FUTURE PETROLEUM PROVINCES

of the United States

A Report of the
National Petroleum Council

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and to the
OFFICE OF OIL AND GAS

Prepared by the
National Petroleum Council
in response to a request from the
Department of the Interior

FUTURE PETROLEUM PROVINCES OF THE UNITED STATES

— A SUMMARY —

July 1970

Prepared by the

NATIONAL PETROLEUM COUNCIL'S COMMITTEE
ON POSSIBLE FUTURE PETROLEUM PROVINCES OF THE U.S.

Otto N. Miller, *Chairman*

PREFACE

THE STUDY EFFORT

In the spring of 1967 the Assistant Secretary of the Interior requested the National Petroleum Council to prepare a report on the future petroleum provinces of the United States (Appendix A). The NPC Committee on Possible Future Petroleum Provinces of the United States was established for this purpose under the Chairmanship of Otto N. Miller, Chairman of the Board, Standard Oil Company of California, and the Vice Chairmanship of D. A. McGee, Chairman of the Board, Kerr-McGee Corporation (Appendix B). The Government Co-Chairman was the Hon. Hollis M. Dole, Assistant Secretary-Mineral Resources, U.S. Department of the Interior.

Early in 1968 an Executive Advisory Committee to the parent committee was appointed with Morgan J. Davis as Chairman (Appendix C). Later the Coordinating Subcommittee was designated with Ira H. Cram as Chairman (Appendix D).

For purposes of this particular study, the country was divided into 11 regions, generally on the basis of geologic provinces (Figure 1, page 2), and coordinators* of each region were appointed as members of the Coordinating Subcommittee. Subsequently, each regional coordinator subdivided his region, mainly along geological lines, and assigned each subdivision to one or more geologists who were also approved as members of the Coordinating Subcommittee.

As finally constituted, the Coordinating Subcommittee included geologists who were selected because of their broad experience in petroleum geology, their specific knowledge of the geology of their respective areas, and their experience in exploring for petroleum. The roster includes geologists from oil and gas companies, independent producers, State Geological Surveys, and the U.S. Geological Survey, as well as self-employed geologists. In addition, an unknown number of geologists contributed advice and data to Subcommittee members.

The contribution of every member of the Coordinating Subcommittee and the many anonymous advisers is gratefully acknowledged.

SCOPE OF STUDY

In his letter of request, the Assistant Secretary of the Interior referred to the "Future Petroleum Provinces of North America," published by The American Association of Petroleum Geologists in 1951 (see reference 1), and pointed out the desirability of bringing such a useful study up to date. The 1951 study was devoted to a description of the geology and petroleum prospects of certain largely unexplored areas. Other areas, including the more thoroughly explored producing areas, were not discussed. Thus, the possibilities for further discovery within the entire country were not assessed in the 1951 survey, and a complete picture of the future of U.S. discovery was not obtained.

In the present study petroleum geologists have examined and reported on the petroleum potential of each geological subdivision of the onshore, and have extended their studies offshore to the approximate base of the continental slope. The areas discussed include those believed to have negligible or no potential as well as those areas known, or generally believed to have, definite potential. Other sources of hydrocarbons such as oil shale, tar sands, solid hydrocarbons, and coal are not considered.

Although the Department of the Interior did not request estimates of potential crude oil and natural gas, the question was discussed at length in early meetings of the Executive Advisory Committee and Coordinating Sucommittee. It was concluded that each author should have the option, but not the obligation, of preparing such estimates, and it was suggested that oil-in-place and gas-in-place estimates were preferable.

Obviously, the immense scope of this study necessitates that a degree of uniformity be achieved in reporting. For this reason, and to clarify the intent of the study, the authors were furnished with a workable outline which is included in Appendix E. Each geologist generally adhered to the outline and assembled information he thought was most significant. Geologists describing the more intensely explored producing provinces had the task of gleaning from the voluminous literature and unpublished data the more significant data. Geologists describing the undrilled or sparsely drilled areas wished for more geological information on which to base an opinion. Fortunately, operators were most cooperative in providing useful information. Many authors elected to prepare estimates of oil-in-place or of recoverable oil to be added in the future, and all coordinators presented estimates for at least parts of their regions.

The wealth of data assembled, all directed to assessment of the petroleum potential of the United States, will be published in a special volume, "Memoir 15," by The American Association of Petroleum

* Throughout this report the term "coordinator" refers to the heads of the regions. The term "author" refers to those individuals who prepared the reports on the subdivisions within the regions.

Geologists under sponsorship of the National Petroleum Council. The volume is sufficiently complete and charged with oil-finding ideas to provoke additional ideas that may well lead to more discoveries. The authors have provided a considerable quantity of new data on area, volume, character, and productivity of the sedimentary rocks—data which should assist others to make their own calculations of the Nation's potential. The excellent references, moreover, provide the interested reader with a means of delving further into a subject of particular interest.

The report which follows is designed to provide a meaningful summary for those who are more interested in the country's crude oil and natural gas potential than in the geology.

IRA H. CRAM

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CHAPTER 1

INTRODUCTION

SUMMARY AND CONCLUSIONS

In this study the entire United States, including the continental shelf and slope, was examined by experienced petroleum geologists in the search for areas with petroleum potential, however remote. The petroleum geology of the chosen areas was described in the detail considered adequate, or in the detail permitted by available data.

One hundred and forty-one geologists participated in the project, 11 of whom coordinated the study in the 11 regions (Figure 1). The report contains an enormous amount of unpublished pertinent data, all directed to appraisal of the Nation's petroleum resources. The potential of each region was assessed qualitatively, and in part quantitatively. The completeness of the report and the ideas and opinions expressed should provoke alternate ideas and opinions leading to more exploratory activity and more discoveries.

The more important observations are as follows.

The prospective basinal area of the United States covers approximately 3.2 million square miles; 1.8 million onshore, 0.9 million continental shelf, and 0.5 million continental slope. Alaska alone covers 940 thousand square miles; 85 thousand onshore, 580 thousand continental shelf, and 275 thousand continental slope.

Estimated cubic miles of sedimentary rock above basement* or 30,000 feet total 6.0 million; 3.4 million onshore, 1.6 million continental shelf, and 1.0 million continental slope. The totals for Alaska alone are 1.4 million cubic miles; 0.2 million onshore, 0.8 million continental shelf, and 0.4 million continental slope.

In addition, large structurally complex areas of thick sedimentary rocks bordering parts of the basinal areas, and some scattered smaller areas, are considered to be prospective but of secondary importance.

None of the 11 regions has been adequately explored. Extensions to old fields and discovery of new fields at conventional depths and deeper are forecast for all regions. The Atlantic, Florida, and Alaska continental shelves, and the entire continental slope, barely have been touched by drilling, and other prospective areas and depths on land and the continental shelf remain largely unexplored. Many high-potential areas are indicated by the geology and extent of exploration, particularly in parts of Alaska, California, Colorado, Louisiana, Mississippi, Montana, New Mexico, North Dakota, Oklahoma, Texas, Utah, and Wyoming. The future of the area east of the Mississippi River and north of the Gulf Coast province is particularly dependent on deeper discoveries in the older Paleozoic rocks, the prospects of which are considered to be favorable. A high percentage of the new petroleum confidently foreseen on land will be found in stratigraphic, combination stratigraphic and structural, and complex structural traps.

Estimates of potential crude oil reserves of the basinal area only, and exclusive of known reserves, range from 227 ("probable" and "possible") to 436 (including "speculative") billion barrels of oil-in-place or from 59 to 112 percent of end of 1968 estimates of proved oil-in-place. The potential probably exceeds the median estimate of 332 billion barrels of oil-in-place.

Estimates of potential recovery of crude oil range from 74 to 141 billion barrels, averaging 107 billion barrels at known rates of recovery of the oil-in-place; from 96 to 185 billion barrels, averaging 140 billion barrels at a recovery rate of 42 percent; and from 136 to 262 billion barrels, averaging 199 billion barrels at a recovery rate of 60 percent.

Estimates of potential natural gas reserves of the entire country furnished by the Potential Gas Committee range from 595 ("probable" and "possible") to 1,227 trillion cubic feet (including "speculative") or from 94 to 194 percent of end of 1968 estimates of ultimate recovery of known fields. The potential probably exceeds the median estimate of 911 trillion cubic feet.

The ultimate petroleum potential of the United States including known reserves and past production, and assuming median estimates of potential and 60 percent recovery of 720 billion barrels of oil-in-place, may exceed 432 billion barrels of crude oil, 1,543 trillion cubic feet of natural gas, and 49 billion barrels of natural gas liquids. The amounts that *will* be discovered are not ventured, but if discovered and produced, future production of crude oil would be 346 billion barrels (4.0 times past production); future production of natural gas would be 1,195 trillion cubic feet (3.6 times past production); and future production of natural gas liquids would be 38 billion barrels (3.5 times past production).

The trend in the last decade of devoting a declining percentage of producing revenue to finding and developing production of crude oil and natural gas has resulted in a drastic decline in exploratory and development drilling which together with deemphasis of the onshore of the conterminous United States is inimical to the development of the country's enormous petroleum resources.

* Basement is defined as an underlying complex of unattractive rocks beneath the sedimentary sequence.

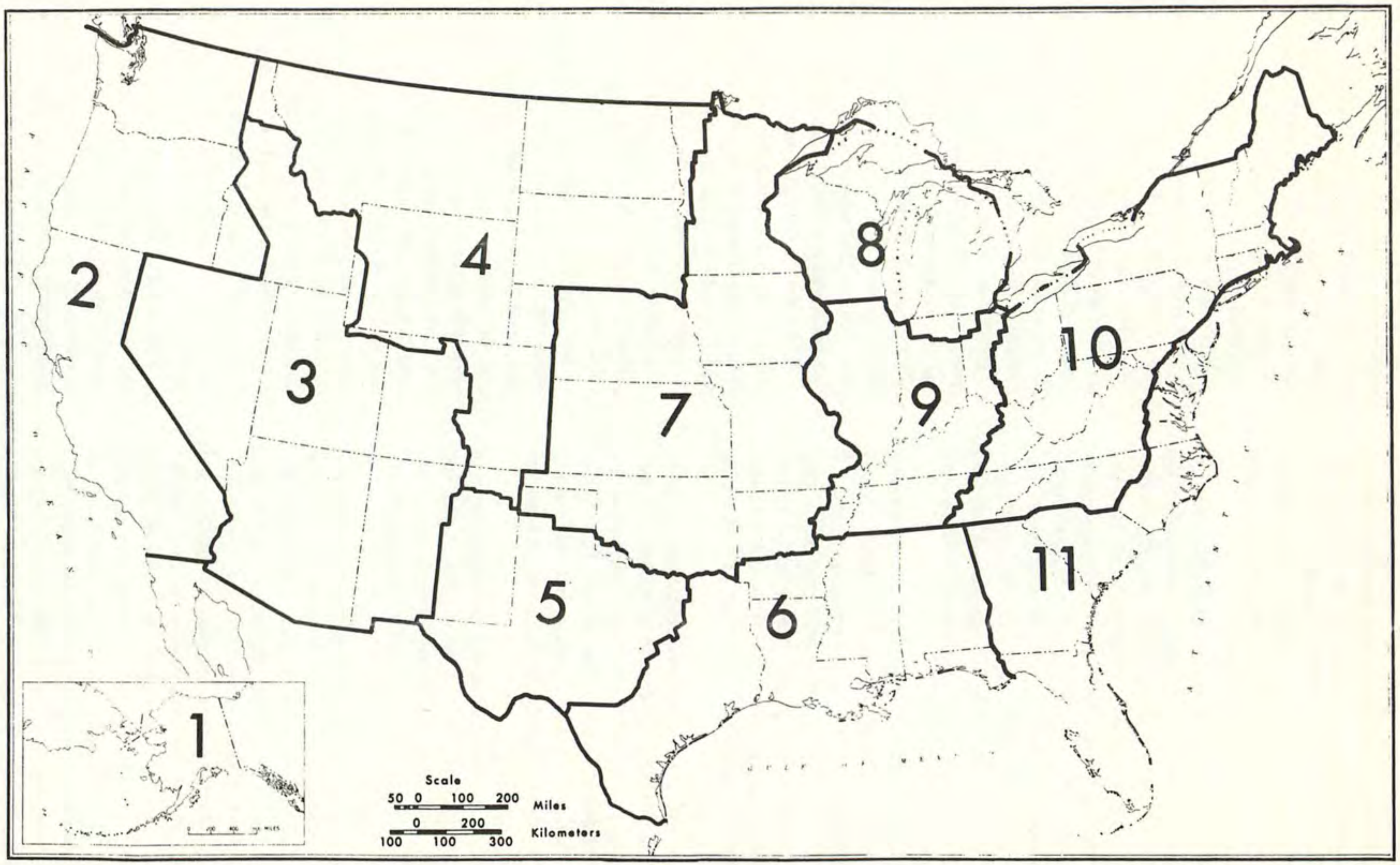

FIGURE 1. Regional Boundaries (Reg. 1—Alaska and Hawaii; Reg. 2—Pacific Coast States; Reg. 3—Western Rocky Mountains; Reg. 4—Eastern Rocky Mountains; Reg. 5—West Texas and Eastern New Mexico; Reg. 6—Western Gulf Basin; Reg. 7—Midcontinent; Reg. 8—Michigan Basin; Reg. 9—Eastern Interior; Reg. 10—Appalachians; Reg. 11—Eastern Gulf and Atlantic Coast)

To the extent that policies of industry and government militate against accelerated exploration, particularly drilling, a high percentage of the petroleum resources of the United States is immobilized.

EXPLORATORY CONCEPTS

NEW TECHNOLOGY

The growth in technology through the years and its impact upon the petroleum industry have been documented in a publication of the National Petroleum Council, "Impact of New Technology on the U.S. Petroleum Industry 1946-1965." [2] As the history of this growth is traced, the overall pattern of evidence clearly reveals that the producing branch of the industry has been supplied with new and effective finding, developing, and producing tools, and procedures, practically regardless of the current economic climate. In the absence of evidence of declining technological innovation, it can be assumed with confidence that constantly improving technology will continue to be the common denominator of future activities.

Technological innovations beget new ideas and new concepts, and success in exploration is particularly dependent on their generation. However, new exploratory ideas and concepts more frequently spring from the results of drilling.

Drilling continues to find crude oil and natural gas fields in unusual and surprising geological environments, and continues to find new geology hardly imagined in advance of drilling. The geologist, being aware of these surprises, is prepared for more. In short, the geologist's understanding of the habitat of oil grows with drilling. Armed with better understanding, he can evaluate more accurately in advance of drilling the petroleum potential of both sparsely explored and more extensively explored areas.

An exploratory concept emerging from new developments any place in the world is applicable worldwide, particularly in areas of diverse and complicated geology such as the United States. The explorationist's horizon broadens as new concepts are added to his fund of knowledge. For example:

1. The sizable discoveries in nonmarine strata in the Cook Inlet area of Alaska have caused geologists to take a second look at other areas of nonmarine rocks. The Groningen gas field in northeastern Netherlands is enormous (estimated ultimate recovery 60 trillion cubic feet) because of an unusual and hardly predictable development of thick, porous sandstone in another nonmarine section.
2. The development of large natural gas fields in the exceedingly complicated overthrust belt of Alberta, Canada, has raised the geologist's appraisal of similar overthrust belts in the United States.
3. The finding of large natural gas fields below 20,000 feet in Cambro-Ordovician carbonate rocks in the Delaware basin of West Texas has given geologists courage to explore more thoroughly the approximately equivalent section of rocks at the same and shallower depths in certain parts of the area between West Texas and New York.
4. After 32 years of development, Michigan's largest crude oil field, Albion-Scipio, was found in a narrow streak of porous dolomite in the Trenton limestone (Ordovician). This discovery has encouraged geologists to look with more favor on other largely undrilled areas of Trenton carbonate rocks east of the Mississippi River.
5. Few, if any, geologists had forecast the occurrence of marine Pleistocene sediments containing important crude oil and natural gas fields only a few miles off the Louisiana coast. This development puts geologists on notice that other favorable geologic sections can develop rapidly in other undrilled areas in Pleistocene or older rocks.

Many other examples of developments that have broadened the geologist's outlook could be cited. Normally, a broadened outlook generates additional exploratory drilling, which in all probability will produce still other surprises. In addition, geologists become more aware of the possibilities for discovery in stratigraphic traps and reefs as they study more carefully the maze of data in the more thoroughly drilled areas in the light of their growing knowledge of sedimentary processes.

BASEMENT DRILLING

The ability to drill deeper wells, the presence of crude oil fields in basement rocks,* and the new Delaware basin developments in rocks just above the basement raise the question of the extent to which our country has been drilled to the basement. By adopting the premise that the only truly dry hole is one drilled to the basement and tested thoroughly, one finds that an enormous amount of untested potential territory remains.

* For example, in the Edison field of California and in the Mara field of western Venezuela.

Basement drilling has been concentrated in areas of regional uplifts, and particularly in the producing fields on them. Most of the basement drilling has been done on the flanks of the Ozark uplift in northeastern Oklahoma, on the Nemaha uplift in Kansas and Nebraska, on the Central Kansas uplift and its extension into Nebraska, on the Wichita Mountain-Amarillo uplift of Oklahoma and Texas, on the Muenster arch of Oklahoma and Texas, on the Matador arch of North Texas, on the Pecos arch-Central basin platform of West Texas and New Mexico, and on the eastern flank of the San Joaquin Valley of California. Very few wells have reached basement east of the Mississippi River.[3]

In general, where the sedimentary column is thicker than about 4,000 feet (except in the Texas-New Mexico uplifts), surprisingly few wells have been drilled through the prospective sedimentary column to the basement. The area with a sedimentary column less than 15,000 feet thick (Figure 2) is large indeed. The area in which the basement may be reached deeper than 15,000 feet, but shallower than 30,000 feet, is much smaller, but still sizable.

OIL OR GAS

Deeper drilling, whether or not to basement, is likely to discover many more natural gas fields than crude oil fields.[4,5] Most of the crude oil in the United States—in fact, in the world—is produced from depths shallower than 10,000 feet. Below 15,000 feet, natural gas and gas condensate fields predominate. The increasing percentage of natural gas found with increasing depth prevails everywhere. This situation could hardly be otherwise because temperature and pressure, which increase with depth, gasify liquid hydrocarbons. The record is particularly clear in South Louisiana where a gradation can be demonstrated from crude oil to increasingly drier gas with increasing depth.

The distribution of crude oil and natural gas fields at shallower depths is somewhat haphazard. The reason for such distribution is unclear. However, it is noteworthy that the large natural gas fields, such as the Hugoton area of Texas, Oklahoma, and Kansas, and those of the Appalachian Plateau, and the deeper ones of the Gulf Coast, are adjacent to thick accumulations of sedimentary rocks. At greater depth, it would appear to be certain that a more predictable distribution will prevail.

The decrease in porosity and permeability of sandstone with increasing depth, because of increasing temperature and pressure, has been well documented in young rocks (Tertiary) as well as old rocks (Paleozoic).[6,7] However, this pattern does not necessarily prevail in carbonate rocks, largely because fracture porosity can develop in the relatively incompressible rock. Fracture porosity in thick carbonate sections on large structural features provides adequate reservoir space in several large fields of the Delaware basin. The depth to which fracture porosity can exist is unknown. Dry gas (methane) is a very indestructible substance which can exist below 30,000 feet, possibly as deep as fracture porosity can exist.

CONCLUDING REMARKS

The fund of geological and production knowledge proliferates, and, equally or more important, the geologist's understanding continues to grow—understanding of what kinds of geologic situations result in crude oil and natural gas accumulations, and where and how they may be found. Thus, the modern geologist is far less inclined to condemn areas than his predecessors. Instead, he is more likely to reduce the area of the "impossible," to expand the area of the "possible," and to forecast more crude oil and natural gas in the basinal areas, which are, and are likely to continue to be, the sites of the major producing areas.

CHAPTER 2
THE PROSPECTIVE AREAS

The total basinal area in the United States (shown in white on Figures 2 and 3 and by the dotted pattern where the sedimentary column is estimated to be thicker than 15,000 feet) now considered favorable for the occurrence of crude oil and natural gas fields is approximately 3.2 million square statute miles (see Table 1 and Figures 2 and 3). The area of abandoned and producing fields, estimated to be 47,500 square miles at the end of 1968,[8] is included in the total (Table 1). In addition, there is a very large area (indicated approximately by the striped pattern) which is not included in the statistics, comprising parts of overthrust belts along the margins of the basinal area and some isolated areas, all of which are considered to be much less prospective than the basinal areas, yet still somewhat prospective.

The unfavorable to impossible area (shown by the reticulated pattern) is composed mainly of complexly folded and faulted mountain systems, less complex areas such as the Ozark uplift in Missouri and Arkansas in which productive formations and the basement crop out, and certain areas considered condemned by drilling such as northern Iowa. Between the Appalachian Mountains and the West Coast, but north of the Gulf Coast, basement consists of Pre-Cambrian igneous and metamorphic rocks. Along the Atlantic and Gulf Coasts, Paleozoic and Triassic rocks generally are considered to be basement. In California, metamorphic and igneous rocks of Jurassic and early Cretaceous age make up the basement. In Washington and Oregon the lower Eocene volcanic sequence and older rocks are considered to be basement. In Alaska the age and character of rocks regarded as the bottom of the prospective sedimentary section (basement) are variable. In southern Alaska east of Cook Inlet, lower Tertiary and older rocks are considered to be basement. On the North Slope, early Paleozoic and older rocks make up the basement.

The very large area comprising eastern Washington, eastern Oregon, eastern California, Idaho, Nevada, western Utah, and western and southern Arizona—large parts of which are covered by volcanics—is geologically very complex and must be regarded generally as unfavorable. But there is a small oil field in eastern Nevada (Eagle Springs) and certain speculative areas are noted by the striped pattern. In Alaska, an area of similar size and geology, centered in Interior Alaska, also contains such speculative areas (see Figure 3).

The estimated volume of sedimentary rock within the basinal area is 6.0 million cubic miles (see Table 2). The onshore total is the sum of several carefully calculated estimates, the accuracy of which is variable because of variations in the density and depth of drilling. The offshore totals are more accurately described as "educated guesses," because the only data available on most of the offshore are of a general geological and geophysical nature (reference 9). In the overthrust belts, volumetric calculations approach the impossible, so none were attempted.

The "productive" area—the more intensively explored area containing the producing fields—was estimated by Hendricks [10] to cover slightly more than 1 million square miles (Figure 4). Drawing the outlines of the productive area cannot be precise, but an estimate of less than 850,000 square miles would appear to be too small. Certain parts of this area assuredly have been explored to such an extent that their contribution to new reserves from new fields must be minimal. Nevertheless, the area is far from being thoroughly explored, either to present producing zones or to deeper ones. The Fairway oil field in East Texas and the Black Lake oil field in northern Louisiana, both included in the "giant" class (ultimate recovery more than 100 million barrels) by the *Oil and Gas Journal* [11] and found in recent years in intensively explored areas, are reminders of the extent to which the productive area has *not* been depleted. Moreover, many fields already discovered have not been defined either laterally or vertically. Their contribution to future proved reserves by extensions and revisions will be very substantial. However, no one can expect such future additions to reserves to be adequate for future needs. They never have been, and it is prudent to expect that new crude oil and natural gas fields in the unknown areas will have to contribute to a greater extent than in the past.

An analysis of the petroleum potential of the 11 regions and their subdivisions follows in Chapters 3 through 13, respectively, in the order of the numbers assigned to the regions. Each chapter begins with a summary of the more significant conclusions of the coordinators and authors. The areas within each region are discussed in the order of the prospectiveness determined by the coordinator. In reporting on the relative prospectiveness of the region's subdivisions, some coordinators have stressed geological factors; others have relied more on estimates of potential oil-in-place or potential ultimate recovery. The discussion following the summary in each chapter is the coordinator's summary of his authors' reports.

The relative potential of the regions is suggested in Tables 22 through 24 (Chapter 14), but only approximately because the amount and quality of data vary from region to region, and because the estimates were not made by the same people employing the same methods. Chapters 15 and 16 present a brief account of the outlook for future development of petroleum resources.

TABLE 1. PROSPECTIVE AREA OF UNITED STATES

(1,000 square statute miles)

Area	Land[1]	Shelf[2]	Slope[3]	Total
Conterminous U. S.	1,726	293	240	2,259
Alaska	85	582	276	943
Total U. S.[4]	1,811	875	516	3,202[5]

[1] Includes lakes and bays.

[2] Water up to 656 feet (200 meters) in depth offshore (see reference 9).

[3] Water between 656 and 8,200 feet (2,500 meters). McKelvey and Wang (1969, World subsea mineral resources: U.S. geol. survey, Misc. geol. investigations, map 1-632) state that a water depth of 8,200 feet generally marks the worldwide base of the continental slope. This was used for purposes of this study only.

[4] Offshore figures represent the total offshore area, and not the offshore area believed to be prospective. Rather than speculate on the size of the unfavorable offshore area, it was decided to present figures on the gross area. To make the offshore figures comparable to the onshore figure of 1.8 million square miles, unfavorable areas (such as parts of the California and New England offshore) should be subtracted.

[5] Includes area of abandoned and producing fields estimated at 47,500 square miles at the end of 1968.

TABLE 2. VOLUME OF SEDIMENTARY ROCKS OF PROSPECTIVE AREA[1]

(1,000 cubic miles)

Area	Land	Shelf	Slope	Total
Conterminous U. S.	3,163	862	650	4,675
Alaska	215	800	350	1,365
Total U. S.	3,378	1,662	1,000	6,040

[1] Sedimentary section above basement or 30,000 feet.

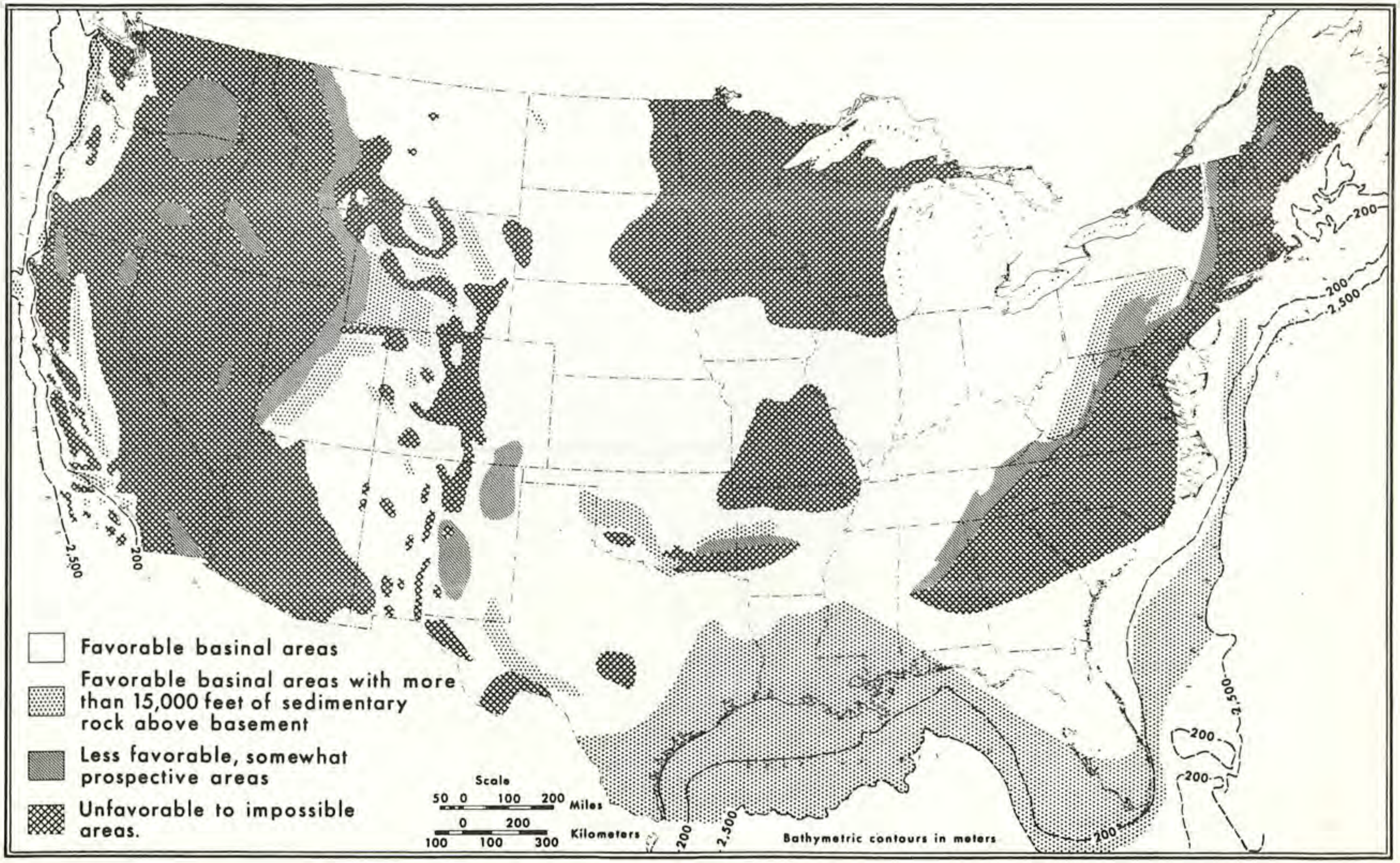

FIGURE 2. Prospective Areas of Conterminous United States

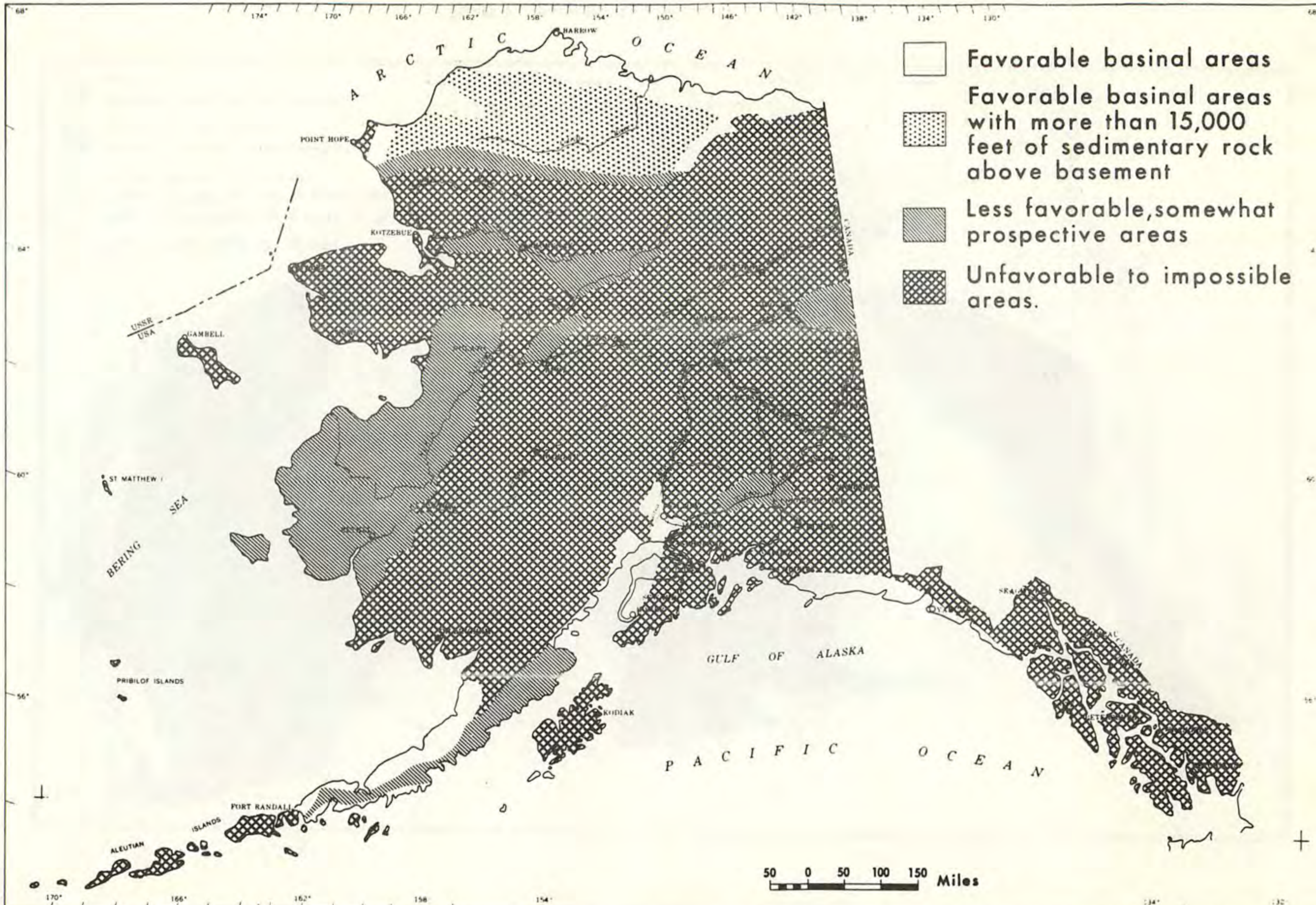

FIGURE 3. Prospective Areas of Alaska

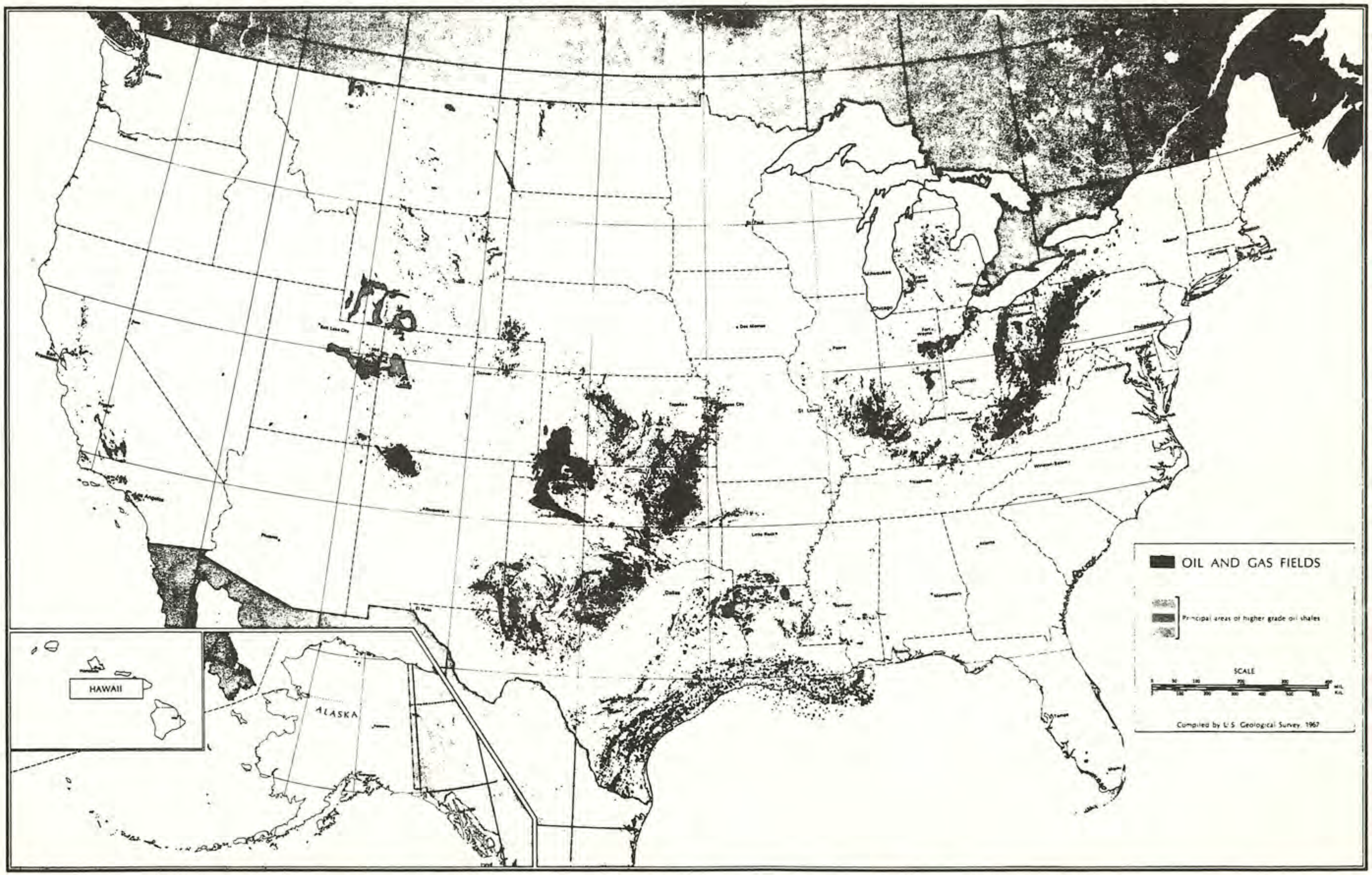

FIGURE 4. Petroleum Producing Areas of Conterminous United States

SUMMARY

ONSHORE

The land area of Alaska and Hawaii* is almost as large as the land area covered by California, Oregon, Washington, Idaho, Nevada, and western Utah. Less than 15 percent of both areas is considered to be favorable for the occurrence of crude oil and natural gas fields. The rest is geologically very complex, and contains only a few areas considered somewhat prospective, or not "impossible." The prospects of these questionable areas as well as the prospects of the favorable areas, onshore and offshore, are evaluated. Potential in-place reserves of crude oil and natural gas of the Cook Inlet subprovince, and a broad range of estimates of recoverable crude oil of the Bristol Bay and North Slope provinces, are ventured. Figure 7 shows location of the areas discussed.

Arctic or North Slope Province

This very prospective petroleum province covers an onshore area of 62,000 square miles comprising the Arctic platform and the Colville geosyncline. Well-developed, clean, porous sandstones and porous carbonates are expected to be found in an area of about 20,000 square miles (on the platform along the Arctic coast) at depths of less than 15,000 feet (Figure 8). The Prudhoe Bay oil and gas field, which is a giant field by any definition, is located in this area, on a plunging anticline apparently uplifted in early Cretaceous time, later truncated, and then covered by younger Cretaceous shales.

Other ancient structures, large or small, highly or poorly productive—even nonproductive—can be expected in the platform area where a negligible amount of exploratory drilling has been done. Meager subsurface control suggests that stratigraphic fields may occur on the south flank of the platform. There is evidence to suggest also that upper Cretaceous and Tertiary shale and sandstone formations thicken as the Arctic platform extends offshore a short distance and then plunges seaward.

South of the preferred area, the basement plunges to perhaps 25,000 feet in front of the Disturbed Belt (Figure 8). In the northern part of this area (the Northern Foothills Section), shallow crude oil fields and natural gas fields have been found in Cretaceous sandstones (Umiat and Gubik, see Figure 7), and more doubtless will be found. The possibility of finding giant fields however, is unlikely, largely because of the poor reservoir characteristics of the Cretaceous sandstones in this belt.

Exploring the pre-Cretaceous formations which produce at Prudhoe Bay is not a simple process of drilling deep holes on the many surface anticlines in the Northern Foothills. It is probable that many of these anticlines are lost in the thick shales or below thrust plates, particularly in the more intensely folded and faulted area in the southern half of the Northern Foothills.

Modern geological and geophysical techniques and a great deal of exploratory drilling will surely reveal substantially more petroleum on the North Slope. However, the remoteness of the area, and the hostile Arctic environment present most formidable operational problems. Also, the Arctic National Wildlife Range east of the Canning River and Naval Petroleum Reserve No. 4 west of the Colville River cover about two-thirds of the area, and cannot be leased under their present status.

Cook Inlet Subprovince

This area covers approximately 15,000 square miles, about 40 percent of which is offshore. Only about one-third of the crude oil and natural gas is believed to have been found. The new petroleum is expected to come from extensions to fields, from new fields in the productive area, from discoveries in the unexplored parts of the subprovince, from stratigraphic traps, and from the deeper Mesozoic rocks.

Development of the area's excellent potential, however, will be slow and costly because of high tides, ice, severe weather, and leasing restrictions.

Pacific Margin Province

Only 6,000 square miles of this area are onshore. The favorable part of the geologic section, which contains many of the oil and gas seeps and the abandoned Katalla oil field, is the middle and upper Tertiary, which ranges in thickness from 10,000 to 15,000 feet. Although structurally complex, the land area has been well explored by the drill, but the area of unconsolidated sediments along the coast and the offshore is believed to be prospective. Geophysical studies indicate that structural traps are present.

* Hawaii is included for completeness and can be eliminated from consideration as a future petroleum province.

Other Land Areas

From time to time several sections in Interior Alaska (see Figure 7) have been mentioned as possible petroleum provinces. However, additional information from geological and geophysical (aeromagnetic and gravity) studies and some exploratory drilling leads to the conclusion that the potential of these areas is not encouraging. Parts of the Kobuk, lower Yukon, Yukon-Kuskokwin, Copper River, and Kandik subprovinces appear to be more promising than the others in Interior Alaska.

The Alaska Peninsula has received considerable exploratory attention because of oil and gas seepages in Mesozoic rocks, but the few wells drilled have found only showings of crude oil. It is generally believed that the prospects of the Mesozoic area are poor, and are better in the flanking Tertiary areas such as the land portion of the Bristol Bay area and the offshore between Shelikof Strait and Unga Island.

OFFSHORE*

Alaska's continental shelf covers about as much area as the land, but about 85 percent of it is in the polar, icebound environment north of the Alaska Peninsula.

Arctic Area

Recent studies indicate that the Brooks Range fold belt in Arctic Alaska extends under the Arctic Ocean to Herald and Wrangel Islands in the U.S.S.R., and that the folded Colville geosyncline also extends to the northwest under the ocean (see Figure 8). Southwest of the Brooks Range trend and northwest of the Seward Peninsula in the Chukchi Sea another basin is indicated which contains a thinner section of sedimentary rocks similar to the Norton basin (see next paragraph).

Bering Sea Area

The Bering Sea continental shelf is about 3 times as large as the Arctic shelf. Reconnaissance reflection seismic profiling so far has revealed the Norton basin between the Seward Peninsula and St. Lawrence Island. Tertiary sedimentary rocks above the Mesozoic or older rocks are about 6,500 feet thick in the bottom of the basin, and are only very slightly deformed. It is estimated that the Norton basin covers an area of 25,000 square miles and a volume of Tertiary sedimentary rock of 15,500 cubic miles. Perhaps additional seismic coverage in the Bering Sea will reveal other interesting areas. Drilling may find areas of pre-Tertiary rocks (now commonly considered to be basement), which are stratigraphically and structurally attractive. Also, the presence of at least 6,000 feet of lower Tertiary carbonate rock on St. Lawrence Island adds to the attractiveness of the Tertiary section.

A survey, utilizing the reflection seismograph, of a part of the Bristol Bay arm of the Bering Sea has been sponsored by oil companies. No information has been released at the writing of this report, however. Bristol Bay appears to offer the most reasonable opportunities, geologically and operationally, for discovery in the Bering Sea.

Pacific Area

The continental shelf off southern Alaska (82,000 square miles) is classified as being the most favorable area of the Alaskan shelf because of the more clement, though still hostile climate, and because of important production in the adjacent land area of Cook Inlet and the attractive sedimentary section containing seeps along the Pacific margin (discussed in a previous paragraph). On the basis of the known onshore geology and inferred offshore geology, parts of this vast area appear to be much more prospective than other parts. An area of about 25,000 square miles containing 50,000 to 75,000 cubic miles of middle and upper Tertiary sedimentary rocks, most of which is offshore in the Gulf of Alaska, appears to have the best reservoir possibilities.

A great deal of reflection seismograph work has been done by oil companies which should contribute considerable information on the geology and the promising areas for exploratory drilling.

Aleutian Islands

The geology of this island chain is unfavorable for the occurrence of petroleum.

DISCUSSION

INTRODUCTION

The discovery of the Prudhoe Bay oil field by the Atlantic Richfield Company in 1968 opened a new cycle of petroleum exploration and development in Alaska. That Alaska's petroleum potential is vast is no longer in question. The size of the reserves at

* Petroleum possibilities of Alaska's continental slope, which is almost half as large as the Alaskan shelf and larger than the slope of the conterminous United States, are not evaluated in this report. If exploration and development move toward the Alaskan slope, it will then be appropriate to speculate on its potential.

CHAPTER 3

REGION 1. ALASKA AND HAWAII

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Prudhoe Bay and the potential resources there and in adjacent areas are in keeping with the size and favorable geological setting of this Arctic sedimentary province.

As part of the National Petroleum Council's effort to assess the possible future petroleum provinces of the United States, a group of knowledgeable Alaskan geologists have been asked to review the petroleum potential of the sedimentary areas of the State.

In addition, two recently published reviews of Alaskan areas, one on the Bering Sea by Scholl and Hopkins [12] and another on the Kandik basin by Churkin and Brabb,[13] contribute new data for petroleum evaluation that are included in this summary.

All of the above areas and other possible petroleum provinces of Alaska were thoroughly reviewed by Gates, Grantz, and Patton [11] in a report that includes a discussion of the physiography, geology, and tectonic history of Alaska, as well as a petroleum evaluation, and constitutes a basic reference for this brief summary. Three maps (Figures 3, 4, and 5) from Gates, Grantz, and Patton [11] are reproduced here with only minor changes as Figures 5, 6, and 7 to provide background on the general geologic and Mesozoic and Tertiary tectonic framework and to depict the areas considered prospective for gas and oil in Alaska.

GEOLOGIC AND TECTONIC SETTING

A comparison of the geology of Alaska with that of the western United States and Canada is commonly drawn to provide an easy and widely known reference.[14,15,16]

The major mountain systems of western U.S. and Canada can be readily traced into Alaska. Recent geologic studies appear to substantiate the stratigraphic and structural comparisons of the Alaska Range and Coast Mountains, and intervening lowlands of Alaska with the Sierra Nevada and Coast Mountains farther south. The Brooks Range has been compared with the Rocky Mountains of the conterminous U.S. and western Canada. Although there are many similarities, both stratigraphic and structural, recent papers by Tailleur,[17] Brosgé and Tailleur,[18] and Churkin [19] draw attention to a tectonic history that may be more closely related to circum-Arctic regions, particularly the Canadian Arctic Islands and Wrangel Island off the coast of Siberia.

A very generalized compilation of the kinds, age, and distribution of Alaskan rocks is shown on Figure 5. Gates, Grantz, and Patton [11] noted that, "It is readily apparent that sedimentary rocks of Paleozoic and Mesozoic ages are widespread, whereas Tertiary sedimentary rocks are of limited extent and generally are restricted to the southern and northern coastal parts of Alaska and to a few elongate areas in interior Alaska. It is also readily apparent that in large parts of Alaska (as much as 25 percent or more) the bedrock is obscured by a cover of unconsolidated Quaternary deposits."

POSSIBLE PETROLEUM PROVINCES OF ALASKA

The possible petroleum provinces of all Alaska and the adjacent continental shelves were first defined and described by Gryc, Miller, and Payne.[20] A more complete review appeared later (see reference 16). The petroleum potential was reviewed again by Grantz and Patton [21] and by Gates, Grantz, and Patton.[11] Each of these reviews, utilizing the latest geologic information then available, slightly modified the areas considered prospective for oil and gas. Figure 7 shows the possible petroleum provinces and oil and gas fields of Alaska as of 1964, when the report by Gates, Grantz, and Patton was written. Fields discovered since 1964, including the Prudhoe Bay field in northern Alaska and some of the new and redefined fields in Cook Inlet, are not shown in detail.

The location and boundaries of the possible petroleum provinces of Alaska have not been changed much in recent years, but the evaluation of these provinces has changed significantly.

Alaska Peninsula-Cook Inlet Province

The Alaska Peninsula-Cook Inlet province extends from the Chitina Valley southwestward across Cook Inlet to the tip of the Alaska Peninsula. It is a lowland area bounded on the north and west by the Alaska Range and on the south by the Kenai-Chugach Mountains. The province includes a long, narrow wedge of moderately deformed marine clastic rocks of late Mesozoic age and predominantly nonmarine rocks of Tertiary age that overlie eugeosynclinal rocks of Paleozoic, Triassic, and early Jurassic age. These rocks extend over an area more than 900 miles long and 5 to more than 50 miles wide. Gates, Grantz, and Patton [11] stated that about 30,000 square miles of this area have petroleum possibilities. If an average thickness of about 2 miles is assumed, there are 60,000 cubic miles of sedimentary rock in the favorable part of the province.

The commercial deposits of oil and gas are in nonmarine Tertiary rocks. These Tertiary rocks, and possible upper Mesozoic rocks, are believed to have the best possibilities for future discoveries.

