Energy Exploration and Expectations Deep Within the Rockies: The Greater Green River Basin and Environs

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Introduction

The Greater Green River basin and environs comprise a major segment of the earth's crust within the Central Rocky Mountain province. As defined herein, this region includes about 35,000 square miles (89,600 square kilometers). It is a plexus of five structural basins separated by interbasinal uplifts and surrounded as a unit by several major mountain uplifts (Figure 1).

The margins of this region are not everywhere clearly defined. This region is not a single natural geologic entity. It is a combination of several. However, as a single potential major oil- and gas-producing region, the several parts have many common aspects and problems. The eastern boundary of the region discussed is arbitrarily selected along the crests of several structurally high areas that extend northward from the Sierra Madre of southern Wyoming through the Rawlins uplift and the Separation Flats

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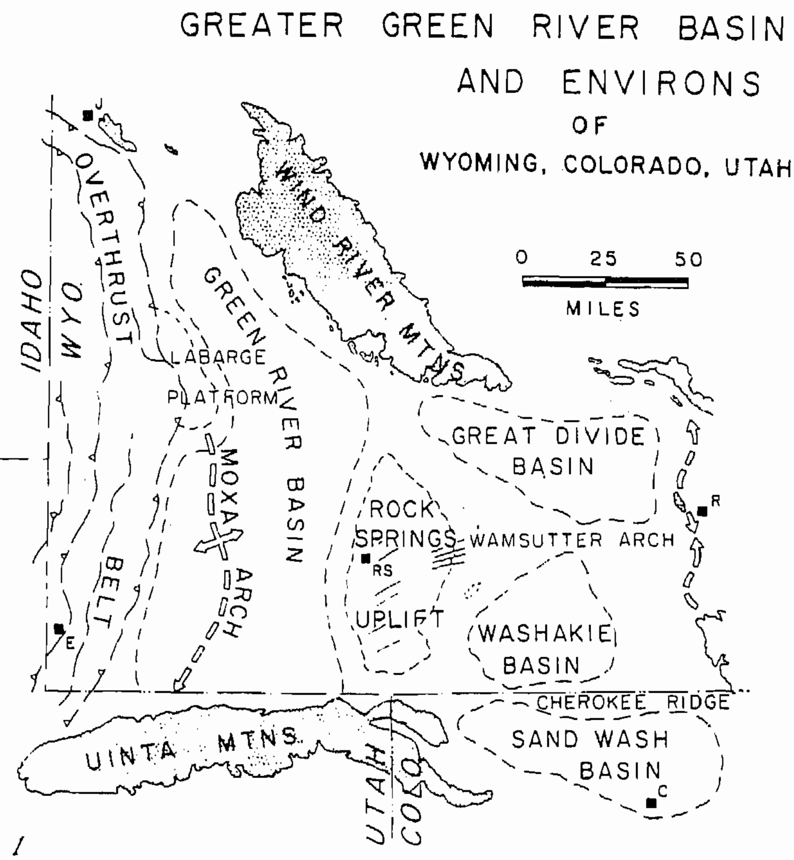

FIG. 1

area to the Wertz-Lost Soldier area adjacent to the south flank of the Sweetwater uplift.

The region is an extremely large storehouse of unexploited fossil fuels and sedimentary minerals. To date, the region has known oil reserves in place in excess of 2 million barrels [1] and known gas reserves in excess of 7 trillion cubic feet.[2] On a volume of sediment basis, there is probably more than 60 percent of the region left to be explored by drilling of an economically rational density.

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[1] Keller and Thomaidis, "Petroleum Potential of Southwestern Wyoming and Adjacent Areas," *Future Petroleum Provinces of the United States—Their Geology and Potential* 656–672 (AAPG, Tulsa, Okla. 1971).

[2] Crews, Barlow, and Haun, "Natural Gas Resources, Green River Basin, Wyoming," *Symposium and Core Seminar on the Geology and Mineral Resources of the Greater Green River Basin* 103–113 (Wyo. Geol. Ass'n, Casper, Wyo. 1973).

Other sedimentary resources include about 16 billion tons of bituminous and subbituminous coal[3] and 8–10 billion barrels of shale oil in the Washakie basin alone in beds greater than 10 feet in thickness with 25 gallons per ton content.[4] Furthermore, more than half the United States' production of trona comes from Eocene deposits in the Green River basin,[5] and there is an extremely large reserve of zeolite minerals in the Eocene strata of the Green River and Washakie basins.[6]

The Greater Green River basin and the contiguous part of the Wyoming overthrust belt have a total sedimentary volume in excess of 100,000 cubic miles. Within much of this volume are favorable oil and gas reservoir strata and oil/gas source rocks. It is estimated that the region could contain a recoverable reserve of 8 billion barrels of oil and 45 trillion cubic feet of gas.

The expectation for new oil and gas discoveries is excellent. The problem is where and how to explore for and develop the reserves that are probably present. This paper discusses why the expectations are good geologically for new discoveries; identifies some of the attendant technical, economic, and political problems facing the exploration industry in this region; and illustrates areas believed to be favorable for future exploration.

History of Exploration and Development

The Greater Green River basin has a long but limited and scattered history of exploration. Relative to oil and gas occurrence, it is noted that the first written account of oil in the region is in the *Mormon Guidebook* of 1848.[7] On that section of the covered-wagon trails between Fort Bridger and Fort Supply to the Salt Lake Valley, the oil seeps in T. 13 and 14 N., R. 119 W., near Aspen Valley, Wyoming, were of importance in lubricating wagon axles.

Geological effort commenced in the late 1800s in parts of the

[3] Glass, "Summary of Coal Mining in Wyoming," *id.* at 115–129.

[4] Roehler, "Mineral Resources in the Washakie Basin, Wyoming, and Sand Wash Basin, Colorado," *id.* at 47–56.

[5] Miller, "Wyoming's Resources—Green River Basin," *id.* at 23–26.

[6] Boles and Surdam, "A Summary of Authigenic Aluminosilicates in the Green River and Wind River Basins of Wyoming," *id.* at 149–162.

[7] Veatch, *Geography and Geology of a Portion of Southwestern Wyoming* (U.S. Geol. Survey Prof. Paper No. 56, 1907).

subject region. Some of the first surveys of the United States Geological Survey and predecessor organizations were made in the Green River basin. These include the 40th Parallel Survey of King and reconnaissance studies of Major Powell. The latter's famous Grand Canyon expedition commenced at Green River, Wyoming, on May 24, 1869.[8]

For the last seventy-five years, the subject region has been the site of many excellent federal and state geologic investigations, university studies, and a multitude of private industry surveys and programs of exploration. The literature on the region is extensive. Relative to oil and gas, attention is called to the many fine contributions by scores of petroleum geologists in the field conference guidebooks and symposia prepared between the late 1940s and the present by the Wyoming Geological Association, the Rocky Mountain Association of Geologists, and the Intermountain Petroleum Geological Association.

This paper contains an extensive list of selected references for those who wish to pursue the geology and the oil and gas potential of the region in greater detail. It is not intended to be a complete bibliography but rather an assembly of references that the writer believes important and which can be used to build a complete bibliography.

Oil and Gas Exploration

Serious exploration for oil and gas in the Greater Green River basin began in 1911 at Spring Valley, Wyoming (Figure 2). Here, several shallow wells were drilled near the previously recorded seeps and dug wells of the late 1800s. Although small wells of a few barrels per day were sometimes completed, no production of any consequence resulted.

The first significant oil discoveries in the region were made in the years 1915 to 1919 on the northeast margin of the Great Divide basin. Here, the well-known surface anticlines of Lost Soldier and Wertz are of major importance. These two fields have produced more than 230 million barrels of oil and 90 billion cubic

[8] Stegner, *Beyond the Hundredth Meridian* 54 (1954).

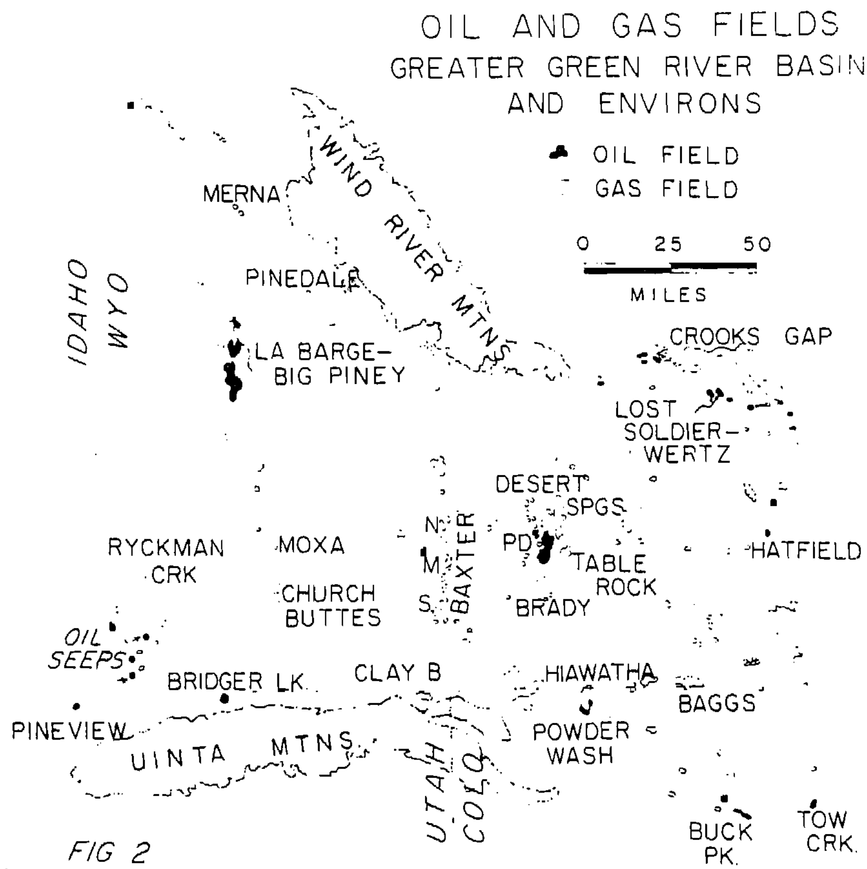

FIG 2

feet of gas.[9] Originally completed in shallow Cretaceous reservoirs, these fields were continually drilled deeper through the years and found production in nearly every reservoir rock between the surface and the granite basement. Production has been obtained from Cretaceous, Jurassic, Triassic, Permian, Pennsylvanian, Mississippian, and Cambrian reservoirs. These fields, originally discovered by Producers and Refiners Corporation, changed ownership during the years and were never fully developed. After AMOCO Production Company acquired them from Pan American Sulfur Corporation, several rigs were busy in 1975 and 1976 drilling in-fill development wells.

