An Introduction to the Geology and Mineral Resources of the Continental Shelves of the Americas

GEOLOGICAL SURVEY BULLETIN 1067

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By JAMES TRUMBULL, JOHN LYMAN, J. F. PEPPER, and E. M. THOMASSON

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A description of the continental shelves of the Americas, their potential mineral resources, and problems of petroleum development in the Gulf of Mexico

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1958

UNITED STATES DEPARTMENT OF THE INTERIOR

FRED A. SEATON, *Secretary*

GEOLOGICAL SURVEY

Thomas B. Nolan, *Director*

For sale by the Superintendent of Documents, U. S. Government Printing Office
Washington 25, D. C.

FOREWORD

The presence of shallow water for varying distances from the shores of continents and many islands of the earth has been known to mariners, and particularly to fishermen, from time immemorial. Many years ago knowledge of the width and configuration of these shallow-water shelf areas of the continents was gained in fishing areas and along the main shipping and oceanic-cable routes. In modern times, oceanographers, geologists, and geophysicists have increased their knowledge of the continental shelves through the use of new techniques of hydrographic surveying, geophysical exploration, bottom sampling, underwater photography, and core drilling. Nevertheless, reliable information concerning continental shelves and the rocks underlying them is scarce, and consequently an understanding of the origin and composition of the submerged borderlands of the continents is still in its infancy.

Scientists who study the configuration of the earth consider the seaward, or outer, margins of the continental shelves to be located where the gently sloping shallow platforms surrounding the continents steepen abruptly and slope toward the abyssal depths of the oceanic basins. Only in local areas of detailed hydrographic surveying are the positions of the outer edges of the shelves well known. Elsewhere, water depths, and consequently shelf widths, as shown on maps and charts are only approximations and are undoubtedly inaccurate in many places.

Thus the limits of the continental shelves of the Americas are not accurately known, nor is much known about the topographic character of important continental-shelf features. This is not surprising, however, for scientific interest in the nature of continental shelves and the means for making accurate and extensive surveys beneath the sea are both recent developments. The need for greatly expanding the fund of factual data about the continental shelves of the Americas is clearly evident.

The current trends toward a rapidly increasing population as well as a greatly improved standard of living make the mineral resources of the continents of interest and concern to all. Mineral resources that remain unknown and undiscovered are of no value. Those that are known but undeveloped are of no immediate benefit. Those that have been discovered, have been developed, and are now producing commodities for world trade, add to the well-being of the international economy. For centuries man has searched the land areas of the world for deposits of precious metals, base metals, fuels, and industrial minerals. Although many valuable mineral deposits undoubtedly remain to be discovered on land, the state of knowledge about the mineral resources of land areas can be considered to be rather advanced. On the other hand, knowledge of mineral resources of the submerged margins of the continents is in its infancy.

Coal has been produced from beneath the ocean floor in Chile and Nova Scotia, and iron ore has been similarly produced in Newfoundland, production in all three instances having been from mines begun on shore and extended beneath the sea floor as much as several miles. In recent years oil fields have been discovered in the Gulf of Mexico and off the west coast of the United States, and special techniques have been devised to permit development of these fields. Tremendous impetus has been given to national an international interest in continental shelves by these discoveries of commercial quantities of petroleum beneath the sea floor. Because knowledge of mineral resources of the continental shelves is adequate for only a few localities, the extent and ultimate value of the mineral resources recoverable from all the shelf areas of the Americas are unknown. The future will without doubt reveal new occurrences of important mineral commodities recoverable from the continental shelves. Man's search for knowledge, his ingenuity, and his fervor to explore the unknown guarantee this. Furthermore the increasing need to discover new mineral sources to augment supplies from our presently known deposits provides a strong economic stimulus to this search.

Matters pertaining to the resources of the continental shelves and overlying waters, including both mineral and living resources, were considered in 1954 at Bogota, Colombia, at the Tenth Inter-American Conference of the Organization of American States (Pan American Union). The Bogota conference recognized the complexities of the subject and the amount of background information necessary to an adequate understanding of the problems involved, and resolved to call a Specialized Inter-American Conference on "Conservation of Natural Resources: The Continental Shelf and Marine Waters." This conference was held at Ciudad Trujillo, Dominican Republic, March 15–28, 1956.

The United States delegation's working group on "The Continental Shelf and its Mineral Resources" prepared the following four technical papers for presentation at the specialized conference: "Continents and Ocean Basins and Their Relation to Continental Shelves and Continental Slopes," by James Trumbull, U. S. Geological Survey; "A Review of Present Knowledge Concerning the Continental Shelves of the Americas," by John Lyman, U. S. Navy Hydrographic Office; "Potential Mineral Resources of the Continental Shelves of the Western Hemisphere", by James F. Pepper, U. S. Geological Survey; "Problems of Petroleum Development on the Continental Shelf of the Gulf of Mexico," by Edwin M. Thomasson, U. S. Geological Survey. Each of these papers represents a compilation and synthesis of the basic information available on the particular subject covered. Because each paper provides a rather concise although simplified summary of the current state of knowledge, and because this information is not readily available from any other single source, the Geological Survey has prepared these papers for this publication in order to make them generally available.

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CONTENTS

CONTINENTS AND OCEAN BASINS AND THEIR RELATION TO CONTINENTAL SHELVES AND CONTINENTAL SLOPES

By JAMES TRUMBULL, U. S. Geological Survey

CONTENTS

ILLUSTRATIONS

ABSTRACT

The rocks underlying the continental segments of the earth's crust are characteristically light in color and weight, whereas the rocks underlying the oceanic segments are characteristically dark and heavy. These segments of different properties can be considered to be floating on a heavy plastic substratum. In addition to being lighter in weight, the continental segments are thicker than the oceanic segments, and thus stand higher. The average difference in elevation between the continental and oceanic segments is on the order of 2 miles (3.2 km). The extra thickness of the continental segments compensates for the lighter weight, and the two kinds of segments are in approximate equilibrium.

The term "Isostasy" (equal standing) is applied both to this condition of floating equilibrium and to the tendency of blocks of the earth's crust to maintain that equilibrium by vertical motion. The resulting relative motion is probably concentrated, but by no means entirely localized, at the boundary of the continental and oceanic segments. For most of the world this zone of adjustment is thought by many authorities to be in the continental slope, which is a submerged escarpment that is in many places steeper and higher than the fronts of most mountain ranges. Between the steep continental slopes and the present shorelines of the continents are the more gently inclined continental shelves which although submerged are part of the continental areas both in terms of rock structure and topography.

The elevation of the surface of the oceans with respect to land (that is, sea level) changes continually, and in the geologically recent past it has been both higher and lower than it is at present. During the glacial age so much water from the oceans was locked in glacial ice that sea level fell an amount usually estimated at 150 to 500 feet (45 to 150 m). At that time the continental shelves were largely exposed; that they are now submerged is almost fortuitous.

By definition the continental shelves extend from the mean low-water line to the sharp change in inclination that marks the beginning of the continental slope (the shelf edge). This change occurs at an average depth of 432 feet (72 fathoms, 132 m) below present sea level, though for convenience the 600-foot (100-fathom, 183-m) line is more often used. Throughout the world the average inclination of the continental shelves is less than one-eighth of 1°. Their average width is 42 miles (67 km), but their width ranges from a fraction of a mile to many hundreds of miles. Stable lowland coasts usually have wide, shallow, uniform continental shelves, whereas the shelves off geologically young mountainous coasts usually are narrow or absent, at great depths, and variable. The continental shelves have been modified in places by glaciation, large rivers, and coral growth. The comparative flatness of the continental shelves seems due to a combination of factors, including both downcutting by erosive forces and upbuilding by deposition of sediments.

The continental slopes extend from the outer margin of the continental shelves to the floors of the deep ocean basins. Their average height above the deep ocean floors is 12,000 feet (3,660 m); their average width is 10 to 20 miles (16 to 32 km); and their average inclination is slightly more than 4° though 25° is common. Off stable lowland coasts, and especially off large rivers, they are more gently inclined; off young mountain ranges they are steeper. The continental slopes are modified by large submarine canyons of unknown origin, and by plateau areas at intermediate depths. Accumulation, flowing, and sliding of sediments take place upon their surfaces. Although the continental

slopes are thought to have been formed by upward faulting (offsetting) of the rocks of the continents relative to those of the ocean basins, this is unproved, and other theories have been advanced.

INTRODUCTION

The oceans and seas cover seven-tenths of the surface of the earth, but man's knowledge of the world is largely limited to the three-tenths on which he lives. In recent years, however, a small amount of information has been accumulated about the shape and nature of the ocean basins, and the minor as well as the major characteristics of the ocean floor are becoming known.

The framework of the continents and ocean basins is more easily considered if for the moment the waters of the oceans are neglected. A mental picture of the earth with its oceans and seas gone as if evaporated is revealing.

THE FLOOR OF THE OCEAN

If all the waters are ignored, the predominent feature of the earth is the floors of the ocean basins. In the overall picture they are low, relatively flat areas of little relief. Closer examination, however, reveals a great number of features of diverse topographic form—some are submarine mountains or plateaus, others are marked depressions.

Elevated areas on the ocean floor include small but broad and flat-topped banks, small isolated peaks called seamounts, broad elevated areas called rises, and long narrow elevated areas called ridges. The best-known example of the latter is the Mid-Atlantic Ridge, which nearly bisects the Atlantic basin for its entire length, from north to south, and rises 10,000 feet (3,000 m) above the ocean floor.

Depressions in the ocean floor include rounded basins, elongate troughs with gentle slopes, and long, narrow, steep-sided trenches. The trenches contain the most depressed areas of the floors; these are called deeps and commonly have names given them. The Philippine Deep extends to more than 34,000 feet (10,360 m) below sea level, and the Brownson Deep, north of Puerto Rico, to 28,500 feet (8,700 m).

Although there are a number of each of these diverse features of the ocean floors, by far the most notable characteristic is the vast uniformity of the floors as a whole.

No less striking is the low level of this tremendously broad and generally level area. The average depth below sea level of the ocean floors, excluding adjacent shallow seas, is about 13,000 feet (3,960 m). About 60 percent of the surface of the earth is more than 7,000 feet (2,134 m) below sea level.

THE SURFACE OF THE LAND

Viewing the overall shape of the land areas of the earth, the great mountain chains immediately draw attention, but these features, although striking in appearance, occupy only a small portion of the land areas. Only about 3 percent of the earth's surface is more than 6,500 feet (1,980 m) above sea level. The mean elevation of the land areas is only about 2,700 feet (823 m). As is true of the ocean floors, most of the land surface of the earth lies within a small range of elevations.

A striking simplicity in the earth's architecture is apparent. Most of the earths' surface falls within two separate general levels of elevation. The continents are high and the ocean basins are low; the transition zone is narrow. This relationship is clearly illustrated in figure 1, which shows the percentage of the earth's surface lying between various levels above and below the surface of the sea. The 2 bulges formed by the bars indicate the 2 major levels of the earth's surface. The short bars separating the two bulges show the area of the earth's surface that is at relatively small depth below sea level. These areas are made up mostly of the transition areas between the continents and the ocean basins.

The following summary of the physical nature of the continental and oceanic segments of the earth's crust will provide an explanation for the predominance of two separate levels of the earth's surface.

PHYSICAL NATURE OF THE CONTINENTAL AND OCEANIC PARTS OF THE EARTH'S CRUST

The rocks that form the continents and the rocks under the floors of the ocean basins are distinctly different in composition and therefore in most of their other characteristics. As will be seen, the great height to which the continents rise above the ocean floors results chiefly from these differences.

STUDIES OF THE DISTRIBUTION OF ROCK TYPES

Direct information about the composition of the earth's crust comes from study of the rocks of the continents, the oceanic islands, and the few actual samples of material that have been recovered from the ocean floors. Though there are exceptions, one type of rock predominates on the continents, and another type predominates in the oceanic areas.

The differences in continental and oceanic rock types are simply stated. The rocks that form the continents are characteristically light in weight and color. Granite is the major rock type, and the continents are commonly described as being granitic. The rocks un-

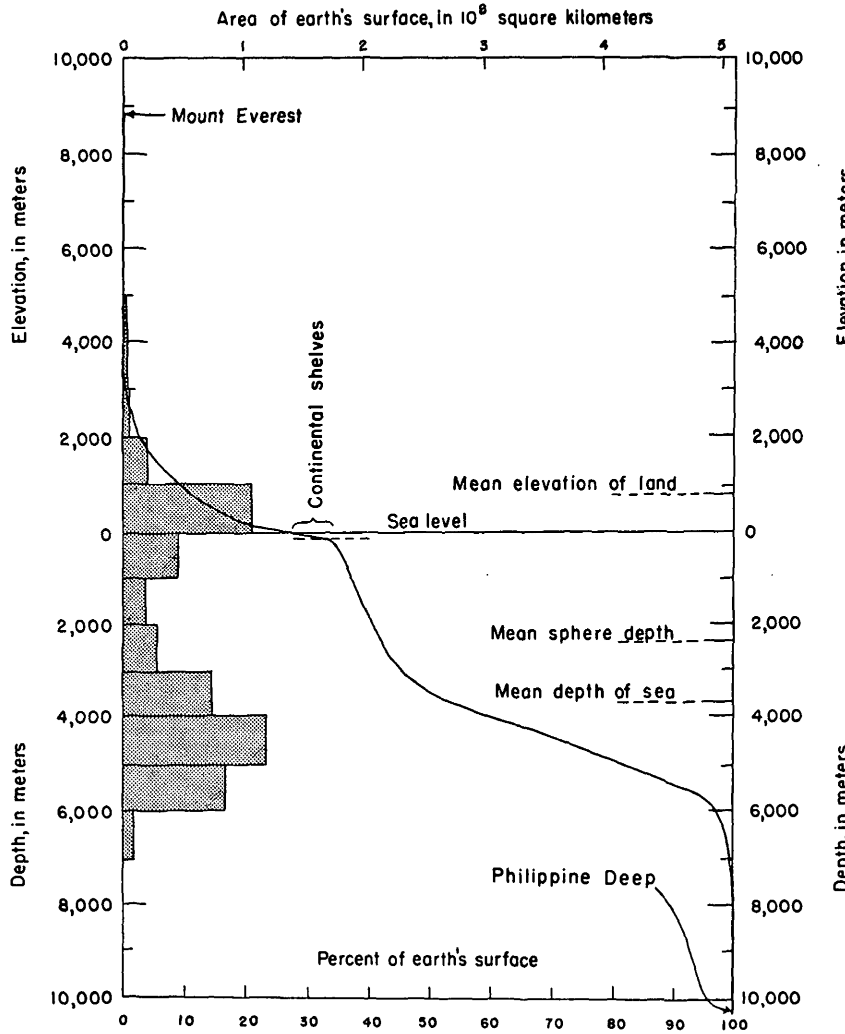

FIGURE 1.—Curve showing the area and percentage of the earth's solid surface above any given elevation or depth. Bars at the left show the frequency distribution of elevations and depths for 1,000-meter intervals. The curved line is a cumulative distribution curve, not a profile. Mean sphere depth is the uniform depth to which water would cover the earth if the solid surface were smoothed off. It should be distinguished from the mean elevation of the earth's surface (not shown), which is determined by the location of the 50-percent point of the curve. (After Sverdrup, Johnson, and Fleming, 1942, p. 19.)

der the floors of the ocean basins are characteristically heavy and dark in color. Basalt is the major rock type, and the oceanic rocks are commonly referred to as being basaltic.

STUDIES OF SEISMOGRAMS

Because the two general rock types that make up the continental and oceanic segments of the earth's crust differ in density, they also differ in the speed with which they transmit pressure impulses; that is, they have different seismic velocities. The records of shock waves from earthquakes and manmade explosions that travel through the rocks are thus another source of information; these records are called seismograms. This information is not restricted to rocks at the surface of the earth, because vibrations from mechanical shocks travel through the earth as well as along its surface. Boundaries of earth layers having different seismic velocities can be accurately located and something about the properties of the layers determined, though they lie deep in the earth.

The two general rock types—granitic on the continents, basaltic in oceanic areas—make up the crystalline crust of the earth. The thin mantle of sedimentary rocks that lies on much of the crystalline crust looks so small in the overall picture that it need not be included in this classification. Though this layer locally may be several miles thick, it results from erosional and depositional processes modifying the surface, and is largely incidental to the study of major features of the earth's structure.

The crystalline crust is conventionally divided from the deepseated, heavier rocks of the earth's interior by a boundary known as the Mohorovičić discontinuity, above and below which the rocks have different seismic properties. The depth from the surface to this boundary, which is about the same thing as the thickness of the crystalline crust of the earth, averages roughly 18 to 25 miles (29 to 40 km). This boundary is at a greater depth under the continents than under the ocean basins, and under high mountain areas such as the Sierra Nevada and the Alps it is at nearly twice the depth that it is under the oceans. The continents thus extend both higher into the air and deeper into the interior of the earth than do the ocean basins. The relation between mountain areas and other continental areas is similar: not only do the high mountains project far into the air, but they have crystalline roots that extend deep into the substratum.

Thus the earth's crust consists of relatively light but thick continental blocks, and dense but thin oceanic blocks.

STUDIES OF GRAVITATION

Much information concerning the crustal structure of the earth is also derived from precise local measurements of the strength of the earth's gravitational field. The basis of such determinations is of course Newton's fundamental law of gravitation: the attraction between any two bodies increases with mass and decreases with distance.

It might be thought that the larger volume of the thick continental blocks would result in higher gravity readings for continents than for ocean basins, but this is not true. Instead, the excess volume of the continents is balanced by the low density of the continental material. Similarly, the deficiency of mass in the water-filled ocean basins is nicely balanced both by the high density of the underlying crustal material and by the nearness of the still denser subcrustal material.

ISOSTASY

The continents float high because of their lower density and greater thickness; the oceanic segments are low because of their higher density and relative thinness. This condition of floating equilibrium between blocks of the earth's crust resting on a somewhat liquidlike interior is called isostasy. The term isostasy also means the tendency of crustal blocks to maintain their floating equilibrium.

One aspect of this concept of maintaining floating equilibrium is of particular interest. Erosive forces continually remove materials from the continents and transport it to the oceans. Over geologically long periods of time the lightened continents would be expected to rise, the weighted ocean floors to sink. Relative motion at the junction of the continents and the deep ocean basins might therefore be expected. This topic will be treated in the subsequent discussion of the origins and nature of the continental slopes.

STRUCTURAL FRAMEWORK OF THE CARIBBEAN AREA

The Antillean island arc, curving through the West Indies and setting off the Caribbean Sea and the Gulf of Mexico from the Atlantic Ocean, exhibits a number of features which merit attention. Close counterparts to this island arc, geologically speaking, are found in the chains of islands that festoon the Pacific coast of Asia: the Aleutian, Kurile, Japanese, Ryukyu, and Philippine island arcs separate the shallow Bering, Okhotsk, Japan, East China, and South China Seas, respectively, from the Pacific Ocean; and the Bonin and Mariana island arcs and undersea ridges separate the Philippine Sea from the Pacific Ocean proper. There are numerous other examples.

These island-arc areas have great contrasts in elevation within short distances, just as is the case where the continents meet the ocean basins. Although study of island-arc areas has been intensive and highly revealing, and forms a fascinating field of interest, it is possible here to sketch only the barest outlines of present information and hypotheses concerning them.

Island arcs have many features in common. They are all convex toward the ocean. On the ocean side of each is a narrow, arcuate, extremely deep trench in the ocean bottom. The Puerto Rico Trench contains the greatest measured depth in the Atlantic Ocean, yet its deepest parts are no more than 100 miles (160 km) north of the Virgin Islands, Puerto Rico, and the eastern end of the Dominican Republic.

Measurements of gravity indicate that the rocks underlying a long narrow zone parallel to these trenches have an unexpectedly low specific gravity. In the Caribbean this narrow strip of low specific gravity extends continuously from eastern Cuba to Trinidad. It coincides with the trench north of the Dominican Republic and Puerto Rico, but southward from the Leeward Islands it coincides with a ridge of which the island of Barbados is an exposed portion.

Volcanoes commonly occur in a narrow line on the concave side of the arcs, at a distance of about 100 miles (160 km) from the axis of the central belt of low gravity. Further, an unusual type of rock called peridotite is commonly found in a nearby narrow belt that is also parallel to the belt of low gravity. This type of rock is uncommon on the surface of the earth, but is thought to be abundant at a deep level within the earth.

The generally accepted explanation of these diverse but apparently related phenomena is that a great linear fold of the earth's crust has buckled downward into the heavy subcrustal material. The resulting deep furrow in the ocean bottom roughly represents the upper surface of the downfold. The central belt of low gravity is explained by the mass deficiency of the downfold of light crustal material. The development of fractures associated with the bending of the crust accounts for the observed volcanism and earthquakes. The fractures have been the routes by which the peridotite has flowed upward to the surface.

If there should be a weakening in whatever force caused the downfold of light rocks into heavier ones, isostatic adjustment would cause the downfold to rise, and a narrow land area might appear on each side of the center of the downfold. Most of the islands of the Caribbean, with certain exceptions including Jamaica, Barbados, and Aves Island, are thought to represent this uplift on the concave side of the furrow.

THE SHIFTING LOCATION OF THE EDGE OF THE OCEANS

It is common knowledge that much of what is now dry land was once covered by the ocean. Assemblages of marine fossils known to be uniquely characteristic of particular intervals of past geologic time are widespread over present land areas. The study of the present distribution of rocks deposited during specific intervals of past time enables the construction of maps showing the distribution of land and sea during those intervals.

Figure 2 is an example of such a map. It shows the extent of land and sea in North America during the time interval extending from about 40 million years ago to about 28 million years ago. That time interval, termed the Oligocene epoch of the Tertiary period, was not long ago in terms of the geologic history of the earth, yet there have been many changes in the outline of the land areas from Oligocene time to the present.

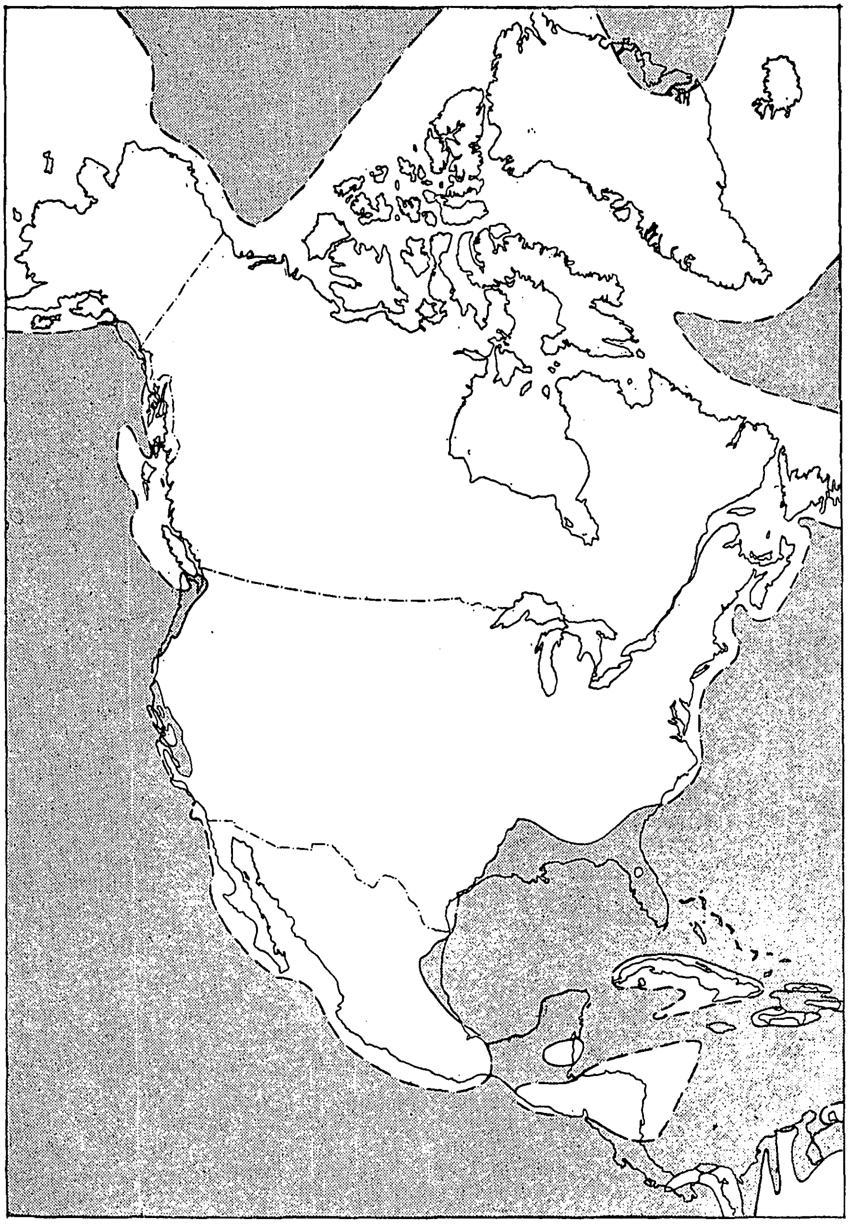

FIGURE 2.—Inferred distribution of land and sea in North America during the Oligocene epoch, a geologically recent period of time. (After Schuchert, 1955, p. 81.)