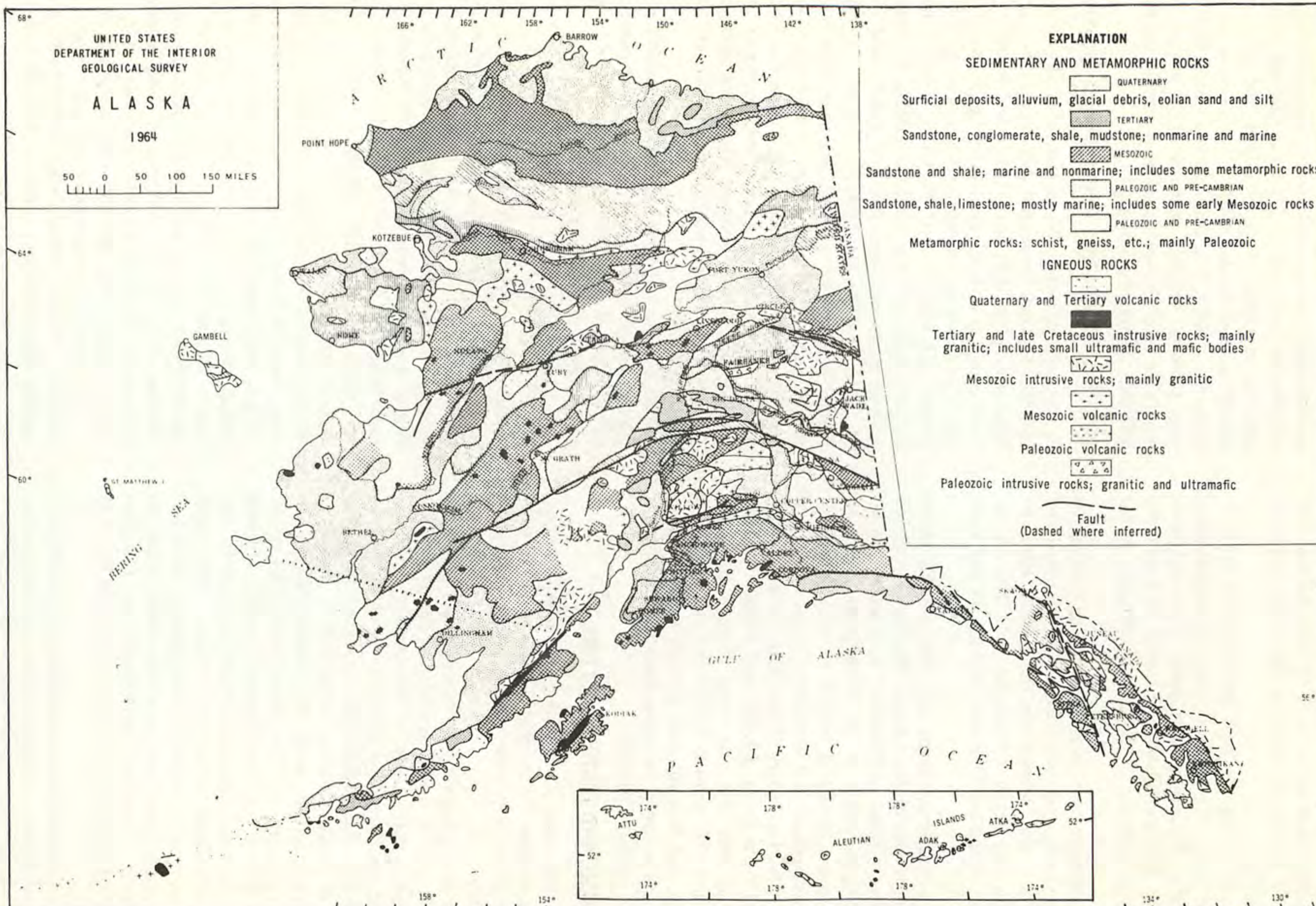

FIGURE 5. Generalized Geologic Map of Alaska (after Gates, Grantz and Patton.[14])

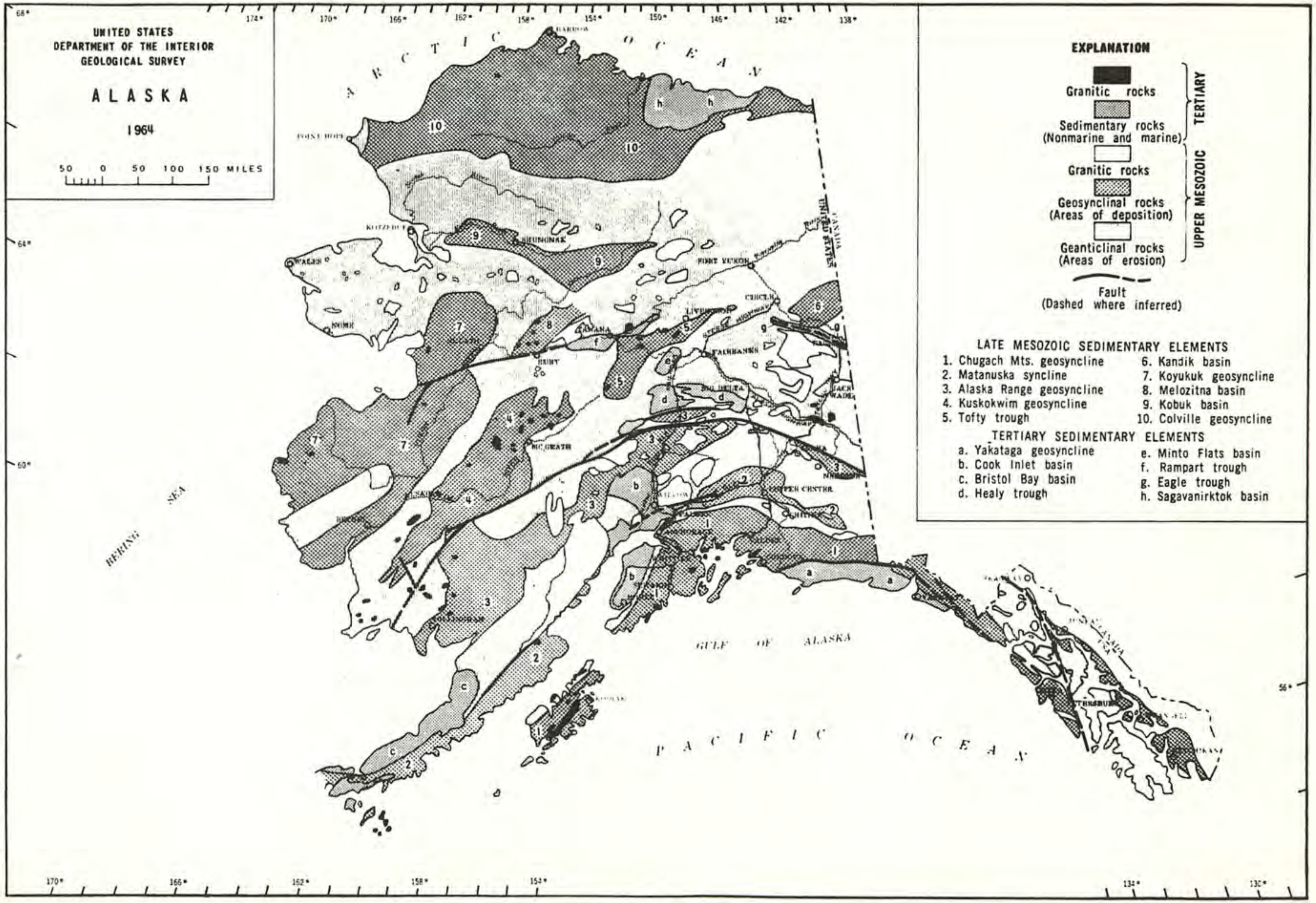

FIGURE 6. Mesozoic and Tertiary Tectonic Elements of Alaska (after Gates, Grantz, and Patton.[14])

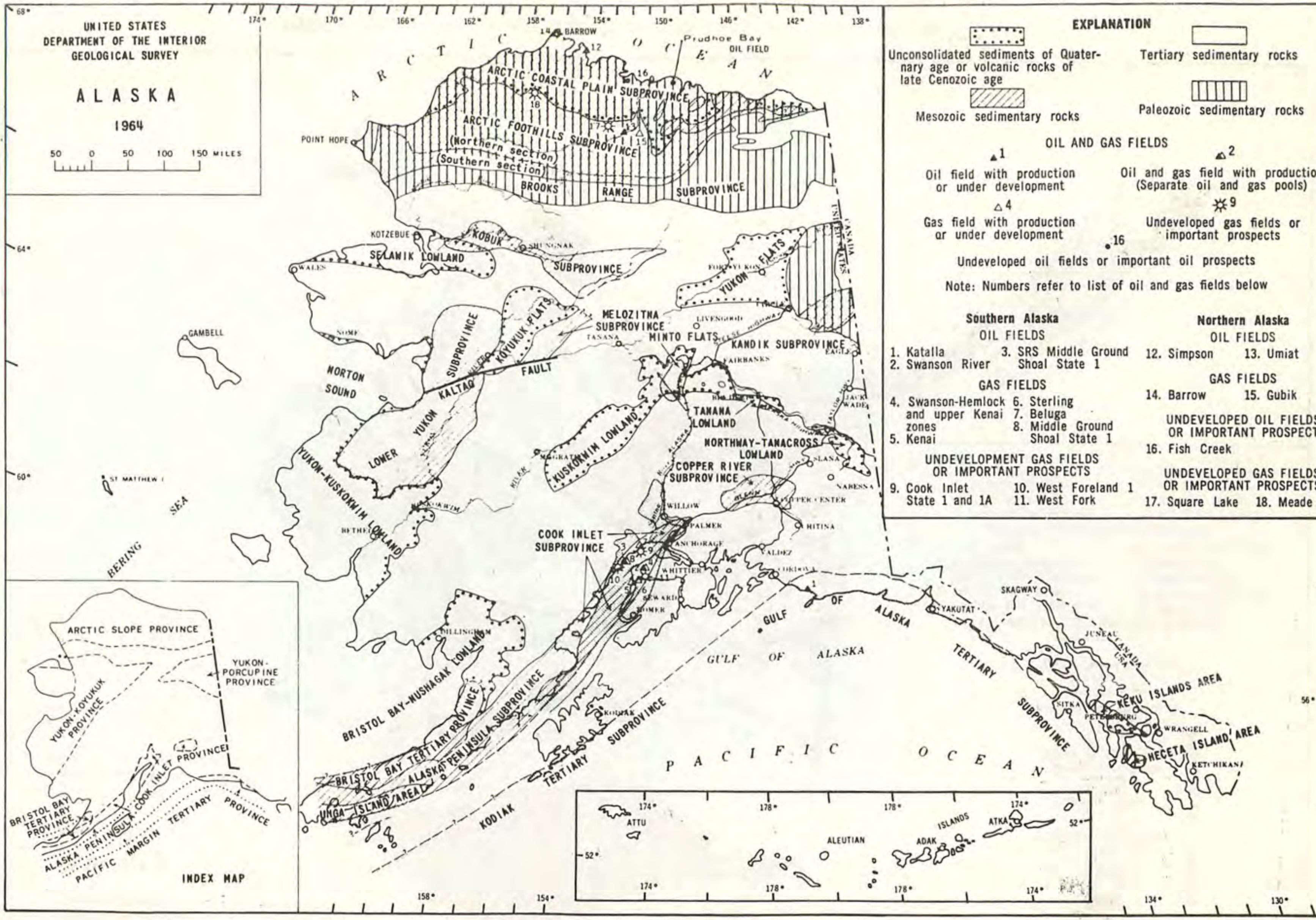

FIGURE 7. Areas considered Prospective for Oil and Gas in Alaska (after Gates, Grantz, and Patton.[14])

The Aleutian Islands extending seaward from the Alaska Peninsula are largely volcanic and are not considered prospective for petroleum.

Cook Inlet Subprovince—The Cook Inlet subprovince has been reevaluated in this report in considerable detail.

Oil in commercial quantities was discovered at Swanson River on the Kenai Peninsula by the Richfield Oil Corporation in 1957. Since 1957 six oil fields have been discovered and developed, and possibly as many as 18 gas fields (depending on the definition of individual fields) have been discovered. In 1968, 42 billion cubic feet of gas was produced from six fields and 66 million barrels of crude oil from the six oil fields. On the basis of a detailed analysis, it is concluded that within the Cook Inlet subprovince there is an area of 15,000 square miles that contains 16,700 cubic miles of Tertiary rocks that are favorable for petroleum accumulations.

The discovered oil-in-place is estimated at 2.6 billion barrels—the gas, at 5 trillion cubic feet. After considering the factors that affect the occurrence of oil and gas in the upper Cook Inlet, it is concluded that the industry may ultimately discover a total of 7.9 billion barrels of oil-in-place, and 14.6 trillion cubic feet of gas-in-place, provided: (1) new reserves are discovered in shallower and deeper pays in existing fields, (2) field limits are extended and new pools are discovered near existing fields, (3) new accumulations are discovered in stratigraphic traps, (4) drilling is conducted in areas now closed to leasing, (5) frontier areas such as the Susitna basin and the Mesozoic rocks which underlie the Cook Inlet subprovince are explored.

Alaska Peninsula Subprovince—Oil and gas seepages are known in middle and upper Jurassic rocks in the Alaska Peninsula subprovince. Shows of oil have been reported in test wells, but no commercial deposits have been discovered. The oil shows were in large broad anticlines in rocks of each series from the upper Jurassic to the upper Triassic. Gates, Grantz, and Patton [11] speculated that the failure to find commercial deposits may be related to facies factors and that large accumulations of petroleum may be difficult to find in Mesozoic rocks. However, they conclude that prospects for large and prolific deposits exist where Mesozoic rocks are overlain by Tertiary rocks containing good reservoir sandstones. A similar geologic setting may exist in the offshore area between Shelikof Strait and Unga Island.

Copper River Subprovince—The Copper River subprovince has been defined (reference 14) as an area of about 3,500 square miles in the southern half of the Copper River lowland underlain by marine sedimentary rocks of late Mesozoic age. Although the composite thickness of sedimentary rocks in the subprovince is about 25,000 feet, the average thickness is probably no more than half that, or perhaps 2 miles. This sequence is correlative with the petroliferous rocks in Cook Inlet and on the Alaska Peninsula.

The subprovince includes a possible source of petroleum in the predominantly marine Mesozoic sedimentary rocks, possible reservoir beds in these same rocks, and possible reservoir beds in Tertiary rocks that may underlie a thick surficial cover in the eastern half of the subprovince. Evidence of petroleum includes fetid odor in a few beds of Cretaceous age, gas shows in one or two test wells drilled in Mesozoic rocks, and several seepages of high-methane and nitrogenous natural gases.

Considering all factors, the Copper River subprovince does not appear to be as promising for commercial petroleum deposits as either the Alaska Peninsula or Cook Inlet subprovinces.

Bristol Bay Tertiary Province

The published information on the geology of this province is mainly from reconnaissance surveys of the few, scattered exposures along the margins of Bristol Bay and the Nushagak Lowland. Gates, Grantz, and Patton [11] summarized the available data and concluded that "The petroleum potential of the Bristol Bay Tertiary province lies in the presence, beneath a large area, of a fairly thick sequence of interbedded and intertonguing marine and coal-bearing nonmarine rocks of Tertiary age. By analogy with the Cook Inlet subprovince these Tertiary rocks are likely to contain porous and permeable beds which could serve as petroleum reservoirs."

Summarization of the exploration activities of the petroleum industry in the Bristol Bay province in recent years and further evaluation of the petroleum potential lead to the conclusion that an estimate of potential reserves in the basin is not possible, but the size and thickness of sediments indicate that recoverable reserves of one billion to five billion barrels of oil (or its gas equivalent) are a reasonable conjecture.

The Bristol Bay Tertiary province is bounded on the south by the Aleutian Range and on the northeast by the Ahklun Mountains and extends offshore in the Bering Sea to the continental slope in the vicinity of the Pribilof Islands. It is estimated that the basin comprises an area of approximately 95,000 square miles and contains sedimentary rocks ranging in thickness from 2,000 to 16,000, as well as volcaniclastic and layered volcanic rocks. An average thickness of 10,000 feet or 1.7 miles of sedimentary rocks seems reasonable. The best possibilities for petroleum deposits are believed to be in a wide belt of transition between a marine Tertiary section in the southwest part of the basin and a nonmarine Tertiary section in the northeast part of the basin. Other accumulations may be found in marine Mesozoic rocks of the southwest portion of the basin where large structures are known to be present.

Nine test wells, at least one with minor oil shows, have been drilled onshore but none offshore. About 80 percent of the basin is offshore. This report is somewhat more optimistic than that of Gates, Grantz, and Patton who point out the general lack of porosity and permeability and structural complexity of the rocks exposed onshore. The best possibilities for large petroleum accumulations are likely to be offshore.

Bering Sea Shelf

Scholl and Hopkins [12] have described and discussed three possible targets for petroleum exploration on the Bering Sea shelf. Using data from recent geophysical surveys and extrapolating the geology from the surrounding land areas, they have redefined the Norton basin, previously postulated and discussed by Payne (references 16 and 22) as an area of about 38,610 square miles (100,000 kilometers) extending from the Alaska shore across the Bering Sea to Cape Chukotsky, and delimited to the north by the Seward Peninsula and to the south by St. Lawrence Island. Scholl and Hopkins concluded that the basin is filled with no more than 6,560 feet (2,000 meters) of marine and nonmarine Cenozoic rocks similar to those in the Bristol Bay Tertiary province. The possible target area east of the International Dateline is about 25,010 square miles (65,000 square kilometers) and the average thickness is about 3,280 feet (1,000 meters) or 0.62 mile. The volume of sedimentary rocks of Cenozoic age above the acoustic basement is thus about 15,500 cubic miles or 65,000 cubic kilometers.

Scholl and Hopkins also described two graben-like structures, the Pribilof and Zemchug depressions, along the outer edge of the shelf, that appear to be filled with Cenozoic sedimentary deposits no more than 6,560 feet (2,000 meters) thick. The petroleum possibilities of these structures appear to be somewhat less than the Norton basin.

The results of studies in the 1969 season suggest that possible reservoir beds in rocks of Mesozoic age may also be present on the Bering Sea shelf (Scholl, personal communication) and Patton and Dutro [23] have reported the presence of at least 6,000 feet of favorable carbonate rock of Paleocene age on St. Lawrence Island.

Pacific Margin Tertiary Province

Abundant oil and gas seepages in the Katalla, Yakataga, and Malaspina districts, known since 1896, have been the major factors in encouraging petroleum exploration in the Pacific Margin Tertiary province. Seventy-one test and development wells have been drilled in this province, and one oil field was discovered at Katalla. From 1902 to 1933, 18 shallow wells in a 60-acre tract produced 154,000 barrels of paraffin-base oil.

The Pacific Margin Tertiary province is 900 miles long and 2 to 60 miles wide onshore. It extends from Chirikof Island (190 miles southwest of Kodiak) on the west to Cross Sound in southeastern Alaska. It is estimated that the total area of land and continental shelf underlain by Tertiary rocks is approximately 40,000 square miles. Roughly 25,000 square miles are believed to be underlain mainly by rocks of middle and late Tertiary age, and that these appear to have the best reservoir possibilities. Rocks of early Tertiary age, where exposed, are hard, tightly cemented, and dirty and appear to have little reservoir potential. The average thickness of the middle and late Tertiary is 10,000 to 15,000 feet, and thus the volume of these rocks is 50,000 to 75,000 cubic miles.

The Tertiary rocks are bordered on the north, and in part underlain, by highly deformed metamorphosed and intruded Cretaceous rocks and possibly older bedded sedimentary and volcanic rocks which are considered to have no potential for commercial petroleum deposits.

Yukon-Koyukuk Province

The Yukon-Koyukuk province was originally defined (reference 16) as an area of about 100,000 square miles underlain by Mesozoic rocks which, at that time, were largely undescribed and unmapped. In 1960-61 two deep test wells were drilled: a 12,000-foot test near Nulato on the Yukon River and a 15,000-foot test at Napatuk Creek in the Yukon-Kuskokwim Coastal Lowland. The wells were apparently dry.

From 1954 to 1968 the U.S. Geological Survey mapped the province at reconnaissance scale, and a few reconnaisance aeromagnetic profiles were flown across it.

The rocks of the Yukon-Koyukuk province are predominantly of Cretaceous age. The oldest Cretaceous (Neocomian) rocks are a thick sequence of volcanic and volcaniclastic rocks with local interbeds of graywacke, mudstone, and impure limestone. These are succeeded by high-rank graywacke and mudstone of late, early Cretaceous (Albian) age and by marine and nonmarine sandstone, shale, conglomerate, and coal of late early and late Cretaceous age.

The Cretaceous rocks are rimmed on the west, north, and southeast by metasedimentary rocks chiefly of Paleozoic age and locally by mafic volcanic and intrusive rocks of probable late Triassic or Jurassic age.

The structure of the Cretaceous rocks over much of the province is exceedingly complex. A major strike-slip fault, the Kaltag, with possibly as much as 40 to 80 miles of right-lateral offset, cuts the province between Unalakleet and Tanana (reference 24).

The general structural complexity of the rocks and the scarcity of favorable reservoir and source beds appear to limit the petroleum possibilities to areas underlain by rocks of shallow marine and nonmarine origin. It is suggested that the possible target areas may be limited to a belt approximately 20 miles wide and 300 miles long extending from the Kateel River southward to the Yukon-Kuskokwim Coastal Lowland and a small area roughly 20 miles wide and 80 miles long on the middle reaches of the Kobuk River. Thus, the favorable areas are confined to about 8,000 square miles containing an estimated total volume of shallow marine and nonmarine strata of about 13,000 cubic miles.

Four alluviated lowlands—Yukon-Kuskokwim Coastal Lowland, Kobuk-Selawik Lowland, Koyukuk Flats, and Innoko Lowlands—comprise about one-third of the Yukon-Koyukuk province. The bedrock geology of these lowlands is unknown. A thick veneer of Quaternary alluvial deposits covers these areas. Their original definition as possible petroleum provinces was based on the possibility of underlying Tertiary and (or) Mesozoic rocks with characteristics favoring accumulation of petroleum.

The Yukon-Kuskokwim Coastal Lowland, sometimes referred to as the "Bethel Basin," covers about 30,000 square miles. Although Quaternary alluvial deposits cover almost all the area there are a few scattered exposures of Cretaceous rocks, so these rocks may underlie part of the area. It is not known whether any Tertiary rocks are present beneath the alluvium. The possible thickness of such rocks is entirely conjectural. Limited aeromagnetic data suggest that the other lowlands mentioned above are not favorable petroleum exploration targets, with the possible exception of the western part of the Kobuk-Selawik Lowland, where relatively smooth profiles suggest that the Kobuk Delta and Kotzebue Sound may be underlain by Cretaceous and (or) Tertiary sedimentary deposits.

Arctic Slope Province

Introduction and History—The Arctic Slope, also called the North Slope, includes an area of more than 100,000 square miles of which at least 70,000 square miles are considered potentially petroliferous. The average thickness of sedimentary rocks is about 3 miles, and the total volume about 210,000 cubic miles.

Oil seepages along the Arctic Coast have been known since early 1900. Oil company geologists made an effort to stake the area in 1921 under the old mining laws. In 1923, President Harding set aside 37,000 square miles of the North Slope as Naval Petroleum Reserve No. 4 (NPR-4). At the request of the U.S. Navy, the U.S. Geological Survey explored the area from 1923 to 1926 and published the results (reference 25).

From 1944 to 1953, the U.S. Navy explored NPR-4 and the adjacent area, using all the modern oil exploration techniques. Fifty-seven test wells were drilled; 36 reached basement and 21 were shallow Cretaceous tests in and near Umiat. Oil fields were found at Umiat (70 to 100 million barrels) and at Simpson Seeps (12 million barrels), and a prospective field was found at Fish Creek. Gas fields were found at Barrow (5 to 7 billion cubic feet) and Gubik (300 billion cubic feet), and prospective gas fields at Meade, Square Lake, and Wolf Creek.

After 1952, seven more shallow Cretaceous tests were drilled by private interests in a small area south and east of Umiat, and a deep test (Susie No. 1) was drilled to the Jurassic.

In 1966 and 1967, two tests that penetrated Mississippian rocks were drilled on the Colville Delta. In 1968 the Atlantic Richfield Company discovered gas and oil in a Triassic sandstone in the Sadlerochit Formation and gas and oil in a Mississippian limestone in the Lisburne Group at Prudhoe Bay. In 1969 oil and gas were discovered in Jurassic and (or) Cretaceous rocks about 30 miles northwest of the Prudhoe field discovery well and a sizable gas deposit was discovered about 65 miles to the southeast. This has led to intensive drilling in that region. Estimates of recoverable oil reserves range from 5 to 50 billion barrels for the North Slope.

In the broadest terms, the geologic framework relevant to the petroleum possibilities of northern Alaska consists of four major structural belts and two major depositional cycles. The structural belts are (1) the Brooks Range geanticline or uplifted belt of faulted structures, mainly involving thick competent Paleozoic rock units; (2) a disturbed belt of shallow thrusts involving Paleozoic and Mesozoic rocks in the southern foothills of the Brooks Range and in the DeLong Mountains; (3) the deep Colville geosyncline consisting of Cretaceous rocks; and (4) a broad northern regional high including the Barrow Arch and the Prudhoe Bay structure. The first depositional cycle, which Tailleur [17] has called the Arctic Alaska basin, began in the Silurian or Devonian and continued to the Jurassic. This basin extended across the site of the present Brooks Range into central Alaska. The northern shoreline oscillated from about the latitude of the present Arctic Coast to the Brooks Range. Early Jurassic to Cretaceous uplift, thrusting, and igneous activity disrupted the arctic Alaska basin and formed a fold belt in the area of the present Brooks Range and a new depositional trough, the Colville geosyncline, to the north. Erosion of the fold belt provided a flood of flysch sediments to a foredeep along the south edge of the Colville geosyncline and, later, of molasse sediments to a succession of basins progressively moving and filling north across the subsiding geosyncline. The source of sediments was from the south, whereas the source of the late Paleozoic and Triassic sediments was primarily from the north.

The 15,000-foot depth to basement has been generalized on Figure 8 from the published reports of Payne et al.[26] and Woolson et al.[27]

The petroleum possibilities of the Arctic Slope have been analyzed periodically (references 14, 16, and 20). Figure 7 depicts the prospective areas by geomorphic units: the Brooks Range, Arctic Foothills, and Arctic Coastal Plain subprovinces.

The North Slope petroleum potential has been reviewed utilizing all available information. Most of the subsurface data from the Prudhoe Bay area have not been published and are unavailable for study because of the competitive aspects of leasing and development.

Brooks Range Subprovince—The southern half of the Brooks Range is composed chiefly of metamorphosed middle and upper Devonian strata and locally large granitic plutons. These rocks are not considered to be potentially petroliferous. The northern half of the western and central Brooks Range consists of upper Devonian, Mississippian, Permian, and Triassic rocks which, although structurally complex, are not metamorphosed and conceivably could be petroliferous. Older rocks, including metamorphosed sediments, are exposed in the eastern Brooks Range.

The limestone of the predominantly Mississippian Lisburne Group appears to have the best reservoir possibilities in the Brooks Range, but it is widely exposed and thus not a prospective drilling target within the range. In the western and central Brooks Range and in the immediately adjacent southern section of the Arctic Foothills, the limestone and associated rocks have been broken and thrust northward onto the Mesozoic rocks of the foothills. This structural unit, about 8,000 square miles, has been called the Disturbed Belt, and its petroleum potential is predicated on the possibility of carbonate reservoir beds in buried thrust plates. The total thickness of sedimentary rocks in this belt is probably no less than 20,000 feet.

Arctic Foothills Subprovince—The southern section of the Arctic Foothills is included in part in the Disturbed Belt, discussed above. Strata of the southern foothills are everywhere complexly folded and faulted.

The Mesozoic rocks in the southern foothills are predominantly poorly sorted and generally impermeable graywackes, with poor reservoir characteristics. However, the possibility of finding Paleozoic limestone or locally cleaner sandstones within drillable depths appears to warrant further exploration in the southern foothills. Oil shale has been found in both Triassic and Jurassic beds, and fracture fillings of asphaltic material have been reported in Cretaceous rocks. These organic shales and the organic Mississippian carbonate rocks may have been a source of petroleum. No wells have been drilled in the southern foothills.

The northern foothills include most of the Colville geosyncline and are underlain by middle and upper Cretaceous clastic sedimentary rocks that range in thickness from 6,000 to 20,000 feet. Structures are generally broad and open at the surface, but structural complications such as thrust plates at depth cannot be ruled out for at least part of these foothills.

Several wells, mostly within NPR-4, have been drilled in the northern foothills, and the results of this drilling have been discussed. The favorable reservoir sandstones in the Cretaceous appear to be limited to strand-line facies in the zone of interfingering marine and nonmarine strata.

Only one test well in the northern foothills within NPR-4, the deep test at Oumalik, penetrated the

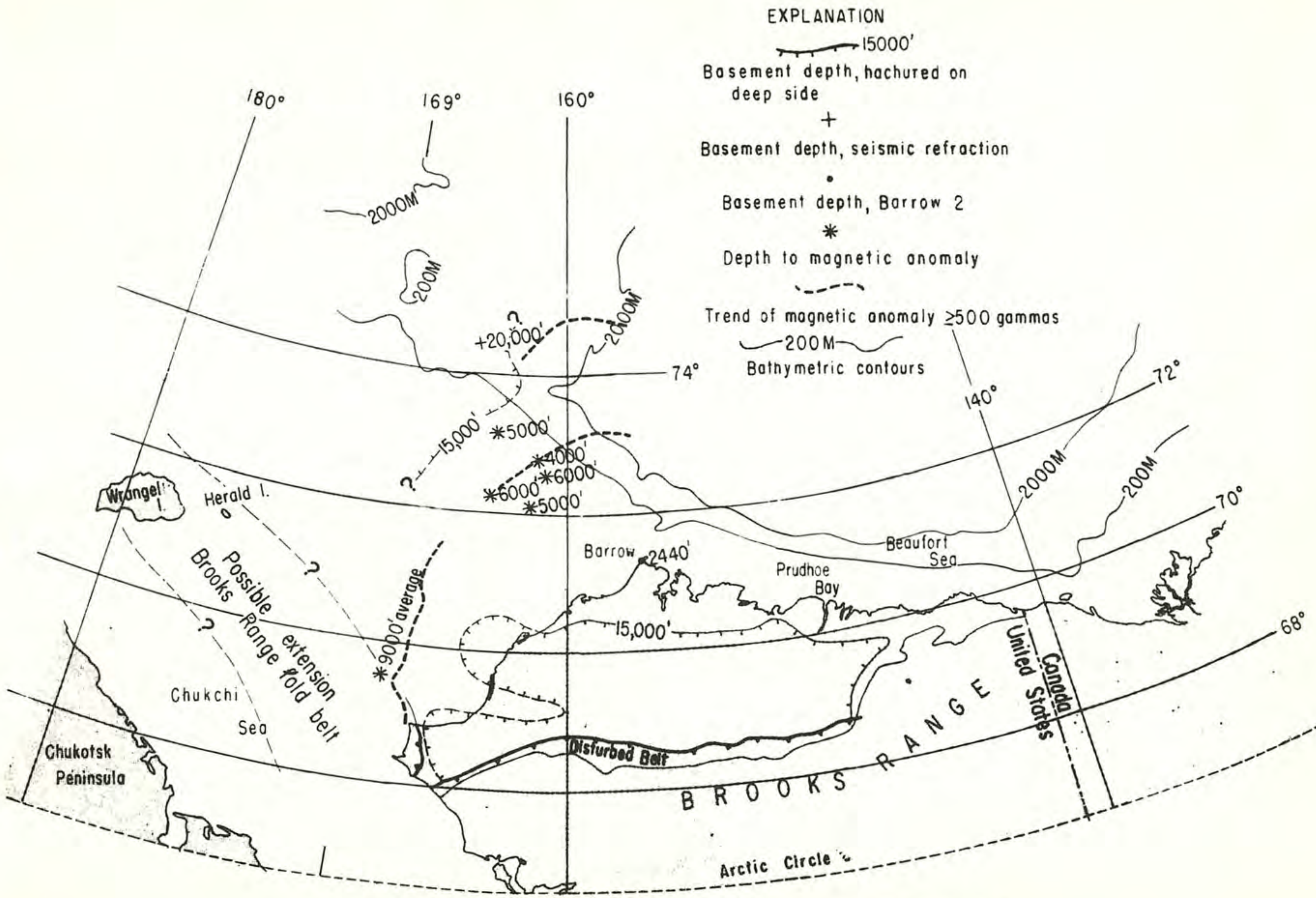

FIGURE 8. Possible Configuration of Basement Onshore and Offshore, Arctic Slope Province

TABLE 3. AREA AND VOLUME OF SEDIMENTARY ROCKS IN THE MORE FAVORABLE PARTS OF THE POSSIBLE PETROLEUM PROVINCES OF ALASKA

Province	Subprovince	Area (square miles)		Volume of Sedimentary Rocks (cubic miles)	
		Subprovince	Province	Subprovince	Province
	Cook Inlet	15,000		16,700	
	Alaska Peninsula	No estimate		No estimate	
	Copper River	3,500		7,000	
Alaska Peninsula-Cook Inlet			30,000		60,000
Bristol Bay			95,000		161,500
	Norton Basin		25,000		15,500
Bering Sea Shelf (exclusive of Norton Basin)		No estimate		No estimate	
Pacific Margin Shelf			25,000		50 to 75,000
	Yukon-Kuskokwim Lowland ("Bethel Basin")	30,000		No estimate	
Yukon-Koyukuk			8,000		13,000
	Brooks Range ("Disturbed Belt" only)	8,000		30,000	
	Arctic Foothills	42,000		140,000	
	Arctic Coastal Plain	20,000		40,000	
Arctic Slope			70,000		210,000
	Chukchi Basin, northern	90,000		270,000	
	Chukchi Basin, southern	30,000		39,000	
	Beaufort Shelf	20,000		40,000	
Arctic Ocean Coastal Shelf			140,000		349,000

lowest Cretaceous (Neocomian) section. East of NPR-4, Susie No. 1 was drilled to the Jurassic. Thus, the petroleum possibilities beneath the northern foothills have not been tested. However, prospective older horizons are apt to be more than 15,000 feet deep, except to the east, where the Cretaceous thins against the Romanzof uplift. If large thrusts extend into the northern foothills, older horizons may be reached at shallower depths.

The reservoir possibilities of separate units of the Cretaceous have been analyzed in considerable detail and the results are generalized in Table 3.

Arctic Coastal Plain Subprovince—The Arctic Coastal Plain has been explored to some extent within NPR-4 and is now being explored extensively east of NPR-4. The Prudhoe Bay field is entirely within the coastal plain.

The dominant structural and stratigraphic feature of the coastal plain is the platform or shelf developed over a basement high of pre-Mississippian rocks that is as shallow as 2,500 feet at Barrow, 8,000 to 10,000 feet deep at Prudhoe Bay, and is exposed in the Romanzof uplift. This feature, the Arctic Platform, was a stable area onto which Mississippian through Jurassic sediments lapped from the south.

The favorable area of the Arctic Platform covers about 20,000 square miles. The thickness of the possible reservoir beds has been analyzed in detail, but only the totals have been included in Table 3 of this report.

Arctic Ocean Coastal Shelf—The continental shelf of the Beaufort and Chukchi Seas, extending from the Alaska-Canada boundary west to the International Dateline (169°W long.) south to the Seward Peninsula and seaward to the 200-meter bathymetric contour, is an area of about 140,000 square miles (see Figure 8). The Arctic Platform structural rise, along which the Barrow gas field and Simpson and Prudhoe Bay oil fields are located, probably extends a short distance off the coast and then dips seaward. In the Beaufort Sea an area of 20,000 square miles adjacent to the Arctic Coast must be considered prospective for oil and gas because of its proximity to onshore deposits. The average thickness of sedimentary rocks is probably less than in the onshore Colville geosyncline and may be assumed to be about 2 miles; the total volume would thus be 40,000 cubic miles.

The work of Ostenso and Parks,[28] Hunkins,[29] and Bassinger[30] provides geophysical evidence for the offshore configuration of the Chukchi basin. This evidence is graphically summarized in Figure 8. Recent work by the U. S. Geological Survey in collaboration with the U. S. Coast Guard indicates a seaward extension of the folded Cretaceous rocks of the Colville geosyncline and an extension of the Brooks Range fold belt, including the zone of thrust faulting, northwest from Cape Lisburne to Herald Shoal, Herald Island, and Wrangel Island (A. Grantz, personal communication).

Grantz has suggested that some 90,000 square miles in the part north of the fold belt is underlain by upper Cretaceous and older sedimentary rocks with an average thickness of 3 miles that are prospective for oil, gas, and coal, and some 30,000 square smiles in the part south of the fold belt is underlain by Tertiary (?) sedimentary rocks that may be prospective for gas, coal, and perhaps oil. The thickness of the Tertiary (?) may average a little over 1 mile, perhaps 1.3 miles. The total volumes are thus 270,000 and 39,000 cubic miles.

Yukon-Porcupine Province

The possibility of petroleum accumulations in east-central Alaska was first noted by Gryc, Miller, and Payne[20] and has been reviewed periodically—most recently by Churkin and Brabb.[13] The province is a triangular area of about 15,000 square miles bounded on the east by the Alaska-Canada boundary, on the northwest by the Porcupine River, and on the south by the Yukon River. About 3,000 square miles of this area are believed to be covered by volcanic rocks.

No wells have been drilled in this province, but several test wells drilled in the Eagle Plain 100 miles east in Canada have yielded natural gas under high pressure, and the geologic setting there is similar to that of this province.

Favorable indications include thick sections of marine sedimentary rocks including oil shale and other organic-rich rocks, reef-like carbonates of Paleozoic age, and suitable structures.

Unfavorable characteristics include complicated and breached structures, scarcity of reservoir rocks at the surface, and igneous activity. The prospective area is relatively small and bounded by structurally complex positive tectonic elements.

A thick section of sedimentary rocks representing nearly every period of geologic time is exposed in this province. Pre-Cambrian rocks, more than 10,000 feet thick, consist mainly of unmetamorphosed shale, limestone, and dolomite. They are overlain with apparent conformity by 12,000 feet of Paleozoic rocks consisting mainly of shale, bedded chert, and some thin limestone units in the Kandik River area. Along the Porcupine River in the northern part of the province more than 5,000 feet of Ordovician to Permian carbonates are exposed. In the Kandik area there is a major unconformity at the base of the Permian. Permian rocks rest on formations as young as Carboniferous and as old as Pre-Cambrian. The Paleozoic rocks are overlain by about 12,000 feet of Triassic, Jurassic, and lower Cretaceous marine rocks, which in turn are overlain with marked unconformity by 3,000 feet of upper Cretaceous and Tertiary nonmarine rocks.

The total aggregate thickness is about 37,000 feet. Estimates of average thickness are highly conjectural because of the structural complexity; a reasonable guess of average thickness may be 3 miles. Although the entire province covers 15,000 square miles, Churkin and Brabb[13] have suggested that the area prospective for oil and gas is relatively small and lies between the Kandik and Nation Rivers. Thus an estimate of 45,000 cubic miles for the total volume of sedimentary rock favorable for the accumulation of oil deposits in this province may be misleading and has not been included in Table 3.

Other Lowlands of Interior Alaska—An arcuate belt of lowlands in interior Alaska was first included with possible petroleum provinces by Miller, Payne, and Gryc.[16] Indications and arguments for possible petroleum accumulation included gas shows in some shallow tests, the possibility that Tertiary marine rocks or other favorable rocks might underlie the Quaternary sediments which fill these topographic basins, and the possibility that some of these basins might be structural as well as topographic.

More recent evidence, including geologic mapping and geophysical surveys, argues against the possibility of commercial petroleum deposits in these lowlands, except for possible small methane gas accumulations.

Southeastern Alaska

Igneous and metamorphic rocks underlie most of southeastern Alaska. However two areas, Heceta and Keku Islands, were noted as being anomalously underlain by unmetamorphosed Paleozoic or Mesozoic rocks and conceivably could contain petroleum.[16] A third area, extending from Admiralty Island to Zarembo Island, includes Tertiary coal-bearing beds and this conceivably could contain petroleum deposits. However, there is no direct evidence of petroleum, and the areas are relatively small. For the purpose of this evaluation, tabulation of area and volume seems unwarranted.

CHAPTER 4
REGION 2. PACIFIC COAST STATES

Coordinator

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SUMMARY

Because the authors for this region ventured estimates of future additions to oil-in-place for most areas, the areas are discussed in the order of the estimates given in Table 4. Location of the areas is shown in Figure 9.

CALIFORNIA

Southern California Offshore

This undrilled area is considered the most prospective area in the region on the basis of the evidence of several northwest-southeast trending basins containing rich "Los Angeles basin-type" Pliocene and upper Miocene source beds, and on the assumption that thick sandstone reservoirs are developed basinward within these basins, as in the Los Angeles basin. Structural and stratigraphic traps are confidently expected. The known and assumed geology certainly justifies the drilling of several exploratory wells in water as deep as 6,000 feet. Until these wells are drilled, however, any appraisal of the potential has to be regarded as highly speculative.

Santa Barbara Channel

This structurally complex area of thick Tertiary and Cretaceous sedimentary rocks (estimated average thickness 40,000 feet) is the seaward extension of the prolific Ventura basin. Oil fields have been found, and more are expected. Confidence in the area is indicated by the very substantial lease bonuses paid for leases. One oil well has been completed in water 1,300 feet deep, and the future of the area depends, in part, upon developing economical means of drilling, completing, and producing wells in still deeper water.

San Joaquin Valley

Several sparsely drilled, prospective areas remain in this extensively explored basin, which include areas where the quality of seismic data has been poor (hence little drilling), areas of low structural relief where the possibility of stratigraphic traps definitely is indicated, and areas underlain by thick, largely untested sedimentary rocks. Crude oil fields rather than natural gas fields are anticipated in the southern part of the valley and additional natural gas fields are expected in the northern, sparsely explored Cretaceous gas area.

Ventura Basin

This important oil-producing basin has been extensively explored, but unquestionably important accumulations of crude oil remain undiscovered in complex structural and stratigraphic traps. Several objectives are at untested depths in a Tertiary and Cretaceous sedimentary column as thick as 55,000 feet. Perhaps important natural gas fields, rather than oil fields, exist below 15,000 or 20,000 feet.

Los Angeles Basin

Exploration of this richest of U. S. oil basins has been, and will continue to be, hampered not by geologic conditions but by urban and suburban growth. Important accumulations of crude oil doubtless remain undiscovered in lower Pliocene and upper Miocene strata in the deeper part of the basin (maximum depth approximately 25,000 feet), in the San Gabriel Valley in the northeastern part of the basin, and in complex traps along known producing trends.

Central Coast Ranges

Unusually complicated structure and stratigraphy occur throughout this area. The three major oil fields, which account for 90 percent of the estimated 2.5 billion barrels of proved oil-in-place, are associated with complex thrust faults, whereas most of the obvious structural featues have been unproductive. It is believed that other important accumulations exist, but that they may be even more thoroughly obscured by complex geology. Obviously, intensive and imaginative geologic study, and a liberal program of exploratory drilling are required to uncover any new discoveries that may be possible here.

Sacramento Valley

This area has been the most important producer of nonassociated (dry) gas in California, and important discoveries of dry gas (but probably not oil), mainly in stratigraphic traps in Eocene and Cretaceous strata, are confidently expected. Important accumulations in deeper strata are considered less likely, but the great volume of untested lower Cretaceous strata on the west side of the valley presents a challenge to the future.

Central and Northern California Offshore

Recent geological and geophysical work and 15 exploratory dry holes have revealed 6 late Tertiary basins which essentially are extensions of onshore basins. Miocene and Pliocene strata resemble their onshore equivalents, but generally are thinner. Sandstone units of reservoir quality are probably present in all areas. The 12 structurally well-located dry holes drilled in the Bodega and Point Arena basins found adequate reservoirs but only a few showings of crude oil. Although results of exploratory drilling have been discouraging, the central and northern California offshore cannot be considered condemned, particularly in water deeper than 1,200 feet.

OREGON AND WASHINGTON, OFFSHORE AND ONSHORE

The section of sedimentary rocks ranging in age from Eocene to Pliocene attains a thickness of approximately 25,000 feet offshore, and contains potential source and reservoir rocks, structural traps, and probably stratigraphic traps. Surface oil, and gas seeps, and showings in exploratory wells are not uncommon. Yet, approximately 150 dry holes have been drilled on land, and 11 dry holes have been drilled offshore, all in geologically favorable areas. The lack of commercial production may be due to the noncoincidence of source rocks, reservoir rocks, and traps in the locations drilled. Offshore basins containing thick upper Miocene and Pliocene strata, which are thin or absent onshore, offer the greatest potential in the Pacific Northwest. The potential appears to be of a low order, but still much higher than the areas mentioned next.

OTHER AREAS

It is likely that some new crude oil will be found in the Santa Maria and Northern Coast Ranges of California. The southern coastal area and Imperial Valley have been extensively drilled without encouraging results. The geology of the Eastern Desert-Sierra Nevada area is not conducive to the occurrence of crude oil or natural gas fields.

Very speculative areas include the Klamath Mountain subthrust area in the Northern Coast Ranges, and five areas in the generally lava-covered area of northeastern California, eastern Washington, and Oregon.

DISCUSSION

INTRODUCTION

For the purposes of this report, Region 2—comprising the Pacific Coast States of California, Oregon, and Washington, and the adjacent continental shelf and slope—has been divided into 18 areas encompassing not only the sedimentary basins, but also the mountains and less promising areas of basement and volcanic rocks. Figure 9 shows the location of these areas.

Total area of the sedimentary basins in Region 2 is calculated to be 124,573 square miles, and the estimated volume of sedimentary rock is 249,750 cubic miles. It is concluded that these basins contain 114.3 billion barrels of undiscovered petroleum in place, including gas equivalents (see Table 4). Most of this total is expected to be found beneath the unexplored waters of the continental shelf; however, the known productive basins still have an attractive exploration future. New ideas, some "far out," have been advanced that make several of the unproductive and untested provinces worthy of further consideration.

In order to summarize the results of this study, it was found desirable to divide the areas into three groups: (1) the offshore areas—all in the early stages of exploration and with much of the geology unknown; (2) the productive onshore basins—most in the late mature stage of exploration; and (3) areas in which no production has been found to date.

OFFSHORE GEOLOGY AND PETROLEUM POTENTIAL

Group 1, the offshore areas, offers the greatest potential for future reserves. The sedimentary basinal areas total 54,795 square miles and contain an estimated 93,350 cubic miles of sedimentary rock. A total of 89 billion barrels of oil-in-place is predicted.

Southern California

Foremost among the prospective areas in Group 1 are the offshore basins on the southern California continental shelf and slope (Area 15). A potential of 75 billion barrels of oil-in-place is indicated, which is nearly three quarters of the total amount predicted for Region 2. The southern California continental shelf and slope are wider than at any other point along the Pacific Coast; they cover an area of 18,750 square miles, and contain several northwest-southeast-trending basins with good evidence of rich "Los Angeles basin-type" Pliocene and upper Miocene source beds. Total sedimentary rock volume is estimated as 17,780 cubic miles compared with 2,250 cubic miles for the Los Angeles basin, and total volume of Pliocene-upper Miocene units indicates 5,323 cubic miles for Area 15 compared with 1,600 cubic miles for the Los Angeles basin. Critical factors in evaluating this area are the amount and quality of reservoir beds in the Pliocene and upper Miocene. Sampling around the margins of these offshore basins has revealed a paucity of reservoir beds. However, a similar condition exists in the Los Angeles basin, where the

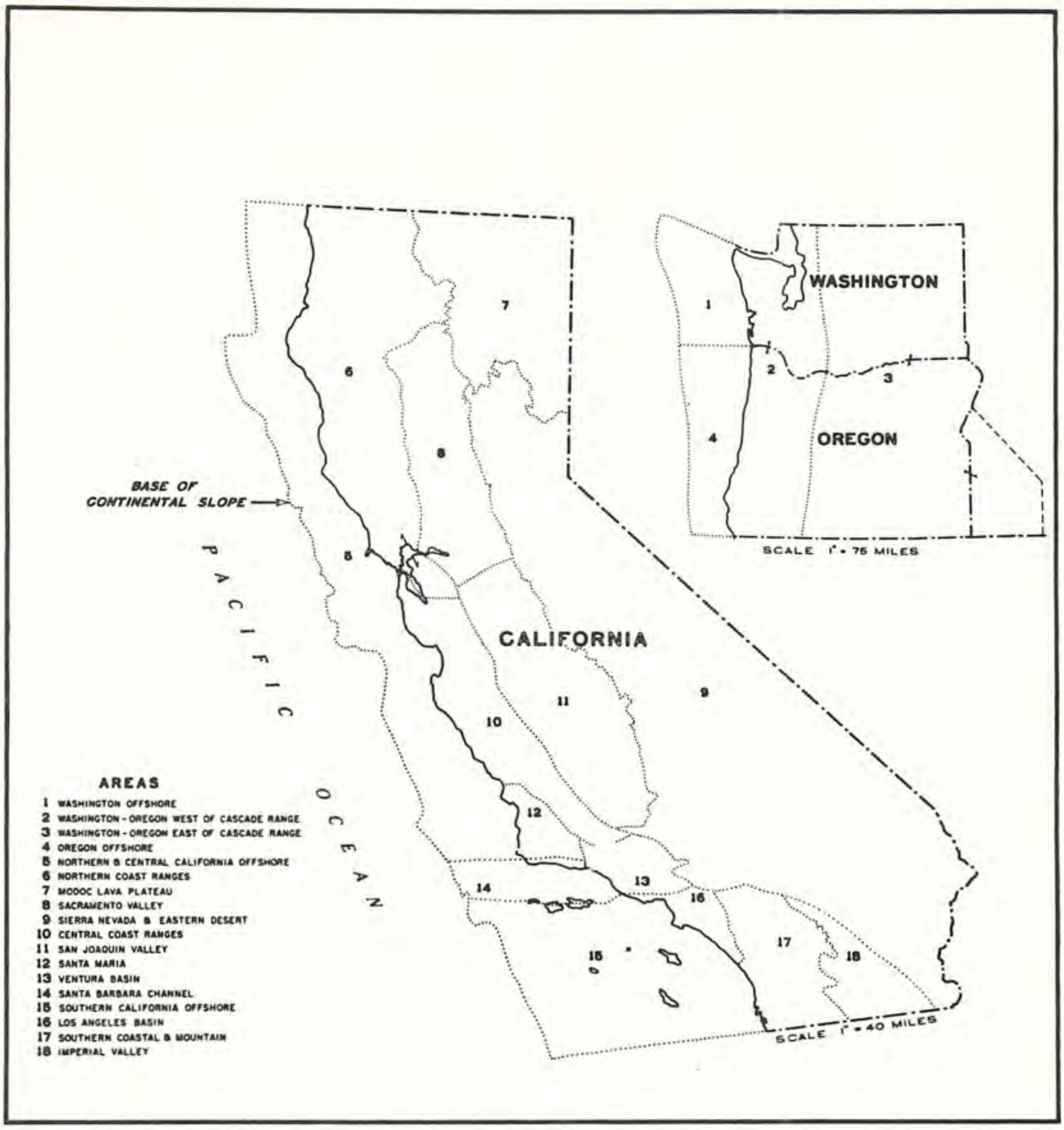

FIGURE 9. Index Map of Region 2, Pacific Coast, Showing Report Areas

thick, prolific, petroleum-bearing sandstones are in the central part of the basin and the exposed rocks around the margins consist primarily of compact shale and siltstone. The great distance of the offshore basins from onshore sources of coarse clastic sediment for reservoirs makes it necessary to postulate the existence of unknown seaward sources, or of long-distance turbidity currents, to furnish reservoir beds comparable with those in the Los Angeles basin. Test holes are needed in the deep-water centers of these offshore basins to determine whether reservoir-quality rocks are present.

The older objective beds, ranging in age from middle Miocene through Eocene, are known from ocean-bottom sampling to contain permeable sandstone, and they constitute a large "plus" value. This part of the section has been very productive in the Ventura basin on the north, but has been insignificant in the Los Angeles basin.

The primary reason for the lack of exploration in Area 15 has been the great water depths (up to 6,000 feet). However, it is expected that advances in drilling technology will permit exploration of this area within the next decade or two.

Santa Barbara Channel

Area 14, the Santa Barbara Channel, is much better known than the other offshore areas. Production has been obtained for many years from fields along the Santa Barbara coastline, and, during the last 10 years, State leases paralleling the shore within the 3-mile limit have yielded substantial new discoveries. Even more recently the oil industry showed its high esteem for this area by paying \$602,719,261 for 74 blocks in Federal waters in the

TABLE 4. REGION 2 SUMMARY OF STATISTICS

	1 (Area Number)	2 Area (square miles)	3 Volume of Sediments (cubic miles)	4 Speculative Areas (square miles)	5 Cumulative Oil Prod. to 1/1/69 (million barrels)	6 Cumulative Gas Prod. to 1/1/69 (billion cubic feet)	7 Est. Recoverable Oil Reserves 1/1/69 (million barrels)	8 Estimated Gas Reserves 1/1/69 (billion cubic feet)	9 Est. Undiscovered Oil in Place (million barrels)	10 Est. Undiscovered Gas in Place (billion cubic feet)
GROUP 1										
OFFSHORE BASINS										
Western Washington and Oregon	1 and 4	20,000	50,000	1,800	0	0	0	0	No estimate	No estimate
Northern and Central California	5	13,645	15,250		0	0	0	0	No estimate	No estimate
Santa Barbara Channel[1]	14	2,400	10,320		208.2	266.5	600.0	210.6[1]	14,000.0	Note[3]
Southern California	15	18,750	17,780		0	0	0	0	75,000.0	Note[3]
Subtotal		54,795	93,350	1,800	208.2	266.5	600.0	210.6	89,000.0	
GROUP 2										
PRODUCTIVE ONSHORE BASINS										
Western Washington and Oregon	2	26,000	50,000		.1	No estimate	No estimate	0	No estimate	No estimate
Northern Coast Ranges	6	4,400	6,600	5,000	.3	45.2	.7	48.7	13.0	50.0
Sacramento	8	11,578	44,000		4.2	4,267.0	5.0	2,445.0	0	5,822.0[1]
Central Coast Ranges	10	4,200	4,500		472.0	7.5	180.0	1.7	2,500.0	Note[3]
San Joaquin	11	15,000	35,000		6,085.9	676.0	1,715.0	537.0	12,666.0	Note[3]
Santa Maria	12	1,700	1,100		556.4	.2	138.0	No estimate	600.0	Note[3]
Ventura	13	2,300	6,600		1,479.8	14.7	307.0	13.9	4,950.0	Note[3]
Los Angeles	16	1,400	1,600		5,867.0	37.6	1,779.3	10.2	4,000.0	Note[3]
Subtotal		66,578	149,400	5,000	14,465.7	5,048.2[1]	4,125.0	3,056.5[1]	24,729.0	5,872.0[1]
GROUP 3										
UNPRODUCTIVE & UNFAVORABLE AREAS										
Eastern Washington and Oregon and Southwest Idaho	3			21,500	0	1.3	0			
Modoc Lava Plateau	7			2,500	0	0	0			
Sierra Nevada & Eastern Desert	9				0	0	0			
Southern Coastal and Mountain	17				0	0	0			
Imperial Valley	18	3,200	7,000		0	0	0			
Subtotal		3,200	7,000	24,000	0	1.3	0			
REGION 2 TOTAL		124,573	249,750	30,800	14,673.9	5,316.0[4]	4.725.0	3,267.1[1]	113,729.0	5,872.0[1]
								Equating all gas to oil—	114,316.2[2,4]	

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political and technological factors in the future.