[9] Wyoming Oil & Gas Comm'n, *Wyoming Oil and Gas Statistics* 34 and 64 (1975).

Through the 1920s and 1930s, numerous wildcats were drilled across the region on many of the obvious surface anticlines. Many of these resulted in the discovery of natural gas. This phase of exploration resulted in the discovery of the following important fields:

Field	**Year**
South Baxter basin	1922
Hatfield dome	1923
La Barge	1925
North Baxter basin	1926
Clay basin	1927
Powder Wash	1931

A more remote and scattered group of fields at that time can hardly be imagined. Gas, practically no market, lack of pipelines —all discouraged development in those days. Mountain Fuel Supply Company did capitalize on this opportunity to develop an energy source for the Salt Lake Valley, and, in the 1930s commenced a pipeline system to connect the Powder Wash, Clay basin, and Baxter basin fields with the towns of southwest Wyoming and the Salt Lake market in Utah. Subsequently, through the 1930s and 1950s, this company was one of the most active explorers in the region. Its effort, however, was probably largely geared to the immediate market needs, which were relatively small.

One of the most important pulses of development in the region began in the 1950s when the La Barge-Big Piney area, already known for some twenty-five years, became an object of interest to Arthur Belfer. He initiated drilling on a 250,000-acre lease block, which subsequently led to the successful building of Belco Petroleum and the introduction of Pacific Northwest Pipeline Company to the region in 1956.[10] Through the next twenty-two years, development on the La Barge platform proceeded at a slow, steady pace and has resulted in the discovery of more than

[10] McDonald, "Big Piney–La Barge Producing Complex, Sublette and Lincoln Counties, Wyoming," *Symposium and Core Seminar on the Geology and Mineral Resources of the Greater Green River Basin* 57 (Wyo. Geol. Ass'n, Casper, Wyo., 1973).

twenty-five fields. These have yielded more than 1.1 trillion cubic feet of gas and 60 million barrels of oil, making the area the most significant gas-producing area in the State of Wyoming.

Elsewhere in the region during the late 1940s to the 1970s, seismic surveys and field geology led to the discovery of several small oil and gas accumulations. A flurry of drilling in the overthrust belt in the 1950s provided no discoveries. Complicated geology, repetition of section in wells, steep dips, and expensive operations in general turned exploration away from this area. Drilling was largely confined to the margins of the basins, particularly the southern and eastern margins of the Sand Wash basin, the east margin of the Washakie basin, the north margin of the Great Divide basin, and along the east flank of the Rock Springs uplift. One technological milestone occurring in this era was the drilling by Superior Oil Company of a 20,521-foot test at Pacific Creek on the north end of the Rock Springs uplift. This test, completed in 1949, was for several years the deepest well in the world. It was almost twenty-five years ahead of its time in this region.

On the east flank of the Rock Springs uplift, a significant success was found in 1946 on a surface anticline at Table Rock. Gas was found in the Eocene Wasatch Formation, but the discontinuous nature of the sands discouraged further devedopment until a deeper test was drilled in 1954. This test encountered gas sands in the Cretaceous Lewis and Mesaverde formations. This discovery encouraged exploration by others and eventually led to nearby developments in the Desert Springs gas field and the Patrick Draw oil and gas field on the Wamsutter arch in 1958 and 1959, respectively. These discoveries demonstrated the presence of large, stratigraphically trapped oil and gas accumulations in Upper Cretaceous strata of the Great Divide and Washakie basins.

With the exception of Patrick Draw, gas was the principal hydrocarbon found, and development was slow. Patrick Draw demonstrated the presence of 20 million barrels of oil in place in a Cretaceous stratigraphic trap.[11]

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[11] Wyoming Geological Ass'n, *Wyoming Oil and Gas Field Symposium* 542 (Supp. 1957 ed. 1961); Weimer, "Time-Stratigraphic Analysis and Petroleum Accumulations, Patrick Draw Field, Sweetwater County, Wyoming," 50 A.A.P.G. Bull. No. 10, pp. 2150–2175 (1966).

Rounding out the areal distribution of discoveries were several finds of natural gas on the Cherokee ridge between the Sand Wash and Washakie basins along the Wyoming and Colorado boundary, west of Baggs, Wyoming, in 1959 to 1961.

From this period until 1972, activity was at a minimum and scattered except for developments along existing pipelines. With the advent of increased gas prices in 1973, the region began to look better economically to explorers.

Coincident with the increasing gas prices came one of the most significant discoveries ever made in southwest Wyoming—the Brady Unit on the east flank of the Rock Springs uplift. This development proved the existence of deeply buried structure, not manifest in younger strata, with a major oil and gas-condensate reserve in the Cretaceous Frontier and Dakota, Jurassic Nugget,

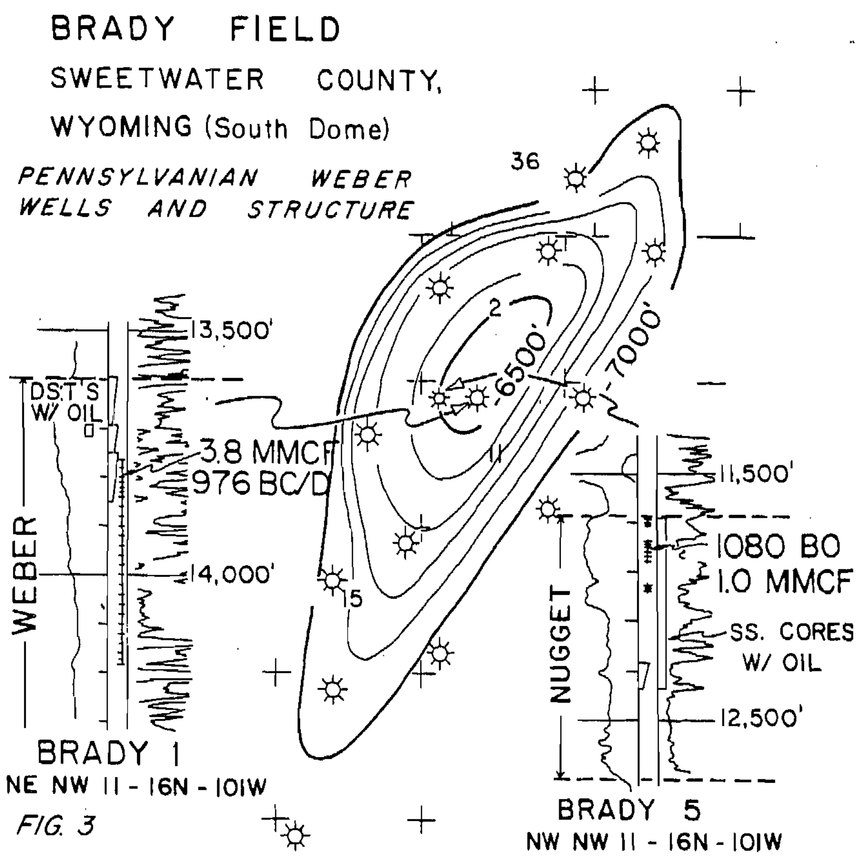

FIG. 3

Permian Phosphoria, and Pennsylvanian Weber reservoirs. In the Weber (Tensleep), this field is filled nearly to the spill point (Figure 3).

This discovery, together with the onset of the energy crisis and a massive exploration effort by AMOCO on Union Pacific Railroad lands, led to a much greater tempo of exploration and interest than the region had ever known previously. This phase has been substantially nourished by further major discoveries at Pineview, Utah, in 1975 and at Ryckman Creek and Yellow Creek, Wyoming, in 1976.

The region is believed about to become a very important contributor to oil and gas production because (1) substantial new discoveries have been made; (2) widespread evidence of oil and gas throughout the region has developed over the last fifty years; (3) there is a vitally important increase in natural gas prices and the demand for the gas; and (4) a very large region exists with untested deep potential in multiple objectives.

Geology

General

The Greater Green River basin and the contiguous part of the Utah-Wyoming-Idaho overthrust belt contain some of the most outstanding geology in North America. The region can be subdivided into several major structural and physiographic areas (Figure 1). These areas include:

Bounding Positives	Interarea Highs	Negative Areas
Overthrust belt	Moxa arch	Green River basin
Wind River Mountains	Rock Springs uplift	Great Divide basin
Sweetwater uplift	Wamsutter arch	Washakie basin
Rawlins uplift	Cherokee ridge	Sand Wash basin
Sierra Madre		
Axial basin uplift		
Uinta Mountains		

The overall region contains a sedimentary rock section ranging from Cambrian to Pleistocene. Nearly every major geologic system except the Silurian is represented someplace within the region.

The aggregate sedimentary section has total thicknesses ranging from nearly 50,000 feet on the Wyoming-Idaho border to some 15,000 feet near Rawlins, Wyoming, on the east.

The sedimentary section is a complex of Paleozoic to Middle Mesozoic miogeosynclinal sediments broken by Laramide tectonic patterns. Coincident with Laramide structural changes came the superposition of a Cretaceous marine and deltaic sequence that transgressed and regressed repeatedly across the region from east to west. Later, all the preceding units were covered by several major thick Tertiary depositional centers of lucustrine and continental aspect. Structurally, the region was also modified by faulting, which in places exhibits outstanding vertical movement of a high-angle reverse nature in Lower Tertiary. This was followed by much normal faulting of lesser magnitude in Middle to Late Tertiary time.

