NRC NAS NAE IOM

Scientific Drilling and Hydrocarbon Resources

Committee on Hydrocarbon Research Drilling
Board on Mineral and Energy Resources
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

DOE/ER/12018--T2

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NATIONAL ACADEMY PRESS
Washington, D.C.
1988

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

Support for this project was provided by the U.S. Department of Energy.

Copies available from

Board on Mineral and Energy Resources
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

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PREFACE

Over the past several years the Geosciences Program of the Department of Energy's Office of Basic Energy Sciences (OBES) has been placing increased emphasis on basic geosciences studies relating to hydrocarbon resources. In December 1985, Secretary of Energy John S. Herrington called upon the Department's Energy Research Advisory Board (ERAB) to initiate a study of geosciences research as an important endeavor for the DOE. The ERAB report, issued in February 1987, recommended an expansion of short- and intermediate-term hydrocarbon research while maintaining a long-term basic research program. During this period, interest was expressed in both houses of Congress in the strengthening of the Department's basic and applied research efforts in areas pertaining to hydrocarbon resources.

The Geosciences Program of OBES and the Office of Fossil Energy have reflected this increased interest. The research supported by the OBES Geosciences Program has included scientific drilling as part of further study of the continental crust.

In 1987, the Department of Energy asked the National Research Council (NRC) to appoint a committee to review scientific drilling options to contribute to a better understanding of the scientific foundations that underlie hydrocarbon technologies.

In response to this request, the NRC established the Committee on Hydrocarbon Research Drilling in September 1987 under the Board on Mineral and Energy Resources. The committee consisted of 10 geoscientists from academia, industry, and government with a broad range of relevant technical and scientific expertise.

The committee was asked to address the following questions:

1. What sorts of Continental Scientific Drilling efforts are likely to contribute in a major way to a deeper understanding of the scientific foundations that underlie hydrocarbon resource technologies? Is a separate initiative in this area justified scientifically?

2. If appropriate efforts are identified in response to (1), what criteria should be used in the selection of drilling sites and projects?

3. What particular sites, or classes of sites, if any, are clearly known to be especially interesting, and, for the sites identified, what are the key scientific issues likely to be illuminated?

Following a planning meeting in October 1987, the committee met as a whole six times, in Washington, Dallas, San Francisco, and Austin. In addition to drawing on the experience of its own members, the committee obtained information from the Department of Energy, the U.S. Geological Survey, the Gas Research Institute, and individual scientists and engineers who attended the meetings.

In considering its charge, the committee focused on research involving, first, scientific drilling to benefit national hydrocarbon energy priorities; second, areas of hydrocarbon research not being undertaken by industry; and third, how scientific drilling could contribute to such research. The committee also considered criteria for selecting drilling sites and projects, and has suggested sites, or classes of sites, as appropriate.

The committee's recommendations include research ranging from exploration to extraction, from reservoir characterization to deep drilling in unknown terrains, and a full spectrum of applied and basic research.

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Over three million holes have been drilled in the search for oil and natural gas in the United States, something on the order of 80 percent of all holes ever drilled for this purpose in the world. Most of these drill holes, and especially the deeper wells, have been drilled in the search for and the development of hydrocarbons. Is such drilling density yet inadequate to understand the crustal geology of the United States? Are there basic scientific problems yet to be solved with the drill? Are there aspects of the remaining resource base of oil and natural gas that justify a publicly supported research drilling effort? The committee concludes that the answer to these questions is yes.

In the recovery of hydrocarbons, our knowledge of the geologic complexity of reservoirs and the behavior of fluids relative to these complexities is such that we still develop reservoirs with wells uniformly spaced, utilizing geography, not geology. Two-thirds of the oil remaining in existing reservoirs is classed as unrecoverable. A knowledge of reservoirs sufficient to exploit them strategically is generally beyond our present reach. Further, in many of the extensively drilled basins, the deeper half of basin fills, which are most productive and the presumed source of hydrocarbon generation, are largely undrilled and unknown. Other frontier areas have been virtually untouched by the drill, and despite remarkable advances in geophysical techniques, many terrains are seismically obscure and uninterpreted. Even in parts of basins presumed to be well known, many aspects defined by advanced seismic profiling methods have yet to be verified by carefully designed transects of drill holes.

The petroleum industry has gathered, and will continue to gather, a wealth of basic data on the occurrence and production of oil and gas. Most of this research is carried out by a few major companies, whereas more than half of continental U.S. production is accomplished by the over 20,000 smaller independent oil companies. Moreover, the research programs of the major companies tend to focus on relatively high-potential, high-risk discoveries in remote parts of the United States and abroad. As a result private sector research may not furnish adequate information on more efficient incremental recovery from existing fields.

Accordingly, the committee concludes that major research frontiers exist, and that a systematic hydrocarbon research drilling program supported by the federal government and conducted complementary to and, as appropriate, in cooperation with private industry and individual states should be pursued. Research drilling is proposed in four main areas:

1. Comprehensive characterization of complex reservoirs for the development of advanced, predictive geological and fluid behavior models to enable optimal hydrocarbon recovery from existing reservoirs.

2. Controlled transects drilled across sedimentary basins within integrated geological and geophysical frameworks to improve fundamental knowledge of basin architecture.

3. Seismically obscure terrains hostile to geophysical imaging, to more fully understand and assess their hydrocarbon potential.

4. Deep, untested portions of productive basins and sparsely drilled frontier basins, to increase basic understanding and to improve capabilities for hydrocarbon assessment.

For the recommended scientific drilling program to be effective and to achieve maximum potential, it is critical that the drilling not be done in isolation, but rather in the broadest possible context. Each site should be evaluated strategically for maximum scientific value. Pre-drilling geophysical studies and evaluations of all existing relevant data should be accomplished. Most research holes should be maintained for long-term monitoring and testing, and all data obtained should be carefully archived. Annual budgets supporting the recommended program should devote about one-third to one-half of the funds to research and non-drilling expenditures, and the balance to actual drilling costs.

The conterminous United States has a substantial resource of hydrocarbons yet to be discovered as well as large volumes suitable for advanced recovery. Improved utilization of this resource is essential if we are to reduce the growing dependency of the United States on foreign hydrocarbon sources. A systematic program of hydrocarbon research drilling, reaching a support level of $200 million annually in three to five years, could be a major contributor in such efforts.

Chapter 1

HYDROCARBON RESEARCH DRILLING

1.1 INTRODUCTION

The discovery and recovery of additional domestic hydrocarbon resources can be enhanced by better understanding the nature of and changes occurring within the earth's crust. The drill is recognized as an essential scientific tool for aiding interpretation of crustal evolution, subsidence history, basin development, and the generation, migration, entrapment, and extraction of hydrocarbons. Employed in conjunction with other geological and geophysical tools, the drill provides information and insights that are unobtainable from other sources. The drill can provide data to prove an inference and the verification of a model, or data that can disprove or refute them.

The earth's crust is a complex arrangement of structures with diverse histories. How these structures formed, how basins are filled with sediments, how heat and compaction contribute to the formation of fossil fuels, how liquids migrate and become entrapped, how rocks and fluids behave when fluids are extracted, and the timing of the events, are questions to be further resolved by scientists involved in hydrocarbon studies. Such geological and geophysical investigations of the earth's surface require the drill to measure and sample the earth's crust directly.

Geoscientists know that extrapolating surface and near-surface geological and geophysical data to depth eventually requires substantiation achieved only by direct observation through drilling. The Energy Research Advisory Board (ERAB) report (1987) emphasized that:

> knowledge is inadequate about the origin, composition, structure, and processes of the continental crust, and the relationship of crustal structures and processes to energy resources . . . . Computer models . . . require actual testing for verification and validation. The ultimate geoscience test is scientific drilling.[1]

The ERAB report summarized specific geoscience study topics, especially crustal research initiatives, applicable to oil and gas environments, including:

- an improved understanding of the behavior of subsurface organic and inorganic fluids in rocks;
- a three-dimensional characterization of the internal properties and structures of rock bodies;
- in situ measurement in high-pressure and high-temperature environments in deep boreholes;
- modeling crustal structures and processes;
- testing crustal models through scientific drilling; and
- exploring the range of hydrocarbon generation in time and space.

1.2 RATIONALE FOR A HYDROCARBON RESEARCH DRILLING PROGRAM

The United States has a broadly based petroleum industry ranging from many one-to-two-person companies to large, multinational corporations. These companies have drilled in the United States more extensively than any nation on earth in the search and development of oil, natural gas, and other minerals, and a resulting extensive data base exists. Further, a recent survey by the National Petroleum Council, to be published in 1988, indicates that U.S. companies are spending in excess of $1 billion annually in petroleum-related research and development.

In considering the merits of a publicly supported hydrocarbon research drilling program, central questions emerge: Is such a program justifiable in view of the existing and historical effort of the U.S. petroleum industry? And if there is appropriate and justifiable research to do, will not the industry, with its large research laboratories, pursue such research in its own economic interest?

In light of these questions, the committee concludes that a major federally supported program in hydrocarbon research drilling, complementary to and, where appropriate and mutually desirable, in cooperation with industry, is justified. In reaching this conclusion we recognize the following:

1. A number of issues related to hydrocarbon formation, migration, and reservoir characterization are of basic scientific interest, long-term in possible application, and not necessarily of immediate concern to the private industry.

2. The U.S. petroleum industry consists of more than 20,000 entities. Internal research capabilities are limited to a dozen or so of the major companies. The vast bulk of the entities constituting the U.S. petroleum industry are the smaller companies and independent operators pursuing smaller reserve increments. They must, of necessity, maintain low overhead costs, and accordingly rely on external, chiefly public, sources for research concepts, techniques, and products. Historically, many independent operators have maintained some access to major company research and development through the mechanism of farm-outs with major companies (i.e., drilling on properties held by major companies for targets not necessarily a part of the lease-holder's strategy). Today, however, there are many areas of the country where the majors no longer maintain interest, and here this historical relationship does not exist.

3. The major companies with internal research structures are generally multinational in scope and interest. A significant part of their research and development expenditure is in support of activities abroad or activities in the United States that are focused in high-potential, high-risk areas such as the deepwater offshore, and hostile environments of the Arctic.

4. A substantial portion of industry research and development is, and will remain, proprietary. This is obviously appropriate to the competitive interest of the companies conducting and financing the research. Results of some of this research, over time, may be released for publication, but much of it never becomes available.

5. The character of the remaining U.S. resource base of oil and natural gas, especially on land in the lower 48 states, is an important consideration, where nearly two-thirds of the onshore oil is produced by smaller, independent operators. By most accounts the total volume of the remaining resource is quite large, but much of this potential resource can be converted to producible resources only in relatively small increments. This is because most future reserve additions, as those of the recent past, must come from discovery of relatively small fields, from extensions of existing fields either areally or vertically, by intensive development of existing fields through extended conventional means (geologically targeted infill drilling), and through deployment of advanced tertiary recovery processes (enhanced oil recovery).

Historically, major multinational oil companies and those commonly with internal research capabilities have logically based their competitive positions on access to large-volume fields. With the potential of large field discovery on-land in the United States largely realized, most major companies have turned their interest and their research investment to potential large field discovery in remote parts of the United States and, increasingly, abroad and offshore.

While economies of scale are realized with large-increment discoveries and production, the economic benefits from small-increment drilling and recovery must come from improved efficiencies, generally available only through specific research and development efforts.

Some major companies do pursue small-increment additions as part of their corporate strategy, and some may gear their research and development efforts to become more aggressive in that pursuit. Others will choose not to, and still others may restrict interest to what they perceive as the most attractive of small-increment targets. However, traditionally it has been the independent and smaller operator who has pursued the smaller-increment targets and who could most benefit from a publicly supported hydrocarbon research drilling program. Indeed, the maintenance of this substantial part of the U.S. petroleum industry may depend on increased efficiency gained by publicly available research and development.

The remaining large, but small-increment resource base in the United States is a real frontier, not extensively pursued and not the target of principal research expenditure, but one with substantial promise.

6. Finally, the committee recognizes that in addition to the private interest in pursuing hydrocarbon development profitably, there is also a profound public interest in the highest realizable level of domestic production of oil and gas. This public interest is manifest in concerns with trade balances, constrained levels of oil imports, reliability and stability of supply, and the economic benefits and stability that domestic development provides.

1.3 CURRENT RESEARCH DRILLING PROGRAMS

The total program of research drilling currently being supported in the United States is small. Drilling projects designed specifically for long-term research are sponsored and financed largely by government agencies. Most do not specifically address hydrocarbon resources research.

