The Discovery of Significant Oil and Gas Fields in the United States

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The Discovery of Significant Oil and Gas Fields in the United States

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January 1981

Prepared for the U.S. Geological Survey/
Department of the Interior and the
U.S. Department of Energy

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PREFACE

This report provides an assessment of the ultimate conventional petroleum resources of the United States. The assessment is based primarily on an analysis of the discovery and development of significant oil and gas fields in the United States, covering both past discoveries and the potential for future discoveries. The subject is one of immediate interest and great controversy. The project was undertaken to contribute to the ongoing task of U.S. petroleum resource assessment, specifically by organizing the available information on significant U.S. oil and gas fields and by applying it to the problems of resource assessment. To facilitate public discussion, most of the data used in drawing the conclusions are provided in the appendixes to this report (R-2654/2-USGS/DOE).

This research is part of The Rand Corporation's program of energy policy studies. Two related reports have been published previously as part of this program of studies: *Giant Oil Fields and World Oil Resources*, R-2284-CIA, and *Mexico's Petroleum and U.S. Policy: Implications for the 1980s*, R-2510-DOE. The section on the United States in a forthcoming report, *The Future of North American Oil Production*, R-2674-DOE, draws heavily from the conclusions of this report.

The study was funded by the Geologic Division of the U.S. Geological Survey, U.S. Department of the Interior, under Contract No. 14-08-0001-16593. Additional support was subsequently provided by the U.S. Department of Energy under Contract No. DE-AC01-79-PE70078.

This report should be of primary interest to those concerned with the question of ultimate conventional petroleum resources in the nation and their significance for energy policy. It is also designed to provide a basic reference work on U.S. oil and gas resources for those engaged in petroleum exploration and production, and to contribute to the literature on petroleum resource assessment.

SUMMARY

The purpose of this report is to provide a quantitative assessment of the ultimate conventional petroleum resources of the United States. Our primary innovations, as compared with earlier national petroleum resource assessments, are to create a consistently constructed and systematically organized data base listing all of the significant oil and gas fields in the United States outside of the Appalachian region and to use this data base to describe what has already been discovered and when these discoveries occurred. From these descriptions, we interpret *why* these discoveries happened when they did and evaluate the remaining geologic prospects to assess future possibilities. We also present extensive supporting data in the six appendixes forming the supplementary volume to this report.

The petroleum resources of the United States are highly concentrated in a few major provinces and in a relatively small number of giant and large fields. The discoveries of these fields reached their peak only after exploration had extended throughout the country, geological concepts and exploration and drilling technology had developed sufficiently to identify and reach most prospects, and petroleum markets had grown substantially. Oil discoveries peaked about 1930, and natural gas discoveries about 1950. Since these peaks, both the number of discoveries and the amounts discovered have declined substantially.

From our interpretation of the reasons behind this decline and our evaluation of the remaining geological possibilities, we conclude that most of the conventional petroleum that will ultimately be produced in the United States has already been discovered and made recoverable. We estimate that ultimate recovery of conventional petroleum liquids (crude oil and natural gas liquids) at a cost of $40 (1980 dollars) per barrel will most likely be between 210 and 285 billion barrels, as compared with a known recovery of 175 billion barrels. Most of the increase in petroleum liquids will come from reserve growth in known fields, not from new discoveries. Ultimate recovery of conventional natural gas at the same per barrel equivalent cost will most likely be between 920 and 1090 trillion cubic feet, as compared with a known recovery of 750 trillion cubic feet. Most of the increase in natural gas will come from new discoveries.

THE SIGNIFICANT OIL AND GAS FIELDS DATA BASE

Our principal research task was to construct according to a common set of defining characteristics a data base, including all of the significant oil and gas fields of the United States, that was organized to facilitate resource assessment. Section II describes this data base (provided in its entirety in App. A), the procedures that we followed in developing it, and its potential limitations.

The data are organized into 12 geographic regions: (1) Alaska, (2) California (Pacific Coast), (3) Rocky Mountain, (4) Permian Basin, (5) North Central Texas, (6) Mid-Continent, (7) Western Gulf, (8) Central Gulf, (9) Northern Gulf, (10) Eastern Gulf, (11) Illinois-Michigan basins, and (12) Appalachian. Because of a lack of systematic field data for the Appalachian region, the data base does not include fields from that region.

The basic unit of data and analysis in this report is the petroleum *field*. A field is generally defined as a single accumulation of petroleum or a set of closely related accumulations of petroleum. The field data are organized by field size category. We define significant fields as all fields with 10 million barrels or more of known recovery in liquid and liquid equivalents (L&LE). Significant fields are divided into six size categories: Class C—10 to 25 million barrels' L&LE, Class B—25 to 50 million barrels' L&LE, Class A—50 to 100 million barrels' L&LE, Class AA—100 to 200 million barrels' L&LE, Class AAA—200 to 500 million barrels' L&LE, and Class AAAA—500 million barrels or more of L&LE. Class AAAA fields are also referred to as giant fields, and Class A to AAA fields are considered to be large fields. Using a variety of procedures to estimate field size and thoroughly reviewing the available data, we compiled a list of 2471 significant oil and gas fields discovered before 1976 in the United States excluding Appalachia. Assuming current estimates of recovery, we estimate that our list of significant oil and gas fields is at least 99 percent complete.

Our list of significant oil and gas fields provides a comprehensive, well-organized, consistently constructed, and detailed data base for national petroleum resource assessment. Geographically, it includes all of the 12 regions of the United States except the Appalachian region, which has only 3.6 percent of U.S. petroleum resources. The fields in the data base contain more than 92 percent of the petroleum discovered before 1976 outside of the Appalachian region. Thus, although the data base includes only 10 to 15 percent of all the oil and gas fields that have been discovered, it contains nearly all of the fields that have been and are most important for U.S. petroleum production and reserves. The data are or can be readily grouped by region, state or area, geologic province, and field size classification. Other groupings, such as by year of discovery or trap type, can be easily constructed. We used a common field definition throughout, providing conceptually similar units of analysis. We defined the variables describing each field rigorously and employed them as consistently as possible, within the limits of data availability. The data base provides a substantial amount of detailed information for evaluating the exploration process. It gives the year of discovery, the discovery method, the trap type, the geologic age of the reservoir rocks, the reservoir lithology, and the spatial location and dimensions of each field. Although minor omissions were unavoidable, these data are essentially complete.

The limitations of the significant oil and gas fields data base are principally limitations in its potential uses. We designed it for national and regional analyses of the distribution of petroleum resources by field size and of broad discovery patterns. The data base is also a useful tool for analysis of individual geologic provinces, both for identifying major exploratory plays within each province and for assessing the significance of those plays. Provided that use of the significant oil and gas fields data base is limited to purposes for which it was designed and is suitable, we believe that it provides a useful, reliable tool for analysis.

THE DISTRIBUTION OF U.S. PETROLEUM RESOURCES BY REGION AND FIELD SIZE

Section III presents the basic facts of the distribution of known, conventional U.S. petroleum resources by region and by field size category. Using our data base, we outline the amounts of known recoverable crude oil, natural gas, and natural gas liquids in each of our 12 regions, indicate the relative importance of each region as a source of petroleum, list the producing provinces of each region, summarize the distribution of crude oil and natural gas resources by field size category in each region, and conclude with a national summary of the regional data. This section is thus a prerequisite to understanding the significance of the regional and national discovery patterns examined in Sec. IV.

The United States, with 151 billion barrels of recoverable crude oil, 751 trillion cubic feet of natural gas, and 24 billion barrels of natural gas liquids in fields discovered before 1976, is either the leading source of petroleum for the world or a close second. However, more than 75 percent of the petroleum discovered and made recoverable in the United States has already been produced.

Most of the producing regions of the United States have substantial amounts of crude oil resources. Natural gas resources are highly concentrated in the Mid-Continent, Central Gulf, and Western Gulf regions. The nation's petroleum resources are, however, highly concentrated in a few major geologic provinces. Nine of the 66 productive provinces have more than 80 percent of the known total recovery of petroleum. The four largest (Gulf Coast, Permian, Anadarko-Amarillo, and East Texas-Arkla) have more than 60 percent of the total.

The petroleum resources of the United States are highly concentrated in giant and large fields. The 81 known giant fields have about 40 percent of the known recoverable petroleum resources. More than 80 percent of the total are in the 873 giant and large fields. Only 6 to 8 percent of the totals for petroleum liquids and natural gas are in the thousands of very small fields (those with less than 10 million barrels' L&LE) that have been discovered. In nearly every province where large amounts of petroleum have been found, giant and large fields predominate.

The giant and large fields are largely structurally trapped. Anticlinal traps alone account for 70 percent of the total number. However, only 8 percent of the giant and large fields can be characterized as subtle stratigraphic traps. Differences in the distribution of petroleum resources by field size category and trap type are, moreover, the result of systematic differences in the geologic characteristics among the major producing provinces. Very small fields, that is, the nonsignificant ones that are Class D or smaller, are highly concentrated in one area—the stable interior between the Rocky Mountains and the Appalachians. This region is characterized by relatively thin total sedimentary sections, thinner individual formations, and little structural deformation. In comparison, provinces in which the petroleum resources are concentrated in giant and large fields are characterized by thick sedimentary sections, thick individual formations, and moderate to substantial deformation.

THE DISTRIBUTION OF SIGNIFICANT OIL AND GAS DISCOVERIES IN THE UNITED STATES BY SIZE OVER TIME

Section IV describes the statistical history of U.S. petroleum exploration. Using our data on the year of discovery and other sources of information, we summarize the patterns of discovery (1) of significant fields by size and (2) of the amounts of crude oil and natural gas discovered over ten-year periods up to 1975 for our 12 regions and the nation as a whole. We particularly emphasize the peaks in discoveries, changes over time in the composition of discoveries, and the influence, if any, of developments in exploratory technology and geological concepts on discoveries. Our focus is on the results of exploration. We also show the relationships between results and efforts, as measured by the number of exploratory wells drilled. These descriptions provide an essential bridge between knowing what has been discovered and estimating what remains to be discovered.

Although the first significant discovery in the United States occurred in 1862, both the number of discoveries and the amounts of crude oil and natural gas discovered did not peak for another 65 to 100 years. Discoveries reached their peak only after exploration had extended throughout the country, geological concepts and exploration and drilling technology had developed sufficiently to identify and reach most prospects, and petroleum markets had grown substantially.

The amount of crude oil discovered peaked in the decade from 1926 to 1935, coinciding with the peak in the number of giant oil discoveries. Since that peak, the amount discovered in the onshore lower 48 states has been declining at an accelerating rate. The number of significant oil discoveries has dropped drastically since its peak from 1935 to 1955, almost disappearing in most of the important oil-producing regions. The amount of natural gas discovered peaked in the decade around 1940 and declined slowly thereafter until 1960 as the natural gas market expanded and several new frontiers, primarily the offshore Gulf of Mexico, were opened to exploration. Except for a major flurry of activity in the offshore Gulf of Mexico in the early 1970s, the number of significant natural gas discoveries has declined steadily since its peak during the 1950s.

The average size of significant oil and gas discoveries has been declining for several decades, as giant and large discoveries have nearly ceased in the mature areas of the country. During the past 25 years, the discoveries of large and giant fields have become increasingly concentrated in the frontier areas, particularly the offshore provinces. In the early 1970s, offshore discoveries accounted for nearly 60 percent of all significant discoveries.

A common pattern over time in the number of discoveries by field size classification can be discerned both nationally and regionally. The largest fields tend to be discovered first. The average size of discoveries declines over time. As the number of larger discoveries declines, the total number of significant discoveries remains stable or even increases as the number of smaller significant discoveries continues to increase. Eventually, as exploration proceeds, the number of smaller significant discoveries also declines.

These discovery patterns suggest that the U.S. petroleum industry is gradually running out of ideas as to where oil and gas may still be found. This is not because of a lack of creativity and imagination, but because of the increasing exhaustion of the geological possibilities region by region. Increased drilling efforts are unlikely to reverse this trend. Historically, intensive drilling activity has followed the peaks in the amount discovered and in the number of significant discoveries by several years, if not decades.

DISCOVERY PATTERNS AND RESOURCE ASSESSMENT

The historical data do not suggest a promising future for U.S. petroleum exploration. Nearly all of the petroleum discovered to date is in significant fields, particularly in giant and large fields. The number of discoveries of these fields, especially the larger ones, peaked several decades ago. Since then, both the number of discoveries and the amount discovered have been declining steadily nationwide, particularly onshore in the lower 48 states.

As a counter to this pessimistic outlook, four hypotheses about where substantial amounts of petroleum may still be found in the United States have been propounded. These hypotheses contend that there are still substantial amounts of petroleum to be found (1) at depths below 15,000 feet, (2) in subtle stratigraphic traps, (3) in very small fields, and (4) in frontier regions. These four general hypotheses exhaust the scientifically plausible possibilities for substantial future petroleum discoveries in the nation. We conclude that each of these hypotheses is qualitatively valid, but that each is subject to quantitative limitations that in some cases are quite severe.

These hypotheses are more explicitly evaluated in our assessment of the ultimate conventional petroleum resources of the United States. In Sec. V, we provide regional assessments of U.S. petroleum potential, summarized into a concluding national assessment. The assessment is limited to the conventional resources of crude oil, natural gas, and natural gas liquids that will ultimately be discovered and produced in U.S. territory and adjacent offshore areas out to a water depth of 1000 meters up to a resource cost of $40 per barrel (or per barrel equivalent) in constant 1980 dollars.

Each regional assessment and the national summary assessment provide a single estimate of *known recovery* (cumulative production and demonstrated reserves) in all fields discovered before 1976 as estimated in 1979. Each gives a range of estimates for *reserve growth* after 1978 in fields discovered before 1976, including reserves added from the development of previously discovered but undeveloped fields, extensions and new pool discoveries in known fields, more intensive development, and enhanced oil recovery. Each also provides a range of estimates for *undiscovered* petroleum resources, defined as all future reserve additions from fields discovered after 1975. We give a range of estimates for both reserve growth and undiscovered resources because of the inescapable uncertainties in estimating these quantities. The three values included in each estimate are the values for which we estimate a 90-percent, 50-percent, and 10-percent probability, respectively, that future reserve growth or discoveries will be greater than the amount indicated. The arithmetic summation of our estimates of known recovery, reserve growth, and future discoveries constitutes our estimate of *ultimate recovery*.

Our subjective cumulative probability distributions by region for both reserve growth and future discoveries were developed with several methods of assessment. Our choice depended on the particular component of reserve growth or future discoveries that we were considering and the extent of available information. In general, our methodological emphasis was on the particular engineering, economic, and geological characteristics of specific fields and plays combined with an appreciation of the relevant historical trends in reserve appreciation and discoveries.

Our outlook for conventional petroleum resources in the United States can at best be characterized as only moderately promising. We estimate that there is a 90-percent probability that ultimate recovery will be greater than 180 billion barrels of crude oil, 920 trillion cubic feet of natural gas, and 28 billion barrels of natural gas liquids; a 50-percent probability that it will be greater than 210 billion barrels of crude oil, 990 trillion cubic feet of natural gas, and 30 billion barrels of natural gas liquids; and a 10-percent probability that it will be greater than 250 billion barrels of crude oil, 1090 trillion cubic feet of natural gas, and 33 billion barrels of natural gas liquids.

At these levels of ultimate resources, it is likely that more than half of the conventional petroleum resources that will ultimately be produced have already been produced. We estimate about a 10-percent probability that ultimate recovery of petroleum liquids and natural gas will at least double cumulative production at the end of 1979. Current demonstrated reserves, plus our most likely ranges of future reserve growth and discoveries, total only 20 to 40 years of production of petroleum liquids and 17 to 26 years of production of natural gas at 1979 rates of production.

Taking into account the combined effects of reserve growth and new discoveries, we estimate that 3200 significant fields, plus or minus 200, will ultimately be discovered and developed in the United States. Approximately 100 of these, plus or minus 10, will be giant fields. Another 900, plus or minus 40, will be large fields.

We consider Alaska and secondarily the Rocky Mountain region, offshore California, and the offshore Central Gulf to have the best potential for future discoveries of crude oil. The potential for major reserve growth in known oil fields is concentrated in the Permian Basin, onshore California, the Mid-Continent, and Alaska. We consider Alaska, the Rocky Mountain region, the onshore and offshore Central and Western Gulf regions, and the Mid-Continent to have the best potential for the discovery of substantial amounts of natural gas. The potential for reserve growth in known natural gas fields is best in the Mid-Continent, the onshore and offshore Central Gulf, and the Rocky Mountain region.

Our estimates of the ultimate petroleum potential of the United States are considerably lower than most other recent estimates. Nearly all of the differences between our estimates and others relate to what remains to be discovered, not to reserve growth. Our estimates of undiscovered potential differ from those by Exxon and Mobil primarily because of differences over the potential of the frontier areas offshore and in Alaska. We believe that the primary reasons for these differences can be traced to the fact that these oil companies' estimates were made before and our estimates were made after the many exploratory disappointments that have occurred in frontier areas during the past five years. Our estimates of undiscovered potential differ from those of Circular 725, the National Petroleum Council, the Potential Gas Committee, and presumably the National Academy of Sciences over the potential of both the frontier areas and the onshore lower 48. Their estimates for the onshore lower 48 are an order of magnitude larger than ours for the undiscovered crude oil potential and a factor of three to five larger than ours for the natural gas potential. We believe that such large estimates for the lower 48 onshore are implausible in view of the extent of petroleum exploration in this area, the historic discovery patterns, and the number of discoveries required to reach the amounts they estimate.

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I. INTRODUCTION

"Oil is first sought in our minds." This aphorism, attributed to Wallace Pratt, a prominent figure in the development of petroleum geology in the United States, expresses a fundamental axiom of petroleum exploration.[1] Exploration begins with hypotheses about where petroleum may be found.[2] As exploration proceeds and geological, geophysical, geochemical, and drilling data accumulate, those hypotheses may be developed, revised, or totally discarded in favor of better ones. But the role of these hypotheses in guiding the exploratory effort remains essential.

Creativity in the formulation of hypotheses about where petroleum may be found is necessary to overcome the prejudices that inhibit the search for petroleum. The history of petroleum exploration is filled with dozens of once firmly held assertions about where oil could not be found that have proved to be dramatically wrong. Examples include: "There is no sand in northeast Texas" (asserted before the discovery of the super-giant *East Texas* field in the Woodbine sandstone); "There is no oil west of the Pecos" (asserted before the discovery of *Yates*, one of the five largest oil fields in the United States, on the west bank of the Pecos River); "There is little oil in carbonate rocks" (asserted before major discoveries in carbonate reservoirs in the Mid-Continent and Permian Basin); "There is no oil in non-marine sediments" (asserted before major discoveries in continental sediments in the Cook Inlet and the Chinese basins); and even "There is no oil in Arabia" (no explanation required).[3]

The mental barriers to oil exploration and the imaginative leaps that hurdled them are not merely relics of the early decades of exploration. Within the past decade, there have been several major discoveries in the United States in areas that were generally thought to have been thoroughly explored (e.g., *Tule Elk* and *Yowlumne* in the San Joaquin Basin and *Hartzog Draw* in the Powder River Basin) or were thought to be unfavorable for major accumulations (the deep Tuscaloosa trend in southern Louisiana). Even with all the technological and conceptual advances in petroleum exploration over the past half-century, the need for creativity and daring in exploration has not disappeared.

Creativity in exploration is indispensable, yet it is not sufficient. The other side of the picture is best expressed by an even older aphorism from the oil patch: "Oil

[1] W. E. Pratt, *Oil in the Earth*, University of Kansas Press, Lawrence, 1942, p. 49. Unfortunately, beginning with Pratt himself, an alternative version of the aphorism has also been used: "Oil is first *found* in our minds" (emphasis ours). The change, although only one word, is nonetheless profound. Ideas are indispensable in guiding the search for petroleum; that search, however, will only be successful if the petroleum is already there, waiting to be found. If it is not there to begin with, all the human ingenuity that can be mustered into the service of exploration cannot put it there. If oil is indeed found in our minds, the literature of the past decade suggests that the best place to look for oil would be in the economics departments of American universities and research institutes (or in the geography departments of Dutch universities), not in sedimentary rocks.

[2] By petroleum we mean crude oil, natural gas, and natural gas liquids.

[3] For these and other historic prejudices, see E. B. Noble, "Geological Masks and Prejudices," *The American Association of Petroleum Geologists Bulletin*, Vol. 31, No. 7, July 1947, pp. 1109-1117; E. DeGolyer, "Plea for Loose Thinking," *The American Association of Petroleum Geologists Bulletin*, Vol. 34, No. 7, July 1960, pp. 1607-1611; W. E. Pratt, "Toward a Philosophy of Oil-Finding," *The American Association of Petroleum Geologists Bulletin*, Vol. 36, No. 12, December 1952, pp. 2231-2236; and A. I. Levorsen, "Big Geology for Big Needs," *The American Association of Petroleum Geologists Bulletin*, Vol. 48, No. 2, February 1964, pp. 141-156.

is where you find it." Once used to deride the early and often unsuccessful attempts at scientific exploration, the statement still makes a valid point now that scientific methods have clearly proved their value. The only petroleum that we know exists is the petroleum that we have found, not the petroleum that we think we may find or that we hope we can find. Moreover, the petroleum that exists in commercially available accumulations does so only because several geologic processes have occurred in an appropriate temporal and spatial relationship with each other. Sufficient organic material must have been produced, accumulated, and preserved. This material must be buried to a depth where sufficient temperature and pressure exist to generate petroleum. After the petroleum is generated, it must be expelled from the source rock into permeable carrier or reservoir rocks. Traps with porous and permeable reservoir rocks must exist where the migrating petroleum can accumulate. These traps must not be breached after accumulation occurs.[4]

Because of the complexity of this process, there are many conditions or combinations of conditions that can prevent petroleum from accumulating. The production of organic material may be insufficient. The organic material that was produced may be oxidized. Unoxidized organic material may be buried to an insufficient depth for thermal maturation. No channels may exist for petroleum to migrate from thermally mature source rocks. Migration may occur before the formation of effective traps. Reservoir rocks may be poor or nonexistent. The reservoir rocks may lack effective seals. Traps with petroleum accumulations may be destroyed by erosion or tectonic activity or flushed by ground water.

These potential deficiencies need to be emphasized because, unlike prejudices, they cannot be overcome by leaps of the imagination. Several large and expensive exploratory efforts during the past decade in the United States—the eastern Gulf of Mexico, the Outer Banks offshore California, and the Gulf of Alaska—have failed, simply because one or more of the essential conditions of petroleum accumulation were largely or wholly absent. Exploratory ingenuity must wrestle seriously with potential limitations on petroleum accumulation. If it does not, it quickly descends from the level of creative thinking to the level of wishful thinking, given the inherent capabilities of the human mind to drift once cast free from the moorings of reality. Although one may postulate a definite figurative relationship between wishful thinking and some varieties of organic material, wishful thinking has yet to be established as an effective source of petroleum. The craft of petroleum exploration requires an appropriate blend of human creativity and known geologic reality, not an emphasis on one to the exclusion of the other.

These two views of petroleum exploration are reflected in the history of petroleum resource assessment in the United States. The most commonly used method of assessment has been the volumetric yield approach. Using geologic analogies to known productive basins or formations, resource estimators have attempted to calculate the potential of unexplored or lightly explored potentially productive basins or formations. These estimators have emphasized the geologic possibilities of the areas they assessed, flexing their imagination to consider what still might be found (even though this emphasis is not inherent in the use of geologic analogy).

[4] A. A. Meyerhoff, "Economic Impact and Geopolitical Implications of Giant Petroleum Fields," *American Scientist*, September-October 1976, pp. 536-541; B. P. Tissot and D. H. Welte, *Petroleum Formation and Occurrence*, Springer-Verlag, Berlin, 1978; J. M. Hunt, *Petroleum Geochemistry and Geology*, W. H. Freeman and Company, San Francisco, 1979.

In sharp contrast to this approach is the method of predicting future discoveries by extrapolating historical discovery rates. Users of this approach have emphasized the decreasing amounts that are being found, stressing the necessity to consider seriously the implications of the historic decline in discovery rates in the United States.[5]

Each approach has been used with little regard for the merits of the other. The volumetric method has almost always been applied with an oblivious attitude toward the realities of past exploration results. The extrapolation of discovery rates has lacked an appreciation of the potential role of new hypotheses, improved technology and economics, and geologic surprises. Consequently, estimates of ultimate U.S. petroleum resources have differed markedly, depending on which approach was employed. Because both approaches have tended to be highly aggregative, the evidence enabling a detailed evaluation of their comparative validity has often been unavailable.

During the past decade, several new approaches to resource assessment have been developed that attempt to blend various insights from both the volumetric method and the extrapolation of discovery rates. These approaches are essentially disaggregative in nature, focusing on specific prospects (or fields), exploration plays (a collection of prospects with several common geological characteristics), and geologic provinces (basins). Emphasis has been placed on looking at the whole by means of a detailed analysis of the parts, using the information gained from past exploration—both favorable and unfavorable—to speculate about future possibilities. The actual analysis may employ a variety of methods, the specific method applied depending on the component of the ultimate resource being estimated and the extent of information available to the estimators. Accompanying this approach has been an appreciation of the importance of incorporating geologic uncertainty and risk within the assessment.

Our purpose in this report is to contribute to the ongoing task of U.S. petroleum resource assessment within the tradition of these disaggregative prospect, play, and province analyses. Our principal innovations are (1) to create a consistently constructed and systematically organized data base that itemizes all of the significant oil and gas fields in the United States outside of the Appalachian region and (2) to use this data base to describe what has already been discovered and when these discoveries occurred. From these descriptions, we interpret why these discoveries occurred when they did and evaluate the remaining geologic prospects to assess future possibilities.

We use our data base to demonstrate that the petroleum resources of the United States are highly concentrated in a few major provinces and in a relatively small number of giant and large fields. The discoveries of these fields reached their peak only after exploration had extended throughout the country, geological concepts and exploration and drilling technology had developed sufficiently to identify and reach most prospects, and petroleum markets had grown substantially. Oil discoveries peaked about 1930, and natural gas discoveries peaked about 1950. Since these peaks, both the number of discoveries and the amounts discovered have declined substantially.

[5] For a survey of methods of petroleum resource assessment, see D. A. White and H. M. Gehman, "Methods of Estimating Oil and Gas Resources," *The American Association of Petroleum Geologists Bulletin*, Vol. 63, No. 12, December 1979, pp. 2183-2192.

From our interpretation of the reasons behind this decline and our evaluation of the remaining geological possibilities, we conclude that most of the conventional petroleum that will ultimately be produced in the United States has already been discovered and made recoverable. We estimate that ultimate recovery of conventional petroleum liquids (crude oil and natural gas liquids) will most likely be between 210 and 285 billion barrels, as compared with a known recovery of 175 billion barrels. Most of the increase in petroleum liquids will come from reserve growth in known fields, not from new discoveries. Ultimate recovery of conventional natural gas will most likely be between 920 and 1090 trillion cubic feet, as compared with a known recovery of 750 trillion cubic feet. Most of the increase in natural gas will come from new discoveries.

Following this introduction, Sec. II describes the significant oil and gas fields data base, the procedures that we followed in developing it, and its potential limitations. The data base itself is provided in its entirety in App. A of the supplementary volume to this report. In Sec. III, we discuss the distribution of known conventional U.S. petroleum resources by type, region, basin, and field size category. The fourth section describes the historic patterns of discovery by field size category and by the amount of oil and natural gas in each region in the United States as a whole. Using the information summarized in the preceding two sections and supplementary geological information, in the concluding section we provide an assessment of ultimate conventional U.S. petroleum resources.

We present additional statistical detail behind the descriptions, analyses, and arguments of the last three sections in the six appendixes of the supplementary volume to this report. Appendix A consists of the significant oil and gas fields data base. Appendix B provides cumulative and current (1975) production data for crude oil and natural gas by field size class for each state or statistical area and region. Appendix C lists the number of significant oil and gas field discoveries in the United States by field size class over five-year periods by region and type of field. Appendix D gives data on the amounts of crude oil and natural gas discovered in the United States by five-year periods up to and including 1975. Appendix E presents data on exploratory drilling by region in the United States from 1936 to 1975. Appendix F provides our estimates of future significant discoveries in the lower 48 states by field size and region.

This report is best read in its entirety from beginning to end. The second section provides the basic organization and definitions used throughout the report. Each succeeding section proceeds to build on the sections that preceded it. The national overviews concluding each of the last three sections are developed from the region-by-region descriptions and analyses that preceded them in each section. Most of the key arguments, however, can be obtained through a more selective reading of the report. Those readers who wish to survey the main points first can do so by reading the introductory sections and concluding national overviews of Secs. III, IV, and V before reading Sec. II and the more detailed regional discussions. The appendixes are provided both as a basic reference tool and for those readers who may wish to explore the subject in greater detail than provided in the text.

II. THE SIGNIFICANT OIL AND GAS FIELDS DATA BASE

The analysis of field size distributions and discovery patterns requires an appropriate data base. Such a data base should ideally be comprehensive or near-comprehensive, well-organized, consistently constructed according to a common set of defining characteristics, and detailed enough to permit sophisticated analysis. When this project began, no such data base existed for oil and gas fields in the United States. Several of the components of such a data base did exist, such as the field and pool records of the Petroleum Data System (PDS), the field file developed for the LORENDAS project at Virginia Polytechnic Institute, and the list of national-class giant oil fields published annually by the *Oil and Gas Journal*. However, these were either inconsistently constructed (such as the PDS and LORENDAS), were too limited in their scope (such as the *OGJ*), or were lacking in accompanying descriptive data (such as the LORENDAS and *OGJ*). Our principal task in preparing this report was to construct such a data base. This section describes our data base (which is provided in its entirety in App. A), the procedures we followed in developing it, and its potential limitations. An expanded version of our data base is also accessible through the Petroleum Data System of the Information Systems Program of the University of Oklahoma.

We describe the means of organizing the data base, supply the items of information included for each field, and provide definitions of each of these items. In this report and in the data base, the basic unit of data and analysis is the petroleum *field*. The field data are organized by *region* and *state* or *statistical area* and by *field size*. We also give information necessary to organize the field data by *geologic province*. Because we developed the data base to provide a means of analyzing discovery patterns and of assessing the potential for future discoveries, we included several basic items of information that are relevant to the discovery process: (1) the year in which the field was discovered; (2) the methods used to discover the field; (3) the general and specific type of trap; (4) the major system and series of the reservoir rocks; (5) the major reservoir lithologies in the field; and (6) the spatial location and dimensions of the field (the depth to the top of major reservoirs, the average net reservoir thickness, and the productive acreage of the field). These variables provide a means of answering questions about the discovery of significant fields: *When?*, *How?*, in *Which* circumstances?, and *Where?* A great variety of analyses are possible using these variables. In the analyses that follow in Secs. III to V, we emphasize the year of discovery and the trap type, although we use all of the variables to some extent.

Because we designed the data base for practical use, we kept both the organizing principles and the categorization of the variables as broad and simple as possible. The data base could have been expanded to incorporate variables more relevant to questions of production engineering and additional recovery. However, we chose not to include such variables because they were not germane to our purposes.

Field size, expressed in volumes of recoverable petroleum liquids and natural gases, is the most important variable used in this report. The data base of App. A provides the following information pertaining to field size: namely, for crude oil, original oil-in-place, cumulative production to December 31, 1975, demonstrated reserves (proved reserves and indicated additions to reserves), and 1975 production; and for natural gas and natural gas liquids, cumulative production, proved reserves, and 1975 production. Our estimates of total field sizes, expressed in barrels of petroleum liquids and natural gas expressed in liquid equivalents, are not given in the data base of App. A. However, they are included for each field in the PDS file developed from the data base of App. A.

We describe the procedures that we followed and the problems that we encountered in developing the data base. Our description of the procedures includes a brief review of current or potential alternative procedures and our reasons for following the procedures that we used. The review of the problems we encountered in acquiring and determining information entries in the data base is presented to provide users of both this report and the data base with a complete picture of the strengths and limitations of the data and thus of the conclusions that might be drawn from further analysis.

We consulted many sources of information to acquire and to determine the information entries in the data base. Because there are more than 40,000 separate items of information and multiple sources for many items, we concluded that citing the source or sources for every item of information would be impractical. We therefore chose the alternative of listing the sources in the Bibliography, which is organized by region and area.

REGIONAL ORGANIZATION

The primary basis for organizing the data and derivative analyses of this report is geographical. We organized the lists of significant oil and gas fields and the subsequent data summaries and analyses into 12 geographic regions. The criteria used to define these regions were that (1) they be geographically contiguous; (2) they approximate geologic boundaries as much as possible, permitting the highlighting of geologically significant differences; (3) they be as consistent as possible with existing aggregations of oil and gas data in order to facilitate a broad variety of analyses; and (4) they avoid unduly high or low concentrations of significant fields. The 12 regions and their components are listed in Table 2.1. Figure 2.1 delineates the regions on a map of the United States.

The components of the regions are either states or traditional statistical areas within states. The regions as mapped include all of the states except Hawaii, which is generally regarded as having no petroleum potential of commercial significance.

The definition of statistical areas within states corresponds to that used by the American Petroleum Institute, the American Gas Association, and the International Oil Scouts Association, with only two exceptions: (1) in California the fields of the Cuyama Basin are included in this report in the Central Coast area instead of the Central and Northern area, and (2) the fields of the Santa Cruz Basin are included in the Central and Northern area instead of the Central Coast area. In both cases, the usage here follows that of the California Division of Oil and Gas.

The states or statistical areas within states listed in Table 2.1 are only those areas that have significant fields discovered before January 1, 1976. The *Trap Springs* field, discovered in 1976, may prove to be a significant field, resulting in the inclusion of Nevada (Region 3) in subsequent compilations. The other states with some oil and gas production but no significant fields are Oregon and Washington (Region 2), South Dakota (Region 3), Iowa, Minnesota, and Missouri (Region 6), and Maryland and Tennessee (Region 12). South Dakota is the only one of these eight states in which the total amount of recoverable petroleum discovered to date in all fields exceeds our minimum level of significance for a single field. The numbering and lettering of Table 2.1 are continued in the tables of Apps. A, B, and C to facilitate use of the data. For example, Table B.4c indicates cumulative and current production of crude oil and natural gas (the subject of App. B) for Texas R.R.C. District 8 in the Permian Basin (area 4c).

Most of the fields in Region 12 (Appalachian) were discovered before 1900. Because of a lack of nineteenth-century records, comprehensive data on field sizes in this region are unavailable.[1] As a result, tables for the six areas of Region 12 are not included in Apps. A, B, and C, even though data on the sizes of some fields in this area are available. This exclusion omits areas from the data base containing 2.5 percent of the recoverable crude oil (3.82 of 151.0 billion barrels), 5.2 percent of the natural gas (39.3 of 751.0 trillion cubic feet), and 2.0 percent of the natural gas liquids (0.48 of 24.1 billion barrels) in fields discovered in the United States to the end of 1975.

The 12 regions used here are similar to the 11 petroleum regions of the United States defined by the National Petroleum Council (NPC).[2] The regions of this report differ from those defined by the NPC to facilitate statistical analyses. Region 3 (Rocky Mountains) combines NPC Regions 3 and 4 because of the relatively small number of significant oil and gas fields in the two regions and the general geologic and geographic continuity between them. Regions 4 (Permian Basin) and 5 (North Central Texas) divide NPC Region 5 because the two areas have substantially different field size distributions and because we encountered major problems in determining field sizes in Texas R.R.C. Districts 7B and 9. We separated the two areas to highlight these differences in the regional analyses. Regions 7 (Western Gulf), 8 (Central Gulf), 9 (Northern Gulf), and 10 (Eastern Gulf) were created out of NPC Region 6 to reduce the concentration of significant fields in any one region. (The Gulf Coast Geosyncline as defined by the NPC contains approximately half of the significant oil and gas fields in the United States.) The division into four areas uses a generally coinciding combination of geological and political/statistical boundaries. Region 11 (Illinois-Michigan) combines NPC Regions 8 and 9 because of the small number of significant fields in the two NPC regions. Region 12 (Appalachian) combines NPC Regions 10 and 11 (excluding Florida) because the absence of significant fields in Region 11 makes its separate designation superfluous. In all cases where the NPC divided states in ways other than the traditional separations in California, Louisiana, New Mexico, and Texas, we modified the NPC definition to have the entire state in one region. Thus, all of Nebraska is included in the Rocky Mountain region, all of Arkansas in the Northern Gulf region, and all of Kentucky in the Appalachian region. This division does minor violence to geologic boundaries, splitting the Cambridge-Chadron Arch, Arkoma Basin, and Illinois Basin, respectively, between two regions, but we judged that this deficiency was offset by the gain in ease of statistical manipulation.

[1] The Committees on Reserves of the American Petroleum Institute and the American Gas Association may have such comprehensive field data for Region 12, but the confidentiality rules of these committees preclude their release.

[2] *Future Petroleum Provinces of the United States*, Washington, D.C., July 1970.

Table 2.1

Petroleum Regions of the United States and Their Composition

Region	Composition
Region 1:	Alaska
Region 2:	California a. Central and Northern b. Central Coast c. Los Angeles Basin
Region 3:	Rocky Mountains a. Arizona b. Colorado c. Montana d. Nebraska e. Northwestern New Mexico f. North Dakota g. Utah h. Wyoming
Region 4:	Permian Basin a. Southeastern New Mexico b. Texas R.R.C. District 7C c. Texas R.R.C. District 8 d. Texas R.R.C. District 8A
Region 5:	North Central Texas a. Texas R.R.C. District 7B b. Texas R.R.C. District 9
Region 6:	Mid-Continent a. Kansas b. Oklahoma c. Texas R.R.C. District 10
Region 7:	Western Gulf a. Texas R.R.C. District 1 b. Texas R.R.C. District 2 c. Texas R.R.C. District 3 d. Texas R.R.C. District 4
Region 8:	Central Gulf a. Offshore Louisiana b. Southeastern Louisiana c. Southwestern Louisiana
Region 9:	Northern Gulf a. Arkansas b. Northern Louisiana c. Texas R.R.C. District 5 d. Texas R.R.C. District 6
Region 10:	Eastern Gulf a. Alabama b. Florida c. Mississippi
Region 11:	Illinois-Michigan Basins a. Illinois b. Indiana c. Michigan
Region 12:	Appalachian a. Kentucky b. New York c. Ohio d. Pennsylvania e. Virginia f. West Virginia

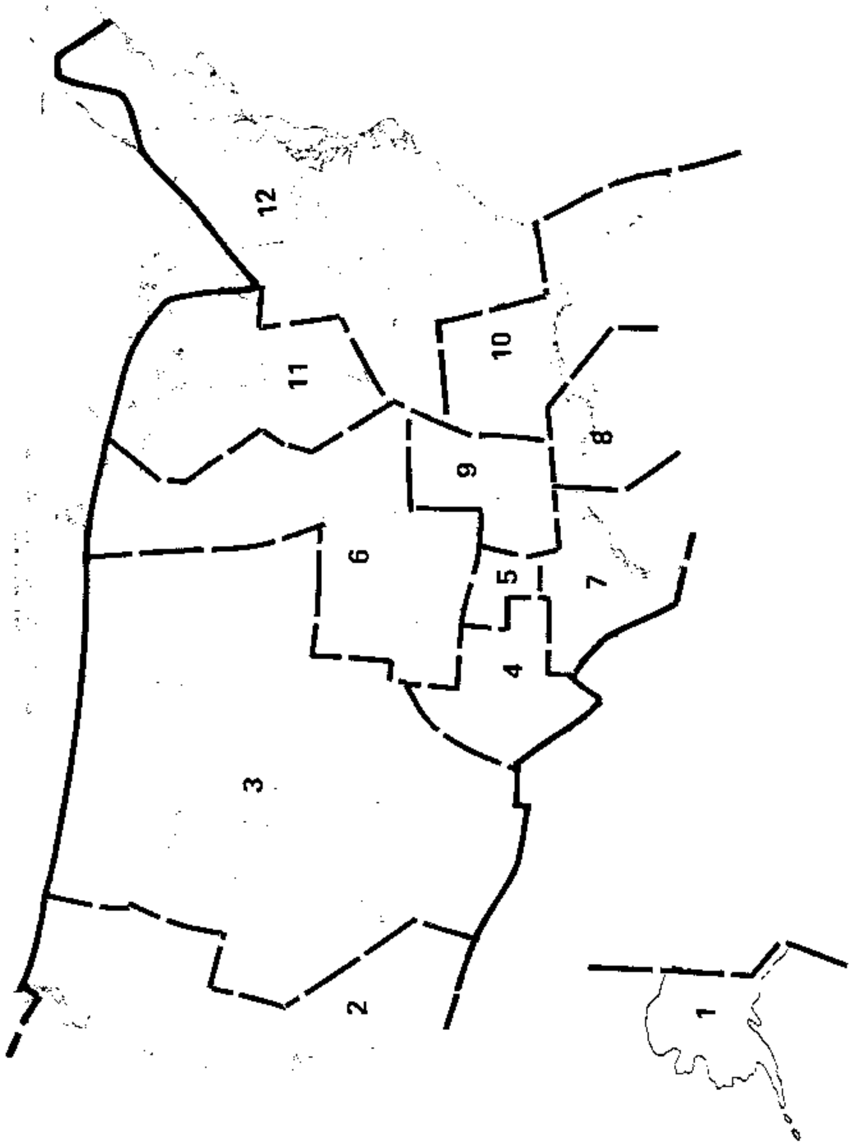

Fig. 2.1—Petroleum regions of the United States

The regions used here present few problems of data analysis. Only five significant fields cross regional boundaries: *Greenwood* (CO and KS), *Sivells Bend* (TX 9 and OK), *Burkburnett-Red River Bed* (TX 9 and OK), *Phoenix Lake* (TX 3 and SW LA), and *Angie* (SE LA and MS). The first three would also cross regional boundaries if we had followed the NPC regional definitions.

FIELD DEFINITION

The basic unit of data and analysis used in this report is the petroleum *field*. We use fields rather than pools or reservoirs for two reasons: (1) From the viewpoint of the exploration process, fields are more important, and they are generally synonymous with exploration prospects. Conversely, a prospect may prove to contain several pools. (2) Comprehensive data on pools are not available for all states. Of the 38 areas listed in Table 2.1 for which comprehensive data on significant fields are available, only 24, with approximately 55 percent of the significant fields, have comprehensive data on individual pools. Because field data can be readily derived from pool data, but pool data cannot be easily inferred where only field data are available, the use of the field as the basic unit of analysis is also preferable from the standpoint of data acquisition.

The choice of field as the basic unit of analysis does pose problems of definition and application. Whereas all states have field designations, no consistent field definition is applied among or even within states. However, without a consistent definition, the use of field data for analytical purposes creates major methodological problems. If the traditional field designations are employed exclusively, dissimilar units would be treated as if they were similar. Thus, if the petroleum field is to be used as the basic unit of analysis, we need to construct a common definition and apply it consistently.

Consistency in the application of any definition is not the only relevant criterion. The definition itself should be unbiased, particularly when it will be used to determine the composition of units for an analysis in which the size of the individual units is an important variable. If the definition is overly conservative, field sizes will be systematically understated. If the definition is overly liberal, field sizes will be systematically overstated.

A third problem is that geologic variability does not permit the wholly unambiguous application of any possible field definition. The term *field* is commonly used to refer to a single accumulation (in which case it is synonymous with a *pool* or *reservoir* or to a set of closely related accumulations of petroleum).[3] However, even when there is definitional agreement as to what constitutes a *closely* related set of accumulations, there will always be marginal cases on which legitimate disagreement may exist as to which accumulations belong in the closely related set.

Our approach in dealing with these three problems is (1) to use a field definition that is consonant with contemporary usage to avoid introducing bias from any preconceptions that we might have on the relative importance of fields of various sizes; (2) to apply this definition as consistently as possible to all areas, combining

[3] See A. I. Levorsen, *Geology of Petroleum*, 2d ed., W. H. Freeman and Company, San Francisco, 1967, p. 30; and G. D. Hobson and E. N. Tiratsoo, *Introduction to Petroleum Geology*, Scientific Press, Beaconsfield, England, 1975, p. 6.

or dividing traditionally designated fields wherever necessary; and (3) to list the components of a field where traditionally separately designated fields are combined into a single field as defined in this report, thus permitting alternative analyses of the data based on different judgments than those we employed on what constitutes a closely related set of petroleum accumulations.

We define a *field* as a producing area containing in the subsurface (1) a single pool uninterrupted by permeability barriers; (2) multiple overlapping pools trapped by a common geologic feature; (3) laterally distinct multiple pools within a common formation and trapped by the same type of geologic feature where the lateral separation between pools does not exceed one-half mile; or (4) stratigraphically trapped multiple overlapping pools where the vertical separation between pools does not exceed 1000 feet. This definition is based on a concept of a single field from the viewpoint of a completed exploration process. After a new field discovery is made, any other pools discovered in the course of determining the lateral and vertical limits of that discovery and testing the effective lateral and vertical limits of its trapping mechanism are considered to be part of the same field.

Most fields in the United States are of the first two types. The first type includes both single pools known by one name, the classic example being the *East Texas* field of Texas R.R.C. District 6, and single pools that have several field designations for administrative purposes, two examples being the *South Cowden* field (*South Cowden-Foster-Johnson*) of Texas R.R.C. District 8 and the *Scurry* field (*Kelly-Snyder-Diamond-M-*) of Texas R.R.C. District 8A.[4] The second type includes (1) sets of overlapping pools of the same or different geologic ages within a single geologic feature such as an anticline, for example, the *Elk Basin* field in Wyoming and Montana and the *Sligo* field in northern Louisiana; (2) sets of tangential pools where the pools are separated by impermeable faults, such as the *Wilmington Trend* field (*Wilmington-Torrance-Belmont Offshore*) of the Los Angeles Basin, and the *Ventura-Rincon* field of the California Central Coast; and (3) sets of adjacent pools around and above the same salt dome, such as the *Timbalier Bay*[5] complex (*Timbalier Bay-Timbalier Bay Block 21*) of southeastern Louisiana and the *Hull-Merchant* field of Texas R.R.C. District 3. A variant of the second type is a field containing one large structural or stratigraphic pool and one or more smaller overlying stratigraphic pools discovered during the process of developing the larger pool, for example, the *Mocane-Laverne* field in Oklahoma and the *Yates* field (including *Toborg*) in Texas R.R.C. District 8. Examples of the third type include the *Round Mountain: Main, Coffee Canyon, Pyramid* field in Central California and the *Cedar Creek Anticline* in Montana and North Dakota. An example of the fourth type is the *Hansford* field in Texas R.R.C. District 10.

The definition of field excludes sets of laterally distinct adjacent pools that (1) are combined as a single field for administrative purposes, such as *McKittrick:*

[4] Neither of these fields is a perfect example of the first type (single reservoir fields), as both have several minor pools. But because the major pool in both fields contains more than 99 percent of the known recoverable petroleum resources in each field, the field essentially consists of a single reservoir.

[5] The *Timbalier Bay* salt dome is on the same salt ridge as the *Caillou Island* and *Bay Marchand Block 2* domes. However, the vertical and lateral separations between the three domes are of such magnitude to justify a separate field designation for each dome. See M. G. Frey and W. H. Grimes, "Bay Marchand-Timbalier Bay-Caillou Island Salt Complex, Louisiana," in M. T. Halbouty (ed.), *Geology of Giant Petroleum Fields*, American Association of Petroleum Geologists Memoir 14, Tulsa, Okla., 1970, pp. 277-291.

Main and *McKittrick: Northeast* in Central California; (2) share a common regional geological feature but are more than one-half mile apart, such as the *Pine* and *Cedar Creek Anticline* fields in Montana; or (3) are separated by a distinctive geologic feature, such as the erosion channel separating *Cogdell* and *Scurry* fields in the Horseshoe Atoll of Texas R.R.C. District 8A. The definition also excludes combining sets of overlapping pools that have substantial vertical separation and different trap types; for example, we separate the shallower, stratigraphically trapped *Waha: Delaware* and *Waha, West: Delaware* fields from the deeper, structurally trapped *Waha: Deep* and *Waha, West: Ellenburger* fields of Texas R.R.C. District 8.

We derived the field lists of App. A by applying these definitional criteria to existing field data, combining an extensive examination of field and pool maps with a consideration of trap type and pool depths. In so doing, we encountered two problems—ambiguity and lack of data. Ambiguity in field composition was a major problem in defining the fields of the Central Basin Platform in southeastern New Mexico and Texas R.R.C. District 8 and a minor problem in the Arkoma Basin of northwestern Arkansas and southeastern Oklahoma and in the Gulf Coast Province. For the Central Basin Platform, we followed a moderately conservative approach, choosing not to combine all of the overlapping pools that form a continuous productive area as seen in plane view but differentiating among fields by dominant trapping features.

In the San Juan Basin of southwestern Colorado and northwestern New Mexico, a natural ambiguity existed that convinced us to resort to an anomalous field designation. The gas fields of the northeastern corner of the basin in northwestern New Mexico are overlapping stratigraphically trapped pools with more than 1000 feet of vertical separation among pools, a difference that clearly merits the separate field designations used here for the *Blanco: Mesa Verde, Basin: Dakota,* and the various Pictured Cliffs formation fields. However, the continuations of the Mesa Verde and Dakota pools into Colorado are primarily located on the Ignacio Anticline and thus constitute one field following common usage (designated as the *Ignacio-Blanco* field in this report). Because both the *Blanco: Mesa Verde* and *Basin: Dakota* fields are in our largest field size category, we decided to let this anomaly stand as it did not affect aggregations by field size.

We encountered two definitional problems because of a lack of pool data in several areas. First, in Oklahoma, we were constrained to define fields according to accepted usage although a few appear to be common administrative designations for sets of laterally distinct pools, such as the *Golden Trend* and *Sooner Trend* fields. Second, in North Central Texas, where most of the oil and gas is in the so-called County Regular fields, we may have omitted several significant fields because we included only those parts of the County Regular fields where we could determine positively approximate field sizes for a set of closely related pools, for example, the *Breckenridge* and *Ranger* fields of Texas R.R.C. District 7B and the *Burkburnett* and *Electra* fields of Texas R.R.C. District 9. Because of these problems, there is a slight understatement of the total amount in significant fields and a slight overstatement of the amount in the larger significant fields.

We use traditional field names in the lists wherever possible. When two or more traditional fields are combined, we usually designate the combined field either by the name of the largest traditionally designated field, for example, *Wilmington*

Trend, *Yates*, and *Bayou Sale*, or in a hyphenated name, combining (1) the names of the largest traditional field designations, for example, *Blinebry-Drinkard* and *Means-McFarland;* (2) the names of all the components, for example, *Brea-Olinda-Sansinena* and *McElroy-Dune;* or (3) the names of the two components on opposite ends of a continuous producing trend, for example, *Ventura-Rincon* and *Penwell-Waddell.* We identify some combinations by the name of the largest component with a descriptive modifier, for example, *Eunice Area, Big Piney-La Barge Complex,* and *Greater Red Wash.* Fields consisting of a combination of pools with a central pool or pools and additional pools of the same name plus a compass direction (e.g., east, southwest) are designated as, for example, *Magnet Withers* (all). Where a traditionally designated field of several pools is divided into several fields in this report, we list the new field by the old name plus (1) the pool name, for example, *Empire: Abo,* (2) a designation combining several pools sharing a common characteristic, for example, *Waha: Deep,* or (3) the name of a productive area, for example, *Honor Rancho: Main* and *Honor Rancho: Southeast.* Wherever possible, we use the field designations of the Conservation Division of the U.S. Geological Survey for offshore fields in the Gulf of Mexico. When a Conservation Division designation does not exist, a category limited to fields that had not begun production by the end of 1979, we designate the field by the number of the most important block in the field.

FIELD SIZE CLASSIFICATION

The second method we used to organize data is by field size, as expressed in volumes of recoverable petroleum. A field size classification system provides a means of aggregating sets of similarly sized fields for a variety of analytical purposes. Currently, one existing system of field size classification and two field size designations are commonly used in the United States. The existing system of field size classification is that of the American Association of Petroleum Geologists (AAPG), as shown below:

Class A	Over 50 million barrels or 300 billion cubic feet
Class B	25 to 50 million barrels or 150 to 300 billion cubic feet
Class C	10 to 25 million barrels or 60 to 150 billion cubic feet
Class D	1 to 10 million barrels or 6 to 60 billion cubic feet
Class E	Less than 1 million barrels or 6 billion cubic feet
Class F	Noncommercial

The two field size designations commonly in use in the United States are those of world-class giant fields (500 million barrels or more)[6] and national-class giant fields (100 million barrels or more).[7]

[6] For representative samples of the use of the world-class designation, see J. D. Moody, J. W. Mooney, and J. Spivak, "Giant Oil Fields of North America," in Halbouty (ed.), *Geology of Giant Petroleum Fields*, pp. 8-27; M. T. Halbouty et al., "World's Giant Oil and Gas Fields: Geologic Factors Affecting Their Formation and Basin Classification," in Halbouty (ed.), pp. 502-555; A. A. Meyerhoff, "Economic Impact and Geopolitical Implications of Giant Petroleum Fields," *American Scientist*, Vol. 64, No. 5,

The AAPG classification system was inadequate for the purpose of analyzing the distribution of oil and gas resources by size of field. Our preliminary analysis indicated that more than 75 percent of the oil and gas discovered to date in the United States was in AAPG Class A fields, a concentration that did not permit analysis with a high degree of discrimination. Moreover, the AAPG system appears to apply only to amounts of crude oil or only to amounts of natural gas, not to the combined amounts of recoverable petroleum in a field. Nonetheless, the system did provide a useful starting point. The field size classification system we used (see Table 2.2) essentially combines the AAPG classification system with the two commonly used field size designations.

We expanded the AAPG field size classification system by making the size limits of Class A fields double that of Class B fields, creating a new classification of Class AA fields with size limits twice that of Class A fields, making world-class giant fields the largest category (Class AAAA), and designating fields between the limits of Class AA and Class AAAA as Class AAA. Further division of the giant fields category (Class AAAA) was considered unnecessary because of the small number of fields in this category.[8] We limit the designation of a *giant* field to world-class giants (Class AAAA fields). *Large* fields are Class AAA, Class AA, and Class A fields. *Small* fields are Class B and C fields. *Very small* fields are Class D and E fields.

The AAPG considers fields of Class D or larger to be significant. Here we limit significant fields to fields of Class C or larger. Our preliminary analysis indicated that fields of Class C or larger had more than 90 percent of the known recoverable oil and natural gas resources of the United States. Including Class D fields in the analysis would add no more than 8 percent of known recoverable amounts of oil and gas at a cost of doubling to quadrupling the task of data collection. The marginal benefit of additional data was not considered to be worth this additional cost. In a few cases, we included Class D components of a field combined from several traditionally designated separate fields in the data base.

As Table 2.2 shows, our size classification system refers to the combined total of recoverable petroleum—crude oil, natural gas, and natural gas liquids—from a field. To use a common denominator of field size, we converted natural gas to liquid equivalents at the standard rate of 6000 cubic feet per barrel.

FIELD SIZE DETERMINATION

The fields listed in the tables of App. A are organized by field size classes and ranked in approximate order of decreasing field size. We estimated original field

September-October 1976, pp. 536-541; H. D. Klemme, "Giant Fields Contain Less Than 1% of World's Fields But 75% of Reserves," *Oil and Gas Journal*, Vol. 75, No. 10, March 7, 1977; and R. Nehring, *Giant Oil Fields and World Oil Resources*, The Rand Corporation, R-2284-CIA, June 1978.

[7] For representative samples of the use of the national-class designation, see M. T. Halbouty, "Giant Oil and Gas Fields in the United States," in Halbouty (ed.), *Geology of Giant Petroleum Fields*, pp. 91-127; and the listing of U.S. giant oil fields published annually in the Forecast/Review issue of the *Oil and Gas Journal* (generally the last issue in January).

[8] In *Giant Oil Fields and World Oil Resources*, p. 30, Nehring proposed a classification system consisting of super-giants (5 billion barrels or more), large giants (2 to 5 billion barrels), medium giants (1 to 2 billion barrels), and small giants (500 to 1000 million barrels). Because the United States has only three super-giant, three large giant, and twenty-one medium giant fields, applying this system here would be an unnecessary proliferation of categories.

Table 2.2

FIELD SIZE CLASSIFICATION SYSTEM

Field Size Category	Field Size
Class AAAA	500 million barrels or more of petroleum liquids and natural gas expressed in liquid equivalents[a]
Class AAA	200 to 500 million barrels
Class AA	100 to 200 million barrels
Class A	50 to 100 million barrels
Class B	25 to 50 million barrels
Class C	10 to 25 million barrels
Class D	1 to 10 million barrels

[a]We use a conversion rate of 6000 cubic feet per barrel. For example, 500 million barrels is equivalent to 3.0 trillion cubic feet, 200 million barrels to 1.2 trillion cubic feet, 100 million barrels to 600 billion cubic feet, and so on.

size from data available as of the end of 1978 for all significant fields discovered by the end of 1975. We used the three-year difference between the year of field size determination and the last year of discovery for fields included in the data base to permit more accurate assessments of the size of recent discoveries, particularly those offshore in the Gulf of Mexico. To maintain consistent treatment of all fields, the sizes of earlier discoveries were also determined as of the end of 1978.

The estimates of field size we used to classify and rank fields in the tables of App. A are strictly estimates of current known total recovery in these fields. Known total recovery is the sum of cumulative production, proved reserves, and indicated additions to reserves. The estimates used do not necessarily indicate ultimate recovery from each field. Field size may increase from extensions of known pools, new pool discoveries, infill drilling, implementation of additional recovery operations, and better-than-anticipated reservoir performance. Field size may also decrease because of poorer-than-anticipated reservoir performance. Because all of these factors are fundamentally uncertain, we made no attempt in determining field sizes to predict their combined effect on ultimate recovery. The effect of this procedure is to make our field size determinations conservative. Some fields are placed in smaller categories than their ultimate production will eventually justify. We excluded other fields from the data base altogether, the estimate of their current known size not being large enough to justify inclusion now, even though some evidence exists that points to ultimate inclusion in a list of significant fields.

Field size is based on the combined total of known recoverable petroleum—crude oil, natural gas liquids, and natural (hydrocarbon) gas expressed in liquid equivalents—in each field. In determining field size, we used the same definitions of crude oil, natural gas, and natural gas liquids that are used by the American

Petroleum Institute (API) and the American Gas Association (AGA).[9] Volumes of *crude oil* are as measured in stock tank barrels of 42 U.S. gallons, excluding water and bottom sediment and including condensate from casinghead gas recovered in lease separators with crude oil. *Natural gas* consists of methane, ethane, small proportions of natural gas liquids, and small proportions of nonhydrocarbons such as carbon dioxide, helium, hydrogen sulfide, and nitrogen. The volumes are as measured in cubic feet at 14.73 pounds per square inch absolute pressure and 60° F temperature. Natural gas volumes are also as measured after shrinkage of the reservoir gas volume that results from removal of its liquifiable portions and any reduction in volume caused by the exclusion of nonhydrocarbon gases existing in sufficient quantity to render the gas unmarketable. Natural gas volumes include produced gas that was vented or flared. In estimating field size, we use a single estimate for natural gas, combining natural gas associated with or dissolved in crude oil and nonassociated natural gas. *Natural gas liquids* are those hydrocarbons in the reservoir natural gas that are separated from the natural gas as liquids in the reservoir through retrograde condensation or at the surface through condensation, absorption, or adsorption. Generally, natural gas liquids consist of propane and heavier hydrocarbons. When ethane is recovered as a liquid, it is also included.

We determined field sizes primarily using data on cumulative production and proved reserves plus indicated additions to reserves or, when reserve data were not available, estimates of reserves based on recent decline rates and inferred reserve-to-production ratios. Preliminary estimates of field size were compared with and adjusted to the data of the API and AGA tables of known recovery by year of discovery. We supplemented this basic information where necessary with statements of production plans, time series of annual production data, gas-oil ratios, gas analyses, liquid-gas ratios, shrinkage factors, and natural gas plant production data. After we made initial estimates of field size, we compared the sum totals of crude oil, natural gas, and natural gas liquids in the significant fields of each state and statistical area and an estimate of the amounts in nonsignificant fields with the API and AGA estimates of known total recovery in each state and statistical area. These supplemental data sources and data checks were essential to overcome major gaps in the usual sources of published data on current cumulative production, recent annual production, and reserves.

In some cases, no current estimate of cumulative production by field as defined in this report was available. Where sufficient information existed—such as historic cumulative production data from a larger unit (e.g., a county), time series of annual production from a field for some portion of its history, or a past estimate of cumulative production or reservoir data—that would enable us to make an estimate with a probable error no greater than ± 10 percent, we included the field in the list. After extensive research of historic production data, we identified 20 fields that compose part of the so-called County Regular fields of North Central Texas: *Breckenridge, Ranger, Desdemona, Cooke, Curry, Strawn, Noodle Creek, Stover, Fry, Bluff Creek, Cross-Cut,* and *Pioneer* in Texas R.R.C. District 7B, and *Burkburnett, Electra, Nocona, Anarene, Landreth, Petrolia, Iowa Park,* and *South Bend* in Texas R.R.C.

[9] American Petroleum Institute, American Gas Association, and Canadian Petroleum Association, *Reserves of Crude Oil, Natural Gas Liquids, and Natural Gas in the United States and Canada as of December 31, 1978,* Washington, D.C., June 1979, pp. 13, 99-104.

District 9; and 37 fields in the Mid-Continent: *Humboldt-Chanute, Peru-Sedan, Jefferson-Sycamore, Wayside-Havanna, Coffeyville-Cherryvale, Iola, Neodesha, Buffalo-Vilas,* and *Bush City* in Kansas, *Red River Bed, Bartlesville-Dewey, Bird Creek-Flat Rock, Coody's Bluff-Alluwe-Chelsea, Delaware-Childers, Osage City, Slick, Duncan West, Hogshooter, Bristow, Depew, Canary-Caney, Empire-Comanche, Loco District, Iron Post, Osage-Hominy, Mannford District, Kellyville, Collinsville, Oscar, Beggs District, Boston, California Creek, Bristow North, Hubbard, Olive, Avant West,* and *Nowata-Claggett* in Oklahoma. These 57 fields include all of the prominent early discoveries mentioned in the literature about these two regions. We would not be surprised, however, if a few other fields in these two regions could be shown to belong in our list of significant fields, particularly if they were Class C fields that were predominantly natural gas producers.

Obtaining complete information on natural gas recovery was a major problem in some areas. Information on cumulative production of casinghead gas does not exist for most fields in Illinois, Indiana, Kansas, New Mexico, Oklahoma, and Texas. We based our estimates for these fields on available information on gas-oil ratios, production time series, and a judicious use of the API and AGA tables on known recovery by year of discovery. This approach produced consistent and generally satisfactory results, except for oil fields in Oklahoma with substantial gas caps. We estimated that there was approximately 6.3 trillion cubic feet of gas cap or associated gas in Oklahoma that belonged in significant fields but that we were unable to allocate among individual fields. Information on cumulative production of nonassociated gas does not exist for most of the fields in Texas. However, because annual production data are available for the past 30 to 40 years, we estimated current cumulative production by assembling time series of the annual production data. In all areas, we used supplemental data to adjust estimated cumulative production data for shrinkage, removal of nonhydrocarbon gases, and reinjection of produced gas.

In nearly every area, readily available comprehensive data on natural gas liquids by field are lacking. In many states, good information on lease condensate production can be found. Plant liquids data are only rarely available in comprehensive form. As a result, our estimates of natural gas liquids by field were pieced together using gas analyses, liquid-gas ratios, fragmentary plant production data, the available lease condensate data, and AGA information on cumulative production and reserves by area. As a result, our estimates in significant fields are slightly conservative on average.

Estimating the size of recent discoveries, most of which are only now beginning production, poses its own particular problems. Because published estimates of peak production are available for most recent discoveries, we generally used peak production times a conservative reserves-to-production ratio to determine field size. For some of the recent discoveries in the Gulf of Mexico, our estimate of field size is based on information from field operators, such as their estimates of field size class, peak production, and field life. When we could make only rough estimates of field size, as is the case for most of the recent offshore discoveries, we placed the field in its approximate position in its size class. Where information was very sketchy, we listed fields at the bottom of the size class in which we judged them to fit.

Except for many of the recent discoveries and a few cases of marginal information, we believe that our field size estimations are accurate as current estimates of known recovery within a range of ± 5 percent. Because of this estimated error factor, we did not differentiate field sizes by more than one-half million barrels of liquids or gas in liquid equivalents except for Class C fields that were nearly or totally depleted. Fields estimated to be of roughly the same size are listed in alphabetical order in the tables. Because we deliberately employed several conservative biases in estimating field size, fields that were on the borderline between two size categories were always placed in the higher of the two categories, partially offsetting the bias in estimation.

Our first list of significant oil and gas fields, compiled after several thorough reviews of the available data, contains 2471 fields. In arriving at this number of significant fields, we also determined field sizes for more than 500 fields between 6.25 and 10.0 million barrels' liquid and liquid equivalents to examine thoroughly all borderline possibilities. Assuming current estimates of recovery, we estimate that our list is at least 99 percent complete for the United States, excluding the Appalachian region. In other words, there is a high probability that additional research would add no more than 25 fields to the list of significant fields discovered before 1976 (excluding fields added from reserve growth after 1978). Because of the varied quality of information among regions, any fields inadvertently omitted from our list are most likely to be Class C fields in North Central Texas (components of the County Regular fields), the Mid-Continent (pre-1920 discoveries), the Western Gulf (pre-1940 gas discoveries), and the Gulf of Mexico (recent discoveries that are not yet producing).

Our estimates of the amount of petroleum in these 2471 significant fields are slightly conservative. Our individual field estimates total 134,880 million barrels of crude oil, 650,467 billion cubic feet of natural gas, and 20,309 million barrels of natural gas liquids. However, on the basis of the cross-checking procedures that we used, we estimate that there are at least another 150 million barrels of crude oil, 12,978 billion cubic feet of natural gas, and 1920 million barrels of natural liquids in significant fields that we were unable to allocate to specific significant fields. On average, this represents an underestimate of 1.6 percent of the total recoverable petroleum in significant fields. The largest absolute underestimate was in the Mid-Continent region (150 million barrels of crude oil, 6300 billion cubic feet of natural gas, and 300 million barrels of natural gas liquids, or an average underestimate of 3.3 percent). The largest proportional underestimate was in North Central Texas (600 billion cubic feet and 80 million barrels of natural gas liquids, or an average underestimate of 4.5 percent).

GEOLOGIC PROVINCE

A producing petroleum province is defined as a set of oil and gas fields that are geographically contiguous and that occur in a similar or related geologic environment.[10] Petroleum exploration in an area generally begins with an overall evaluation of a known or potential province before focusing on specific plays and prospects within that province. Including the geologic province in which each signifi-

[10] Levorsen, *Geology of Petroleum*, p. 31; and Hobson and Tiratsoo, *Introduction to Petroleum Geology*, p. 6.

cant field is located within the data base permits aggregation of the data by a basic geologic unit in addition to the political-statistical units that we use to organize the tables of significant field data in App. A.