[1] Nonassociated or dry gas only.

[2] Formula used for equating gas to oil: 10 thousand cubic feet = 1 barrel.

[3] Figures equated to oil and included in column 9 figures.

[4] Includes sum of oil total (column 9) plus total (column 10) equated to oil.

channel. Since this last sale, at least two major discoveries have been made on Federal leases.

Area 14 contains 4,200 square miles and is the westerly extension of the onshore Ventura basin; it is believed to have an average of more than 40,000 feet of sedimentary section along the axis of the westerly-trending sedimentary trough. The existence of 14 billion barrels of oil-in-place is predicted in reservoirs ranging in age from late Pliocene through Cretaceous. The geology of the area is favorable for the presence of many traps, both structural and stratigraphic, where petroleum accumulations may exist.

A sizable part of the inner channel has not been put up for bid, and the area west of the Channel Islands is completely unexplored, but probably contains some oil-bearing sedimentary strata.

Central and Northern Shelf and Slope

Area 5 comprises the northern and central California offshore. Recent geological and geophysical work and exploratory drilling have revealed the presence of six Tertiary sedimentary basins covering a total area of 13,645 square miles and having an estimated total sedimentary rock volume of 15,250 cubic miles. These basins began to form late in middle Miocene time, and all have a Plio-Miocene section closely resembling their onshore equivalents. The offshore Santa Maria basin (Figure 10, Basin F) is the only one whose onshore counterpart has yielded major production, and it was primarily from fractured shale. Sandstone units of reservoir quality are found in all of the basins, but the best sandstone development is in the Bodega basin (Figure 10, Basin D). In general, the sedimentary section in all of the basins is thinner than it is onshore.

Fifteen unsuccessful exploratory wells have been drilled on offshore structures. Eight of them were drilled in the Bodega basin on apparently closed structures with good reservoir sandstones. However, most of these basins have not been tested adequately because large parts of them are in water deeper than 1,200 feet. Encouragement is offered by the numerous oil and gas showings logged in coreholes and ocean-bottom samples. No estimate has been made of the petroleum potential of Area 5, but the area certainly should be considered as a "probable" petroleum province.

Oregon and Washington, Offshore and Onshore

This area, Oregon and Washington, offshore (Areas 1,4) and onshore (Area 2), has a marine Tertiary section with sufficient area, thickness, and volume (100,000 cubic miles) to be attractive for exploration. The main basin syncline is offshore, where geophysical surveys have revealed still-untested structural features. Commercial production eventually may be found despite the lack of good shows in the few wells drilled to date, the few reservoir beds, the eugeosynclinal nature of the sediments, and the rather common occurrence of gabbroic intrusive rocks and basic volcanic flows. The onshore area with 150 significant dry holes is less attractive.

Résumé

In Group 1, exploration of offshore areas will be facilitated by modern seismic techniques, which already have led to the discovery of favorable anticlinal structures, many yet untested. Most of the future offshore petroleum probably will be found in structural traps, but exploration should reveal stratigraphic traps that could contain substantial accumulations. The rugged relief of the Pacific Coast continental shelf and the extreme water depths pose a difficult drilling problem, but modern technology is overcoming this obstacle.

CALIFORNIA ONSHORE

Group 2, California's productive onshore basins, offers the most promising source for future petroleum reserves. It is estimated that a total of 24.729 billion barrels of petroleum is present in this area. These accumulations may be more difficult to find than those offshore, because many of them may be present in small or deep traps, and economics will greatly affect exploration for such accumulations. Experience suggests that large oil fields may be found which are completely hidden by the complexity of the subsurface, as well as the outcrop.

San Joaquin Valley

Area 11, the San Joaquin Valley, has produced more petroleum and probably has more undiscovered reserves than any other California onshore basin. A reserve of 12,666 billion barrels of oil-in-place (including gas equivalents) is estimated. Of this total, 33 percent is expected to come from the central valley area; 18 percent from the Bakersfield arch; 7.5 percent from the west side; 7.5 percent from the relatively unknown, deep synclinal area at the south end of the valley; 3.75 percent from the east side; and 3.75 percent from the extreme south end. The northern San Joaquin Valley Cretaceous gas area has been explored only sparsely and could contain the gas equivalent of as much as 3.3 billion

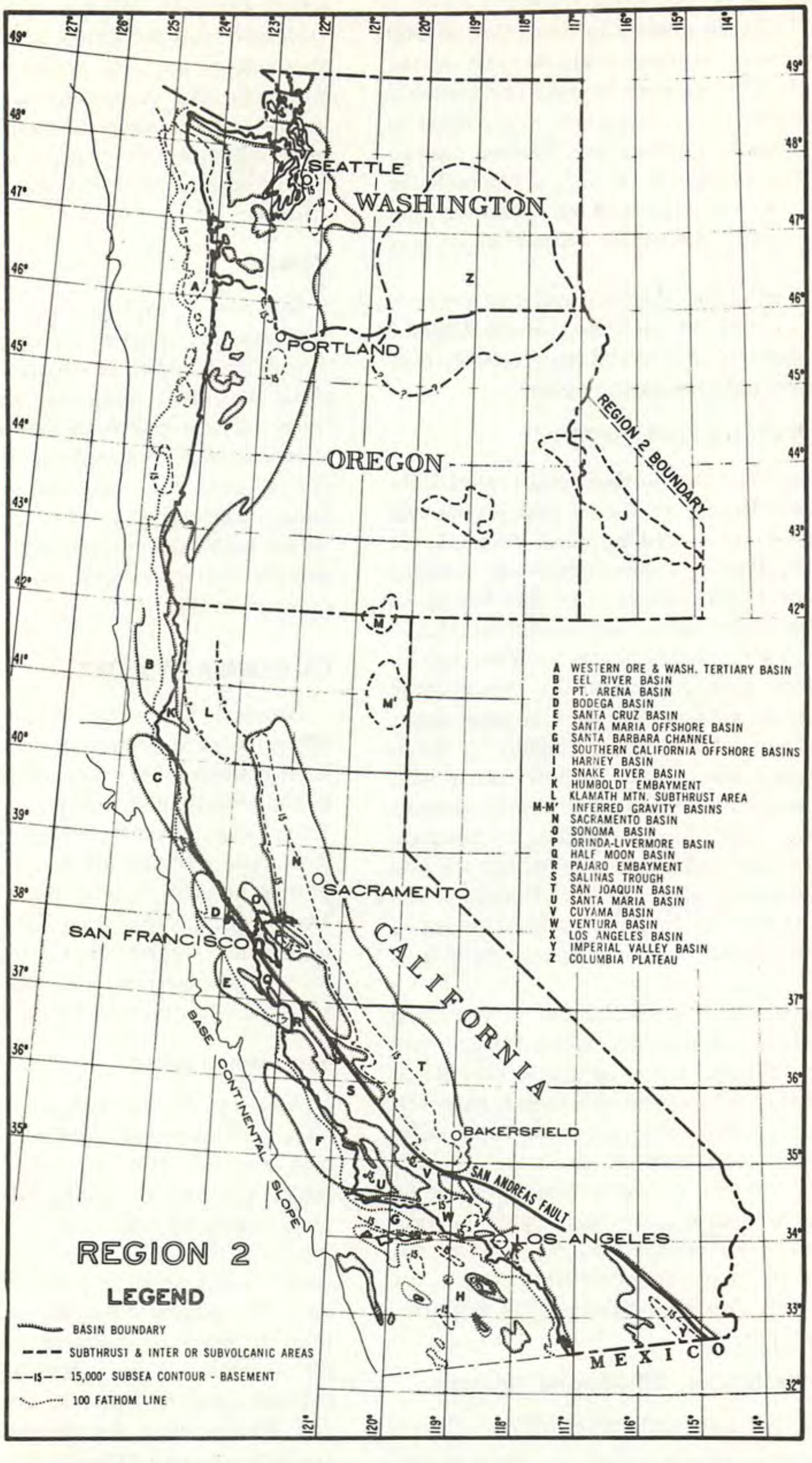

FIGURE 10. Map Showing Geologic Basins, Northern and Central California Offshore Areas

barrels of oil-in-place, mainly in upper Cretaceous sandstones (26.5 percent of the Area 11 total). Future reserves in Area 11 will be found in stratigraphic traps and subtle, well-hidden structures; they will be mostly deep, and will be located mainly in areas where well control is sparse and seismic resolution poor. Miocene, Eocene, and Cretaceous objectives offer the most promise.

Ventura Basin

Area 13, the Ventura basin, offers considerable future promise. Ultimate production from known fields is estimated at 1.755 billion barrels, and 4.95 billion barrels of oil remain to be discovered. This prediction is based on several factors: (1) the tremendous thickness of sedimentary rocks, ranging from 40,000 to 55,000 feet along the present major synclinal axis; (2) numerous untested objectives at great depths; (3) the complexity of the structural features which has made it difficult to test all of the potential structural traps; and (4) the numerous stratigraphic changes, many unpredictable and undefinable except by the drilling of many exploratory wells.

Several of the subprovinces around the margins of the Ventura basin that have so far failed to yield commercial production are geologically favorable enough to warrant and encourage future exploratory drilling. These subprovinces have a total of 3,240 cubic miles of sedimentary strata, and their total estimated petroleum in place is 1.15 billion barrels. Depths to objective zones in these subprovinces are moderate compared with the much deeper part of the main Ventura trough.

Los Angeles Basin

The Los Angeles basin (Area 16), richest in production per square mile of all California basins, has a good future. The probable existence of at least 4 billion barrels of oil-in-place, and a maximum of possibly 8 billion barrels is predicted. New production most likely will come from the lower Pliocene and upper Miocene section, and probably will be found in the unexplored deeper part of the basin, in the San Gabriel Valley in the northeast part of the basin, and in complex traps along established trends. Population growth and suburban development will continue to hamper exploration.

Central Coast Ranges

The Central Coast Ranges (Area 10) includes the Half Moon basin, the Pajaro embayment, the Salinas Valley trough, and the Cuyama basin; the area covers 4,200 square miles and has an estimated 4,500 cubic miles of sedimentary rock. Three major oil fields account for 90 percent of the estimated 2.5 billion barrels of known oil-in-place. This province is unique in California because most of the large, obvious structural features are barren, and the three large oil fields are obscured on the surface by complex thrust faults. The complex nature of the geology in this province may hide other substantial accumulations. However, it is estimated that an additional 2.5 billion barrels of undiscovered oil remain, probably in Miocene sandstone, at moderate depths in the Salinas Valley or the Cuyama basin.

Santa Maria Basin

The Santa Maria basin (Area 12), having an area of 1,700 square miles and a sedimentary rock volume of 1,100 cubic miles, appears to be the most thoroughly explored basin in California. Fifteen commercial fields, which have produced 556 million barrels of oil, were discovered between 1902 and 1952. No significant fields have been discovered during the past 20 years. More than 75 percent of the production comes from fractured Miocene cherty shale. From 100 to 600 million barrels of in-place oil may be discovered if prices improve so as to make exploration for the exceptionally low-gravity oil profitable. Future objectives include currently productive zones in the central area and older early Miocene and Cretaceous clastic reservoirs in a subsidiary basin on the northeast.

Sacramento Valley

Production in the Sacramento Valley (Area 8), which is the largest of the California basins (11,578 square miles in area and 44,000 cubic miles of sedimentary rock), to date has been almost entirely dry gas. Producing zones have been almost exclusively Eocene and Cretaceous. The latter comprises considerably more than half the volume of the basin sedimentary strata. An undiscovered potential of 5.822 trillion cubic feet of gas is believed to be present—in sandstones in the known part of the geologic section and, to some extent, in deeper units. Most of the future production should be found in stratigraphic traps. A major unknown factor is the large volume of untested sedimentary rock in the lower Cretaceous on the west side of the valley. The pace of exploration for gas in the Sacramento Valley will be determined by the policies of the public utility serving the area.

Northern Coast Ranges

Area 6, the Northern Coast Ranges of California, consists mostly of outcropping Franciscan (Cretaceous-Jurassic undifferentiated) and other old Cretaceous rocks. Two small basins, the Humboldt Tertiary basin subprovince and the Sonoma-Orinda-Livermore Tertiary basin, offer the possibility of additional small reserves. It is speculated that unaltered Paleozoic rocks having a thickness of about 12,000 feet and covering an area of 5,000 square miles could be present under, or near, the South Fort Mountain fault (Figure 10, L), where they may underlie metamorphosed Franciscan rocks. These Paleozoic rocks could contain good source and reservoir beds.

Cretaceous Potential

An analysis of California's exploration future would not be complete without some consideration of the "Cretaceous problem." Unlike other parts of the United States, where the Cretaceous has been highly productive, in California Cretaceous production has been limited largely to the Sacramento Valley and has been predominantly gas; only a few small oil fields have been discovered in Cretaceous rocks. The oldest sedimentary rocks in California's oil- and gas-producing basins are Cretaceous rocks present in thick sequences and large volumes. Much of this section is marine, consisting of dark organic shale and sandstone of different reservoir quality. Total volume is comparable with that of the Tertiary sedimentary rocks. Considerably more closed-Cretaceous anticlines have been tested and found barren than have been found productive. Many deep tests on large structures, such as Kettleman Hills, have flowed high-pressure salt water. In some basins, such as the Santa Maria and Cuyama, the Cretaceous has been metamorphosed to such an extent that locally it is considered "basement"; yet production has been found in fractured rocks of this age in the Santa Maria Valley, where Miocene shale onlaps the producing "basement." In the Sacramento and northern San Joaquin valleys, nearly all Cretaceous fields have an important stratigraphic-trap component. Although very little exploration has been directed toward Cretaceous objectives in the Los Angeles and Ventura basins, minor oil production in rocks of this age has been found in each. In summary, the Cretaceous is an enigma and a challenge that could offer some surprises in future exploration. A thorough exploration of the Cretaceous, however, will require many deep wells.

LOW-POTENTIAL AREAS

The third classification, Group 3, consists of areas which have been, and continue to be, considered unfavorable for prospecting for oil and gas.

Columbia Plateau

Eastern Oregon and Washington (Area 3) are characterized by vast floods of basalt of Cenozoic age. This section ranges in thickness from a few hundred feet to tens of thousands of feet, and unconformably overlies older rocks, including some potential source and reservoir beds. Gas and questionable oil shows have been found in units interbedded in the volcanic and intervolcanic nonmarine Pliocene sedimentary basins. Very little exploratory drilling has been undertaken and no commercial production has been found to date. Although not an attractive area, this extensive volcanic province is so little known that prospects for commercial production cannot be eliminated. Speculative areas I, J, and Z are outlined in Figure 10.

Modoc Plateau

The Modoc lava plateau (Area 7) is similar to Area 3. Gravity surveys have indicated two possible subvolcanic basinal areas (M and M′, Figure 10). The western part of the province has a few windows of marine Cretaceous rocks, but no shows have been reported in the few wells that have been drilled.

Sierra Nevada-Great Basin-Mojave Desert

Area 9 encompasses the Sierra Nevada, the Great Basin, and the Mojave Desert geomorphic provinces. It is of a low-order importance because of intensive tectonism, plutonic activity, and different degrees of metamorphism of the Paleozoic section. Mesozoic strata are scarce, and the Tertiary rocks are terrestrial and are associated with volcanic rocks in narrow basins. Limited areas of marine Tertiary rocks adjacent to the San Andreas fault and the Colorado River offer a remote chance for hydrocarbon entrapment.

Southern Coastal California

Area 17, the southern coastal and mountain region, occupies about 7,000 square miles in the southwestern corner of California. It is a predominantly mountainous area underlain by the southern California mid-Cretaceous strata and a narrow fault trough along the eastern margin of the Los Angeles basin may aggregate 50 cubic miles of sedimentary rock. The 175 exploratory wells drilled to date have tested the area fairly well.

Imperial Valley

Area 18, the Imperial Valley, covers an area of 3,200 square miles and contains about 7,000 cubic miles of sedimentary strata. Diastrophism has produced structures comparable with those in the oil- and gas-producing basins of California. Rocks of marine origin comprise about 22 percent of the total sedimentary rock volume. It is estimated that there are 125 cubic miles of permeable sandstone which may be of reservoir quality and 1,060 cubic miles of fine-grained clastic rocks which may be source beds. However, the 51 exploratory wells drilled to date, several on what appear to be the best surface geologic and seismic structures, have had no oil and gas shows. Except for the remote possibility of detrital oil shale transported from the oil shale deposits of Utah and Colorado and distilled by the heat from the Salton Sea steam field, the possibility of finding commercial production in the Imperial Valley is very slight.

CHAPTER 5
REGION 3. WESTERN ROCKY MOUNTAINS

Coordinator

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SUMMARY

The first two areas are discussed in the order of estimates of future oil-in-place as given in Table 5. No estimate was made for the third area nor for other prospective areas except for the Idaho-Wyoming thrust-belt. Location of the areas is shown on Figure 11.

ARIZONA, NEW MEXICO, UTAH, AND COLORADO

Paradox Subregion

The general geology of the several geologically distinct segments of this large area is well known, but the subsurface geology is almost unknown in many areas because of the relatively small amount of drilling outside the productive San Juan and Blanding basins.

Devonian, Mississippian, Pennsylvanian, and Permian fields account for approximately two-thirds of the crude oil produced in the subregion. Most of the production comes from stratigraphic traps in lower Pennsylvanian carbonate rocks. Practically all future discoveries of crude oil will be in Paleozoic rocks (mainly carbonate rocks). Permian sandstones and carbonate rocks have the greatest potential, and stratigraphic traps will be the dominant mode of entrapment in all Paleozoic rocks. These conclusions are based on the demonstrated occurrence of paleostructure with associated unconformities and many facies changes, and on the existence of large undrilled areas and depths.

Cretaceous sandstone fields in the San Juan basin have produced approximately one-third of the crude oil and most of the natural gas. However, the potential of the Mesozoic and Tertiary rocks is low because the San Juan basin has been intensively drilled, and because these rocks generally are too thin. Tertiary rocks generally are thin except in the San Juan basin, Rio Grande trough, and San Luis Valley. However, Mesozoic rocks (mostly Cretaceous) are sufficiently buried in other areas as well, including part of the Kaiparowits and Henry Mountain basins and part of the plateau region between the San Rafael swell and the Sevier fault. In the latter area, commercial natural gas is produced on the Clear Creek anticline and ultimate recoverable reserves of the natural gas fields of the San Juan basin are estimated by the American Gas Association [31] to be more than 15 trillion cubic feet. The Mesozoic seems to offer a fair potential of natural gas.

Exploration costs generally are high for most of the area. Rough topography in some areas hampers seismic surveys, and exploration is not permitted in national parks and monuments. The possibility of finding one or more giant fields is attractive and should compensate for the exploration costs and risks involved.

Uinta-Piceance Basins

Every geologic system from Pennsylvanian through Tertiary produces crude oil and natural gas in this area. Most of the larger fields are folded stratigraphic traps. Except for fracture production in Tertiary and Cretaceous rocks, production is from porous sandstone reservoirs.

Most of the future oil and gas accumulations are expected to be found in sandstone reservoirs in stratigraphic or stratigraphic-structural traps in strata now productive. Pennsylvanian and Mississippian carbonate rocks may contribute to a limited extent. The same stratigraphic section attains a thickness of approximately 25,000 feet in the Piceance basin, and approximately 35,000 feet in the Uinta basin. In the deeper parts of these basins structural traps outlined by seismic surveys would be potential fields. However, decreasing porosity with increasing depth (except for fracture porosity in carbonate rocks) may prove to be an adverse factor, and the percentage of natural gas should increase as depth increases.

The possibilities for the development of significant petroleum reserves appear to be very good to excellent. The average depth of exploratory wells is less than 5,000 feet, which indicates that much of the attractive sedimentary section remains untested. The probability of discovery of several small-to-medium-size fields and, at least, one additional giant is good.

Northeast Arizona

Although development in this area has been retarded largely because of inert gases and leasing restrictions on Indian lands and national monuments, the discovery of the Dineh-bi-Keyah oil field, Arizona's largest, which produces from an igneous sill of Tertiary age intruded into Pennsylvanian rocks, should have the effect of making geologists less wary of similar geology here and elsewhere. The portion of the Paradox basin crossing northeastern Arizona offers the best potential in the area. The potential of the Black Mesa and Holbrook basins is expected to be moderate.

Southern Arizona and Southwestern New Mexico

The geologically complex southern Arizona and southeastern New Mexico area contains several local basins which have been explored to a limited extent by drilling. These basins are in Basin and Range country, the petroleum potential of which generally is regarded by geologists to be decidedly secondary to the basin areas to the east (Permian) and to the north (Paradox).

IDAHO, NEVADA, AND UTAH

Great Basin and Idaho-Wyoming Thrust Belt

The geologically complicated Great Basin area of Nevada and western Utah and the Idaho-Wyoming overthrust belt are highly speculative, but not "impossible" petroleum provinces. The Eagle Spring oil field in eastern Nevada (perhaps 10 million barrels ultimate recovery) is located in an unusual geologic environment. Other such accumulations may be found, but the Great Basin can hardly be expected to contain large resources of petroleum. The general geology of the southwestern Wyoming thrust belt and the natural gas production to the east seem to stamp this area as one of the more attractive segments of the Rocky Mountain thrust belt.

DISCUSSION

INTRODUCTION

The Western Rocky Mountains, Region 3, covers approximately 500,000 square miles and includes all or parts of the states of Nevada, Arizona, Utah, New Mexico, Colorado, Wyoming, and Idaho (see Figure 11). This summary is based on reports on the six areas shown on Figure 12.

Most of the region is west of the Continental Divide and represents one part of the continental United States which has considerable potential for future population growth and economic expansion. Geologically, the region is diverse and complex. The spectrum of structural and stratigraphic geologic problems represented ranges from relatively simple to very complex.

Although the region has been subjected to several periods of exploration by the petroleum industry, certain provinces and deeper zones in other provinces are unexplored. The region has produced significant quantities of petroleum and has the geologic potential to contribute additional quantities in the future. Several important observations and estimates regarding past discoveries and future oil and gas possibilities of the region are summarized in Table 5.

Present petroleum reserve estimates derived from established production data indicate that approximately 5.223 billion barrels of oil are in place, of which about 1.465 billion barrels are recoverable (28 percent). The total natural gas recoverable is estimated to be 20.13 trillion cubic feet.

Approximately 1.044 billion barrels of oil have been produced from five of the six geographic-geologic areas within the region. Approximately 99 percent (1.036 billion barrels) of the total production of the region has come from two areas—Area 4, Paradox region, and Area 5, Uinta and Piceance basins. Most of the natural gas produced also has come from these two areas.

The preciseness of the estimates of the total future petroleum potential ranges considerably from area to area and varies with the methods used. Quantitative estimates have been made of three areas where significant geologic data are available (Areas 4 to 6), and qualitative appraisals are given for each of the six areas.

Quantitatively, the total in-place oil reserves may approximate 50 billion barrels from 175,000 cubic miles of potential source and reservoir rocks within the designated prospective area (222,750 square miles) shown on Figure 12. Total recoverable oil reserves ranging from 6.8 billion barrels (probable and possible) to 14.1 billion barrels (probable, possible, and speculative) are projected for the region, provided that the future exploratory effort is sufficient to evaluate the total volume of the potentially productive sedimentary rocks. About 26 trillion cubic feet of gas also may be projected on essentially the same basis. The number and size of the fields which may contain these projected reserves are extremely conjectural. The presence of one or more giant accumulations is possible; however, history would indicate that much of the potential reserves will be contained in numerous small-to-medium-size accumulations scattered through the 175,000+ cubic miles of sedimentary rocks. The projected future oil reserves are several magnitudes greater than the currently discovered, developed, and produced reserves (6.8 billion versus 1.465 billion). Several critical questions arise regarding this large estimate of undiscovered reserves: (1) Why have the reserves not been discovered by past exploratory activities? (2) What exploratory activities are necessary to prove or disprove the presence of these potential reserves? (3) Will the future discoveries be economic?

The answers to questions (1) and (2) are primarily that insufficient exploratory drilling (either in well density or depth) has been done to evaluate the total volume of the potentially productive strata. For example, approximately 5,500 exploratory wells have been drilled, through 1968, in the 500,000-square mile region. Most of these wells did not pen-

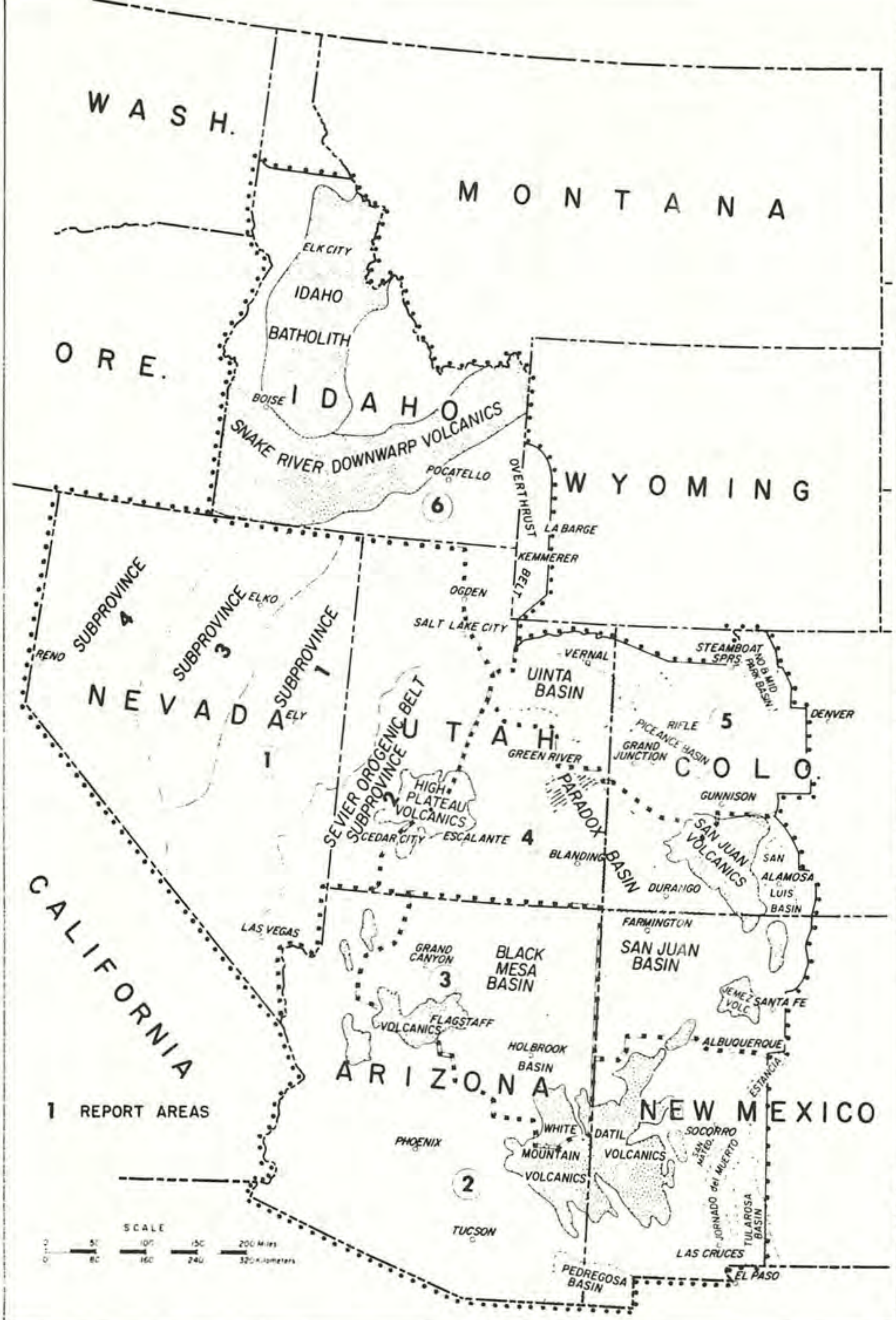

FIGURE 11. Index Map of Region 3, Western Rocky Mountains, Showing Report Areas and Locations of Geologic Basins

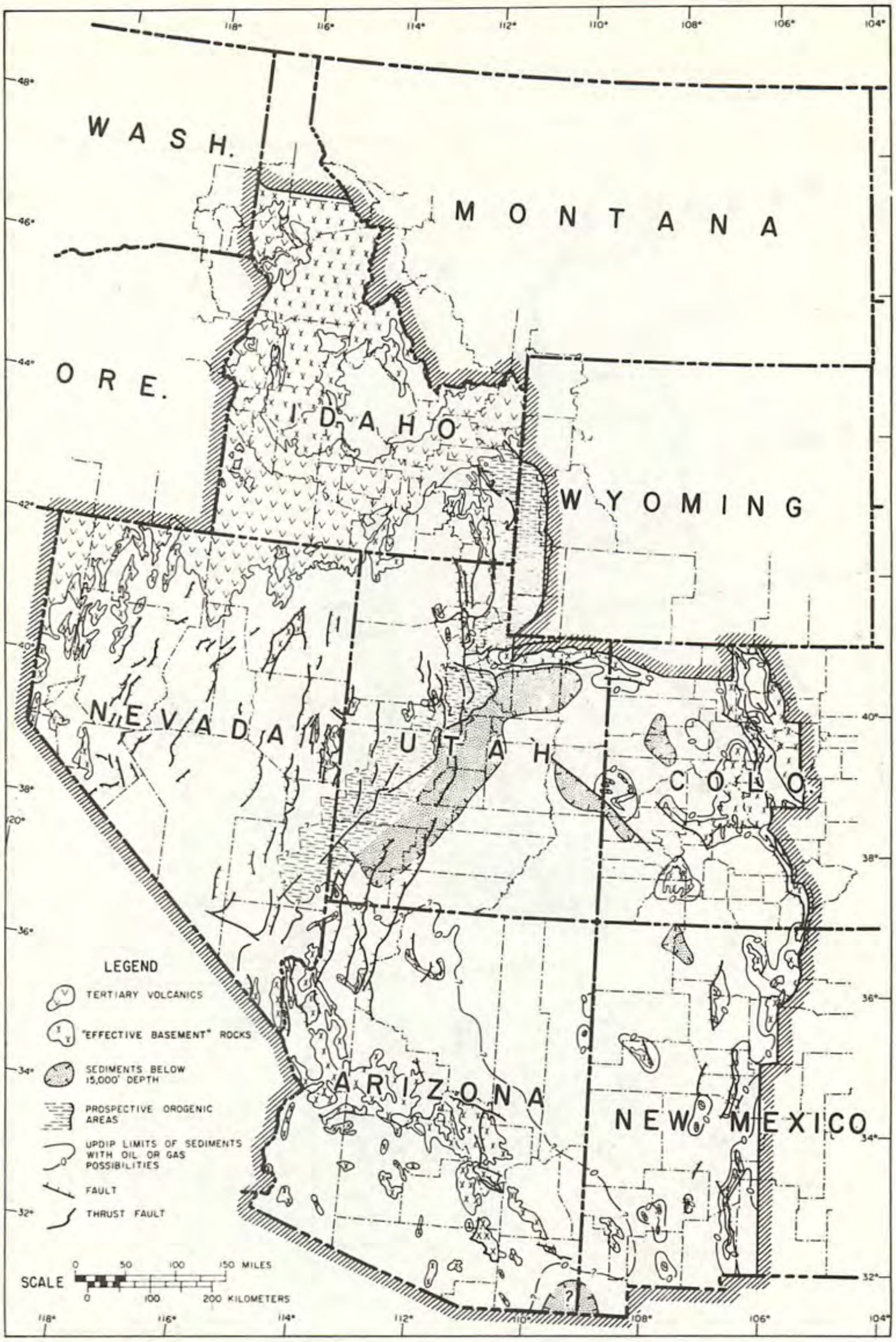

FIGURE 12. Summary Map of Region 3, Western Rocky Mountains, Showing Areas Considered to be Prospective for Petroleum Occurrence

TABLE 5. SUMMARY OF REGION 3 FUTURE OIL AND GAS POSSIBILITIES

		Area I Great Basin Nevada-W. Utah	Area II S.W. New Mexico & S. Arizona	Area III N.E. Arizona	Area IV Paradox Region	Area V Uinta-Piceance	Area VI Idaho-Wyoming Overthrust Belt	Region-3 Totals
Estimate of Present Reserves	Oil-In-Place (million barrels—1967)	36	0	57	2,130	3,000	NE	5,223
	Oil Recoverable (million barrels—1967) (cul. production through (million barrels)	10 (1.7—1967)	0	11 (6.9—1968)	528 (413—1968)	916 (623—1968)	NE (0.23—1968)	1,465 (1,044.83)
	Gas Recoverable (trillion cubic feet—1967)	NE	NE	30	17,800	2,300	NE	20,130
Estimate of Future Reserves	Oil-In-Place (million barrels—1969)	NE	NE	NE	30,000	8,140—11,750	8,200	49,950
	Oil Recoverable (million barrels)	NE	NE	NE	2,100—4,500	4,700—6,300	0—3,300	6,800—14,100
	Gas-In-Place (trillion cubic feet—1969)	NE	NE	NE	NE	NE	NE	—
	Gas Recoverable (trillion cubic feet)	NE	NE	NE	NE	6,500—12,300	NE	>6,500
Area Distribution	Potential (square miles)	100,000	15,000+	29,000	36,000+	32,750	10,000	222,750
	Minimum—No Potential (square miles)	41,250	98,500	9,000	39,000	7,250	78,000	273,000
Volume of Potential Source & Reservoir Rocks (cubic miles)		NE	10,400+	28,000	43,000	72,750	21,000	>175,150
Exploratory Drilling through 1968	Average Well Density (well per square mile)	1/500	1/65	1/79	1/15	1/15	1/128	1/41
	Success Ratio (discoveries/expl. wells)	1/200	0/230	30/366	176/2370	395/2215	7*/78	609/5459
	Footage Drilled (feet)	700,000	757,000	1,043,000	9,367,000	10,700,000	5,400,000	27,967,000

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

NE = No estimate * Includes Hogsback & Tiptop Expl. Wells $1\ mi^2 = 2.589\ km^2$: $1\ mi^3 = 4.166\ km^3$

etrate the entire sedimentary section. Approximately 45 percent of the region (222,750 square miles) has petroleum potential, and an evaluation based on one well per square mile would require about 40 times as many future exploratory wells (±220,000 wells) as have been drilled. The capital required to finance this type of effort is staggering. Predrilling exploration technology must be developed and applied judiciously to reduce the required exploratory drilling.

Question (3) is difficult to assess. However, the geologic parameters indicate that many of the potential accumulations may be localized in stratigraphic and/or combination stratigraphic-structural traps. In the past, such accumulations have yielded favorable economic returns at shallow and intermediate depths. Economic deep-drilling projects will require either a reduction of drilling costs, land and royalty costs, and predrilling exploratory costs, or an appropriate increase in the price of the petroleum discovered and marketed. Present cost trends indicate that the finding cost per barrel will increase unless the expended capital is concentrated on those projects which have the potential of discovering large accumulations.

SUMMARIES BY AREAS

The following qualitative statements are included to emphasize the potentials and the exploration problems of each report area (Figure 11).

Area 1 (Great Basin)

This area may not contain large reserves of petroleum, even though several of the necessary geologic parameters are present. There is a high probability that any large petroleum accumulations present have been destroyed by the repeated severe structural deformation which characterizes this area. The area is essentially unexplored, having an average of one exploratory well per 500 square miles of prospective area. Large quantities of open-access land are readily available for future exploration. Discovery of additional petroleum reserves will be hindered by: (1) the widespread structural deformation; (2) the deep erosion at different times in the history of the area of preexisting sedimentary units (i.e., multiple unconformities); (3) the presence of fresh water in most of the prospective reservoirs; and (4) the limited geologic data available for much of the prospective area. Geologic data are sparse because of the limited surface outcrops and lack of sufficient subsurface well control; furthermore, use of present geophysical techniques to map structure below the valley fills and/or the many unconformities has not been very successful. No estimates of volume of sedimentary rocks or of reserves are possible from the present data. Subprovinces 1 and 2 (Figure 11) appear to offer the greatest potential for future petroleum production in the Great Basin area.

Area 2 (Southwest New Mexico and South Arizona)

Area 2 contains several local basins that merit further exploration before their potential can be assessed properly. These basins represent approximately 15,000 square miles or 13 percent of the total area. Geologic information on scattered areas indicates that approximately 10,400+ cubic miles of lower Mesozoic and Paleozoic rocks have favorable source and reservoir characteristics. Large quantities of open-access land are available for future exploration. However, prospects for finding large reserves in the area are lessened because of (1) the lack of established production, (2) the intense structural deformation and extensive erosion, and (3) the presence of fresh water in many of the possible reservoirs. Exploration for future production will be hindered because of (1) the presence of extensive surface and subsurface volcanic sequences, which complicate normal geological and geophysical exploratory techniques; (2) the obscuring of the local trap geometry by structural deformation and erosion; (3) the possibility of flushing of the prospective reservoirs by the abundant fresh water; and (4) the presence of several military and other government reservations. No estimates of the future oil and gas resources are feasible now; however, future exploration may result in discoveries of economic value.

Area 3 (Northeast Arizona)

This area has a moderate-to-poor overall potential for the future discovery and development of significant petroleum reserves. Geologic studies indicate that future fields will contain small to modest reserves. These accumulations probably will be in stratigraphic traps or in combination stratigraphic-structural traps. Approximately 29,000 square miles of the area are considered prospective and contain approximately 28,000 cubic miles of source and reservoir rocks. Some factors favoring the discovery of additional reserves within the prospective area are (1) the presence of several undrilled anticlines, (2) the possible presence of several potential stratigraphic accumulations, (3) a favorable history of reservoir-fluid preservation in pre-Permian strata, and (4) drilling depths of generally less than 8,000 feet which are adequate for testing to the basement throughout the area. Inert gases bearing helium have completely filled several likely petroleum traps. These occurrences will deter future petroleum exploration because the presence of helium increases the predrilling prospect risk and adversely affects the economics. Parts of the prospective area are composed of Indian and National Park and Monument lands, which are at present unavailable for oil and gas leasing. No estimate of the future oil and gas reserves is now feasible. Past drilling has tested only a small percentage of the prospective area and volume. This low-drilling density makes geologic appraisal difficult. Another complicating factor involves discovery of the most prolific oil field in the area (Dinch-bi-Keyah) in an igneous intrusion.

Area 4 (Paradox Region)

This area has a very good potential for future development of significant oil and gas reserves from Paleozoic rocks. Approximately 43,000 cubic miles of potential source and reservoir rocks are present within a favorable area of 36,000 square miles. "Speculative" in-place oil reserves of up to 30 billion barrels are predicted. Postulated recoverable oil reserves range from 2.1 billion barrels (probable and possible categories) to 4.5 billion barrels (probable, possible, and speculative).

Stratigraphic and combination stratigraphic-structural traps probably will continue to be most important in future discoveries. The presence of paleostructure and associated facies changes in the Devonian, Mississippian, Pennsylvanian, and Permian rocks enhances the probability of finding many favorable reservoir traps. Past drilling has tested less than 0.2 percent of the prospective sedimentary rock volume in this area. Vast parts of the area are essentially virgin territory in terms of exploratory activity, including drilling. For example, the geology beneath the San Luis Valley and the Rio Grande trough is essentially unknown, as are the deeper parts of the Paradox and San Juan basins. Exploration costs and risks generally are high for most of the area. However, the possibility of finding one or more giant fields is attractive and should compensate for the exploration costs and risks.

Area 5 (Uinta and Piceance Basins)

The potential for the development of significant future petroleum reserves in this area is very good to excellent. The area contains the largest volume of potential source and reservoir rocks (72,750 cubic miles) of any area in Region 3. Potential objectives include Paleozoic, Mesozoic, and Cenozoic strata within a 32,750-square mile prospective area. The "speculative" in-place oil reserves range from 8.1 to 11.7 billion barrels; reserves ranging from 4.7 (probable and possible categories) to 6.3 billion barrels (probable, possible, and speculative) are classified as recoverable. Natural gas recoverable reserves are estimated to be more than 6.5 trillion cubic feet. This area contains the bulk of the present oil reserves and is the most densely drilled part of Region 3. Even so, the average depth of the exploratory wells is less than 5,000 feet, indicating that much of the sedimentary section remains untested (Figure 12). Most of the predicted future oil and gas reserves are expected to be found in stratigraphic or combination stratigraphic-structural traps in strata that are now productive. Continued exploration, especially in the deeper and untested parts of the basins, probably will result in the discovery of several small-to-medium-size fields and at least one additional giant field.

Area 6 (Idaho-Wyoming Overthrust Belt)

This area now produces a small amount of hydrocarbons, but the Overthrust Belt part of the area has a fair-to-poor potential to become a significant petroleum province. The Overthrust Belt occupies approximately 10,000 square miles, or 12 percent of Area 6. The remaining 78,000 square miles include the Idaho batholith, the Snake River volcanic rocks, and a part of the Great Basin province where there is little or no petroleum potential. Approximately 21,000 cubic miles of favorable source and reservoir rocks are present in the Overthrust Belt. All of the classic geologic requirements are present, but the major barrier to successful exploration involves the location of the wells necessary to test crestal positions of the complex structures. Improved seismic techniques may assist in overcoming this barrier. Fifty surface anticlinal trends remain to be tested.

The average well density of the prospective area is about one well per 128 square miles, which is not considered sufficient to evaluate fully the area or the sedimentary rock volume.

Based on analogy with other thrust belts and volumetric comparison with other adjacent explored areas in Wyoming, an estimated upper limit of "speculative" oil-in-place is 8.2 billion barrels. A maximum of approximately 3.3 billion barrels of oil (speculative) may be recoverable.

CHAPTER 6
REGION 4. EASTERN ROCKY MOUNTAINS

Coordinator

William H. Curry
Consultant
(Authors Listed in Appendix D)

SUMMARY

The relative petroleum potential of the various subdivisions of this large region is easily discernible by reviewing the estimates of in-place oil and gas in Tables 6 through 8. The location of the areas studied is shown in Figure 14.

Every geologic system—from Cambrian to Tertiary—produces crude oil and natural gas in this region. Upper Cretaceous and Tertiary sandstones yield most of the natural gas fields. According to estimates published by the AGA and API,[31] approximately two-thirds of the crude oil and three-fourths of the natural gas found to date are contained in structural traps. Most of these are large surface anticlines.

However, approximately two-thirds of the undiscovered crude oil, and approximately three-fourths of the undiscovered natural gas, are believed to be in stratigraphic traps and, to an extent, in structural-stratigraphic traps. The recent discoveries of important stratigraphic accumulations of crude oil in Permian carbonate rock (such as the Cottonwood Creek in the Big Horn basin) and in upper Cretaceous sandstones (Patrick Draw in Green River basin and several fields in the Powder River basin), as well as the accumulations in combination low structural relief-stratigraphic traps in North Dakota, encourage the belief that more such accumulations remain to be found in the large sparsely drilled areas. Stratigraphic traps may exist at any depth, but it is likely that additional exploratory wells in the deeper parts of the basins (see Figure 13) will be on closures discovered by geophysical surveys.

The petroleum potential of the region is assuredly high. It is estimated that discoverable oil-in-place exceeds the amount already discovered, and that discoverable natural gas is 2½ times past discoveries.

The more prospective areas (see Figures 13 and 14) in order of decreasing estimated potential are:

Powder River basin—Area 5
Green River basin—Area 7
Big Horn basin—central Area 6
Northern Montana—Area 2
North Dakota—Area 3
Eastern Colorado and adjacent Nebraska and Wyoming—Area 8
Wind River basin—southern Area 6

Crude oil is produced in the Crazy Mountain-Bull Mountain syncline in Montana (northern Area 6) and in South Dakota (Area 4), but neither area appears to have high potential. The Disturbed Belt (Area 1) is part of the speculative overthrust belt mentioned earlier. The Cretaceous of North Dakota and South Dakota, the pre-Mississippian of eastern Colorado, and the Raton basin of northern New Mexico, all of which are now nonproductive, are considered to be somewhat prospective. The crests of the Sierra Grande arch and the Apishapa uplift in southeastern Area 8 are not attractive for further exploratory drilling.

DISCUSSION

Region 4 consists of the States of Montana, North Dakota, South Dakota, and Wyoming, and western Nebraska, eastern Colorado, and a small part of northeastern New Mexico. Exact area boundaries within the region are controlled by natural geologic features (Figure 13). Figure 14 shows the location of the report areas.

The region covers 483,000 square miles, of which 368,000 square miles, or 76 percent, are considered favorable for the possible occurrence of oil and gas. The total volume of favorable sedimentary rock is 568,032 cubic miles, of which approximately 5 percent or 28,973 cubic miles are below a drilling depth of 15,000 feet (Figure 15). The general geologic structure of the western, central, and northern sections is that of sedimentary intermontane basins separated by major ranges. The eastern parts of Region 4 are composed of sedimentary basins along the eastern front of the Rocky Mountains, where the Midcontinent region joins the mountain provinces (see Figure 13).

A summary estimate of the total possible potential for future discovery of oil in each area within the region is shown in Table 6. Figures for oil are shown also by geologic age groupings (Table 7). Figures for gas are given by States (Table 8), as those figures were unavailable by area.

The figures under "Undiscovered Oil- (or Gas) In-Place" fit the combined categories of "probable" and "possible" of the Potential Gas Committee.[33] The Committee's "speculative" classification is not used here, because the unknown quantities are so great that quantitative figures are very questionable. Moreover, a lack of consistency in reporting data makes it impossible to compile figures for this category with any degree of uniformity. For example, one large potential for North Dakota and South Dakota may be Cretaceous production from Muddy sandstone reservoirs, but none has been found to date and oil shows, thus far, have been few. Another area for a "speculative" category would be in the small basins and thrust sheets of the Disturbed

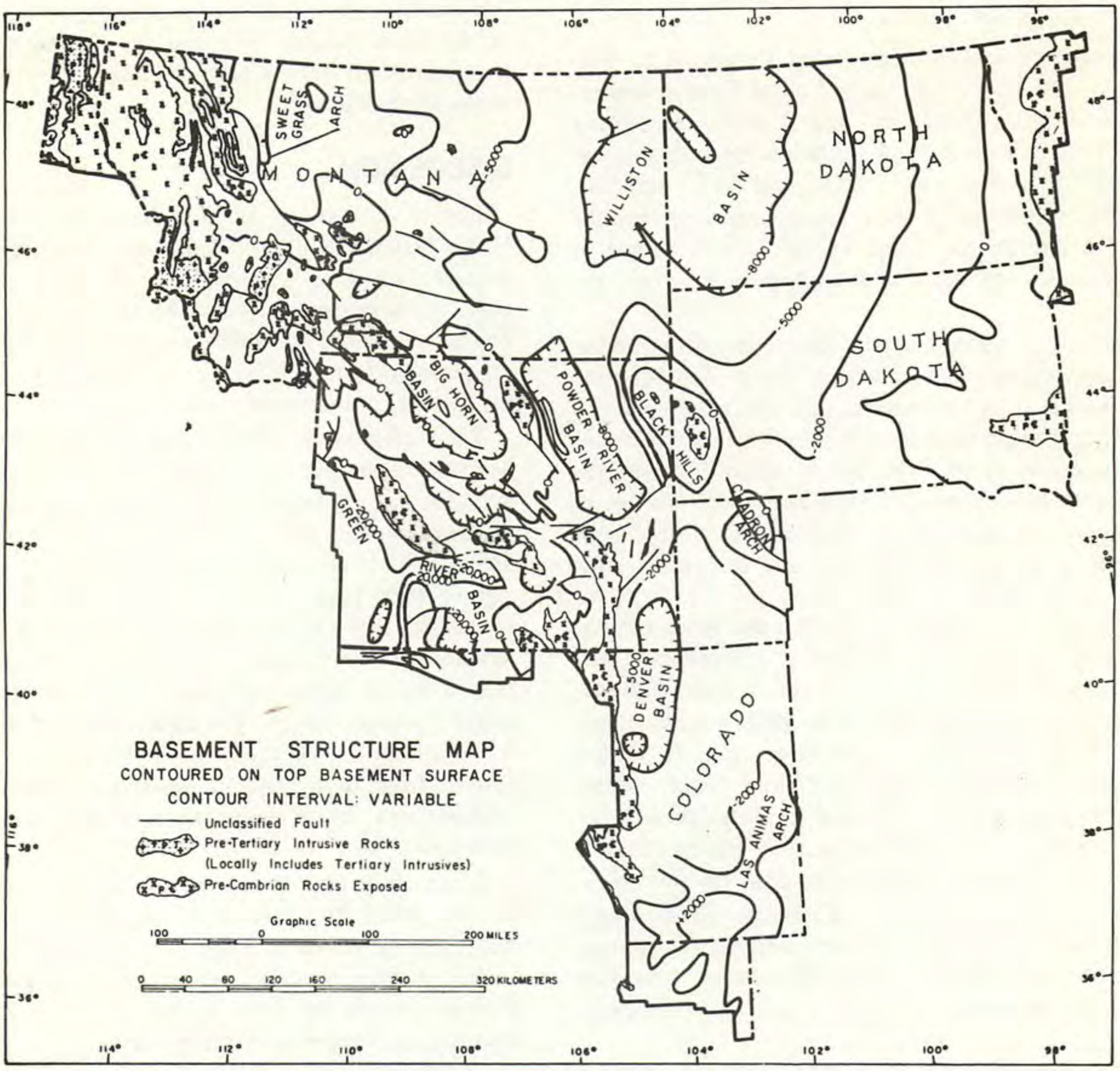

FIGURE 13. Outline Map of Region 4, Eastern Rocky Mountains, Showing Generalized Contours of Top of Basement (after Flawn et al.[32])

Belt of western Montana, where there has been no commercial production. A third large unproductive and "speculative" area is the Raton basin and the pre-Mississippian section of southeastern Colorado. In fact, there is a considerable "speculative" element in the "possible" aspects of these estimates. Not all authors included their views of "speculative" reserves.

The figures for gas are based mainly on 1967 estimates of ultimate recoverable reserves and cumulative production. For eastern Colorado and western Nebraska (Area 8, Figure 14; Table 8), 1968 figures were available. Where 1967 figures are used, 1968 production has been accounted for to give estimates of future reserves as of December 31, 1968.