Stratigraphic test wells, generally contracted by a consortium of exploration groups, provide detailed information on the stratigraphy and lithology of geologic sections. An example is the Continental Offshore Stratigraphic Test (COST) program. The COST program has been effective in determining the geological character of strata in a number of U.S. offshore frontier regions, including Alaska, California, the Gulf of Mexico, and the Atlantic coast. Although the principal purpose of COST wells is to gather information for industry and government use in evaluating tracts to be leased, considerable scientific information can be gathered in the process. While COST wells have provided useful stratigraphic information for application in oil and gas exploration of some frontier areas, vast regions offshore remain with little or no well control. No comparable program of this magnitude exists onshore.

An occasional scientific hole is drilled with funds provided solely by a petroleum company's research laboratory, or in cooperation with the firm's operating affiliate. Such holes commonly involve proprietary research, and results may be retained by the investing company for extended periods of time.

An example of research based on holes financed by private companies is Project Upper Crust, designed and directed by geoscientists from the University of Kansas and now partly funded by the Deep Observation and Sampling of Earth's Continental Crust, Inc. (DOSECC) program. This project covers a large portion of the U.S. midcontinent region and has as its primary goal a better understanding of the midcontinent Proterozoic crust. The composition and age of the crust are being determined by the examination of cores and cuttings from completed commercial drill holes, and from "holes of opportunity" drilled by private companies or other groups. A hole of opportunity can provide the basis for a public extension of a privately drilled hole at very reasonable, if any, cost. It sometimes involves convincing the organization funding a drilling project to continue drilling into the basement complex in order to obtain samples of Precambrian rocks. Project Upper Crust scientists have obtained a large number of cores and cutting samples by this method in recent years. Other holes drilled by private companies might be deepened if there were a more coordinated and expanded program for disseminating information on drilling activities, and an organized program to take advantage of selected holes.

An interagency group comprising the Department of Energy (DOE), the U.S. Geological Survey (USGS), and the National Science Foundation (NSF) plans and coordinates the U.S. Continental Scientific Drilling Program. DOSECC, on behalf of the USGS and the NSF, manages part of the program. To date, the only dedicated drilling project is a

11,515-ft hole drilled in Cajon Pass, California and designed for research on the San Andreas fault.

An example of successful use of the drill as a scientific tool was the federally funded Deep Sea Drilling Project (DSDP). This multinational program, which is being continued as the Ocean Drilling Program (ODP), has produced data on the earth's crust that have changed basic geologic concepts. The DSDP was developed in the mid-1960s as a scientific program to explore the nature of the seafloor, the sedimentary units overlying the oceanic basaltic crust, and the oceanic crust itself. Drilling sites were chosen where geophysical data indicated worthwhile scientific targets and offered opportunities to maximize the yield of new scientific information.

In recent years, various units of the Department of Energy have participated in drilling projects with scientific goals, although these projects were not targeted to hydrocarbon research. These projects include the Hot Dry Rocks Program near Los Alamos, New Mexico, supported by the Office of Geothermal Energy, and drilling of potential geothermal regions with funds supplied by the Office of Basic Energy Sciences (OBES). The Salton Sea Project in California, also geothermally oriented, is basically a scientific drilling project. This well is presently at a depth of 10,564 ft and has been the source of significant new data contributing to improved understanding of active hydrothermal systems.

In a few instances, the DOE's Office of Fossil Energy has drilled holes to help evaluate the hydrocarbon potential of government-controlled lands. In some cases, such wells may provide a basis for acceptable lease bid levels; in other instances drilling has been a cooperative venture in testing a particular geologic environment.

Because these drilling projects are aimed chiefly at testing potential for production, the amount of research performed has been erratic; for example, under the Office of Fossil Energy, DOE drilled a 24,466-ft well in the Naval Petroleum Reserve No. 1 in California. The area, known as Elk Hills, is considered to have additional petroleum potential and is periodically reviewed for possible leasing to private exploration/development groups. The well, completed in 1987, was designed to drill through a thick section of sediments and penetrate crystalline basement, but was stopped in overlying sediments. Discussion within the scientific community regarding the site selection process and the scientific studies performed was held largely while drilling was in progress. Minimal pre-drilling seismic profiling was done; few scientific experiments were conducted while the hole was being drilled. The project was more of a wildcat exploration than a research drilling project. The hole probably could have been used for a number of research objectives, but it was not so designed, and its research potential was not realized.

Other nations are conducting or planning a number of extensive and costly research drilling projects with both direct and indirect bearing on hydrocarbons.[2] The Soviet Union has embarked on an ambitious drilling program with eight holes currently being drilled, and at least seven others in the planning stage. This program is designed to acquire a broad spectrum of geoscientific data while testing areas for resource potential. Approximately half of the drilling targets involve regions considered to have some oil or gas potential. The most publicized of these projects is on the Kola Peninsula in northwest Russia, where a world-record 12,065-m (39,557 ft) hole has been drilled over the past 18 years. Although the Soviets have published only limited information on scientific conclusions from the drill hole, some results have been reported. These include indications that liquids and gases have apparently seeped into the drill hole through fractures within the crystalline host rocks at great depths. The Soviet scientists also have stated that seismic reflection horizons detected by geophysical surveys on the surface were not identifiable in the drill hole. Thermal gradients increased unexpectedly below 3 km, resulting in temperatures in the range of $200^{o}C$ at a depth of 12 km. The target depth for the Kola Superdeep Drill Hole is 15 km (49,180 ft). A number of holes in the Soviet program identified specifically as hydrocarbon research projects have been drilled to depths of over 30,000 ft.

A scientific drilling project in the Federal Republic of Germany was begun in September 1987 to define an area of structural complexity in northwest Bavaria. Although the planned 12- to 14-km (40,000 ft) hole is not expected to provide specific hydrocarbon-related data, geologic and geophysical information from the drill hole will be applied in interpreting regional paleogeographic features. A $250 million commitment has been made by the German government to this project, which involves drilling a 3-km (10,000 ft) pilot hole before the deeper drilling is begun.

A third drilling project in Europe is the Gravberg No. 1, drilled in the Siljan meteorite impact structure of central Sweden. The hole was financed principally by the Swedish State Power Board in an attempt to penetrate a series of high-amplitude seismic reflectors, interpreted to possibly indicate significant concentrations of natural gas. The project had serious drilling problems and is currently dormant for lack of funds at a depth of 6,600 m (21,640 ft). Limited scientific experiments have been performed in the drill hole and on the few core samples recovered. The drilling fluid and rock cuttings were analyzed for gases. The three high-amplitude reflectors drilled to date have been identified as dolerite sills intruded into the granitic basement rocks. Apart from its problems, there had been an extensive program involving analysis of logs, drill samples and fluids collected from the hole. Elaborate geochemistry run on the fluids has provided much useful scientific information. A report in preparation by the Gas Research Institute (GRI) will document the findings.

1.4 GOALS OF A RESEARCH DRILLING PROGRAM

Numerous reviews have been made and conclusions drawn by groups both within and outside the Department of Energy regarding the growing need for additional hydrocarbon research. These studies, conducted over a span of 10 years, unanimously conclude that only a dedicated scientific drilling program and related scientific experiments can resolve particular questions concerning hydrocarbon formation and concentration.

After reviewing previous recommendations and accessing what new knowledge is needed, the committee has organized its recommendations under four main themes, each with specific goals for a hydrocarbon research drilling program. The goals are not mutually exclusive; they serve as an organizational framework for an envisioned program.

Theme 1: Reservoir characterization and geologic modeling. Recovery from most hydrocarbon fields ranges from 15 percent to 55 percent for primary and secondary conventional techniques. Most potential reserves in the United States are in already-discovered fields and are considered to be nonrecoverable resources. Goals: To develop a better understanding of reservoir heterogeneity, in situ rock and fluid properties, and enhanced oil recovery techniques. Major oil companies with internal staff and facility capabilities are conducting research in this area; however, economic considerations severely limit the amount of basic research conducted in the private sector. Short-term and long-term publicly funded research would include drilling closely controlled by previous holes and high-resolution geophysical surveying. Expected result: Improved recovery, thereby augmenting the resource base and adding to reserves.

Theme 2: Sedimentary sequences and crustal geology. Drilling controlled transects across basins to integrate geological and geophysical frameworks would provide essential data on basin development, sequence packages, rock properties, and the generation, migration, and entrapment of hydrocarbons. Goals: To characterize sedimentary sequences in different basin settings; to develop and test predictive models of the distribution of reservoir-prone and source-rock-prone facies and of those factors controlling the generation, maturation, migration, and entrapment of hydrocarbons. Expected results: Improved fundamental knowledge basic to identifying hydrocarbon concentrations, improving prediction and identification of subtle traps in mature basins, and reducing exploration risk.

Theme 3: Seismically obscured terrains. Drilling to determine the nature of complex and difficult terrains where seismic data will not permit reliable interpretation would develop basic information in areas hostile to geophysical imaging. Goal: To identify and characterize those terrains, and to provide basic scientific data useful in modeling them. Expected result: Improved data base for accurately interpreting obscured terrains and for modeling and predicting hydrocarbon locations and potential.

Theme 4: Frontier areas. Drilling should be done in deep sedimentary basins, below zones of current exploration, and in rifted or wrench/fault-related basin settings, to better understand rock properties and hydrocarbon sources, maturation, and rock-fluid interactions. Goals: To identify and characterize rock strata, to develop more reliable bases for predicting hydrocarbon occurrences, and to test models of basin formation and hydrocarbon generation.

Expected results: Improved capabilities for predicting hydrocarbon occurrences and reducing exploration risk.

1.5 HYDROCARBON RESEARCH METHODS AND TOOLS

Besides detailed analyses of rock and fluid samples obtained from a research drill hole, there is an equally important need for in situ downhole, hole-to-hole, and hole-to-surface measurements to aid in the interpretation of subsurface environments. Improved methods and techniques becoming available for in situ measurements and experiments during and after drilling include geophysical and geochemical well logging, fluid sampling, vertical seismic profiling, hydrofracture experiments, temperature measurements and flow testing. Slant hole or horizontal drilling techniques should also be considered.

Once completed, a scientific drill hole offers the opportunity for continual physical and chemical monitoring. Long-term experiments can be designed to identify permeabilities by use of natural or injected tracers in formations and monitoring tracer movement in drill holes. In situ teleseismic measurements distinguish crustal structure with diminished attenuation and dispersion signal loss caused by the fractured upper crust. Downhole temperature measurements taken over extended periods can aid in defining undisturbed thermal gradients and fluid motion within the formations.

Although a number of instruments and tools designed for measuring physical and chemical parameters are generally available, additional trial development of refined models is necessary. Successful use of such instruments will depend on a number of factors, including temperature and pressure variances along with hole conditions such as diameter and hole deviation. Trade-offs in tool selection may be needed to balance the relative value of measurements with drill hole restrictions.

As measurements of additional physical and chemical properties are sought by geologists and geophysicists, researchers need to develop new capabilities, such as measuring permeability, evaluating fracture patterns, performing downhole elemental analyses, determining fluid flows, and predicting and measuring excessive borehole breakouts.

Sample and hole curation are as important as drill hole sample collection and downhole measurements. All hydrocarbon research drilling projects should include plans for rock and fluid sample curation, as well as for maintaining the hole as an observation or test well for periods of time. The principal form of rock samples from a research drill hole should be core. Consideration must be given for native-state core and fluid recovery and storage. Improved coring, sampling, and storage techniques may have to be developed to retain drill hole samples in the most acceptable condition for future scientific studies.

Although in situ research is necessary to define and interpret rock units in and near a drill hole, parallel laboratory investigations must also be conducted to characterize the drill hole environment under simulated subsurface conditions. Thus processes involved in fossil fuel formation can be studied both by sampling through drilling and by laboratory experiments to achieve optimum scientific results.

The chapters that follow will develop the four major themes and their goals for an effective hydrocarbon research drilling program, describe the types of research for reaching each goal, and discuss requirements for implementing a successful program.

NOTES

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Chapter 2

RESEARCH GOALS OF A SCIENTIFIC DRILLING PROGRAM

2.1 INTRODUCTION

Although projects for scientific drilling are broadly addressed in current and planned programs, few focus on specific goals that would promote research on hydrocarbon discovery and recovery. In 1979, for example, the U.S. Geodynamics Committee emphasized that a principal purpose of scientific drilling is to define materials, structures, conditions, and processes of rock-fluid interaction beneath the earth's crust. The committee recommended:

> that a Continental Scientific Drilling Program be initiated to achieve expanded knowledge and understanding of the uppermost part of the crust of the earth in the United States . . . . This program would provide a central focus for the scientific aspects of federal drilling activities and a mechanism for communication and cooperation with academic, industrial, and state scientific constituencies.[1]

In 1983, the Committee on Opportunities for Research in the Geological Sciences of the National Research Council (NRC) concluded:

> Deep holes drilled entirely for scientific reasons of 'dedicated deep drilling' have been a wistful gleam in the eyes of geologists but have always seemed too expensive in comparison with other needs. Now, however, based on the information we are getting about the deep continental structures from geophysical probes, we are rapidly approaching the time when direct sampling by drilling will be the only way to calibrate geophysical data . . . A program of drilling holes dedicated to scientific studies is highly recommended over the next few years . . . . Just as critical areas of the oceanic crust have been tested by the drill with remarkable results, similar existing discoveries can be anticipated from a program of continental scientific drilling.[2]

Other impartial review groups have defined scientific drilling objectives to advance geological knowledge of active fault zones, thrust belts and mineral resources.