Table 2.3 breaks down the productive petroleum provinces of the United States by region. The left-hand column lists those provinces containing significant oil and gas fields as given in the tables of App. A. The abbreviation of the state or statistical unit containing the significant oil and gas fields in each province is included in parentheses following the province name. Because our listing in the left-hand column is derived with minor modifications from the list of provinces developed by the American Association of Petroleum Geologists—Committee on Statistics of Drilling (AAPG-CSD),[11] we include the AAPG-CSD list of provinces with their appropriate code numbers in the right-hand column. The AAPG-CSD provinces listed in brackets at the end of the regional listings are productive provinces that lack significant oil and gas fields in that region. The indented provinces in the left-hand column that have no counterparts in the right-hand column are distinct geologic subunits of five larger provinces: the Coastal basins of California, the Powder River Basin, the Greater Green River Basin, the Permian Basin, and the Palo Duro Basin. In particular, the Permian and Green River basins are divided into their individual components because of their large area and complex geology. The subdivisions are from K. K. Landes.[12]

Our listing and boundaries of the provinces differ from the AAPG-CSD listing and boundaries in only two respects: (1) The AAPG-CSD list has separate designations for offshore areas. Our listing combines onshore provinces (Ventura, Los Angeles, and Gulf Coast basins) with their offshore continuations because the two constitute one geologic unit. The AAPG-CSD approach imposes an additional geographical-political distinction on the geologic boundaries. In the tables of App. A, fields that are partially offshore are designated by a single asterisk and fields that are wholly offshore are designated by a double asterisk. (2) The AAPG-CSD listing adjusts province boundaries to county boundaries to avoid potential reporting problems. Generally, this poses no problem, because county boundaries closely approximate geologic boundaries in nearly all cases. However, in a few instances, the two diverge noticeably. To conform with geologic boundaries, we made the following adjustments to the AAPG-CSD boundaries: (1) combined the southern part of Santa Barbara County and the northwest part of Los Angeles County (CA) with the Ventura Basin; (2) included Blaine County (MT) in the Sweetgrass Arch; (3) added the eastern half of Natrona County (WY) to the Powder River Basin; (4) split off the Laramie Basin from the Greater Green River Basin, the former consisting of Albany County and the eastern half of Carbon County (WY); (5) added the western third of Carbon County (UT) to the Wasatch Uplift; and (6) included the Matador Arch, that is, the southern part of Lamb and Hale counties (TX 8A), in the Permian Basin.

DISCOVERY YEAR

We include the discovery year of each significant field in the data of App. A to

[11] R. F. Meyer, "Geologic Provinces Code Map for Computer Use," *The American Association of Petroleum Geologists Bulletin*. Vol. 54, No. 7, July 1970, pp. 1301-1305.

[12] *Petroleum Geology of the United States*, Wiley-Interscience, New York, 1970.

Table 2.3

Productive Geologic Provinces of the United States by Region

This Report	AAPG-CSD
Region 1: ALASKA	
Cook Inlet (AK)	820: Cook Inlet Basin
Arctic Foothills (AK)	885: Arctic Foothills Province
Arctic Slope (AK)	890: Arctic Slope Basin
	[810: Gulf of Alaska Basin]
Region [illegible]: CALIFORNIA	
Eel River (CA-CN)	720: Eel River Basin
Sacramento (CA-CN)	730: Sacramento Basin
Coastal (CA-CC)	740: Coastal Basins
Cuyama (CA-CC)	
Salinas (CA-CC)	
San Joaquin (CA-CN)	745: San Joaquin Basin
Santa Maria (CA-CC)	750: Santa Maria Basin
Ventura (CA-CC)	755: Ventura Basin
Los Angeles (CA-LA)	760: Los Angeles Basin
	957: California Pacific Offshore--General
	958: California Pacific Offshore--State
	959: California Pacific Offshore--Federal
	[710: Western Colombia Basin]
	[725: Northern Coast Range Province]
	[735: Santa Cruz Basin]
Region [illegible]: ROCKY MOUNTAINS	
Anadarko (CO)	360: Anadarko Basin
Chadron-Cambridge (NE)	390: Chadron Arch
Williston (MT + ND)	395: Williston Basin
Las Animas Arch (CO)	450: Las Animas Arch
Sweetgrass Arch (MT)	500: Sweetgrass Arch
Central Montana Uplift (MT)	510: Central Montana Uplift
Powder River (MT + WY)	515: Powder River Basin
Casper Arch (WY)	
Big Horn (MT + WY)	520: Big Horn Basin
Wind River (WY)	530: Wind River Basin
Greater Green River (CO-UT-WY)	535: Green River Basin
Great Divide (WY)	
Overthrust Belt (UT + WY)	570: Uinta Uplift
Rawlins Uplift (WY)	
Rock Springs Uplift (WY)	
Sand Wash (CO-WY)	
Wamsutter Arch (WY)	
Washakie (WY)	
Laramie (WY)	535: Green River Basin

Table 2.3—continued

Denver (CO, NE, + WY)	540:	Denver Basin
Uinta (UT)	575:	Uinta Basin
San Juan (CO + NW NM)	580:	San Juan Basin
Paradox (CO + UT)	585:	Paradox Basin
Black Mesa (AZ)	590:	Black Mesa Basin
Piceance (CO)	595:	Piceance Basin
Wasatch Uplift (UT)	630:	Wasatch Uplift
Plateau: Kaiparowits (UT)	635:	Plateau Sedimentary Province
	[335:	Forest City Basin]
	[380:	Salina Basin]
	[545:	North Park Basin]
	[625:	Great Basin Province]
Region 4: PERMIAN BASIN		
Permian (SE NM-TX 7C, 8, + 8A)	430:	Permian Basin
Central Basin Platform (SE NM-TX 7C, 8, 8A)		
Delaware Basin (SE NM-TX 8)		
Eastern Shelf (TX 7C, 8, + 8A)		
Horseshoe Atoll (TX 8 + 8A)		
Matador Arch (TX 8A)	435:	Palo Duro Basin
Midland Basin (TX 7C, 8, + 8A)		
North Basin Platform (SE NM + TX 8A)		
Northwest Shelf (SE NM)		
Ozona Platform (TX 7C)		
San Simon Channel (SE NM)		
Sheffield Channel (TX 8)		
Tatum Basin (SE NM)		
Val Verde Basin (TX 7C, 8)		
	[420:	Llano Uplift]
Region 5: NORTH CENTRAL TEXAS		
South Oklahoma (TX 9)	350:	South Oklahoma Folded Belt Province
Strawn (TX 7B)	415:	Strawn Basin
Fort Worth (TX 9)	420:	Fort Worth Syncline
Bend (TX 7B, 9)	425:	Bend Arch
Permian (TX 7B, 9)	430:	Permian Basin
Eastern Shelf (TX 7B, 9)		
Palo Duro (TX 9)	435:	Palo Duro Basin
Hardeman Basin (TX 9)		
Red River Arch (TX 9)		
Region 6: MID-CONTINENT		
Forest City (KS)	335:	Forest City Basin
Arkoma (OK)	345:	Arkoma Basin
South Oklahoma (OK)	350:	South Oklahoma Folded Belt Province
Chautauqua (OK)	355:	Chautauqua Platform
Anadarko (KS-OK-TX 10)	360:	Anadarko Basin
Cherokee (KS)	365:	Cherokee Basin
Nemaha (KS)	370:	Nemaha Anticline
Sedgwick (KS)	375:	Sedgwick Basin

Table 2.3—continued

Central Kansas (KS)	385:	Central Kansas Uplift
Palo Duro (OK)	435:	Palo Duro Basin
Amarillo (TX 10)	440:	Amarillo Arch
	[325:	Iowa Shelf]
	[380:	Salina Basin]
	[400:	Ouachita Tectonic Belt Province]
	[430:	Las Animas Arch]
Region 7: WESTERN GULF		
Gulf Coast (TX 1, 2, 3, + 4)	220:	Gulf Coast Basin
	954:	Texas Gulf of Mexico Offshore--General
	955:	Texas Gulf of Mexico Offshore--State
	956:	Texas Gulf of Mexico Offshore--Federal
Ouachita (TX 1)	400:	Ouachita Tectonic Belt Province
Permian (TX 1)	430:	Permian Basin
Region 8: CENTRAL GULF		
Gulf Coast (OFF, SE, + SW LA)	220:	Gulf Coast Basin
	951:	Louisiana Gulf of Mexico Offshore--General
	952:	Louisiana Gulf of Mexico Offshore--State
	953:	Louisiana Gulf of Mexico Offshore--Federal
Region 9: NORTHERN GULF		
Arkla (AR-N LA)	230:	Arkla Basin
East Texas (TX 5 + 6)	260:	East Texas Basin
Arkoma (AR)	345:	Arkoma Basin
Region 10: EASTERN GULF		
South Florida (FL)	140:	South Florida Province
Warrior (MS)	200:	Warrior Basin
Mid-Gulf Coast (AL, FL, MS)	210:	Mid-Gulf Coast Basin
Region 11: ILLINOIS-MICHIGAN		
Cincinnati (IN)	300:	Cincinnati Arch
Michigan (MI)	305:	Michigan Basin
Illinois (IL + IN)	315:	Illinois Basin
Region 15: APPALACHIAN		
Appalachian (KY, NY, OH, PA, VA, WV)	160:	Appalachian Basin
Cincinnati (OH)	300:	Cincinnati Arch
Illinois (KY)	315:	Illinois Basin

indicate *when* the field was first known to contain a commercial accumulation of petroleum. The inclusion of this variable is a necessary prerequisite for the analysis of discovery patterns by size of field over time found in Sec. IV.

There are several ways of conceiving the discovery year. It could be (1) the year in which the first well was completed that indicated the presence of recoverable petroleum, (2) the year in which the first producing well was completed and tested, (3) the year in which the first well was completed in the first significant pool, or (4) the year in which the first well was completed in the largest significant pool. In constructing the data base of App. A, we used the first concept for two reasons. First, this concept is the one that is most consistent with our theoretical approach emphasizing the exploration process. In comparison, the other three concepts also can incorporate development considerations, such as the state of the domestic oil market or the state of drilling technology. The difference between the first two concepts is a subtle but important one, particularly for offshore fields. Typically, exploratory wells in offshore fields are drilled, tested, and abandoned using mobile drilling rigs. The producing wells are only drilled after a fixed platform is installed. However, it is the successful exploratory wells that indicate that a fixed platform is worth installing; hence, the first of these exploratory wells merits the designation of the discovery well. Second, data are more readily available and more complete for the first concept than they are for the other three.

We encountered two problems in determining the discovery year of the significant fields listed in App. A: a lack of data and disagreements among sources. Several of the offshore fields discovered in the Gulf of Mexico since 1965 have no discovery year listed in the literature because successful discoveries are frequently not announced when there are one or more unleased tracts adjacent to the discovery tract. In such cases, we inferred the discovery year by considering the year in which the tract was leased, the year(s) in which exploratory wells were drilled, and the year(s) in which production platforms were ordered and installed.

For approximately 5 to 10 percent of the fields listed in App. A, the various sources that we consulted gave different discovery years for the same field. For most of these fields, the difference was only one or two years. For a few, nearly all of which were discovered before 1920, the differences among sources exceeded ten years. Because it was impossible in most cases to verify the sources to ascertain the "true" discovery year, we adopted the policy of relying first on the official state oil and gas commission determinations; second, on the International Oil Scouts Association determinations; and finally, on whatever other sources existed. We made exceptions to this general rule when other sources provided a description of the discovery well or of the exploratory history of the field that satisfied the criterion of the discovery year and was deemed sufficiently detailed to override conflicting designations by the state oil and gas commission or the International Oil Scouts.

Some fields cross state or statistical area boundaries, and they are listed in two or more of the tables of App. A. Because we generally use the official state determination of the discovery year, the discovery year of the separate areas of the field may differ, reflecting the year in which the field was discovered in each state. In such cases, the earlier of the separate discovery years is also given in parentheses below the year in which the discovery was made. In the analyses by region of discovery patterns over time, we use the earliest year exclusively. When a field is combined from several components, each with different names, and data for the components are listed as well, the discovery year for each component indicates when that component was discovered; the discovery year for the entire field indicates when the first component was discovered.

DISCOVERY METHOD

The method(s) used to discover each significant field are included in the data of App. A to show *how* the field was discovered, that is, the means that were used to determine the location of the discovery well. The analysis of discovery methods reveals the interplay over time among the geologic characteristics of fields, the state of exploration technology, and the state of general geological knowledge.

Table 2.4 lists the discovery method designations used in App. A and a brief description of each. The ten methods are grouped here into three general categories: pre-scientific methods, methods using a scientific evaluation of surface evidence, and methods using a scientific evaluation of subsurface evidence.

Our principal problem in determining discovery methods for the fields listed in App. A was a lack of data, particularly for recent offshore discoveries. Although we used a wide selection of sources to obtain field information, the data were not always complete. Sources included the Petroleum Data System, the *International Oil Scouts Annual Report*, the annual surveys of exploration in the United States

Table 2.4

FIELD DISCOVERY METHODS

Method	Description of Means of Location
	Pre-Scientific
Random	Random or "wildcat" location; no scientific evidence used
Trend	Perceived geographic or physiographic relationship to a known adjacent field or fields
	Surface Evidence
Surface	Structural mapping and other evaluations of surface geology
Seepage	Presence of oil and/or gas seepages or oil-impregnated rocks on the surface
Geo-chemistry	Soil analysis for microseeps
Photo-geology	Geologic interpretation of aerial or satellite photographs
	Subsurface Evidence
Seismic	Interpretation of reflection or refraction seismic surveys
Geophysics	Interpretation of geophysical surveys other than seismic, namely, gravity and magnetic surveys
Core-drilling	Core-drilling for subsurface structural and stratigraphic information
Subsurface	Mapping and evaluation of subsurface geology

published in the *American Association of Petroleum Geologists Bulletin*, guidebooks, and journal and symposia articles. In some cases where no information was available, the discovery method(s) could be inferred with a high degree of accuracy. For example, the discovery methods for fields found offshore in the Gulf of Mexico since 1960 (the area where published data were most incomplete) are almost invariably seismic or seismic and subsurface geology. However, we chose to give the discovery method(s) only when we could locate a definite source, as we found that conjectures were sometimes only partially correct.

In nearly every case, all of the methods used to discover a field that are listed in the various sources that we consulted are included in App. A. We adopted this general practice because the sources are not sufficiently detailed to permit us to make our own determinations of which discovery methods were employed and which were most important. There were two exceptions to this rule: (1) When the sources conflicted, listing the discovery as both random and based on a positive method of location, we excluded the "random" location on the grounds that it was logically incompatible with a positive method of location. (2) In a few cases, where a detailed history of the exploration process before the discovery of the field was available, we used it to make our own determinations of the methods used to discover the field.

TRAP TYPE

We include the type of trap in which the petroleum has accumulated in each field to indicate the information that could have been available to explorationists before drilling. The evidence pointing to the existence of some traps is highly obvious, making them easy to discover. For others, it is extremely subtle, making them very difficult to discover. The evidence that in fact was available and was used to determine the location of the discovery well depends to a large degree on the state of geological knowledge and exploratory technology at the time of location. Traps that were unrecognized as a distinct type 50 to 75 years ago and that were impossible to locate with the exploratory technology of that period can be a basic objective of the geologist's search today and are moderately "obvious" to the full array of technologies used in the exploration process. Correlation of trap type with discovery patterns thus permits the formulation and testing of hypotheses about the role of knowledge and technology in the exploration process.

Table 2.5 presents the classification system of trap types used here and in the data of App. A. The system is a broad and simple one, reflecting the purposes of this report. The terminology follows standard American usage.[13] In App. A we give

[13] There are many classification systems of traps. The one used here generally follows that of Levorsen (*Geology of Petroleum*, Chaps. 6, 7, and 8), but also reflects the treatment in K. K. Landes, *Petroleum Geology*, 2d ed., John Wiley & Sons Inc., New York, 1959, Chaps. 10-14; Hobson and Tiratsoo, *Introduction to Petroleum Geology*, Chap. 4; and the usage of the PDS. The Levorsen system of classification lacks precision, particularly with respect to all the trap types lumped together as stratigraphic traps. The system of trap classification used in the Soviet Union is more precise because it distinguishes among stratigraphic, unconformity, diagenetic, and paleogeomorphic traps. (See A. A. Meyerhoff, *Petroleum Exploration in the Soviet Union and China*, Canadian Society of Petroleum Geologists and the University of Calgary, 9th Annual C.S.P.G. Seminar, Calgary, 1978, pp. 149-156.) We used the Levorsen system because it is the basis of nearly all U.S. field data and the Soviet classification system is unfamiliar to many.

Table 2.5

GENERAL AND SPECIFIC TRAP TYPES

General	Specific
Structural	Anticline
	Nose
	Fault
	Fracturing
	Salt dome
Stratigraphic	Facies change
	Porosity-permeability pinchout
	Organic reef
	Unconformity
	Tar seal
Hydrodynamic	Hydrodynamic
Combination	

both the general and specific trap type of each field. The general types are *structural* traps, *stratigraphic* traps, *hydrodynamic* traps, and any *combination* of two or more of these general types. Structural traps are traps formed by deformation of the reservoir rock and are differentiated by the type of deformation. *Anticlines*, which in the system used here include buried hills and deep-seated salt domes, are traps caused by folding of the reservoir rocks. Anticlinal *noses* are typically found in conjunction with other trap types, and we have listed them separately. *Fault* and *fracture* traps, as the name indicates, result, respectively, from faulting and fracturing of the reservoir rock. *Salt dome* traps are formed by an intrusion of evaporites under and through the reservoir rocks. Stratigraphic traps are created by a lateral variation in the reservoir lithology or by a break in its continuity. In this report, a *facies change* refers to a relatively sharp variation in lithology, such as is found in bar, channel, deltaic or dune sandstones, or in productive igneous lenses. A *porosity-permeability pinchout* signifies a more gradual change, including post-depositional changes resulting from differential cementation and dolomitization.[14] *Organic reefs* or bioherms indicate local (as opposed to blanket) organic carbonate deposits, usually steep-sided deposits of substantial thickness. *Unconformity* traps are created by a break in the geologic sequence, sedimentation being followed by uplift and erosion or at least a period of nondeposition. Where the erosion surface is the present surface and the seal to the reservoir is formed by solid petroleum fractions such as asphalt, we denote the trap as a *tar seal* trap. *Hydrodynamic* influences, generally found in association with anticlines, occur when water flowing through the reservoir rock displaces the petroleum from its normal crestal position in the trap.

[14] In nature, facies change and porosity-permeability pinchout traps are not sharply divided from each other. We maintain the distinction between them in the data base, following differences in field descriptions encountered in the literature. However, in our subsequent analyses we combine these two categories.

Each of these general and specific trap types is a pure type, indicating the essence of a single characteristic. Natural conditions, however, can be both highly complex and immensely variable. Our primary problem in determining trap type was dealing with this natural variability, because of the uneven quantity and quality of information available about the fields in the data base. Wherever possible, we based our determinations of trap type on subsurface field maps and detailed field descriptions. However, these were not always available, and we were forced to rely on the determinations of others without being able to judge whether they were correct and consistent with our own usage. The result is probably an overstatement of the number of structural and stratigraphic traps and an understatement of the number of combination traps. For example, obvious structural elements are present in most of the fields of the Gulf Coast. But important stratigraphic factors may also exist, even though they may have been overlooked in the early development of the field. On the other hand, subtle structural controls could be present in many of the stratigraphic traps of the Mid-Continent but may have been overlooked in the early years of development. The information in nearly all cases was sufficient to identify the dominant trapping feature. In some cases, it did not indicate secondary, but nonetheless important, trapping features. The only significant omissions in the data on trap type are those for some recent discoveries in the Gulf of Mexico.

GEOLOGIC AGE OF THE RESERVOIR ROCK

The geologic age of the reservoir rocks within each field listed in App. A serves two purposes of classification and aggregation for analyses of the exploration process. First, together with the trap type, geologic age helps us identify fields within the same exploration *play*—a subset of fields and prospects within a province with a common productive formation and the same type of trap. Second, geologic age provides a means of determining the relative importance of different geologic periods both within and among regions for petroleum accumulation. The geologic age of the reservoir rock is limited in two ways: It does not necessarily indicate the unit of geologic time during which the petroleum in the reservoir originated, and it does not necessarily indicate the unit of geologic time during which the petroleum migrated into the reservoir. Comprehensive, authoritative information about both the time of origination and the time of migration of petroleum in significant fields in the United States is lacking, primarily because the evidence for both is not always conclusive.

The geologic ages of the reservoir rocks of each significant field are given in the time-stratigraphic units of *system* and *series*, corresponding to the geologic time units of period and epoch. We decided that including the era was unnecessary because it is indicated unambiguously by the system. Geologic age could be broken down in even finer units, such as stages or even individual formations. We chose not to do so because as useful as this may be in elaborate analyses of individual provinces, such a level of detail was not germane to the broad-brush approach of this report. Moreover, because no common system exists for finer divisions than the series, the use of a finer system complicates comparisons among regions. The system and series names we used are those of the common North American system of the geologic time scale as codified by the American Association of Petroleum Geologists. Nomenclature for the various eras, systems, and series is listed in Table 2.6, together with code numbers for geologic age.

The major system and series of the reservoir rocks are provided for each significant field listed in App. A. We considered two ways of providing system and series data: (1) The system and series of all reservoirs within the field could be listed in declining order of importance of each system and series. (2) The system and series of individual reservoirs within the field could be listed in the declining order of importance of each reservoir. In the vast majority of cases, there is no difference between these two criteria. However, for those cases where there is a difference, we decided to use the first criterion. It was more in accord with our emphasis on

Table 2.6

TIME-STRATIGRAPHIC NOMENCLATURE

Era	System	Formal and Provincial Series	AAPC Code
Cenozoic			100
	Quaternary		110
		Holocene	111
		Pleistocene	112
	Tertiary		120
		Pliocene	121
		Miocene	122
		Oligocene	123
		Eocene	124
		Paleocene	125
Mesozoic			200
	Cretaceous		210
		Upper	211
		Gulf	212
		Lower	217
		Comanche	218
		Coahuila	219
	Jurassic		220
		Upper	221
		Middle	224
		Lower	227
	Triassic		230
		Upper	231
		Middle	234
		Lower	237
Paleozoic			300
	Permian		310
		Upper	311
		Ochoa	312
		Guadalupe	313
		Lower	317
		Leonard	318
		Wolfcamp	319
	Pennsylvanian		320
		Upper	321
		Virgil	322
		Missouri	323
		Middle	324
		Des Moines	325
		Atoka	326
		Lower	327
		Morrow	328

Table 2.6—continued

Era	System	Formal and Provincial Series	AAPG Code
	Mississippian		330
		Upper	331
		Chester	332
		Meramec	333
		Lower	337
		Osage	338
		Kinderhook	339
	Devonian		340
		Upper	341
		Chautauquan	342
		Senecan	343
		Middle	344
		Erian	345
		Lower	347
		Ulsterian	348
	Silurian		350
		Upper	351
		Cayugan	352
		Middle	354
		Niagaran	355
		Lower	357
		Alexandrian	358
	Ordovician		360
		Upper	361
		Cincinnatian	362
		Middle	364
		Champlainian	365
		Lower	367
		Canadian	368
	Cambrian		370
		Upper	371
		Croixian	372
		Middle	374
		Albertan	375
		Lower	377
		Waucoban	378
Precambrian			400

total field size and it avoided problems of geologic age designation in fields with many pools, none of which contained a major proportion of the field's total recoverable resources.

We define a major system and series of a single reservoir or a set of reservoirs as one containing at least 10 percent of the total recoverable petroleum liquids and gas in liquid equivalents within the field. For each significant field, no more than three different series are listed to avoid occasionally unwieldy listings. (Only a few oil and gas fields have been found in the United States in which more than three major series are represented in the reservoir rocks of the field.) The system and series are both listed in order of decreasing importance. In a few cases, this results in the smaller of two series in the more important system being listed ahead of a series in another system that is more important for total field resources. Here again, we considered that avoiding a cumbersome designation was worth a small lack of accuracy.

In determining the major systems and series of the reservoir rocks in individual fields, we were hampered by the lack of complete pool data for individual fields in

Illinois, Indiana, Kansas, Louisiana, Oklahoma, and Wyoming. Complete information does exist about which systems and series are represented in each field in these six states. The question is how to determine which of these are major and the relative importance of the major systems and series. We used existing information on pool thickness and area and whatever information we could glean from the literature on the absolute and relative importance of specific systems and series in an individual field. We believe the resulting determinations provide a reasonably accurate estimate of the most important system and series in each field and a somewhat less accurate estimate of the other major systems and series and their relative order of importance.

RESERVOIR LITHOLOGY

The lithology of the reservoir rock within each field, when combined with the geologic age of the reservoir rock, can provide an additional indicator of the important stratigraphic units for petroleum accumulation within an area or region. Conceptually, reservoir lithology could be treated in either of two ways. It could be indicated only by the primary constituent of the reservoir rock (e.g., "sandstone"), or it could be indicated by the primary constituent as modified by secondary constituents (e.g., "sandy limestone"). Because the first alternative is more consistent with our objective of avoiding unnecessary complications in the data base and because existing information does not permit nationwide consistency in applying the second alternative, we conform to the first alternative in describing the reservoir lithology in the tables of App. A.

The lithologies of the reservoir rocks in significant U.S. petroleum fields can be organized into three general categories:[15] (1) Fragmental or clastic rocks, aggregates of minerals and rock particles washed from areas that have been eroded, include *sandstone, siltstone,* and *shale.* In keeping with our practice of using broad, simple categories for our variables, sandstones include conglomerates, arkose, and granite wash. (2) Chemical reservoir rocks, formed from chemical or biochemical precipitates, include *limestone, dolomite, anhydrite, chalk,* and *chert.* (3) The few miscellaneous reservoir rocks are predominantly fractured or weathered *igneous* rock. Sandstone, limestone, and dolomite clearly predominate among the reservoir rocks in the significant fields of both the United States and other countries of the world.

Reservoir lithology is given by field in the tables of App. A in order of decreasing importance within the field as a whole. We list only the major lithologies, that is, those containing at least 10 percent of the total recoverable petroleum liquids and gas in liquid equivalents within each field. For each significant field, no more than three lithologies are listed. Where one lithology grades into another within the same reservoir or reservoirs in a field, we list both in estimated order of decreasing importance.

Generally, information on reservoir lithology by field is readily available. Again, our major problem was the lack of complete pool data for individual fields in Illinois, Indiana, Kansas, Louisiana, Oklahoma, and Wyoming. In southern Loui-

[15] For a more detailed discussion, see Levorsen, *Geology of Petroleum*, Chap. 3.

siana, where the reservoirs are all sandstone, this omission could easily be surmounted. In the other areas, we approached the problem in the same way as we did in determining geologic age in these areas. The results were similar, with reasonably accurate estimates of the major lithology in each field and somewhat less accurate estimates of other major lithologies and their relative order of importance.

SPATIAL LOCATION AND DIMENSION

One measure of spatial location (the depth to the top of major reservoirs) and two measures of spatial dimension (average net reservoir thickness and field acreage) are also provided by field in the data base. The depth to the top of major reservoirs and field acreage are particularly important for analyses of the discovery process. Depth is important because the petroleum industry only gradually acquired the ability to locate potential traps at depth and to drill to them. Record drilling depths did not exceed 5000 feet until 1909, 10,000 feet until 1931, 15,000 feet until 1938, 20,000 feet until 1949, and 25,000 feet until 1958. The ability to locate structural traps at such depths followed by several years the development of the ability to drill to them. Deeper discoveries have clearly been dependent on these advances in drilling and exploration technology. Field acreage is an important variable because it indicates the size of the exploratory target. Even when we assume the limiting case of random drilling without the use of scientific approaches to determine exploratory well locations, the fields that cover a larger surface area will tend to be discovered first. Rational approaches to exploration that emphasize the drilling of the largest structures first are likely to be even more efficient than the "random" approach in discovering the largest fields first.

Appendix A provides the average depth to the top of major reservoirs in each field. We define a major reservoir as one containing at least 10 percent of the total recoverable petroleum liquids and gas in liquid equivalents within the field. Our attempt to apply this concept uniformly nationwide was thwarted by the geological complexities of the Louisiana and Texas Gulf Coast, where many of the fields contain large numbers of small reservoirs. In such cases, we give the depth ranges of the important concentrations of reservoirs. For each significant field, we list the depths to the top of the major reservoirs or the depth ranges of the important concentrations of reservoirs in decreasing order of importance, with no more than three depths or depth ranges. The depths are rounded off to the nearest 100 feet, because closer accuracy is neither necessary nor uniformly attainable.

Again, our major problem in determining depth to the top of major reservoirs was the lack of complete pool data for individual fields in Illinois, Indiana, Kansas, Louisiana, Oklahoma, and Wyoming. We were plagued by the same problem in determining geologic age and reservoir lithology, and we tackled it in the same manner, using a broad variety of sources to identify the more important reservoirs. In the case of depth, the resulting determinations provide a reasonably accurate list of the depths of the more important reservoirs. The relative order of importance is probably less accurate. In some cases, particularly recent discoveries offshore, we could not obtain any information on depths to the tops of major reservoirs.

The average net reservoir thickness of the major reservoir in each field is also given in App. A. This variable can be usefully correlated with trap type, providing an indication of the range of thickness associated with various types of traps. It may in some cases provide a rough indicator of effective reservoir volume in the field when multiplied by field acreage. (It does not always do so because the area of individual reservoirs is not always coextensive with the area of the entire field.) We used average net thickness rather than gross thickness or total oil column to provide a more meaningful indicator of effective reservoir porosity in each field. Here also a major reservoir is defined as one with 10 percent or more of the total recoverable resources. We rounded off the numbers to the nearest five feet because closer accuracy was not uniformly attainable and not necessary.

There were several major problems in determining average net reservoir thickness. The information in most of the major sources is not always consistent, occasionally showing only gross thickness (thus overstating net thickness) or the thickness of perforated intervals (thus understating net thickness). Because verifying information in the sources was always difficult, and often impossible, some of the thicknesses given are probably not accurate. For some Gulf Coast fields with large numbers of relatively small reservoirs, no meaningful estimates were available. The lack of individual pool data for fields in Illinois, Indiana, Kansas, Louisiana, Oklahoma, and Wyoming also had adverse effects on accuracy. Data for recent offshore discoveries were rarely available.

We give the surface area of each significant field to the nearest 20 acres. Because well spacing is rarely less than 20 acres and because of uncertainties in measurement resulting from extrapolations from well-bore information, we thought that any attempt to be more precise would only provide a spurious sense of accuracy. The surface area for each field includes all known productive acreage, past and present. The main problem in determining surface area was a lack of information, particularly for more recent discoveries. For recent discoveries that are still being developed, either no published estimates exist or the ones that do are likely to have been rendered totally obsolete by further development since the estimate was published. The same problem applies to older fields that have recently been extended. To supplement published data on area, we used well counts, information on spacing, and recent field maps. When a field in this listing is a combination of two or more overlapping productive units but the extent of overlapping is unknown, we could not give an estimate for the total area.

PRODUCTION AND RESERVES

Appendix A provides information by field on cumulative and 1975 production and reserves of crude oil, natural gas, and natural gas liquids. These are included as rough indicators of field size. The estimates of cumulative and annual production of crude oil and natural gas are of wellhead production less reinjected amounts and, in the case of natural gas, less significant amounts of nonhydrocarbon gases. Consequently, a few of the estimates of cumulative and 1975 production of natural gas are negative numbers, more having been injected than produced. The estimates of natural gas production do not deduct subsequent shrinkage from the extraction of plant liquids. These estimates include volumes of produced gas that were vented or flared. The estimates of cumulative and annual production of natural gas liquids are specified as lease condensate, plant liquids, or both, depending on the extent of available information. The estimates of reserves of crude oil include additions to reserves as defined by the API.

The numbers in App. A are taken primarily from official or semiofficial sources such as the annual reports of state and federal oil and gas regulatory agencies, the annual reports on reserves of the API and AGA, and the annual review of the International Oil Scouts Association. They thus reflect both the strengths and the omissions of those sources. The 1975 production data for crude oil, natural gas, and lease condensate are complete because they are reported for all areas by field (except for casinghead gas in Illinois, Indiana, Kansas, and Oklahoma). Because production of natural gas liquids from plants frequently combines production from several fields, data by field for production of plant liquids are generally not available. Cumulative production data for crude oil are also complete. In some cases, namely, many old discoveries in the Mid-Continent and the fields composing part of the County Regular fields in North Central Texas, the cumulative production data are our own estimates. Their approximate character is indicated by a "c." for "circa." Cumulative production data for casinghead gas do not exist for most fields in Illinois, Indiana, Kansas, New Mexico, Oklahoma, and Texas. Published estimates of cumulative production data for nonassociated gas are not available for most fields in Texas. However, for some post-1945 discoveries, we were able to ascertain cumulative production of natural gas with confidence by constructing and summing annual time series of production.

Only the Alaska, California, Florida, and Montana agencies provide estimates of crude oil reserves by field. The API provides reserve estimates for the 100 fields with the largest amounts of reserves, and reserve and original oil-in-place data often can be reliably inferred from its tables on oil in place and total recovery by year of discovery. We supplemented these data with our own analysis of decline curves to provide nearly complete oil reserve data. Alaska and California are the only states that provide estimates of natural gas reserves by field. When the natural gas contains no appreciable liquids, reserve data can occasionally be inferred from the AGA tables on total recovery by year of discovery or estimated from decline curves. However, App. A does not contain many estimates of natural gas reserves because most gas fields do contain natural gas liquids, our information on gas liquids was often questionable, and the cumulative production data for gas do not exclude subsequent shrinkage from the extraction of plant liquids. Estimates of natural gas liquids reserves are only rarely available.

SUMMARY

We have shown that the significant oil and gas fields data base largely satisfies the criteria for an adequate data base stated at the beginning of this section. It is *nearly comprehensive*. Geographically, it includes all of the regions of the United States except the Appalachian region, which has only 3.6 percent of U.S. petroleum resources. The fields in the data base contain more than 92 percent of the petroleum discovered before 1976 in the United States outside of the Appalachian region. Thus, although the data base includes only 10 to 15 percent of all the oil and gas fields that have been discovered in the United States, it contains nearly all of the fields that have been and are most important for U.S. petroleum production and reserves. The data base is *well organized.* The data are or can be readily grouped by region, state or area, geologic province, and field size classification. Other groupings, such as by year of discovery or trap type, can be easily constructed. The data base is *consistently constructed.* We used a common field definition throughout, providing conceptually similar units of analysis. In constructing the data base, we defined the variables describing each field rigorously and employed them as consistently as possible, in view of the problems of data availability. The significant oil and gas fields data base provides a substantial amount of *detailed information* for evaluating the exploration process. The data base gives information on the year of discovery, the discovery method, the trap type, the geologic age of the reservoir rocks, the reservoir lithology, and the spatial location and dimensions of each field. Although minor omissions are unavoidable, these data are complete. Except for potential reporting errors in the primary sources from which the data base was derived, these data are also highly accurate and have been extensively researched, reviewed, and revised.

The limitations of the significant oil and gas fields data base are principally limitations in its potential uses. We designed it for national and regional analyses of the distribution of petroleum resources by field size classifications and of broad discovery patterns. The data base is also a useful tool for analysis of individual geologic provinces, both for identifying major exploratory plays within each province, and, to a large extent, assessing the significance of those plays. It is not sufficiently detailed for complete analyses of all plays in all provinces or for comprehensive studies of the importance of individual formations or lithologies. Such analyses would require that the data base be expanded to include smaller fields and more detailed field information. The data base also lacks the appropriate variables for detailed engineering studies of significant fields. Provided that use of the significant oil and gas fields data base is limited to purposes for which it was designed and is suitable, we believe that it provides a useful, reliable tool for analysis.

III. THE DISTRIBUTION OF U.S. PETROLEUM RESOURCES BY REGION AND FIELD SIZE

The primary purpose of this report is to demonstrate the utility of an analysis of the patterns of discovery of U.S. oil and gas fields by size of field over time for U.S. oil and gas resource assessment. However, understanding the significance of various regional and national discovery patterns requires some knowledge of the distribution of U.S. petroleum resources, both by region and by field size category. This knowledge is indispensable to the task of distinguishing between those discoveries that make a difference and those that are basically insignificant with respect to national petroleum resource assessment.

The purpose of this section is to present the basic facts of the distribution of known conventional U.S. petroleum resources by region and by field size category. Using the significant oil and gas fields data base (App. A) and other supplementary sources of information (including App. B), we outline the amounts of known recoverable crude oil, natural gas, and natural gas liquids in each of our 12 regions, indicate the relative importance of each region as a source of petroleum, identify the producing provinces of each region and estimate their absolute importance as sources of petroleum, summarize the distribution of crude oil and natural gas resources by field size category, and briefly indicate several key geologic characteristics of the significant fields in each region. We conclude with a national summary of the regional data. In an Excursus, we also examine several aspects of the distribution of petroleum resources by field size category in the productive petroleum provinces of the United States.

The petroleum resources of each region are stated in billions of barrels of recoverable crude oil and natural gas liquids and trillions of cubic feet of natural gas in all fields, significant or otherwise, discovered before 1976. The amounts are as determined in 1979, in order to allow sufficient time to establish the size of discoveries made in the early 1970s. The sizes of earlier discoveries are calculated on the same basis in order to include recent reserve changes. In general, our estimates of regional petroleum resources are closely comparable to the estimates of the American Petroleum Institute (cumulative production, proved reserves, and indicated additions to reserves of crude oil) and the American Gas Association (cumulative production and proved reserves of natural gas and natural gas liquids). We estimated slightly more crude oil in the Permian Basin (subsequently included by the API in its 1980 report), slightly more crude oil and natural gas in recent offshore discoveries in the Ventura Basin of California, and slightly more natural gas in the 1972 to 1975 discoveries in the Gulf of Mexico (because of API and AGA policy not to include reserves until a platform is being installed or a field has begun production). Each regional summary gives the absolute importance of that region, its proportional share of national petroleum resources, and its relative rank among regions. We indicate the overall importance of each region in terms of its total amount of known recoverable petroleum resources (cumulative production and demonstrated reserves) expressed in billions of barrels of liquids and liquid-equivalent (L&LE) resources. These estimates use a conversion factor of 6000 cubic feet of natural gas per barrel of petroleum liquids. We also show the relative composition by type of hydrocarbon (liquid or gas) of each region. The composition of each region is as defined in Sec. II.

For each region, we list the number of significant fields discovered before 1976. We also name fields in each region discovered before 1976 that are not included in the significant oil and gas fields data base, but nevertheless have a high probability of eventually being recognized as significant fields, including all fields between 9 and 10 million barrels' L&LE.

For each region, we summarize the distribution of known recoverable crude oil and natural gas resources by field size category. Estimation errors, especially the possible underestimation of the amount of natural gas in significant fields, are indicated as well. We do not include regional summaries of the distribution of natural gas liquids by field size category, because the lack of comprehensive natural gas liquids data and our conservative procedures for estimating field size led to numerous underestimates of the amount in significant fields. In general, the distribution of natural gas liquids by field size category in each region correlates closely with the distribution of natural gas by field size category.

We illustrate the distribution within each region in a series of figures showing the absolute amount in each field size category (the scale on the left), the proportional share of each size category in the regional total (the scale on the right), and the number of fields containing crude oil or natural gas in each significant field size category (the numbers in parentheses). Underestimates of the amounts in significant fields are indicated by cross-hatching on the amounts in nonsignificant (other) fields. Because both the total amounts and the distribution by size category vary substantially among regions, these figures do not use the same scales. We emphasize three points in our discussion of the distribution by field size: (1) the amount in giant fields (Class AAAA), (2) the amount in large and giant fields (Class A and larger), and (3) the amount in all significant fields. The distribution by field size in each major province of the region is briefly described in this section and subsequently elaborated in the Excursus.

For each region, we discuss briefly the dominant trap type or types in the significant fields of the region, the geologic age and lithology of the major reservoirs in these fields, the average net thickness of these reservoirs, and the average range of recoverable resources per acre. We also point out differences among the provinces of a region, if any.

ALASKA

According to data available as of 1979, the oil and gas fields of Alaska discovered before 1976 contained, when discovered, 10.73 billion barrels of recoverable crude oil (7.1 percent of the national total), 33.9 trillion cubic feet of natural gas (4.5 percent of the national total), and 0.41 billion barrels of natural gas liquids (1.7 percent of the national total). Despite its recent prominence following the discovery and development of the *Prudhoe Bay* field, Alaska only ranks eighth overall among the 12 regions of the United States as a source of conventional petroleum (seventh for crude oil, eighth for natural gas, and ninth for natural gas liquids). The total known recoverable liquid and liquid-equivalent petroleum resources of Alaska in

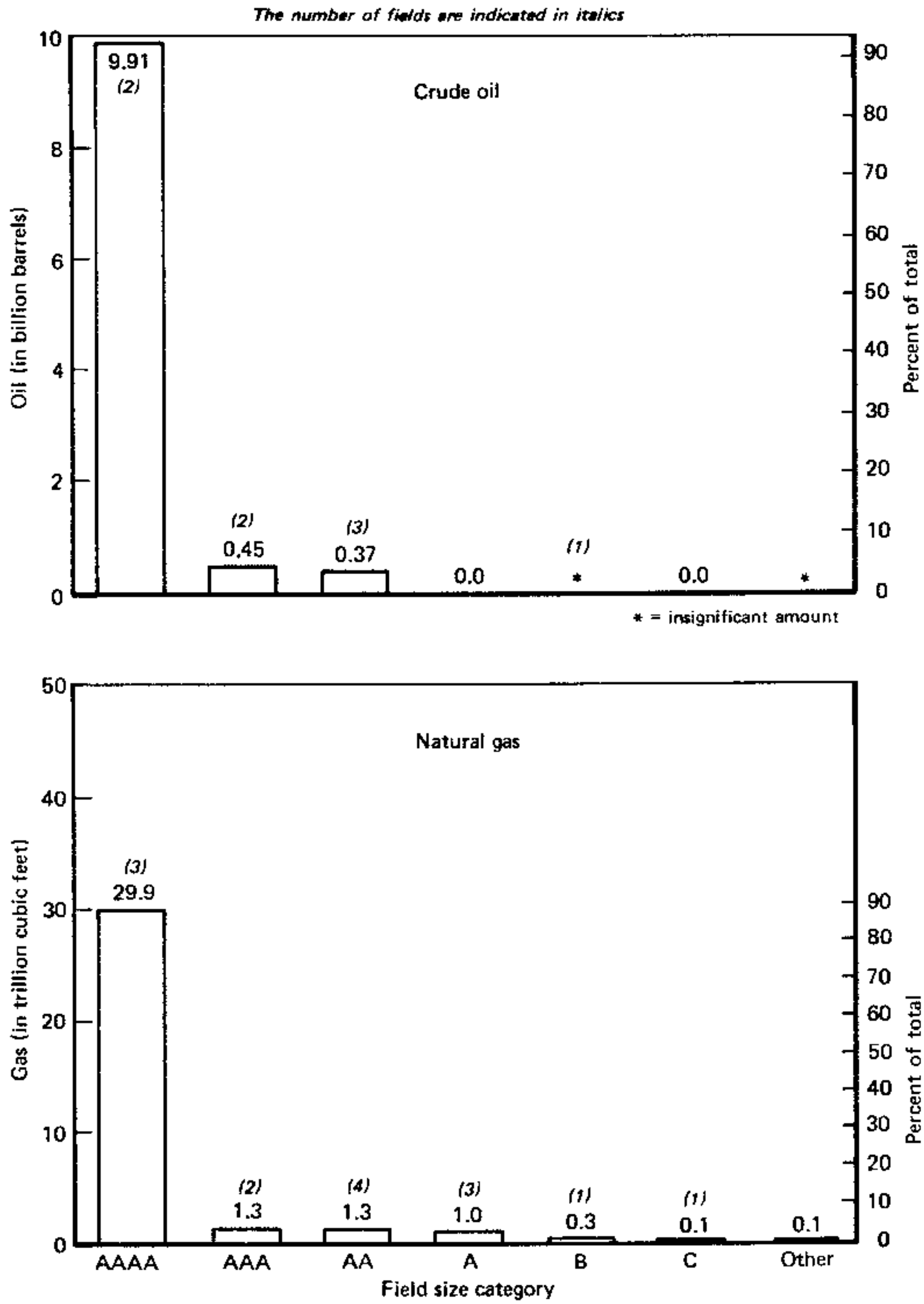

Fig. 3.1—Distribution of crude oil and natural gas by field size category in Alaska

fields discovered before 1976 are 16.78 billion barrels, 5.6 percent of the national total. The petroleum resources of Alaska are predominantly liquids, approximately two-thirds (66.4 percent) of the total being either crude oil or natural gas liquids. Of the amounts that have been discovered and made recoverable, 1.36 billion barrels of crude oil (12.7 percent of the total), 1.6 trillion cubic feet of natural gas (4.8 percent of the total), and 0.004 billion barrels of natural gas (1.0 percent of the total) had been produced by the end of 1978.

Oil and gas fields have been discovered in four different provinces of Alaska to date: the Arctic Slope, the Arctic Foothills, the Cook Inlet, and the Gulf of Alaska Basin. The productive areas of the Cook Inlet Basin extend offshore. The Arctic Slope predominates with 14.39 billion barrels' L&LE (85.7 percent of the total), the Cook Inlet ranks second with 2.30 billion barrels' L&LE (13.7 percent), and the Arctic Foothills ranks third with 0.10 billion barrels' L&LE (0.6 percent). Only negligible amounts have been found in the Gulf of Alaska Basin.

At least 15 significant oil and gas fields had been discovered in Alaska before 1976 (Table A.1). At least four more may be added to this list with further development, including *Umiat* (Class A-AA), *Simpson Seeps* (Class C), and *Gubik* (Class A) in the Arctic Slope Province, and *Moquawkie* (Class C) in the Cook Inlet Basin. There are several more pre-1976 discoveries in both of these provinces that may also prove to be marginally significant.

Almost all of the known petroleum resources of Alaska are in significant fields (see Fig. 3.1). More than 99.9 percent of the crude oil and 99.6 percent of the natural gas discovered before 1976 are located in these 15 significant fields.[1] Because Alaska's petroleum resources are predominantly in the *Prudhoe Bay* field (14.13 billion barrels' L&LE), one of only three super-giant oil and gas fields in the United States, both the crude oil and the natural gas of Alaska are heavily concentrated in the three giant (Class AAAA) fields. The 13 Class A or larger fields contain 99.9 percent of the crude oil and 98.7 percent of the natural gas.

The dominant trap type in the significant fields of Alaska is the anticline. Unconformities are also of major importance in the *Prudhoe Bay* and *Kuparuk River* fields. Triassic and Jurassic sandstone reservoirs predominate in the Arctic Slope and Arctic Foothills provinces, while the reservoirs of the Cook Inlet fields are all Tertiary sandstones. The combined net thicknesses of the significant fields in all three provinces typically exceed 100 feet. Because the reservoirs are generally thick and of good quality, the areas of the significant fields of Alaska are small relative to the volumes of petroleum they contain. Most of the fields contain between 20,000 and 60,000 barrels' L&LE per surface acre.

CALIFORNIA

According to data available as of 1979, the oil and gas fields of California discovered before 1976 contained, when discovered, 23.66 billion barrels of recoverable crude oil (15.7 percent of the national total), 33.2 trillion cubic feet of natural

[1] The number of fields in each significant field size category is given in parentheses on the figures. Because some fields do not contain crude oil or natural gas in more than negligible quantities, the total number of significant fields indicated on the figures may not necessarily add up to the total number of significant fields in the region, as indicated in the tables of Apps. A, B, and C.

gas (4.4 percent of the national total), and 1.20 billion barrels of natural gas liquids (5.0 percent of the national total). As a region, California ranks fifth overall as a source of conventional petroleum, with 30.39 billion barrels' L&LE (10.1 percent of the total). California is the second most important source of crude oil, but its overall importance is reduced by its ranking ninth as a source of natural gas and seventh as a source of natural gas liquids. As the difference among rankings indicates, the petroleum resources of California are predominantly liquids, 81.9 percent being either crude oil or natural gas liquids. Of the amounts that have been discovered and made recoverable, 18.10 billion barrels of crude oil (76.5 percent of the total), 28.2 trillion cubic feet of natural gas (84.9 percent of the total), and 1.13 billion barrels of natural gas liquids (94.2 percent of the total) had been produced as of the end of 1978.

Petroleum has been discovered in eight different provinces in California to date: the San Joaquin, Sacramento, and Eel River basins in central and northern California; the Salinas, Cuyama, Santa Maria, and Ventura basins in coastal California, and the Los Angeles Basin in southern California. The productive areas of the Los Angeles and Ventura basins extend offshore. The San Joaquin Basin with 13.27 billion barrels' L&LE (43.7 percent of the state total) and the Los Angeles Basin with 9.84 billion barrels' L&LE (32.4 percent of the total) contain most of the petroleum resources of the region. The Ventura Basin (3.96 billion barrels' L&LE), the Sacramento Basin (1.34 billion barrels' L&LE), and the Santa Maria Basin (1.05 billion barrels' L&LE) contain most of the rest. The Salinas Basin (0.57 billion barrels' L&LE) and the Cuyama Basin (0.35 billion barrels' L&LE) are only of minor importance, while the Eel River Basin (0.01 billion barrels' L&LE) is a negligible source. The Sacramento and Eel River basins are almost entirely nonassociated (dry) gas provinces. All of the rest are overwhelmingly crude oil provinces.

At least 155 significant oil and gas fields had been discovered in California before 1976 (Tables A.2a, A.2b, and A.2c). There are another five fields containing between 9 and 10 million barrels' L&LE (*Kettleman Middle Dome* in the San Joaquin Valley, *Kirby Hills* and *Thornton* in the Sacramento Valley, *Timber Canyon* in the Ventura Basin, and *East Los Angeles* in the Los Angeles Basin). Three undeveloped pre-1976 discoveries in the Ventura Basin may also prove to be significant: *Pacoima* in the San Fernando Embayment, the offshore *Pitas Point* field, and an unnamed offshore field in the Santa Clara unit.

Nearly all of the known recoverable oil and gas resources of California are in significant fields (see Fig. 3.2). These 155 fields contain 98.9 percent of California's crude oil and 95.9 percent of its natural gas. The 15 giant (Class AAAA) fields have 63.4 percent of the crude oil and 52.6 percent of the natural gas. The 79 fields that are Class A or larger contain 94.5 percent of California's crude oil and 82.6 percent of its natural gas. The distribution of both crude oil and natural gas resources by field size category is a uniformly decreasing one, each category having less than the next larger one. The petroleum resources of each of the major California provinces are highly concentrated in Class AAAA and AAA fields. Except for the Sacramento Province, 60 to 90 percent of the recoverable oil and gas resources in each province are in the two largest field size categories. Nearly half of the natural gas in the Sacramento Province is in one Class AAAA field (*Rio Vista*). Most of the rest is in Class C and D fields.

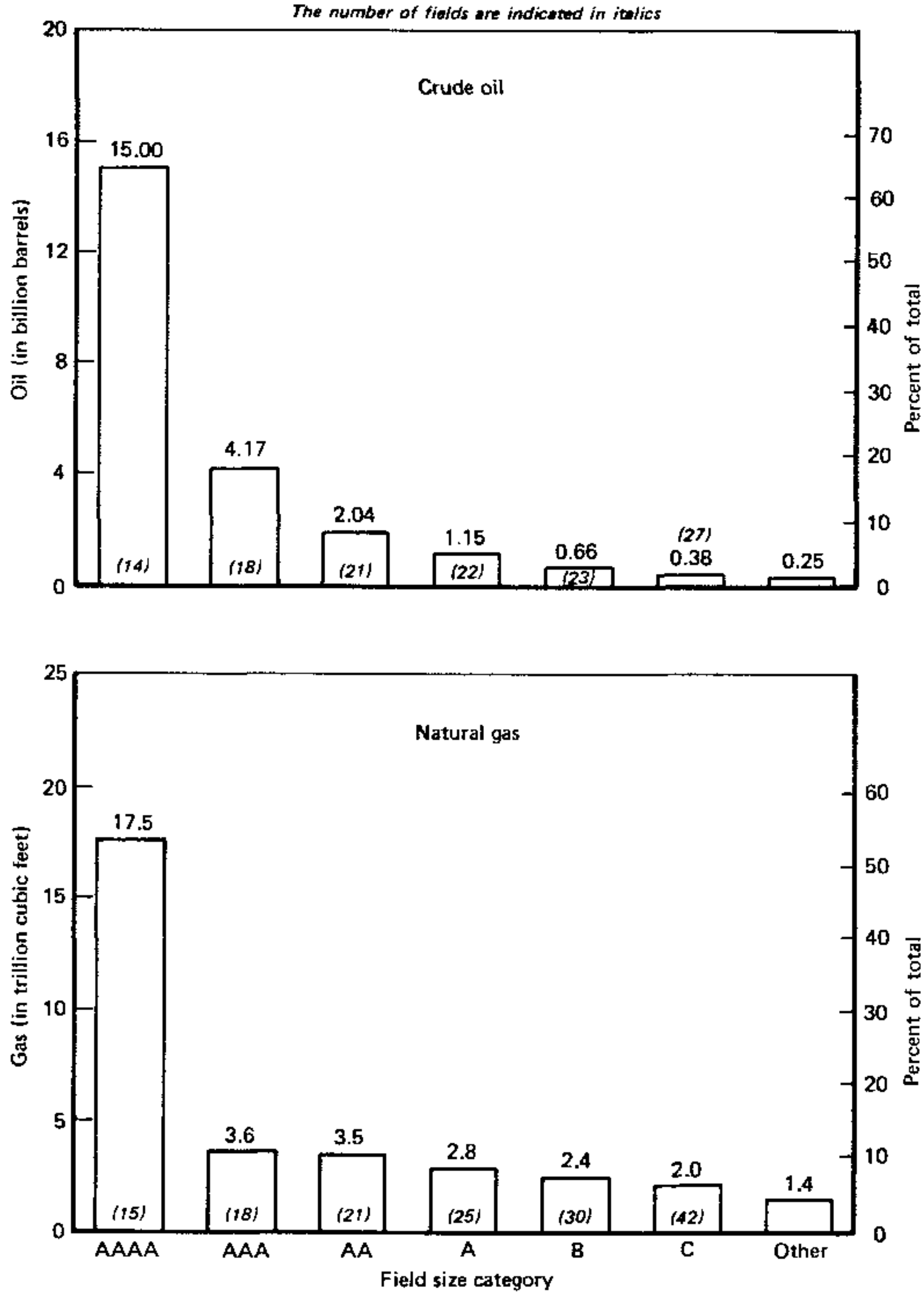

Fig. 3.2—Distribution of crude oil and natural gas by field size category in California

Anticlines are the dominant trap type of the significant oil and gas fields of California. Nearly all the significant fields of the Los Angeles Basin are anticlines or faulted anticlines. Anticlines predominate in the coastal California basins; however, these also contain some fault and combination traps. Combination traps, typically stratigraphic variations on an anticline, are common in the San Joaquin Valley, along with pure structural traps, while faulting and unconformities are the major source of trapping in the Sacramento Valley. Except for some Cretaceous sandstone reservoirs in the Sacramento Valley fields, all of the reservoir rocks of the significant oil and gas fields of California are Tertiary clastics (predominantly sandstone). The combined net thicknesses of the reservoirs in these fields are typically between 100 and 500 feet, with only a few less than 50 feet thick and with some more than 1000 feet thick. Because these reservoirs generally have good porosity as well, the significant oil and gas fields are small in area relative to the volumes of petroleum they contain. Most of the fields contain between 20,000 and 100,000 barrels' L&LE per surface acre. Only a few fields in the Sacramento and San Joaquin basins are significantly below this range. At the other extreme, the *Santa Fe Springs* field in the Los Angeles Basin contains more than 500,000 barrels' L&LE per surface acre.

ROCKY MOUNTAINS

According to data available as of 1979, the oil and gas fields of the Rocky Mountain region discovered before 1976 contained, when discovered, 10.06 billion barrels of recoverable crude oil (6.7 percent of the national total), 44.0 trillion cubic feet of natural gas (5.9 percent of the national total), and 1.24 billion barrels of natural gas liquids (5.1 percent of the national total). As a region, the Rocky Mountain area ranks seventh overall, with 18.63 billion barrels' L&LE (6.2 percent of the total). The Rocky Mountain area ranks eighth overall as a source of crude oil and sixth as a source of natural gas and natural gas liquids. The distribution by type of the petroleum resources of the Rocky Mountain region closely approximates the national average. Petroleum liquids predominate, but only moderately so, constituting 60.7 percent of the total. Of the amounts that have been discovered and made recoverable, 8.39 billion barrels of crude oil (83.4 percent of the total), 27.0 trillion cubic feet of natural gas (61.3 percent of the total), and 0.74 billion barrels of natural gas liquids (59.7 percent of the total) had been produced as of the end of 1978.

There are 18 geologic provinces in the Rocky Mountain region that have at least one significant field (from southwest to northeast): Black Mesa (AZ), San Juan (CO, NM), Paradox (CO, UT), Plateau (UT), Wasatch Uplift (UT), Uinta (UT), Piceance (CO), Greater Green River (CO, UT, WY), Wind River (WY), Laramie (WY), Las Animas Arch (CO), Denver (CO, NB), the Cambridge-Chadron Arch (NB), Powder River (MT, WY), Big Horn (MT, WY), Sweetgrass Arch (MT), Central Montana Uplift (MT), and Williston (MT, ND). The Williston Province is also a significant producing area in Canada. The North Park (CO) Province has one field almost of significant size (*McCallum*). The northwest corner of the Anadarko Basin, with a small fraction of the Class AAA *Greenwood* field, extends into southeastern Colorado. The discovery of the *Trap Springs* field in 1976 may add the Great Basin

(NV, UT) Province to the list of provinces with significant fields. Commercial but nonsignificant fields have also been discovered in the Forest City (NB) and Eagle (CO) basins.

No one province contains a predominant share of the petroleum resources of the Rocky Mountain region. The San Juan Province is the most important with 4.46 billion barrels' L&LE (23.9 percent of the regional total). Other major provinces are the Big Horn (2.68 billion barrels' L&LE), the Powder River (2.65 billion barrels' L&LE), the Greater Green River (2.01 billion barrels' L&LE), the Williston (1.60 billion barrels' L&LE), the Denver (1.37 billion barrels' L&LE), and the Piceance (1.06 billion barrels' L&LE). Provinces of minor importance include the Wind River (0.82 billion barrels' L&LE), the Paradox (0.66 billion barrels' L&LE), the Sweetgrass Arch (0.52 billion barrels' L&LE), and the Uinta (0.46 billion barrels' L&LE). The remainder make only negligible contributions to the total resource. Most of the Rocky Mountain provinces are predominantly oil provinces. The San Juan Province, with half the gas resources of the entire region, is overwhelmingly a dry gas province. The Greater Green River Province is also predominantly a gas province. Other than in the Denver and Sweetgrass Arch provinces, natural gas in the other Rocky Mountain provinces is predominantly gas in association with or dissolved in crude oil.

At least 205 significant oil and gas fields were discovered in the Rocky Mountain region before 1976 (Tables A.3a, A.3b, A.3c, A.3d, A.3e, A.3f, A.3g, and A.3h). Another nine fields—*Roggen* (CO), *Goose Lake* and *Keith Block* (MT), *Enders* (NB), *Black Slough* (ND), and *South Ash Creek, Happy Springs, Lake Creek,* and *Little Mitchell Creek* (WY)—are within 1 million barrels' L&LE of being significant.

Significant fields contain 86.2 percent of the crude oil resources and at least 88.5 percent of the natural gas resources of the Rocky Mountain region (see Fig. 3.3). We estimate that there is probably another 348 billion cubic feet (0.8 percent of the regional total) in significant fields in the Greater Green River Basin, but we were unable to allocate this amount to individual fields. The five giant fields contain only 20.5 percent of the crude oil, but 40.0 percent of the natural gas. The 59 fields that are Class A or larger contain two-thirds (67.0 percent) of the crude oil and at least three-fourths (74.9 percent) of the natural gas. The distribution of crude oil resources among the different field size categories is more uniform than it is in any other region of the country. This distribution is the result of two factors: the large number of Class C and D fields in the Denver (and to a lesser extent) the Powder River and the Williston provinces and the large number of small provinces in the Rocky Mountain region. Because most of the provinces contain between 0.50 and 2.50 billion barrels' L&LE, the largest field in each province, even though it has from 20 to 80 percent of the total recoverable petroleum resource of the province, is typically only a Class AA to small Class AAAA field.

The distribution of petroleum resources by field size category varies sharply among the various Rocky Mountain provinces. In the major western Rocky Mountain provinces (Paradox, Piceance, San Juan, and Uinta), large and giant fields predominate, the three Class AAAA fields containing 62.6 percent of the total petroleum resource (4.15 of 6.63 billion barrels' L&LE) and the 12 Class A or larger fields containing 89.5 percent of the total (5.91 billion barrels' L&LE). In the major provinces of the central and northern Rocky Mountains (Greater Green River, Wind River, Big Horn, and Sweetgrass Arch), large fields predominate, the 28 Class

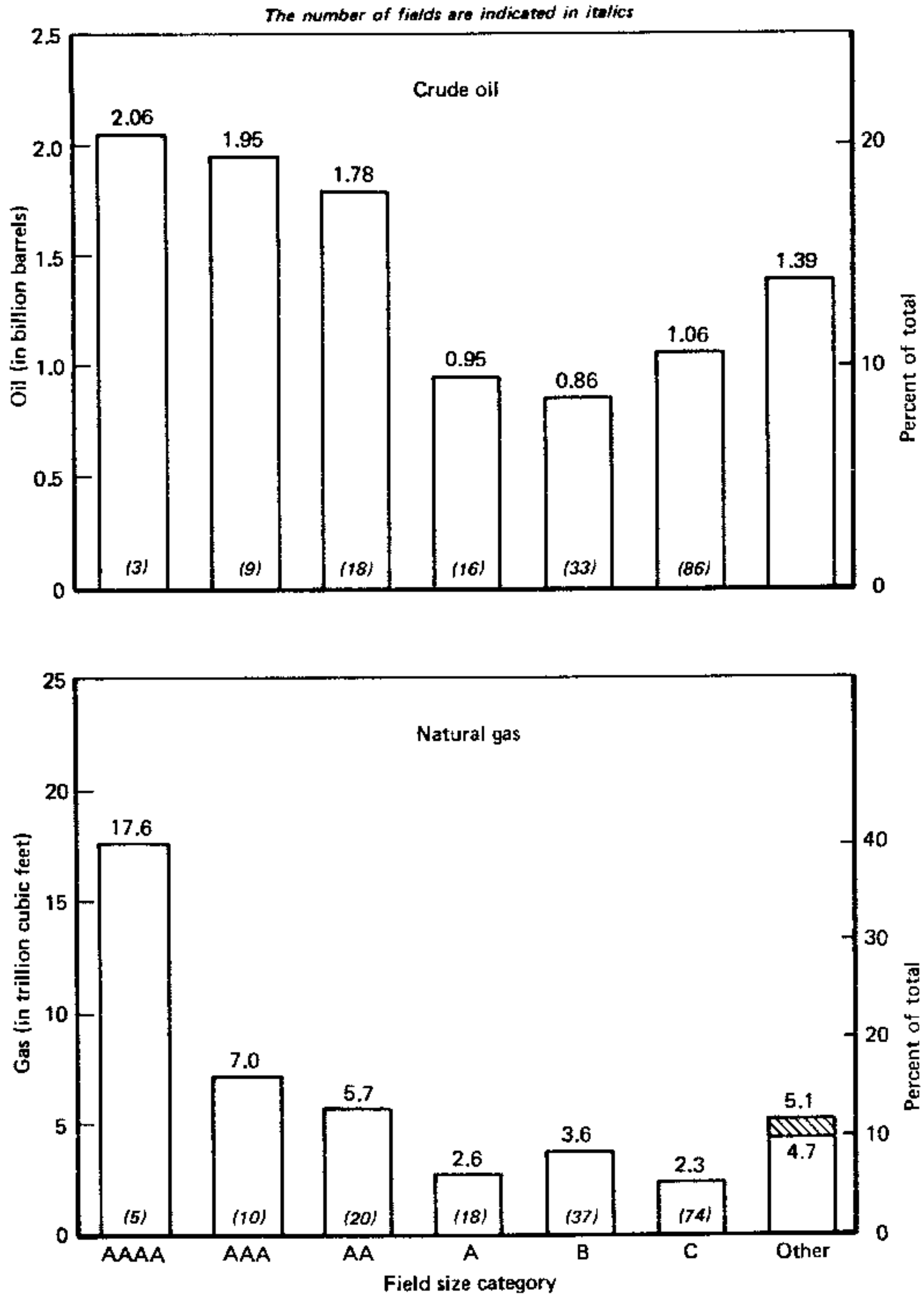

Fig. 3.3—Distribution of crude oil and natural gas by field size category in the Rocky Mountain region

A or larger fields containing 74.5 percent of the total (4.62 of 6.02 billion barrels' L&LE). In both groups, more than 95 percent of the total resource is in significant fields. In the major provinces of the eastern Rocky Mountain region (Denver, Powder River, and Williston), the 18 Class A or larger fields have only 50.0 percent of the total petroleum resources (2.81 of 5.62 billion barrels' L&LE). Class B and C fields contain another 23.7 percent, and Class D and E fields (which are particularly prominent in the Denver Basin) contain the remaining 26.3 percent.

The geologic characteristics and productivity of significant fields vary substantially among the major producing provinces of the Rocky Mountain region. The major fields of the San Juan Basin are predominantly stratigraphic (facies change) traps with Cretaceous sandstone reservoirs averaging 50 to 100 feet thick. Because the porosity and permeability of these reservoirs are very low, recovery per surface acre averages only 500 to 2000 barrels' L&LE. The significant fields of the Big Horn Basin are predominantly anticlines with multiple sandstone and carbonate reservoirs of Mississippian, Pennsylvanian, Permian, and Cretaceous age with a combined average thickness of 50 to 250 feet. Recovery per surface acre averages 25,000 to 75,000 barrels' L&LE. Except for some anticlines on the western and southeastern fringes of the basin, the major fields of the Powder River Basin are predominantly stratigraphic traps with Cretaceous sandstone reservoirs averaging 10 to 30 feet thick. Recovery per surface acre in these fields averages 2500 to 10,000 barrels' L&LE.