Nearly every geologic factor believed necessary to localize economically significant oil and gas deposits in a variety of stratigraphic and structural traps is present in the region.

Structure

The general structural fabric and style of the region is discussed below. Also, some of the unique and more interesting aspects of the structure are discussed.

As to how the general fabric and style developed, it appears that perhaps there was a general westward movement of the basement beneath the thick sedimentary pile in western Wyoming and eastern Idaho which could have induced a thrust-fault regime of major proportion in the Paleozoic and Mesozoic strata overlying basement. In conjunction with and following this was the dominantly vertical uplift of the Uinta and the Wind River mountains.

The overthrusting along the west produced a complicated anticline and syncline fold belt some 180 miles in length from north to south along the western Wyoming border. Figure 4 is a classic diagram of this structural style taken from the very comprehensive discussion of the overthrust area by Royse et al. in 1975.[12]

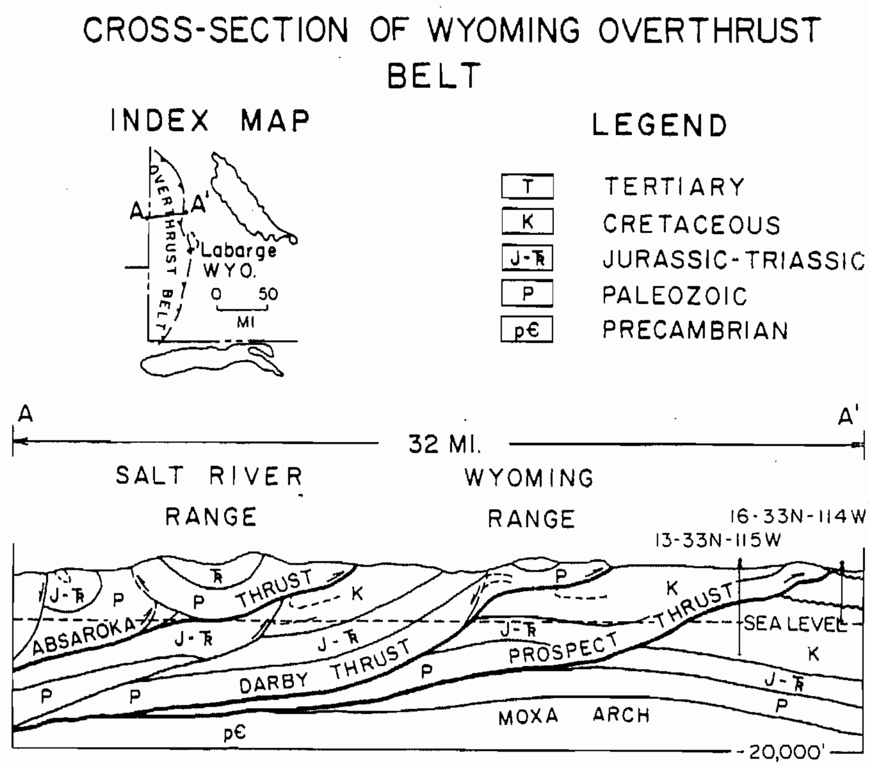

FIG. 4 (AFTER ROYSE ET AL., 1975)

Opinions published by various authors who have mapped and studied the area range from 50 to 150 miles concerning the amount of crustal shortening across the overthrust belt.

There are at least four major north-trending thrust-fault systems within this belt. It does not seem inconsistent with observations, as expressed so ably by Royse et al. that the earlier faults were probably those to the west which rode eastward, "piggy-back," on subsequently younger thrust-fault sheets. The faults involve progressively younger strata from west to east. From west

[12] Royse, Warner, and Reese, "Thrust Belt Structural Geometry and Related Stratigraphic Problems Wyoming–Idaho–Northern Utah," *Symposium on Deep Drilling Frontiers in the Central Rocky Mountains* 41–54 (Rocky Mountain Ass'n Geol. 1975).

to east, four of the more important fault systems are (1) Bannock thrust; (2) Absaroka thrust; (3) Darby thrust; and (4) Prospect thrust.

With respect to oil and gas, this belt has provided literally scores of structural closures, fracture-induced porosity, and permeability, and placed multiple Paleozoic and Mesozoic reservoir objectives within medium to deep drilling range. In 1971, Monley estimated that only sixteen of some sixty-six prominent surface anticlines in the overthrust area had been tested.[13] The economic potential of this area has been clearly demonstrated by discoveries of major size at Pineview, Utah, and Ryckman Creek, Wyoming.

Although the western margin of thrusting is geologically amazing, it is rivaled in geologic interest by the southern and northeastern margins of the region. The structural style elsewhere along the margins of the area is shown on Figure 5. On the south, the Uinta Mountains form one of the largest east-west trending structural features in the United States. This feature is bounded on the north by an anastomosing system of high-angle reverse faults that have an estimated 25,000 to 40,000 feet of vertical displacement on basement.[14]

An equally amazing displacement occurs along the southwest margin of the Wind River Mountains. Gannet Peak, the highest point in Wyoming, exposes crystalline basement at an elevation of 13,785 feet above sea level. Only 20 miles or less to the southwest, drilling and seismic data indicate the presence of the Cretaceous Mesaverde Formation below 12,000 feet, and basement is estimated at 25,000 feet below sea level or deeper. This again suggests a vertical relief on basement approaching 40,000 feet, resulting in part from high-angle reverse faulting.

Figure 5 demonstrates the widespread occurrence of these somewhat unusual large-scale structurally disturbed boundaries of the Greater Green River basin. These margins are still rela-

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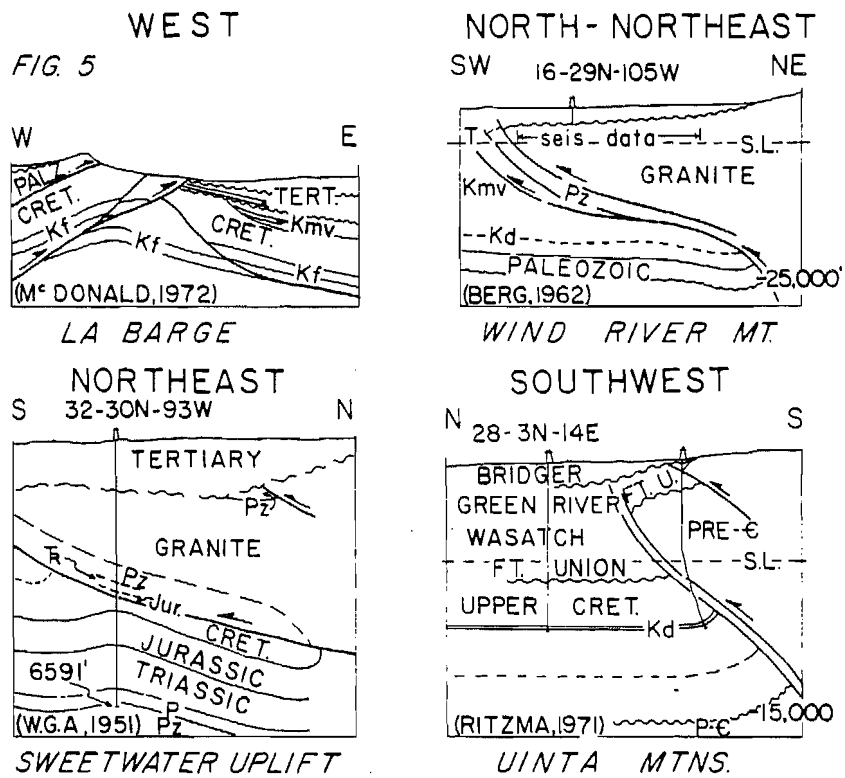
[13] Monley, "Petroleum Potential of Idaho–Wyoming Overthrust Belt," *Future Petroleum Provinces of the United States—Their Geology and Potential* 509–537 (AAPG, Tulsa, Okla. 1971).

[14] Ritzma, "'Faulting on the North Flank of the Uinta Mountains, Utah and Colorado," *Symposium on Wyoming Tectonics and Their Economic Significance* 148 (Wyo. Geol. Ass'n, Casper, Wyo. 1971).



STRUCTURAL STYLE ALONG MARGIN OF GREATER GREEN RIVER BASIN

tively unexplored and could be the site of significant structural traps for future oil and gas discoveries.

Within the more basinal part of the subject region, there are three major north-south structural ridges or uplifts. These uplifts essentially traverse the north-south width of the region. They are progressively deeper in the crust structurally from east to west across the region. From east to west these structurally positive areas are the Rawlins uplift, which brings basement rocks to the surface at an elevation of about 7,000 feet above sea level; the Rock Springs uplift, which has basement at an estimated depth of 1,600 feet below sea level at South Baxter basin on the crest of the uplift; and the Moxa arch, with basement at an estimated 14,000 feet below sea level at Church Buttes.

The Rawlins uplift is considered the east boundary of the region under discussion. It is asymmetrical, with a steep west flank accompanied by a zone of steep high-angle reverse faulting. About 5,000 feet of vertical movement has occurred. A later stage of normal faulting is also present, which in some places was coincident with the planes of earlier reserse faults.[15] Major oil and gas accumulation is found at Wertz and Lost Soldier on the northward extension of this trend.

One hundred miles west of Rawlins lies the Rock Springs uplift. This structure is one of the United States' larger closed anticlines in Cretaceous rocks. The closed area is some 75 miles long and 30 miles wide, covering about 1,500 square miles. There is more than 9,000 feet of vertical closure. Allah was unkind, though, and Wyoming did not receive its Ghawar! Structurally, it had the chance, but, unfortunately, the time of development was perhaps too late. By the time the trap was formed, it is possible that migrating hydrocarbons had already gone east.