This chapter identifies recommended goals for scientific drilling that relate directly to research on exploration and production of hydrocarbons. Specifically addressed is the question, "What drilling is needed to advance the science related to oil and gas discovery and recovery?"

The committee considered a matrix of scientific drilling activities and target environments in this area. Figure 2.1 summarizes this matrix, integrating scientific drilling goals to (1) identify and characterize, (2) model and predict, and (3) test and verify various hydrocarbon elements of a topical or functional nature. Functional themes range from basic geological framework studies to processes affecting hydrocarbon generation, maturation, migration, entrapment, and extraction.

We have organized the discussion under the following topical themes:

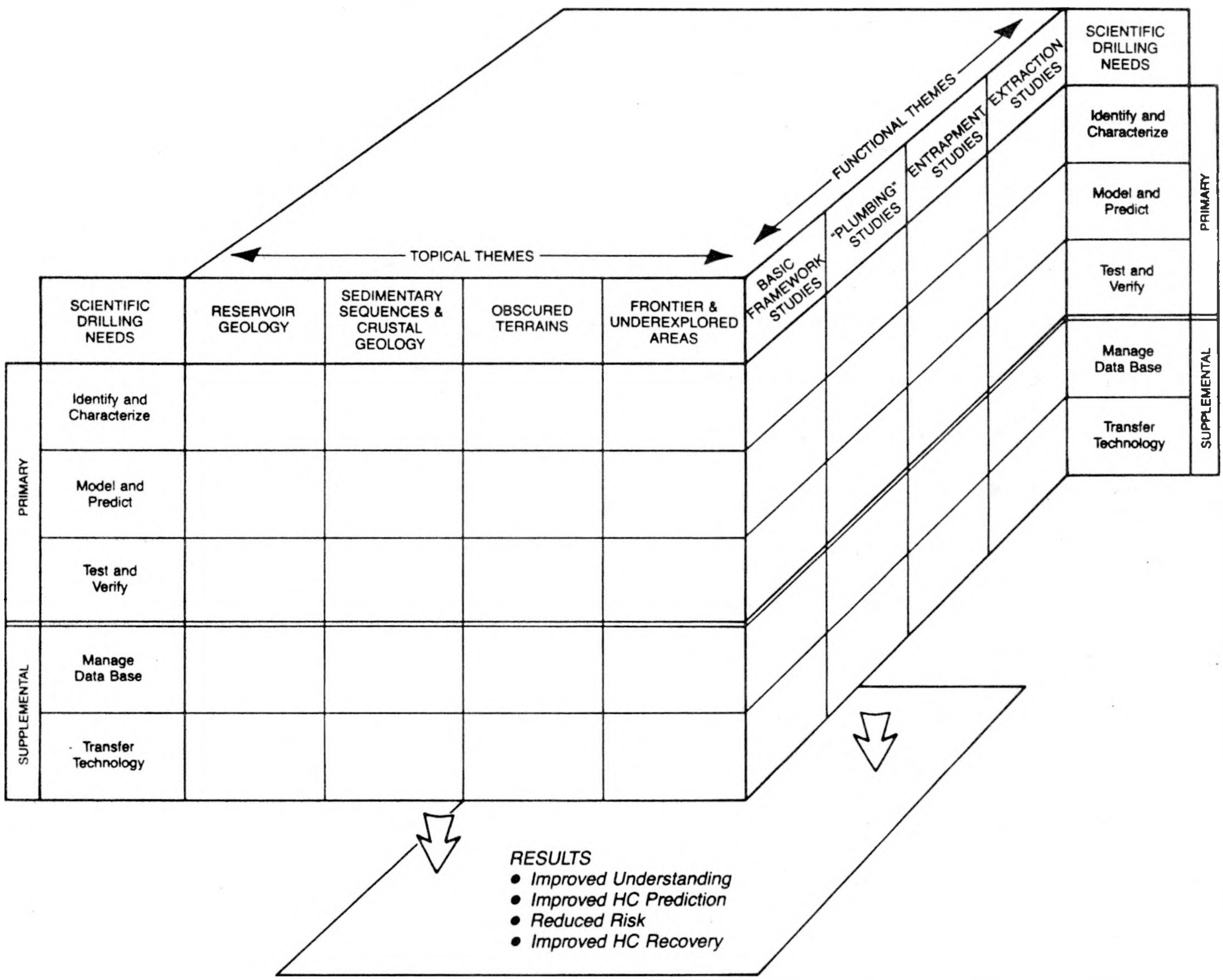

FIGURE 2.1 Matrix of drilling needs to advance the science related to oil and gas discovery and recovery.

(1) reservoir characterization and geologic modeling, (2) sedimentary sequences and crustal geology, (3) seismically obscured terrains, and (4) frontier and underexplored areas. The role of drilling and suggested research studies are discussed under these four headings. After each discussion is a section giving examples of types of drilling sites to be considered in a dedicated scientific hydrocarbon drilling program.

The expected results of a comprehensive research drilling program include (1) improved understanding of geological frameworks and processes controlling hydrocarbon distribution, (2) improved methods and techniques for predicting hydrocarbon occurrences, (3) improved hydrocarbon recovery, and (4) reduced exploration risk.

2.2 RESERVOIR CHARACTERIZATION AND GEOLOGIC MODELING

About 330 billion barrels of oil will remain in known U.S. reservoirs after current primary and secondary recovery operations are completed.[3] This resource base, discovered during more than 125 years of exploration and exploitation, is more than twice the cumulative U.S. production to date, and continues to be the target of improved oil recovery. Recovery for most U.S. fields ranges from 15 percent to 55 percent by conventional, primary, and secondary techniques. Thus the largest fraction of potential resources in the United States is in already-discovered fields but is considered to be "remaining oil-in-place." Recovering a portion of these resources will require a better understanding of reservoir heterogeneity and in situ rock and fluid properties. Certain major oil companies have research programs in this area of incremental recovery from existing reservoirs, but many known U.S. onshore fields are being exploited by smaller companies that have neither the means nor the organization to support the type of research directed toward more efficient recovery of known sources. A federal program of research in reservoir characterization is therefore appropriate, and should involve industry, not-for-profit and academic institutions, and state geological surveys.

Although expanded scientific knowledge regarding reservoir characteristics will aid development of new fields, the first target would be oil that is currently considered nonrecoverable. Of the estimated 330 billion barrels so classified, some 230 billion are trapped by viscosity and capillary properties of the fluid in the reservoir rock. About 100 billion barrels are potentially mobile, representing oil that has been bypassed or uncontacted by conventional drilling and producing methods. A portion of this oil could be produced if located and properly contacted. Some of the 230 billion barrels can be mobilized and displaced by tertiary processes if detailed reservoir models were available. Recovering part of the 100 billion barrels of unswept mobile oil offers the most immediate contribution to domestic production, since such recovery could use extensions of current technology.

Locating and extracting mobile oil concentrations require more accurate and detailed reservoir characterization. The exact location of these resources is uncertain because many wells in existing fields were drilled years ago without an attempt to identify the percentage extraction taking place. In addition, most wells were drilled with a uniform geographic spacing to extract the oil and gas from their reservoirs. In many instances, this uniform spacing assumed that the reservoirs and the fluids contained were homogeneous and behaved uniformly.

Most current geologic models of reservoirs were developed for exploration rather than exploitation. They emphasize the importance of external reservoir configuration and do not adequately explain the internal reservoir compartments that control hydrocarbon recovery. Research indicates a definite relationship between reservoir genesis, reservoir drive energy, and the volume of unrecovered mobile oil in the reservoir. In complex reservoirs, from 50 to 85 percent of the mobile oil may remain unrecovered at abandonment. This mobile oil is prevented from migrating to existing wells by internal reservoir flow barriers, and it remains trapped in geologically controlled compartments. For example, subtle heterogeneity patterns produced by circulating water result in isolated pools of oil held static as water flows through bypass channels. In-fill drilling and alteration of pressure gradients could mobilize some of these potentially significant sources of oil.

A thorough understanding of a reservoir's physical continuity and its relation to lithofacies, porosity, and permeability is prerequisite to recovery of additional mobile and related immobile oil. Reservoir geologists and engineers need improved geologic models and interpretive procedures that address the complexity of internal reservoir geometries. New models should describe the internal architecture of reservoirs with respect to the geometry of unconformities, bedding and fracture surfaces, their relation to the lithofacies, and both primary and secondary porosity and permeability.

Reservoir types vary widely, and a representative number should be studied. For example, submarine fan deposits offer a potential for increased production in known fields. The commonly accepted model of deep sea fans, based on studies of submarine sedimentary cores, visualizes progradational units of upper, middle, and lower fan facies. However, recent seismic, stratigraphic, and outcrop studies of ancient submarine fans indicate that this model is inadequate and can be misleading. Translating some of the new concepts into use in known reservoirs will require a blend of geophysical studies calibrated by the ground truth of drilling.[4]

Research drilling and related experiments should also focus on reservoir heterogeneities that control the effectiveness of well completion and stimulation practices. Secondary processes often have altered primary features and established different migration paths, seals, and flow units. Further insight into the chemistry and physics of these processes is needed to help operators optimize completion and stimulation practices. Answers are needed to the question, "What works best, where, and why?"

The program of reservoir characterization and model development should identify basic reservoir types with a wide range of physical parameters (see Table 2.1). The scientific goals of such a program are better understanding of:

- Primary depositional processes. Reservoirs need to be described in terms of the continuity of physical chronostratigraphy, unconformities, bedding and fracture surfaces, and their relation to lithostratigraphic depositional systems and facies architecture. We should be able to recognize the system that created the reservoir, and especially the location of any particular reservoir in the depositional system. Closely spaced drilling will be needed to construct a three-dimensional picture of the reservoir.

- Secondary alteration processes, including fracturing and diagenesis. These need to be defined so that their overprint on primary processes can be predicted and mapped for optimum design of well location and production programs.

- Fluid drive mechanisms. These are understood in terms of classical physics, but too little is known of the in situ properties of reservoir fluids and rocks and how they affect sweep efficiency and flow in heterogeneous media.

- Chemical and physical processes affecting well stimulation and completion. These need to be understood for varying subsurface conditions so as to establish optimum stimulation and completion practices, ensure maximum producing and recovery rates, and avoid formation damage.

A research program studying a group of representative reservoir types, defined by combinations of the processes listed above, would require designation of research areas or "fields of opportunity." Closely spaced drilling, detailed fluid and rock sampling, and eventual creation of long-term observation wells would allow the following research to be conducted:

TABLE 2.1 Examples of research drilling sites for reservoir characterization studies
(Heterogeneous reservoir types and typical fields. Fields are ranked in terms of decreasing complexity in both major lithologic categories.)

System	Field	State
CLASTICS		
Submarine-slope/fan	Paduca	NM
	Indian Draw	NM
	Spraberry Trend	TX
Fluvial	McCallum	CO
	Big Sandy	KS
	Lazy Creek	LA
	Main Consol.	IL
Back barrier	Desert Springs	WY
	Coyote Creek	WY
	Government Wells (N)	TX
	Calhoun (gas)	LA
	Louden	IL
Fluvial-dominated delta	Katz	TX
	Victory E	OK
	Voorhee (gas)	CO
	Storms Consol.	Il
Fan-deltas	Velma(W)	OK
	Manarte	TX
	Mobeete	TX
Shelf sands	Bear Creek	WY
	Hartzog Draw	MT
	Grass Creek	WY
Sandy-rich slope-submarine fans	Jameson	TX
	San Joaquin	CA
	Kettleman Middle Dome	CA
	Dear Creek	CA
	St. James	IL
Lacustrine sandstones	Altamont	UT
	Monument Butte	UT
Wave-modified delta	Happy Springs	WY
	Cimarron	CO
	Swearingen	NB
	Waterburg (gas)	CO
	Marco	IL
CARBONATES		
System	**Reservoir**	**State**
Dolomotized restricted platform	Cow Creek E	MT
	Beaver Creek	ND
	Seminole	TX
	Eunace-Monument	NM
	McElroy-Dune	TX
Shelf-edge reefs/drapes	Hume	NM
	Kingdom	NM
	Claytonville	TX
	Marine	IL
	Patoka	IL
Karst-modified carbonates	Frederick SE	OK
	Caddo	OK
	Emma	TX
Unconformity-related	Block 31 NW	TX
	Groesbeck Creek	TX
	Aldrich	KS
	Carr City	OK
	Buckhorn Consol.	IL
	Mt. Auburn	IL
Open shelves, platform, ramps	Lisbon	UT
	Cottonwood Creek	WY
	Coyote Creek	ND
	Buffalo	SD
	Sherwood	ND
Oolitic bars, shoals	Horace S	KS
	Farnsworth E, N	TX
	Welcome	AR
	Bayou Middle Fork	LA
	Walker Creek	AR
	Mt. Vernon	AR
	Clay City	IL
	Keenville	IL

- Detailed reservoir description, including fluid properties, petrography, sedimentology, porosity, permeability and other rock properties;

- Surface and well geophysics and geochemistry, including seismic, electrical, magnetic, and chemical properties of rocks and fluids;

- Access to subsurface occurrences of rocks known at their outcrops;

- Development of detailed geologic models for prediction of complex flow patterns; and

- A combination of laboratory experimentation and drill hole testing to understand processes affecting well stimulation and completion, to predict optimum practices under varying subsurface conditions, and to check and verify the predictions and procedures.