For Region 4, the geologic conditions are favorable for providing in the future about as much oil and gas as already have been found (Tables 6 through 8). Whereas the 23.5 billion barrels of in-place oil and 13 trillion cubic feet of recoverable gas already discovered have been delineated within sedimentary rock volumes in the order of hundreds

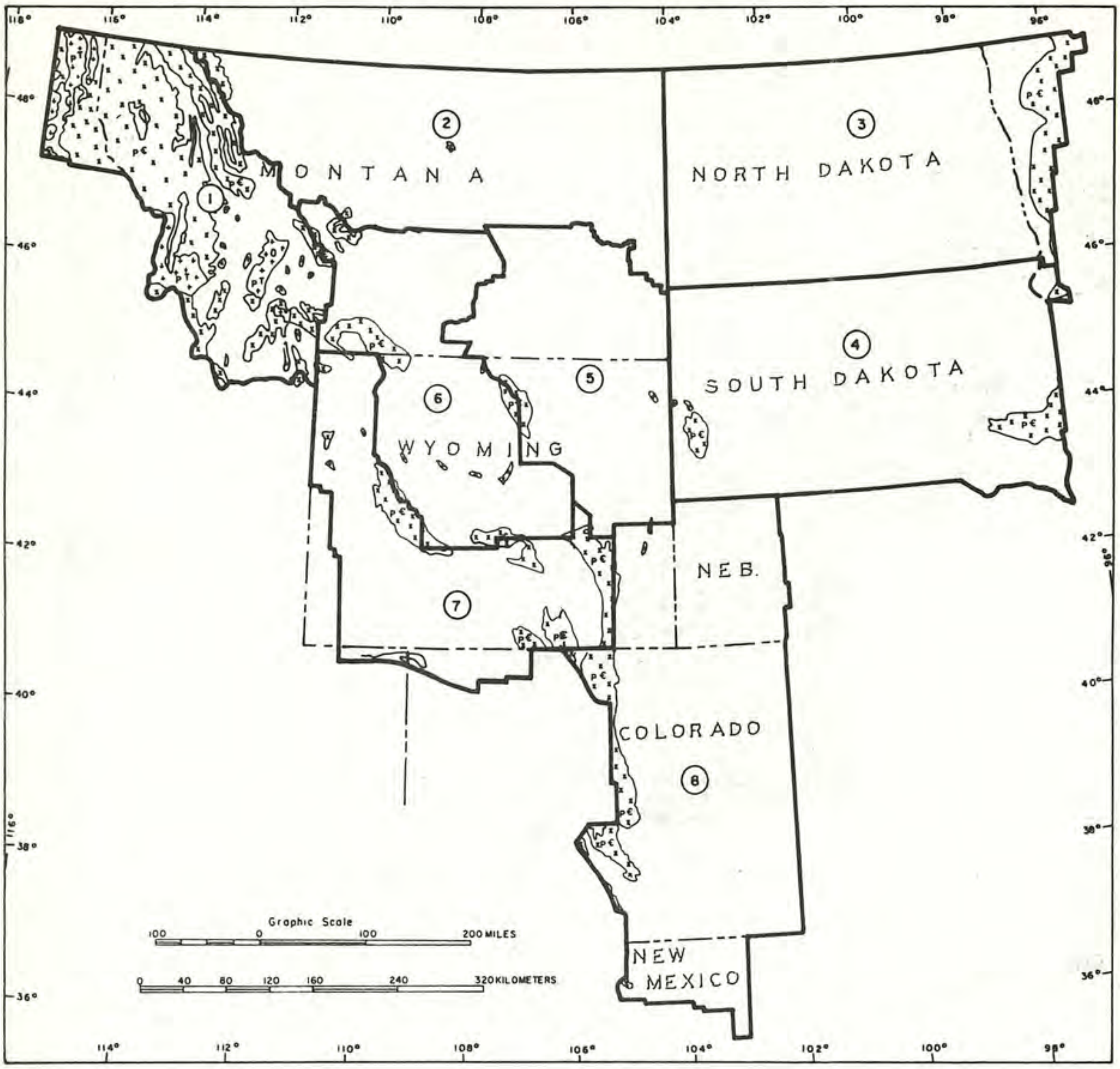

FIGURE 14. Index Map of Region 4, Eastern Rocky Mountains, Showing Report Areas

of cubic miles, the future undiscovered 25.7 billion barrels of in-place oil and 30.3 trillion cubic feet of recoverable gas are scattered through tens of thousands of cubic miles of sedimentary rock.

The exploration problem is at once apparent. If the "well-years" it has taken to establish the present oil- and gas-in-place are considered the task of discovering the future postulated oil and gas cannot possibly be accomplished by the year 2000 A.D. It would take more than 60,000 wells per year in Wyoming alone for the next 30 years—a ridiculous figure!

In conclusion, geologists believe that there is as much petroleum yet to be discovered in Region 4 as has been found in the past. These hydrocarbons will be scattered through tens of thousands of cubic miles of sedimentary rock and may occur in generally smaller accumulations than those found to date. Therefore, the exploration problem will be great, the cost of finding hydrocarbons will be more per barrel, and the pace of discovery will be slower. The future success in discovery thus will be related more to economic conditions and incentives than to the geologic aspects of the region.

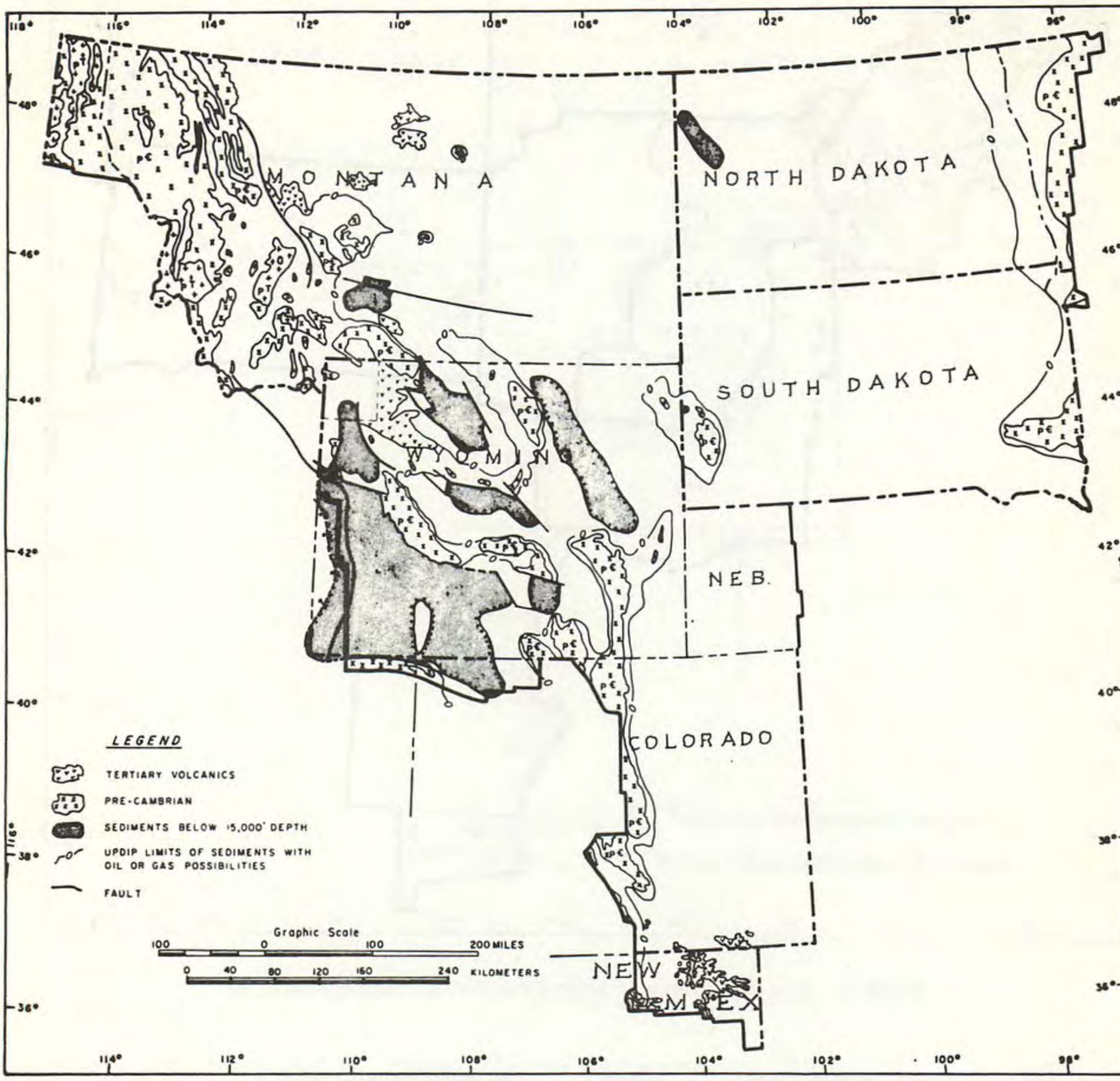

FIGURE 15. Map of Region 4, Eastern Rocky Mountains, Showing Areas of Sedimentary Rocks Below 15,000-Foot Depth

TABLE 6. SUMMARY OF TOTAL POSSIBLE OIL POTENTIAL, EASTERN ROCKY MOUNTAINS (REGION 4), BY AREA, AS OF DECEMBER 31, 1968

Area	Volume of Sedimentary Rocks (cubic miles)	Discovered Oil-In-Place (million barrels)	Cumulative Production (million barrels)	Remaining Oil-In-Place (million barrels)	Undiscovered Oil-In-Place (million barrels)	Total Future Oil-In-Place (million barrels)
Area 2—No. Montana	96,000	2,970.6	502.0	2,468.6	2,916.0	5,384.6
Area 3—Williston Basin	83,156	2,137.4	307.2	1,830.2	2,085.0	3,915.2
Area 4—South Dakota	19,201	18.1	2.4	15.7	16.1	31.8
Area 5—Powder River Basin	71,795	3,497.0	549.6	2,947.4	6,804.0[1,2]	9,751.4
Area 6—Crazy Mtn.; Big Horn, and Wind River Basins	72,000	10,885.9	2,406.1	8,479.8	6,472.0	14,951.8
Area 7—Green River Basin	89,420	1,742.8	324.4	1,418.4	6,250.0	7,668.4
Area 8—E. Colorado, etc.	136,460	2,231.0	586.0	1,645.0	1,120.0[3]	2,765.0
Total	568,032	23,482.8	4,677.7	18,805.1	25,663.1	44,468.2

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Plus 5,750.0 barrels "speculative."

(2) Includes minor gas converted to oil on basis of 20 thousand cubic feet = 1 barrel.

(3) Plus 1,250.0 barrels "speculative."

TABLE 7. SUMMARY OF TOTAL POSSIBLE OIL POTENTIAL, EASTERN ROCKY MOUNTAINS (REGION 4), BY GEOLOGIC AGE, AS OF DECEMBER 31, 1968

Geologic Age	Volume of Sedimentary Rocks (cubic miles)	Discovered Oil-In-Place (million barrels)	Cumulative Production (million barrels)	Remaining Oil-In-Place (million barrels)	Undiscovered Oil-In-Place (million barrels)	Total Future Oil-In-Place (million barrels)
Post-Mesozoic	43,820	189.1	36.7	152.3	845.0	997.3
Mesozoic	314,381	9,046.3	2,069.6	6,976.7	11,012.0	17,988.7
Permian-Pennsylvanian	74,746	7,935.0	1,675.8	6,259.2	7,222.3	13,481.5
Pre-Pennsylvanian	135,085	6,312.4	895.5	5,416.9	6,583.8	12,000.7
Total	568,032	23,482.8	4,677.6	18,805.1	25,663.1	44,468.2

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

TABLE 8. SUMMARY OF TOTAL POSSIBLE GAS POTENTIAL, EASTERN ROCKY MOUNTAINS (REGION 4), BY STATE, AS OF DECEMBER 31, 1967

State	Ultimate Recovery of Discovered Gas (billion cubic feet)	Cumulative Production (billion cubic feet)	Remaining Recoverable Reserves (billion cubic feet)	Undiscovered Gas-In-Place (billion cubic feet)	Undiscovered Gas Recoverable (80% of col. 4) (billion cubic feet)	Total Future Gas Recoverable (billion cubic feet)	1968 Gas Production (billion cubic feet)	Total Future Gas Recoverable [3] (billion cubic feet)
Montana	1,869.24	488.49	1,380.75	2,447.12	1,957.70	3,338.45	44.51[1]	3,293.94
North Dakota	1,329.11	386.74[2]	942.37	2,710.50	2,168.40	3,110.77	41.25[2]	3,069.52
South Dakota	.24	.17[1]	.07	—	—	.07	.01[3]	.06
Wyoming	8,322.12	4,263.05	4,059.07	31,515.00	25,212.00	29,271.07	310.94[1]	28,960.13
E. Colorado and W. Nebraska	1,471.50[3]	573.50[3,4]	898.00	1,225.00[3,5]	980.00[3]	1,878.00[3]	—	1,878.00
Total	12,992.21	5,711.95	7,280.26	37,897.62	30,318.10	37,598.36	396.71	37,201.65

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Source: Petroleum Information.

(2) Source: North Dakota Geological Survey.

(3) As of December 31, 1968.

(4) Nebraska figures from Petroleum Information; Colorado figures from Colorado Oil and Gas Commission.

(5) Plus 1,433,000 million cubic feet "speculative."

CHAPTER 7
REGION 5. WEST TEXAS AND EASTERN NEW MEXICO

Coordinator

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Geological Consultant
(Authors Listed in Appendix D)

SUMMARY

The relative petroleum potential of the divisions of the geologic column is portrayed by estimates of oil-in-place and gas-in-place (Table 10). Figures 16 and 17 show location of areas discussed.

Permian and Pennsylvanian fields have produced most of the crude oil and associated natural gas in this region, and extensions to these old fields and new discoveries in these rocks are expected to provide a major proportion of the region's future crude oil and associated natural gas. The most promising possibilities lie in stratigraphic traps in the less densely drilled parts of the currently producing areas. Possibly 50 to 75 percent of the future Permian petroleum will be found in these areas. The remainder will be found in stratigraphic traps in the sparsely drilled Palo Duro basin, Southern shelf, and flanks of the Diablo platform.

Because of the deep development of Ellenburger (Cambro-Ordovician) nonassociated (dry) natural gas in the Delaware and Val Verde basins, the pre-Pennsylvanian now furnishes about two-thirds of the region's proved reserves of nonassociated natural gas. Discoveries of Ellenburger natural gas are expected to continue in the Delaware and Val Verde basins, with a fair part coming from extensions. These two areas will provide most of the new pre-Pennsylvanian dry-gas discoveries. The pre-Pennsylvanian oil and gas fields in this region are now generally structural traps, but there are possibilities for more stratigraphic traps.

In addition to these more favorable areas, the north and east flanks of the Midland basin are considered attractive for new stratigraphic oil fields in Permian and Pennsylvanian formations. The Pennsylvanian in the eastern part of the Fort Worth basin still offers possibilities for the discovery of natural gas fields and the Cambrian has hardly been touched.

Nonproducing areas considered to be prospective are (1) the Rowe-Mora basin for Pennsylvanian

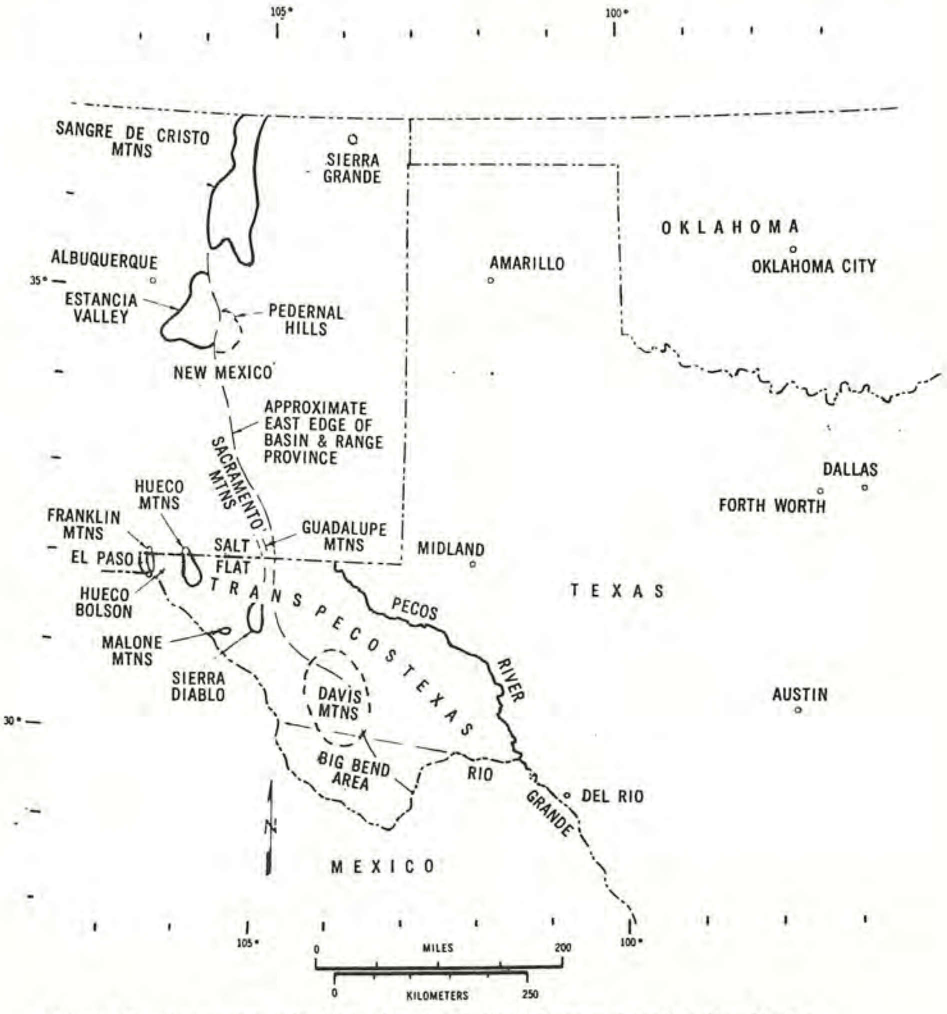

FIGURE 16. Geographic Index Map of Region 5, West Texas and Eastern New Mexico

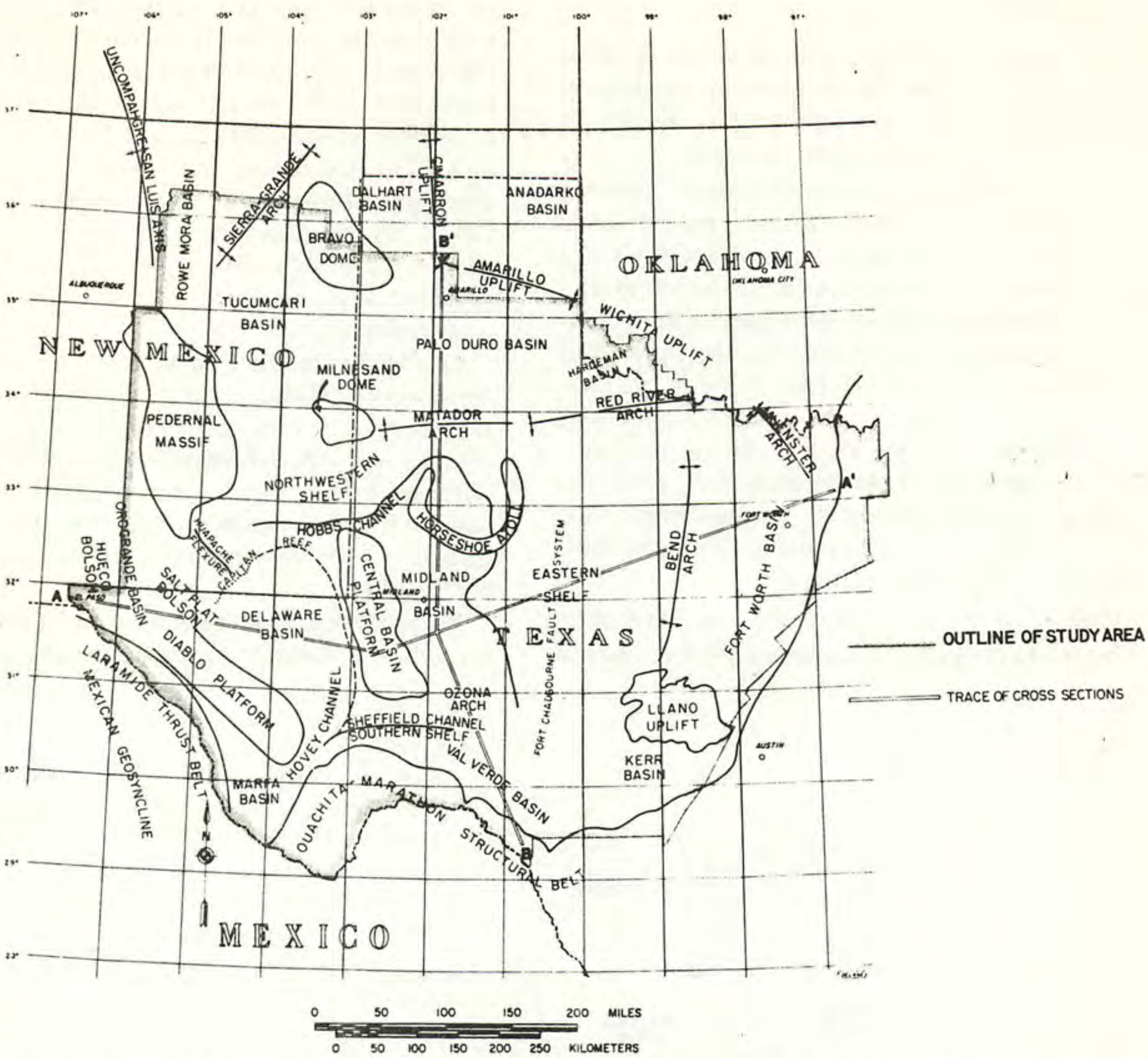

FIGURE 17. Outline Map of Region 5, West Texas and Eastern New Mexico, Showing Major Geologic Features (Cross sections are not included in this summary.)

stratigraphic traps, (2) the Kerr basin for structural and stratigraphic traps in Cambrian to Pennsylvanian strata, and (3) the Marfa basin for pre-Pennsylvanian structural traps. History, of course, will prove the order of their importance. The important observation is that Region 5 still has a large number of areas beyond the producing fields that offer interesting prospects for future discovery.

The sparsely drilled Basin and Range country along the western border of the region (Figure 16) is considered to be unfavorable, although not "impossible." The unattractive geology revealed by drilling suggests the prospects of the Sierra Grande arch and of a large area south of the Pedernal Hills in New Mexico to be doubtful also.

However, the possibilities for important discoveries in the region are excellent, and all prospective areas east of the Sierra Grande-Pedernal-Diablo positive elements, and north of the Ouachita fold belt, are expected eventually to produce crude oil or natural gas.

On the basis of the results of a study of the large volumes of hydrocarbons minutely disseminated in nonreservoir rocks, and of gaseous hydrocarbons dissolved in formation waters, the estimated volumes in Region 5 are 3.7 trillion barrels of crude oil and 6,000 trillion cubic feet of natural gas. *However, whether any of these unconventional resources ever will be exploitable is highly questionable.*

DISCUSSION

INTRODUCTION

Region 5 (Figure 17) encompasses all the Paleozoic producing provinces of Texas and eastern New Mexico except the Panhandle field on the Amarillo uplift and producing areas north of it. It also includes three counties south of the Wichita Mountains in southwestern Oklahoma. It includes nonproducing areas of Paleozoic strata, except those extending under the Ouachita overthrusts east of Del Rio and north of Austin, Texas, as well as some nonproducing areas of Mesozoic and Cenozoic strata in the Trans-Pecos counties of Texas.

Pre-Mississippian sedimentation in Region 5 occurred in a stable shelf environment, whereas late Mississippian and Pennsylvanian sedimentation was accompanied by orogenic pulsations which strongly influenced the depositional environment and the character of the rocks. The Permian period was characterized by shrinking seas in deep basins surrounded by evaporite lagoons behind organic reefs.

Future reserves of petroleum will be found in (1) pre-Mississippian strata, mainly of rather uniform carbonate lithology, in structural traps; (2) Pennsylvanian sandstone and limestone reservoirs, especially in stratigraphic traps associated with lithofacies complexities, but also in structural traps; and (3) Permian shelf and basin environments, mainly in stratigraphic traps, although structural relief also will be important. Mississippian strata appear to be petroliferous, but good reservoir beds are scarce. Post-Permian beds are expected to provide little oil or gas.

Cumulative production for Region 5 to December 31, 1967, was 15.9 billion barrels of oil and 41.2 trillion cubic feet of gas.

A total of 133.2 billion barrels of oil is estimated to be in-place in the subsurface of Region 5; about one-third of that quantity should be found in new fields or extensions of old fields. A total of 165.5 trillion cubic feet of gas, both associated and nonassociated, still is in-place. About one-half of the associated gas remains to be found, and about two-thirds of the nonassociated gas.

The new discoveries will be in the area east of the Sierra Grande-Pedernal-Diablo axis (Figure 17). Some of the far-west region may share in the discoveries, but prospects there are dimmer because of Mesozoic and Cenozoic volcanism and tectonism.

In addition to conventional accumulations of oil and gas, large volumes of hydrocarbons minutely disseminated in non-reservoir rocks, and of gaseous hydrocarbons dissolved in formation waters, are known to be present. The estimated volumes in Region 5 are 3.7 trillion barrels of oil and 6,000 trillion cubic feet of gas. *However, whether any of these resources ever will be exploitable is highly speculative.*

GENERAL DESCRIPTION

Region 5 is one of the more thoroughly explored and developed producing regions, although its producing history began relatively late in the history of the American oil industry. Nevertheless, it still contains some scarcely explored provinces in which future production possibilities are sufficiently enticing to attract the adventurous wildcatters.

Geologically, Region 5 is bounded on the south and east by the front of the Ouachita fold belt, on the north by the south flank of the Amarillo-Wichita uplift, on the northwest by the Sierra Grande uplift, on the west by the Sangre de Cristo uplift and the east edge of the Sacramento section of the Basin-Range province, and on the southwest by the Mexican geosyncline or "Laramide thrust belt" (Figures 16 and 17).

The predominantly marine Paleozoic history of Region 5 terminated before the end of the Permian period. Continental conditions continued through Triassic and Jurassic times, except in the Mexican geosyncline. Cretaceous strata, mostly marine, covered the entire region. Events of the Laramide orogeny, concurrent and subsequent volcanism, and the Basin-Range episodes exposed, buried, reexposed, tilted, folded, and faulted the Paleozoic strata in the western part of Region 5, severely altering the hydrologic patterns.

Paleozoic strata, from the base of the Cambrian to the lower Permian, are now exposed in the Sierra Diablo and the Hueco and Franklin Mountains of Trans-Pecos Texas, along the faulted front of the Sacramento Mountains near the border of Region 5 in southern New Mexico, and elsewhere northward into Colorado. A part of the Capitan reef (upper Permian), which once rimmed the Delaware basin, is exposed near the crest of the Guadalupe Mountains, but an adjacent part of it has dropped several thousand feet into the Salt Flat graben. A large part of the Diablo platform is buried at depths of 5,000 feet or more beneath the volcanic lava pile of the Davis Mountains. Other Paleozoic strata are buried beneath Cretaceous, Tertiary, and Quaternary rocks in the mountains and bolsons of the Basin-Range province of the Big Bend area, part of which is underlain by an arcuate segment of the Ouachita fold belt. Estimates of petroleum resources in such provinces obviously are fraught with uncertainties.

HYDROCARBON POTENTIAL

Present Production

Oil and gas in Region 5 are obtained from reservoirs in all Paleozoic systems (Figure 18). Noncommercial amounts of gas were recorded during the

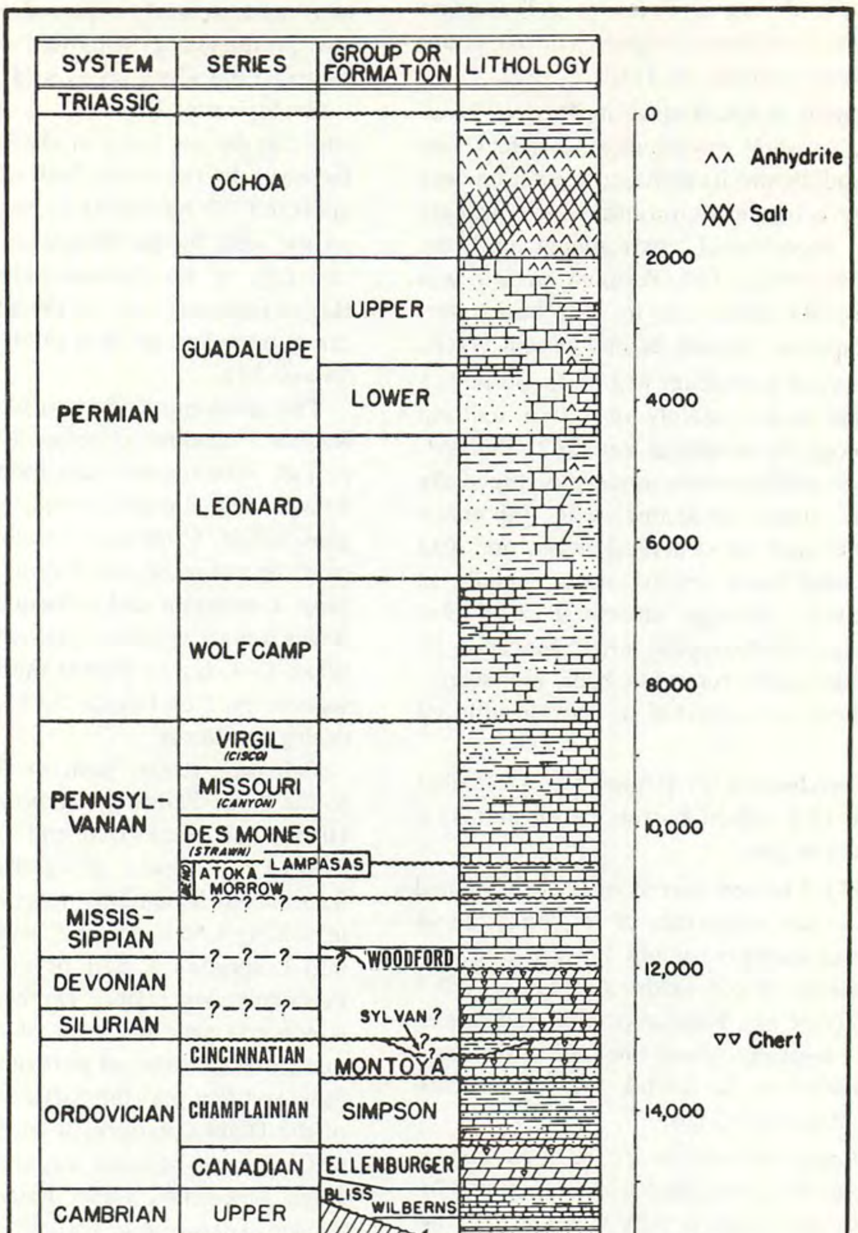

FIGURE 18. Generalized Stratigraphic and Lithologic Column for the Permian Basin

drilling of water wells in Texas in 1872 (Young County) and 1888 (Palo Pinto County), and oil was reported in 1878 (Brown County; reference 34). The earliest commercial production of oil was from shallow beds of Pennsylvanian age in North Texas in 1904 (Clay County) and 1910 (Wichita County), and from shallow beds of Permian age in eastern New Mexico in 1909 (Eddy County). The first commercial production of dry gas was in 1907 in Clay County, Texas. Production from the deeper strata in West Texas and southeast New Mexico followed in late years, beginning with the Ordovician discovery at Big Lake in Reagan County, Texas, in 1928. The producing provinces, the ages and lithologies of the reservoir strata, and the principal types of traps are listed in Table 9.

The most comprehensive studies of possible sources and migration of petroleum in the Permian basin part of Region 5 are those by Jones and Smith[35] and Holmquest et al.[36] They conclude that the most likely source beds are Simpson (Ordovician), Woodford (Devonian-Mississippian), and various Mississippian and Pennsylvanian shale beds, and basinal shale beds of various Permian ages. The same sources may be considered as likely for petroleum found elsewhere in Region 5.

Natural gas is associated with oil in many of the oil fields. Large volumes of nonassociated gas are found at depths ranging from 12,000 to 16,000 feet in the Delaware and Val Verde basins in chiefly anticlinal traps.

Total production for the year 1967 in Region 5 was 713.9 million barrels of oil and 2.17 trillion cubic feet of gas. The oil production was 22 percent of the total oil production in the United States for 1967. Cumulative production at year-end was 15.9 billion barrels of oil and 41.2 trillion cubic feet of gas (Table 10).

Future Resources

Pre-Pennsylvanian geologic events are separated easily from those of the Pennsylvanian and Permian (post-Mississippian). Because of this natural division, future reserves of Region 5 were studied in two parts: pre-Pennsylvanian and post-Mississippian.

Pre-Pennsylvanian—Seven wildcat provinces have been selected as suitable for future exploration: the Palo Duro, Hollis-Hardeman, Fort Worth, Kerr, Val Verde, and Marfa basins, and the Ouachita fold belt. Thickness maps show that all six of the prospective stratigraphic units are present in only three of the provinces (Marfa and Val Verde basins and Ouachita fold belt), and not uniformly through all of them. Only pre-Simpson and Mississippian prospective units are present in the Palo Duro basin, and perhaps in the Kerr basin. The units are present in the Hollis-Hardeman and Fort Worth basins only in part, if at all.

The Woodford shale contains no reservoir beds but is especially important as a probable source rock; therefore, its presence in a wildcat province is highly desirable. Reservoir quality in Ellenburger dolomite is erratic, but this unit yields large volumes of fluids in many places. Sophisticated studies of sedimentary facies in pre-Simpson strata are a prerequisite to exploration for these deeper objectives. Simpson, Montoya, and Mississippian reservoirs have proved to be second-rate, whereas Silurian-Devonian reservoirs have proved to be first-rate. Because of the good source rock quality of much of the Mississippian section, testing of a favorable reservoir bed in that interval might result in discovery of a major oil field.

All present producing provinces are good prospects for new discoveries. The Delaware and Val Verde basins are outstanding, especially for gas accumulations in large anticlines.

The wildcat provinces of Trans-Pecos Texas west and south of the Delaware basin are essentially untested; only a few exploratory wells have been drilled. The area long has been regarded as unfavorable for oil and gas exploration because of the history of intense tectonism and volcanism, and because of a persistent belief among geologists that the entry of meteoric water into the edges of reservoir strata greatly reduces the possibility for oil and gas accumulations.

Post-Mississippian—Although complex stratigraphy and tectonic disturbances are factors impeding a straightforward analysis and estimate of future petroleum resources in the Pennsylvanian and Permian systems, these characteristics heighten the chances for discovery of new oil fields. Suitable trapping mechanisms can be found in the older beds, for lower Paleozoic reservoir rocks have been affected by all late Paleozoic tectonics, whereby additional structural traps have been formed. Truncated edges of lower Paleozoic strata around eroded anticlines also offer stratigraphic-trap possibilities. The special characteristics of late Paleozoic sedimentation have created innumerable wedge-edges of various types of sandstone bodies and limestone lenses of various shapes, all enclosed in shale that could represent source beds. Many such stratigraphic traps in Region 5 have been found, but countless others are yet to be discovered. All of the currently producing provinces, as well as the wildcat provinces, have

TABLE 9. PALEOZOIC PRODUCING PROVINCES OF WEST TEXAS AND EASTERN NEW MEXICO

Province	Reservoir Formations ("Pays")		Principal Types of Traps
	Geologic Age	Dominant Lithology	
Northwest Shelf	Permian	Dolomite, sandstone	Reef, other stratigraphic, structural, combination
	Pennsylvanian	Limestone, sandstone	Bioherms, other stratigraphic, structural, combination
	Siluro-Devonian	Dolomite	Structural
Eastern Shelf	Permian	Dolomite, limestone, sandstone	Structural, stratigraphic, combination
	Pennsylvanian	Limestone, sandstone	Reef, bioherms, limestone and sandstone lenses and pinchouts, low-relief anticlines
	Mississippian	Limestone	Structural
	Ordovician	Dolomite	
Ft. Chadbourne Trend	Pennsylvanian	Limestone, sandstone	Structural, stratigraphic
	Cambro-Ordovician	Sandstone, dolomite	Eroded high-relief anticlines
Central Basin Platform	Permian	Dolomite, sandstone	Stratigraphic, structural, combination
Central Basin Uplift	Pennsylvanian	Limestone, chert conglomerate	Structural, stratigraphic
	Devonian Silurian	Dolomite, limestone, chert conglomerate	Eroded high-relief anticlines, faults, subcrop bands
	Ordovician	Dolomite, sandstone	
Ozona Arch	Permian	Dolomite, sandstone	Structural, stratigraphic
	Pennsylvanian	Limestone	Reef, other stratigraphic, structural
	Ordovician	Dolomite	High-relief anticlines
Bend Arch and North Texas	Permian Pennsylvanian	Limestone, sandstone, conglomerate	Structural, stratigraphic (many sandstone pinchouts and limestone reefs), combination
	Mississippian	Limestone	Structural, stratigraphic
	Ordovician	Dolomite	
Matador-Red River Arch	Permian Pennsylvanian	Limestone, dolomite, sandstone, arkose, granite wash	Structural, stratigraphic, combination
	Mississippian	Limestone	
	Ordovician	Dolomite	
Muenster Arch	Pennsylvanian	Limestone	Structural, stratigraphic, combination
	Ordovician	Dolomite, sandstone	
Fort Worth Basin	Pennsylvanian Mississippian Ordovician	Limestone, sandstone, dolomite, conglomerate	Structural, stratigraphic
Hardeman Basin and Palo Duro Basin	Pennsylvanian	Limestone, sandstone, granite wash	Structural, stratigraphic, combination
	Mississippian	Limestone	
	Ordovician	Dolomite	
Midland Basin	Permian	Dolomite, limestone, sandstone, siltstone	Structural, stratigraphic, fractures in siltstone
	Pennsylvanian	Limestone, sandstone	Reefs, other stratigraphic, structural
	Mississippian Siluro-Devonian Ordovician	Dolomite, limestone	Structural, stratigraphic
Delaware Basin	Permian	Sandstone, limestone, conglomerate	Structural, stratigraphic
	Pennsylvanian Siluro-Devonian Ordovician	Dolomite, limestone, sandstone, conglomerate	Structural (especially eroded high-relief anticlines), stratigraphic
Val Verde Basin	Permian Pennsylvanian Siluro-Devonian Ordovician	Dolomite, limestone, sandstone	Structural (especially high-relief anticlines), stratigraphic

TABLE 10. PETROLEUM RESOURCES IN REGION 5 BY STRATIGRAPHIC DIVISIONS

	Stratigraphic Units	Sedimentary-Rock Volume (thousand cubic miles)	Crude Oil (billion barrels)					Associated-Dissolved (Wet) Gas (trillion cubic feet)					Nonassociated (Dry) Gas (trillion cubic feet)				
			Known fields			Unknown	Known and Unknown	Known fields			Unknown	Known and Unknown	Known fields			Unknown	Known and Unknown
			Original Oil-In-Place	Cumulative Production	Current Oil-In-Place	Undiscovered Oil-In-Place	Remaining Resources	Original Gas-In-Place	Cumulative Production	Current Gas-In-Place	Undiscovered Gas-In-Place	Remaining Resources	Original Gas-In-Place	Cumulative Production	Current Gas-In-Place	Undiscovered Gas-In-Place	Remaining Resources
			A	B	(A—B)	C	(A—B)+C	A	B	(A—B)	C	(A—B)+C	A	B	(A—B)	C	(A—B)+C
Permian	U. Guadalupe	13.0	8.6	1.9	6.7	3.0	9.7	13.4	7.8	5.6	4.9	10.5	0.9	0.3	0.6	0.3	0.9
	L. Guadalupe	23.0	34.7	4.9	29.8	18.4	48.2	20.6	10.1	10.5	11.0	21.5	0.6	0.2	0.4	0.3	0.7
	Leonard	35.8	14.8	1.4	13.4	8.0	21.4	10.6	4.9	5.7	5.7	11.4	0.9	0.3	0.6	0.5	1.1
	Wolfcamp	46.2	3.6	0.5	3.1	1.6	4.7	1.9	0.9	1.0	0.8	1.8	1.7	0.1	1.6	5.1	6.7
Penn.	U. Penn.	41.7	23.7	4.1	19.6	10.3	29.9	13.7	7.3	6.4	5.6	12.0	3.6	0.8	2.8	3.2	6.0
	L. Penn.	16.6	1.9	0.4	1.5	0.6	2.1	1.6	1.0	0.6	0.6	1.2	5.3	1.7	3.6	5.8	9.4
	Subtotal Post-Miss.	176.3	87.3	13.2	74.1	41.9	116.0	61.8	32.0	29.8	28.6	58.4	13.0	3.4	9.6	15.2	24.8
Pre-Penn.	Miss.	14.1	1.2	0.2	1.0	0.6	1.6	0.01	—	—	0.39	0.40	0.14	0.01	0.13	0.30	0.43
	Siluro-Dev.	8.8	6.0	1.1	4.9	0.9	5.8	4.56	1.14	3.42	0.59	4.01	2.86	1.53	1.33	6.79	8.12
	Montoya	2.8	0.2	—	0.2	0.1	0.3	—	—	—	0.08	0.08	0.10	—	0.1	0.25	0.35
	Simpson	8.5	0.9	0.1	0.8	0.5	1.3	—	—	—	0.33	0.33	0.10	0.01	0.1	0.40	0.50
	Pre-Simpson	32.8	6.7	1.3	5.4	2.8	8.2	5.00	1.45	3.55	1.83	5.38	20.20	1.65	18.54	44.20	62.74
	Subtotal Pre-Penn.	67.0	15.0	2.7	12.3	4.9	17.2	9.57	2.59	6.98	3.22	10.20	23.4	3.2	20.2	51.94	72.14
	Total Paleozoic	243.3	102.3	15.9	86.4	46.8	133.2	71.4	34.6	36.8	31.8	68.6	36.4	6.6	29.8	67.1	96.9

NOTES: 1. Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

2. Volumes of rock in Mississippian and Siluro-Devonian are exclusive of Woodford shale, which has a volume of 1,500 cubic miles. Columns A and B are current data as of December 31, 1967.
Estimated resources in Cretaceous are 0.5 billion barrels of oil and no gas.
Estimated resources in Ochoa Series of Permian are 0.0036 billion barrels of oil, 3.9 billion cubic feet of gas; rock volume is 9,400 cubic miles.
Volume of sedimentary rocks of post-Permian age is 29,400 cubic miles.

such possibilities; none have been explored completely.

In fact, it is thought that all provinces east of the Sierra Grande-Pedernal-Diablo positive elements and north of the Ouachita fold belt eventually will be proved productive of oil or gas, with the exception of those areas in which the Pre-Cambrian basement is bared or is covered only by a veneer or redbeds. The far-western provinces were affected by Mesozoic and Cenozoic tectonism. The post-Mississippian there, like the pre-Pennsylvanian of the Trans-Pecos area, is mainly unexplored. Even the Mesozoic and Cenozoic sections in a few localities may contain minor amounts of oil, either indigenous or derived from underlying Paleozoic strata.

Quantitative Estimates—A total of 133.2 billion barrels of oil-in-place is estimated (Table 10) to remain in the ground, about one-third being in accumulations which have not been discovered, either as new fields or as extensions to known fields. A sum of 68.6 trillion cubic feet of associated and dissolved gas remains in-place, about one-half being undiscovered; and 96.9 trillion cubic feet of nonassociated gas remain in-place, two thirds of it being still undiscovered. The reason cited for the difference in proportions discovered and undiscovered is that nonassociated gas production in Region 5 is a newer development than the production of oil and associated gas. The total volume of gas still in-place in Region 5 is thus on the order of 165.5 trillion cubic feet.

Unconventional Resources—In addition to free fluids in reservoir rocks, laboratory analyses have revealed that most of the subsurface nonreservoir sedimentary rocks also contain disseminated hydrocarbons, which can be extracted only by pulverizing the rock and treating it with solvents.[37,38] *At present there is no technology for profitable exploitation of the disseminated hydrocarbons, and they may, for all industrial purposes, be "locked forever within the rocks."* There is a possibility that advanced technology—perhaps by the year 2070 A.D.—will have developed methods for *in situ* production of such hydrocarbons.

However, inasmuch as the possible effects of future economics and technology are to be ignored herein, an estimate of the total volume of disseminated hydrocarbons in subsurface rocks of Region 5 has been made and the result is startling: 3.7 trillion barrels of oil. Contemplation upon the "petroliferous" lithology of rocks such as the thick Mississippian and the lower Pennsylvanian strata that have poor reservoir characteristics suggests that the estimate is realistic.

In the same vein, an estimate of the volume of hydrocarbon gas dissolved in formation waters in Region 5 is speculated to amount to 6,000 trillion cubic feet. Just as for the oil present as disseminated hydrocarbons, no one knows how much, *if any,* of this formation-water gas can be produced.

Obstacles to Exploration

Present obstacles to exploration in Region 5 fall into four general categories: geologic, technologic, economic, and psychologic. The principal geologic obstacles are the many tectonic complexities and the thick volcanic cover in parts of Trans-Pecos Texas.

Geophysical technology improves constantly, but geophysicists must not become so preoccupied with techniques that their perspective of exploration goals becomes distorted. The full use of advanced geophysical techniques may be limited by old prejudices in certain provinces and by management's reluctance to reinvest in areas of earlier disappointments.

Advances in subsurface geology in recent years have been mainly in the field of sedimentation and, to a lesser degree, in the application of hydrodynamic principles to studies of migration and accumulation. Investigations of crude oil characteristics as related to possible source beds and migration paths are under way, but much ground needs to be covered before useful results can be obtained. Little or nothing has been done about the application of gas analyses to similar problems. Studies of tectonic principles have been minimal. Techniques of routine subsurface office and laboratory procedures have advanced very little since before World War II.

Prudent management does not risk capital expenditures for "way-out" technologies as long as exploration can be conducted less expensively with at least a modicum of success. As oil becomes scarcer and the demand greater, the economic imbalance may lead to decisions for larger budgets in subsurface geology, including a greater number of exploratory wells. Greater financial rewards then might induce geologists to improve subsurface technology.

However, the obstacles to exploration do not stop with economic problems. The mental outlook of the earth scientist in petroleum exploration often has been self-restricting. Fresh, imaginative approaches and discerning scrutiny of the rocks can lead to new knowledge.

In large part, the obstacles to exploration are not insurmountable. Ingenuity, urgency, economic incentives, aggressiveness, open-mindedness, and a will to achieve—these attributes can overcome all of the obstacles to exploration in Region 5.

CHAPTER 8
REGION 6. WESTERN GULF COAST

Coordinator

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Humble Oil & Refining Company
(Authors Listed in Appendix D)

SUMMARY

The relative potential of the nine main divisions of the stratigraphic section is shown by estimates of recoverable oil in Table 11. Figure 19 shows location of areas discussed.

This region has been highly explored to customary depths, but still contains substantial areas of unexplored, thick, marine, sedimentary rocks with high potential above 30,000 feet. These are primarily lateral and downdip extensions to existing producing trends, frontier or unexplored areas, and, to a limited extent, areas with deeper objectives within currently producing trends. It is expected that they will supply more new petroleum than further exploration within the producing trends.

LOUISIANA-TEXAS CONTINENTAL SHELF

After 20 years of active exploratory drilling, this area remains the prime prospective area of Region 6. The generally productive areas, or trends, in Mio-Pliocene and Pleistocene sedimentary rocks have not been nearly completely explored, and their limits have not been established by drilling. Extension of favorable marine shale-sandstone relationship to the edge of the continental shelf is likely in Pleistocene strata, but less likely in Pliocene strata (Figure 20). Reflection-seismic surveys have revealed undrilled, or inadequately drilled, structures, including salt diapirs, throughout the areas.

As shown in Table 11, approximately two-fifths of the volume of favorable strata outside the present limits of production is considered to be prospective for crude oil, and three-fifths are prospective for natural gas. The lower Miocene, which is present in the southwest Louisiana and Texas offshore below 20,000 feet, is prospective for gas if adequate reservoir rocks extend into the area.

East of Louisiana, the Oligocene to Pleistocene clastic strata thin and grade into the carbonate platform facies of the west Florida offshore. However, reefs, which may contain petroleum, may be present offshore in Miocene-Oligocene strata east of the Mississippi delta.

UPPER CRETACEOUS BELT OF SOUTHEASTERN LOUISIANA, SOUTHERN MISSISSIPPI, SOUTHERN ALABAMA, AND NORTHWESTERN FLORIDA

This area is considered to be the second most potential area for crude oil discoveries. A large unexplored prospective belt is postulated south of the productive Tuscaloosa (lower part of the upper (Cretaceous) area which extends into the offshore. The possibilities for accumulation of crude oil are thought to be excellent in either stratigraphic or structural traps in lenticular Tuscaloosa sandstones between 8,000 and 20,000 feet. Prospects exist also in the overlying Eutaw sandstones. Structurally, the belt extends westward into Texas where good reservoir beds are not expected.

LOWER CRETACEOUS BELT OF SOUTHERN TEXAS, LOUISIANA, MISSISSIPPI, ALABAMA, AND NORTHWESTERN FLORIDA

The prospective belt in lower Cretaceous strata practically coincides with the upper Cretaceous belt. It extends basinward from producing fields to where the base of the section is estimated to be 25,000 feet deep and into the offshore east of Louisiana. It extends farther west into Texas than the upper Cretaceous belt. A speculative area at greater depths extends basinward to the edge of the continental shelf. The favorable conditions for crude oil and natural gas occurrence in basal lower Cretaceous sandstones and in younger lower Cretaceous carbonate rocks demonstrated in the producing belt continue across the prospective belt. Most of the lower Cretaceous accumulations are on positive structures. New oil fields and gas fields are expected on structure in both the producing and prospective belts. The petroleum potential of the lower Cretaceous is considered to be very large.

BLACK WARRIOR BASIN

The Black Warrior basin of Mississippi and Alabama is geologically the southern extension of Regions 9 and 10 (Eastern Interior and Appalachians, respectively). In addition to the possibilities of the older Paleozoic formations (Cambro-Ordovician), upper Paleozoic strata (Mississippian and Pennsylvanian) have produced some natural gas, and have not been extensively explored. Improved seismic techniques should be able to outline the fault traps expected. Perhaps, more natural gas than crude oil should be expected because of results to date and experience to the north in Region 10.

CONTINENTAL SLOPE OFFSHORE LOUISIANA AND TEXAS

This area is the focus of a great deal of exploration by both commercial and scientific organizations, and, undoubtedly, proprietary information is growing at a rapid pace. The literature strongly suggests that most of the slope is not a geological carbon copy of the favorable combination of stratigraphy and structure prevailing on the shelf. Also the depth of water increases from 600 feet to at least 8,200 feet. Until the potential is more definitely indicated by drilling, one must assess the possibilities of important discovery as highly speculative.

OTHER AREAS

The lower Miocene-Oligocene trends of the lower Gulf Coast (mainly onshore and at greater depths) are particularly attractive for more natural gas discoveries. The Eocene-Paleocene trends to the north are attractive for further natural gas discoveries in Texas and crude oil discoveries in Louisiana, mainly at greater depths.

The possibilities of finding new, important fields in Cretaceous strata outside the area discussed above are not considered good.

Discovery of new fields in Jurassic strata in the well-explored producing area of North Louisiana and South Arkansas depends mainly on successful drilling of nonconventional traps. Although there is more room in the semideveloped areas in Texas and Mississippi for discoveries in conventional (structural) traps, here too, the future of discovery depends on success in probing nonconventional traps such as stratigraphic traps and fracture reservoirs, and salt diapirs. A prospective belt extends from South Texas to Florida generally north of the lower Cretaceous belt, but overlaps it in southeast Mississippi, Alabama, and Florida. Depths to objectives range from 10,000 to 20,000 feet. Available subsurface control suggests that favorable reservoir rocks do not occur consistently, although favorable structure may be expected.

A few wells in southwestern Arkansas and northeastern Texas have found marine, relatively undeformed, porous sandstones and carbonate rocks of early through middle Pennsylvanian age below the Jurassic at depths less than 6,000 feet. Aside from the fact that the discovery of these rocks was an outstanding geologic surprise, the occurrence of such rocks at shallow depths is of great exploratory significance. Their extent is unknown, but they could be present in a belt gulfward from the Ouachita front from South Texas to western Mississippi.

DISCUSSION

INTRODUCTION

Region 6, the western Gulf Coast, extends from the Rio Grande on the Mexican border eastward through Alabama to the Georgia border. Northward it includes the southern part of Arkansas and extends to the Mississippi-Tennessee border (Figure 19). The basic approach to the assessment of the potential reserves in the area was to study the hydrocarbon controls in the producing provinces and then to project these controls into the unknown or unexplored areas. Volumes of favorable unexplored sedimentary rock were calculated, giving no weight to the presence or absence of discrete prospects, or to economics. A drilling depth of 30,000 feet was the agreed base of the sedimentary wedge to be evaluated.

Future crude oil reserve additions were estimated by determining favorable volumes of sedimentary rock in cubic miles and applying a judgment factor of crude yield per cubic mile of rock. This approach necessarily differs from that used by the Potential Gas Committee,[39,40] because they have access to company proprietary information that can be used effectively in calculating future natural gas reserves.