This uplift has nearly a dozen small oil and gas fields along its crestal trace. This uplift area was the site of important stratigraphic development in the Cretaceous System that localized the accumulation of several stratigraphically controlled oil and gas fields on its eastern flank (Patrick Draw, Desert Springs).

The major Brady field was found on a fault-related closure on the southeast flank of the Rock Springs uplift in 1973. This structure dies out upwards and is not present in uppermost Cretaceous strata. It is possible that other deep prospects might occur elsewhere around the periphery of the uplift.

The deeper Moxa arch is still little explored on the southern and deepest part of the trend. It is a structural element of significance which might have acted as an abutment and determined in part the eastward extent of the overthrust belt. Its economic importance as a focal point for oil and gas accumulation is demonstrated by the more than one trillion cubic feet of gas and 60 million barrels of oil already produced from the La Barge-Big Piney area on the north end of the arch.

On the south end of the arch, deep potential is demonstrated by Lower Cretaceous and Pennsylvanian reservoirs at Church

[15] Barlow, "Structure of the Rawlins Uplift, Carbon County, Wyoming," *Wyo. Geol. Ass'n 10th Field Conference Guidebook* 138–139 (1955).

Buttes and Moxa. Figure 6 illustrates the presence of stratigraphic wedging on the east flank of the arch. This suggests future stratigraphic-structural possibilities to explore.

SEISMIC CROSS-SECTION OF THE MOXA ARCH, WYOMING

(SECTION FROM STERNS ET AL. 1975)

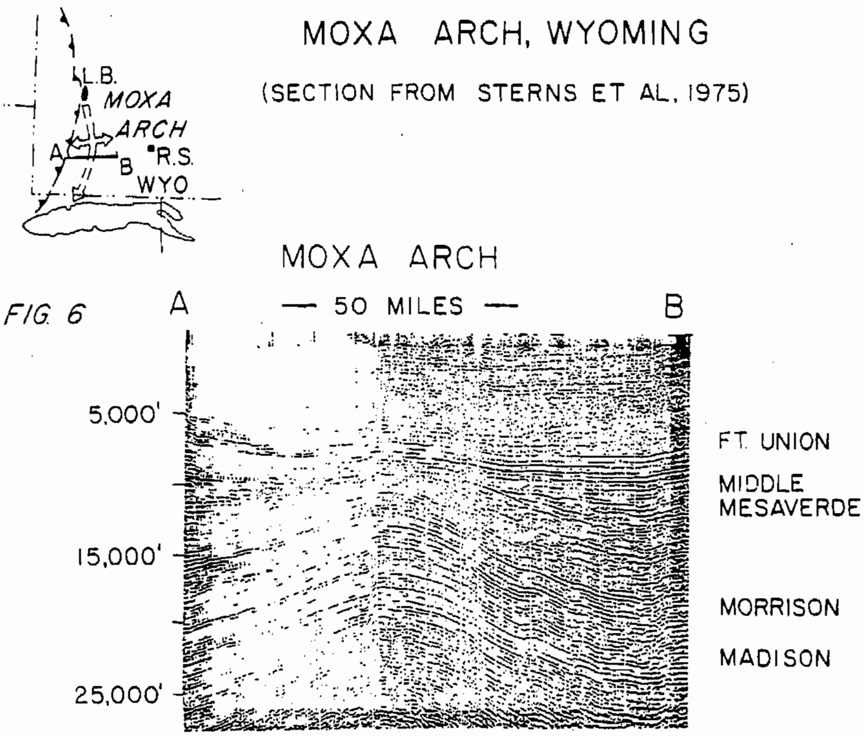


FIG. 6

In a region of 35,000 square miles with ample evidence of major fault movements with tremendous vertical and horizontal displacements and attendant stress and strain regimes, it is obvious that hundreds of structural traps have been formed. It is equally evident that with 100 years of surface geologists having moved through the region, most of the obvious structures expressed in surface strata have been found.

However, with major discoveries having been made in the last three years in deeper and more complex traps mapped in part by seismic methods, it is apparent that much future effort needs to be spent in search of deep prospects. In the 10,000- to 25,000-foot depth levels below the surface, the region probably has many structural traps that have not been tested as well as many others, the existence of which is not yet known.

Stratigraphy

A generalized stratigraphic column is given on Figure 7. This shows the general rock formation names that are in current use between the overthrust belt of Wyoming and the Rawlins uplift.

SIMPLIFIED STRATIGRAPHIC CHART

OF SELECTED ROCK UNITS & OIL/GAS PRODUCING ZONES

	OVERTHRUST BELT	GREATER GREEN RIVER BASIN
EOCENE		GREEN RIVER
		WASATCH
PALEOCENE	EVANSTON	FT. UNION
UPPER CRETACEOUS		LANCE
		LEWIS
	ADAVILLE	MESAVERDE GROUP
	HILLIARD	NIOBRARA
	FRONTIER	FRONTIER
LOWER CRETACEOUS	ASPEN	MOWRY
	BEAR RIVER	DAKOTA
JURASSIC		MORRISON
	TWIN CREEK	
	NUGGET	NUGGET
TRIASSIC	WOODSIDE	
PERMIAN	PHOSPHORIA	PHOSPHORIA
PENNSYLVANIAN	WELLS/ WEBER	WEBER/ TENSLEEP
MISSISSIPPIAN	BRAZER MADISON	MADISON
ORDOVICIAN	BIGHORN	BIGHORN
CAMBRIAN	GALLATIN FLATHEAD	FLATHEAD

FIG. 7

The stratigraphy of the region has been discussed in numerous papers by dozens of authors. For more detailed discussions of many aspects of the stratigraphy, the reader is referred to the many geological field conference guidebooks mentioned previously and listed in the selected references. Other significant studies are those of Armstrong and Oriel[16] and Asquith.[17]

Only those aspects of stratigraphy will be discussed here that relate to some known, currently important oil- and gas-bearing reservoirs of the region. These include certain Mississippian, Pennsylvanian, Jurassic, Cretaceous, and Tertiary rocks. It is realized that petroleum reservoirs can and do occur in rocks of other ages. Oil has even been found in Cambrian sandstones at Lost Soldier, and, although oil is not necessarily indigenous to the Cambrian, its discovery there serves to illustrate that reservoir rocks of any age in the region might have had the opportunity to be loaded with hydrocarbons by migration from younger rocks if the geologic events and timing enabled this to occur.

Mississippian

Figure 8 illustrates the distribution, thickness, and oil and gas shows that have been found in the Mississippian Madison Limestone and equivalent strata in southwest Wyoming and continuous areas.

The Madison is a fossiliferous, normal marine limestone which exhibits a variety of facies with different porosity and permeability characteristics. It produces oil and gas at Lost Soldier and, more importantly, has recently demonstrated a large gas potential in an ultradeep test at Table Rock field on the east flank of the Rock Springs uplift. The Texaco Table Rock Unit 19 well yielded gas through perforations from the interval 18,020 to 18,368 feet at a calculated absolute open flow potential of 44 million cubic feet per day.

Elsewhere, shows of largely noncombustible gas have been encountered in the Madison at Church Buttes and Tip Top fields on the Moxa arch and La Barge platform, respectively.

The Madison varies in thickness from 1,500 feet on the Wyoming-Idaho border to a wedge edge along the Sierra Madre south

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[16] Armstrong and Oriel, "Tectonic Development of Idaho–Wyoming Thrust Belt," 49 A.A.P.G. Bull. 1847–1866 (1965).

[17] Asquith, "Depositional Topography and Major Marine Environments, Late Cretaceous, Wyoming," 54 A.A.P.G. Bull. 1184–1224 (1970); and Asquith, "Sedimentary Models, Cycles, and Deltas, Upper Cretaceous, Wyoming," 58 A.A.P.G. Bull. 2274–2283 (1974).

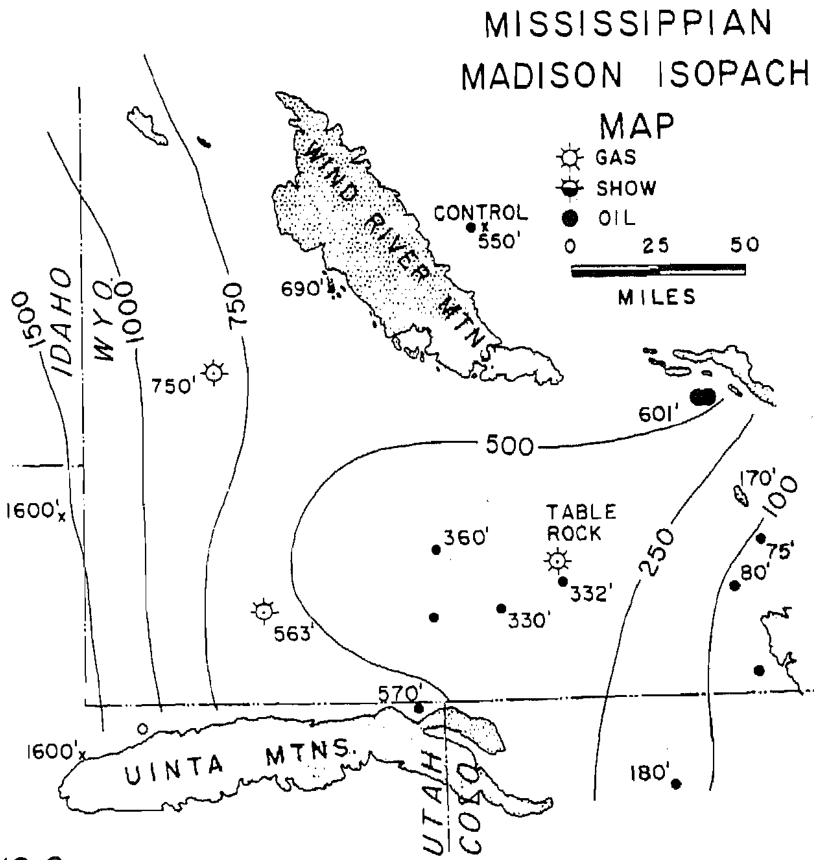

FIG. 8

of Rawlins. It affords a good reservoir potential over a broad region. It should always be tested by deep wells, particularly if located on structural prospects.