Some of the recommended wells would obtain information regarding the reservoir seals and migration pathways to test theories of migration and trapping in development of reservoir models. In addition, a high-density well suite can be used to physically test flow path models developed from limited data, to further improve modeling of the internal architecture of reservoirs. Use of slant and horizontal drilling should be considered to determine lateral variations, especially for correlation with geophysical data. This type of research drilling could be done in the near-depleted, water-flooded portion of a mature reservoir. Adequate testing of existing wells, modification of injection patterns, and special logging will require a long-term commitment by the research groups. Consequently, adequate access arrangements must be negotiated with the property owner and operator. Tests of this type should be carried on in various geologic settings to characterize reservoir rock heterogeneity and the resulting quantitative trapping of oil during water displacement.

Geophysics can be especially important in maximizing the significant investments made in a drilling program. High-resolution methods, downhole and crosshole tomography, improved logging methods and tools, and possible application of other geophysical parameters such as electric fields, should be considered. These studies are essential to modeling existing fields in order to "see" beyond the drill hole.

2.3 SEDIMENTARY SEQUENCES AND CRUSTAL GEOLOGY

"Geoscience Research for Energy Security," the 1987 report by the Energy Research Advisory Board (ERAB) to the DOE, placed a priority on research for the detection of subtle stratigraphic traps, on basin analysis, and on improved knowledge of reservoir heterogeneity.[5] The report further noted the importance of better understanding both basic crustal structure and tectonic processes. The subsequent development of computer models to predict structures and processes will require testing for verification and validation, followed by the ultimate test of drilling.

This committee strongly endorses these views and concludes that further expansion of these concepts is warranted. The committee recognizes that crucial elements of crustal analysis must be combined with basin analysis, herein referred to as crustal geology, to improve the understanding of basin evolution (basin-subsiding, basin-filling, and basin-deforming processes), of thermal history, and of the impacts of sea level and climatic changes. Each of these elements requires further research to establish the controls on hydrocarbon generation, migration, entrapment, and preservation.

Basin-filling processes depend on rates of subsidence and deposition, sea-level position, and climate. Each exerts strong controls on the succession of sedimentary sequences and the stratal patterns and facies distribution within them. These in turn govern the three-dimensional aspects of reservoirs, source rocks and seals, and the physical nature of fluid systems.

Crustal elements exterior to the basins also require consideration; factors such as rates of uplift and sediment supply also influence the nature of sedimentary sequences. Information on heat flow, paleotemperatures, subsidence, and tectonic uplift is needed to characterize basin-forming and basin-deforming processes more fully. Only drilling can provide the basic subsurface data regarding these critical parameters.

Post-depositional changes in temperature and pressure produce changes in rock properties and in contained organic matter and fluids. These changes promote interactions that affect the quality of reservoirs and seals and the ability of source rocks to generate hydrocarbons. Calibration is needed for the reactions producing these changes in different basin settings, under differing conditions of pressure and temperature, and in different physical and chemical environments.

The key to improved hydrocarbon predictions is obtaining additional information on the nature of sedimentary sequences, the processes that control them, and basin dynamics. Especially needed are data on the timing of tectonic events and thermal history, to establish kinetics of processes and reactions. Added information on impedance to fluid flow is also vital. Such information would provide greater capability for modeling and predicting those factors controlling the distribution of hydrocarbons.

The processes that control vertical and lateral variations in crustal geology need to be examined in more detail. The drill is a tool that should be used extensively, both to establish a statistically and scientifically sound data base of required measurements and to obtain information to test and verify models and predictions. The committee has grouped into two categories the goals for scientific drilling in this topical area: (1) those related to the development of sedimentary sequences and concentrating on lateral variations, depositional history of a given sequence, and the detection of subtle traps within that sequences; and (2) those related to crustal geology, emphasizing the vertical succession of rock sequences; their thermal, subsidence, and deformational histories; and the resulting conditions controlling hydrocarbon generation and rock-fluid interactions. The former stresses basin-filling processes and resulting geometric and lithologic configurations. The latter emphasizes basin-forming and basin-modifying processes and the physics and chemistry of hydrocarbon generation, migration, entrapment, and preservation.

• <u>Sedimentary Sequences</u>. The ERAB report highlighted the need to develop a more advanced technology base to aid in subsurface definition of regional stratigraphy, sedimentology, biostratigraphy, geochronology, and geochemistry of source rocks. It urged efforts toward a better understanding of the relationship between exploration concepts and sequence stratigraphy, noting especially the need for research to improve seismic stratigraphic methods for defining subtle traps.

Sequence stratigraphy involves subdividing, correlating, mapping and analyzing cyclic changes in sedimentary rocks observed in outcrop, drill hole, and seismic data. Seismic stratigraphy, well control, and generic discontinuity boundaries have shown chronostratigraphic depositional intervals, referred to as sequences, that have been recognized throughout a number of basins. These boundaries can be recognized across facies changes and sites of non-deposition, suggesting such correlations can be established independent of formation boundaries and rock type. Each sequence contains depositional intervals and stratal patterns that can be interpreted in terms of depositional environment, lithofacies, and paleogeography. Some of these sequences have been integrated with biostratigraphy and with physical stratigraphy to define a precise relationship among biostratigraphic zones, environmental indicators, and position within sequence cycles.

Additional documentation is required to demonstrate the full potential of sequence stratigraphy and to predict stratal patterns and lithofacies in different settings. Promising results have been obtained to date in predicting the distribution of effective seals and migration pathways. What is needed now is a systematic approach to further expand and develop the concepts of sequence stratigraphy by drilling.

Research drilling of selected continuously cored holes could provide the information needed for the development of detailed, three-dimensional profiles of biostratigraphy, magnetic reversal, isotopic variations of minerals and fluids, source rock characteristics, fluid types, and lithofacies, some of which are not available from outcrops or conventional well logs. Research drilling would provide critical data to allow scientists to interpret and correlate well logs, integrate geologic data with interpretations of seismic sections and other geophysical and geochemical data, refine and develop concepts, and understand the conditions for entrapment of hydrocarbons. These studies could result in the location of subtle hydrocarbon traps and in more accurate identification of reservoir rocks, seals, and traps.

The recommended program is best carried out through a multidisciplinary approach involving selected basin transects in a variety of tectonic settings and rock systems. The data base would consist of high-resolution geophysical profiles, available well and outcrop control data, and continuously cored drill holes in the sequences of interest.

The major steps in this program should include (1) analyzing representative basin types and stratigraphic sequences across selective transects (lines of profile); (2) compiling and analyzing available data; (3) conducting scientific drilling as needed to complete the initial data base; (4) basin modeling and simulation; (5) verifying concepts and hypotheses using coring, sampling, and analysis of specific sequence intervals; and (6) using new information for further analysis to better predict hydrocarbon occurrences. This procedure should be repeated as drilling continues along individual basin transects.

Carrying out this recommended scientific research program should involve the following approach:

- The classification of all major producing basins should be reviewed in terms of structural type and major rock systems such as siliciclastics, carbonates, evaporites, or combinations of these. Based on this review, groups of transects of the same general age with different tectonic settings and rock systems should be selected. Basin-scale transects are preferred. Some of the transects that have been described in Geological Society of America and American Association of Petroleum Geologists publications may be suitable for this project.

- Emphasis should be placed on hydrocarbon potential when selecting transect locations and stratigraphic intervals.

- The structure, stratigraphy, depositional systems, depositional environments, and lithofacies should be analyzed along each transect prior to new drilling. The structural analysis should be based on tectonic subsidence profiles and analysis of post-depositional stratal patterns to determine structural style. Stratigraphy and structural timing should be integrated utilizing tectonic subsidence profiles. The stratigraphic analysis should be based on seismic stratigraphic techniques, dating the resulting sequences and packets of stratal patterns with biostratigraphic or other appropriate data. Depositional systems, environments, and lithofacies within each system should be identified on well logs and seismic and adjacent outcrops and then integrated and mapped along the transect.

- Heat flow history should be interpreted from present day values and the tectonic subsidence curves. Fluid type, pressures, and hydrocarbon maturation and generation data should be compiled for modeling.

- Should the data base then indicate that scientific drilling is needed to complete a transect to provide either lateral or vertical control, then scientific drilling should be planned.

- Participation of industry, not-for-profit institutes, state geological surveys, professional societies, and universities should be encouraged in the data collection phase to ensure an optimum data base, to maximize understanding of the variables likely to affect the results, and to optimize the use of the data. They should be distributed on request to interested research, academic, and industrial groups. Close integration of these data with other data should be encouraged. This will allow the rapid appraisal and evaluation of various exploration methods and techniques.

- Modeling along the interpreted transects should be done with the latest techniques to simulate stratal patterns, discontinuities, and lithofacies distribution. Such variables as rates of tectonic subsidence, sediment supply, and sediment accretion; climate; paleo-oceanography; and sea-level fluctuations should be considered in developing the models. From the simulated sections, models should be developed to predict fluid dynamics, hydrocarbon generation, hydrocarbon migration, and the most likely areas for hydrocarbon entrapment.

- Computer simulation studies should be considered in basins where extensive basin transects are carried out.

- Testing and verifying the models by scientific drilling should proceed only after the research steps described above have been taken and the objectives for drilling and coring have been clearly stated. All relevant questions dealing with the entire process of hydrocarbon generation, migration, and entrapment should be considered. Gathering core material is imperative and should be given the highest priority. Most importantly, widespread prior notification of the location of the transect, the selection of coring sites and depths, and the announcement of curation procedures should be made.

- Workshops should be held to explain results and interpretations in order to transfer technology, including derived data, methods, techniques, and concepts.

This type of research program would allow the development of concepts, techniques, and interpretation procedures to better locate subtle hydrocarbon traps. A cooperative approach involving industry, not-for-profit institutes, state geological surveys, and professional societies will promote the implementation, execution, and rapid use of the results. This program could provide a unifying concept for stratigraphy, much as the ocean drilling program has provided a global structure through its revelations of plate tectonics. The recommended scientific effort will address (1) sequence stratigraphy concepts and the impact of oceanography and relative sea level changes, (2) concepts and techniques for analyzing and interpreting subtle structures and traps, and (3) the ability of computer-generated models to simulate basin-scale fluid dynamics. Together with the research effort described in the following section on crustal geology, the research drilling would also document the geological history of basin profiles and evaluate crustal evolution theories for different basin types and for the stratigraphic intervals selected for study in basin transects.

- Crustal Geology. The ERAB report highlighted the need for establishing more detailed reference sections for basins. It called for integrating data regarding physical, geochemical, and geophysical properties of rock sequences. Specific research on the thermal and hydrodynamic history of basins, particularly in relation to maturation of source rocks, migration, and accumulation, was recommended. Modeling of crustal structures and processes and subsequent testing through drilling were noted as the sequential steps after initial assimilation of data.

Sampling of representative basin settings controlled by high-quality seismic lines should prove helpful in (1) understanding the processes controlling the vertical succession and nature of rock sequences, (2) quantifying those parameters needed for modeling basins and sequences and for predicting hydrocarbon distribution, and (3) providing an added dimension for sequence analyses by placing lateral changes in the context of dynamic geologic events that preceded and followed the sequence interval of interest. It should be noted that the objectives of sequence stratigraphy would require a number of shallow drill holes with continuous coring, whereas the objectives of crustal geology require fewer, deeper drill holes with information from logs, sample cuttings, and selected cores.