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From the geologic standpoint, then, the present location of the edge of the sea is only temporary. The oceans have been both higher and lower in relation to the land in the recent past.

The several causes of change in sea level relative to land may be divided into two groups. The land in any particular area might rise or fall, sea level remaining stationary. Or on the other hand, the amount of water in the ocean basins (or the capacity of the basins) might change, and sea level rise or fall accordingly, the land areas remaining unmoved. Both processes have been operating throughout geologic time and are operating now.

VERTICAL MOVEMENTS OF LAND AREAS RELATIVE TO THE SEA

The coasts of Scandinavia and of the northeastern United States and Canada are today rising at a geologically rapid rate as an isostatic adjustment to the removal of the weight of the glaciers that recently covered those areas. Other vertical land movements include the uplifting of mountain and high plateau areas by deformational processes acting within the earth, and the previously mentioned isostatic rise resulting from loss of weight by erosion at the surface of the earth.

Erosion does not proceed at the same rate everywhere, and apparently all vertical movements of the land vary in amount from place to place. Consequently, any change in sea level found to be uniform on a worldwide basis is to be attributed to changes in the volume of water in the oceans, or perhaps to changes in the volume of the ocean basins.

CHANGES IN SEA LEVEL RELATIVE TO LAND

Ample evidence exists of repeated great advances and retreats of glaciers during the Pleistocene epoch, or roughly the last million years. The advances are thought by most authorities to have been four in number, generally of diminishing intensity. During the intervening three interglacial periods the world climate was markedly warmer than at present.

These repeated glacial advances cannot have occurred without corresponding reductions of sea level, as all the water bound up in the glacial ice was obtained from the oceans. The area once occupied by the glaciers is fairly well known, but the thickness of the ice can be estimated only roughly. The calculated ice volume is therefore only an estimate of the order of magnitude, but it generally corresponds to a lowering of sea level of some 150 to 500 feet (45 to 150 m) below the present position. Estimates of as much as 3,500 feet (1,070 m) have been made, however, in an attempt to explain features on the ocean floor at that depth that appear to be the result of stream erosion.

THE PRESENT OVERFULLNESS OF THE OCEAN BASINS

The overall relation of present sea level to the continents is revealed by maps showing the shape of the sea bottom outward from land, and by cross sections such as those of figure 4. They show that off many of the coasts of the world the sea floor is gently inclined for a considerable distance seaward, but then at a fairly well-defined line the sea floor steepens rather abruptly, and thereafter the water deepens rapidly and continuously until the floor of the deep ocean is reached. Geologically, the abrupt change in inclination of the sea bottom, rather than the present shoreline, marks the true edge of the continents. The water depth at the change in inclination is usually between 350 and 600 feet (58 and 100 fathoms, 107 and 183 m), and averages 432 feet (72 fathoms, 132 m).

The ocean basins can thus be characterized as overfull—water not only fills the ocean basins proper, but extends out over the low margins of the continents. The submerged and relatively flat-lying margins of the continents inshore of the abrupt change in slope are called the continental shelves. The abrupt change in slope is properly referred to as the shelf edge. The more steeply inclined surface that lies seaward from the shelf edge is referred to as the continental slope.

The shelf edge and the bottom of the continenal slope form boundaries between three major topographic and structural areas of the earth. Those three areas are the floors of the ocean basins, occupying roughly 50 percent of the earth's surface; the continental slopes, occupying about 15 percent; and the continental shelves together with the land, occupying the remaining 35 percent.

THE CONTINENTAL SHELVES

The submerged margins of the continents have been intensively sounded at some places for the benefit of navigation, but in most places knowledge of shelf topography is still meager, and the more difficult examination of bedrock and sediments on the shelves has only begun. Any but the most general statements about the shelf areas are thus founded on extremely incomplete data. On numerous points of information there now exist two or more hypotheses which cannot be definitely proved or disproved.

Much of the available information on the shelf areas of the world has come from the work of Francis P. Shepard, professor of submarine geology at the Scripps Institution of Oceanography of the University of California at La Jolla. The discussion of the continental shelves and slopes in this report is largely based on the work of Dr. Shepard.

The figure of 432 feet (132 m) for the average water depth at the shelf edge was determined by Shepard from thousands of charts covering all parts of the world. Previous to his work the continental shelf was generally considered to extend to a depth of about 600 feet (100 fathoms, 183 m). That figure is useful as an approximation, and the 100-fathom contour line is found on most available charts of the ocean bottom. The 100-fathom line bounds the continental shelf of the Americas that is shown in figure 3.

Only a few coastlines lack continental shelves. Such coastlines are those formed by major faults, or those on which there has been extensive glacial deepening. In some places the shelves are very narrow, ranging from a fraction of a mile to a few miles at most; in other places the shelves are hundreds of miles wide. Their average width throughout the world is 42 miles (67 km), and the maximum width, along the Arctic coast of Europe, is 750 miles (1,200 km). The shelves constitute more than 7 percent of the marine area of the earth.

The average inclination of the continental shelves is only about 12 feet per mile (2.3 m per km; 0°07′; 0.2 percent). They are slightly steeper in the inner (nearshore) half than in the outer. In some places sediments are being deposited on the shelves, in other places they are apparently only being transported across them, and in still other places the shelf surface is bare of sediments. The shelf edge is usually rather straight, though in some places it is sharply indented by submarine canyons that cut deeply into the continental slopes farther offshore (see fig. 4).

The continental shelves are a simple underwater continuation of the adjacent land, and, as would be expected, their geology is merely an extension of the geology of the bordering land areas. The surface of the shelves has the many small irregularities that are characteristic of low-lying coastal areas on land.

TYPES OF CONTINENTAL SHELVES AS EXEMPLIFIED IN THE AMERICAS

The continental shelves are by no means as uniform as the preceding overall description and average measurements might indicate. On the contrary, they are highly variable in size, shape, and composition. The shelves of the Americas give a wide range of examples, and can be grouped in accordance with their characteristics and the forces that act upon and modify them.

BROAD SHELVES OFF STABLE LOWLAND COASTS

Most of the Atlantic coastal area of the Americas is a low-lying plain. Even in once-mountainous low coastal areas like New England

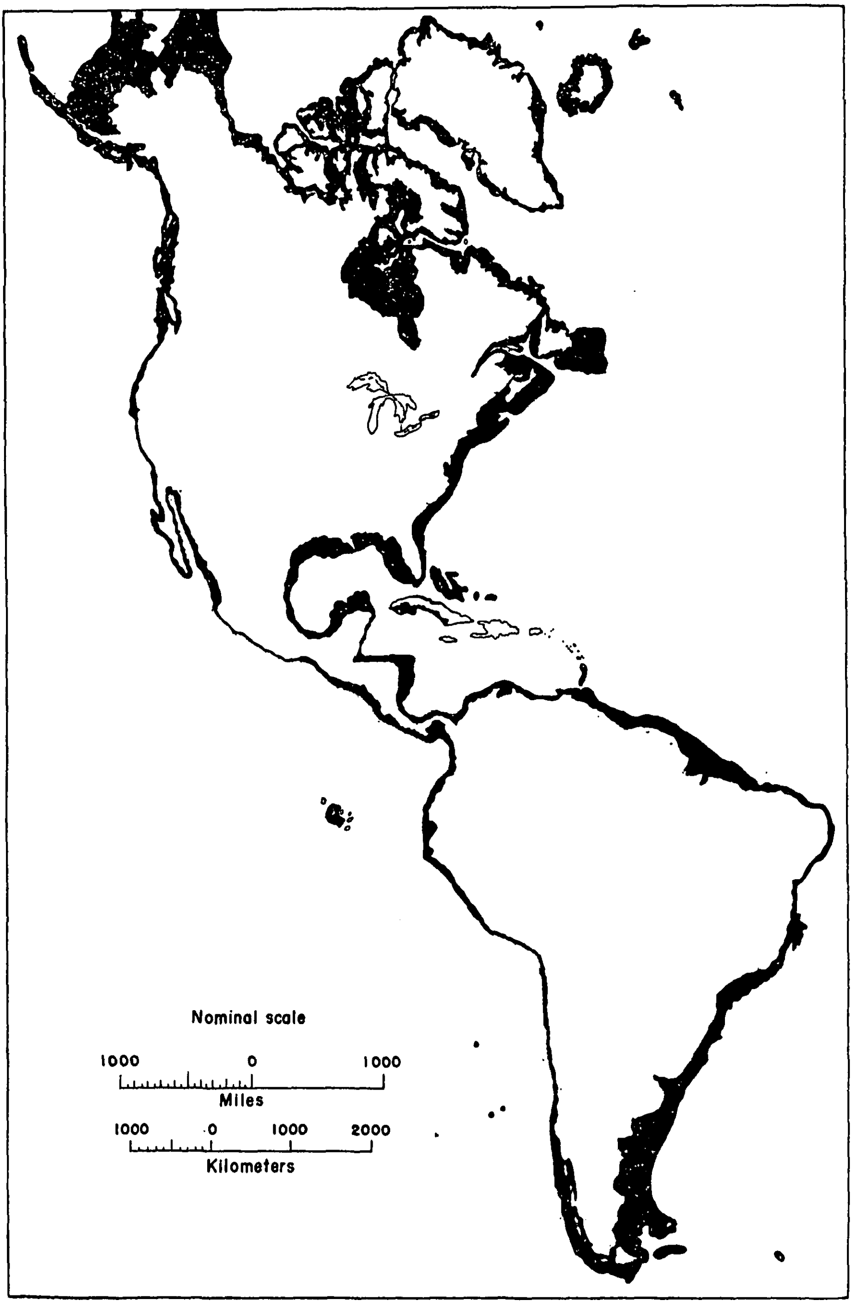

FIGURE 3.—The continental shelves of the Americas.

and the Brazilian Highlands, the age of mountain building has passed, and for a long interval of geologic time crustal stability has allowed erosion to proceed.

The continental shelf of these stable lowland areas is commonly of great and somewhat constant average width. Though there are a number of exceptions, the shelf for long distances along the Atlantic coast of the Americas is 50 to 100 miles (80 to 160 km) wide (fig. 3). Such areas are in strong contrast with the narrow shelves along the Pacific coast of the Americas. This is illustrated by the profiles shown in figure 4; the upper two profiles cross the Atlantic coastline, the lower crosses the Pacific coastline.

NARROW SHELVES OFF YOUNG MOUNTAIN COASTS

The Pacific coastal area throughout the length of the Americas is bordered almost entirely by geologically young mountain ranges (fig. 4C). For the most part the mountains are still in the process of formation, as evidenced by recurrent earthquakes. Faults along which blocks of the earth's crust have slipped great vertical distances are commonly located near these coasts, and in places they coincide with and determine the location of the coastline.

Along these geologically active coasts the continental shelves are narrow or even lacking, and are irregular both in width and depth. In some of the fjords along the coast of Chile the water is almost a mile deep, and along the Chilean and southern Peruvian coast in general there are only local, narrow shelves, and they are of greater than average depth and inclination. The shelf width along the west coast of North America over long distances does not exceed 50 miles (80 km), and is only 10 to 20 miles (16 to 32 km) off the United States and negligible off long sections of the west coast of Mexico. The continental shelf off the west coast of the United States is at markedly greater average depth than that off the east coast, with large areas exceeding 300 feet (50 fathoms, 91.5 m), and terminations that are close to 600 feet (100 fathoms, 183 m).

From the above relations it can be said that the American continents are bordered by two general types of shelves: the wide, relatively shallow and uniform shelves off the stable lowland coasts; and generally narrow, deep, and variable shelves along coastlines of young mountain ranges. This correlation of shelf type and coastal type is only to be expected, for the shelves are but drowned coastal areas.

MODIFICATIONS OF THE TWO GENERAL SHELF TYPES

Geologic processes of a generally smaller or more local nature than mountain building have also had a direct effect on the nature of the continental shelves. These processes include glaciation, the building

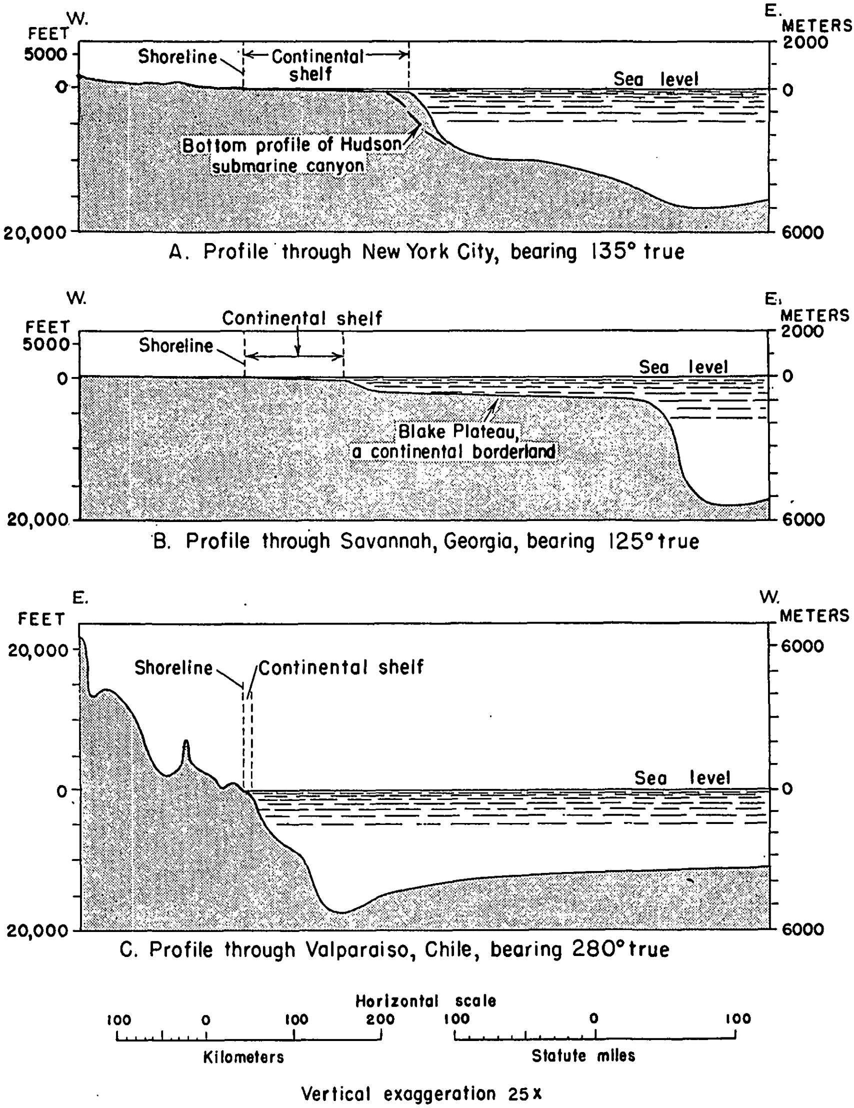

FIGURE 4.—Generalized profiles of the earth's surface from the continents to the deep ocean basins at selected places in the Americas. The vertical scale is the same and the horizontal scale is the same in each profile, but the vertical scale is 25 times the horizontal, and thus there is a 25-fold vertical exaggeration in the relief. Note that the orientation of the Valparaiso section has been reversed to make comparison easier. (Constructed from the 1 : 5,000,000 scale "Map of the Americas" of the American Geographical Society of New York.)

of deltas off the mouths of large rivers, and the formation of coral reefs.

GLACIATED SHELVES

Glaciers of the recently concluded Pleistocene ice age are known to have affected the coasts of northeastern North America, the Pacific coasts of Canada and Alaska, and part of the coast of South America. The great changes in terrestrial topography caused by glaciation are well known: trough-shaped valleys are formed and enlarged, large lakes come into being, and great quantities of loose rock are picked up, carried, and dumped irregularly at the terminal end of the glacier.

Each of these effects seen on land has its counterpart on the glaciated portions of the continental shelves. The resulting characteristics of glaciated shelves set them strikingly apart from all others.

Nonglaciated areas of the shelves normally become increasingly deep from their inner to their outer margins. In contrast, glaciated shelves are characterized by banks and shoals rising offshore, with deeper water between them and the coasts. Not all banks and shoals occur off glaciated areas, but those at a considerable distance from shore are much more common there than elsewhere.

The linear chain of banks so famous in the annals of Atlantic fishing that extends from far at sea off the coast of Newfoundland southwestward to the waters off Cape Cod is of this type. Sable Island off the Nova Scotian coast is simply an emergent part of Sable Island Bank. These banks are known to be composed of morainal material, which is made up of heterogeneous rock debris carried in tremendous quantity by glaciers. Morainal deposits both on land and in glaciated shelf areas have a hummocky topography.

Contour charts showing the shape of the surface of the glaciated shelf areas reveal great trough-shaped valleys that in many places extend out from the coasts as continuations of glacially formed estuaries or fiords, and cross the continental shelf to a termination on the continental slope. Just as on land, these glacially deepened troughs are generally straight, wide, and deep. The troughs have reversals in their longitudinal profiles formed by large basin-shaped depressions in the sea floor. If the seas were to be withdrawn, these basins would contain some of the largest lakes in the world, comparable in size and perhaps in origin to the Great Lakes. One would be present in the Gulf of St. Lawrence, another in the Gulf of Maine.

A further notable characteristic of the glaciated shelves is that their width is almost everywhere great, though the shelves of western South America (an area of young mountains) are a striking exception. Even including that exception, all the world's glaciated shelves average 100 miles (160 km) in width, as compared to the overall average shelf width of 42 miles (67 km).

SHELVES OFF LARGE RIVERS

The tremendous volume of sediments carried to the oceans by large rivers might be expected to produce especially wide continental shelves near their mouths.

Although the average shelf width off the great rivers of the world is considerably greater than the average for all shelves, no direct genetic connection has been demonstrated. The outer edge of the continental shelf off most large rivers, for example, is found to be straight rather than bowed seaward, as might be expected. The tentative conclusion is that rivers do not in general selectively widen the shelves directly off their mouths.

Near the mouth of the Amazon River the shelf is almost 200 miles (322 km) wide, and at the estuary of the Río de la Plata (between Uruguay and Argentina) its width is 260 miles (416 km). These are deceptively large figures, for they are due not a seaward bulge of the outer margin of the shelf, but to the unusually great distance that the broad river estuaries extend inland into the continent (fig. 3). In contrast, the shelf at the mouth of the Mississippi River is very narrow. This is another deception, for the great Mississippi delta is a ramplike land area about 80 miles (128 km) long that has been built across the true shelf almost to the inner edge of the continental slope. The process has been much the same as the building of a stone quay out from shore into the deep waters of a harbor.

Features directly related to river action are the broad horizontal terraces found at various depths on the surface of the shelf offshore from the mouths of large rivers. They are especially common at depths of 30 to 108 feet (9 to 34 m). They are thus decidedly shallower than similar flat terraces not related to large rivers, although the offshore river-deposited terraces are also present to depths of 330 feet (100 m). Near the mouth of the Amazon one such shallow terrace at a depth of 60 feet (18 m) is 60 miles (96 km) across, and another at a depth of 24 feet (7.3 m) is 25 miles (40 km) across.

It is thought that the flat terraces at shallower depths off the mouths of large rivers are surfaces of earlier deltas that have been submerged by compaction, by outward flow of the underlying sediments, or by isostatic sinking due to increased weight. No clear explanation of the origin of the flat surfaces in deeper water has yet been found. They may be delta surfaces formed at a lower sea level during the ice age.

SHELVES IN AREAS OF CORAL GROWTH

Where coral-forming organisms are growing actively, continental shelves differ from normal in being at very shallow depths and having numerous shoals and reefs. The Bahama Banks and the Great Barrier Reef of Australia are good examples. The depth of water on many of these shelves is commonly less than 120 feet (36.6 m).

LOOSE SEDIMENTS ON THE CONTINENTAL SHELVES

The distribution of sediments of various particle size over the continental shelves is highly irregular, showing little overall relation either to the depth of water or to the distance from land. Some control appears to be exerted by the nature of the bottom topography and by the character of the adjoining coastal area. A few generalizations seem valid, although local conditions vary.

One of the most decided differences in sediment grain size is found in the sediments of open shelves as compared with those of relatively closed bays and gulfs. On the open shelves sand is by far the most common type of deposit, whereas mud predominates in the protected bays and inland seas. Protected bays without strong currents tend to have coarse particles near shore, and finer particles in the deeper water. The reverse is more often true in bays with strong currents, and is generally true on the open shelves: fine material near shore, coarser material seaward. The outer part of the open shelves has on the average more coarse material, as well as more bedrock bottom, than the middle part, and in many places has more than the part nearest land.

The shelves off glaciated coasts have a wide and patternless range of particle size, and only a few areas of bedrock are exposed. Mud bottom is more common off the mouths of large rivers than anywhere else, but sand predominates at the outer margin of such areas. In general, narrow constricted areas and the bottom off points of land are exposed to strong water movements, and coarse sediment or even bare rock is present. Conversely, depressions in the shelf generally have finer grained sediments. As would be expected, the bottom off long areas of beach is usually sandy.

ORIGINS OF CONTINENTAL SHELVES

Hypotheses of continental-shelf origins can be divided into two general types. Some investigators think that the continental margins were originally higher and have been eroded down to their present position; others think that the shelves have been built up to their present position.

In regard to downcutting, the zone of breaking surf is known to be an area of highly active erosion. The cutting and grinding are limited to the zone of great wave turbulence, and they result in the formation of flat floors that mark the lower limit of cutting. The flat areas formed in this way are called wave-cut terraces or benches. As would be expected, the less resistant the exposed rock, the greater the dimensions of the wave-cut terrace.

Some small parts of the continental shelves may have been formed by long-continued wave erosion resulting in wide wave-cut platforms. The present depth of such platforms below the zone of effective wave erosion could be caused by a rise of sea level since their formation. The decreasing depth of water on the shelves from their outer margins toward the land might then represent the progressively rising zone of erosion of a gradually rising sea.