The larger fields of the Greater Green River Basin are predominantly anticlines or anticlinal combination traps. Reservoirs of Paleozoic, Mesozoic, and Cenozoic age are found in the basin, with Cretaceous and Tertiary sandstones averaging 20 to 100 feet thick being the most important ones. Recovery ranges from more than 100,000 barrels per surface acre in a few anticlines to less than 5000 in poorer quality, thinner sands. Median recovery is about 5000 to 10,000 barrels' L&LE per acre. The larger fields in the Williston Basin are all anticlines; stratigraphic trapping is widespread in the smaller significant fields. Reservoirs are predominantly Paleozoic carbonates 10 to 100 feet thick, the Mississippian and Ordovician being most important. Recovery per surface acre averages 1000 to 5000 barrels' L&LE. The significant fields of the Denver Basin are predominantly stratigraphic (facies change) traps with reservoirs 5 to 25 feet thick in Cretaceous sandstones. Recovery averages 1000 to 10,000 barrels' L&LE per surface acre. The significant fields in the Wind River Basin are predominantly anticlinal with Permian carbonate and Pennsylvanian sandstone reservoirs averaging 100 to 300 feet in combined net thickness and recoveries of 10,000 to 50,000 barrels' L&LE per surface acre. Because none of the other provinces have more than five significant fields each, generalizations about them are not very meaningful and are thus not included here.

PERMIAN BASIN

According to data available as of 1979, the oil and gas fields of the Permian Basin (southeastern New Mexico and Texas R.R.C. Districts 7C, 8, and 8A) contained, when discovered, 26.61 billion barrels of recoverable crude oil (17.6 percent of the national total), 73.4 trillion cubic feet of natural gas (9.8 percent of the national total), and 3.81 billion barrels of natural gas liquids (15.8 percent of the national total). As a region, the Permian Basin ranks third overall nationally, with 42.65 billion barrels' L&LE (14.2 percent of the total). It is the single most important source of crude oil, but ranks only fourth in natural gas and natural gas liquids resources. As the difference in rankings suggests, the Permian Basin is predominantly an oil province, with 71.3 percent of the total petroleum resources being petroleum liquids. Of the amounts that have been discovered and made recoverable, 19.97 billion barrels of crude oil (74.9 percent of the total), 59.3 trillion cubic feet of natural gas (80.8 percent of the total), and 2.97 billion barrels of natural gas liquids (78.0 percent of the total) had been produced as of the end of 1978.

The Permian Basin region is essentially coextensive with the province of the same name. However, the eastern fringes of the province also extend into Texas R.R.C. Districts 1, 7B, and 9. The southeastern corner of the region forms the western part of the Llano Uplift. The province has been divided into 13 subprovinces: the Central Basin Platform in the center; the Delaware Basin to the southwest; the Val Verde Basin and Sheffield Channel to the south; the Ozona Platform to the southeast; the Midland Basin and Eastern Shelf to the east; the Horseshoe Atoll superimposed on the Midland Basin and Eastern Shelf; the North Basin Platform, Matador Arch, San Simon Channel, and Tatum Basin to the north; and the Northwest Shelf to the northwest. The Central Basin Platform clearly dominates, containing nearly half of the total recoverable resources of the province. The North Basin Platform contains more than 10 percent, while the Midland Basin, Horseshoe Atoll, Delaware Basin, Eastern Shelf, and Northwest Shelf contain between 5 and 10 percent of the province total. The Val Verde and Tatum basins each contain approximately 1 billion barrels' L&LE. None of the other four subprovinces have more than 1.0 percent each of the regional total. Like the region itself, the subprovinces are predominantly oil regions. However, the petroleum resources of the four southernmost subprovinces—the Delaware Basin, the Val Verde Basin, the Sheffield Channel between the two preceding basins, and the Ozona Platform—are, however, almost entirely nonassociated natural gas.

At least 293 significant oil and gas fields were discovered in the Permian Basin before 1976 (Tables A.4a, A.4b, A.4c, and A.4d). Another 11 pre-1976 discoveries are within 1 million barrels' L&LE of being significant: *Dean* and *East Hobbs* in southeastern New Mexico; *Beall, Parker, Putnam, Roberdeau-Lyles* (all), and *West Rojo Caballos* in Texas R.R.C. District 8; and *Brown, Southwest Fluvanna, South G-M-K*, and *Rocker -A-* in Texas R.R.C. District 8A.

The oil and natural gas resources of the Permian Basin are highly concentrated in significant fields (see Fig. 3.4). The 18 giant fields, the most in any region, contain 53.8 percent of the crude oil resources and at least 47.3 percent of the natural gas resources of the region. The 107 fields that are Class A or larger contain 85.2 percent of the crude oil and at least 78.0 percent of the natural gas. Together, all the significant fields contain 94.6 percent of the crude oil and at least 90.7 percent of the natural gas. We estimate that another 2910 billion cubic feet (4.0 percent of the regional total) is likely to be in significant fields, but we were unable to allocate this amount to individual fields. The distribution by field size category among the significant categories is a uniformly decreasing one. Class D and E fields together are more important than Class C fields.

The distribution by field size among subprovinces varies considerably. Giant fields account for nearly two-thirds of the petroleum resources of the Central Basin

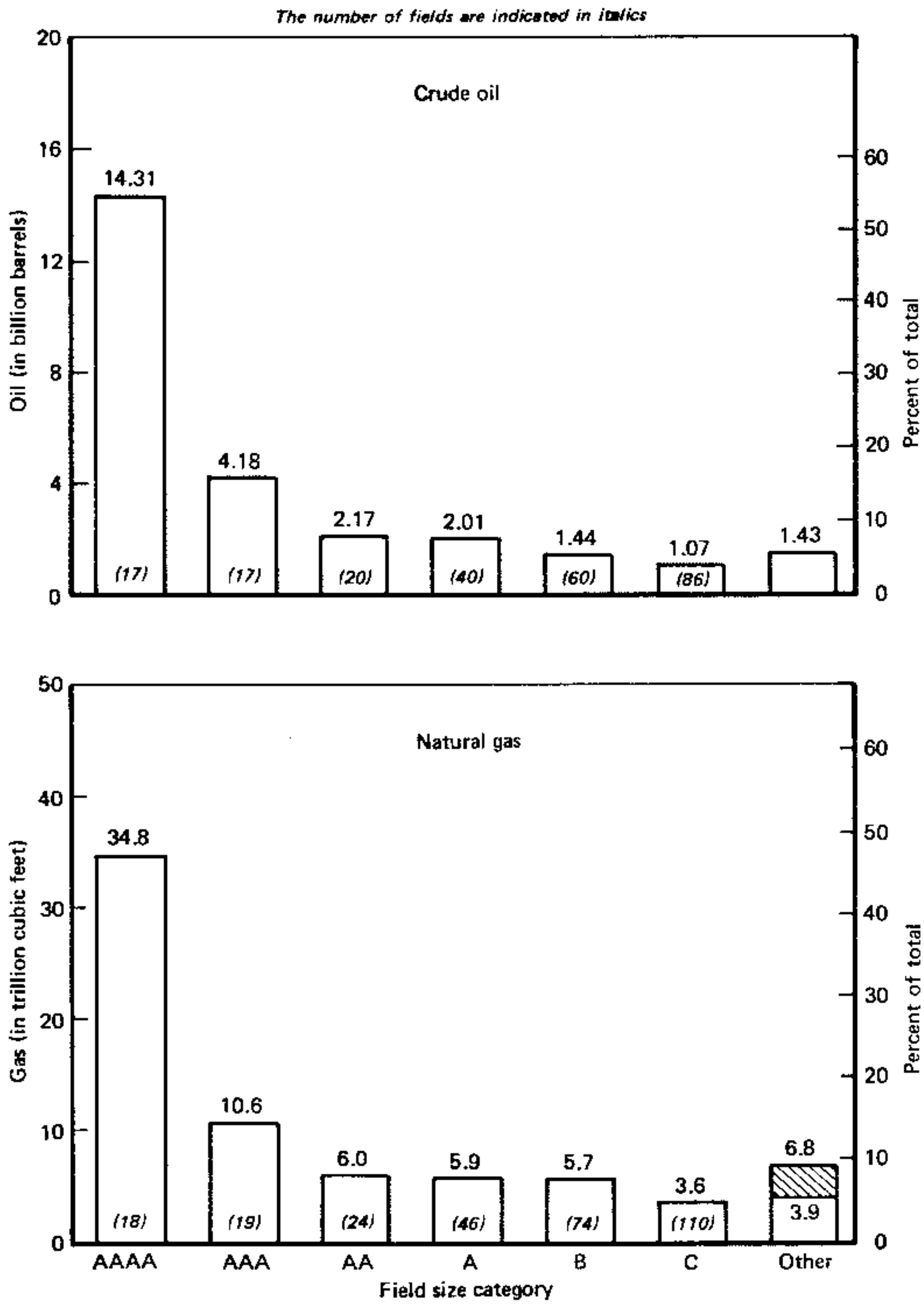

Fig. 3.4—Distribution of crude oil and natural gas by field size category in the Permian Basin

Platform and the Horseshoe Atoll and more than 85 percent of the total of the North Basin Platform. If we had used a more liberal field definition, the concentration in giant fields on the Central Basin Platform would be even more pronounced. The major fields on both the eastern and western flanks of the Central Basin Platform can be considered as two super-giant fields. Together, these two sets of fields contain more than 25 percent of the crude oil in the entire region and more than 35 percent of the natural gas and natural gas liquids. The two sets consist of *Eunice Area, Blinebry-Drinkard, Keystone, South Sand Belt,* and *South Ward* on the western flank, with more than 2.5 billion barrels of crude oil, 21 trillion cubic feet of natural gas, and 900 million barrels of natural gas liquids; and *McElroy-Dune, Penwell-Waddell, Harper-Moss, South Cowden, Goldsmith-Andector, North Goldsmith-Block 11, TXL, North Cowden, Emma-Triple N, Fuhrman-Mascho, Shafter Lake-Deep Rock, Fullerton,* and *Means-McFarland-Nolley* on the eastern flank, with more than 4.5 billion barrels of crude oil, 5.4 trillion cubic feet of natural gas, and 450 million barrels of natural gas liquids. At the other extreme, the distribution of oil and gas resources in the Delaware Basin, the Midland Basin, the Eastern Shelf, and the Tatum Basin tends more toward uniformity among size classes. A few fields of Class A size or larger contain approximately three-fourths of the petroleum resources of the Val Verde Basin and Northwest Shelf.

The significant fields of the Permian Basin vary widely by trap type among the subprovinces. The fields of the Central Basin Platform are predominantly combination traps (anticlines with facies changes or porosity-permeability pinchouts) with sandstone and carbonate reservoirs of Permian age (predominantly Guadalupe and secondarily Leonard) with combined net thicknesses averaging 200 to 500 feet. Because the porosity of these thick reservoirs is poor, recovery per surface acre typically ranges only between 10,000 and 30,000 barrels' L&LE. The major fields of the North Basin Platform are either anticlines or stratigraphic traps (porosity-permeability pinchouts) with Permian/Guadalupe dolomitic reservoirs 100 to 300 feet thick and reservoir characteristics and recovery per surface acre similar to that of the Central Basin Platform fields. Both faulted anticline and porosity-permeability pinchouts are common in the Midland Basin. The reservoirs are predominantly Permian and Ordovician carbonates with combined net thicknesses of 40 to 200 feet. Recoveries per surface acre range between 10,000 and 20,000 barrels' L&LE. The fields of the Horseshoe Atoll are all Pennsylvanian limestone reefs 50 to 240 feet thick with recoveries per surface acre between 10,000 and 50,000 barrels' L&LE. The larger significant fields in the Delaware Basin are all faulted anticlines with carbonate reservoirs of Ordovician, Silurian, or Devonian age 100 to 800 feet thick. Because the porosity of these reservoirs is very low, recovery per surface acre normally ranges between 5000 and 20,000 barrels' L&LE. Most of the significant fields on the Eastern Shelf are either organic reefs and other stratigraphic traps with carbonate reservoirs of Pennsylvanian age or anticlines with carbonate reservoirs of Permian age. Most of the larger fields on the Northwest Shelf are combination traps (anticlines with stratigraphic variations) with dolomitic reservoirs of Permian/Guadalupe age 50 to 300 feet thick. The smaller significant fields of the province are predominantly Pennsylvanian sandstone stratigraphic traps with reservoirs 20 to 80 feet thick. Recovery per surface acre averages 10,000 to 50,000 barrels' L&LE for the larger fields on the Northwest Shelf and 2000 to 10,000 barrels' L&LE for the smaller fields.

NORTH CENTRAL TEXAS

According to data available as of 1979, the oil and gas fields of North Central Texas discovered before 1976 contained, when discovered, 4.89 billion barrels of recoverable crude oil (3.2 percent of the national total), 10.8 trillion cubic feet of natural gas (1.4 percent of the national total), and 0.70 billion barrels of natural gas liquids (2.9 percent of the national total). Because the total petroleum resources of the region are so small (7.39 billion barrels' L&LE or 2.5 percent of the national total), the region is often combined with the Permian Basin to the southwest or the Mid-Continent region to the north, both of which are geologically related to North Central Texas. However, because the distribution of petroleum resources in the region is unique when compared with any other region, we chose to treat it separately to highlight this uniqueness. The petroleum resources of the region are predominantly liquids, with 75.6 percent of the total being either crude oil or natural gas liquids. Of the amounts that have been discovered and made recoverable, 4.52 billion barrels of crude oil (92.4 percent of the total), 9.2 trillion cubic feet of natural gas (84.9 percent of the total), and 0.58 billion barrels of natural gas liquids (82.9 percent of the total) had been produced as of the end of 1978.

North Central Texas comprises all or part of six different producing provinces: the Bend Arch, the Fort Worth Syncline, the Strawn Basin, the South Oklahoma Folded Belt, part of the Eastern Shelf of the Permian Basin, and the Hardeman Basin and Red River Arch of the Palo Duro Basin. Because a large proportion of the petroleum resources of the region is not in significant fields, the amount of petroleum resources in each province is not easy to determine. However, the Bend Arch is clearly the most important province with about 43 percent of the total petroleum resources. The Fort Worth Syncline has about 18 percent of the total, the Red River Arch 16 percent of the total, and the Eastern Shelf about 13 percent of the total. The South Oklahoma Folded Belt has approximately 8 percent of the total while the Hardeman and Strawn basins have only negligible amounts of petroleum. Except for the Fort Worth Syncline, which has one Class AAA nonassociated gas field, all of these provinces are preponderantly oil provinces.

North Central Texas has at least 85 significant oil and gas fields (Tables A.5a and A.5b). Three more fields—*Meeker* in Texas R.R.C. District 7B and *Ringgold* and *Seymour* in Texas R.R.C. District 9—have between 9 and 10 million barrels' L&LE. One unusual characteristic of the region is the large amount of the total oil and gas resources in the so-called County Regular fields, an administrative designation that encompasses many fields within a single county. We separated 20 significant fields from this catchall designation. There could easily be several more, especially natural gas fields, that we were unable to distinguish.

North Central Texas is the only region of the country in which petroleum resources are not concentrated in significant fields (see Fig. 3.5). There are no giant fields in the region. The 17 fields of Class A size or larger contain only 32.1 percent of the crude oil and 38.7 percent of the natural gas of the region. All the significant fields contain only a bare majority of the petroleum resources of the region (51.4 percent of the crude oil and at least 52.5 percent of the natural gas). We estimate that there is probably another 600 billion cubic feet (5.6 percent of the regional total) in significant fields that we were unable to allocate to individual fields. The County Regular fields clearly contribute to the underestimation here, but this is unlikely to add more than another 10 percent to the proportion in significant fields.

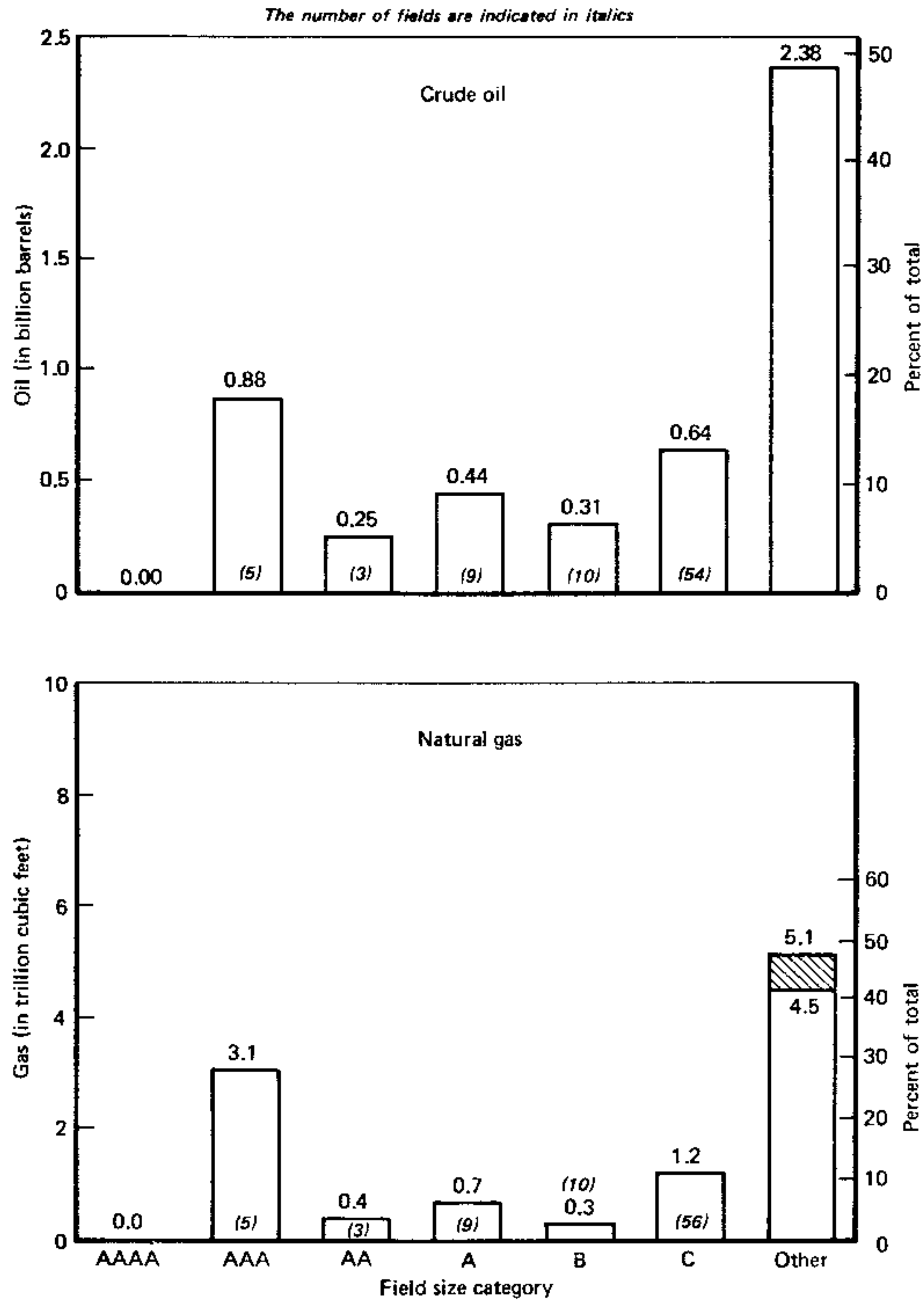

Fig. 3.5—Distribution of crude oil and natural gas by field size category in North Central Texas

The distribution of crude oil and natural gas resources by field size category differs markedly among the various provinces of North Central Texas. On the Bend Arch, Class C and D fields contain more than three-fourths of the total. At the other extreme, three Class AAA fields contain more than 70 percent of the total on the Red River Arch. Significant fields from Class C to Class AA in size contain most of the oil and gas in the South Oklahoma Folded Belt and the Eastern Shelf. Except for the Class AAA *Boonsville* gas field that has 20 percent of the natural gas resources of the region, the resources of the Fort Worth Syncline are predominantly in Class D fields.

The significant fields in all the provinces of North Central Texas have Pennsylvanian limestone and sandstone reservoirs with combined net thicknesses of 20 to 100 feet. The trap types of the larger significant fields are predominantly anticlines or anticlines with stratigraphic variations. Class C and D fields tend to be either combination or stratigraphic traps. Recovery per surface acre is generally between 5000 and 20,000 barrels' L&LE.

MID-CONTINENT

According to data available as of 1979, the oil and gas fields of the Mid-Continent region contained, when discovered, 19.66 billion barrels of recoverable crude oil (13.0 percent of the national total), 152.0 trillion cubic feet of natural gas (20.3 percent of the national total), and 4.78 billion barrels of natural gas liquids (19.8 percent of the national total). The Mid-Continent ranks second overall as a source of petroleum with 49.77 billion barrels' L&LE (16.66 percent of the national total). The region is a major source of all types of petroleum, ranking third as a source of crude oil and second as a source of natural gas and natural gas liquids. The petroleum resources of the region are nearly balanced by type, natural gas being slightly more important with 50.9 percent of the total. Of the amounts that have been discovered and made recoverable, 17.92 billion barrels of crude oil (91.1 percent of the total), 122.0 trillion cubic feet of natural gas (80.2 percent of the total), and 3.78 billion barrels of natural gas liquids (79.1 percent of the total) had been produced as of the end of 1978.

There are 10 provinces with significant fields in the Mid-Continent region (from southwest to northeast): the Palo Duro Basin (OK, TX 10), the Anadarko Basin-Amarillo Arch (KS, OK, TX 10), the South Oklahoma Folded Belt (OK), the Arkoma Basin (OK), the Chautauqua Platform (OK), the Sedgwick Basin (KS), the Central Kansas Uplift (KS), the Nemaha Anticline (KS), the Cherokee Basin (KS), and the Forest City Basin (KS). The Palo Duro and South Oklahoma provinces also extend into North Central Texas; the Arkoma Basin extends into west central Arkansas, and the Forest City Basin extends into southeastern Nebraska. The Anadarko Basin-Amarillo Arch clearly predominates with slightly more than half of the total petroleum resources of the region (approximately 26.3 billion barrels' L&LE). Three other provinces are of national significance: the Chautauqua Platform with approximately 11.0 billion barrels' L&LE, the South Oklahoma Folded Belt with approximately 5.7 billion barrels' L&LE, and the Central Kansas Uplift with approximately 2.9 billion barrels' L&LE. Other provinces that are important to the total resources of the region are the Arkoma Basin (roughly 1.4 billion barrels'

L&LE), the Sedgwick Basin (1.2 billion barrels' L&LE), the Cherokee Basin (0.8 billion barrels' L&LE), and the Nemaha Anticline (0.8 billion barrels' L&LE). Only the Palo Duro and Forest City provinces contain modest amounts of petroleum resources. The Anadarko Basin-Amarillo Arch, the Arkoma Basin, and the Palo Duro Basin are predominantly nonassociated gas provinces; the other provinces are largely oil provinces.

At least 399 significant oil and gas fields were discovered in the Mid-Continent region before 1976 (Tables A.6a, A.6b, and A.6c). Another 30 fields have between 9 and 10 million barrels' L&LE: *Arkalon, Davis Ranch, Dopita, Drach, Florence,* and *Novinger NW* in Kansas; *East Ada, Barnsdall, Southwest Cheyenne, Coalton, Northeast Davis, Garr, North Hitchland, Southwest Hope, South Kaw, Southeast Laffoon, South Logan, Norfolk, Orlando, Red Fork, Southwest Rush Springs, North Searight, East Sparks, Spring, Stone Bluff, Tangier,* and *West Wellston* in Oklahoma; and *Cree-Flowers, Howe Ranch,* and *Parnell* in Texas R.R.C. District 10. Because production records, particularly for natural gas, are incomplete for the region, several significant fields discovered before 1920 probably were inadvertently excluded in our data base of significant oil and gas fields.

The distribution of petroleum resources by field size category in the Mid-Continent differs markedly by type (see Fig. 3.6). Natural gas resources are highly concentrated in giant fields (61.4 percent of the total), primarily in the super-giant *Hugoton-Panhandle* field (80 trillion cubic feet plus liquids), which is the largest oil and gas field in North America and the largest gas field in the Western Hemisphere. The 105 Class A or larger fields contain at least 80.5 percent of the total. All significant fields contain at least 90.6 percent of the natural gas. We estimate that another 6.3 trillion cubic feet of gascap (associated) gas in Oklahoma (4.1 percent of the regional total) was in significant fields, but we lacked the information to allocate it among individual fields. With the appropriate adjustments for this estimation error, the amount of natural gas in each of the five smaller field size categories is remarkably similar, each having about 5 percent of the regional total. The eight giant fields contain 27.5 percent of the crude oil resources of the region; the Class A or larger fields contain at least 65.4 percent of the crude oil total; all of the significant fields contain at least 82.5 percent of the total. We estimated that another 150 million barrels of crude oil were in significant fields, but we were unable to allocate them to individual fields. Except for the Class D and E fields, the amounts of crude oil in the smaller field size categories are also quite uniform, each about 8 to 10 percent of the total.

The distribution of petroleum resources by field size category varies considerably among the different producing provinces of the Mid-Continent region. In the Anadarko Basin-Amarillo Arch, more than 70 percent of the total is in giant fields, nearly 90 percent is in Class A or larger fields, and more than 95 percent is in significant fields. The petroleum resources of the South Oklahoma Folded Belt are also concentrated in the largest fields, with more than 50 percent in giant fields, 80 percent in Class A or larger fields, and more than 90 percent in significant fields. Petroleum resources are more evenly distributed in the fields of the Chautauqua Platform, only 25 percent being in giant fields, about 60 to 65 percent in Class A or larger fields, and approximately 85 percent in significant fields. Five Class AA and AAA fields in the Oklahoma portion of the Arkoma Basin have 80 percent of its petroleum resources. The distribution by field size in the Central Kansas Uplift

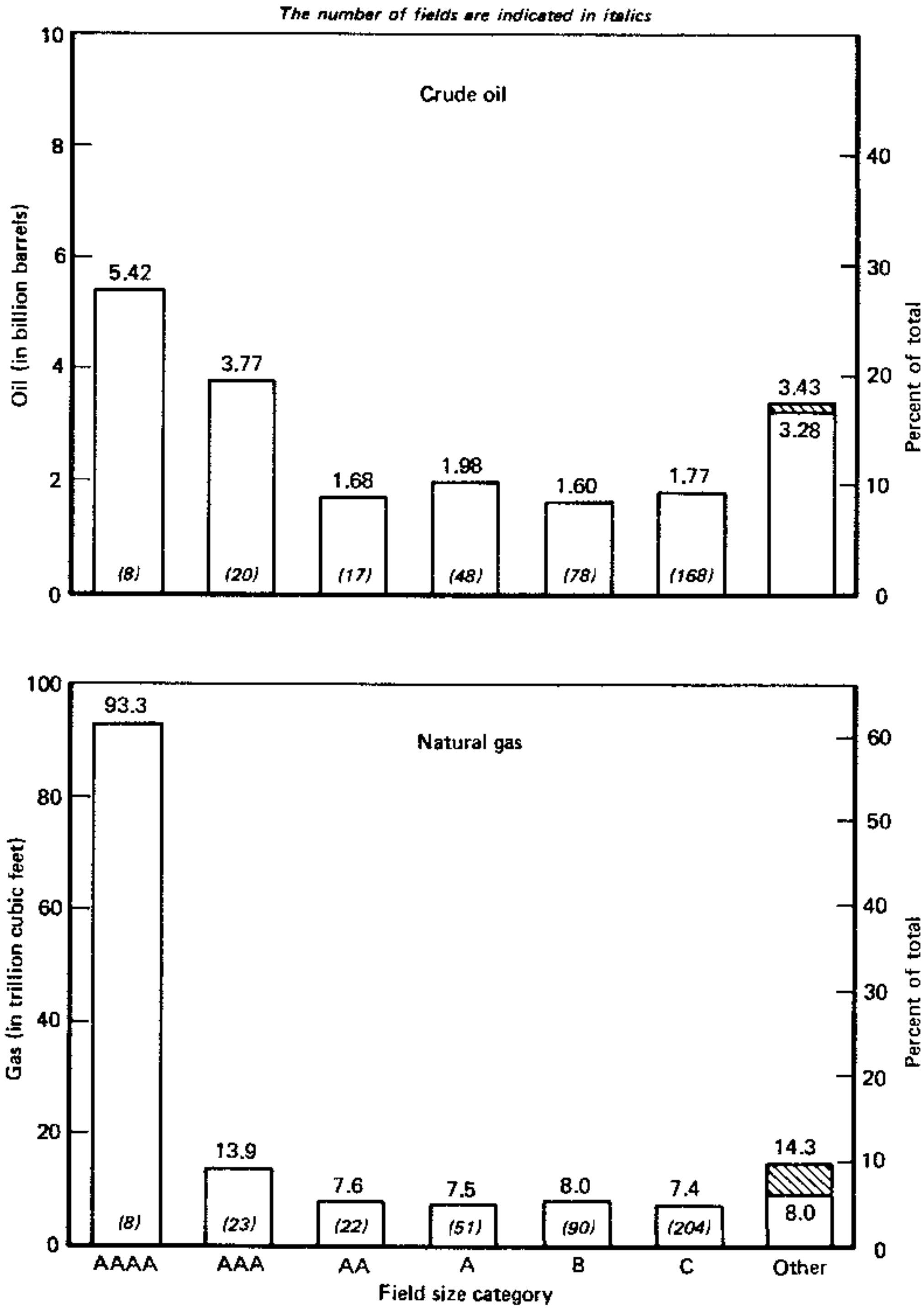

Fig. 3.6—Distribution of crude oil and natural gas by field size category in the Mid-Continent

is bimodal and is concentrated in Class AAA and D fields. The distribution in both the Cherokee and Sedgwick basins is relatively uniform across field size categories, each category from Class A to D having between 20 and 35 percent of the total resources of Cherokee and each category from Class AA to D having between 15 and 25 percent of the total resources of Sedgwick.

The significant fields of the Mid-Continent consist predominantly of combination traps, typically low-relief anticlines combined with facies changes, porosity-permeability pinchouts, or unconformities. Faulting is also common in the more southerly provinces (Arkoma, South Oklahoma, and Chautauqua). Stratigraphic traps (facies changes) are also important, particularly in the Anadarko Basin. The reservoir rocks are all of Paleozoic age. Pennsylvanian sandstones and carbonates are prominent in nearly every province. The reservoir rocks of the *Hugoton-Panhandle* field are Permian carbonates. Mississippian limestones provide major reservoirs in the South Oklahoma and Sedgwick provinces. Silurian carbonates are of some importance in the Anadarko and Chautauqua provinces. Ordovician carbonates play a similar role in the Central Kansas, Chautauqua, and South Oklahoma provinces. The normal range of combined average net thicknesses varies substantially from province to province, ranging from very thick in the South Oklahoma Province (60 to 600 feet) to moderately thick in the Chautauqua (30 to 300 feet) and Arkoma (50 to 200 feet) provinces. Because of differences in reservoir quality among provinces, the average range of recovery per surface acre is only partially correlated with the differences in thickness. Heading the list is the South Oklahoma Province (10,000 to 50,000 barrels' L&LE). The Arkoma and Chautauqua provinces have a similar range (5000 to 25,000 barrels' L&LE). Recovery in the Central Kansas fields is 5000 to 10,000 barrels' L&LE, while the poorer quality Anadarko Basin reservoirs range between 1000 and 10,000 barrels' L&LE.

WESTERN GULF

According to data available as of 1979, the oil and gas fields of the Western Gulf region contained, when discovered, 14.26 billion barrels of recoverable crude oil (9.4 percent of the national total), 130.4 trillion cubic feet of natural gas (17.4 percent of the national total), and 3.89 billion barrels of natural gas liquids (16.1 percent of the national total). The region ranks fourth overall as a source of petroleum, with 39.88 billion barrels' L&LE (13.3 percent of the national total). The Western Gulf ranks third as a source of natural gas and natural gas liquids, but only fifth as a source of crude oil. As the relative difference among rankings suggests, natural gas is the predominant petroleum type in the region, constituting 54.5 percent of the total. Of the amounts that have been discovered and made recoverable, 12.70 billion barrels of crude oil (88.7 percent of the total), 101.5 trillion cubic feet of natural gas (77.8 percent of the total), and 3.20 billion barrels of natural gas liquids (82.3 percent of the total) had been produced as of the end of 1978.

The region consists predominantly of the western part of the Gulf Province. The western edge of the province forms the southern part of the Ouachita Tectonic Belt. A small southwestern corner forms the southeastern corner of the Permian Basin Province.

At least 481 significant oil and gas fields were discovered in the Western Gulf region before 1976 (Tables A.7a, A.7b, A.7c, and A.7d). Another 20 fields are within 1 million barrels' L&LE of being significant: *Imogene* in Texas R.R.C. District 1; *Pawnee, Poesta Creek, Sherman Offshore,* and *South Tuleta-Wilcox* in Texas R.R.C. District 2; *Cleveland Cecil, Noble, Devillier, Fostoria, Hortense, South Matagorda Bay, Mykawa* (all), *North Silsbee,* and *Sugar Creek* in Texas R.R.C. District 3; and *South Davis, Headquarters, Petrox, Sam Fordyce, South Santellana,* and *South Weslaco* in Texas R.R.C. District 4. Several offshore fields (not listed in App. A) discovered before 1976 on the Texas outer continental shelf may also prove to be significant.

The 13 giant fields in the Western Gulf region are the most important source of oil and gas in the area, but their importance is not as great as in other regions with a sizable number of giant fields (see Fig. 3.7). Class AAAA fields provide 33.7 percent of the crude oil and 26.9 percent of the natural gas. Large fields are more important; the 140 fields that are Class A or larger have 77.5 percent of the crude oil and at least 65.4 percent of the natural gas of the region. The significant fields of the region contain 91.5 percent of its crude oil and at least 86.3 percent of its natural gas. We estimated that another 2.0 trillion cubic feet (1.5 percent of the regional total) were in significant fields, but we were unable to allocate this amount among specific fields. Excluding giant fields, the distribution of the natural gas resources by region among field size categories is remarkably uniform, each category having between 10 and 14 percent of the total amount.

Trapping in the significant fields of the Western Gulf is predominantly structural. Most of the major fields are faulted anticlines. Salt domes are also important, particularly in Texas R.R.C. District 3. Stratigraphic variations associated with structural traps are common. Except for Texas R.R.C. District 1, where the reservoirs of the major fields are primarily Cretaceous, and the far offshore fields in the High Island and High Island East areas, where the reservoirs are predominantly Pleistocene sandstones, the reservoirs of the significant fields of the Western Gulf are Tertiary sandstones, primarily of Oligocene and Eocene ages. Combined net thicknesses vary widely, ranging from 5 to more than 500 feet in some fields with numerous reservoirs. For most fields, the range is 25 to 100 feet thick. Recovery per surface acre is between 10,000 and 50,000 barrels' L&LE, although in some of the larger fields it reaches 100,000 barrels per acre and in some of the fields near the margins of the region it is as low as 1000 barrels per acre.

CENTRAL GULF

According to data available as of 1979, the oil and gas fields of the Central Gulf region discovered before 1976 contained, when discovered, 17.17 billion barrels of recoverable crude oil (11.4 percent of the national total), 169.3 trillion cubic feet of natural gas (22.6 percent of the national total), and 4.83 billion barrels of natural gas liquids (20.0 percent of the national total). The Central Gulf region is the leading source of petroleum for the nation, with 50.22 billion barrels' L&LE (16.7 percent of the national total). It is also the principal source of natural gas and natural gas liquids, but ranks only fourth as a source of crude oil. As the difference in relative rankings suggests, the Central Gulf is predominantly a natural gas region, with natural gas constituting 56.2 percent of the recoverable petroleum in the region.

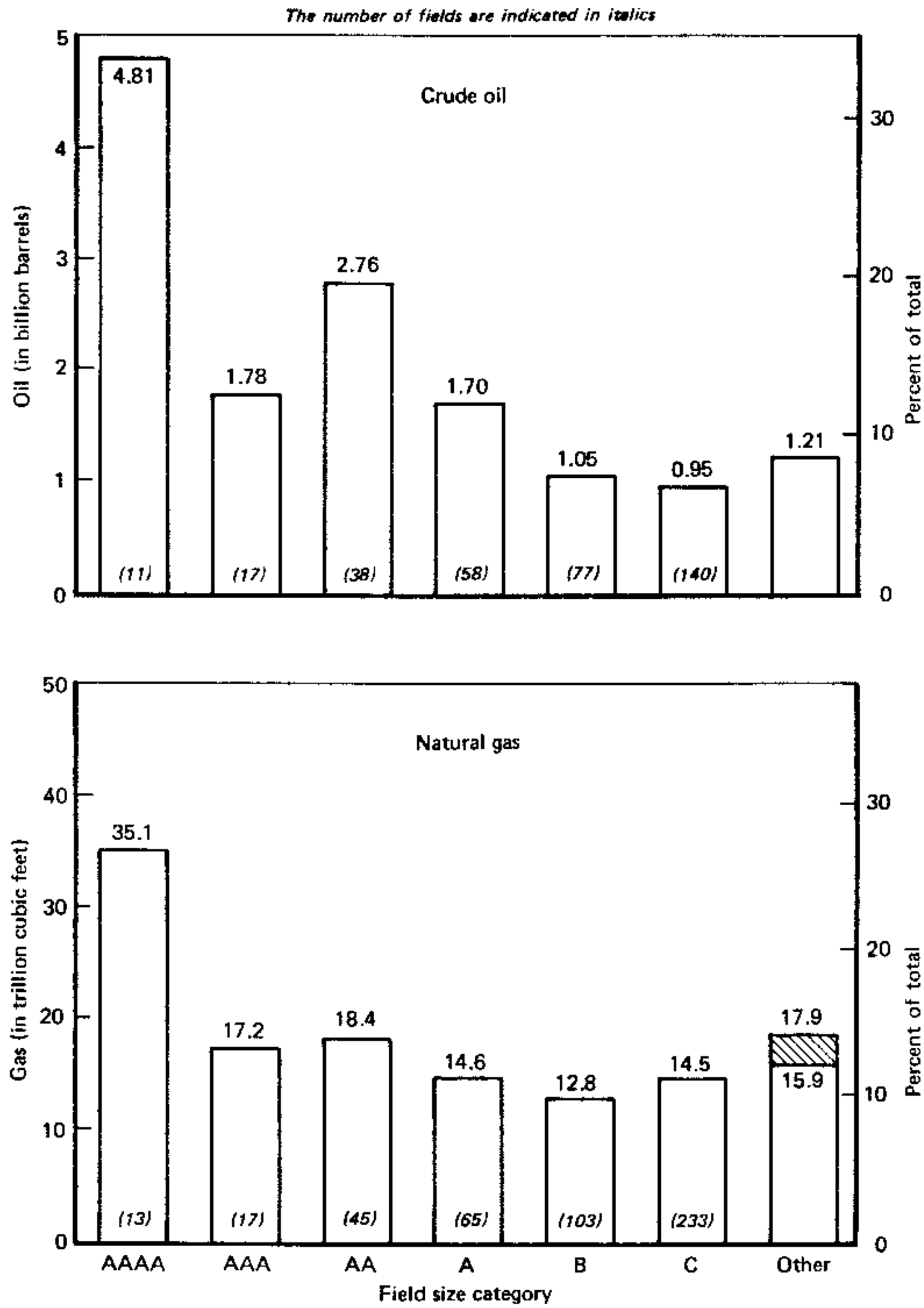

Fig. 3.7—Distribution of crude oil and natural gas by field size category in the Western Gulf

Of the amounts that have been discovered and made recoverable, 13.87 billion barrels of crude oil (80.8 percent of the total), 122.2 trillion cubic feet of natural gas (72.2 percent of the total), and 3.61 billion barrels of natural gas liquids (74.6 percent of the total) had been produced as of the end of 1978.

The region is in the central portion of the Gulf Coast, and, using the AAPG-CSD province definitions, it consists of the eastern half of the Gulf Coast Province. Some geologists consider southern Louisiana as a separate province and designate it as the Mississippi Delta.

The Central Gulf has more significant fields than any other region. At least 530 significant fields were discovered before 1976 (Tables A.8a, A.8b, and A.8c). Another 15 fields are between 9 and 10 million barrels apiece: *Eugene Island Block 327, Ship Shoal Block 40, Ship Shoal Block 271, South Timbalier Block 8, Vermilion Block 164,* and *Vermilion Block 340* offshore Louisiana; *Bayou Perot, East Golden Meadow, Southwest Lake Boeuf, Lake Campo, Lake Gero,* and *Livonia* in southeastern Louisiana; and *East Holly Beach, Oberlin,* and *Richie* in southwestern Louisiana. Several other offshore discoveries of the early 1970s probably merit designation as significant fields, but we omitted them from the data base of significant oil and gas fields because we could not obtain sufficient information.

The distribution of crude oil and natural gas resources by field size category in the Central Gulf region is unique (see Fig. 3.8). It is the only region in the country with a substantial number of giant fields (13 in all) that does not have Class AAAA fields as the most important field size category. Both Class AAA and AA fields contain more petroleum than Class AAAA fields in the Central Gulf region, partly because the region has 30 percent of all the Class AAA and AA fields in the country. Giant fields contain 21.2 percent of the crude oil and 14.7 percent of the natural gas. However, the 257 Class A or larger fields contain 87.4 percent of the crude oil and 82.3 percent of the natural gas. Significant fields contain nearly all of the petroleum resources of the region—98.4 percent of the crude oil and 97.1 percent of the natural gas. After the peak in Class AAA fields, the declines in amounts through successively smaller field size categories are remarkably uniform for both crude oil and natural gas.

Trapping in the Central Gulf is predominantly structural, even more so than in the Western Gulf region. Most of the significant fields are either faulted anticlines or faulted salt domes. Some combination traps occur as well, the distribution of petroleum within a structure also being determined by facies change. Except for a good number of Pleistocene sandstone reservoirs in the far offshore fields and a few deep Cretaceous reservoirs, the reservoir rocks of the Central Gulf are Tertiary sandstones. Miocene reservoirs predominate, although Pliocene reservoirs are common offshore and Eocene and Oligocene reservoirs have been found in the onshore fields. Thick multiple reservoirs are commonplace, combined net thicknesses ranging from 50 to 1000 feet. (Lesser thicknesses listed in the tables of App. A typically indicate either the thickness of only one reservoir in a field or only the perforated interval within that reservoir.) Because of these thick, good-quality reservoirs, recovery per surface acre in the significant fields is between 20,000 and 100,000 barrels' L&LE.

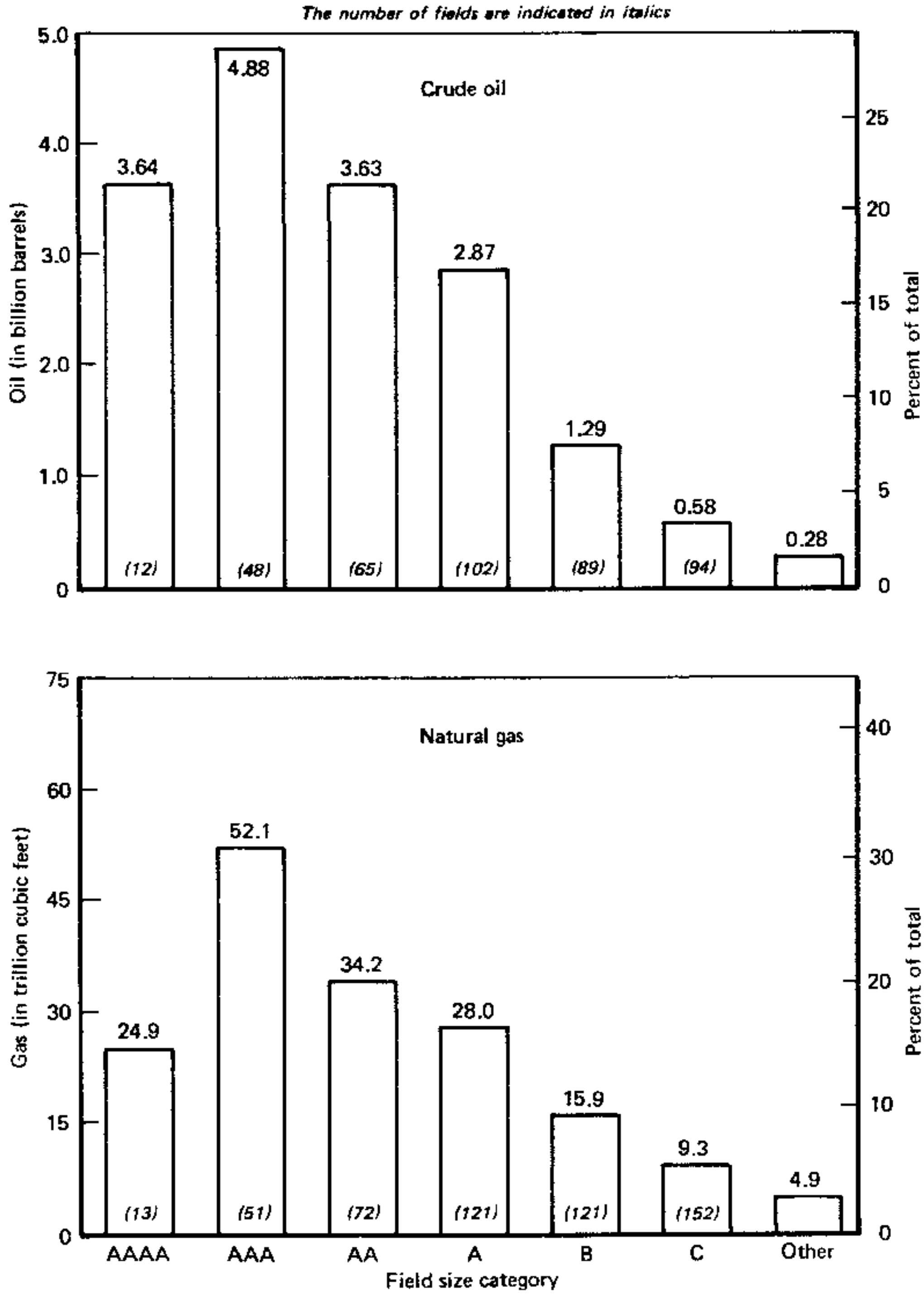

Fig. 3.8—Distribution of crude oil and natural gas by field size category in the Central Gulf

NORTHERN GULF

According to data available as of 1979, the oil and gas fields of the Northern Gulf region discovered before 1976 contained, when discovered, 12.95 billion barrels of recoverable crude oil (8.6 percent of the national total), 53.4 trillion cubic feet of natural gas (7.1 percent of the national total), and 2.24 billion barrels of natural gas liquids (9.3 percent of the national total). The region ranks sixth overall, with 24.10 billion barrels' L&LE, 8.0 percent of the national total. It is also the sixth most important source of crude oil, and it ranks fifth as a source of natural gas and natural gas liquids. The petroleum resources of the region are predominantly liquids, 63.0 percent of the total being crude oil and natural gas liquids. Of the amounts that have been discovered and made recoverable, 10.94 billion barrels of crude oil (84.5 percent of the total), 45.2 trillion cubic feet of natural gas (84.6 percent of the total), and 1.81 billion barrels of natural gas liquids (80.8 percent of the total) had been produced as of the end of 1978.

The region is essentially coextensive with the East Texas-Arkla Province. The East Texas Province consists of Texas R.R.C. Districts 5 and 6; the Arkla Province consists of northern Louisiana and southern Arkansas. Because several major fields straddle the Texas-Louisiana boundary and because of the clear geologic continuity between the two provinces, we consider them as a single province. The Northern Gulf region, as we define it, also includes the eastern part of the Arkoma Province, with slightly more than 3 trillion cubic feet of dry gas resources.

At least 177 significant oil and gas fields were discovered in the Northern Gulf region before 1976 (Tables A.9a, A.9b, A.9c, and A.9d). Another 10 fields are within 1 million barrels' L&LE of being significant: *Caspiana, Cheniere Creek, Converse, Epps* (all), *Hodge, Killen's Ferry, Patton Church,* and *Roseland* in northern Louisiana; and *Boggy Creek* and *Pone* in Texas R.R.C. District 6.

Giant fields contain most of the petroleum in the Northern Gulf region, being particularly prominent as a source of crude oil (see Fig. 3.9). The *East Texas* field, one of three super-giant fields in the United States, is the primary factor shaping this distribution. The six giant fields contain 59.8 percent of the crude oil of the region and 31.9 percent of the natural gas. The 61 Class A or larger fields contain 87.6 percent of the crude oil and 79.4 percent of the natural gas. Significant fields contain 95.7 percent of the crude oil and 93.8 percent of the natural gas. As Fig. 3.9 shows, none of the field size categories from Class A on down are particularly important in the region, each having only between 3 and 5 percent of the crude oil and 5 and 8 percent of the natural gas in the region.

Trapping in the Northern Gulf region is predominantly structural, although stratigraphic trapping is very evident. Most of the significant fields are either faulted anticlines or anticlines combined with various stratigraphic elements, including unconformities, facies changes, and porosity-permeability pinchouts. There are also some major stratigraphically trapped fields including *East Texas* (unconformity), *Fairway* (organic reef), and *Delhi* (unconformity). The East Texas-Arkla Province is of Mesozoic age, the reservoirs consisting primarily of Cretaceous sandstones and carbonates. Jurassic reservoirs have also been found. Reservoirs in the anticlinal or combination anticlinal fields of the eastern Arkoma Basin are predominantly Paleozoic Pennsylvanian sandstones. The combined net thickness of the reservoirs in most of the fields in the East Texas-Arkla Province is between 20

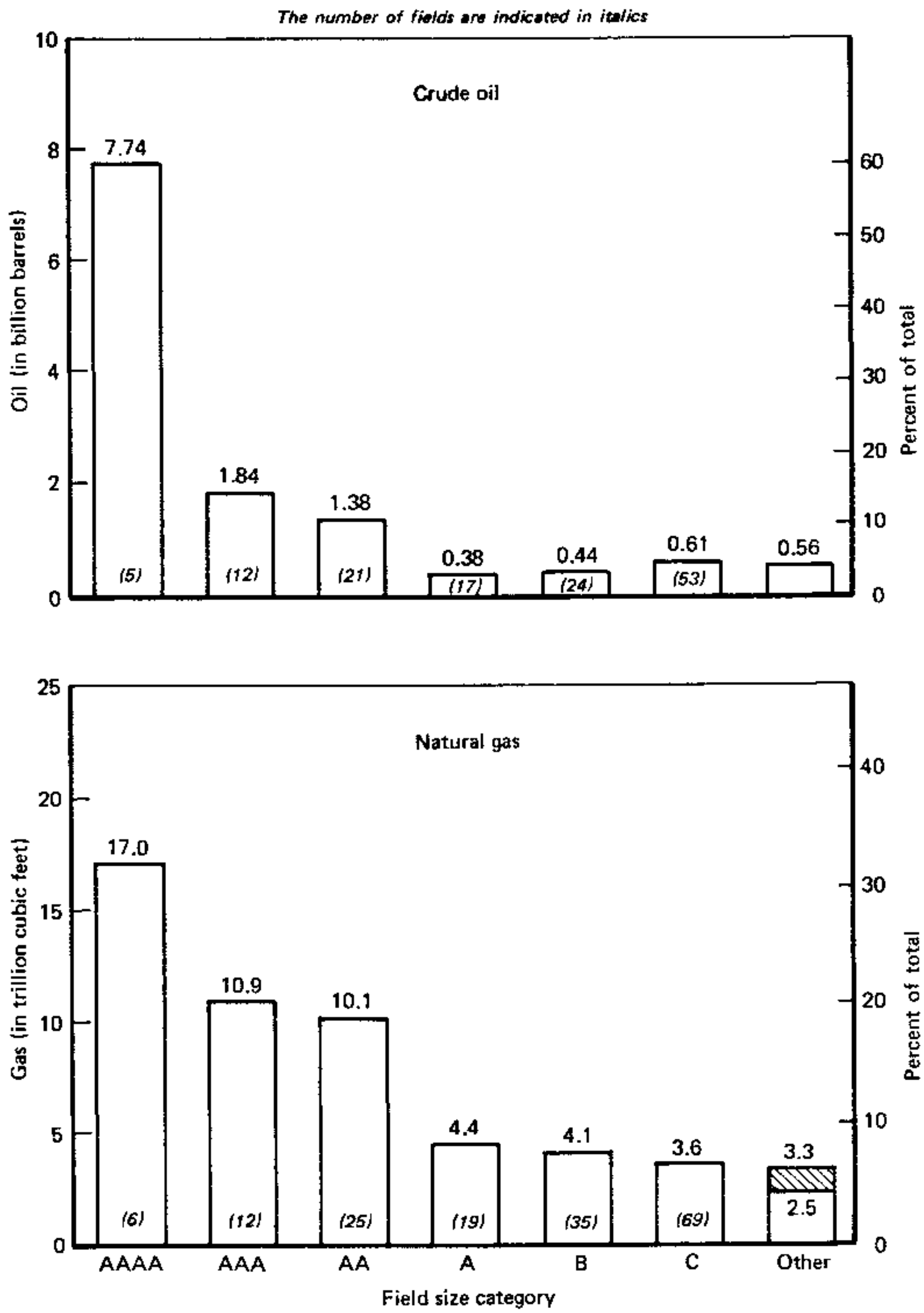

Fig. 3.9—Distribution of crude oil and natural gas by field size category in the Northern Gulf

and 100 feet. Recovery in most of the fields ranges between 5000 and 30,000 barrels per acre, although in a few of the thickest fields (e.g., *Hawkins* and *Van*) it reaches 100,000 barrels' L&LE per acre.

EASTERN GULF

According to data available as of 1979, the oil and gas fields of the Eastern Gulf region discovered before 1976 contained, when discovered, 2.55 billion barrels of recoverable crude oil (1.7 percent of the national total), 7.8 billion cubic feet of natural gas (1.0 percent of the national total), and 0.35 billion barrels of natural gas liquids (1.4 percent of the national total). As these small proportional shares suggest, the region is the least important of any of our 12 regions, with only 4.20 billion barrels' L&LE (1.4 percent of the national total). It ranks last as a source of crude oil and eleventh as a source of both natural gas and natural gas liquids. The region is predominantly an oil region, with 69.0 percent of its petroleum resources consisting of petroleum liquids. Of the amounts that have been discovered and made recoverable, 2.12 billion barrels of crude oil (83.1 percent of the total), 5.8 trillion cubic feet of natural gas (74.0 percent of the total), and 0.14 billion barrels of natural gas liquids (40.0 percent of the total) had been produced as of the end of 1978.

There are three provinces with significant oil and gas fields in the region: the Mid-Gulf Coast Basin, the South Florida Province, and the Warrior Basin. However, the Mid-Gulf Coast Basin contains nearly all of the petroleum in the region, with 4.09 billion barrels' L&LE. The South Florida Province has only 0.08 billion barrels' L&LE while the Warrior Basin has a modest 0.04 billion barrels' L&LE. The South Florida Province is almost entirely an oil province; the Warrior Basin is almost entirely a gas province. The Mid-Gulf Coast Basin, like the region as a whole, is predominantly an oil province.

At least 67 significant oil and gas fields were discovered in the Eastern Gulf region before 1976 (Tables A.10a, A.10b, and A.10c). Another four fields in Mississippi (*Lake Como, Magee, Reedy Creek,* and *Smithdale*) contain between 9 and 10 million barrels' L&LE.

The distribution of crude oil and natural gas resources by field size category in the Eastern Gulf region is similar to that in other regions or provinces with relatively small amounts of petroleum (see Fig. 3.10). There are no giant fields in the region. The 21 Class A or larger fields contain 58.7 percent of the crude oil and 72.5 percent of the natural gas. The significant fields of the region contain 83.0 percent of the crude oil and 93.4 percent of the natural gas. Because of the relatively small number of significant gas fields, the distribution of natural gas resources by field size is rather uneven.

The significant fields of the Eastern Gulf region are primarily structural traps (anticlines, faults, salt domes) or combination traps (anticlines with stratigraphic variations). The Mid-Gulf Coast Province is largely of Mesozoic age, the reservoir rocks being predominantly Cretaceous sandstones or Jurassic carbonates. The Warrior Basin, on the other hand, is of Paleozoic age. Combined net thicknesses in the significant fields of the Mid-Gulf Coast Province are between 30 and 150 feet thick. Recovery per surface acre is between 5000 and 30,000 barrels' L&LE.

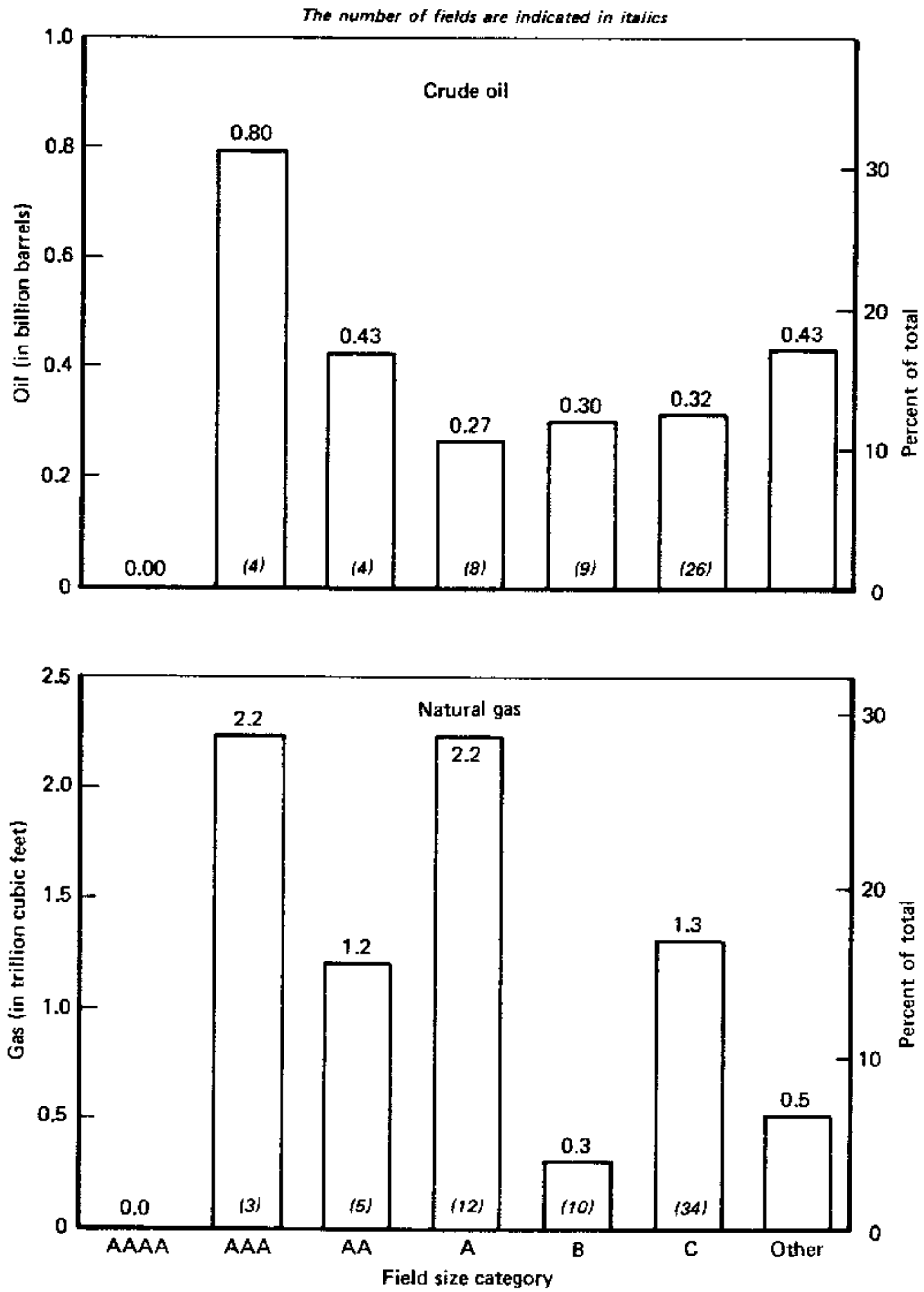

Fig. 3.10—Distribution of crude oil and natural gas by field size category in the Eastern Gulf

ILLINOIS-MICHIGAN

According to data available as of 1979, the oil and gas fields of the Illinois-Michigan region contained, when discovered, 4.67 billion barrels of recoverable crude oil (3.1 percent of the national total), 3.5 trillion cubic feet of natural gas (0.5 percent of the national total), and 0.22 billion barrels of natural gas liquids (0.9 percent of the national total). Overall, the region ranks eleventh among our 12 regions, with 5.47 billion barrels' L&LE. It is the tenth most important as a source of crude oil, but ranks last as a source of natural gas and natural gas liquids. The region is overwhelmingly an oil region, with petroleum liquids constituting 89 percent of the petroleum resources. Of the amounts that have been discovered and made recoverable, 4.33 billion barrels of crude oil (92.7 percent of the total), 2.7 trillion cubic feet of natural gas (77.7 percent of the total), and 0.16 billion barrels of natural gas liquids (72.7 percent of the total) had been produced as of the end of 1978.

The region contains all or part of three provinces with significant oil and gas fields: the Illinois Basin, the Michigan Basin, and that part of the Cincinnati Arch between these two basins. The Illinois Basin is the predominant province in the region, the portion of the basin in Illinois and Indiana containing 4.02 billion barrels' L&LE. The Michigan Basin contains 1.35 billion barrels' L&LE, while the Indiana part of the Cincinnati Arch contains 0.11 billion barrels' L&LE. All three are predominantly oil provinces.

At least 69 significant oil and gas fields had been discovered in the Illinois-Michigan region before 1976 (Tables A.11a, A.11b, and A.11c). Another nine fields in the region contain between 9 and 10 million barrels' L&LE: *Boulder, Concord Consolidated, South Maunie Consolidated,* and *Olney Consolidated* in Illinois; *Welborn Consolidated* in Indiana; and *North Adams, Crystal-Shaver, Hamilton & North,* and *Marion-Winterfield* in Michigan. A few of the larger Silurian pinnacle reef fields discovered in Michigan in the early 1970s may also prove to be significant oil and gas fields once secondary recovery begins.

The distribution of crude oil and natural gas resources by field size category in the Illinois-Michigan region is markedly bimodal (see Fig. 3.11). There are no giant fields. Class A or larger fields contain 65 percent of the total petroleum in the Illinois Basin, but only 23 percent of the total in the Michigan Basin. All significant fields contain 84 percent of the total petroleum in the Illinois Basin, but only 46 percent of the total in the Michigan Basin.

The petroleum resources of the significant fields of both the Illinois and Michigan basins are predominantly trapped in anticlines or anticlines with some stratigraphic variations. Some of the smaller fields are stratigraphically trapped, particularly in the Michigan Basin where pinnacle reefs are common. Both basins are of Paleozoic age. In the Illinois Basin, multiple Mississippian and Pennsylvanian sandstone and carbonate reservoirs 25 to 100 feet thick predominate. In the Michigan Basin, petroleum has been found primarily in Devonian and Silurian reservoirs 5 to 50 feet thick. Recovery per surface acre is between 3000 and 20,000 barrels' L&LE in most of the Illinois Basin fields and between 2000 and 10,000 barrels' L&LE in most of the Michigan Basin fields.

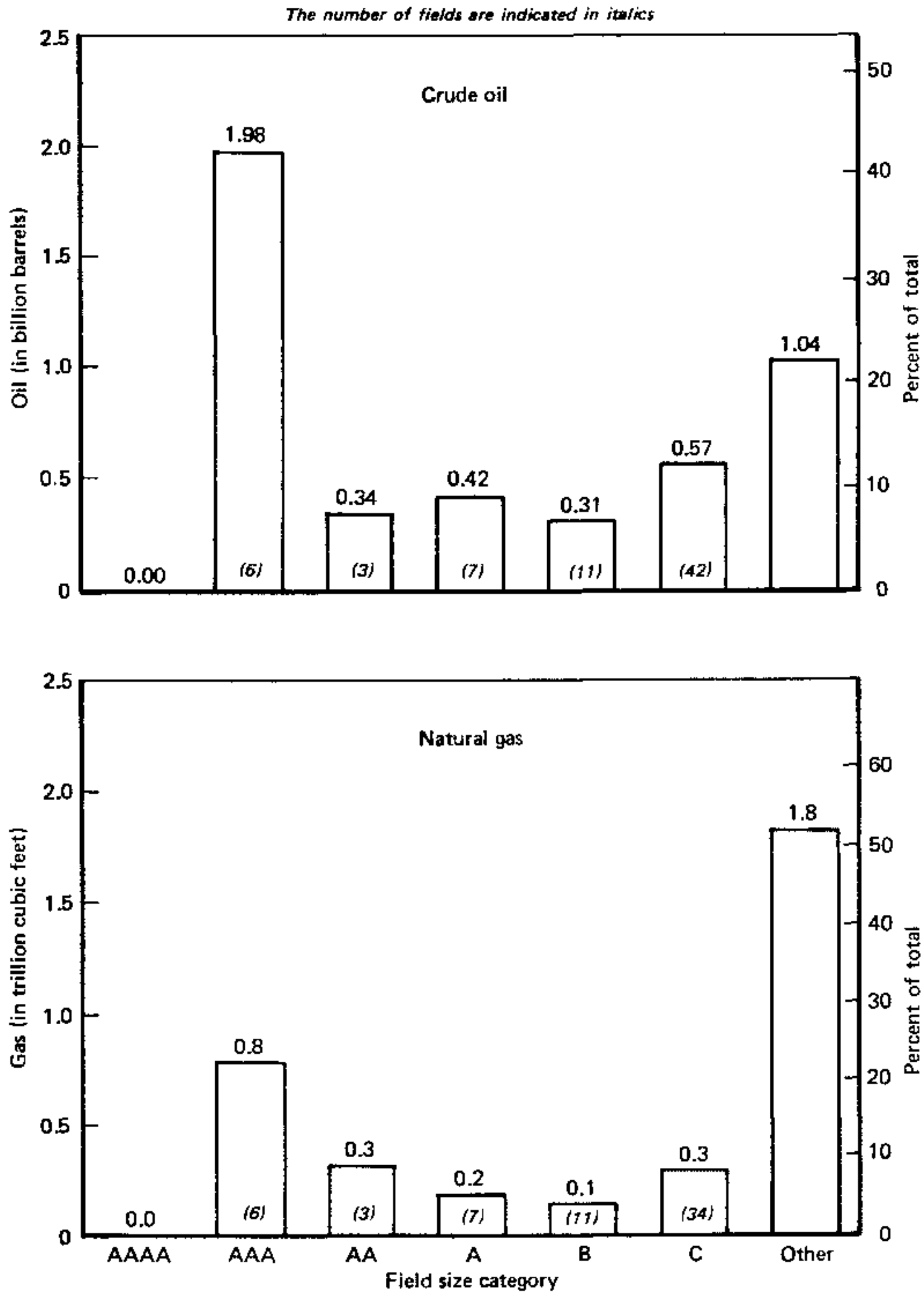

Fig. 3.11—Distribution of crude oil and natural gas by field size category in the Illinois-Michigan basins

APPALACHIAN

According to data available as of 1979, the oil and gas fields of the Appalachian region contained, when discovered, 3.82 billion barrels of recoverable crude oil (2.5 percent of the national total), 39.3 trillion cubic feet of natural gas (5.3 percent of the national total), and 0.48 billion barrels of natural gas liquids (2.0 percent of the national total). Overall, the region ranks ninth in importance, with 10.85 billion barrels' L&LE. The region is predominantly a natural gas region, gas accounting for 60.4 percent of its total known petroleum resources. It thus ranks seventh among the 12 regions as a source of natural gas, but only eleventh as a source of crude oil and tenth as a source of natural gas liquids. Of the amounts that have been discovered and made recoverable, 3.55 billion barrels of crude oil (92.9 percent of the total), 33.9 trillion cubic feet of natural gas (86.2 percent of the total), and 0.35 billion barrels of natural gas liquids (72.9 percent of the total) had been produced as of the end of 1978.