Crustal geologic processes help control the vertical succession and nature of rock sequences. For example, formation and deformation control the size and shape of the structural setting that receives the sediments, contribute to the rate of sediment supply, partially control sea-level and shoreline locations, and produce structures capable of hosting hydrocarbons. Heat flux and internal stresses deep within the earth may well be the underlying controls of basin evolution. The interplay among the rates of uplift of adjacent areas, rates of subsidence and heat influx, and sea-level and climatic fluctuations contributes to the ultimate nature of rock sequences and their contained fluids. Vertical sampling of representative basin types and crustal settings from the surface down to and into crystalline rocks below the sediments can provide insight into the interplay of these processes and their relative contributions. Drilling carried out to provide appropriate sample material can provide details on geochronology, geothermometry, and rates of sediment influx to better characterize the basic processes of basin evolution.

It should be noted that conventional exploration drilling taps a biased sample, a structure or feature that is not representative of a basin. This program, designed to drill off-structure, could provide vital information not obtainable any other way. Thus it can yield a better statistical representation of total basin setting.

Drilling of selected basin types and crustal settings will provide quantitative information on the parameters used in modeling and predicting hydrocarbon generation, fluid dynamics, fluid entrapment, and fluid preservation. Source rocks are rarely drilled deliberately, and this drilling could fill an important gap. Geochronology can be established by both biostratigraphic and radiometric age-dating techniques. Geothermometry can be used to establish temperature history. Combining time and temperature measurements will provide more reliable information on the kinetics of maturation under different basin settings and conditions of heat influx for a variety of organic facies.

Time, temperature, and pressure conditions for different rock compositions can also be determined by adequate sampling and in situ measurements to allow modeling of porosity change and impacts on permeability for both reservoir rocks and seals. In situ measurements of heat flow, thermal conductivities, electrical conductivities, and other parameters will allow further improvements in modeling diagenetic changes affecting fluid transmissibility and reservoir quality.

The evolution of a basin and its environs before, during, and after the depositon of a sedimentary sequence strongly influences the generation, migration, and entrapment of hydrocarbons within that setting. A detailed understanding of these events assists in placing the analysis of sequence stratigraphy in perspective. Basin evolution analyses involve determination of the presence and distribution of regional aquifers and regional seals above or below a given sequence, which influence the vertical as well as the lateral migration of hydrocarbons.

The approach for selecting hydrocarbon research drill sites to examine crustal geology is similar to that proposed for sequence stratigraphy. Both involve a review of producing basins and their classification into structural types with major rock systems. Transects across representive types then should be selected for further investigation. In some cases, the same transects could be selected for both sequence stratigraphy and crustal geology studies. High-quality geophysical profiles will be required along some transects to select the most appropriate scientific drilling locations to provide the required information. It is estimated that one deep hole per transect would be the minimal requirement. Each deep hole should be regarded as a linchpin in a regional network of high-quality geophysical profiles. Table 2.2 gives examples of possible drilling sites for this area of research.

Scientists can process drill hole data to calibrate various sequences recognized from seismic signatures, and incorporate the data on thickness, geochronology, paleo-temperatures, rate-dependent information, and other parameters in modeling and predicting source rock deposition, hydrocarbon maturation and generation, fluid dynamics, reservoir and aquifer quality, and hydrocarbon migration, entrapment, and preservation. The objectives of these recommended scientific drill holes for sequence stratigraphy and crustal geology bear many similarities to the offshore COST well program. The committee specifically recommends that such drilling be carried out in cooperation within industry, other DOE groups, state and federal agencies, nonprofit organizations, and universities as appropriate.

2.4 SEISMICALLY OBSCURED TERRAINS

Two kinds of exploration problems are at times insurmountable: Imaging complex subsurface structures from the surface, and imaging below high seismic velocity layers near the surface. These are referred to as "obscured terrains," i.e., portions of concealed crust that do not readily transmit energy to provide coherent reflections, thus resulting in seismic reflection records of limited quality in such areas.

TABLE 2.2 Examples of research drilling sites for sequence stratigraphy/crustal geology, obscured terrains, and frontier areas

Sequence Stratigraphy and Crustal Geology	Obscured Terrains	Frontier and Underexplored Areas
Transects:	Complex Structures:	Rift Systems:
- Cretaceous Basins	Thrust Belts	East Coast Rifts
Paleozoic Basins	Appalachian	Mid Continent Rifts
	Brooks Range	New Madrid Rift
Crustal Geology:	Chugach Terrain	Thrust Belts
- Basins	Oachita Mountains	Rome Trough
Anadarko	Rocky Mountains	Rough Creek-Shawneetown
Appalachian		
Ardmore	Imaging Difficulties:	Sevier Basin
Big Horn	- Volcanic Cover	
Delaware	Absaroka	Wrench Features:
Denver	Columbia River	Ardmore Basin
East Texas	Snake River Province	California Basins
Great Valley		
Green River	Yukon-Koyakuk Province	Deeper Basins:
Gulf Coast		Anadarko
Illinois	- Ice Cover	Appalachian
Los Angeles	Arctic shelves	Delaware
Michigan	Permafrost areas	Great Valley
Paradox	- Subduction Wedges	Green River
Permian	Aleutian Arc	Gulf Coast
Powder River	Cordillerian Subduction Margin	Illinois
San Joaquin		Ventura
Ventura		Wind River
Warrior		
Williston		Growth Faults:
Wind River		Gulf of Mexico
- Arches		
Cincinnati Arch		Salt Tectonics:
Lima Arch		Gulf of Mexico
Sabine Uplift		
San Marcos Arch		Untested Concepts:
		Continental Rises
		Monterrey Fans
		Other Frontiers:
		Alaska North Slope
		Alaska Interior Basin
		Beaufort Shelf
		Chuckchi Shelf
		Great Basin
		Puerto Rico/Virgin Islands
		SE U.S. Offshore Margin
		W U.S. Offshore Margin

• Structurally complex areas. Some subsurface structures are too complex to be described adequately, even with dense three-dimensional seismic data. Difficulties can arise because of the complexity of structures such as thrust belts, irregular rock interfaces found around salt domes, heavily faulted areas such as the basin and range province in the western United States, or areas that lack coherent horizontal seismic reflectors, such as major transcurrent fault systems. The difficulty arises from the fact that seismic rays, which are generated and recorded at the earth's surface, have poor resolving capability when rock interfaces dip steeply or are very irregular. To determine accurately the shape of such boundaries, seismic imaging is needed in additional directions. Such measurements are often possible by using drill holes in the area of interest. Establishment of the surface and downhole source and receiver sites permits the necessary measurements between the surface and downhole receivers or sources. If more than one drill hole is available, cross-hole seismic data can be obtained. It is noteworthy that such measurements are useful not only in designing exploration programs but also to monitor hydrocarbon recovery in complex structures.

• Imaging difficulties. In some areas impediments inhibit the penetration or return of seismic waves from underlying rock strata, rendering such areas difficult to explore and interpret. These areas include volcanic plateaus, regions of thick salt beds, thick carbonate sequences, and regions of permafrost and ice cover. Areas in the United States concealed by volcanics include the Columbia Plateau region and portions of the Basin and Range province, which are covered with thick sequences of basalt flows. The basaltic rocks have higher seismic velocities than the sedimentary rocks they cover, and consequently seismic penetration is poor. Alaska's North Slope permafrost creates a similar high-seismic-velocity zone near the surface.

Drill holes that penetrate below the high-velocity zones could provide the key for exploring the underlying sedimentary sequences. Not only would the drill hole provide information about the nature of underlying sediments, but the hole itself could be used for the emplacement of seismic imaging tools to expand knowledge of these obscured terrains. The most promising approach involves the use of powerful or repeatable seismic sources placed in available drill holes, and the recording of signals with widespread seismic arrays on the earth's surface. With this arrangement, much stronger signals will be obtained, consisting of direct arrivals as well as reflections from deeper layers, thus revealing geologic details which at present cannot be seen.

Unlike Vertical Seismic Profiling measurements, in which a limited number of receivers are placed in a drill hole and a source is moved to various sites on the surface, many surface receivers can be used with one source location in a drill hole with the recommended system. Thus it will become practical to collect relatively large amounts of seismic data quite rapidly and hence economically. A program of research drilling would provide:

- rock samples for measurement of rock physical properties,
- downhole measurement of rock and fluid physical properties,
- change in the state of stress with depth, and
- downhole source and/or sensor placement for geophysical measurements below and up/through velocity anomalies.

Table 2.2 suggests examples of research drilling sites for seismically obscured terrains.

2.5 FRONTIER REGIONS AND UNDEREXPLORED AREAS

Drilling funded by the private sector is generally designed within a context of economic incentives that influence the selection of exploration and production sites for hydrocarbon drilling targets. Areas that do not meet investment criteria, have technical problems, or are considered too risky, are generally excluded from exploration drilling programs. Consequently, regions within the United States that may contain significant concentrations of petroleum and natural gas have never been adequately tested by drilling. These areas are defined here as frontier regions or underexplored areas. Current information on these areas is not adequate to develop exploration models.

Continental rift systems, areas of thrust faulting, wrench fault settings, deep portions of sedimentary basins, portions of growth fault systems, and areas of salt tectonics are examples of underexplored areas in the United States. A scientific drilling program for systematically collecting data on such environments could stimulate future exploration by private groups and eventually result in significant discoveries of hydrocarbon resources.

Three major rift systems of North America include the Precambrian (1.1 billion years) Midcontinent Rift, the late Proterozoic to Cambrian (500 to 700 million years) rift basins around the edge of the late Precambrian continental margins, and the Early Mesozoic (190 million years) rift basins on the continental margin of the eastern United States. The Midcontinent Rift in the Lake Superior region contains sedimentary sequences up to 10 km thick and extends to the southwest underlying parts of Iowa, Nebraska, Kansas, and Oklahoma. Subsidence of the central grabens and flanking basins has been highly variable along this rift system.

The most important factors determining whether rift sediments contain hydrocarbons are a combination of tectonic timing or rapid sediment deposition during rifting, and paleoclimate, or stable stratified lakes with anoxic bottom water for the accumulation of source rocks. Acquisition and study of potential field data, especially gravity, coupled with deep seismic reflection profiling and subsequent drilling, could permit reconstruction of the tectonic history of such rift systems and the location of the major depocenters. The original hydrocarbon source character and the present state of thermal alteration of sediments will be important factors for the possible occurrence of liquid hydrocarbons in the Midcontinent Rift. A scientific drilling program as a component of an integrated rift system study would contribute to economic evaluation of areas that could develop into hydrocarbon producers.

Similarly, a scientific drilling program could assist in evaluating the series of late Proterozoic to Cambrian rifts that extended inland from the late Precambrian Margins in the interior of the United States and of Mesozoic rifts along the Atlantic Margin. Examples of these rifts are listed in Table 2.2. Some of the rifts have passed through a rift phase into a broader cratonic sag status. Acquisition of high-quality seismic data and potential field data, followed by scientific drilling, could provide information to reconstruct the tectonic, burial, and thermal histories of such areas. This information, together with data on sequence thicknesses, rock type, and organic facies, could be used to model and predict types of hydrocarbons, and the nature of porosity reduction, destruction, or enhancement. It could also provide basic data for modeling fluid dynamics and predicting hydrocarbon generation, migration, entrapment, and preservation.

In each of the rift systems, the original character of the hydrocarbon source and current thermal alteration of organic matter and sediments are critical factors controlling the occurrence of liquid or gaseous hydrocarbons.

Wrench tectonic features also may constitute new frontiers or underexplored areas. Recent work has speculated on the origin of these features.[6] The various hypotheses proposed should be tested and verified by drilling. Information should be gathered concurrently on internal geometries of rock sequences, pore pressures, and orientation of stress fields and fractures. All of these require verification only through drilling. Again, it is emphasized that drilling must be preceded by seismic lines of high quality and high resolution to permit extrapolation beyond the drill holes.

Basins with sedimentary sequences up to 15 km thick have developed in some regions of the United States. Deep portions of such basins may contain large amounts of natural gas. High costs and technical problems associated with deep drilling have limited the exploration and exploitation of this potential resource, and only a small fraction of sediments has been drilled to a depth of more than 8 km. Indeed, very few areas have been drilled to basement below 6 km (about 20,000 ft). These prospective regions have been tested by a total of 16 wells, as shown in Figure 2.2. Extrapolations of reservoir quality with increasing depth have resulted in generally pessimistic expectations of deep gas occurrences. However, during a brief period of regional decontrol of gas prices in the late 1970s, large gas resources were identified in the Anadarko basin. Deep wildcat wells (below 4.6 km) had a success ratio of two/three, or three times the U.S. average for successful natural gas wells to date. A hydrocarbon research drilling program committed to advancing the understanding of such deep basin gas occurrences would clearly be beneficial to the economic and national security of the United States.