This explanation cannot be applied to all shelves, for the cutting process is extremely slow in areas of resistant rocks. The small hills and valleys on nearly all the surfaces of the continental shelves also argue against wave cutting as the only means of origin, for in general that process would be expected to yield flatter surfaces.

The simplest concept of the formation of the continental shelves includes the development of a narrow inshore portion of the shelf as a wave-cut terrace, and the building out of the outer portion of the shelf by the deltalike deposition of the resulting debris. But other lines of evidence tend strongly to negate this concept.

In many places it can be demonstrated that the shelves are not being built outward by the accumulation of rock debris resulting from erosion. The frequently observed areas of solid rock bottom on the outer shelf are the strongest argument that extensive shelf areas are not now receiving sediments. The walls of submarine canyons that cut into the outer shelf also commonly are of solid rock.

Furthermore, if rock debris of all particle sizes were being carried outward to the edge of the shelves, the heavier, larger particles would be expected near the shore, and the smaller, lighter, more easily transported particles would be expected near the outer margins. This condition apparently exists in only a few shelf areas. Instead, coarse material such as cobbles, gravel, and large sand grains are common on the outer part of the shelves. It is indeed difficult to explain how they could be transported there, and fragile marine plants and animals growing on them indicate that they are now stationary. It thus seems probable that the larger rock fragments on the outer part of the shelves are not now being carried there, but have simply been left there by the selective removal of the smaller particles.

The portion of the Gulf of Mexico off the coast of the United States, however, is a notable exception to the concept of a widespread lack of sedimentation on the outer shelf. Nearly constant sinking of the earth's crust under a large part of the Gulf of Mexico is indicated by the steady and extremely thick accumulation there of sediments apparently representing nearly all recent geologic time intervals, including the present.

The prevailing absence of sedimentation on the outer parts of the continental shelves does not preclude the effectiveness of sedimentation as a shelf-forming agency farther inshore. In some areas during past geologic time there may have been chains of islands along the coast that were separated from the mainland by relatively deep basins, like the island-bordered seas of the eastern Asiatic coast of today. Such islands might have been leveled by wave erosion at low stands of sea level, and then deeply submerged at today's higher sea levels. The deep areas inside such offshore islands and banks may have been filled with sediments, and the result would be similar to the present concept of shelf structure in some areas.

One of the merits of this theory is that it explains the presence of rock bottom and large rock fragments on the outer shelf edges. Another merit is that it is in accord with recent seismic investigation of the shelf off the eastern coast of the United States. The results of that work to date indicate that at some places the surface of the solid rock under the sediments is higher near the shelf's outer margin than it is farther inshore.

The most definite knowledge of shelf development applies to the glaciated areas. The shelves there appear to have been deepened, especially in their middle part, by the movement of glaciers out across them. Deposition far offshore of the debris derived from glacial erosion on the land may well be the cause of the prevailing wideness of such shelf areas.

In summary of the possible origins of the continental shelves, it can be said that their present condition is not due to any one process alone, but is due to a combination of processes. In the present state of inadequate knowledge, it appears that both downcutting and deposition have been operating.

THE CONTINENTAL SLOPES

The sea bottom from the outer edge of the continental shelves to the floors of the deep ocean is generally one long unbroken slope, appropriately called the continental slope. This is the zone of transition from the continental blocks to the oceanic blocks of the earth's crust, and is thus a highly critical part of the earth. It is also by far the greatest topographic feature of the earth's surface.

As already noted, knowledge of the shallow continental shelves is woefully inadequate, but far less is known of the continental slopes. The development of sonic depth finders capable of measuring great depths has resulted in a large number of soundings, but data about many parts of the world are sparse or entirely lacking. Additional information has come from seismic, gravimetric, and other geophysical investigations, and from a small amount of bottom sampling. But indirect reasoning and speculation of necessity play a large part in any discussion of the continental slopes.

The continental slopes have an average height above the ocean floors of about 12,000 feet (3,660 m), and in places they attain the tremendous height of 30,000 feet (9,150 m). For about half of their length throughout the world they continue directly into the great ocean deeps. Their average inclination is only 4°17′ for the first 6,000 feet (1,830 m) of vertical descent. The fronts of most high mountain ranges on land have the same angle with respect to the adjacent lowlands as have the continental slopes with respect to the adjacent ocean floor. The typical continental slope is steep at the top and more gently inclined near the bottom: the transition to the ocean floor is more gradual than the transition to the continental shelves. The steepest known submarine slope of large magnitude in the world is found along the south coast of Cuba, where in the first 6,000 feet (1,830 m) of descent it averages about 17° and in some places appears to exceed 45°.

The overall lengthwise trend of the continental slopes is generally straight or gently curving. A large number of basin-like depressions, hills, and ridges have been found on the surface of the slopes, but in only a few places does the concentration of depth measurements allow precise contouring or the recognition of small topographic features. The slope is cut by numerous canyons fully comparable to but not as closely spaced as those in mountain ranges on land.

Bedrock is commonly exposed in the walls of the submarine canyons and on the upper parts of the continental slope. In the limited areas where the bottom has been sampled, mud covers about 60 percent and sand about 25 percent of the continental slopes. Rock and gravel are reported in about 10 percent of notations of the character of the bottom, and shells and ooze are mentioned in about 5 percent.

CONTINENTAL-SLOPE CHARACTERISTICS IN RELATION TO TYPES OF COASTAL AREAS

Continental slopes off stable lowland coasts lacking large rivers have an average inclination of only about 3°. This average includes a number of extremes that are not typical of the group. For example, the slope off the Brazilian Highlands, where the coast is of the stable lowland type, is one of the steepest in the world. There are old low mountains near this coast, and the continental shelf is anomalously narrow there.

Off large deltas on stable coasts the average inclination of the continental slope is unusually and uniformly low, averaging only 1°20′. Bottom sediments there are predominantly mud. So far as is known, the topography of the slope in such areas is irregular, and includes plateaus, valleys, and canyons, as well as rounded hills and depressions.

Fault coasts in general lack continental shelves, and the continental slopes of those coasts are the steepest of any group, averaging 5°40′ from the ocast to a depth of 6,000 feet (1,830 m), though 25° is commonly attained. Rock bottom is more common on these than on other slopes, and canyons are rare. In some places the inclination of the slopes off faulted shelves increases with depth.

Continental slopes off unfaulted young mountain-range coasts are slightly more gently inclined than those off faulted coasts, and are cut by numerous submarine canyons. Continental borderlands are more common off young mountain coasts than elsewhere. They are described on page 23.

The continental slopes encircling the Pacific Ocean include most of the high and steep slopes in the world. All the known areas where the continental slopes steepen below a depth of 6,000 feet (1,830 m) are in the Pacific Ocean. This circumstance seems to be directly related to the presence of young mountain ranges on the lands bordering nearly all of the Pacific Ocean, and to the occurrence of the long linear or arcuate deeps in the ocean floor adjacent to these mountains.

MODIFYING FEATURES OF THE CONTINENTAL SLOPES

The most prominent of the several features modifying the continental slopes are submarine canyons (see fig. 4A). A large number of them have been discovered off the relatively intensively sounded coasts of the United States, and they are widely distributed throughout the remainder of the world. In general, submarine canyons have steep walls with heights of hundreds or thousands of feet, narrow floors, V-shaped cross sections, and continuously downward-sloping bottom profiles. In these ways, and in their overall dimensions and winding courses with entering tributary valleys, they are comparable with land canyons.

Their similarities to land canyons strongly suggest that submarine canyons were formed by fresh-water stream erosion, but this would require a past sea level on the order of 12,000 feet (3,660 m) lower than that of the present. Most geologists consider this figure so great that neither the withdrawal of sea water as glacier ice nor the vertical movement of crustal blocks is adequate to explain it. Yet there are no alternatives if the canyons were formed on land. As a consequence of this stalemate, such underwater agencies as submarine landslides and erosion by locally strong currents or dense turbidity currents of suspended sediment have been mentioned as possible causes of the canyons. In general, these underwater erosive forces, with the possible exception of turbidity currents, do not seem to be of sufficient magnitude to form such large-scale features. Their origin remains a mystery.

The surface of the continental slopes in areas without submarine canyons is not everywhere one unbroken incline from the shallow continental shelf to the deep ocean floor. In some parts of the slopes, at depths intermediate between the deep ocean floor and the shallow continental shelves, are found terraces, plateaus, and areas characterized by the alternation of basins and large elevated areas. They are referred to as the continental borderlands. Where their surfaces are generally flat and plateaulike they may represent subsided areas that were originally part of the continental shelf, or they may represent the base of effective erosion by oceanic currents, perhaps at a previously lower level of the sea.

A notable example of a continental borderland is the Blake Plateau, located off the southeastern coast of the United States in the area between Cape Hatteras and eastern Florida. (See fig. 4B.) The Blake Plateau is nearly flat, is at depths of from 1,800 to 3,000 feet (550 to 915 m), and is as much as 150 miles (240 km) wide. The continuation of the continental slope at the outer margin of the plateau has inclinations of about 15° and is directly in line with the continental slope to the north of Cape Hatteras.

The continental borderland off southern California has alternate high areas and depressions. The deep basins, elevated areas, and long straight escarpments between them are similar to those on the land nearby. Because those features on land are known to be the result of slipping of crustal blocks relative to one another (faulting), that origin has also been ascribed to the continental borderland of that area.

Because the continental slopes extend far below the range of most erosive agencies, deposition of sediments on them would seem to have been going on at some rate or other ever since their formation. Their original shape may thus have been modified to some extent. The numerous reports of bare bedrock (indicating no sedimentation) on the slopes have been obtained largely from the parts at depths less than 3,000 feet (915 m), where the inclination of the bottom is relatively high, and from the commonly precipitous walls of submarine canyons.

Fine-grained water-saturated sediments are thus abundant on the relatively steep continental slopes. Experimental work in soil mechanics and other fields has shown that fine-grained sediments saturated with water will flow under water on surfaces of extremely gentle inclination. The previously mentioned underwater turbidity currents are dense suspensions of sediments in water, and, having a high over-all specific gravity, they can attain high velocities on relatively gentle slopes and can transport rock fragments of large size. Such things as slumps, slides, mudflows, and turbidity currents might thus be expected on the continental slopes.

These phenomena have not been directly witnessed, but several observed effects may be attributed to them. On several occasions submarine cables have been broken, mangled, and buried by debris over wide areas of the ocean bottom. Where several cables in the same general area have been broken within a day's time, the appreciable amount of time that elapsed between the breaking of each successive cable is thought to represent the traveltime of turbidity currents.

New surveys of water depths over areas of moderately large size have sometimes shown consistent changes from the depths recorded by previous surveys. Such changes are almost certainly due to slumping of the bottom and the pattern of the small-scale hills and basins that have been found on parts of the slopes resembles the hummocky topography of landslide areas on land.

At any rate, the lower and more gently inclined parts of the slopes are largely mantled with loose sediments. It is not yet known how much of whatever is beneath the surface of the slopes is actually made up of such material.

STRUCTURE AND ORIGIN OF THE CONTINENTAL SLOPES

As previously mentioned, isostatic or other vertical movements of the continental masses with respect to the floors of the ocean have almost certainly taken place, and the continental slopes seemingly should have been the sites of the relative movement. A number of direct and indirect lines of evidence substantiate the view that the continental slopes have assumed their present form because of such relative movements; that is, that the continental slopes are areas of movement along faults between major blocks of the earth's crust. Other theories to account for the origin of the continental slopes have been advanced, however, and they will next be examined briefly.

The simplest and one of the oldest concepts of slope origin is that the continental slope is simply the steep front edge of a great pile of sediments derived from the erosion of the continents. There are a number of observations for which this theory cannot account. Chief of these are the demonstrated absence of deposition on the outer edges of large parts of the continental shelves, the absence of decreasing grain size of sediments with increasing distance from land where there is sedimentation, and the presence of large areas of bedrock on both the shelves and the slopes. Nor would sediments coming to rest under water be expected to form such highly inclined surfaces as those of the continental slopes.

Another theory is that the slopes are the downwarped or downward-flexed surfaces of the continental blocks. Objections to the theory of downwarping of the continental margins are largely based upon the lack of observed downward bending of the rock strata on the continental slopes and at the outer edges of the continental shelves. As mentioned previously, there are indications from seismic work off the east coast of the United States that the rock strata underneath the outer shelf margins may actually be tilted slightly upward. Furthermore, downwarped surfaces should have become buried by sediment, yet bedrock is common on the continental slopes. Finally, it would seem that the downwarping of portions of the continental margins would violate the principle of isostasy. If the light material of the continents were bent downward toward the same level as the heavy material of the deep ocean areas, instead of floating higher, the resulting disturbance of the earth's gravity field would be considerable. No such disturbance has been observed.

The theory that the continental slopes have achieved their present form as a result of faultslippage at the contact of the continental blocks with the oceanic blocks of the earth's crust seems to accord with more observed facts than do other theories. A certain amount of such faulting is to be expected as a result of the rise of the continents in reaction to erosional lightening. Earthquakes are caused by fault slippage within the earth or at its surface, and the continental slopes are among the most active earthquake zones in the world. The trend of faults and fault zones on land is generally straight or slightly curved, and so is the trend of the continental slopes. Another similarity between the continental slopes and faults on land is that the trends of both are often at an angle with the general geologic trend of nearby areas. The presence of bedrock at the outer continental-shelf margin and high on the continental slopes is also in accord with the fault-zone theory.

On the other hand, if this postulated zone of faulting is still active as is indicated by earthquakes in many areas, the river deltas of the Nile and the Niger that have built outward onto the continental slope should have been disturbed, but apparently they have not been. The gentle inclination of the continental slopes off most other large rivers also fails to reveal the expected fault offsetting. It has further been argued that faulting would be expected to result in steep longitudinal escarpments on the slopes. No such features have been observed, but sedimentary debris would probably round the original sharp profile of such escarpments.

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Despite a multiplicity of conjecture, the origins of the continental slopes remain obscure.

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A REVIEW OF PRESENT KNOWLEDGE CONCERNING THE CONTINENTAL SHELVES OF THE AMERICAS

By JOHN LYMAN, U. S. Navy Hydrographic Office[1]

CONTENTS

ILLUSTRATIONS

ABSTRACT

The earth's surface is composed in general of continents and ocean basins, different in elevation because the rocks underlying the continents are lighter than those under the oceans. The volume of water now in the oceans slightly exceeds the capacity of the ocean basins, with the result that parts of the continents which were a few hundred feet above water in the immediate geologic past are now submerged. These shallow submerged areas are the continental shelves. Changes in sea level are still taking place, although for much of the Western Hemisphere tide-gage records are not yet available to reveal the details of these changes.

[1] Opinions or assertions contained herein are not to be construed as being official or reflecting the view of the Navy Department or the Naval establishment.

Although more is known about the topography and sediments of the continental shelves than about their other characteristics, owing to the importance of this information for navigation, accurate surveys are available for only a small part of the shelves of the Western Hemisphere.

Methods have been developed for conducting magnetic, seismic, and gravity surveys at sea. The information resulting from such surveys is of great value in studying the continental shelves, particularly in locating mineral deposits, but such studies are still in their infancy. Modern navies possess the primary capability of surveying the continental shelves. Fishery investigations and oceanographic institutions can also assist.

INTRODUCTION

Geophysicists today are in general agreement that the composition of the crust of the earth beneath the continents is fundamentally different from that underlying the ocean basins (Bullard, 1954; Ewing and Press, 1955). In recent years the properties of the earth's crust have been sampled by several different geophysical methods, which will be described later in this paper. A general summary of the findings is contained in the following quotation from Ewing and Press (1955).

> Seismic-refraction measurements have established beyond doubt that the silicic crust under ocean basins is no more than one-fifth as thick as that under continents, and corresponds in composition to the more mafic parts of the continental crust. This crustal structure, revealed by seismic measurements, confirms the isostatic equilibrium determined by gravity measurements. Remarkable uniformity of crustal structure within continents or within ocean basins is revealed when obviously anomalous areas such as margins, mountains, and trenches are omitted. Magnetic measurements are meager, but those available indicate that over certain large oceanic areas the magnetic field is unusually smooth.

In simple terms, the earth's crust is composed of large patches of light rocks, surrounded by larger patches of heavy rocks. The lighter patches, floating higher on the plastic core of the earth, make up the continents, while the surrounding lower areas of heavier rock compose the ocean basins. The evidence from seismic, magnetic, and gravity measurements seems to support this hypothesis, although not all geologists (Lees, 1954; Gilluly, 1955; Stetson, 1955) are in full agreement with this view.

It is generally recognized that at the present instant of geologic time, the quantity of sea water in the oceans somewhat exceeds the capacity of the ocean basins (see fig. 1, p. 5).

Figure 1 shows the statistical distribution of elevations of the earth's surface. Two levels are much more frequent than any others—one slightly above present sea level, representing the characteristic level of the dry land of the continents, and the other 4,000 to 5,000 meters below present sea level, corresponding to the depth of the floor of the ocean basins. Mountains and ocean deeps, although striking features, are shown by this figure to be of uncommon occurrence. Also of uncommon occurrence are depths in the range 1,000 to 2,000 meters below sea level. Although the lower boundary of this region of the hypsographic curve passes rather smoothly into the region representing the ocean floor, there is a very abrupt transition at the upper edge, at a depth between 100 and 200 meters below sea level.

This abrupt transition, which is usually even more pronounced when individual sections off the coasts of continents, rather than statistical averages, are studied, has been named the shelf edge by the International Committee on the Nomenclature of Ocean Bottom Features (Wiseman and Ovey, 1953). The area between the shelf edge and the low-water line is the continental shelf. The declivity from the shelf edge into great depths is the continental slope. Wiseman and Ovey (1953, p. 14) point out that although conventionally the edge of the shelf is designated as being at a depth of either 100 fathoms (600 ft or 183 m) or 200 meters (109 fathoms), areas are known where the increase in slope occurs at more than 200 fathoms (365 m) or less than 65 fathoms (120 m). The common use of 100 fathoms or 200 meters results from the fact that international practice in the construction of ordinary nautical charts does not provide for depth contours intermediate to 50 and 100 fathoms or to 100, 200, and 300 meters (International Hydrographic Bureau, 1953, p. 49). Since these charts are the primary source of published information on submarine topography, their use has often resulted in a somewhat restricted and oversimplified view of the character and location of the shelf edge.

The hypsographic curve shows clearly that, as far as the statistical distribution of elevations is concerned, no distinction can be made between the dry-land portion of the continents and the continental shelf. When it is considered further that as recently (geologically speaking) as 20,000 years ago, sea level stood about 50 fathoms (100 m) lower than at present because of the water that was trapped in the glacial ice sheets of the Pleistocene (Kuenen, 1955), the identity of at least part of the continental shelf with the adjacent land is at once apparent.

Likewise there is no reason to believe that present sea level is a permanent feature. On the contrary, some land areas such as Finland and Scandinavia are known to be rising as a result of isostatic adjustment after melting of the ice sheets that formerly covered them. Elsewhere the continued melting, presumably of the Greenland icecap, has resulted in a rise in sea level.

SEA LEVEL

Virtually the only means of detecting sea-level changes is through the analysis of tide-gage records, carefully taken over a long period of years. The availability of such stations in the Western Hemisphere, as far as can be determined, is indicated in figure 5. For much of the coast the records do not yet permit conclusions as to long-term changes in sea level.

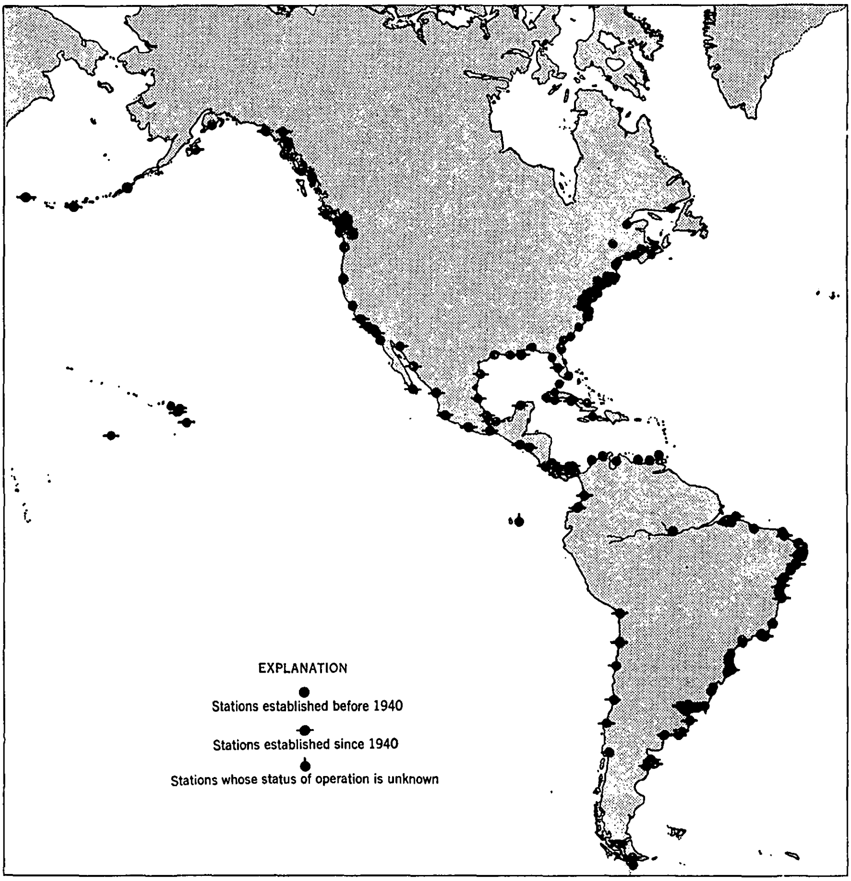

FIGURE 5.—Tide-gage stations of the Western Hemisphere. (After International Hydrographic Bureau, 1955.)

Marmer (1949) discussed the United States records, which show everywhere, except at Ketchikan, Alaska, a rise in sea level relative to the land (or a relative subsidence of the land). Since 1930 this rise has amounted to about 1/4 inch (6 mm) per year for the Atlantic Ocean and Gulf of Mexico stations, but only about 1/12 inch (2 mm) per year for the Pacific Ocean stations. Bigelow (1949) found a rise of nearly 1/4 inch (6 mm) per year from the record at Cristobal, Canal Zone, from 1933 to 1943, while at Balboa, at the Pacific entrance to the Panama Canal, the rise was 1/8 inch (3 mm) per year from 1908 to 1942.

BATHYMETRY

Nearly all bathymetric investigations of the continental shelves that have been carried out in the Western Hemisphere were conducted for the purpose of constructing nautical charts and associated sailing directions. Certain basic features of such charts tend to limit the amount of information that is available for the whole shelf, particularly where it is wide. Plate 1 shows charts of the American coasts that were available in 1955.

Practical problems connected with producing, shipping, stowing, and handling nautical charts limit their greatest dimension to about 48 inches (122 cm). At a scale of 1:250,000, which is approximately the minimum that provides satisfactory delineation of topography, this length is equivalent to a distance of about 160 nautical miles (300 km). Therefore, in the many areas of the Western Hemisphere where the continental shelf extends farther seaward than 300 kilometers, the outer edge of the shelf will not be properly delineated.

Charts of a scale greater than 1:300,000 out to the 100-fathom (183 m) contour are available for only a few areas, the best coverage being along the west coast of Greenland, along the Ungava Peninsula and Labrador, in the Gulf of St. Lawrence and off Nova Scotia, and along the coasts of Cuba, Hispaniola, Puerto Rico, Venezuela, Brazil, Panama, Costa Rica, and North America between Cabo San Lucas, Mexico, and the Aleutians.