Substantial areas and volumes of potential source and reservoir rock remain unexplored in the western Gulf basin. This potential is primarily in extensions to producing trends; in frontier or unexplored areas; and, to a limited extent, in deeper objectives within producing trends. This technical assessment indicates a minimum volume of 454,000 cubic miles of sedimentary rock with a favorable potential for future discovery of hydrocarbons, either gas or oil. Table 11 shows the volumes of favorable sedimentary rock, by geologic age, remaining to be explored. Except for the Pleistocene and Jurassic, where 23,000 and 7,650 cubic miles of sedimentary rock, respectively, lack any intensive exploration, this entire volume lies beyond the present limits of production. Volumes of favorable and untested sedimentary rock within the other producing trends were not calculated because of the proprietary nature of prospect information and because reserve additions probably will be insignificant when compared to the possible new-play or new-area crude reserve additions. This omission, of course, does not imply that the industry will not find some good oil and gas fields in these more mature areas. The total volume of favorable sedimentary rock is probably understated. The lack of subsurface control or the unavailability of company proprietary information made volumetric calculations impossible in a few of the speculative plays (most plays are shown in Table 11).

Of the total rock volume considered to be potentially productive in the western Gulf Coast, 261,000 cubic miles are believed to have gas potential and the remaining 193,000 cubic miles of sedimentary rock, oil potential. Table 11 indicates the amount of the total favorable sedimentary rock volume, by

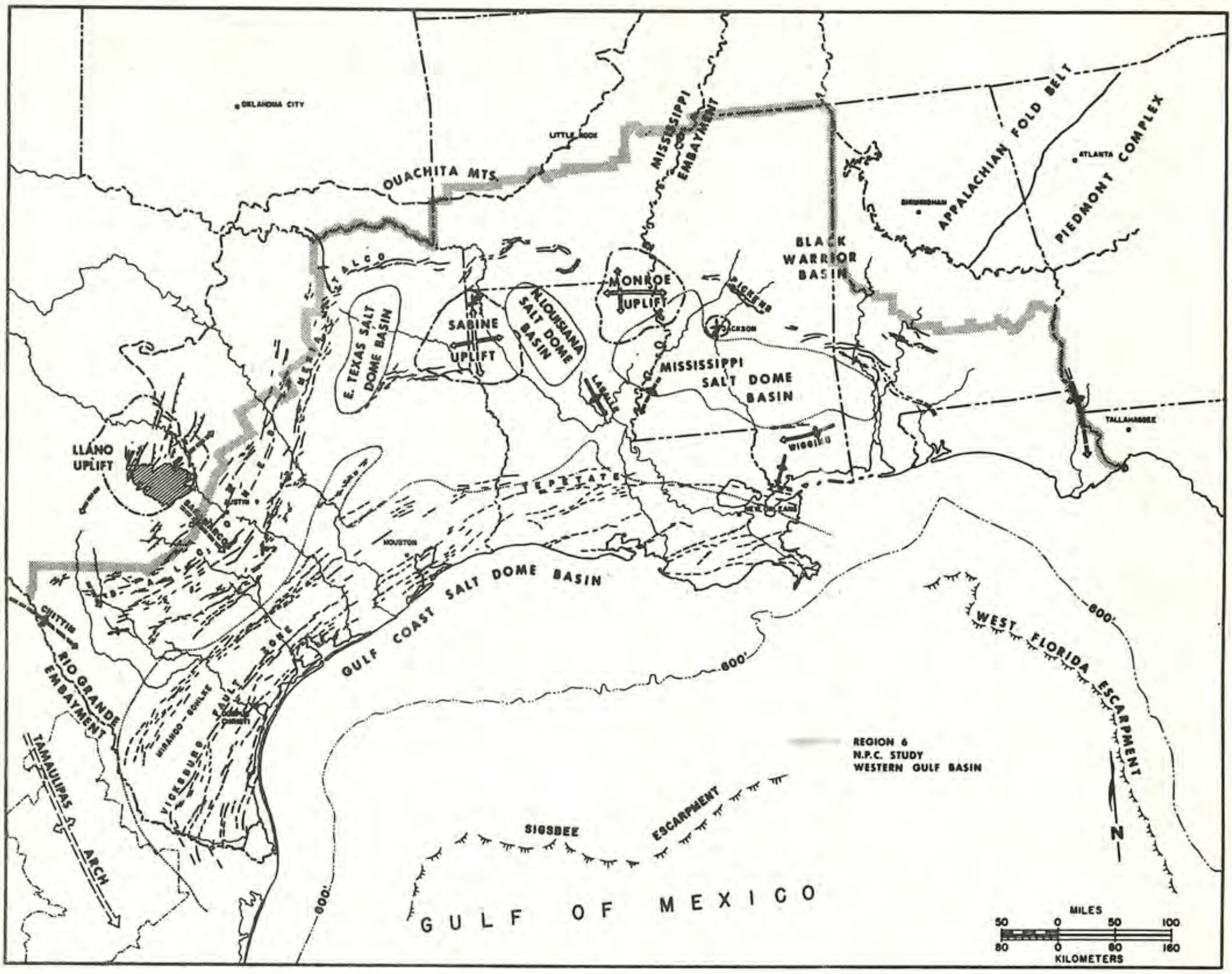

FIGURE 19. Map of Region 6, Western Gulf Coast, Showing Major Geologic Features

geologic age, thought to have possibilities for oil production. As reported by the Potential Gas Committee,[40] "possible" and "speculative" gas reserve additions in the western Gulf Coast should be about 275 trillion cubic feet. Recoverable crude oil reserves added in this region after December 31, 1968, will be approximately 15 billion barrels. This figure represents an additional volume of recoverable crude reserves equal to about 38 percent of the API estimate of ultimate crude recovery of 40 billion barrels from fields found prior to January 1, 1969. Application of a statistical growth factor (see reference 41) to the current API estimate (40 billion barrels) suggests an ultimate crude recovery from these fields of about 51.8 billion barrels. If this ultimate recovery is attained, the predicted 15 billion barrels of reserves to be added, after December 31, 1968, will amount to about 29 percent of the ultimate recovery from fields found prior to January 1, 1969.

The Potential Gas Committee [40] estimates gas reserve additions of 131 trillion cubic feet in the "probable" category. No attempt was made to calculate crude oil reserve additions which would fall in this category.

The potential of the sedimentary rock volume considered favorable for crude oil recovery and the various yields predicted are shown in Table 11. The lowest yield is an estimate of the average for all United States producing basins.[42] The intermediate yield is based on crude recovery per cubic mile of sedimentary rock for the western Gulf Coast. The highest yield of 150,000 barrels of crude oil per

TABLE 11. FAVORABLE SEDIMENT VOLUMES AND AREAS FOR FUTURE HYDROCARBON EXPLORATION— WESTERN GULF BASIN

Geologic Age	Volume of Favorable Sediment (cubic miles)	Favorable Area (square miles)	Potential Rating of Volumes and/or Areas: Good	Fair	Poor	Speculative	Volume of Favorable Sediment with Oil Potential (cubic miles)	Estimated Oil Yield [1] (barrels per cubic mile)
Pleistocene								
Partially Explored	4,500	4,300	X				2,250	A
Partially Explored	17,500	25,700		X			8,750	B
Unexplored	13,450	10,700	X				2,690	A
Unexplored	9,550	8,300		X			1,910	B
Continental Slope	51,800	52,000				X	10,360	C
Pliocene								
Sand and Sand-Shale								
Magnafacies		21,000						
La.	14,000		X				7,000	A
Texas	3,000		X				1,500	A
Shale Magnafacies	20,000	60,000				X	4,000	C
Upper Miocene								
Sand and Sand-Shale								
Magnafacies		23,000						
La.	16,000		X				8,000	A
Texas	13,000			X			2,600	B
Shale Magnafacies	10,000	20,000				X	2,000	C
Lower Miocene-Oligocene								
Probable	4,800	4,700	X				0	
Possible	4,400	4,900		X			0	
Eocene-Paleocene								
Texas Wilcox	12,000	8,700		X			0	
La. Wilcox	3,800	5,800		X			3,800	B
Texas and La. Claiborne	7,000	8,000		X			7,000	B
Upper Cretaceous								
Tuscaloosa	17,000	36,410	X				17,000	A
E. Texas-Unexplored	3,600	9,599		X			3,600	B
Other-Unexplored	14,900	14,957			X		14,900	C
Lower Cretaceous								
Prospective	70,000	94,000	X				35,000	C
Possible	50,000	77,000				X	25,000	C
Jurassic								
Semideveloped	7,650	19,307		X			1,530	B
Immature	30,800	74,230		X			6,160	B
Pre-Jurassic								
Black Warrior Basin	55,000	35,000	X				27,500	C
Ouachita Tectonic Belt	Unknown	30,000				X	0	
Coastal Plain								
Triassic	Unknown	Unknown			X		0	
Paleozoic	Unknown	35,000		X			0	
Total	453,750						192,550	

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

[1] Oil Yields utilized in Computing Future Recoverable Reserve Additions.
A—150,000 barrels per cubic mile—Derived from portion of Upper Miocene Fleming Trend.
B— 80,000 barrels per cubic mile—Avg. Gulf Coast Yield.
C— 50,000 barrels per cubic mile—Avg. U. S. Producing Basin Yield.
Using these yields, added recoverable crude oil reserves would be approximately 15 billion barrels.

cubic mile is based on calculations for a part of the upper Miocene Fleming. The calculated number was actually twice this; consequently, estimated future reserve additions from the rock volume with the highest potential yield may be understated substantially.

It is apparent from Table 11 that the most favorable objectives are (1) the partially explored and the unexplored sedimentary rocks of the Pleistocene and upper Miocene-Pliocene, (2) the upper Cretaceous Tuscaloosa in the southeastern part of Region 6 (Figure 19), (3) lower Cretaceous sandstone and carbonate rocks of Trinity age, and (4) lower Paleozoic rocks in the Black Warrior basin. Of several interesting, but highly speculative, areas listed in Table 11, the largest potential exists in sediments that were deposited on the continental slope. The potential in strata of other geologic ages is not considered as good as for those mentioned. However, with the proper economic environment and incentives, plus improved technology in all phases of exploration activity, it is entirely possible that these lower-rated areas will contribute significantly to the total ultimate production of oil and gas.

POTENTIAL BY GEOLOGIC AGE

A summary of the technical assessment of the western Gulf Coast by geologic age follows.

Pleistocene

The greatest potential is in an area of 15,000 square miles on the outer continental shelf offshore from Louisiana and Texas. There, the overall objective section, the neritic interbedded sandstone and shale facies, is from 3,000 to more than 8,000 feet thick. Approximately one-third (4,300 square miles) of the area is in an early stage of development, and two-thirds (10,700 square miles) are unexplored.

Potential source and reservoir rocks of the Pleistocene neritic facies are similar to those of the older, highly productive Tertiary section. Structural and stratigraphic conditions favoring entrapment of oil are as common in the most favorable Pleistocene area as in nearby areas of prolific Tertiary fields.

The continental slope of the Gulf of Mexico offshore from Texas and Louisiana is also underlain by a large volume of Pleistocene sedimentary rocks, but its potential cannot be assessed at our current stage of knowledge.

Upper Miocene-Pliocene

During the Miocene and Pliocene, sediments were introduced into the basin by deltas and were distributed by marine currents gulfward and laterally across persistently broad shelf areas. During deposition, three facies were being developed simultaneously in bands mainly parallel with the shoreline. These facies are referred to as the sand magnafacies, the sand-shale magnafacies, and the shale magnafacies.

Most hydrocarbons found in the upper Miocene-Pliocene section have been in structural traps formed by salt diapirs and growth faults in the inner- and middle-neritic zones of the sand-shale magnafacies. Future additions to hydrocarbon reserves will be made by the extension and fill-in of the trends now producing in the sand and sand-shale magnafacies.

A possible future source exists in the shale magnafacies, because it is reasonable to expect that turbidite sands were deposited on the updip flanks of salt structures and in the lows between them. The search for traps of this nature, particularly in the younger sections, will involve operations beyond the continental shelf.

Lower Miocene-Oligocene

Sedimentary rocks downdip from present lower Miocene production in Louisiana and Texas, and in the Texas offshore area on strike with this producing trend, provide the major future petroleum province in lower Miocene-Oligocene beds. This province is about half the size of the present lower Miocene trend and is divided into two roughly equal parts: a *probable* producing area where an environment favoring hydrocarbons is known to exist, and a *possible* producing area where such an environment reasonably can be inferred.

Future lower Miocene-Oligocene discoveries should be found under conditions similar to those controlling present production, where reservoirs are typically sandstone and traps are usually associated with salt domes, fault closures, anticlines, residual highs, and, less commonly, stratigraphic changes. Deep-water shale replaces sandstone downdip, limiting the extent of production.

Miocene-Oligocene strata of Mississippi, Alabama, and Florida are thin, nonpetroliferous carbonate rocks. They show little promise for future discoveries, although thicker and deeper reef-carbonate rocks may be present east of the Mississippi Delta.

Additional reserves will be found from the Rio Grande to southeastern Louisiana within present producing trends, where the most productive areas in successively younger units commonly are found progressively downdip and northeast along strike.

Eocene-Paleocene

Of these two series, current production is only from the Eocene in the western Gulf Coast, and future petroleum discoveries are expected to be made in Eocene rocks. The Wilcox Group represents two future hydrocarbon provinces—gas in Texas and oil in Louisiana. A possible future oil province covering parts of Texas and Louisiana is predicted for the Claiborne Group. No new province is foreseen for the currently productive Jackson Group. Structurally, these provinces will prove similar to the established trends, in which parallel to subparallel regional growth faults predominate. Fault-line and salt-related structures will be prevalent.

Northeast Thompsonville and North Milton fields, with reserves estimated at 500 billion to 1 trillion cubic feet of gas, are on the landward edge of the predicted Wilcox gas province of Texas; they provide significant clues to future possibilities within this province. Fordoche field, with oil reserves rumored to be 70 to 120 million barrels, is on the landward edge of the predicted Wilcox oil province of Louisiana, and suggests excellent future potential for that area.

Upper Cretaceous

The prospects for significant additions of reserves in the Gulfian Series are good in southeast Louisiana, Mississippi, Alabama, and Florida, but only fair to poor in the remainder of the area.

In the explored area of southeast Louisiana-Mississippi-Alabama-Florida, which contains 30,000 cubic miles of sedimentary rock, limited additional reserves can be expected in new discoveries and extensions. In the unexplored area, which contains 17,000 cubic miles of sedimentary rock, Tuscaloosa sandstone lenses should provide excellent possibilities for both structurally and stratigraphically trapped oil. Fair possibilities exist in similar sandstones of the lower Eutaw. Carbonate buildups of reeflike limestone are possible in the Navarro beds on the carbonate banks off the Florida coast.

Continuing exploitation may result in minor additions for the Louisiana-Arkansas explored sedimentary rock volume (10,000 cubic miles). The unexplored part (4,700 cubic miles) in South Louisiana has poor potential, but prospects are fair where Woodbine turbidite or deep-water sands were swept out past the Comanchean shelf.

The explored sedimentary rocks of East Texas (11,200 cubic miles) will furnish minor additions to reserves through further exploitation. The potential of the unexplored rock volume (3,600 cubic miles) is rated as poor to fair. In the Woodbine, possibly turbidite and marine sandstone units on the south and southwest flanks of the Sabine uplift offer fair prospects. In the Austin-Eagle Ford section, possibilities are poor to fair on the south and southeast flanks of the Sabine uplift.

For South Texas, potential in the explored sedimentary rocks (8,800 cubic miles) and the unexplored rocks (10,200 cubic miles) is rated as poor in view of the expected absence of reservoir beds.

Lower Cretaceous

Favorable sedimentary rocks probably underlie most of the western Gulf Coast, though they are deeply buried in much of the area and have not been penetrated by wells. Average thickness in the productive and prospective belts is about 4,000 feet; the area is 177,000 square miles, and the sedimentary rock volume is approximately 130,000 cubic miles. A speculative belt, which extends basinward from the prospective belt to the outer edge of the continental shelf, has an area of 77,000 square miles; its volume of sedimentary rock may be more than 50,000 cubic miles.

The section is composed of carbonate rocks and terrigenous clastic beds; much of the sediment was deposited in environments favorable for the generation and accumulation of oil and gas. Approximately 300 fields in Texas, Louisiana, Arkansas, Mississippi, and Alabama have produced about 1.5 billion barrels of oil and 10.5 trillion cubic feet of gas from lower Cretaceous sandstone and carbonate rocks. The ultimate recovery from the fields and their extensions, and from new discoveries within the productive belt, probably will be more than the amount already produced. In the more seaward, unexplored province, especially in the Mississippi and Rio Grande embayments and in the East Texas basin, numerous accumulations will be found in limestone reefs, shell mounds, porous dolomite, and deltaic sandstone. The petroleum potential of the thick, widespread lower Cretaceous in Region 6 is very great.

Jurassic

Reservoir beds of porous sandstone and carbonate rocks are widespread in the Jurassic of the Gulf Coast. Petroleum accumulations in these rocks due to structural or stratigraphic situations have yielded nearly 613 million barrels of oil and condensate and 3.9 trillion cubic feet of gas. Virtually all of the production is confined to the mature areas in Arkansas and Louisiana, and to the semideveloped areas in Texas and Mississippi, principally from the Schuler, Haynesville, and Smackover formations.

If long-range growth is to be realized in the mature provinces which are in the stage of declining production, or in the semideveloped areas which are being exploited rapidly, exploration must turn to unconventional traps and to other Jurassic formations. The immature areas, which are commonly in the greater depth range, have had varied degrees of investigation. Trends which now are undergoing rapid development in semideveloped areas may be extended into adjacent immature areas. In other immature regions, present data suggest that greater areal selectivity must be exercised and that a higher incidence of areas of poor reservoir-rock quality should be expected. Jurassic formations at depths greater than 20,000 feet are not expected to be of widespread productive significance.

Pre-Jurassic

In the western Gulf Coast, there is good potential for future petroleum provinces in upper Paleozoic rocks of the Black Warrior basin and on the Gulf of Mexico side of the Ouachita tectonic belt. There is a remote possibility for finding hydrocarbons in subthrust lower Paleozoic foreland carbonate rocks beneath the interior part of the Ouachita fold belt. The hydrocarbon potential of geosynclinal sedimen-

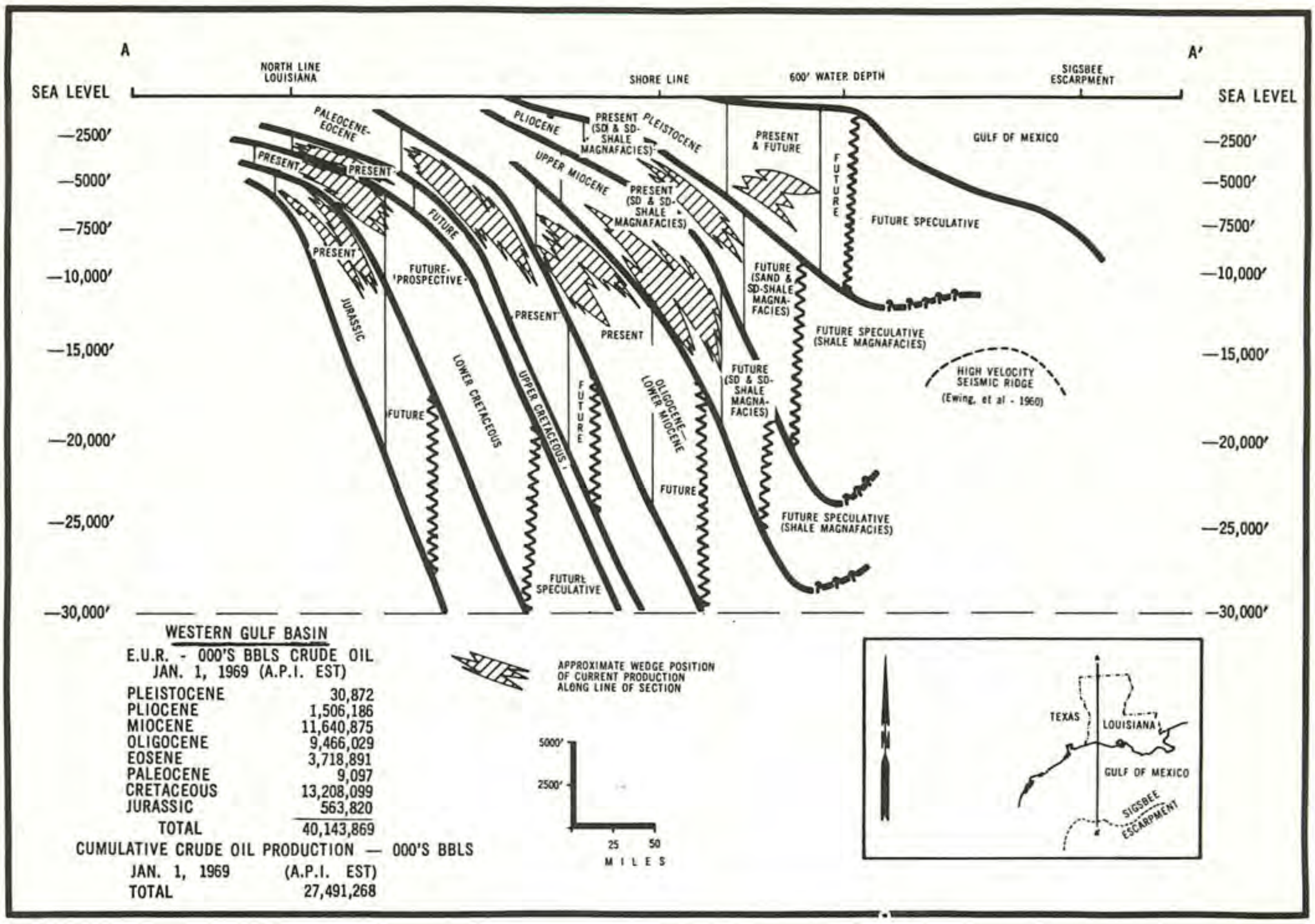

FIGURE 20. Diagrammatic Dip Section Across Region 6, Western Gulf Coast

tary rocks of the Ouachita tectonic belt and of the post-orogenic Triassic section is considered to be negligible.

The Black Warrior basin of Mississippi and Alabama contains a thick section of Paleozoic foreland sediments. The basin tectonics should be comparable to those of the other foreland basins, in which large, buried, normal faults are characteristic. Improved seismic techniques should reveal similar anomalies in the Black Warrior basin, and large hydrocarbon accumulations ultimately may be found in deep fault traps in lower Paleozoic carbonate rocks.

There is no production from pre-Jurassic rocks gulfward from the Ouachita front. Most wells drilled below the Jurassic have encountered either tight, highly deformed, geosynclinal facies of the Paleozoic Ouachita fold belt, or redbeds and igneous rocks of the late Triassic Eagle Mills formation.

Since 1960, a few wildcats have penetrated relatively undeformed, very fossiliferous, shallow-water shelf-carbonate and clastic rocks of Pennsylvanian age beneath the coastal plain. These strata, identified as Desmoinesian from fusulinids, were found on the Gulf of Mexico side of the Ouachita fold belt in northeast Texas and southwest Arkansas. Good porosity has been found in both sandstone and carbonate rocks. The presence of these strata suggests that a potentially large, virtually unexplored, petroleum province may exist in upper Paleozoic rocks of the Gulf coastal plain.

CONCLUSIONS

Figure 20 illustrates where production is obtained in Cenozoic and Mesozoic units of the western Gulf Coast. Possible future producing sections of this giant wedge of sedimentary rocks also are indicated. The National Petroleum Council Subcommittee believes a good future potential for new reserves of both oil and gas exists in the western Gulf Coast. The bulk of the new reserves will be found at greater depths in extensions to existing trends onshore and in the fill-in of, and extensions to, existing trends in the offshore, probably in much deeper water than has been explored. New reserves will be costly to locate, develop, and produce, but they are there.

CHAPTER 9

REGION 7. MIDCONTINENT

Coordinator

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Phillips Petroleum Company
(Authors Listed in Appendix D)

SUMMARY

The petroleum potential of the various parts of this large region is easily discernible by reviewing the estimates of potential recoverable reserves (Tables 12 through 15). Location of the areas discussed is shown on Figure 21.

Obviously, Oklahoma and the Texas Panhandle will provide more than one-half of the future crude oil and approximately three-fourths of the future natural gas. Kansas will rank second in new crude oil, and Arkansas second in new natural gas. Nebraska will become more important as a producer of crude oil. Significant new reserves of crude oil are expected in the region from structural and stratigraphic traps in Pennsylvania strata, but pre-Pennsylvanian rocks should become the most important future reservoirs as exploration for structural traps continues in the deeper parts of the basins.

TEXAS PANHANDLE AND OKLAHOMA

The northern shelf of the Anadarko basin (especially the Oklahoma portion) still offers good possibilities for the discovery of significant crude oil and natural gas reserves in Pennsylvanian sandstones and carbonate rocks (mainly in stratigraphic traps) and in older rocks (mainly in structural traps). In the less extensively explored deeper parts of the basin, significant discoveries of natural gas have been made in Hunton carbonate rocks (Siluro-Devonian), and more are anticipated in these strata and in younger and older rocks. Because drilling depths are between 15,000 and 30,000 feet, structural traps outlined by seismic surveys will be the main targets for exploratory drilling.

In extensively explored southern Oklahoma, additional accumulations may well be discovered in the deeper parts of the Ardmore and Anadarko basins, which have not heretofore been subjected to intensive search. While drilling to more than 20,000 feet will be required, faith in the results of prospecting at such depths is not unfounded in view of the surprising results produced by this very petroliferous and geologically complex area.

The producing area of central and northern Oklahoma is expected to continue to provide new crude oil (but at a declining rate) through extensions to old fields and occasional discoveries of new, small fields. It is believed that undiscovered prospects may be found in the relatively untested, lower-Ordovician and upper-Cambrian section of carbonate rocks (Arbuckle) in northeastern Oklahoma and southeastern Kansas. The known and inferred geology certainly justifies more extensive drilling (maximum depth 5,000 feet) through the entire Arbuckle.

The Arkoma basin in eastern Oklahoma and western Arkansas produces important quantities of nonassociated (dry) natural gas (but no crude oil) largely from stratigraphic traps in Pennsylvanian strata. Minor amounts are produced from Mississippian and lower Devonian and Silurian rocks. Significant discoveries are expected in other stratigraphic traps in Pennsylvanian sandstones. The older formations (mainly the predominantly carbonate section from the top of the Devonian to the base of the Cambrian) are also considered to have potential. However, the exploratory problem may be difficult because the structure in the older rocks may differ radically from the structure in the younger rocks.

The petroleum potential of the Ouachita Mountains on the southern border of the Arkoma basin is assessed as extremely speculative, apparently because of complex structure and indurated rocks. However, solid hydrocarbon deposits, liquid oil seeps, and a small shut-in gas well are known in this area. Moreover, geologists now generally regard overthrust belts at least slightly more favorably than they did in the past.

KANSAS

The Hugoton embayment in western Kansas stands out as the most potential area in Kansas. Substantial discoveries of crude oil are expected mainly in stratigraphic traps in Pennsylvanian strata, and in structural traps in older rocks. Stratigraphic traps in Permian, Pennsylvanian, and Mississippian strata are anticipated to yield substantial new reserves of natural gas. Exploration will continue to be hampered by the enormous amount of land held by owners of shallow gas production.

In eastern Kansas, where lenticular Pennsylvanian sandstones produce crude oil from a wide variety of stratigraphic traps, it is anticipated that additional shallow crude oil will be found by random drilling. The Arbuckle of southeastern Kansas, discussed earlier, and the younger Ordovician and Mississippian rocks offer additional possibilities.

The Salina and Forest City basins extending into Nebraska are thought to have limited potential because of the poor results of considerable exploratory drilling. Perhaps, the western flank of the Salina basin, where the Pennsylvanian overlaps older rocks, is the most favorable part of these basins.

NEBRASKA

Most of the crude oil reserves of this area are in stratigraphic traps in Pennsylvanian sandstones on the Cambridge arch. Other such accumulations should occur on the top or flanks of the arch. The Salina basin on the east is less thoroughly explored than the Kansas part of it. Drilling in this basin and on its preferred western flank may well discover small fields which are commercial at the shallow depth of approximately 3,000 feet. In northwestern Nebraska, lower Permian reefs containing petroleum may fringe an area of evaporite deposits.

ARKANSAS, MISSOURI, IOWA, AND MINNESOTA

The potential of the Boston Mountains area on the north of the Arkoma basin is negligible. The petroleum potential of Missouri and Iowa also is negligible, and Minnesota has no potential.

DISCUSSION

INTRODUCTION

The Midcontinent region as defined in this report includes the Texas Panhandle, Oklahoma, northern Arkansas, Missouri, Kansas, Nebraska (excluding the Panhandle), Iowa, and Minnesota (Figure 21). The entire area covers approximately 446,590 square miles and, excluding the Ouachita Mountains of Arkansas and Oklahoma, contains about 324,200 cubic miles of sedimentary rock overlying the Pre-Cambrian basement. The productive and potentially productive area covers approximately 278,600 square miles and, excluding the Ouachita Mountains of Arkansas and Oklahoma, contains about 290,200 cubic miles of sedimentary rock. Minnesota, the north half of Iowa, northeastern Nebraska, and the Ozark area of Missouri, Arkansas, and Oklahoma are believed to have little or no potential for hydrocarbon accumulation.

The Midcontinent structural province is that part of the North American craton geographically west of the Mississippi River; the regional dip is gentle, structural features are of low relief (except in southern Oklahoma), and the periods of major deformation occurred during late Paleozoic time. The thickest and most complete section of Paleozoic rocks is in the Anadarko and Ardmore basins of Oklahoma (Figures 22 and 23). An incomplete section of Mesozoic rocks overlies the Paleozoic in the western, northern, and southern parts of the Midcontinent. Tertiary and Quaternary units locally form a surficial cover.

Production of oil and gas has been an important factor in the economy of this region for more than 70 years. Based upon published API and AGA data, as of December 31, 1967, approximately 15 percent of the original total ultimately recoverable crude oil reserves and 21 percent of the original total ultimately recoverable gas reserves in the United States were present in the Midcontinent region.

Proved reserves of ultimately recoverable oil and gas in the Midcontinent (17.3 billion barrels and 130.0 trillion cubic feet, respectively) are approaching depletion. Production through 1967 of 14.9 billion barrels (86.1 percent of the oil) and 81.4 trillion cubic feet (62.6 percent of the gas) dictates this conclusion. A review of Midcontinent geology indicates that future potential oil and gas reserves of 1.7 billion barrels and 44.5 trillion cubic feet, respectively, remain to be found. These figures represent the total of "probable," "possible," and "speculative" potential reserves as defined by the Potential Gas Committee.[10]

Future potential oil reserves should be found in the Texas Panhandle and Oklahoma, which should furnish 54 percent (932.0 million barrels) of the estimated new potential reserves; in Kansas, 32 percent (561.3 million barrels); in Nebraska, 12 percent (201.8 million barrels); and in Missouri and Iowa, 2 percent (26.6 million barrels). The Pennsylvanian is considered to be the most important potential reservoir, having 32.7 percent (563.0 million barrels) of the estimated new reserves; the middle and upper Ordovician are next (20.4 percent or 352.3 million barrels), then the lower Devonian-Silurian (16.7 percent or 286.9 million barrels), the Mississippian (13.8 percent or 237.0 million barrels), the Cambrian-lower Ordovician (12.2 percent or 210.0 million barrels), the Permian (2.3 percent or 39.0 million barrels), the middle and upper Devonian (1.9 percent or 32.5 million barrels), and the Cretaceous (about 0.5 percent or 1.0 million barrels).

Old established producing areas should continue to furnish new potential reserves through infill drilling and stepouts, but at a decreasing rate. Potential reserves attributed to reservoirs in southeast Kansas and northeast Oklahoma (Pennsylvanian, Mississippian, middle Devonian, Silurian, middle Ordovician, and Cambrian-lower Ordovician) and in southern Oklahoma (Cretaceous, Permian, Pennsylvanian, Mississippian, lower Devonian-Silurian, middle Ordovician and Cambrian-lower Ordovician) are optimistic estimates based upon anticipated exploration activity.

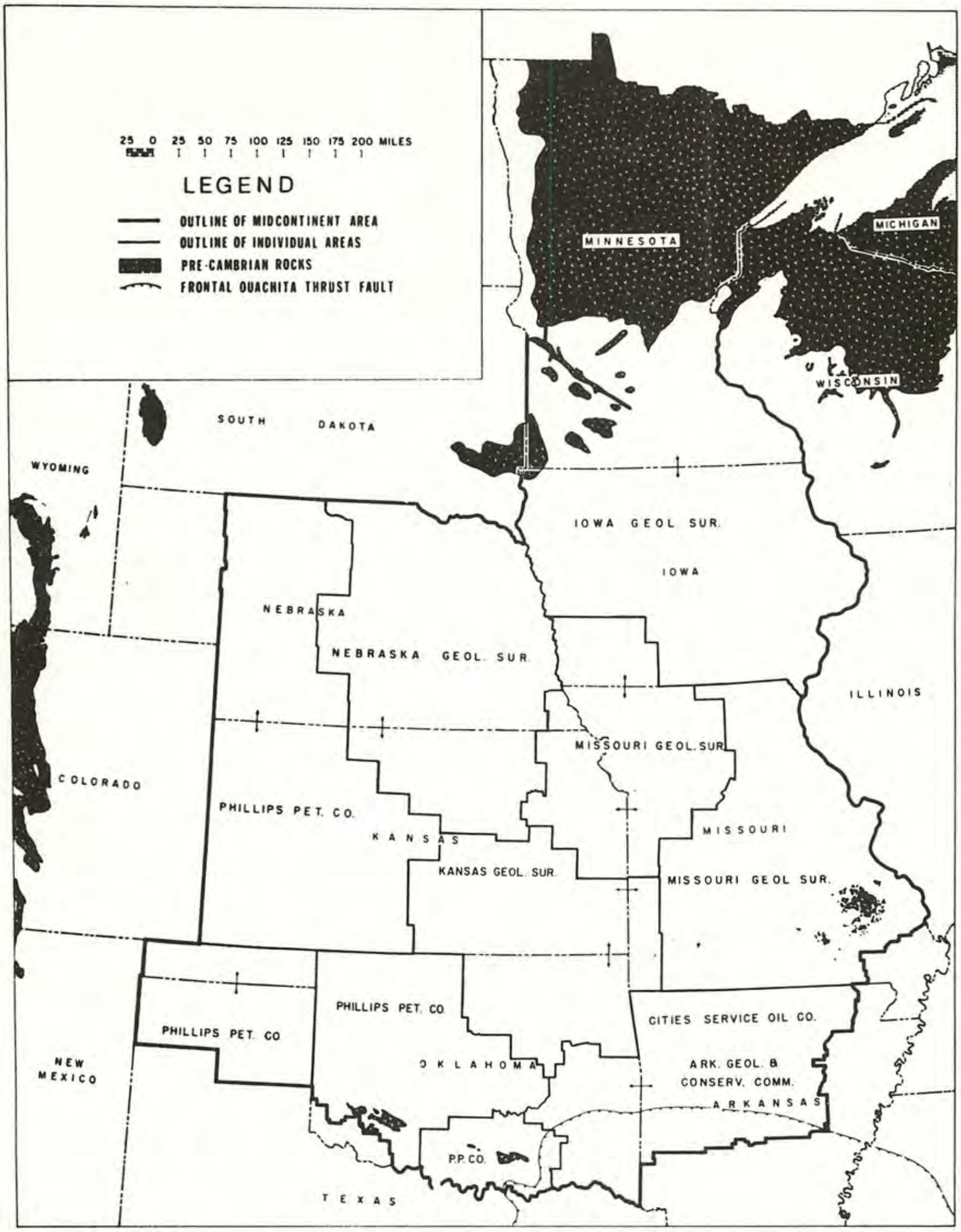

FIGURE 21. Index Map of Region 7, Midcontinent, Showing Report Areas (Cross sections are not included in this summary

Sequences	System	Series	ANADARKO BASIN & ADJACENT SHELVES: C. NEBRASKA & C. & W. KANSAS	TEXAS & OKLAHOMA PANHANDLES	C. & W. OKLAHOMA	S. OKLAHOMA	NE OKLAHOMA SE KANSAS	N. ARKANSAS & C & S. MISSOURI	OUACHITA TROUGH: OUACHITA MTS.	MISSOURI KANSAS, NEBRASKA, IOWA BASIN & ADJACENT SHELVES: N. MISSOURI	NE KANSAS & E. NEBRASKA	IOWA	MINNESOTA
ZUNI	CRETACEOUS	UPPER	PIERRE SH NIOBRARA FM CARLISLE SH GREENHORN LS GRANEROS SH. DAKOTA SS	GREENHORN LS GRANEROS SH. DAKOTA SS		EAGLE FORD SH WOODBINE SS		NAVARRO GP TAYLOR GP AUSTIN GP			NIOBRARA FM. CARLISLE SH. GREENHORN LS GRANEROS SH DAKOTA SS	CARLISLE SH. GREENHORN LS GRANEROS SH DAKOTA SS	PIERRE SH(?) NIOBRARA FM. CARLISLE SH GREENHORN FM GRANEROS SH DAKOTA SS
		LOWER	KIOWA SH. CHEYENNE SS	KIOWA SH. CHEYENNE SS		WASHITA GP. FREDERICKS-BURG GP. TRINITY GP.							
	JURASSIC		MORRISON FM.	MORRISON FM.								FORT DODGE BEDS	
ABSAROKA	UPPER TRIASSIC			DOCKUM									
	PERMIAN	GUADALUPE	TALOGA FM. DAY CREEK DOL. WHITE HORSE SS.	QUARTERMASTER FM. WHITEHORSE GP	QUARTERMASTER FM CLOUD CHIEF FM WHITEHORSE GP								
		LEONARD	NIPPEWALLA GP. SUMNER GP	BLAINE FM GLORIETTA SS CLEARFORK GP WICHITA FM	EL RENO GP HENNESSEY SH WELLINGTON FM.						NIPPEWALLA GP SUMNER GP		
		WOLFCAMP	CHASE GP. COUNCIL GROVE GP ADMIRE GP	BROWN DOL	CHASE GP. COUNCIL GROVE GP ADMIRE GP.	PONTOTOC GP. UPPER PART					CHASE GP COUNCIL GROVE GP ADMIRE GP		
	PENNSYLVANIAN	VIRGIL	WABAUNSEE GP SHAWNEE GP DOUGLAS GP			CISCO GP	WABAUNSEE GP. SHAWNEE GP. DOUGLAS GP			WABAUNSEE GP SHAWNEE GP. DOUGLAS GP			
		MISSOURI	LANSING GP KANSAS CITY GP PLEASANTON GP		OCHELETA GP SKIATOOK GP	HOXBAR (CANYON) GP	LANSING GP KANSAS CITY GP. PLEASANTON GP			LANSING GP KANSAS CITY GP PLEASANTON GP			
		DES MOINES	MARMATON GP CHEROKEE GP.		BIG LS OSWEGO LS.	DEESE (STRAWN) GP	MARMATON GP. CHEROKEE GP	BOGGY FM SAVANNA FM. MC ALESTER FM. HARTSHORNE SS.		MARMATON GP CHEROKEE GP			
		ATOKA	13 FINGER LS			UPPER DORNICK HILLS		ATOKA FM.	ATOKA FM.	TOKAN			
		MORROW	KEARNY FM.	U. MORROW L. MORROW	MORROW	MORROW		BLOYD SH. HALE FM.	JOHNS VALLEY SH JACKFORK SS.				
KASKASKIA	MISSISSIPPIAN	CHESTER	CHESTER	CHESTER	SPRINGER SS GODDARD SH.	SPRINGER SS GODDARD SH	PENN. CANEY CHESTER (MISS CANEY)	PITKIN LS FAYETTEVILLE SH. BATESVILLE SS.	STANLEY SH.				
		MERAMEC	STE. GENEVIEVE LS ST. LOUIS LS. SPERGEN LS WARSAW LS		MISS. LS. UNDIF	CANEY FM (SYCAMORE)	WARSAW LS.	RUDDELL SH MOOREFIELD FM		STE. GENEVIEVE LS. ST. LOUIS LS. SALEM (SPERGEN) LS WARSAW LS			
		OSAGE	OSAGE UNDIF.				KEOKUK-BURLINGTON FM. FERN GLEN LS.	BOONE FM.		KEOKUK & BURLINGTON LIMESTONES			
		KINDERHOOK	KINDERHOOK UNDIF.			WELDEN FM	SEDALIA FM CHOUTEAU LS.	ST. JOE MBR.	ARKANSAS NOVACULITE	CHOUTEAU GP. HANNIBAL SH.	GILMORE CITY LS. HAMPTON GP. BOICE SH.	GILMORE CITY LS. HAMPTON GP NORTH HILL GR.	
	DEVONIAN	UPPER		WOODFORD (CHATTANOOGA) SH. IS BOTH U. DEV. & L. MISS. INCLUDES BASAL SAND CALLED MISENER IN OKLAHOMA AND KANSAS, SYLAMORE IN ARKANSAS						GRASSY CREEK FM	"CHATTANOOGA" SH.	YELLOW SPGS. GP LIME CREEK FM. SHELL ROCK FM.	
		MIDDLE						CLIFTY (ARK.) OR FORTUNE (MO.)		CALLAWAY FM.	CEDAR VALLEY FM WAPSIPINICON FM.		CEDAR VALLEY FM
TIPPECANOE		LOWER			HUNTON: FRISCO FM BOIS D'ARC—HARAGAN FM.		HUNTON: SALLISAW FM FRISCO FM.	PENTERS CHT.				LA PORTE CITY CHT.	
	SILURIAN	MIDDLE		HUNTON: HENRYHOUSE FM	HENRYHOUSE FM.		ST. CLAIR LS	LAFFERTY LS ST. CLAIR LS	MISSOURI MTN. SH BLAYLOCK SS.		SILURIAN UNDIF.	GOWER DOL. HOPKINTON DOL. KANKAKEE DOL.	
		LOWER		CHIMNEY HILL FM.	CHIMNEY HILL FM.			BRASSFIELD LS.		SEXTON CREEK FM EDGEWOOD FM		EDGEWOOD DOL.	
	ORDOVICIAN	UPPER		SYLVAN SH	SYLVAN SH.	SYLVAN SH		CASON SH.	POLK CRK. SH.	MAQUOKETA	MAQUOKETA	U. MAQUOKETA-1	MAQUOKETA
		UPPER MIDDLE	VIOLA LS.		VIOLA LS (INCL. FERNVALE LS WHICH IS LOWER UPPER ORD.)		FERNVALE LS KIMMSWICK FM DECORAH SH.	FERNVALE LS KIMMSWICK FM	BIG FORK CHERT	KIMMSWICK	KIMMSWICK	L. MAQUOKETA-2 GALENA	DUBUQUE FM GALENA FM.
		LOWER MIDDLE	SIMPSON UNDIF.		SIMPSON: BROMIDE TULIP CREEK MC LISH OIL CREEK JOINS		PLATTEVILLE FM ST. PETER SS	PLATTIN FM. ROCK LEVEE FM JOACHIM FM. DUTCHTOWN FM. ST. PETER SS. EVERTON FM.	WOMBLE SH.	DECORAH FM PLATTIN FM JOACHIM DOL ST. PETER SS.	DECORAH FM. PLATTEVILLE FM ST. PETER SS.		
SAUK		LOWER	ARBUCKLE GP	ARBUCKLE GP (ELLENBURGER)	ARBUCKLE GP	ARBUCKLE: W. SPRING CRK FM KINDBLADE FM COOL CRK FM MC KENZIE-HILL FM CHAPMAN-RANCH FM	ARBUCKLE GP	BLACKROCK FM SMITHVILLE FM. POWELL FM COTTER FM. JEFFERSON CITY FM ROUBIDOUX FM GASCONADE-VAN BUREN FM	BLAKELY SS MAZARN SH CRYSTAL MTN SS	COTTER DOL JEFF CITY DOL ROUBIDOUX FM GASCONADE DOL	ARBUCKLE GP	PRAIRIE DU CHIEN FM	PRAIRIE DU CHIEN FM.
	CAMBRIAN	UPPER	REAGAN SS	REAGAN SS	REAGAN SS.	TIMBERED HILLS: SIGNAL MTN. FM FORT SILL FM. HONEY CREEK FM REAGAN SS	LAMOTTE SS	EMINENCE FM POTOSI FM. ELVINS GP BONNETERRE FM. LAMOTTE SS	COLLIER SH. (CAMBRO-ORD.?)	EMINENCE DOL POTOSI DOL ELVINS GP BONNETERRE FM LAMOTTE SS.	LAMOTTE SS	TREMPEALEAU GP FRANCONIA FM EAU CLAIRE FM. MT. SIMON SS	JORDAN SS ST. LAWRENCE FM FRANCONIA FM. DRESBACH FM.
	PRE-CAMBRIAN		IGNEOUS ROCKS	IGNEOUS ROCKS	LO & MID CAMBRIAN: METASEDIMENTS & IGNEOUS ROCKS PE: IGNEOUS ROCKS	IGNEOUS ROCKS	PE SEDIMENTS & IGNEOUS ROCKS	METASEDIMENTS & IGNEOUS ROCKS	OLDER ROCKS NOT EXPOSED	METASEDIMENTS & IGNEOUS ROCKS	METASEDIMENTS & IGNEOUS ROCKS	METASEDIMENTS & IGNEOUS ROCKS	PE SEDIMENTS, METASEDIMENTS, & IGNEOUS ROCKS

1 UPPER MAQUOKETA IN IOWA INCLUDES BRAINARD & FORT ATKINSON MEMBERS. 2-LOWER MAQUOKETA IN IOWA INCLUDES CLERMONT & ELGIN MEMBERS.

FIGURE 22. Generalized Stratigraphy, Region 7, Midcontinent

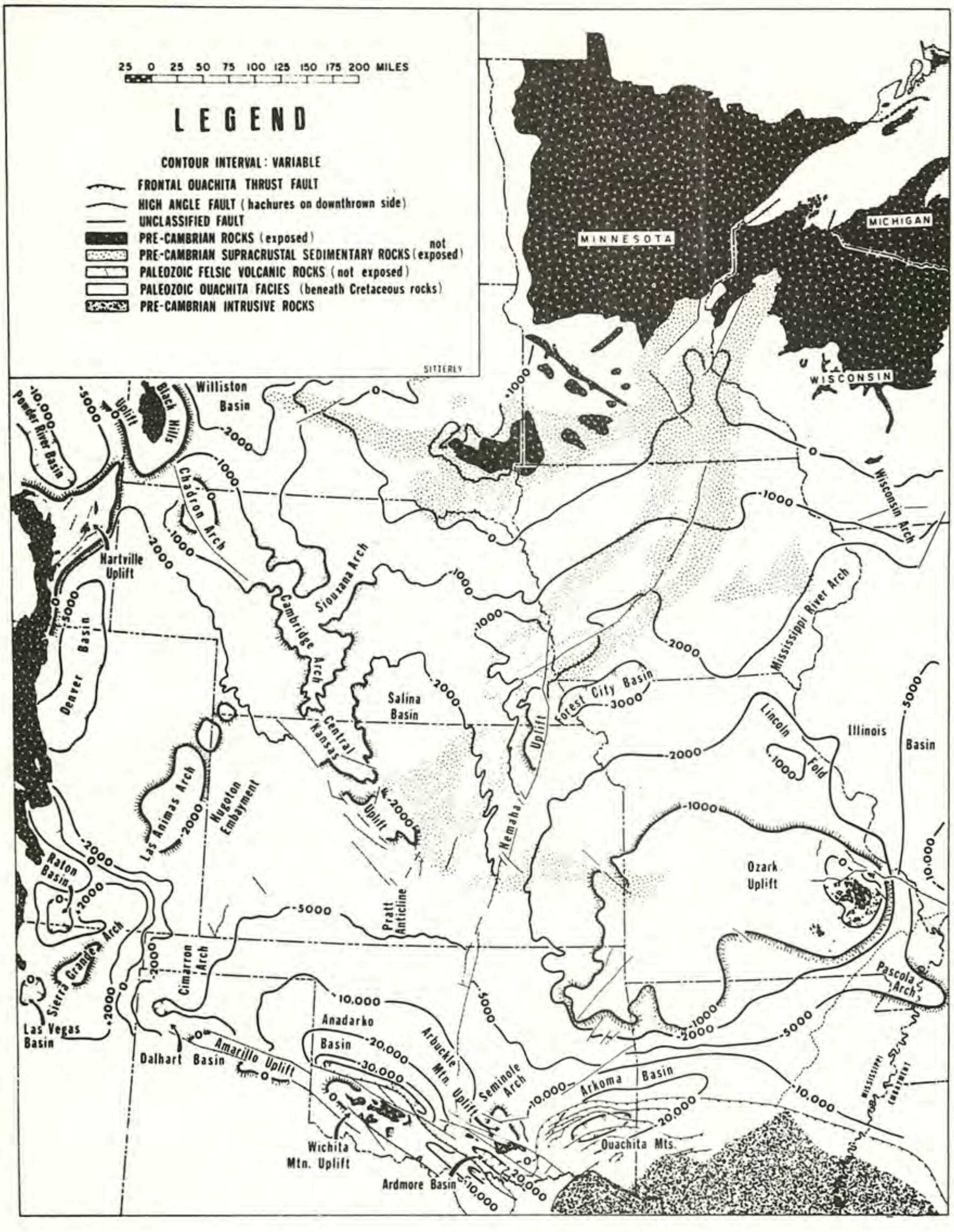

FIGURE 23. Structural Map of Basement, Region 7, Midcontinent

The Cambridge arch in Nebraska, the northern shelf of the Anadarko basin, and the Hugoton embayment should furnish significant new potential reserves from Pennsylvanian rocks. The pre-Pennsylvanian section should become the most important future reservoir as exploration for structural traps continues in the deeper portions of the Anadarko and Ardmore basins, the Hugoton embayment, and the Salina and Forest City basins.

Future potential gas reserves should be found in the Texas Panhandle and Oklahoma, which should furnish 75.3 percent (33,543 billion cubic feet) of the estimated new potential reserves; in northern Arkansas, 19.3 percent (8,600 billion cubic feet); and in Kansas, 5.4 percent (2,400 billion cubic feet). The lower Devonian-Silurian is the most important future reservoir, having 38.0 percent (16,900 billion cubic feet) of the estimated new potential reserves; the Pennsylvanian is next (24.5 percent or 10,900 billion cubic feet), then the Mississipian (17.7 percent or 7,900 billion cubic feet), the Cambrian-lower Ordovician (10.8 percent or 4,810 billion cubic feet), the middle Ordovician (6.0 percent or 2,685 billion cubic feet), and the Permian (3.0 percent or 1,348 billion cubic feet).

The deeper parts of both the Anadarko and Arkoma basins should furnish significant new reserves from Pennsylvanian and pre-Pennsylvanian formations. The Hugoton embayment should furnish new reserves from Permian, Pennsylvanian, and Mississippian formations. Structural traps will be of major importance initially in the deep Anadarko basin. Stratigraphic traps will be important in the Arkoma basin and the Hugoton embayment.

OIL PROSPECTS

The major oil-producing states in the Midcontinent are Oklahoma, Kansas, and Texas (only the Panhandle of Texas is included; Table 12). Oklahoma (excluding the Panhandle) and Kansas will continue to furnish significant potential oil reserves in the future. The Texas and Oklahoma Panhandles should diminish in importance as the shallow producing formations become depleted or as exploration becomes uneconomical. Nebraska may contribute important potential oil reserves if exploration is intensified. No significant reserves are anticipated from Missouri, Iowa, or Minnesota.

Known reserves and estimated future potential oil reserves in the Midcontinent region have been analyzed from a geologic viewpoint (Table 13). The most important oil reservoirs have been, in order of importance, the Pennsylvanian (mainly Cherokee sandstone units), middle Ordovician (mainly Simpson sandstone units), Cambrian and lower Ordovician (Arbuckle), Mississippian, Permian (mainly Wolfcampian carbonate rocks), lower Devonian and Silurian (Hunton), middle Devonian, and Cretaceous. The bulk of these known reserves has been found on the shallow shelf of the Anadarko and allied basins, and on major uplifts like the Amarillo arch (Panhandle field), Nemaha ridge (Oklahoma City field), Seminole arch, and Central Kansas uplift. These areas will continue to furnish new potential reserves, but at a decreasing rate.