Pennsylvanian

The Pennsylvanian System in the subject region consists of a basal sequence of interbedded carbonates and clastics ranging up to a few hundred feet in thickness (the Morgan Formation). This is overlain by a massive quartzose sandstone unit known as the Weber or Tensleep Formation. Both of these major stratigraphic sequences produce oil and gas in the Greater Green River basin. The Morgan produces at Church Buttes, Moxa, and Bruff on the Moxa arch.

South of the Uinta Mountains at Rangely, Colorado, one of the largest oil fields in the United States occurs in the Weber Sandstone (750 million barrels ultimate recovery by primary and secondary methods). In the Greater Green River basin, the Weber produces oil and gas at Buck Peak, Colorado, in the Sand Wash basin. It has long been a major reservoir at Lost Soldier and Wertz fields and has yielded some oil at Hatfield dome—all on the Rawlins uplift trend.

Of great importance in the subject region is the discovery of a major gas-condensate and oil reservoir in the Weber at Brady field on the east flank of the Rock Springs uplift. Figure 3 illustrates the structural configuration of the Weber Sandstone on the south dome of Brady field and the electric log character of the producing reservoir.

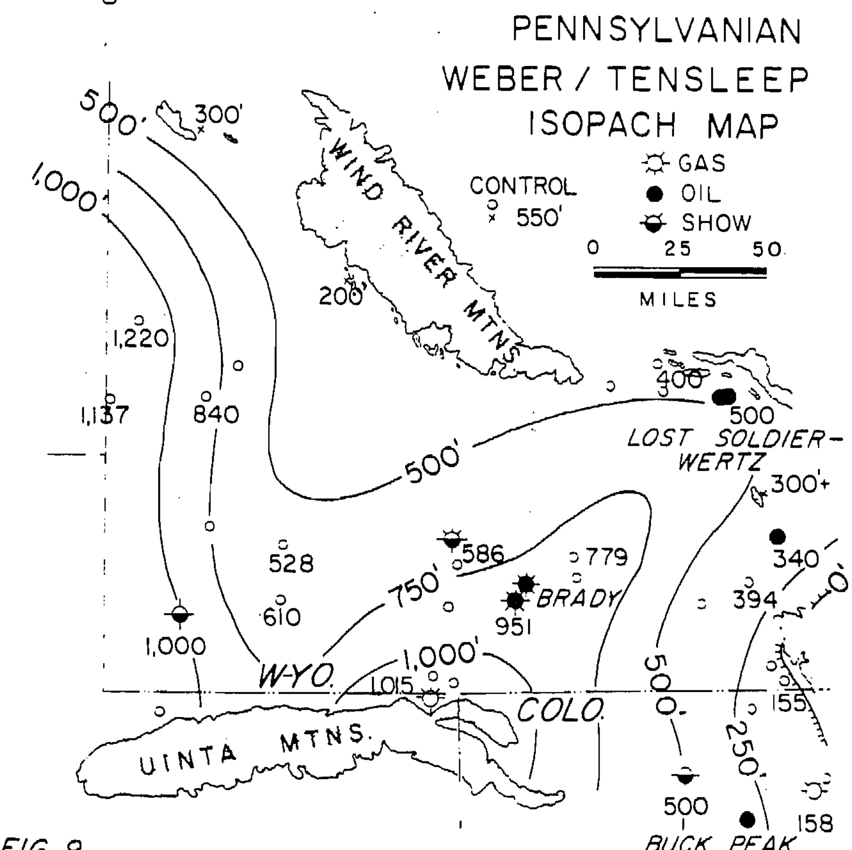

FIG. 9

Figure 9 illustrates the areal distribution, thickness, and areas of oil and gas production and shows in the Weber Formation in the Greater Green River basin and contiguous areas. The Weber varies in thickness from about 1,000 feet along the west and south boundary of the Green River basin to a wedge edge along the flank of the Sierra Madre south of Rawlins.

The Weber provides an extremely thick quartz sandstone reservoir. It can contain and produce oil and gas in very large quantities. Over much of the Greater Green River basin, the formation either has not been tested in proper geologic settings or has not been tested at all. It is an excellent objective in any well that is scheduled to test deep in the geologic section, particularly on structure.

Jurassic

Figure 10 illustrates the thickness, distribution, and oil and gas shows and production of the Jurassic Nugget Sandstone in the Greater Green River basin and adjacent areas.

The Nugget extends across the entire region. It ranges in thickness from more than 1,100 feet at Pineview, Utah, to less than 100 feet east of Rawlins.

Throughout this region, the Nugget is a porous and permeable unit. With the recent discoveries of major oil and gas accumulations at Pineview and at Ryckman Creek and Yellow Creek, Wyoming, together with major oil reserves in the Nugget at Brady field and long-known production at Lost Soldier and Wertz, the Nugget is clearly demonstrated to be one of the best reservoirs with good potential in the Greater Green River basin.

Cretaceous

Cretaceous strata occur throughout the subject region. Thicknesses range from some 20,000 feet in the west and adjacent to the overthrust belt to some 10,000 feet along the Rawlins uplift.

The framework of deposition for Cretaceous rocks is considerably different from that which prevailed during most of preceding geologic time. Paleozoic through Jurassic represented a time of miogeosynclinal shelf deposits in which transgression was from west to east. In Cretaceous, the sedimentary pile to the west of Wyoming commenced to be uplifted. Concurrently, there was a broad epi-continental seaway extending from the Gulf of Mexico to the Arctic.

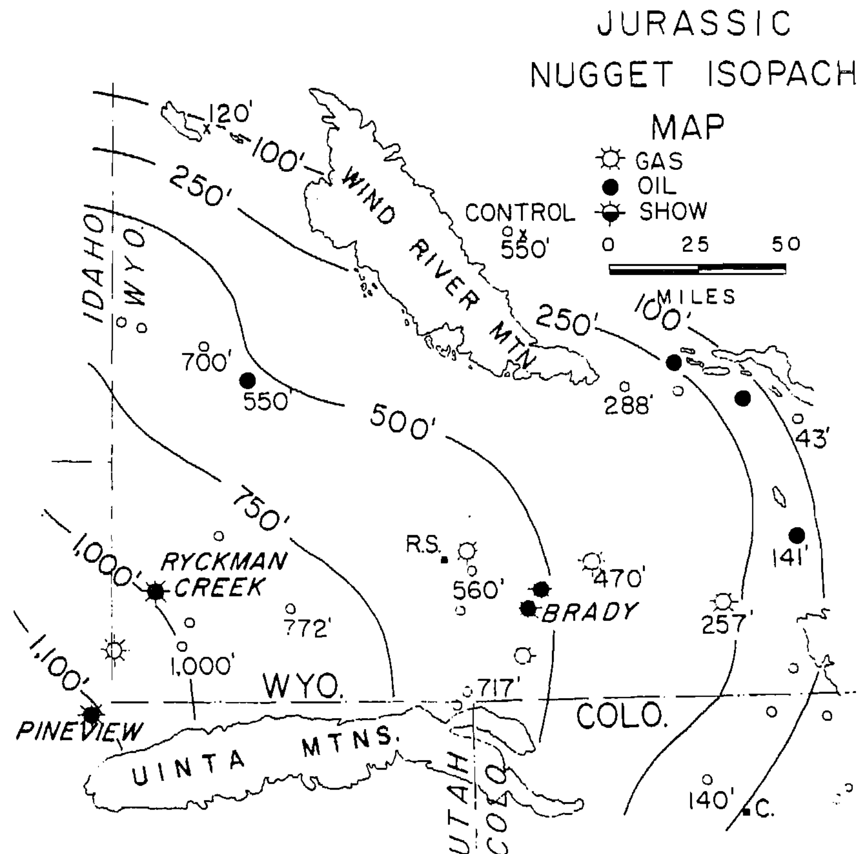

FIG. 10

Along the west margin of the seaway, there were transgressions from east to west across Wyoming and Colorado. Within this framework, continental deposits formed to the west and varied progressively eastward into coastal plain, deltaic marginal marine, and open marine deposits.

Progressively through Upper Cretaceous, there were three major periods of delta formation of significance to oil and gas accumulation in the Greater Green River basin. These major cycles are represented by three important areas of deltaic sedimentation that migrated progressively eastward across the subject region. The three major delta systems are herein called the Frontier, Mesaverde, and Lewis deltas (Figure 11).

A diagrammatic cross section (Figure 12) illustrates the transgressions and regressions represented by Cretaceous rock units,

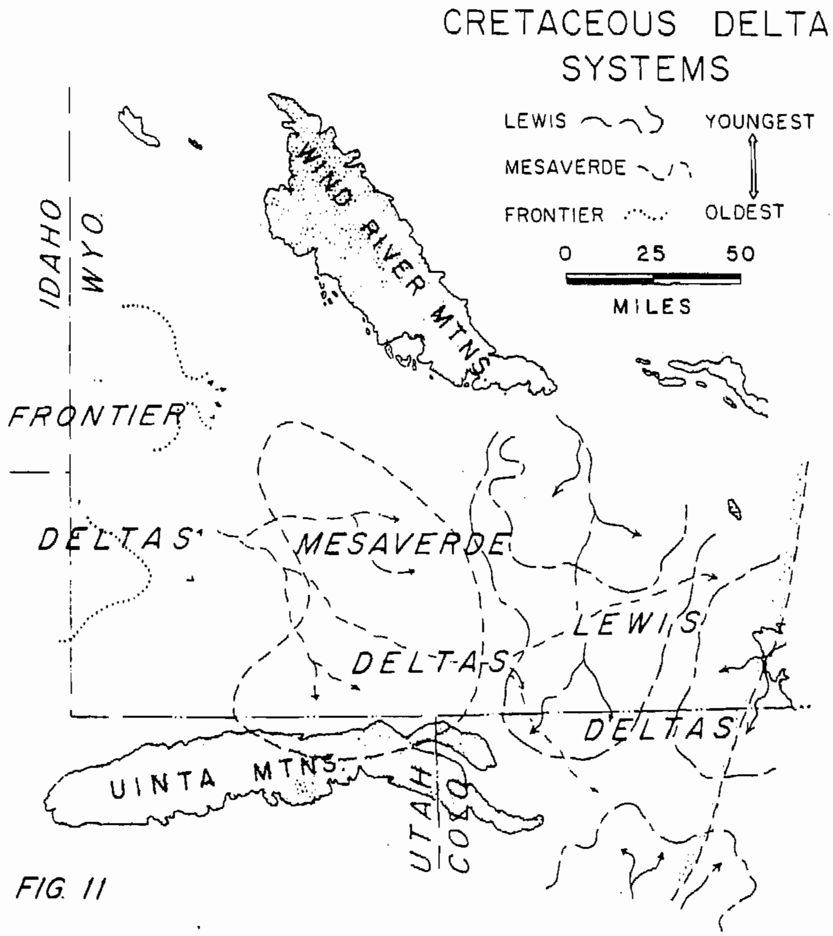

FIG. 11

formation nomenclature and relationships, and the position of various oil and gas accumulations within the Cretaceous System in the Greater Green River basin.