Even as scales between 1:300,000 and 1:1,000,000, there are gaps in the chart coverage of the 100-fathom (183 m) isobath, the most obvious being in the Canadian Arctic archipelago and in the Bering Sea. Other gaps appear to exist off Patagonia and southern Brazil.

The chart coverage shown by plate 1 may tend to give a misleading picture of the density of the actual sounding lines plotted on the chart. Plate 2, from Karo (1955), reveals that a great deal of the coverage shown in plate 1 is actually based upon scattered track lines rather than systematic surveys. According to Karo:

> The most serious deficiencies in the Western Hemisphere are along the coasts of Mexico and Central America, the northeastern coast of South America, the Arctice coat of Canada, the northern half of Greenland, and of course antarctica. Many other areas need more detailed and large-scale coverage than presently exists, but the most pressing need is for reliable medium-scale coverage.

In only a very few areas of the Western Hemisphere have bathymetric surveys been carried out for purposes other than the construction of nautical charts. A notable exception is the survey of the Gulf of California made by the *E. W. Scripps* in 1939 and 1940, results of which were published by Shepard (1950) as a chart the gulf on the scale of 1: 1,300,000.

Two other examples of the publication of charts of areas adjacent to the continents, for purposes other than navigation, are the series of the area off the coast of California by Shepard and Emery (1941), and the charts by Veatch and Smith (1939) of the waters off the northeastern United States.

The relatively few regions where adequate surveys have been carried out and the results published display great variations in the extent and character of the continental shelf. From the scientific point of view it may be seriously questioned whether statements as to a "typical" form of a continental shelf, or an "average" depth for its outer limit have any general application in nature. Ewing and Press (1955), discussing the continental margins, the transition zones between the shores of the continents and the ocean basins, propose the following worldwide classification:

1. Stable margins, usually associated with a broad continental shelf, such as that off the north Atlantic coast of the United States or the west coast of Florida.
2. Active margins bordered by basins and ridges, as off the California coast.
3. Active margins bordered by deep-sea trenches, as off the Pacific coast of South America.

The continental shelf off the northeastern United States, where adequate surveys exist, has been described by Veatch and Smith (1939). Much of it has a well-defined change in slope at a depth of about 100 fathoms or 200 meters, to seaward of which is a remarkable series of submarine canyons. In the words of Veatch and Smith (1939, p. 2):

> Beyond a belt of the sea bottom that extends seaward from our northeastern coast for a distance of 60 to 125 miles [95 to 200 km] and shows only characteristic sea-made forms, there is another belt which is deeply and intricately dissected, shows none of the forms characteristic of sea action but on the contrary many of the things characteristic of subaerial erosion, and which has local relief in many places much greater than that found in the Appalachian Mountains and in fact is more nearly comparable to that of our western mountains. This break between the shelf and the slope is one of the most striking and startling changes in topography to be found anywhere in the world.

In these canyons the 100-fathom or 200-meter contour is many dozen miles closer to the land than it is in the zones between the canyons. Over a considerable distance to the east of the most prominent of these canyons, which lies off the Hudson River, the abrupt change in slope is at a depth of about 500 fathoms (900 m). Farther east, north of Georges Bank, is another type of valley. Here, in the Gulf of Maine, a broad, shallow basin apparently was scooped out of the ocean floor by Pleistocene glaciers. Many soundings are in excess of 140 fathoms (250 m), and the bottom is extremely irregular where it has been surveyed in detail.

The continental shelf of the Gulf of Mexico has been described in some detail by Price (1954). In general, west of Florida, as north of Yucatan, there is a submerged limestone shelf, with the abrupt change in slope at depths as shoal as 33 fathoms (60 m) and everywhere less than 55 fathoms (100 m) but as far as 60 to 120 nautical miles (100 to 200 km) offshore. The outer edges of these limestone plains seem to lack the canyons found by Veatch and Smith in the Atlantic Ocean, as does the northwestern part of the Gulf of Mexico as contoured by Gealy (1955). However, just as a prominent canyon exists seaward of the Hudson River, so there is a very large canyon off the mouth of the Mississippi River.

The basin-and-ridge topography off the coast of California is so different from what is commonly understood by the term continental shelf that it has been designated a continental borderland (Shepard and Emery, 1941, p. 9). This is a region of alternating ridges and basins, extending as far as 135 nautical miles (250 km) to sea; many of the ridges rise nearly to sea level as banks or above it as islands, and the basins have depths as great as 1,000 fathoms (2,000 m).

The third category mentioned by Ewing and Press (1955), the active margin bordered by deep-sea trenches, cannot be so well demonstrated by published work. An example off the coast of South America was reported, however, by Trask (1956). He found a trough 500 miles (925 km) long with depths of 4,000 to 4,300 fathoms (7,300 to 7,900 m) roughly parallel to the coast of Chile. In lat 25° S. it was only 40 miles (74 km) from shore.

These examples of variation in characteristics of well-surveyed continental shelves, when taken with the vastly greater areas too poorly surveyed at the present time to permit any definite statements to be made, only serve to emphasize the futility of attempting to generalize in any description of the continental shelves as a whole. No arbitrarily selected depth or distance from shore can, from the scientific point of view, distinguish all the submerged land areas of the continents from the adjacent floors of the ocean basins.

On one of the most recent charts of a continental margin (Rosfelder, 1955), this concept of the true character of the edge of the continental shelf is clearly brought out. Here the usually prominent 100- and 200-meter isobaths are subordinated to a line demarcating the zone where the gentle slope of the continental shelf gives way to the steeper continental slope. This line has the mean depth prominently marked on it at 4-kilometer intervals. In Algerian waters the depth at the edge of the continental shelf varies from 27 to 93 fathoms (50 to 170 m), with a mean value of 52 fathoms (96 m).

SEDIMENTS

In the past, in addition to taking soundings for hydrographic charts, it was customary to sample the bottom. Seamen have recognized for centuries that there exist great differences in the character and texture of the sediments on the bottom, even within relatively short distances, and the identification and description of these sediment types was an important part of the science of hydrography. Originally both surveyors and navigators took soundings with the armed lead, which has a concavity at its lower end that is filled with tallow or other sticky substance to retain a sample of the bottom. With that technique some information about the bottom, though often misleading in rocky areas, was readily obtainable. In recent years, however, the use of echo-sounding devices has almost completely replaced the leadline in hydrographic surveying, and likewise to a great extent in navigation. The result is, that, although the speed with which the surveyor can obtain and record soundings has been greatly multiplied, the facility of obtaining and describing bottom samples has not been appreciably increased.

Even the most recent navigational charts fall far short of modern soil maps in depicting the complex variations that exist over relatively short distances. A scale of at least 1:250,000 is required before justice can be done to the sediment patterns. At this scale, the ordinary hydrographic chart is insufficient as a source, and special surveys are necessary. The lack of precision that results without such special surveys is illustrated by a comparison of bottom-sediment charts compiled by the German Navy and the United States Navy during World War II but kept secret until after the war. Although largely drawn from common sources, many of the resulting charts for the same areas had only the vaguest general resemblance.

An example of one of the few areas of the continental shelves in the Western Hemisphere for which bottom sediments are known in adequate detail is the zone immediately outside San Diego Bay described by Emery and others (1952). In an area about 20 kilometers wide and 50 kilometers long (1,000 sq km), they obtained 1,656 samples and 184 bottom photographs, which enabled them to map the sediments on the scale of 1:160,000.

Although the echograms obtained during surveying with an acoustic sounding device can be interpreted to yield useful information on the nature of the bottom (Pratje and Schüler, 1952; Hough, 1952), such analysis can only support, not replace, the information obtained by actual sampling. Pratje and Schüler prepared a chart of the sediments of the North Sea on a scale of 1: 2,200,000, using a sample density of about 1 per 100 square kilometers (as compared with the average figure of 165 per 100 sq km available off San Diego) and deducing intermediate features from the echograms. Allowing for the change in scale, this use of echograms permitted mapping with about one-tenth the density of sediment samples available to Emery and others (1952).

STRUCTURE

Knowledge of the sediments that cover the submerged land adjacent to the continents is poor compared with the corresponding knowledge of soils ashore, and knowledge of what lies beneath the surface layers is considerably poorer. The visible outcrops that exist on land and serve as clues to the geologic structure are masked in the sea both by the overlying water and by the fact that in general the land is a region of erosion, whereas the sea is a region of deposition. The frequent cuts and borings that are made on land as a concomitant of numerous commercial and industrial enterprises, and that yield much information on the nature of land formations, are still almost entirely lacking on the sea bottom. Only in recent years, in the few places where the occurrence of petroleum has been suspected, such as off the coasts of southern California, Louisiana, and Texas, and at Cape Hatteras, has exploratory drilling been carried out in coastal waters.

GRAVITY

Since gravity observations in deep water are not yet (1956) feasible from surface vessels, the possibility of making such measurements is limited to countries possessing seagoing submarines. Recently, for use in shallow water, instruments have been developed that can be lowered to the bottom or taken to the bottom by divers. Observations with such instruments, however, have been mainly in regions where active prospecting for petroleum has been carried out.

The existing oceanic gravity coverage has been summarized as to extent by Worzel, Shurbet, and Ewing (1955) and by Woollard (1955), and as to extent and quality by Karo (1955). The areas most seriously deficient in coverage in the Western Hemisphere appear to be Antarctica, the east coast of South America between Trinidad and the mouth of the Amazon River, and the entire Arctic from Point Barrow, Alaska, eastward to Labrador. More precise and more closely spaced measurements are still needed for most of the rest of the hemisphere.

Interpretation of gravity measurements on a worldwide scale yields useful information on the shape of the earth. For smaller areas, the measurements provide information on the crustal structure. As already mentioned, such gravity measurements as have been made in shallow water demonstrate that the continental shelves are structurally part of the continents, whereas measurements over deep oceanic areas confirm the conclusion drawn from other geophysical evidence that the earth's crust under the ocean basins differs fundamentally from the continental land masses.

GEOMAGNETISM

The earth's magnetic field varies over periods of time, so that, unlike most of the other types of investigation that have been mentioned, geomagnetic observations must be repeated from decade to decade. Until recently it was impossible to conduct such observations at sea except from specially built nonmagnetic vessels, and none has existed in American waters since the loss of the Carnegie in 1929. The extent of current knowledge of the geomagnetic field has been shown by Karo (1955). His chart appraising world magnetic data indicates that for a large part of North America and most of South America the error of the present values for magnetic declination or variation averages 2°. Recently developed airborne magnetometers have made it possible to conduct magnetic surveys from aircraft. Much of the United States and small sectors of the Gulf of Mexico have already been surveyed in this way. Instruments are also available which can be towed behind a ship, out of the range of its magnetic influence.

Magnetic observations are of practical value in connection with the magnetic compass and for detecting local variations in geologic structure connected with mineral deposits. They also can yield information on general structure of the earth's crust.

SEISMIC INVESTIGATIONS

The seismic waves generated by earthquakes or by shocks induced by explosives have provided geophysicists with meager but basic data on the structure and thickness of the crust of the earth. Marked differences in the traveltime of these waves through oceanic and continental sections of the earth, as recorded by seismographs, agree with and support the evidence derived from other data of a difference in composition between oceanic and continental rocks. Recent investigations by Gutenberg (1955), Båth (1954), and Press and Ewing (1955) of a particular type of seismic wave (channel wave), which is confined to continental rocks, give promise of making it possible to delimit the margins of the continents when a sufficient number of seismologic stations is developed along the seaboard.

At present, in the Western Hemisphere, a few cross sections of the outer edge of the continent of North America have been obtained by recording reflected or refracted waves produced by manmade explosions at sea. These sections are confined primarily to the western North Atlantic Ocean (Bentley and Worzel, 1956), the Gulf of Mexico (Ewing and others, 1955), and the coast off California (Tatel and Tuve, 1955).

In the expanded search for oil and other minerals of economic importance, seismic methods have been the most important of the various geophysical techniques used in investigating the continental shelf. In small areas of the Gulf of Mexico and off the coast of California intensive seismic investigations have been conducted in recent years in order to establish the presence or absence of structural features which might localize accumulations of such minerals as oil, gas, and sulfur. This exploration has been limited generally to shelf waters less than 20 fathoms (40 m) in depth leaving a broad area of the shelf unexplored.

IMPROVING THE KNOWLEDGE OF CONTINENTAL SHELVES

In the days of Malaspina and Cook, hydrographic surveying was recognized as part of the profession of the naval officer. Later, increased application of technology to naval problems tended to produce specialization into various branches of the naval sciences, with the result that today in such important maritime nations as Canada and Norway the hydrographic service operates as a purely civilian establishment. In the United States, also, the surveys of home waters are carried out chiefly by the Coast and Geodetic Survey, a civilian organization with its own commissioned service.

Today more than ever before, however, the principles and techniques used in conducting hydrographic and geophysical surveys are linked to the requirements of contemporary naval warfare. The recording echo sounder, for example, which has vastly speeded up the work of obtaining details of the ocean bottom, is no different in principle from the sonar (sound navigation and ranging) with which a destroyer determines the range and bearing of a submerged submarine. The accurate electronic navigation systems required for controlling a hydrographic survey are precisely those needed for laying or clearing a minefield. A naval vessel is an obvious first choice for transporting and handling the tons of explosives required in seismic exploration, and the hydrophones used to record the resulting sound waves are almost identical with the equipment by which a submarine detects approaching vessels. The airborne magnetometer, which has found wide application in surveys of the continental shelves, was first developed as a means of finding submerged submarines. The techniques of aerial photogrammetry employed in mapping a coast are identical whether the product is to be a nautical chart for the use of fishermen or a bombardment chart for a fleet.

This list of parallel items could be extended, but it should be sufficient to emphasize the value to a modern naval power of maintaining a surveying force in the waters in which it is interested. There is no better index of the technical efficiency and state of readiness of a navy than the quality and quantity of its hydrographic and geophysical investigations.

The geophysical information than can be collected simultaneously from a properly equipped survey vessel while under way includes, in addition to continuous fathograms that yield water depth and information on bottom sediments; the temperature structure of the upper 900 feet (275 m) of water, by means of bathythermographs; bottom samples, obtained with "underway" samplers; and observations of total magnetic intensity, by means of towed magnetometers. Since all the data are referred to the same system of position location, their value is greatly enhanced.

Position location has been found to be one of the key items in modern geophysical surveying. Because of the expense of operating survey vessels and the necessity of having accurate geographic positioning at all times, the ordinary navigational procedures are inadequate. Veatch and Smith (1939, p. 6) give examples of soundings made before 1930, the positions of which were determined by means of the most accurate astronomical and dead-reckoning methods, but which proved later to be in error at least 6 or 7 statute miles (10 or 11 km). This discrepancy is 3 or 4 times as great as the error customarily admitted to by the ordinary navigator. New electronic methods of positioning, however, have been developed which are accurate to distances comparable to the length of the ship. The EPI (electronic position indicator) system, for example, developed by the U. S. Coast and Geodetic Survey (Burmister, 1954), shows an error of less than 200 feet (60 m) in over 80 percent of observations for distances up to 300 miles (500 km); shoran (short range navigation) is even more accurate over shorter distances (Roussel, 1955); and several other methods are available (International Hydrographic Bureau, 1956).

In contrast to the types of observation listed above that can be taken simultaneously from a moving vessel, certain other investigations must be conducted from a motionless vessel. These include sampling of the water for accurate determination of its chemical and physical properties at various levels, measuring ocean currents, taking core samples of the ocean bottom for elucidating geologic history and structure, making shallow-water gravity observations, and conducting seismic and acoustic studies. Deep-water gravity observations require the use of a submarine. The data obtained by these means supplement the results derived from surveys made under way.

Although navies can play a major part in investigations of the continental shelf, the results to be obtained are by no means of interest to them alone. Most countries with important fishing interests employ vessels in investigations of the ocean and its bottom as well as of the oceanic flora and fauna. Fisheries research vessels search for bottom features that may turn out to be new and undeveloped fishing banks, they carry out extensive investigations of the bottom in studying the organisms that live on and over them, and they examine the circulation of the waters and their chemical and physical properties. In many countries there also exist oceanographic institutions with active programs of investigation of the sea floor, not for any immediate practical benefit to be obtained therefrom, but primarily to increase man's knowledge of the planet on which he lives.

ACKNOWLEDGMENT

The assistance of Mrs. Suzanne Bershad and Gordon H. MacDougall of the Division of Oceanography of the U. S. Navy Hydrographic Office is gratefully acknowledged.

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POTENTIAL MINERAL RESOURCES OF THE CONTINENTAL SHELVES OF THE WESTERN HEMISPHERE

By James F. Pepper, U. S. Geological Survey

CONTENTS

ILLUSTRATIONS

ABSTRACT

The continental shelves are the marine terraces that extend from the shoreline to the sharp change in the slope of the sea bottom that occurs at water depths of generally somewhat less than 600 feet (183 m). Beyond this outer edge of the shelves the depth of water increases rapidly toward the ocean basins.

Geologically speaking, the continental shelves are integral parts of the continents, and their geology and mineral resources are simply an extension of those of the adjacent land. Exploration for mineral resources in the shelf areas is far more difficult and expensive than on land. One relatively small area, a part of the shelf of the Gulf of Mexico off the coast of the United States, has been prospected intensively, and economically recoverable deposits of oil and gas have been discovered there. The undersea parts of iron ore deposits in Newfoundland and coal beds in Nova Scotia and Chile are being mined from portals on land.

Continental-shelf areas where prospecting might be successful border land areas that contain mineral fuels or other minerals. For example, oil and gas may be found in shelf areas in parts of the general Caribbean Sea area, Tierra del Fuego and scattered other parts of South America, Lower and southern California, and Alaska; sulfur in part of the Gulf of Mexico; and phosphate on the western shelf of Florida. So-called heavy minerals are found in present-day or ancient beach deposits in widespread areas: monazite, ilmenite, rutile, and zircon in Florida and in Brazil; gold, platinum, and chromite in Oregon; and gold in Alaska.

The ever-expanding economy of the world may in the future come to depend in substantial part on the mineral resources of the continental shelves.

INTRODUCTION

DEFINITION OF THE CONTINENTAL SHELF

The continental shelf is that part of the ocean floor lying between the seacoast and a seaward margin where the slope steepens abruptly and plunges rapidly into the abyssal depths of the ocean. The depth of water where this change of slope takes place may vary, but for convenience of usage most oceanographers assume a depth of 600 feet (183 m). The continental shelf is wide where the sea floor inclines gently under the sea from a flat coastal plain, but is narrow at places where the flanks of mountains plunge into the sea.

The continental shelf is simply the continuation of the continent under the sea. It is composed of the same kind of rocks as those of the coast of the continent, and the strata under the sea floor usually are continuations of rock formations on the coast. Much of the shelf surface is a nearly smooth or gently rolling plain dissected at places by channel-like depressions which deepen near the outer edge of the shelf. At some places, the shelf surface is rough, with hills and valleys. At a few places shallow basinlike depressions have been formed by solution of underlying limestone, as on the continental shelf off western Florida.

At many places rocks of the continental shelf are covered by loose sediments derived from the land. These sediments may consist of sand, silt, and mud transported to the ocean by large and small river systems and deposited over wide areas in geologically recent time, as, for example, the sediments of the Mississippi River which are spread along the shelf in the western part of the Gulf of Mexico. Elsewhere, as along the northern Atlantic shelf, the sediments may consist in large part of glacial clay and gravel deposited during the ice age. In many areas, however, the rocks of the continental shelf are barren of loose sediments, either because such sediments were not deposited or because they were swept away by ocean currents.

ECONOMIC MINERALS OF THE SHELF AREA

The mineral resources of the shelf are similar to those of the contiguous land. Where oil and gas fields are present along a seacoast other fields can be expected in similar strata and in similar structures offshore. Off the coast of Louisiana to a water depth of 100 feet (about 30 m) the frequency of occurrence of major geologic structures that produce or can be expected to produce oil is almost exactly the same as that on the adjoining land (Atwater, 1956, p. 2626).

Research groups of geologists from university and State organizations and groups of geologists from oil companies have carried out large and expanding programs of geologic and oceanographic studies on several North American shelf areas with a view toward exploration, especially for oil and gas. Although much has been accomplished toward preliminary mapping of relatively small areas of the sedimentary rocks and their structures, a more detailed knowledge of the geology of the shelf can be obtained only after a long period of exploration, which will involve much effort and money.

Bedded deposits of minerals, such as coal and iron ore, where present along the shore, may dip under the sea and continue in the same rocks for many miles offshore. Iron ore in Newfoundland, present under the sea floor in millions of tons, is currently being mined about 2 miles (3.2 km) from land.

Minerals eroded from the land may be concentrated in placer deposits in beaches and bars along the coasts. Gold, for example, is found at Nome, Alaska, and monazite, ilmenite, rutile, and zircon are present in some of the ancient beaches in Florida and in present-day beaches in Brazil (fig. 6). Similar placer deposits can be expected farther offshore, beneath the ocean.

Materials such as seashells, sand, and gravel, which are used in cement work and roadbuilding, are taken in great quantities from deposits along the seashore, or dredged from shallow bayous or bays. Inasmuch as these resources are in plentiful supply on most beaches and in the shallow bays along the coast, dredging them from the continental shelf is usually not practical at the present time.

The shelf areas of the Western Hemisphere and the insular shelves of the West Indies are described in the following pages. The occurrence of oil and other minerals or the prospect of finding them is discussed for each area. The information is a synthesis of published data from many sources. For more detailed information on any subject or area mentioned, the appropriate report in the appended bibliography may be consulted.

