandstone that comprise the Upper Cretaceous and Tertiary. Low amplitude structural movement may have occurred during post-Frontier and pre-Lance deposition, evidenced by rapid lateral facies variability and small-scale local unconformities (Merewether and Cobban, 1986; Merewether, Cobban, and Ryder, 1975). This movement may have influenced the early accumulation of petroleum in stratigraphic traps.

Some structures formed within the play area at a time when overburden stresses were sufficient to cause generation and migration of fluids from source rocks into adjacent lenticular sandstone reservoirs in the upper Lance and lower Fort Union. Entrapment seems to be most favorable in those areas where reservoirs had undergone some structural arching, as discussed previously in the deep basin structure play. However, some fields in the center of the Wind River basin are clearly stratigraphic traps. Flushing of all hydrocarbons formerly trapped in the basin center did not take place. Untapped oil and gas traps related to facies changes, unconformities, zones of pre-Laramide folding, and other features may still be present locally downdip along the flanks of the Wind River and Bighorn basins.

Depth of occurrence - The Mesaverde, Lance, and Tertiary reservoirs are prime drilling objectives in many areas of these basins because they are not as deep as the older reservoirs. However, depth to production in the play area ranges from about 5,000 to in excess of 20,000 ft.

Drilling depth to Lance and Fort Union reservoirs range from about 3,500 to greater than 16,000 ft. Gas and condensate are the principal commodities. Depths to the Wind River and Indian Meadows are generally shallower.

Exploration status - The basin center gas play is a demonstrated play with the level of exploration in the category of lightly explored. Although there are about 14 fields in this play in the Wind River basin, only one can be categorized as having more than 1 MMBOE ultimate recoverable reserves. An estimated 1.5 BCF of nonassociated gas and a little over 1 MMBO have been discovered to date. The play is virtually unexplored in the Bighorn basin.

Sub-Absaroka Play - Bighorn basin:

Play description and type - The sub-Absaroka play is a play in which oil and gas are trapped in anticlines and fault-related structural features formed during the Laramide orogeny and over which Eocene volcanic and volcaniclastic rocks were subsequently deposited (Sundell, 1983; Brittenham and Tadewald, 1985). Structures are on trend with producing structures to the east, which may be representative of the sizes and structural style of the structures and amount of petroleum expected to occur. At the surface of the Absaroka volcanics are numerous oil seeps along fractures, evidence of oil in the play area (Bailey and Sundell, 1986). The limits of this play are shown on figure 15. The eastern limit is defined by the extent of the overlying volcanics, the northern limit defined by the approximate Precambrian contact, and the western limit defined by the approximate position of truncated subcropping strata.

Reservoirs - Based on nearby production from structural traps, the Tensleep has the greatest potential as a hydrocarbon reservoir in this play area. The reservoirs are quartzose sandstones of marginal marine to eolian facies and with very good primary reservoir rock potential. The degree to which secondary cementation has destroyed the primary porosity is highly variable, as indicated