Cretaceous rocks produce oil and gas throughout the subject region. Unlike some of the older stratigraphic units (Madison, Weber, and Nugget), the Cretaceous strata produce from a multitude of stratigraphic as well as structural traps. These rocks provide a very large potential for future oil and gas fields.

Although not discussed herein, the Lower Cretaceous Dakota Sandstone and the Upper Cretaceous Mowry Shale and Niobrara formations can yield oil and gas in commercial quantities. The Dakota is an important reservoir at Bridger Lake and Church

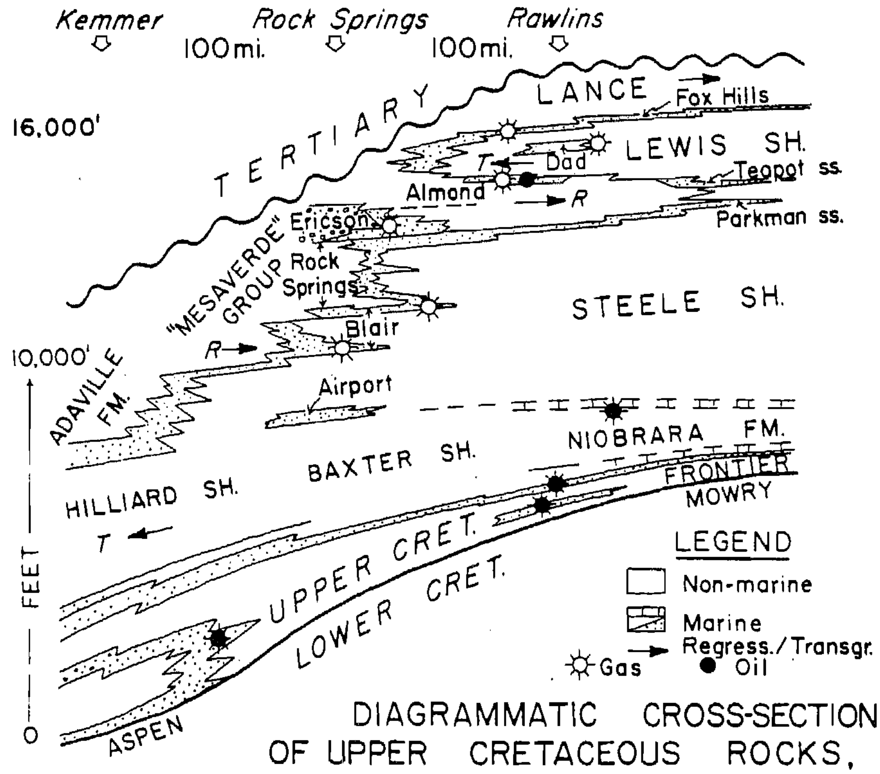

FIG. 12 DIAGRAMMATIC CROSS-SECTION OF UPPER CRETACEOUS ROCKS, GREATER GREEN RIVER BASIN

(After Weimer, 1960 & Asquith, 1970)

Buttes on the Moxa arch, on the crest of the Rock Springs uplift, at Brady arch on the east flank of the Rock Springs uplift, and along the margins of the Sand Wash, Washakie, and Great Divide basins.

Tertiary

The early Tertiary, Paleocene Fort Union, and Evanston formations have an areal distribution much like the Upper Cretaceous. This rock unit varies in thickness from absence on the edge of the Sand Wash, Washakie, and Great Divide basins, where the Fort Union crops out, to more than 5,000 feet in the deeper parts of the Green River basin near Pinedale.

These formations are an alternating sequence of sandstones and shales formed in dominantly continental, lucustrine, and paludal environments. Paleocene sandstones produce oil and gas on the La Barge platform in the Green River basin and at Hiawatha and Powder Wash in the Washakie basin, and there is a very isolated occurrence of oil at Continental Divide field in the Great Divide basin.

Overlying the Paleocene, a somewhat different cycle of sedimentation, characterized by continental and marginal lacustrine (Wasatch) and lucustrine (Green River) sediments, occupies the central portions of the Green River, Washakie, Great Divide, and Sand Wash basins.

The Wasatch Formation produces gas in the Washakie and Sand Wash basins, as at Table Rock and Powder Wash, respectively. Although not immediately available because of several economic, environmental, and technical reasons, it is important to note that the Green River oil shales of the Washakie and Powder Wash basins have an estimated 8 to 10 billion barrels of shale oil that might one day be recoverable.[18]

Oil and Gas Fields

Some of the recent major oil and gas discoveries of the region are discussed below. Comment is also made relative to certain other previous discoveries that demonstrate deep potential in the basins discussed.

Recent Discoveries

Brady Unit

The Brady field was discovered in late 1973. It contains multiple pay zones, including the Lower Cretaceous Dakota Sandstone and Jurassic Entrada Sandstone, which yield gas; oil in the Jurassic Nugget Sandstone; and gas condensate in the Permian Phosphoria Formation and Weber Formation of Pennsylvanian. It is interesting to note that this field, containing in excess of 385 million barrels of oil and perhaps several hundred billion cubic feet of gas below 10,000 feet, was discovered by a well that is a 160-acre offset to the Mountain Fuel Supply Company's Jack Knife Springs 1 well, completed as an Upper Cretaceous gas well and terminated at a depth of 6,630 feet in 1960.

[18] See N. 4 *supra.*

Figure 3 illustrates the south dome of the Brady structure as mapped on top of the Pennsylvanian Weber Sandstone. This culmination is reported to have about 800 feet of vertical closure and a hydrocarbon column of 791 feet in the Weber Sandstone.[19]

It is estimated by the writer that this field probably contains more than 385 million barrels of recoverable oil and several hundred billion cubic feet of gas.

Pineview

This Utah discovery, the site of a major oil and gas field which had eight wells completed as of February 1977, was the location of the first production of consequence ever found in the overthrust belt. Production comes from the Jurassic Nugget Sandstone and in a few wells from the overlying Twin Creek Limestone. The discovery well was completed in January 1975.

The field has recently been described by Maher.[20] The discovery well was drilled as a follow-up to a 1972 wildcat that had good shows in the Nugget Sandstone at a depth of 10,220 feet. The difficulty and ensuing misconceptions that can result from seismic work and geological interpretations based thereon are clearly illustrated by comparing the published reports of Maher [21] and Loucks.[22]

Drilling, to date, does not indicate that the Pineview structure is a normal anticline or even a recumbent fold. Rather, the trap seems to be where the Twin Creek and Nugget are part of a thrust sheet. There is probably some warping of this sheet, but the trap itself is apparently closed updip to the east, where the reservoir rocks are in contact with impervious Cretaceous shales. Cretaceous shales in the subthrust block are possibly the oil source, too.

In-place reserves of the field are estimated at more than 100

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[19] Brock and Nicolaysen, "Geology of the Brady Unit, Sweetwater County, Wyoming," *Symposium on Deep Drilling Frontiers in Central Rocky Mountains* 226 (Rocky Mountain Ass'n Geologists 1975).

[20] Maher, "Geology of the Pineview Area, Utah" (Rocky Mountain Ass'n Geologists, being published).

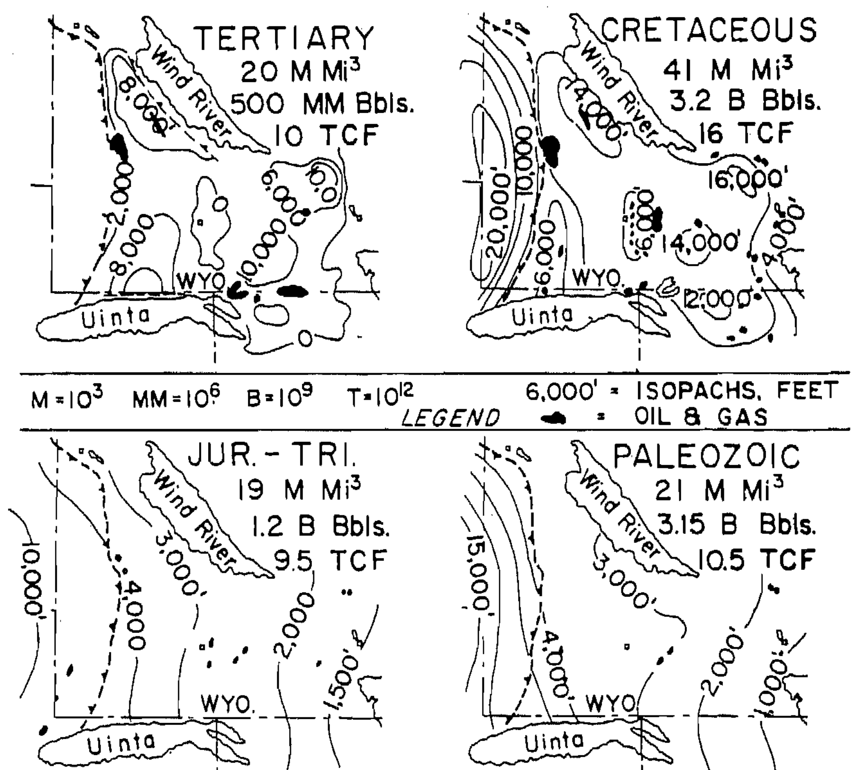
[21] *Ibid.*

[22] Loucks, "The Search for Pineview Field, Summit County Utah," *Symposium on Deep Drilling Frontiers in Central Rocky Mountains* 255–264 (Rocky Mountain Ass'n Geologists 1975).

million barrels of oil and up to 100 billion cubic feet of gas. The American Quasar et al. discovery well flowed oil from the Jurassic Nugget Sandstone through perforations from within the interval 9,928 to 10,036 feet at a rate of 540 barrels per day. A recent test, American Quasar et al. 10–1 Bingham completed dually, flowed 840 barrels of oil per day from the Twin Creek Limestone and the underlying Nugget. The oil column in the Nugget Sandstone at Pineview may exceed 1,000 feet.