GULF OF MEXICO—WESTERN SHELF AREA

OIL AND GAS

Perhaps no area off the coast of any country has received such an intensive examination as the continental shelf off Texas and Louisiana. The Gulf of Mexico is shallow for many miles offshore, and the sedimentary rocks of the gulf floor are similar to those which are highly productive in the coastal area of Texas and Louisiana. Structures similar to those on the adjacent coastal plains from which oil or gas are produced have been found on the shelf by intensive geophysical exploration (fig. 7). These structures extend along this coastal belt eastward through Mississippi into southwestern Alabama, and are either known or presumed to be closely related to salt domes. These domes, more properly described as salt plugs, are cylindrical masses of rock salt, of small horizontal cross section but great vertical dimension, that have been forced upward through great thicknesses of gulf-coast sediments from a salt layer far below. The salt in this layer is believed to have been a bedded sedimentary deposit that probably formed originally as a single mass in one large basin, rather than as disconnected masses in separate basins. This widespread basin apparently extends southward to a termination in the northern part of the Isthmus of Tehuantepec, Mexico. The area now occupied by the

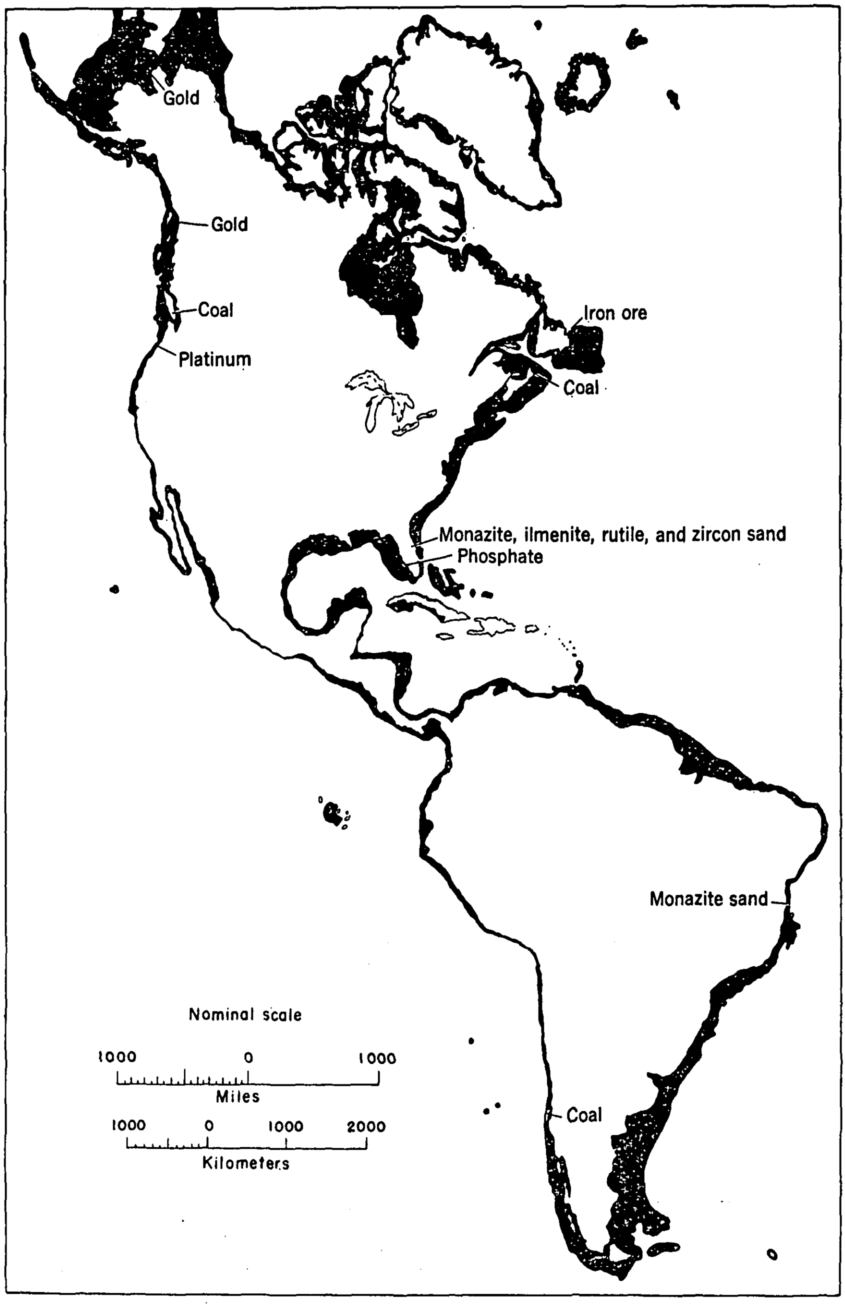

FIGURE 6.—The Western Hemisphere showing location of continental shelf and known mineral deposits exclusive of petroleum near shore. Continental shelves are shown in black.

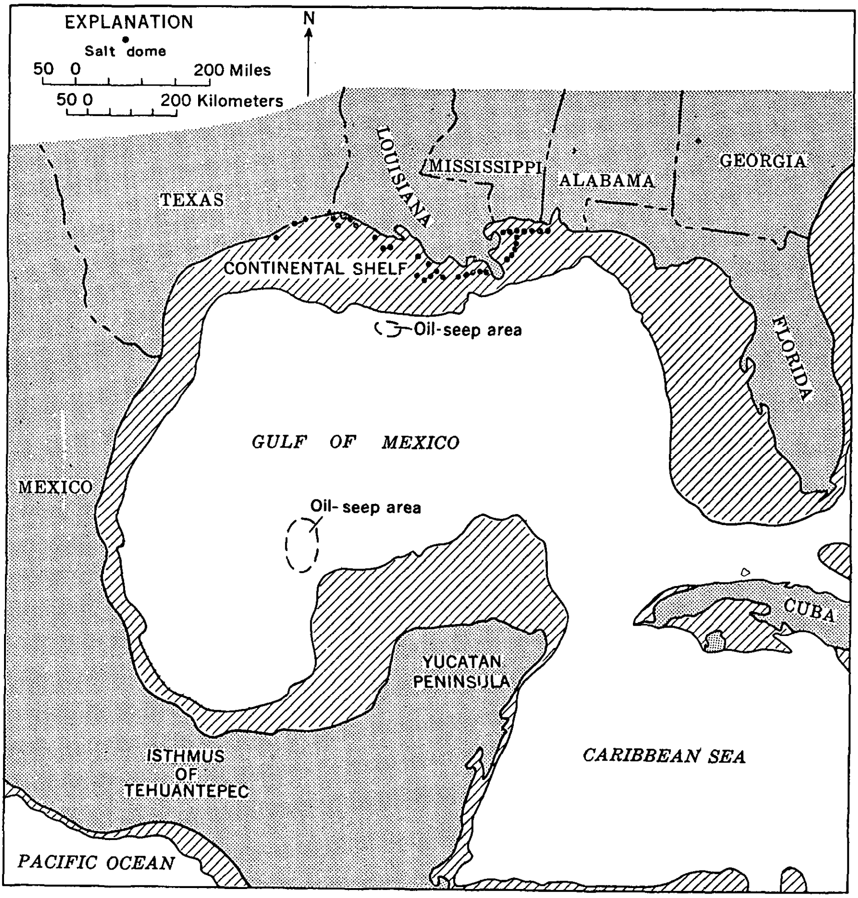

FIGURE 7.—Salt domes and oil seeps in the Gulf of Mexico. Continental shelves are shown by diagonal pattern.

Gulf of Mexico was probably a continuous salt-depositing basin enclosed on the north, south, and west, and connected with the ocean on the east by a relatively narrow, shallow strait.

In the gulf coastal area, exploration spread rapidly following the passage by the United States Congress of the Submerged Lands Act in 1953. In that year, 73 wells were completed in the Louisiana tidelands area. The successful completion of a number of these wells as producers of oil and gas encouraged interested oil companies to extend known production and to test other prospective areas on the continental shelf. As of November 1, 1955, about 840 wells had been drilled off the shore of Louisiana, and 65 off Texas. More than 70 percent of the wells drilled in 1955 in these areas found oil or gas in commercial quantities. Offshore fields which are connected to pipelines produced about 90,000 barrels daily in 1955, but many fields are shut-in off the Louisiana coast awaiting the installation of pipelines, and, for the same reason, only a few fields in the Texas tidelands area are producing.

Gradually, as exploration continues, prospective drilling sites will be located in deeper water farther from the coast. In January 1956 a well drilled 50 miles (80 km) offshore in 101 feet (30.8 m) of water held the record for depth of water and distance from shore. Platforms are now being designed for possible use in water 250 feet (76 m) deep. Engineers believe that platforms capable of standing in 600 feet (183 m) of water will be possible in a few years.

In the area between the oil fields on the continental shelf of east Texas and Veracruz, Mexico, about 750 miles (1,200 km) to the southward, the sedimentary rocks of the continental shelf may be as much as 20,000 feet (6,100 m) thick. Much of the geology of these rocks is imperfectly known, but the probability of their containing reservoirs of oil or gas is considered fair.

At some places the continental shelf of Mexico is narrow, as along the coast north and southeast of Veracruz; few suitable sites for locating offshore drilling rigs are available.

The continental shelf of the Gulf of Mexico broadens northward and eastward from the Isthmus of Tehuantepec to the Yucatan Peninsula. Oil and some gas have been obtained from the narrow coastal-plain regions of northeast Mexico, the Tampico Embayment, and the Isthmus of Tehuantepec. The oil fields in the isthmus region occur on structural domes formed over deep salt plugs, similar to the oil fields that are found over salt plugs off the coast of Texas and Louisiana. The salt plugs are thought to have been extruded from the same salt beds that underlie the Gulf of Mexico.

Although no oil is produced from the Yucatan Peninsula at the present time, many geologists believe that it is a geologically favorable area for oil. The broad shallow shelf that lies along the northwest coast of the peninsula is believed to be underlain by a thick section of sedimentary rocks. These rocks may contain pools of oil trapped on structures in domes over salt plugs or in other types of structural or sedimentary traps.

SULFUR

Sulfur ranks second to oil and gas as a potential mineral of the shelf area in the western part of the Gulf of Mexico. The sulfur is found in the cap rock of some salt domes. Much sulfur has been produced from the cap rock of the Lake Washington dome, Plaquemines Parish, La., on the Mississippi delta. The surface plant at Lake Washington is constructed on piles and concrete mats covered with hydraulic fill, and the sulfur is barged from the site through channels dredged through the surrounding salt marshes. In 1954, announcement was made of the discovery of sulfur about 6 miles (9.6 km) off the south coast of Louisiana near Grand Isle. This is apparently the first discovery of sulfur ever made offshore. Test wells are being drilled to estimate the extent of the deposit. Of the 230 domes discovered by early 1956 in Texas, Louisiana, and Mississippi, 18 contained sulfur in sufficient quantity and purity to warrant recovery. Additional deposits of sulfur will undoubtedly be discovered both onshore and offshore. Despite the many mechanical problems involved in the drilling for and the recovery of sulfur from offshore deposits, the development of these shelf deposits is expected in the foreseeable future.

GULF OF MEXICO—EASTERN SHELF AREA

OIL AND GAS

The continental shelf between the Mississippi delta and the Florida coast is an area of change in subsurface geology from the area to the west. As presently evaluated, the rocks of the eastern gulf shelf do not appear to be as favorable for the occurrence of oil and gas as the rocks to the west.

The two oil fields discovered in southern Florida produce oil from beds at approximately depths of 11,400 to 12,000 feet (3,480 to 3,660 m) within a rock sequence that consists largely of limestone, dolomite, and anhydrite. These rocks are presumed to extend under the continental shelf off the west coast of Florida and are probably present under parts of the Gulf of Mexico and the Caribbean Sea. A forecast of the future of exploration in northern and southern Florida, its offshore areas, and southern Alabama should be cautiously optimistic.

A well located offshore in Florida Bay about 7 miles (11.2 km) south of East Cape, was completed as a dry hole in November 1955 at a depth of 12,631 feet (3,850 m). Small oil shows and some salt water in this well supplied encouraging verification of the presence of hydrocarbons in porous rocks in the Florida shelf area. Structural and stratigraphic features that could hold great amounts of oil and gas are reported throughout the coastal areas of western Florida and southern Alabama, but the depth to which exploratory wells would need to be drilled is a deterrent at the present time. If new pools of oil are found along the shore between Alabama and southern Florida it will be reasonable to assume that local areas in which the stratigraphic and structural relations are favorable for oil and gas accumulation may exist within this large shelf area. Systematic regional and geophysical surveys might provide evidence of structural features suitable for oil accumulation.

PHOSPHATE

The land pebble-phosphate beds of north-central Florida have become one of its most exploited mineral resources. Many tons are processed and shipped each year as mineral fertilizer. Because phosphate is a valuable resource, other areas in Florida and on the gulf shelf have been prospected for possible deposits. The Florida phosphates contain a small amount of uranium but they are not processed for this element at the present time.

In the eastern Gulf of Mexico, geologic investigations have shown that the phosphate-bearing rocks were confined to the inner 20 miles (32 km) of the continental shelf. The phosphate content was not high, however; only a few areas on the shelf contained as much as 13.5 percent phosphorous pentoxide (P_2O_5). The pebble phosphate now being mined in the interior of Florida has a phosphorous pentoxide content of between 30 and 35 percent.

EASTERN NORTH AMERICA FROM SOUTHERN FLORIDA TO NEWFOUNDLAND

OIL AND GAS

The shelf along the Atlantic coast northward from the Florida Keys is practically unknown geologically as compared to the continental shelf of the Gulf of Mexico. Much of the shelf area borders coasts where the sedimentary rocks are thought to be relatively thin and are not generally considered to be promising for the production of oil or gas at the present time.

Long stretches of the coastal plain and continental shelf between Florida and New Jersey have not been explored by test wells; the few scattered wells drilled to date in this coastal area have failed to find deposits of petroleum or natural gas. Geophysical investigations, however, have indicated the presence of sediments 12,000 feet (3,660 m) thick at places only 60 miles (96 km) seaward from the present coastline, but the mineral potential cannot be guessed at without further knowledge of the rock type and associated structures.

From New Jersey to Maine, also, the continental shelf is not considered geologically favorable for accumulations of oil and gas. The sedimentary sequence of rocks in many places is thin, and some of the older rocks are metamorphosed.

Farther north small amounts of oil and gas have been produced from wells drilled inland from the coastal areas of Newfoundland, Nova Scotia, and New Brunswick. No oil wells have been drilled along the shores of this region, so far as is known to the writer, and the possibility of finding oil in commercial quantities in any of the shelf areas between New Jersey and Newfoundland is not considered to be favorable.

COAL

Cape Breton Island, Nova Scotia, contains two general areas which have produced coal from beneath the sea. These are the Sydney coal field in the eastern part and the four small coal fields of Port Hood, Mabou, Inverness, and St. Rose-Chimney Corner in the western part.

The Sydney coal field yields about 80 percent of the total output of coal in Nova Scotia. The coal is found in 12 beds, ranging in thickness from 3 to 7 feet (0.9 to 2.1 m), and is mostly high volatile bituminous in rank. On the basis of developed reserves, about 80 years of mining operations remain, although on the basis of other estimated reserves perhaps as much as 180 years of mining can be expected. The total estimated reserves for the Sydney field are more than 2 billion tons (MacKay, 1947, p. 69).

The coal fields of western Cape Breton Island are located in four small structural basins along the coast. The coal in these basins is of lower rank and grade than that of the Sydney coal field. According to the Canadian Geological Survey the coal seams on the west coast are restricted in immediate economic importance by their quality, steep dip, and almost entirely submarine position. Mining in these fields will be confined largely to supplying the domestic market until such time as the Sydney fields are depleted.

IRON ORE

The Wabana iron ore of Newfoundland is the one metal deposit mined at the present time from an area in the inner edge of the American continental shelf under the Atlantic Ocean. The iron ore is an oolitic hematite occurring in sedimentary rocks that crop out on Bell Island in Conception Bay and dip 8° to 10° NNE. under the bay. The iron reserves of this area under the shelf are truly enormous, but only the thicker beds are mined under the bay at the present time. It has been stated that 3½ billion tons of economic ore are available within a 5-mile (8-km) radius of Bell Island; other billions of tons are present but are not readily available. One ore deposit where the hematite is 30 feet (9.15 m) thick is estimated to contain about 90 million tons to the square mile (35 million tons per sq km).

MONAZITE AND ILMENITE

The sea has not always remained at its present level along the coasts. Throughout the Western Hemisphere, terraces now lying above sea level show that the sea once stood at much higher levels.

These higher terraces and their attendant beaches and bars, similar to those of today, are composed of sand and gravel that were eroded from the land and transported by streams to the sea. Certain minerals, because they were heavier than others comprising this sand and gravel, were concentrated along the shore at places where currents were no longer strong enough to move them. These "heavy" minerals became concentrated in ancient and recent beaches in sufficient quantity to be of economic importance to industry. Among the minerals mined from these deposits are monazite, ilmenite, rutile, and zircon in Florida, monazite in Brazil, gold in Alaska, and platinum in Oregon. Monazite contains the rare-earth elements thorium and cerium, ilmenite and rutile contain titanium (an element which is finding greatly increased usage), and zircon contains the rare element zirconium.

Ancient beach deposits in northeastern Florida which lie about 50 feet (15 m) above sea level are being mined for their heavy minerals. These minerals constitute only 4 percent of the beach sand, and of this 4 percent, monazite is present in amounts of less than 0.5 percent, whereas ilmenite constitutes about 40 percent.

Not all the beach deposits that lie at or above sea level have been mapped geologically. The location and extent of those that lie beneath the sea can barely be guessed at in the present state of knowledge; for example, a gentle terracelike break in the seaward slope of the sea floor off the coast of New Jersey extends for about 190 miles (300 km) along the east coast of the United States at a depth ranging from about 250 to 328 feet (76 to 100 m) and may represent an ancient beach. Similar beachlike features have been reported from Alaska.

Submarine deposits of heavy minerals are most likely to be concentrated offshore in areas where such minerals are present along the seashore. Offshore deposits may be concentrated in beaches built during a lower stage of the sea, or they may be concentrated in pockets on the sea floor by a winnowing action of stream currents flowing from the land or by strong ocean currents flowing along the coast. Prospecting for these minerals will be difficult, and recovering them after their discovery will be expensive. Their discovery and exploitation must await some economic necessity of the future.

CARIBBEAN SHELF AREA AND THE INSULAR SHELVES OF THE ANTILLES AND THE BAHAMAS—OIL AND GAS

The Greater Antilles, bordering the Caribbean Sea on the north, include the islands of Cuba, Jamaica, Hispaniola, and Puerto Rico. This island chain is in part a gigantic structural arch that exposes a thick series of sedimentary rocks representing a long span of geologic history. The islands and their associated shelf areas have potential reserves of mineral fuels and other minerals.

Oil has been produced from metamorphosed rock in the Bacuranao field in northwest Cuba since 1915. Subsequent exploration was slow because a large number of test wells were dry, but after the discovery of the Jatibonico field in central Cuba in May 1954 the southern shelf became of interest; the Cuban government has since granted oil concessions for many hundred square miles of the shelf area off the south shore. In January 1955 a second oil field, the Cruz Verde, was opened one-half mile (0.8 km) to the south of the Bacuranao field, but it was not until a new oil well was completed north of the Bacuranao field in December 1955 that interest was shown in the northern shelf. Companies holding concessions will reportedly spend an estimated $35 million in exploration work and in drilling by 1960. Long-range plans include offshore drilling and exploration on the Cuban shelf, although the extent of this exploration may depend on the success of drilling in the nearby coastal plain.

The discovery of new fields in Cuba will undoubtedly intensify the search for oil in other islands of the Antilles and, where practicable, on the shelf areas along their coasts. Although to date there has been no production of oil and gas on the island of Jamaica, the area is of interest because the first test well, completed in June 1955, contained shows of heavy oil and some gas. The well was completed at a depth of 6,300 feet (1,921 m) in green sandy shale, the rock section penetrated being predominantly limestone with numerous beds of sand and shale. Later an oil company purchased the concession to all the nonmountainous area on both the north and south coasts. The concession includes the right to prospect for petroleum, bauxite, bentonite, and other minerals not only on this land but also in the area of the Jamaican shelf and the Cayman Islands to the west of Jamaica. The oil company reportedly planned to spend at least $2 million in exploration by June 1956.

The regional geology of the island of Hispaniola is somewhat similar to that of Cuba and Puerto Rico. The sedimentary rocks that border the coastal plains consist mainly of limestone and clastic rocks that are highly compressed, folded, and faulted. To date the search for oil on Hispaniola has been only partly successful. In Haiti, 4 wells had been drilled by 1948; the deepest of these was abandoned at 8,769 feet (2,673 m). Shows of oil and gas were reported in some of the wells, but all were completed as dry holes, and the concessions were abandoned. Shows of gas were found in a well drilled in 1955 in the northern part of the Ile de la Gonave, off Haiti.

In the Dominican Republic, 13 test wells were drilled between 1939 and 1947. About 13,000 barrels of heavy oil was produced from the first of these. Future exploration for oil on the island of Hispaniola may be more successful, but the shelf area around the island is very narrow and few wells could be located offshore.

No direct evidence of oil or gas accumulation has been found on Puerto Rico, but recent investigations made by the U. S. Geological Survey have been followed by geophysical investigations in the north and south coastal areas. Results of the mapping show that along the north coast gently inclined sedimentary rocks of Tertiary age underlie a strip as much as 10 miles (16 km) wide, and that more sharply folded rocks of this age occur in a narrower strip along the central and western parts of the south coast. Furthermore, oil has been found in similar rocks in the Dominican Republic, and oil seeps are present in somewhat older but similar rocks in Cuba. The sea floor slopes relatively steeply along the north side of the island. A strip only a few thousand feet (about a km) wide lies at depths of less than 90 feet (27.5 m) along this coast, and the edge of the continental shelf, at a depth of approximately 600 feet (183 m), is at most only 2 miles (3.2 km) offshore. Along the south coast an area having a maximum width of almost 10 miles (16 km) lies under depths of less than 90 feet (27.5 m).

The Virgin Islands to the east have geologic features similar to those of Puerto Rico, but there is only a narrow belt of sedimentary rocks; these rocks are believed to have only slight possibilities for oil.

The Bahama Islands and the Bahama Banks lie east and south of the Florida Peninsula and were once probably a southern continuation of it. No reasonable assumption can be made as to whether or not the Bahamas contain deposits of oil or gas until sufficient test wells have been drilled to determine the presence of sedimentary rocks sufficiently porous to contain pools of oil or gas. The only subsurface data currently available are from a well completed in the northern part of Andros Island (the largest island in the Bahama group) in 1947. The well, drilled to a depth of 14,587 feet (4,446 m), was reported to contain no shows of oil or gas. The deepest formations reached were similar stratigraphically to those of southern Florida. The Bahamas were completely surveyed by airborne magnetometer during a joint project financed by the several companies that hold exploration licenses on the group. The results of this survey are said to indicate that structures are present which may be favorable for the accumulation of oil.

The Lesser Antilles bordering the Caribbean Sea to the east include many small islands, most of which have a volcanic-rock core but some of which are capped by marine limestones. They hold little promise for production of petroleum except for Barbados, the easternmost island of the British West Indies. Structurally Barbados seems to have affinities with the Bahamas, for it is part of the outer zone of low banks and islands to which the Bahamas belong. Its sedimentary rocks, however, seem in part related to those of Trinidad, to the southwest. The core of the island of Barbados is a thick series of sedimentary rock consisting of coarse grit, brownish sand, and dark sandy clay which are in places saturated with petroleum and contain lenticular beds of asphalt. No volcanic rocks are present in this sequence, and the early geologic history of the island, both stratigraphically and structurally, differs, therefore, from that of the volcanic islands of the group to the west. Several test wells have been drilled on the island of Barbados. Some contained shows of oil or gas but only one, a gas well, had commercial production.

The shores of the island of Barbados slope steeply into the ocean, and any exploration under the sea floor will likely be by directional drilling from the shore.

The northwest part of the coast of Venezuela consists of sedimentary rocks. These and similiar rocks of the contiguous shelf areas may prove to be productive of oil or gas. Parts of the northern and eastern Venezuelan coasts and islands off the coast contain areas of metamorphic rocks; at a few places basic igneous rocks are also present. The belt of metamorphic rocks continues eastward through the northern part of the island of Trinidad and the island of Tobago. Southern Trinidad contains unmetamorphosed sedimentary rocks, however, from which oil has been produced. Some of the oil fields extend down to the shore, and in expectation of possible future development, nearly a million acres of the shallow shelf area is under lease. In 1952 a directional well which produced oil was completed at La Brea on the Gulf of Paria, and since that time several successful oil wells have been drilled from platforms in the Gulf of Paria.

Along the west perimeter of the Caribbean Sea active prospecting for petroleum is taking place in a number of Central American countries. In British Honduras seismic and geologic explorations have been carried on, and data obtained from two nonproductive drill tests made in the northern interior are being studied as a guide to possible further exploration. Concession blocks include coastal and offshore areas. In Guatemala the coastal area and the Departamento del Petén in the interior are thought to be favorable for prospecting for oil, and geologic exploration is being carried on in these areas. Some concessions have been granted for offshore exploration.