Future potential oil reserves will result also from deeper drilling in the Anadarko basin and exploration of relatively untested areas like Nebraska. Pennsylvanian and middle Ordovician reservoirs will continue to be the most important. However, the Hunton probably will replace the Arbuckle in third place and the Permian will drop to sixth place.

Of the known reserves, approximately 69 percent is found in sandstone reservoirs, and about 57 percent is localized in stratigraphic traps. Sandstone reservoirs have been most important in Oklahoma, the Texas Panhandle, and Nebraska; carbonate rocks have been most important in Kansas and Missouri. Although stratigraphic traps are predominant in the Midcontinent, almost half the known reserves in Oklahoma are in structural traps.

Carbonate reservoirs and structural traps should become more important in Oklahoma as exploration is extended to the deeper parts of the Anadarko basin. Carbonate reservoirs should maintain their importance in Kansas, because the future potential is mainly in the pre-Pennsylvanian carbonate rocks.

GAS PROSPECTS

The major gas-producing fields are in the Texas Panhandle, Oklahoma, Kansas, and northern Arkansas (Table 14). These areas will continue to furnish significant potential gas reserves in the future, although their relative importance will change. Oklahoma should assume the lead and Kansas should drop to last place. No potential gas reserves are assigned to Nebraska, Missouri, Iowa, or Minnesota.

Established gas reserves have been found primarily on the shallow shelf of the Anadarko and allied basins. The most important reservoirs (Table 15) have been the Permian Wolfcampian carbonate rocks, Pennsylvanian sandstone and limestone units, middle Ordovician sandstone and carbonate rocks (primarily associated gas with Simpson oil), Mississippian carbonate rocks (mainly Chesteran), lower Devonian and Silurian units (Hunton), Cambrian

TABLE 12. MIDCONTINENT OIL RESERVES

State	Production and Known Oil Reserves (million barrels) Cumulative Production (1)	Remaining Recoverable Reserves	Ultimate Recovery From Known Fields (1)	Estimated Future Potential Oil Reserves (million barrels) Probable Potential	Possible Potential	Speculative Potential	Total Potential
Texas Panhandle and Oklahoma	10,870	1,741	12,611	369.0	563.0	0	932.0
Kansas	4,014	625	4,639	91.0	470.0	0.3	561.3
N. Arkansas	0	0	0	0	0	0	0
Nebraska	35	10	45	4.8	157.0	40.0	201.8
Missouri	2	0	2	1.0	14.0	0.9	15.9
Iowa	0	0	0	0	10.0	0.7	10.7
Minnesota	0	0	0	0	0	0	0
Total	14,921	2,376	17,297	465.8	1,214.0	41.9	1,721.7

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Production and reserve data through December 31, 1967.

TABLE 13. MIDCONTINENT OIL RESERVES AND GEOLOGIC SEQUENCE

Sequence	System	Production and Known Oil Reserves (million barrels) Cumulative Production (1)	Remaining Recoverable Reserves	Ultimate Recovery From Known Fields (1)	Estimated Future Potential Oil Reserves (million barrels) Probable Potential	Possible Potential	Speculative Potential	Total Potential
Zuni	Cretaceous	1	0	1	0	1	0	1.0
Absaroka	Permian	1,221	227	1,448	0	4	35	39.0
	Pennsylvanian	6,567	1,033	7,600	133	430	0	563.0
Kaskaskia	Mississippian	1,339	422	1,761	52	185	0	237.0
	Middle & Upper Devonian	50	25	75	2.5	30	0	32.5
Tippecanoe	Lower Devonian & Silurian	361	42	403	159	124	3.8	286.9
	Middle & Upper Ordovician	3,594	279	3,873	87.3	265	0	352.3
Sauk	Cambrian & Lower Ordovician	1,788	348	2,136	32	175	3	210.0
	Total	14,921	2,376	17,297	465.8	1,214	41.9	1,721.7

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Production and reserve data through December 31, 1967.

TABLE 14. MIDCONTINENT GAS RESERVES

State	Production and Known Gas Reserves (billion cubic feet) Cumulative Production [1]	Remaining Recoverable Reserves	Ultimate Recovery From Known Fields [1]	Estimated Future Potential Gas Reserves (billion cubic feet) Probable Potential	Possible Potential	Speculative Potential	Total Potential
Texas Panhandle and Oklahoma	64,663	31,548	96,211	9,148	21,295	3,100	33,543
Kansas	15,562	15,190	30,752	1,200	1,200	0	2,400
N. Arkansas	1,217	1,842	3,059	1,000	2,000	5,600	8,600
Nebraska	0	0.4	0.4	0	0	0	0
Missouri	0	0.5	0.5	0	0	0	0
Iowa	0	0	0	0	0	0	0
Minnesota	0	0	0	0	0	0	0
Total	81,442	48,580.9	130,022.9	11,348	24,495	8,700	44,543

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

[1] Production and reserve data through December 31, 1967.

TABLE 15. MIDCONTINENT GAS RESERVES AND GEOLOGIC SEQUENCE

Sequence	System	Ultimate Recovery From Known Fields[1] (billion cubic feet)	Estimated Future Potential Gas Reserves (billion cubic feet) Probable Potential	Possible Potential	Speculative Potential	Total Potential
Zuni	Cretaceous	2	0	0	0	0
Absaroka	Permian	71,283	128	1,220	0	1,348
	Pennsylvanian	39,789	5,400	5,500	0	10,900
Kaskaskia	Mississippian	6,742	2,800	3,300	1,800	7,900
	Middle & Upper Devonian	21	0	0	0	0
Tippecanoe	Lower Devonian & Silurian	2,314	2,500	11,400	3,000	16,900
	Middle & Upper Ordovician	8,890	520	665	1,500	2,685
Sauk	Cambrian & Lower Ordovician	982	0	2,410	2,400	4,810
	Total	130,023	11,348	24,495	8,700	44,543

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

[1] Reserve data through December 31, 1967.

and lower Ordovician rocks (Arbuckle, primarily associated gas), and middle Devonian rocks (associated gas).

Future potential gas reserves will be found, in order of importance, in Hunton, Pennsylvanian, Mississippian, Arbuckle, middle Ordovician, and Permian reservoirs. This prediction reflects the anticipated results of exploration in the deep Anadarko and Arkoma basins.

Of the known gas reserves, approximately 63 percent is found in carbonate reservoirs and about 83.7 percent is in stratigraphic traps. Carbonate reservoirs should continue to be the most important, as the future potential lies essentially in the pre-Pennsylvanian carbonate section. However, structural traps should gain in importance, at least initially, because most of the anticipated future potential gas reserves will be found in the deep parts of the Anadarko and Arkoma basins at depths of 17,000 feet or more.

EVALUATION OF AREAS

Northern Arkansas

Northern Arkansas, together with southeastern Oklahoma, includes the Arkoma Basin, the southern Ozark area, and the Ouachita Mountains. The entire region is essentially a nonoil associated-dry-gas province. The principal reservoirs are lower Pennsylvanian sandstone units, which contain approximately 96 percent of the total known gas reserves. Minor gas reserves are present in Chesteran (Mississippian) and lower Devonian-Silurian rocks.

The future potential of the Arkoma basin in Arkansas lies in (1) continued exploration for and development of stratigraphic traps in lower Pennsylvanian sandstone, and (2) exploration of the relatively unexplored, deeper lower Devonian-Silurian, Ordovician, and Cambrian strata, which possibly, or speculatively, contain substantial potential gas reserves.

The southern Ozark area produces minor amounts of gas from Pennsylvanian, Mississippian, and Devonian rocks. Future potential gas reserves probably will be similar in amount and occurrence. Minor potential oil reserves might be found in the Boston Mountains or the southern part of the Ozark area in the same formations. The speculative nature of these minor potential oil reserves precludes quantification.

Estimates of the Ouachita Mountains as a potential oil and gas province in Arkansas and Oklahoma are extremely speculative; therefore, no quantitative data are submitted. A minor show of dry gas in a water well in Arkansas, a few isolated shallow oil and gas wells in Oklahoma, the presence of at least 26 known asphalt and grahamite deposits, the presence of liquid oil seeps, and particularly a shut-in gas well (initial daily potential of 1.8 million cubic feet from the fractured Bigfork chert in the Potato Hills of Oklahoma) indicate the possibility of major accumulations in the province. The major obstacles have been, and probably will continue to be (1) structural complexity, (2) the apparent scarcity of porous and permeable rock, and (3) hard and expensive drilling.

Iowa

No oil or gas production has been established in Iowa. One well produced 400 barrels of oil from lower-middle Ordovician rocks before being depleted. The southwest part of the state offers the best opportunity for future production, although anticipated reserves would be minor. Pennsylvanian sandstone, middle Devonian carbonate rocks and basal sandstone units, middle Ordovician carbonate and sandstone units, and Cambrian sandstone could be possible reservoirs. The thick layer of glacial drift which covers the state is a major obstacle to exploration. This drift ranges up to 600 feet thick and masks most of the regional geology and local structural features. Estimates of future potential oil reserves were made only for the Forest City basin; any attempt to quantify reserves for the rest of the state would be conjectural.

Kansas

Oil—Important oil reserves have been established in the Central Kansas uplift (Arbuckle and Pennsylvanian), Cherokee and Sedgwick basins (Pennsylvanian, Mississippian, and middle Ordovician), Pratt anticline (middle Ordovician), Hugoton embayment (Pennsylvanian), Forest City basin (Pennsylvanian), and Salina basin (middle Ordovician).

Pennsylvanian and Arbuckle rocks contain about 74 percent of the known oil reserves, Mississippian and middle Ordovician rocks contain 25 percent, and the remaining 1 percent is in Permian, middle Devonian, and Silurian rocks.

Approximately 66 percent of the Pennsylvanian oil production is from eastern Kansas, where numerous lenticular sandstone units produce from a wide variety of stratigraphic traps. This is the oldest producing area in the state and production is now essentially stripper. Random drilling by individuals and small independent operators in this area will provide a significant part of the estimated "probable" and "possible" potential reserves for the Pennsylvanian.

About 90 percent of the Arbuckle oil production in Kansas is from the Central Kansas uplift, where oil is found in topographic-structural traps beneath the Pennsylvanian unconformity. This area has been explored and developed extensively for more than 40 years, and it is doubtful if additional significant oil reserves will be found. Most of the new potential reserves attributed to the Arbuckle are based on estimates for southeast Kansas.

In western Kansas, significant new potential oil reserves may be anticipated from structural and stratigraphic traps below the base of the Wolfcampian Series in the Hugoton area, mainly in Morrowan, Chesteran, and pre-Chesteran (Mississippian) rocks.

The Salina and Forest City basins also may furnish additional potential reserves. Pennsylvanian, pre-Chesteran (Mississippian), and Viola reservoirs could be productive from structural traps in the southern part of the Salina basin. The extreme western margin of the Salina basin beneath the Pennsylvanian subcrop is considered to be a favorable area for future exploration. Less favorable is the Nemaha uplift, because fresh water recovered in tests of the Paleozoic carbonate rocks suggests flushing and thus minor potential reserves. In the Forest City basin the main reservoirs are the Pennsylvanian, middle Devonian, and middle and upper Ordovician (Kimmswick, Viola), which could be productive from both structural and stratigraphic traps. At the present time, virtually all Pennsylvanian production in the Forest City basin is in the stripper category. Therefore, new Pennsylvanian reserves, although potentially large, may never be produced because the difficulty of locating small potential fields ($160\pm$ acres) and the low production rates (up to 10 barrels of oil per day) make exploration for these reserves unattractive.

Additional significant future potential oil production from southeast Kansas may come from pre-Chesteran (Mississippian), Viola, Simpson, and Arbuckle rocks.

Gas—Major known gas reserves present in the Hugoton field (Wolfcampian) comprise about 73 percent of the total gas in the state.

Future important potential gas reserves should be found in western Kansas in stratigraphic traps in Morrowan, Chesteran, and pre-Chesteran (Mississippian) rocks. Significant potential reserves also may be found in Leonardian rocks (Runnymede or Red Cave sandstone), and lesser amounts of gas may be found in Wolfcampian units.

Minnesota

No potential oil or gas reserves are projected for Minnesota. A thin sedimentary section (less than 1,500 feet), consisting of middle Devonian, Ordovician, and Cambrian rocks, crops out and is present in the subsurface in the southeastern part of the state. In the southwestern part of the state, a thin veneer (up to 500 feet) of Cretaceous rocks overlies the Pre-Cambrian.

Missouri

The Ozark uplift, which covers most of Missouri, is a major structural feature from which strata have been stripped exposing the Pre-Cambrian in the core area. Possible areas for oil production therefore are limited to the northern and eastern parts of the state where the sedimentary section is thicker. Future potential oil reserves are estimated to be minor.

The most favorable area is the Forest City basin, where Pennsylvanian, pre-Chesteran (Mississippian), middle Devonian, and middle and upper Ordovician (St. Peter, Kimmswick, Viola) rocks may produce minor amounts of oil from structural and stratigraphic traps. Oil may be found in the Cambrian in the counties adjacent to the Mississippi River, but the potential of the Cambrian rocks is impossible to evaluate at this time. Minor accumulations of oil may be found in northeastern Missouri in Devonian and possibly in "post-St. Peter" Ordovician rocks. A fourth area which may produce is near St. Louis, where Kimmswick or Viola production similar to that from the Florissant field might be found.

No potential gas reserves are projected for Missouri.

Nebraska

Approximately 78 percent of the known oil reserves in Nebraska (excluding the Panhandle) has been found in stratigraphic traps in Pennsylvanian sandstone units on the Cambridge arch. Future significant potential oil reserves should be found in similar Pennsylvanian traps on or flanking this arch. "Speculative" potential reserves may be found in northwestern Nebraska in possibly Wolfcampian (upper Minnelusa) "reefs," which fringe the evaporite deposits in the Nebraska Panhandle on the southwest.

The remaining 22 percent of the established oil reserves is in extreme southeastern Nebraska in the Forest City basin, where middle Devonian and middle Ordovician rocks are productive. Fresh water produced with the oil suggests flushing; hence, future potential reserves probably will be minor.

The Nebraska part of the Salina basin is relatively unexplored, but much of the basin can be evaluated by tests to depths of less than 3,000 feet. Pennsylvanian (mainly Desmoinesian and some Missourian) sandstone units and Mississippian and older Paleozoic formations would be the objectives. Although most individual reservoirs would be considered small, multiple pay zones are possible. The most favorable areas are along the extreme western margin of the basin beneath the Pennsylvanian subcrop and on small structures deeper in the basin. Another potential, but less favorable, area is located on the flanks of the Southeast Nebraska arch, where Arbuckle rocks have been truncated; however, fresh water associated with the Paleozoic carbonate rocks suggests flushing and thus minor reserves.

No potential gas reserves are projected for Nebraska.

Texas Panhandle and Oklahoma

Oil—An estimated 73 percent of the known recoverable oil reserves in the Midcontinent is in the Texas Panhandle and Oklahoma. Approximately 94 percent is in Permian (Wolfcampian carbonate rocks and granite wash), Pennsylvanian (mainly Cherokee sandstone), Mississippian (mainly Springer sandstone), and middle Ordovician (mainly Simpson sandstone) reservoirs.

These reservoirs have produced about 10.3 billion barrels of oil, the bulk of which has come from northeast Oklahoma (3.5 billion barrels), the Seminole arch and Nemaha ridge (3.0 billion barrels), southern Oklahoma (2.2 billion barrels), and the Texas Panhandle (1.2 billion barrels). Permian oil is mainly from the Panhandle field, which is a huge, combination structural and stratigraphic trap. Pennsylvanian production is primarily associated with lenticular sandstone units. Oil is produced from structural and stratigraphic traps in the Springer in southern Oklahoma. Simpson production is from structural traps.

Future potential oil reserves in these old areas from Permian, Pennsylvanian, Mississippian, and middle Ordovician reservoirs probably will result from extensions to known production and from infill drilling. Such reserves comprise more than half the estimated "probable" potential reserves for Pennsylvanian and middle Ordovician formations. More than half the estimated "possible" potential reserves is attributable to northeast and southern Oklahoma. New "possible" potential oil reserves in southern Oklahoma will result from testing the deep (20,000 or more feet), relatively unexplored parts of the Ardmore and Anadarko basins. The Texas Panhandle probably will not add significant potential reserves from Pennsylvanian and younger formations, as this area has been explored extensively.

Significant new "probable" and "possible" potential oil reserves may be found in western Oklahoma in structural and stratigraphic traps, on the northern shelf of the Anadarko basin, in Pennsylvanian sandstone and limestone, in Hunton dolomite, and in Simpson sandstone. Important "possible" potential oil reserves also may be found in the deep part of the basin in Springer, Hunton, Simpson, and Arbuckle units, probably as condensate associated with gas.

Significant "possible" potential oil reserves may be anticipated in northeastern Oklahoma from the Arbuckle dolomite. Exploratory drilling through the Arbuckle has not been extensive; therefore, proper evaluation of the unit has not been made. Discoveries probably will be in stratigraphic traps.

Gas—An estimated 84 percent of the total gas production of the Texas Panhandle and Oklahoma has come from the Amarillo uplift and the Anadarko basin. The rest was mainly from southern Oklahoma, but lesser amounts were from the Arkoma basin and northeastern Oklahoma. At present, gas production is primarily from Pennsylvanian, middle Ordovician, Mississippian (mainly Chesteran), and Silurian-Devonian (Hunton Group) rocks.

Future significant potential gas reserves will be found mainly in stratigraphic traps on the northern shelf of the Anadarko basin in Pennsylvanian sandstone and limestone. In the deeper part of the basin, which is virtually untested, important potential gas reserves should be found in Springer sandstone units, pre-Chesteran (Mississippian) limestone, Hunton dolomite, Simpson sandstone, and possibly in Arbuckle dolomite. Because of deep drilling depths (15,000 to 25,000+ feet), structural traps will be of primary importance.

The Arkoma basin should furnish significant potential gas reserves from lower Pennsylvanian sandstone units. The relatively unexplored, deeper lower Devonian-Silurian and Ordovician rocks also may contain substantial potential reserves.

CHAPTER 10
REGION 8. MICHIGAN BASIN

Coordinator

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SUMMARY

The Southern Peninsula of Michigan (see Figure 24), at about the center of the Michigan basin, has been, and will continue to be, the most productive area in Region 8. Small fields are found each year, but the last major discovery (Albion-Scipio) was made in 1957. Nevertheless, the deeper center of the basin (not exceeding 15,000-foot depths) is almost untested to Silurian and Ordovician units which produce on the south flank, and to deeper lower Ordovician and Cambrian formations. There is much sparsely drilled territory tributary to the shallower producing areas, including the Devonian producing areas in the center of the basin.

The basin is surely a future petroleum province, but the economic and exploratory problems are formidable. About 85 percent of the producing fields are in the less than 1 million barrels class, and only about 2.5 percent are expected to produce 10 million barrels or more. Only one field, Albion-Scipio, is rated over 50 million barrels. This field is producing from an anomalous streak of porous dolomite in the Trenton limestone, and accumulation in other fields is controlled by low-relief structure (some reefs) and variations in porosity. The geologist's problem of locating such traps is complicated by the poor geophysical data in this drift-covered country. Nevertheless, there appears to be no geologic reason why satisfactory traps and production cannot be found in the large untested areas.

DISCUSSION

INTRODUCTION

Region 8, designated as the Michigan basin, comprises part of northwestern Ohio, northern Indiana, that part of Illinois within the Lake Michigan basin, and essentially all of Wisconsin and Michigan, as shown on Figure 24. The region contains three geologic provinces; the Wisconsin arch on the west, the Lake Superior basin on the north, and the Michigan basin lying east of the Wisconsin arch. The Michigan basin is the central point of interest in this report; outlying sections of Region 8 have been ignored because they are considered to be essentially nonproductive of hydrocarbons.

The Michigan basin geographically covers about 122,000 square miles and contains about 108,000 cubic miles of sedimentary rock. About 37,000 cubic miles of this volume is considered to be potentially productive.

Hydrocarbons have been produced in the basin since their discovery in the 1880's near the southeastern edge of the state. Important production dates from 1925 in the central part of the basin. No oil or gas has been produced from the Wisconsin and Illinois parts of the basin, but there has been production from the Indiana and Ohio parts. To date, more than 27,000 wells have been drilled, and, through 1967, about 600 oil and gas fields had been found. Geologic age of the productive reservoirs ranges from Ordovician to Pleistocene. Exploration and development drilling has been cyclic, shifting within the basin in response to the size or importance of new field discoveries. Analysis of drilling data shows an irregular distribution of drilling. For example, most drilling to the Silurian or older rocks has been around the shallow parts of the basin margin, whereas the deeper parts of the basin are virtually unexplored in Silurian and older formations. Most of the basin production has come from rocks of Devonian and Mississippian ages, but increasing amounts have been coming from Ordovician and Silurian rocks. Michigan's largest oil field, based on reserves, produces from the Ordovician. More exploration in the past few years has been directed toward Silurian reef production. Lower Ordovician and Cambrian strata of the basin are virtually unexplored, and very little is known, with any degree of certainty, concerning these lower rocks. Seismic surveys have been used in the basin, and gravity has been an aid in the search for Silurian reefs in the southeastern part of the state. In general, many operators rely on subsurface geology, coupled at times with geophysical data.

REGIONAL GEOLOGIC SETTING

The Michigan basin is bounded by several important geologic features that establish the basin framework (Figure 24). The southern rim of the basin is bounded by the Kankakee-Cincinnati and Findlay arches, and the western side by the Wisconsin arch. The north and northeast sides are bounded by the Canadian shield area, which includes the Lake Superior basin on the north. The east side is bounded by the Algonquin arch in Ontario.

The Michigan area is a structural basin with a circular outline; the deepest part is in central Michigan, west of Saginaw Bay. It is estimated that Pre-Cambrian basement would be about 14,000 to 15,000 feet below the surface in the deep center of the basin. Regional dip is 25 to 60 feet per mile toward the center of the basin on most important marker beds. Centers of sediment accumulation have varied at different geologic times, but they generally have been near the present deep part of the basin.

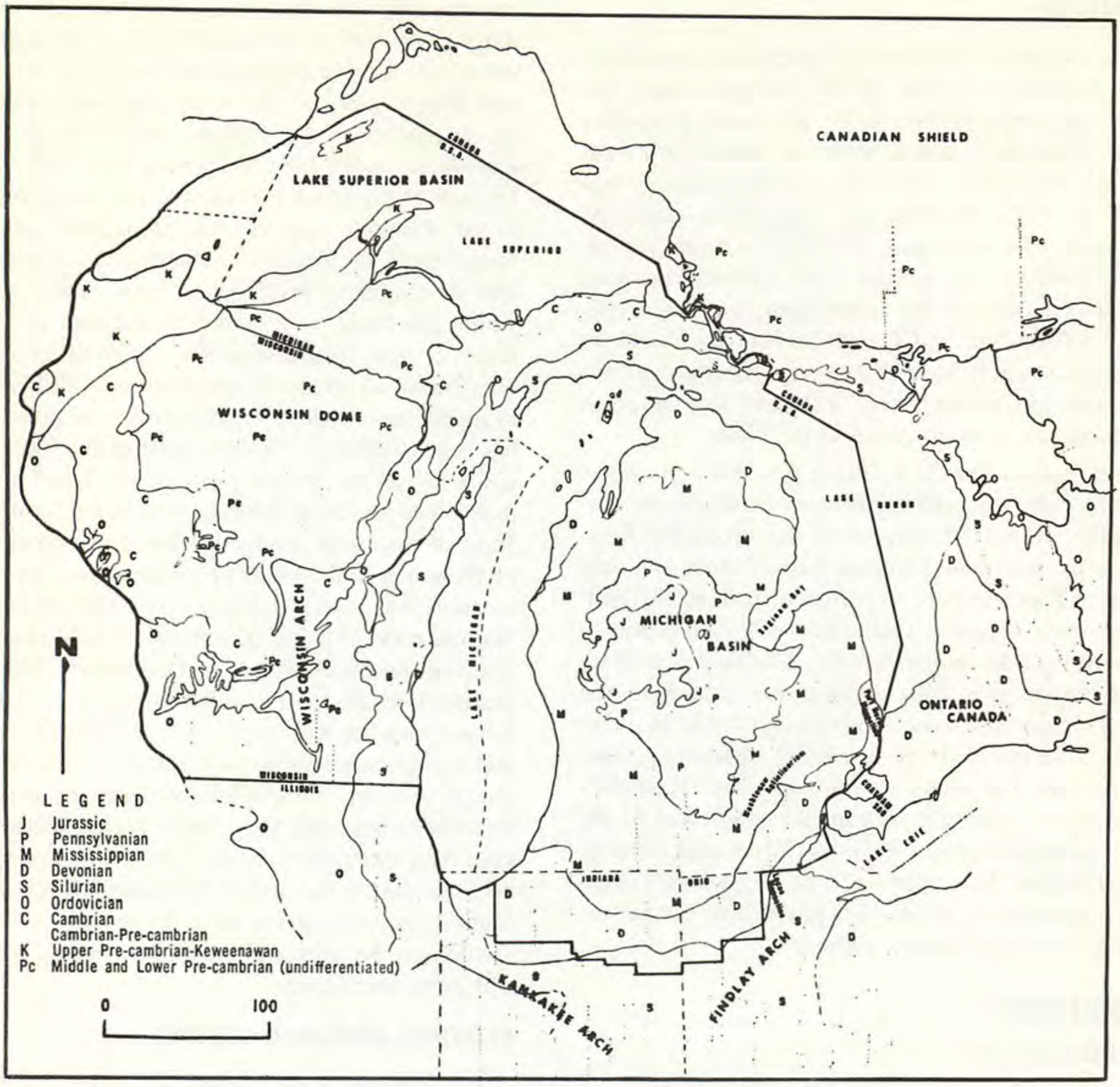

FIGURE 24. Index Map of Region 8, Michigan Basin, Showing Main Geologic Features

Northwest-southeast-trending anticlinal folds make up the common "grain" of the central part of the basin. Numerous folds are mildly asymmetric in cross section and demonstrate similar folding from the base of the Devonian up through the Mississippian beds. Around the southern margins of the basin, structural patterns vary from the general trends, probably as a result of salt tectonics and local draping of beds over reefs or reef-related features, and some faulting.

The sedimentary rock volume of the basin is estimated to be about 108,000 cubic miles.[43] Pennsylvanian and Mississippian rocks make up 6 percent, Devonian 15.4 percent, Silurian 30.7 percent, Ordovician 21.1 percent, and Cambrian 26 percent. Carbonate rocks comprise almost half (47 percent) of the basin rocks; 23 percent is sandstone, 18 percent shale, and 12 percent evaporites. Most of the evaporites are in the upper Silurian rocks and most of the sandstone is in the Cambrian. Nearly all the basin area is covered with a veneer of glacial debris. All Paleozoic rocks, with the exception of the Pennsylvanian, are of marine deposition. Pennsylvanian rocks are both marine and terrestrial.

HYDROCARBON POTENTIAL

Production

Through 1967, 552 million barrels of oil and 580 billion cubic feet of gas have been produced from the Michigan basin. Production records for Indiana and Ohio are incomplete and thus are not used. All the Paleozoic systems of Michigan, with the exception of the Cambrian, have produced oil and gas.

Statistics reveal that the size of oil and gas fields varies from single-well fields to fields containing more than 10,500 "drilled acres" and more than 575 wells capable of production. Drilling units were 10, 20, or 40 acres until 1963, when 40-acre-minimum drilling units were created by statute.

Size ranges of Michigan hydrocarbon accumulations have been ranked according to AAPG size gradations (Tables 16 and 17; see also reference 44). Most of the pools are of class E size—less than 1 million barrels of oil or 6 billion cubic feet of gas. This size-range analysis provides some insight as to the probable size of the pools yet to be discovered.

Undiscovered Reserves

The part of Region 8 deemed most favorable for future discoveries is the Southern Peninsula of the Michigan basin. Estimates apply only to the land area of the Southern Peninsula of Michigan and, with the exception of estimates based on method No. 1, listed below, do not include potentially productive areas underlying the Great Lakes. Future reservoir formations appear to be, in the foreseeable future, the same as those now being exploited. A possible exception would be the deeper and relatively unexplored lower Ordovician and Cambrian zones.

Three methods of estimating undiscovered oil and gas reserves of the Michigan basin were used in this study, for comparative purposes:

1. Estimates based on hydrocarbon yield per cubic mile of potentially productive sedimentary rocks (column 3, Table 18);
2. Estimates based on hydrocarbon recovery per square mile of proved productive acreage in an "adequately" explored area (column 4, Table 18);
3. Estimates based on recovery per square mile of "adequately" explored territory (column 5, Table 18).

Hopefully, through these comparisons (see Table 18; note figures in columns 3, 4, and 5 are considered to be *oil-in-place,* and not *recoverable* oil), the reader can obtain an overall range of estimates that should provide him with some reasonable guidelines.

Estimates based on method No. 1 include all of the Michigan basin as generally defined, and thus include parts of Canada not in Region 8. Estimates based on methods Nos. 2 and 3 apply only to the land areas of the Southern Peninsula of Michigan and do not include potential areas under the Great Lakes. Below is a summary of reserve estimates.

	Estimate of Undiscovered Hydrocarbons (barrels)		
	Probable	Possible	Speculative
Oil-in-Place[1]	650,000,000	680,000,000	1,290,000,000
Recoverable Oil[2]	292,500,000	306,000,000	580,000,000

[1] Figures modified from Table 18.
[2] Assuming 25 percent primary and 20 percent secondary recovery of the oil-in-place.

Obstacles to Exploration

The history of exploratory drilling in Region 8 has been cyclic and is closely related to new discoveries. For the period 1958 to 1967, an average of 13 new oil or gas pools has been found each year. However, the number of well completions, exploratory and development, has declined steadily. This gradual decline in activity, plus the small size of new discoveries, does not augur well for the future. Economic factors enter into the picture, and the cost of finding these small fields probably will discourage many operators.

TABLE 16. SIZE GRADATIONS OF MICHIGAN OIL POOLS DISCOVERED FROM 1925 THROUGH 1967

Geologic System	Reservoir Formation	AAPG Field Size Gradations (1) A	B	C	D	E (2)	Number of Pools(3)	First Year of Recorded Production
MISSISSIPPIAN	Stray and Marshall					1	1	1938
	Berea (Includes Western "Berea")				1	13	14	1925
DEVONIAN	Traverse			1	15	150	166	1927
	Rogers City—Dundee		3	4	23	77	107	1927
	Reed City		1			10	11	1941
	Detroit River—Sour Zone				1	21	22	1939
	Detroit River—Richfield				8	22	30	1946
SILURIAN	Salina E Zone					1	1	1958
	Salina A-2 Carbonate						0	—
	Salina A-1 Carbonate					7	7	1956
	Salina A-1 Carbonate and Niagaran Combined				2	7	9	1952
	Niagaran					13	13	1957
ORDOVICIAN	Trenton—Black River	1			1	10	12	1935
	Prairie du Chien					1	1	1960
CAMBRIAN							0	

(1) Field size gradations: A = 50 million barrels or more; B = 25 to 50 million barrels; C = 10 to 25 million barrels; D = 1 to 10 million barrels; E = less than 1 million barrels.

(2) A small number of Class F pools or fields has been included as Class E. All have produced some oil which has been sold on the market.

(3) Includes abandoned pools and fields.

NOTE: Concentration of pools in the size "D" and "E" columns.

TABLE 17. SIZE GRADATIONS OF MICHIGAN GAS POOLS DISCOVERED FROM 1929 THROUGH 1967

Geologic System	Reservoir Formation	AAPG Field Size Gradations (1) A	B	C	D	E(2)	Number of Pools(3)	First Year of Recorded Production
QUARTERNARY	Glacial Drift					1	1	1949
PENNSYLVANIAN	Parma Sandstone					2	2	1928
MISSISSIPPIAN	Stray Sandstone				10	60	70	1931
	Stray-Marshall Sandstone					1	1	1931
	Marshall Sandstone					2	2	1931
	Weir Sandstone					1	1	1949
	Berea Sandstone (Includes Western "Berea")					15	15	1936
DEVONIAN	Antrim Shale					3	3	1947
	Traverse Limestone					11	11	1934
	Rogers City—Dundee					8	8	1929
	Reed City					1	1	—
	Detroit River—Sour Zone					5	5	1946
	Detroit River—Richfield					2	2	1946
SILURIAN	Salina E Zone						0	—
	Salina A-2 Carbonate					2	2	1957
	Salina A-1 Carbonate				2	9	11	?
	Salina A-1 Carbonate and Niagaran Combined				5	13	18	1929
	Niagaran				1	10	11	
ORDOVICIAN	Trenton—Black River					1	1	
	Prairie du Chien						0	
CAMBRIAN							0	

(1) Field size graduations: A = 50 million barrels or more; B = 25 to 50 million barrels; C= 10 to 25 million barrels; D = 1 to 10 million barrels; E= less than 1 million barrels.

(2) A small number of Class F pools or fields has been included as Class E. All have produced some gas or were capable of making small, noncommercial amounts.

(3) Includes abandoned pools and fields.

NOTE: Concentration of pools in the "E" column.

TABLE 18. ESTIMATES OF UNDISCOVERED BARRELS OF HYDROCARBONS IN REGION 8

Geological Interval and Reservoir Formations	Actual Cumulative Production Through 1967 [1] (million barrels)	Method 1 Estimates Based on Rock Volume x 50,000 Barrels Per Cubic Mile (million barrels)	Method 2 Estimates Based on Yield Per Square Mile of Proved Productive Acreage (million barrels) [7]	Method 3 Estimates Based on Recovery Per Square Mile of "Adequately" Explored Territory (million barrels)[7]	Range of Probable Pool Sizes
PENNSYLVANIAN	Not Recorded	Not Calculated			Class F
MISSISSIPPIAN	39.788	Not Calculated			Class F to E
DEVONIAN					
Traverse	96.898[2]	100.000			
Rogers City / Dundee / Reed City	333.421	50.000	275.000	272.000	Class F to D
Detroit River	51.292	215.000			
Sylvania-Bois Blanc	No Production Established	125.000			
SILURIAN					
Bass Islands & Salina	No Production From Bass Islands	200.000	368.000	362.000	Class F to C
Niagaran	35.350[3]	100.000			
ORDOVICIAN					
Trenton—Black River	91.778	250.000	37.000 to 572.000[4]	39.000 to 589.000	Class F to A
Sub-Trenton—Black River Lower Ordovician & Cambrian	.005 from Lower Ordovician	800.000	Not Calculated	Not Calculated	?
TOTAL BARRELS	648.532	1,840.000[5]	680.000[6] to 1,252.000	673.000 to 1,262.000	

NOTES: 1. Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

2. Estimates of reserves in columns 3, 4, and 5 are considered to be **oil-in-place** and not **recoverable** oil in the generally accepted parlance.

[1] From Tables 20 and 22, Annual Statistical Summary 8, Michigan's Oil and Gas Fields, 1967. Gas Figures were converted to equivalent barrels of oil (6 thousand cubic feet = 1 barrel) and included in the above cumulative production.

[2] Includes a small amount of Antrim Shale gas.

[3] Combined Salina and Niagara production. Figure derived from 7,897,209 barrels of oil and 164,714,974 thousand cubic feet gas.

[4] Estimate based on expectations of finding future Class A fields similar to Albion-Scipio trend.

[5] Actual cumulative production, in the column on left, should be subtracted from this figure.

[6] These figures are for volumes in addition to the amount of hydrocarbons already produced through 1967. Further, these estimates apply only to the Southern Peninsula of Michigan.

[7] Rounded figures.

CHAPTER 11
REGION 9. EASTERN INTERIOR

Coordinator

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Illinois State Geological
Survey
(Authors Listed in Appendix D)

SUMMARY

The three subregions (see Figures 25 and 26) are unalike from either a geologic or production standpoint. Estimates of potential undiscovered reserves are presented by geologic age rather than by area, but the relative potential of the areas seems obvious.

ILLINOIS BASIN

Substantial new crude oil is expected from new fields and new pools in the Mississippian. Less substantial amounts of new crude oil is expected from the Devonian and Silurian. The future of the Trenton (middle Ordovician) depends mainly on development of streaks of porosity such as Albion-Scipio in Michigan.

CINCINNATI ARCH

Substantial amounts of new crude oil are not expected in Mississippian, Devonian, and Silurian rocks. The future of the Trenton depends mainly on development of "Michigan-style" streaks of porosity.

MISSISSIPPI EMBAYMENT

The prolific Pennsylvanian and Mississippian formations of the Illinois basin have not been found in this area, and no production has been found by the few exploratory wells drilled into the older formations. The regional structure in Paleozoic rocks is dominated by the Pascola arch which is the southeastern extension of the Ozark uplift. Paleozoic rocks are considered to be much more prospective than the thin Mesozoic-Cenozoic section. A more definite opinion must await the drilling of more exploratory wells. Determination of local structure in the objective Paleozoic beneath the thin Mesozoic-Cenozoic cover by geophysical surveys is exceedingly difficult.

CAMBRO-ORDOVICIAN

All of Region 9 is underlain by a thick section of lower Ordovician carbonate rocks and Cambrian sandstones and carbonate rocks. The volume of these sedimentary rocks is approximately 125,000 cubic miles, or more than 60 percent of the total sedimentary volume of the region. Four structurally well-located dry holes which reached basement in the Illinois basin are discouraging, but several zones of porosity are known and regional studies suggest important lateral variations in stratigraphy. Additional testing of this section of older rocks is definitely justified, and will determine to a large extent the future of Region 9 as a producing province.

It is speculated that the Cambro-Ordovician may ultimately produce 1.3 billion barrels of crude oil, or more than 3 times the amount of new oil expected from the presently productive formations. By comparison, the total volume of essentially the same geologic section west of the Mississippi River, Regions 5 and 7, is approximately 97,000 cubic miles. Ultimate recovery of Arbuckle-Ellenburger fields (Cambro-Ordovician) in Kansas, Oklahoma, and Texas has been estimated by the API and AGA [31] as 3.8 billion barrels of crude oil and 19.4 trillion cubic feet of natural gas.

DISCUSSION

INTRODUCTION

Region 9 consists of the Illinois basin, the Cincinnati arch province, and the northern part of the Mississippi embayment. It also includes northern Illinois, which usually is not considered with the Illinois basin (Figures 25 and 26).

Region 9 covers about 166,000 square miles and contains approximately 204,000 cubic miles of sedimentary rocks. If the northern part of Illinois, which has negligible potential for oil and gas accumulations, is excluded, the region has a net prospective area of about 155,000 square miles and a net prospective volume of about 197,000 cubic miles of sedimentary rocks (Table 19).

The ultimate recovery from known oil reservoirs in Region 9 is estimated at 4.3 billion barrels. Reservoirs that are expected to be discovered should produce, in addition, 1.7 billion barrels (Table 20). The petroleum possibilities of the three provinces in Region 9 are discussed in the following sections.

GEOLOGIC PROVINCES

Illinois Basin

Northern Illinois (Figure 27) has negligible potential for oil and gas accumulations. This area, 11,000 square miles, contains about 7,000 cubic miles of sedimentary rocks. Although it is in Region 9, it is not included in the following discussion of the Illinois basin.

The Illinois basin contains about 68,000 square miles of prospective area and about 100,000 cubic miles of sedimentary rocks. Of the total volume of sedimentary rocks, 53,500 cubic miles are in the deeper rocks below the St. Peter sandstone which have had very little testing.

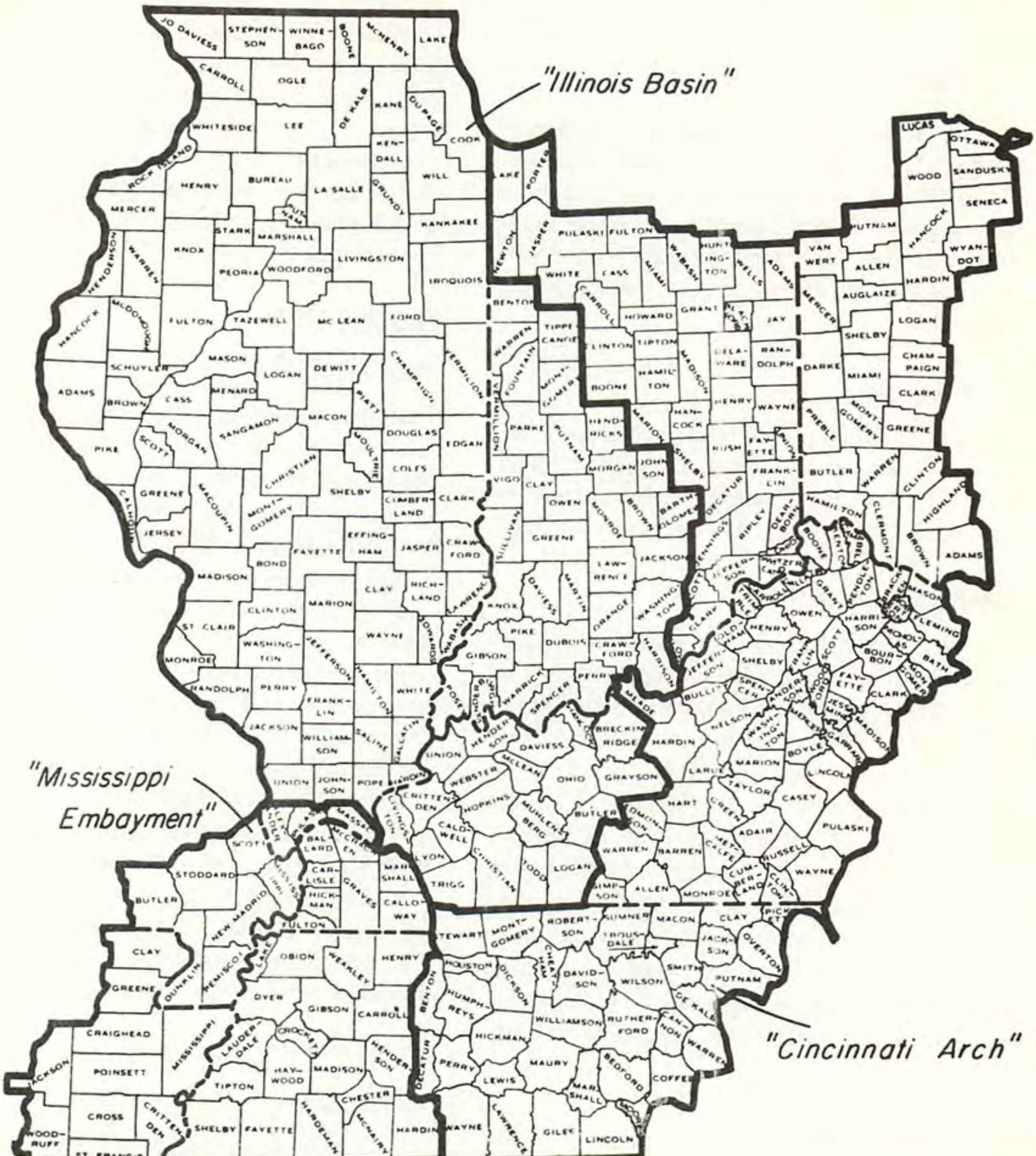

FIGURE 25. Index Map of Region 9, Eastern Interior

FIGURE 26. Tectonic Elements of Region 9, Eastern Interior (Italics indicate that features are buried and not evident in younger rocks.)

TABLE 19. SURFACE AREA AND VOLUME OF SEDIMENTARY ROCKS, REGION 9

	Illinois Basin plus Northern Illinois [1]	Cincinnati Arch	Mississippi Embayment	Total
Surface area (square miles)	79,246	63,021	23,887	166,154
Volume of sedimentary rock (cubic miles)				
Cenozoic-Mesozoic	—	—	1,234	
Pennsylvanian	8,452	13		
Chester (Upper Mississippian)	3,634	73		
Knobs-Mammoth Cave (Upper Devonian, Lower and middle Mississippian)	11,693	1,230		
Hunton (Silurian, Lower and Middle Devonian)	9,674	1,940		
Maquoketa (Upper Ordovician)	3,682	6,128		
Ottawa (Middle Ordovician)	8,233			
Glenwood (Middle Ordovician)	10	7,406[2]	37,747[3]	
St. Peter (Middle Ordovician)	1,880	41		
Knox (Cambrian-Ordovician)	30,385	27,267		
Potsdam (Cambrian)	29,983	13,664		
Total Volume	107,626	57,762	38,981	204,369

NOTE: Future potential reserves are estimates of discoverable hydrocarbons. The volumes that will be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

[1] Approximately 11,000 square miles, with 7,000 cubic miles of sedimentary rock, in northern Illinois, having negligible potential for oil and gas.

[2] Ottawa and Glenwood.

[3] Pennsylvanian through Cambrian.

TABLE 20. CRUDE OIL IN REGION 9 (BILLION BARRELS)

Known Reservoirs				Reservoirs Expected to be Discovered and Produced in the Future						Total	
Original Oil-In-Place	Ultimate Recovery	Cumulative Production	% Recoverable $\left(\frac{\text{Ultimate}}{\text{OOIP}^{(1)}} \times 100\right)$	Original Oil-In-Place			Ultimate Recovery			Original Oil-In-Place	Ultimate Recovery
				Penn-St. Peter	Knox & Deeper	Total	Penn-St. Peter	Knox & Deeper	Total		
11.7	4.3	4.0	37	1.1	6.4	7.5	0.4	1.3	1.7	19.2	6.0

NOTE: Future potential reserves are estimates of discoverable hydrocarbons. The volumes that will be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

[1] Original oil-in-place.

The Illinois basin, as of January 1, 1969, produced 3,395 million barrels of oil and a considerable volume of solution gas. Known reserves are about 384 million barrels. Gas produced from gas reservoirs has totaled about 1 trillion cubic feet.

Of the recoverable oil found, 13.1 percent has been in the Pennsylvanian, 82.3 percent in the Mississippian, 4.1 percent in the Devonian and Silurian, and 0.4 percent in the Ordovician. One-fourth of the oil has been produced by waterflooding. Two-thirds of the current production result from waterflood operations. Waterflooding already is under way in most of the oil reservoirs that have prime properties for economic flooding.

The current (1968) producing rate is about 80 million barrels per year. It is expected to drop to about 40 million barrels per year by 1980, if no major discoveries are made and if no breakthrough occurs in secondary or tertiary recovery methods.

Following are the prospects for new production in currently productive systems:

1. Pennsylvanian
   Prospects are slight.
2. Mississippian
   Discoveries of new fields and of new pools in old fields should add several tens of millions of barrels of reserves. New fields are expected to be found south of the Rough Creek fault zone.
3. Devonian and Silurian
   Pools containing from one to several million barrels each may be found in Silurian reefs and in Devonian rocks draped over reefs. Accumulations in Devonian reservoirs in tectonic structures could be substantial.
4. Ordovician
   a. No major discoveries are expected in the Trenton (Ottawa) except in fracture-controlled, dolomitized streaks.
   b. Below the Trenton, in the deeper rocks which have not yet produced oil or gas, the best prospects are in the Cambrian and Ordovician rocks shown below.

   (1) Ordovician

   (a) Joachim Dolomite—There is a possibility of finding oil accumulations in the upper part where anhydrite forms a seal bed, and in scattered lenses of sandstone and dolomite in the lower part.

   (b) Dutchtown Limestone—Prospects for finding oil are best along the northern edge of the Dutchtown, south of the Rough Creek fault zone.

   (c) St. Peter Sandstone—Prospects are best along the eastern margin of the Illinois basin—in Indiana, western Kentucky, and perhaps in easternmost Illinois, where the St. Peter wedges out updip. However, these prospects are not encouraging.

   (2) Ordovician (lower part) and Cambrian (upper part): Knox.

   (a) Shakopee Dolomite—This unit is prospective in southeastern Illinois and southwestern Indiana.

   (b) Gunter Sandstone—This and other sandstone units are possible prospects for production in the Illinois basin.

   (c) Potosi Dolomite ("Trempealeau") —Dolomite units in the upper part of this formation are prospective.

   (3) Cambrian

   (a) Eau Claire Sandstone—This formation is prospective where sandstone, shale, and carbonate rocks interfinger, especially in the southern sector of the Illinois basin, possibly extending into Kentucky.

   (b) Mount Simon Sandstone—The Mount Simon is prospective possibly where it pinches out against Pre-Cambrian buried hills and, in the southern part of the Illinois basin, where it may pinch out or interfinger with dolomite.

Extent of Testing—The Pennsylvanian and Mississippian have been well tested. The rocks below the Mississippian in Kentucky and the rocks below the Devonian in Illinois have had very little testing in the deep part of the Illinois basin. Four of the major structures have had basement tests, and three others have had tests that went to dolomite of the Cambrian-Ordovician Knox. One of the deep tests, in Wayne County, Illinois, produced some noncommercial oil in a drillstem test in the Knox; the other deep tests were dry. Oil has been produced from the Knox in two pools on the edge of the Illinois basin in Indiana (Jay County) and Kentucky (Adair County). The deeper, relatively unexplored rocks lie at depths of about 5,000 to 13,000 feet. Objectives in the Cambrian-Ordovician Knox are about 8,000 feet deep, or less.

In the southwestern quadrant of Illinois, massive beds of chert in the Devonian and Silurian make drilling difficult. In extreme western Illinois, chert in the lower part of the Mississippian causes some difficulty in drilling.

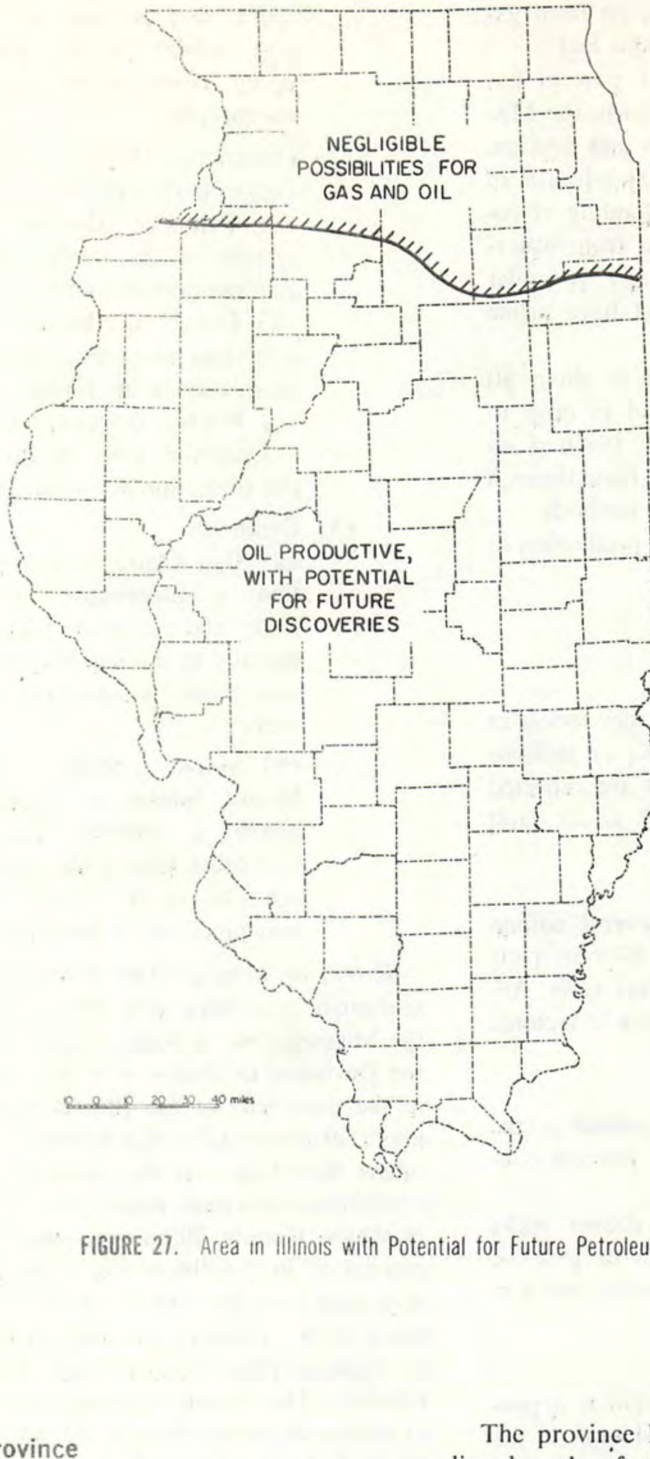

FIGURE 27. Area in Illinois with Potential for Future Petroleum Discoveries

Cincinnati Arch Province

The 63,021 square miles of the Cincinnati arch province contain 57,762 cubic miles of Paleozoic sedimentary rocks. Thickness of the sedimentary section ranges from less than 3,000 feet on the crests of the Lexington dome and the Findlay arch to more than 9,000 feet on the western flank of the Nashville dome (Figure 26).