The region consists primarily of the Appalachian Province. However, parts of two other producing provinces—the Cincinnati Arch in western Ohio and central Kentucky and the Illinois Basin in western Kentucky—are also in the region. Because we lack comprehensive data on significant fields, the distribution of petroleum resources by province is somewhat uncertain. The best available data indicate that the Appalachian Province has approximately 10.1 billion barrels' L&LE and that the portions of the Cincinnati Arch and the Illinois Basin in the region each have about 0.41 and 0.34 billion barrels' L&LE, respectively.

Because we lack comprehensive field data on most of the oil and gas fields of the Appalachian region, the number of significant fields is unknown, and the distribution of petroleum resources among the various field size categories can only be crudely estimated. The one clearly recognized giant oil field in the region, the *Bradford* field, with nearly 700 million barrels' estimated ultimate recovery, contains nearly 20 percent of the total amount of recoverable crude oil discovered to date in the region. All Class A or larger fields, including *Big Sinking* (KY), possibly *Busti* and *Richburg* (NY), *Lima* and *Canton East* (OH), *Allegheny* (PA), and *Griffithsville* (WV) contain at least 1.6 billion barrels and possibly as much as 2.0 billion barrels, slightly more than 50 percent of the total. Because field size data for gas fields are even less available and because field definition for most of these fields is an extremely murky area, even the crudest estimates of the distribution of natural gas resources by field size are little more than conjecture. There may be one or two giant gas fields in Pennsylvania and West Virginia. The *Big Sandy* field in eastern Kentucky contains at least 1 trillion cubic feet.

The lack of field data for the Appalachian region also precludes any systematic overview of predominant field characteristics. The region is entirely of Paleozoic age, with reservoirs ranging in age from Pennsylvanian to Ordovician. A wide range of lithologies has also been encountered in these reservoirs. Most of the major fields appear to be either combination traps (anticlines with stratigraphic variations) or stratigraphic traps. The typical range of reservoir thickness and of recovery per surface acre is unknown.

NATIONAL OVERVIEW

According to data available as of 1979, we estimate that 151 billion barrels of crude oil, 751 trillion cubic feet of natural gas, and 24 billion barrels of natural gas liquids had been discovered and made recoverable in all of the oil and gas fields discovered throughout the United States before 1976 (see Table 3.1). The total known recoverable conventional petroleum resource in these fields was 300 billion barrels' L&LE, 17.5 percent of the known recoverable conventional petroleum resources in the world as of the end of 1978.[2] The United States is thus either the leading source of petroleum for the world to date or a close second, depending on which estimates of the oil and gas reserves of the Soviet Union are correct. Only Saudi Arabia—with an estimated 218 billion barrels' known total recovery—is known to have more petroleum liquids. And only the Soviet Union—with an estimated 1100 to 1200 trillion cubic feet of known total recovery—is known to have more natural gas.

Of these amounts, 117.77 billion barrels of crude oil (78.1 percent of the total), 558.4 trillion cubic feet of natural gas (74.4 percent of the total), and 18.46 billion barrels of natural gas liquids (76.3 percent of the total) had been produced by the end of 1978. Thus, less than one-fourth of the total amount discovered and made recoverable to date remains to be produced and consumed.

The proportion remaining to be discovered and produced varies substantially by region. Alaska is at one extreme; by the end of 1978, only 10 percent of the amount of petroleum in fields discovered before 1976 had been produced. At the other extreme—the Illinois-Michigan basins and the Appalachian region—nearly 90 percent of the amount of petroleum in fields discovered before 1976 had been produced by the end of 1978.

Regional Distribution

Most of the producing regions of the United States have substantial amounts of crude oil resources (see Table 3.1). No region dominates the national total. Only California and the Permian Basin have more than 15 percent of the total. In contrast, natural gas resources are highly concentrated in only three regions. The Mid-Continent and the Central Gulf regions each have more than 20 percent of the known recoverable natural gas resources of the nation. The Western Gulf region is also prominent, with 17.4 percent of the total. Together, these three regions contain more than 60 percent of the known recoverable natural gas resources of the United States. No other region has more than 10 percent of the total. The picture for natural gas liquids is similar to that of natural gas, with the addition of the Permian Basin to the three major natural gas regions. Together, these four regions have more than 70 percent of the national total. Individually, each has between 15 and 20 percent of the total.

Distribution by Province

According to the province designations of Sec. II (Table 2.3), there are 66

[2] R. Nehring, *The Outlook for Conventional Petroleum Resources*, The Rand Corporation, P-6413, November 1979.

Table 3.1

THE KNOWN RECOVERABLE PETROLEUM RESOURCES OF THE UNITED STATES BY REGION AND TYPE
(In pre-1976 discoveries as determined in 1979)

Region	Crude Oil (10^9 bbl)	Natural Gas (Tcf)	Natural Gas Liquids (10^9 bbl)	Petroleum (10^9 bbl L&LE)
1. Alaska	10.73	33.9	0.41	16.79
2. California	23.66	33.2	1.20	30.39
3. Rocky Mountains	10.06	44.0	1.24	18.63
4. Permian Basin	26.61	73.4	3.81	42.66
5. North Central Texas	4.89	10.8	0.70	7.38
6. Mid-Continent	19.66	152.0	4.78	49.76
7. Western Gulf	14.26	130.4	3.89	39.88
8. Central Gulf	17.17	169.3	4.83	50.20
9. Northern Gulf	12.95	53.4	2.24	24.09
10. Eastern Gulf	2.55	7.8	0.35	4.21
11. Illinois-Michigan	4.67	3.5	0.22	5.48
12. Appalachian	3.82	39.3	0.48	10.85
United States[a]	151.04	751.0	24.14	300.35

[a]Numbers in this row do not total because of rounding.

productive geologic provinces in the United States. In 55 of these, at least one significant field had been discovered before 1976. This could suggest that significant amounts of petroleum are common. However, the distribution of petroleum resources tells a different story. Table 3.2 shows the major petroleum provinces of the United States. The standard for inclusion is whether a province has at least 2.5 billion barrels' L&LE known recovery, a level equivalent to three months of current national consumption of petroleum products and natural gas.

Only 18 of the 66 productive provinces are currently known to have had at least 2.5 billion barrels' L&LE. Together they contain 276.3 billion barrels' L&LE, 92.0 percent of total known recovery in the nation from fields discovered before 1976. This concentration holds for both petroleum liquids and natural gas. The 18 largest provinces contain 91.3 percent of national petroleum liquids and 92.9 percent of national natural gas resources. The four largest provinces, those with a level of known recovery greater than two years' current national consumption, contain 61.1 percent of the total known recovery of petroleum nationwide (53.3 percent of the petroleum liquids and 72.2 percent of the natural gas). The nine largest provinces, those with a level of known recovery equal to or greater than one year's current national consumption, contain 80.7 percent of the total known recovery (77.4 percent of the petroleum liquids and 85.3 percent of the natural gas). There are another 18 provinces with a known total recovery between 0.5 and 2.5 billion barrels' L&LE.

Table 3.2

THE MAJOR PETROLEUM PROVINCES OF THE UNITED STATES

Province	Geologic Age of Reservoirs	Petroleum Resources			Distribution of Petroleum Resources by Field Size Category		
		Petroleum Liquids	Natural Gas	Petroleum			
		(10^9 bbl)	(Tcf)	(10^9 bbl L&LE)	AAAA	AAAA-A	AAAA-C
1. Gulf Coast	Cenozoic	40.1	299.5	90.0	22%+	77%+	94%
2. Permian	Paleozoic	c. 31.3	c. 74.4	c. 43.7	51%+	82%+	94%
3. Anadarko-Amarillo	Paleozoic	c. 6.7	c. 117.6	c. 26.3	72%	87%	96%
4. East Texas-Arkla	Mesozoic	15.2	50.6	23.6	48%	84%	94%
5. Arctic Slope	Mesozoic	10.1	26.0	14.5	98%	100%	100%
6. San Joaquin	Cenozoic	11.4	11.3	13.3	67%	95%	99%
7. Chautauqua	Paleozoic	c. 8.5	c. 15.0	c. 11.0	22%+	61%+	86%
8. Appalachian	Paleozoic	c. 3.6	c. 39.0	c. 10.1	N.A.	N.A.	N.A.
9. Los Angeles	Cenozoic	8.6	7.4	9.8	70%	98%	99%
10. South Oklahoma	Paleozoic	c. 4.0	c. 10.2	c. 5.7	49%+	74%+	93%
11. San Juan	Mesozoic	0.8	22.0	4.5	75%	90%	96%
12. Illinois	Paleozoic	4.1	1.7	4.4	0%	59%	78%
13. Mid-Gulf Coast	Mesozoic	2.8	7.7	4.1	0%	68%	88%
14. Ventura	Cenozoic	3.1	5.3	4.0	44%	81%	97%
15. Bend	Paleozoic	c. 2.2	c. 5.4	c. 3.1	0%	18%+	38%
16. Central Kansas	Paleozoic	c. 2.6	c. 1.8	c. 2.9	0%	51%+	73%
17. Big Horn	Paleozoic, Mesozoic	2.4	1.5	2.7	23%	83%	95%
18. Powder River	Mesozoic, Paleozoic	2.4	1.3	2.6	30%	63%	86%
Total		159.9	697.7	276.3	43%+	81%+	94%

Together these 18 contain 22.1 billion barrels' L&LE (7.4 percent of the national total). The other 28 known productive provinces contain only 1.9 billion barrels' L&LE (0.6 percent of the national total). The petroleum resources of the United States are thus highly concentrated in a handful of productive provinces.

The four largest provinces in terms of amounts of known recoverable petroleum resources are also among the largest in terms of area. But the correlation between surface area and productivity, while positive, is not very robust. Several areally small provinces are significant in terms of their resources (e.g., the Los Angeles, Ventura, South Oklahoma, and Big Horn provinces). Several areally large provinces are not yet significant in terms of their resources (e.g., the Basin and Range, Denver, Greater Green River, and Williston provinces). The largest province in area, the Appalachian Province, has less than one-tenth the known recovery per unit of area of the Gulf Coast Province, the largest province in terms of known recovery.

The geologic history and characteristics of these provinces are more important in explaining the amounts of recoverable petroleum within them than their surface area, or even their sedimentary volume. As we stated earlier in Sec. I, if large accumulations of petroleum are to exist, several conditions must have existed in an appropriate temporal and spatial relationship with each other. Sufficient organic material must have been produced and preserved. This material must be buried to a depth where sufficient temperature and pressure exist to generate petroleum. Following generation, the petroleum must be expelled into permeable carrier or reservoir rocks. Traps with porous and permeable reservoir rocks covered by impermeable sealing rocks must exist where the migrating petroleum can accumulate. These traps must not be breached or flushed after accumulation occurs. As a general rule, the significant provinces are those provinces where these conditions have been met to a sufficient degree.

Distribution by Field Size

The petroleum resources of the United States are not only concentrated in a small number of significant provinces but are also located in a relatively small number of significant fields. Figures 3.12 and 3.13 show the distribution by field size category of known recoverable resources of crude oil and natural gas, respectively, in all fields discovered before 1976 in the United States excluding the Appalachian region. The figures also show the number of fields in each field size category. The numbers of fields differ between the two figures because we included only those fields with some crude oil or some natural gas in the count on each figure.

Crude oil resources are highly concentrated in the largest fields. The 72 Class AAAA fields with crude oil have 62.89 billion barrels of the 147.22 billion barrels in the United States ex-Appalachia, 42.7 percent of the total. The ten largest fields—*Prudhoe Bay, East Texas, Wilmington Trend, Yates, Midway-Sunset, Wasson, Kern River, Scurry, Slaughter-Levelland,* and *Sho-Vel-Tum*—contain 30.29 billion barrels, 20.1 percent of the national total including Appalachia. The 158 Class AAA fields add another 18.1 percent; the 212 Class AA fields provide 11.4 percent of the national total ex-Appalachia; and the 327 Class A fields contribute 8.3 percent of the total. Together, the 769 giant and large fields with crude oil have 118.58 billion barrels, 80.5 percent of the national total ex-Appalachia. Assuming that roughly half of the crude oil resources in Appalachia are in Class A or larger fields, the proportion of crude oil resources in giant and large fields nationwide is only marginally less than 80 percent. With the amount in the 1193 Class B and C fields added to the Class A or larger fields, the total amount in the 1962 significant fields with crude oil is 134.81 billion barrels, 91.6 percent of the national total ex-Appalachia. The amount in Class D and E fields, which are probably in excess of 10,000 in number, is only 12.41 billion barrels, 8.4 percent of the national total ex-Appalachia.

Natural gas resources are only slightly less concentrated in the largest fields. The 81 Class AAAA fields with natural gas have 270.1 billion cubic feet of the 711.7 trillion cubic feet in the United States ex-Appalachia, 38.0 percent of the total. The ten largest fields—*Hugoton-Panhandle, Prudhoe Bay, Blanco: Mesa Verde, Eunice Area, Borregos-Seeligson-T.C.B., Monroe, Carthage, Aqua Dulce-Stratton, Basin,* and *Katy*—contain 165.0 trillion cubic feet, 22.0 percent of the national total including Appalachia. *Hugoton-Panhandle* dominates the other natural gas fields. Its 79.9 trillion cubic feet constitute 10.6 percent of the national total, equaling as much as the total of the next eight largest fields. The 166 Class AAA fields add another 17.3 percent to the national total ex-Appalachia; the 244 Class AA fields provide 12.5 percent of the total; and the 376 Class A fields contribute 9.8 percent of the total. Together, the 867 giant and large fields with natural gas have at least 551.5 trillion cubic feet, 77.5 percent of the national total ex-Appalachia. With the amount in the 1533 Class B and C fields added to the Class A or larger fields, the total amount in the 2400 significant fields with natural gas is at least 650.5 trillion cubic feet, 91.4 percent of the national total ex-Appalachia. We estimate that another 13.0 trillion cubic feet of the amount shown in other fields is also in significant fields, even though we were unable to allocate it to specific fields. This amount adds another 1.8 percent to the total in significant fields. With this adjustment, the proportion of known natural gas resources in significant fields appears to be slightly greater than the proportion of crude oil resources in significant fields.

Our estimates of the distribution of natural gas liquids by field size category are not as accurate as those for crude oil and natural gas. However, the data for natural gas liquids, when adjusted for probable errors in estimation, show a distribution similar to that for crude oil and natural gas (see Fig. 3.14). Class AAAA fields have at least 9.61 billion barrels, 40.6 percent of the total of 23.66 billion barrels for the United States ex-Appalachia. Class AAA, AA, and A fields contribute at least another 8.58 billion barrels. Together, giant and large fields have at least 18.19 billion barrels, 76.9 percent of the national total. Class B and C fields together add at least another 2.12 billion barrels. At a minimum, the significant fields have 20.31 billion barrels, 85.8 percent of the national total ex-Appalachia. However, because of the lack of published data on natural gas liquids by field and because of the conservative procedures we used to estimate natural gas liquids by field, we believe that at least another 1.92 billion barrels of the remaining 3.35 billion barrels belong in significant fields, even though we could not allocate this amount with confidence to specific fields. With this adjustment, we get a total of 22.23 billion barrels in significant fields, 94.0 percent of the total amount in the United States ex-Appalachia.

The preceding distributions of petroleum resources by field size category are strictly distributions of *current* estimates of recovery. They do not indicate the *ultimate* distribution of resources by field size, even for those fields discovered before 1976. In the future, we can expect that estimates of total recovery from many

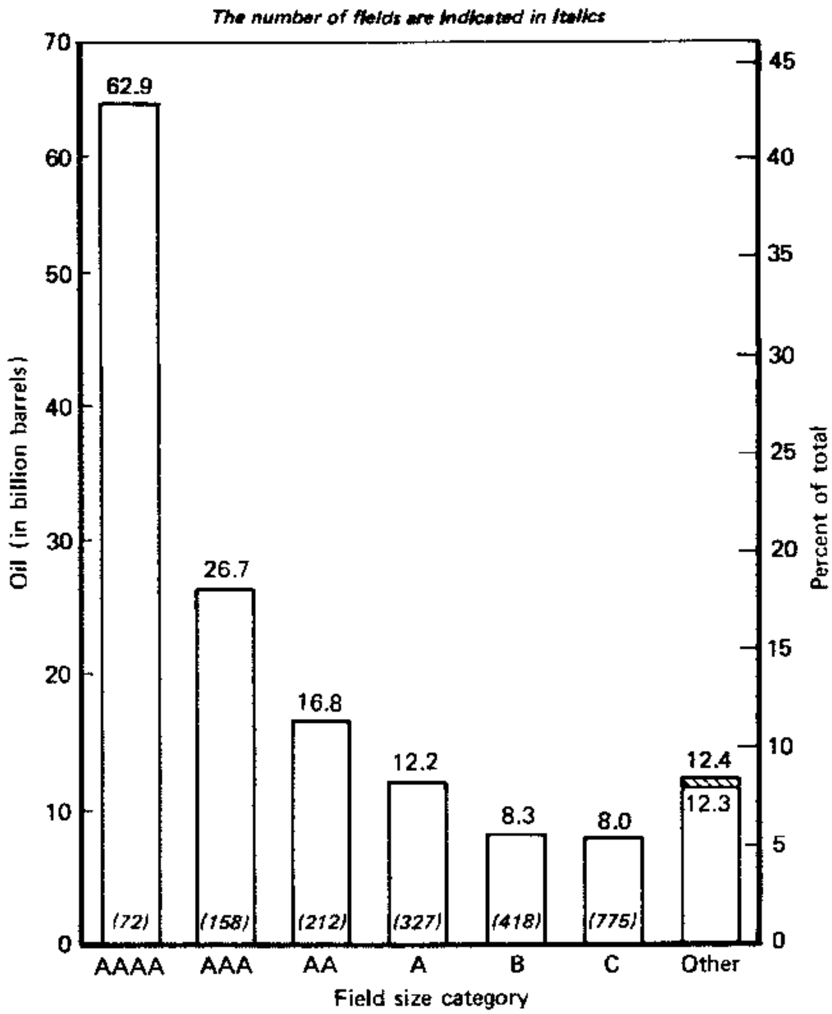

Fig. 3.12 —Distribution of crude oil by field size category
in the United States (ex-Appalachia)

of these fields will increase. Additional amounts of oil and gas will be recovered from known pools with more intensive development in response to higher prices. The productive limits of known pools will be extended, and new pools will be discovered and developed in known fields. Better data will make possible more accurate estimates of field size, reducing or eliminating many of the underestimates in our own data. In a few cases, estimates of total recovery could be reduced because of poorer than anticipated reservoir performance (e.g., *Hawkins* in Texas R.R.C. District 6). But, because cumulative production is already such a substantial proportion of total recovery in most significant fields and because current reserve-to-production ratios in most significant fields are already quite low, we conclude that

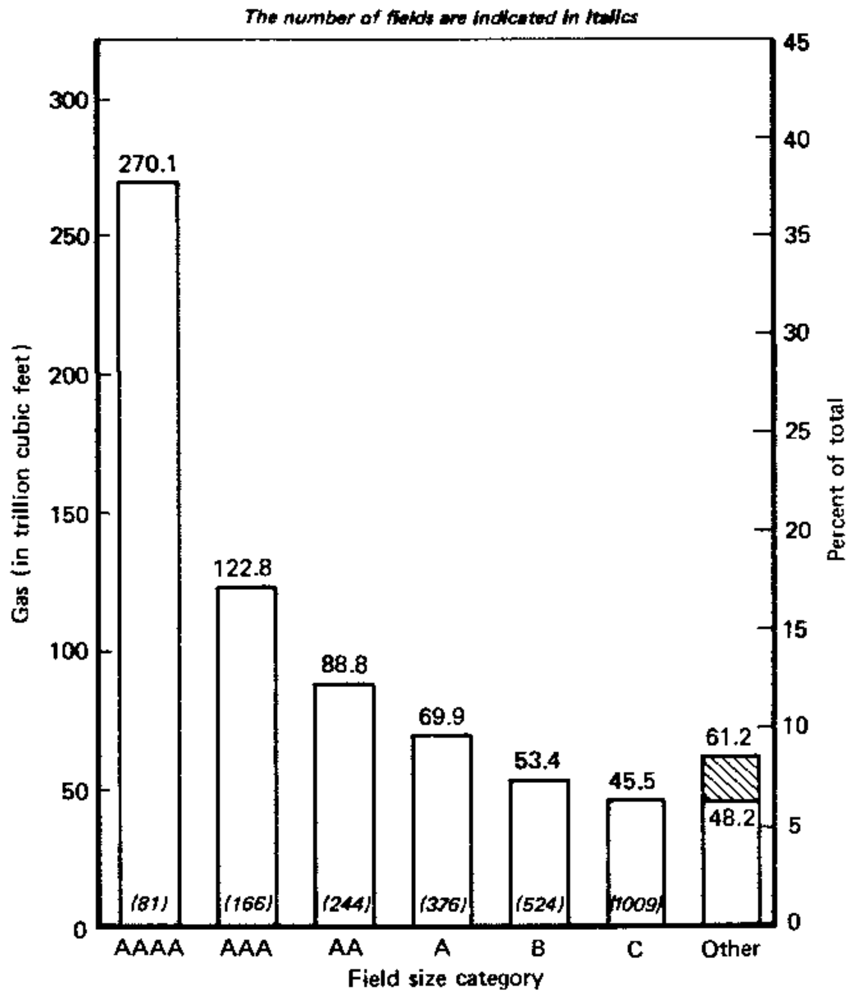

Fig. 3.13 —Distribution of natural gas by field size category in the United States (ex-Appalachia)

any downward revisions that may occur cannot appreciably affect the overall distribution of oil and gas resources by field size category nationwide.

To assess some of the implications of reserve growth for the distribution of petroleum resources by field size category, we examined three possible changes: (1) the effect of elevating all fields between 450 and 500 million barrels' L&LE and all other Class AAA fields with a reasonable probability of sufficient additional recovery and field expansion into the Class AAAA category; (2) the effect of elevating all Class B fields between 45 and 50 million barrels' L&LE into the Class A category; and (3) the effect of elevating all Class D fields between 9 and 10 million barrels' L&LE into the Class C category. Only the first change has an appreciable effect on the distribution of petroleum resources by field size category.

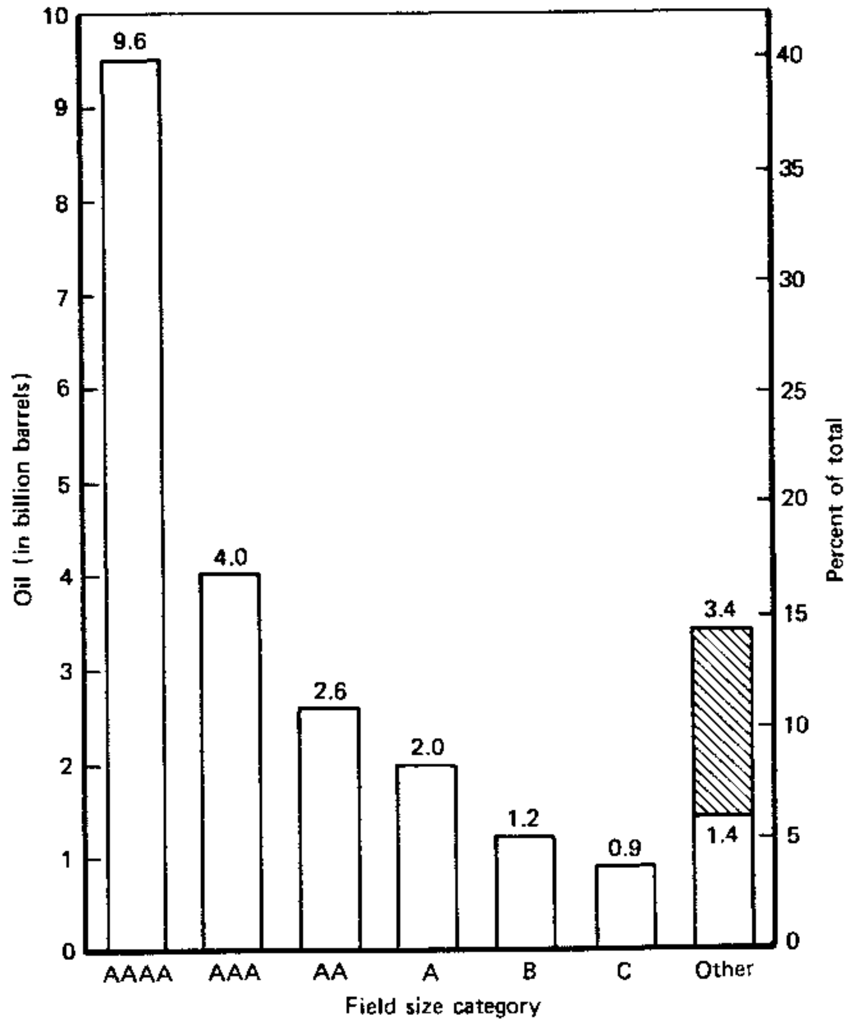

Fig. 3.14—Distribution of natural gas liquids by field size category in the United States (ex-Appalachia)

We identified 23 Class AAA fields with a strong probability of becoming giants in the future: *Kuparuk River* (Alaska); *South Belridge* (California); *Aneth*, *Big Piney-LaBarge*, and *Oregon Basin* (Rocky Mountains); *Artesia-Maljamar*, *Hobbs*, *Howard Glasscock*, *Penwell-Waddell*, *Puckett*, and *TXL* (Permian Basin); *Glenn* and *Healdton* (Mid-Continent); *Grand Isle Block 43*, *Lake Arthur*, *Lake Barre*, and *West Delta Block 27* (Central Gulf); *Rodessa* and *Sligo* (Northern Gulf); *Jay* (Eastern Gulf); and *Lawrence*, *Louden*, and *Salem* (Illinois-Michigan). The inclusion of these fields in the Class AAAA category would add, without any adjustments for the reserve growth that would merit such a change, another 6.24 billion barrels of crude oil, 19.0 trillion cubic feet of natural gas, and 0.68 billion barrels of natural gas liquids. With this inclusion, giant fields would have 47.0 percent of the crude oil, 40.6 percent of the natural gas, and at least 43.5 percent of the natural gas liquids in the United States ex-Appalachia. The 71 fields between 45 and 50 million barrels each would add another 1.33 billion barrels of crude oil, 10.4 trillion cubic feet of natural gas, and 0.27 billion barrels of natural gas liquids to Class A and larger fields. The 116 fields between 9 and 10 million barrels' L&LE would add only 0.55 billion barrels of crude oil, 3.0 trillion cubic feet of natural gas, and 0.05 billion barrels of natural gas liquids to the total amount in significant fields. The combined effect of adjustments for reserve growth and for potential estimation errors puts nearly 50 percent of the crude oil and slightly more than 40 percent of the natural gas and natural gas liquids in the United States ex-Appalachia in Class AAAA (giant) fields, 80 percent or more of all three types of petroleum in Class A or larger (giant and large) fields, and 92 to 94 percent of all three types of petroleum in significant fields.

Distribution by Geologic Characteristics

Because giant and large fields contain the vast majority of U.S. oil and gas resources, any serious attempt to evaluate future possibilities must take into account the geologic characteristics of these fields. One of the most important characteristics is the type of trap in which petroleum has accumulated. It is a major indicator of the information that could have been available to explorationists before drilling, assuming recent technology. Some types of traps are obvious, that is, they are readily detected by surface geology or seismic investigation. Other types of traps are more subtle, their possibility being indicated largely by piecing together subsurface information.

Table 3.3 summarizes by region the trap types of all giant and large oil fields discovered in the United States ex-Appalachia before 1976. We have simplified the categorization from Table 2.5 to highlight several key points. Traps are divided into three general categories: structural, combination, and stratigraphic. We have divided structural traps into three specific categories: anticlines or faulted anticlines, salt domes or faulted salt domes, and other (faults, fracturing, nosing); combination traps into two categories: those that include anticlines or faulted anticlines and those that do not; and stratigraphic traps into two categories: facies changes or porosity-permeability pinchouts and other (unconformities or organic reefs). In a few cases where the trap type was more complex (e.g., a stratigraphic trap with both facies changes and unconformities), we placed the field in the category that we judged to be more important.

The giant and large fields of the United States are predominantly structural traps. Of the 873 fields discovered before 1976 in these size categories, 568 (65.1 percent) are structural traps. These traps are predominantly anticlines or faulted anticlines (427 or 48.9 percent of the total). Anticlinal traps, either by themselves or in combination with other types of traps, account for 607 (69.5 percent) of the total number of giant and large fields. This predominance extends across all regions. Anticlines or combination anticlinal traps account for at least 58 percent of giant and large fields in each of the 12 regions. Salt domes, whether by themselves or in combination with stratigraphic trapping, are the only other major category, accounting for 131 (15.0 percent) of the total. Nearly all of the giant or large fields associated with salt domes are in southern Louisiana or Texas R.R.C. District 3.

Table 3.3

TRAP TYPES OF THE GIANT AND LARGE OIL AND GAS FIELDS IN THE UNITED STATES BY REGION
(In number of fields)

Region	Trap Type							Total Number of Fields
	Structural			Combination		Stratigraphic		
	Anticlines	Salt Domes	Other	Anticlinal	Other	Facies Change, Pinchouts	Other	
Alaska	11	0	0	1	1	0	0	13
California	40	0	5	20	11	3	0	79
Rocky Mountains	29	0	2	5	7	15	0	58
Permian Basin	56	0	0	27	2	12	10	107
North Central Texas	6	0	0	9	1	0	1	17
Mid-Continent	23	0	1	54	6	19	1	104
Western Gulf	70	19	8	23	17	2	1	140
Central Gulf	143	99	3	7	5	0	0	257
Northern Gulf	30	0	1	23	4	0	3	61
Eastern Gulf	11	3	0	6	1	0	0	21
Illinois-Michigan	8	0	0	5	0	3	0	16
United States (Ex-Appalachia)	427	121	20	180	55	54	16	873

Stratigraphic traps comprise only 8.0 percent of the total. Most are located in the Rocky Mountain region, the Permian Basin, or the Mid-Continent.

As an upper bound, subtle traps can be defined as all stratigraphic traps formed by facies changes or porosity-permeability pinchouts and all such traps in combination with hydrodynamic trapping, fracturing, or nosing. This definition is an upper bound because some nosing may be obvious to seismic investigations and some shallow stratigraphic traps may have surface seepages. By this definition, at most only 72 (8.2 percent) of the 873 giant and large fields of the United States may be characterized as subtle traps. This proportion is not appreciably different from the proportion of subtle traps in giant fields worldwide, despite the major differences in drilling density between the United States and the rest of the world. H. D. Klemme, using a definition slightly more restrictive than the one we used, found that only 5.6 percent of giant fields worldwide could be considered to be nonvisible or subtle traps.[3]

Although stratigraphic traps are a small proportion of the total number of giant and large fields, they constitute a major proportion of the largest fields. Four of the ten largest crude oil fields—*East Texas, Kern River, Scurry*, and *Slaughter-Levelland*—are generally recognized as pure stratigraphic traps.[4] Four of the other six are anticlines modified by stratigraphic variations. Two of the ten largest gas fields—*Blanco: Mesa Verde* and *Basin*—are also pure stratigraphic traps, while *Hugoton-Panhandle* and *Carthage* are combination traps with prominent stratigraphic variations. While most of these largest fields may be considered subtle traps, it is important to note that they also cover immense areas. *Hugoton-Panhandle* extends over 7000 square miles, an area greater than that of Connecticut and Rhode Island combined. *Blanco: Mesa Verde* covers over 2300 square miles, an area greater than Delaware. Excluding *Kern River* (located by seepage at the surface) and *Scurry* (a prominent reef), the other fields cover between 200 and 1200 square miles each. Although their trap types may be relatively nonvisible to conventional exploration techniques, at any appreciable density of exploratory drilling (e.g., one well in every two townships) fields of this size cover such a large area that they are almost impossible to miss once exploration begins in earnest.

The concentration of the oil and gas resources of the United States in significant, and particularly giant and large, fields appears to be the result of systematic geologic factors. There are only two regions—North Central Texas and the Illinois-Michigan basins—in which the proportion of the total known petroleum resource in very small (Class D and E) fields exceeds 20 percent. Because the known petroleum resource in both regions is relatively small, the amount in very small fields in each is still not absolutely large. In almost every place where large amounts of petroleum have been found, giant and large fields predominate.

More important, very small fields are highly concentrated in one area of the United States—the stable interior between the Rocky Mountains and the Appalachians. The five regions within this area—Rocky Mountain, Permian Basin, North Central Texas, Mid-Continent, and Illinois-Michigan—contain 44.8 percent of the

[3] "Structure-Related Traps Expected To Dominate World-Reserve Statistics," *The Oil and Gas Journal*, Vol. 71, No. 53, December 31, 1973, and Vol. 72, No. 1, January 7, 1974.

[4] The *East Texas* field could, however, be considered to be formed in part by a broad regional nose on the west flank of the Sabine Uplift. The *Carthage* field is also related to structural aspects of the Sabine Uplift.

crude oil and 39.9 percent of the natural gas in the United States ex-Appalachia. The very small fields in these five regions, after adjustments for overestimates, contain 77.6 percent of the crude oil and 47.6 percent of the natural gas in very small fields in the United States ex-Appalachia. With the addition of the amounts in very small fields in the highly faulted Western Gulf to the amount in these five regions, 87.5 percent of the crude oil and 80.6 percent of the natural gas in very small fields are found in regions that account for only 54.4 percent of the crude oil and 58.2 percent of the natural gas in the United States ex-Appalachia.

The stable interior area of the United States has several characteristics that are not conducive to the occurrence of large and giant deposits of petroleum. The sedimentary cover of the region is relatively thin, often being only 5000 to 10,000 feet thick. In the more shallow areas, organic material is not likely to be buried to a sufficient depth for petroleum generation to occur, even over the hundreds of millions of years from the Paleozoic era. Individual formations in the area are typically thin, indicating relatively low gross rates of deposition. Thinner reservoirs are generally associated with lower rates of recovery per surface acre. Slow rates of sedimentary deposition may mean that organic material is less likely to be preserved. Because most of the area is characterized by great geologic stability since Paleozoic time, there has been little or no deformation of the sediments. This stability contributes to the preservation of whatever petroleum has accumulated in traps. However, it does not contribute to the formation of large, high-relief anticlines, by far the most common trap type in giant and large fields. The strength of these generalizations is supported by the exceptions to the typical distribution of petroleum resources by field size among the provinces of the stable interior. The petroleum resources of the Permian Basin (excepting the Midland Basin and Eastern Shelf), the Anadarko-Amarillo Province, and the South Oklahoma Folded Belt Province are highly concentrated in giant and large fields (Table 3.2). These three provinces either have thick sedimentary sections (Permian and Anadarko-Amarillo), thick reservoirs (all three), or have undergone substantial deformation (Permian and South Oklahoma). Because their geologic characteristics differ from the other provinces in the area, their field size distributions differ as well.

In comparison with the majority of the provinces in the stable interior, the major provinces outside the stable interior are characterized by thick sedimentary sections, typically exceeding 15,000 feet. Individual formations are thick, indicating rapid rates of deposition. Substantial deformation has occurred, creating a multitude of structural traps. Such structural deformation is not always conducive to the formation of giant fields—witness the concentration of resources in numerous large fields in the Central Gulf region. In the Western Gulf region, intense faulting combined with some thinner reservoirs has even created a large number of small and very small traps. Generally, however, the combination of structural traps with moderate to high relief and thick reservoirs is closely associated with fields of significant size, even when the surface area of the field is only several hundred acres in size.

SUMMARY

The United States, which had 151.04 billion barrels of recoverable crude oil, 751.0 trillion cubic feet of natural gas, and 24.14 billion barrels of natural gas liquids in fields discovered before 1976, is either the leading source of petroleum for the world or a close second. However, more than 75 percent of the petroleum discovered and made recoverable in the United States has already been produced. The petroleum resources of the United States are highly concentrated in a few major provinces. Nine of the 66 productive provinces have more than 80 percent of known total recovery of petroleum in the nation. The petroleum resources of the United States are highly concentrated in giant and large fields. More than 80 percent of the total are in the 873 known fields having 50 million barrels' L&LE or more known total recovery. Only 6 to 8 percent of the totals for petroleum liquids and natural gas are in the thousands of very small fields (those with less than 10 million barrels' L&LE) that have been discovered. In nearly every province where large amounts of petroleum have been found, giant and large fields predominate. The giant and large fields are largely structurally trapped. Anticlinal traps alone account for 70 percent of the total number. On the other hand, only 8 percent of the giant and large fields can be characterized as subtle stratigraphic traps. Differences in the distribution of petroleum resources by field size category and trap type are, moreover, the result of systematic differences in the geologic characteristics among the major producing provinces.

Excursus

The Distribution of Petroleum Resources by Field Size in the Geologic Provinces of the United States

In Sec. III, we describe the distribution of U.S. petroleum resources by geographic region, our principal unit of organization for the data discussed and analyzed in this report. The distribution by geologic province is also considered, but only as a secondary theme. In this Excursus to Sec. III, we focus on the distribution of petroleum resources by field size in the productive geologic provinces of the United States, examining our two basic geologic units of analysis in one systematic, unified treatment. Using the significant oil and gas fields data base (App. A) and other supplementary sources of information, we summarize the number of fields and amounts of petroleum by field size category in each productive province and provide some basic supplemental information about each province: its AAPG-CSD province code number(s), the region(s) in which it is located, its province type, the geologic age(s) of the reservoir rocks in each, and the years in which the first and latest (before 1976) significant discoveries were made in each province. (See Table 3.4, p. 82.) Using this summary data, we discuss key similarities and differences among the major petroleum provinces by type.

With a few minor exceptions, the provinces listed in Table 3.4 are the same as those described in Sec. II and listed in Table 2.3. For Table 3.4, we combined the Anadarko Basin and Amarillo Arch into the Anadarko-Amarillo Province and the East Texas and Arkla provinces into the East Texas-Arkla Province because in each case one or more major fields cross the province boundaries as defined by the AAPG-CSD. We also combined the Arctic Slope and Arctic Foothills provinces into one because of a lack of clear geologic separation between the two. We separated the Gulf Coast Province into the Texas Gulf Coast and Mississippi Delta provinces because each exemplifies a different province type. Two provinces with significant fields—the Appalachian Basin and the Cincinnati Arch—were excluded from Table 3.4 because we lacked comprehensive field data for them. Five other productive provinces—Gulf of Alaska, Western Columbia, Northern Coast Range, Santa Cruz, and Iowa Shelf—were excluded from our list because none had as much as 5 million barrels' L&LE known recoverable resources in fields discovered before 1976. With these combinations, divisions, and exclusions, Table 3.4 lists 55 productive provinces.

Our analysis of the productive provinces includes a grouping and analysis of these provinces by type. Such groupings facilitate comparisons of provinces with similar geologic characteristics and of groups of provinces with different geologic characteristics. Several province classification systems have been proposed. We use the one proposed and developed by Klemme,[1] because it is the best developed and most widely used of any of the classification systems proposed to date.

[1] This classification system has been developed in a number of articles over the past decade. For the most recent description of the system, see H. D. Klemme, "Petroleum Basins: Classifications and Characteristics," *Journal of Petroleum Geology*, Vol. 3, No. 2, 1980, pp. 187-207.

Klemme's classification system employs two basic categories and eight province types. The three *intracontinental* types (*interior, composite/complex*, and *rift* provinces) are those found within cratonic plates. The five *extracontinental* types (*downwarp, pull-apart, subduction, median*, and *delta*) are those found on the boundaries of cratonic plates. We will refer to interior provinces as *craton center* provinces and composite/complex provinces as *craton margin* provinces, because we believe these two substitute terms provide a more descriptive name for each of the two types.[2] Six of Klemme's types are represented in the productive petroleum provinces of the United States: craton center, craton margin, rift, downwarp, subduction, and delta. The two rift provinces are very minor. There is at least one major province exemplifying each of the other five types. The other two types (pull-apart and median) characterize several geologic provinces of the United States, none of which were productive before 1976. Because 32 of the 55 provinces listed in Table 3.4 are classified as craton margin provinces, we have divided them into three groups:

1. Those in the interior of the United States between the Rocky Mountains and Appalachians where the maximum depth of the sedimentary rocks is less than 15,000 feet (*interior shallow*).
2. Those in the interior of the United States where the maximum depth exceeds 15,000 feet (*interior deep*).
3. Those in the northern and western Rocky Mountains.

Our assignment of types to specific provinces follows those of Klemme.

We describe the distribution of petroleum resources by field size in Table 3.4 using a geometric field size classification system based on the one provided in Table 2.2. The size boundaries for Class B (25-50 million barrels' L&LE), Class A (50-100), and Class AA fields (100-200) remain the same as they were in Table 2.2. The boundaries of the size categories greater than this range are double those of the next smaller category (e.g., 200-400, 400-800, etc.). The boundaries of the size categories less than this range are half those of the next larger category (e.g., 25-12.5, 12.5-6.25). We did not separate fields less than 6.25 million barrels' L&LE into different categories because we did not estimate sizes for fields having less than that amount. Table 3.4 provides both the number of fields in each size category beginning with 6.25 million barrels' L&LE (the upper number) and the amount of known recoverable petroleum in millions of barrels' L&LE in each size category (the lower number). The total number of fields with at least 6.25 million barrels' L&LE and the amount of known recoverable petroleum in each province is indicated as well. The percentage of the petroleum resources of each province in fields containing at least 400 million barrels' L&LE (giant fields), between 50 and 400 million barrels' L&LE (large fields), at least 50 million barrels' L&LE (giant and large fields), and less than 6.25 million barrels' L&LE (very small fields) is also provided. These definitions differ slightly from those for giant, large, and very small fields used elsewhere in the report. Because many of the fields between 400 and 500 million barrels' L&LE are likely to become Class AAAA (giant) fields and many of

[2] The terms *craton center* and *craton margin* are from the modification of an early version of the Klemme classification system by R. G. McCrossan and J. W. Porter, "The Geology and Petroleum Potential of the Canadian Sedimentary Basins: A Synthesis," in Canadian Society of Petroleum Geologists, *Future Petroleum Provinces of Canada: Their Geology and Potential*, Memoir One, Calgary, 1973, pp. 589-720.

the fields between 6.25 and 10.0 million barrels' L&LE are likely to become Class C fields, we do not consider these differences to affect our analysis seriously.

A geometric (or logarithmic with a base 2) field size scale readily lends itself to an analysis of possible distributions of the number of fields by field size. It is commonly asserted that the underlying distribution in nature of fields by size forms a regular pattern. Several such patterns are possible, the leading candidates being those (1) where the number of fields increases steadily, generally at a constant percentage rate, as field size decreases; and (2) where the number of fields first increases, then decreases as field size decreases, forming various unimodal distributions. The differences between the observed distribution of numbers of fields by size and a postulated distribution have been used to estimate the number and size of fields that remain to be discovered. Because we did not make estimates of the numbers of fields by size below 6.25 million barrels' L&LE, Table 3.4 does not provide all of the data necessary to evaluate the possible relevance of various theoretic distributions for prediction. However, it is sufficient to justify a number of pertinent preliminary observations about this problem.

In the following pages, we describe each group of provinces by type, using Klemme's basic descriptions. We indicate the geographic location of each type within the United States and its overall importance to national petroleum resources. The field size distribution characteristic of each type is emphasized in the discussion, particularly the proportion in giant, giant and large, and very small fields. In our analysis, we concentrate on the 37 provinces of significant size (those with 0.5 billion barrels or more of L&LE). We conclude the Excursus with a brief overview of key similarities and differences among the provinces by type.

PETROLEUM PROVINCES BY TYPE

Craton center (interior) provinces are simple, areally large, roughly circular basins with a symmetrical profile. They are generally areas of Paleozoic platform deposition located in the central portion of cratons near or upon Precambrian shield areas. They are found in the north-central United States, the southern edge of the North American Precambrian shield. They tend to be relatively shallow, the maximum thickness in any of these provinces barely exceeding 12,500 feet. Despite their large area, they do not provide a substantial proportion of U.S. petroleum resources. The five producing craton center provinces contain only 2.5 percent of the known recoverable petroleum resources of the United States. Three of these provinces (Illinois, Michigan, and Williston) are significant, exceeding 500 million barrels' L&LE total recovery. Only one (the Illinois Basin) is a major province, exceeding 2.5 billion barrels' total recovery.

Unlike those of the country as a whole, the petroleum resources of the craton center provinces are not highly concentrated in giant and large fields. Only 17.4 percent of the known recoverable resources of these five provinces is in giant fields ($\geq$400 million barrels' L&LE), and only 50.9 percent is in giant and large fields. Nearly one-fourth (23.0 percent) is in very small fields (less than 6.25 million barrels). The proportions in giant and large fields and in very small fields vary greatly among the three major craton center provinces. Where one or more regional arches exist within the province (e.g., the La Salle, Clay City, and Louden-Salem anticlines in the Illinois Basin and the Cedar Creek and Nesson anticlines in the Williston Basin), 50 to 60 percent of the petroleum resources of the province is in giant and large fields and about 15 percent is in very small fields. Where there are no regional arches (e.g., the Michigan Basin), less than 25 percent of the petroleum resources is in giant and large fields and nearly 50 percent is in very small fields.

Craton margin (composite/complex) provinces are generally areally large, linear to elliptical basins with an asymmetric profile. Most are areas that were initially sites of Paleozoic platform deposition and in late Paleozoic or Mesozoic time subsequently underwent a second cycle of sedimentation derived from an uplift on the exterior margin of the craton. The 32 craton margin provinces are the dominant source of U.S. petroleum resources. Together, they contain 117.3 billion barrels, 39.0 percent of the known recoverable petroleum resources of the United States. (The Appalachian Basin and the Cincinnati Arch, the two substantial producing provinces not included in Table 3.4, add another 10.6 billion barrels to this total.) Geographically, they occupy most of the country north of the Gulf Coast from the Appalachian Mountains to the Great Basin, excluding the north-central region occupied by the five craton center provinces. As indicated earlier, we have divided the craton margin provinces into three groups: the interior shallow, the interior deep, and the northern and western Rocky Mountain provinces.

Half of the craton margin provinces are interior shallow provinces. Ten of these are significant (Chautauqua, Bend Arch, Central Kansas, Powder River, Palo Duro, Denver, Fort Worth Syncline, Sedgwick, Nemaha, and Cherokee), but only the first four are major provinces. Thus, despite the large area that they cover, the interior shallow provinces provide only 9.0 percent of U.S. petroleum resources. Only three of the interior shallow provinces have giant fields, and in these three the proportion of the total petroleum resource in giant fields is only about 30 percent. Overall, only 15.1 percent of the petroleum resources of the interior shallow provinces is in giant fields, and only about 50 percent (after adjustments for underestimates) is in giant and large fields. Nearly one-fourth (23.0 percent) is in very small fields. Within the significant interior shallow provinces, there is a considerable variability in the distribution of known recoverable resources by field size categories, the result primarily of differences in the degree of structural deformation among these provinces and secondarily of differences in the amount of petroleum in each province. The proportion in giant and large fields varies from 20 to 65 percent, and the proportion in very small fields varies from 10 to 60 percent of the total petroleum resources of the province.

There are only four interior deep craton margin provinces (Permian, Anadarko-Amarillo, South Oklahoma, and Arkoma). Yet all are significant, and all but the Arkoma Province are major provinces. Together, these four provinces contain 77.6 billion barrels' L&LE, more than a quarter of known U.S. petroleum resources. (The Appalachian Province would also be classified as an interior deep craton margin province, adding another 10.1 billion barrels to this amount.) Most of the petroleum resources of these four provinces are in giant fields (60.8 percent of the total). Giant and large fields account for 82.8 percent of the total, while very small fields provide only 4.2 percent. Except for the Arkoma Province, which has no giant fields, the distribution of petroleum resources by field size in each of these four provinces is similar to the average for the subtype. About 55 to 70 percent is in giant

Table 3.4

THE DISTRIBUTION OF PETROLEUM RESOURCES BY FIELD SIZE CATEGORY IN THE GEOLOGIC PROVINCES OF THE UNITED STATES

Province	AAPG-CSD Province Code(s)	Region(s)	Province Type	Geologic Age of Reservoirs	First Significant Discovery	Latest Significant Discovery	Percentage of Petroleum in Fields ≥400	50–400	≥50	≤6.25
1. Cook Inlet	[illegible]	Alaska	Subduction	Cenozoic	1957	1967	50.7	46.1	96.8	0.7
2. Arctic Slope and Foothills	885, 890	Alaska	Downwarp	Mesozoic	1968	1972	97.5	2.4	99.9	0.1
3. Eel River	720	California	Subduction	Cenozoic	1937	1937	0	0	0	*
4. Sacramento	730	California	Subduction	Cenozoic, Mesozoic	1932	1972	43.8	14.7	58.5	8.6
5. Cuyama	740	California	Subduction	Cenozoic	1948	1949	0	99.1	99.1	0.9
6. Salinas	740	California	Subduction	Cenozoic	1947	1947	99.5	0	99.5	0.5
7. San Joaquin	745	California	Subduction	Cenozoic	1887	1974	70.6	24.2	94.8	[illegible]
8. Santa Maria	750	California	Subduction	Cenozoic	1903	1946	0	92.4	92.4	0.5
9. Ventura	755, 957, 958, 959	California	Subduction	Cenozoic	1887	1971	43.6	37.5	81.1	1.7
10. Los Angeles	760, 958, 959	California	Subduction	Cenozoic	1880	1968	69.8	27.7	97.5	0.4
11. Chadron-Cambridge	390	Rocky Mountain	Craton Margin	Paleozoic	1960	1960	0	0	0	10.0
12. Williston	395	Rocky Mountain	Craton Center	Paleozoic, Mesozoic	1912	1972	0	52.0	52.0	13.6
13. Las Animas	450	Rocky Mountain, Mid-Continent	Craton Margin	Paleozoic	1959	1959	0	0	0	61.0
14. Sweetgrass Arch	500	Rocky Mountain	Craton Margin	Mesozoic, Paleozoic	1918	1967	0	71.6	71.6	[illegible]
15. Central Montana Uplift	510	Rocky Mountain	Craton Margin	Paleozoic, Mesozoic	1925	1958	0	0	0	15.9
16. Powder River	515	Rocky Mountain	Craton Margin	Mesozoic, Paleozoic	1889	1975	29.7	32.8	62.5	9.4
17. Big Horn	520	Rocky Mountain	Craton Margin	Phanerozoic	1884	1968	38.7	44.3	83.0	2.4

Table 3.4—continued

	Number of Fields and Amounts of Petroleum by Field Size Category (in millions of barrels' L&LE)												
[illegible]6.25	6.25- 12.5	12.5- 25	25- 50	50- 100	100- 200	200- 400	400- 800	800- 1,600	1,600- 3,200	3,200- 6,400	6,400- 12,800	12,800- 25,600	Province Total
16	--	1 13	1 44	1 60	4 590	2 412	2 1,169	--	--	--	--	--	11 2,304
5	--	--	--	2 100	--	1 250	--	--	--	--	--	1 14,133	4 14,488
0	--	1 14	--	--	--	--	--	--	--	--	--	--	1 14
147	10 85	11 204	5 156	3 196	--	--	1 585	--	--	--	--	--	30 1,335
3	--	--	--	1 78	--	1 264	--	--	--	--	--	--	2 345
3	--	--	--	--	--	--	1 565	--	--	--	--	--	1 568
95	9 75	8 143	11 372	6 504	13 1,841	4 873	2 1,099	2 2,871	3 5,399	--	--	--	61 13,273
8	--	--	2 72	2 110	--	3 864	--	--	--	--	--	--	7 1,054
69	7 63	9 256	12 461	4 269	5 329	3 699	--	--	1 1,727	--	--	--	41 3,964
40	5 46	6 111	2 55	7 527	3 425	6 1,779	1 559	3 3,266	1 3,041				34 9,849
7	2 15	--	1 48	--	--	--	--	--	--	--	--	--	3 70
215	10 101	8 122	9 329	1 55	2 236	2 543	--	--	--	--	--	--	34 1,604[a]
30	2 19	--	--	--	--	--	--	--	--	--	--	--	2 49
12	3 27	3 47	2 61	--	1 105	1 265	--	--	--	--	--	--	10 517
17	2 18	--	2 72	--	--	--	--	--	--	--	--	--	4 107
25[illegible]	24 210	16 270	9 263	5 321	4 547	--	1 787	--	--	--	--	--	59 2,648
65	13 115	6 107	5 167	1 56	6 891	1 240	2 1,037	--	--	--	--	--	34 2,678

Table 3.4—continued

Province	AAPG—CSD Province Code(s)	Region(s)	Province Type	Geologic Age of Reservoirs	First Significant Discovery	Latest Significant Discovery	Percentage of Petroleum in Fields >400	50–400	≥50	<6.25
18. Wind River	530	Rocky Mountain	Craton Margin	Phanerozoic	1884	1968	0	65.0	65.0	4.2
19. Greater Green River	535	Rocky Mountain	Craton Margin	Phanerozoic	1916	1975	21.4+	53.1+	74.5+	2.8
20. Laramie	535	Rocky Mountain	Craton Margin	Mesozoic, Paleozoic	1918	1934	0	0	0	10.4
21. Denver	540	Rocky Mountain	Craton Margin	Mesozoic, Paleozoic	1862	1972	0	23.2	23.2	54.3
22. North Park	545	Rocky Mountain	Craton Margin	Mesozoic	--	--	0	0	0	46.7
23. Uinta	575	Rocky Mountain	Craton Margin	Phanerozoic	1948	1967	0	86.9	86.9	2.0
24. San Juan	580	Rocky Mountain	Craton Margin	Mesozoic, Paleozoic	1921	1965	74.5	15.4	89.9	2.7
25. Paradox	585	Rocky Mountain	Craton Margin	Paleozoic	1956	1960	73.5	14.6	88.1	8.2
26. Black Mesa	590	Rocky Mountain	Craton Margin	Cenozoic	1967	1967	0	0	0	17.4
27. Piceance	595	Rocky Mountain	Craton Margin	Phanerozoic	1902	1956	78.1	9.2	87.3	2.1
28. Great Basin	625	Rocky Mountain	Rift	Cenozoic	--	--	0	0	0	100.0
29. Wasatch Uplift	630	Rocky Mountain	Craton Margin	Mesozoic	1951	1951	0	0	0	*
30. Plateau: Kaiparowits	635	Rocky Mountain	Rift	Paleozoic	1964	1964	0	0	0	0
31. Llano Uplift	410	Permian Basin	Craton Margin	Paleozoic	--	--	0	0	0	100.0
32. Permian Basin	430, 435	Permian, N.C. Texas, W. Gulf	Craton Margin	Paleozoic	1920	1975	57.0+	24.7+	81.7+	4.7
33. Strawn Basin	415	N.C. Texas	Craton Margin	Paleozoic	1920	1920	0	0	0	9.5
34. Fort Worth Syncline	420	N.C. Texas	Craton Margin	Paleozoic	1902	1954	32.2	8.4	40.6	36.1

Table 3.4—continued

Number of Fields and Amounts of Petroleum by Field Size Category (in millions of barrels' L&LE)													
<6.25	6.25–12.5	12.5–25	25–50	50–100	100–200	200–400	400–800	800–1,600	1,600–3,200	3,200–6,400	6,400–12,800	12,800–25,600	Province Total
34	7 68	6 94	3 90	5 371	1 161	--	--	--	--	--	--	--	22 818
56	5 35	7 112	7 251	4 301	3 326	2 439	1 429	--	--	--	--	--	29 1,949[b]
7	1 6	1 13	1 41	--	--	--	--	--	--	--	--	--	3 67
743	19 172	8 137	--	1 87	2 230	--	--	--	--	--	--	--	30 1,369
7	1 8	--	--	--	--	--	--	--	--	--	--	--	1 15
9	--	3 51	--	--	1 191	1 207	--	--	--	--	--	--	5 458
121	11 100	3 58	4 172	1 73	2 282	1 331	--	1 1,157	1 2,269	--	--	--	24 4,463
54	1 7	1 17	--	1 96	--	--	1 482	--	--	--	--	--	4 656
4	--	1 19	--	--	--	--	--	--	--	--	--	--	1 23
20	2 16	--	2 97	1 97	--	--	--	1 826	--	--	--	--	6 1,058
5	--	--	--	--	--	--	--	--	--	--	--	--	0 5
[illegible]	--	1 23	--	--	--	--	--	--	--	--	--	--	1 23
--	--	1 24	--	--	--	--	--	--	--	--	--	--	1 24
18	--	--	--	--	--	--	--	--	--	--	--	--	0 18
2,036	112 965	87 1,561	76 2,627	58 3,507	24 3,441	13 3,855	14 7,497	4 4,270	6 13,119	--	--	--	386 42,898[c]
2	--	1 19	--		-	--	--	--	--	--	--	--	1 21
489	13 126	7 119	2 71	2 113	-	-	1 435	--	--	--	--	--	27 1,353

Table 3.4—continued

Province	AAPG-CSD Province Code(s)	Region(s)	Province Type	Geologic Age of Reservoirs	First Significant Discovery	Latest Significant Discovery	Percentage of Petroleum in Fields >400	50-400	>50	<6.25
35. Bend Arch	425	N.C. Texas	Craton Margin	Paleozoic	1910	1951	0	18.3+	18.3+	60.8
36. Palo Duro	435	N.C. Texas, Mid-Continent	Craton Margin	Paleozoic	1911	1962	0	66.1	66.1	20.5
37. Forest City	335	Mid-Continent	Craton Center	Paleozoic	1923	1923	0	0	0	76.1
38. Arkoma	345	Mid-Continent, Northern Gulf	Craton Margin	Paleozoic	1904	1964	0	70.4+	70.4+	4.0
39. South Oklahoma	350	Mid-Continent, N.C. Texas	Craton Margin	Paleozoic	1906	1970	55.6+	18.7+	74.3+	5.5
40. Chautauqua	355	Mid-Continent	Craton Margin	Paleozoic	1889	1956	25.9+	34.6+	60.5+	10.8
41. Anadarko-Amarillo	360, 440	Mid-Continent	Craton Margin	Paleozoic	1910	1975	72.5	14.8	87.3	3.1
42. Cherokee	365	Mid-Continent	Craton Margin	Paleozoic	1873	1924	0	25.0	25.0	19.2
43. Nemaha	370	Mid-Continent	Craton Margin	Paleozoic	1906	1954	0	46.9	46.9	30.4
44. Sedgwick	375	Mid-Continent	Craton Margin	Paleozoic	1920	1961	0	37.9	37.9	22.1
45. Salina	380	Mid-Continent	Craton Center	Paleozoic	--	--	0	0	0	100.0
46. Central Kansas	385	Mid-Continent	Craton Margin	Paleozoic	1924	1961	0	51.1	51.1	21.6
47. Texas Gulf Coast	220, 954, 955, 956	Western Gulf	Downwarp	Cenozoic, Mesozoic	1896	1975	34.6+	34.8+	69.4+	6.9
48. Ouachita Tectonic Belt	400	Western Gulf, Mid-Continent	Downwarp	Mesozoic	1911	1911	0	0	0	45.6
49. Mississippi Delta	230, 951, 952, 953	Central Gulf	Delta	Cenozoic, Mesozoic	1901	1975	23.9+	59.7+	83.6+	1.6
50. East Texas-Arkla	230, 260	Northern Gulf	Downwarp	Mesozoic, Cenozoic	1895	1975	53.9+	30.4+	84.3+	2.9

Table 3.4—continued

Number of Fields and Amounts of Petroleum by Field Size Category (in millions of barrels' L&LE)													
<6.25	6.25–12.5	12.5–25	25–50	50–100	100–200	200–400	400–800	800–1,600	1,600–3,200	3,200–6,400	6,400–12,800	12,800–25,600	Province Total
1,915	17 163	14 232	2 82	2 147	1 140	1 290	--	--	--	--	--	--	37 2,969[d]
297	6 56	1 20	3 117	--	1 110	3 847	--	--	--	--	--	--	14 1,447
86	1 9	1 18	--	--	--	--	--	--	--	--	--	--	2 113
76	15 104	10 183	4 157	1 73	3 476	3 774	--	--	--	--	--	--	34 1,843[e]
316	17 146	16 277	9 329	3 319	3 405	1 540	1 400	1 860	1 1,910	--	--	--	54 5,302[f]
1,157	53 464	38 656	29 950	19 1,241	8 1,129	6 1,431	5 1,696	1 1,150	--	--	--	--	157 9,884[f]
828	61 540	55 921	31 1,039	16 1,202	6 759	7 1,944	1 733	1 950	--	--	--	1 17,387	179 26,302
150	1 5	8 147	8 282	3 196	--	--	--	--	--	--	--	--	20 783
243	12 112	4 70	--	1 51	--	1 324	--	--	--	--	--	--	18 800
259	13 176	9 159	6 193	4 276	1 168	--	--	--	--	--	--	--	33 1,177
27	--	--	--	--	--	--	--	--	--	--	--	--	0 27
633	26 224	17 282	7 294	4 265	3 418	3 814	--	--	--	--	--	--	60 2,930
3,554	159 1,458	166 2,846	104 3,425	65 4,477	45 6,293	12 3,078	12 5,849	5 5,887	1 2,050	--	--	--	569 38,917[g]
26	2 14	1 17	--	--	--	--	--	--	--	--	--	--	3 57
797	90 543	125 1,922	121 4,267	121 8,271	72 10,154	43 11,557	30 10,830	1 1,163	--		--	--	581 49,804[h]
688	63 585	50 885	33 1,166	18 1,276	23 3,271	9 2,680	5 2,498	5 3,940	--	1 6,260	--	--	205 23,193[i]

Table 3.4—continued

Province	AAPG-CSD Province Code(s)	Region(s)	Province Type	Geologic Age of Reservoirs	First Significant Discovery	Latest Significant Discovery	Percentage of Petroleum in Fields ≥400	50-400	>50	<6.25
51. South Florida	140	Eastern Gulf	Downwarp	Mesozoic	1943	1972	0	0	0	2.4
52. Warrior	200	Eastern Gulf	Craton Margin	Paleozoic	1952	1972	0	0	0	23.1
53. Mid-Gulf Coast	210	Eastern Gulf	Downwarp	Mesozoic, Cenozoic	1930	1974	11.3	55.9	67.2	10.1
54. Michigan	305	Illinois-Michigan	Craton Center	Paleozoic	1925	1971	0	22.0	22.0	48.7
55. Illinois	315	Illinois-Michigan	Craton Center	Paleozoic	1900	1962	29.7	31.3	61.0	16.7
United States total							49.0+	33.4+	82.4+	6.0

Subtotals by Province Type	Number of Provinces	Percentage of Petroleum in Fields ≥400	50-400	≥50	<6.25
I. Craton Center	5	17.4	33.5	50.9	23.0
II. Craton Margin					
a. Interior Shallow	16	15.1+	34.0+	49.1+	23.2
b. Interior Deep	4	60.8+	22.0+	82.8+	4.2
c. Northern and Western Rocky Mountains	12	47.6+	34.6+	82.1+	3.1
III. Rift	2	0.0	0.0	0.0	17.2
IV. Downwarp	6	50.0+	28.8+	78.8+	5.7
V. Subduction	9	62.0	30.6	92.6	1.0
VI. Delta	1	23.9+	59.7+	83.6+	1.6

Table 3.4—continued

Number of Fields and Amounts of Petroleum by Field Size Category (in millions of barrels' L&LE)

<6.25	6.25-12.5	12.5-25	25-50	50-100	100-200	200-400	400-800	800-1,600	1,600-3,200	3,200-6,400	6,400-12,800	12,800-25,600	Province Total
2	2 2[illegible]	1 19	1 41	--	--	--	--	--	--	--	--	--	4 83
9	1 11	1 19	--	--	--	--	--	--	--	--	--	--	2 39
411	24 218	20 369	9 346	12 764	5 755	3 764	1 460	--	--	--	--	--	74 4,057
655	19 169	9 161	2 58	2 106	1 191	--	--	--	--	--	--	--	33 1,347
727	32 293	19 328	11 349	5 361	1 112	3 889	3 1,293	--	--	--	--	--	73 4,354
57,440	875 7,832	749 12,951	536 18,545	378 25,879	244 34,176	136 36,741	73 38,405	24 26,340	14 29,415	1 6,260	--	2 31,520	3,031 285,528[j]

Number of Fields and Amounts of Petroleum by Field Size Category (in millions of barrels' L&LE)

<6.25	6.25-12.5	12.5-25	25-50	50-100	100-200	200-400	400-800	800-1,600	1,600-3,200	3,200-6,400	6,400-12,800	12,800-25,600	Province Type Total
1,714	63 574	37 635	22 756	8 522	4 539	5 1,432	3 1,293	--	--	--	--	--	142 7,445
6,239	192 1,702	125 2,123	68 2,341	41 2,697	20 2,742	14 3,706	5 2,918	1 1,150	--	-	-	--	466 25,618[k]
3,256	203 1,775	168 2,942	120 4,152	72 5,101	36 5,081	34 6,910	16 8,632	6 6,080	7 15,029	--	--	1 17,357	655 76,345[l]
401	45 394	31 528	25 920	13 994	14 1,956	6 1,482	4 1,948	2 1,983	1 2,169	--	--	--	141 12,765[m]
5	--	1 24	--	--	--	--	--	--	--	--	--	--	1 29
4,686	250 2,296	238 4,136	147 4,980	97 6,559	73 10,319	25 6,772	18 8,807	8 9,827	1 2,050	1 6,260	--	1 14,133	859 80,825[n]
347	31 269	36 641	33 1,162	26 1,735	25 3,385	19 4,882	7 3,977	6 6,137	5 10,167	--	--	--	188 32,697
797	90 843	113 1,922	121 4,267	123 6,271	72 10,154	43 11,537	20 10,830	1 1,163	--	--	--	--	581 49,802[o]

NOTES TO TABLE 3.4

[a]United States portion only.

[b]Ex 348 Bcf (58 x 10^6 bbl, L&LE) for 2007 total.