An important upwarp of the Antillean region passes westward through southern Hispaniola and Jamaica and across the Caribbean Sea into Honduras and Nicaragua. Where this structural feature enters Central America the upwarped rocks lie near the surface of the Caribbean, thus forming a broad platform on the continental shelf. Large concessions have been taken along the coasts of Honduras and Nicaragua, both onshore and offshore, and sites for offshore drilling have been selected. Other areas of islandlike platforms which lie along the arch between Nicaragua and Jamaica under less that 150 feet (46 m) of water may also be prospected.

Several test wells drilled inland from the Caribbean coast of Costa Rica have found oil but did not make commercial production because of excessive amounts of salt water. Additional tests are planned in several areas, some of which are near the Caribbean coast.

Exploration in Panama has been renewed since oil was found in Costa Rican test wells. Earlier drilling programs in Panama dating back as far as 1928 did not produce oil in commercial quantity. Recent concessions cover the entire area, and extensive preliminary geological surveys and some drilling operations have been undertaken.

EASTERN SOUTH AMERICA FROM BRITISH GUIANA TO CAPE HORN

OIL AND GAS

The continental shelf from British Guiana to easternmost Brazil, where the coast swings southward, is relatively broad. No oil or gas has been produced to date, however, along the coast or on the shelf in this area. One company has a concession in the northeastern coastal region of British Guiana that comprises 3,275 square miles (8,482 sq km) and includes offshore lands out to the 3-mile (4.8-km) territorial limit. In the Marajo basin of Brazil near the mouth of the Amazon River exploration of the past several years has included geophysical surveys and the drilling of several test wells. One well, drilled through more than 13,000 feet (3,960 m) of sediments, had at least one show of oil. The basin undoubtedly extends into the continental shelf. Exploration has recently been active in the inland embayment and coastal areas of São Luís in Estado do Maranhão.

The shelf is narrow from easternmost Brazil southward to the town of Canavieiras, in the southern part of Estado de Bahia, but broadens markedly from there to southern Argentina. The broad shelf passes around the Falkland Islands and continues to Tierra del Fuego.

Two basin areas along the coast in easternmost Brazil contain thick accumulations of sedimentary rocks. These are the Sergipe-Alagoas basin to the north, in which test wells yielded shows of oil and gas,

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and the Bahia basin to the south, which is now producing oil. Both basins apparently project into the narrow continental shelf, and seismic mapping is planned for the shelf areas.

In Argentina the Comodoro Rivadavia oil field, discovered in 1907, lies on the Golfo San Jorge. Exploratory drilling has been difficult in this field because faulting has produced numerous structural complications, the formations are irregularly bedded, and the sand bodies pinch out. Even though the Golfo San Jorge is within the continental shelf, the water over much of it appears to be too deep to encourage prospecting for oil and gas at the present time.

The basin that lies in the southern part of Chile within the limits of Tierra del Fuego has long been known to contain seepages of gas and oil. Test wells drilled in the late 1920's near Punta Arenas failed to discover commercial quantities of oil. A test well drilled in 1945 northeast of Punta Arenas on the Isla Grande of Tierra del Fuego, 6 miles (9.6 km) south of the north end of the Straits of Magellan, was completed as an oil well producing from beds at depths of 7,419 to 7,438 feet (2,261 to 2,267 m). Producing wells completed later in this vicinity and in the Argentine sector of Tierra del Fuego are not on the seacoast, but these oil discoveries do extend the possible areas of exploration in South America and may encourage exploration of nearby shelf areas where the water is shallow (fig. 8).

MONAZITE

The beaches of Brazil have been an important source of monazite, especially along the coasts of Estado do Espírito Santo and Estado de Bahia. In former years, the monazite sand was skimmed from the surface of the beaches after each high tide and was then sacked and shipped without further separation of monazite from other minerals in the sand. Later, as this source was depleted, the higher beaches were prospected, and placer deposits along watercourses leading to the sea were mined. Submarine deposits of heavy minerals may be concentrated off the shores of Brazil.

PACIFIC COAST OF SOUTH AMERICA AND CENTRAL AMERICA

OIL AND GAS

On the west coasts of South America and of Central America, shelf areas beneath less than 50 feet (15 m) of water are narrow. Some interest has been shown in offshore Peru and Ecuador by companies which have leased large areas on the shelf. Geophysical surveys offshore from Peru indicate that suitable structures may be present. Some successful wells have been developed there by directional drill-

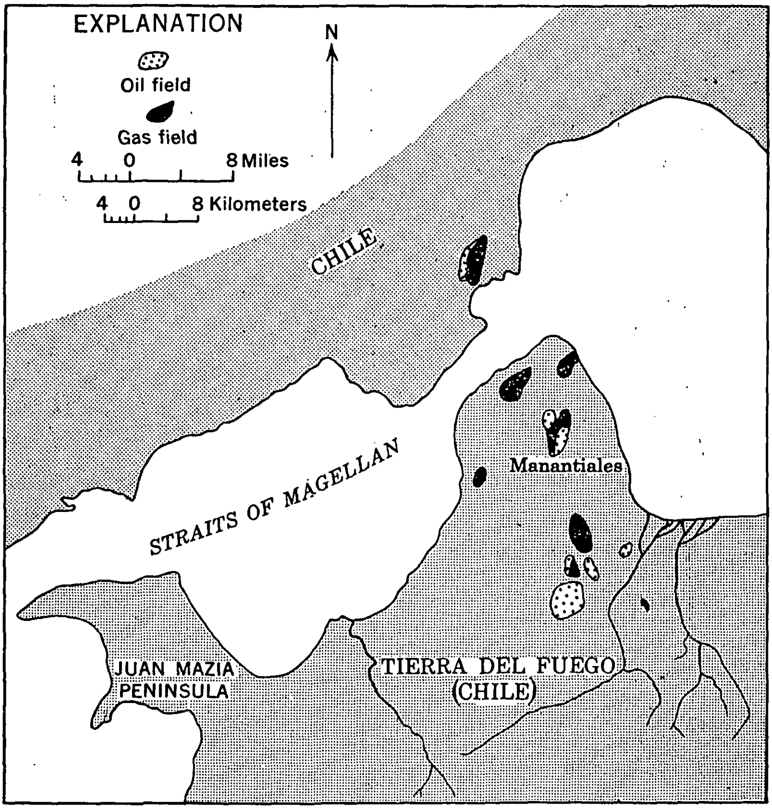

FIGURE 8.—Oil and gas fields near shore in Tierra del Fuego, Chile.

ing from the shore. If depth of water permits, drilling on the shelf may be undertaken along the coastal areas of Peru and Ecuador. Areas where petroleum has been produced along the coast and tidelands in Peru and Ecuador are shown in figure 9.

COAL

Coal was mined from under the sea on the Golfo de Arauco in the Provincia de Arauco and Provincia de Concepción in central Chile soon after 1852. The mine openings were located on land near the beach, and slope entries were driven southwestward under the Pacific Ocean. The original workings of one mine were flooded by the sea and have long since been abandoned. Coal is being produced in other mines from below the sea in the gulf area. The coal, which occurs in 3 beds to depths of about 1,300 feet (400 m) below sea level, is high-volatile bituminous in rank, bright in appearance, and fragile in structure. A system of complex faults in the area has greatly in-

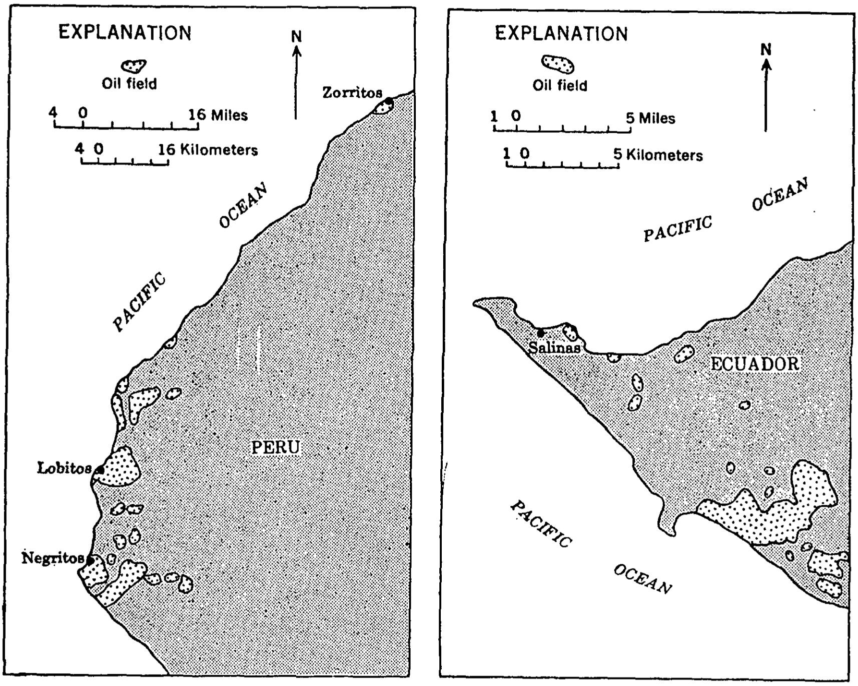

FIGURE 9.—Oil fields near shore in Peru and Ecuador.

fluenced the location of mines on land and has raised many difficulties in mining beneath the sea.

Coal production is reported along the fiordlike channels of southern Chile in the Provincia de Magallanes, about 90 miles (144 m) north of Punta Arenas. Information is not specific as to whether any of the coal beds extend under these narrow inlets or to the continental shelf.

WESTERN NORTH AMERICA FROM MEXICO TO ALASKA

OIL AND GAS

Geologists for Pemex, the Mexican government oil monopoly, have been exploring the peninsula of Lower California since 1942 and have located two sedimentary basins in the central and southern part of the peninsula which they believe may contain oil or gas. These basins, known as the Sebastian Vizcaino and the Purisima-Iray, have been mapped in detail during the past 5 years. Test wells have been drilled in both basins, but those drilled in the Purisima-Iray basin were the only one with shows of oil and gas. The area has been insufficiently tested, however, and a continued program of well drilling is planned by Pemex.

Bathymetric charts of the area show that a narrow shelf is present along the shoreline of these basins. If oil deposits are found along the shore of this shelf, their extension by drilling offshore might be justified.

The topography of the seafloor along the Pacific coast of the United States is in marked contrast to the topography of the submerged areas off Texas and Louisiana. The submarine topography along the California coast is very irregular and is similar in many ways to the topography of the adjoining mountain belts on land. The strip of ocean floor between the 100-fathom (600-ft, 183-m) line and the shore along the California coast is very narrow, generally less than 10 miles (16 km), and at places is less than 1 mile (1.6 km) wide.

Oil fields along the California coast are localized in deep sedimentary basins containing sharply folded rocks. Great quantities of oil have been found in the relatively small Los Angeles, Ventura, and Santa Maria basins, but elsewhere in the California coastal region only a few small pools have been discovered (fig. 10).

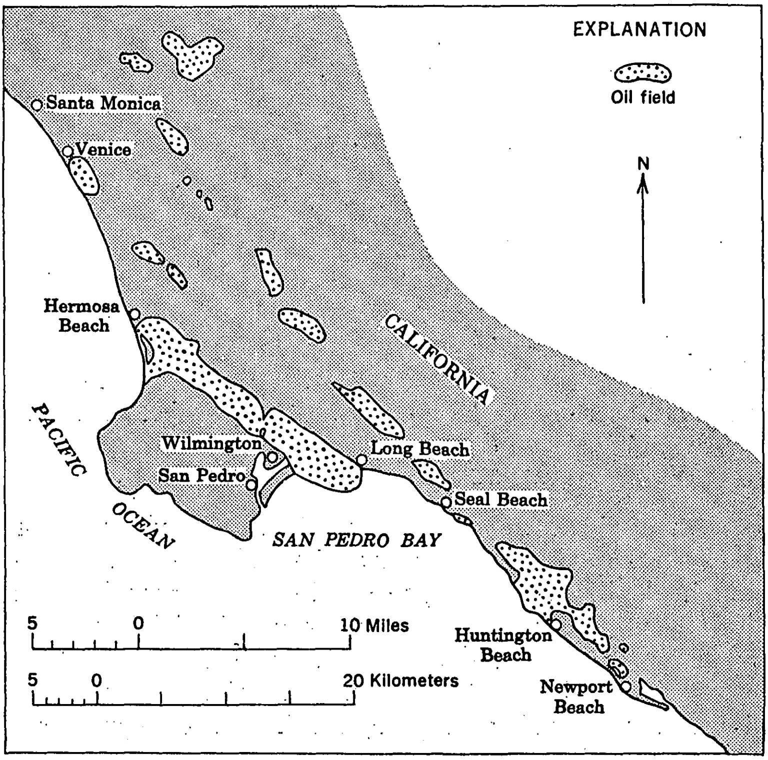

FIGURE 10.—Oil fields near shore in the Los Angeles basin, California.

The productive basins are at an angle to the general trend of the coast and extend westward under the sea. These submerged areas offer excellent prospects for the discovery of additional reserves of petroleum.

Divers have mapped the extension of known anticlines under sea off the coast of California. In many of the areas mapped, high-pressure jets were used to wash away sand deposits that obscured the strata; however, this was practicable only if the deposits were less than 25 feet (7.6 m) thick. Exploration with the reflection seismograph has met with considerable success in California, and its use offshore will probably be of great value as exploration is undertaken for new possibly oilbearing structures that are entirely beneath the water. Ship-mounted drilling equipment capable of recovering cores from rocks lying below 1,500 feet (457.2 m) of water has recently been perfected.

The coastal belts of Washington, Oregon, and central and northern California have been prospected at geologically favorable points, but wells drilled in these areas have not found large accumulations of oil or gas. Available information does not suggest that offshore exploration along this part of the Pacific coast and northward to Alaska would offer promise of greater success than has been achieved on land. Production of some oil from two wells that were drilled below high tide level along the coast of Washington indicates that the general area is not unsuitable for further prospecting.

COAL

Coal-bearing rocks of Cretaceous age are present along the eastern side of Vancouver Island, British Columbia, in the Nanaimo district. They crop out along the coast for a distance of 40 miles (64 km) and dip generally seaward. Two coal beds had been mined for a distance of 2 miles (3.2 km) under the harbor at Nanaimo by 1926, and at that time about 20 percent of the coal produced on Vancouver Island was by subsea mining.

PLATINUM AND CHROMITE

Deposits of "black sand," which consist mostly of magnetite and small amounts of gold, platinum, chromite, and traces of monazite, are present in the beaches of Oregon and in streams that flow into the Pacific Ocean. Platinum, which usually contains iridium, and chromite, containing the element chromium, have not been found in sufficient quantities to justify dredging for them alone. A few ounces of platinum is recovered each year, usually as a byproduct after separation from placer gold.

ALASKA

OIL AND GAS

The continental shelf off the south, west, and north coasts of Alaska includes a Pacific Ocean area of approximately 140,000 square miles (360,000 sq km), a Bering Sea area of approximately 320,000 square miles (830,000 sq km), and an Arctic Ocean area which is less definitely delineated. As parts of each shelf area are contiguous to known petroliferous areas and the geologic conditions in the shelves offshore from these areas are presumably similar to the contiguous land areas, the shelf areas may also have potentialities as sources of petroleum. Evaluation of the shelf area must necessarily be based mainly on comparison with the adjacent land area.

Considerable exploration has been carried on recently in coastal areas around the Gulf of Alaska and the Alaskan peninsula. Offshore exploration in some parts of this shelf might be difficult, for although some places are relatively sheltered, much of the Pacific Ocean shelf area of Alaska is exposed to the notoriously violent storms of the northern Pacific.

Direct information on the nature of the rocks underlying the shelf in the Bering Sea area is provided only by a few islands. Any attempt to recover petroleum from most of this shelf area or from shelf areas of the Arctic Ocean would be subject to special hazards and difficulties arising from the continual or periodic presence of ice.

GOLD

Placer gold, discovered at Nome, Alaska, in 1899, is found at 3 levels above water and 1 below. The highest level, an ancient beach now 70 feet (21.3 m) above the sea, was the richest. The lowest level, known as the submarine beach, lies 19 feet (5.8 m) below the present level of the sea, and is thought to be the oldest.

CONCLUSIONS

The continental shelf contains a vast store of minerals, some of which are sufficiently concentrated to form deposits of great potential value. For example, oil is present over salt domes in the Gulf of Mexico in known reserves of many millions of barrels. Sulfur, which is in ever-increasing demand by industry, is present also in some shelf salt domes and will soon be produced through offshore installations. Other minerals, such as iron ore in Newfoundland, and coal in Nova Scotia and in Chile, underlie the continental shelf in deposits whose reserves are known to be in millions of tons. These materials are becoming increasingly important because as the population of the world increases a greater mineral supply will be required to maintain a high standard of living. Thus all countries will be forced to intensify the search for new deposits within their borders, and as some of these deposits become depleted, the mineral potential of the continental shelf will become increasingly important as a means of maintaining reserves adequate for the ever-expanding economy.

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PROBLEMS OF PETROLEUM DEVELOPMENT ON THE CONTINENTAL SHELF OF THE GULF OF MEXICO

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CONTENTS

ILLUSTRATIONS

TABLES

ABSTRACT

The continental shelf is an extension of the continental land mass which at present is covered by the ocean. The geologic characteristics of the shelf are similar to those of the adjoining land area, and mineral accumulation on the land extends into the continental shelf.

In economic value, oil and gas are the most important minerals produced from the continental shelf. Production of oil and gas from the shelf areas of the Western Hemisphere is presently confined to the Gulf of Mexico and to the Pacific Ocean off the California coast. The development off California has been limited to extension of fields discovered on shore, and almost all wells are drilled from shore sites. In the Gulf of Mexico oil and gas development has proceeded at a rapid rate, and wells are now located as much as 50 miles (80 km) from shore in water almost 120 feet (36.57 m, 20 fathoms) deep.

The problems involved in developing oil and gas on the continental shelf of the Gulf of Mexico are both technologic and economic. In addition to normal oil-field problems, the offshore operator must consider hydrographic, oceanographic, and meteorologic factors. The design of drilling structures is closely related to these factors.

The cost of continental-shelf petroleum operations ranges from 2 to 10 times that of equivalent operations on land. These high costs cause most of the problems in offshore operations, as the products recovered from the shelf must compete with products recovered from oil and gas fields on land. Much research is being done in the petroleum industry to devise methods of reducing these costs.

INTRODUCTION

The continental shelf has been defined as that part of the continental land mass which is shallowly submerged by the ocean. The continental shelf begins at the line of mean low tide wherever land areas meet the open ocean, or at the mouths of rivers, bays, and other inland waters wherever they meet the open ocean. It extends seaward to the point where the slope of the continental mass changes quite abruptly and descends more steeply into the oceanic depths. The continental shelf is an integral part of the continent, distinguished only by being covered with a shallow mantle of water.

Throughout the Western Hemisphere the continental shelves vary greatly in their extent. The width of the continental shelf off the United States varies from less than 10 miles (16 km) along the coast of the Pacific Ocean to approximately 250 miles (402 km) along the northern part of the Atlantic Ocean. The average width of the shelf off the Atlantic coast of the United States is approximately 73 nautical miles (135 km), the average width in the Gulf of Mexico is approximately 59 nautical miles (109 km), and the average width off the Pacific coast of the United States is about 18 nautical miles (33 km) (U. S. Dept. Interior, 1953, p. 191). The continental shelves off the coast of Central and South America show similar variations in extent. The total area of the continental shelf adjoining the United States is approximately 290,000 square miles (751,100 sq km).

As the continental shelf is an extension of the continental land mass which is now covered by the ocean, it may reasonably be inferred that the geologic characteristics of the shelf will be quite similar to those of the adjoining land area. In general, where sufficient data are available, this inference has proved true. For example, the structure of the sedimentary rocks and the occurrence of numerous salt domes in the shelf in the Gulf of Mexico are essentially the same as those of the contiguous coastal-plain area.

If the continental shelf is geologically similar to the adjoining land area, then it can reasonably be inferred that mineral accumulations on the land area will continue into the shelf. Again, where suitable data exist, this inference has largely proved true. Several oil fields in the United States along the Pacific coast and the Gulf of Mexico extend from the land area into the continental shelf. Other fields, lying wholly in the shelf, are geologically similar to fields on land.

HISTORICAL BACKGROUND

Although the continental shelves have been known for centuries, mineral development on the shelves is a very recent accomplishment. Oil was first produced from the continental shelf some time between 1894 and 1899 in the Summerland field, Santa Barbara County, Calif. The field was discovered on land near the shore of the Pacific Ocean in 1894, and by 1899 several wells had been drilled from wooden wharves extending several hundred feet into the ocean.

Later production of oil from the continental shelf started in the Rincon oil field, Ventura County, Calif., in 1927; Capitan and Elwood fields, Santa Barbara County, in 1929; and Huntington Beach field, Orange County, in 1933. As in the Summerland field, these were all discovered on land and were extended a short distance onto the continental shelf. Drilling operations were conducted from shore locations through directional (slant) wells, or from piers or wharves extending from the land for short distances into the sea.

Oil operations on the continental shelf of the Gulf of Mexico began in 1936 in the High Island field, Galveston County, Tex. In 1938, oil production was started in the Creole field, Cameron Parish, La., and in 1941–42 production was established in the Sabine Pass field, Jefferson County, Tex.; the Caplan field, Galveston County, Tex.; and the Rabbit Island field, Iberia Parish, La. In all these fields, the continental-shelf activity was an extension of discoveries made on shore, and drilling operations were conducted from shore by means of directional drilling, from piers or wharves built from the shore, or by submersible barges in protected waters, such as had been previously used in the marshes of southern Louisiana. The entry of the United States into World War II generally ended active exploration and development of the petroleum resources of the continental shelf for the period of the war.

The greatest impetus to exploration and development of the petroleum reserves in the continental shelf was the discovery of oil about 12 miles (19 km) off the coast of Louisiana in the open, unprotected waters of the Gulf of Mexico, in November 1947. It proved conclusively that oil accumulations exist under the continental shelf at a considerable distance from the shore, and it also demonstrated that technological methods had been devised which were suitable for the exploration, development, and production of oil and gas from the continental shelf.

A major problem in the orderly development of the mineral resources of the continental shelves of the United States has been the controversy between the United States and the coastal States, particularly Louisiana, Texas, and California, concerning jurisdiction over the shelves. Although it is beyond the scope of this paper to present a detailed analysis and account of this controversy, some concept of the dispute is necessary for an understanding of petroleum development on the continental shelf.

In October 1945, the Attorney General of the United States invoked the original jurisdiction of the Supreme Court of the United States by instituting a suit against the State of California. As of that time the State of California had issued oil and gas leases for approximately 10,700 acres of the continental shelf, from which approximately 950,000 barrels of oil per month was being produced. The following passages concerning the actions before and decisions of the Supreme Court are quoted from a report of the U. S. Department of Interior (1953, p. 192–195).

The complaint against California alleged that the United States "is the owner in fee simple of, or possessed of paramount rights in and powers over, the lands, minerals and other things of value underlying the Pacific Ocean, lying seaward of the ordinary low-water mark on the coast of California and outside of the inland waters of the State, extending seaward three nautical miles [5.56 km];" that California had unlawfully issued oil and gas leases on lands underlying such ocean area; and that the State's lessees had entered upon such lands and taken oil and gas from them. The Government sought a decree declaring the rights of the United States in the area as against California, and enjoining California, together with all persons claiming under the State, from continuing to trespass on the area in violation of the rights of the United States.