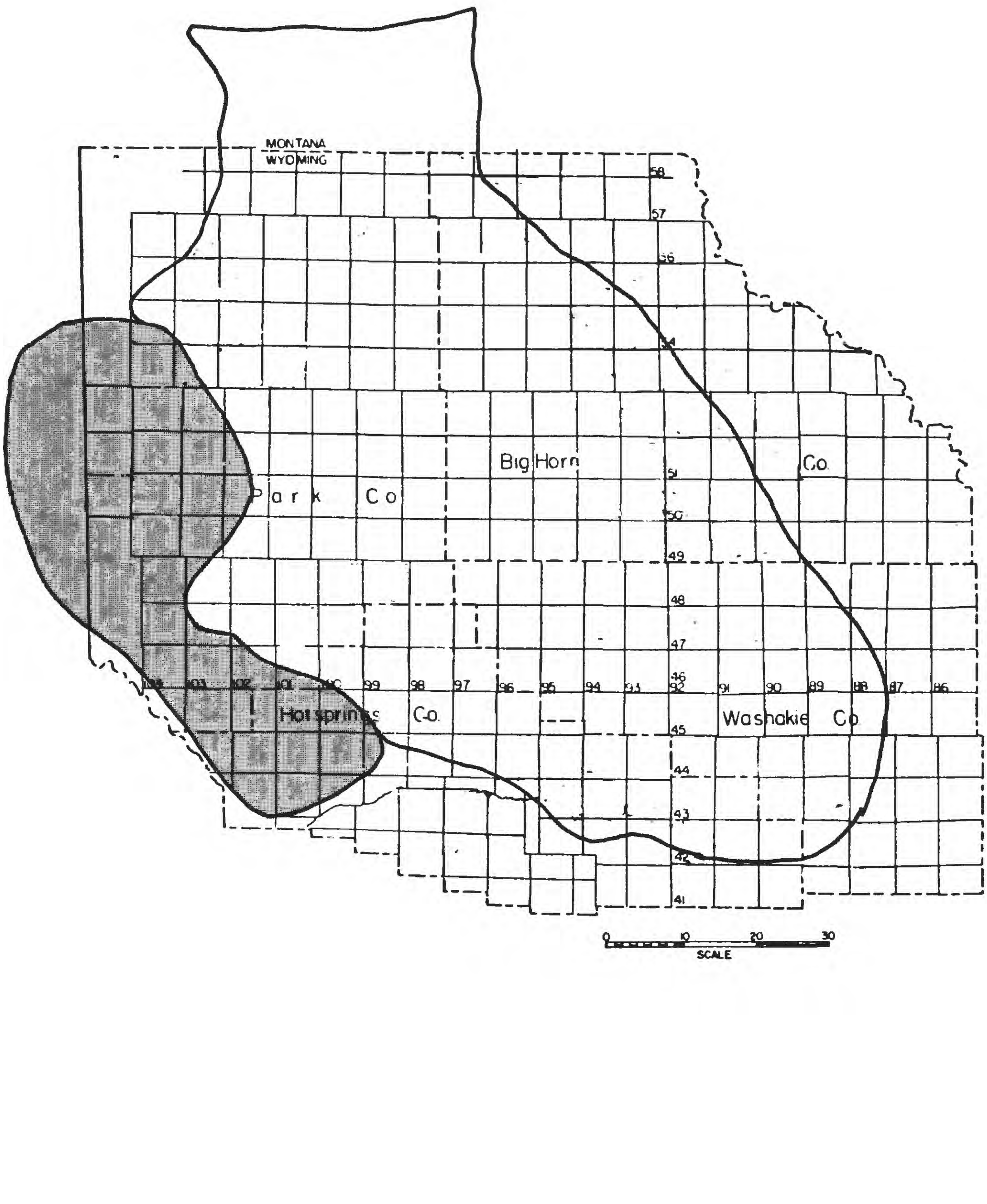

Figure 15. Base map of the Bighorn basin showing the limits of the sub-Absaroka play.

in previous studies by Fox and others (1975). Phosphoria and Madison carbonate reservoirs represent secondary objectives as do Lower Cretaceous sandstones.

Traps and seals - Domes and plunging anticlines could provide the trapping mechanism for hydrocarbons in this play area. In some cases they may be combined with faults and possibly fault traps within the anticlines. Impermeable interbeds of shale could act as seals. The play area was overlain by basaltic volcanic flows after the Laramide Orogeny. Therefore, on-trend structural traps could exist under the volcanics.

Source rocks, geochemistry, timing, and migration - Abundant carbon-rich source rocks exist in Paleozoic and Mesozoic formations within the Bighorn basin and many of them were buried deeply enough even before the Laramide Orogeny to generate hydrocarbons. This play area is near the basin axis where hydrocarbons were most likely being formed earliest. A considerable amount of faulting resulted from the Laramide on this western side of the basin and these faults could easily have been conduits for the migration of hydrocarbons upward until they reached porous and permeable reservoir beds and a trap. Most of the trapping structures formed during the Laramide, so oil may have been redistributed after its early migration or oil may have been generated during the Laramide.

Depth of occurrence - The depth range of the objective interval is difficult to predict considering the rugged topography of the Absaroka Mountains.

Exploration status - The sub-Absaroka Play has not been extensively explored because of the difficulty of exploring under the Absaroka volcanics. The potential for hydrocarbons in this area is uncertain and estimates are highly speculative.

Phosphoria Play - Wind River and Bighorn basins:

Play description and type - This play includes oil in stratigraphic traps along the eastern margin of the carbonate tongue of the Ervay Member of the Phosphoria Formation (Permian). The transition from carbonate rocks of the Phosphoria or Park City Formation eastward to redbeds of the Goose Egg Formation takes place along a north-south line across the east-central part of the Wind River basin (Keefer, 1969). Sheldon (1967) discussed this facies change and noted its importance as a barrier to eastward migration of hydrocarbons through the Park City Formation. This facies transition to the north in the Bighorn basin has resulted in the entrapment of oil in the Cottonwood Creek field (McCaleb and Willingham, 1966; Rogers, 1971; Pedry, 1975). The play area is located in the eastern Bighorn and Wind River basins (figures 16 and 17), where, regionally, Ervay carbonates grade into red shales and evaporites of the Goose Egg Formation, and occupies a transitional position between what are in large part sabkha and supratidal redbeds bordering the seaway and marine carbonates and dark shales to the west.