[c]Ex 2910 Bcf and 300 x 10^6 bbl, NGL (785 x 10^6 bbl, L&LE) for 43,683 total.

[d]Ex 600 Bcf and 80 x 10^6 bbl, NGL (180 x 10^6 bbl, L&LE) for 3149 total.

[e]Ex 210 Bcf (35 x 10^6 bbl, L&LE) for 1878 total.

[f]Ex 150 x 10^6 bbl, crude oil, 6300 Bcf, and 300 x 10^6 bbl, NGL (1500 x 10^6 bbl, L&LE) for totals of approximately 5700 and 10,985, respectively.

[g]Ex 1980 Bcf and 560 x 10^6 bbl, NGL (890 x 10^6 bbl, L&LE) for 39,807 total.

[h]Ex 400 x 10^6 bbl, NGL for 50,204 total.

[i]Ex 630 Bcf and 280 x 10^6 bbl, NGL (385 x 10^6 bbl, L&LE) for 23,578 total.

[j]Ex 150 x 10^6 bbl, crude oil, 12,978 Bcf, and 1920 x 10^6 bbl, NGL (4233 x 10^6 bbl, L&LE) for 289,761 total plus approximately 10,100 in the Appalachian Basin and 490 on the Cincinnati Arch for 300,351 total.

[k]Ex 110 x 10^6 bbl, crude oil, 5220 Bcf, and 300 x 10^6 bbl, NGL 1280 x 10^6 bbl, L&LE) for 26,898 total.

[l]Ex 40 x 10^6 bbl, crude oil, 4800 Bcf, and 380 x 10^6 bbl, NGL (1220 x 10^6 bbl, L&LE) for 77,565 total.

[m]Ex 348 Bcf (58 x 10^6 bbl, L&LE) for 12,823 total.

[n]Ex 2610 Bcf and 840 x 10^6 bbl, NGL (1275 x 10^6 bbl, L&LE) for 82,100 total.

[o]Ex 400 x 10^6 bbl, NGL for 50,204 total.

fields, 70 to 85 percent in giant and large fields, and 3 to 5 percent in very small fields.

The other twelve craton margin provinces are in the northern and western Rocky Mountain region. Eight of these are significant (San Juan, Big Horn, Greater Green River, Piceance, Wind River, Paradox, Sweetgrass Arch, and Uinta), but only the first two have attained major province status. The subtype is not very important nationally, accounting for only 12.8 billion barrels' L&LE (4.3 percent of the national total). Because most of these provinces are not major provinces, there are only seven giant fields in all twelve, but these seven account for 47.6 percent of the petroleum resources of the subtype. Giant and large fields account for 82.1 percent of the total, while very small fields contain only 3.1 percent. The proportion in giant and large fields and in very small fields in each significant province of the subtype is tightly clustered around the subtype averages. The former ranges from 70 to 90 percent of the total, while the latter is only about 2 to 4 percent. In the four western Rocky Mountain provinces (San Juan, Piceance, Paradox, and Uinta), the distribution is extremely close, each having 87 to 90 percent in large and giant fields, and all but the Uinta Province having 74 to 78 percent in giant fields.

Rift provinces are small, linear basins with an irregular profile. They are primarily Upper Paleozoic, Mesozoic, and Tertiary in age and are located on or near cratonic areas. Worldwide, they are important sources of petroleum. In the United States, their contribution is negligible as they provide only 0.01 percent of the total. There are two productive rift basins in the United States, both of which are located between the Rocky Mountains and the Sierra Nevada. Because each is so small, we omit discussion of the distribution of their petroleum resources by field size categories.

Downwarp provinces in the United States are areally large, linear basins opening up into small ocean basins. They are asymmetric seaward, having received their sediments from the landward side. The sedimentary rocks in downwarp provinces are of Mesozoic and Cenozoic age. In each of the four major downwarp provinces, the maximum thickness of the sedimentary section exceeds 15,000 feet. There are six downwarp provinces in the United States, either opening into the Gulf of Mexico or the Arctic Ocean. Four are major provinces (Texas Gulf Coast, East Texas-Arkla, Arctic Slope and Foothills, and Mid-Gulf Coast). Altogether, the six account for 82.1 billion barrels of known U.S. petroleum resources, 27.3 percent of the national total.

The distribution of petroleum resources by field size categories in the downwarp provinces is very similar to the distribution nationwide. Slightly more than 50 percent is in giant fields (compared with slightly more than 49 percent nationwide), and slightly more than 79 percent is in giant and large fields (compared with slightly more than 82 percent nationwide). Only 5.7 percent of the known petroleum resources in downwarp provinces is in very small fields. Among the downwarp provinces, the proportion in giant fields varies greatly. Excluding the lightly explored Arctic Slope and Foothills, the range in giant and large fields is about 65 to 85 percent, and the proportion in very small fields is about 5 to 10 percent, a much tighter spread.

Subduction provinces are small, linear basins with an irregular profile. Their sedimentary rocks are generally Tertiary in age and can reach substantial depths. They are located along subducting, that is, convergent plate margins. In the United States, they are found along the Pacific Coast. There are nine productive subduction provinces in the United States, seven of which are significant (San Joaquin, Los Angeles, Ventura, Cook Inlet, Sacramento, Santa Maria, and Salinas). The first three of these also qualify as major provinces. Together, these nine provinces account for 32.7 billion barrels' L&LE, 10.9 percent of the national total.

The petroleum resources of subduction provinces are highly concentrated in giant and large fields. The 17 giant fields in these provinces contain 62.0 percent of their total petroleum resources. Giant and large fields contain 92.6 percent of the total, while very small fields account for only 1.0 percent of the total. Except for the Sacramento Province, this concentration of petroleum resources in a few giant and large fields is typical of the significant subduction provinces. Generally, more than 90 percent of the total is in giant and large fields and less than 1 percent is in very small fields. In the two largest provinces (San Joaquin and Los Angeles), about 70 percent of the petroleum resources is in giant fields.

Delta provinces are generally areally small to medium size, circular-shaped depocenters with a very thick sedimentary wedge prograding seaward. They are predominantly Upper Tertiary in age. Their sedimentary fill is derived from major continental drainage areas. The only productive one in the United States, the Mississippi Delta, has developed over an earlier downwarp basin. Although there is only one producing delta province in the United States, it is the largest province in the country, by itself accounting for 50.2 billion barrels' L&LE, 16.7 percent of the national total.

The Mississippi Delta has a unique field size distribution when compared with the other largest productive provinces of the United States. Despite its size, only about 24 percent of its known resources is in giant fields. In only two of the other nine provinces with more than 5 billion barrels' L&LE is this proportion less than 50 percent. However, about 60 percent of its total resources is in large fields, compared with no more than 35 percent in any of the other nine provinces. Only 1.6 percent of the total is in very small fields.

NATIONAL OVERVIEW

The Klemme system of classifying petroleum provinces by type, based on such geologic characteristics as basin architecture and evolution, also provides a useful means of predicting the distribution of petroleum resources by gross field size groups. Each type (taking our three craton margin subtypes as distinct types) tends to have its own particular distribution of petroleum resources in giant, giant and large, and very small fields. Generally, the differences among types are greater than the differences among provinces within a single type, particularly when we control for differences in province size. Subduction and delta provinces are particularly distinct. The interior deep, northern and western Rocky Mountain, and downwarp provinces form a group with basically similar average distributions by type, but with still noticeable differences, particularly when adjusted for province size. The craton center and interior shallow provinces are the only two types between which there are no discernible differences in field size distributions.

These differences in gross field size distributions are the result of basic geologic differences among the province types. As we pointed out earlier in Sec. III, very small fields are only proportionally important in provinces that are relatively shallow, have thin individual formations, and little structural deformation. These characteristics also serve to describe the craton center and interior shallow provinces of the interior United States. Where the sedimentary section is thick, individual formations are thick, and there is substantial structural deformation, most of the petroleum resources are highly concentrated in giant and large fields. These characteristics are typical of the other province types. Generally speaking, the greater the degree of these characteristics in a province, the greater will be the proportion in giant and large fields, and the less will be the proportion in very small fields.

The distribution of the *number* of fields by field size categories is closely related to the distribution of the *amount* of petroleum by broad field size categories in each province type and individual province. No one distribution of the number of fields is characteristic of all of the significant provinces and province types. In Table 3.4, four different distributions are apparent in the geometric field size scale that we use. Craton center and interior shallow craton margin provinces are characterized by a monotonically increasing number of fields as field size decreases, the number of fields increasing at a rate of 40 to 70 percent from one category to the next smaller one from Class A fields downward. Interior deep craton margin and downwarp provinces are characterized by a monotonically increasing number of fields as field size decreases, the number of fields increasing at a rate of 20 to 40 percent from one category to the next smaller one. Northern and western Rocky Mountain craton margin provinces are characterized by an irregular but basically unimodal distribution peaking about 6.25 million barrels. Subduction and delta provinces are characterized by a distribution that essentially levels out about the Class A or B level after a rapid proportional increase from the largest field sizes.

These four different distributions in the number of fields closely coincides with differences in the proportion of petroleum resources in giant, large, and very small fields among the province types. When the proportion in very small fields is itself very small, we would not expect that the number of fields would increase steadily as field size decreases. However, if this proportion is relatively significant, the number of fields has to be increasing steadily as field size decreases. The differences among distributions are predominantly geologic differences, not differences in the intensity of exploration or the result of economic truncations. Nearly all of the provinces listed in Table 3.4 have been explored extensively for decades. The main inflection points in the distribution of the number of fields in subduction and delta provinces occur at a field size level well above any historic minimum economic field size for exploration and development.

The differences in distributions by type and the many irregularities in the distributions of individual provinces would lead us to recommend caution in the use of postulated distributions to predict the number and size of future discoveries. First, the postulated distribution used should be appropriate to the type of province being examined. Second, geologic factors that may make a specific province a typical or an atypical representative of its province type need to be considered. Third, irregularities in an observed distribution are not necessarily indicators of fields remaining to be discovered. They may instead be indicators of the peculiar geologic characteristics of the province, such as multiple productive plays, concentrations on regional uplifts, and the like.

Province type is a strong predictor of both the distribution of petroleum resources and of the number of fields by field size category. It is a much weaker predictor of the timing of discovery. The size of the province (in terms of the amount of petroleum) is a stronger predictor of the timing of the first and latest significant discoveries. Excluding the North Slope, at least one significant field had been discovered by 1920 in each of the largest provinces of the country (i.e., the nine listed in Table 3.4 with more than 7.5 billion barrels' L&LE). In each of the nine provinces between 2.5 and 7.5 billion barrels' L&LE, a significant field had been discovered by 1930. In six of the other 19 significant provinces, the first significant field was not found until after 1920. In other words, the largest petroleum provinces in the United States were recognized as petroliferous early in the history of domestic petroleum exploration. By 1905, there had been at least one significant discovery in one province characteristic of each of our seven types or subtypes.

Discoveries also stretch across a longer period of time in the largest provinces. Since 1970, at least one significant field has been discovered in every one of the nine largest provinces except the Chautauqua Province. In only three of the nine between 2.5 and 7.5 billion barrels' L&LE and in only five of the other 19 significant provinces has there been a significant discovery since 1970. Province type appears to have some value as a predictor of the cessation of discovery. No significant discovery has occurred in 10 of the 37 provinces since 1960. Five of these were interior shallow provinces that could have been extensively explored with earlier drilling technology. Four of the other five were western Rocky Mountain or subduction provinces in which nearly all of the known petroleum resources are concentrated in less than ten fields.

IV. THE DISTRIBUTION OF SIGNIFICANT OIL AND GAS DISCOVERIES IN THE UNITED STATES BY SIZE OVER TIME

The preceding section addressed the questions *how much* petroleum has been discovered *where* and in *which* circumstances in the United States. By itself, this information is only a necessary preliminary to the problem of resource assessment. What is lacking is an understanding of how our knowledge of known domestic petroleum resources has developed over time. A region may have substantial amounts of petroleum, but if the fields containing them were discovered decades ago, it may have only minimal potential for future discoveries. On the other hand, the known resources in another region may be small, but exploration in the region could be just beginning and there may be substantial areas with great promise remaining to be explored. A description and an analysis of the patterns of discovery for significant fields and for amounts of petroleum provide an essential bridge between knowing what has been discovered and estimating what remains to be discovered.

The purpose of this section is to describe statistically the history of U.S. petroleum exploration by region and for the nation as a whole. Using the data on year of discovery and field size from the significant oil and gas fields data base (App. A) and data from other supplementary sources of information, we summarize the patterns of discovery of significant fields by size and the amounts of crude oil and natural gas discovered over ten-year periods up to 1975 for our 12 regions. In particular, we single out the peak of discoveries, changes in the composition of discoveries, and the influence, if any, of developments in exploratory technology and geological concepts on the pattern of discoveries. Although our focus is on the results of exploration, we also show the relationships between the number of discoveries and the amounts discovered on one hand, and the number of exploratory wells drilled between 1936 and 1975 on the other hand.

We have simplified the data shown in the figures of this section in three key ways to permit a visually clearer presentation. All of the discoveries of Class A and larger fields are aggregated into a single category to avoid nearly invisible distinctions in many instances. All discoveries are combined into a single type, whether they are predominantly oil fields, predominantly natural gas fields, or in between. All of the information given on the number of discoveries, the amounts discovered, and the number of wells drilled are aggregated into ten-year periods. The tables in Apps. C, D, and E provide data with finer aggregations. Appendix C lists the number of discoveries of significant oil and natural gas fields by region over five-year periods broken down by field size category and by the predominant type of hydrocarbon in each field. We include four tables of discovery data for each region and for the nation: one for all significant fields, one for predominantly oil fields, one for predominantly natural gas fields, and one for composite oil and gas fields in which neither petroleum liquids nor natural gas predominates, that is, neither provides more than two-thirds of the total L&LE recoverable resource of the field. In App. D we list the amounts of crude oil and natural gas discovered in

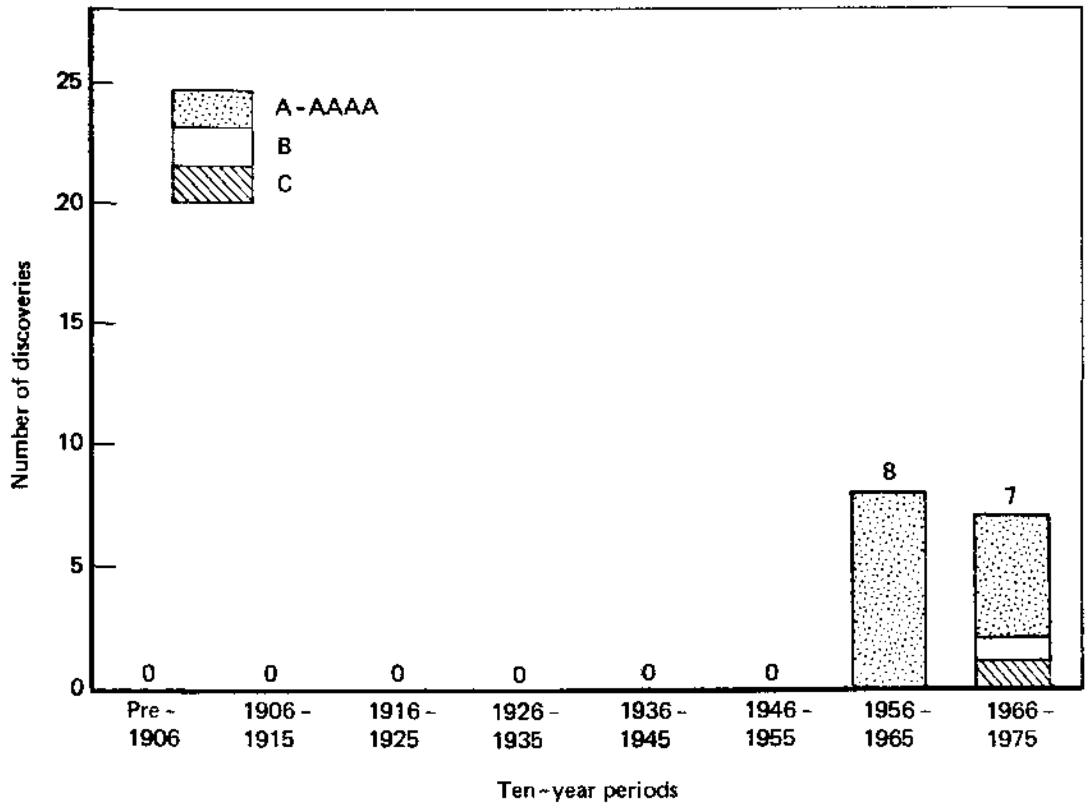

Fig. 4.1—Number of significant oil and gas discoveries by field size category over ten-year periods in Alaska

the United States by region over five-year periods. Appendix E gives the number of exploratory wells drilled and the amount of exploratory footage drilled by year and by region between 1936 and 1975. We use the data from these three appendixes in the text to identify finer points that are only partially illustrated in the figures. The introductions to Apps. C., D, and E describe the sources of our data.

Two points of clarification are in order. (1) Wherever possible, we backdated the data on the amounts of crude oil and natural gas discovered to the year of discovery of the field containing them, not the year in which a field was first recognized to be of a certain size and not the year in which major pools in the field were subsequently discovered. The amounts discovered by time-period thus indicate what was known in 1979 about the sizes of past discoveries. (2) The drilling data are for all exploratory wells drilled, including new field wildcats, new pool wildcats, and extensions. A series incorporating new field wildcats alone would be more appropriate for comparison with the number of significant discoveries. However, because such data are not available for any substantial period of time, we used the total number of exploratory wells drilled as a second-best solution.

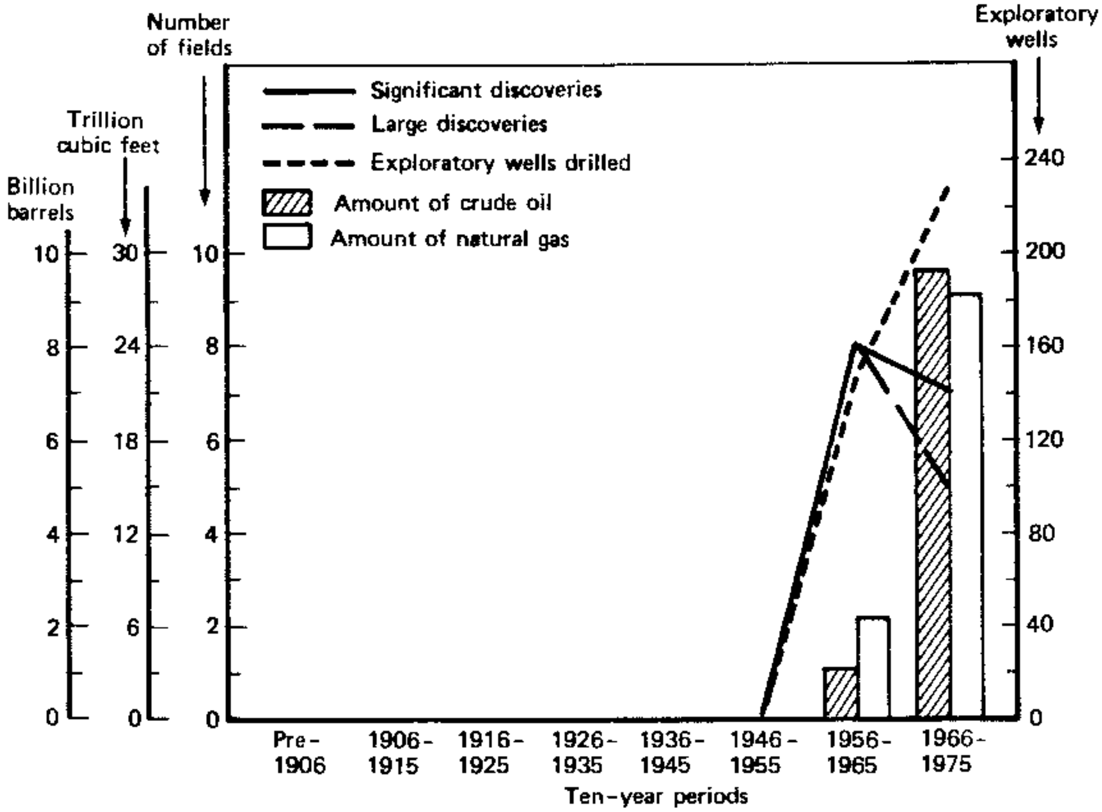

Fig. 4.2—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in Alaska

ALASKA

Because of the harsh environmental challenges that had to be overcome, concerted petroleum exploration in Alaska is a recent phenomenon. The first significant discovery, *Swanson River*, did not occur until 1957 (excluding the discoveries in the National Petroleum Reserve in the late 1940s). This discovery initiated a relatively active drilling play lasting for a decade in the Cook Inlet Province during which at least 10 other significant fields were discovered. In 1968, *Prudhoe Bay* was discovered in the Arctic Slope Province, setting off a modest burst of exploratory drilling there and in the Arctic Foothills that resulted in three more significant discoveries between 1969 and 1972. Alaska is thus one of the few regions of the country in which discoveries were at or near their all-time peaks in the decade from 1966 to 1975. (See Fig. 4.1 and Tables C.1, C.1a, and C.1b.)

Petroleum exploration in Alaska does, however, exhibit a few of the indicators characteristic of more mature regions. Exploration in the upper Cook Inlet Province located the largest fields first, and the size of discoveries declined as exploration progressed. Because so much acreage in the Arctic Slope Province onshore and offshore has yet to be opened to exploratory drilling and because the number of

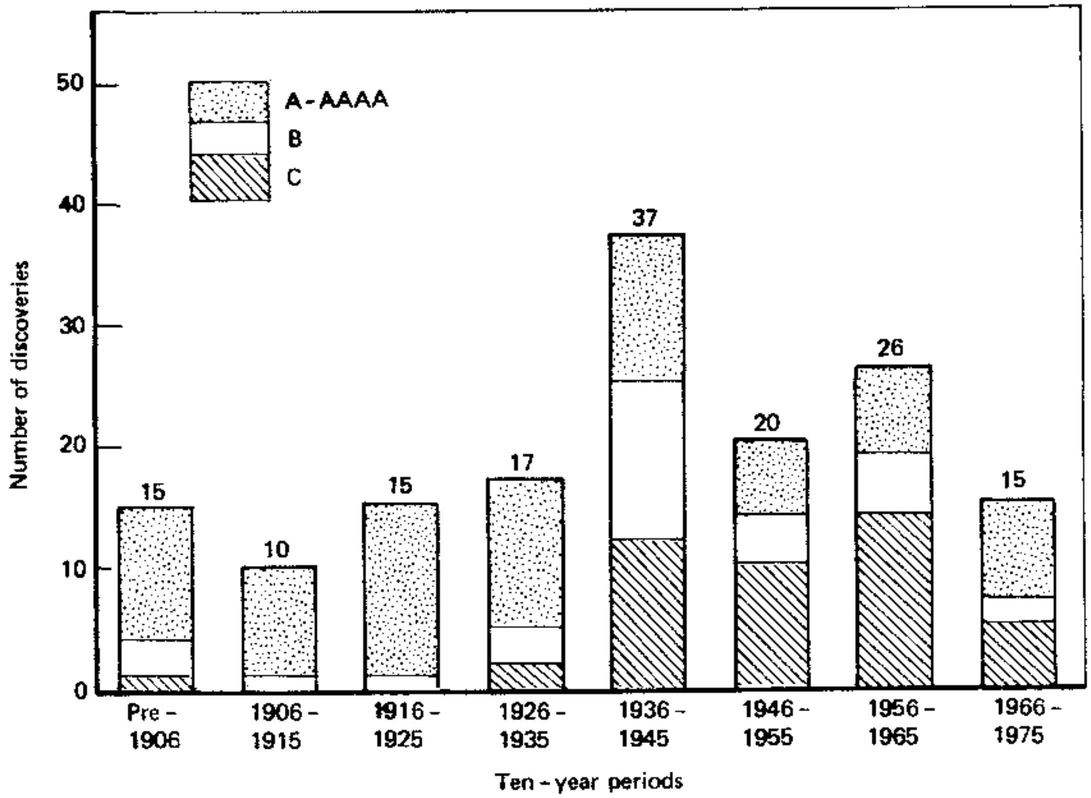

Fig. 4.3—Number of significant oil and gas discoveries by field size category over ten-year periods in California

discoveries to date is so small, no meaningful exploration trends have appeared in that area.

Because the *Prudhoe Bay* field dominates the known petroleum resources of Alaska, there is no normal relationship between the number of significant discoveries or even the number of giant and large discoveries and the amount discovered. (See Fig. 4.2.) Most of the oil and gas discovered to date was found with the discovery of *Prudhoe Bay*, the largest oil field in the United States. Exploratory drilling peaked in the late 1960s. However, most of the drilling followed, rather than preceded, the discovery of *Prudhoe Bay*. Despite the major amounts discovered, exploratory drilling effort in Alaska was by far lower than in any other region of the nation in the decades from 1956 to 1975.

CALIFORNIA

Petroleum exploration in California spans most of the history of the petroleum industry. The first significant discoveries occurred in all three major provinces in the 1880s, beginning with *Brea-Olinda-Sansinena* (1880) in the Los Angeles Basin,

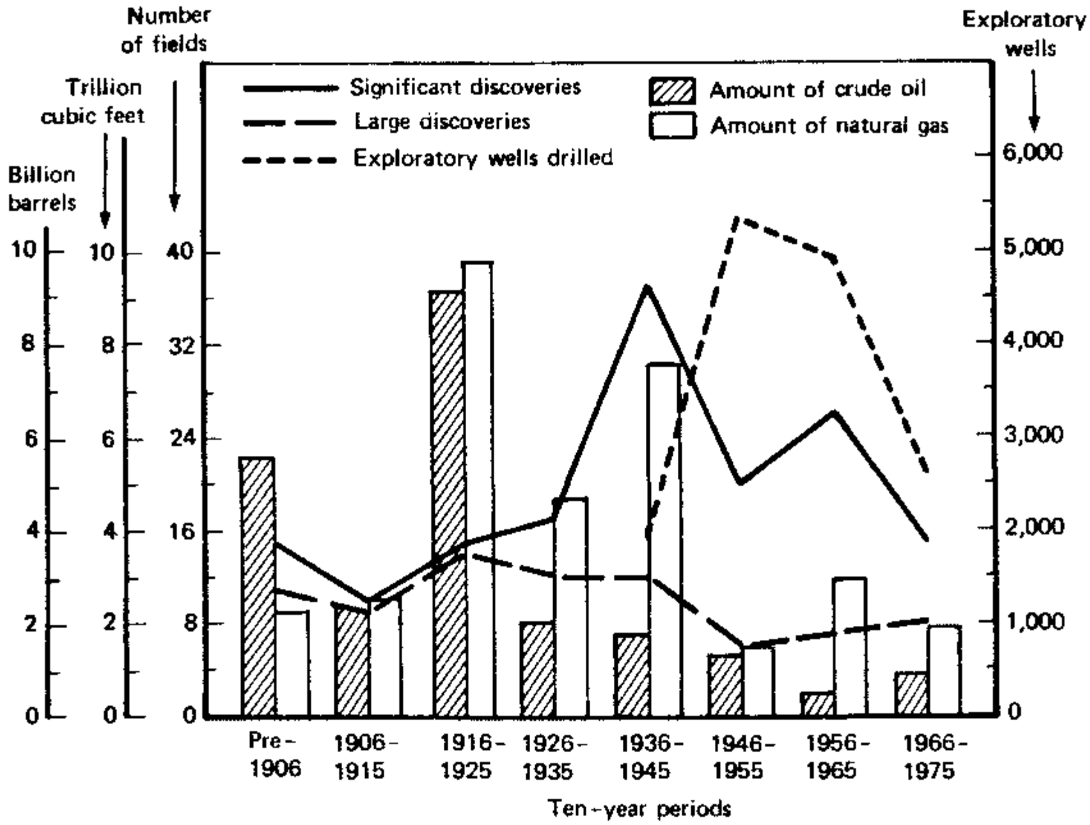

Fig. 4.4—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in California

Sespe (1887) in the Ventura Basin, and *McKittrick: Main* (1887) in the San Joaquin Basin. The earliest discoveries, based primarily on drilling near surface seeps of oil, nonetheless managed to locate 4 of the 15 known giant fields in the state. Shortly after 1900, surface geologic investigations began, culminating in a flurry of major discoveries around 1920, particularly in the Los Angeles Basin. During the decade from 1916 to 1925, six giant oil fields and eight other large oil fields were discovered, the largest number of giant and large fields discovered in California in any ten-year period.

By 1930, most of the major fields had already been discovered in the Los Angeles Basin, and the focus of exploration shifted to deeper or more elusive structures in the San Joaquin Basin. Seismic methods and electric well-logging were first used in California in the early 1930s. Their application in the San Joaquin and Sacramento provinces created the peak in significant discoveries in the decade around 1940, a list, however, comprised primarily of Class B and C fields. In the next decade, the number of discoveries declined by nearly 50 percent. The focus of exploration shifted to the coastal provinces, resulting in a few giant and large discoveries in the Salinas and Cuyama basins and in numerous smaller discoveries in the Ventura Basin. The number of significant discoveries increased in the decade around 1960, buoyed up by a peak in the number of natural gas discoveries in the Sacramento Basin, the beginning of offshore exploration in the Ventura Basin, and a minor resurgence of exploration in the Los Angeles Basin. However, only the offshore discoveries could be sustained, and the number of significant discoveries declined again about 1970. (See Fig. 4.3 and Tables C.2, C.2a, C.2b, and C.2c.)

Because of the variety in the techniques that could be employed and because of the variety of plays, the number of significant discoveries in California shows the greatest uniformity of any region in the nation over the eight time-periods we survey. Underlying this uniformity is an orderly progression in the size of discoveries: The number of Class AAAA and A-AAAA discoveries peaked about 1920; the number of Class A-AAA (large) discoveries peaked about 1930; the total number of significant discoveries and the number of Class B discoveries peaked about 1940; and the number of Class C discoveries did not peak until about 1960. The most recent giant discovery—*San Ardo* (1948)—was discovered more than 30 years ago.

Because giant fields contain most of the oil and gas resources of California, the peaks in the amount discovered correlate closely with the peaks in giant discoveries. (See Fig. 4.4.) The initial peak in the amount of oil discovered before 1906 is primarily the result of the discovery of only three giant fields: *Midway-Sunset*, *Kern River*, and *Coalinga*. The historic peaks in the amount of oil and natural gas discovered about 1920 coincide with the peak in the number of giant discoveries. The secondary peak in the amount of natural gas discovered coincides with the discovery of the *Rio Vista* field, the only giant gas field in the state. Since these peaks occurred, the amount discovered, particularly of crude oil, has declined to relatively low levels despite a greater exploratory effort, the opening up of a sizable offshore frontier, and the application of substantially improved technology and geologic knowledge.

The exploratory drilling effort in California has clearly lagged behind the peaks in the amount of oil and natural gas discovered and in the number of significant discoveries. The peak period in exploratory drilling activity from the late 1940s to the early 1960s coincides only with the peak in small (Class C) discoveries. The decline in exploratory drilling beginning in the late 1960s coincides with an upturn in significant oil discoveries associated with leasing in the offshore Ventura Basin.

ROCKY MOUNTAINS

The first significant discovery in the Rocky Mountain region—the *Florence-Canon City* field (1862)—occurred only three years after the first oil discovery in the United States. However, because of the distance of the Rocky Mountain provinces from major markets and from the centers of petroleum development in the United States, a sizable exploration effort did not begin until 40 years later. The peaks in exploration did not occur until 90 to 100 years after the discovery of *Florence-Canon City*, the first significant field discovered in the United States outside of the Appalachian region. (See Fig. 4.5 and Tables C.3, C.3a, C.3b, and C.3c.)

Intensive mapping of surface structures in the Rocky Mountain region began about 1910 and resulted in the discovery of the major anticlines in the Big Horn, Powder River, and Wind River basins of Wyoming. By 1930, the use of surface geology and exploratory drilling had spread throughout the Rocky Mountain re-

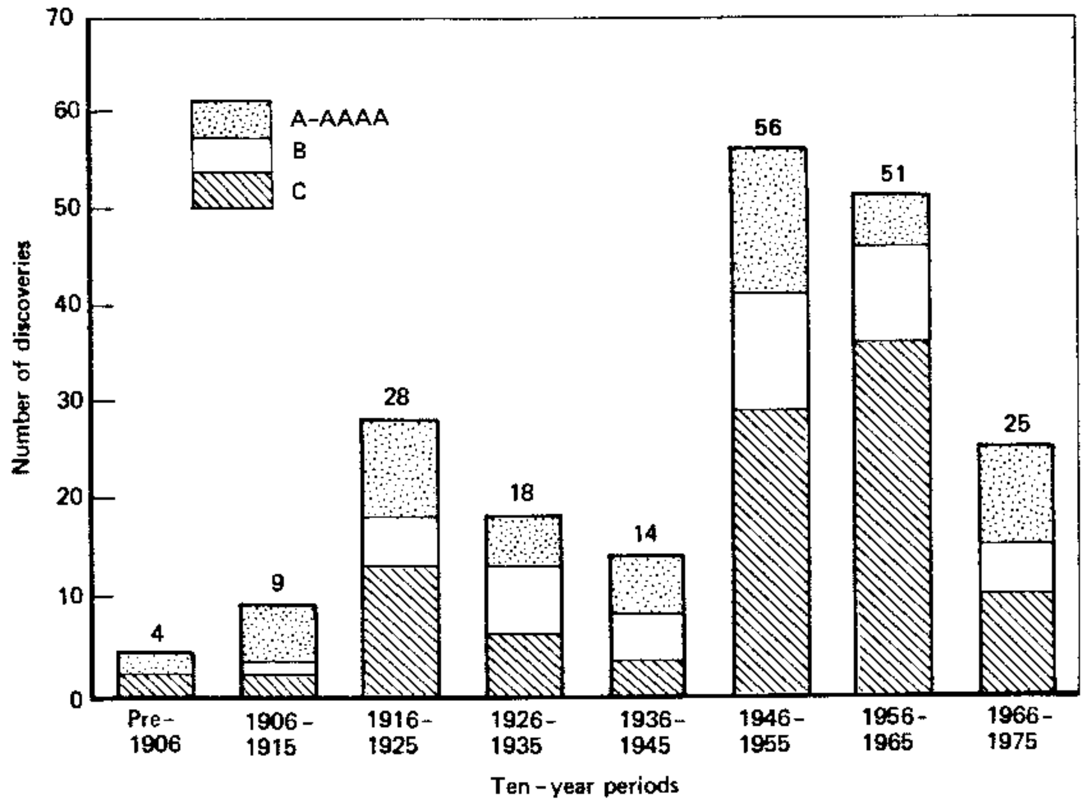

Fig. 4.5—Number of significant oil and gas discoveries by field size category over ten-year periods in the Rocky Mountain region

gion, resulting in the initial discoveries in Montana and the western Colorado provinces. By this year, 4 of the 5 Class AAAA fields, 6 of the 12 Class AAA fields, and 9 of the 22 Class AA fields discovered before 1976 in the Rocky Mountain region had already been discovered.

After a pronounced lull in exploration during the Great Depression, the number of significant discoveries began to rise again in the early 1940s with the use of seismic surveys in the several Wyoming provinces. The total number of discoveries peaked in the decade around 1950 as exploration spread throughout the region, particularly into the Denver and Williston basins. Although the total number of significant discoveries did not decline appreciably into the decade around 1960, the size composition changed sharply. The number of Class A or larger discoveries dropped from 15 to 5; the number of Class C discoveries peaked, increasing from 29 to 36. This presaged a 50-percent decline in the total number of discoveries in the decade around 1970. Only exploration for stratigraphic traps in the Denver and Powder River basins and a few isolated discoveries in the several provinces of Utah managed to keep the number from declining even more sharply. The end of the period surveyed here marked the beginning of two significant Rocky Mountain exploration plays: the initial discoveries in the Overthrust Belt and exploration for deeper fields in the Williston Basin.

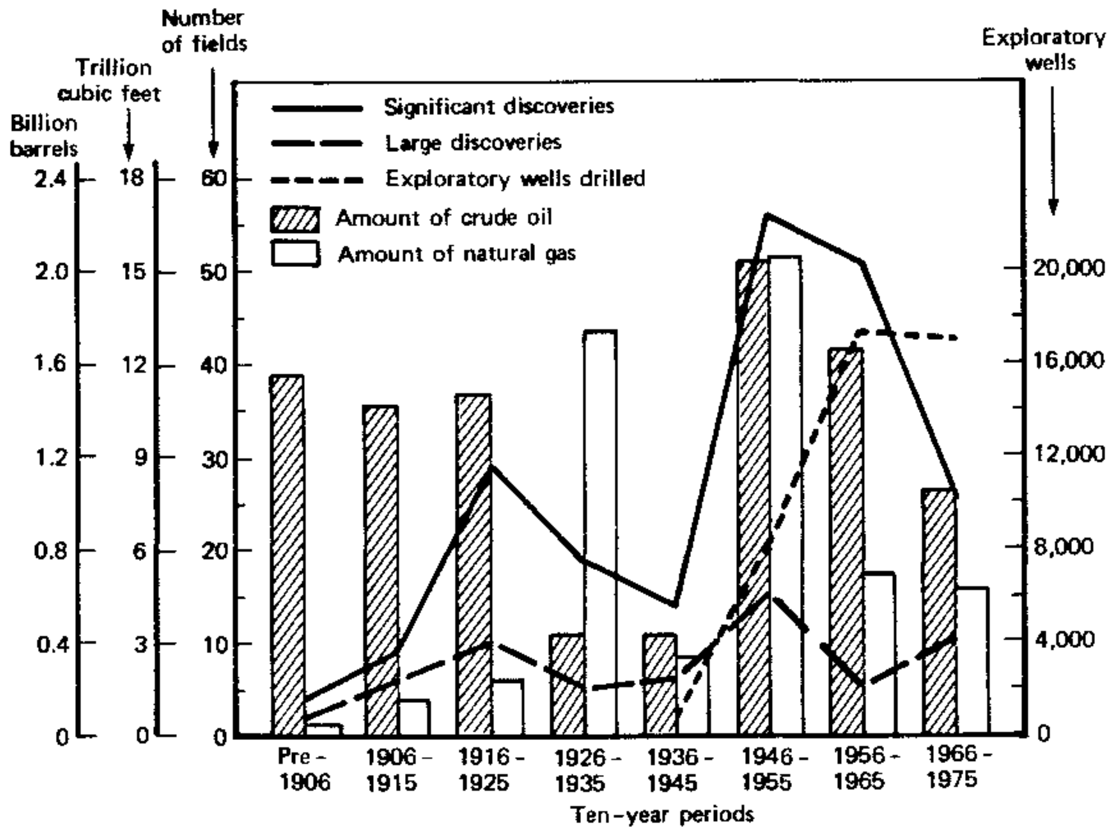

Fig. 4.6—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Rocky Mountain region

The distribution of crude oil resources by field size category in the Rocky Mountain region is the most even of any region in the country. The distribution over time of the amount discovered is also the most even of any region. (See Fig. 4.6.) The early peaks in the amount of oil discovered coincide with discoveries of the only giant oil fields in the region—*Salt Creek*, *Rangely*, and *Elk Basin*—and most of the large oil fields in Colorado, Montana, and Wyoming. After the Depression low, the subsequent peaks about 1950 and 1960 correlate closely with the peak in the total number of significant discoveries. The subsequent decline in the amount of crude oil discovered closely follows the decline in the total number of significant discoveries. Because the San Juan Basin contains more than half of the natural gas discovered to date in the Rocky Mountain region, the peaks in the amount of natural gas discovered coincide with the discoveries of the giant *Blanco: Mesa Verde* (1927) and *Basin: Dakota* (1947) fields in that province.

Exploratory drilling in the Rocky Mountain region has lagged behind the number of significant discoveries and the amount discovered. As the number of significant discoveries and the amount discovered rose sharply during the 1940s, exploratory drilling increased as well. But while the amount of natural gas discovered peaked in the late 1940s and the amount of crude oil discovered and the number of significant discoveries peaked in the early 1950s, exploratory drilling in the Rocky Mountain region did not peak until the late 1950s. Since then, drilling effort has undergone only a small decline, while the number of significant discoveries and the amounts of crude oil and natural gas discovered have declined sharply. The principal reason for this discrepancy is that since 1955 the bulk of exploratory drilling in the Rocky Mountain region has been directed toward finding small stratigraphic traps in the Denver and Powder River basins, an endeavor that is not conducive to finding significant discoveries or appreciable amounts of crude oil and natural gas.

PERMIAN BASIN

As a region, the Permian Basin is a relative latecomer to petroleum exploration in the United States. The first significant discovery in the region—*Westbrook* in Texas R.R.C. District 8—did not occur until 1920. Although there were a few scattered discoveries throughout the region during the early 1920s, exploration began in earnest with a series of giant discoveries in reservoirs of Permian age on the Central Basin Platform during the decade from 1926 to 1935. During this period, 11 of the 18 giant oil and gas fields found to date in the Permian Basin were discovered. As extensive exploration spread throughout the region, the number of significant discoveries increased. The decade around 1940 was marked by the discovery of most of the larger fields on the North Basin Platform and the beginning of deeper Devonian and Ordovician discoveries on the Central Basin Platform. At the peak of significant discoveries about 1950, the most noticeable single exploratory play was in the reefs of the Horseshoe Atoll. However, during this period significant discoveries were still being made throughout the Permian Basin. (See Fig. 4.7 and Tables C.4, C.4a, C.4b, and C.4c.)

Since the early 1950s, the number of significant discoveries in the Permian Basin has declined sharply. This has been accompanied by a pronounced change in the composition of discoveries by type of hydrocarbon. Since that time, the number of significant oil discoveries has declined roughly 50 percent every five-year period. (Beginning with the 1951-1955 period, significant discoveries in the Permian Basin that were predominantly oil fields numbered 40, 21, 9, 5, and 3, respectively.) In sharp contrast, significant discoveries that were predominantly gas fields did not peak until the decade around 1970. The boom in recent natural gas discoveries consisted primarily of deep Ordovician, Silurian, and Devonian anticlines in the Delaware and Val Verde basins and, to a lesser degree, of Pennsylvanian stratigraphic traps on the Northwest Shelf and in Texas R.R.C. District 7C. Even though the total number of natural gas discoveries remained at peak levels in the early 1970s, the size of discoveries had dropped dramatically since the early 1960s when deep gas exploration began. Since the deep natural gas play began, 21 significant discoveries with major reservoirs more than 15,000 feet deep have been made.

The amounts of oil and natural gas discovered in the Permian Basin peaked in the decade around 1930 with the discovery of most of the giant oil and gas fields in the region. (See Fig. 4.8.) The amount of oil discovered during the next two decades declined slowly as a sharp increase in the total number of significant and

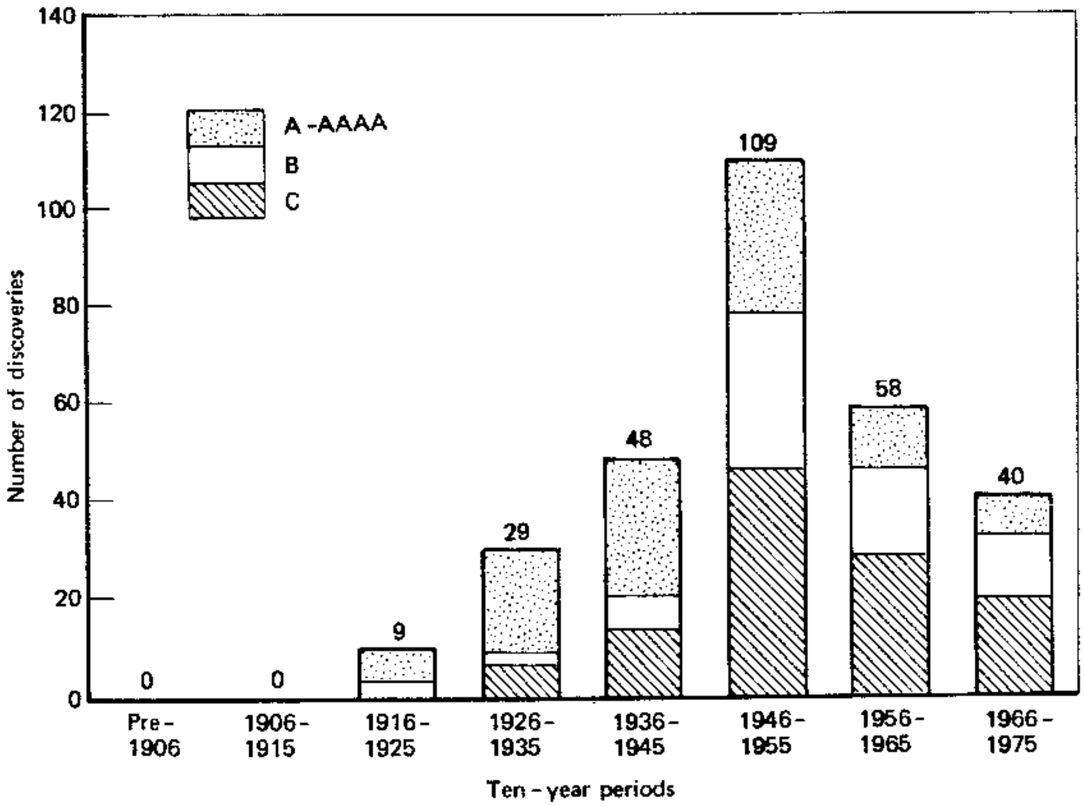

Fig. 4.7—Number of significant oil and gas discoveries by field size category over ten-year periods in the Permian Basin

large discoveries compensated for the decline in giant discoveries. Once significant discoveries declined as well, the amount of crude oil discovered dropped sharply. By the early 1970s, the amount discovered had declined to only 3 percent of the amount discovered during the late 1940s, the last period of major oil discoveries in the Permian Basin. The amount of natural gas discovered remained relatively stable over four decades as predominantly gas fields followed the discovery of large amounts of associated-dissolved gas in the major oil discoveries. Once the size of gas discoveries began to decline, the amount of natural gas discovered began to decline as well.

Increases in the number of exploratory wells drilled during the decade around 1940 continued through the decade around 1950 and paralleled the increase in the number of significant discoveries. However, exploratory drilling continued to increase into the late 1950s despite sharp declines in both the number of significant discoveries and in the amount of oil discovered. The subsequent decline of exploratory drilling that began in the 1960s was in belated recognition of the decrease of major prospects.

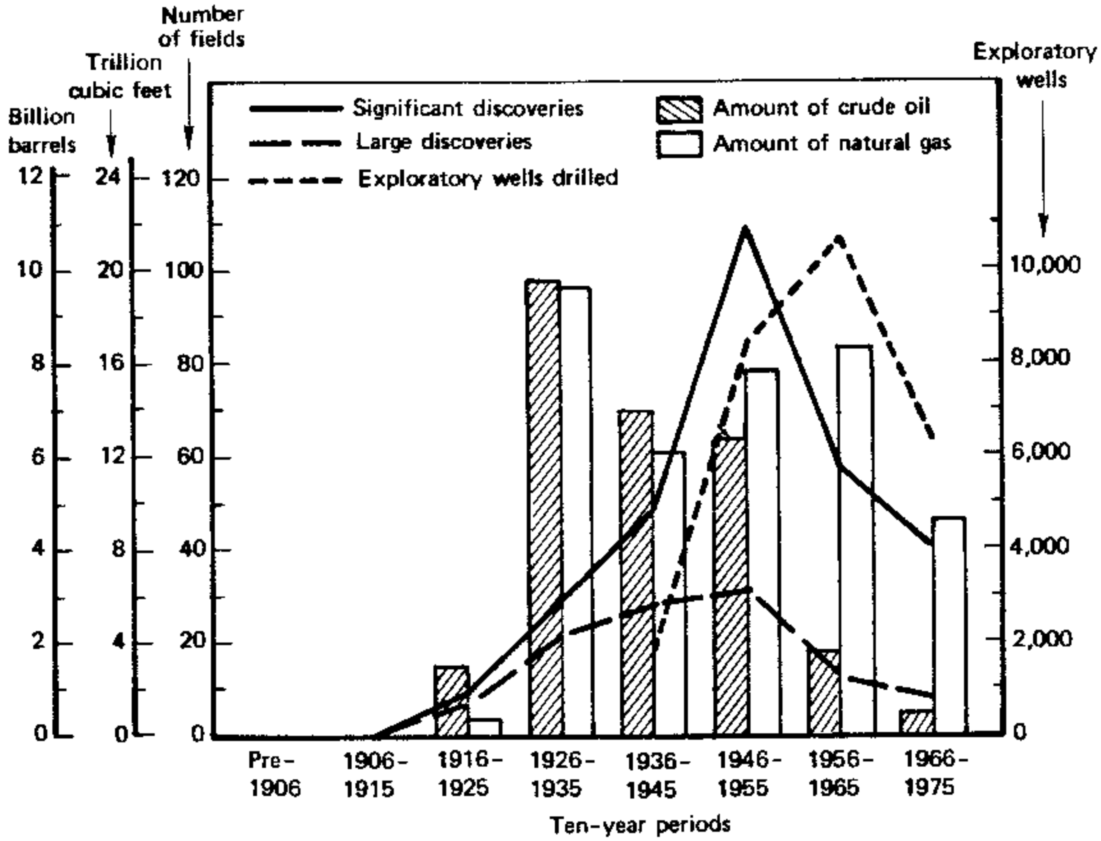

Fig. 4.8—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Permian Basin

NORTH CENTRAL TEXAS

Petrolia (1902), the first discovery in North Central Texas, was the result of exploration spilling over into northern Texas from Oklahoma. As serious exploration began in the late 1910s, a small oil boom developed following the discovery of most of the largest oil fields in the region. This continued into the 1920s as surface geology was used to locate several smaller anticlines. Because of depressed oil prices during the Depression, there were no significant discoveries in the region during the early 1930s. Significant discoveries resumed in the late 1930s, growing to a peak in the decade around 1950. Immediately following this peak, significant discoveries practically disappeared, plunging from 17 in the early 1950s to a lonely 1 in the late 1950s. Since the late 1950s, the number of significant discoveries in North Central Texas has persisted at negligible levels. (See Fig. 4.9 and Tables C.5, C.5a, C.5b, and C.5c.)

The distribution over time of the amount of crude oil discovered in North Central Texas is strongly bimodal. (See Fig. 4.10.) The two peaks about 1920 and

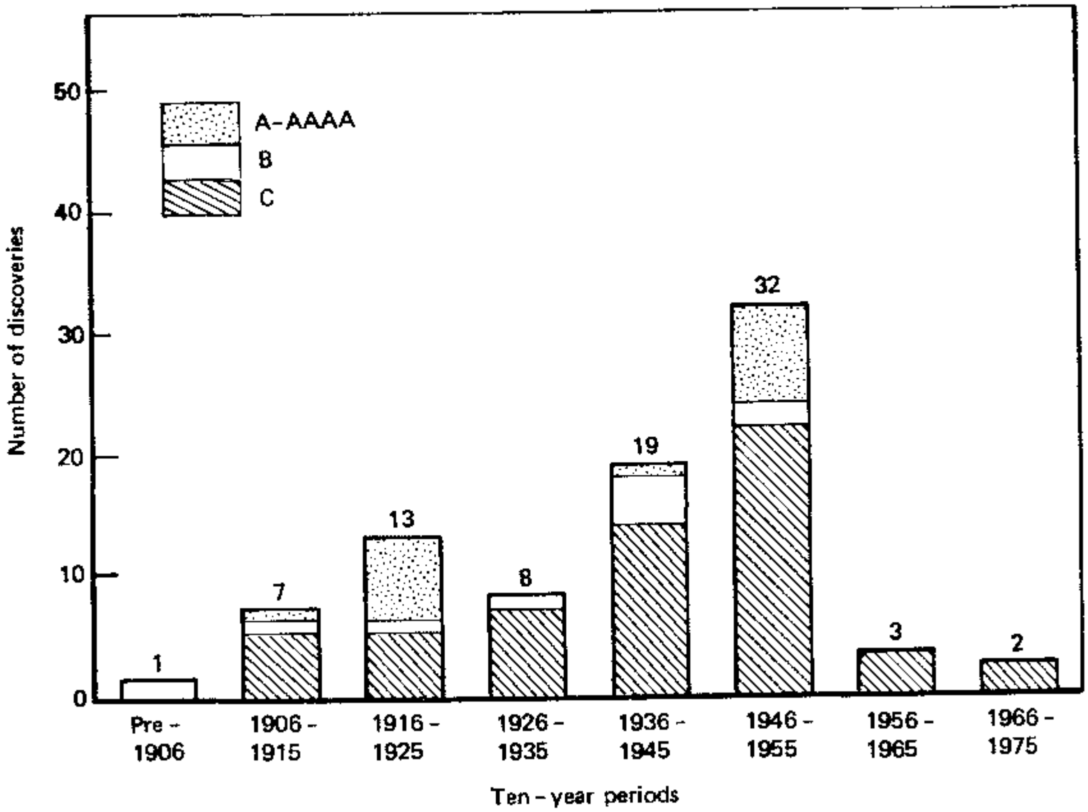

Fig. 4.9—Number of significant oil and gas discoveries by field size category over ten-year periods in North Central Texas

1950 in the amount discovered coincide with the peaks in the number of large discoveries in the region. The markedly larger number of significant discoveries about 1950 offsets the effect of the concentration of the largest oil discoveries about 1920. The amount of gas discovered peaked in the decade about 1950 with the discovery of the Class AAA *Boonsville* field in Fort Worth Basin. The sharp declines in the amounts of crude oil and natural gas discovered since the early 1950s closely parallel the decline in the number of significant discoveries.

North Central Texas has been the region *par excellence* of the independent wildcatter. During the early 1950s, 9704 exploratory wells were drilled, a total that has been exceeded by only one region over any five-year period (the Mid-Continent in both the early and late 1950s). But even the most successful wildcatter eventually has to concede to the harsh reality of sharp declines in discoveries. After an 18-percent decline from the early to the late 1950s, the number of exploratory wells drilled in North Central Texas fell 55 percent between the late 1950s and the early 1960s. Although the decline in exploratory drilling lagged slightly behind the decline in the number of significant discoveries and in the amount discovered, North Central Texas has the distinction of being the only region of the nation in which the peaks in the number of significant discoveries, the amounts of crude oil and natural gas discovered, and the number of exploratory wells drilled coincide.

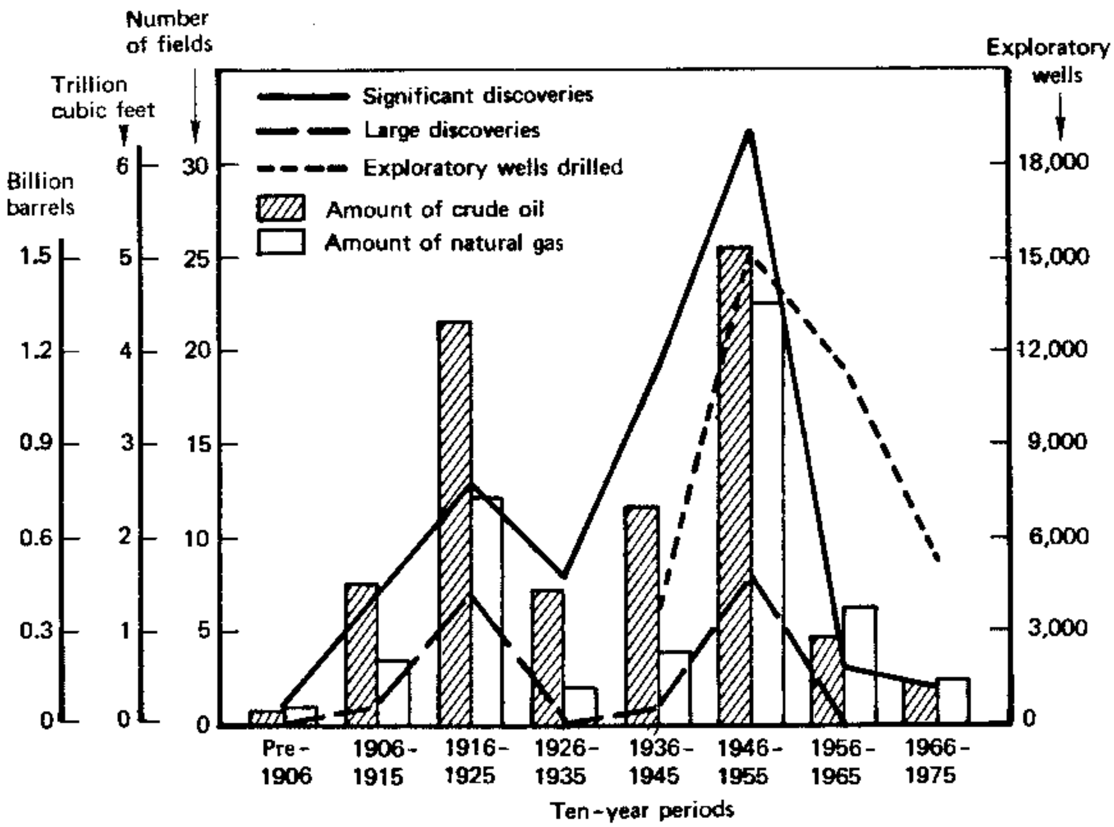

Fig. 4.10—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in North Central Texas

MID-CONTINENT

The Mid-Continent region is notable in that the number of significant discoveries both increased quickly and persisted at high levels for more than 60 years. Although *Iola*, the first significant discovery in the region, was found in Kansas in 1873, there were only nine other discoveries by 1900. The beginning of the century also marked the beginning of major exploration in the region. Most of the discoveries in the first 25 years following 1900 occurred in the Chautauqua Province of north central Oklahoma, nearly all of the rest being in the adjacent South Oklahoma Province and the provinces of central and eastern Kansas. Only one significant discovery was made in the Anadarko-Amarillo Province during this period, but because that discovery was the super-giant *Hugoton-Panhandle* field, it was a significant one indeed. (See Fig. 4.11 and Tables C.6, C.6a, C.6b, and C.6c.)

After a steady series of increases, the number of significant discoveries reached their initial peak in the late 1920s, buoyed upward by the discovery of most of the significant fields on the Seminole Platform covering the southern part of the Chautauqua Province. During the decade around 1930, the number of giant and

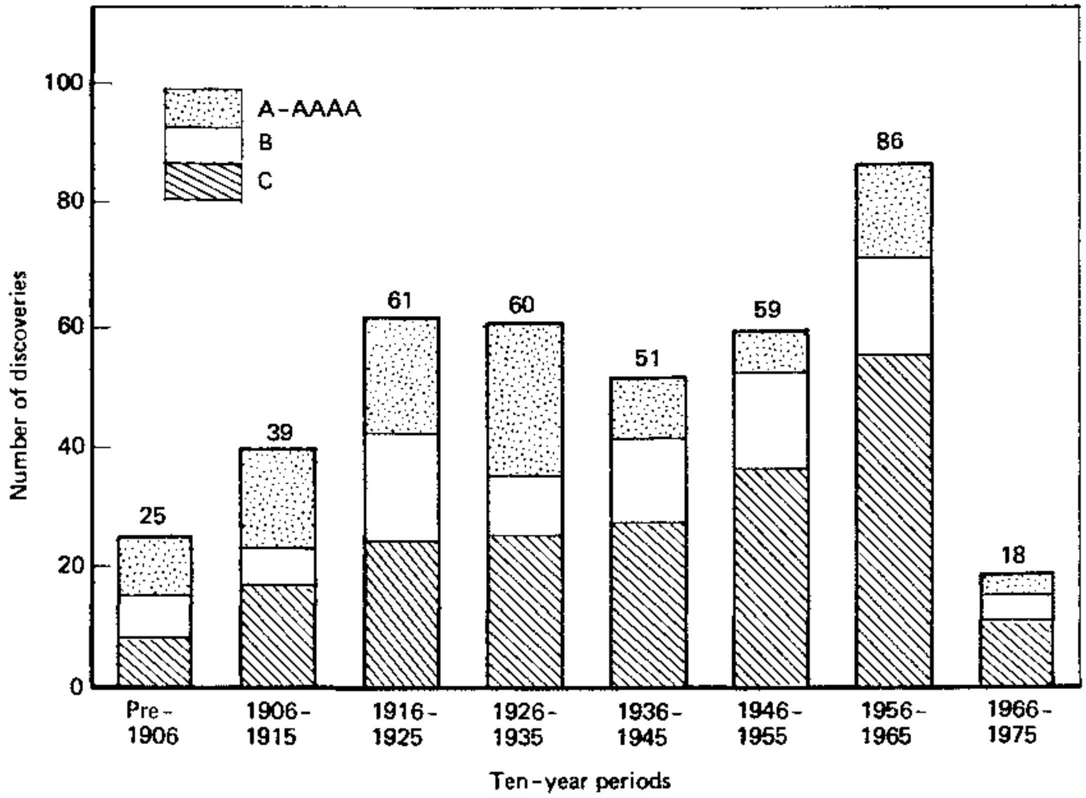

Fig. 4.11—Number of significant oil and gas discoveries by field size category over ten-year periods in the Mid-Continent

large discoveries in the Mid-Continent reached its historic peak. The total number of significant discoveries declined only modestly during the next decades. However, as the possibilities in the provinces of central and eastern Kansas and Oklahoma were continually subject to the tests of exploratory drilling, the number of giant and large discoveries dwindled.

Beginning about 1950, the number of significant discoveries surged upward with the intensive exploration of the Anadarko Basin and reached its historic peak. The number of large discoveries also increased substantially. After being highly rewarding for the 15 years from 1951 to 1965, this exploratory play also lost momentum, and the number of significant discoveries dropped sharply despite the initiation of deep drilling in the basin. Nonetheless, the Anadarko-Amarillo Province still remains the center of Mid-Continent exploration. Since 1961, all but one of the significant discoveries in the region have been in this province. These include seven new field or new pool discoveries more than 15,000 feet deep.

The uniformity in the total number of significant discoveries in the Mid-Continent masks major changes in the composition of discoveries in the region by type of hydrocarbon. Discoveries of predominantly crude oil fields rose steadily to their peak in the 1920s and declined continuously thereafter until their near disappearance in the early 1970s. Discoveries of predominantly natural gas fields remained

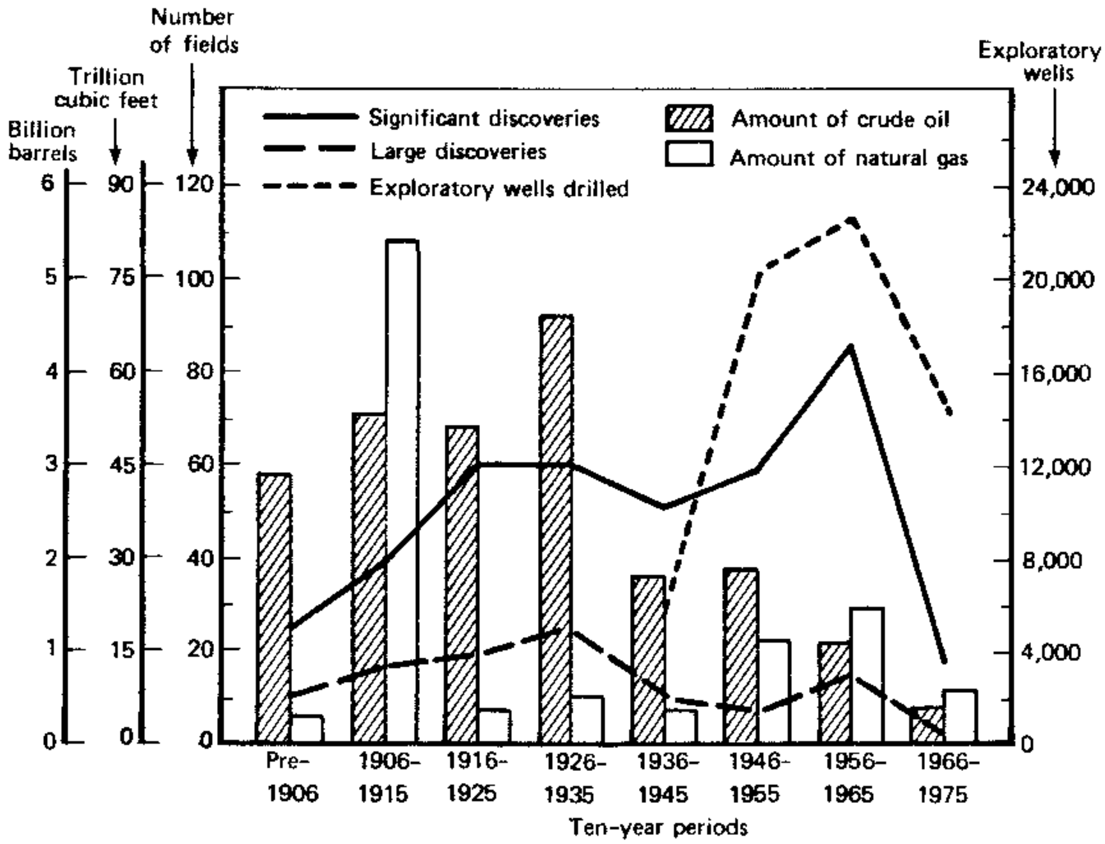

Fig. 4.12—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Mid-Continent

at a uniformly low level until the late 1940s, then rose quickly to a peak about 1960 before declining in the late 1960s.

Unlike the number of significant discoveries, discoveries of large amounts of crude oil and natural gas did not persist beyond 1930. Substantial amounts of crude oil were discovered in each of the first four periods shown in Fig. 4.12, reaching their peak with the discovery of the *Oklahoma City* field and the fields of the Seminole Platform in the late 1920s. However, as the number of significant crude oil discoveries declined, particularly Class A or larger fields, the amount discovered dropped sharply as well. Because the *Hugoton-Panhandle* field had more than half of the natural gas resources discovered to date in the Mid-Continent region, the period of its discovery was also the peak period for the amount of natural gas discovered. Its dominance is such that the amount discovered from 1906 to 1915 is nearly four times as great as that discovered from 1956 to 1965, the peak of significant gas field discoveries in the Anadarko Basin.

The peak in exploratory drilling in the Mid-Continent region coincides with the peak of Anadarko Basin discoveries during the 1950s and early 1960s, and thus with the peak in significant Mid-Continent discoveries. However, it lags several decades behind the peak in giant and large discoveries and thus in the amounts of crude oil and natural gas discovered. Since the peak in exploratory drilling during the late 1950s, the number of wells drilled in the Mid-Continent region has declined by slightly more than 50 percent. But this follows a more than 80-percent decline in the number of significant discoveries. During the 40 years between 1936 and 1975, nearly 63,000 exploratory wells were drilled in the Mid-Continent region, the most of any region in the country.