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The Supreme Court rendered its decision in the case of *United States* v. *California* on June 23, 1947 (332 U. S. 19). The Court found * * * that the Thirteen Original States did not, upon the attainment of independence, acquire any rights of ownership in the lands underlying the 3-mile [5.56-km] marginal belt of open sea contiguous to their shores, because at that time there was no settled international custom of understanding among nations relative to the control by a littoral nation of a marginal belt of ocean waters along its coast; and * * * that the acquisition of the 3-mile belt was subsequently accomplished by the National

Government, and "protection and control of it has been and is a function of national external sovereignty." Accordingly, the Court held * * * "that California is not the owner of the 3-mile marginal belt along its coast, and that the Federal Government rather than the State has paramount rights in and power over that belt, an incident to which is full dominion over the resources of the soil under that water area, including oil" * * *.

* * * * * * *

As of the date (June 23, 1947) when the Supreme Court rendered its decision in the case of *United States* v. *California*, the State of Louisiana had issued oil and gas leases covering a total of approximately 1,419,700 acres of land in the continental shelf extending seaward from the coast line of that State. Actual development work under such leases had not been extensive, however, and oil production from the Continental Shelf off the Louisiana coast was averaging only about 30,000 barrels per month at that time.

The State of Louisiana continued, after the announcement by the Supreme Court of its decision in the *California* case, to issue oil and gas leases on submerged lands of the continental shelf off the Louisiana coast. By December 21, 1948, the total acreage of the continental shelf covered by Louisiana-issued oil and gas leases amounted to approximately 2,043,990 acres. Many of the continental shelf areas covered by these State leases were situated seaward of the 3-mile [5.56-km] limit and, hence, were within the portion of the continental shelf as to which the rights of the United States had been expressly proclaimed under the principles of international law by Proclamation No. 2667 of September 28, 1945 (10 F. R. 12303). (A State statute enacted in June 1938 (Louisiana Acts, 1938, p. 169) had purported to extend the seaward boundary of Louisiana to a line in the Gulf of Mexico 27 nautical miles [50 km] from the shore.)

On December 21, 1948, the Attorney General instituted before the Supreme Court a suit against the State of Louisiana. The complaint in this case was similar to the complaint which had been filed against the State of California in 1945, except that the complaint in the case against Louisiana stated that the area in dispute extended seaward for a distance of 27 marine miles [50 km] (rather than three nautical miles) from the Louisiana coast.

The Supreme Court decided the *Louisiana* case on June 5, 1950 (339 U. S. 699). The Court followed its previous decision in the *California* case, stating * * * that "If, as we held in California's case, the 3-mile belt is in the domain of the Nation rather than that of the separate States, it follows *a fortiori* that the ocean beyond that limit also is."

* * * * * * *

On the same day when the Attorney General filed the submerged lands suit against the State of Louisiana, he also filed with the Supreme Court a suit against the State of Texas. The complaint against Texas indicated that the area in dispute was the whole of the continental shelf extending seaward from the Texas coast line.

The Supreme Court announced its decision in the case of *United States* v. *Texas* on June 5, 1950 (339 U. S. 707). It was necessary for the Court to devote special consideration to an argument vigorously urged by the State of Texas respecting the portion of the continental shelf situated within a distance of three marine leagues [16.7 km] (9 nautical miles or 10½ land miles) from the Texas coast line. The State of Texas was not created by the United States out of Federal territory (as were the States of California and Louisiana). Instead, Texas had been an independent nation, and it was admitted into the

Union as a State through the process of annexation. During the period of Texas' independence, the Congress of the Republic of Texas, by the act of December 19, 1836 (1 Laws of Republic of Texas, p. 133), had fixed the seaward boundary of the Republic of Texas in the Gulf of Mexico at a distance of "three leagues from land." Texas contended before the Supreme Court that the Republic of Texas had maintained open, adverse, and exclusive possession of, and had exercised jurisdiction and control over, the submerged lands underlying that part of the Gulf of Mexico within the 3-league limit; and that, under the annexation legislation pursuant to which Texas entered the Union as a State, it was provided that Texas should retain "all the vacant and unappropriated lands lying within its limits" (5 Stat. 798), which, according to Texas, included the lands of the continental shelf within the 3-league limit.

With regard to the point mentioned in the preceding paragraph, the Supreme Court held * * * in a 4 to 3 decision that when Texas ceased to be an independent nation and entered the Union, she became, under the terms of the annexation legislation (9 Stat. 108), a sister State on an "equal footing" with the other States, none of which had acquired or been granted rights in the submerged lands of the Continental Shelf; and that as an incident of the transfer of national external sovereignty from the Republic of Texas to the United States, any claim that Texas may have had to the lands of the Continental Shelf inside the 3-league limit was relinquished to the United States, since property rights in this area are so subordinated to the rights of sovereignty as to follow sovereignty.

The Supreme Court in the Texas case, also upheld the rights of the United States in the Continental Shelf lands situated seaward of the 3-league limit. However, the Court apparently regarded this as being so plain that it did not require any particular discussion.

The Court's opinion in the Texas case made it clear that, as regards the submerged lands of the Continental Shelf off the coast of the United States, the Federal Government has both imperium (governmental powers of regulation and control) and dominium (ownership or proprietary rights).

Following the decisions and decrees of the Supreme Court in the Louisiana and Texas cases, practically all oil and gas operations on the continental shelf came to a halt except for production from wells already drilled and the drilling of a few wells approved by the Secretary of the Interior for conservation purposes. However in 1953 legislation was enacted which clarified the legal status of the leases in the continental shelf. The first of these laws, known as the "Submerged Lands Act" (Public Law 31, 83d Cong., 1st Sess., 67 Stat. 29), was approved May 22, 1953. This act provides:

SEC. 3 (a). It is hereby determined and declared to be in the public interest that (1) title to and ownership of the lands beneath navigable waters within the boundaries of the respective States, and the natural resources within such lands and waters, and (2) the right and power to manage, administer, lease, develop, and use the said lands and natural resources all in accordance with applicable State law be, and they are hereby, subject to the provisions hereof, recognized, confirmed, established, and vested in and assigned to the respective States or the persons who were on June 5, 1950, entitled thereto under the law of the respective States in which the land is located, and the respective grantees, lessees, or successors in interest thereof.

Seaward boundaries of the coastal States are defined in the act as follows:

SEC. 4. The seaward boundary of each original coastal State is hereby approved and confirmed as a line three geographical miles [5.56 km] distant from its coast line or, in the case of the Great Lakes, to the international boundary. Any State admitted subsequent to the formation of the Union which has not already done so may extend its seaward boundaries to a line three geographical miles distant from its coast line, or to the international boundaries of the United States in the Great Lakes or any other body of water traversed by such boundaries. Any claim heretofore or hereafter asserted either by constitutional provision, statute, or otherwise, indicating the intent of a State so to extend its boundaries is hereby approved and confirmed, without prejudice to its claim, if any it has, that its boundaries extend beyond that line. Nothing in this section is to be construed as questioning or in any manner prejudicing the existence of any State's seaward boundary beyond three geographical miles if it was so provided by its constitution or laws prior to or at the time such State became a member of the Union, or if it has been heretofore approved by Congress.

The act also retains certain powers in the United States:

SEC. 6 (a). The United States retains all its navigational servitude and rights in and powers of regulation and control of said lands and navigable waters for the constitutional purposes of commerce, navigation, national defense, and international affairs, all of which shall be paramount to, but shall not be deemed to include, proprietary rights of ownership, or the rights of management, administration, leasing, use, and development of the lands and natural resources which are specifically recognized, confirmed, established, and vested in and assigned to the respective States and others by section 3 of this Act.

The net effect of the Submerged Lands Act was to grant the coastal States jurisdiction over the submerged lands of the continental shelf and ownership of all minerals therein within the so-called "territorial sea."

Following the enactment of the Submerged Lands Act, the Congress provided for the administration of the continental shelf beyond (that is, seaward of) the "territorial sea" by the enactment of the Outer Continental Shelf Lands Act (Public Law 212, 83d Congress, 1st Session, 67 Stat. 462). This act, in its first major section, establishes the basic policy of the United States as follows:

SEC. 3 (a). It is hereby declared to be the policy of the United States that the subsoil and seabed of the outer Continental Shelf appertain to the United States and are subject to its jurisdiction, control, and power of disposition as provided in this Act.

(b) This Act shall be construed in such manner that the character as high seas of the waters above the outer Continental Shelf and the right to navigation and fishing therein shall not be affected.

The term "outer Continental Shelf" is defined as "* * * all submerged lands lying seaward and outside of the area of lands beneath navigable waters as defined in section 2 of the Submerged Lands Act

(Public Law 31, Eighty-third Congress, first session), and of which the subsoil and seabed appertain to the United States and are subject to its jurisdiction and control." (Sec. 2 (a).) The act also provides the framework for the issuance of mineral leases in the "outer Continental Shelf" and for the supervision and regulation of operations conducted pursuant to such leases.

These two acts did much to resolve the basic conflict concerning jurisdiction over the continental shelves contiguous to the United States and the ownership of the minerals therein and provided a substantial legal foundation on which private industry can develop and produce these mineral resources.

EXPLORATION

In the continental shelf adjoining the United States, exploration for oil and gas includes three major phases: prospecting by geologists and geophysicists, leasing of potential producing areas, and drilling to prove the existence of oil and gas. Prospecting is usually divided into reconnaissance surveying and detailed surveying.

RECONNAISSANCE SURVEYING

Reconnaissance surveys are usually conducted to locate those areas in which geologic structures favorable for the accumulation of petroleum may occur. If the structures are sufficiently promising, a more detailed survey is conducted. Reconnaissance surveys are generally either a measure of the magnetic characteristics or of the specific gravity of the earth's crust in the area of interest. Instruments known as magnetometers and gravity meters are used in making such surveys.

In the continental shelf of the Gulf of Mexico, most oil and gas accumulations now known are associated with geologic structures called salt domes. Throughout the gulf coast region of the United States, including the shelf, geologic evidence indicates that the sedimentary formations are underlain by a deep layer of salt. In some places, during various periods of geologic time, this deep-lying salt bulged, pushing the overlying sediments (including any potentially mineral-bearing strata) into arches or domes. The resulting structures are known as deep-seated domes. The arching that produced them was usually accompanied by faulting, which is a breaking of the strata into large blocks.

In other places, the deep-lying salt pushed up as irregular cylindrical bodies through overlying strata to form cores of salt surrounded by sedimentary deposits. The name "piercement dome" has been given to this type of geologic structure. In such structures salt may be found at any depth, from the surface of the land to 10,000 feet below the surface. Oil and gas are sometimes found in the strata overlying the salt mass, but the more usual occurrence is in irregular areas at varying depths around the flanks of the salt core.

The sedimentary rocks of the gulf coast region, including the continental shelf, consist mostly of sand and clay. Although they have relatively low magnetism, salt has practically none. Thus, by use of the magnetometer, areas of abnormally low magnetism can be located, with sound justification for the belief that such areas represent a salt dome.

It was not until World War II that the magnetometer was successfully adapted for work in areas covered by water. By about 1945, the magnometer had been so perfected that it could be towed through the water behind a boat, and continuous readings could be taken along a fixed course. An even faster method of making a magnetometer survey consists of towing the instrument through the air behind an airplane flying at a fixed altitude, thus covering large areas very rapidly. These methods are ideally suited for reconnaissance surveys in the continental shelf as they are both rapid and comparatively inexpensive.

The gravity-meter survey measures the difference in the force of gravity over the earth's surface. As the specific gravity of salt is considerably less than that of the normal sedimentary rocks, it is comparatively easy to locate salt-dome structures by this method.

In the continental shelf, the first gravity-meter surveys were made by stationing the instrument on a tripod in very shallow water. Later, the instrument was placed in a diving bell, with an operator, and lowered into deeper water. Instruments have now been developed which can be lowered from a boat to the sea bottom very rapidly, and the readings made by remote control from the boat. This has greatly simplified the making of gravity surveys although this method is still somewhat slower than with the magnetometer.

DETAILED SURVEYING

The most reliable method of finding the exact location of individual geologic structures is by use of the seismograph, which measures the time interval required for shock waves to travel from the earth's surface to a reflecting stratum and return. Shock waves are generated by exploding small charges of dynamite or powder, and the returning waves are picked up by small instruments known as geophones.

Seismic operations on the open sea have created many problems. As the exact location of each shot point is vital to the success of the operation, accurate surveying is critical. Near land, conventional surveying, such as visual methods with transit or alidade, can be used, but for use beyond the sight of land other methods had to be devised. Modifications of radar-base navigational aid systems are now in widespread use. In one such system, boats as far as 75 miles (121 km) at sea can be located rapidly and precisely by triangulation from shore stations through use of electronic signals.

The protection of aquatic life is another major problem during seismic operations. It has been found that damage to aquatic life, particularly oysters and shrimp, can be minimized, if not avoided altogether, by limiting the size of the explosion and by suspending the explosive charge about midway between the surface of the water and the ocean bottom. This shooting procedure does not affect the accuracy of the survey and has become the usual practice in continental-shelf seismic prospecting.

As a measure of protection for marine life, inspectors are required to accompany all geophysical surveys. These inspectors are employed by the Coastal States and are empowered to enforce all State regulations concerning the size of the explosive charge, method of detonation, and like matters. The United States Government, through the Secretary of the Interior, has entered into cooperative agreements with the various States, whereby the regulations of the States are adopted as Federal regulations applicable to that part of the continental shelf under Federal jurisdiction adjoining the State. Under these agreements, the inspectors also accompany seismic crews operating in the Federal portion of the continental shelf.

Seismograph exploration of the continental shelf is expensive. The cost of maintaining a seismic crew operating on the continental shelf is from $60,000 to $100,000 a month as compared to $15,000 to $25,000 for a crew operating on land. Because there is usually no necessity to drill shot holes, however, a crew can map considerably faster on the continental shelf, thus reducing the cost per unit area to below comparable land costs.

As in all other continental-shelf operations, weather is a major factor. The crews are not allowed to leave port during periods of storms or rough weather, but seismic boats must be large enough to withstand relatively high seas safely in case of unexpected storms.

LEASING PROCEDURES

From the passage of the Submerged Lands Act and the Outer Continental Shelf Lands Act in 1953 until the present (1956) few problems have been encountered by the oil industry in obtaining leases on the continental shelf of the Gulf of Mexico. Leases have been issued competitively, on the basis of the highest cash bonus bid offered, by the agency having jurisdiction over the lands pursuant to the above-cited acts. Sealed bids, rather than auction, are the usual rule. Generally, industry nominates certain tracts as suggested areas to be offered for leasing. Following such nominations the agency selects all or part of these nominations, and after suitable advertising, accepts and opens the sealed bids at a specified time and place, and awards the leases to the successful bidder.

In the Gulf of Mexico, a substantial part of the shelf has been plotted on a coordinate system based on the Lambert projection. For leasing purposes, maps have been prepared showing the individual tracts with coordinates and descriptions thereof.

The provisions of leases follow a general pattern, regardless of the leasing jurisdiction, and are usually for a primary term of 5 years "and so long thereafter as oil and gas (or other minerals) can be produced." The leases usually provide for an annual rental payment prior to discovery and production of the leased minerals and a royalty (generally ⅛ or ⅙ of the value of the gross production in the case of oil and gas) after production. Other provisions of the leases vary considerably, depending on the agency having jurisdiction over the shelf.

DEVELOPMENT PROBLEMS

Once an operator has decided, after conducting preliminary prospecting surveys and obtaining a lease, to test drill an apparently favorable geologic structure, he is confronted with a new series of problems. First among these is choosing and obtaining suitable equipment on which to base the drilling rig.

In general, two basic types of foundations for drilling rigs are used on the continental shelf. The first, which is seldom used, is a rock- or earth-filled artificial island sufficiently large to support all necessary equipment. One such island is being successfully used in relatively shallow water off the coast of California. The construction of such an island in water of considerable depth involves excessive costs and under current economic conditions is not considered economically feasible, although it is theoretically possible. To date, no artificial island has been used in the Gulf of Mexico.

In more general use are platforms supported on pilings sunk deep into the ocean bottom and extending a sufficient distance above the ocean surface to escape wave action. These platforms are of four general types: self-contained platforms; small drilling platforms with mobile drilling tenders; drilling barges; and mobile platforms.

The self-contained platform (pl. 3) is large enough to support all drilling equipment and supplies, crew quarters, mess and kitchen facilities, and even recreation facilities for off-duty crew members.

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Self-contained platforms have a serious disadvantage in that they are difficult to salvage and almost impossible to move intact from one location to another. They are also expensive to construct, costing from a minimum of about $750,000 to more than $1.5 million. However, they have the advantage of providing a permanent base from which several wells can be drilled and, if production is obtained, can easily be modified to support necessary production facilities such as separators and storage tanks.

In order to avoid the high cost of the self-contained platform, the oil industry has developed a smaller platform, serviced by a tender vessel moored alongside (pl. 4). Only a minimum of equipment, such as the derrick and drawworks, is located on the platform itself. Motive power (usually diesel), liquid and dry storage, drill pipe, casing, crew quarters, and mess, kitchen, and recreation facilities are located on the tender. Originally surplus LSTs (landing ship—tank) were purchased from the United States Government after World War II and converted to use as tenders. More recently, as the supply of LSTs became exhausted, the industry began building special vessels for tenders.

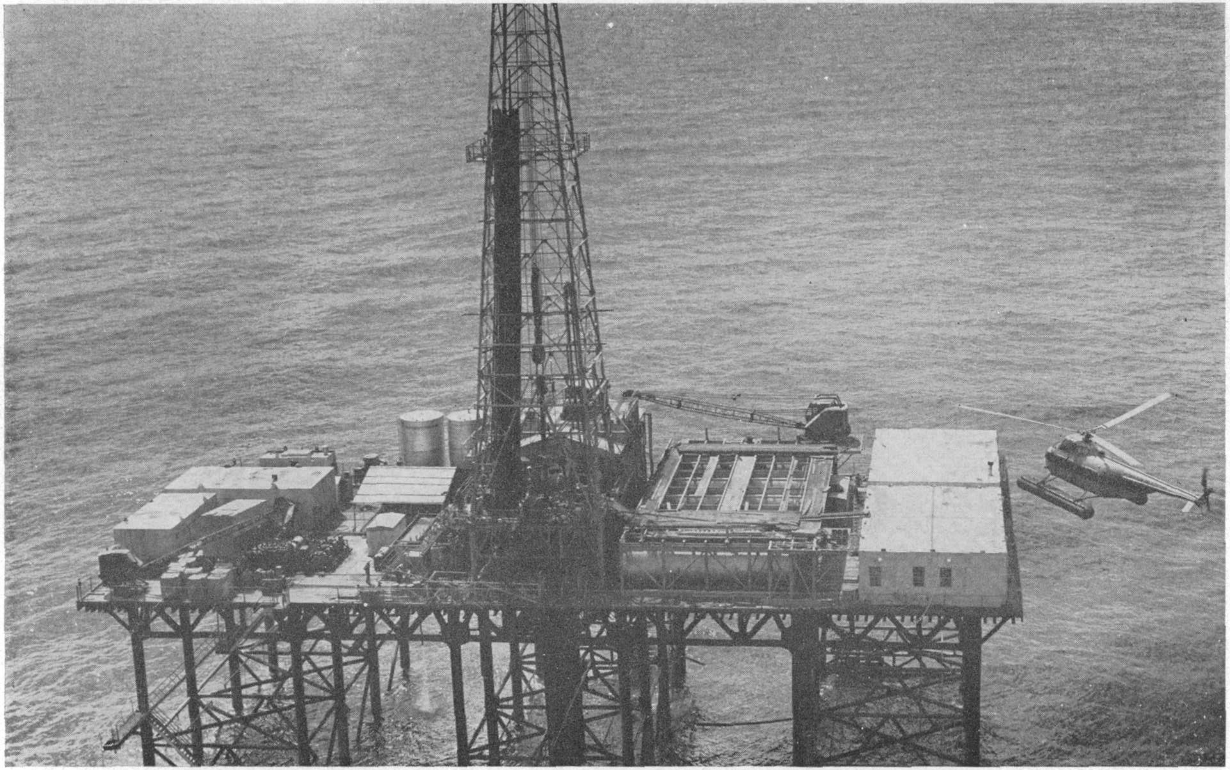
In order for a tender to serve as a base for drilling operations, it must not only be sufficiently large for storage and quarters, but also must be sufficiently seaworthy to withstand considerable rough weather. As a result, the average tender is as much as 300 feet (121 m) or more in length. As an economic and space-saving measure many tenders contain no motive power, and depend upon tugs to move them from one location to another.

The platform-and-tender combination has several advantages over the self-contained platform but also has several disadvantages. The chief advantages are low cost and high versatility—the fixed-platform cost is considerably reduced and the tender can be moved easily from one drilling site to another. Also, in the event of serious storms, the tender can be moved to a protected location, thus lessening the risk of serious damage to valuable equipment.

The chief disadvantage of the platform-and-tender combination is that the tender moves with the waves. This is a particularly bad feature when operating at substantial distances from shore because the ground swell of the ocean often makes it impossible to transfer men and materials to and from the tender, resulting in costly rig shutdown.

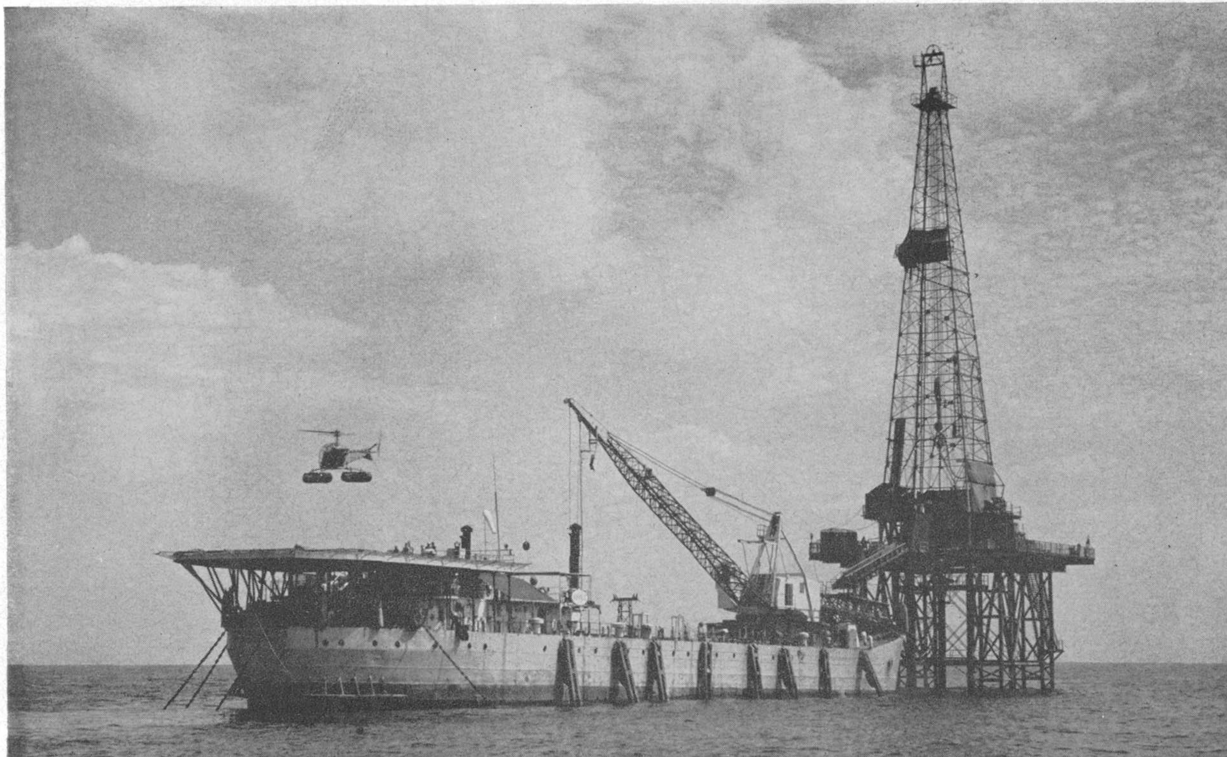
The initial cost of a tender is high, from $1.5 to $2.5 million, but the cost is partly offset by using the tender in the drilling of a number of wells.