Ryckman Creek

Lying forty miles northeast of Pineview in the Wyoming portion of the overthrust belt, the AMOCO Production Champlin 224 Amocol-A discovery well at Ryckman Creek tends to confirm the existence of a very prospective oil and gas province (Figure 13).



POTENTIAL OIL AND GAS RESERVES,
FIG. 13 GREATER GREEN RIVER BASIN

Unlike Pineview, Ryckman Creek appears to be a better defined linear northeast trending faulted recumbent fold. Logs indicate that the producing Jurassic Nugget Sandstone was penetrated at a depth of 7,450 feet. Porosity logs indicate an average porosity of about 14 percent in the Nugget. The gas-condensate oil interface is at about 7,760 feet and the oil-water contact is at about 7,933 feet. Approximately 483 feet of hydrocarbon column is indicated.

Drill stem tests in the upper part of the Nugget flowed gas at the rates of 4.9 million and 5.8 million cubic feet per day. Subsequently, the well was completed through perforations at 7,804 to 7,808 and 7,860 to 7,880 feet, flowing oil at a rate of 280 barrels per day and 310,000 cubic feet of gas per day. It is estimated that the Ryckman Creek structure has in excess of 600 billion cubic feet of gas in place and perhaps more than 100 million barrels of oil.

Other Significant Occurrences

Earlier discoveries of oil and gas that point to the future potential of the Greater Green River basin in deep objectives include two that are fairly recent and one undeveloped area found in 1955.

Moxa-Bruff

The Moxa-Bruff area is in the deep part of the Green River basin (Figure 2) about midway on the Moxa arch anticlinal trend that extends from La Barge on the north to the vicinity of Bridger Lake oil field, Utah, adjacent to the Uinta Mountains. This trend is about 90 miles in length.

The Moxa arch area has been the site of recent deep drilling to evaluate gas reserves in the Cretaceous Frontier Formation. This area is not newly discovered. The Texaco 1 Unit, NE SE 22, T. 19 N., R. 112 W., was completed in November 1961 in the Frontier Sandstone. This test flowed gas through perforations between 11,416 and 11,456 feet at the rate of 1,300,000 cubic feet per day. More recently, in 1973, Mountain Fuel completed the Bruff 1 in SW SW 22, T. 19 N., R. 112 W., flowing from perforations in the Pennsylvanian Morgan Formation (below the Weber) between 17,295 and 17,345 feet at the rate of 360 barrels of oil per day and 1,379,000 cubic feet of gas per day.

Table Rock

In July 1975, Texaco completed its Table Rock 19 Unit well at a total depth of 18,368 feet. This well was completed open hole in the Madison Limestone between 18,020 and 18,368, flowing gas at a calculated absolute open flow rate of 44 million cubic feet per day. In January 1977, the deep Madison pool was confirmed by an offset about 2 miles to the southwest, the Table Rock 21 Unit well, which was completed through perforations at 18,287 to 18,330 feet flowing 19 million cubic feet per day.

Pinedale

Gas shows were found in a test drilled on this feature before World War II, but it was not until 1955 that a later test was drilled and completed as a gas well. The Pinedale anticline, about 40 miles in length with more than 1,500 feet of vertical closure, is something to make an explorationist excited. Eight wells have been drilled along the crest of the structure. The deepest penetrated the Upper Cretaceous Mesaverde at about 13,066 feet and bottomed in the same formation at 15,020 feet.

Most of the wells have been completed in what are reported to be low-permeability sandstones in the Paleocene Fort Union Formation. One completion has been made in the upper part of the Mesaverde. Initial flow rates have varied from 1,250,000 to 3,850,000 cubic feet of gas per day. With a structure of this size, bottom-hole pressures ranging from 2,770 to 7,500 psi in existing wells, and multiple thick reservoir sands, if proper stimulation and drilling techniques are found, this structure may yet prove to be a gas-producing bonanza.

The temptations of the deeper and untested Frontier, Dakota, Nugget, Weber, and Madison are fascinating, a very exciting potential, and deep!

All the aforementioned recent and not-so-recent deep drilling developments are clearly a demonstration of the vast potential that is present throughout the Greater Green River basin and peripheral areas.

Regional Reserves and Potential

Figure 13 and Table 1 illustrate a summary of possible recoverable oil and gas reserves in the region. This is a synthesis of work done previously by other workers [23] and modified in view of recent developments, together with certain subjective interpretations by the writer.

The region has been subdivided into four major time-rock sequences for analysis of recoverable oil and gas reserves that might be found in unexplored parts of the region. The units so selected are (1) Tertiary; (2) Cretaceous; (3) Jurassic-Triassic; and (4) Paleozoic.

Isopach maps showing areal extent and thickness of the above units form the basis of calculated volumes of sedimentary rock in each unit. The amount of known recoverable oil and gas in all fields found to date in the region can be compared against the total volume of sedimentary rock in the region or against the estimated volume of known, explored sediments to obtain a minimum and a maximum amount of oil and gas per cubic mile to be applied to the volume of unexplored sedimentary rock that remains. This can also be done for any subdivision of stratigraphic units.

Estimates made by previous workers show large variations in the amounts of recoverable hydrocarbons per cubic mile to be found in the overthrust belt versus the contiguous Greater Green River basin. An attempt has been made to reduce such differences and yet provide a new estimate that is not overly conservative or too optimistic.

Of the estimates of volume of natural gas per cubic mile of unexplored sedimentary rock within the Greater Green River basin as determined by previous workers, it is believed that that of Keller and Thomaidis[24] is closest to the one used herein. The estimate of Crews et al. appears too optimistic. The writer estimates that no more than 7.5 percent of the region's sedimentary volume has been explored. This has resulted in nearly 8 trillion cubic feet of recoverable gas being discovered. Of the remaining 92.5 percent of sediment volume, probably no more than half

[23] See Ns. 1, 2, 13 *supra*.
[24] *Ibid*.

TABLE 1

Possible Recoverable Hydrocarbons in
Greater Green River Basin and Wyoming Overthrust Belt

Age	Overthrust Area			Basin Area			Total		
	Rock Vol. MI^3	Oil (Bbls)	Gas (cu. ft.)	Rock Vol. MI^3	Oil (Bbls)	Gas (cu. ft.)	Rock Vol. MI^3	Oil (Bbls)	Gas (cu. ft.)
Tertiary				20,000	$500x10^6$	$10x10^{12}$	20,000	$500x10^6$	$10x10^{12}$
Cretaceous	9,000	?	?	32,000	$3.2x10^9$	$16x10^{12}$	41,000	$3.2x10^9$	$16x10^{12}$
Jurassic-Triassic	5,000	$500x10^6$	$2.5x10^{12}$	14,000	$700x10^6$	$7x10^{12}$	19,000	$1.2x10^9$	$9.5x10^{12}$
Paleozoic	6,000	$900x10^6$	$3.0x10^{12}$	15,000	$2.25x10^9$	$7.5x10^{12}$	21,000	$3.15x10^9$	$10.5x10^{12}$
Total	20,000	$1.4x10^9$	$5.5x10^{12}$	81,000	$6.65x10^9$	$40.5x10^{12}$	101,000	$8.05x10^9$ *	$45.5x10^{12}$ *

* Nothing has been included for the Cretaceous of the overthrust belt.

will be explored. If a similar rate of discovery is maintained, then perhaps 45 trillion cubic feet of recoverable gas will yet be found. For the total sediment volume of about 100,000 cubic miles, a factor of 500 million cubic feet of gas per cubic mile is estimated. This is more than Keller and Thomaidis' estimate of 240 million and somewhat less than the 3.3 billion cubic feet per cubic mile determined by Crews et al.

For estimates of future oil discoveries, the producible reserves per cubic mile determined by Keller and Thomaidis are retained for most of the Greater Green River basin. The estimate for the Jurassic has been increased. Monley's estimate for the overthrust belt is believed too large and has been reduced. The volumes of oil and gas per cubic mile as applied here are as follows:

(1) Natural gas—500 million cubic feet per cubic mile
(2) Oil
- (a) Tertiary—25,000 barrels per cubic mile
- (b) Cretaceous—100,000 barrels per cubic mile
- (c) Jurassic-Triassic—50,000 barrels per cubic mile (basin) and 100,000 barrels per cubic mile (overthrust)
- (d) Paleozoic—150,000 barrels per cubic mile

As shown on Table 1, it is believed that the Greater Green River basin and environs might ultimately provide up to 8 billion barrels of oil and 45 trillion cubic feet of natural gas.

Exploration Problems

As they are in other regions, the major problems facing the industry, other than geology and risks involved, are political and economic.

Political problems relate in large part to land ownership in the Greater Green River basin and overthrust belt. Of much importance are the constraints placed upon explorers by the owners and the problems or difficulty in assembling acreage on prospects because of land ownership. In this region, there are basically two landlords to contend with—namely, the United States Government and the Union Pacific Railroad.