WESTERN GULF

Although the first significant discovery in the Western Gulf region was made in 1896 (*Saratoga*), subsequent discoveries over the next three decades occurred at a slow pace, hampered by a lack of surface expression of the many structures of the region. Most of the discoveries that were made were based either on evidence of surface seepage or the identification of minor surface mounds over buried salt domes. Probably because of their more obvious nature, 19 of the 32 significant discoveries made during this period were large fields. (See Fig. 4.13 and Tables C.7, C.7a, C.7b, and C.7c.)

With the introduction of seismic technology and other geophysical methods in Texas Gulf Coast exploration, the number of discoveries leapt to record heights. In the decade around 1940, more significant fields were discovered in the Western Gulf region than have been discovered in any decade in any other region of the country. Early geophysical technology was particularly effective in locating the largest fields in the region. Between 1928 and 1940, all of the Class AAAA fields wholly in the region and 10 of the 17 Class AAA fields were discovered.

In the decade from 1946 to 1955, the total number of discoveries declined by a third, primarily because of a more than 60-percent decline in the number of giant and large discoveries. As the exploration effort became more intensive, the number of Class C discoveries remained relatively stable. By the decade around 1960, Class C discoveries also joined the continued decline of the larger discoveries, producing a nearly 50-percent decline in the total number of significant discoveries. This decline was stabilized in the decade around 1970, the number of significant discoveries rising sharply in the early 1970s.

The recent aggregate trends in the number of discoveries mask two important changes in the composition of significant discoveries in the Western Gulf region. The first is the substantial shift from onshore to offshore discoveries. Significant onshore discoveries have declined severely since the decade around 1950, dropping from 101 in that period to 42 in the decade around 1960 and subsequently to only 19 in the decade around 1970. The increase in significant discoveries in the decade around 1970 is entirely the result of a sharp upturn in the early 1970s in offshore discoveries, mostly in the High Island area off Texas R.R.C. District 3.

The second major change is the growing dominance of natural gas discoveries. More than twice as many fields containing predominantly natural gas have been discovered in the Western Gulf than fields containing mainly crude oil. Before 1935, these proportions were more than reversed. More than two-thirds of the early discoveries were predominantly oil fields. After reaching their peak in the late

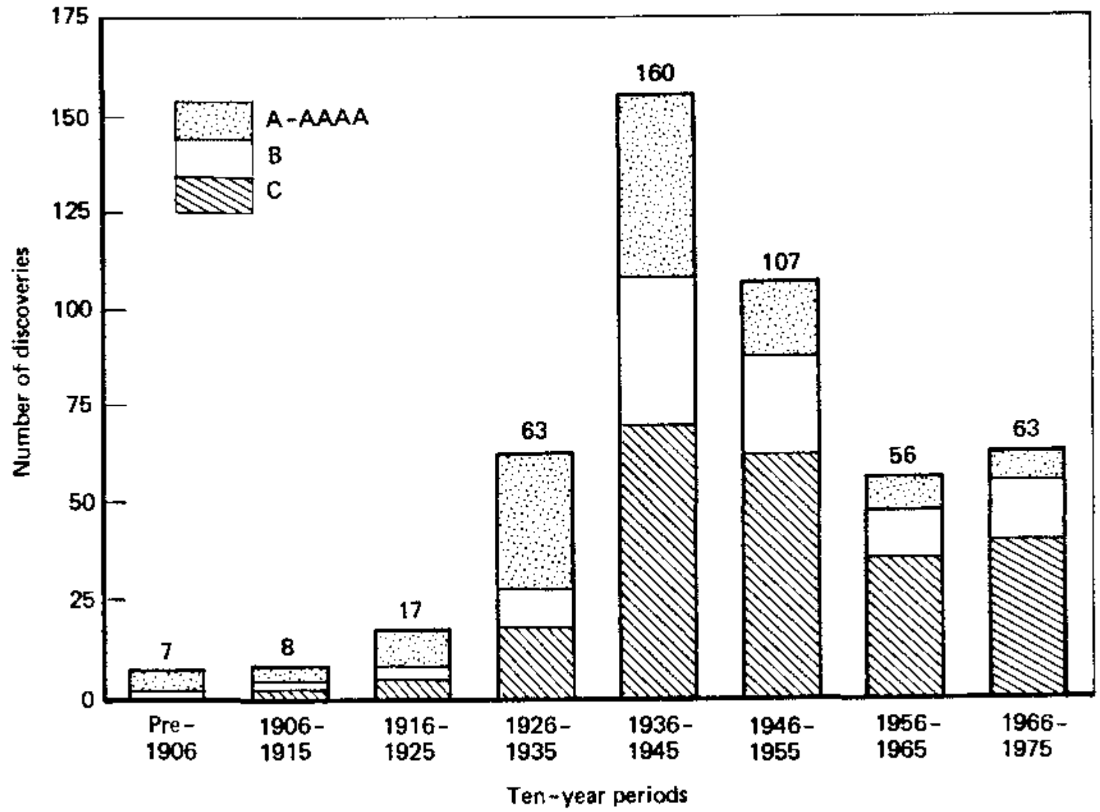

Fig. 4.13—Number of significant oil and gas discoveries by field size category over ten-year periods in the Western Gulf

1930s, significant oil discoveries in the Western Gulf quickly dwindled away. Only five significant oil fields have been discovered in the region since 1955. Discoveries of significant natural gas fields in the Western Gulf remained on a high plateau from the late 1930s to the early 1950s. After declining steadily from this plateau until 1970, they reached their peak in the early 1970s in company with the peak in offshore discoveries.

The trends in the amounts of oil and natural gas discovered in the Western Gulf region parallel the trends in the number of significant discoveries. (See Fig. 4.14.) The amount of crude oil discovered peaked in the decade around 1930, coinciding with the peak in the number of giant and large oil fields discovered in the region in the early 1930s. As both the number and size of oil discoveries have dwindled to minimal amounts, the amount of crude oil discovered has also dwindled. The amount discovered in the early 1970s was only slightly more than 1 percent of the amount discovered in the early 1930s. The amount of natural gas discovered peaked in the decade around 1940, coinciding with the peak in large natural gas discoveries in the late 1930s. Because the number of significant gas discoveries remained high, even though their sizes were declining, the amount of natural gas discovered did not decline as rapidly as the amount of crude oil. The peak in natural

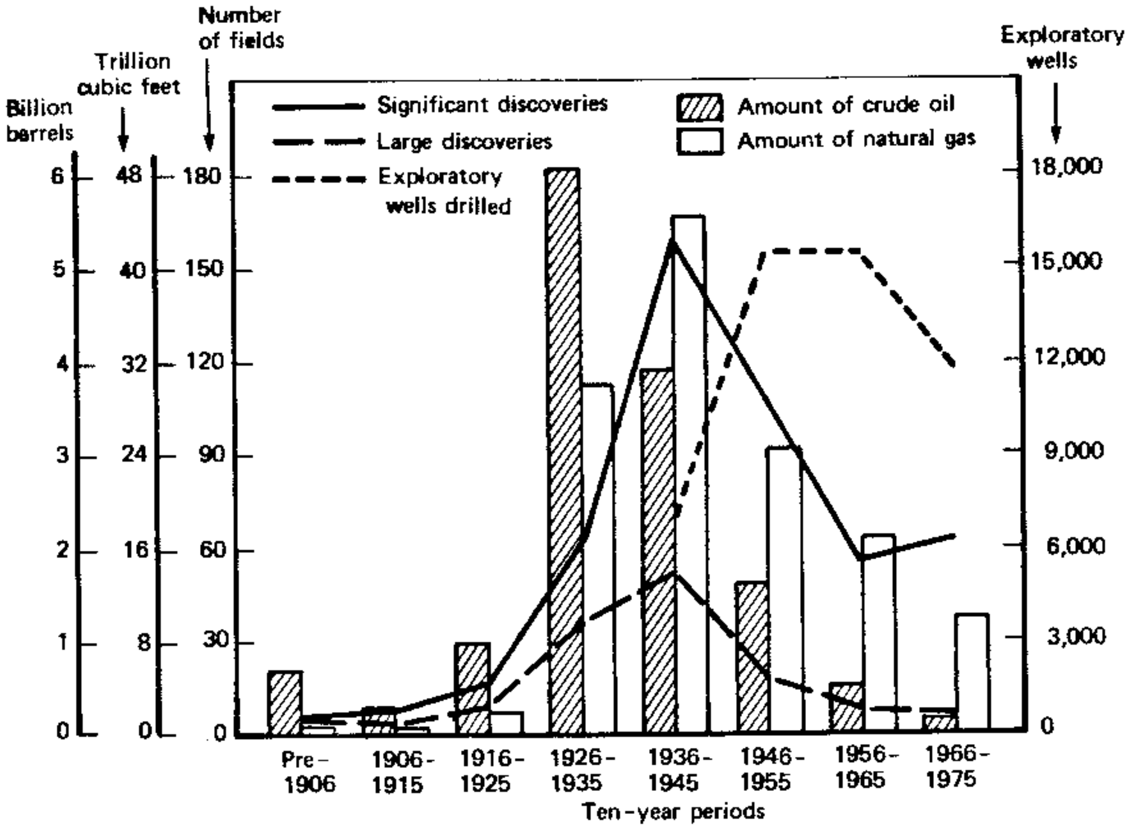

Fig. 4.14—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Western Gulf

gas discoveries in the early 1970s reversed the decline in the amount of gas discovered during the 1960s, but because most of these discoveries were Class B and C fields, less natural gas was discovered in the Western Gulf region in the early 1970s than in the late 1950s.

The trend in exploratory drilling in the Western Gulf region appears to be a reverse mirror image of the aggregate trend in significant discoveries. As the number of discoveries declined, exploratory drilling increased sharply to its peak during the 1950s. As the number of discoveries jumped sharply in the early 1970s, total exploratory drilling remained constant. The aggregate data do, however, hide a noticeable increase in exploratory drilling after 1972, coinciding with the rise of discoveries.

CENTRAL GULF

Like the Western Gulf, discoveries in the Central Gulf region have depended heavily on the use of seismic and other geophysical exploration technologies. The first discovery—*Jennings*—was made in 1901. Only nine more had occurred by 1925. The combined effect of the Depression and the discovery of the super-giant *East Texas* field on the Gulf Coast oil market restrained the pace of discoveries briefly during the early 1930s. But by the late 1930s, the number of significant discoveries reached the high levels at which they were to persist until the early 1970s. Underlying this gross trend, the five-year aggregations for the number of discoveries in the region indicate a peak during both halves of the 1950s, followed by a substantial decline during the 1960s and a resurgence to near peak levels in the early 1970s. (See Fig. 4.15 and Tables C.8, C.8a, C.8b, and C.8c.)

The slow decline in the total number of discoveries camouflages a sharp change in the location of significant discoveries in the Central Gulf region. In the decade around 1950, onshore discoveries outnumbered offshore discoveries by 94 to 48. As offshore discoveries increased and onshore discoveries declined, this relationship was sharply reversed by the decade around 1970, offshore discoveries outnumbering onshore discoveries by 92 to 15. By the early 1970s, onshore discoveries had dwindled to 5, their lowest level since the introduction of geophysical methods in Central Gulf Coast exploration. In contrast, significant offshore discoveries reached a peak of 67 with the intensive exploration of the Pleistocene trend during the early 1970s.

One unique characteristic of the pattern of discoveries in the Central Gulf region is the persistence of substantial numbers of discoveries of Class A or larger fields over the last four decades. Unlike other regions, the Central Gulf incorporates a sizable frontier area with many major prospects that was only gradually opened up to exploration with the development of offshore technology and the progression of government lease offerings. The number of large discoveries finally did decline substantially during the decade around 1970, accounting for nearly all of the drop in the total number of discoveries, but it still reached a healthy total of 38, an amount exceeded only once in any other region (the Western Gulf during its peak decade of discovery about 1940).

Like the Western Gulf, the number of significant discoveries in the Central Gulf region that are predominantly natural gas are more than double the number of discoveries that are largely crude oil. The peak in significant natural gas discoveries also did not occur until the early 1970s. But unlike the Western Gulf, significant crude oil discoveries have only declined moderately in the Central Gulf region. Significant discoveries of composite oil and gas fields are also prominent in the Central Gulf, with a total of 114 by the end of 1975. Their pattern of discovery almost coincides with that of predominantly oil fields, both peaking in the decade around 1950.

The trends in the amounts of crude oil and natural gas discovered in the Central Gulf are closely related to the trends in the number of significant discoveries of oil and gas fields. (See Fig. 4.16.) The amount of oil discovered peaked in the decade around 1950, the same period in which the number of significant oil discoveries reached its peak. The subsequent decline in the amount discovered is only moderately greater than the decline in the number of discoveries, the result of the slow decline in the average size of discoveries. The amount of natural gas discovered peaked in the decade around 1960, the same period in which the number of significant gas discoveries reached its peak. Because of a sharp decline in both the number of discoveries and the average size of discoveries during the 1960s, the amount

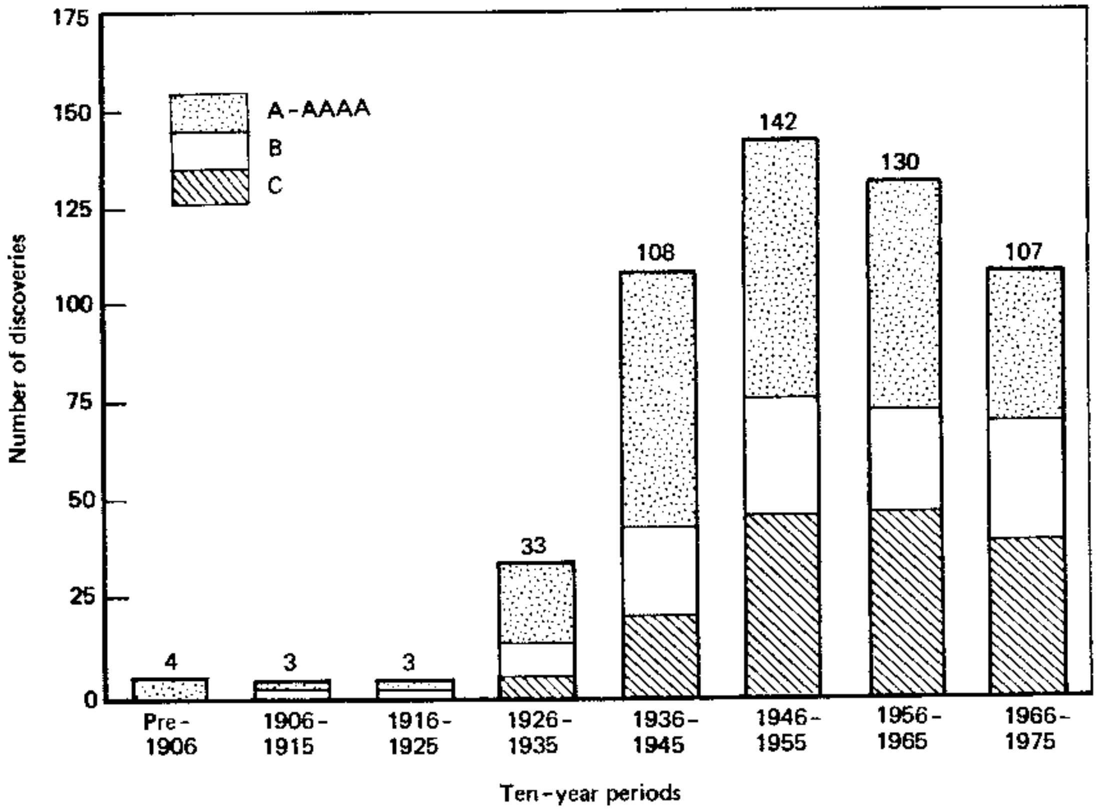

Fig. 4.15—Number of significant oil and gas discoveries by field size category over ten-year periods in the Central Gulf

discovered in the decade around 1970 dropped 50 percent from this peak, despite the resurgence in discoveries during the early 1970s.

As in most other regions, exploratory drilling peaked in the Central Gulf in the decade around 1960 and declined slowly into the 1970s. It lagged behind both the peaks in the total number of significant discoveries and in the amount of crude oil discovered, but coincided with the peak in the amount of natural gas discovered.

NORTHERN GULF

Corsicana, the first significant discovery in the Northern Gulf region, was found in 1895, but discoveries in any appreciable number did not occur for another two decades. The round of discoveries in the decade around 1920, concentrated in northern Louisiana and southern Arkansas, depended on drilling anticlines visible on the surface, on drilling seepages, and on sheer wildcatting. The latter recorded its greatest achievement in U.S. petroleum exploration with the discovery of the super-giant *East Texas* field in 1930. (See Fig. 4.17 and Tables C.9, C.9a, C.9b, and C.9c.)

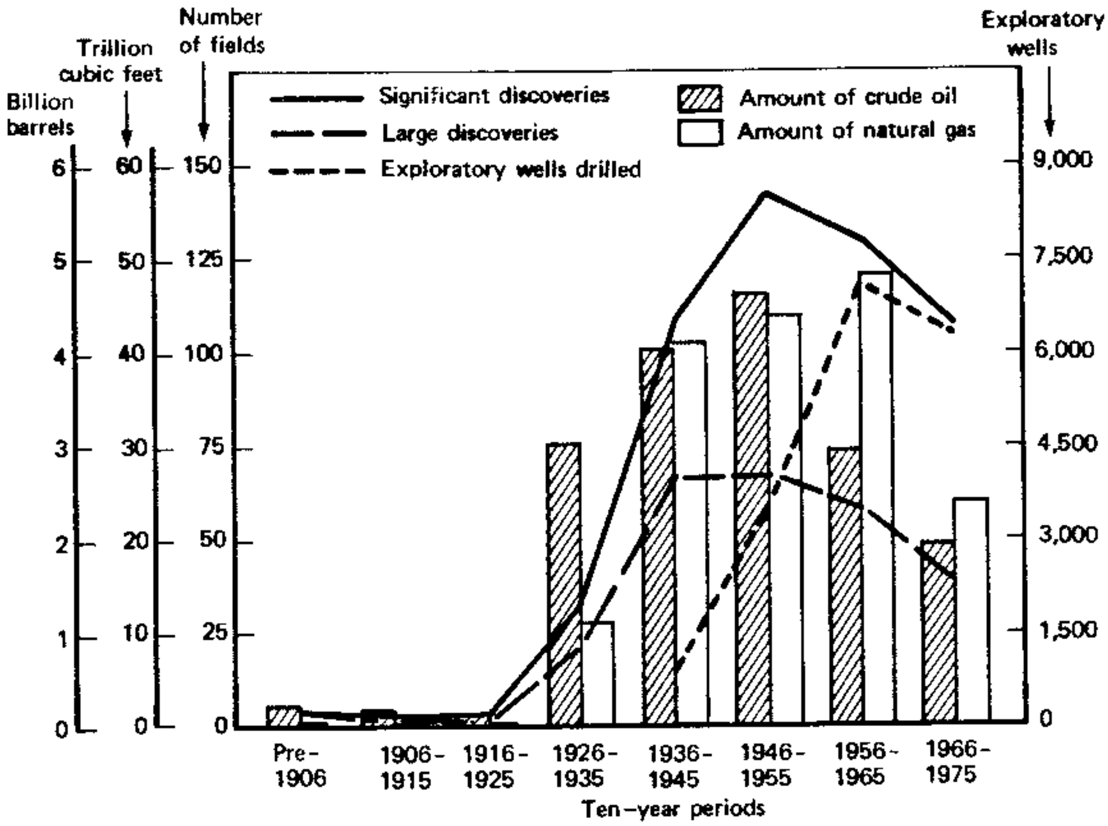

Fig. 4.16—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Central Gulf

The discovery and development of the *East Texas* field exercised a temporary depressing effect on exploration in the Northern Gulf region. Only four significant discoveries were made in the region during the early 1930s. Once *East Texas* production was brought under control, the speculation it encouraged about the possibility of more major discoveries in the region, coupled with the widespread use of seismic and other geophysical techniques, quickly pushed the number of significant discoveries in the Northern Gulf region to its historic peak. During the decade around 1940, one-third of all the significant fields and nearly half of the Class A or larger fields discovered before 1976 in the Northern Gulf region were discovered.

This flurry of activity came close to exhausting the larger possibilities in the region. In the subsequent three decades, only 8 Class A or larger fields (compared with 27 in the decade around 1940) and only 9 Class B fields (compared with 17 in the decade around 1940) were discovered. The total number of significant discoveries did not decline as rapidly, as Class C discoveries did not reach their peak until the decades around 1950 and 1960. However, once these smaller prospects were picked over, the total number of significant discoveries plunged to its lowest level since the introduction of surface geology in Northern Gulf exploration.

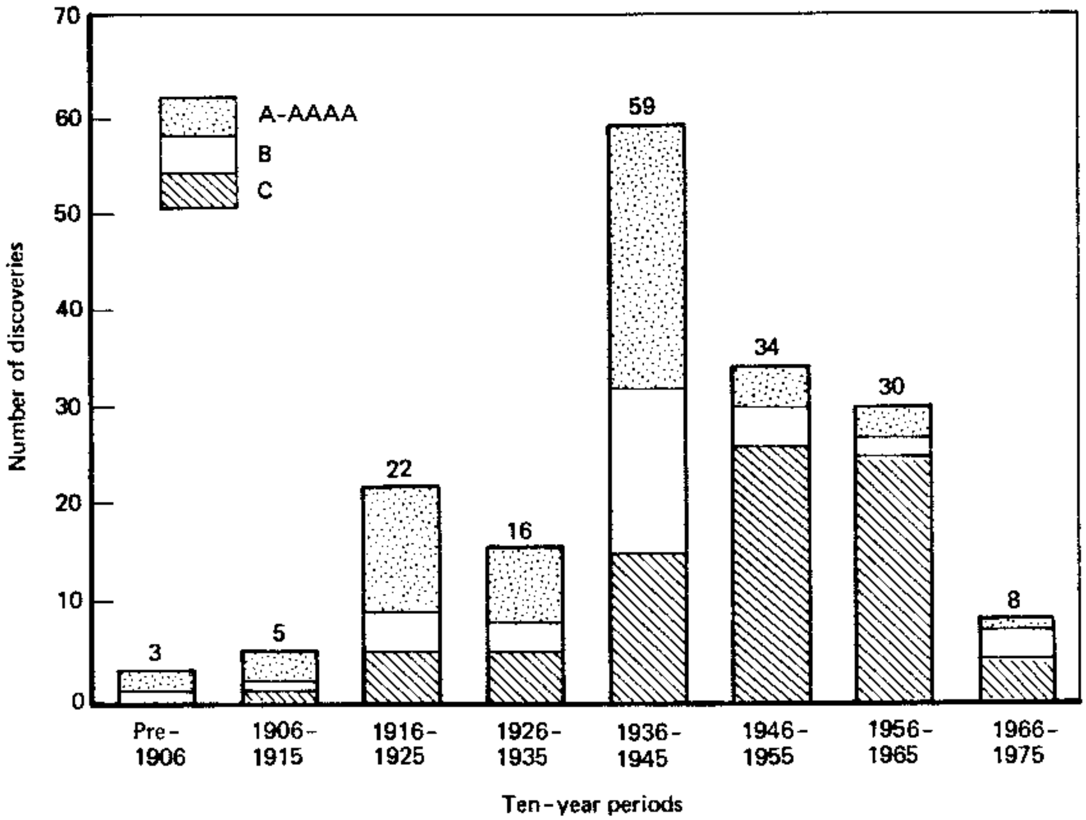

Fig. 4.17—Number of significant oil and gas discoveries by field size category over ten-year periods in the Northern Gulf

Unlike most other regions with sizable numbers of both oil and natural gas discoveries, in which natural gas discoveries lag behind oil discoveries, the patterns of discovery for the two types of fields in the Northern Gulf region reasonably coincide. Both first became prominent in the decade around 1920, both peaked in the decade around 1940, and both have declined at roughly similar rates, although natural gas discoveries have suffered less of a decline since 1960.

Because the crude oil and natural gas resources of the Northern Gulf region are highly concentrated in a few Class AAAA, Class AAA, and Class AA fields, the peaks in the amounts discovered coincide with the timing of those discoveries. (See Fig. 4.18.) The initial peak in the amount of natural gas discovered in the decade around 1920 is primarily the result of the discovery of the giant *Monroe* field. The discovery of the super-giant *East Texas* field produced the obvious peak in the amount of oil discovered in the decade around 1930. The discovery of the giant *Carthage* field together with several more Class AAA and Class AA fields produced the peak in the amount of natural gas discovered in the decade around 1940. The subsequent sharp drops in the amounts discovered are primarily the result of the substantial decline in the average size of significant discoveries and secondarily of the decline in the total number of significant discoveries.

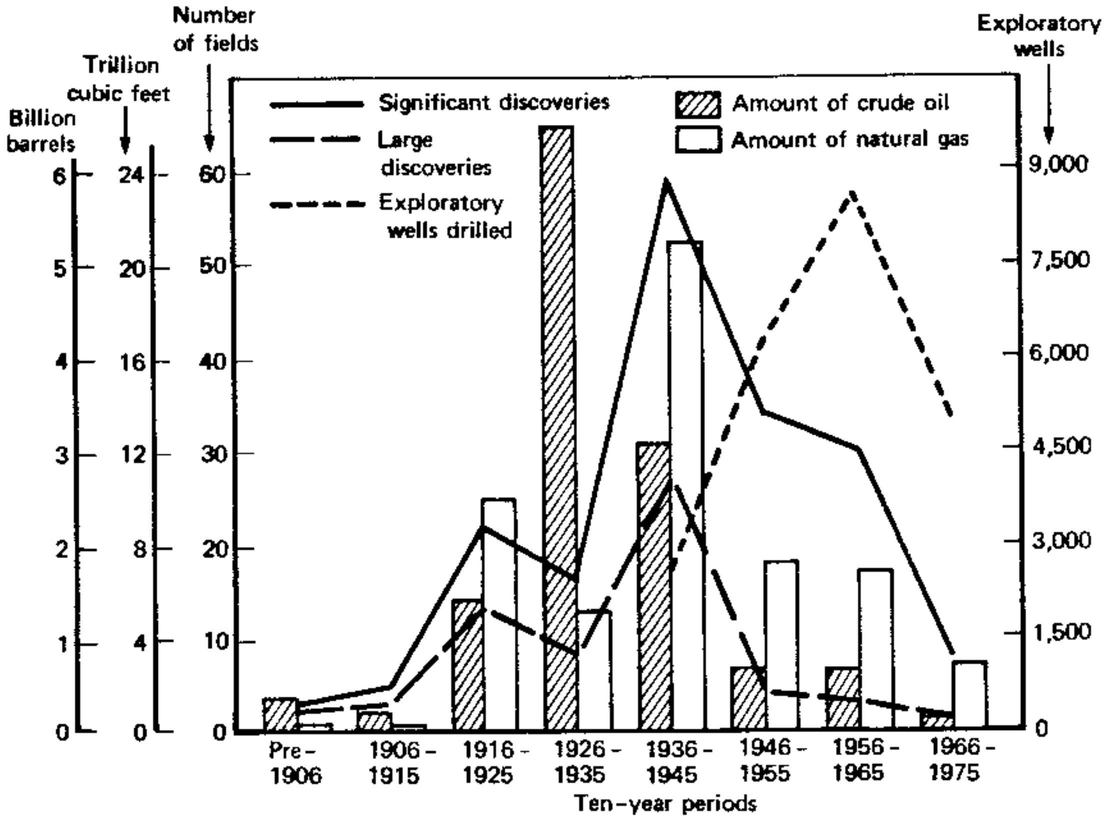

Fig. 4.18—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Northern Gulf

The trend in exploratory drilling in the Northern Gulf region from the late 1930s to the early 1960s is the reverse of the trends in the number of significant discoveries and in the amounts discovered, both of which declined at a relatively steady pace. In contrast, drilling grew steadily, not peaking until the late 1950s and lagging behind the peak in discoveries by two decades. The subsequent decline in drilling during the 1960s and early 1970s is a belated recognition of the diminishing possibilities of the region.

EASTERN GULF

The Eastern Gulf is the last region in the lower 48 states to see a significant discovery. *Jackson*, the first significant discovery in the region, was not found until 1930. Since that discovery, three distinct waves of exploration have occurred in the Mid-Gulf Coast Province. (See Fig. 4.19 and Tables C.10, C.10a, C.10b, and C.10c.) The first, occurring primarily in the early 1940s, concentrated on moderate depth Cretaceous objectives. During this period, all of the largest fields in Mississippi

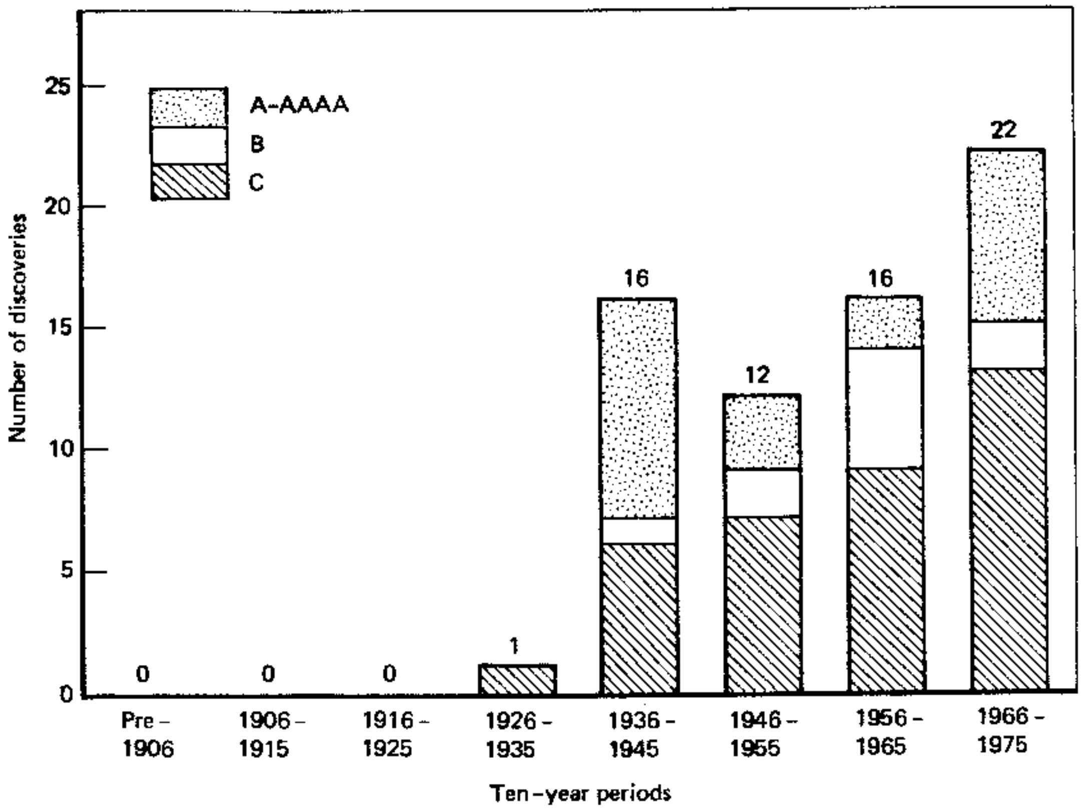

Fig. 4.19—Number of significant oil and gas discoveries by field size category over ten-year periods in the Eastern Gulf

were discovered, creating the historic peak in the discovery of large fields in the Eastern Gulf. After a gradual diminishing of these shallower discoveries, the second major exploratory play, that for deeper Cretaceous objectives, occurred primarily in the late 1950s. This was quickly followed by the search for deep Jurassic objectives in the decade around 1970. This third play yielded 17 discoveries from 1965 to 1974, 11 of which were deeper than 15,000 feet. This play also produced a resurgence in large discoveries in the region, including *Jay*, the largest field found to date in the Eastern Gulf. The six significant discoveries that have been made in the South Florida and Warrior provinces have occurred sporadically over a period of 30 years.

Because of the concentration of the largest discoveries in the first exploration play to occur in the Eastern Gulf, the amounts of both crude oil and natural gas discovered in the region reached their peaks in the decade around 1940. (See Fig. 4.20.) With the subsequent decline in the size of discoveries in the decades around 1950 and 1960, the amounts discovered declined as well. The second peak in the amounts discovered, associated with the wave of Jurassic exploration, may eventually prove to be as high as the initial peak. The possibility exists for moderate reserve growth in both the amounts of crude oil and natural gas discovered in this

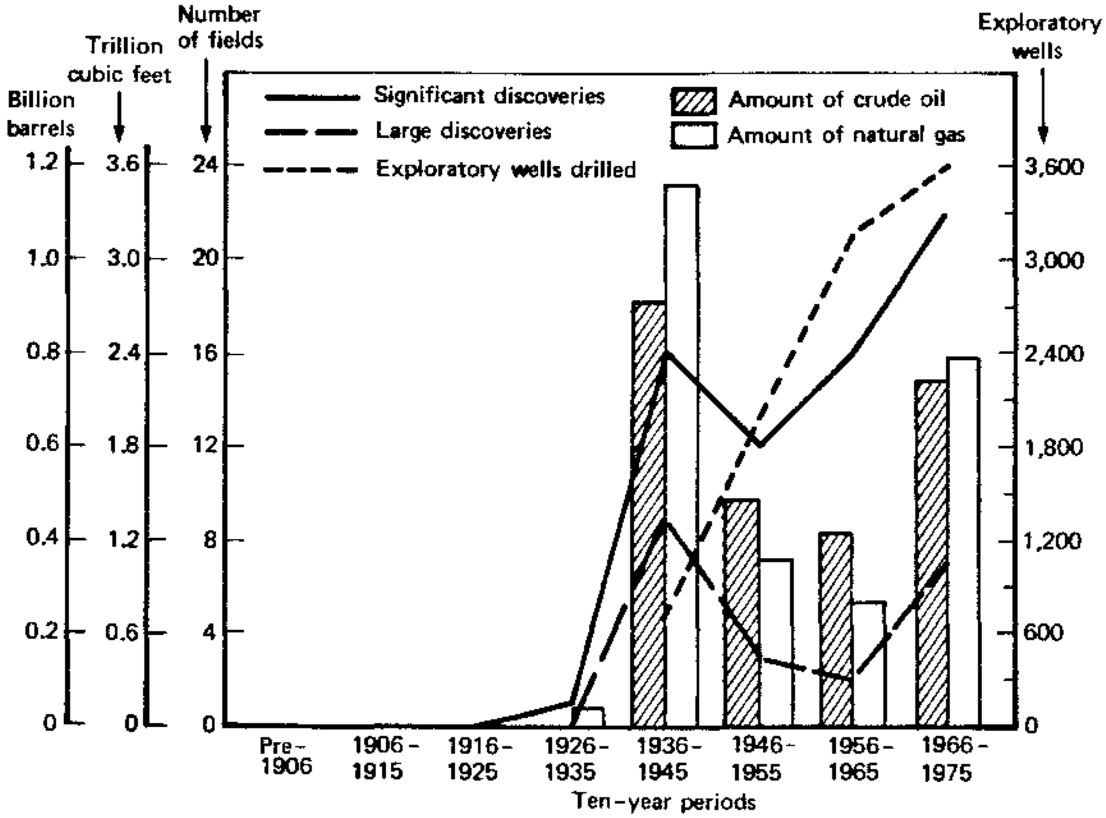

Fig. 4.20—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Eastern Gulf

play. Much of the natural gas liquids discovered in the region were also in these deep Jurassic fields.

The number of exploratory wells drilled in the Eastern Gulf region does not exhibit a close relationship to either the number of significant discoveries or the amounts of crude oil and natural gas discovered, which fluctuate substantially, particularly over five-year periods. Exploratory drilling shows only a pattern of steady growth.

ILLINOIS-MICHIGAN

No region in the United States provides as good an illustration as Illinois-Michigan of how efficient petroleum exploration can be in locating the significant fields within a province once the appropriate technology is available. Although the first significant field in this region was discovered in 1886 (*Trenton*), the number of significant discoveries in both the Illinois and Michigan basins sputtered along at negligible levels until the late 1930s. Because of the geologically recent glacial

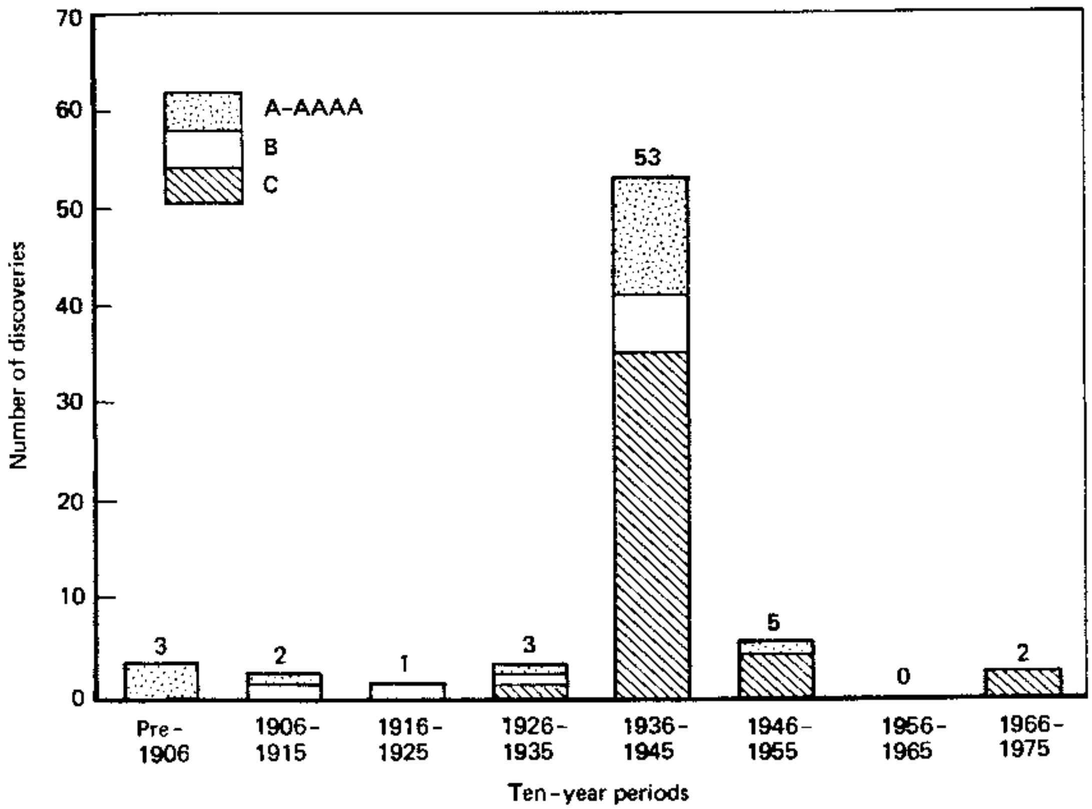

Fig. 4.21—Number of significant oil and gas discoveries by field size category over ten-year periods in the Illinois-Michigan basins

debris covering most of the region, it was not possible to locate fields by surface geology—the most widely used scientific exploration technique between 1910 and 1930. Once seismic methods were employed in the Illinois Basin, this situation changed dramatically. (See Fig. 4.21 and Tables C.11, C.11a, and C.11c.)

Between 1937 and 1948, 42 of the 47 significant fields discovered to date in the Illinois and Indiana portions of the Illinois Basin were discovered. Since 1948, despite extensive exploratory drilling, not one significant field has been found in this area. (Two were found in the Kentucky portion of the basin in 1956 and 1962.) Exploration in the Michigan Basin proved to be slightly more difficult because early seismic technology was not particularly useful there. Nonetheless, using core-drilling and subsurface geology, explorationists were able to locate 12 of the 21 significant fields discovered to date in only six years from 1937 to 1942. Although only two significant discoveries have been made in exploration for Silurian pinnacle reefs in the Michigan Basin during the 1970s, impressive numbers of Class D discoveries have occurred.

Because such a large proportion of the total number of significant discoveries in the Illinois-Michigan basins occurred in the decade around 1940, the amount of crude oil discovered also shows a marked peak during this period. (See Fig. 4.22.)

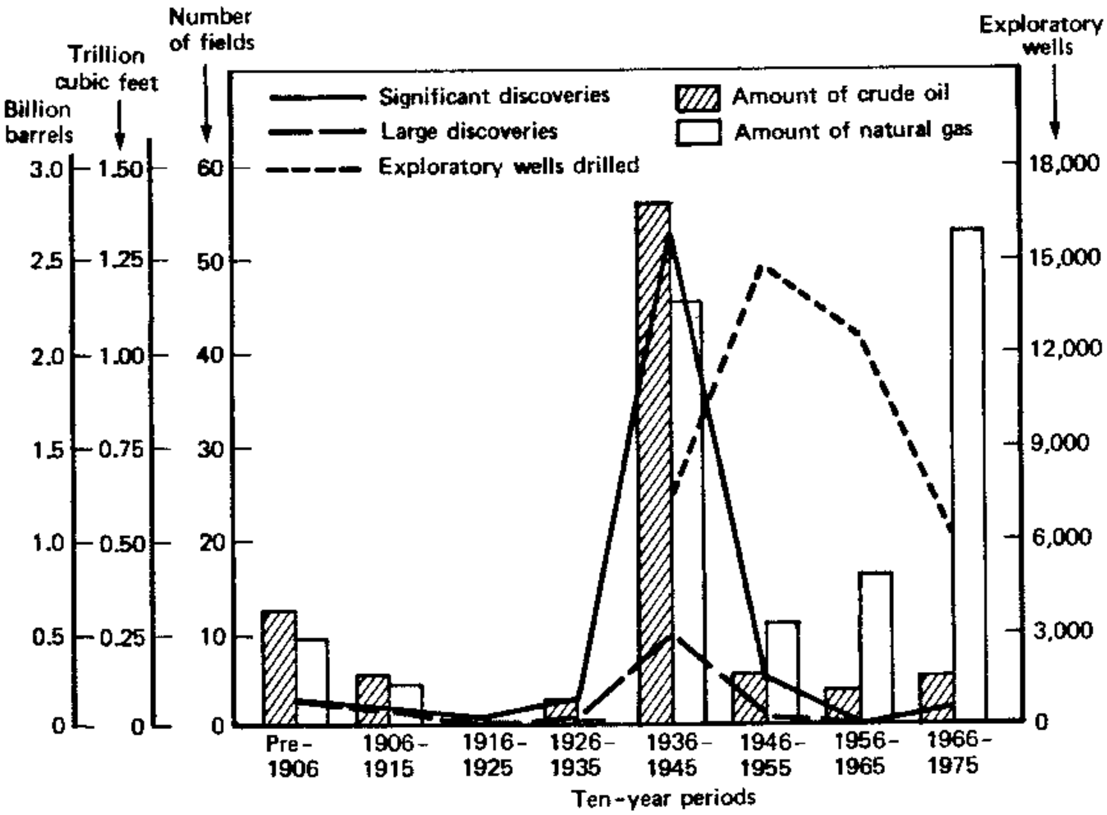

Fig. 4.22—Significant discoveries, the amounts of crude oil and natural gas discovered, and exploratory drilling over ten-year periods in the Illinois-Michigan basins

The Illinois Basin contains little natural gas and the amount discovered in the region has two peaks: one for associated-dissolved gas about 1940 and one for nonassociated gas in the pinnacle reefs of the Michigan Basin in the early 1970s. In both cases, the amounts discovered were low.

Exploratory drilling in the region lagged behind the peak in discoveries by a decade. The late 1940s and 1950s were the peak period of drilling effort following the successes of the late 1930s and early 1940s. Because of the high success rates that resulted from employing advanced seismic exploration, the intensive exploration effort for pinnacle reefs in the Michigan Basin has not reversed the decline since 1960 in the number of exploratory wells drilled in the region.

APPALACHIAN

The first oil well drilled in the United States was drilled in Pennsylvania in 1859. Although data do not exist to enable us to describe precisely the history of petroleum exploration in the Appalachian region since that first discovery, it is obvious that most of the significant fields in the region were discovered in the nine-

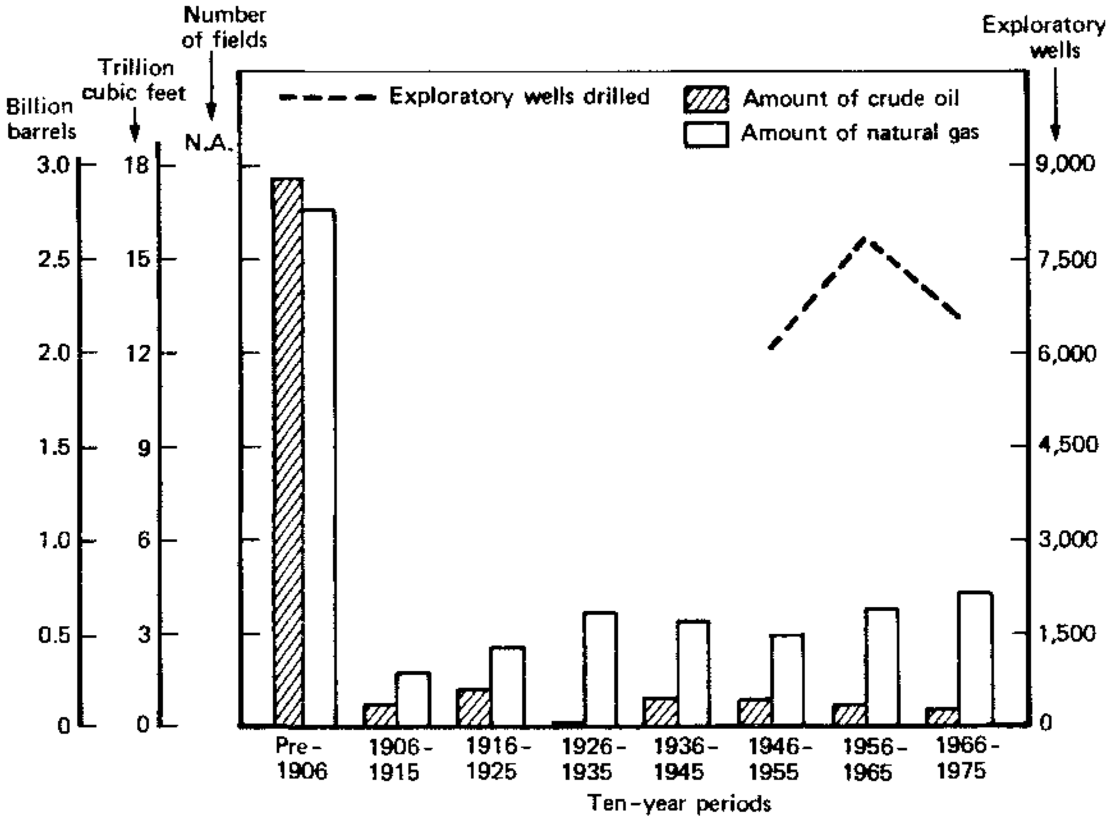

Fig 4.23—The amounts of oil and gas discovered and exploratory drilling over ten-year periods in the Appalachian region

teenth century. (See Fig. 4.23.) Nearly three-fourths of the crude oil and nearly half of the natural gas discovered to date were in fields discovered before 1900. Since then, there were a few significant oil discoveries in eastern Kentucky in the late 1910s, western Kentucky during the 1940s, and eastern Ohio during the 1960s. The amounts of natural gas discovered have remained stable over the past six decades from 1916 to 1975, averaging about 300 to 400 billion cubic feet per year. In all probability, there are a number of significant discoveries buried in this trend, but the meager data on natural gas fields in the region (other than a few deep gas discoveries in Pennsylvania) do not permit their identification. The data on exploratory drilling in the region only go back to the mid-1940s. They indicate the most stable pattern of drilling activity of any of the 12 regions, with a mild peak in the early 1960s.

NATIONAL OVERVIEW

Following the first significant discovery outside the Appalachian region—*Florence-Canon City* in Colorado in 1862—petroleum exploration in the United States proceeded at a slow pace for the next four decades. The reasons for this slow advance are clear. Petroleum geology was still in its primitive stages, and, even in those situations where it could have conceivably provided some positive guidance to exploration, it was largely ignored. Other scientific exploration techniques, such as geochemistry and geophysics, did not even exist. Drilling technology was also primitive, its capability being limited to reaching shallow targets (less than 2500 feet deep). Petroleum exploration before 1900 was also restricted geographically to the Appalachian region and to a few other areas with prominent surface indications of oil, such as California and the Rocky Mountain region.

With the application of surface geology on a systematic basis and the gradual development of drilling capabilities, the number of significant discoveries began to grow at a steady pace after 1900. (See Fig. 4.24 and Table C (Summary).) The peak in the number of significant discoveries did not, however, occur until the introduction and widespread use of geophysical techniques during the 1930s. In only five years, from the early 1930s to the late 1930s, the number of significant discoveries nearly tripled, reaching a peak plateau that was to be maintained into the early 1950s. During the 20 years between 1936 and 1955, nearly half of the significant fields discovered before 1976 in the United States were found. Since this peak, the number of significant discoveries has been declining at an increasing rate, dropping 19 percent from the decade around 1950 to the decade around 1960 and 33 percent from the decade around 1960 to the decade around 1970.

The asymmetric pattern of discoveries reflects the interaction among technology, the regional distribution and characteristics of significant fields, the petroleum market, and governmental regulation. More than 84 percent of the significant fields in the United States discovered before 1976 have been in six regions: the Central Gulf, Western Gulf, Mid-Continent, Permian Basin, Rocky Mountains, and Northern Gulf (listed in decreasing order of importance). The number of significant discoveries reached its peak in the Western Gulf and Northern Gulf regions in the decade around 1940 following the systematic use of early seismic technology. The number of significant discoveries in the Rocky Mountain and Permian Basin regions peaked in the decade around 1950 as the consumption of petroleum grew and oil prices rose after World War II. The peak in discoveries in the Central Gulf region during this same period coincided with large-scale leasing of the offshore Gulf of Mexico for petroleum exploration and development. The peak in significant discoveries in the Mid-Continent during the decade around 1960 came with the extensive exploration of the gas-prone Anadarko Basin to meet the rapidly growing demands of the national natural gas market. As the number of discoveries in these regions has declined, the national total has tailed off as well.

During the past 40 years, the composition of discoveries by location has changed in another important way. Offshore discoveries have grown from insignificance (6 of 561 in the decade around 1940) to more than half of total discoveries (144 of 309 in the decade around 1970, and 105 of 179 (59 percent) during the early 1970s). The sharp growth in offshore discoveries in the early 1970s was even sufficient to create a temporary reversal in the decline of significant discoveries. Without offshore discoveries, the number of significant discoveries in the United States would have declined at a rapidly increasing rate from the decade around 1940 to the decade around 1970. The number of significant discoveries onshore declined 8 percent from the decade around 1940 to the decade around 1950, followed by a

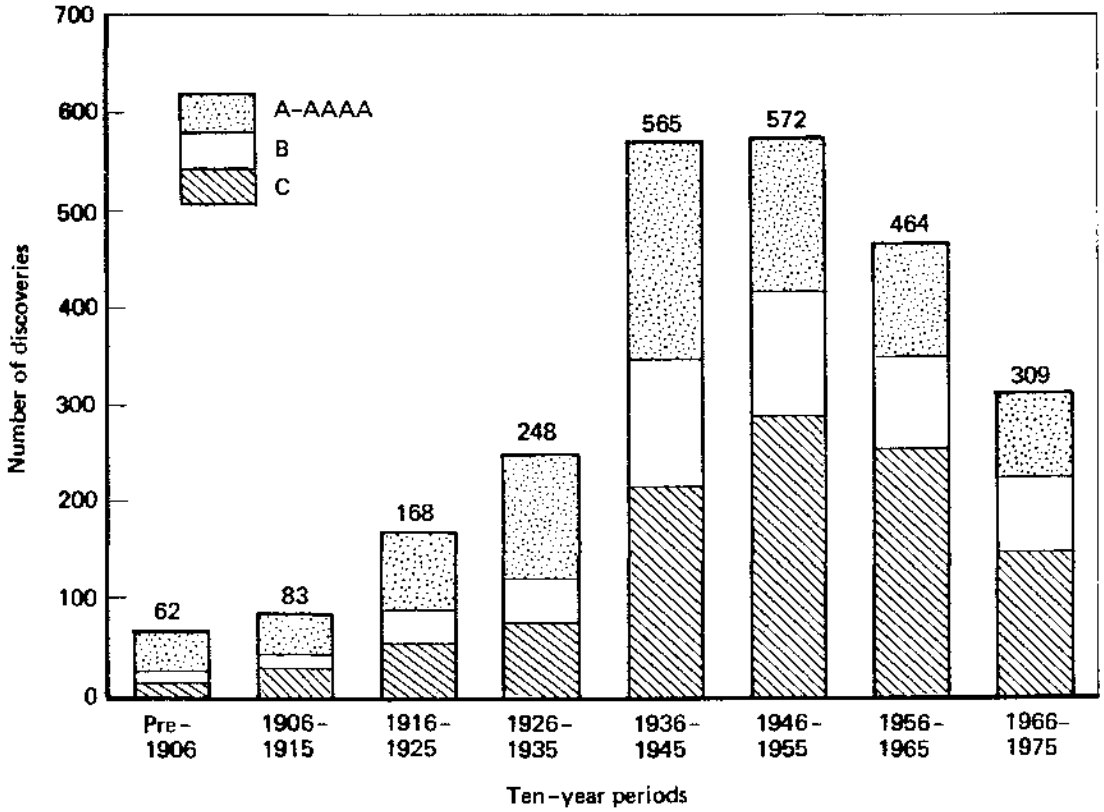

Fig. 4.24—Number of significant oil and gas discoveries by field size category over ten-year periods in the United States (ex-Appalachia)

30-percent decline during the next decade and a 54-percent decline from the decade around 1960 to the decade around 1970.

The temporal pattern nationwide of the number of discoveries by size classification shows a common pattern. Giant (Class AAAA) discoveries peak first, 40 of the 81 being found from the late 1920s to the late 1930s. Since the decade around 1940, the number of giant fields discovered has dropped on average 50 percent every decade. The number of large discoveries (Class A-AAA) peaked in the decade around 1940. Since then, they have declined steadily at a rate of about 25 percent per decade. The peak in Class B discoveries stretched from the late 1930s to the early 1950s. Since the decade around 1950, they have declined at a rate of about 20 to 25 percent per decade. The number of Class C discoveries did not peak until the early 1950s, then underwent a sharp decline during the 1960s that was temporarily reversed by a large number of Class C discoveries offshore in the Gulf of Mexico during the early 1970s. The national pattern thus duplicates the regional patterns. The largest fields tend to be discovered first. The average size of discoveries declines over time. As the number of larger discoveries declines, the total number of significant discoveries remains stable or even increases as the number of smaller significant discoveries continues to increase. But eventually the number of smaller discoveries also declines as exploration proceeds.

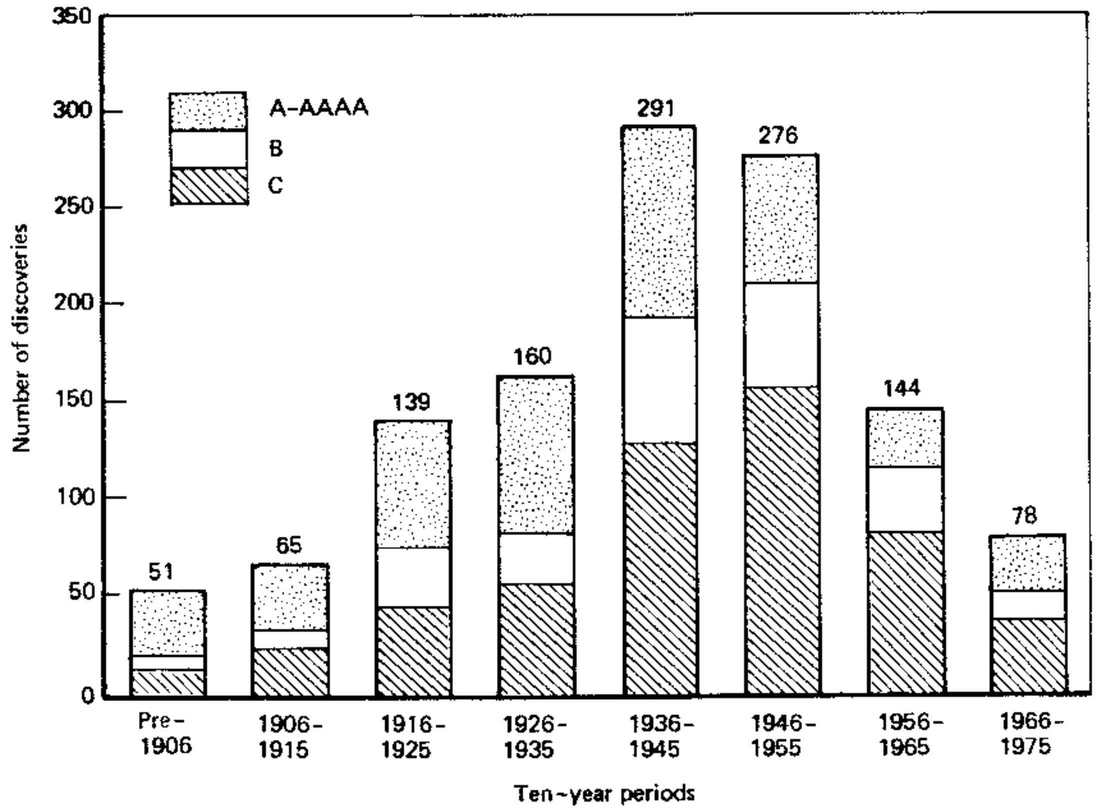

Fig. 4.25—Number of significant oil discoveries by field size category over ten-year periods in the United States (ex-Appalachia)

Oil Discoveries

Because of an early peak in the number of oil discoveries in the Mid-Continent region during the decades around 1920 and 1930, the number of significant discoveries that are predominantly liquids (i.e., those with crude oil and natural gas liquids providing at least two-thirds of total recoverable resources in L&LE) rises more gradually to a peak in the decade around 1940. (See Fig. 4.25 and Table C.a (Summary).) This peak was essentially maintained into the early 1950s. Since that period, the number of significant oil discoveries in the United States has dropped rapidly, declining 45 to 50 percent every decade. Adjustments for future reserve growth in discovered fields are not likely to alter this rapid decline to any appreciable degree.

The peak periods in the number of significant oil discoveries nationwide coincide with most of the peak discovery periods in the major oil-producing regions. The number of significant discoveries in California, the Western Gulf, the Northern Gulf, and the Illinois-Michigan basins peaked in the decade around 1940. The number of significant discoveries in the Rocky Mountains, the Permian Basin, and the Central Gulf peaked in the decade around 1950. In most of these regions, the decline in the number of significant oil discoveries since their peaks has been very pronounced. During the decade around 1940, eight regions had 19 or more significant oil discoveries. During the decade around 1950, eight regions had 15 or more significant oil discoveries. During the decade around 1970, there were only three regions with 10 or more significant discoveries: the Central Gulf (17), Rocky Mountains (16), and Eastern Gulf (12). In the Permian Basin, the Mid-Continent, the Western Gulf, and Northern Gulf regions, four of the six most important oil regions in the country, the number of significant oil discoveries during the decade around 1970 had declined 90 to 95 percent from the number in the peak decade in each region.

The peaks in the number of significant oil discoveries by field size class slightly precede the peaks for all fields by size class. Giant fields peaked from the late 1920s to the late 1930s. Large fields peaked in the late 1930s. Class B fields peaked from the late 1930s to the late 1940s. Class C fields peaked in the decade around 1950. From the decade around 1940, the number of giant oil discoveries has dropped about 50 percent every decade. The number of Class B and C discoveries has declined by a similar rate since the decade around 1950. The number of large oil discoveries declined steadily from the late 1930s to the early 1960s until a temporary and short-lived resurgence during the late 1960s.

Natural Gas Discoveries

The peak in the number of significant natural gas discoveries (fields in which at least two-thirds of the L&LE recoverable resources are natural gas) lags two decades behind the peak in the number of significant oil discoveries. The pattern of natural gas discoveries reflects the high concentration of gas fields in the Western Gulf and Central Gulf regions, the slow development of the natural gas market in the United States before 1950, and the gradual development of deep drilling capabilities. Until the decade around 1940, when large numbers of discoveries were made in the Gulf Coast regions, the number of significant gas discoveries was relatively minor. Since the decade around 1960, natural gas discoveries have constituted the majority of all significant discoveries in the United States. The number of significant natural gas discoveries began to decline about one-third every five-year period after the peak in the late 1950s. The large number of offshore discoveries in the Plio-Pleistocene trend offshore Texas and Louisiana temporarily reversed this pattern during the early 1970s. (See Fig. 4.26 and Table C.b (Summary).)

The high plateau in the number of significant natural gas discoveries reflects a succession of peaks in the number of discoveries in the major gas-producing regions. The number of significant gas discoveries peaked in the Western Gulf and the Northern Gulf regions in the decade around 1940, in the Rocky Mountain region in the decade around 1950, in the Mid-Continent and Central Gulf regions in the decade around 1960, and in the Permian Basin in the decade around 1970. Most of the decline from the decade around 1960 to the decade around 1970 occurred in the Mid-Continent region. Significant natural gas discoveries in the Western Gulf and Central Gulf regions remained at high levels throughout the decade around 1970 because of peaks in the number of offshore gas discoveries.

The discovery patterns of the larger size classes of natural gas fields show no pronounced peaks. Most of the giant natural gas fields were discovered from the late 1920s to the late 1940s. The peak period of large natural gas discoveries spans

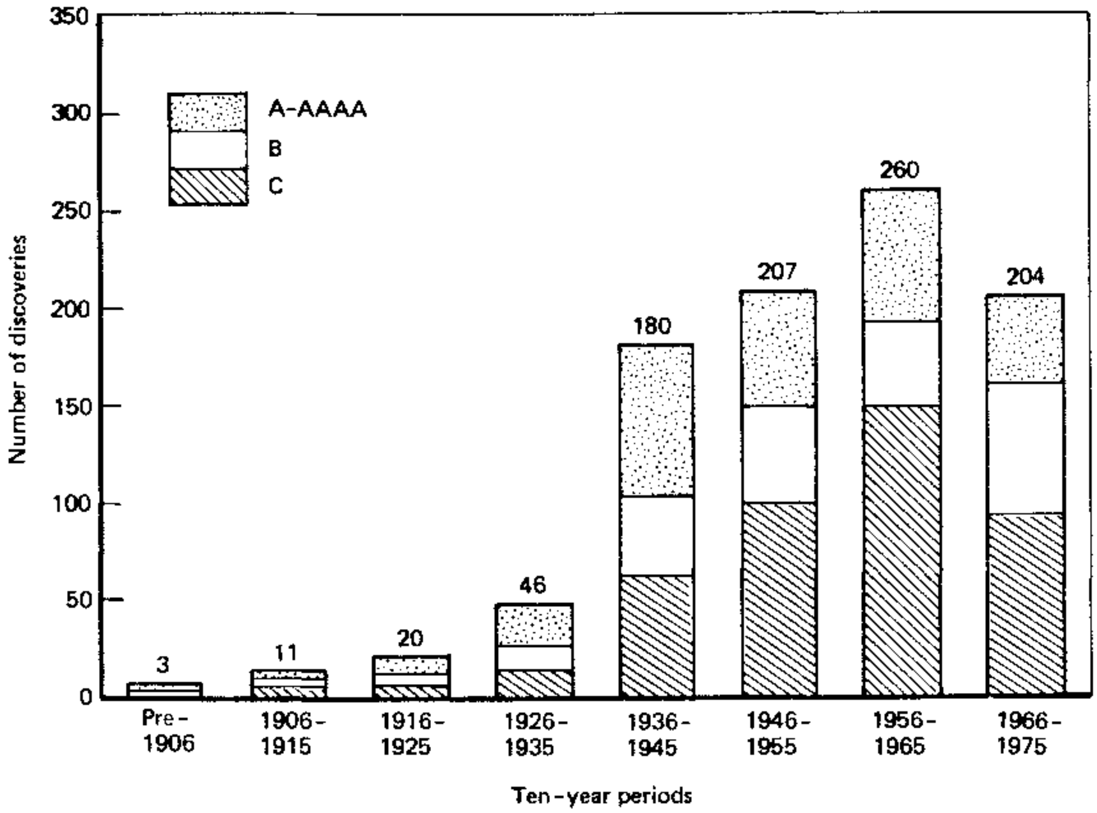

Fig. 4.26—Number of significant gas discoveries by field size category over ten-year periods in the United States (ex-Appalachia)

the quarter-century between the late 1930s and the late 1950s. Class B discoveries did not peak until the early 1970s after a steady plateau throughout the 1940s and 1950s. Class C discoveries peaked in the late 1950s and again in the early 1970s. These prolonged peaks in the number of discoveries stem from the gradual replacement of onshore gas discoveries nationwide by offshore gas discoveries in the Gulf of Mexico.

Composite Oil and Gas Discoveries

The pattern of discoveries before 1926 for significant composite oil and gas fields (those that are neither predominantly petroleum liquids or natural gas) is similar to that of natural gas fields. Both were at low levels. Beginning in the decade around 1930, the pattern closely parallels that of discoveries of significant oil fields, peaking in the decade around 1940, declining modestly in the next decade, followed by a steady, sharp decline to the present. (See Fig. 4.27 and Table C.c (Summary).)

This temporal pattern of discovery reflects the regional concentration of significant composite oil and gas fields in the Central Gulf and Western Gulf regions and, to a lesser extent, in the Mid-Continent and Permian Basin. Western Gulf composite discoveries peaked in the decade around 1940. Central Gulf and Permian Basin

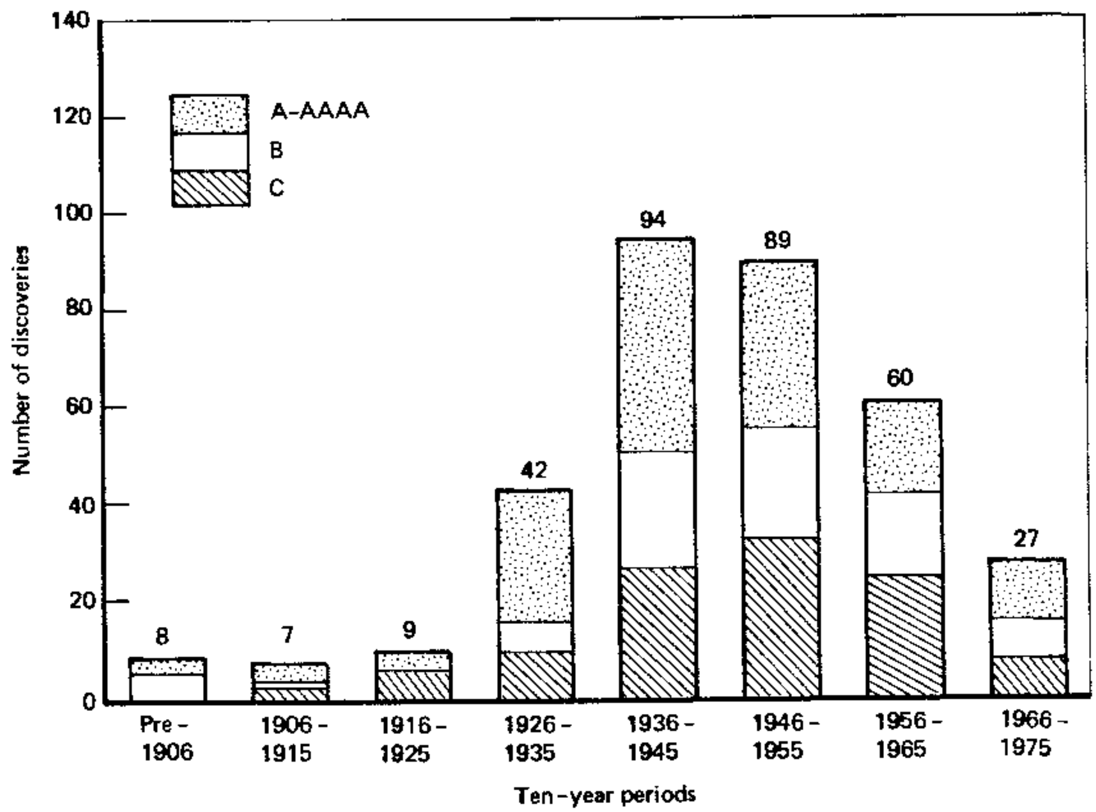

Fig. 4.27—Number of significant composite oil and gas discoveries by field size category over ten-year periods in the United States (ex-Appalachia)

composite discoveries peaked in the decade around 1950. Mid-Continent composite discoveries peaked in the decade around 1960. Only Central Gulf composite discoveries were maintained into the decade around 1970. In the other three regions, the number of significant composite discoveries had declined to negligible levels by this period.