The province has produced more than 500 million barrels of oil. Known oil reserves are small. Known oil reservoirs of the Cincinnati arch province are at shallow depths, most of them between 1,000 and 1,500 feet, although some are shallower and others deeper. The Trenton-Black River (489 million barrels) and the Hunton (58 million barrels) have been the principal producing units. Some gas has been found, most of it in the Trenton (Lima-In-

5. Cambrian (Upper Part) and Ordovician (Lower Part)

   There is a significant potential for oil and/or gas discoveries in strata of these ages on the Cincinnati arch. Geologic conditions offer the probability of diverse types of entrapment—i.e., erosional prominences on the surface of the Cambrian-Ordovician Knox, pinchouts of porous beds beneath impermeable strata of the Glenwood formation, and structural closures discordant with the structure of younger beds. The Knox has been tested only to a limited degree, but oil has been produced from several small reservoirs in Indiana, Ohio, Kentucky, and Tennessee.

6. Cambrian

   There is potential for oil and gas discoveries in Cambrian units. The best potential is for stratigraphic accumulations (1) in sandstone units interfingered with argillaceous Eau Claire units and (2) in the Conasauga-Rome beds, especially in the Rome trough. Only one well per 500 square miles (approximately) has been drilled to a depth sufficient to reach these objectives, and only one well per 850 square miles has been drilled through them.

Several factors are conducive to petroleum exploration in the Cincinnati arch province: the objective strata are shallow; very little acreage is under lease; and laws, rules, and regulations are acceptable to the petroleum industry.

Mississippi Embayment

The northern part of the Mississippi embayment, as defined in this report, covers 23,887 square miles, containing 38.981 cubic miles of sedimentary rocks. Of the total sedimentary rock volume, 1,234 cubic miles are Mesozoic-Cenozoic rock with poor potential for petroleum production. The remaining 37,747 cubic miles are Paleozoic and fulfill all of the criteria required for a prospective petroleum-producing province.

Very few wells (less than 6 per county) have been drilled into the Paleozoic in this area. Three deep tests have been drilled to total depths of 6,000, 7,000, and 10,000 feet; the deepest test penetrated 8,000 feet of Paleozoic rocks. No commercial oil or gas has been produced.

The major potential of the Mississippi embayment is in the Cambrian-Ordovician Knox, especially in (1) porous sandstone units of the Roubidoux and Gunter formations, and (2) porous dolomite, where it interfingers with nonporous limestone.

diana field); total production has been about 1 trillion cubic feet. Prospects for future petroleum discoveries are in the following:

1. Upper Devonian and Mississippian (Lower and Middle)

   The best prospects are in the St. Louis, Warsaw, and Ft. Payne formations. Future discoveries probably will be limited to the Cumberland saddle area and probably will be small.

2. Silurian and Lower-Middle Devonian

   Hunton rocks have some potential for petroleum discovery in and adjacent to the present productive area on the west side of the Cumberland saddle in Kentucky; however, the high density of drilling in the productive area precludes large discoveries there. The most favorable objectives are the porous zones beneath unconformities at the top of the Hunton and between the Silurian and Devonian parts of the Hunton.

3. Ordovician (Upper Part)

   Future discoveries probably will be small and limited to the present producing areas, which are in the Cumberland saddle and on the flanks of the Nashville dome.

4. Ordovician (Middle Part)

   Linear bands of porous secondary dolomite, associated with faults and fractures, provide promising possibilities for significant entrapment of oil and gas. (Such traps have been found in the adjacent Michigan basin.) Discovery of small stratigraphic accumulations is expected in the Cumberland saddle area. The most prospective formations are the Trenton and Black River (or Stones River).

Stratigraphic or possibly fault traps are most likely to be found around the Pascola arch. Away from the arch, domes and anticlines can be expected, and igneous intrusions may have produced structural and pinchout traps.

Depth of drilling required to test these objectives ranges from about 3,000 to 8,000 feet. The loosely consolidated Mesozoic and Cenozoic sediments must be cased off if satisfactory drill samples are to be recovered from the Paleozoic section. The karst surface of the Paleozoic rocks usually creates drilling problems, resulting in lost circulation and contamination of samples.

Interpretation of gravity and magnetic profiles may be difficult in areas of faulting and igneous intrusion. Within the Paleozoic rocks, delineation of structure by seismic methods would be complicated by the truncated Paleozoic surface and the lithologic similarity of the formations.

CHAPTER 12
REGION 10. APPALACHIANS

Coordinator

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(Authors Listed in Appendix D)

SUMMARY

This region is divided into two areas on either a geological or geographical basis (Figure 28).

The western or Appalachian plateau area has produced nearly all of the region's crude oil and natural gas, and is considered to be the most promising area for future discovery. Extensions of the older natural gas producing areas are still being made in Mississippian, Devonian, and Silurian rocks.

The Valley and Ridge area to the east is geologically complex, but is not without potential. This is a highly speculative area in which no important field has been found.

The region definitely is one where natural gas is most likely to be found. Estimates of ultimate recovery of hydrocarbons found to date (reference 31) indicate that two-thirds are natural gas (BTU basis). Almost 8 times as much natural gas has been found in the last 20 years as crude oil (BTU basis; reserve estimates dated back to year of discovery).

Although ultimate recoveries of crude oil and natural gas only approximate those of Kansas (less crude oil and more natural gas in Region 10), the location in and near large consuming centers gives the region a definite economic advantage.

The future of discovery in this region, as in Region 9, depends to a large extent on discovering important fields in the Ordovician and Cambrian carbonate rocks and sandstones which underlie the entire region. The possibilities of the 92,000 cubic miles of lower Ordovician and Cambrian section below the Beekmantown erosional unconformity underlying the plateau are viewed with enthusiasm. Crude oil has been produced from patchy accumulations beneath this erosional surface at shallow depths along the west flank of the Appalachian plateau province in Tennessee, Kentucky, and Ohio; the only important production has come from central Ohio. Recently, natural gas was found in the lower Ordovician at 8,100 feet in Columbiana County, Ohio, near the Pennsylvania boundary. Deeper in the basin very few wells have reached the section. Although production has been associated with the unconformity, it is important to observe that showings of oil and gas have been found in the seldom-drilled older strata.

The central Ohio Cambro-Ordovician accumulations are geologically similar to the Cambro-Ordovician oil fields of the Central Kansas uplift where topography developed on an old erosional surface controls most of the production. Elsewhere, in Regions 5 and 7, most of the Cambro-Ordovician fields are on prominent local structural closures where fracture porosity plays an important role, particularly in the deeper fields of West Texas. Perhaps one can expect similar large structural closures and fracture porosity in the deeper portion of the Appalachian plateau area as the highly deformed Valley and Ridge province is approached. The meager data suggest that lithologic changes in the section (perhaps more of them than in Kansas, Oklahoma, and Texas) will play an important role.

The volume of younger Ordovician sedimentary rock underlying the plateau is approximately 71,000 cubic miles, or about twice the volume of these rocks on the west in Regions 8 and 9. The Trenton limestone near the top of the section has produced substantial amounts of oil in northwestern Ohio, northern Indiana, and southern Michigan; and minor amounts in Illinois, eastern Kentucky, and Lee County, Virginia. It has been extensively tested without finding production in many wells drilled to the Cambrian in central Ohio. The few wells drilled deeper in the Appalachian basin have not found production in this section. The middle and upper Ordovician rocks would be secondary objectives in wells drilled to the lower Ordovician, although the Trenton of West Virginia, Virginia, and Maryland may be a primary objective.

It will take a large number of exploratory wells to depths of as much as 25,000 feet, although much shallower in most of the area, to encourage or discourage further exploration. Geophysics will play an important role in localizing prospects, particularly in the deeper parts of the Appalachian plateau.

The geologically complex Valley and Ridge belt on the east may in time yield surprising results. A little crude oil has been produced in the Rose Hill field, Lee County, Virginia, and there are small gas fields in Hardy and Hampshire Counties, West Virginia. In Pennsylvania, drilling through thrust plates has found gently dipping, unmetamorphosed sediments beneath them. It is reasonable to expect accumulations of petroleum beneath thrust plates in the Appalachians, but they are difficult to locate as explorationists in Alberta, Canada, have learned.

DISCUSSION

INTRODUCTION

Region 10, the Appalachian area, includes a large part of the Appalachian basin; the region extends west approximately to the axis of the Cincinnati arch, east to the boundary of the Fall Line with the Atlantic coastal plain, north to the Canada border (including all of New England), and south to include eastern Tennessee and western North Carolina.

The major tectonic features of the area are shown in Figure 28. The text treatment of Region 10 is handled on a state or contiguous-state (e.g., New England) basis. Arbitrary geologic divisions of the basin area could have been established as a basis for discussion, but from northeast to southwest the basin geology largely reflects gradual change rather than abrupt geologic boundaries. This basin, in fact, is unusual for its relative tectonic uniformity in a northeast-southwest direction. Stratigraphic changes also are relatively gradual in this direction. More distinct geologic divisions are evident from northwest to southeast, but, as approximately half the geologists engaged in the Region 10 study were state geological personnel having particular expertise in their own areas, and as the bulk of the favorable petroleum area is in the rather uniform Appalachian Plateau province, the decision was made to treat the study on a state basis.

In the New England part of the study, a section was included on the Atlantic offshore potential (discussed also in the Region 11 report), since there is a close geologic relation between the New England onshore and offshore areas.

In regard to potential gas and oil resources, that is resources beyond the proved reserve category, the Potential Gas Committee's determination of 53 trillion cubic feet of gas has been accepted for the Region 10 area. The Committee's October 1969 report showing "Area A" encompasses not only NPC Region 10 but parts of adjacent NPC regions; separate Region 10 potential gas figures have been obtained from the Committee. A detailed study of potential oil resources has not been made for the Region 10 area, but 100 million barrels of oil are considered a reasonable potential oil figure for Region 10. Reserve figures are given in Table 21.

Quantitative Data

Area (square miles)
- Total, Region 10: 303,000
- Most favorable area:* 130,000
- Intermediate favorable:† 35,000
- Marginal:‡ 500
- Unfavorable:§ 137,000

Sedimentary Rock Volumes in Most Favorable Area (cubic miles)||

- Total volume: 305,000
- Surface to top Onondaga: 95,000
- Top Onondaga to top Ordovician: 47,000
- Top Ordovician to top Beekmantown (Knox) unconformity: 71,000
- Top Beekmantown unconformity to top basement: 92,000

PRODUCTION POSSIBILITIES

Despite its long productive history of more than a century, the Appalachians—birthplace of the U.S. oil and gas industry—still has abundant prospects for the future. Appalachian oil and gas production has an added economic value since it is in the heavily industrialized and populous East. Furthermore, production there will assume increasing importance as the Nation's demand for oil and gas climbs to increasingly higher levels.

In Region 10, the most favorable area is the Appalachian plateau (Figure 28). In this province, the thickest total sedimentary section combined with multiplicity of objectives is in Pennsylvania and West Virginia. Ranking close behind Pennsylvania and West Virginia are adjacent parts of eastern Ohio and eastern Kentucky, followed by southern New York, eastern Tennessee, western Maryland, and western Virginia. Northern New Jersey has questionable prospects. Large areas of metamorphic and/or igneous rocks in New England and western North Carolina rule out much of these areas, but even these districts have some localized prospects.

STRATIGRAPHIC EVALUATIONS

The Appalachian plateau's major oil and gas prospective section ranges primarily from the Devonian through the Cambrian. The Pennsylvanian has limited potential. The Mississippian, although extensively drilled, is prospective in parts of West Virginia, Ohio, Kentucky, Tennessee, Virginia, and Pennsylvania—in a few areas it is a primary objective; in others it is a secondary objective in deeper drilling.

Sparked by the advent of hydraulic fracturing in the mid-1950's, production from the great oil- and gas-producing system of the Appalachians—the Devonian—still is being expanded, both horizontally and vertically. Continued expansion can be expected for many years.

* Includes area from west boundary of Region 10 to the Appalachian front. The Appalachian front is a structural feature close to the Allegheny front, a geomorphic feature.

† Valley and Ridge province, including Lake Champlain valley.

‡ Moose River synclinorium, Maine; areal extent questionable.

§ Blue Ridge and Piedmont provinces to Fall Line.

|| Same note as (*) above. Volumes of intermediate and marginal areas are indeterminate because of complex folds, faults, and lack of data.

In the Silurian, the "Clinton" sandstone units, so productive of gas and oil (particularly gas) in Ohio, are still the source of substantial reserve additions. A major enlargement of the "Clinton" gas-producing province is under way in Guernsey and adjacent counties of southeastern Ohio. Very substantial "Clinton" reserves ramain to be found in Ohio and nearby Kentucky. The Silurian Williamsport ("Newburg"), currently the target of an intensive drilling play in West Virginia and adjacent Ohio, is furnishing some of the largest open-flow gas wells ever drilled in the Appalachians.

The prospects of the great frontier of Appalachian oil and gas potential—the Cambrian-Ordovician—are viewed with enthusiasm. Approximately one-half of the total sedimentary volume of the most favorable area, the Appalachian Plateau province, consists of rocks of these two systems. A large part of this geologic section is virtually unexplored. Even after subtracting the volume of Cambrian-Ordovician section considered to have unfavorable lithology, and the somewhat better drilled areas such as

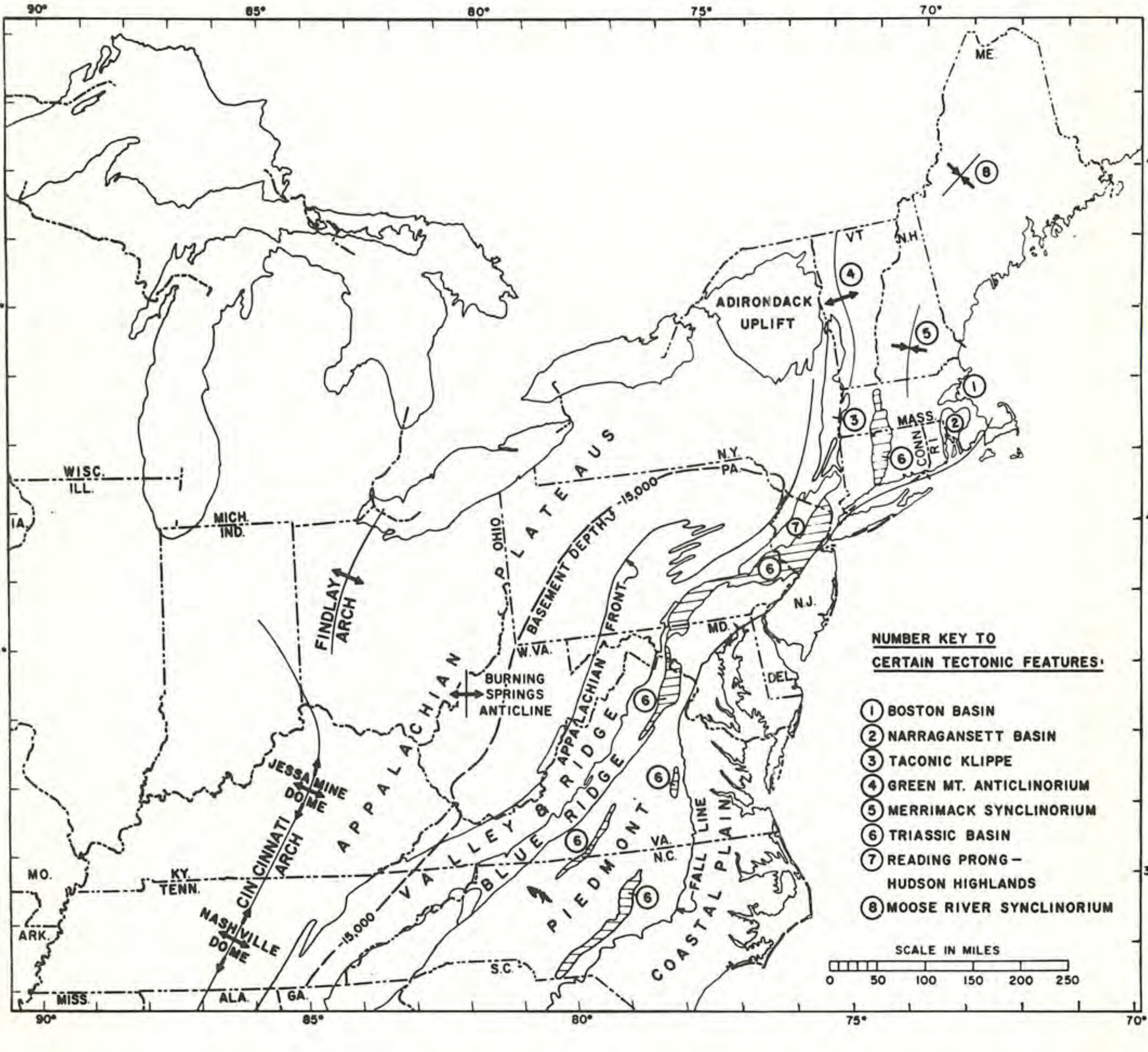

FIGURE 28. Major Tectonic Features of Region 10, Appalachians

TABLE 21. PROVED API-AGA RESERVES AS OF DECEMBER 31, 1968

State	Oil (million barrels)	Gas [1] (billion cubic feet)	Gas [2] (billion cubic feet)	Gas in Storage Native and Injected (billion cubic feet)
New York	13.0	124.1	27.7	96.4
Pennsylvania	59.2	1,345.0	858.5	486.5
Ohio[3]	132.3	783.9	351.2	432.6
West Virginia	53.6	2,585.6	2,238.0	347.6
Maryland[4]	—	—	—	—
Virginia[4]	—	34.3	34.3	—
Kentucky[3]	79.5	923.3	875.1	48.1
Tennessee[4]	—	—	—	—

[1] Includes gas in underground storage (native and injected).
[2] Excludes gas in underground storage (native and injected).
[3] Includes all of Ohio and Kentucky, as separate Region 10 reserves are not available.
[4] Dashes represent figures not available from API-AGA sources.

central Ohio and northern New York State, there remains approximately one-third of the total sedimentary rock volume of the Appalachian Plateau province as unexplored Cambrian-Ordovician in the favorable area of Region 10.

Few wells have been drilled in the fold and thrust belt of the Valley and Ridge province (Figure 29), bordering the Appalachian plateau on the east. Those that have generally substantiate the intense tectonism evident from the surface. This province, little known in the subsurface, is probably not as attractive as the Appalachian Plateau province if geologic, exploratory, and economic factors are considered, but it cannot be classified as "unfavorable." Production is obtained from similar, structurally complex areas such as the Foothills belt of western Canada. In both the Appalachian Plateau province and the Valley and Ridge province, flat thrust faults may be present at depth, beneath which the structure may be less complex.

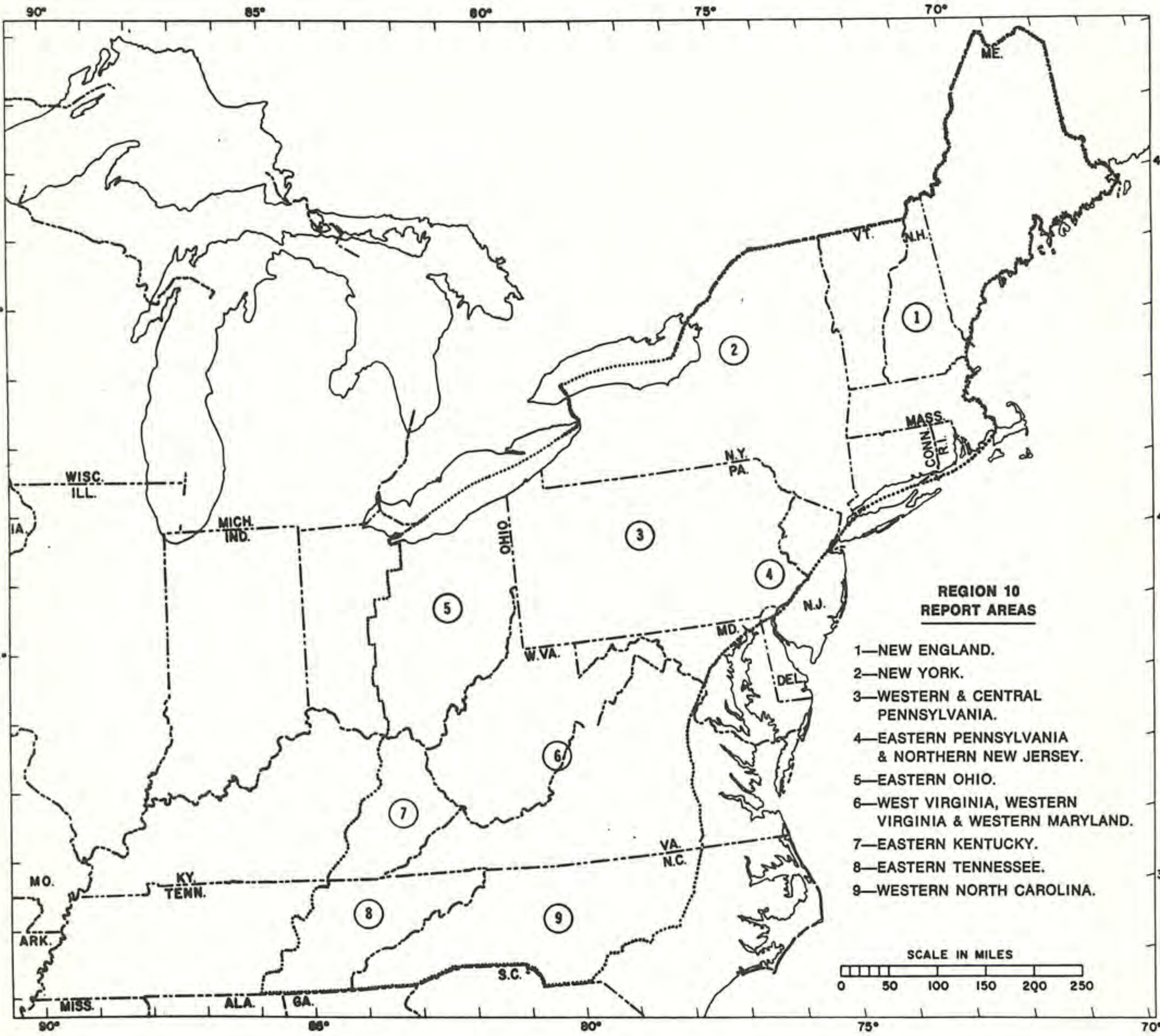

FIGURE 29. Outline Map of Region 10, Appalachians, Showing Report Areas

CHAPTER 13
REGION 11. EASTERN GULF AND ATLANTIC COASTS

Coordinator

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(Authors Listed in Appendix D)

SUMMARY

Figure 30 shows location of the areas reported on in this region.

The geology of this region is not as well known as the geology of the other regions in the conterminous United States because the results of exploration have been so poor (no natural gas fields, and only four small crude oil fields in southern Florida) that extensive exploratory drilling has been discouraged. However, the general geologic framework of the land area is fairly well known, and although no wells have been drilled offshore in the Atlantic Ocean south of Sable Island (Canada), projection of the stratigraphy and structure of the onshore into the offshore, aided by published geophysical data and seafloor samples, provides a broad picture of the geology of the offshore.

Estimates of potential recoverable reserves of crude oil and natural gas for this region are regarded as highly speculative.

OFFSHORE

The continental shelf covers an area twice as large as the shelf off Louisiana, Texas, California, Oregon, and Washington, and is the largest, almost-undrilled prospective area in the conterminous United States. The general geology bears little resemblance to the Louisiana offshore. In a general way it resembles the geology of the upper Gulf Coast (East Texas, North Louisiana, southern Arkansas, and Mississippi) where prolific production of crude oil and natural gas is obtained from Mesozoic rocks. Enough is known about the geology to support the belief that petroleum was generated and trapped in structural and/or stratigraphic traps. The lower Cretaceous is believed to offer the best possibilities for future production. However, the productive possibilities of the offshore cannot be predicted with any certainty until many more exploratory wells are drilled. Knowledge of local and regional structure, and broad variations in stratigraphy are in the hands of companies who have participated in geophysical surveys.

ONSHORE

Although the offshore is considered the more prospective, discoveries are still expected onshore in sparsely drilled areas. A belt of interfingering lower Cretaceous sandstones and carbonate rocks on the south flank of the Peninsular arch in Florida, north of the producing area, offers the most potential. Upper Jurassic sandstones and carbonate rocks are believed to be present to the south, and are considered to be prospective. The mode of entrapment is expected to be more stratigraphic than structural. The lower Cretaceous and Jurassic trends extend into the offshore.

The area of unmetamorphosed Ordovician, Silurian, and possibly Devonian shales and quartzitic sandstones underlying the Mesozoic in northern Florida, southern Georgia, and southern Alabama may also have potential.

DISCUSSION

INTRODUCTION

Region 11 covers the Atlantic Coastal plain, the Atlantic offshore, and the eastern Gulf of Mexico (Figure 30).

On the Atlantic costal plain and adjacent continental shelf in the Atlantic Ocean and the eastern Gulf of Mexico, there is no gas production, and the limited oil production is from a very small area in the southern part of the Florida Peninsula. In Florida, more than 300 exploratory tests have resulted in the discovery of only four oil fields in the past 26 years: Sunniland (1943), Forty Mile Bend (1954), Sunoco Felda (1964), and Lake Trafford (1969). Forty Mile Bend field was abandoned in 1956, shortly after its discovery. The Lake Trafford field was discovered in May 1969 and contains but one well. Production in all the fields is from carbonate rocks at a depth of approximately 11,500 feet—the Sunniland Limestone of early Cretaceous age. Cumulative oil production in Florida, since the first discovery in 1943 through December 31, 1968, amounted to 15.31 million barrels of 20° gravity oil. Although there is a small amount of closure (less than 50 feet) at the Sunniland field, the oil traps in the four Florida fields are controlled more by stratigraphy than by structure.

North of Florida, questionable oil or gas shows have been reported in five of the wells drilled on the Atlantic coastal plain, where the density is approximately one well per 390 square miles. In central Georgia, oil seeps occur in Telfair, Pulaski, and Johnson Counties, where Miocene and possibly Oligocene beds crop out. One of these seeps is reported to yield 30° API-gravity oil.

GEOLOGICAL ENVIRONMENT

Well control on the coastal plain has established a seaward-dipping and seaward-thickening wedge of Cretaceous and Tertiary rocks. Sea-floor samples and seismic-refraction data indicate that these sediments continue to dip and thicken seaward beneath the continental shelf and slope. Coarse continental

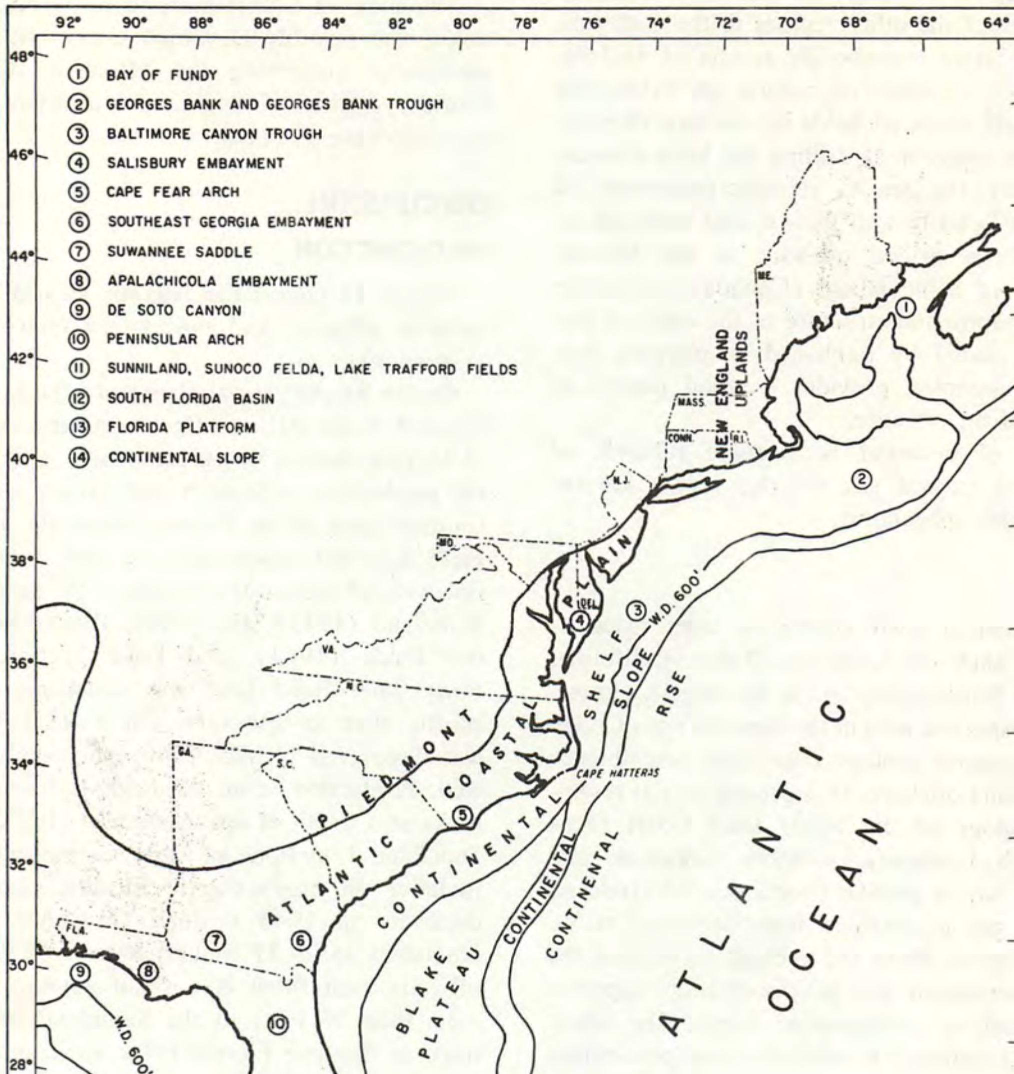

FIGURE 30. Map of Region 11, Eastern Gulf and Atlantic Coasts, Showing Major Structural Features

clastic sediment in updip exposures grades to finer clastic sediment and the percentage of marine beds increases seaward. Carbonate rocks are predominant south of Cape Fear, and clastic sedimentary rocks are predominant north of the cape. In the northern area the sedimentary rocks probably average 7,500 feet in thickness and may be 16,000 feet or more in thickness seaward from New Jersey. They continue to thicken beneath the continental shelf and may exceed 30,000 feet beneath the Blake Plateau.

The generalized sedimentary section and approximate thicknesses in Florida and the adjacent offshore area are as follows:

	Feet
Tertiary, carbonate rocks	2,000 to 5,500
Upper Cretaceous, limestone and dolomite	4,000
Lower Cretaceous, carbonate rocks and evaporites	7,000
Wedges of sandstone and shale on south and west flanks of Peninsular arch	0 to 4,000
Jurassic, carbonate and terrigenous clastic rocks and evaporites in southern Florida and continental shelves	1,300+
Triassic, redbeds, probably confined to grabens	Unknown
Lower Paleozoic, sandstone and shale in northern Florida	Unknown

The above units, except for the Jurassic, have been penetrated by wells in Florida.

The regional structure of the coastal plain is essentially monoclinal, dipping seaward from the edge of the Appalachian Piedmont and New England Upland provinces. The dip of the basement surface in feet per mile from the Piedmont to Cape Hatteras, North Carolina, varies from 20 feet at the Piedmont to 100 feet near the coastline and 135 feet at Cape Hatteras. In the same area the top of the upper Cretaceous has a fairly uniform dip of about 30 feet per mile. In southern North Carolina the monoclinal dip is interrupted by the Cape Fear arch, which forms a broad, southeast-plunging nose that was a positive area in early Cretaceous and pre-Miocene times. The Salisbury embayment, a basement feature in parts of Virginia, Delaware, Maryland, and New Jersey, began to receive sediments in Cretaceous time.

The northwest-southeast-trending Peninsular arch in Florida was the principal positive feature of the region and remained so until early in late Cretaceous time, when waters covered it. The South Florida basin is the dominant negative feature. The Apalachicola embayment (Florida), the Suwannee saddle (Georgia), and the associated Southeast Georgia embayment make up a more or less east-west, mildly negative feature north of the Peninsular arch.

Surface and subsurface data from wells indicate that the monoclinal seaward dip of the strata is uninterrupted by faults or folds of the types found in important oil-producing areas. There have been no offshore tests, and knowledge of the structure beneath the continental shelf and slope comes from geophysical measurements, dredge samples, and cores from shallow drilling (JOIDES*). Regional structural dip of the basement is seaward, and seismic work indicates a depth of more than 40,000 feet beneath the upper continental rise. A basement ridge, first reported by Drake et al.[45] interrupts the regional seaward dip from Newfoundland south to Delaware, and perhaps farther south. Drake et al. also described two large structural depressions beneath the continental shelf, which Maher [46,47] named the Baltimore Canyon trough and the Georges Bank trough.

In the northern part of this province, on the sea floor beyond the continental shelf, seamounts form sharp conical mountains. The seamounts, probably igneous intrusions, can be delineated by sharp magnetic anomalies. Structures which are thought to be salt intrusions are common on the Grand Banks of Newfoundland and are indicated by sparker profiles as far south as the Nova Scotian shelf. They may extend into the United States Atlantic, but no such structures have been reported south of this shelf area.

HYDROCARBON POTENTIAL

From the foregoing brief geologic résumé, it is apparent that a seaboard or offshore producing area that is comparable to this Atlantic province is hard to find. The apparent differences may be due in part to lack of information, especially in offshore areas. Nevertheless, we cannot recognize many of the features that are common to onshore and offshore oil and gas production in areas such as the Gulf Coast or California.

There is a general absence of evidence of rapid deposition and rapid burial of great quantities of sediment, as well as an absence of growth or contemporaneous faults of the type that formed structural and stratigraphic traps in which many of the prolific Gulf Coast oil and gas fields are found. There is little evidence of Mesozoic or Cenozoic tectonic activity that may have formed structures of the type that produce in California. On the favorable side, it is known that the sedimentary rocks of the Atlantic Coast were deposited mainly in a transitional or shallow marine environment that offered a favorable mix of potential reservoir and source beds.

* Joint Oceanographic Institutions for Deep Earth Sampling.

In this area of clastic rocks there is a possibility of stratigraphic traps because of the rapid thinning of the section updip. Structural traps may be present offshore. In the south, in the carbonate-rock area, oil and gas accumulations may be found in reefs and stratigraphic traps, especially where there is an intermingling of the terrigenous clastic and carbonate rocks and evaporites.

The lower Cretaceous strata are thought to offer the best possibilities for future production. However, in attempting to make some estimates as to possible future recoverable hydrocarbons, all of the possible producing units are considered. In a region that has produced only 15.31 million barrels of oil and has only a limited number of wells onshore, and none offshore in the Atlantic, estimates of future reserves must be *highly speculative*.

Because the Atlantic Coast has no history of petroleum production, and very little is known about the geology of the offshore area, it was concluded that the best method of quantifying hydrocarbon potential is to relate potential to the volume of sedimentary rock. The upper 1,500 feet of sediment or sedimentary rock is excluded from the area, thickness, and volume values. The estimates of potentially recoverable hydrocarbons on the coastal plain, continental shelf, and continental slope from Canada through Georgia are 13.3 billion barrels of oil and natural gas liquids and 74.0 trillion cubic feet of gas.

Because there is more geologic information on the Florida area, and some production there, hydrocarbon potential can be related to volume of sedimentary rocks that have had a depositional history conducive to the formation and entrapment of hydrocarbons. "Speculative" future reserves are estimated at 7.8 billion barrels of oil and 13.0 trillion cubic feet of gas on the Florida Peninsula and adjacent continental shelves in the Atlantic and eastern Gulf of Mexico.

Total *highly speculative* estimates of recoverable hydrocarbons on the Atlantic coastal plain and adjacent continental shelves from Canada south through Peninsular Florida are 21.1 billion barrels of oil and natural gas liquids and 87 trillion cubic feet of gas.

CHAPTER 14
POTENTIAL RESERVES

THE PROBLEM OF ESTIMATING

Obviously, there is no way of knowing the amount of undiscovered petroleum. Even the amount in the fields already discovered is quite imperfectly known (Figure 31). Estimates of what remains to be found in a particular area range from quite reliable in an extensively explored area with a long producing history to very unreliable in an undrilled area. Since the former areas cannot be expected to contribute substantially to future discoveries, there is a wide range of reliability in the estimates presented by this study.

In producing provinces where oil and gas fields are still being found, with much room for more, the estimator relies mainly on his knowledge of the geology of the undrilled areas, on his knowledge of the productivity of fields, and on his and the industry's experience in searching for oil and gas in the area. He may or may not be impressed with estimates suggested by projection of statistics on finding and developing petroleum. At any rate, his estimate stems from experience, and quite obviously, it would be coincidental if another estimator reached the same conclusion. Undoubtedly, some of the estimates of potential reserves are probably averages of several estimates.

In large nonproducing areas where few, if any, exploratory wells have been drilled, the geologist can adopt either of two attitudes: (1) that estimates of future productivity based on known geology, on estimates of area, volume, and character of sedimentary rocks, and on productivity of well-explored areas with similar geological characteristics, are meaningful, or (2) that such data are too skimpy to be the basis of any meaningful estimate.

Area, volume, and character of the sedimentary rock, as well as productivity, are considered in any estimate regardless of the extent to which the area in question has been explored. Particularly pertinent when considering largely or practically unexplored areas are the choice of the geologically most similar producing province and the choice of estimates of the productivity of the province chosen. Choice of province is obviously a hazardous geological decision. Productivity of the chosen province is difficult to assess even though masses of data are available. The numbers change as old fields are extended, new fields are discovered, and an increasing percentage of the oil-in-place is recovered. For example, in 1950 Weeks,[48] assuming production practices and economics of the day. estimated that 100 billion barrels of crude oil eventually would be produced from 2 million cubic miles of effective basin strata (50,000 barrels per cubic mile), or 36 billion barrels more than the estimated ultimate recovery of all fields then producing. It now is estimated (reference 31) that the fields producing at the end of 1949 alone will produce almost 97 billion barrels, an increase of over 50 percent in 20 years. Moreover, the productivity of these old fields is still growing (see Figure 31). Thus, estimates of the potential of an area based on current estimates of ultimate recovery of an established, but still growing, producing province can be understated. If the province elected for comparison is in the early stages of development, the resulting estimates can be overstated.

The coordinators elected to present estimates of potential reserves on either an oil-in-place or ultimate recovery basis, or both, for at least parts of each region. Since potential natural gas reserves were not reported by the authors as consistently as potential crude oil reserves, it was decided to follow the procedure in Region 6 (Chapter 8) and quote the estimates of the Potential Gas Committee.[40] (This committee estimates biennially the "Potential Supply of Natural Gas in the United States," and has done so for several years. The committee is well organized, and the personnel includes highly competent geologists, engineers, and other experts from the oil and natural gas industry.) Estimates of potential reserves are shown in tabular form in Tables 22 through 24.

CRUDE OIL

In the Atlantic Coast part of Region 11, the volumetric method was used to obtain estimates. Inasmuch as segments of this area seem to be geologically comparable with different producing provinces, different productivity factors were used for each segment, averaging 45,500 barrels per cubic mile. In the Florida onshore and offshore, where more data are available, the petroleum potential was related to volume of sediments that have had a depositional history conducive to the formation and entrapment of petroleum. Of course, it is recognized that all such estimates are highly speculative, and that they can prove to be embarrassing, at least temporarily. For example, a few years ago, one could have estimated the potential of the West Coast offshore from Point Conception north to Canada to be 6 billion barrels of crude oil on the basis of 60,000 square miles of sedimentary rock, 2 miles thick, and the popular 50,000 barrels per cubic mile. Since then 29 intelligently located dry holes have been drilled.

The problem of estimating the potential of the lower Ordovician and Cambrian in Regions 8, 9 and 10 is similar to that of Region 11. The author of Region 9 elected to make an estimate on a volumetric basis, but the author of Region 8 elected to make no estimates for these deeper formations. The author of Region 6 used the volumetric method and a range of productivity factors. He also included estimates for two poorly known areas on the fringes of the region. Estimates for similar nonproducing, but prospective, areas within regions were made in some regions and avoided in others. The authors of Regions 5 and 7 included estimates for such areas in the totals. No estimates were attempted for parts of Regions 1 through 4. The authors could have used a volumetric method, but elected not to.

Thus, the sum of the regional estimates does *not* represent the estimated potential of the entire United States. Among the areas excluded by the authors are the offshore of Alaska outside the Cook Inlet and Bristol Bay, the onshore and offshore of Washington and Oregon, the offshore of central and northern California, much of the Cretaceous area of Region 3, the Cretaceous of North Dakota and South Dakota, the lower Ordovician and Cambrian of Region 8, the overthrust belts (except the southwestern Wyoming thrust belt), and all of the somewhat prospective areas.

Because a broad range of estimates for Region 1 was presented, except for the Cook Inlet, the writer of the U.S. Summary elected to include in columns 5 and 6 of Table 22, 31.3 billion barrels of oil-in-place and 12.5 billion barrels of recoverable crude oil from the Prudhoe Bay field on the North Slope of Alaska on the basis of sketchy published data. These appear to be reasonable estimates which only by chance will prove to be nearly accurate after the field has been developed and producibility established by producing the wells. Because the geology indicates that other discoveries in Alaska are probable, the writer added "speculative" estimates of 43.5 billion barrels of oil-in-place and 17.4 billion barrels of recoverable crude oil.

Since regional estimates were reported on different bases, it was necessary to convert oil-in-place to recoverable oil, and vice versa in order to provide a picture of the portion of the area covered. This was done on a percentage basis. For example, if the present estimated recovery of region "x" is 25 percent of estimated oil-in-place (column 4, Table 22), future recovery is assumed to be 25 percent of the oil-in-place figures presented. The numbers marked E in Table 22 are those so derived. This calculation introduces errors not believed to be serious. Oil-in-place (column 5) is discoverable (findable) oil, and is additive to known oil-in-place. The authors do not suggest how much *will* be found. Column 6—ultimate recovery—contemplates that all of it will be found.

The estimates in columns 5 and 6 of Table 22 are the sum of the "probable," "possible," and "speculative" categories as defined by the Potential Gas Committee.[10] There is "probable" oil (new oil from horizontal and vertical extensions to existing fields) and "possible" oil (new oil from new discoveries in a producing province) in all the regional estimates, although not consistently identified. There is also "speculative" oil in the strict sense (oil from new discoveries in provinces not now producing or in presently nonproductive strata in producing provinces). Some of the oil termed "speculative" appears to be more exactly categorized as a higher estimate of "possible" oil. Patently, all estimates of petroleum to be found are speculative, so no judgment is passed on the individual regional estimates, or on the methods of calculation used.

The range of estimates of future additions shown in Table 23 is a reasonable interpretation of the data presented. It is assumed that the optimistic and pessimistic average out in the totals. Regarding the large "speculative" estimate, it would be larger if estimates of the excluded areas had been made. The calculated median estimates appear to the writer to be too small.

It is instructive to review these estimates in the light of the historic pattern. The growth in cumulative proved reserves of past discoveries has been stressed by several observers (references 10, 49, and 50) and is shown graphically in Figure 31. Curve A depicts the growth in cumulative proved reserves of crude oil, and curves labeled B depict the growth in cumulative gross additions to reserves for fields discovered before certain dates.[31] For example, the ultimate recovery of fields discovered through 1938 was then estimated to be 38.5 billion barrels of crude oil. By the end of 1968 the ultimate recovery of the same fields was estimated to have grown to 73.2 billion barrels, an increase of 90 percent above the 1938 estimate. Fields simply grow by development, extension, deeper drilling, and improved recovery practices.

Curve E, Figure 31, suggests ultimate recovery (cumulative gross additions to reserves) of 176 billion barrels at the end of the century for fields discovered before 1969 (exclusive of Prudhoe Bay), or 51 billion barrels more than now estimated.[31] Other projections can be made, but an estimate of less than 40 billion seems unreasonable. The additional

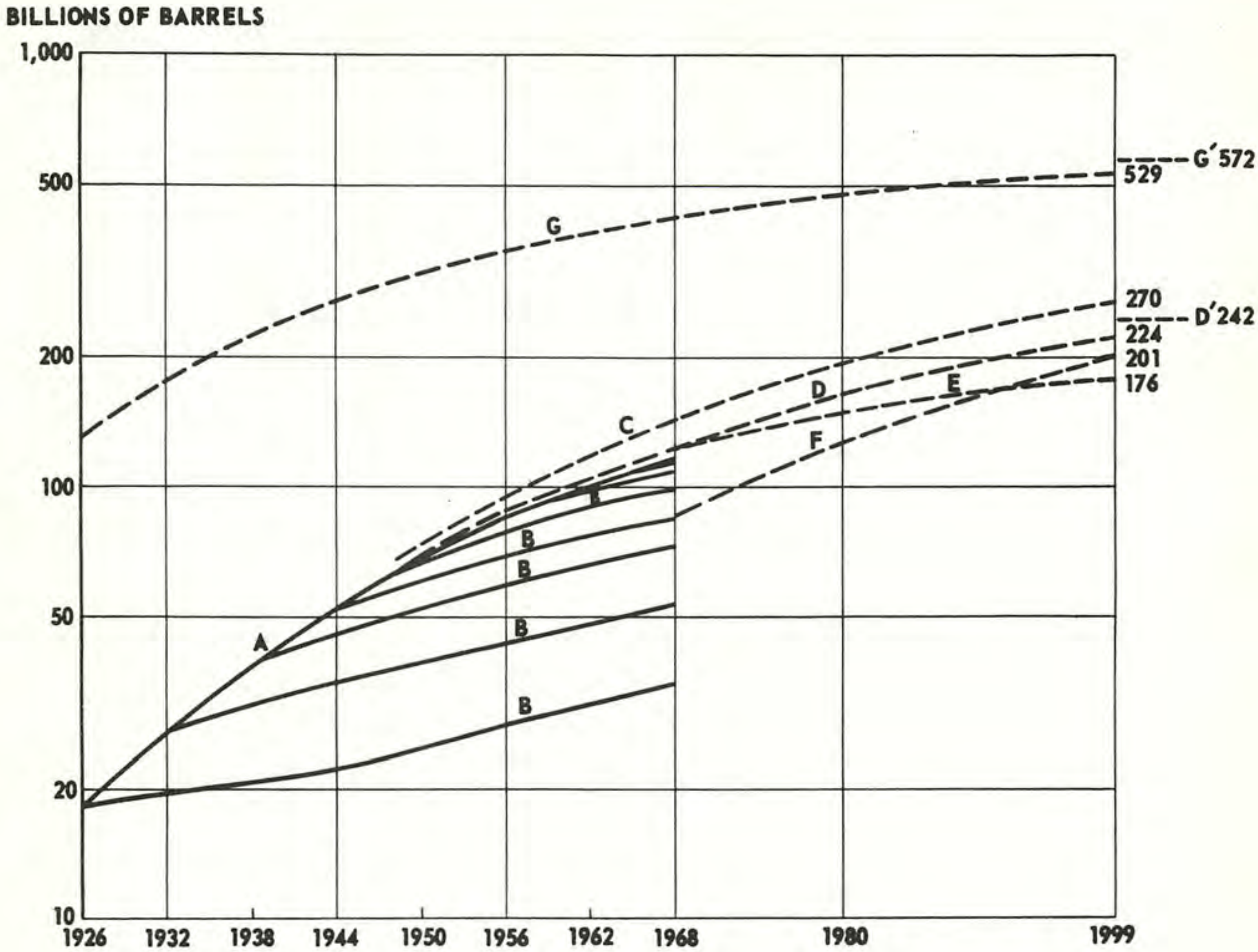

FIGURE 31. Growth in Cumulative Crude Oil Reserves (Semi-Log Scale)

A = Cumulative Gross Additions to Proved Natural Gas Reserves at End of Year (AGA)
B = Present and Periodic Estimates of Ultimate Recovery from Fields Discovered by End 1926, 1932, etc. (API, NPC, PAW)
C = Cumulative Gross Additions of Proved Reserves of Natural Gas Liquids Added to A (AGA and API—Projection Beyond 1968 by Moore [Appendix F])
D = A Adjusted for 7.0 Billion Barrels Indicated Additional Reserves—Projected Beyond 1968 by Moore (Appendix F)
D′ = Upward Adjustment of D for Reserves—Production Ratio of 10:1
E = Projection of Ultimate Recovery of Pre-1969 Fields
F = Projection of Cumulative Production of Crude Oil by Moore (Appendix F)
G = Oil-In-Place and Projections by Moore (Appendix F)
G′ = Upward Adjustment of G Required by D′

TABLE 22. POTENTIAL RESERVES OF CRUDE OIL

(billion barrels)[1]

		Known [2]				Future [4]		Total [5]	
Region No. [9]	Year	1 Original Oil-In-Place	2 Ultimate Recovery	3 Cumulative Production	4 Percent Recoverable	5 Original Oil-In-Place	6 Ultimate Recovery	7 Original Oil-In-Place	8 Ultimate Recovery
Region 1	1968[3]	2.6	.5	.2	21	*80.0[7] (46.7)[6]	32.0[7] (18.5)[6]	82.6	32.5
Region 2	1968	81.5	19.0	14.6	23	*107.0 (74.0)	24.9E (17.2E)	188.5	43.9
Region 3	1967	5.2	1.5	1.0	28	*49.9 (23.6)	14.1 (7.3)	55.1	15.6
Region 4	1968	23.5	6.5	4.7	28	32.7 (7.0)	9.0E (1.9E)	56.2	15.5
Region 5	1967	102.0	24.2	15.9	24	46.8	11.1E	148.8	35.3
Region 6	1968	86.4	40.1	27.5	46	57.8E (4.1E)	26.8 (1.9)	144.2	66.9
Region 7	1967	56.3	17.3	14.9	31	5.6E	1.7	61.9	19.0
Region 8	1967	1.8	.6	.5	34	1.3	.6	3.1	1.2
Region 9	1969	11.7	4.3	4.0	37	7.5 (6.4)	1.7 (1.3)	19.2	6.0
Region 10	1968	16.9	3.0	2.7	18	.6	.1	17.5	3.1
Region 11	1968			Note[8]		*(47.3E)[6]	(18.9)	47.3	18.9
Total U. S.		387.9	117.0	86.0	30	436.5	140.9	824.4	257.9

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Figures rounded to tenths of billions.

(2) Estimates by American Petroleum Institute.

(3) End of year estimates used in text.

(4) Estimates by authors, except (7).

(5) Known plus future.

(6) Estimates in parentheses are "speculative."

(7) Estimate by writer of U.S. Summary suggested by text.

(8) Cumulative production 15.3 million barrels.

(9) No estimates were made for certain areas. The larger areas include the offshore of Alaska outside the Cook Inlet and Bristol Bay, the onshore and offshore of Washington and Oregon, the offshore of central and northern California, much of the Cretaceous area of Region 3, the Cretaceous of North Dakota and South Dakota, the lower Ordovician and Cambrian of Region 8, the overthrust belts (except the southwestern Wyoming thrust belt), and all of the somewhat prospective areas.

* Estimates more speculative than others.

TABLE 23. INTERPRETATION OF TABLE 22

(billion barrels)

	Known	Future				Total [4]
		Probable Possible	Speculative	Total	Median [1]	
Original Oil-In-place	388	227	209	436	332	720
Ultimate Recovery (known rate)	117	74	67	141	107	224
Ultimate Recovery (42 percent rate)[2]	164	96	88	185	141	305
Ultimate Recovery (60 percent rate) [3]	233	136	125	262	199	432

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political and technological factors in the future.

(1) Total less 50 percent of speculative.

(2) Rate of recovery in 2000 A.D. estimated by Moore (Appendix F).