Gas occurrences have been confirmed in the deep Paleozoic basins

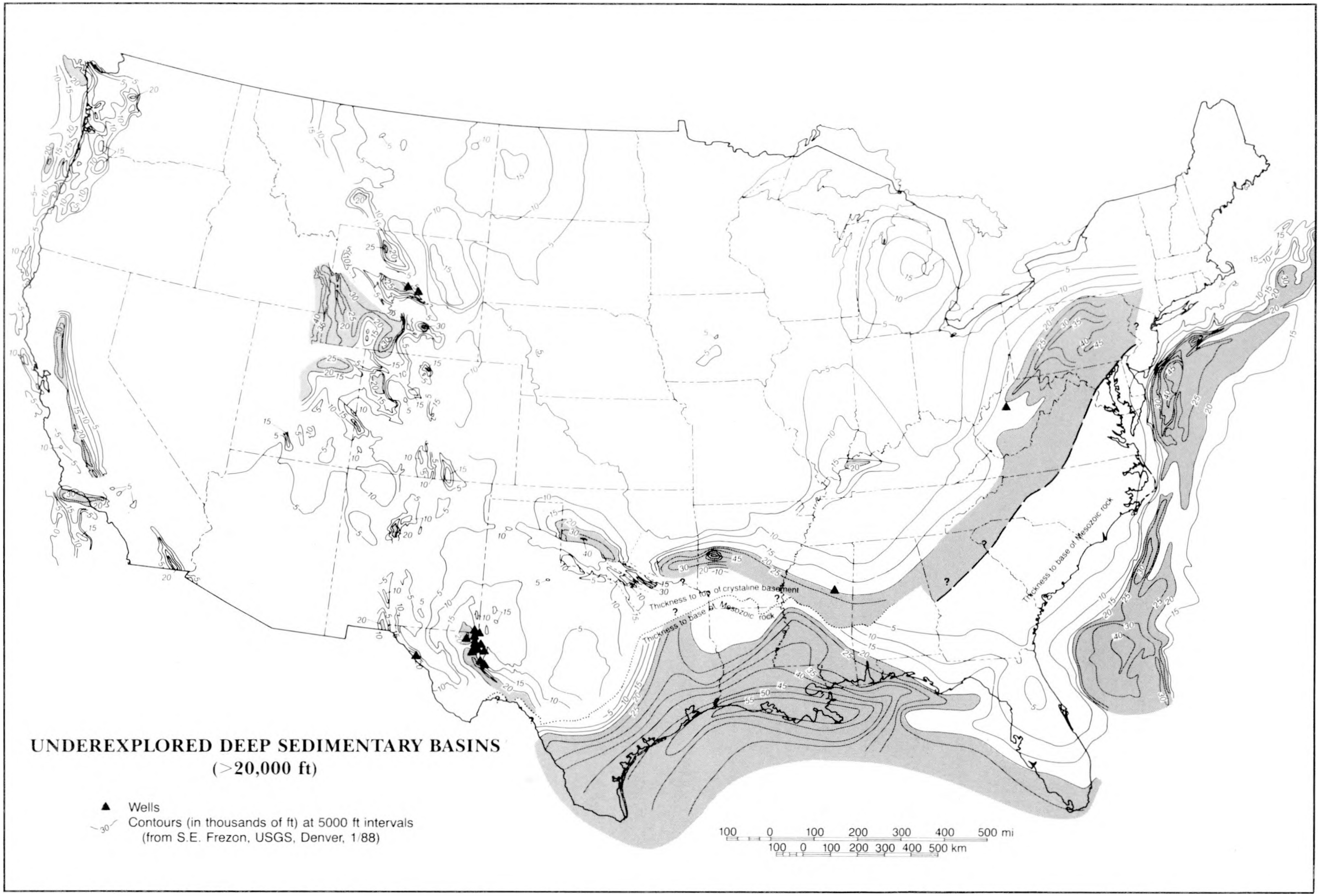

FIGURE 2.2 Wells reaching precambrian basement in the conterminous United States and offshore areas where sedimentary rocks are more than 20,000 ft thick.

of the midcontinent region and Mesozoic basins of the Gulf Coast. Deep buried sediments in other structurally complex environments such as wrench related areas, subduction zones, and overthrust belts should also be evaluated for deep gas potential. Eventually, drilling in deep basins will be required to test concepts of deep basin gas occurrence to determine limits on volumes and producing rates. Research in drilling technology to lower drilling costs will be an important factor in the eventual realization of new deep basin gas resources.

Growth fault environments also offer attractive targets for scientific drilling. Although the upper portions of growth faults within delta systems have been studied for many years, the lower, deep-water portions are not well-defined. For example, structures created by thrusting at the downdip toes of growth faults should be studied in detail, particularly their relationship to reservoir rock. Large hydrocarbon-bearing turbidite fans have been discovered in the lower portions of growth faults in the Gulf of Mexico and may be much more common than previously recognized.

Although structures associated with salt tectonics have been studied for years, many frontier hydrocarbon exploration opportunities are still untested. Of particular significance are areas such as the Gulf of Mexico, where salt seals extend over possible reservoir rock. Subtle traps associated with salt-rich features offer a high probability for finding future reserves.

Another goal of a scientific hydrocarbon drilling program should be to elucidate the depths of fracture systems and their effectiveness in transmitting fluids, and the partitioning of basins into separate pressure systems. Questions exist about the role of fractures in oil and gas migration and entrapment. How deep do fracture systems penetrate the earth's crust? What is the nature of fracture openings in situ under varying conditions of stress? Can open fractures be identified in boreholes and mapped as to their azimuth and geometry? Can their effectiveness as conduits be established over geologic time? A related question is whether fault zones are major pressure barriers within basins, major conduits for the migration of petroleum, or both.

Flow data from producing fields can be supplemented by scientific drilling designed to provide pressure data. Knowledge of pressure systems could significantly affect the design and location of hydrocarbon exploration projects, especially those designed to investigate large-scale partitioning of basins into distinct pressure-isolated chambers.

Three sites are noted here as examples of frontier regions and underexplored areas. Others are listed in Table 2.2. Specific hydrocarbon research drilling sites should be developed through joint meetings with industry, state geological surveys, and interested scientists.

The first example is an untested environment in the San Marcos arch region of the Texas Gulf Coast, which includes a major rift system and a thick, partially explored sedimentary section.

Geophysical studies have indicated that a transitional crust underlies the sediments. This could be due to rifted basement rocks, to buried portions of the Ouachita trend, to an accreted island arc, or to exotic continental basement related to a proto-South American continent. It has been proposed that a hole be drilled southeast of the reef trend to penetrate the thick sequence of abyssal sediments, sample the formation within the underlying rift, and eventually enter the basement beneath the sediments. What processes led to diagenesis and lithification, and what are the sedimentary fill hydrodynamics of this basin? Mass flux from basement units and convective recycling of deep waters are considered as explanations for the pervasive diagenetic features and for the mineral and hydrocarbon occurrences encountered in sediments by the few shallow drill holes in the region.

Research drill holes within the San Marcos arch could lead to an understanding of the nature of the underlying crust; superjacent sediments and their contained waters; the timing of rifting; fluid dynamics; geochemistry; diagenesis and early depositional history of the sedimentary sequence; thermal history and thermal gradients; hydrocarbon generation and migration; and fluid pressure regime in the deep sedimentary section. Scientific experiments conducted in the course of drilling a hole in this region should include organic geochemical investigations guided by two primary goals. First, a hole drilled to basement would allow investigators to examine active burial metamorphism in a greenschist facies. This is critical because some hypotheses suggest that fluid and heat fluxes generated at depth in the crust drive shallower diagenetic processes. The flux of fluids, especially of methane and carbon dioxide, may have major impacts on deep energy resources. Second, a continuously cored hole could provide information about the origin and distribution of petroleum resources in a geologically active sedimentary basin. Although the Gulf of Mexico has been drilled extensively, the factors controlling oil and gas distribution and the migration pathways are largely unknown. Detailed sampling of continuously cored intervals could define the distribution of source sediments and depositional environments. Careful sampling of fluids in situ would place constraints on migration mechanisms of any petroleum present. By integrating these observations with measurements of the thermal history of these rocks, mathematical models of petroleum generation and migration in the Gulf Coast basin can be assembled.

The second example is the Illinois Basin of southeastern Illinois, a rift-related intracratonic basin. A drill hole has been proposed at or near the thickest section of stratified rocks (7 to 8 km) in the basin. The hole could test and verify several models that have been proposed for basin origin. It could also help to define and characterize seismic sequences, determine the thermal and burial histories, and obtain data to model hydrocarbon maturation and generation as well as porosity preservation.

Despite more than 140 years of study based on exploration for oil, gas, and minerals, the deeper section of the 23,000-ft-thick Illinois Basin is poorly known and essentially untested. Most of the drilling has been concentrated above 5,000 ft. Deep drilling and core samples are rare, and the lower 8,000 ft of layered rocks has not been penetrated. The primary objectives of scientific drilling in this region would be to investigate the nature of the previously unsampled rift-fill rocks in the deeper part of the Illinois Basin; study the quality of reservoir and source rocks; establish the geochronology and geothermometry required to construct a detailed thermal and subsidence history of this portion of the basin; and develop models to predict the maturation, generation, and preservation of hydrocarbons in the deeper parts of the basin.

The third example is the southern Appalachian region, where a consortium of scientists from academia, government agencies, and private industry have conducted extensive studies to select a site for one or more research-oriented drill holes. The principal goals of drilling in the southern Appalachians are to test the hypothesis of thin-skinned thrusting of large sheets of crystalline rocks; to study the petrology of Grenville basement rocks; to determine stress in the crust at seismogenic depths; to compare pressure-temperature metamorphism in similar assemblages of surface exposures and core; and to study brittle and ductile fault rocks at several depths.

The proposed drilling would permit in situ studies of pore fluid chemistry, hydrocarbon maturation limits and potential accumulations, chemical transport and metals accumulation, and the hydraulics and fluid dynamics of an intact overthrust terrain. In addition, drilling could provide new information on reservoir hydraulics, the effects on continental margin sediments of emplacement of large composite crystalline thrust sheets over a well-developed carbonate platform, and the hydraulic effects of emplacement of a crystalline mass on the dynamics of foreland thrust sheets beneath. Studies of hydrocarbon maturation would enhance the assessment of viability of hydrocarbon plays beneath large crystalline sheets.

Proponents of drilling in the southern Appalachian region believe the crystalline sheet may have been thrust over potential hydrocarbon source rocks. The occurrence of hydrocarbons in the platform assemblage could be an important indicator that these rocks experienced minimal thermal readjustment after emplacement of the crystalline allochthon. A primary goal of the southern Appalachian project would be to measure directly the degree of conversion and thermal maturity of deeply buried sediments encountered during coring. Thermal maturity is a key factor controlling the generation of hydrocarbons from source rock organic matter, and the eventual destruction of hydrocarbons in deep, hot reservoirs. Conversion and thermal maturity can also be estimated by study of hydrocarbons extracted from core samples or from reservoir intervals encountered during coring. These data will be applied to computer models based on organic facies, burial history, and heat flow information. Such models are most useful when measured conversion indices and thermal maturities are available for calibration purposes. Once the thermal maturity history of the southern Appalachian location is measured and models designed, other models can be constructed to predict the thermal maturity histories at other locations in similar tectonic environments.

Table 2.2 lists examples of scientific drilling sites for frontier and underexplored areas.

2.6 CRITERIA AND PRIORITIES FOR SCIENTIFIC DRILLING SITES

The committee recommends that the following criteria be used to ensure that the selection of scientific drill holes will maximize scientific and technological returns. They are listed below.

1. Scientific impact. The research objectives should address fundamental scientific questions with potentially broad impact on the understanding of hydrocarbon distribution and extraction.

2. National needs. The research objectives should address research that is relevant to national needs (e.g., hydrocarbon resources inventory, in-depth understanding of the factors controlling hydrocarbon distribution, enhanced exploration or extraction techniques, and energy development).

3. Representative examples. The targets of the inquiries should represent generic classes of hydrocarbon problems, so that the scientific results can be generalized and applied to exploration and recovery of hydrocarbons in other areas as well as to the local region.

4. Background data available. Comprehensive pre-drilling studies are essential and include the design of a siting study and a timely site selection process for specific research drilling sites.

5. Scientific focus. The drilling investigation should be specific and focused for the research effort to achieve its scientific objectives with minimum expenditure of time and funds.

6. Site accessibility. The drill location must be accessible to scientists and suitable for surface and subsurface geological, geochemical, and geophysical studies.

7. Data integration. Results of geophysical studies are to be integrated with the geological and geochemical studies, so that well data can be extrapolated beyond the well bore.