The temporal pattern of significant composite discoveries by field size class is the usual one. The number of giant composite discoveries peaked in the decade around 1930. The number of large composite discoveries peaked in the decade around 1940. Class B and C composite discoveries peaked during the 1950s. There has been only one giant composite discovery since the decade around 1940. The number of large composite discoveries has been declining by more than 40 percent per decade since the decade around 1950. In the late 1960s and early 1970s, the number of Class B and C discoveries was only a third of what it was in the late 1950s.

Amounts Discovered

Because of the concentration of oil resources in a relatively small number of giant and large fields, the peak in the amount of crude oil discovered precedes the

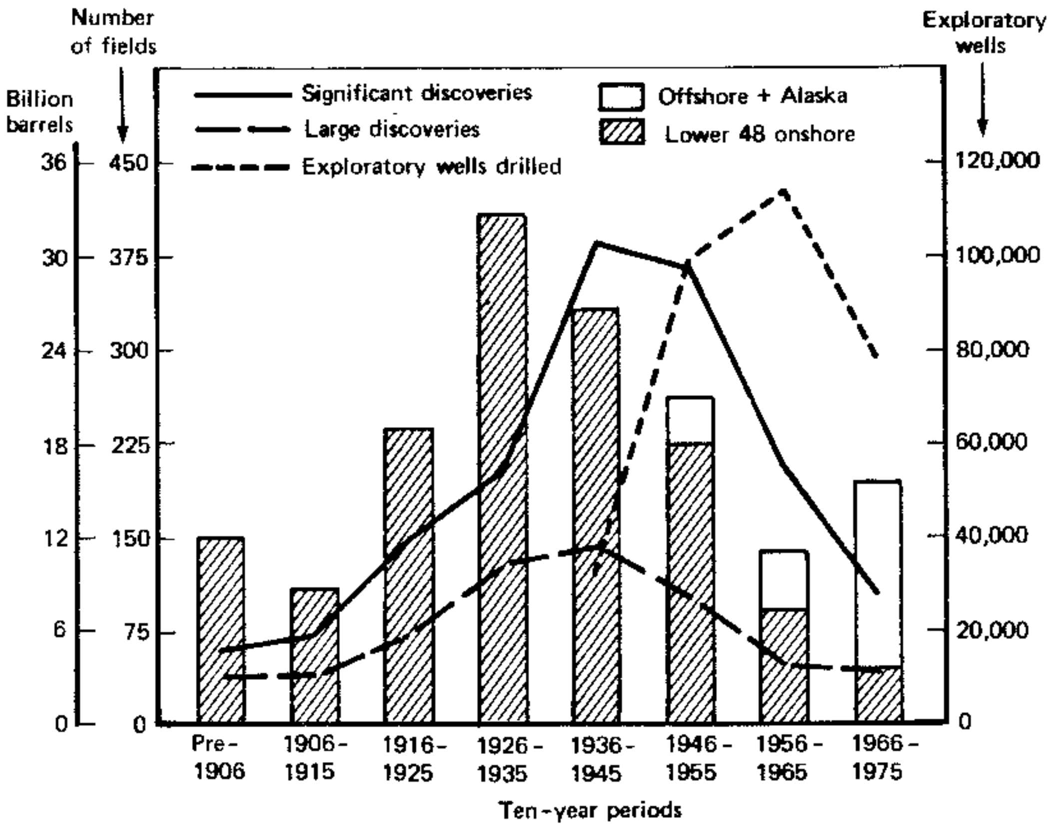

Fig. 4.28—Significant oil and composite discoveries, the amount of crude oil discovered, and exploratory drilling over ten-year periods in the United States (ex-Appalachia)

peak in the number of significant oil and composite oil and gas discoveries. (See Fig. 4.28 and Tables D.1 and E.1.) The total peaked in the decade around 1930, coinciding with the peaks in the amount discovered in the Permian Basin, Mid-Continent, Western Gulf, and Northern Gulf regions. If it had not been for the discovery of the *Prudhoe Bay* field in 1968, the amount discovered would have declined continuously since that peak. Even if one permits current estimates of recoverable oil resources from discoveries of the early 1970s to nearly double from future reserve growth, the amount of crude oil discovered in the early 1970s in the entire United States is the least discovered in any five-year period in this century.

Excluding the amounts discovered offshore and in Alaska, the amount of crude oil discovered in the onshore lower 48 states has declined at an accelerating rate since the peak in the decade around 1930. From this decade to the decade around 1940, it dropped 15 percent, another 34 percent in the decade around 1950, and 59 percent in the decade around 1960. Because of some major discoveries in the Rocky Mountain and Eastern Gulf regions, the decline was only 51 percent from the decade around 1960 to the decade around 1970. Except for the two tails, the pattern by decade in the amount discovered in the onshore lower 48 states is nearly sym-

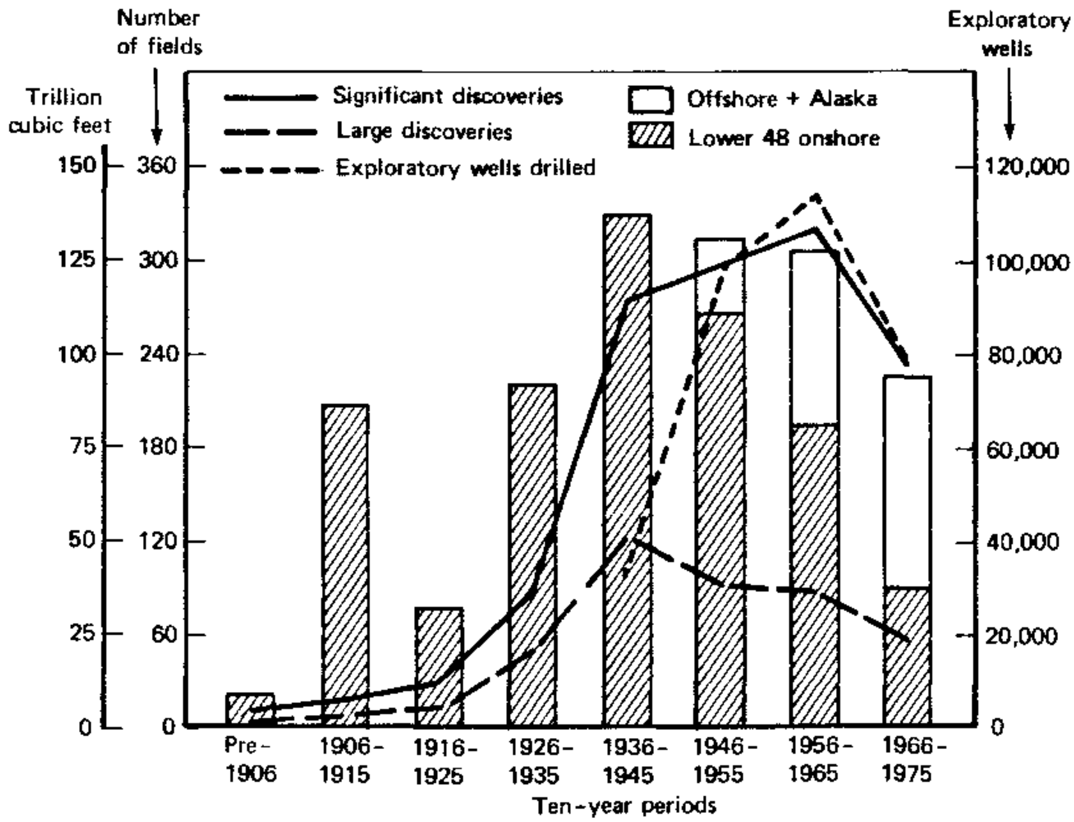

Fig. 4.29 Significant gas and composite discoveries, the amount of natural gas discovered, and exploratory drilling over ten-year periods in the United States (ex-Appalachia)

metric. The amount discovered in the decade around 1950 is nearly equal to that discovered in the decade around 1920. The amount discovered in the decade around 1960 is only slightly below that discovered in the decade around 1910.

The peak in the amount discovered coincides with the peak in the number of giant oil and composite discoveries. The peaks in the total numbers of significant discoveries and of large discoveries follow this peak by a decade. The peak in the number of small significant oil and composite discoveries occurs a decade later. The peak in the number of exploratory wells drilled does not occur until the decade around 1960. The lag between the amount of crude oil discovered and the number of exploratory wells drilled is thus a full three decades.

The amount of natural gas discovered in the United States exhibits a more even temporal distribution than the amount of crude oil discovered. (See Fig. 4.29 and Tables D.2 and E.1.) After an initial peak in the decade around 1910 (the discovery period of *Hugoton-Panhandle*), the amount of natural gas discovered reached its peak in the decade around 1940. In the subsequent two decades, it declined very slowly, if at all, considering the potential for future reserve growth. Only in the decade around 1970 did it finally begin to decline.

The stability over time in the amount discovered has depended primarily on the opening up of new frontiers, particularly the offshore lower 48 and Alaska and, to a lesser extent, areas more than 15,000 feet deep. In the onshore lower 48, which includes the deep discoveries made since 1960, the amount of natural gas discovered has been declining at an increasing rate since its peak in the decade around 1940. It fell 19 percent in the decade around 1950, another 25 percent in the decade around 1960, and 49 percent in the decade around 1970.

The sharp declines in the amount discovered onshore over the past three decades indicate that the correlation among the aggregate amounts discovered, the total number of significant discoveries, and the total number of exploratory wells drilled (as shown in Fig. 4.29) are spurious. Less than 5 percent of the exploratory wells drilled in the decade around 1970 were in Alaska or offshore. Yet more than half of the significant gas and composite discoveries and of the amount of natural gas discovered in this decade were in these two areas. The peak in exploratory drilling in the onshore lower 48 lags behind the peak in the amount of natural gas discovered by two decades. As one would expect, the peak in the amount discovered coincides with the peak in the number of large and giant natural gas and composite discoveries.

Drilling and Discoveries

From the relationships among the number of exploratory wells drilled, the number of significant discoveries, and the amounts of crude oil and natural gas discovered in the onshore lower 48 states, and in the various regions of the United States, it should be clear that historically, and in the aggregate, drilling follows discovery. Although this is the exact opposite of how the relationship between the two is usually conceived, a little reflection should make it apparent that such a relationship is a normal consequence of a typical exploration process. Until major discoveries are made in a province, relatively little drilling occurs, as the risk does not justify a major drilling effort. If substantial amounts of crude oil or natural gas are discovered in a province, these will generally be concentrated in a small number of large and giant fields. Because these fields are either obvious to modern exploration techniques or cover large areas, most will be discovered early, along with much of the petroleum in the province. These discoveries whet the interest of the industry, and a drilling boom begins. But by the time a major effort can be mounted, most of the remaining prospects are the smaller fields. Because of their smaller area and greater subtlety, these fields require a more intensive drilling effort if they are to be found. The peak in drilling effort will either coincide with the peak in the number of smaller significant discoveries or will lag behind it by five to ten years—the time it takes the more optimistic explorationists, promoters, and investors to realize that the promise of the province has already been fulfilled.

This pattern suggests a useful indicator of the stage of exploration, namely, the number of exploratory wells per significant discovery. The common indicator of the relationship between exploratory efforts and exploratory results is the average amount discovered per foot of exploratory drilling. Although this is a very helpful indicator when used properly, that is, dynamically, it is all too often used statically to argue that, with more drilling, declines in the amount discovered can be overcome. The plausibility of this argument is severely undercut if we take the number of wells per significant discovery as an indicator. As the number of significant discoveries declines, the number of wells per significant discovery soars, eventually reaching infinity. Therefore, this indicator clearly shows that once the good prospects that can be conceived in a province have been tested, additional drilling cannot be expected to discover substantial amounts of petroleum.

Table 4.1 shows the number of exploratory wells per significant discovery in the United States (ex-Appalachia) by region over five-year periods from 1936 to 1975. The typical pattern in each region is a steady increase during this period, generally approaching one order of magnitude. This change is so great that it overwhelms any inadequacies in the drilling data, particularly a potential underreporting of up to 25 percent in the total number of exploratory wells in the late 1930s. Except for the early 1970s, the number of exploratory wells per significant discovery in the United States as a whole increases steadily throughout the period. The decline in the index from the late 1960s to the early 1970s is entirely the result of the high exploration efficiency achieved in the offshore Gulf of Mexico during the exploration of the Plio-Pleistocene trend.

The numbers in Table 4.1, when compared with regional trends in the amounts of petroleum discovered and in the number of significant discoveries, suggest the following rules of thumb: As long as the number of wells per significant discovery is less than 100, both the amounts discovered and the number of significant discoveries are likely to be substantial. When the number of wells per significant discovery is between 100 and 500 in a province, the province is either small to begin with or is on the decline. Once this index exceeds 500, the remaining prospects are likely to be highly marginal, unless there are a large number of Class D prospects (e.g., as in the Denver and Powder River basins in the decade around 1970 and in the Michigan Basin in the early 1970s). These numbers hold for all exploratory wells (new field wildcats, new pool wildcats, and extensions). If only new field wildcats are used, the numbers should be halved to less than 50, 50 to 250, and more than 250, respectively.

Recent Giant and Large Discoveries

Large and giant fields contain approximately 80 percent of all the conventional petroleum discovered in the United States before 1976. Their importance to total recovery justifies a closer look at recent discovery patterns of large and giant fields. Figure 4.30 shows the number of large and giant oil and gas discoveries in the United States by location over five-year periods during the third quarter of the century. The number of discoveries is broken down into two primary categories: those in frontier areas and those in mature areas. The frontier areas are defined as of 1950. Frontier discoveries include (1) all in Alaska, onshore and offshore; (2) all in the offshore lower 48, specifically California and the Gulf of Mexico; (3) all in the Rocky Mountain region; and (4) all with major reservoirs more than 15,000 feet deep in the mature regions. Mature area discoveries are defined as all those with reservoirs less than 15,000 feet in the onshore lower 48 excluding the Rocky Mountain region. They are divided into three categories: (1) all discoveries with reservoirs 10,000 to 15,000 feet deep, (2) all stratigraphically trapped discoveries with reservoirs less than 10,000 feet deep, and (3) all other discoveries.

During the 1950s, most of the large and giant discoveries in the United States

Table 4.1

THE NUMBER OF EXPLORATORY WELLS PER SIGNIFICANT DISCOVERY IN THE UNITED STATES (EX-APPALACHIA) BY REGION, 1936-1975

Region	1936-1940	1941-1945	1946-1950	1951-1955	1956-1960	1961-1965	1966-1970	1971-1975
1. Alaska	--	--	--	--	16	19	27	66
2. California	36	67	177	435	219	165	144	263
3. Rocky Mountains	74	44	82	181	305	386	547	918
4. Permian Basin	34	43	54	100	174	196	156	159
5. North Central Texas	128	203	366	571	7938	1779	∞	1419
6. Mid-Continent	79	135	341	345	258	269	887	703
7. Western Gulf	35	57	115	178	271	283	373	124
Onshore	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	640	446
Offshore	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	29	13
8. Central Gulf	6	12	17	31	49	62	103	37
Onshore	N.A.	N.A.	N.A.	N.A.	N.A.	331	229	341
Offshore	N.A.	N.A.	N.A.	N.A.	N.A.	13	47	15
9. Northern Gulf	37	52	118	263	242	365	980	446
10. Eastern Gulf	104	35	178	159	137	297	148	186
11. Illinois-Michigan	82	263	2360	3814	∞	∞	∞	1370
United States (Ex-Appalachia)	41	73	123	200	242	250	324	190

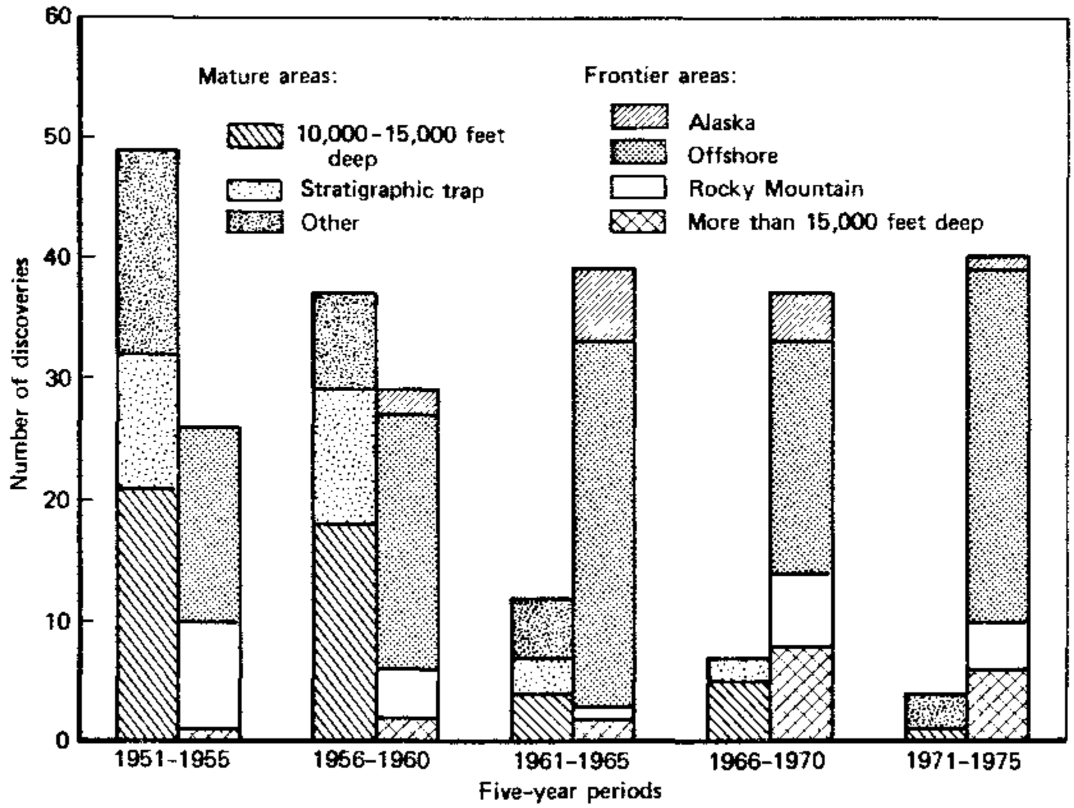

Fig. 4.30—Number of large and giant oil and gas field discoveries in the mature and frontier areas of the United States by type, 1951-1975

were occurring in the mature areas, primarily of fields with reservoirs between 10,000 and 15,000 feet deep. During the 1960s, large and giant discoveries in the mature areas fell drastically, almost disappearing by the early 1970s. Of the four made between 1971 and 1975, one—*Yowlumne* in the San Joaquin Basin—is a subtle combination oil and gas trap 11,000 feet deep; the other three could be considered semi-frontier discoveries: *Laredo* and *J. C. Martin* in a corner of Texas R.R.C. District 4 just across the Rio Grande from Mexico and *Tule Elk* straddling the boundary of the Elk Hills Petroleum Reserve where no exploration had occurred for decades. The decline in large discoveries in the mature areas began with other discoveries in the late 1950s, but the drop-off in deeper and stratigraphically trapped discoveries lagged behind by only five years.

Discoveries of large and giant fields in the frontier areas became predominant in the early 1960s after a steady rise during the 1950s. Since then, they have averaged about seven or eight per year. Among the various frontier areas, the offshore has clearly been most important, with more than double the number of large and giant discoveries in the other three areas combined. Although the number of large and giant discoveries in Alaska has been limited, the amount discovered has been very substantial because of the *Prudhoe Bay* discovery. Large and giant discoveries in the Rocky Mountain region and in deep basins around the country have not been significant either in the number or the amount. Our preliminary analysis of 1976-1980 discoveries indicates that large and giant discoveries in frontier regions could decline by more than 50 percent from the early to the late 1970s. Very deep large discoveries, primarily in the Tuscaloosa trend, apparently remained about the same level as they were in the early 1970s. Large discoveries in the Rocky Mountain region, primarily in the Overthrust Belt, have increased slightly. Large discoveries in Alaska have been small in number, primarily because of drilling constraints. Large and giant offshore discoveries, however, have dropped drastically from 29 in the early 1970s to less than one-third that number in the late 1970s. Our overview of 1976-1980 discoveries offshore California, the Gulf of Mexico, and the Atlantic indicates at least five but no more than ten large discoveries offshore since 1975.

SUMMARY

Although the first significant discovery in the United States occurred in 1862, both the number of discoveries and the amounts of crude oil and natural gas discovered did not peak for another 65 to 100 years. Discoveries reached their peak only after exploration had extended throughout the country, geological concepts and exploration and drilling technology had developed sufficiently to identify and reach most prospects, and petroleum markets had grown substantially. The amount of crude oil discovered peaked in the decade from 1926 to 1935, coinciding with the peak in the number of giant oil discoveries. Since that peak, the amount discovered in the onshore lower 48 states has been declining at an accelerating rate. The number of significant oil discoveries has dropped drastically since its peak about 1950, almost disappearing in most of the important oil-producing regions. The amount of natural gas discovered peaked in the decade around 1940 and declined slowly thereafter until 1960 as the natural gas market expanded and several new frontiers, primarily the offshore Gulf of Mexico, were opened to exploration. Except for a major flurry of activity in the offshore Gulf of Mexico in the early 1970s, the number of significant natural gas discoveries has declined steadily since its peak in the late 1950s. The average size of significant oil and gas discoveries has also been declining for several decades, as giant and large discoveries have nearly ceased in the mature areas of the country.

These discovery patterns suggest that the U.S. petroleum industry is gradually running out of ideas as to where oil and gas may still be found. This is not because of a lack of creativity and imagination, but because of the increasing exhaustion of the geological possibilities region by region. Increased drilling efforts are unlikely to reverse this trend. Historically, intensive drilling activity has signaled a sharp decline in remaining possibilities, lagging behind the peaks in the amount discovered and the number of significant discoveries by several years, if not decades.

V. DISCOVERY PATTERNS AND RESOURCE ASSESSMENT

INTRODUCTION

The historical data presented and summarized in the preceding two sections do not suggest a promising future for U.S. petroleum exploration. Nearly all of the conventional petroleum (both liquids and natural gas) discovered to date in the United States has been found in significant fields. More than 80 percent has been found in less than 900 giant and large fields (fields that contained at least 50 million barrels' L&LE). The number of discoveries of these fields, particularly of the larger fields, peaked several decades ago. The amount of crude oil discovered peaked 50 years ago. The amount of natural gas discovered peaked 40 years ago. Since those peaks, both the number of discoveries and the amount discovered have been declining steadily nationwide, particularly onshore in the lower 48 states. None of the many advances in geological knowledge or in exploration technology made during the past 40 years succeeded in preventing these declines, although they clearly precluded a more rapid drop-off.

These patterns have been apparent for at least two decades. As a counter to the pessimistic prognosis suggested by the trends in the number of significant discoveries and in the amounts discovered, four hypotheses about where substantial amounts of petroleum may still be found in the United States have been propounded. These hypotheses contend that substantial amounts of petroleum remain to be found in the United States (1) at depths below 15,000 feet, (2) in subtle stratigraphic traps, (3) in very small fields, and (4) in frontier regions, such as Alaska, offshore areas, and onshore areas that are geologically complex. These four general possibilities exhaust the scientifically plausible arguments for substantial future petroleum discoveries in the nation. Because they are exhaustive, we will summarize and review these general ideas about where petroleum remains to be found as an appropriate introduction to our assessment of ultimately recoverable conventional petroleum resources of the United States.

Deep Discoveries

The argument that substantial amounts of petroleum remain to be discovered in sedimentary rocks deeper than 15,000 feet acknowledges that nearly all of the shallower prospective sedimentary regions onshore in the lower 48 states have been extensively explored. Hence, few large or giant discoveries can be expected to occur in these regions in the future. However, because of the high costs of deep drilling and the low prices that prevailed before the mid-1970s, relatively few exporatory wells have been drilled to date deeper than 15,000 feet. The few that were drilled scored major successes in the Delaware Basin, the Anadarko Basin, the Gulf Coast Basin, and the Mid-Gulf Coast Basin. Similar successes in these and other provinces are assumed to be possible with additional drilling.

This hypothesis is qualitatively correct. However, the potential of deep sedimentary rocks is subject to several stringent conditions that place major quantitative constraints on the amounts of petroleum that may exist at depths greater than

15,000 feet. Because increasing temperatures at depth cause thermal cracking, converting liquids to gases, substantial amounts of crude oil and natural gas liquids are likely to be preserved between 15,000 and 20,000 feet only in basins with low thermal gradients or with a recent sedimentary fill. Elemental sulfur, sulfate ions, and polysulfides are common at depths below 15,000 feet, and they readily convert methane to carbon dioxide at the temperatures encountered at those depths, possibly creating a floor for the occurrence of natural gas as well. Reservoir porosity may be lacking in many areas because of increasing compaction and cementation with depth of burial. Porosity in carbonate reservoirs can occur at great depths only with preservation of secondary porosity or, more commonly, because of fracturing associated with structural uplift. Porosity in sandstones generally decreases linearly with depth of burial, unless compaction and cementation are inhibited by early migration, overpressure, the development of secondary porosity, or the precipitation of chloride coatings on the sand grains.

The area covered by deep sedimentary rocks is a relatively small fraction of the total prospective sedimentary area of the United States. Onshore in the lower 48 states, sedimentary rocks appreciably thicker than 15,000 feet are found in only 15 provinces, including 9 of the major ones. Only in the Gulf Coast and Appalachian areas are large volumes of sedimentary rocks found at these depths. The relatively small area of the deep basins and the general requirement of geologic structure to provide adequate reservoir and trapping conditions at these depths suggest that exploratory plays in any deep basin are not likely to exceed more than a few dozen significant fields. Despite the relatively small number of deep exploratory wells drilled, most of the potentially productive significant structures in several of the deep basins of the United States have already been tested, particularly in the Delaware Basin, Val Verde Basin, and Mid-Gulf Coast. Thus, although we believe that a substantial number of significant deep discoveries remain to be made in the United States, their total contribution to U.S. petroleum resources will be only a small fraction of the overall total.

Stratigraphic Traps

The second hypothesis is that substantial amounts of petroleum remain to be found in stratigraphic traps. Advocates of this position argue that both the number of significant discoveries and the amounts of petroleum discovered have declined because explorationists have continued to look only for structural traps. Because most structures, except for deep or complex ones, were located decades ago, the observed declines in discoveries were inevitable without a redirection of exploratory effort. With a thorough, systematic search for subtle stratigraphic traps, proponents of this theory assert that many discoveries can still be made.

This hypothesis is only partially correct. During the past three decades, several major exploration plays have focused entirely on stratigraphic traps in the Anadarko, Permian, Denver, and Powder River basins and in much of the rest of the Rocky Mountain region. The peak in the number of significant discoveries in subtle stratigraphic traps may have already occurred during the 1950s and 1960s when these plays were most intense. Moreover, it is questionable whether large numbers of significant subtle stratigraphic traps remain to be discovered. The ones found to date are highly concentrated in the stable interior provinces of the United States between the Rocky Mountains and the Appalachians. Provinces elsewhere, such as the Gulf Coast or the California basins, typically have so many structural trapping possibilities with effective migration routes from the likely source rocks that it is improbable that a large number of pure stratigraphic traps could exist in them.

Generally, subtle stratigraphic traps have single, thin reservoirs; thus, if they are to constitute large fields, they must cover large areas. The drilling density and depths of penetration to date in most onshore provinces of the United States, particularly the shallower interior provinces, make it unlikely that more than a few fields covering more than 10,000 acres (roughly half a township) could have been missed. Moreover, preservation of petroleum in very large stratigraphic traps is highly problematic. Because such traps require huge gathering areas, they are usually located on the flanks of basins. As such, they are vulnerable to breaching, flushing, bacterial attack, and other causes of degradation or dissipation.[1] We consider it probable that hundreds, if not thousands, of subtle stratigraphic traps remain to be discovered in the United States. But because of the number and nature of those already discovered and the existing drilling density in most basins, we believe that nearly all of these discoveries will be only Class D and E fields, covering 100 to 2000 acres each.

Very Small Fields

The third hypothesis is that substantial amounts of petroleum remain to be discovered in very small fields. Advocates of this position agree that discoveries of significant fields are declining, particularly in the onshore lower 48 states. But they argue that because of past economics, the search for petroleum has essentially ignored Class D and E fields. With an intensive exploration effort, many very small fields could be discovered, sizably augmenting known U.S. petroleum resources.

This hypothesis is only partially correct and faces substantial quantitative limitations as well. About 20,000 very small fields have already been discovered in the United States. In some provinces, major exploration plays have occurred during the past several decades that were essentially directed at finding large numbers of Class D fields, for example, in the central Kansas and Oklahoma provinces, on the Bend Arch, and in the Denver, Michigan, Powder River, and Williston basins. Moreover, both the historic record and a modest amount of geologic theorizing strongly suggest that very small fields are likely to be proportionately important only in some provinces of the United States, namely, those provinces in the stable interior with thin sedimentary sections, thin reservoirs, and minor structural deformation. In those provinces with thick sedimentary sections, thick reservoirs, and moderate to extensive structural development, very small fields contribute an insignificant amount to the total resource.

The argument that large numbers of very small fields remain to be discovered in the provinces in which they are liable to occur is, moreover, highly theoretical. It is based on statistical inferences from the number and size distribution of fields that have already been discovered. These inferences depend on the assumptions made about both the characteristics of the exploratory process (i.e., the means by

[1] Most of the tar sand or heavy oil deposits of the world were found in such circumstances. G. J. Demaison, "Tar Sands and Supergiant Oil Fields," *The American Association of Petroleum Geologists Bulletin*, Vol. 61, No. 11, November 1977, pp. 1950-1961.

which the known number of fields were discovered or sampled) and the eventual distribution of fields in the province. Depending on which assumptions are used, one can infer possibilities ranging from a relatively small number to a very large number of very small fields remaining to be discovered. The optimistic assumption lacks a geologic rationale and is increasingly subject to criticism on statistical grounds.

Although thousands of very small fields have been discovered in the United States, they still provide only a small proportion of total U.S. petroleum resources. The two largest fields discovered to date in the United States, *Hugoton-Panhandle* and *Prudhoe Bay*, contain 45 percent more petroleum in liquids and liquid equivalents than has been found in all of the very small (Class D and E) fields. This indicates another key point about very small fields: A very large number have to be discovered to provide even a modest amount of petroleum resources. If we find 5000 fields with 200,000 barrels each, we have still found only a billion barrels of oil.

We do not doubt that there are still several thousand very small fields remaining to be discovered. However, because most will be Class E fields (less than 1 million barrels' L&LE), we believe the amount remaining to be discovered in very small fields is unlikely to exceed a few billion barrels' L&LE.

New Frontiers

The fourth hypothesis is that there are substantial amounts of petroleum remaining to be discovered in frontier areas. This argument acknowledges that the observed declines in both the number of significant discoveries and the amount discovered in the onshore lower 48 states are what one would expect to occur in a heavily explored region. However, this decline has not yet occurred in Alaska, in the offshore lower 48 states, or in onshore areas of complex geology such as the Overthrust Belt, none of which has yet been extensively explored. These frontier regions offer the promise of many giant and large discoveries and correspondingly the potential for substantial additions to known U.S. petroleum resources.

We agree that the frontier regions of the United States offer the greatest potential for major discoveries. As Fig. 4.30 indicated, most of the recent large and giant discoveries in the United States have come from applying old ideas in new areas, not from new ideas in old areas. Nevertheless, this enthusiasm needs to be qualified by several key considerations. Some of our frontier regions, particularly the Gulf of Mexico out to water depths of 200 meters, should now be classed as mature areas, with most of the major prospects having been tested. Furthermore, the petroleum industry has not been successful in opening up new major provinces. Only two of the 31 provinces in the United States with known recoverable reserves greater than 1 billion barrels' L&LE have been opened up (i.e., seen their first significant discovery) since 1932. Both of these two provinces (the Cook Inlet and the Arctic Slope) were recognized as highly prospective decades before their first significant discovery.

Other frontier provinces that have been tested have proved to be expensive disappointments, for example, the Gulf of Alaska, the Outer Banks of California, the eastern Gulf of Mexico, the Southeast Georgia Embayment, and the Baltimore Canyon. The relatively small number of exploratory wells drilled in each of these areas was sufficient to establish that each suffered from one or more fundamental deficiencies, principally a lack of either rich, thermally mature source rocks or good reservoir rocks or inadequate protection and preservation. There is no guarantee that the remaining frontier provinces will not suffer similar shortcomings. Some unexplored to lightly explored provinces, however, do have high promise, specifically the Arctic Slope and the adjacent offshore Beaufort Sea, the offshore Ventura Basin, the deepwater Gulf of Mexico, the Overthrust Belt, and possibly the Bering Sea and Chukchi Sea provinces.

As general propositions, each of these four hypotheses about where petroleum remains to be discovered makes a valid point. Each, however, is also subject to quantitative limitations that in a few cases are severe. In the remainder of this section, we will examine these ideas in greater detail within the context of our overall assessment of conventional U.S. petroleum resources.

In our assessment, we conclude that most of the conventional petroleum that will ultimately be produced in the United States has already been discovered and made recoverable. We estimate that ultimate recovery of conventional petroleum liquids (crude oil and natural gas liquids) will most likely be between 210 and 285 billion barrels, as compared with a known recovery of 175 billion barrels. Ultimate recovery of conventional natural gas will probably be between 920 and 1090 trillion cubic feet, as compared with a known recovery of 750 trillion cubic feet. Most of the increase in crude oil will come from reserve growth in known fields, not from new discoveries. Only the frontier areas—primarily Alaska, and secondarily the Rocky Mountains, California offshore, and Central Gulf offshore—have any realistic promise of substantial oil discoveries. Most of the increase in natural gas and natural gas liquids will come from new discoveries. Both the frontier areas (Alaska, Rocky Mountains, and Gulf Coast offshore) and deep areas (Central Gulf onshore and Mid-Continent) offer promise of substantial future discoveries of natural gas.

METHODS AND DEFINITIONS

This section summarizes our assessment of the ultimate conventional petroleum resources of the United States. We provide individual assessments for each region and then combine these assessments into a concluding national summary. The area covered by the assessment is all of the territory of the United States, including the adjacent offshore areas out to a water depth of 1000 meters. The assessment thus includes all of the continental shelf and much of the continental slope.

We limited the assessment to conventional petroleum resources: crude oil, natural gas, and natural gas liquids. *Crude oil* includes heavy oil from currently or historically producing fields, but excludes heavy oil from discovered fields that have yet to produce. The assessment excludes petroleum liquids produced from tar sands or oil shale. *Natural gas* includes natural gas from currently producing fields with low permeability ("tight" sandstone) reservoirs or with Devonian shale reservoirs, but otherwise excludes natural gas from these two nonconventional sources. The assessment excludes natural gas occluded in coal or contained in geopressured brine reservoirs. The assessment includes those conventional petroleum resources that can be discovered and produced up to a resource cost of $40 per barrel (or per barrel equivalent) in constant 1980 dollars. These resource costs exclude all transfer payments such as lease costs, royalties, and taxes.

Each regional assessment and the national summary assessment provide a single estimate of known recovery and a range of estimates for reserve growth in known fields and recoverable amounts in fields that are yet to be discovered. The arithmetic summation of these three quantities provides a range of estimates for ultimate recovery of crude oil and natural gas in each region and in the nation as a whole. Known recovery is the sum of cumulative production and demonstrated reserves (proved reserves plus indicated additions to reserves) in all fields discovered before 1976, as estimated in 1979. Reserve growth includes all petroleum added to known recovery after 1978 in all fields discovered before 1976. This includes reserves added as a result of development of previously discovered but undeveloped fields, extensions to known fields, new pool discoveries in known fields, more intensive development of existing fields (e.g., infill drilling, well stimulation, and a shift from peripheral to pattern water floods), and enhanced oil recovery. The range of estimates for undiscovered petroleum includes reserve additions from all fields discovered after 1975.

Because of the inherent uncertainties in any resource assessment, we provide a range of estimates for both reserve growth and the undiscovered potential. Our current knowledge about the petroleum potential of any region is not sufficient to justify any single estimate for that region. The three values provided in each estimate are, respectively, the 90-percent, 50-percent, and 10-percent values on the subjective cumulative probability distributions we developed for each region. These levels express our subjective cumulative probabilities that ultimate reserve growth or future discoveries will be "greater than" the amount indicated. A tight spread among the three values indicates a very narrow range in the possibilities (a steep curve when graphed). A wide spread indicates a substantial range of uncertainty (a flatter curve when graphed). The range of each distribution and its corresponding shape thus provide useful indicators of our judgments concerning the current degree of knowledge about the resource base. As exploration and development proceed, the ranges shown here should be progressively reduced. However, we do not exclude the possibility that major surprises in one or two regions may increase our estimates of undiscovered resources.

As is true of any resource assessment, our conclusions are ultimately a matter of judgment. We have attempted to make our judgments both informed and reasoned. In each regional discussion, we have tried to state in sufficient detail the more important facts and reasoning from which these judgments were made to enable the reader to reach similar conclusions with some level of confidence, or, at least, to know why we reached the conclusions that we did.

Reserve Growth

Estimating reserve growth, which incorporates several disparate elements, is a complex problem for which no single method is wholly appropriate. In particular, because of the radical changes that have occurred in petroleum markets and economics since 1973, we believe that the use of historic appreciation factors to estimate future reserve growth is no longer very useful for this task. Most of the potential reserve growth has little historic precedent. We thus used a number of methods, our choice of methods depending on the particular component of reserve growth that we were estimating.

We estimated the amount of crude oil and natural gas in fields that were discovered before 1976, but that have not been developed or have only been partially developed, using available information on reservoir volume, planned and potential production rates, and production practices. Most of these fields are either in the offshore Gulf of Mexico or offshore California. In estimating reserve growth from extensions to known pools in known fields, we concentrated primarily on potential extensions to (1) post-1965 significant discoveries and (2) pools whose historic boundaries have been determined more by economic than by geologic limitations (e.g., the gas fields of the San Juan Basin). For the first, we used historic appreciation factors adjusted by our knowledge of field development to date. For the second, we used available subsurface geologic information to estimate potential geologic limits. Because historical data indicate that recent new pool discoveries have been heavily concentrated in the highly faulted Gulf Coast regions or in areas of large numbers of multiple reservoirs such as the Mid-Continent, our estimates of future new pool discoveries are concentrated in these regions. In most other regions, both the horizontal and vertical limits of significant fields generally appear to be well established. To estimate future new pool discoveries, we primarily used extrapolations of adjusted historic new pool discoveries and secondarily considered the potential sizes of deep new pool discoveries.

To estimate reserve growth from intensive development and enhanced oil recovery, we examined the current state of development in all Class AA or larger fields (which contain two-thirds to three-fourths of known recovery), the basic reservoir and fluid characteristics in each of these fields, and the general economic and technical feasibility of various patterns of intensive development and of known and potential methods of enhanced oil recovery. For the large oil fields, we also considered their residual oil saturations after secondary recovery and the enhanced oil recovery method that appeared most promising in each field. We then used these in conjunction with field operator interview data, recent studies on enhanced oil recovery potential nationwide, and current reports on the degree of success in enhanced oil recovery projects to develop estimates by field of future reserve growth. We next extrapolated these results to other fields in each region, generally by considering all other fields in individual plays of similar reservoir and fluid characteristics. The studies of national enhanced oil recovery potential[2] were particularly useful as informed estimates of the middle range of enhanced oil recovery possibilities.

Most of future reserve growth nationwide is estimated to come from new pool discoveries (gas), more intensive development (oil and gas), and enhanced oil recovery (oil). The relative importance of each component of reserve growth is indicated in each regional discussion. In our discussions, we also state the changes we estimate for the recovery factor of crude oil. Both statistical independence (particularly in new pool discoveries) and statistical dependence (particularly in intensive devel-

[2] The three major studies that we used were Lewin and Associates, Inc., *The Potential and Economics of Enhanced Oil Recovery*, Washington, D.C., April 1976; National Petroleum Council, *Enhanced Oil Recovery*, Washington, D.C., December 1976; and Office of Technology Assessment, *Enhanced Oil Recovery Potential in the United States*, Washington, D.C., January 1978. We also had access to the data base used by the Office of Technology Assessment in making their estimates.

opment and enhanced oil recovery) are present in our estimates. Because the latter strongly predominate, the nationwide estimates we show are the arithmetic summations of the regional estimates.

Each of the three estimates of reserve growth shown has roughly the same conceptual meaning across regions. The estimates at the 90-percent probability level indicate a conservative rate of new development, extensions, and new pool discoveries, moderate success from a moderate rate of additional intensive development, and a conservative assessment of the potential of the known and less costly methods of enhanced oil recovery. The estimates at the 50-percent probability level indicate a moderate rate of new development, extensions, and new pool discoveries, moderate success from a high rate of additional intensive development, and a moderate assessment of the potential of all the known methods of enhanced oil recovery. The estimates at the 10-percent probability level indicate a high rate of new development, extensions, and new pool discoveries, high success from a high rate of additional intensive development, and a high assessment of the potential of both known and eventual methods of enhanced oil recovery. Our estimates of reserve growth at the lower probability levels thus explicitly incorporate amounts that will only be added to existing reserves if innovations in stimulation and recovery technology occur.

Our estimates of reserve growth, particularly in the lower half of the probability levels, are sensitive to the economic limits we assumed for production costs. A higher resource cost limit supports higher estimates, principally for reserve growth from more intensive development and enhanced oil recovery. The extent of the possible increase is highly speculative, primarily because of the total lack of historic experience for assessing the impetus that a substantially higher cost limit would give to recovery efforts and technology, given known geologic and engineering constraints on recovery.

New Discoveries

Our approach to estimating as yet undiscovered amounts of petroleum depended on whether we were estimating undiscovered amounts in regions or provinces that have been explored to a reasonable degree or in regions or provinces in which little or no exploratory drilling has occurred. We limit the latter (the true frontier provinces) to most of the Alaskan provinces, the Atlantic offshore provinces, the Pacific offshore provinces north of the Ventura Basin, and the areas of the remaining offshore provinces with water depths greater than 200 meters.

Three key presuppositions underlie our approach to estimating the undiscovered potential of provinces that have been explored to a reasonable degree. The first is that *petroleum exploration is an intentional process.* Serious petroleum exploration, as opposed to some of the dubious promotional ventures that masquerade under the same label, is directed by specific ideas as to where petroleum may be found. It is not random. Moreover, it is nonrandom both in intent and in result.

In the language of our second presupposition, *petroleum exploration is an efficient process.* The historic efficiency of petroleum exploration is, however, a constrained efficiency. At any given time, petroleum explorationists are efficient in locating oil and gas fields within the limits of existing geological concepts, existing exploratory and drilling technology, and existing economics, provided that exploration within any particular geographic area is not legally constrained. By an efficient process, we mean that if oil and gas fields exist and fall within the constraints that apply at any given time, the existence of those fields will be hypothesized, the potential prospects will be drilled within a few years, and exploratory drilling of these prospects will enjoy high success rates.

Our third presupposition is that *petroleum exploration is a highly advanced process*. Our knowledge of petroleum geology is such that all trap types containing appreciable amounts of petroleum have been known for decades. The state of geological knowledge, exploration technology, and drilling technology is sufficiently advanced that nearly all possible traps can now be located and reached with the drill bit. With current domestic market conditions, everything that can be found can also be produced and sold. Current prices are high enough to pursue all major prospects. This does not mean that further developments will not occur in our understanding and technology. It only means that past developments were sufficient to remove the major conceptual and technological constraints on earlier exploration efforts and bring recent exploration efforts to a high level of unconstrained efficiency.

These three presuppositions are supported by the historical patterns of discovery as outlined in Sec. IV. They also provide an efficient, powerful means for using those patterns as a guide to predicting further discoveries. In using them to predict the undiscovered potential of the explored regions, we first reviewed and considered possible extrapolations of the discovery patterns of significant fields by size and type over time (App. C) and the trends in the amounts of crude oil and natural gas over time (App. D). Our review incorporated both the aggregate trends and a disaggregative analysis of the various plays comprising the aggregate patterns and the developments in understanding, technology, and economics that made each play possible. Using this historical review of the successful exploratory hypotheses that had been pursued in each region, we then estimated the likely range of amounts remaining to be discovered in the known producing plays in the light of drilling densities and depths of penetration, past legal or economic restrictions on exploration activity, possible geologic complexity or subtlety, and available geological information on source rock potential, migration paths, extent of reservoir rock, trapping mechanisms, and preservation conditions associated with each play.

We next assessed the possibilities for amounts remaining to be discovered in new exploratory plays or in plays that were only beginning in the mid-1970s. This involved identifying undrilled or lightly drilled formations with reservoir potential; possible source rocks for these reservoirs and the likely type of hydrocarbons from each; the number, type, and volume of potential traps; the potential areal extent of new plays; and notable exploratory failures within each region or province. Because there can be reasonable doubts as to any petroleum occurrence within a possible new play, all major new play estimates were risked according to the available information on the probability of the existence of adequate mature source rocks, reservoirs, traps, and preservation over time. The key factors in each of these assessment processes are summarized in the regional discussions. For all of the mature regions, we also state our range of estimates of the number of significant fields remaining to be discovered. Appendix F lists these estimates at the 90-percent, 50-percent, and 10-percent probability levels.

Our procedures for estimating the potential of the true frontier regions depended on the amount of information available to us. For some areas, such as the deepwater Central Gulf offshore, the deepwater Ventura Basin, and most of the onshore Arctic Slope and Arctic Foothills, sufficient information was available to estimate a range of the number and size distribution of potential prospects and the likelihood that they might contain petroleum. For other areas and provinces, we focused primarily on the fragmentary information available on basic geologic parameters such as source rock volume, quality, and maturation; the volume and quality of potential reservoir rocks; the types and sizes of traps; and conditions of preservation. We checked the most recent resource estimates available for these areas prepared by geologists using proprietary data unavailable to us against both these factors and the most likely province analogs and adjusted them accordingly. In particular, for our estimates of the petroleum potential of Alaska, we relied heavily on the descriptions and evaluations in the recent Open-File Reports of the U.S. Geological Survey (as listed in the Bibliography). For these areas, our estimates are thus largely derived from those of other estimators. Like the other estimates, the key factors in our assessments are summarized in the discussion of the petroleum resource potential of each region.

Our estimates of the undiscovered potential of a specific region or province are independent of our estimates of the potential of the other regions or provinces. Our estimates of the undiscovered potential nationwide for the lower 48 onshore and offshore and for several of the regions are thus the statistical summations of our subjective cumulative probability distributions for smaller areas. To develop the summary estimates, we used a Monte Carlo technique to select randomly and sum a value from each relevant regional cumulative probability distribution. The summary probability distributions are the statistical distributions of 5000 repetitions of this process.

Like the estimates of reserve growth, the three estimates provided for undiscovered petroleum resources have roughly the same conceptual meaning across regions. The estimates at the 90-percent probability level indicate conservative expectations of what remains to be discovered at the tail end of exploration of old plays and in recently developed plays. The estimates at the 50-percent probability level incorporate moderate expectations of what remains at the tail end of old plays, the potential of recently developed plays, and conservative expectations for wholly new exploration plays, if any. The estimates at the 10-percent probability level indicate optimistic expectations of the ultimate potential of both old and recently developed plays and moderate expectations for wholly new plays, if any. Because of the risk factors we assign to new plays, optimistic expectations of their potential are considered to have less than a 10-percent probability of occurrence. In the last 10 percent of our range, we also include amounts to account for major surprises beyond the possibilities that we could positively identify.

Comparative Estimates

Our estimates of the ultimate petroleum potential of each region and of the nation as a whole are explicitly compared with other well-known estimates published during the 1970s. Three of these studies have provided regionally disaggregated estimates: the National Petroleum Council (NPC),[3] the Resource Appraisal Group of the U.S. Geological Survey (Circular 725),[4] and the Potential Gas Committee (PGC).[5] We provide the estimates of each of these studies in our regional assessments and discuss the key differences between them and our own estimates. They are also listed, along with other national estimates, and discussed in the concluding national summary.

In comparing these estimates with our own, we have tried to exhibit them in ways that are conceptually similar, if not equivalent, to our own estimates. Because each study followed its own procedures, this was not always possible. Key similarities and differences are as follows: The estimates of all of the studies shown here refer to conventional petroleum resources only, excluding nonconventional sources of petroleum, just as we do. Occasionally they use different regional boundaries. These are indicated in the subsequent tables showing regional resource potentials. Circular 725 includes resources offshore to a water depth of 200 meters; the PGC specifies a water depth limit of 1500 feet; and the NPC does not specify a water depth limit. Circular 725 assumes price-cost relationships as of 1974 and the then prevailing technological trends; the PGC assumes an unspecified adequate price and normal technological improvement; and the price and technology assumptions of the NPC pertaining to resource assessment (as opposed to the finding rate) are unclear. Circular 725's concept of inferred reserves is a subset of our concept of reserve growth, excluding most enhanced oil recovery and intensive development resulting from higher prices. Its estimates for undiscovered resources specify 95-percent, mean, and 5-percent probability levels. We assume that the PGC's single-point estimate of probable resources is conceptually equivalent to our maximum estimate of reserve growth. We compare the PGC's single-point estimate of possible resources with our 50-percent probability level and the sum of its estimates of possible and speculative resources with our 10-percent probability level, although it is probably conceptually equivalent to a 25- to 50-percent probability level and a 1.0- to 0.1-percent probability level, respectively. The NPC only estimates reserve growth for oil for the period 1971 to 1985. We assume that its single-point estimate of the undiscovered potential is conceptually equivalent to our maximum estimate of the undiscovered potential.

REGIONAL RESOURCE ASSESSMENTS

Alaska

Alaska is the last great frontier for petroleum exploration in the United States. Substantial areas of moderate to great promise still have yet to be drilled because

[3] *U.S. Energy Outlook: Oil and Gas Availabilit* Washington, D.C., July 1970; and I. H. Cram (ed.), *Futur- troleum Provinces of the United States— Their Geology and Poten...* Am... can Association of Petroleum Geologists, Tulsa, Okla., 1971.

[4] B. M. Miller et al., *Geological Estimates of Undiscovered Recoverable Oil and Gas Resources in the United States*, Geological Survey Circular 725, Washington, D.C., 1975.

[5] *Potential Supply of Natural Gas in the United States (as of December 31, 1976)*, Potential Gas Agency, Colorado School of Mines, Golden, 1977. Updated estimates as of December 31, 1978, are available from the PGC. We chose to use the earlier estimates because of their closer temporal comparability with our own.

of a variety of economic, political, and technological constraints. But this promise does not mean that future exploration in Alaska is likely to transform radically the outlook for future discoveries in the United States as a whole.

We foresee a moderate potential for future reserve growth in Alaska, particularly for crude oil. (See Table 5.1.) Most of the potential for additions to crude oil reserves in known fields comes from waterflooding the Sadlerochit reservoir in the *Prudhoe Bay* field, further development of the *Kuparuk River* field (which could become one of the ten largest oil fields in the country), and development of the deeper Lisburne reservoirs in each of these fields. The Cook Inlet fields have only a small potential for future reserve growth. Overall, we project that the recovery factor will increase from its present level of about 37.5 percent of oil in place to about 40 percent (at 90-percent probability), about 45 percent (at 50-percent probability), and about 50 percent (at 10-percent probability). Most of the future reserve growth in natural gas resources will be from additions to associated-dissolved gas reserves in the major oil reservoirs on the North Slope. There is also some potential from extensions and further development in some of the nonassociated gas fields in the Cook Inlet Province.

The potential for future discoveries in Alaska is heavily concentrated in the provinces north of the Brooks Range and in the Bering Sea. The various areas of the Gulf of Alaska appear to lack good reservoir rocks, sufficiently rich source rocks, or both. However, there is a low probability of a few medium-size discoveries (most likely natural gas) in the eastern part of the Gulf. The Alaskan interior and the lower Cook Inlet also appear to be relatively unpromising. The upper Cook Inlet has already been explored. However, a few Class A to C gas discoveries still appear possible. Preliminary investigations of the Bering Sea provinces have indicated promising reservoirs and traps. The primary remaining uncertainty is the quality of source rock in the various gas source rocks in the several basins. Preliminary indications are that source rocks are at best only moderately favorable and are more conducive to natural gas than to oil accumulations. We consider the Bering Sea provinces to have substantial potential (a maximum of about 10 billion barrels' L&LE). However, the uncertainties about petroleum source rocks make their potential moderately risky.

The North Slope has already demonstrated substantial potential with respect to good reservoirs, large traps, and rich, mature source rocks. The major uncertainties relate to the extent and characteristics of future discoveries along the Barrow Arch and the possibilities for new plays in the Beaufort Sea north of the arch and in the Colville Geosyncline south of the arch. We estimate a good probability of a few substantial (Class AA to smaller Class AAAA) oil discoveries with substantial amounts of associated-dissolved gas in combination traps along the Barrow Arch, particularly east of *Prudhoe Bay*. The Cretaceous and Tertiary formations of the Beaufort Sea appear to have substantial petroleum potential, because of the existence of rich, mature source rocks, at least adequate reservoirs, and several trapping possibilities. The lesser degree of subsurface information makes these a slightly more risky play than the onshore. Onshore south of the Barrow Arch, there are several structurally trapped Class A to AAA prospects. Preliminary seismic information about the Chukchi Sea indicates a sedimentary fill similar to that in the Beaufort Sea with several potentially large and giant traps. This area is promising,

Table 5.1

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN ALASKA

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
This Report (12-31-75)	10.7	1.8-3.5-6.0	6.5-11.2-23.4	19- 25- 40
Circular 725 (12-31-74)	10.7	6.2	12-27- 49	29- 44- 66
NPC (12-31-70)	10.5	1.9[a]	54.8	67
		Natural Gas (trillion cubic feet)		
This Report (12-31-75)	33.9	2.1-4.0-6.6	31.3-49.0-83.8	67- 87-124
Circular 725 (12-31-74)	32.8	14.8	29-76-132	77-124-180
NPC (12-31-70)	31.4	N.E.[b]	327	358
PGC (12-31-76)	33.0	23.0	-45-202	-101-258

NOTE: The range of numbers shown for this report is for the 90-, 50-, and 10-percent probability levels of our estimates. The range of numbers shown for Circular 725 is for the 95-, mean, and 5-percent probability levels of their estimates.

[a]To 1985 only.

[b]No estimate.

but with a moderate degree of risk because of the low level of information about its characteristics.

From our combined appraisal of these areas, we estimate that there is a 90-percent probability that the ultimate recovery of crude oil in Alaska will exceed 19 billion barrels, a 50-percent probability that it will exceed 25 billion barrels, and a 10-percent probability that it will exceed 40 billion barrels. We estimate a 90-percent probability that ultimate recovery of natural gas in Alaska will exceed 67 trillion cubic feet, a 50-percent probability that it will exceed 87 trillion cubic feet, and a 10-percent probability that it will exceed 124 trillion cubic feet. These estimates are substantially lower than those of Circular 725, the NPC, and the PGC for several reasons. Since these three estimates were made, unsuccessful exploratory drilling and further geological investigations in some areas of Alaska such as the Gulf of Alaska and the National Petroleum Reserve have resulted in downward revisions. The Circular 725 and PGC estimates of future reserve growth in existing natural gas fields are clearly too high, a fact acknowledged by a more than 40-percent downward revision of the PGC estimate in its most recent study. None of the three appear to have applied geologic risk factors to their estimates as we did.

Finally, the NPC and PGC estimates for undiscovered natural gas seem to have overestimated source rock potential and the volume of effective reservoir rocks in likely traps in Alaska.

California

The known petroleum resources of California are highly concentrated in giant and large fields. Except for the offshore areas, nearly all of these fields were discovered by 1950. However, California has substantial potential for crude oil reserve growth. Other than the offshore, the outlook for future discoveries is not promising. (See Table 5.2.)

The best prospects for reserve growth in California oil fields lie in the use of thermal recovery methods in the heavy oil fields, particularly in the San Joaquin Valley. Application of these methods has already resulted in substantial reserve additions during the 1970s. We foresee that this process will continue through the remainder of the century. Enhanced oil recovery in the medium-gravity California fields will be both more costly and technologically more difficult. The potential is there, but realizing it may require some innovations in recovery technology because of the poor quality of the reservoirs. Full development of the offshore fields discovered about 1970 in the offshore Ventura Basin should also contribute to future reserve growth. Overall, we project that the recovery factor will increase from its present level of about 27.5 percent of oil in place to about 31 percent (90-percent probability), about 34 percent (50-percent probability), and 38 percent (10-percent probability). The potential for future reserve growth in natural gas is limited primarily to new pool discoveries in the Sacramento Valley gas fields, full development of the offshore fields, and more dissolved gas from medium-gravity oil fields.

Onshore, the best prospects for future oil discoveries appear to be medium-depth combination or stratigraphic *Yowlumne*-type traps along the flanks of the major arches in the San Joaquin Province. We also estimate that a few smaller significant discoveries can be made along the Santa Monica fault zone in the Los Angeles Basin. There is a lesser probability of a few combination or stratigraphically trapped oil discoveries in the center of the Los Angeles Basin. Prospects elsewhere are most likely to be nonsignificant Class D and E fields. Offshore, the best possibilities for both oil and gas occur on the known structural trends in the Santa Barbara Channel. South of the Channel Islands, the only good potential is found in the seaward extensions of existing structural trends and a possible new trend or two in the Los Angeles Basin. The Outer Banks area appears to lack sufficiently rich source rock for major accumulations, although we estimate a low probability that some significant discoveries may still be made there. Other than a few small prospects in the offshore extensions of the Santa Maria and Salinas basins, the petroleum potential of the Pacific offshore basins north of Point Arguello appears to be very limited. Onshore, the prospects for natural gas appear to be limited primarily to future Class C and D discoveries in the Sacramento Valley and in the basins of the Pacific Northwest. If any substantial surprises occur in Pacific Coast exploration, they will most likely be significant gas discoveries in Oregon and Washington. Because of the near disappearance of porosity and permeability below 15,000 feet in typical California sandstone reservoirs, major deep gas discoveries are unlikely.

Table 5.2

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN CALIFORNIA (PACIFIC COAST)

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
ONSHORE				
This Report (12-31-75)	22.8	3.1-6.7-12.9	0.2-0.5--0.8	26-30-37
Circular 725 (12-31-74)	19.0	0.3	4-7-11	23-26-30
NPC (12 31-70)	18.6	3.8[a]	11.2	34
OFFSHORE				
This Report[b] (12-31-75)	0.9	0.6-0.9-1.4	1.0-1.7-3.2	3--4--6
Circular 725 (12-31-74)	2.6	0.2	2-3-5	5--6--8
NPC (12-31-70)	0.8	0.1	12	13
		Natural Gas (trillion cubic feet)		
ONSHORE				
This Report (12-31-75)	31.8	1.2-3.3-6.5	0.7-1.8-3.4	34-37-42
Circular 725 (12-31-74)	30.2	4.0	8-13-20	42-47-54
NPC (12-31-70)	31.1	N.E.	22.5	54
PGC[b] (12-31-76)	31.0	4.0	-9-26	-44-61
OFFSHORE				
This Report[c] (12-31-75)	1.4	0.7-1.4-2.6	2.2-3.3-5.1	4--6--9
Circular 725 (12-31-74)	1.9	0.4	2-3-6	4-5-8
NPC (12-30-70)	1.0	N.E.	13	14
PGC (12-31-76)	1.0	0	-7-10	-8-11

[a]To 1985 only.

[b]Excludes oil and gas in fields that are only partially offshore.

[c]Potential Gas Committee Area L, which includes Idaho and Nevada.

We estimate a 90-percent probability that ultimate recovery onshore California will exceed 26 billion barrels and 34 trillion cubic feet, a 50-percent probability that it will exceed 30 billion barrels and 37 trillion cubic feet, and a 10-percent probability that it will exceed 37 billion barrels and 42 trillion cubic feet. Offshore, we estimate a 90-percent probability that ultimate recovery will exceed 3 billion barrels and 4 trillion cubic feet, a 50-percent probability that it will exceed 4 billion barrels and 6 trillion cubic feet, and a 10-percent probability that it will exceed 6 billion barrels and 9 trillion cubic feet. We estimate that future significant discoveries will most likely be between 9 and 32 fields onshore and 22 and 51 fields offshore.

The primary real difference (other than conceptual ones) between our estimates and the other three shown in Table 5.2 is the assessment of onshore potential. The much higher estimates of Circular 725, the NPC, and the PGC have to imply either a substantial number of large and giant discoveries or a very large number of small and very small discoveries onshore. We consider either possibility to be extremely implausible because of the limited areal extent of the onshore basins, their long exploration histories, and, subsequently, their well-known geology.

Rocky Mountains

The Rocky Mountain region has the best potential for major significant discoveries of any onshore region in the lower 48 states. However, because this potential is limited to a handful of new exploratory plays, we do not foresee more than a doubling of ultimate recovery within the region. (See Table 5.3.)

Infill drilling and more intensive waterflooding provide much of the high-probability potential for reserve growth in the oil fields of the region. The achievement of higher levels will depend on the successful application of enhanced oil recovery methods in the large and giant oil fields. Overall, we project that the recovery factor will increase from its present level of about 29.5 percent of oil in place to about 32 percent (90-percent probability), about 34.5 percent (50-percent probability), and about 38 percent (10-percent probability). Infill drilling in the gas fields of the San Juan Basin will be the major source of reserve growth for natural gas. Deep new pool discoveries in the Big Horn, Green River, and Wind River provinces and extensions to Piceance Basin fields also promise to provide some growth in natural gas reserves.

The best potential for major new discoveries in the region is the portion of the Overthrust Belt where Idaho, Utah, and Wyoming meet. This area has numerous structures with thick, multiple Paleozoic and Mesozoic reservoirs adjacent to rich, mature source rocks. Its potential is limited to some degree by the small area of most of the traps and the poor quality of most of the productive reservoirs. Also, the productive trend may not cover an area much larger than its current limits. The area appears to be primarily a natural gas/natural gas liquids play. Since 1975 several large discoveries and at least one giant discovery have been made in the Overthrust Belt.

Another good play has developed since 1975 in moderately deep Mississippian, Devonian, and Ordovician formations in the Williston Basin. However, because reservoir quality in these formations is very poor and structures are generally fairly small in area, most of the discoveries in this play are Class D prospects. Some significant discoveries, such as *Little Knife* and *Mondak*, are being made, however, the latter having the potential to be a Class AA or AAA field. There also appear to be reasonable prospects for future significant gas discoveries in the deeper portions of the Big Horn, Green River, and Wind River basins and in parts of the Overthrust Belt in Montana immediately south of the Canadian border. Otherwise, we estimate that there will be only a few isolated significant discoveries in the other Rocky Mountain provinces together with a substantial number of Class D and E discoveries.

Overall, we estimate that there will most likely be another 80 to 128 significant discoveries in the Rocky Mountain region. About 60 percent will be Class B and C

Table 5.3

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE ROCKY MOUNTAIN REGION

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
Crude Oil (billion barrels)				
This Report (12-31-75)	10.1	0.9-2.0- 3.4	1.6-2.1-2.6	13-14- 16
Circular 725[a] (12-31-74)	9.3	1.9	7-11-19[d]	18-22- 30
NPC[a] (12-31-70)	8.3	0.9[c]	25.2	34
Natural Gas (trillion cubic feet)				
This Report (12-31-75)	44.0	3.9-9.9-16.0	22.7-31.7-44.7	71-86-105
Circular 725[a] (12-31-74)	38.0	8.2	24-43-72[d]	70-89-118
NPC[a] (12-31-70)	34.4	N.E.	86.8	121
PGC[b] (12-31-76)	40.0	17.0	-34-54	-91-111

[a]NPC Regions 3 and 4, which exclude central and eastern Nebraska.

[b]Potential Gas Committee areas H and I, which exclude Idaho and Nevada.

[c]To 1985 only.

[d]The arithmetic sums of Circular 725s estimates for Regions 3 and 4.

fields, there being numerous large discoveries in the Overthrust Belt and the deeper prospects. With these future discoveries, we estimate a 90-percent probability that ultimate recovery in the Rocky Mountain region will exceed 13 billion barrels and 71 trillion cubic feet, a 50-percent probability that it will exceed 14 billion barrels and 86 trillion cubic feet, and a 10-percent probability that it will exceed 16 billion barrels and 105 trillion cubic feet. We also estimate substantial amounts of undiscovered natural gas liquids, primarily in the Overthrust Belt.

Our estimates of the undiscovered potential for crude oil are substantially lower than the other two estimates shown in Table 5.3. Both implicitly overestimate the number of significant oil prospects remaining in the Rocky Mountain region. Because of the extent of exploration to date in most of the Rocky Mountain basins, the indicated field sizes and hydrocarbon content of the new plays in the Overthrust Belt and Williston Basin, and the lack of very rich source rocks or good preservation in many of the Rocky Mountain basins, the other two estimates lack plausibility, even if one counts likely natural gas liquids in the Overthrust Belt as crude oil. Their estimates for natural gas are similar to our own, although their estimates of undiscovered potential tend to be slightly higher.

Permian Basin

During the 50 years of petroleum exploration in the Permian Basin since 1925, most of the sedimentary section to basement rocks has been thoroughly tested. As a result, crude oil discoveries had dropped off to minor levels by the 1960s and natural gas discoveries were declining sharply in the 1970s. Because of the lateral and vertical extent of exploratory drilling in the region, these trends will not be reversed. Future reserve additions, particularly for crude oil, in the Permian Basin will come primarily from reserve growth in pre-1976 discoveries. (See Table 5.4.)