(3) Final rate of recovery estimated by Moore (Appendix F).

(4) Known plus median future.

oil contributed by old fields is new oil, none of which is contributed by the discovery of new fields. If the pre-1969 fields should contribute 51 billion barrels of new recoverable crude oil by the end of the century, and if cumulative gross additions to reserves should reach 242 billion barrels by then (curve D', Figure 31), 66 billion barrels of new gross additions to reserves from new fields would have to be added. The Prudhoe Bay discovery has already accomplished about 20 percent of the task. The estimated potential (Table 23) appears to be adequate.

The totals (columns 7 and 8, Table 22) suggest that ultimately 824 billion barrels of in-place crude oil will be discovered which would provide 495 billion barrels of recoverable crude oil assuming 60 percent eventual recovery. Lower estimates of 720 and 432 are obtained by using the median oil-in-place estimate of Table 23. The latter estimates turn out to be middle-of-the-road estimates when listed along with five recently published estimates of the Nation's potential resources of crude oil (Table 25).

These published estimates were calculated in different ways by knowledgeable observers. Hubbert,[51] Moore (Appendix F), and Elliott and Linden[52] projected the historic pattern by different statistical methods. Hendricks and Schweinfurth[53] employed the geological-statistical approach of Hendricks.[50] The estimates of Weeks,[54] and Nelson and Burk[9] apparently are based mainly on geologic judgment.

Projection of the historic pattern implies the probable future inclusion of currently nonproducing areas. However, the inclusion of an outstanding discovery such as Prudhoe Bay on the North Slope of Alaska may well, in time, change the pattern. Hubbert raised his U.S. estimate after the Prudhoe Bay discovery. Moore may also raise his estimates when the effect of Alaska upon his historic pattern is known.

The wide range in offshore estimates should be expected because so few data are available. The authors of this report estimate about 60 billion barrels of recoverable crude oil (median estimate, 60 percent recovery) for the shelf and slope exclusive of the Pacific coast north of the Santa Barbara Channel and of Alaska outside the Cook Inlet and Bristol Bay.

A critique of the estimates in Table 25, and a search of the literature for more recent estimates would be a study in itself. The wide range in estimates is inevitable because different methods were used in an attempt to solve an unsolvable problem.

NATURAL GAS

As indicated above, since potential natural gas reserves were not reported by the authors as consistently as potential crude oil reserves, it was decided to follow the procedure in Region 6 (Chapter 8) and quote the estimates of the Potential Gas Committee.[50] Table 24 was constructed after checking with Chairman Richard J. Murdy and his staff.

Estimates by authors of this study are included in the table when an area appears to have been covered in adequate detail. The total of the four estimates is 13 percent smaller than the estimates of the Potential Gas Committee, due in part to the exclusion of associated gas in Region 7. The sample is too small to indicate the relative optimism of the committees.

The pattern of growth of cumulative proved reserves of natural gas is almost identical to that of crude oil (see Figure 32). For example, natural gas (including associated gas) discovered before 1939 grew by approximately 133 trillion cubic feet, or 88 percent by the end of 1968 compared with 90 percent for crude oil (reference 31). Projection of ultimate recovery of all fields discovered before 1969 (curve D, Figure 32) suggests growth to 900 trillion cubic feet in 2000 A.D. or 268 trillion cubic feet more natural gas from these old fields. This happens to be 45 percent of the combined "probable" and "possible" new supply (column 2, Table 24) and is almost identical to the "probable" estimate of 260 trillion cubic feet. If the pre-1969 fields should contribute 268 trillion cubic feet of new recoverable natural gas by the end of the century, and if cumulative gross additions to reserves should reach 1,560 trillion cubic feet by then (curve C, Figure 32), 660 trillion cubic feet of new gross additions to reserves would have to be added. This amount is 70 percent of the combined "possible" and "speculative," which suggests that the estimated gas potential is less ample than the estimated oil potential, partly because the percentage of recoverable oil-in-place is expected to increase materially while the percentage of gas-in-place is not. Obviously, the gas potential would be insufficient if only the median level (Table 24) were achieved.

The estimated total ultimate recovery of 1,543 trillion cubic feet (known plus median estimate of future) is 2.4 times the present estimate of ultimate recovery (reference 31), and, like the oil estimate, is a middle-of-the-road estimate (Table 25). Offshore estimates vary widely because of the paucity of data.

TABLE 24. POTENTIAL RESERVES OF NATURAL GAS

(trillion cubic feet)

Region	Known (1) Ultimate Recovery	Future (2) Probable and Possible	Future (2) Speculative	Future (2) Total	Total (3)
Region 1	4	40	387	427	431
Region 2	31	21	33	54	85
Region 3	20	22	14	36	56
Region 4	14	27	14	(32)(4)	55
Region 5	74	61	17	(79)(4)	152
Region 6	322	304	96	400	722
Region 7	131	67	14	(45)(5)	212
Regions 8 and 9	4	8	3	11	15
Region 10	32	45	8	53	85
Region 11			46	(57)(6)	46
Total U. S.	632	595	632	1,227	1,859
Total U.S. (Median Estimate)	632	595	316	911	1,543

NOTES: 1. Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

2. Figures in parentheses are estimates by authors of this study.

(1) End 1968 estimates by American Gas Association.[31]

(2) End 1968 estimates of ultimate recovery by Potential Gas Committee.[40] Published figures recast to conform approximately with regional areas.

(3) Known plus future.

(4) Eighty percent recovery of gas-in-place.

(5) Nonassociated (dry) gas only.

(6) Excludes continental slope.

SUMMARY

All of the numbers calculated are merely estimates, but they are informed estimates arrived at after careful study of the geology and other exploratory factors. Neither discussion nor opinion is ventured on the individual regional estimates. It is believed that the totals are reasonable. They are additional evidence of the high petroleum potential of the United States.

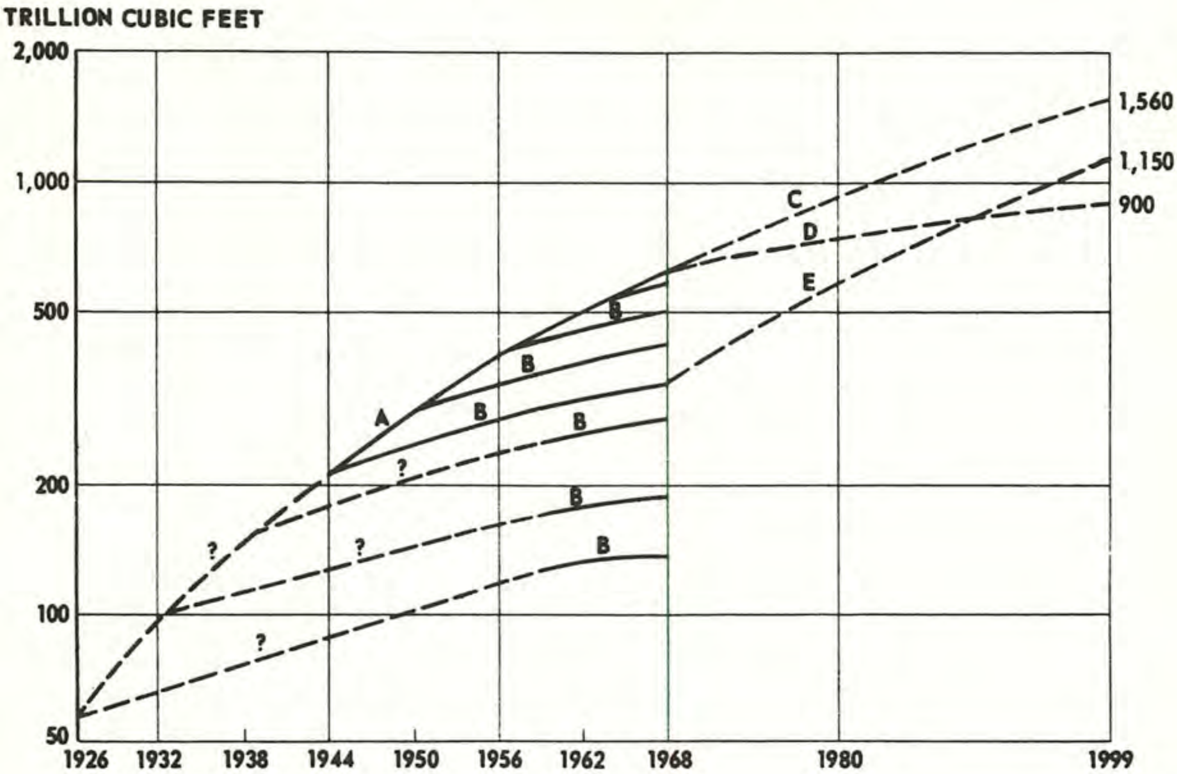

FIGURE 32. Growth in Natural Gas Reserves (Semi-Log Scale)
A = Cumulative Gross Additions to Proved Natural Gas Reserves at End of Year (AGA)
B = Present and Periodic Estimates of Ultimate Recovery from Fields Discovered by End of 1926, 1932, etc. (AGA, NPC, PAW)
C = Projection of A Using Median Demand Projection and Reserves Production Ratio of 12:1 (Elliot and Linden.)
D = Projection of Ultimate Recovery from Pre-1969 Fields
E = Projection of Cumulative Production

TABLE 25. ESTIMATES OF U. S. PETROLEUM POTENTIAL

(billion barrels—trillion cubic feet)

Area	Crude Oil	Natural Gas Liquids	Total Liquids	Natural Gas	Source
Conterminous U. S. Including					
Continental Shelf	165	36	201	1,050	Ref.
Alaska	25	5	30	150	51
Total U. S.	190	41	231	1,200	
Conterminous U. S. Including					
Continental Shelf	397			1,305	Present
Alaska	35			238	Study
Total U. S.	432[1]	49	481	1,543	
United States	353[2]	83	436	1,547	Appendix F
Land and water	433	27	460	1,000	Ref. 54
United States	450			1,740	Ref. 52
Includes Alaska and					Ref.
Continental Shelf	500[3]	75	575	2,500	53
Continental Shelf					
Conterminous U. S.	50			341	Ref.
Alaska	24			137	60
Total U. S.	74			478	
Continental Shelf					
Conterminous U. S.			14	82	
			to 29	to 142	
Alaska			2	6	Ref.
			to 6	to 26	9
Total U. S.			16	88	
			to 35	to 168	
Continental Shelf and Slope			100+	300+	Ref.
Including Alaska			to 200+	to 1,000+	61

NOTE: Future potential reserves are estimates of **discoverable** hydrocarbons. The volumes that **will** be discovered and developed depend upon the interplay of economic, political, and technological factors in the future.

(1) Sixty percent recovery of 720 billion barrels of oil-in-place (median estimate) of Table 23.

(2) Sixty percent recovery of 587 billion barrels of oil-in-place.

(3) Forty percent recovery of 1,250 billion barrels of oil-in-place.

CHAPTER 15
EXPLORATORY DRILLING

Estimates in 1969 by the API and AGA [31] indicate that almost 36 percent of the crude oil and natural gas found to date is in stratigraphic traps. Drilling to less than 5,000 feet, based on little or no specific geological information, found most of the stratigraphically entrapped petroleum. Waiting for the intrepid wildcatter to make the almost certain discovery of such fields was good planning in the past, but it appears certain that the task ahead necessitates finding them by design. There is less "room" at shallow depths than in the past, but explorationists now have more information and understanding. Nevertheless, considerable and sustained drilling remains the key to discovery of the resource.

The relatively simple exploratory process of locating drillable prospects by reflection seismograph surveys will continue to be effective *offshore* for some time to come. However, this popular exploratory procedure—simple structure hunting—is destined to be of secondary effectiveness *onshore* (except in Alaska) because a significant percentage of the visualized undiscovered crude oil and natural gas is in stratigraphic traps, combination stratigraphic and structural traps, reefs and complex structural situations. Petroleum found in such traps can be termed "hard to find petroleum"—meaning more exploratory wells are required to find it. The future of sizable discovery in the following onshore areas particularly depends on defining such traps:

1. Most of the area east of the Mississippi River and west of the Appalachian Mountains in Paleozoic strata above the Cambro-Ordovician, including the eroded top of the Cambro-Ordovician.
2. Arkoma basin of eastern Oklahoma and western Arkansas.
3. Hugoton embayment of western Kansas.
4. Shelf of Anadarko basin of western Oklahoma and Texas.
5. Pennsylvanian and Permian rocks of West Texas and New Mexico.
6. Pennsylvanian rocks in North and Central Texas.
7. All Rocky Mountain basins.
8. San Joaquin and Sacramento Valleys of California.

In addition, important stratigraphically controlled fields continue to be found in the intensively explored Gulf Coast onshore, and it cannot be presumed that the last one has been found.

Moreover, in the Gulf Coast, onshore and offshore, finding and outlining a field on a piercement salt dome is frequently far less simple than finding the dome itself, because of structural and stratigraphic complexities. Many exploratory and development dry holes commonly are required.

Pinpointing any of such traps requires careful and imaginative integration of all geological and geophysical data at hand, and—most important—a liberal exploratory drilling program. Geologists do not doubt that this procedure will be rewarding. The additional drilling required to find stratigraphically controlled fields is but a part of the expanded drilling needed. Many other exploratory wells are required in the unexplored areas, including deeper waters, to provide geologic and production data to point the way to further exploration.

CHAPTER 16
THE FUTURE OF DISCOVERY

THE PROBLEM

The problem of finding and developing the recognized petroleum resource potential fast enough to supply the rising demand is formidable. According to a projection of the historic pattern (see Appendix F), which is a projection of industry's performance in finding and developing new supplies, cumulative gross additions to crude oil reserves would reach about 167 billion barrels by the end of 1980. This is 4 billion barrels short of the Department of Interior's estimate of the requirements for oil by 1980 given the maintenace of a reserves-production ratio of 10:1 (reference 55). Gross additions to natural gas reserves would reach 860 trillion cubic feet in 1980, or 90 trillion cubic feet short of the Department's indicated 1980 requirements for gas given the maintenance of a 15:1 ratio.

By 2000 A.D., the remaining crude oil proved reserves are projected to only 22 billion barrels, or 18 billion barrels short, if a reserves-production ratio of 10:1 is to be maintained (see curves D and D′, Figure 31). An estimate of 1,120 trillion cubic feet of cumulative gross additions to natural gas reserves at the end of the century is short according to almost any published projection of demand. A median domestic demand in 1999 of 34.3 trillion cubic feet (reference 52) would require cumulative gross additions of 1,560 trillion cubic feet if the reserves-production ratio declined only to 12:1 (see curve C, Figure 32) or 440 trillion more than Moore's projection.

This subject could be belabored at length. Apparently, it is easier to forecast a bigger problem than a smaller one. For example, estimates by the Bureau of Mines of domestic consumption of liquid petroleum in 2000 A.D. would require about 60 billion barrels more gross additions to crude oil reserves than projected by Moore (Appendix F), assuming 20 percent imports and a reserves-production ratio of 10:1 (see reference 56). In all, it seems certain that new supplies of both crude oil and natural gas will have to be developed faster than in recent years. The problems of developing production rapidly mount in hostile environments. For example, at the end of 1968, after 20 years of generally accelerating exploration and development in the offshore of Louisiana and Texas, ultimately recoverable reserves of crude oil and natural gas were estimated to be only 4.3 billion barrels and 46.2 trillion cubic feet (reference 31), and annual production only 0.35 billion barrels and 2.5 trillion cubic feet.

ECONOMIC FACTORS

The extent to which the discoverable petroleum will be found and recovered depends on the impact of ever-changing economic and political events upon the rising tide of technological competence and knowledge. Because there have been changes in the business aspects of finding crude oil and natural gas in recent years with which the future has to contend, a brief account of the evolution of these changes is given. It is important to note that the following discussion is intended only to point out the changes that have taken place in the business of finding and developing sources of petroleum which will influence the future of oil finding. No attempt is made to project trends into the future.

Many of the points made in this brief discussion were treated in greater detail in another report of the National Petroleum Council made in 1967, entitled "Factors Affecting U.S. Exploration, Development and Production [of petroleum] 1946-1965."

The more significant statistics are charted in Figures 33 * and 34. These, of course, reflect the interplay of economic, political, technological, and psychological forces through the years.

PRE-1958

Looking at Figure 33, note that before 1958, industry's expenditures for finding and developing activities (curve B) were closely in tune with gross production revenue (curve A). The peaks and valleys indicate an almost instantaneous adjustment of expenditures to revenue. In the 20 years 1937 to 1957, exploration and development expenditures averaged 50 percent of revenue. The majors† rather consistently spent 52 percent of the money (curve C) and the independents† spent 48 percent (curve D). The drilling pattern (curve H)‡ was, of course, essentially the same as the expenditure pattern.

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* The statistics on finding and developing expenditures (curves B, C, and D) are contained in two reports issued annually by the Chase Manhattan Bank.[57,58] Revenue (curve A) is reported annually as value of production by the U.S. Bureau of Mines.[59]

† The term "majors" refers to the group of large integrated companies reported upon annually by the Chase Manhattan Bank, and the term "independents" refers to all other producers.

‡ Curve H—dry holes drilled, whether exploratory or development, is used to indicate effort, because the record is more complete and because such indicators as total footage, new field wildcat wells, and dry new field wildcat wells follow the same pattern.

However, the tremendous increase in expenditures and effort following World War II, and peaking in 1957, did not produce a commensurate increase in gross additions to proved reserves,* particularly in the 5-year period 1952 to 1957. In this period the rate of crude oil gross additions (curve G) actually declined, and natural gas gross additions (curve F) were insufficient to produce a very material increase in equivalent crude oil (total hydrocarbons) additions (curve E).

Obviously, cash outlay per barrel of gross additions to reserves had to increase substantially. The relationships can be seen more clearly in Figure 34, which recasts in 5-year averages on a per barrel basis, some of the Figure 33 data and footage drilled. Between 1938 and 1958, expenditures per barrel of equivalent crude oil produced (curve B) climbed faster than revenue per barrel (curve A), and expenditures per barrel of gross additions to reserves (curve C) climbed still faster. The expenditure of $1.10 per barrel found in 1953 to 1957 (curve C) would have been $0.78 if finding results (barrels added) had kept pace with production. Interestingly, overall costs shown in curve F, which allocates all expenditures to footage drilled, rose only slightly faster than revenue per barrel (curve A). Obviously, in these 20 years the really adverse factor was the failure to discover and develop enough crude oil and natural gas.

POST-1957

Even casual study of Figures 33 and 34 reveals the great differences between the 1958 to 1968 pattern and the pre-1958 pattern. Gross revenue (curve A, Figure 33) increased after 1958, but at a lesser rate. With about constant finding and developing expenditures, except in 1968 (curve B, Figure 33), the percentage of revenue devoted to the effort declined and averaged only 40 percent. During this period, expenditures by the major companies (curve C, Figure 33) rose about in line with industry revenue, and counteracted the drastic decline in expenditures by the independents (curve D, Figure 33). In spite of the decline in drilling (curve H, Figure 33), the decline in gross additions to crude oil reserves was arrested (curve G) and gross additions to total hydrocarbon reserves (curve E, Figure 33) increased slightly because of an increase in gross additions to natural gas reserves. Expenditures per bar-

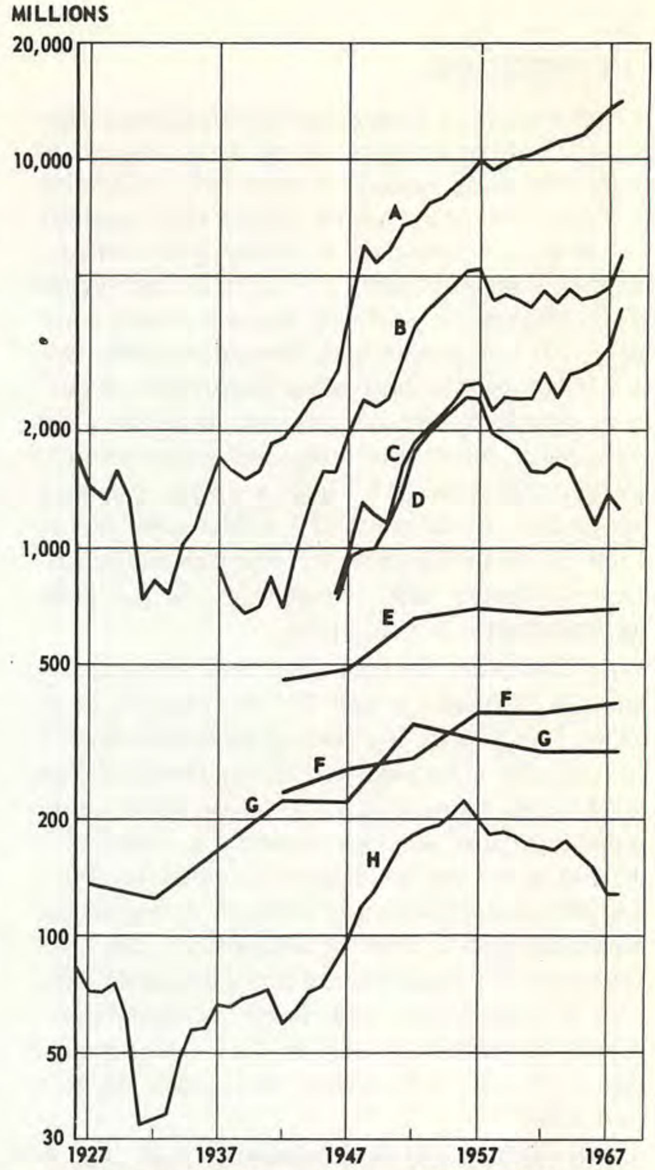

FIGURE 33. Basic Industry Statistics 1926 to 1967 Inclusive (Semi-Log Scale). (Curves A, B, C, D, H = Annual U.S. Statistics at End of Year; Curves E, F, G = 5-Year Averages Plotted at End of Each 5th Year Except 1963 to 1968 Inclusive.)

A = Dollar Value of Crude Oil and Natural Gas at Well Plus Value Natural Gas Liquids at Plant (Bureau of Mines)

B = Production and Plant Capital Expenditures Plus Geological and Geophysical Expenses and Lease Rentals (Chase Manhattan Bank)

C = Same as B for the 30-Odd Major Companies, but Capital Expenditures for Plants Excluded

D = Same as C for the Rest of the Industry

E = 5-Year Averages Except 1963 to 1968 Inclusive of Gross Additions to Reserves of Crude Oil, Natural Gas and Natural Gas Liquids as Estimated by API and AGA Converted to Crude Oil on BTU Basis—Figures Plotted are One-Tenth of Estimates (One gets approximately the same picture by using 3-year running averages.)

F = Same as E but Natural Gas and Natural Gas Liquids Only

G = Same as E but Crude Oil Only Adjusted for 7.0 Billion Barrels Indicated Additional Reserves (API [31]; Moore, Appendix F)

H = Dry Holes Drilled—World Oil. (Figures plotted are 10 times actual.)

* Gross additions to proved reserves (5-year averages except 1963 to 1968) are used rather than the system of dating back reserves to the year of discovery because the latter system is less widely understood and has less influence on the level of current expenditures.

rel of gross additions declined (curves C, D, Figure 34), but only slightly.

Scaling down expenditures after a period of exuberance that did not produce hoped-for results is normal business procedure. The lesser tempo was not caused by increased emphasis on foreign exploration and development, because the ratio of domestic to foreign expenditures remained very constant, domestic expenditures being a little more than twice foreign. However, since 1962 other branches of the domestic business have been consuming a greater share of total domestic capital and exploration expenditures (see references 57 and 58). In 1962 finding and developing expenditures were almost 73 percent of the total, but they were only 56 percent in 1967 and 62 percent in 1968, even with rising expenditures.

More to the point, and with implications for the future of oil finding, is the change in exploratory emphasis that evolved. Naturally, operators sought the presumably less risky areas, and most of the majors and a few independents chose to concentrate on the offshore at the expense of the onshore of the conterminous U.S. This choice reduced the help that independents have received from majors through the years, contributing to further decline in their activities (curve D, Figure 33). This reduced activity by independents is unfortunate, because it is clear that in spite of growing understanding and know-how, the business of finding petroleum is still an imaginative one which requires a multiplicity of ideas acted on by a multiplicity of operators to achieve maximum results.

Moreover, general acceptance of the offshore (and now Alaska) results in expenditure of very substantial sums for Federal and State leases under the system of competitive bidding. The upswing in finding and developing expenditures in 1967 and 1968 (curve B, Figure 33) is due entirely to such expenditures. Bonuses paid for State and Federal leases since 1958 were about $2.5 billion more than normal expenditures for leases.[57,58] When subtracted from total expenditures (curve B, Figure 33), the trend for expenditures that do the work (geology, geophysics, drilling, and completing wells, etc.) has remained practically flat since 1958.

CONCLUDING REMARK

From the foregoing discussion it appears obvious to an explorationist that, if the "flat" trend in exploration expenditures, the declining trend in drilling, and the trend away from the onshore (except for Alaska) persist for long, a high percentage of the tremendous potential visualized by this report will rest uselessly in the ground.

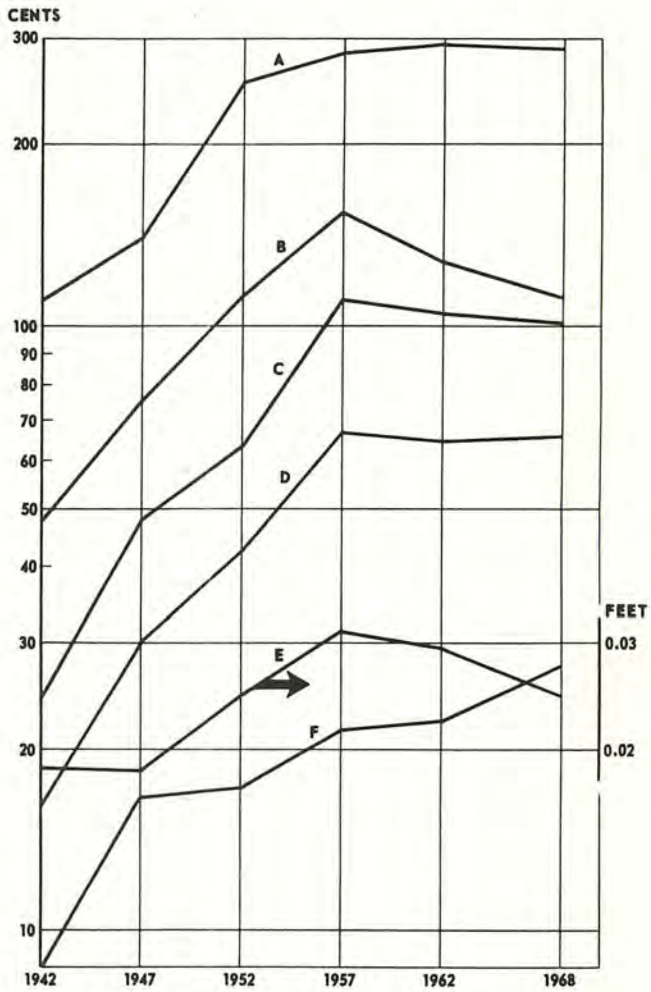

FIGURE 34. Per Barrel Data Using Same Figures as Figure 33 (Semi-Log Scale)

- A = Average Price per Barrel Crude During 5-Year Periods Except 1963 to 1968 Inclusive Plotted at End of Each Period
- B = Finding and Developing Expenditures per Barrel of Equivalent Crude Produced (Price Basis or Conversion of Gas and NGL to Crude on Basis of Current Prices)
- C = Finding and Development Expenditure per Barrel of Gross Additions to Reserves (Price Basis)
- D = Finding and Development Expenditures per Barrel of Gross Additions to Reserves (BTU Basis)
- E = Footage per Barrel of Gross Additions to Reserves (BTU Basis)
- F = Cost per Foot Drilled Allocating All Expenditures to Footage (Dollar costs are plotted as cents or $20 = 20¢, etc.)

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APPENDIXES

APPENDIX A

UNITED STATES
DEPARTMENT OF THE INTERIOR
OFFICE OF THE SECRETARY
WASHINGTON, D.C. 20240

C
O
P
Y

May 29, 1967

Dear Mr. Donnell:

It is the responsibility of the Federal Government to make long-range policy decisions in regard to future energy supplies. Such decisions must be based in part upon the size and distribution of those places in the earth which are favorable to the accumulation of petroleum and natural gas resources. Coal and related fuels may be mapped and measured at the earth's surface with considerable accuracy, however, measurement of petroleum and natural gas resources is less precise.

The American Association of Petroleum Geologists in 1951 published a review entitled, "Future Petroleum Provinces of North America," which was utilized by the National Petroleum Council in its 1952 report on "Productive Capacity." Since that time, new petroleum provinces have been discovered and significant additional data have been acquired. It is therefore essential that the habitat of our potential petroleum resources be reassessed. The requested study, used in conjunction with recent studies by the Council on advances in technology and on exploration, would provide a very important basis for future policy decisions in the energy field. The review is requisite to an intelligent evaluation of the Nation's petroleum and natural gas resource potential.

It is requested that the National Petroleum Council prepare a report on the future petroleum provinces of the United States.

Sincerely yours,

/s / J. Cordell Moore

Assistant Secretary of the Interior

Mr. J. C. Donnell II
Chairman
National Petroleum Council
1625 K Street, N. W.
Washington, D.C. 20006

APPENDIX B

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Kerr-McGee Corporation

Special Assistant to Chairman
K. H. Crandall, President
American Association of Petroleum Geologists (1969-70)

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Division of the Pittston Company

REGION 11—EASTERN GULF AND ATLANTIC COASTS

REGIONAL COORDINATOR

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Mobil Oil Corporation

E. H. Rainwater
Tenneco Oil Company

O. B. Shelburne
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Joseph Spivak
Mobil Oil Corporation

APPENDIX E

OUTLINE

I. Introduction

In addition to a statement of the purpose of the study important literature bearing on the area might be listed.

II. General Geologic Framework of Area (particularly as relating to hydrocarbons).

1. Stratigraphy
   a. Regional
   b. Reservoir rocks
   c. Source beds
2. Structure
   a. Regional structure with particular reference to geologic framework of area
   b. Possibilities of local structure (where known)

III. Present Production Horizons (if any)

1. Reservoir beds (types)
2. Traps (types)
3. Quality of production and volume if available
   a. Examination of factors relating either to high productivity or poor performance of existing fields

(These first three divisions should be handled as briefly as consistent with their importance.)

IV. Having dealt with the known and explored areas and horizons, those areas and horizons which are unknown and unexplored are now studied in detail.

1. Nature of potential future production
   a. Same as known (projections)
   b. Deeper horizons
   c. Radically different geologic conditions
   d. Possible types of traps in unexplored sediments

V. Apparent or expected obstacles to finding new production.

1. Economic
2. Technological
3. Special or local deterrents, e.g., wildlife areas, missile ranges, etc.

VI. Quantitative aspects of present studies (only where feasible or deemed possible by contributors).

1. Thickness of sediments
   a. Percentage of reservoir rocks
   b. Percentage of favorable facies in source rocks
2. Volume of sediments
   a. Explored and/or productive
   b. Unexplored
3. Calculation of volumes of hydrocarbons in place or estimates of ranges of such volumes in place where feasible

APPENDIX F

ANALYSIS AND PROJECTION OF HISTORIC PATTERNS OF U.S. CRUDE OIL AND NATURAL GAS

Charles L. Moore

HISTORIC PATTERN OF U.S. CRUDE OIL DISCOVERY AND RECOVERY (FIGURE F-1)

Gompertz Curve on Cumulative Discoveries of Crude Oil Originally in Place

The calculated initial quantity as of January 1, 1920 is 89 billion barrels. The projected quantity as of January 1, 1970 is 431 billion barrels. The aggregate quantity for the 50-year period 1920 to 1970 is 342 billion barrels, or an average annual quantity of 6.84 billion barrels. The projected quantity as of January 1, 2000 is 529 billion barrels. The aggregate quantity for the 30-year period 1970 to 2000 is 98 billion barrels, or an average annual quantity of 3.27 billion barrels. The projected ultimate discovery of crude oil originally in place is 587 billion barrels. The projected remaining undiscovered crude oil originally in place as of January 1, 2000 is 58 billion barrels, or 9.7 percent of the ultimate.

The equation of this Gompertz curve as fitted to the given data is:

$$\log Y = 2.768723 - .964445^{t} \times .791411$$

where:

Y = cumulative quantities of crude oil discovered as of time t;

t = time in years from January 1, 1921.

In the linear regression of the logarithmic increments of Y on the logarithms of Y, the ratio of the correlation coefficient to the critical correlation coefficient, based on a 5 percent level of significance, is 2.394.

Gompertz Curve on Cumulative Gross Additions to Crude Oil Reserves

The projected quantity as of January 1, 1970 is 129 billion barrels. The anticipated percent recovery of crude oil originally in place as of that date is 129/431 or 30 percent. The projected quantity as of January 1, 2000 is 224 billion barrels. The anticipated percent recovery is 224/529 or 42 percent. The aggregate gross additions to crude oil reserves for the 30-year period is 95 billion barrels or an average annual quantity of 3.17 billion barrels. The projected ultimate quantity of gross additions to reserves is 353 billion barrels. The projected ultimate percent recovery of crude oil originally in place is 353/587 or 60 percent. The remaining gross additions to reserves as of January 1, 2000 is 129 billion barrels or 36.6 percent of the ultimate.

The equation of this Gompertz curve as fitted to the given data is:

$$\log Y = 2.547557 - .974019^{t} \times 1.156445$$

where:

Y = cumulative quantities of gross additions to reserves as of time t;

t = time in years from January 1, 1933.

In the linear regression of the logarithmic increments of Y on the logarithms of Y, the ratio of the correlation coefficient to the critical correlation coefficient, based on a 5 percent level of significance, is 2.559.

Gompertz Curve on Cumulative Crude Oil Production

The projected quantity as of January 1, 1970 is 90 billion barrels. The projected quantity as of January 1, 2000 is 201 billion barrels. The projected aggregate crude oil production for the 30-year period 1970 to 2000 is 111 billion barrels, or an average annual production of 3.70 billion barrels. The aggregate production during this 30-year period exceeds the aggregate gross additions to reserves by 16 billion barrels. This will lower the crude oil reserves from a projected value of 39 billion barrels as of January 1, 1970 to 22 billion barrels as of January 1, 2000. For this analysis crude oil reserves = API Proved Reserves + API Indicated Additional Reserves. The projected reserve/production ratio as of January 1, 1970 is 12.4, and for January 1, 2000 it is 5.5.

The equation of this Gompertz curve as fitted to the given data is:

$$\log Y = 2.792955 - .982182^{t} \times 1.518890$$

where:

Y = cumulative crude oil production as of time t;

t = time in years from January 1, 1937.

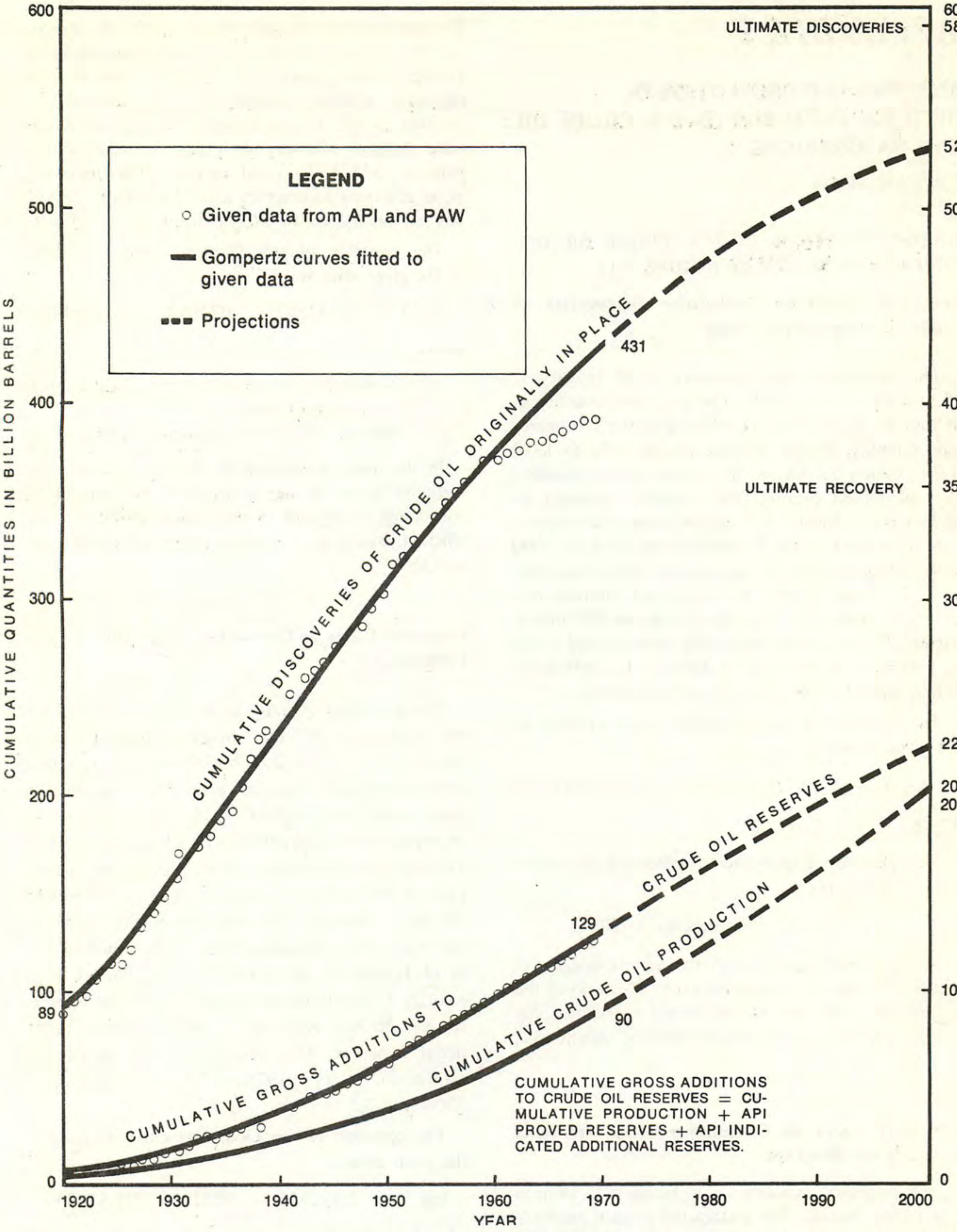

FIGURE F-1. Analysis and Projection of Historic Patterns of U.S. Crude Oil Discovery and Recovery (Note that recent discoveries are underestimated because of lack of data.)

HISTORIC PATTERN OF DISCOVERY AND RECOVERY OF U.S. NET NATURAL GAS (FIGURE F-2)

Gompertz Curve on Cumulative Discoveries

The calculated initial quantity as of January 1, 1920 is 89 trillion cubic feet. The projected quantity as of January 1, 1970 is 704 trillion cubic feet. The aggregate quantity discovered during the 50-year period 1920 to 1970 is 615 trillion cubic feet, or an average annual quantity of 12.3 trillion cubic feet. The projected cumulative discoveries as of January 1, 2000 is 1,089 trillion cubic feet. The aggregate natural gas discoveries during the 30-year period 1970 to 2000 is 385 trillion cubic feet, or an average annual quantity of 12.8 trillion cubic feet. The projected ultimate discovery of net natural gas in the United States is 1547 trillion cubic feet. The remaining undiscovered net natural gas as of January 1, 2000 is 458 trillion cubic feet, or 29.6 percent of the ultimate.

The equation of this Gompertz curve as fitted to the given data is:

$$\log Y = 3.205576 - .975204^{t} \times .977093$$

where:

Y = cumulative quantities of natural gas discovered as of time t;

t = time in years from January 1, 1930.

In the linear regression of the logarithmic increments of Y on the logarithms of Y, the ratio of the correlation coefficient to the critical correlation coefficient, based on a 5 percent level of significance, is 1.441.

Gompertz Curve on Cumulative Gross Additions to Reserves

The projected cumulative gross additions to net natural gas reserves as of January 1, 1970 is 670 trillion cubic feet. The projected quantity as of January 1, 2000 is 1122 trillion cubic feet. The projected aggregate gross additions to net natural gas reserves for the 30-year period 1970 to 2000 is 452 trillion cubic feet, or an average annual gross addition to reserves of 15.1 trillion cubic feet. During this period the gross additions to reserves will exceed discoveries by 67 trillion cubic feet. Because of the nature of the given data, it is assumed that the projected ultimate gross additions to net natural gas reserves will be identical with the ultimate discoveries, or 1547 trillion cubic feet. Actually this 1547 trillion cubic feet is the median between the projected ultimate discoveries of 1605 trillion cubic feet and the projected ultimate additions to reserves of 1489 trillion cubic feet. It is therefore properly expressed as 1547 trillion cubic feet plus or minus 58 trillion cubic feet or 3.75 percent. The projected remaining gross additions to reserves as of January 1, 2000 is 425 trillion cubic feet, or 27.5 percent of the ultimate.

The equation of this Gompertz curve as fitted to the given data is:

$$\log Y = 3.172806 - .965941^{t} \times .915017$$

where:

Y = cumulative gross additions to net natural gas reserves at time t;

t = time in years from January 1, 1942.

Gompertz Curve on Cumulative Production

As of January 1, 1970 the projected cumulative net natural gas production in the U.S. is 385 trillion cubic feet. As of January 1, 2000 the projected cumulative net natural gas production is 1447 trillion cubic feet. For the 30-year period 1970 to 2000, the aggregate net natural gas production will be 1062 trillion cubic feet, based on this Gompertz curve projection. This projected rate of natural gas production is far above the projected discoveries and additions to reserves as shown on Figure F-2. A substantial increase in the economic incentives to explore and discover natural gas plus the successful application on a large scale of nuclear stimulation for gas recovery from tight deposits may accelerate natural gas discovery above the Gompertz curve shown on Figure F-2. However, it appears that imported and synthetic gas must be available to meet demand for the future.

HISTORIC PATTERN OF CUMULATIVE GROSS ADDITIONS TO U.S. RESERVES OF NATURAL GAS LIQUIDS AND OF THE RATIOS OF ADDITIONS ANNUALLY TO RESERVES OF NATURAL GAS LIQUIDS VS. ANNUAL ADDITION TO RESERVES OF NATURAL GAS (FIGURE F-3)

Gompertz Curve on Cumulative Gross Additions to U.S. Reserves of Natural Gas Liquids

As of January 1, 1970 the projected cumulative quantity of gross additions to natural gas liquids reserves is 21 billion barrels. The corresponding projected quantity as of January 1, 2000 is 46

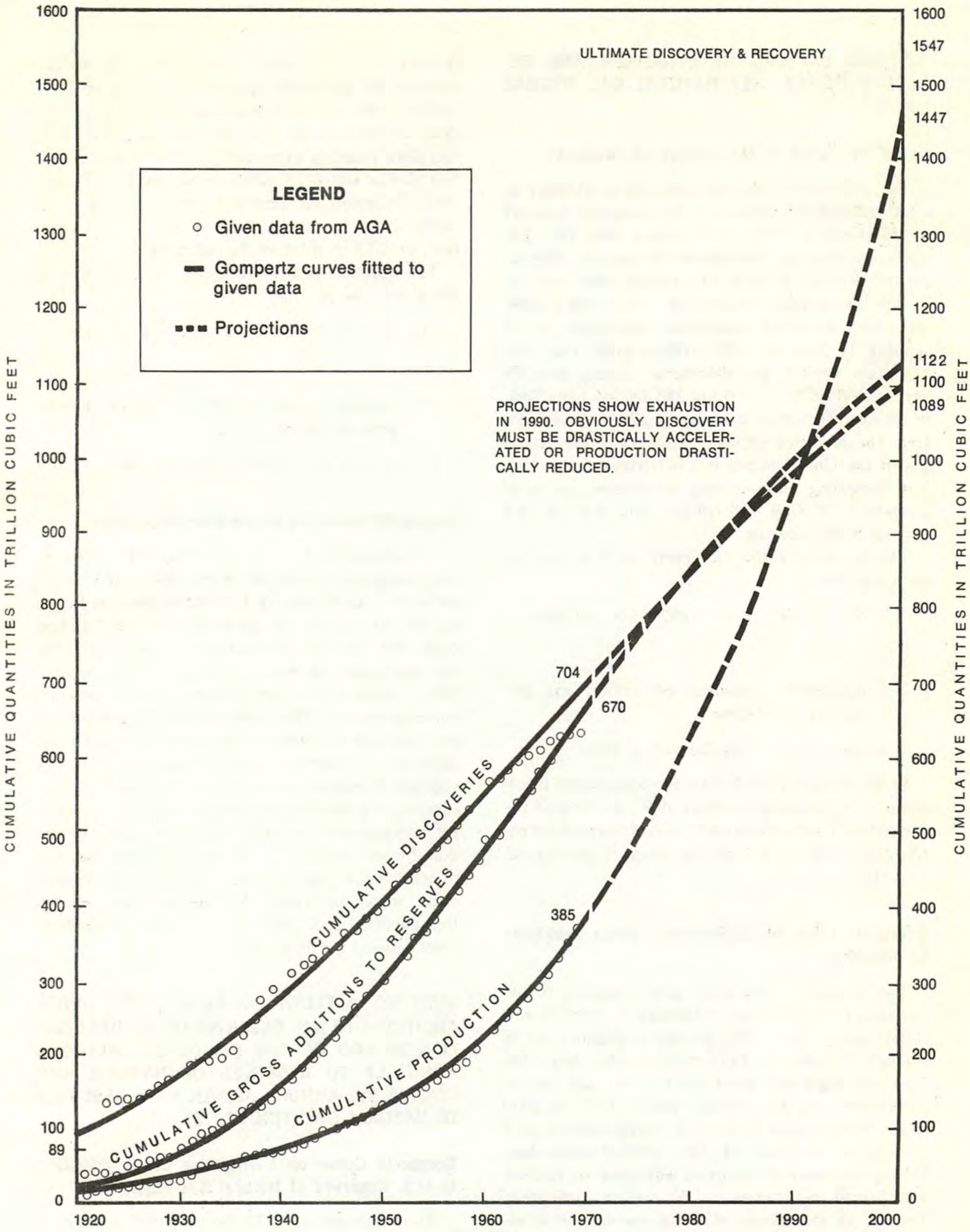

FIGURE F-2. Analysis and Projection of Historic Patterns of Discovery and Recovery of U.S. Net Natural Gas (Note that recent discoveries are underestimated because of lack of data.)

billion barrels. The aggregate gross additions to natural gas liquids reserves for the 30-year period 1970 to 2000 is 25 billion barrels, or an average annual quantity of 0.83 billion barrels. The projected ultimate gross additions to natural gas liquids reserves is 83 billion barrels. The remaining gross additions to natural gas liquids reserves as of January 1, 2000 is 37 billion barrels, or 44.6 percent of the ultimate.

The equation of this Gompertz curve is:

$$\log Y = 1.919959 - .971866^{t} \times 1.135556$$

where:

Y = cumulative quantities of gross additions to natural gas liquids reserves;

t = times in years from January 1, 1948.

In the linear regression of the logarithmic increments of Y on the logarithms of Y, the ratio of the correlation coefficient to the critical correlation coefficient, based on a 5 percent level of significance, is 1.425.

Curve showing the ratios of annual additions to reserves of natural gas liquids to the annual additions to reserves of natural gas is in barrels of natural gas liquids per million cubic feet of natural gas.

The annual additions to reserves of natural gas liquids were derived from the Gompertz curve shown on Figure F-3. The annual additions to natural gas reserves were derived from the corresponding Gompertz curve shown on Figure F-2. The curve is the successive annual ratios of these two annual gross additions to reserves, expressed as barrels of natural gas liquids per million cubic feet of natural gas. The given data are quite erratic, but they nevertheless provided an adequate basis for establishing a significant trend. As of January 1, 1970 the projected quantity is 45 barrels of natural gas liquids per million cubic feet of natural gas. The corresponding quantity projected as of January 1, 2000 is 71 barrels per million cubic feet. There has been a rapid increase in recent years of the extraction of ethane as a component of natural gas liquids. If this trend continues and eventually includes some methane in natural gas liquids, it may be that this trend projected to 2000 is significant.

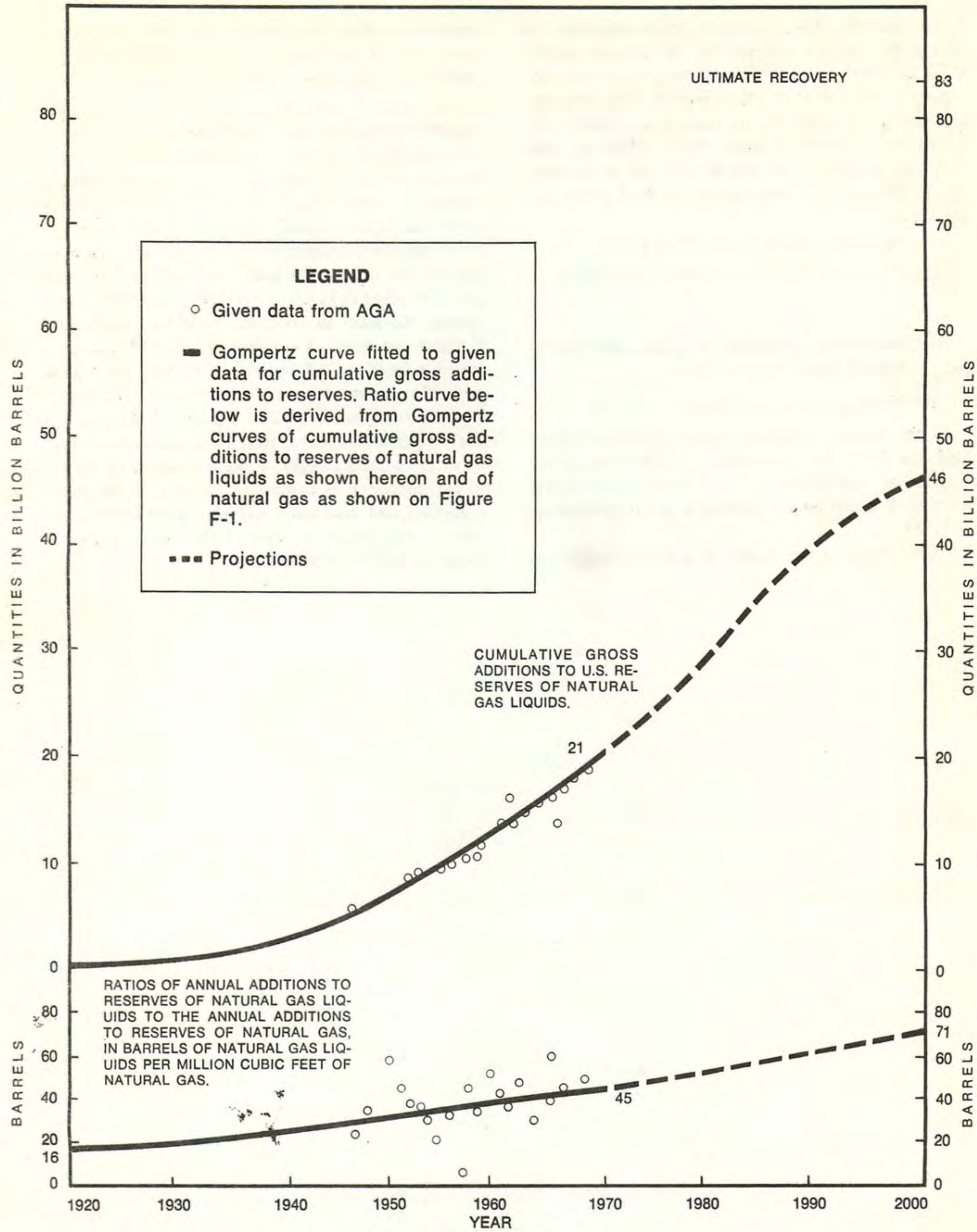

FIGURE F-3. Analysis and Projection of Historic Patterns of Cumulative Gross Additions to U.S. Reserves of Natural Gas Liquids and of the Ratios of Additions Annually to Reserves of Natural Gas Liquids vs Annual Additions to Reserves of Natural Gas.