8. Detailed models. Geological models should be detailed, based on all available geological and geophysical data on the geometry and physical state of the region to be investigated by the drill hole.

To meet these criteria, research drilling should be carried out where opportunities exist for (1) recovering extensive core and fluid samples, (2) using techniques that allow in situ experiments if needed, and (3) the option of maintaining access to the hole for a number of years, for continuous monitoring and future scientific research. In addition, scientific drilling should always be tied to high-quality, high-resolution geophysical seismic data. The committee also urges that all sites be selected, if possible, in cooperation with industry, state and federal agencies, and research institutions.

The committee further suggests that the four topical themes for scientific drilling be considered in a general order of importance. Because of the large volume of already-discovered oil left in the ground and the magnitude of potential benefits if the proposed program for reservoir characterization is successful, the committee recommends that this topical area receive top priority in the research drilling effort. It is recognized that ownership problems on privately held oil fields will need to be worked out in the implementation of the nontechnical aspects of the program.

Second in importance should be drilling needed to carry out the proposed program of sequence stratigraphy and crustal geology. The other two themes on obscured terrains and on frontier or underexplored areas are considered to be of about equal importance.

Details of a dedicated hydrocarbon research drilling program can be considered after an inventory of existing holes available for appropriate scientific studies has been completed, and data compilation is in progress. An initial annual program of approximately four rig-years in reservoir characterization, three rig-years in sequence stratigraphy and crustal geology, and two rig-years each in obscured terrains and frontier or underexplored areas may provide an appropriate order of magnitude and balance for a beginning hydrocarbon research drilling program. The level of effort should be subject to review every two years once drilling commences. Drilling should not commence until an appropriate support organization is in place; adequate plans have been drafted, thoroughly reviewed, and approved; funds are in place; and contracts have been drafted, reviewed, and approved.

In developing the drilling program plans, business arrangements should be carefully considered to provide cooperative programs with industry and other federal and state agencies--to lease sites, to protect interests of private industry and landowners, to ensure adequate control of the operations and access to research results, and to ensure safety and environmental protection. The committee is aware of various models of cooperative arrangements with industry, e.g., those utilized by the Gas Research Institute and those developed for the COST programs, and believes that with diligence, equally suitable arrangements can be developed for this proposed effort.

Milestones for the scientific drilling effort should be developed and targeted, and may include the following examples, as shown in Table 2.3.

When the program reaches full capacity at the end of the third year, the annual cost will then be approximately $200 million per year. Table 2.4 suggests the possible components of a scientific drilling program totalling about $200 million per year.

TABLE 2.3 Possible sequence of milestones in the development of a scientific research drilling program

Period	Goals	Cost (M = millions)
End of First Year	Establish an appropriate organizational plan, inventory of drill holes, and data banks. Staff the organization and implement the planning process.	$ 5 M
End of Second Year	Have an approved plan for each programmatic area and secure funding in place. Have contracts in place and commence drilling in each program area.	$ 50 M
End of Third Year	Up to full rig count in each program area.	$ 100 M
4th - 5th Years	Periodic revisions made in the plan depending on results and changes in perceived needs. Program in full operation.	$ 200 M

TABLE 2.4 Possible budget components of a research drilling program in its third year

Example Program

Program Components		Cost/Year (M = millions)
Drilling & Ancillary Support		
• Reservoir Characterization		$ 35 M
2 shallow rigs	2,500-5,000' capability	
2 intermediate rigs	5,000-10,000' capability	
• Sequence Stratigraphy and Crustal Geology		27 M
2 intermediate rigs	5,000-10,000' capability	
1 ultradeep rig	30,000'+ capability	
• Obscured Terrains		22 M
1 deep rig	20,000' capability	
1 ultradeep rig	30,000'+ capability	
• Frontier and Underexplored Areas		16 M
1 ultradeep rig	25,000' capability	
	Subtotal	$100 M
Geophysical Site Surveys		50 M
• Initial Data Collection Analysis		
• Geophysical Surveying, Processing		
• Interpretation		
• Workshops		
Scientific Research		40 M
• Laboratory, Field and Office Studies		
• Sample Curation		
• Data Base Management		
• Workshops		
Administration/Management		10 M
• Office expenses		
• Planning, Coordination, Oversight		
• Contracts and Grants		
• Other		
	Grand Total	$200 M

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Chapter 3

FACILITIES AND SUPPORT OPERATIONS

3.1 INTRODUCTION

A hydrocarbon research drilling program should include appropriate geological, geochemical, geophysical, and engineering studies conducted before, during, and after drilling. Many of the methods used in conducting such studies will be state-of-the-art and modified as new instruments are developed. Another critical component of all research drilling projects will be handling and curation of cores, fluids, data, and other materials produced from the drilling program. Although the largest proportion of funds invested in such projects will be devoted to actual drilling, it is the resulting information that will affect the nation's hydrocarbon resource future.

3.2 SAMPLE AND DATA MANAGEMENT

3.2.1 Sample Collection and Retention

A hydrocarbon research drilling program must provide for collection, curation, and storage of cuttings, cores, and fluids obtained from the drill holes. Thus it is necessary that detailed protocols be established for data and sample collection, handling, and curation, and that a sample facility be established and maintained. This is an important investment to build into the program.

Sample-handling protocols should address the objectives of the drill hole, methods of drilling, drilling fluids, downhole logs, cutting and core collection, fluid recovery, and preservation desired. The cuttings, cores, and recovered fluids should be treated to assure quality samples, and a control program for material collected should be established and agreed upon by all parties concerned before drilling begins. These materials should be recognized as vital scientific data bases.

Within the federal government, several organizations have proposed major core and sample storage facilities, including the Department of Energy, the U.S. Geological Survey, and the U.S. Bureau of Mines. The Ocean Drilling Porgram maintains three active core repository and curation facilities. Several state geological surveys maintain comprehensive facilities. The location of a sample-and-data-curation facility for material produced in a hydrocarbon research drilling program is an administrative decision that will depend on the nature of the program. A decision regarding this important component of the program should be made early to ensure that sample protocols and storage facilities are in place or designated before the drilling begins.

3.2.2 Sample Curation

Procedures for curation of rock and fluid samples produced from a hydrocarbon research drilling project should ensure that material will not be lost, damaged, improperly stored, or otherwise mishandled. Decisions must be made about how long cores and fluids are to be maintained and how they are to be preserved. Curation procedures will vary depending on the types of drilling fluids used. A core used for organic geochemistry or maturation studies requires special curation. Some experiments may require that cores be kept moist, frozen, encased in wax or epoxy, or otherwise specially handled. If specialty drilling is used in the program, new curation technology may be required. Such requirements need to be assessed as part of the overall rock sample handling protocol. Similar considerations must be given to the collection and preservation of fluid samples.

3.2.3 Archiving Selected Holes

It may be appropriate to maintain access to selected research drill holes for extended periods after drilling has been completed. This requires early consideration of drill hole and casing design, the research potential of a particular hole, and relative costs before drilling. Casing, cementing, and other hole conditioning should be done with consideration for the long-range potential for downhole geophysical measurements of rock, reservoir and fluid properties;

organic material; and experimental drilling techniques. Other critical considerations for maintaining a drill hole are its local geologic setting and complexities involved in retaining the hole in an accessible condition.

3.2.4 Costs

A balance must be achieved between the amount spent for actual drilling and the amount invested in the research portion of a scientific drilling project before it is implemented. Hydrocarbon research should be the primary goal of a drilling program, and the information obtained from proper core and fluid curation and downhole data are the critical elements in accomplishing this goal. The ratio of drilling to other costs should be based on reliable case-history drilling data, and the anticipated scientific information required. We recommend that representatives from the agencies involved in the drilling program, associated scientists, and experienced drilling engineers assess the objectives, environment, and anticipated infrastructure, and that they discuss detailed budget options with the sponsoring agency.

3.3 RESEARCH METHODS AND TOOLS

Research measurements made before, during, and after drilling should be focused on identifying and characterizing hydrocarbon source rocks and reservoirs, on seismic sequences, and on measuring parameters required for modeling and predicting sources of hydrocarbons. Such measurements will depend on samples obtained during drilling and subsequently analyzed in the laboratory, and on in situ observations made directly in the drill hole. Many of the tools and instruments for such studies are currently available, although some will require modification and others will require refined theories for complete interpretation of results.

Instruments designed for in situ measurement of physical and chemical parameters currently include:

- three-component wide-band downhole seismometer;
- pore pressure monitor;
- volumetric tensor and vertical strainmeter;
- downhole tiltmeter;
- self-potential (piezoelectric) detector;
- temperature/heat flow thermometers;
- deep circulating fluids analysers;
- high-frequency acoustic emission detector;
- vibroseis stacking for high-gain, high-precision seismic velocity monitoring;
- borehole gravimeter; and
- natural gamma ray spectroscopy.

Not all instruments are compatible in a single hole. Some require casing perforation, and others are effective only in an open hole.

Anticipated hole conditions also affect the choice of downhole tools. Hole diameter and hole deviation are two critical elements in considering downhole tools. In many instances, trade-offs must be made in instrument and tool selection depending on the relative value of each measurement and on hole conditions.

Slant hole or horizontal drilling may also be considered in designing a hydrocarbon research project. These could prove useful in determining lateral variation and inhomogeneities such as fractures, the frequency and spatial orientation of which may go undetected in vertical drill holes. Careful planning and further tool development will be required in considering such variances in drilling techniques.

3.3.1 Seismic Studies

Seismic profiling, both reflection and refraction, is a standard surveying technique in the oil industry. In recent years, remarkable advances have been made in reflection seismic profiling methods. Improved resolution has allowed more sophisticated interpretation of results. The advent of seismic stratigraphy is a case in point. Interpretation procedures for seismic stratigraphy result in geologic time lines and reflection packages related to discontinuity bound stratigraphic units. These genetically linked depositional systems in time and space are called systems tracts. The application of these observations to drill holes and outcrop data has resulted in an interpretation procedure to predict stratigraphy and facies ahead of the drill and to identify reservoir geometry.

A relatively new and largely undeveloped application of seismic waves is the determination of rock properties in the reservoir itself. Along with the recognition of the heterogeneous nature of a reservoir, there has been a major shift in the use of seismic methods. One aspect of this shift involves relating seismic properties of reservoir-related rock to production properties (e.g., porosity and permeability) and to physical state (e.g., mineralogy, saturation, and pore pressure). Wave velocities in reservoir wells are influenced by factors such as porosity, clay content, stress, pore pressure, fluid types, phase behavior of the pore fluid, and temperature. High-resolution seismology has a potential for deciphering the configuration of reservoirs, mapping porosity and permeability, and monitoring recovery processes. When calibrated with logs and sample information, the downhole seismic tool may be capable of playing a major role in explaining problems of recovery and production.

Although three-dimensional, vertical seismic profiling surveys and cross-hole tomography are coming into use, additional high-resolution downhole methodology needs to be developed to seismically "see" deep into surrounding formations and reservoirs. This methodology will need to be tested in drill holes during drilling. New drill holes with sample control and extensive, high-quality well logs also will be needed for evaluating and calibrating some of the new methodology and tools. Examples of developing technology requiring drilling for testing and evaluation include:

• Using the Drill Bit as Seismic Source. The elastic waves generated by the drill bit as it breaks the rock during drilling can provide seismic information about the rock mass surrounding the well. By placing a number of geophones on the earth's surface near and away from the well, a continuous inverted multichannel offset VSP survey can be carried out at relatively modest costs. Thus, when drilling is completed, a three-dimensional image of the rock volume surrounding the well can be obtained. Recent developments in signal processing have enabled successful implementation of this technology, and results suggest that data can be obtained at modest costs.

• Cross-well Tomography. Not unlike x-ray or NMR medical CAT scans, cross-well seismic tomography can provide detailed information on the spatial and even temporal distribution of acoustic properties between wells. A typical arrangement involves a seismic source, or an array of such sources lowered into one well, and a receiver or receiver array lowered into a second well. Both arrays are moved up and down independently in their respective drill holes, so that many seismic rays can be obtained.

The details thus obtained about spatial heterogeneities between the wells depend strongly on the frequency of the waves, which in turn depend on the spacing between wells and the attenuation factor of the rocks to be imaged. This implies that resolving heterogeneities of one to three meters across may become practical.

• Downhole Seismic Source. Where a drill hole already exists, and a second hole is not available, or when repeated imaging is needed, an active downhole seismic source may be extremely useful. Such a source will be activated repeatedly without returning to the surface. Such sources may provide a whole new dimension in imaging heterogeneities in difficult terrains, such as overthrust belts or basalt-covered regions, in which an exploratory well can be used as a "window" into the complex structure, which is otherwise difficult or even impossible to image.