The potential for reserve growth in the giant and large oil fields of the Permian Basin is substantial. Reserves are already being added through major infill drilling programs, the effects of which should continue to show up for several more years. Enhanced oil recovery through carbon dioxide miscible flooding should substantially augment Permian Basin oil reserves over the next several decades. Overall, we estimate that the recovery factor will increase from its present level of about 29 percent of oil in place to about 32 percent (90-percent probability), about 35.5 percent (50-percent probability), and about 40.5 percent (10-percent probability). Proportionately, the potential for reserve growth for natural gas is much less, but we foresee some potential from infill drilling, extensions, and more well stimulation.

The possible exploratory plays of the Permian Basin are close to exhausting their potential. Future discoveries in the deep gas play for Ordovician, Silurian, and Devonian structures in the Delaware Basin that began in the 1960s are most likely limited to a few Class C and D fields. Future stratigraphic trap possibilities in the Pennsylvanian formations for gas also appear to be limited to Class C and D fields. Future significant oil discoveries, if any, are likely to be isolated accumulations rather than the forerunners of major new plays. Overall, we estimate that significant discoveries in the Permian Basin after 1975 will most likely be between 13 and 44 fields, 80 to 90 percent of which will be Class C in size. Most of these discoveries will be natural gas fields. We also foresee hundreds of Class D and E discoveries in the basin.

Overall, we estimate a 90-percent probability that ultimate recovery in the Permian Basin will exceed 30 billion barrels and 78 trillion cubic feet, a 50-percent probability that it will exceed 34 billion barrels and 83 trillion cubic feet, and a 10-percent probability that it will exceed 40 billion barrels and 93 trillion cubic feet. Our estimates of potential differ only modestly from the recent ones of the Interagency Oil and Gas Supply Project,[6] an assessment effort using approaches similar to our own. Its estimate includes a few Class A deep gas discoveries, more future discoveries in very small fields, and more gas recovery through massive hydraulic fracturing than we do. By comparison, the other estimates tend to be around an order of magnitude higher than our own for both undiscovered crude oil and natural gas resources. If such estimates were to be true, they would require a massive reversal in the historic discovery trends. The extent of exploratory drilling in the basin and the geological limits it has indicated to the known producing plays make such a reversal impossible.

[6] *Future Supply of Oil and Gas from the Permian Basin of West Texas and Southeast New Mexico*, Geological Survey Circular 828, U.S. Geological Survey, Washington, D.C., 1980.

Table 5.4

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE PERMIAN BASIN

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
Crude Oil (billion barrels)				
This Report (12-31-75)	26.6	3.2-7.2-13.0	0.2-0.4-0.7	30- 34- 40
Circular 725[a] (12-31-74)	30.4	1.6	4- 8- 14	36- 40- 46
NPC[a] (12-31-70)	26.0	8.0[b]	19.9	54
Interagency (12-31-76)	25.7	6.2[c]	1.5[c]	33
Natural Gas (trillion cubic feet)				
This Report (12-31-75)	73.4	1.8-4.4- 9.6	2.4-5.2-9.8	78- 83- 93
Circular 725[a] (12-31-74)	83.3	23.3	35-70-101	142-177-208
NPC[a] (12-31-70)	74.9	N.E.	93.4	168
PGC (12-31-76)	74.0	18.0	-37- 38	-129-130
Interagency (12-31-76)	74.0	20.8[c]	17.2[c]	112

[a]Includes North Central Texas (Texas R.R.C. Districts 7B and 9).

[b]To 1985 only.

[c]At $40 per barrel and a 5-percent discount rate.

North Central Texas

Significant fields are of lesser importance in North Central Texas than in any other region of the nation. Future exploration will not alter this situation. Future discoveries in the region will be almost entirely Class D and E fields, primarily on the Bend Arch and in the Fort Worth Syncline. We estimate that at best only one or two more significant discoveries are likely to be made. Future discoveries will be predominantly gas fields. Some reserve growth is likely from infill drilling, extensions, and new pool discoveries (both crude oil and natural gas) and from enhanced oil recovery. We estimate that the recovery factor will increase from its present level of about 24.5 percent of oil in place to about 26.5 percent (90-percent probability), about 29 percent (50-percent probability), and about 32 percent (10-percent probability). Overall, we estimate a 90-percent probability that ultimate recovery in North Central Texas will be at least 5.7 billion barrels and 12 trillion cubic feet, a 50-percent probability that it will be at least 6.4 billion barrels and 13 trillion cubic feet, and a 10-percent probability that it will be at least 7.6 billion barrels and 15 trillion cubic feet. (See Table 5.5.)

Table 5.5

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN NORTH CENTRAL TEXAS

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
This Report (12-31-75)	4.9	0.7-1.3-2.3	0.1-0.2-0.4	6- 6- 8
Circular 725 (12-31-74)		(Included in Table 5.4)		
NPC (12-31-70)		(Included in Table 5.4)		
		Natural Gas (trillion cubic feet)		
This Report (12-31-75)	10.8	0.3-0.9-1.8	0.8-1.6-2.8	12-13-15
Circular 725 (12-31-74)		(Included in Table 5.4)		
NPC (12 31-70)		(Included in Table 5.4)		
PGC (12-31-76)		(Included in Table 5.9)		

Mid-Continent

The Mid-Continent is the second most important source of known petroleum resources in the United States. It has also been asserted to have substantial future potential, particularly for natural gas in the deep Anadarko Basin. We consider this potential to be highly overrated. There is a substantial potential for future reserve additions in the region, but it will come primarily from reserve growth in existing fields, not from new discoveries. Most of the significant discoveries in the region have already been made. (See Table 5.6.)

The major initial impetus to reserve growth in the Mid-Continent region will come from infill drilling in existing fields, increasing the proportion of reservoir volume that has been effectively swept. Some extensions and new pool discoveries are also possible, particularly in gas fields in the Anadarko Basin. The potential for enhanced oil recovery is substantial; however, the enhanced oil recovery methods that can be used are also likely to be quite expensive. Therefore, we consider that major reserve additions from enhanced oil recovery in the Mid-Continent have only a medium to low probability of occurrence. Overall, we estimate that the recovery factor will increase from its present level of about 32 percent of oil in place to about 34 percent (90-percent probability), about 37 percent (50-percent probability), and about 40 percent (10-percent probability).

Most of the shallower provinces in the region have been explored extensively down to the basement rocks. We therefore think that nearly all future significant

Table 5.6

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE MID-CONTINENT

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
	Crude Oil (billion barrels)			
This Report (12-31-75)	19.7	1.9- 5.2- 9.2	0.2-0.4-0.8	22- 25- 30
Circular 725[a] (12-31-74)	19.2	1.3	3- 6- 12	24- 27- 33
NPC[a] (12-31-70)	18.0	2.5[b]	2.5	23
	Natural Gas (trillion cubic feet)			
This Report (12-31-75)	152.0	6.1-13.4-30.7	4.8-10.1-17.6	163-178-200
Circular 725[a] (12-31-74)	141.9	20.6	50-72-101	213-235-264
NPC[a] (12-31-70)	133.8	N.E.	122.5	255
PGC (12-31-76)	148.0	27.0	-72-80/130	-247-255/305

[a]Includes central and eastern Nebraska and northwestern Arkansas.

[b]To 1985 only.

discoveries are likely to occur in the Anadarko Basin, with the possibility of a few in the South Oklahoma and Arkoma provinces. These will be predominantly natural gas fields. We estimate that there will most likely be 22 to 70 significant discoveries in the region after 1975. About two-thirds of these will be Class C in size. The few larger significant discoveries will most likely be medium-depth to deep gas discoveries within the Anadarko Basin.

Overall, we estimate that there is a 90-percent probability that ultimate recovery in the Mid-Continent region will exceed 22 billion barrels and 163 trillion cubic feet, a 50-percent probability that it will exceed 25 billion barrels and 178 trillion cubic feet, and a 10-percent probability that it will exceed 30 billion barrels and 200 trillion cubic feet. Our estimates for the crude oil potential of the region do not differ appreciably from the total Circular 725 and NPC estimates, given the conceptual differences among the three. The Circular 725 estimate for undiscovered oil resources is implausibly high, because of the trend in oil discoveries in the region since 1960 and the density of exploratory drilling.

Our estimates of the amount of natural gas remaining to be discovered are substantially lower than the other estimates, primarily because of the lower potential we place on the deep Anadarko Basin. We have downgraded the region principally because of its exploratory history. In the 15 years of exploration of the basin area below 15,000 feet between 1961 and 1975, only seven significant fields with major reservoirs below 15,000 feet were discovered, the largest of which was only a Class AA field. If a basin of the same type as the Anadarko Basin were to have very large volumes of natural gas, all of the relevant basin analogies suggest that they would be concentrated in Class AAA and AAAA fields. Assuming that deep fields of this size will be limited to structural traps and that the productivity of future discoveries would equal the known deep Hunton formation average of about 20 billion cubic feet of reserves per well on 640-acre spacing, estimates of 50 to 100 trillion cubic feet of natural gas in the deep Anadarko Basin would imply several fields covering two to ten townships each. Both the current deep drilling density in the basin and its basic geologic structure preclude this theoretical possibility.

Western Gulf

The potential for future discoveries in the Western Gulf region is primarily offshore. Onshore significant discoveries have been declining rapidly since the decade around 1950. Most of the recent significant discoveries that have occurred onshore have been in the peripheral, less explored areas of the region.

Unlike most of the other major petroleum-producing regions of the country, the potential for reserve growth in the Western Gulf is relatively limited. Because reservoir quality is generally good to excellent, recovery rates in the major oil fields are already high. Selective infill drilling promises minor improvements in sweep efficiency. Extensions to the Austin Chalk fields have some potential as well. There will also be additions from new pool discoveries. Because of low residual oil saturations in the swept portions of known fields, enhanced oil recovery is not highly promising. Overall, we estimate that the recovery factor will increase from its present level of about 42 percent to about 43.5 percent (90-percent probability), about 45 percent (50-percent probability), and about 48 percent (10-percent probability). The potential for reserve growth in the natural gas fields should be assessed cautiously because of the large negative revisions that have occurred in the natural gas reserves of the region over the past decade. We believe that nearly all of the negative revisions that had to be made have already been made, and therefore see a minor potential for some net reserve growth from new pool discoveries onshore and extensions and full field development offshore. (See Table 5.7.)

Onshore and offshore, the potential for new discoveries in the Western Gulf region is practically limited to natural gas. Future discoveries of crude oil onshore will be almost entirely in Class D and E fields with a possibility of only a few Class C discoveries. The offshore is overwhelmingly a gas-prone region as well, although a few modest oil discoveries are possible. Many of the significant natural gas discoveries that were expected to be made offshore Texas were made during the peak of exploration in the High Island and High Island East Addition areas from 1973 to 1977. However, a few still remain to be made to the southwest and beyond the 200-meter water depth contour. We estimate that there will most likely be between 28 and 60 significant discoveries in the offshore Western Gulf after 1975. We also see a possibility of several hundred Class D discoveries. Onshore, we estimate that the majority of natural gas reserve additions from new discoveries will come from Class D and E fields. However, we estimate that between 7 and 32 significant fields will be discovered, primarily in the peripheries of the region outside of the major productive trends.

Table 5.7

Estimates of Ultimately Recoverable Amounts of Crude Oil and Natural Gas in the Western Gulf Region

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
Crude Oil (billion barrels)				
ONSHORE				
This Report (12-31-75)	14.0	1.1- 2.3-4.1	0.1-0.2-0.2	15-17-18
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
OFFSHORE				
This Report (12-31-75)	0.3	0.0- 0.0-0.1	0.1-0.2-0.3	*- 1- 1
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
Natural Gas (trillion cubic feet)				
ONSHORE				
This Report (12-31-75)	117.6	0.6- 2.1- 4.7	3.2-6.8-11.5	122-127-134
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
FPC (12-31-76)	c. 121.1	19	-24-28	-164-168
OFFSHORE				
This Report (12-31-75)	12.8	0.4- 1.0-1.8	6.2-10.0-14.9	19-24- 30
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
FPC (12-31-76)	c. 7.0	20	-26-26	- 53- 53

NOTE: An asterisk (*) indicates that the amount is either less than 0.05 (undiscovered) or 0.5 (ultimate discovery) billion barrels.

Overall, we estimate a 90-percent probability that ultimate recovery onshore in the Western Gulf will exceed 15 billion barrels and 122 trillion cubic feet, a 50-percent probability that it will exceed 17 billion barrels and 127 trillion cubic feet, and a 10-percent probability that it will exceed 18 billion barrels and 134 trillion cubic feet. Offshore, we estimate a 90-percent probability that ultimate recovery will be at least 19 trillion cubic feet, a 50-percent probability that it will exceed 24 trillion cubic feet, and a 10-percent probability that it will exceed 30 trillion cubic feet. We do not foresee that ultimate recovery offshore will exceed 1 billion barrels.

Central Gulf

Since 1950, the Central Gulf region has been the principal location for major new discoveries of both crude oil and natural gas in the United States outside of Alaska and a comparatively steady source of significant discoveries. Although there is still substantial potential for future discoveries in the region, it appears that it will soon relinquish its leading role.

The potential for reserve growth in the oil fields is limited. Because the major oil fields typically have reservoirs with good porosity and permeability and with natural water drives, the recovery factor in the region already exceeds 50 percent. With some selective infill drilling to get better reservoir drainage and improve sweep efficiency, this can be improved slightly. Some potential also exists for new pool discoveries and extensions, particularly offshore, because of the complex geology of many of the fields. Applications of enhanced oil recovery methods will be expensive and should increase ultimate recovery by only modest proportions. Overall, we estimate that the recovery factor will increase from its present level of about 52.5 percent to about 54.5 percent (90-percent probability), about 57 percent (50-percent probability), and about 60 percent (10-percent probability). Future growth in natural gas reserves in existing fields will come primarily from new pool discoveries, extensions, and full development of some of the more recent offshore discoveries. (See Table 5.8.)

Since 1950, significant discoveries onshore in the Central Gulf region have been rapidly diminishing. The exploration of the deep Tuscaloosa trend should reverse this decline, but the reversal will only be temporary. We estimate that there will most likely be between 24 and 58 significant discoveries onshore in the Central Gulf region after 1975, most of which will be natural gas discoveries below 15,000 feet deep. However, the deep gas potential onshore appears to be limited by streaky porosity and permeability within the substantial gross thickness of the Tuscaloosa sandstone. With indicated average reserves per well on 1280-acre spacing of 20 to 40 billion cubic feet and structures that typically will take three to twelve wells to develop, most of the fields within the trend will be Class C to A in size, with a possibility of a few Class AA or AAA fields on the largest structures with better porosity.

Offshore, the potential for major significant discoveries is heavily concentrated in water depths greater than 200 meters. Nearly all of the larger anticlines and salt domes have been drilled in lesser water depths. Future discoveries within the 200-meter contour will be largely limited to Class C and D fields. We estimate that there will most likely be between 65 and 121 significant discoveries offshore after 1975. However, unlike previous offshore discoveries in the Central Gulf, only about 10 to 20 percent of these will be Class A or larger fields.

Overall, we estimate a 90-percent probability that ultimate recovery onshore in the Central Gulf will be greater than 11 billion barrels and 99 trillion cubic feet, a 50-percent probability that it will be greater than 12 billion barrels and 107 trillion cubic feet, and a 10-percent probability that it will be greater than 13 billion barrels and 119 trillion cubic feet. Offshore, we estimate a 90-percent probability that it will exceed 9 billion barrels and 91 trillion cubic feet, a 50-percent probability that it will exceed 10 billion barrels and 102 trillion cubic feet, and a 10-percent probability that it will exceed 13 billion barrels and 118 trillion cubic feet.

Table 5.8

Estimates of Ultimately Recoverable Amounts of Crude Oil and Natural Gas in the Central Gulf Region

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
ONSHORE				
This Report (12-31-75)	9.7	0.8- 1.7-3.0	0.1-0.2-0.4	11--12--13
Circular 725[a] (12-31-74)	39.0	8.6	5-- 8--12	53--56--60
NPC[a] (12-31-70)	36.7	9.6[b]	14.2	- 61
OFFSHORE				
This Report[c] (12-31-75)	7.5	1.0- 1.9-3.4	0.6-1.0-1.6	9--10--13
Circular 725[a] (12-31-74)	6.4	2.4	3- 5- 8	12--14--17
NPC[a] (12-31-70)	5.5	0.3[b]	13.6	19
		Natural Gas (trillion cubic feet)		
ONSHORE				
This Report (12-31-75)	90.9	3- 8- 16	5.2-7.8-12.4	99-107-119
Circular 725[a] (12-31-74)	279.8	58.7	85-135-196	424-472-535
NPC[a] (12-31-70)	c. 278.0	N.E.	203.8	482
PGC (12-31-76)	c. 92.5	18.0	- 19- 19	-130-130
OFFSHORE				
This Report[c] (12-31-75)	78.3	4- 10- 19	8.9-13.8-20.8	91-102-118
Circular 725[a] (12-31-74)	67.5	67.0	18- 50- 91	153-185-226
NPC[a] (12-31-70)	c. 55.0	N.E.	174.8	230
PGC (12-31-76)	c. 71.0	31.0	- 50- 50	-152-152

[a] Includes the Western Gulf, the Northern Gulf excluding northwestern Arkansas, and the Eastern Gulf excluding southern Florida.

[b] To 1985 only.

[c] Defined as all fields, significant or otherwise, in the Louisiana offshore area, thereby excluding offshore fields in the bays of southeastern and southwestern Louisiana.

Because the Circular 725 and NPC estimates combine all of the Gulf regions into one, comparisons among the estimates are not as straightforward as they are for other regions. But for the region as a whole, several points are clear. The Circular 725 and NPC estimates for reserve growth in oil fields onshore are within the same range as our own. Their estimates of the undiscovered oil potential onshore are an order of magnitude higher than ours. Their estimates are totally inconsistent with the sharp declines since 1950 in the amount of crude oil discovered onshore in the Gulf Coast region, the drilling density within the region, and the high concentration of the region's known oil resources in large fields. Offshore, their estimates of the undiscovered crude oil potential are also an order of magnitude higher, adjusting for the limitation of Circular 725's estimate to the potential within the 200-meter depth contour. With the exploration of the larger structures in the Pleistocene trend now being essentially complete, it is difficult to conceive where the large discoveries could be made that are necessary to justify their estimates.

Both the Circular 725 and the PGC estimates for natural gas reserve growth offshore in the Gulf region are substantially higher than our own. Although some uncertainty exists about the areal and vertical limits of the region's gas fields, we cannot believe that it is so great as to justify future upward revisions of 50 to 100 percent offshore, particularly because of the good to excellent seismic control that the operating companies have over known fields in the offshore Gulf of Mexico. Onshore, the estimates of Circular 725 and the NPC for the undiscovered natural gas potential are nearly an order of magnitude larger than our own. Again, we consider these estimates to be totally inconsistent with the amounts of natural gas discovered onshore in the Gulf Coast since 1960, the drilling density within the region, the high concentration of the region's natural gas resources in large fields, and the characteristics of the major remaining prospects. Offshore, the three different estimates of the undiscovered potential for natural gas are two to four times our own. Because of the concentration of natural gas resources offshore in significant fields, particularly those Class A or larger, and the great extent to which the larger structures have already been drilled offshore, realizing the higher range of their estimates would require hundreds of Class C discoveries and a thousand or more Class D discoveries. This number of prospects appears to be beyond the imagination of even the most optimistic operator in the Gulf of Mexico.

Northern Gulf

The Northern Gulf has historically been one of the more important petroleum regions of the United States. Its importance will, however, be increasingly of historical interest. The potential for both reserve growth and future discoveries in the region is but a small fraction of what has already been discovered. (See Table 5.9.)

Oil recovery factors in Texas R.R.C. Districts 5 and 6 already exceed 60 percent. Additional infill drilling in the major fields is likely to increase this figure by only a small fraction. Partially offsetting this potential increase are some recent major negative revisions in estimated recovery for the giant *Hawkins* field. Because of the high degree of recovery achieved from waterflooding in most of the major fields in Texas R.R.C. Districts 5 and 6, the potential for enhanced oil recovery in the region is primarily limited to a few large and giant fields in northern Louisiana and

Table 5.9

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE NORTHERN GULF REGION

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
	Crude Oil (billion barrels)			
This Report (12-31-75)	12.9	0.3-1.1-2.2	0.1-0.1-0.3	13-14-15
Circular 725 (12-31-74)	(Included in Table 5.8)			
NPC (12-31-70)	(Included in Table 5.8)			
	Natural Gas (trillion cubic feet)			
This Report (12-31-75)	53.4	0.9-2.3-4.2	2.8-4.3-6.5	57-60-64
Circular 725 (12-31-74)	(Included in Table 5.8)			
NPC (12-31-70)	(Included in Table 5.8)			
PGC[a] (12-31-76)	63	8	-21-46	-92-117

[a] Includes North Central Texas.

southern Arkansas. Overall, we estimate that the recovery factor will increase from its present level of about 48.5 percent of oil in place to about 49 percent (90-percent probability), about 50.5 percent (50-percent probability), and about 53 percent (10-percent probability). The best potential for natural gas reserve growth in the Northern Gulf lies in additional discoveries and development of deeper Jurassic gas pools in the East Texas-Arkla Province. Some potential also exists for deeper pool discoveries in the Arkoma Basin and from infill drilling in known pools in some of the larger gas fields of the region.

Both the number of significant discoveries and the amount of crude oil and natural gas discovered in the Northern Gulf have declined to minor levels during the past 20 years. Because of the drilling density within the region and its lack of a large very deep sedimentary section, we foresee no possibility that this trend could be substantially reversed. Few significant oil fields remain undiscovered. We estimate that there will most likely be between 10 and 29 significant discoveries in the region after 1975. Most of these discoveries will be in Jurassic and Lower Cretaceous reservoirs 7500 to 15,000 feet deep and will be Class C in size. However, a few Class B and A gas discoveries are also possible.

Overall, we estimate a 90-percent probability that ultimate recovery in the Northern Gulf region will exceed 13 billion barrels and 57 trillion cubic feet, a 50-percent probability that it will exceed 14 billion barrels and 60 trillion cubic feet, and a 10-percent probability that it will exceed 15 billion barrels and 64 trillion cubic feet.

Eastern Gulf

The Eastern Gulf is the least important of any of the 12 petroleum regions in the United States. Future exploration and development will not alter its relative ranking. The potential for future reserve growth is limited in an absolute sense by the size of the known recoverable petroleum resource base. Some potential for enhanced oil recovery exists in the larger oil fields of the region. However, we estimate that the recovery factor will only increase from its present level of about 38 percent of oil in place to about 40 percent (90-percent probability), about 41.5 percent (50-percent probability), and about 44 percent (10-percent probability). Infill drilling will also add to known reserves of both crude oil and natural gas. There is a lesser, but still real probability of new pool discoveries for natural gas. (See Table 5.10.)

Onshore, the Mid-Gulf Coast Province has already gone through three major waves of exploration. The last two, the search for deep lower Cretaceous and Jurassic objectives, still have some potential, particularly for natural gas. A few small significant fields may be discovered in the South Florida and Warrior basins. We estimate that there will probably be between 9 and 31 significant discoveries in the region after 1975 and most will be predominantly gas fields. Most of these discoveries will also be Class C fields, although there will also be a few Class B and A discoveries. One or two deep gas prospects could have the reservoir volume to be a Class AA field, but because a substantial fraction of this volume is likely to be occupied by nonhydrocarbon gases, the realized field size will be smaller.

After the major exploratory failures in the eastern Gulf of Mexico in the mid-1970s, expectations for the region have had to be severely reduced. We still envision some nearshore potential, such as in a modest offshore continuation of the Cretaceous oil-producing trend in the South Florida basins and deep Jurassic gas in the Mobile Bay area. Other possibilities cannot be summarily excluded, but they must be assigned a high risk factor because of the exploratory failures to date. We estimate that there will most likely be between 4 and 14 significant discoveries offshore in the region after 1975.

Overall, we estimate a 90-percent probability that ultimate recovery onshore in the Eastern Gulf will be at least 2.9 billion barrels and 9 trillion cubic feet, a 50-percent probability that it will be at least 3.2 billion barrels and 11 trillion cubic feet, and a 10-percent probability that it will be at least 3.7 billion barrels and 13 trillion cubic feet. Offshore, we estimate a 90-percent probability that it will be at least 800 billion cubic feet, a 50-percent probability that it will be at least 100 million barrels and 1.4 trillion cubic feet, and a 10-percent probability that it will be at least 400 million barrels and 2.7 trillion cubic feet.

Illinois-Michigan

The potential for future reserve additions in the Illinois-Michigan region is split sharply by type between the two basins. The Illinois Basin has most of the potential for future crude oil reserve growth. The potential for future oil discoveries and all reserve additions for natural gas is highly concentrated in the Michigan Basin. In either case, the potential is not substantial. (See Table 5.11.)

The combination of infill drilling and the use of some of the more expensive

Table 5.10

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE EASTERN GULF REGION

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
ONSHORE				
This Report (12-31-75)	2.6	0.2-0.4-0.7	0.1-0.2-0.4	3--3--4
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
OFFSHORE				
This Report (12-31-75)	0	0	0 --0.1-0.4	0--*--*
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
		Natural Gas (trillion cubic feet)		
ONSHORE				
This Report (12-31-75)	7.8	0.2-0.5-1.2	1.4-2.5-4.3	9-11-13
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
PGC (12-31-76)	7	5	-6-22	-18-34
OFFSHORE				
This Report (12-31-75)	0	0	0.8-1.4-2.7	1--1--3
Circular 725 (12-31-74)		(Included in Table 5.8)		
NPC (12-31-70)		(Included in Table 5.8)		
PGC (12-31-76)	0	0	-0-24	- 0-24

NOTE: An asterisk (*) indicates that the amount is either less than 0.05 (undiscovered) or 0.5 (ultimate discovery) billion barrels.

means of enhanced oil recovery should increase oil recovery in the Illinois Basin by a respectable percentage. If the application of these methods is highly successful, the largest Class AAA fields in the basin are likely to become giant fields. Further development, including secondary recovery, of the discoveries of the early 1970s in Michigan, should result in small increases in the recoverable oil and gas resources. Overall, we estimate that the recovery factor will increase from its present level of about 34.5 percent of oil in place to about 37 percent (90-percent probability), about 40 percent (50-percent probability), and about 44.5 percent (10-percent probability).

Neither basin is likely to see many significant discoveries in the future. There

Table 5.11

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE ILLINOIS-MICHIGAN REGION

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
Crude Oil (billion barrels)				
This Report (12-31-75)	4.7	0.4-1.0-1.9	0.1-0.2-0.4	5--6--7
Circular 725[a] (12-31-74)	5.3	0.5	0.9-2-4	7- 8-10
NPC[a] (12-31-70)	4.9	0.4	2.3	8
Natural Gas (trillion cubic feet)				
This Report (12-31-75)	3.5	0.1-0.3-0.6	1.1-1.6-2.4	5--5--7
Circular 725[a] (12-31-74)	5.6	1.3	1.5-3-6	8-10-13
NPC[a] (12-31-70)	4	N.E.	13.2	17
PGC (12-31-76)	3.0	0	-4-6	- 7- 9

[a]Includes western Ohio and western Kentucky.

should be a substantial number of Class D discoveries in Michigan when previously off-limits areas onshore and offshore are explored for Niagaran pinnacle reefs. A few Class C discoveries may occur in the remainder of this play. Most of the future discoveries in the Illinois Basin will be no larger than Class E fields.

Overall, we estimate a 90-percent probability that ultimate recovery in the Illinois-Michigan region will be at least 5.2 billion barrels and 4.7 trillion cubic feet, a 50-percent probability that it will be at least 5.9 billion barrels and 5.4 trillion cubic feet, and a 10-percent probability that it will be at least 7 billion barrels and 6.5 trillion cubic feet. Adjusting for variations in the area covered by the different estimates, the other three estimates are slightly above our own. Each appears to assign a slightly higher oil potential to the Michigan Basin and a slightly higher gas potential to the Illinois Basin.

Appalachian-Atlantic

The Appalachian-Atlantic region contains both the oldest and the newest petroleum province in the nation. The former, the Appalachian Province, still has some potential for reserve growth and new discoveries, particularly for natural gas. The Atlantic offshore basins have modest potential, because of their high exploratory risks. (See Table 5.12.)

The recovery factor in the oil fields of the Appalachian Province is the poorest of any region in the nation, averaging about 19.5 percent. This is partly because

Table 5.12

ESTIMATES OF ULTIMATELY RECOVERABLE AMOUNTS OF CRUDE OIL AND NATURAL GAS IN THE APPALACHIAN-ATLANTIC REGION

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Crude Oil (billion barrels)		
ONSHORE				
This Report (12-31-75)	3.8	0.3-1.0-2.2	*-0.1-0.1	4--5--6
Circular 725[a] (12-31-74)	2.9	0.1	0.6- 2- 4	4- 5- 7
NPC[a] (12-31-70)	3.0	0.2	0.3	4
OFFSHORE				
This Report (12-31-75)	0	0	0-0.2-0.6	0- *- 1
Circular 725 (12-31-74)	0	0	0- 3- 6	0- 3- 6
NPC (12-31-70)	0	0	4.8	5
		Natural Gas (trillion cubic feet)		
ONSHORE				
This Report (12-31-75)	39.3	3.2-6.1-9.4	3.9-6.2-10.7	46-52-59
Circular 725[a] (12-31-74)	37.0	3.3	5.4-11-19	46-53-59
NPC[a] (12-31-70)	33	N.E.	63	96
FPC (12-31-76)	39	25	- 9-41	-73-105
OFFSHORE				
This Report (12-31-75)	0	0	1.8-5.5-11.3	2-6-11
Circular 725 (12-31-74)	0	0	0-10-22	0-10-22
NPC (12-31-70)	0	0	58	58
FPC (12-31-76)	0	0	- 0-36	- 0-36

NOTE: An asterisk (*) indicates that the amount is either less than 0.05 (undiscovered) or 0.5 (ultimate discovery) billion barrels.

[a]Includes southern Florida; excludes western Ohio and western Kentucky; the estimates are the arithmetic sums of the estimates for NPC Regions 10 and 11.

reservoir quality in many of the fields is poor and partly because most of the major fields were discovered and developed in the earliest years of the petroleum industry when production practices were appallingly inefficient. We estimate a high probability of very modest improvements in the recovery factor from infill drilling and well stimulation. With major technological improvements in recovery methods, we estimate a 10-percent probability that the recovery factor may eventually exceed 28 percent, still the lowest of any region in the nation. Infill drilling, extensions, and new pool discoveries should augment reserves in the region's known gas fields.

Future major oil discoveries in the Appalachian region are extremely unlikely.

Its shallow sedimentary rocks have been extensively explored for over a century. Deeper hydrocarbon reservoirs have contained natural gas exclusively. We estimate that substantial amounts of natural gas may be discovered, primarily in early Paleozoic reservoirs in deep or subtle structural traps, such as in the Eastern Overthrust Belt, but the potential of such traps is likely to be limited by both reservoir and source rock considerations.

The Atlantic offshore provinces have been considered to have substantial petroleum potential, primarily because they have both the traps and reservoir rocks necessary for major petroleum accumulations. However, because of shortcomings in the accumulation, maturation, and preservation of petroleum source material, we estimate that the potential of the region within the 1000-meter water depth contour is limited. Because of low to moderate rates of deposition and moderate wave action, it is unlikely that high concentrations of organic material were ever buried except in localized protected environments. Because of the low thermal gradient, late Cretaceous and Tertiary source rocks are immature and thus have not generated petroleum. Moreover, some of the petroleum that has been trapped is likely to have been destroyed as some reservoirs were flushed. Because of the predominant type of effective source material indicated by drilling, we estimate that the petroleum potential of the Atlantic provinces will be primarily Jurassic and early Cretaceous natural gas located in one or more narrow trends parallel to the coastline around the transition from the continental shelf to the continental slope. We also see a low probability of a few major oil deposits, most likely in a *Hibernia*-type "pocket."

Overall, we estimate a 90-percent probability that ultimate recovery onshore will exceed 4 billion barrels and 46 trillion cubic feet, a 50-percent probability that it will exceed 5 billion barrels and 52 trillion cubic feet, and a 10-percent probability that it will exceed 6 billion barrels and 59 trillion cubic feet. Offshore, we estimate a 90-percent probability of no oil and 2 trillion cubic feet of natural gas, a 50-percent probability of 200 million barrels and 6 trillion cubic feet, and a 10-percent probability of 600 million barrels and 11 trillion cubic feet. Our estimates of onshore oil potential are similar to those of Circular 725 and the NPC, except for the anomalously high estimate of undiscovered potential in the former. Both the NPC and PGC appear to overstate substantially the onshore gas potential, given the limited success of deep exploration in the region to date. The other estimates of offshore potential, having been made before recent exploratory drilling, appear to have insufficiently risked the source rock potential of the area.

NATIONAL SUMMARY

Our regional assessments of ultimately recoverable amounts of crude oil and natural gas in the United States are summarized in Tables 5.13 and 5.14. We organize the regions into three broad areas: (1) the onshore lower 48, (2) the offshore lower 48, and (3) Alaska, both onshore and offshore. The subtotal and total amounts are the arithmetic summations of the different ranges of the regional reserve growth estimates and the statistical summations of the regional cumulative probability distributions for undiscovered recoverable resources. We have rounded off the estimates for known recovery, reserve growth, and undiscovered recovera-

Table 5.13

ESTIMATED ULTIMATE RECOVERABLE AMOUNTS OF CRUDE OIL IN THE UNITED STATES
(In billions of barrels)

Region	Known Recovery[a]	Reserve Growth[b]	Undiscovered[c]	Ultimate Recovery[d]
Onshore Lower 48				
2. California	22.8	3.1-6.7-12.9	0.2-0.5-0.8	26-30-37
3. Rocky Mountains	10.1	0.9-2.0--3.4	1.6-2.1-2.6	13-14-16
4. Permian Basin	26.6	3.2-7.2-13.0	0.2-0.4-0.7	30-34-40
5. North Central Texas	4.9	0.7-1.3--2.3	0.1-0.2-0.4	6--6--8
6. Mid-Continent	19.7	1.9-5.2--9.2	0.2-0.4-0.8	22-25-30
7. Western Gulf	14.0	1.1-2.3--4.1	0.1-0.2-0.3	15-17-18
8. Central Gulf	9.7	0.8-1.7--3.0	0.1-0.2-0.4	11-12-13
9. Northern Gulf	12.9	0.3-1.1--2.2	0.1-0.2-0.3	13-14-15
10. Eastern Gulf	2.6	0.2-0.4--0.7	0.1-0.2-0.4	3--3--4
11. Illinois-Michigan	4.7	0.4-1.0--1.9	0.1-0.2-0.4	5--6--7
12. Appalachian	3.8	0.3-1.0--2.2	*--0.1-0.1	4--5--6
Subtotal	131.7	13.0-29.9-54.9	4.0-4.7-5.5	149-166-192
Offshore Lower 48				
2. California	0.9	0.6-0.9--1.4	1.0-1.7-3.2	3--4--6
7. Western Gulf	0.3	0.0-0.0--0.1	0.1-0.2-0.3	*--1--1
8. Central Gulf	7.5	1.0-1.9--3.4	0.6-1.0-1.6	9-10-13
10. Eastern Gulf	0	0	0-- 0.1-0.4	0--*--*
12. Atlantic	0	0	0-- 0.2-0.6	0--*--1
Subtotal	8.7	1.6-2.8-4.9	2.3-3.3-5.1	13-15-19
1. Alaska	10.7	1.8-3.5-6.0	6.5-11.2-23.4	19-25-40
U.S. total	151.0	16.4-36.2-65.8	14.4-19.6-32.0	182-207-249

NOTE: An asterisk (*) indicates that the amount is either less than 0.05 (undiscovered) or 0.5 (ultimate recovery) billion barrels.

[a]All crude oil in fields discovered before 1976 produced or known to be recoverable as of 1979.

[b]Anticipated additions to recoverable amounts in all fields discovered before 1976.

[c]Anticipated recovery from all fields discovered after 1975.

[d]The sum of known recovery, reserve growth, and undiscovered.

ble resources to the nearest 100 million barrels or 100 billion cubic feet. The estimates for ultimate recovery are rounded off to the nearest billion barrels or trillion cubic feet.

Our regional assessments of ultimately recoverable amounts of natural gas liquids in the United States are summarized in Table 5.15. To estimate future reserve growth in natural gas liquids, we generally assumed that the amount of natural gas liquids per million cubic feet of natural gas would be approximately the same in future reserve additions to known fields within a region as the historic ratio between the two (the historic national average is approximately 32 barrels per million cubic feet, as calculated from Table 3.1). In a few regions, we assumed that this proportion will grow, continuing recent trends. The estimates of the undiscovered potential were made using our judgments about the probable characteristics of future natural gas discoveries by region. Because we foresee relatively little associated-dissolved natural gas, which generally is rich in liquids, and substantial

Table 5.14

ESTIMATED ULTIMATE RECOVERABLE AMOUNTS OF NATURAL GAS IN THE UNITED STATES
(In trillions of cubic feet)

Region	Known Recovery[a]	Reserve Growth[b]	Undiscovered[c]	Ultimate Recovery[d]
Onshore Lower 48				
2. California	31.8	1.2-3.3--6.5	0.7--1.8--3.4	34--37--42
3. Rocky Mountains	44.0	3.9-9.9-16.0	22.7-31.7-44.7	71--86-105
4. Permian Basin	73.4	1.8-4.4--9.6	2.4--5.2--9.8	78--83--93
5. North Central Texas	10.8	0.3-0.9--1.8	0.8--1.6--2.8	12--13--15
6. Mid-Continent	152.0	6.1-15.4-30.7	4.8-10.1-17.6	163-178-200
7. Western Gulf	117.6	0.6-2.1--4.7	3.2-6.8--11.5	122-127-134
8. Central Gulf	90.9	3.0-8.0-16.0	5.2--7.8-12.4	99-107-119
9. Northern Gulf	53.4	0.9-2.3--4.2	2.8--4.3--6.3	57--60--64
10. Eastern Gulf	7.8	0.2-0.5--1.2	1.4--2.5--4.3	9--11--13
11. Illinois-Michigan	3.5	0.1-0.3--0.6	1.1--1.6--2.4	5---5---7
12. Appalachian	39.3	3.2-6.1--9.4	3.9--6.2-10.7	46--52--59
Subtotal	624.5	21.3-54.5-100.9	68.3-82.6-99.4	714-762-825
Offshore Lower 48				
2. California	1.4	0.7-1.4--6.5	2.2--3.3--5.1	4---6---9
7. Western Gulf	12.8	0.4-1.0--1.8	6.2-10.0-14.9	19--24--30
8. Central Gulf	78.3	4.0-10.0-19.0	8.9-13.8-20.8	91-102-118
10. Eastern Gulf	0	0	0.8--1.4--2.7	1---1---3
12. Atlantic	0	0	1.8--5.5-11.3	2---6--11
Subtotal	92.5	5.1-12.4-23.4	27.2-35.4-45.6	125-140-162
1. Alaska	33.9	2.1-4.4--6.6	31.3-49.0-83.8	67--87-124
U.S. total	750.9	28.5-71.3-130.9	142.5-169.7-209.0	922-992-1091

[a] All natural gas in fields discovered before 1976 produced or known to be recoverable as of 1979.

[b] Anticipated additions to recoverable amounts in all fields discovered before 1976.

[c] Anticipated recovery from all fields discovered after 1975.

[d] The sum of known recovery, reserve growth, and undiscovered.

amounts of deep gas, which generally has little or no liquids, we estimate that the average liquids content in the undiscovered recoverable amounts of natural gas will be about 22 to 23 barrels per million cubic feet. We estimate that the liquids content in most regions will be between 10 and 25 barrels per million cubic feet. The national average is increased substantially by our estimate of rich gas-condensate discoveries in the Overthrust Belt. Because of the relatively small amounts involved, all of the estimates are rounded off to the nearest 100 million barrels.

The outlook for conventional petroleum resources in the United States can at best be characterized as only moderately promising. We estimate that there is a 90-percent probability that ultimate recovery will be greater than 180 billion barrels of crude oil, 920 trillion cubic feet of natural gas, and 28 billion barrels of natural gas liquids, a 50-percent probability that it will be greater than 210 billion barrels of crude oil, 990 trillion cubic feet of natural gas, and 30 billion barrels of natural gas liquids, a 10-percent probability that it will be greater than 250 billion

Table 5.15

ESTIMATED ULTIMATE RECOVERABLE AMOUNTS OF NATURAL GAS LIQUIDS IN THE UNITED STATES
(In billions of barrels)

Region	Known Recovery[a]	Reserve Growth[b]	Undiscovered[c]	Ultimate Recovery[d]
Onshore Lower 48				
2. California	1.2	*-0.1-0.3	* - * -0.1	1.3-1.4-1.6
3. Rocky Mountains	1.2	0.1-0.3-0.4	1.1-1.4-1.8	2.5-2.9-3.4
4. Permian Basin	3.8	0.1-0.2-0.5	* -0.1-0.1	3.9-4.1-4.5
5. North Central Texas	0.7	*-0.1-0.1	* - * - *	0.7-0.8-0.9
6. Mid-Continent	4.8	0.2-0.5-1.2	* -0.1-0.2	5.1-5.4-6.2
7. Western Gulf	3.8	* -0.1-0.2	0.1-0.1-0.2	3.9-4.0-4.1
8. Central Gulf	3.0	0.1-0.3-0.6	0.1-0.2-0.3	3.2-3.4-3.8
9. Northern Gulf	2.2	*-0.1-0.2	0.1-0.1-0.1	2.3-2.4-2.5
10. Eastern Gulf	0.3	* - * -0.1	* -0.1-0.1	0.4-0.4-0.5
11. Illinois-Michigan	0.2	* - * - *	* -0.1-0.1	0.3-0.3-0.4
12. Appalachian	0.5	* -0.1-0.1	* -0.1-0.1	0.6-0.6-0.7
Subtotal	21.9	0.7-1.8-3.7	1.9-2.3-2.8	24.5-26.0-28.3
Offshore Lower 48				
2. California	*	* -0.1-0.1	* -0.1-0.2	0.1-0.2-0.3
7. Western Gulf	0.1	* - * - *	0.1-0.1-0.2	0.1-0.1-0.2
8. Central Gulf	1.8	0.1-0.2-0.5	0.1-0.2-0.3	2.0-2.3-2.6
10. Eastern Gulf	0	0	* - * -0.1	* - * -0.1
12. Atlantic	0	0	* -0.1-0.2	* -0.1-0.2
Subtotal	1.9	0.2-0.3-0.6	0.4-0.6-0.8	2.5-2.8-3.3
1. Alaska	0.4	* -0.1-0.1	0.6-1.0-1.7	1.0-1.5-2.2
U.S. total	24.2	0.9-2.2-4.4	3.2-3.9-4.8	28.3-30.3-33.4

NOTE: An asterisk (*) indicates that the amount is less than 0.05 billion barrels.

[a] All natural gas liquids in fields discovered before 1976 produced or known to be recoverable as of 1979.

[b] Anticipated additions to recoverable amounts in all fields discovered before 1976.

[c] Anticipated recovery from all fields discovered after 1975.

[d] The sum of known recovery, reserve growth, and undiscovered.

barrels of crude oil, 1090 trillion cubic feet of natural gas, and 33 billion barrels of natural gas liquids, and a 1-percent probability that it will be greater than 290 billion barrels of crude oil, 1180 trillion cubic feet of natural gas, and 35 billion barrels of natural gas liquids.[7]

At these levels of ultimate resources, it is likely that more than half of the conventional petroleum resources that will be ultimately produced in the United States has already been produced. At the end of 1979, cumulative production totaled 120.7 billion barrels of crude oil, 578 trillion cubic feet of natural gas, and 19.1 billion barrels of natural gas liquids. We estimate only about a 10-percent probability that ultimate recovery of petroleum liquids (crude oil and natural gas liquids) and natural gas will be at least double cumulative production. At the 90-percent probability level, nearly two-thirds of the petroleum liquids and natural

[7] These and subsequent national estimates used in the text are rounded off from the tables to avoid conveying a false sense of precision about our estimates.

gas that will ultimately be produced have already been produced. (See Figs. 5.1 and 5.2.) Moreover, taking the range between the 90- and 10-percent probability levels as the most likely set of possibilities, we estimate that the amounts that will be produced after 1979 vary between only 20 and 44 years of crude oil production, 17 and 26 years of natural gas production, and 13 and 21 years of natural gas liquids production at 1979 levels.

The large majority of conventional petroleum that will ultimately be produced is in fields that were discovered before 1976. At our median estimates of ultimate recovery, nearly 90 percent of the crude oil, nearly 83 percent of the natural gas, and nearly 87 percent of the natural gas liquids are in fields discovered before 1976. In most regions, the amounts that remain to be discovered are an even smaller proportion of ultimate recovery. Nationwide, we estimate that more natural gas remains to be discovered (most likely 140 to 210 trillion cubic feet) than will probably be added to reserves in known fields (most likely 30 to 130 trillion cubic feet). However, the majority of future additions to crude oil reserves will come from reserve growth in known fields (most likely 16 to 66 billion barrels), not new discoveries (most likely 15 to 32 billion barrels). Overall, the recovery factor in known fields nationwide should increase from its present level of about 33.5 percent of oil in place to about 35.5 percent (90-percent probability), about 38.5 percent (50-percent probability), about 42.5 percent (10-percent probability), and about 46 percent (1-percent probability). Significantly higher prices beyond our $40 resource cost limit could raise the recovery factor even more. However, the effect of higher prices at this range would be primarily an indirect one, the result of the long-term impetus higher prices would provide to major innovations in recovery technology. Because it is difficult to conceive the characteristics and economics of future major innovations in recovery technology, estimating their potential effects is too speculative to be included in this report.

There are fundamental reasons for this assessment. Put simply, large amounts of petroleum will be discovered only if giant and large fields are discovered. There is only one major producing province—the Bend Arch—in the United States for which this generalization does not hold, and it is both one of the smallest of the major provinces and a type of province that is not encountered in the frontier regions. Moreover, once a province or an area within a province is open to exploration, these giant and large fields are discovered relatively early, either because they are obvious to modern exploration techniques or because they cover large areas. If new exploration plays are conceived later in the exploration process, they are likely to consist of smaller fields, unless they were technologically, economically, or politically inaccessible to earlier exploratory drilling.

The United States, particularly the lower 48 onshore area, is the most intensively explored country in the world. Despite this intensity of exploratory drilling, a good number of attractive prospects are yet to be drilled. But these remain primarily because they are in areas (1) where the complex geology frustrated early explorationists, (2) which were inaccessible to earlier exploration and drilling technologies, (3) which were closed to exploration by political decisions, or (4) which were uneconomic. Very few giant and large accumulations remain undiscovered in the lower 48 onshore United States that do not belong in at least one of the first three categories. Giant and large discoveries are more probable both offshore and in Alaska. Nonetheless, the exploratory drilling that has occurred in the provinces of

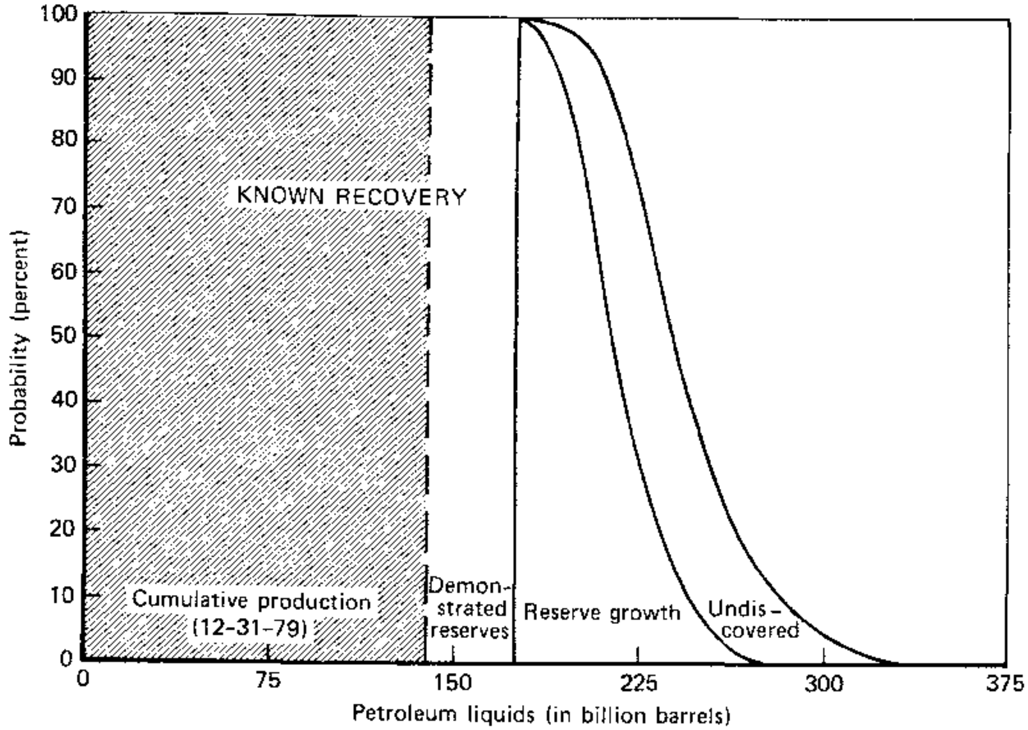

Fig. 5.1—Estimated ultimate recovery of conventional petroleum liquids in the United States (cumulative percent probability distribution)

these regions has indicated that many of these frontier provinces suffer from basic geological deficiencies.

Our most likely range of remaining undiscovered petroleum resources in the United States assumes that approximately 250 to 370 more significant oil and gas fields will be discovered onshore in the lower 48 states after 1976. Approximately 55 to 60 percent will be Class C fields. Our most likely range for the offshore lower 48 states assumes approximately 170 to 230 more significant oil and gas discoveries, about 40 percent of which will be Class C fields in the Gulf of Mexico. At an average size of 3.0 million barrels' L&LE for a Class D field and 0.25 million barrels' L&LE for a Class E field, approximately 1100 to 1500 Class D fields and 13,000 to 18,000 Class E fields will most likely be discovered in the lower 48 states after 1976.

The size distribution of future discoveries will thus be substantially different from that of past discoveries. In the lower 48 states, small (Class B and C) and very small (Class D and E) fields should account for slightly more than half the amount remaining to be discovered (compared with less than 20 percent of past discoveries). Giant fields will account for less than 10 percent of the amount discovered. Nationwide, the North Slope and Beaufort Sea of Alaska offer the best probability of future giant field discoveries. Both the Chukchi Sea and the Bering Sea provinces may also have giant fields. The Rocky Mountain region has the best probability of one or more giant discoveries in the lower 48 states. The Atlantic and California offshore regions have a very low probability, when risked, of more giant discover-

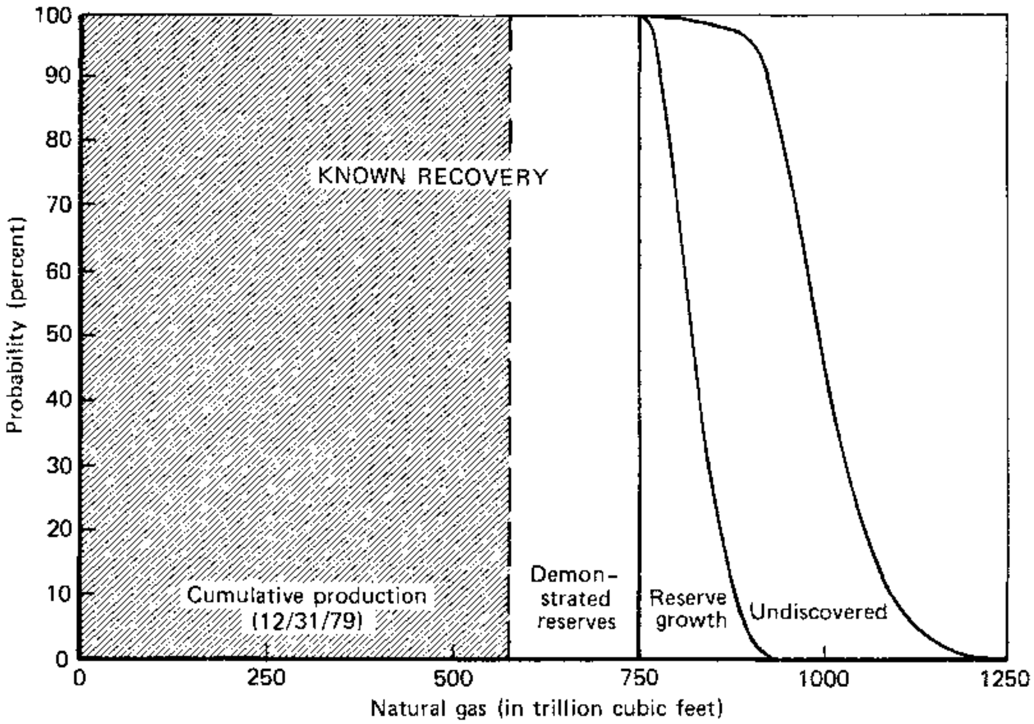

Fig. 5.2—Estimated ultimate recovery of conventional natural gas in the United States (cumulative percent probability distribution)

ies. The only other regions of the country in which giant discoveries have any meaningful possibility are the Mid-Continent, Central Gulf onshore, Appalachian (deep giant gas discoveries), and the deepwater offshore Central Gulf.

Taking into account the combined effects of reserve growth and new discoveries, we estimate that 3200 significant fields, plus or minus 200, will be ultimately discovered and developed in the United States. Approximately 80 percent of these fields will have been discovered before 1976. Approximately 100 of these, plus or minus 10, will be giant fields. These giant fields will account for nearly 50 percent of ultimate production of crude oil and slightly more than 40 percent of ultimate recovery of natural gas and natural gas liquids. Another 900 of these significant fields, plus or minus 40, will be large fields. The remaining 2200, plus or minus 150, will be Class B and C fields.

Beyond making Alaska and the Rocky Mountain region more important, future discoveries and reserve growth are unlikely to alter the relative rank of the regions of the United States as sources of petroleum. We consider Alaska and secondarily the Rocky Mountain region, offshore California, and the offshore Central Gulf to have the greatest potential for the discovery of substantial amounts of crude oil. The potential for major reserve growth in crude oil fields is concentrated in the Permian Basin, onshore California, the Mid-Continent, and Alaska. We consider Alaska, the Rocky Mountain region, the onshore and offshore Central and Western Gulf regions, and the Mid-Continent to have the best potential for the discovery of substantial amounts of natural gas. The potential for reserve growth in known natural gas fields is best in the Mid-Continent, the onshore and offshore Central Gulf, and the Rocky Mountain region. Because the potential for new reserves, whether from reserve growth or new discoveries, is spread throughout the major petroleum-producing regions, most are likely to retain their current relative national importance.

COMPARISONS WITH OTHER ESTIMATES

Because many estimates of the petroleum potential of the United States have been made, comparisons between our estimates and others are unavoidable. Such comparisons can play a valuable part in the process of resource estimation, highlighting key differences in method, logic, evidence, and attitude toward risk among estimators. But if comparisons are to assist the process of resource estimation, they must be made carefully. Comparing estimates of ultimate recovery is only the beginning of the task of comparison. Proper comparisons should also include consideration of the composition of the estimates, the conceptual boundaries of each estimate, and the time when each estimate was made. Numerical estimates of ultimate recovery can be very similar and yet in reality quite different, incorporating dissimilar assumptions about geographic extent, economic limits, and technology. Conversely, numerical estimates of ultimate recovery may differ substantially, but only because they have different assumptions about geographic extent, economics, and technology. One estimate may differ from another primarily because it was made at a later date, benefiting from access to better information. Moreover, small differences among estimates should not be overemphasized. Because of the many uncertainties inherent in the task of resource estimation, differences as great as 50 percent more or 33 percent less in estimates (at the same probability level) of undiscovered potential are generally within the range of legitimate differences in professional opinion. Only differences of 100 percent more or 50 percent less between conceptually similar estimates of undiscovered potential can be considered serious differences.

Our estimates of the ultimate petroleum potential of the United States are considerably lower than most other recent estimates. In most cases, these differences are real, not conceptual. Tables 5.16 and 5.17 show our estimates of ultimate recovery of crude oil and natural gas compared with the more prominent estimates made during the past decade. Besides the three estimates we considered in our regional assessments by the National Petroleum Council, the U.S. Geological Survey, and the Potential Gas Committee, we show five other estimates, two by major oil companies (Exxon[8] and Mobil[9]), one by the National Academy of Sciences (NAS),[10] and two by King Hubbert,[11] possibly the best-known estimator of U.S.

[8] J. D. Langston, "A New Look at the U.S. Oil and Gas Potential," paper presented at the Sixteenth Annual Institute on Petroleum Exploration and Economics, Dallas, March 10, 1978.

[9] As reported in J. West, "U.S. Oil-Policy Riddle: How Much Left To Find?" *The Oil and Gas Journal*, September 16, 1974, pp. 25-28.

[10] *Mineral Resources and the Environment*, Washington, D.C., 1975.

[11] M. K. Hubbert, "Techniques of Prediction as Applied to the Production of Oil and Gas," paper presented before the Symposium on Oil and Gas Supply Modeling, Washington, D.C., June 1980; idem,

Table 5.16

Recent Comparative Estimates of Ultimate Recovery of Crude Oil in the United States
(In billions of barrels)

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
Lower 48 Onshore				
This Report (12-31-75)	132	13-31-56	4-5-6	149-166-192
Mobil (12-31-72)	119	N.E.	-13-	-132+-
Circular 725 (12-31-74)	125	14	29-44-64	169-184-204
NPC (12-31-70)	116	25	76	217
Lower 48 Total				
This Report (12-31-75)	140	15-34-61	7-8-10	162-182-211
Hubbert (12-31-79)	137	N.E.	24-26-28[a]	161-163-165
Hubbert (12-31-72)	126	17	29	172
Circular 725 (12-31-74)	134	17	36-55-81	187-206-232
NPC (12-31-70)	122	26	106	254
United States Total				
This Report (12-31-75)	151	16-36-66	14-20-32	182-207-249
Mobil (12-31-72)	136	N.E.	-88-	-214-
Hubbert (12-31-72)	136	24	55	215
Circular 725 (12-31-72)	145	23	50-82-127	218-250-295
Exxon (12-31-74)	140	57	32-55-90	229-252-287
NPC (12-31-70)	132	28	161	321
NAS (12-31-72)	136	105	113	354

[a]This estimate is most likely the sum of some traditional reserve growth and new discoveries.

petroleum resources over the past 20 years. The tables give estimates for the lower 48 onshore, the entire lower 48, and the entire United States. The estimates are listed after our own in order of increasing amount.

Our estimates differ significantly from most of those shown in the two tables with respect to what remains to be discovered. Except for some estimates of future reserve growth in known natural gas fields, our range of estimates for reserve growth generally encompasses the point estimates of the others, particularly when considering the conceptual differences among the estimates. The apparent differences in reserve growth between the others and ours are because we include and they exclude enhanced oil recovery. If we exclude enhanced oil recovery potential from our estimate of future crude oil reserve growth at the 10-percent probability level, our estimate for the United States would be about 15 to 20 billion barrels, a level only slightly less than the estimates of Hubbert and Circular 725. The high estimates of reserve growth in natural gas are primarily the result of applying historic appreciation factors to recent discoveries in the Gulf Coast regions. We consider these factors to be inapplicable, not only because today's market condi-

U.S. Energy Resources: A Review as of 1972, Senate Committee on Interior and Insular Affairs, Washington, D.C., June 1974; and idem, "Energy Resources," in National Academy of Sciences, *Resources and Man*, W. H. Freeman and Company, San Francisco, 1969.

Table 5.17

RECENT COMPARATIVE ESTIMATES OF ULTIMATE RECOVERY OF NATURAL GAS IN THE UNITED STATES
(In trillions of cubic feet)

Estimate	Known Recovery	Reserve Growth	Undiscovered	Ultimate Recovery
		Lower 48 Onshore		
This Report (12-31-75)	625	21-55-101	68-83-99	714-762-825
Mobil (12-31-72)	606	N.E.	-65-	-671+-
PGC (12-31-76)	619	141	-235-410	-995-1170
Circular 725 (12-31-74)	616	119	246-345-453	981-1080-1188
NPC (12-31-70)	591	N.E.	605	1196+
		Lower 48 Total		
This Report (12-31-75)	717	26-67-124	102-119-138	922-992-1091
Hubbert (12-31-79)	734	N.E.	106-136-162[a]	840-870-896
Hubbert (12-31-66)	604	222	218	1044
PGC (12-31-76)	698	192	-318-556	-1208-1446
Circular 725 (12-31-74)	685	187	286-408-529	1158-1280-1401
NPC (12-31-70)	647	N.E.	851	1498
		United States Total		
This Report (12-31-75)	751	29-71-131	143-170-209	922-992-1091
Exxon (12-31-74)	714	111	190-287-405	1015-1112-1230
Mobil (12-31-72)	699	N.E.	-443-	-1142+-
NAS (12-31-72)	699	N.E.	530	1229
PGC (12-31-76)	731	215	-363-758	-1276-1671
Circular 725 (12-31-74)	718	202	322-484-655	1242-1404-1575
NPC (12-31-70)	679	N.E.	1178	1857

[a]This estimate is most likely the sum of some traditional reserve growth and new discoveries.

tions are different from those that prevailed at the time of discovery but also because the geology of the more recent discoveries is simpler, on average.

On undiscovered resources, we differ with some estimates primarily over the potential of frontier areas (offshore and Alaska). For other estimates, the differences are profound for both the frontier areas and the lower 48 onshore. The differences between our estimates and those of Exxon and Mobil are almost entirely of the former type. We believe this is primarily the result of differences in the time each estimate was made. We could discount the high hopes once held for these regions because we had the advantage of information gained from a substantial number of dry holes offshore and in Alaska that occurred after the Exxon and Mobil estimates were made. With similar adjustments, their range of estimates of ultimate recovery in the United States for both crude oil and natural gas are likely to overlap most of our own range of estimates.

The differences between our estimates and those of Circular 725, the NPC, the PGC, and, presumably, the NAS are not amenable to a similar reconciliation. There are fundamental differences between their estimates and our own regarding the potential of the onshore lower 48. The Circular 725 and NPC estimates of the undiscovered crude oil potential of the onshore lower 48 are an order of magnitude larger than ours. Their estimates, and those of the PGC and NAS, for the undiscovered natural gas potential of this area are roughly three to five times larger than ours. Moreover, their estimates are substantially higher than ours even though their economic, geographic, and technological assumptions are considerably more conservative than our own.

We do not believe that anyone could develop a plausible list of geologic prospects (including probable trap types, depth, formation, and field size) in the lower 48 onshore containing an amount of petroleum even approaching the estimates of Circular 725, the NPC, and the PGC. The number of fields involved is staggering. For example, assuming the same proportional distribution of undiscovered resources among field sizes as we do in our median estimate of lower 48 onshore potential, the mean estimates alone of Circular 725 for undiscovered resources of crude oil, natural gas, and natural gas liquids for the lower 48 onshore would require nearly 1700 more significant discoveries (including almost as many Class C fields as have already been discovered in the entire United States), about 6000 Class D discoveries, and over 70,000 Class E discoveries. By comparison, we counted only 57 significant discoveries in the onshore lower 48 from 1971 to 1975. Further, the Committee on Statistics of Drilling of the American Association of Petroleum Geologists estimates, after a three-year review, that there were 455 Class D discoveries and 3041 Class E discoveries in the entire United States between 1972 and 1976.

If such large numbers of significant fields are to be discovered, a wholesale reversal of historic discovery patterns by field size would be required. Such a reversal has no historic precedent. It could occur only if one assumed that *every* exploration geologist, geophysicist, and geochemist working in the United States over the past 40 years had been operating with massive mental blinders, which rendered them oblivious to such a great and lucrative potential.[12] This is most unlikely given the wealth of subsurface geological information available from the intensive drilling that has occurred in the United States, the great variety of exploratory hypotheses that have been pursued over the past several decades, and the major advances in exploratory technology and geological understanding that have occurred during this same period.

The differences among the estimates of Tables 5.16 and 5.17 are attributable primarily to differences in method. The estimates of Circular 725, the NPC, and the PGC were developed using a basin-by-basin volumetric yield approach, emphasizing the potential of the total volume of sedimentary rocks within each basin. The Exxon and Mobil estimates were developed using a more focused volumetric approach, emphasizing the effective volume of reservoir rocks trapped in specific plays and prospects fed by effective source materials. Our approach combines such specific geologic analyses with an analysis and extrapolation of disaggregated discovery trends and patterns. The estimates of King Hubbert, those closest to our own for undiscovered resources, are based on various extrapolations of aggregate discovery trends. Adjusting for conceptual differences in reserve growth (Hubbert's estimate of ultimate recovery of crude oil does not include enhanced oil recovery to any appreciable degree), Hubbert's estimates are closest to our own. Despite his

[12] There is an important asymmetry at work here. If a field is to be found, only *one* person or company with the right idea is needed to find it. However, if a field is to be missed, *all* of the people and companies exploring an area must miss it.

widespread reputation for pessimism about the petroleum resource outlook, in our judgment Hubbert was, if anything, too optimistic about future discoveries.

We began this report with the aphorism "Oil is first sought in our minds." Although coined four decades ago, this aphorism remains relevant today. Finding what oil is left to be discovered in the United States will require substantial exploratory creativity. The continuing relevance of exploratory creativity, however, should not obscure the fact that the need for creativity in petroleum exploration is now of less importance than the need for creativity in petroleum production. Whether we are speaking of conventional or of unconventional petroleum resources, we have already found the large majority of what we will ultimately find. The biggest challenge today is to develop economic means of producing more of what we have found. To rephrase our original aphorism, looking toward the future we need to remember that "Petroleum is first produced in our minds."

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The following list of sources is our working bibliography for preparing App. A, the significant oil and gas fields data base. The list also includes many of the sources that we used as background material for the petroleum resource assessments of Sec. V.

Because the bibliography has over a thousand entries, we have organized it into 13 major sections, one for the United States as a whole and one for each of our 12 regions. We have further broken down most of these sections into smaller groupings, the typical regional breakdown being a general grouping for the region as a whole and individual groupings for each state or statistical area within the region. Within each grouping, we list the more important sources first (in alphabetical order), following them with less important sources (also in alphabetical order).

Despite its length, the bibliography is not comprehensive. Specifically, we did not include the many articles on U.S. oil and gas fields that have been published in the *American Association of Petroleum Geologists Bulletin* over the past sixty years. These can be located in the bibliographies of AAPG publications that we do list, particularly with the use of the bibliography of North American oil and gas fields from AAPG publications by E. M. Tidwell.

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