It seems likely that the platform-and-tender combination will remain a favorite of the oil industry for operations in water less than



SELF-CONTAINED DRILLING PLATFORM

This platform is located in 95 feet of water 20 miles from land in the Gulf of Mexico. The deck is 50 feet above sea level, and pilings were driven 190 feet below the floor of the gulf. As many as 10 wells can be drilled by moving the derrick approximately 6 feet for each new well. (Photograph by courtesy of the Continental Oil Co.)



SMALL DRILLING PLATFORM AND MOBILE DRILLING TENDER

This platform is located in the Gulf of Mexico. (Photograph by courtesy of the Humble Oil Co.)

100 feet (30 m) deep. It should be of particular advantage in drilling exploratory wells by avoiding excessive cost until oil or gas accumulation is definitely proved.

Although the design of both types of platforms varies somewhat, the general construction is similar. A template, which is a framework of hollow, vertical, tubular caissons cross braced both horizontally and vertically and of sufficient length to reach from the ocean bottom to above the water level, is constructed on shore. The template (more than one may be used, depending on the size of the platform) is moved to the drilling location by barge and lowered until it rests on the ocean bottom. Piling is then driven through the upright caissons and fastened at the top of the template. The piling is cut off and leveled at a predetermined height above the water, and a prefabricated deck is lowered and fastened into place atop the piling. The platform is completed by installing necessary equipment on the deck.

The third and fourth types of platforms are the drilling barge and the mobile platform. The concept of a drilling barge is not new, as such equipment has been used for a number of years in inland waterways and swamp and marsh land of the gulf coast. All necessary equipment is mounted on a barge and then, by flooding the hull with water, the barge is sunk until it rests firmly on the bottom. After drilling operations are completed, the water is pumped from the hull and the barge is floated to another drilling site.

Barges were successfully used in drilling in 10 to 20 feet (3 to 6 m) of water in marshes and swamps prior to World War II. However, the adaption of barges for use in water 50 feet (15 m) or more in depth is fraught with difficulties. The latest development consists of a barge that can be flooded, but it is mounted with caissons rather than drilling equipment. A deck is erected on the caissons well above the hull level, and the drilling equipment is mounted on this deck.

Another variation of the drilling barge consists of mounting air or hydraulic jacks on the caissons and deck, thus making it possible to raise or lower the deck after the barge is in position. Several such mobile platform-barges are now in use in the Gulf of Mexico in water as much as 100 feet (30 m) deep.

The primary advantages of the mobile platform-barge are stability and mobility. The barge hull, resting on the ocean floor, provides an extremely stable base for drilling operations, and upon completion of the well the entire unit can be floated and moved rapidly to a new location.

The chief disadvantage of this type of unit is the extremely high cost of both construction and maintenance. Initial construction costs of the completed units have been as much as $4 million, and operating costs range from $8,000 to $10,000 per day, compared to operating costs of about $3,500 per day for self-contained platforms and about $5,000 per day for the platform-and-tender combinations.

In spite of the high cost, it is expected that the mobile platform-barge unit will find great use in future operations, particularly in drilling exploratory wells.

The fourth type of platform, the mobile platform, has only limited use. It consists of a watertight, seaworthy hull through which several steel caissons are fitted. All drilling equipment is mounted on the deck of the hull. The platform is floated into position, and the caissons are lowered and are forced into the ocean bottom by air jacks. When sufficient resistance is reached, the hull literally climbs up the caissons, raising itself well above the water. Upon completion of the well, the air jacks are reversed, the hull is lowered to the water, and the caissons are lifted out of the bottom. The unit is then moved to the next location. In actual operation the hull can be lowered, the caissons raised, the unit moved, the caissons lowered, the hull raised, and drilling commenced in 24 hours or less. The unit has a limited weight-bearing capacity, however, and can be used only for relatively shallow wells. It was used successfully to drill a series of shallow core-test wells (averaging about 2,500 feet (762 m) in depth) to evaluate a sulfur deposit in the continental shelf off the coast of Louisiana.

Regardless of the type of platform used on the continental shelf, several design factors must be considered before the platform can be built. These can be considered in three groups: oceanographic considerations, drilling depth, and windload.

The oceanographic factors considered in the design of offshore structures include storm tides, maximum wave height, length and period of maximum waves, horizontal water velocities, and wave forms. Usually it is necessary to call on the services of a trained oceanographer who can predict within reasonable limits, these factors.

Related to the oceanographic factors, but requiring somewhat different consideration, are those concerning bottom conditions. Such conditions vary greatly. Along the western part of the coast of Louisiana, for example, the bottom sediments are relatively firm and will support considerable weight without the necessity of driving piling to excessive depths. On the other hand, in the East Bay area near the Mississippi River delta, it was necessary to drive piling about 200 feet (61 m) before any kind of solid bottom was reached, and 375 feet (114 m) to gain sufficient bearing strength to support a particular drilling platform. The piles for this platform, located in 72 feet (22 m) of water, were 465 feet (142 m) in length.

In planning and designing offshore structures it is often necessary to drive test piles at the proposed location to determine bottom characteristics, bearing strength, and similar factors.

Factors relating to the load imposed on the offshore structure by the drilling operations are relatively easy to calculate, but a basic decision must be made concerning whether to design only for the projected depth of the well or to design for the maximum capabilities of the drilling rig and derrick. The smaller the total design load, the less expensive the overall cost of the structure. In general, platforms intended for exploratory drilling are designed to support drilling operations at or near the maximum drilling capability of the rig, whereas platforms to be used in drilling development wells are usually designed for the projected well depths.

Windload factors are comparatively simple considerations. Usually offshore structures are designed to withstand hurricane-force winds of about 125 miles an hour. Such meterologic factors as storm expectancy, direction, frequency, and violence also must be considered in the design of offshore structures.

Space considerations are of the utmost importance. It is obvious that the cost of offshore structures increases with size. The cost increases are not directly proportional to size increases, and at some point there is an optimum ratio of size to cost. It is necessary, therefore, to design the structure to conform, as nearly as possible, to the optimum size and still incorporate all necessary features.

One of the early self-contained platforms used in the Gulf of Mexico is located about 7 miles (11 km) off Grand Isle. It is a double-deck platform, with the decks located 34 feet (10 m) and 45 feet (14 m) above mean water level and measuring 206×110 feet (63×34 m). The structure, which provides living quarters for 54 men, is designed to withstand 120 mile per hour (193 km per hr) winds and 34-foot (10-m) waves. It is of template construction, employing 25 templates through which are driven 100 steel pilings. The platform weighs about 10 million pounds and costs about $1.2 million.

Corrosion, while primarily an operating problem, nevertheless influences the design of offshore structures to some extent. In all offshore operations a constant battle must be waged against the corrosive effect of salt water, and continual scraping and painting are the rule. To lessen the corrosive effect of the sea on the steel drilling structure, anticorrosion devices, such as cathode protection, monel-metal sheathing on piling (usually at the contact between the water and the air), concrete or cement sheathing, and special paints developed to protect against corrosion are often incorporated in the design.

OPERATION AND PRODUCTION PROBLEMS

Once the drilling platform or other structure is erected, the actual drilling operations vary little from drilling operations on land. Rotary drilling equipment, drill pipe, casing, and other tools are identical with those used for wells of comparable depth on land. However, oil and gas operations in the continental shelf create new and unique problems, some of which are discussed in the following section.

The extremely high cost of platform construction has led to the perfection of directional (controlled deviation from vertical) drilling techniques in the shelf. While directional drilling has been used for many years in land operations, it was used very sparingly and usually for specialized purposes. One example is in the Oklahoma City field, where wells were directionally drilled in order to end almost directly beneath the State Capitol Building. In the Gulf of Mexico, however, directional drilling has become routine, and single platforms often support 4, 6, or even 10 wells.

Such widespread use of directional-drilling techniques has led to the development of much specialized equipment. Most noteworthy is the derrick having an unusually broad base and a unique guide-sheave arrangement in the crown-block area. This permits the crown block and the rotary table to be moved slightly to 6 or more prefixed locations; thus 6 or more wells can be drilled without moving the derrick. This has been so successful that several more are on order, and other modifications of the design are currently being developed.

Another technique widely used is dual completions—completing a single well in two separate formations and producing from both simultaneously. Dual completions are not new but are used much more extensively in continental-shelf operations than in land operations.

One of the major concerns to operators in the continental shelf is the ever-present danger of oil-or gas-well blowouts. A few disastrous blowouts of gas wells have occurred in the Gulf of Mexico, with almost total loss of the platforms. That no blowout of an oil well has occurred is due largely to the extreme caution of the operators and to the rigid specifications for the equipment used. Gas-well blowouts, although causing heavy financial loss, do not pollute or contaminate the water or damage aquatic life as would an oil-well blowout. The oil industry is well aware of the hazards of blowouts, as are the Federal and State supervisory agencies, and as as a result, automatic storm chokes and other specialized equipment are installed on all wells.

The protection of aquatic life and respect for the rights of fishermen also pose serious operational problems for the oil industry. Protection of aquatic life is especially serious in conducting seismic surveys. Every reasonable effort is made to avoid any damage to aquatic life around offshore structures during drilling and producing operations. Waste materials are thoroughly treated before being dumped in the sea in order to prevent any pollution or contamination. That these measures are effective is shown by the increase in the number of fish near offshore structures. Probably the fish are attracted by the lights and by garbage and other materials dropped from the platforms.

Every effort is made to avoid disturbing the ocean bottom or leaving discarded material which could cause damage to fishing nets. Upon removal of a drilling structure all piling or other protruding material is cut below the level of the mud to avoid leaving anything which might snag fishing nets or trawls.

All offshore structures are required to be equipped with adequate lights and other devices to warn vessels of their existence, and drilling platforms can not be erected in shipping fairways. Beyond the 3-mile (5.56-km) limit the character of the high seas is preserved as directed by the Congress of the United States in the Outer Continental Shelf Lands Act.

The safety and welfare of the workmen is of utmost concern to the operators. Standby boats are in constant attendance during drilling operations to remove any seriously injured personnel. Radio or radiotelephone communication is maintained at all times with the shore base, and life preservers and life jackets are standard equipment on all platforms.

TRANSPORTATION

Transportation has created relatively few serious problems. Personnel are usually transported by boat or helicopter. Crews are rotated about once a week and regular trips can be planned and scheduled. As boats are slow many companies use helicopters for personnel transportation. Landing space is now incorporated on many offshore structures, and helicopters are able to transport full drilling or operating crews in a fraction of the time required by boats. Weather conditions, however, often limit the use of helicopters.

Personnel transportation is expensive, regardless of the means used. Crew boats must be sufficiently large and have sufficient power to operate safely during severe weather. As a result, most of the boats are 65 to 85 feet (20 to 26 m) long and are expensive to purchase and maintain. Helicopters require a much greater initial investment and involve greater operational and maintenance costs. Therefore, many oil companies lease boats or helicopters from service companies. Contract service is usually on a monthly basis at a fixed fee, regardless of the actual service time of the vessel.

Equipment transportation, particularly of heavy massive equipment, is by seagoing barge and tugboat. Heavy-duty cranes mounted on barges are used to transfer equipment from towed barges to the platform and, during construction of platforms, to lower templates and to lift prefabricated deck sections. Weather limits the movement of equipment barges, and weather forecasting plays an important part in scheduling their movement.

A substantial fleet of vessels is necessary to supply a well being drilled in the continental shelf. A minimum requirement would probably be three crew boats, one stationed at the platform, one at the shore base, and the third in a standby capacity; one or more equipment barges with tugs or a self-propelled vessel capable of transporting heavy supplies; and possibly one or more helicopters, either in routine service or on standby for emergency.

The transportation of oil and gas to markets on shore involves many economic and engineering problems. As on shore, pipelines are the most economical and efficient method of moving large quantities of oil and gas. In fact, natural gas cannot yet be transported in substantial quantities by any other method. However, the construction of a pipeline from an individual field cannot be justified economically unless that field has sufficient reserves to amortize the cost of the line within a reasonable period of time and sufficient productive capacity to supply the line with enough oil or gas to maintain efficient operations. In many fields in the Gulf of Mexico these two requirements have not yet been fulfilled. Much of the drilling to date has been exploratory, and as a result many fields are only partly developed. Even though the results of this exploratory drilling have indicated that the proved reserves of the fields are substantial, the daily productive capacity of the fields has remained low.

A pipeline project in the continental shelf is tremendously expensive. On the basis of the few lines constructed to date, it is estimated that underwater pipelines in the Gulf of Mexico cost from $80,000 to $100,000 per mile.

In the Eugene Island and the Grand Isle areas off the coast of Louisiana, underwater pipelines are in operation. The construction of these pipelines was an engineering task of major proportions. After the route of the line was selected, necessary permission obtained from government agencies, and men and materials assembled at the shore base, the pipe was prepared for its underwater service. This preparation included strengthening the pipe by welding additional steel plate around it, coating the pipe with suitable anticorrosion asphaltic compounds, wrapping it with fiberglass or other material, and finally coating the entire pipe with a 1 to 3 inch layer of concrete. The prepared pipe was then placed on a barge and, as sections were welded and the welded joints coated and wrapped, gently lowered to the ocean bottom. Hydraulic jets were used to cut ditches in the sea bottom. Ocean currents and wave action supplied the backfill necessary to cover the pipe. Elaborate testing procedures were used at each step of the process to insure a strong leakproof line.

Consideration is being given by the oil industry to the construction of a major oil pipeline roughly parallel to the coast of Louisiana to service several fields in the Gulf of Mexico, but construction is not expected for some time.

Oil is transported by barge in most of the fields. Wells usually produce into storage barges moored nearby or into tanks on the platforms, which contain all the usual production facilities including tanks, separators, and heat-treaters. Transport barges load at these facilities when assured of a full load.

Barge transportation of oil is unsatisfactory because of excessive cost and undependability. Whereas pipelines can transport a barrel of oil to shore at costs ranging from 5 to 10 cents, barging costs have been as high as $1.00 a barrel and average from 15 to 25 cents (Petroleum Week, 1955 a-c). Furthermore, adverse weather often makes it impossible to undertake barge movement, necessitating a shutdown in production. A shutdown not only is costly to the operator but can, under some conditions, cause severe damage to the well.

It seems certain that as development progresses in the continental shelf, more pipelines will be constructed and barge transportation of liquid hydrocarbons will be only a temporary measure.

ECONOMICS OF CONTINENTAL-SHELF OIL DEVELOPMENT

The heart of all problems faced by the operator of offshore oil operations is the high cost. Every operation, from supplying drinking water for the drilling crew to constructing storage tanks, costs from 2 to 10 times the amount expended for equivalent services on dry land.

Oil and gas operations on the shelf have created a substantial industry in the adjacent coastal areas. While it is difficult to obtain exact figures, it is estimated that the oil industry has invested more than $1 billion in the shelf operations of the Gulf of Mexico since 1946. Much of this has been for capital expenditures including lease acquisition, marine equipment, drilling rigs, and platforms. Other expenditures include the cost of seismic and other surveys, establishment of shore bases, weather forecasting facilities, and radio and navigation-aid stations, and drilling and production costs.

In return the oil industry has received less than $250 million for oil and gas produced. However, tremendous new reserves have been discovered, and production reached approximately 80,000 barrels of oil daily by January 1, 1956. Shelf oil and gas operations should in the future return a profit on this tremenodous investment.

There are wide variations in the conditions under which oil and gas wells are drilled in the continental shelf. It has been said that there is no such thing as an "average" well in the Gulf of Mexico. However, the cost and effort that might go into the drilling of a hypothetical well located on the shelf can be examined briefly. The hypothetical well will be located about 9 miles (14 km) from the nearest land in 40 to 50 feet (12 to 15 m) of water and about 50 miles (80 km) from the nearest deep-water harbor. Twelve thousand feet (3658 m) may be assumed as the projected depth of the well, and a combination platform and tender will be used throughout the operation.

About 200 men will be engaged in drilling the well during its various stages. This will include about 36 members of the seismic-exploration crew; 24 men engaged in the construction of the platform and drilling rig; 30 members of the drilling crew; 10 men supplying special services such as well cementing and electrical and mud logging; 64 marine workers including crew members on the construction vessel, the drilling tender, and the crew boats; and 36 supervisory administrative, and unclassified personnel.

The platform will require a minimum of 200 tons of steel beams, 100 tons of steel plates and bracing, more than 350 tons of steel piling, and 30,000 board-feet of heavy lumber for decking. After the drilling platform is constructed, 7 vessels will be required, including a 3,500-ton drilling tender, 3 crew boats, 2 special-service combination lifeboats and workboats, and 1 water cargo barge.

The well will require 80,000 barrels of fresh water, 4,000 sacks of oil-well cement, 10,000 sacks of drilling mud and mud chemicals, and about 250 tons of steel casing and tubing. Three 1,000-kilowatt generators, driven by diesel engines, will supply motive power for the mud pumps, draw works, and rotary table. The diesel engines will consume about 120,000 gallons of fuel during the drilling operations. Large quantities of food will be consumed during the 4 months or more of drilling operations. Miscellaneous supplies, such as handtools, paint, cable, rope, bolts, and nuts, must be added to the supply list. Operational costs will average about $5,000 per day throughout the drilling of the well.

A shore base will be required, at which will be located a dock, warehouse, office, communication facilities, and quarters for base personnel.

The above figures, while hypothetical, present some idea of the magnitude of effort required to drill and complete a well on the continental shelf of the Gulf of Mexico.

Most operators believe that offshore costs can be reduced to provide more incentive for the exploration and development of the continental shelf. New platform designs, new operating techniques, added experience, and favorable economic conditions will tend to reduce operational expenses and provide added incentive. However, reserves and production rates must be maintained at high levels to insure sufficient operating capital. In the opinion of most operators stripper wells have litle or no place on the continental shelf.

MAGNITUDE OF THE OFFSHORE PETROLEUM INDUSTRY IN THE UNITED STATES

Although the previous section gave some indication of the magnitude of the offshore petroleum industry in the United States in terms of the approximate total investment in continental-shelf facilities, dollar amounts are difficult to translate into actual wells drilled, reserves proved, or production obtained.

Table 1 shows the growth of drilling activity in the continental shelf of the Gulf of Mexico, by years, since 1948. The figures have been compiled from various sources and may not conform exactly to other published data, though the magnitude of the figures shown is believed to be accurate. One difficulty in compiling such data is determining just which wells are located on the continental shelf rather than in inland waters such as bays and estuaries.

TABLE 1.—*Wells completed on the continental shelf of the Gulf of Mexico*

Year	Total	Oil wells	Gas wells	Dry wells
1948	20	7	6	7
1949	73	29	11	33
1950	68	36	9	23
1951	8	4	4	0
1952	67	47	4	16
1953	79	59	5	15
1954	234	150	25	59
1955	360	220	38	102
1956	548	324	60	164
Total	1, 457	876	162	419

The table shows very vividly the continued expansion of the continental-shelf oil industry since its beginning. The low drilling rates during the years 1951 and 1952 are explained by the injunctions issued by the Supreme Court of the United States in the cases *United States* v. *Louisiana* and *United States* v. *Texas*. Following these injunctions, the Secretary of the Interior permitted no exploratory wells to be drilled but did permit the drilling of wells necessary to protect proven reservoirs from waste or unequal withdrawals. This was done in the interest of conservation.

Production from the continental shelf of the Gulf of Mexico has grown steadily. Table 2 shows the approximate annual and cumulative production of liquid hydrocarbons. These data are subject to the same criticisms as table 1, but are also believed accurate so far as magnitude is concerned.

TABLE 2.—*Estimated production of liquid hydrocarbons from the continental shelf of the Gulf of Mexico*

Year	Production (barrels)	
	Annual	Cumulative
1947 [1]	3, 500	20, 000
1948	133, 000	153, 000
1949	1, 100, 000	1, 253, 000
1950	4, 360, 000	5, 613, 000
1951	6, 560, 000	12, 173, 000
1952	6, 900, 000	19, 073, 000
1953	10, 040, 000	29, 113, 000
1954	15, 850, 000	44, 963, 000
1955	25, 900, 000	70, 893, 000
1956	40, 100, 000	110, 993, 000

[1] There was some production from the continental shelf prior to 1947.

On January 1, 1956, about 70 wells were being drilled in the continental shelf of the Gulf of Mexico. An even greater increase can be expected as new drilling platforms, more tenders, and more barges are completed and placed in operation.

The proved reserves of the continental shelf of the Gulf of Mexico have been estimated (Cram, 1956) to be approximately 1.5 billion barrels of liquid hydrocarbons.

THE FUTURE OF CONTINENTAL-SHELF MINERAL OPERATIONS

It seems safe to assume that exploration, drilling, and production of hydrocarbons in the continental shelf will go forward at an ever-increasing rate and in ever-increasing water depths. Development of methods and equipment to withstand the greater forces generated by the deeper ocean waters will be necessary for each new depth of shelf area explored. The ultimate water depth in which oil and gas operations can be successfully conducted is problematical. A few years ago, 100 feet (30 m) was viewed as the limiting depth. Now successful drilling operations have been conducted in water depths of 100 feet, (30 m) and equipment in the design or construction stage can support drilling operations in even greater water depths, perhaps as much as 200 feet (60 m). Thus, so far as the continental shelf is concerned, with water depths of approximately 600 feet (183 m), exploration, drilling, and production appear to be limited only by the imagination and ingenuity of the oil operators and the equipment designers.

Many predictions, including those of the National Petroleum Council, agree that the average daily production from the shelf areas of the Gulf of Mexico will reach 250,000 barrels within the next 5 years. This increase in production will be accompanied by new methods and lower cost.

Already in the experimental stage is electronic remote-control equipment which will allow an operator, located at a shore base, to control production, to start any well flowing, to switch the well flow from one tank to another, and to gage tanks merely by pushing a button on a control panel. The system works by very high frequency radio, and experiments indicate that its effective range may extend to 100 miles (161 km). Such a system would eliminate the necessity of maintaining production crews on offshore platforms and would minimize shutdowns due to adverse weather conditions.

Ships from which all drilling operations can be conducted, without the necessity of erecting a platform, also represent a future possibility. One such vessel, capable of drilling very shallow holes for stratigraphic studies, is currently being tested off the coast of California. Future development of this type of equipment might make it possible to drill exploration and development wells to depths in excess of 10,000 feet (3,048 m) without having to erect a platform, thus eliminating one of the major cost factors of continental-shelf development.

It can reasonably be expected that as production increases more and more pipelines will be constructed to handle the oil and gas produced. Future pipelines will undoubtedly incorporate automatic control equipment which can regulate all operations of the line from control points at land bases.

The storage of liquid hydrocarbons in cavities dissolved in shallow salt domes represents another possibility. Such storage space has been used successfully on land, and if deemed feasible in the continental shelf, might allow ocean-going tankers to load at the site, thus reducing transportation and handling costs and speeding the shipment of products to market.

Better and more accurate methods of electronic surveying will probably be developed, as will more accurate navigation aids. Seismic-exploration methods capable of locating favorable geologic structures more rapidly and more accurately are also a possibility.

These are but some of the promises technology holds for the future. But technology cannot replace the vision, judgment, and courage of the men who explore for and develop the mineral resources underlying the oceans.

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INDEX

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