Reservoirs - Reservoirs are typically dolomitized grainstones and packstones, although locally algal rocks containing fenestrate porosity contribute. Reservoir matrix porosities average about 10%, but are often fracture enhanced.

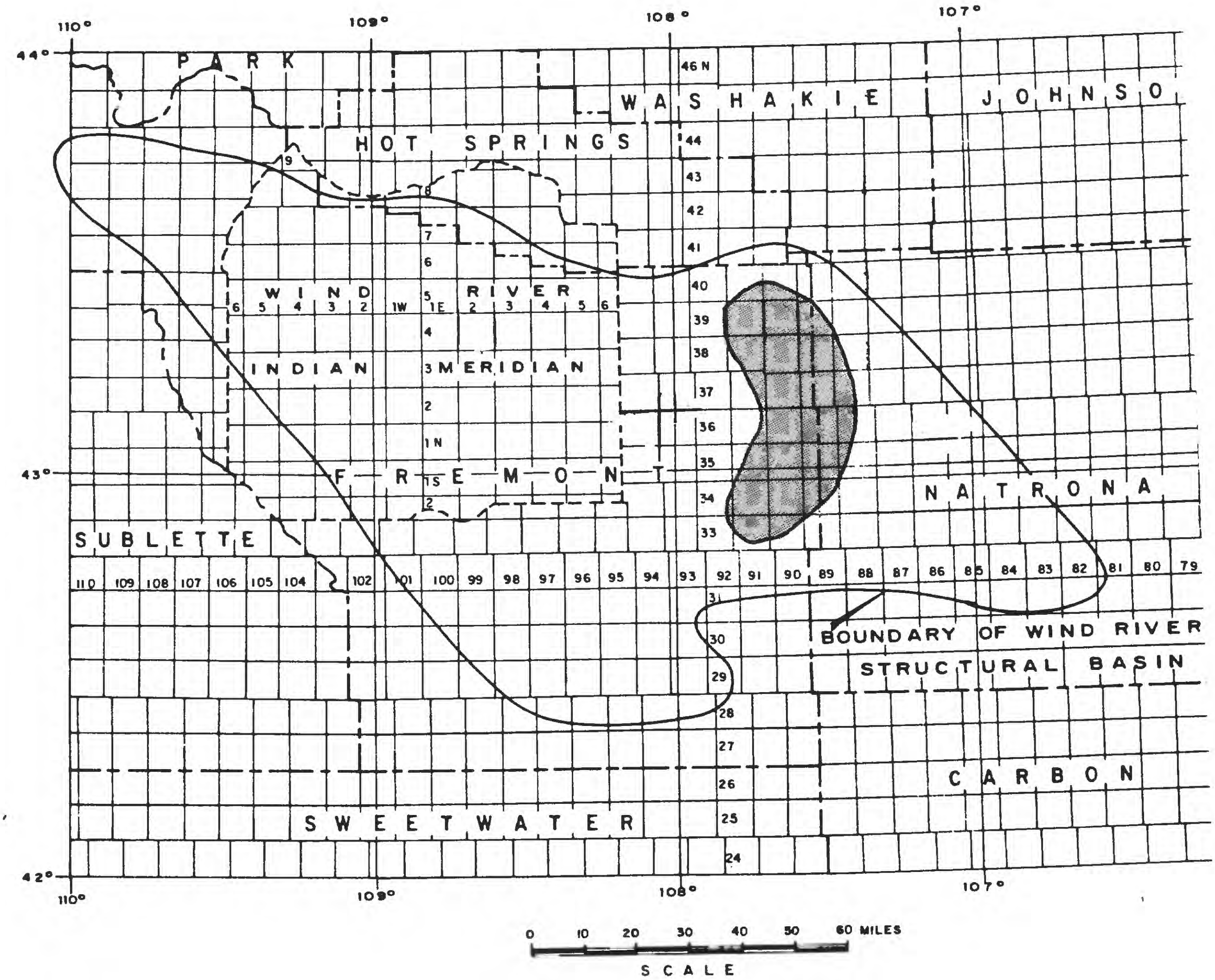

Figure 16. Base map of the Wind River basin showing the limits of the Phosphoria play.