Although integration of seismic information with magnetic and gravity survey results has become standard procedure in regional studies, it has not been employed as extensively in modeling individual fields or reservoirs. To improve the efficiency of stratigraphic and structural interpretations developed by this research, interactive computer work stations would provide a systematic approach to interpretation that could be learned and applied readily by exploration and reservoir geologists in large and small companies. Geophysical techniques should be used extensively in all of the topical areas recommended by this committee for hydrocarbon research drilling programs.

3.3.2 Geochemical Methods

Most geochemical research on hydrocarbons has focused on the fluid content and organic matter of rocks. An important but neglected factor has been the composition of nonhydrocarbon components of the fluids and their interaction with the wall rock of the holes. Periodic sampling of drilling fluids, formation fluids, and host rocks can result in better reservoir modeling. For instance, sample analyses can be critical in predicting flow behavior, diagenetic impacts, formation damage, and even the success of completion practices. Appropriate geochemical studies in drill holes can also provide critical data regarding oil formation, explusion, migration, and maturation. Existing analytical instruments and techniques required for such studies are probably adequate, although improved methods of downhole sampling and in situ measurements may be required for specific drilling projects.

3.3.3 Downhole Instrumentation

Logging of boreholes is standard procedure in the petroleum industry. Most of the downhole measurements are focused on determining the bulk composition of fluids or the density and porosity of the host rocks. The Ocean Drilling Program has an ongoing program of downhole research designed to expand the scope of logging, with a focus on obtaining greater detail regarding the composition and state of rocks and fluids. Natural gamma ray spectroscopy can also provide in situ determination of a number of inorganic elements, such as potassium, uranium, thorium, aluminum, iron, sulfur, silicon, calcium, carbon, and oxygen content of the formations being pentrated.

New tools are being developed to allow drill-hole imaging of fractures and other textures; measurement of the total magnetic field, including inclination and declination; and in situ stress measurements. New logging tools could be important adjuncts to the research drilling program, especially in holes drilled in difficult or obscured terrains.

The importance of in situ measurements of viscosity, surface properties, solubility, and chemical composition of petroleum in place is recognized.[1] These characteristics are key properties that could determine petroleum's response to primary, secondary, and tertiary recovery efforts. Drill holes are necessary to obtain samples taken and preserved under downhole pressure, volume, and temperature conditions and to make direct measurements of these physical properties.

3.3.4 Associated Laboratory Studies

Some critical laboratory investigations must be conducted in parallel with in situ drill hole experiments. Optimum scientific results can be obtained by coordinating laboratory studies with downhole measurements. The contribution of data points by downhole measurements on a curve of predicted results can "position" or calibrate the curve. Laboratory investigations, however, can simulate a variety of subsurface conditions and shapes of the curve. These strategic efforts should expand the results and interpretations of downhole data beyond local environmental conditions of the drill holes for broader applications.

3.4 ORGANIZATION OF A RESEARCH DRILLING PROGRAM

A carefully designed organizational structure with well-defined crosscutting relationships is needed to implement a program of scientific drilling for hydrocarbon research. It must be staffed with capable scientists, engineers, and support staff to design and implement program, negotiate cooperative business arrangements, execute contracts, oversee drilling operations, coordinate research activities internally and externally, evaluate results, publish scientific and technical conclusions, and direct a program most beneficial to the nation.

An effective hydrocaron research drilling program will require input and close coordination with a number of groups both within and outside DOE. Those within should include, but are not limited to, the Office of Basic Energy Sciences, the Office of Geosciences Research, the Office of Fossil Energy, and the National Laboratories. Outside DOE, close coordination should be maintained with the U.S. Geological Survey, the National Science Foundation, other federal agencies, state geological surveys, professional societies, industry, and academic and nonprofit institutions.

NOTE

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Chapter 4

RECOMMENDATIONS

4.1 SUMMARY AND RECOMMENDATIONS FOR IMPLEMENTING THE PROGRAM

A program of hydrocarbon research drilling reaching a level of $200 million annually over the next three to five years could be a very effective measure in a multifaceted national effort to reduce our dependence on foreign sources of petroleum. This level of investment would represent only a fractional percentage of the U.S. dollars exported yearly for hydrocarbons. Annual budget planning should consider devoting perhaps one-third to one-half of the funds to research, and one-half to two-thirds to actual drilling expenditures. A successful program should allow the United States to identify and develop its remaining potential resources, to produce the known resource base more effectively, to help slow the rate of dependency on foreign sources of petroleum, and to help improve the balance of trade.

In addition to the stated recommendations for substantive research, the following hydrocarbon research opportunities are advanced for immediate consideration by the Office of Basic Energy Sciences along with other DOE entities and outside groups as appropriate:

1. • Establish and maintain an inventory of the holes drilled and supported by all government agencies;

   • Notify the scientific community of government-sponsored drilling projects to encourage proposals for hydrocarbon-related studies;

   • Invest in scientific goal-oriented hydrocarbon research experiments to be undertaken before, during, and after drilling;

   • Consider assuming ownership of and responsibility for completed holes that could serve as long-term scientific observatories and laboratories;

   • Provide funds for drilling to accommodate hydrocarbon research goals;

   • Assure appropriate handling, distribution, and curation of samples and downhole data from hydrocarbon research drill holes for use by the scientific community, including industry;

   • Promote the dissemination of research results and technology transfer.

An inventory of holes drilled should be published and periodically updated, identifying specific opportunities for scientific experiments involving such holes. The initial tabulation of information pertaining to holes drilled to date, and related geological and geophysical data relevant to individual drill sites, could begin immediately at relatively low cost.

2. Actively seek opportunities to participate with private industry in hydrocarbon research projects, including drilling, to resolve critical questions regarding basic concepts.

3. Provide funds for hydrocarbon research experiments to be coordinated with the goals of the sponsors of privately drilled holes.

4. Improve the technology used in drilling, logging, and downhole measurement, so that the recommendations for a DOE hydrocarbon research drilling program can be better implemented. OBES should encourage and, as appropriate, invest in the development of drilling tools. This may be done through the Department of Energy's Small Business Innovative Research Program, the Office of Fossil Energy, the National Laboratories, and other appropriate research-and-development channels.

4.2 RATIONALE FOR RESEARCH

Improved characterization of subsurface rock units and their contained fluids will provide a better understanding of processes that control source and reservoir rock deposition, and the generation, migration, entrapment, and extraction of hydrocarbons. The dynamics of earth processes are becoming better known as a consequence of advances in many fields, such as global tectonics, seismic stratigraphy, and thermal history. A key to continuing these advances is the use of the drill as a scientific tool.

A program of hydrocarbon research drilling will increase understanding of the processes that continue to shape the earth. The objectives of research conducted under the recommended program are (1) to identify and characterize rock and fluid properties; (2) to improve models and predictions of subsurface conditions for source and reservoir rock occurrence, and for oil generation, migration, entrapment, and extraction; and (3) to test and verify or modify existing models and predictions.

A hydrocarbon research drilling program, generated by the Department of Energy with the support and cooperation of the petroleum industry, is in the nation's best interest. The petroleum industry should be approached to share in these research activities. Background data from industry should be sought to determine the most effective drill hole locations to achieve scientific research goals.

The following recommendations for an effective hydrocarbon research drilling program result from the deliberations and findings of the Committee on Hydrocarbon Research Drilling.

4.2.1 Recommendations for Research Themes

The recommended topical themes of the program should be considered as a cohesive effort, and drilling should be viewed in the broadest possible context. For example, if geoscientists are to understand the heterogeneity of subsurface reservoirs, it is essential that appropriate geophysical, geochemical, and engineering data bases be assembled and studied on areas selected prior to hydrocarbon research drilling. In all instances, pre-drilling geophysical studies and a complete set of any available logs should be incorporated into drilling plans, to maximize the interpretation of rock sections penetrated by the drill. These studies should include all available geophysical survey results. A broad suite of downhole measurements should be made to measure critical reservoir, fluid, and rock properties. Acquisition of cores, cuttings, and fluid samples, along with the in situ measurements, should be standard procedures in every hydrocarbon research drilling project. All material and data from drill holes should be properly organized and curated for use by future investigators.

A hydrocarbon research drilling program must provide important information on several key substantive areas. The committee has identified four such themes:

1. Reservoir characterization and geologic modeling;
2. Sedimentary sequences and crustal geology;
3. Seismically obscured terrains; and
4. Frontier areas.

1. Reservoir characterization and geologic modeling. Only recently have scientists and engineers begun to appreciate fully the heterogeneity of hydrocarbon reservoirs and other complications that have limited petroleum recovery. On average, 65 percent of the petroleum in reservoirs will not be recovered with existing levels of development because of limited knowledge of reservoir characteristics and technical and mechanical limitations. To improve recovery levels, a series of closely spaced holes should be drilled in existing fields and carefully analyzed to better define basic reservoir

characteristics. These holes may include some already drilled by industry, supplemented by new holes dedicated specifically for hydrocarbon research. Resulting information should be coupled with high-resolution geophysical data.

Type reservoirs in representative environments could be evaluated by using data from and access to existing boreholes, and by drilling new holes as required. Reservoirs selected for study should be typical of an exploration play, or should include suites of producing holes with common geologic and production characteristics. A high density of wells could allow development of detailed geologic models and prolonged flow tests to develop fluid-behavior models not feasible with information and technology currently in the public domain. If resulting experiments are satisfactorily tested and instrumented, important scientific information may be obtained with relevance to broader areas beyond immediate test sites.

Knowledge of reservoir characteristics and rock properties can be increased by an order of magnitude through systematic acquisition of appropriate subsurface data. Specific reservoir properties requiring further study are:

- comparisons between subsurface data and outcrop areas;
- controls on primary depositional systems;
- effects of secondary alteration (e.g., fracturing and diagenesis);
- factors affecting drive mechanisms;

- detailed reservoir descriptions for fluids, petrography, sediment variation, porosity, permeability, and other rock properties, such as acoustic velocities;

- detailed measurement of reservoir heterogeneities and their relation to in situ measurements, which is especially important in assessing unrecovered mobile oil; and

- fluid modeling as related to production problems.

2. Sedimentary sequences and crustal geology. A series of holes should be drilled in or across petroleum-productive basins of various structural types. Sites should be selected on the basis of multiple factors, including available or subsequently obtained high-resolution regional seismic data. The recommended locations are expected to be off-structure in most instances to maximize scientific information from more complete sedimentary sections. Such locations could minimize problems of ownership, control, liability, and other business aspects commonly associated with holes designed for perceived economic targets. The objective is to acquire details on the geologic setting and processes affecting the distribution of fluids in such basins, which would allow a more comprehensive analysis of factors controlling hydrocarbon occurrence.

3. Seismically obscured terrains. Regions where geologic complexities make geophysical interpretations unusually difficult must be drilled if the search for hydrocarbons is to extend into such environments. For example, substantial volumes of hydrocarbons may exist beneath overthrust belts, under basaltic cover, in regions of

extensive salt tectonic activity, in subduction zones, within complex structural settings, beneath ice and permafrost regions, and beneath thick carbonates. Geophysical studies in most of these potential target environments are hindered by velocity problems, as normal geophysical tools are rendered unreliable or unusable. Seismic profiles obtained, for example, in basalt or permafrost areas are not easily interpreted. Drill holes in selected obscured terrains could extend our understanding of the geology of important potential hydrocarbon areas. A full suite of logs and geochemical and geophysical tests in conjunction with the drilling could confirm or modify basic concepts regarding such regions.

4. Frontier regions. Although geologists have a reasonable understanding of many regions producing oil and gas, there still remain numerous underexplored areas, or frontier regions, such as ultra-deep sedimentary basins, shallow and deep rifts, and wrench fault terrains. Current opinion suggests that some frontier regions have a high potential for adding to domestic hydrocarbon resources. These areas have not been explored fully because of costs and lack of knowledge about the nature of source rocks, reservoir quality, fluid flow and behavior, rock properties, diagenesis, and thermal properties. Without considerably more subsurface data regarding these environments, the potential for hydrocarbon generation migration, entrapment, and preservation cannot be determined.

4.2.2 Facilities for Sample and Data Curation

Proper handling and distribution of fluid samples, logs, cores, cuttings, and geophysical data obtained from holes drilled under the proposed hydrocarbon research program are essential. Information acquired should be reduced to common data bases readily accessible to the scientist and engineer, and curation may be provided at existing federal or state geological facilities. As part of the curation procedure, samples and data from holes drilled under the hydrocarbon research program should be selectively retained. This requires designing the hole for instrumentation after drilling is completed, and the option of re-entry to allow further tests in the hole. This design should be carried out with proper quality controls in place to ensure that data obtained from drill holes are reusable and accessible.

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