The federal lands are principally administered by the Bureau of Land Management. Other Government agencies that play a role in administration and policies include the U.S. Forestry Service and the National Park Service. These agencies introduce many rules and regulations by which exploration must be conducted, if allowed at all.

Another problem attendant with federal land is the availability of oil and gas leases. Nearly every acre of federal and state land in the region is under lease. About the only way to obtain new leases on federal acreage is to win them in the monthly simultaneous filings (lotteries) or purchase them from those who do win.

Another factor that acts as a deterrent to assembling large blocks in many prime areas is related to the Union Pacific land grant. Figure 14 shows that belt of land which extends for approximately 20 miles on either side of the Union Pacific railroad. In this area, the mineral rights on nearly all the odd-numbered sections were given to the railroad in the 1800s.

Recently, this area has been the subject of one of the most intense exploration operations in the Rocky Mountains. In 1969, AMOCO Production Company entered into an agreement whereby it undertook to explore the entire 19,456,000-acre holding across parts of Colorado, Nebraska, Wyoming, and Utah. This agreement, of course, helped AMOCO, but at the same time placed much of the region out of the grasp of other explorers except through farmouts from AMOCO. By virtue of the agreement, AMOCO has certain payments, work obligations, and relinquishment obligations. For every well drilled or caused to be drilled on railroad land, the company earns the mineral rights subject to a 15 percent override reserved to the railroad (Champlin Oil Company) in twelve sections, except for the northeast quarter of each section, which is reserved to Champlin. This agreement is scheduled to terminate in November 1977.

Elsewhere in the region, oil and gas lease prices are often quite high. Prices vary from $15 to $20 per acre in less active areas to as much as a reported $1,100 per acre in the overthrust belt near Ryckman Creek.[25]

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[25] West, "Exploration Flares Along Rockies' Overthrust Belt," 74 Oil & Gas J. No. 50, pp. 23–27.

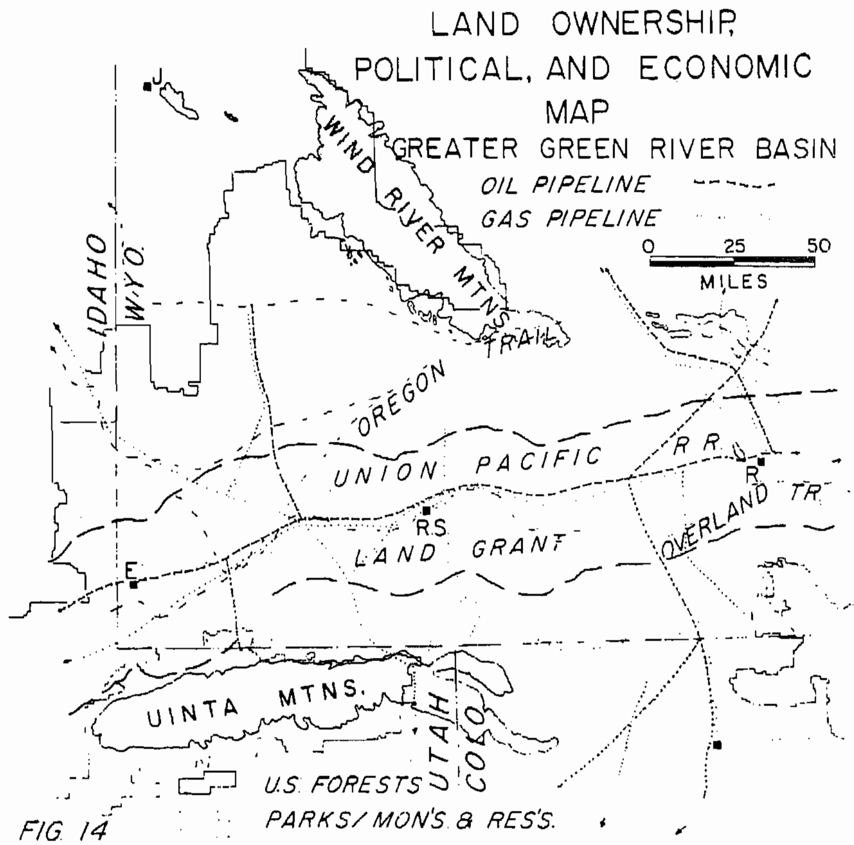

FIG. 14

Prospects

Figure 15 illustrates general and specific areas of interest for future exploration in the Greater Green River basin and overthrust belt. The writer believes the following areas have much potential:

(1) The eastern edge of the overthrust belt. In particular, where the reservoir potential of Paleozoic and Mesozoic formations are in fault contact with probable oil and gas source rocks of the Cretaceous System.

Other general areas of interest occur in the subthrust block or basinward areas immediately adjacent to the overthrust belt. Examples include the Lookout Mountain area north of La Barge and the Cache Creek anticline southeast of Jackson, Wyoming.

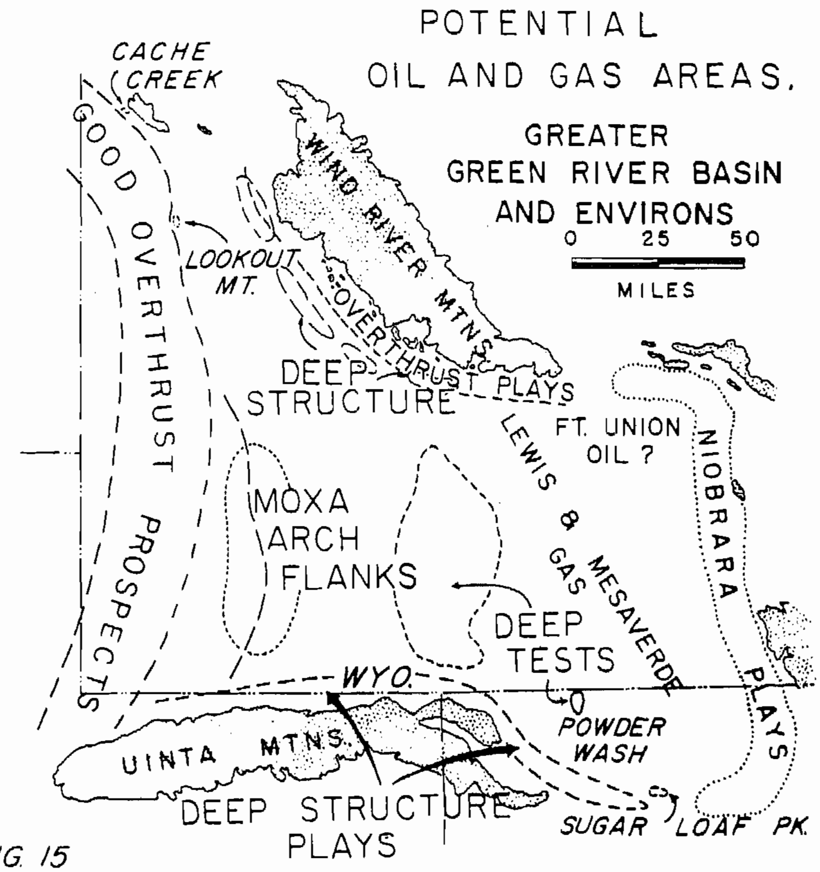

FIG. 15

(2) Along the crest of the Moxa arch in Paleozoic and Cretaceous Dakota and Frontier reservoirs. Also, on the flanks of this feature there are known stratigraphic wedge outs that might contain hydrocarbons and form traps.

(3) Possible deep, structure-related traps along the steep west flank of the Rock Springs uplift.

(4) Deep prospects on trend to the north and southeast of Pinedale anticline along the southwest margin of the Wind River Mountains.

In this general area and type of prospect, the Pacific Creek anticline has still not been tested to the Nugget and Paleozoic.

(5) The Madison Limestone is probably worth testing at several untested locations along the crest of the Rock Springs uplift. The only deep test to date was at North Baxter

basin (through the Cambrian to granite wash) and is some 1,200 feet structurally lower than South Baxter Basin.

(6) Deep structural prospects along the faulted margins of the southwest flank of the Wind River Mountains and the northern edge of the Uinta Mountains.

(7) A test to the Madison Limestone on Powder Wash anticline in the Sand Wash basin. The deepest test to date stopped in the Cretaceous Mesaverde.

(8) A myriad of relatively shallow, Cretaceous Lance, Lewis, and Mesaverde stratigraphic traps to be tested in the Great Divide, Washakie, and Sand Wash basins. The northwest plunge of Big Gulch anticline is an ideal place for such tests.

(9) The Paleocene Fort Union Formation has yielded oil at one location, Continental Divide field, in the Great Divide basin. Is this sandstone reservoir with an initial production of 144 barrels of oil per day the only occurrence in this sequence of alternating sandstones and shales covering hundreds of square miles?

(10) An area along the east margins of the Sand Wash, Washakie, and Great Divide basins where shallow- to medium-depth wells can explore for fractured Cretaceous Niobrara shale reservoirs.

The potential of this area is demonstrated by production history at Espy field, Wyoming, and at Buck Peak and Tow Creek fields, Colorado. At Buck Peak, a single well, the ARCO Voloshin 1, has yielded more than one million barrels of oil since 1958!

Conclusion

The Greater Green River basin and the contiguous area of the Wyoming overthrust belt afford a variety of oil and gas reservoirs in structural and stratigraphic traps.

It is possible that this region has more than 8 billion barrels of recoverable oil and up to 45 trillion cubic feet of producible gas left to explore for and recover. The region is still underexplored relative to other Rocky Mountain areas, and the possibilities of deep prospects and discoveries are excellent. There are many known structures that have yet to be tested below the Cretaceous Mesaverde. Also, there are literally scores of shallow- to medium-depth Cretaceous stratigraphic traps to explore for and drill.

The Greater Green River basin and the Wyoming overthrust belt have an excellent chance of becoming the largest oil- and gas-producing region in the Rocky Mountains.

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