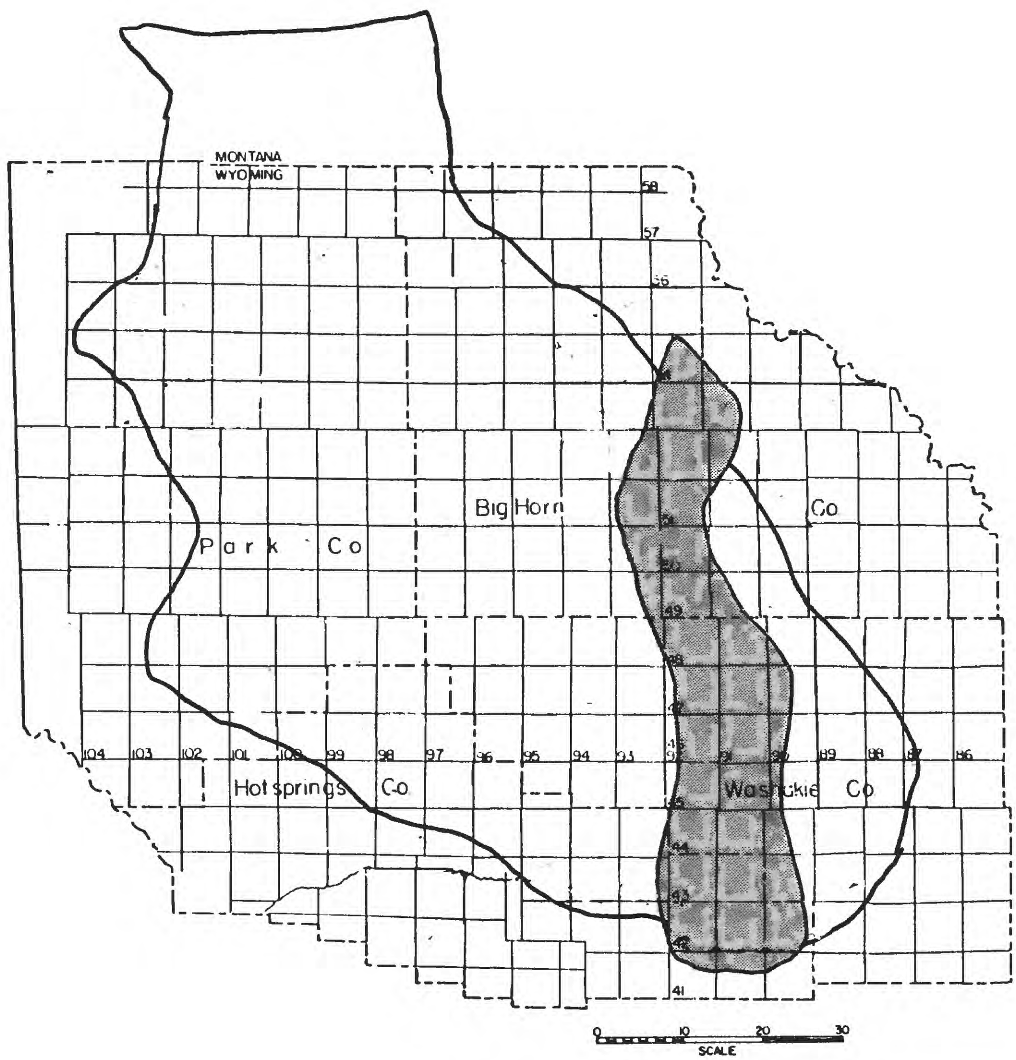

Figure 17. Base map of the Bighorn basin showing the limits of the Phosphoria play.

Traps and seals - Lateral seals for traps are the mud-supported carbonate rocks of the Ervay Member, although the regional trap can be viewed as the facies change from carbonate into redbeds. Oil is trapped locally at Cottonwood Creek near the edge of this carbonate tongue in stratigraphic traps in porous detrital carbonate reservoirs which were deposited within high energy regimes of tidal channels on a coastal flat, sealed updip by tight, fine-grained carbonates of intertidal and supratidal origin (McCaleb and Willingham, 1967; Rogers, 1979). Vertical seals are the fine grained rocks of the overlying Triassic Dinwoody and Chugwater Formations and internal footseals are provided by fine grained redbeds or carbonates.

Source rocks, geochemistry, timing, and migration - Source rocks for this play are the organic-rich Phosphoria shales to the west, which are at a depth in the basin sufficient to have generated oil. Most of the oils are high in sulfur; API gravities range from 19 to 29 degrees.

Exploration status - Exploration of the Phosphoria play was stimulated by the discovery of Cottonwood Creek field in the Bighorn basin in 1953. This field, which is the largest in the play, is in excess of 50 MMBO. Subsequent discoveries have been infrequent and smaller in size, approximately 10 in number. Manderson field, a combination trap, contains substantial sour gas, as does Cottonwood Creek. Exploration in the Wind River basin has resulted in discovery of only 1 or 2 very small accumulations. Undiscovered pools in both basins are estimated at be of small size and, in the Wind River basin, this play was assessed collectively with other occurrences.

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